TraceGuard: Taint-Guided Symbolic Execution

Bachelor Thesis Presentation

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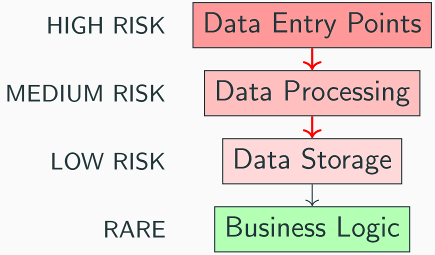
Today's Journey

1. **The Challenge:** Software vulnerabilities and current detection limits
2. **The Problem:** Why symbolic execution struggles
3. **The Insight:** Taint-guided exploration concept
4. **The Solution:** TraceGuard's approach and implementation
5. **The Evidence:** Evaluation results and performance gains
6. **Seeing It Work:** Live demonstration
7. **Looking Forward:** Future directions and broader impact

The Problem

Where Do Software Vulnerabilities Actually Hide?



Vulnerability Hotspots:

- **Data Entry:** Network I/O, file parsing, user input
- **Data Processing:** String operations, format parsing, validation
- **Data Storage:** Memory allocation, buffer operations
- **Business Logic:** Complex algorithms, decision trees

Risk decreases as data moves away from external sources

Common Vulnerability Patterns

Input-Related Vulnerabilities:

- **Buffer overflows:** `strcpy(small_buf, user_input)`
- **Format string bugs:** `printf(user_string)`
- **Injection attacks:** SQL, command injection
- **Integer overflows:** Size calculations from input

Example Attack Flow:

Malicious Input

↓ crafted data

Parsing Function

↓ insufficient check

Memory Operation

↓ buffer overflow

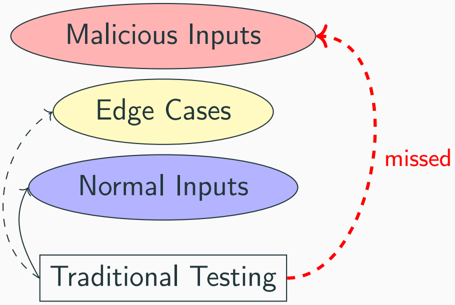
Code Execution

Key Insight: Following the data flow from input to vulnerability

The Challenge: Finding These Vulnerabilities

Traditional Testing Approaches:

- **Manual code review:** Time-intensive, incomplete coverage
- **Unit testing:** Limited to expected inputs
- **Integration testing:** Misses edge cases
- **Static analysis:** High false positive rates



The Gap: Security vulnerabilities often trigger under specific, unexpected input conditions

Symbolic Execution - The Promise

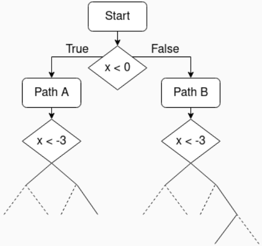
Goal: Find all possible bugs automatically

Method: Treat inputs as mathematical symbols

Power: Can generate test cases for any reachable code

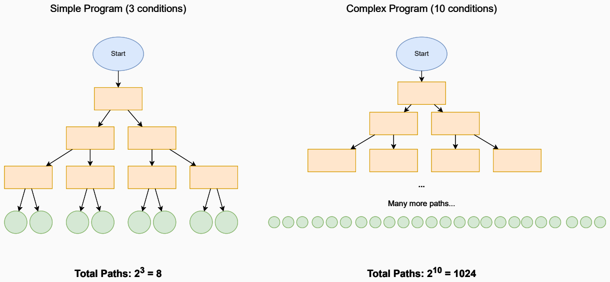
Advantage: Handles complex conditions that random testing cannot reach

```
void read(int x) {
  if (x < 0) {
    if (x < -3) {
      foo(x);
    } else {
      ...
    }
  } else {
    if (x > 5) {
      bar(x);
    } else {
      ...
  ...
}
```



Instead of testing with specific values, explore ALL possible values

The Reality - Path Explosion Problem



- 3 conditions → 8 possible paths
- 10 conditions → 1,024 possible paths
- 20 conditions → 1,048,576 possible paths
- Real programs: Millions of conditions = computational infeasibility

