SolQDebug: Debug Solidity Quickly for Interactive Immediacy in Smart Contract Development

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Abstract

As Solidity becomes the dominant language for blockchain smart contracts, efficient debugging grows increasingly critical. However, current Solidity debugging remains inefficient: developers must compile, deploy, set up transactions, and step through execution line-by-line to examine each variable. This process is too slow for practical use. To address this challenge, this paper presented SolQDebug, the first edit-time debugging assistant for Solidity that focuses on a single contract/transaction context, providing abstract value summaries with millisecond feedback directly on source code. Developers specify symbolic interval inputs through annotations and compare them against abstract interpretation results, thereby enabling exploration of contract behavior across multiple execution paths. SolQDebug was evaluated on 30 real-world functions from DAppSCAN, achieving millisecond-scale feedback during code editing. The evaluation provided debugging insights: overlapping annotation patterns improved precision in most Solidity debugging scenarios, while analysis of diverse loop patterns demonstrated improved convergence while preserving soundness guarantees. These results demonstrated that SolQDebug enabled interactive debugging for Solidity development.

Keywords: Smart Contract Development, Solidity, Debugging, Abstract Interpretation, Incremental Analysis

1 Introduction

Blockchain technology has evolved from a simple cryptocurrency platform into a comprehensive ecosystem for decentralized applications. At the center of this evolution, Ethereum ranks second in market capitalization at over $460 billion (CoinMarketCap, 2025). This ecosystem is powered by smart contracts written primarily in Solidity (Solidity, 2025), the dominant language for contract development. As these contracts grow more complex and handle increasing value, ensuring their correctness becomes critical. This is especially critical because once deployed to the blockchain, contracts are immutable and cannot be easily fixed. Recently, many developers rely on large language models (LLMs) such as ChatGPT (ChatGPT, 2025) or Llama (Llama, 2025) for code generation assistance. However, these tools cannot provide formal correctness guarantees. Therefore, developers must still rigorously understand program behavior at the statement level during editing.

Unfortunately, the debugging workflow for Solidity lacks the maturity of traditional programming environments. Even a single inspection requires full compilation, deployment, manual state initialization, and manual bytecode-level tracing. Moreover, once a transaction modifies contract state, reverting to previous conditions requires costly redeployment or manual reconstruction, making iterative debugging impractical. Tools like Remix IDE (Remix IDE, 2025), Hardhat (Hardhat, 2025), and Foundry Forge (Foundry Forge, 2025) suffer from these fundamental limitations. A prior study found that 88.8% of Solidity developers described debugging as painful. Moreover, 69% attributed this pain to the absence of interactive source-level tooling (Zou et al., 2019). To the best of our knowledge, no existing research or tooling provides interactive feedback during Solidity code editing, a gap that this paper aims to fill.

This paper presented SolQDebug, an edit-time debugging assistant for Solidity that focused on a single contract/transaction context, powered by abstract interpretation (AI) with interval domain. Unlike conventional step-through debuggers that require compilation and deployment, SolQDebug provided abstract value summaries as developers type, enabling exploration of function behavior at the statement level. To achieve this goal, SolQDebug built on two core ideas. First, it provided incremental analysis through interactive parsing and incremental CFG construction via line-to-node indexing. As developers type each statement, the system efficiently determines insertion sites and extends the CFG, recomputing abstract states only for affected program points. Second, it enabled annotation-guided exploration. Developers specified symbolic interval inputs directly in source code, and the interpreter used these ranges to analyze multiple execution paths in a single pass.

To validate these design choices, SolQDebug was evaluated on 30 real-world functions from DAppSCAN (Zheng et al., 2024). The evaluation demonstrated millisecond-scale responsiveness and examined how annotation structure affected precision across common smart contract patterns. The results also showed how annotation-guided analysis addressed the precision challenges typically encountered in loops.

This paper makes the following contributions, focusing on function-level, single-contract analysis during code editing:

```
contract Example {
    address public owner;
    uint256 public totalSupply = 1000;
    mapping(address => uint256) private balances;

    modifier onlyOwner() {
        require(msg.sender == owner, "not␣owner");
        _;
    }
    function burn(uint256 amount) public onlyOwner {
        uint256 bal = balances[msg.sender];
        uint256 delta;
        if (bal >= amount) {
            balances[msg.sender] = bal - amount;
            delta = amount;
        }
        else {
            delta = 0;
        }
        totalSupply -= delta;
    }
}
```

Fig. 1: Minimal example used to illustrate grammar elements relevant to our analysis

- This work identified the main barriers to interactive Solidity debugging: (1) temporal inefficiency from compilation, deployment, and state initialization, and (2) iterative inefficiency from EVM constraints that prevent repeated execution with different states.
- An interactive parser with seven specialized entry rules and line-to-node indexing was designed that enables incremental CFG construction with efficient statement insertion during live editing.
- An annotation-guided abstract interpreter with adaptive widening was introduced that mitigates precision challenges in loop analysis while maintaining termination guarantees.
- SolQDebug was evaluated on 30 real-world functions from DAppSCAN, achieving millisecond-scale feedback latency (median 0.15s). The evaluation demonstrated that overlapping annotation patterns improve precision in common smart contract patterns and provided guidance on annotation design.

2 Background

2.1 Structure of Solidity Smart Contract

Figure 1 illustrates the key structural elements of a Solidity smart contract. At the top level, Solidity programs may declare contracts, interfaces, and libraries. A contract is composed of variables and functions. The following first describes the variable categories.

Variables are categorized by their scope and lifetime. Global variables such as `msg.sender` (appearing at line 7) and `block.timestamp` represent read-only EVM metadata provided implicitly by the runtime. State variables such as `owner`, `totalSupply`, and `balances` (lines 2–4) persist across transactions and provide the contract's permanent storage. Local variables such as `bal` and `delta` (lines 12–13) are scoped to a single function call and do not persist beyond execution.

Functions such as `burn` (lines 11–22) use control flow constructs including `if/else`, `while/for/do-while`, `break/continue`, and `return`. Functions can be augmented with modifiers. The `onlyOwner` modifier (lines 6–9) performs a precondition check before the function body executes. The placeholder underscore at line 8 marks where the original function body is inserted when the modifier is inlined. These structural elements define Solidity contracts.

2.2 Solidity Execution and Debugging Workflow

Unlike traditional programs, Solidity contracts operate within a blockchain environment that imposes strict execution constraints. The execution model is strictly state-based, where state variables persist across transactions and modifications become permanent once confirmed. To debug Solidity code, developers must follow a multi-stage workflow as described in Steps 1–4.

Step 1: Compile. Figure 2 shows the compilation step in Remix IDE, where the contract source code is compiled into EVM bytecode.

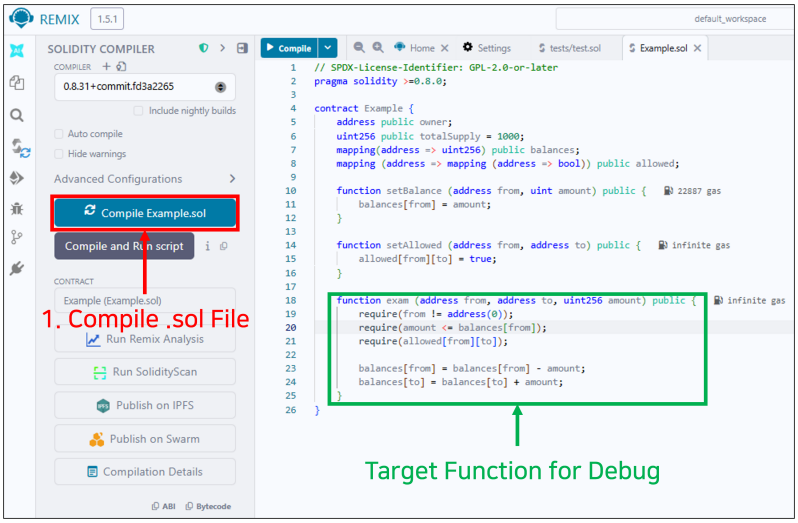

Fig. 2: Traditional Solidity debugging workflow: Compile step

Step 2: Deploy. Figure 3 illustrates selecting the target contract and deploying it. Deployment is a one-time transaction that stores compiled bytecode on-chain and invokes the constructor. Once deployed, the bytecode becomes immutable.

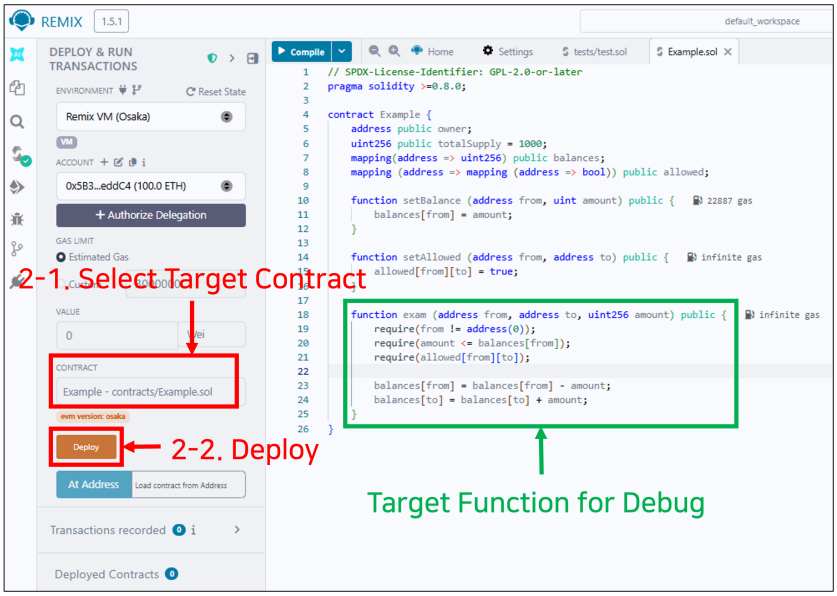

Fig. 3: Traditional Solidity debugging workflow: Deploy contract

Step 3: Initialize State and Execute. Figure 4 shows entering parameters and executing the target function for debugging. Before invoking the target function, developers must first execute setup functions to initialize the contract state and satisfy conditions enforced by `require` statements. Once the state is prepared, the target function is executed by clicking the transact button.

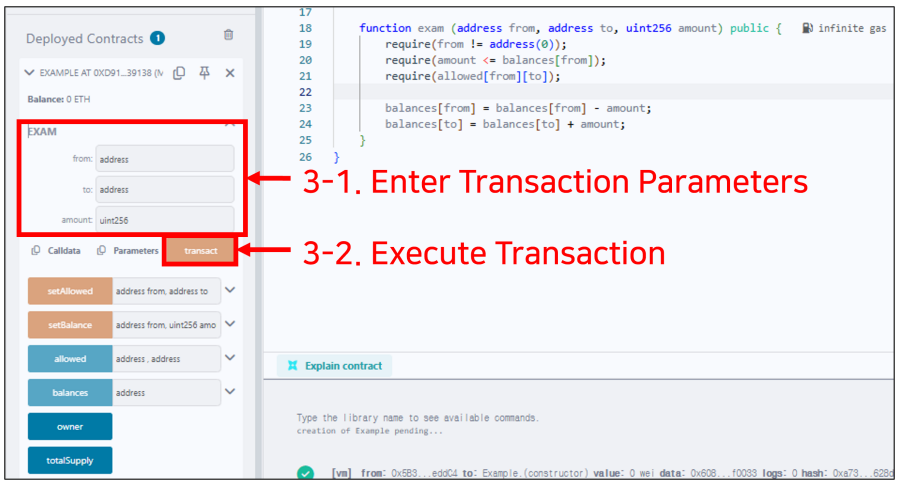

Fig. 4: Traditional Solidity debugging workflow: Initialize state and execute target function

Step 4: Debug. Figure 5 shows clicking the debug button and stepping through bytecode instructions. Once the target function is executed, its execution is traced step by step at the bytecode level.

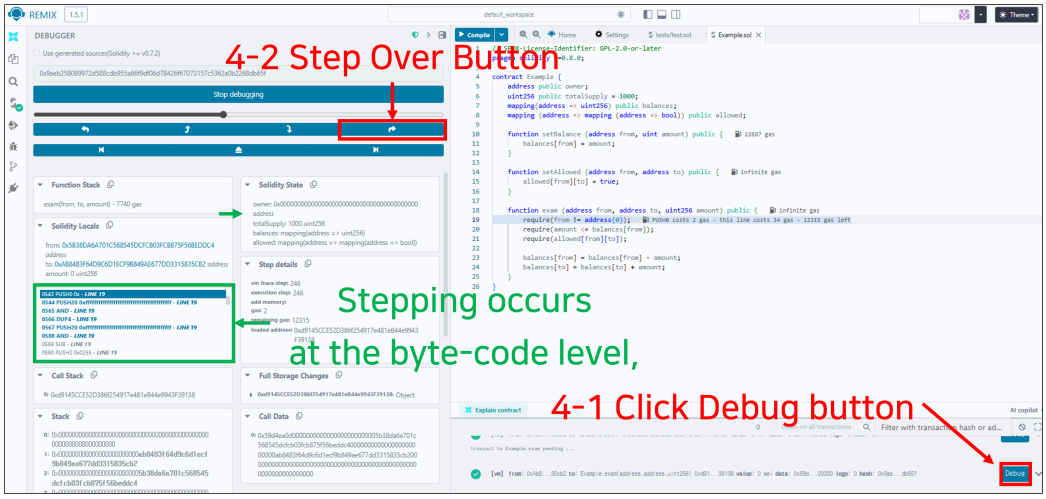

Fig. 5: Traditional Solidity debugging workflow: Bytecode-level debugging

This state-based execution model introduces a critical constraint: changes to contract state cannot be undone automatically and require costly external actions such as redeployment or manual state reconstruction. This workflow interacts with

these execution model constraints, introducing significant challenges in the debugging process.

2.3 Two Sources of Inefficiency in Solidity Debugging

The workflow described above reveals temporal and iterative inefficiencies. These issues stem from two orthogonal obstacles that make debugging Solidity programs significantly slower than traditional application development.

