RAID 2021

SyML: Guiding Symbolic Execution Toward Vulnerable States Through Pattern Learning

Nicola Ruaro, Lukas Dresel, Kyle Zeng, Tiffany Bao, Mario Polino, Andrea Continella, Stefano Zanero, Christopher Kruegel, Giovanni Vigna

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Dynamic Symbolic Execution?

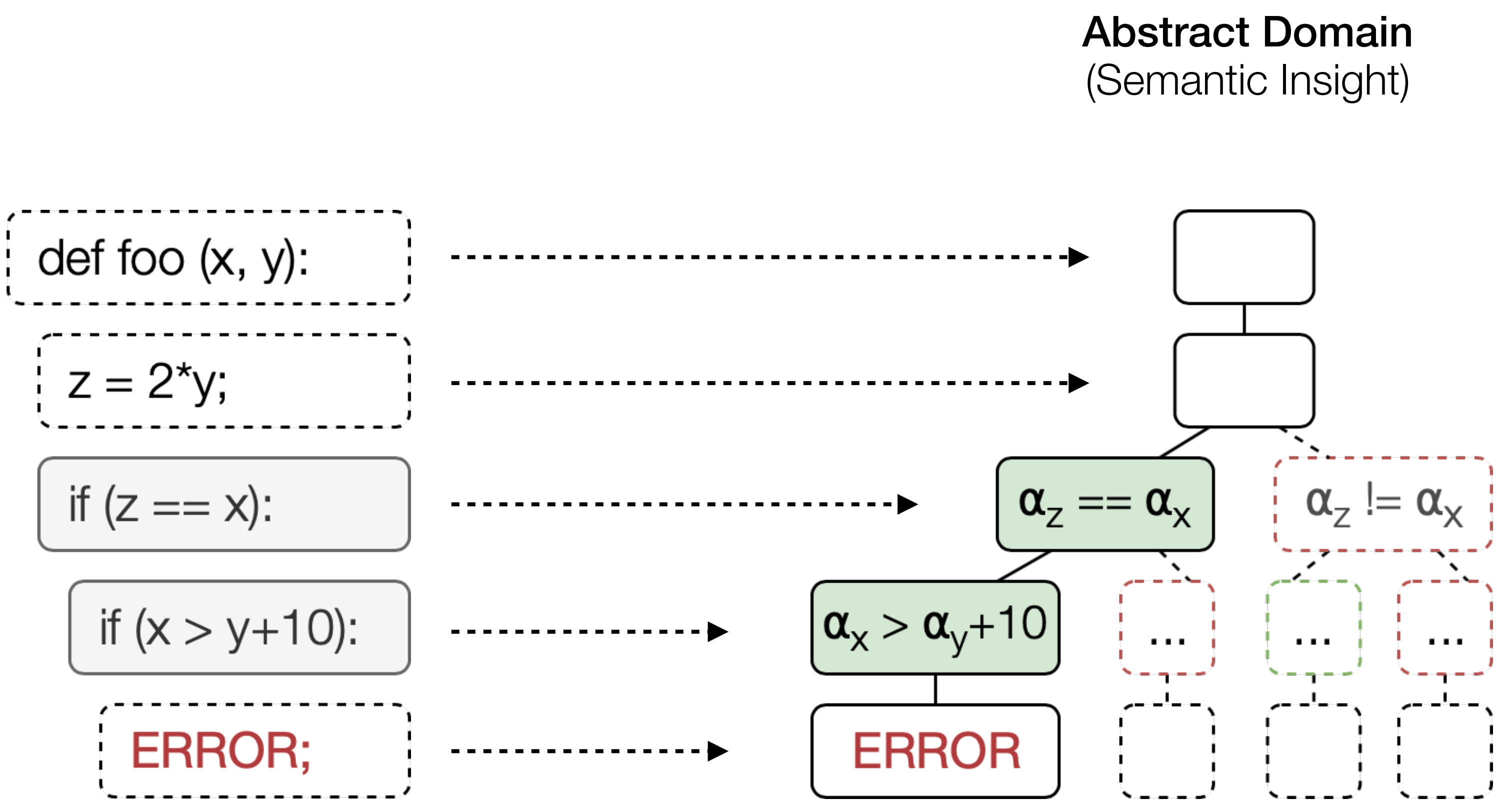
Dynamic Symbolic Execution

Dynamic?

Emulated Environment
(Replayability)

```
def foo (x, y):
  z = 2*y;
  if (z == x):
    if (x > y+10):
      ERROR;
```

Symbolic?