Exponential growth kills practical application

Comparing Approaches - Fuzzing vs. Symbolic Execution

Fuzzing	Symbolic Execution
Fast, lightweight	Slow, resource-intensive
Shallow bug discovery	Deep path exploration
Random/guided input generation	Systematic path coverage
Struggles with complex conditions	Handles complex logic well

Challenge

Both struggle with scale, but in different ways:

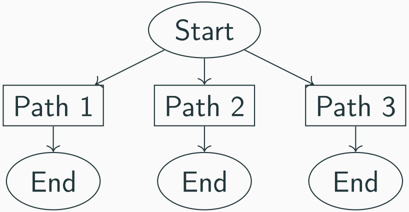
- **Fuzzing:** Hard to reach deep code paths
- **Symbolic Execution:** Exponential path explosion

We need the systematic power of symbolic execution with better efficiency

The Insight

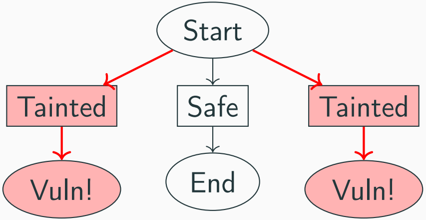
The Core Insight - Taint as a Guide

Classical Exploration:



Explores everything

Taint-Guided Exploration:



Follows the data

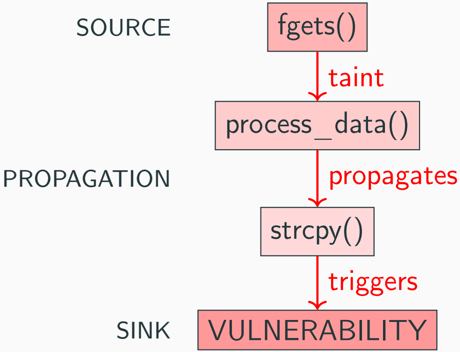
Key Realization

- Not all execution paths are equally likely to contain vulnerabilities
- Paths processing user-controlled data deserve priority

What is Taint Analysis?

Definition: Track data derived from untrusted sources

- **Sources:** User input functions (fgets, scanf, network recv)
- **Propagation:** Through assignments, function calls, memory operations
- **Sinks:** Security-sensitive operations (strcpy, system calls)




```c
char buffer[100];
fgets(buffer, 100, stdin);  // TAINT SOURCE
process_data(buffer);       // TAINT PROPAGATES
strcpy(dest, buffer);       // POTENTIAL VULNERABILITY
```

Traditional Approach vs. TraceGuard

Traditional Symbolic Execution:

- Explore all paths uniformly
- Hope to eventually reach vulnerable code
- Often times out before finding bugs
- Wastes resources on irrelevant paths

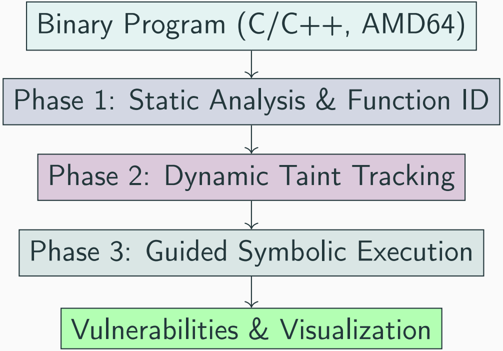
TraceGuard's Taint-Guided Approach:

- Real-time taint tracking during symbolic execution
- Dynamic prioritization based on taint interaction
- Focus computational resources on security-relevant paths
- Find more vulnerabilities with focused exploration

