Investigating the Effects of T-Wise Interaction Sampling for Vulnerability Discovery in Highly-Configurable Software Systems

Meeting on Feature-Oriented Software Development 2025

Tim Bächle, Erik Hofmayer, Christoph König, Tobias Pett, Ina Schaefer | 25. March 2025

Test, Validation, Analysis

Background

```
1  void foo() {
2      int x = source();
3      if(x < MAX){
4          int y = 0;
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6          y = 2 * x;
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A variable C function inspired by the example provided by Yamaguchi et al. [Yam+14]

Highly-Configurable Software Systems

- Often implemented as Software Product Lines (SPLs)
- Common core and variable features
- Product-based strategy common for analysis [Lie+13; Thü+14]

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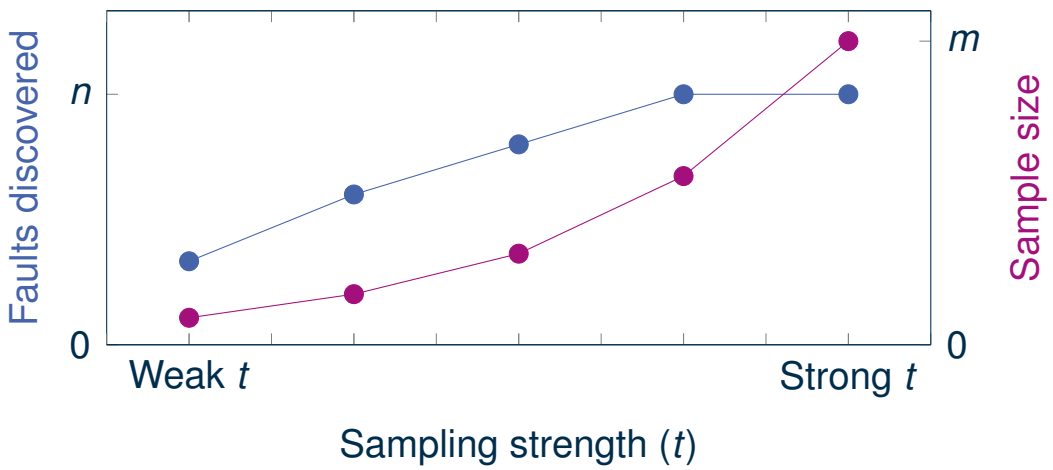
T-Wise Interaction Sampling

- **Idea**: All possible t-tuples of features appear in at least one sampled configuration
- t represents the interaction strength

Interaction Strength	PROCESS_INPUT	SEND_DATA
$t = 1$	✓	✓
	✗	✗
$t = 2$	✓	✓
	✗	✗
	✓	✗
	✗	✓

Background / Motivation

Observations of Medeiros et al. [Med+16] and Halin et al. [Hal+19]



Do these insights extend to the special class of faults/bugs that represent vulnerabilities?

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Vulnerabilities in Highly-Configurable Systems

Inspiration: Bugs in Configurable Software

Variability Bug: A bug that occurs in one or more but not all configurations of a configurable system [Aba+17; ABW14; Mor+19]

Feature-Interaction Bug: A variability bug whose occurrence requires the interaction of at least two features [Aba+17; ABW14; GC11]

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Variability-Induced Vulnerability (VIV)

A **vulnerability** that is **present in some but not all configurations** of a configurable system.

```
1  void foo() {
2      int x = source(); // Attacker-controlled.
3      if(x < MAX){ // Does not enforce x >= 0.
4          int y = 0;
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Feature-Interaction Vulnerability (FIV)

A **variability-induced vulnerability (VIV)** whose **presence is dependent** on the **interaction of two or more features'** selection or unselection.