(1) Environmental disconnect between editor and execution engine causes temporal inefficiency. Unlike conventional IDEs such as PyCharm (JetBrains, 2025) or Visual Studio (Microsoft, 2025), where the source editor and execution engine run in the same process, Solidity development involves external coordination with a blockchain node at every stage. The multi-stage workflow described in the previous subsection introduces several seconds to minutes of latency per iteration, preventing the immediate feedback that developers expect when writing and testing code.

Given this workflow overhead, developers often rely on `emit` logs or event outputs to observe intermediate values. However, such instrumentation provides only runtime snapshots and lacks the structural insight needed to understand symbolic variation or control-flow behavior. Moreover, modifying the expression of interest typically requires recompilation and redeployment, compounding latency and disrupting iteration. The final stage, tracing raw EVM opcodes, is particularly costly because developers are forced to mentally reconstruct source-level semantics. This not only adds execution overhead but also imposes significant cognitive burden during fault localization and fix validation.

(2) Architectural limitations of EVM cause iterative inefficiency. The EVM's state-based execution model makes state modifications irreversible. This constraint fundamentally conflicts with iterative debugging, which requires repeatedly re-executing the same function under different conditions.

Additionally, if a function includes conditional guards that depend on the current state such as account balances or counters, then any debugging session must first ensure that those conditions are satisfied. For example, consider a function that enforces a check on `_balances[account]`. Developers must manually assign a sufficient balance before they can observe the downstream effects on `_totalSupply`. Without such setup, the function exits early, preventing inspection of the intended execution path.

In short, these constraints make repeated debugging iterations costly and fragile. According to a developer study (Zou et al., 2019), 88.8% of Solidity practitioners reported frustration with current debugging workflows, with 69% attributing this to the lack of interactive, state-aware tooling. The next subsection outlines our proposed approach to address these two root causes.

2.4 Proposed Approach Overview

SolQDebug addresses the two root causes of Solidity's debugging inefficiency through an integrated design. Rather than independent optimizations, the two components jointly constitute the interactive debugging paradigm: incremental analysis

provides line-by-line responsiveness during editing, while annotations enable input specification—a prerequisite for any debugging activity that observes how inputs affect program behavior.

(1) Incremental analysis to address temporal inefficiency. The traditional debugging workflow requires compilation, deployment, transaction-based state setup, and bytecode tracing. Each of these stages incurs significant latency. SolQDebug replaces this round trip by performing both parsing and abstract interpretation directly inside the Solidity Editor. To support live editing, the Solidity grammar was extended with interactive parsing rules tailored for isolated statements, expressions, and control-flow blocks. When the developer types or edits code, only the affected region is reparsed incrementally.

Each parsed statement is inserted into an incremental CFG, and abstract interpretation resumes from the edit point. Abstract interpretation with interval domain was used because it provides three key properties for edit-time debugging: guaranteed termination through widening, explainable results as variable ranges, and millisecond-scale responsiveness. This enables immediate feedback on code structure and control flow without compilation or chain interaction.

(2) Annotation-guided interpretation to address iterative inefficiency. The EVM does not support reverting to a prior state without redeploying the contract or replaying transactions. Both approaches disrupt iteration. SolQDebug introduces batch annotations as a mechanism for symbolic state injection. In essence, this reflects a core debugging activity, which involves varying inputs or contract state to observe control-flow outcomes. Rather than reconstructing such conditions through live transactions, developers can write annotations at the top of the function to define symbolic interval inputs. These inputs are injected before analysis begins and rolled back afterward, ensuring test-case isolation.

This approach brings the debugging workflow closer to the source by making state manipulation explicit and reproducible within the code itself. Developers can explore alternative execution paths by editing annotations alone without modifying the contract logic or incurring compilation and deployment overhead. It effectively decouples symbolic interval input configuration from the analysis cycle while preserving the intuitive debugging process developers already follow.

3 The design of SolQDebug

SolQDebug is designed to analyze single-contract, single-transaction Solidity functions through incremental statement-by-statement processing. As developers write code, the system maintains an evolving abstract interpretation of the program, enabling immediate feedback on variable values and potential errors without requiring compilation or deployment. The following subsections detail the architecture (§3.1), provide a running example (§3.2), and explain the core mechanisms for parsing (§3.3) and incremental analysis (§3.4).

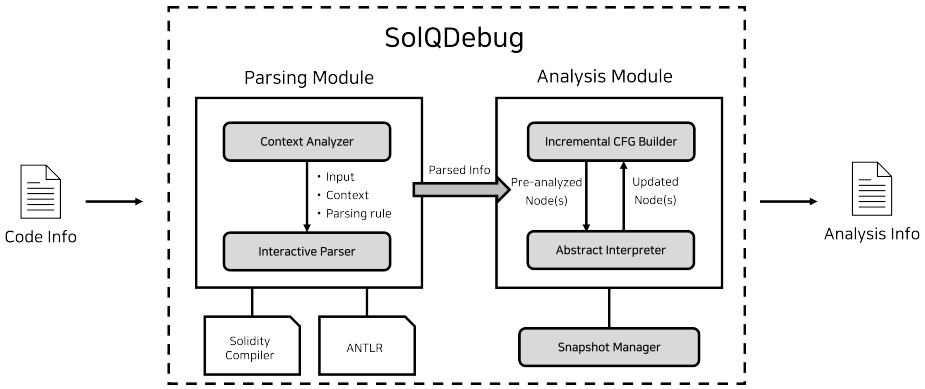

Fig. 6: SolQDebug architecture

3.1 System Architecture

Figure 6 illustrates the overall architecture of SolQDebug. The system accepts either single Solidity statements or batch debug annotations as input, processing them through two main modules before producing line-level output:

(1) Parsing Module. Each input passes through the `Context Analyzer`. For source code fragments, it identifies existing code structures when needed (e.g., an `if` statement for an `else` branch). For debug annotations, it identifies the target function and extracts its context. The `Interactive Parser`, built on ANTLR (ANTLR, 2025), applies an extended grammar with seven specialized entry rules that enable parsing of partial constructs. To ensure correctness, the system performs syntactic recovery to reconstruct complete source from partial fragments and validates it using the official Solidity compiler before proceeding to analysis, ensuring semantic consistency and rejecting malformed input early.

(2) Analysis Module. The Analysis Module operates through three coordinated components. The `Incremental CFG Builder` maintains a control-flow graph that supports structural updates as statements are added, creating nodes and rewiring edges to reflect the evolving structure. The `Abstract Interpreter` analyzes the updated CFG incrementally, reusing previous results and recomputing abstract values only for affected program points. The `Snapshot Manager` preserves and restores abstract memory states, ensuring that debug annotations can be modified and re-executed without side effects from previous runs.

Output. Following analysis, SolQDebug produces a line-level summary showing computed intervals for variables affected by each statement, including declarations, assignments, and return values. All outputs are mapped to their corresponding source line numbers and displayed inline within the editor, providing immediate feedback as developers write and modify code.

Table 1: Incremental inputs for the running example

Step	Lines of Input Fragment	Fragment
1	11--12	`function burn(uint256 amount) public onlyOwner {` `}`
2	12	`uint256 bal = balances[msg.sender];`
3	13	`uint256 delta;`
4	14--15	`if (bal >= amount) {` `}`
5	15	`balances[msg.sender] = bal - amount;`
6	16	`delta = amount;`
7	18--19	`else {` `}`
8	19	`delta = 0;`
9	21	`totalSupply -= delta; // new input`

3.2 Running Example

To illustrate how the proposed architecture functions in practice, we presented a concrete example using the `burn` function from Figure 1. As the developer incrementally constructs this function, the system (1) parses each input fragment, (2) updates the control-flow graph, and (3) performs abstract interpretation to compute variable intervals. Additionally, when batch debug annotations are present, the system re-analyzes the function using the annotated symbolic interval inputs as starting points. This example demonstrates these two key analysis modes: incremental source code analysis (§3.2.1) and batch annotation analysis (§3.2.2).

3.2.1 Incremental Source Code Analysis

Table 1 shows how the developer incrementally constructs the `burn` function through nine distinct input steps, each introducing a new code fragment.

SolQDebug accepts two kinds of code fragments as input:

- **Block fragment:** Includes contract and function definitions and control-flow constructs (if/else blocks, while loops). When the developer types an opening {, most editors auto-insert the closing }, so the complete block arrives at once (e.g., Steps 1, 4, and 7 in Table 1).
- **Statement fragment:** Includes declarations, assignments, and expressions that end with semicolons. Each statement arrives individually as the developer completes typing, triggering immediate parsing and analysis (e.g., Steps 2, 3, 5, 6, 8, and 9 in Table 1).

As the developer types each fragment, SolQDebug incrementally extends the CFG and recomputes abstract values only for affected program points. Figure 7 visualizes the CFG structure after Steps 1–8 have been integrated. To illustrate incremental analysis, we focus on Step 9 (`totalSupply -= delta;`). By this point, Steps 1–8 have been analyzed, and their results are already in the CFG. When Step 9 arrives, it processes the statement as follows:

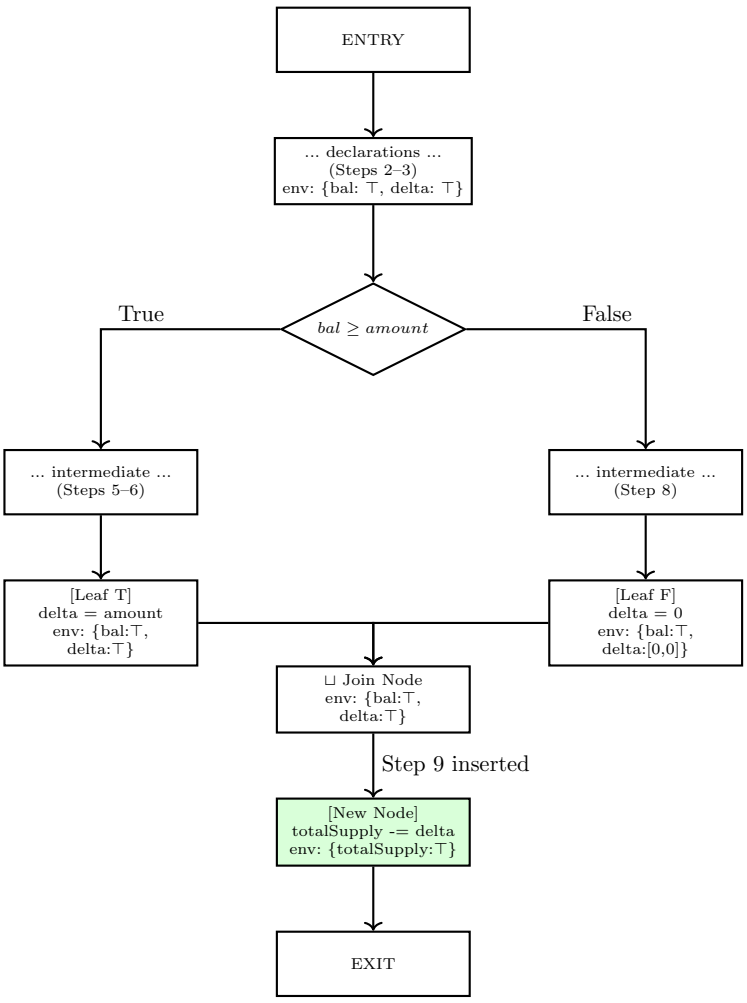

Fig. 7: CFG structure showing Step 9 insertion. Each statement occupies a separate basic node; intermediate nodes along each branch are omitted, showing only the leaf nodes before the join point. The join point node computes the least upper bound of environments from both branches

1. The `Interactive Parser` recognizes `totalSupply -= delta;` as an assignment.
2. The `Incremental CFG Builder` determines the insertion point by examining the edit context and existing CFG. In this case, the insertion point is after the join node that merges the if/else branches.
3. A new node is created for the assignment, and edges are rewired: the join node now flows into this new node, which in turn connects to the exit.
4. The new node receives the environment from the join node, which holds the least upper bound ($\sqcup$) of environments from both branches.

```
1  uint256 public totalSupply = 1000;
2
3  function burn(uint256 amount) public onlyOwner {
4      // @Debugging BEGIN
5      // @StateVar balances[msg.sender] = [100,200]
6      // @LocalVar amount = [50,70]
7      // @Debugging END
8      uint256 bal = balances[msg.sender];
9      uint256 delta;
10     if (bal >= amount) {
11         balances[msg.sender] = bal - amount;
12         delta = amount;
13     }
14     else {
15         delta = 0;
16     }
17     totalSupply -= delta;
18 }
```

Fig. 8: Burn function with batch annotations

5. The `Abstract Interpreter` performs worklist-based reinterpretation, propagating the updated environment from the newly inserted node to all affected nodes in the CFG.

This reinterpretation ensures soundness by propagating each edit's effects to all affected nodes. Subsequent inputs can then safely reuse the computed abstract values without re-analyzing the entire program.

3.2.2 Batch Annotation Analysis

While incremental analysis supports the edit-test cycle, developers often need to explore how their program behaves under different testing scenarios. Batch annotations enable this by letting developers specify test inputs declaratively and obtain line-level results in a single run.

Figure 8 shows the `burn` function with batch annotations. Annotation blocks are enclosed by `// @Debugging BEGIN` and `// @Debugging END`. Each annotation line specifies a variable type (`@StateVar` for state variables, `@LocalVar` for local variables) and assigns a symbolic interval input, supporting both simple variables and nested accesses like `balances[msg.sender]`.

In this example, we annotate `balances[msg.sender]` with the interval $[100, 200]$ and `amount` with $[50, 70]$ to explore how the `burn` function behaves under different balance and amount scenarios. The analysis propagates these intervals through the conditional branches, computing `delta` as $[0, 150]$ at the join point and reducing `totalSupply` from $[1000, 1000]$ to $[850, 1000]$.

When SolQDebug processes a batch annotation block, it follows this pipeline:

Table 2: Interactive parser entry rules

Type	Entry Rule	Purpose
Primary	interactiveSourceUnit	Top-level declarations: functions, contracts, interfaces, libraries, state variables, pragmas, imports
	interactiveBlockUnit	Statements and control-flow skeletons inside function bodies
Continuation	interactiveEnumUnit	Enum member items added after the enum shell is defined
	interactiveStructUnit	Struct member declarations added after the struct shell is defined
	interactiveDoWhileUnit	The while tail of a do-while loop
	interactiveIfElseUnit	else or else-if branches following an if statement
	interactiveCatchClauseUnit	catch clauses following a try statement

1. **Parse and validate.** Each annotation line is parsed, type-checked, and converted to the corresponding abstract domain (e.g., intervals for integers).
2. **Save state and overlay.** The unannotated abstract memory is saved, and the annotated values replace it for the analysis run.
3. **Single-pass analysis.** SolQDebug re-analyzes the pre-built CFG with the annotated environment.
4. **Restore previous state.** After analysis, the unannotated abstract memory is restored.