Key Innovation: Integration, not post-processing

The Solution

TraceGuard Architecture - Overview



CFG construction, function hooks

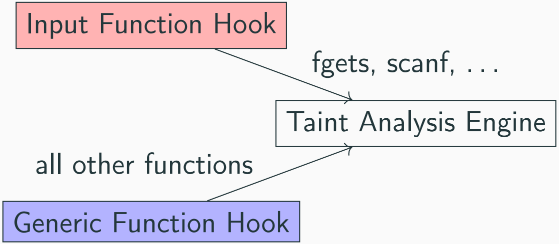
Real-time taint propagation

Priority-based state exploration

Integration Point

- Built on Angr symbolic execution framework

How TraceGuard Works - Function Hooking

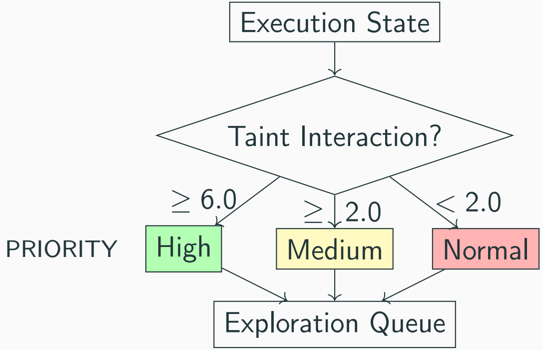


Function Hooking Strategy:

- **Input Function Hooks:** Detect taint introduction
- **Generic Function Hooks:** Monitor taint propagation
- **Real-time Detection:** Analyze register/memory contents
- **Taint Marking:** Create symbolic variables with taint IDs

Example: When `fgets()` is called → Create `"taint_source_fgets_001"` symbolic variable

Dynamic State Scoring Algorithm



Scoring Components:

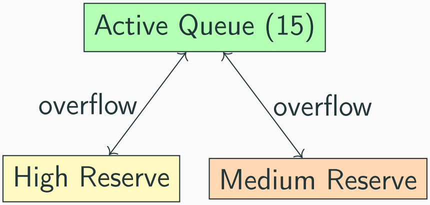
- **Base Score:** From taint interactions (+20.0 for input functions)
- **Bonuses:** Execution within tainted functions (+3.0)
- **Penalties:** Excessive execution depth (×0.95 for deep paths)
- **Classification:** High (≥ 6.0), Medium (≥ 2.0), Normal (< 2.0)

Result: Three-tier exploration queue prioritizing security-relevant states

Exploration Strategy

Bounded Exploration:

- Maximum 15 active states
- Priority queues: High $\rightarrow$ Medium $\rightarrow$ Normal
- Dynamic replacement: New high-priority states replace low-priority ones
- Overflow management: Store excess states in reserve pools



Advantage

- Prevents path explosion while maintaining security focus

The Results

Evaluation Methodology

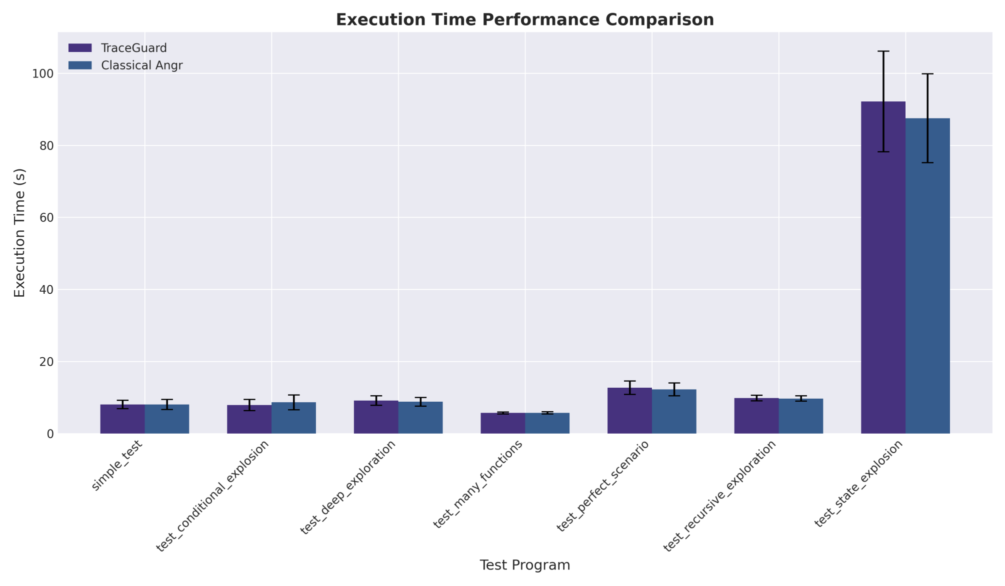
Test Suite Design

- **7 synthetic programs** targeting different challenges
- **Known vulnerabilities** with clear taint flow patterns
- **Controlled comparison:** TraceGuard vs. Classical Angr strategy