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Sample-Based Vulnerability Discovery

Vari-Joern

- An analysis platform **realizing sample-based vulnerability discovery**
- **Built around** the static source code analysis tool **JOERN** [24c; Yam+14]

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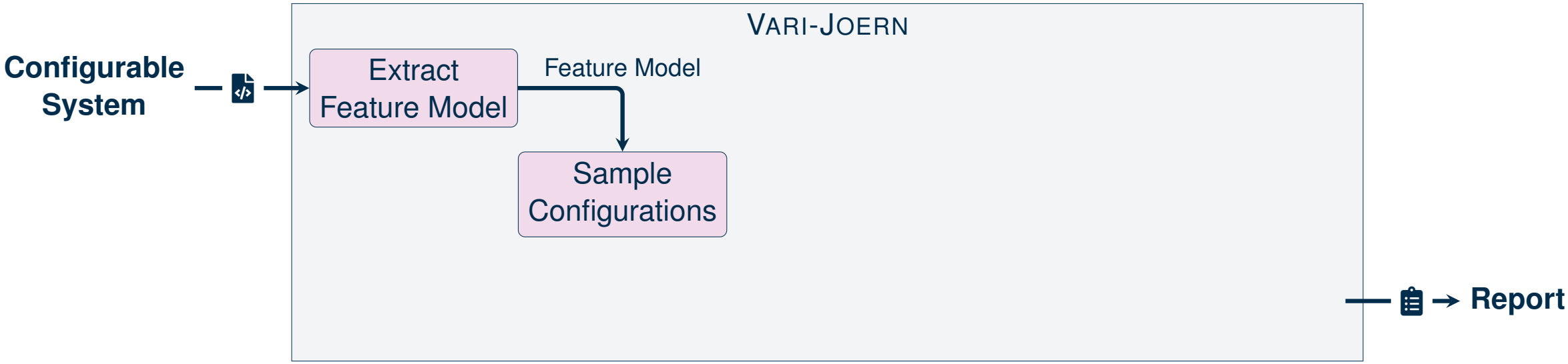

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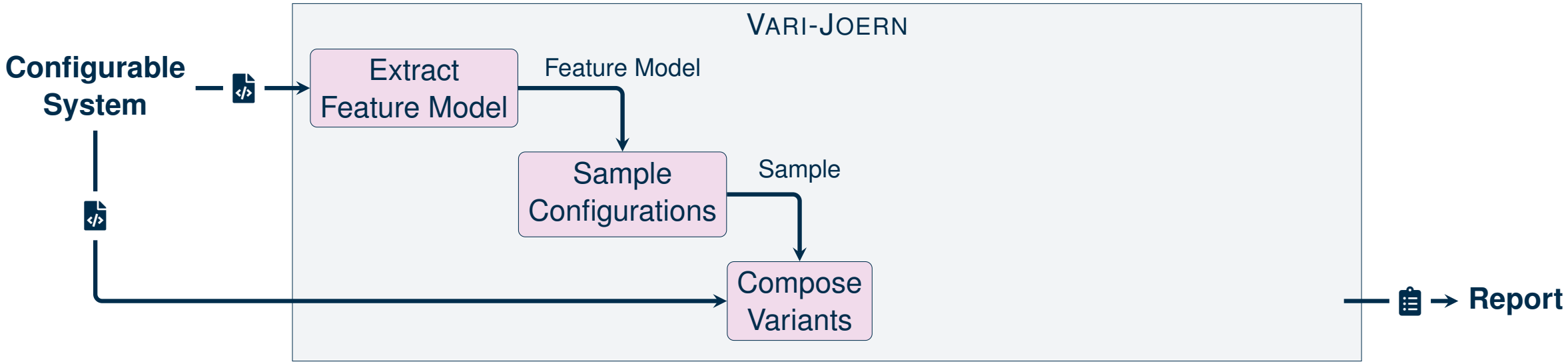