Details of these mechanisms appear in §3.3–§3.4.

3.3 Interactive Parser

The `Interactive Parser` extends the official Solidity language grammar (Solidity Language Grammar, 2025) with specialized entry rules that accept partial code fragments during incremental editing. The parser defines eight specialized entry rules: seven for incremental code edits and one for batch annotations.

Table 2 shows the seven rules for Solidity constructs, divided into two categories that differ in how they interact with existing code:

- **Primary rules** parse constructs that stand alone, requiring no context from previous edits.
- **Continuation rules** require context from existing structures. They explicitly depend on previously parsed constructs (e.g., `interactiveIfElseUnit` requires a preceding `if` statement to attach the `else` branch).

This distinction maintains syntactic validity during incremental edits. SolQDebug validates that continuation rules have their required antecedent structure, ensuring that the resulting program structure remains well-formed at each step.

For concreteness, we refer to the burn function in Table 1. When the developer types the function definition (Step 1), it is parsed by `interactiveSourceUnit`, which creates a function with an empty body. Subsequent inputs within the function body are parsed by `interactiveBlockUnit`, which handles both statement fragments (Steps 2, 3, 5, 6, 8) and block fragments (Step 4). Step 7 illustrates how continuation rules work: the `else` block is parsed by `interactiveIfElseUnit`, which depends on the preceding `if` from Step 4 (see Appendix A).

Beyond these seven interactive rules for Solidity constructs, the parser includes a specialized `debugUnit` rule for batch annotations. The grammar defines three annotation types:

- **GlobalVar** assigns values to global variables such as msg.sender or block.timestamp
- **StateVar** assigns values to contract state variables, supporting nested access patterns like balances[msg.sender] or user.balance
- **LocalVar** assigns values to function parameters

The complete grammar specification appears in Appendix A, with the full ANTLR4 implementation available at (SolQDebug Language Grammar Rule, 2025).

3.4 Incremental CFG Construction and Abstract Interpretation

Incremental CFG construction maintains a control-flow graph that evolves as developers insert new statements. Rather than rebuilding from scratch, our approach modifies the graph in place. The following first describes the hierarchical organization of CFGs at the contract and function levels (§3.4.1), then explains how individual statements are incrementally spliced into the function-level CFG (§3.4.2), how the insertion site is determined (§3.4.3), and how reinterpretation propagates abstract values only through affected regions (§3.4.4).

Our CFG consists of the following node types:

- `entry node`: The unique entry point where execution begins. Contract-level CFGs have a contract entry, and function-level CFGs have a function entry.
- `state variable node`: A contract-level node that holds all state variable declarations. Since state variables have no branching logic, they are collected into a single node.
- `basic node`: Holds exactly one statement (e.g., a variable declaration, an assignment, or a function call).
- `condition node`: Represents branching constructs such as `if`, `else if`, `while`, `require`/`assert`, and `try`.
- `join node`: Merges control flow from multiple branches (e.g., `if join`, `else-if join`).
- `fixpoint evaluation node` (ϕ): The loop join point used for widening and narrowing during fixpoint computation (§3.4.3).
- `loop exit node`: The false branch that exits a loop when the loop condition fails.

- `return exit node`: A sink node that aggregates return values from all return statements. When a return statement is inserted, its containing node's outgoing edge is rewired to this node.
- `error exit node`: The function's unique exceptional exit (targets the exceptional path via `revert`, `require`, or `assert` failures).
- `exit node`: The unique normal exit point where execution terminates successfully. Contract-level CFGs have a contract exit, and function-level CFGs have a function exit.

3.4.1 CFG Hierarchy

SolQDebug organizes control flow at two levels. At the contract level, a `ContractCFG` sequences state variable initializations, the constructor, and function definitions. This ordering reflects how Solidity deploys contracts. State variables are initialized first, then the constructor executes and may modify those state variables. Function definitions receive the environment that results from constructor execution.

At the function level, each `FunctionCFG` represents control flow starting from a function's entry point. When a function declares modifiers, the function body is spliced into the modifier's control flow at the placeholder (_) position. When a function invokes another function, the callee's `FunctionCFG` is incorporated as part of the caller's control flow graph. The complete CFG hierarchy structures are shown in Appendix B.

3.4.2 Statement-Local, Incremental Construction

Having described the hierarchical organization of CFGs, we now focus on how individual statements are incrementally spliced into the function-level CFG. Each insertion operates at the `current node`, the insertion point for new statements. The following statement types create their corresponding CFG structures:

- **Simple statements** are spliced between the current node and its successors, creating a single `basic node`. This includes variable declarations, assignments, function calls, and expression statements. The environment flows sequentially through the new node, updated by the statement's semantics (Figure 13).
- **If statement** creates a `condition node`, true/false `basic nodes`, and an `if join`. The environment propagates from the current node to the condition, then branches to the true/false arms with the environment refined by the branch condition, and merges at the join node via the least upper bound operation (Figure 14).
- **Else-if clause** replaces the preceding false branch with a new `condition node` and its own join, which then connects to the outer `if join`. The environment flows through the else-if condition, branches to its true/false arms with refinement, merges at the else-if join, and continues to the outer join (Figure 15).
- **Else clause** replaces the false branch node of the preceding `if`/`else if` with a new else node, which connects to the `if join`. The environment is refined by the negated condition and merges at the join (Figure 16).

Table 3: Line-to-node index mapping by statement type

Simple Statements			Compound Statements		
Statement	**Maps Start Line To**	**Maps End Line To**	**Statement**	**Maps Start Line To**	**Maps End Line To**
`simple statement`	basic node	(none)	`if`	condition node	join node
			`else if`	condition node	join node
`break`	basic node	(none)	`else`	else node	join node
`continue`	basic node	(none)	`while`	condition node	exit node
`return`	return node	(none)			
`require`	condition node	(none)			

- **While loop** creates a `fixpoint evaluation node` ϕ, a `condition node`, a loop body node, and a `loop exit node`. The body connects back to ϕ for fixpoint iteration. The environment propagates through ϕ to the condition, then branches to the body or exit with the environment refined by the loop condition, with the body flowing back to ϕ until convergence (Figure 17).
- **Break statement** is inserted in the loop body with its outgoing edge redirected to the `loop exit node` (Figure 18).
- **Continue statement** is inserted in the loop body with its outgoing edge redirected to the loop's ϕ node (Figure 19).
- **Return statement** is inserted with its edge rewired to the function's unique `return exit node`, detaching original successors. The environment flows directly to the return exit node (Figure 20).
- **Require statement** creates a `condition node` with the true edge connecting to a continuation node and the false edge pointing to the `error exit node`. The environment propagates with refinement based on the predicate to the continuation or error exit node (Figure 21).

These construction patterns enable SolQDebug to build the CFG incrementally as the user types each statement, with environment updates propagating only through affected nodes. Representative CFG construction patterns are provided in Appendix B. The complete implementation supports all Solidity statements (SolQDebug Implementation, 2025).

3.4.3 Line-to-Node Indexing for Incremental Insertion

The key challenge in incremental CFG construction is determining where to insert each new node. Traditional CFG construction processes complete programs sequentially, building the entire graph in a single pass. In contrast, SolQDebug must handle partial code edits that specify only target line numbers. Since CFG edges encode control flow rather than source positions, we cannot determine where an edit belongs

Algorithm 1 Dependent-Context Insertion

Input: CFG G, line-to-node index M, current line L
Output: Condition node c
function GetBranchContext(G, M, L)
    $queue \leftarrow$ `FindJoinNode`(M, L) ▷ find join node at or before line L
    if $queue = \emptyset$ **then**
        error "No join node found at or before line L"
    end if
    $visited \leftarrow \emptyset$
    while $queue \neq \emptyset$ **do** ▷ BFS through predecessors
        $n \leftarrow$ `Dequeue`$(queue)$
        if $n \in visited$ **then continue**
        end if
        $visited \leftarrow visited \cup \{n\}$
        if `IsCond`(G, n) **and** `CondType`$(n) \in \{$`if`, `else_if`$\}$ **then**
            return n
        end if
        for $p \in$ `Pred`(G, n) **do**
            if $p \notin visited$ **then**
                `Enqueue`$(queue, p)$
            end if
        end for
    end while
    error "No matching condition node found"
end function

without additional context. To enable incremental insertion, we maintain a line-to-node index during construction. Table 3 summarizes how statement types map lines to nodes.

`Simple statements` index only their start line. Most statements map to a basic node, though return maps to a return node and require maps to a condition node. Compound statements index both start and end lines. Conditionals (`if` and `else if`) map their start line to a condition node and end line to a join node, while `else` maps its start line to an else node and end line to the join node. Loops (`while`) map their start line to a condition node and end line to an exit node.

This indexing scheme enables Algorithms 1 and 2 to locate insertion sites efficiently. These algorithms handle the representative statement types shown in Table 3. Both algorithms rely solely on the line-to-node index without mutating the graph.

The choice between these algorithms depends on whether the statement can exist independently:

- **Dependent contexts:** `else`/`else if` must attach to a preceding `if`/`else if` condition. Algorithm 1 traverses CFG predecessors to find the condition node.

Algorithm 2 Independent-Context Insertion

```
1: Input: CFG G, line-to-node index M, insertion position at line L
2: Output: Insertion-site node A
3: function GetInsertionSite(G, M, L)
4:     s ← FindPostNode(M, L)                          ▷ find first node after line L
5:     if IsLoopExit(G, s) or IsJoin(G, s) then        ▷ closing a loop or selection
6:         n ← FindPreviousNode(M, L)                  ▷ condition if exists, else last node
7:         if IsCond(G, n) then
8:             return BranchBlock(n, true)             ▷ insert in TRUE branch
9:         else
10:            return n
11:        end if
12:    else                                            ▷ basic successor
13:        pred ← Pred(G, s)
14:        if |pred| = 1 then
15:            return the unique element of pred
16:        else
17:            error "Basic successor must have exactly 1 predecessor"
18:        end if
19:    end if
20: end function
```

- **Independent contexts:** All other statements can exist independently. Algorithm 2 uses a successor-first strategy, leveraging the fact that successors are already inserted and have complete CFG structure.

Algorithm 1: Dependent-Context Insertion. Dependent contexts (`else`/`else if`) cannot exist independently and must attach to a preceding `if`/`else if` condition node. The algorithm proceeds as follows:

- **Initialization (Lines 4–8):** Uses the line-to-node index M to retrieve the join node at or before line L, initializing the Breadth-First Search (BFS) queue. This node serves as the starting point for backward traversal to find the preceding conditional. If no node is found, the dependent context is invalid (Lines 5–7). The visited set is initialized to track explored nodes (Line 8).
- **BFS traversal (Lines 9–22):** Performs BFS through CFG predecessors to find the matching condition node of type `if` or `else_if`. The BFS ensures we find the *nearest* enclosing condition.
- **Error handling (Line 23):** Reports an error if no matching condition is found.

Algorithm 2: Independent-Context Insertion. For independent contexts, which include all statements except `else`/`else if`, we use a successor-first strategy. By identifying the post node—the next statement by line number—we determine the correct insertion point based on its CFG structure. This approach handles all statement types uniformly:

- **Find post node (Line 4):** `FindPostNode`(M, L) retrieves the first node after line L from the line-to-node index.
- **Loop-exit/join case (Lines 5–11):** If the post node s is a loop-exit or join node, we search backward using `FindPreviousNode`(M, L) to find the previous node. This returns a condition node if present (loop condition node or `if`), otherwise the last node before L.
  - If it is a condition node, we return its TRUE branch to place the new statement inside the construct (Line 8).
  - Otherwise, we return the node itself (Line 10).
- **Basic post node (Lines 12–19):** Otherwise, s is a basic statement node (Line 12). The CFG predecessors are retrieved and verified to be exactly one (Lines 13–15), which must hold by construction since conditionals are created with their join nodes and loops are created with their exit nodes. Any other count indicates a malformed CFG (Lines 16–18).

3.4.4 Abstract Interpretation for Incremental Analysis

SolQDebug provides instant feedback on source code edits by propagating updates only along affected CFG paths, avoiding full re-analysis. When the user inserts statements, new nodes are spliced into the CFG. Incremental reinterpretation then propagates updates from these insertion points as seed nodes. While for debug annotations, SolQDebug performs full interpretation from the function entry node, ensuring all inspection points receive complete abstract states. Algorithm 3 performs incremental interpretation by propagating abstract states through a worklist-based dataflow analysis. When encountering loop condition nodes, it delegates to Algorithm 4 for loop fixpoint computation.

Algorithm 3: Incremental Interpretation.