Abstract Domain
(Semantic Insight)
def foo (x, y):
z = 2*y;
if (z == x):
if (x > y+10):
ERROR;
$\alpha_z == \alpha_x$
$\alpha_z != \alpha_x$
$\alpha_x > \alpha_y+10$
...
...
...
ERROR

Dynamic Symbolic Execution

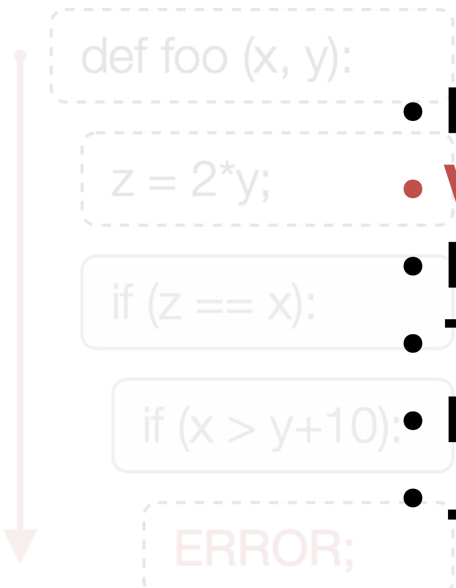
Emulated Environment
(Replayability)

Abstract Domain
(Semantic Insight)

- **Program Verification**
- **Vulnerability Analysis**
- **Exploit Generation**
- **Test-case Generation**
- **De-obfuscation**
- **...**

Dynamic Symbolic Execution

Emulated Environment
(Replayability)



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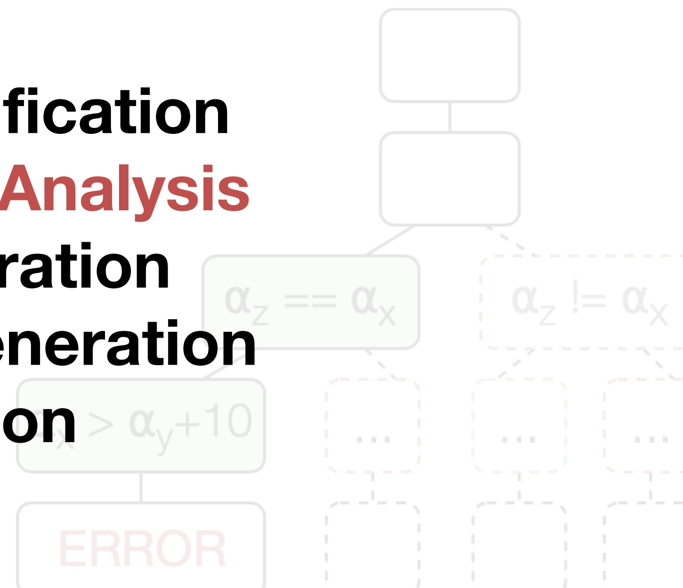

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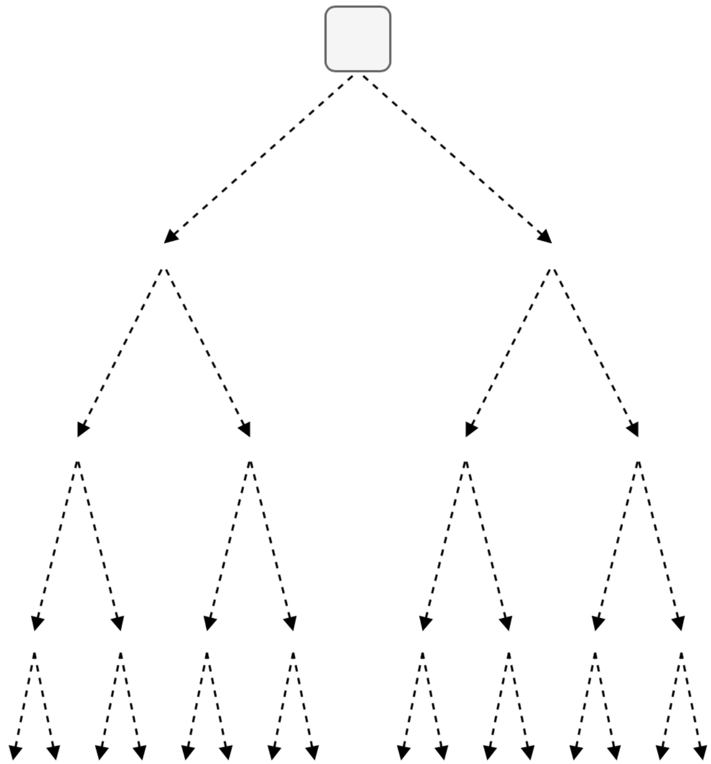
Path Explosion Problem