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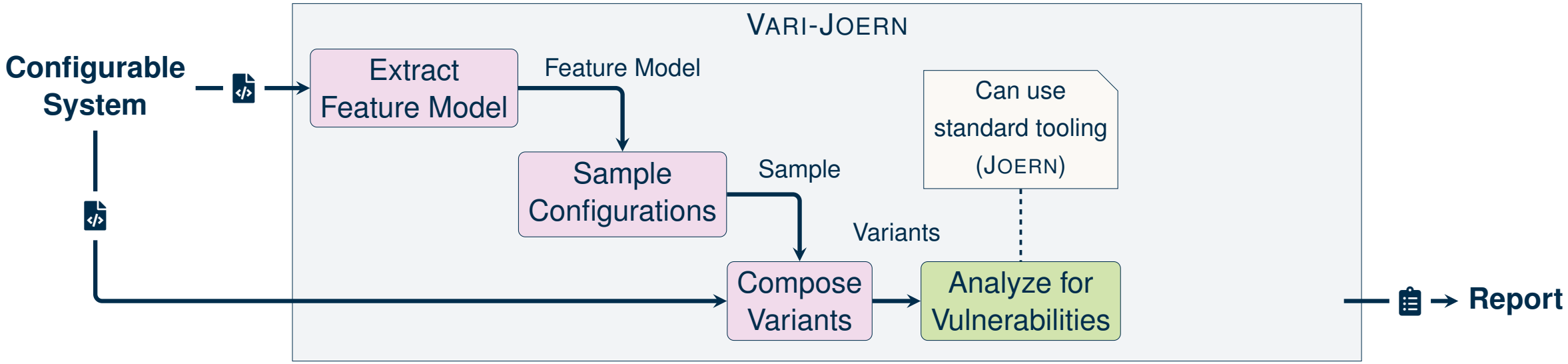

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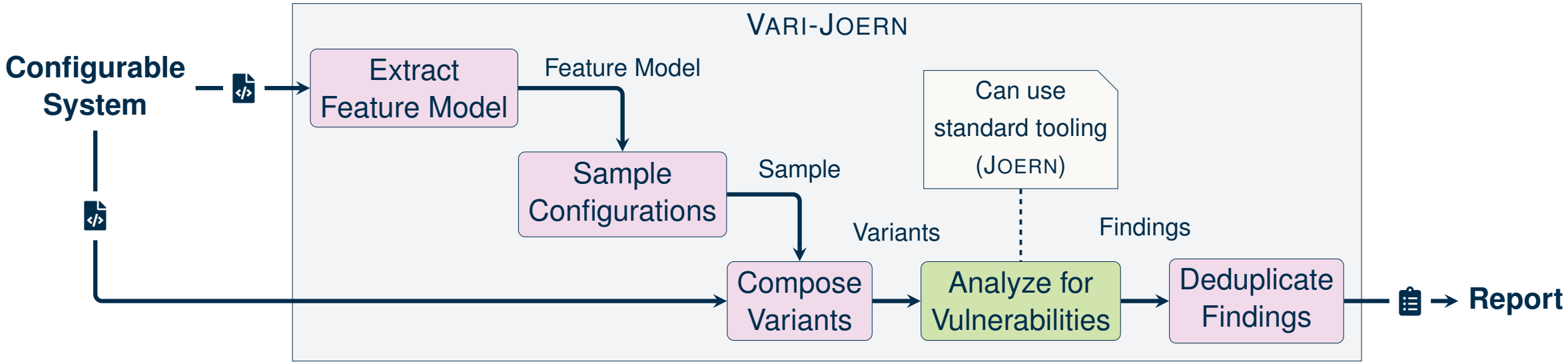

Research Questions

Motivation $\mathbf{RQ_1}$

Previous work [Hal+19; Med+16] showed:

1. Greater interaction sampling strength leads to the identification of more variability bugs
2. Sample size rapidly increases

⇒ Do these insights extend to the special class of bugs that are vulnerabilities?

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RQ_1: What is the **trade-off between** the **sample size** and the **number of findings** when **using t-wise interaction sampling** of different strength **for vulnerability discovery** in highly-configurable software?

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Motivation $\mathbf{RQ_2}$

- Interaction sampling of strength t should reliably identify FIVs of interaction degree $\leq t$

⇒ Is this the case in reality, or are FIV identified by:
- Lesser interction sampling strength due to coincidence?
- Greater interaction sampling strength due to a discrepancy between problem and solution space?