- **Worklist and output cache initialization (Line 4):** Initialize empty worklist wl, in-queue set inq to track enqueued nodes, and output map out to store previous node outputs for change detection.
- **Seed node initialization (Lines 5–9):** Enqueue all seed nodes $s \in S$, which mark insertion points for incremental edits or function entry for batch annotations. Sink nodes (exit, error, return) with no successors are filtered out.
- **Worklist iteration (Lines 10–31):** The while loop processes nodes until the worklist is empty. Each iteration performs the following steps for the dequeued node n:
- **Incoming environment computation (Lines 11–12):** For each predecessor p, `RefineByCondition` examines the edge from p to n. If p is a condition node, it prunes the predecessor's output environment based on the branch direction (true or false), removing infeasible paths. For non-condition predecessors, no pruning is applied. At join nodes with two predecessors, the resulting states are merged via $\sqcup$. Single-predecessor nodes receive the (possibly pruned) state directly as $\hat{\sigma}_{\text{in}}$. For `require` and `assert`, which create condition nodes, the true branch receives the pruned environment while the false branch leads to the error exit node. For `revert`, control transfers directly to the error exit node without creating

Algorithm 3 Incremental Interpretation

```
1:  Input: CFG G, seed set S
2:  Output: Environments updated along forward-reachable paths from S
3:  function IncrementalInterpretation(G, S)
4:      wl ← ⟨⟩;    inq ← ∅;    out ← output map
5:      for all s ∈ S do
6:          if ¬IsSink(G, s) ∧ s ∉ inq then
7:              wl.enqueue(s);    inq ← inq ∪ {s}
8:          end if
9:      end for
10:     while wl ≠ ⟨⟩ do
11:         n ← wl.dequeue();    inq ← inq \ {n}
12:         σ̂_in ← ⨆_{p∈Pred(G,n)} RefineByCondition(p, n)
13:         if IsLoopHeader(G, n) then
14:             exit ← Fixpoint(G, n)          ▷ compute loop fixpoint (Algorithm 4)
15:             for all s ∈ Succ(G, exit) do
16:                 if ¬IsSink(G, s) ∧ s ∉ inq then
17:                     wl.enqueue(s);    inq ← inq ∪ {s}
18:                 end if
19:             end for
20:             continue
21:         end if
22:         σ̂_out ← Transfer(n, σ̂_in)
23:         if σ̂_out ≠ out[n] then
24:             Env(n) ← σ̂_out;    out[n] ← σ̂_out
25:             for all s ∈ Succ(G, n) do
26:                 if ¬IsSink(G, s) ∧ s ∉ inq then
27:                     wl.enqueue(s);    inq ← inq ∪ {s}
28:                 end if
29:             end for
30:         end if
31:     end while
32: end function
```

a condition node. Since the error exit node is a sink node, the `IsSink` check filters it out and propagation terminates along exceptional paths.

- **Loop condition node delegation (Lines 13–21):** When encountering a loop condition node, delegate to Algorithm 4 to compute the loop fixpoint. After fixpoint converges, enqueue the loop-exit node's successors to continue analysis beyond the loop.
- **Transfer function (Line 22):** Apply the abstract transfer function to node n, computing output environment $\hat{\sigma}_{\text{out}}$ by interpreting statements (assignments, calls, etc.) using interval arithmetic and domain operations.
- **Change detection and propagation (Lines 23–30):** Compare $\hat{\sigma}_{\text{out}}$ with the previously stored output $out[n]$. Only if changed, update node environment and

Algorithm 4 Loop Fixpoint with Adaptive Widening

Input: CFG G, loop condition node h
Output: Loop exit node with converged environment
function LoopFixpoint(G, h)
    $L \leftarrow \texttt{LoopNodes}(G, h)$; $start \leftarrow \bigsqcup\{Env(p) \mid p \in \texttt{Pred}(G, h) \setminus L\}$
    $\tau \leftarrow \texttt{EstimateIterations}(h, start)$ ▷ annotation-aware threshold
    $vis[\cdot] \leftarrow 0$; $in[h] \leftarrow start$
    // **Widening phase**
    $wl \leftarrow \langle h \rangle$
    while $wl \neq \langle\rangle$ **do**
        $n \leftarrow wl.\texttt{dequeue}()$; $vis[n] \leftarrow vis[n] + 1$
        if $in[n] = \bot$ **then** ▷ compute input if not initialized
            $in[n] \leftarrow \bigsqcup_{p \in \texttt{Pred}(G,n) \cap L} \texttt{RefineByCondition}(p, n)$
        end if
        $\hat{o}_{\text{raw}} \leftarrow \texttt{Transfer}(n, in[n])$
        if $\texttt{IsFixpointEvalNode}(n) \ \wedge \ vis[n] > \tau$ **then**
            $\hat{o} \leftarrow \texttt{Widen}(out[n], \hat{o}_{\text{raw}})$ ▷ widen at fixpoint eval node after τ visits
        else
            $\hat{o} \leftarrow out[n] \sqcup \hat{o}_{\text{raw}}$
        end if
        if $\hat{o} = out[n]$ **then**
            $out[n] \leftarrow \hat{o}$; **continue** ▷ fixpoint reached, skip propagation
        end if
        $out[n] \leftarrow \hat{o}$
        for all $s \in \texttt{Succ}(G, n) \cap L$ **do**
            $wl.\texttt{enqueue}(s)$
        end for
    end while
    $\texttt{NarrowingPhase}(L)$ ▷ standard descending iteration
    $exit \leftarrow \texttt{FindLoopExit}(G, h)$
    $Env(exit) \leftarrow \bigsqcup_{p \in \texttt{Pred}(G,exit)} \texttt{RefineByCondition}(p, exit)$ ▷ join with false-branch pruning
    return $exit$
end function

the stored output, then enqueue successors. This ensures fixpoint termination by stopping propagation when environments stabilize.

Algorithm 4: Loop Fixpoint with Adaptive Widening. While Algorithm 3 handles general incremental propagation, loop analysis with the interval domain faces a well-known precision challenge. To guarantee termination, widening operators must be applied after a bounded number of iterations, often causing intervals to expand to $\top$ or $[0, \infty]$ even when the actual loop bounds are finite. However, Solidity's properties create opportunities for mitigation. Gas costs limit loop complexity, and loop

conditions commonly depend on simple values such as array lengths, mapping sizes, or bounded counters.

Algorithm 4 computes loop fixpoints using annotation-aware adaptive widening to address this challenge. The key innovation is that `EstimateIterations` analyzes loop conditions to compute an adaptive threshold τ that defers widening. When debug annotations provide precise interval bounds for condition operands such as array lengths or parameter values, the analyzer raises τ to delay widening and preserve precision. The fixpoint iteration terminates when all variables converge, meaning node outputs equal their previously stored values, ensuring soundness.

- **Identify loop nodes and pre-loop environment (Line 4):** Collect all nodes within the loop body. Compute *start* by joining environments from all loop-entry predecessors, specifically those from outside the loop rather than from within the loop body itself.
- `EstimateIterations` **(Line 5):** Evaluate both operands of the loop condition in the pre-loop environment *start*. For comparison operators ($<, \leq, >, \geq$), compute adaptive threshold τ as follows:
  - When both operands evaluate to concrete constant intervals, τ is computed as the difference between operand bounds. For example, given `i < array.length` where `i = [0,0]` and `array.length = [10,10]`, $\tau = 10 - 0 = 10$. The operands may be variables or complex expressions, but both must reduce to constant intervals through annotation-provided values.
  - When either operand cannot be reduced to a constant interval, τ defaults to 1, allowing one iteration to initialize node environments before widening is applied.
- **Initialization (Line 6):** Initialize visit counts *vis* to track iterations and node input environments *in*, setting $in[h] \leftarrow start$ for the loop condition node.
- **Widening phase (Lines 9–27):** Perform fixpoint iteration with worklist-based propagation. Each iteration performs the following steps:
  - Dequeue node and increment visit count (Line 10); compute incoming environment if not initialized (Lines 11–13).
  - Apply transfer function to compute raw output (Line 14).
  - Apply adaptive widening (Lines 15–19): use widening operator if visit count exceeds τ (Line 16), otherwise use join (Line 18).
  - Check for convergence (Lines 20–22): if output unchanged, skip propagation (Line 21); otherwise, store output (Line 23) and enqueue successors (Lines 24–26).
- **Narrowing phase and exit node (Lines 28–31):** Apply standard narrowing using descending iteration with narrowing operator at fixpoint evaluation nodes to refine over-approximations from widening (Line 28). Then compute the exit node environment (Lines 29–30) by joining predecessor outputs where the loop condition node's false-branch is refined by the negated loop condition. Return the exit node with its computed environment (Line 31).

Abstract Interpretation Framework. Our approach builds upon abstract interpretation frameworks for Solidity smart contracts (Halder et al., 2023; Halder, 2024). SolQDebug computes sound over-approximations of variable ranges using interval domains for integer and boolean types ($\widehat{\mathbb{Z}}_N, \widehat{\mathbb{U}}_N$), set abstractions for addresses, and on-demand materialization for composite types such as arrays, mappings, and structs. Unlike prior work focusing on invariant generation (Halder, 2024) or information flow analysis (Halder et al., 2023), we target interactive debugging with incremental refinement. The complete formal semantics (Tables 5 and 6) are in Appendix C.

4 Evaluation

To evaluate the benefits of SolQDebug in real-world development scenarios, we structure our empirical analysis around three key questions:

- **RQ1 – Responsiveness**: How much does SolQDebug reduce debugging latency compared to Remix?
- **RQ2 – Impact of Annotation Patterns on Precision**: How should developers structure annotations to improve precision in arithmetic operations involving multiplication and division?
- **RQ3 – Loops**: How does SolQDebug's analysis approach affect precision in loop structures?

To answer these questions, we conducted experiments under controlled conditions.

4.1 Experimental Setup

SolQDebug was evaluated on single-contract, single-transaction functions to validate the contributions of incremental CFG construction and annotation-guided abstract interpretation, with multi-contract analysis as future work.

Experimental Setting. The evaluation environment consists of an 11th Gen Intel® Core™ i7-11390H CPU at 3.40GHz with 16.0 GB RAM, running Windows 10 (64-bit). SolQDebug is implemented in Python 3.10 and operates directly on Solidity source code without requiring compilation or deployment, using the ANTLR4-based parser described in Section 3.

Dataset Collection. The dataset was derived from DAppSCAN (Zheng et al., 2024), a large-scale benchmark containing 3,344 Solidity contracts compiled with version `>=0.8.0`. To ensure representative coverage across contract sizes, contracts smaller than 4 KB (2,142 samples) were first excluded, which typically contain minimal logic unsuitable for debugging analysis. From the remaining 1,202 contracts, approximately 10% were sampled from each of three size brackets:

- 4–10 KB (735 contracts): 70 samples
- 11–20 KB (304 contracts): 30 samples
- Over 20 KB (163 contracts): 20 samples

yielding 120 candidate contracts. From these candidates, two filtering criteria were then applied: (1) excluding functions with multi-contract interactions such as accessing variables or invoking functions from other contracts, as the analysis focuses on single-contract scenarios, and (2) excluding logic-free functions that contain only assignments or return statements.

After applying these filters, representative functions were selected based on three dimensions of debugging complexity:

- **Computational complexity**—complex arithmetic patterns with chained computations across multiple statements, making value ranges hard to predict manually.
- **Data structure complexity**—structs with multiple fields, nested mappings, dynamic arrays, and mapping-to-struct patterns.
- **Control flow complexity**—loops with varying termination conditions, nested conditionals, and modifier-based access control.

Based on these criteria, we select 30 representative functions for evaluation from diverse DeFi scenarios including token transfers with custom logic, staking/vesting mechanisms, liquidity pool operations, oracle data processing, and marketplace transactions. Table 4 lists all 30 benchmark contracts with their source files, target functions, and line counts.

The following presents the findings for each research question.

4.2 RQ1 - Responsiveness

To evaluate responsiveness, debugging latency was measured, defined as the time required to step through the execution of a function line-by-line. For Remix IDE, this corresponds to the duration from opening the debugger to stepping through the entire execution using the "step forward" button. For SolQDebug, it represents the time from a code modification to the display of updated variable information.

Since Remix IDE lacks built-in automated benchmarking capabilities, `remix_benchmark` (Remix Benchmark, 2025) was developed, a Selenium (Selenium with Python, 2025)-based automation framework that programmatically controls the Remix web interface, automating compilation, deployment, and step-through debugging.

Unlike Remix's concrete execution model, which requires stepping through every bytecode instruction for each test input, SolQDebug uses AI with interval domain (Section 3.4.4) that operates directly on the Solidity AST. Rather than enumerating concrete values one by one, the abstract interpreter represents inputs as intervals and computes abstract states over those intervals, analyzing all possible behaviors in a single pass without blockchain deployment. With this interval-based approach, SolQDebug maintains consistent latency regardless of test-case width Δ, which specifies the width of each symbolic interval input in debug annotations. In contrast, Remix must execute each concrete input value separately, so its latency scales linearly with the number of test inputs.

File Name	Function	Lines
AloeBlend.sol	`_earmarkSomeForMaintenance`	537-552
Amoss.sol	`_burn`	453-467
AOC_BEP.sol	`updateUserInfo`	422-436
ATIDStaking.sol	`_insertLockedStake`	127-172
AvatarArtMarketPlace.sol	`_removeFromTokens`	163-176
Balancer.sol	`_addActionBuilderAt`	79-91
BitBookStake.sol	`viewFeePercentage`	205-208
CitrusToken.sol	`transferFrom`	53-60
Claim.sol	`getCurrentClaimAmount`	65-72
Core.sol	`revokeStableMaster`	147-163
CoreVoting.sol	`quorums`	38-50
Dai.sol	`transferFrom`	72-83
DapiServer.sol	`calculateUpdateInPercentage`	838-854
DeltaNeutralPancakeWorker02.sol	`getReinvestPath`	392-405
Dripper.sol	`_availableFunds`	111-119
EdenToken.sol	`transferFrom`	227-240
GovStakingStorage.sol	`updateRewardMultiplier`	103-120
GreenHouse.sol	`_calculateFees`	328-344
HubPool.sol	`_allocateLpAndProtocolFees`	907-923
Lock.sol	`pending`	49-63
LockupContract.sol	`_getReleasedAmount`	75-89
Meter_flat.sol	`_transfer`	349-361
MockChainlinkOracle.sol	`latestRoundData`	114-130
OptimisticGrants.sol	`configureGrant`	62-79
PercentageFeeModel.sol	`getEarlyWithdrawFeeAmount`	72-95
PoolKeeper.sol	`keeperTip`	235-247
ThorusBond.sol	`claimablePayout`	531-538
ThorusLottery.sol	`isWinning`	708-714
TimeLockPool.sol	`getTotalDeposit`	90-96
WASTR.sol	`withdrawFrom`	211-232

Table 4: Benchmark dataset: 30 representative contracts from DAppSCAN with diverse debugging scenarios.

Although SolQDebug is designed for interactive use within a Solidity editor, all experiments simulate this behavior in a controlled scripting environment. For each function, a sequence of incremental edits and annotations was reconstructed that mimic realistic developer activity. These fragments are streamed into the interpreter to measure latency and interval growth under reproducible conditions.

30 functions were evaluated across 4 test-case widths $\Delta \in \{0, 2, 5, 10\}$, yielding 120 total measurements for SolQDebug. For Remix, each function was measured once per Δ value to demonstrate the linear scaling behavior. Figure 9 illustrates the latency comparison across these dimensions.