Programs Test:

- Simple baselines, conditional explosions, deep exploration
- Multi-function analysis, perfect scenarios, recursive calls
- State explosion stress test

Key Results - Execution Time Performance

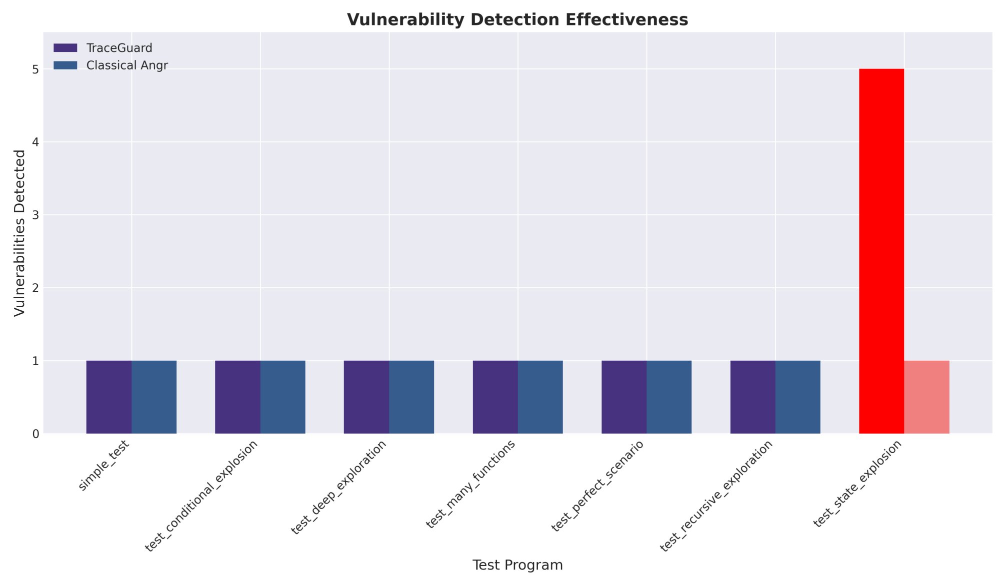


Key Results - Execution Time Performance

Key Insights

- **Competitive Performance:** TraceGuard shows -5.3% to +8.5% time variation compared to Classical Angr.
- **Complex Branching Improvement:** Achieved an 8.5% time improvement in the `test_conditional_explosion` scenario.
- **Scalability in Stress Test:** Maintained comparable execution time in the `test_state_explosion` scenario, despite its complexity.