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$\mathbf{RQ_1}$: What is the **trade-off between** the **sample size** and the **number of findings** when **using t-wise interaction sampling** of different strength **for vulnerability discovery** in highly-configurable software?

$\mathbf{RQ_2}$: Can the **increase in vulnerability warnings** reported using stronger t-wise interaction sampling be **attributed to** potential **FIVs of stronger interaction strength** being identified?

Experimental Setup

Subject Systems

- Real-world systems
- Significant share implemented in C
- Configuration management via KCONFIG

Name	Version	C-LoC	#Features
AXTLS [24a]	2.1.5	17,556	63
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- Perform an analysis with VARI-JOERN for the subject systems
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- Compare sample sizes and number of findings for different sampling strengths (t)
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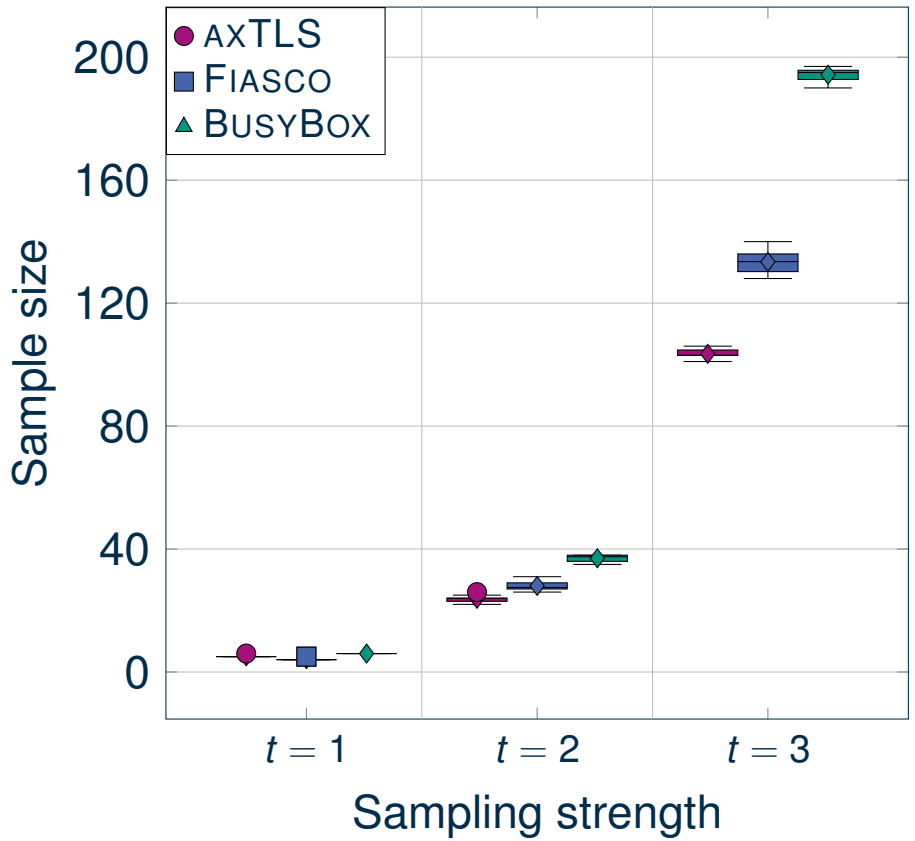
RQ_2 - Reason for Increase in Findings

- Focus on BUSYBOX
- Analyze presence condition of vulnerability warnings not identified by weaker sampling
- Compare required sampling strength (t) and true interaction strength of vulnerability warnings