For Remix, the debugging latency ranged from 25.1 to 124.6 seconds (median: 53.0s), reflecting the time required to step through bytecode operations in the debugger, with latency scaling linearly with test-case width as each additional input value

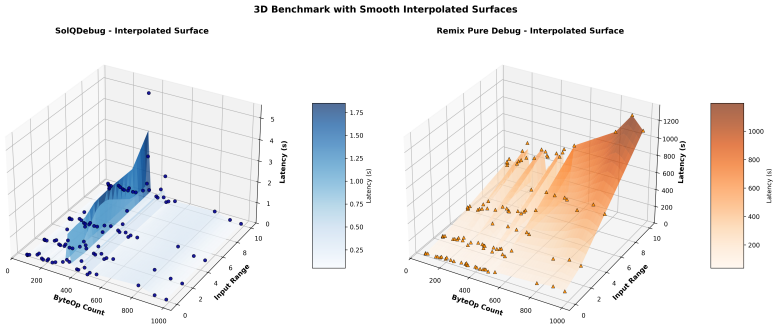

Fig. 9: Debugging latency comparison between SolQDebug and Remix across varying ByteOp counts and test-case widths Δ. SolQDebug maintains consistent sub-second latency regardless of function complexity or symbolic interval input width, while Remix's latency scales linearly with both dimensions.

requires a separate transaction execution and complete bytecode step-through. In contrast, SolQDebug completed analysis in 0.03–5.09 seconds (median: 0.15s) across all 120 measurements. SolQDebug's latency remains nearly constant regardless of test-case width, as AI analyzes all input combinations symbolically in a single pass. This results in a median feedback time of 0.15s compared to 53s with Remix. This comparison reflects debugging workflow time, measuring how quickly developers gain insights into function behavior rather than comparing equivalent computational tasks. Remix requires compilation, deployment, and concrete execution tracing, while SolQDebug provides immediate statement-level abstract summaries during editing.

Answer to RQ1: SolQDebug achieves millisecond-scale feedback (median 0.15s), reducing debugging workflow time compared to Remix's compile-deploy-debug cycle (median 53s). The two tools take fundamentally different approaches: SolQDebug generates statement-level abstract summaries over symbolic inputs, while Remix traces concrete execution paths. Unlike Remix, whose latency scales linearly with input space size, SolQDebug's performance through abstract interpretation does not depend on test-case width.

4.3 RQ2 - Impact of Annotation Patterns on Precision in Complex Arithmetic Operations

Real-world smart contracts frequently use complex arithmetic operations involving multiplication and division to compute financial quantities such as rewards, fees, and vesting schedules. These operations inherently amplify interval widths during AI due to the combinatorial nature of interval arithmetic. Understanding how annotation structure influences precision in such contexts is critical for practical adoption of SolQDebug.

To investigate this, the `pending` function from `Lock.sol` in the benchmark dataset was examined. The function uses complex arithmetic operations involving multiplication and division. Multiplication is critical: in interval arithmetic,

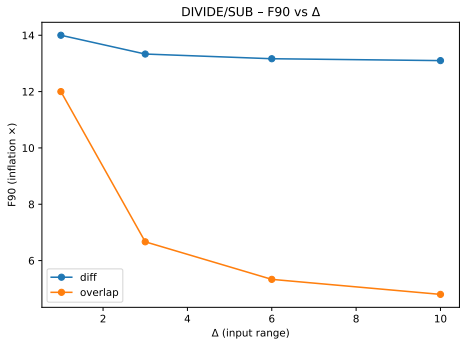

Fig. 10: F90 (90th percentile of interval inflation) for `Lock::pending` under `overlap` and `diff` annotation patterns. As input width (Δ) increases, `overlap` achieves progressively tighter precision (F90: 12.0 $\rightarrow$ 4.8), while `diff` maintains near-constant inflation (F90 $\approx$ 13–14).

it computes the Cartesian product of endpoint combinations $\{a_{\min} \times b_{\min}, a_{\min} \times b_{\max}, a_{\max} \times b_{\min}, a_{\max} \times b_{\max}\}$. Consequently, when operand intervals are disjoint, this combinatorial expansion generates significantly wider output ranges.

To assess this effect, two annotation strategies were evaluated under varying input widths $\Delta \in \{1, 3, 6, 10\}$. In the `overlap` style, all input variables share a common base range (e.g., $[100, 100 + \Delta]$). In the `diff` style, each variable occupies a distinct range (e.g., $[100, 100 + \Delta]$, $[300, 300 + \Delta]$, $[500, 500 + \Delta]$). F90 was measured, the 90th percentile of the inflation factor $F = \frac{\text{exit\_width}}{\text{input\_width}}$.

As shown in Figure 10, the `overlap` strategy consistently produces tighter bounds: as Δ increases from 1 to 10, F90 decreases from 12.0 to 4.8, indicating that wider inputs lead to proportionally smaller relative growth. In contrast, the `diff` strategy maintains nearly constant inflation (F90 $\approx$ 13–14) regardless of input width. This difference arises from interval multiplication semantics: when annotations align operands to overlapping ranges, the extreme products remain closer to the midpoint, limiting excessive interval expansion. Conversely, disjoint ranges maximize the distance between endpoint combinations, causing output intervals to span unnecessarily large ranges.

Moreover, similar patterns were observed in other contracts from the benchmark dataset that use multiplication or division in their arithmetic. These include reward computations (GovStakingStorage_c), fee calculations (GreenHouse_c, HubPool_c), vesting schedules (LockupContract_c), and proportional payouts (ThorusBond_c). Across these contracts, overlapping annotations consistently yield tighter precision than disjoint ranges, demonstrating that developers can significantly improve analysis precision by choosing overlapping rather than disjoint annotations.

Answer to RQ2: For real-world contracts using multiplication or division, overlapping annotations yield significantly lower interval inflation than disjoint annotations, due to interval multiplication's combinatorial nature. Developers should prefer overlapping annotation patterns to improve analysis precision in such contexts.

4.4 RQ3 - Loops

To evaluate the effectiveness of annotation-guided adaptive widening for loop analysis, the five loop-containing functions from the benchmark dataset (Table 4) were analyzed: `updateUserInfo` (AOC_BEP), `_addActionBuilderAt` (Balancer), `revokeStableMaster` (Core), `getTotalDeposit` (TimeLockPool), and `_removeFromTokens` (AvatarArtMarketPlace). These functions exhibit four distinct patterns that demonstrate varying levels of precision under this approach.

Pattern 1: Constant-Bounded Loops with Simple Updates. When loop conditions reference only constants and the loop body contains only simple assignments, `EstimateIterations` computes precise thresholds without annotations. For example, `updateUserInfo` (AOC_BEP) uses `for (uint256 i = 1; i <= 4; i++)` with $\tau = 4$ computed from the constant bound. The small constant bound and simple updates allow convergence without triggering widening. The analysis produces precise interval `userInfo[account].level` $\in [1, 4]$.

Pattern 2: Annotation-Enabled Convergence. When loop bounds depend on dynamic values but the loop body performs only simple updates, annotations enable precise convergence. `_addActionBuilderAt` (Balancer) uses `for (uint8 i = 0; i < additionalCount; i++)` where `additionalCount` is computed from function inputs. With appropriate annotations for `actionBuilders` and `index`, the analyzer computes `additionalCount = 1`, allowing it to set $\tau = 1$ and achieve precise convergence with `i = [0,1]`.

`revokeStableMaster` (Core) exhibits similar behavior. It iterates `for (uint256 i = 0; i < stablecoinListLength - 1; i++)` with simple index-based operations. The annotation `// @StateVar _stablecoinList = arrayAddress[2,3,4];` yields `stablecoinListLength = 3`, so the loop bound becomes `3 - 1 = 2`, setting $\tau = 2$ and achieving precise convergence with `i = [0,2]`.

Pattern 3: Uninitialized Local Variables (Developer-Fixable). When local variables lack explicit initialization, precision loss can occur. `getTotalDeposit` (TimeLockPool) declares `uint256 total;` without initialization and then accumulates values in a loop. For example, when appropriate annotations are provided for the `depositsOf` array elements, the analyzer infers a loop bound of 3 (setting $\tau = 3$) and correctly computes `i = [0,3]` after the loop. However, SolQDebug conservatively models uninitialized variables as $\top$ (unknown), causing `total` to remain $\top = [0, 2^{256} - 1]$ regardless of the precise loop bound.

This pattern represents a developer-fixable limitation. Explicitly initializing `total = 0` would enable precise tracking (yielding `total = [700,1000]` for the annotated example). Annotations cannot compensate for missing initialization because the interval domain soundly treats uninitialized reads as arbitrary values.

Pattern 4: Data-Dependent Accumulation. Even when loop bounds are precisely known, variables that accumulate based on data-dependent conditions may diverge under widening. `_removeFromTokens` (AvatarArtMarketplace) illustrates this limitation. The loop iterates `for (uint tokenIndex = 0; tokenIndex < tokenCount; tokenIndex++)` where `tokenCount` is known from annotations. With appropriate annotations for `_tokens` and `tokenId`, the analyzer infers `tokenCount = 3` (setting $\tau = 3$) and correctly computes `tokenIndex = [0,3]` after the loop. However, `resultIndex` inside the loop increments conditionally (`if (tokenItemId != tokenId) resultIndex++`) based on array element comparisons, depending on data values rather than the loop index itself.

Once the widening threshold is exceeded, SolQDebug widens `resultIndex` to $[0, \infty]$. The interval domain cannot track correlations between array contents and conditional accumulation. This pattern represents an inherent limitation of the interval domain. Annotations of iteration bounds cannot prevent widening when variable updates depend on unpredictable data rather than iteration count.

Answer to RQ3: SolQDebug improves loop analysis precision for constant-bounded and annotation-enabled dynamic loops. Remaining precision loss arises from developer-fixable initialization issues and inherent interval domain limitations in tracking data-dependent accumulation.

4.5 Threats to Validity

Internal Validity. The Remix benchmark was implemented using Selenium-based automation, which may introduce communication latency between the Python script and the Remix web interface. To mitigate this threat, we isolated the pure debugging time and measured it using the JavaScript `performance.now()` API within the browser, minimizing the impact of automation overhead.

External Validity. The 30 benchmark functions used in our evaluation may not fully represent the diversity of real-world smart contracts. Additionally, due to the current scope limitation, a user study with developers has not yet been conducted.

Construct Validity. We compared SolQDebug only against Remix IDE, without direct comparison to other debugging tools such as Hardhat Debugger or Foundry Forge Debug. However, Remix is the most widely used Solidity IDE, and these alternative tools share the same concrete execution model, exhibiting similar characteristics in terms of deployment requirements and step-through debugging.

5 Discussion

5.1 Why use Abstract Interpretation with Interval Domain for Debugging

In this work, debugging refers to a developer-led, interactive exploration activity that occurs during code editing. Developers specify debug annotations and immediately observe program behaviors at the source level. This edit-time feedback loop imposes

strict requirements on the analysis technique. Unlike conventional step-through debuggers that trace concrete execution, SolQDebug provides abstract value summaries that characterize possible behaviors across symbolic interval inputs.

Why Abstract Interpretation? Compared to other static analysis, dynamic analysis, and machine learning techniques, AI provides two properties essential for interactive debugging:

- **Termination.** AI enforces convergence through widening at loops and joins at control-flow merges, guaranteeing bounded analysis time regardless of program complexity.
- **Explainability.** AI produces explicit abstract values that developers can inspect and interpret at the statement level.

Why Interval Domain? Among abstract domains, intervals were chosen for responsiveness. Intervals require only basic arithmetic on bounds, enabling millisecond-scale updates. In contrast, relational domains (e.g., zones, polyhedra) track variable correlations through expensive constraint solving that would break the interactive feedback loop.

Precision-Responsiveness Tradeoff. AI with interval domain prioritizes responsiveness over precision, a tradeoff justified by the interactive debugging context. Edit-time debugging fundamentally requires sub-second feedback to maintain developer flow. Developers iterate rapidly through code edits, and analysis delays that exceed even a few seconds would break this interactive loop, forcing developers back to the traditional compile-deploy-debug cycle. SolQDebug achieved millisecond-scale feedback latency (RQ1), keeping developers in flow. Although AI's precision is inherently conservative, this limitation was mitigated by providing developers with annotation-based techniques to control precision where needed. The evaluation shows that such techniques can reduce imprecision in practice for common smart contract patterns (cf. RQ2, RQ3).

5.2 Practical Guidelines for Annotation and Loop Design

The experimental findings from RQ2 and RQ3 yield actionable strategies for developers to maximize analysis precision. Table **??** synthesizes these findings into a unified framework that includes annotation strategies for both arithmetic and loops, as well as code design patterns specifically for loop constructs.

For arithmetic operations, developers should minimize interval expansion by using singleton intervals for all but one operand, and when multiple intervals are necessary, choose appropriate positioning based on the operator (overlapping for multiplication/division, disjoint for unsigned subtraction).

For loop constructs, precision depends on: (1) explicit initialization of local variables before the loop, (2) proper annotation of loop bounds, and (3) whether arithmetic operations inside the loop involve operands related to the loop index. Operations on index-unrelated variables cause unavoidable widening, and such widened variables should be isolated from subsequent computations when precise analysis is required.

Table 5: Practical guidelines for maximizing analysis precision, synthesized from RQ2 (arithmetic operations) and RQ3 (loop constructs). Guidelines include annotation strategies and code design patterns.