Vulnerability Detection Effectiveness

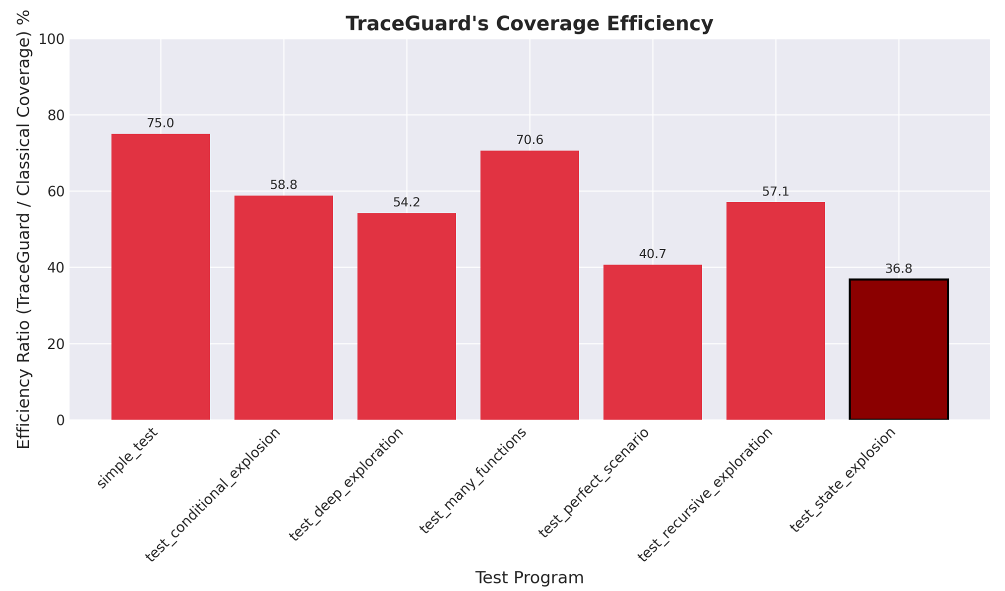


Vulnerability Detection Effectiveness

Perfect Detection with Superior Performance

- **100% Vulnerability Coverage**
- **Strategic Advantage in Complexity:** TraceGuard found 5$\times$ **more vulnerabilities** in the challenging `test_state_explosion` scenario.
- **Consistent and Enhanced Reliability:** TraceGuard maintains consistent detection for all test types while providing a significant leap in highly complex environments.

Coverage vs. Effectiveness



Efficiency: Quality Over Quantity

Paradigm Shift

- **Traditional Metric:** More coverage $\implies$ better analysis
- **Our Finding:** Focused exploration $\implies$ more critical vulnerabilities
- **The Proof (Example: `test_state_explosion`):**
  - TraceGuard found $5\times$ **more vulnerabilities** with only **36.8% of Classical's coverage**.

Quality of exploration matters more than quantity

Live Demo

Live Demo - TraceGuard in Action

Demo Setup

Target: `examples/program6`

What we'll see:

1. Taint source detection (fgets)
2. Real-time taint propagation tracking
3. Guided exploration prioritization
4. Vulnerability discovery and reporting
5. Interactive visualization

[LIVE DEMO]

Future Directions

Future Research Directions

Immediate Extensions:

- **Real-world validation:** Large-scale commercial software
- **Enhanced taint sources:** Network protocols, file formats
- **Multi-architecture:** ARM, RISC-V support
- **Integration:** Fuzzing tools, static analysis

Advanced Research:

- **Machine learning guidance:** AI-driven exploration
- **Distributed analysis:** Cloud-scale symbolic execution
- **Formal verification:** Soundness guarantees
- **Byte-level tracking:** Enhanced taint granularity

Broader Impact & Applications

Academic Impact

- **Methodology:** Security-aware program analysis paradigm
- **Tool:** Open source platform for continued research
- **Validation:** Empirical evidence for taint-guided approaches

Industry Applications

- **Security auditing:** Automated vulnerability discovery
- **DevSecOps:** Pre-deployment security testing
- **Penetration testing:** Target identification for manual analysis
- **Critical Infrastructure:** Security validation for high-stakes systems

Conclusion

Summary and Conclusion

What We Achieved

- **Solved fundamental problem:** Path explosion in security analysis
- **Demonstrated effectiveness:** 100% vulnerability detection, 5$\times$ improvement
- **Practical implementation:** Ready for real-world deployment
- **Research foundation:** Platform for future security-aware analysis

Deployment Context

- **Continuous Integration:** Automated security testing in CI/CD pipelines
- **Red Team Operations:** Efficient vulnerability discovery
- **Research Platform:** Foundation for advanced program analysis

Research Contributions

Novel Integration

- First comprehensive framework for real-time taint-guided symbolic execution
- Dynamic state prioritization based on security relevance
- Practical implementation demonstrating feasibility

Technical Achievements

- Custom Angr exploration technique
- Function-level taint tracking system
- Adaptive scoring algorithm with configurable thresholds
- Comprehensive benchmarking infrastructure

Questions?

Thank You

Questions and Discussion

TraceGuard: Taint-Guided Symbolic Execution

for Enhanced Binary Analysis

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Available Resources:

- **Live Tool:** github.com/ruben-hutter/TraceGuard