First Results

RQ_1 - Trade-off: Sample Size $\Leftrightarrow$ Findings



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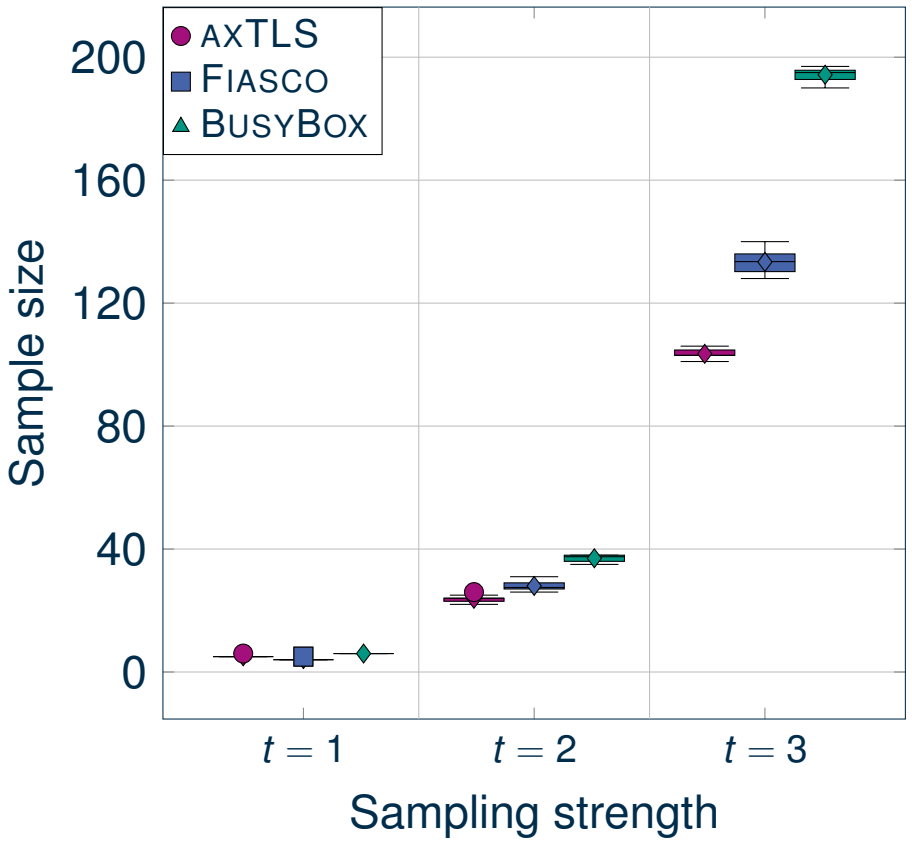