Scenario	Detail	Guideline	Rationale
Arithmetic Operations (RQ2)			
1. Basic principle	All operators	Annotate **one operand as interval** (e.g., `[100,110]`), others as **singleton** (e.g., `[100,100]`).	Minimizes interval expansion from combinatorial endpoint calculations.
2. Multiple intervals needed	`*`, `/`	Use **overlapping** ranges (e.g., `[100,110]` and `[100,115]`).	Disjoint ranges maximize spread of endpoint products.
	`+`	Position (overlapping vs. disjoint) does not matter.	Result width equals sum of input widths.
	`-` (`int`)	Position (overlapping vs. disjoint) does not matter.	Result width equals sum of input widths.
	`-` (`uint`)	Use **disjoint** ranges where minuend $>$ subtrahend (e.g., `[100,110] - [50,70]`).	Overlapping ranges risk underflow, degrading precision.
	`%`	Position does not matter.	Result depends on divisor magnitude only.
Loop Constructs (RQ3)			
1. Before loop	Initialization	**Initialize local variables explicitly** (e.g., `uint x = 0;`).	Uninitialized locals start as $\top$; annotations cannot recover precision.
	Bounds annotation	Annotate state variables or parameters determining loop bounds (e.g., array lengths).	Enables precise iteration estimation and widening threshold.
2. Inside loop	Simple assignment	Assignments without arithmetic (e.g., `x = arr[i]`) can converge.	No interval expansion occurs from arithmetic operations.
	Index-related arithmetic	Arithmetic where operands relate to loop index (e.g., `i`, `arr[i]`) can converge with proper annotation.	Bounds-aware analysis tracks index-correlated computations.
	Index-unrelated arithmetic	Arithmetic on variables unrelated to loop index (e.g., `if (...) count++`) causes widening.	Interval domain cannot track data-dependent correlations.
3. After loop	Propagation	Avoid using widened variables in subsequent statements when precise analysis is needed.	Widened intervals propagate imprecision to all dependent computations.

5.3 Limitations

The current implementation focuses on single-contract, single-transaction functions within a subset of Solidity language features. We identify four categories of limitations and outline concrete next steps toward addressing real-world challenges.

Language Coverage. The current implementation does not support inline assembly blocks. Inline assembly allows developers to write raw EVM opcodes within Solidity, bypassing the type system and enabling low-level optimizations. Since assembly instructions operate directly on stack and memory without Solidity's semantic abstractions, the current CFG construction and abstract interpretation cannot reason about their effects. As a minimal viable step, assembly blocks could be treated conservatively by assigning TOP to all variables potentially modified within the block. A more refined approach would pattern-match common assembly idioms (e.g., `mload`/`mstore` for memory operations, `sload`/`sstore` for storage) and translate them into equivalent abstract operations.

Contract Interaction. Inter-contract calls, inheritance hierarchies, and multi-transaction workflows are currently out of scope. For multi-contract support, a summary-based approach would analyze callee contracts separately and represent their effects as function summaries (input-output interval relations) at call sites. This avoids full inlining while preserving soundness. Multi-transaction analysis would additionally require serializing abstract states between transaction boundaries.

Bug Detection. The current system functions as a debugging assistant that displays variable values and execution paths. A natural extension is proactive bug detection: once interval information is available, a validation engine can check for common vulnerability patterns. The target bugs are logic errors, particularly numerical defects such as arithmetic overflow, precision loss, and accounting errors (**???**). This evolution from "showing values" to "detecting problems" aligns with the debugging assistant paradigm and with developer preferences for development-integrated tools with sound guarantees (**?**).

User Experience Validation. A formal developer study has not yet been conducted. Since SolQDebug currently operates without full GUI/IDE integration, a developer study at this stage would not accurately reflect usability in complete development settings. Meaningful usability evaluation requires additional HCI/GUI research to provide intuitive interfaces for annotation input, result visualization, and seamless editor integration. We plan to conduct formal usability studies once the above extensions are implemented alongside comprehensive IDE integration.

6 Related Works

6.1 Solidity IDEs and Debuggers

Modern Solidity development environments either embed a debugger or integrate external debugging plug-ins. Remix IDE (Remix IDE, 2025) is the most widely used web IDE. It supports syntax highlighting, one-click compilation, and a bytecode-level debugger that lets users step through EVM instructions and inspect stack, memory, and storage. Hardhat (Hardhat, 2025) is a Node.js-based framework that couples

the Solidity compiler with an Ethereum runtime. It integrates with Visual Studio Code extensions to provide step-by-step debugging of transaction execution. Foundry Forge (Foundry Forge, 2025) is a command-line toolchain oriented toward fast, reproducible unit testing. The command `forge test` spins up an ephemeral fork, deploys contracts, executes annotated test functions, and enables replay through Forge Debug. Solidity Debugger Pro (Solidity Debugger Pro, 2025) is a Visual Studio Code extension that performs runtime debugging over concrete transactions and integrates with Hardhat.

In summary, these debuggers operate on compiled artifacts or post-deployment traces. By contrast, SolQDebug targets pre-deployment authoring, accepts partial fragments and symbolic annotations, and reports line-level effects via AI during editing.

6.2 Solidity Vulnerability Detection and Verification

Security analysis of smart contracts can be categorized into four main families of techniques. First, static analysis tools reason over source or bytecode without running the contract. Representative systems include rule-based analyzers such as Securify and Slither (Tsankov et al., 2018; Feist et al., 2019), symbolic-execution tools like Mythril (Yao et al., 2022), knowledge-graph approaches such as Solidet (Hu et al., 2023), and CFG refinement techniques as in Ethersolve (Pasqua et al., 2023). Second, dynamic testing and fuzzing exercise deployed or locally simulated contracts to uncover faults and security issues. ContractFuzzer mutates Application Binary Interface (ABI)-level inputs (Jiang et al., 2018), Echidna brings property-based fuzzing into developer workflows (Grieco et al., 2020), sFuzz adapts scheduling for higher coverage (Nguyen et al., 2020), TransRacer finds transaction-ordering races (Ma et al., 2023), and Ityfuzz leverages snapshotting to decouple executions from chain nondeterminism (Shou et al., 2023). Third, formal verification aims to prove safety properties or refute counterexamples at compile time. Examples include ZEUS, VeriSmart, and SmartPulse (Kalra et al., 2018; So et al., 2020; Stephens et al., 2021). Finally, learning-based approaches train models to predict vulnerabilities or triage candidates, e. g., via data-flow–aware pretraining, IoT-oriented classifiers, or prompt-tuning for detector adaptation (Wu et al., 2021; Zhou et al., 2022; Yu et al., 2023).

These approaches have substantially advanced vulnerability detection and property checking for smart contracts. However, they target complete programs and focus on vulnerability detection rather than providing edit-time feedback. In contrast, SolQDebug provides interactive analysis as developers write code, enabling immediate understanding of program behavior without requiring complete contracts.

6.3 Solidity-Specific Abstract Interpretation Frameworks

AI is a well-established framework for static analysis and has been adapted to many programming languages. Two recent studies apply it to Solidity (Halder et al., 2023; Halder, 2024). The first uses the Pos domain to construct a theoretical model for taint (information-flow) analysis (Halder et al., 2023), while the second uses the Difference-Bound Matrix (DBM) domain to generate state invariants and detect re-entrancy

vulnerabilities, including the DAO attack (Halder, 2024; Mehar et al., 2019). However, both approaches operate on fully written contracts and provide no support for line-by-line interpretation or developer interaction within an IDE.

SolQDebug builds upon these AI frameworks but targets interactive debugging rather than invariant generation or information flow analysis. Unlike these approaches that analyze complete contracts, SolQDebug incrementally updates the control-flow graph and abstract state during editing, allowing developers to use debug annotations to guide interval analysis and receive edit-time feedback without requiring complete contracts.

6.4 Interactive Abstract Interpretation for Traditional Languages

Beyond Solidity, the broader programming languages community has increasingly focused on making abstract interpretation interactive. Recent work integrates static analysis directly into IDEs for C, Java, and other traditional languages, delivering live feedback during editing (Stein et al., 2021 2024; Erhard et al., 2024; Riouak et al., 2024; Chimdyalwar, 2024). While these systems share SolQDebug's goal of edit-time responsiveness, they differ in language semantics, domain requirements, and input mechanisms. Stein et al. (2021) proposed demanded abstract interpretation, which incrementally rebuilds only the analysis nodes touched by an edit. A follow-up Stein et al. (2024) generalized this to procedure summaries, enabling inter-procedural reuse. Erhard et al. (2024) extended Goblint with incremental support for multithreaded C, selectively recomputing only genuinely affected facts and maintaining IDE-level responsiveness. Riouak et al. (2024) introduced IntraJ, a Language Server Protocol (LSP)-integrated analyzer for Java 11 that computes only the Abstract Syntax Tree (AST) and data-flow facts needed for the current view, keeping feedback under 100 ms. Chimdyalwar (2024) achieved fast yet precise interval analysis on call graphs via one top-down and multiple bottom-up passes, and later introduced an incremental variant that revisits only the impacted functions.

While these frameworks demonstrate the feasibility of interactive abstract interpretation in traditional languages, SolQDebug represents the first application of this paradigm to Solidity. Beyond language adaptation, it introduces an annotation-guided approach where developers specify debug annotations directly in source code to explore multiple execution scenarios in a single analysis pass. This enables Solidity developers to benefit from interactive static analysis without deploying contracts to a blockchain.

7 Conclusion

This paper presented SolQDebug, the first interactive source-level debugger for Solidity that eliminates the traditional compile-deploy-debug cycle. Through interactive parsing, line-to-node indexing for incremental CFG construction, and annotation-guided abstract interpretation, SolQDebug provides millisecond-scale feedback directly within the editor.

Evaluation on 30 real-world DAppSCAN functions demonstrated millisecond-scale feedback latency. Our analysis showed that annotation-guided interpretation enables precise analysis across diverse execution paths while maintaining soundness guarantees. These results demonstrated that SolQDebug effectively bridges the interactivity gap in Solidity debugging, bringing the development experience closer to modern IDEs and enhancing software quality in the blockchain ecosystem.

Future work includes extending language coverage to inline assembly, supporting inter-contract calls and multi-transaction workflows, and evolving the debugging assistant into a proactive bug detection system with IDE integration.

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Author Contributions

Inseong Jeon participated in conceptualization, methodology design, system implementation, data collection, experiments, and manuscript writing. Sundeuk Kim and Hyunwoo Kim assisted in experiments, data collection and analysis, and contributed to manuscript writing. Hoh Peter In provided resources, assisted in editing the manuscript, and supervised the entire project. All authors reviewed and approved the final version of the manuscript.

Data Availability

The curated benchmark dataset of 30 Solidity contracts derived from DAppSCAN (Zheng et al., 2024), along with the evaluation scripts and experimental results, are available at https://github.com/iwwyou/SolDebug/tree/main.

Declarations

Competing interests The authors declare no competing interests.
Ethical approval Not applicable since there are no human and/or animal studies included in this paper.

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A Interactive Parser Grammar Specification

This appendix provides the complete grammar specification for SolQDebug's interactive parser.

A.1 Entry Rules for Solidity Program Fragments

A.1.1 Rule 1: `interactiveSourceUnit`

Purpose. Accepts top-level declarations: functions, contracts, interfaces, libraries, state variables, pragmas, and imports.
Grammar:

```
interactiveSourceUnit
  : (interactiveStateVariableElement | interactiveFunctionElement
    | interfaceDefinition | libraryDefinition | contractDefinition
    | pragmaDirective | importDirective)* EOF ;
```

A.1.2 Rule 2: `interactiveEnumUnit`

Purpose. Accepts enum member items added after the enum shell.
Grammar:

```
interactiveEnumUnit : (interactiveEnumItems)* EOF;
interactiveEnumItems : identifier (',' identifier)*;
```

A.1.3 Rule 3: `interactiveStructUnit`

Purpose. Accepts struct member declarations added after the struct shell.
Grammar:

```
interactiveStructUnit : (structMember)* EOF;
structMember : typeName identifier ';' ;
```

A.1.4 Rule 4: `interactiveBlockUnit`

Purpose. Accepts statements and control-flow skeletons inside function bodies.
Grammar:

```
interactiveBlockUnit
  : (interactiveBlockItem)* EOF;

interactiveBlockItem
  : interactiveStatement | uncheckedBlock;

interactiveStatement
  : interactiveSimpleStatement
  | interactiveIfStatement
```

```
  | interactiveForStatement
  | interactiveWhileStatement
  | interactiveDoWhileDoStatement
  | interactiveTryStatement
  | returnStatement
  | emitStatement
  | revertStatement
  | requireStatement
  | assertStatement
  | continueStatement
  | breakStatement
  | assemblyStatement;

interactiveIfStatement
  : 'if' '(' expression ')' '{' '}' ;

interactiveForStatement
  : 'for' '(' (simpleStatement | ';') expression? ';' expression? ')' '{' '}' ;

interactiveWhileStatement
  : 'while' '(' expression ')' '{' '}' ;

interactiveDoWhileDoStatement
  : 'do' '{' '}' ;

interactiveTryStatement
  : 'try' expression ('returns' '(' parameterList ')')? '{' '}' ;
```

The `interactiveStatement` production includes skeleton rules for control structures with empty bodies (e.g., `interactiveIfStatement`, `interactiveForStatement`), enabling incremental construction of control flow. As developers type statements inside these empty bodies, `interactiveBlockUnit` is recursively invoked to parse each new line.

A.1.5 Rule 5: `interactiveDoWhileUnit`

Purpose. Accepts the `while` tail of a `do{...}` loop.
Grammar:

```
interactiveDoWhileUnit : (interactiveDoWhileWhileStatement)* EOF;
interactiveDoWhileWhileStatement : 'while' '(' expression ')' ';' ;
```

A.1.6 Rule 6: `interactiveIfElseUnit`

Purpose. Accepts `else` or `else if` branches.
Grammar:

```
interactiveIfElseUnit : (interactiveElseStatement)* EOF;
interactiveElseStatement : 'else' (interactiveIfStatement | '{' '}') ;
```

A.1.7 Rule 7: `interactiveCatchClauseUnit`

Purpose. Accepts `catch` clauses following a `try`.
Grammar:

```
interactiveCatchClauseUnit : (interactiveCatchClause)* EOF;
interactiveCatchClause : 'catch' (identifier? '(' parameterList ')')? '{' '}' ;
```

A.2 Entry Rule for Debugging Annotations

A.2.1 `debugUnit`

Purpose. Parses batch-annotation lines that specify initial abstract values for variables.
Annotation types:

- `@GlobalVar`: Assigns values to global variables (e.g., `msg.sender`, `block.timestamp`)
- `@StateVar`: Assigns values to contract state variables
- `@LocalVar`: Assigns values to function parameters and local variables

Grammar:

```
debugUnit : (debugGlobalVar | debugStateVar | debugLocalVar)* EOF;
debugGlobalVar : '//' '@GlobalVar' identifier ('.' identifier)? '=' globalValue ';' ;
debugStateVar : '//' '@StateVar' lvalue '=' value ';' ;
debugLocalVar : '//' '@LocalVar' lvalue '=' value ';' ;
```

Supported L-value patterns: Simple variables, array/mapping access (`arr[i]`, `map[key]`), struct fields (`s.field`), and nested combinations.
Value specification: Integer intervals `[l,u]`, symbolic addresses `symbolicAddress n`, boolean values, and symbolic placeholders.