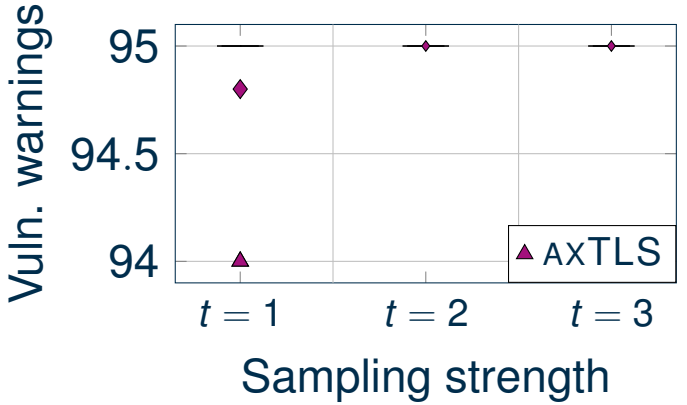

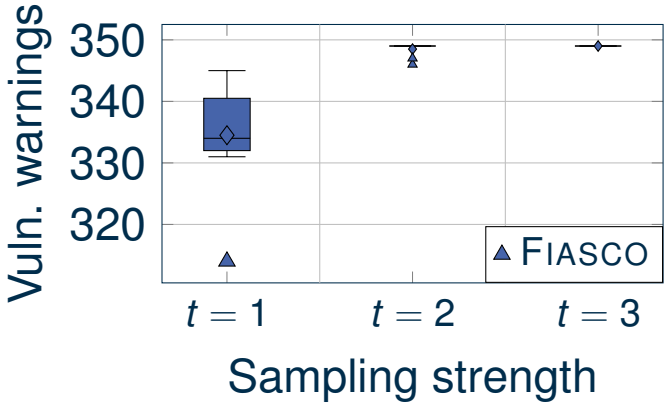

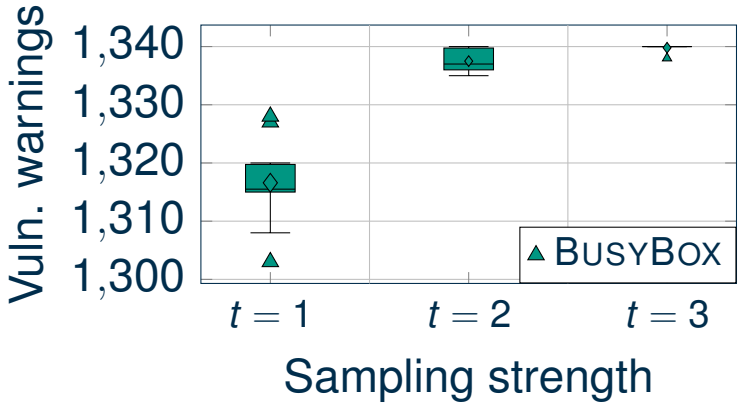

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- Findings identified by t-wise but not $t-1$-wise sampling are **mostly of interaction strength** t
- By **collateral effect** [Pet+13], some findings of **higher interaction strength** can be identified
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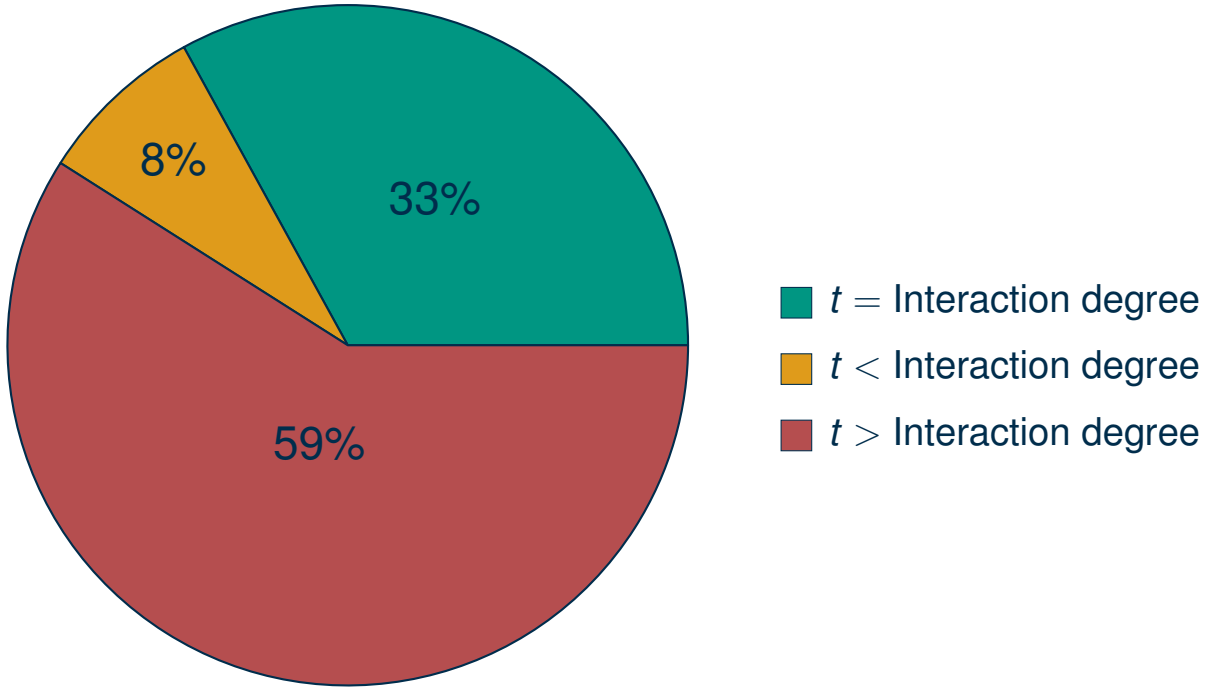