B Incremental CFG Construction Patterns

This appendix provides the complete CFG construction patterns for SolQDebug's incremental CFG builder. The patterns show how each statement type is incrementally spliced into the existing control-flow graph.

B.1 CFG Hierarchy

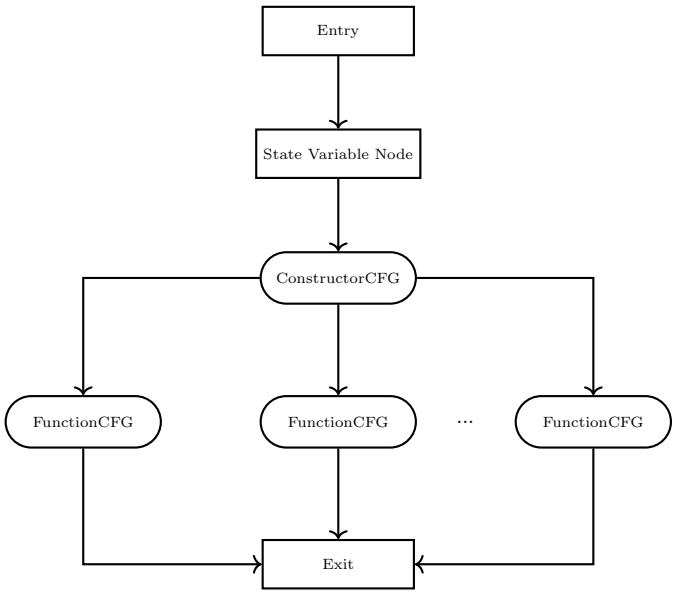

Fig. 11: Structure of ContractCFG. The contract-level CFG sequences state variable initialization, constructor execution, and all function definitions.

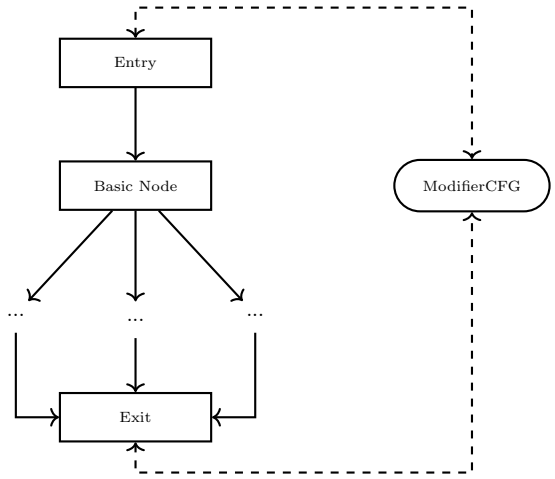

Fig. 12: Structure of FunctionCFG. Each function maintains its own control-flow graph. When modifiers are present, control flows from the function entry to the modifier, and returns from the modifier's placeholder (_) back to the function body, eventually reaching the function exit.

B.2 Statement-Level Construction Patterns

The following patterns show how each statement type is incrementally spliced into the existing control-flow graph. All patterns assume an initial state with a current node connected to successors (`...`), as illustrated in the simple statement example.

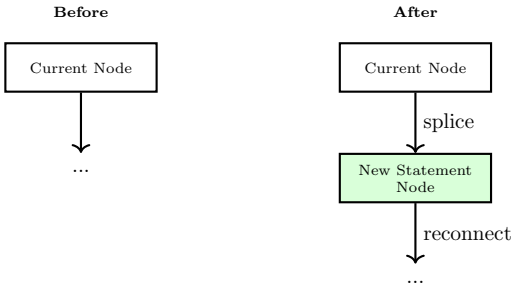

Fig. 13: Simple statement insertion: single node spliced between current node and successors

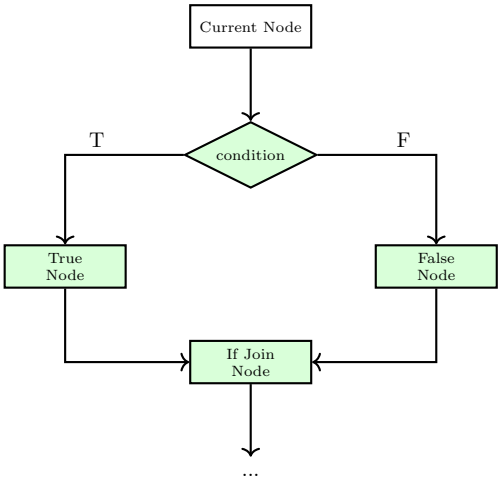

Fig. 14: If statement insertion. The builder creates a `condition node`, two nodes for true/false arms, and an `if join`

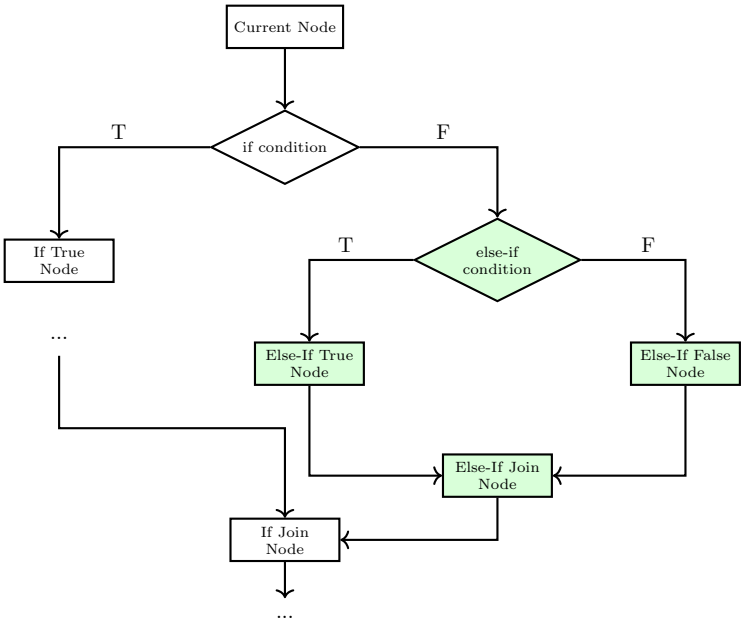

Fig. 15: Else-if statement insertion. The builder replaces the false arm with a new `condition node`, two nodes, and an `else-if join`

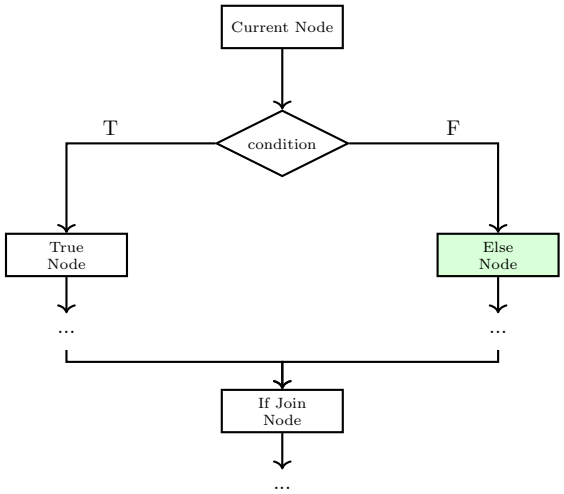

Fig. 16: Else statement insertion. The builder replaces the false branch node with a new else node, connecting to the `if join`

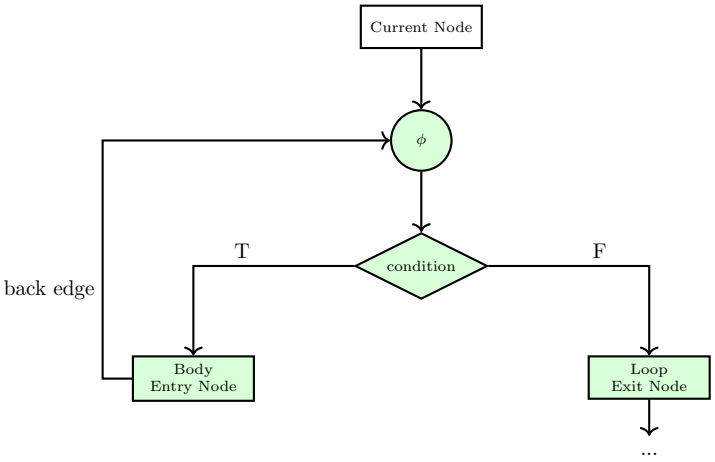

Fig. 17: While loop insertion. The builder creates a `fixpoint evaluation node` ϕ, a `condition node`, a loop body node, and a `loop exit node`

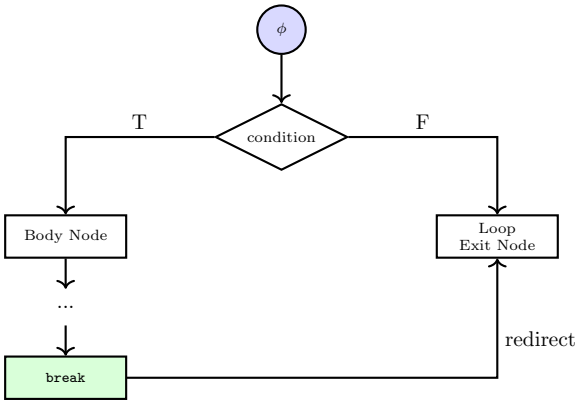

Fig. 18: Break statement insertion. The `break` node's outgoing edge is redirected to the `loop exit node`

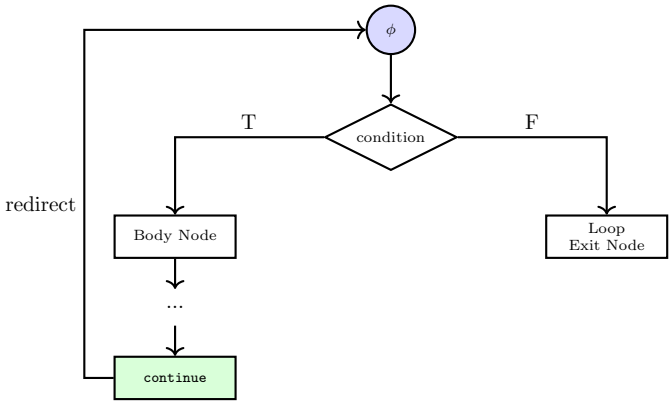

Fig. 19: Continue statement insertion. The `continue` node's outgoing edge is redirected to the loop's `fixpoint evaluation node` ϕ

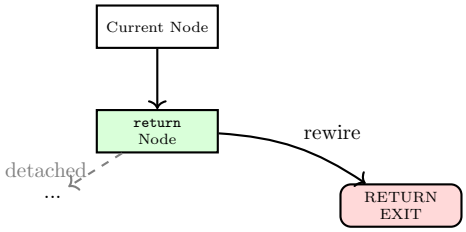

Fig. 20: Return statement insertion. The containing node's edge is rewired to the function's unique `return exit node`

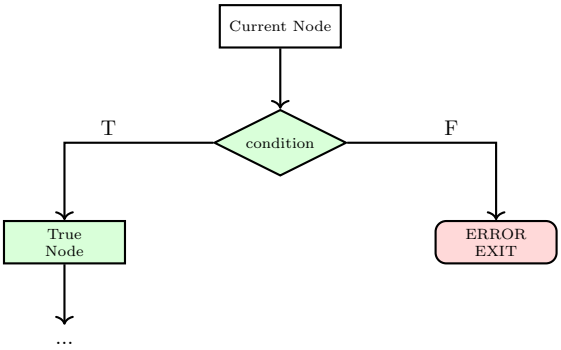

Fig. 21: Require statement insertion. The builder creates a `condition node` with true edge to a node and false edge to the `error exit node`

C Abstract Domain and Formal Semantics

This appendix presents the abstract domain definitions and formal semantics used by SolQDebug's abstract interpreter. The framework is based on interval analysis for numeric types, set domains for addresses, and lazy materialization for composite data structures.

C.1 Language Syntax

This work considers a subset of Solidity focusing on core control structures, expressions, and state manipulation relevant to the analysis.
Expressions:

$$\begin{aligned} e \in \mathsf{Expr} \ ::= \ & n \mid x \mid \mathsf{true} \mid \mathsf{false} \mid \mathsf{address\_literal} \\ & \mid e_1 \oplus e_2 \mid e_1 \ \odot \ e_2 \mid e_1 \ ? \ e_2 : e_3 \\ & \mid e.f \mid e_1[e_2] \mid f(\overline{e}) \mid \neg e \mid \mathsf{delete}\ e \end{aligned}$$

where $\oplus \in \{+, -, *, /, \%, **, \&\&, ||, \&, |, \wedge, <<, >>\}$ and $\odot \in \{<, \leq, >, \geq, ==, \neq\}$.
Statements:

$$\begin{aligned} s \in \mathsf{Stmt} \ ::= \ & \mathsf{skip} \mid s_1; s_2 \mid \tau\ x; \mid \tau\ x = e; \\ & \mid lv := e \mid \mathsf{delete}\ lv \\ & \mid \mathsf{if}\ p\ \mathsf{then}\ s_t\ \mathsf{else}\ s_f \\ & \mid \mathsf{while}\ p\ \mathsf{do}\ s \\ & \mid \mathsf{for}\ init; p; incr\ \mathsf{do}\ s \\ & \mid \mathsf{do}\ s\ \mathsf{while}\ p \\ & \mid \mathsf{return}\ e \mid \mathsf{assert}(p) \mid \mathsf{require}(p) \\ & \mid \mathsf{revert}(\cdots) \mid \mathsf{try}\ e\ (\mathsf{returns}\ (x))\ s_t\ \mathsf{catch}\ s_c \\ & \mid f(\overline{e}) \end{aligned}$$

where τ ranges over types (`uint`, `int`, `bool`, `address`, structs, arrays, mappings), lv denotes l-values (variables, fields, array/mapping elements), and p denotes boolean expressions.