Ongoing Work

Current Issues

1. Some vulnerability warnings are raised only at a **sampling strength greater than** their actual **interaction strength**

Objectives

1. Analyze why certain findings are raised only by sampling stronger than their interation strength
   - Heuristics used in the analysis tool JOERN?
   - Discrepancy between problem space and solution space?

Identified by	JOERN query	File name	Line	Interaction strength	Presence condition
...	...	...	...	...	...
3-wise but not 2-wise	file-operation-race	miscutils/man.c	146	1	And(MAN)
3-wise but not 2-wise	file-operation-race	archival/bbunzip.c	75	1	Or(ZCAT ··· XZ)
...	...	...	...	...	...

Ongoing Work

Current Issues

1. Some vulnerability warnings are raised only at a **sampling strength greater than** their actual **interaction strength**
2. Calculation of actual **interaction strength does not yet consider feature model constraints**

Objectives

1. Analyze why certain findings are raised only by sampling stronger than their interation strength
   - Heuristics used in the analysis tool JOERN?
   - Discrepancy between problem space and solution space?
2. Devise a scalable method for calculating interaction strengths taking into account presence conditions and the feature model constraints

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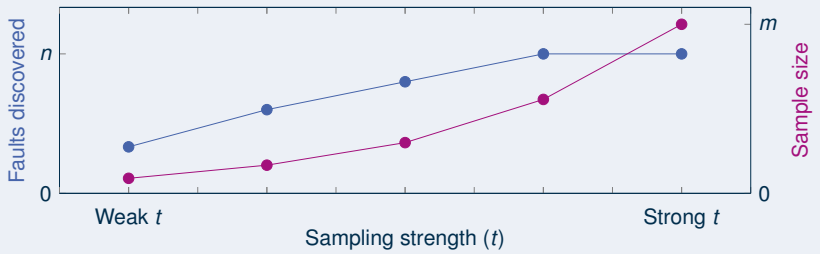

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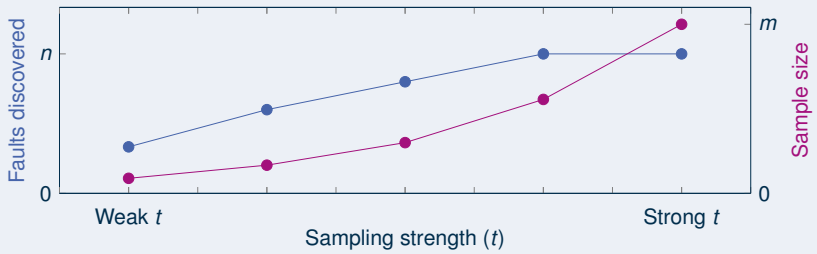

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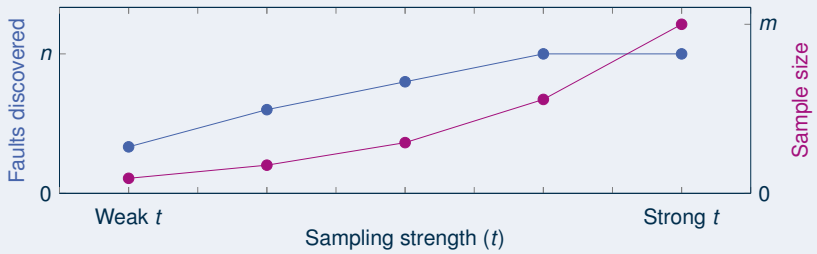

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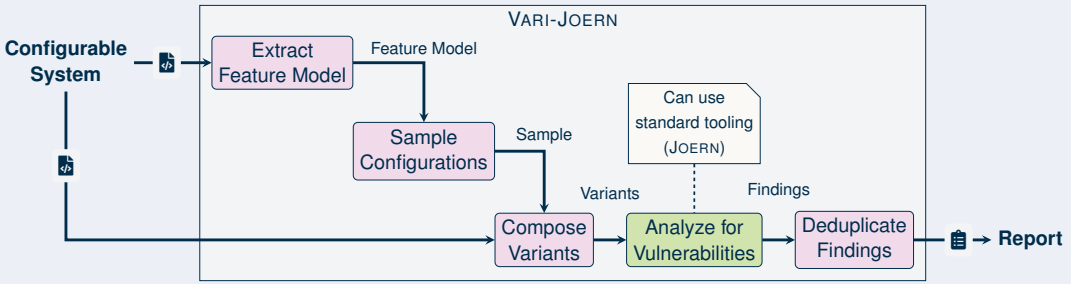

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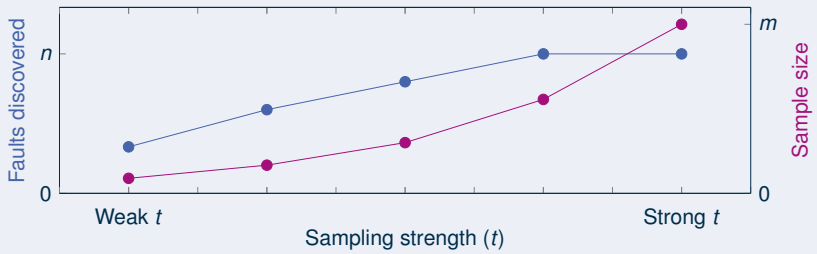

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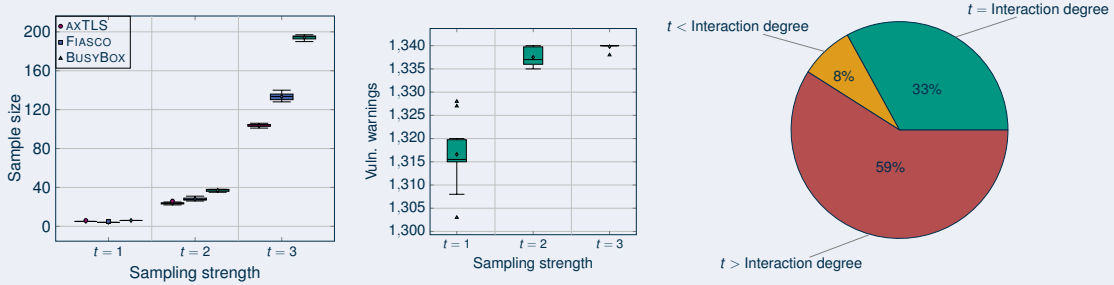
Results and Ongoing Work



- ☑ **RQ_1**: Can confirm previous observations
- ☐ **RQ_2**: Further analysis and work required

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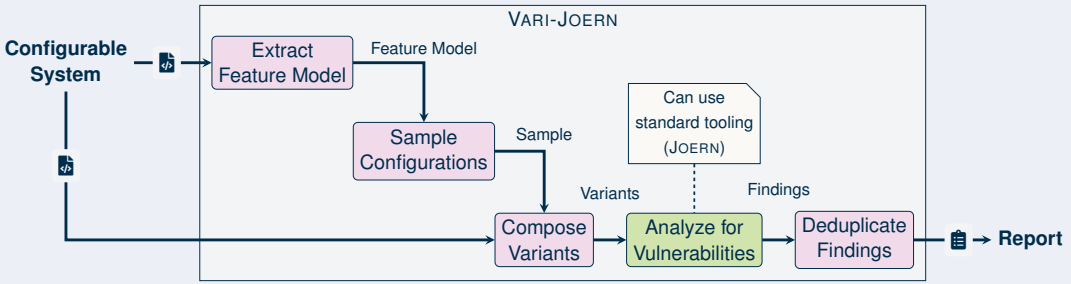

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