C.2 Abstract Domain

Atomic abstract values:

- **Unsigned integers:** $\widehat{\mathbb{U}}_N = \{[\ell, u] \mid 0 \leq \ell \leq u \leq 2^N - 1\} \cup \{\bot, \top_N^{\mathbb{U}}\}$
- **Signed integers:** $\widehat{\mathbb{Z}}_N = \{[\ell, u] \mid -2^{N-1} \leq \ell \leq u \leq 2^{N-1} - 1\} \cup \{\bot, \top_N^{\mathbb{Z}}\}$
- **Booleans:** $\widehat{\mathbb{B}} = \{\bot, \widehat{\mathsf{false}}, \widehat{\mathsf{true}}, \top\}$
- **Addresses:** $\widehat{\mathbb{A}} = \{\bot\} \cup \wp_{\text{fin}}(\mathsf{AddrID}) \cup \{\top\}$ where $\bot = \emptyset$ (finite set of symbolic address identifiers)
- **Bytes:** $\widehat{\mathbb{BY}}_K = \{\bot, \top_K\}$ (symbolic/opaque)

- **Enums:** $\widehat{\mathsf{Enum}}(E) = \{[\ell, u] \mid 0 \le \ell \le u \le |E| - 1\} \cup \{\bot, \top_E\}$

Composite values:

- **Structs:** $\widehat{\mathsf{Struct}}(C) = \prod_{f \in \mathsf{fields}(C)} \widehat{\mathsf{Val}}_f$ (pointwise order)
- **Arrays:** $\widehat{\mathsf{Arr}}(\tau) = (\hat{\ell}, \hat{d}, M)$ where $\hat{\ell} \in \widehat{\mathbb{U}}_{256}$ is length, $\hat{d}$ is default element, $M : \mathbb{N} \rightharpoonup \widehat{\tau}$ stores observed indices
- **Mappings:** $\widehat{\mathsf{Map}}(\kappa \Rightarrow \tau) = (\hat{d}, M)$ with default $\hat{d}$ and finite map M for observed keys

Standard interval domain operations (order, join, meet, widening, narrowing) apply to integer and enum domains.

C.3 Concrete Semantics

Result types: Semantics return $\mathsf{Norm}(\sigma)$ (normal termination), $\mathsf{Ret}(v, \sigma)$ (return statement), or Abort (revert).

- **Variables:** Var = set of variable identifiers
- **Values:** Val includes:
  - Unsigned integers: $\mathbb{U}_N = \{0, 1, \ldots, 2^N - 1\}$
  - Signed integers: $\mathbb{Z}_N = \{-2^{N-1}, \ldots, 2^{N-1} - 1\}$
  - Booleans: $\mathbb{B} = \{\mathsf{true}, \mathsf{false}\}$
  - Addresses: $\mathbb{A} = \mathsf{AddrID}$ (symbolic identifiers)
  - Composite values: structs, arrays, mappings with concrete elements
- **Stores:** $\sigma \in \Sigma = \mathsf{Var} \rightharpoonup \mathsf{Val}$

L-value resolution $\mathrm{loc}_\sigma(lv)$ and write $\mathrm{write}(\sigma, \ell, v)$ update the store. Expressions are pure: $[\![e]\!]_\sigma \in \mathsf{Val}$.
Array/mapping materialization: $\mathrm{loc}_\sigma(a[i])$ extends a up to i with defaults if needed; $\mathrm{loc}_\sigma(m[k])$ creates $m[k]$ lazily if absent.

C.4 Collecting Semantics

For abstraction, we lift concrete semantics to sets of states.
Collecting function semantics: Given a function f with concrete semantics $[\![f]\!] : \Sigma \times \mathsf{Val} \to \mathit{Result}$, the collecting semantics over state sets is:

$$\mathcal{S}[[f]](S) = \{\sigma' \mid \exists \sigma \in S,\, v_{\mathrm{in}} \in \mathsf{Val}.\, [\![f]\!](\sigma, v_{\mathrm{in}}) = \mathsf{Norm}(\sigma') \vee [\![f]\!](\sigma, v_{\mathrm{in}}) = \mathsf{Ret}(v_{\mathrm{out}}, \sigma')\}$$

Reachable states: The set of all reachable states during contract execution forms the collecting semantics, serving as the basis for abstract interpretation.

Table 6: Concrete semantics (denotational)

Statement	**Meaning**
skip	$[\![\mathsf{skip}]\!](\sigma) = \mathsf{Norm}(\sigma)$
$s_1; s_2$	$[\![s_1; s_2]\!](\sigma) = \big([\![s_1]\!](\sigma)\big) \triangleright (\lambda\sigma'.\, [\![s_2]\!](\sigma'))$
$\tau\ x;$	$[\![\tau\ x;]\!](\sigma) = \mathsf{Norm}\big(\sigma[x \mapsto \mathrm{zero}_\tau]\big)$
$\tau\ x = e;$	$[\![\tau\ x = e;]\!](\sigma) = \mathsf{Norm}\big(\sigma[x \mapsto [\![e]\!]_\sigma]\big)$
$lv := e$	$[\![lv := e]\!](\sigma) = \mathsf{Norm}\big(\mathrm{write}(\sigma,\, \mathrm{loc}_\sigma(lv),\, [\![e]\!]_\sigma)\big)$
delete lv	$[\![\mathsf{delete}\ lv]\!](\sigma) = \mathsf{Norm}\big(\mathrm{write}(\sigma,\, \mathrm{loc}_\sigma(lv),\, \mathrm{zero}_{\tau(lv)})\big)$
if p then s_t else s_f	$[\![\cdot]\!](\sigma) = \begin{cases} [\![s_t]\!](\sigma) & \text{if } [\![p]\!]_\sigma = \mathsf{true}, \\ [\![s_f]\!](\sigma) & \text{if } [\![p]\!]_\sigma = \mathsf{false} \end{cases}$
while p do s	$F(H)(\sigma) = \begin{cases} \big([\![s]\!](\sigma)\big) \triangleright H & \text{if } [\![p]\!]_\sigma = \mathsf{true}, \\ \mathsf{Norm}(\sigma) & \text{if } [\![p]\!]_\sigma = \mathsf{false} \end{cases}$; $[\![\mathsf{while}\ p\ \mathsf{do}\ s]\!] = \mathrm{lfp}(F)$
for $init$; p; $incr$ do s	$F(H)(\sigma) = \begin{cases} \big([\![s]\!](\sigma)\big) \triangleright (\lambda\sigma'.\, [\![incr]\!](\sigma') \triangleright H) & \text{if } [\![p]\!]_\sigma = \mathsf{true}, \\ \mathsf{Norm}(\sigma) & \text{if } [\![p]\!]_\sigma = \mathsf{false} \end{cases}$; $[\![\mathsf{for}\ init; p; incr\ \mathsf{do}\ s]\!](\sigma) = [\![init]\!](\sigma) \triangleright (\lambda\sigma'.\, \mathrm{lfp}(F)(\sigma'))$
do s while p	$F(H)(\sigma) = [\![s]\!](\sigma) \triangleright (\lambda\sigma'.\, \begin{cases} H(\sigma') & \text{if } [\![p]\!]_{\sigma'} = \mathsf{true}, \\ \mathsf{Norm}(\sigma') & \text{if } [\![p]\!]_{\sigma'} = \mathsf{false} \end{cases})$; $[\![\mathsf{do}\ s\ \mathsf{while}\ p]\!] = \mathrm{lfp}(F)$
return e	$[\![\mathsf{return}\ e]\!](\sigma) = \mathsf{Ret}([\![e]\!]_\sigma,\, \sigma)$
assert(p), require(p)	$[\![\cdot]\!](\sigma) = \begin{cases} \mathsf{Norm}(\sigma) & \text{if } [\![p]\!]_\sigma = \mathsf{true}, \\ \mathsf{Abort} & \text{if } [\![p]\!]_\sigma = \mathsf{false} \end{cases}$
revert($\cdots$)	$[\![\mathsf{revert}(\cdots)]\!](\sigma) = \mathsf{Abort}$
try e (returns (x)) s_t catch s_c	$[\![\cdot]\!](\sigma) = \begin{cases} [\![s_t]\!](\sigma[x \mapsto v]) & \text{if call succeeds with } v, \\ [\![s_c]\!](\sigma) & \text{if call reverts} \end{cases}$
call($\overline{e}$)	Internal: parameter binding; external: unspecified

C.5 Abstract Semantics (Denotational)

Our abstract semantics is based on the well-established Galois connection for interval domains between concrete and abstract semantics, ensuring soundness. The abstraction function α and concretization function γ connect concrete and abstract domains, guaranteeing that abstract computations safely over-approximate concrete behaviors.

Abstract semantic domains:

- **Abstract values:** $\widehat{\mathsf{Val}}$ = union of atomic abstract values ($\widehat{\mathbb{U}}_N$, $\widehat{\mathbb{Z}}_N$, $\widehat{\mathbb{B}}$, $\widehat{\mathbb{A}}$, etc.) and composite abstract values ($\widehat{\mathsf{Struct}}$, $\widehat{\mathsf{Arr}}$, $\widehat{\mathsf{Map}}$) from §C
- **Abstract stores:** $\hat{\sigma} \in \widehat{\Sigma} = \mathsf{Var} \rightharpoonup \widehat{\mathsf{Val}}$

Auxiliary functions:

- refine$(\hat{\sigma}, p, b)$: narrows operands of p by interval meets
- $\widehat{\mathrm{write}}(\hat{\sigma}, lv, \hat{v})$: strong update if singleton index/key, weak update otherwise
- joinRes(r_1, r_2): componentwise join of abstract results

Table 7: Abstract semantics (denotational)

Statement	**Meaning**
skip	$[\![\mathsf{skip}]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Norm}}(\hat{\sigma})$
$s_1; s_2$	$[\![s_1; s_2]\!]^\sharp(\hat{\sigma}) = \big([\![s_1]\!]^\sharp(\hat{\sigma})\big) \triangleright^\sharp (\lambda\hat{\sigma}'.\, [\![s_2]\!]^\sharp(\hat{\sigma}'))$
$\tau\ x;$	$[\![\tau\ x;]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Norm}}\big(\hat{\sigma}[x \mapsto \hat{\mathrm{init}}(\tau)]\big)$
$\tau\ x = e;$	$[\![\tau\ x = e;]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Norm}}\big(\hat{\sigma}[x \mapsto \alpha_\tau([\![e]\!]^\sharp_{\hat{\sigma}})]\big)$
$lv := e$	$[\![lv := e]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Norm}}\big(\widehat{\mathrm{write}}(\hat{\sigma},\ lv,\ [\![e]\!]^\sharp_{\hat{\sigma}})\big)$
delete lv	$[\![\mathsf{delete}\ lv]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Norm}}\big(\widehat{\mathrm{write}}(\hat{\sigma},\ lv,\ \hat{\mathrm{zero}}_{\tau(lv)})\big)$
if p then s_t else s_f	$\hat{\sigma}_t = \mathrm{refine}(\hat{\sigma}, p, \mathsf{true}),\ \hat{\sigma}_f = \mathrm{refine}(\hat{\sigma}, p, \mathsf{false});\ [\![\cdot]\!]^\sharp(\hat{\sigma}) = \mathrm{joinRes}\big([\![s_t]\!]^\sharp(\hat{\sigma}_t),\ [\![s_f]\!]^\sharp(\hat{\sigma}_f)\big)$
while p do s	$G^\sharp(H)(\hat{\sigma}) = \mathrm{joinRes}\big([\![s]\!]^\sharp(\mathrm{refine}(\hat{\sigma}, p, \mathsf{true})) \triangleright^\sharp H,\ \widehat{\mathsf{Norm}}(\mathrm{refine}(\hat{\sigma}, p, \mathsf{false}))\big);\ [\![\mathsf{while}\ p\ \mathsf{do}\ s]\!]^\sharp = \mathrm{lfp}^\nabla(G^\sharp)$
for $init$; p; $incr$ do s	$G^\sharp(H)(\hat{\sigma}) = \mathrm{joinRes}\big([\![s]\!]^\sharp(\mathrm{refine}(\hat{\sigma}, p, \mathsf{true})) \triangleright^\sharp (\lambda\hat{\sigma}'.\, [\![incr]\!]^\sharp(\hat{\sigma}') \triangleright^\sharp H),\ \widehat{\mathsf{Norm}}(\mathrm{refine}(\hat{\sigma}, p, \mathsf{false}))\big);$ $[\![\mathsf{for}\ init; p; incr\ \mathsf{do}\ s]\!]^\sharp(\hat{\sigma}) = [\![init]\!]^\sharp(\hat{\sigma}) \triangleright^\sharp (\lambda\hat{\sigma}'.\, \mathrm{lfp}^\nabla(G^\sharp)(\hat{\sigma}'))$
do s while p	$G^\sharp(H)(\hat{\sigma}) = [\![s]\!]^\sharp(\hat{\sigma}) \triangleright^\sharp (\lambda\hat{\sigma}'.\, \mathrm{joinRes}\big(H(\mathrm{refine}(\hat{\sigma}', p, \mathsf{true})),\ \widehat{\mathsf{Norm}}(\mathrm{refine}(\hat{\sigma}', p, \mathsf{false}))\big));$ $[\![\mathsf{do}\ s\ \mathsf{while}\ p]\!]^\sharp = \mathrm{lfp}^\nabla(G^\sharp)$
return e	$[\![\mathsf{return}\ e]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Ret}}([\![e]\!]^\sharp_{\hat{\sigma}},\ \hat{\sigma})$
assert(p), require(p)	$\widehat{\mathsf{Norm}}(\mathrm{refine}(\hat{\sigma}, p, \mathsf{true}))$ if p must-hold; $\widehat{\mathsf{Abort}}$ if p must-fail; joinRes otherwise
revert($\cdots$)	$[\![\mathsf{revert}(\cdots)]\!]^\sharp(\hat{\sigma}) = \widehat{\mathsf{Abort}}$
try e (returns (x)) s_t catch s_c	$[\![\cdot]\!]^\sharp(\hat{\sigma}) = \mathrm{joinRes}\big([\![s_t]\!]^\sharp(\hat{\sigma}[x \mapsto \top]),\ [\![s_c]\!]^\sharp(\hat{\sigma})\big)$
call($\overline{e}$)	Internal: parameter binding; external: havoc footprint or $\widehat{\mathsf{Abort}}$