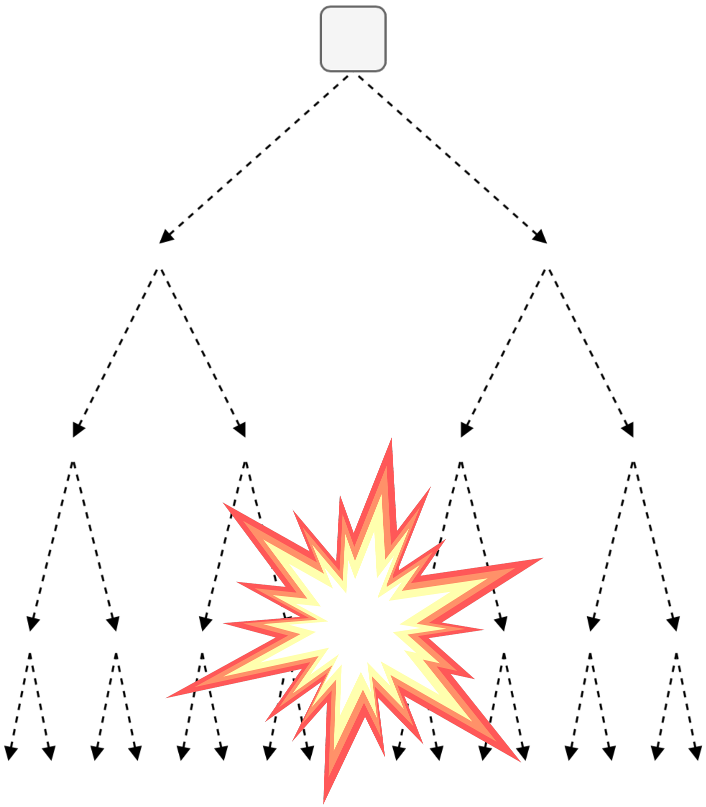
N Conditional Nodes



Path Explosion Problem

N Conditional Nodes
2^N Execution Paths

Limit exploration to a selected subset of execution paths



State-of-the-art

1. Symbolic-Assisted Fuzzing (Driller)
2. Under-Constrained Symbolic Execution
3. Merging Execution Paths (Veritesting)
4. Interleaved Symbolic Execution (Symbion)
5. Path Prioritization

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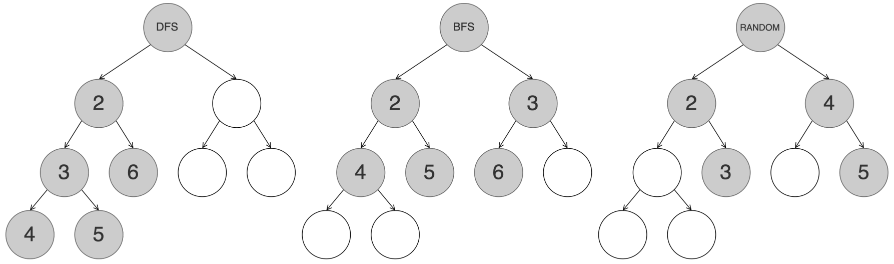
5. **Path Prioritization**
    A. Classic Tree Traversal
        - Depth First
        - Breadth First
        - Random
    B. Heuristic-Based
        - Loop Exhaustion
        - Coverage Optimization
        - ...



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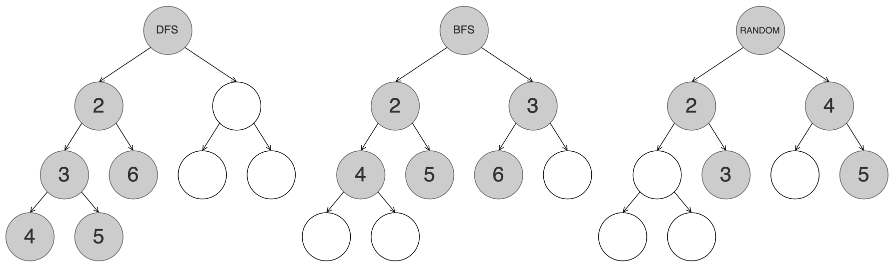
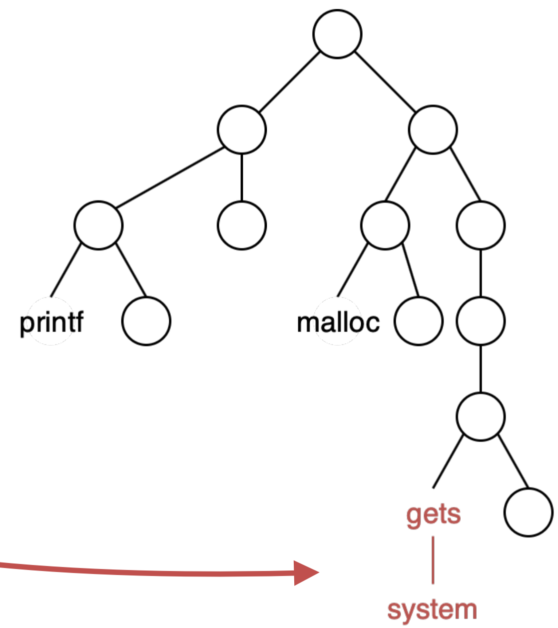


⇨ Shallow and Vulnerability-specific

Approach

Intuition

- More **coverage != ** more **bugs**
- Replicate the expertise of a **human analyst**
- Similar bugs == **similar patterns**
  (API calls, complex functions, etc.)
- Find **interesting execution contexts**



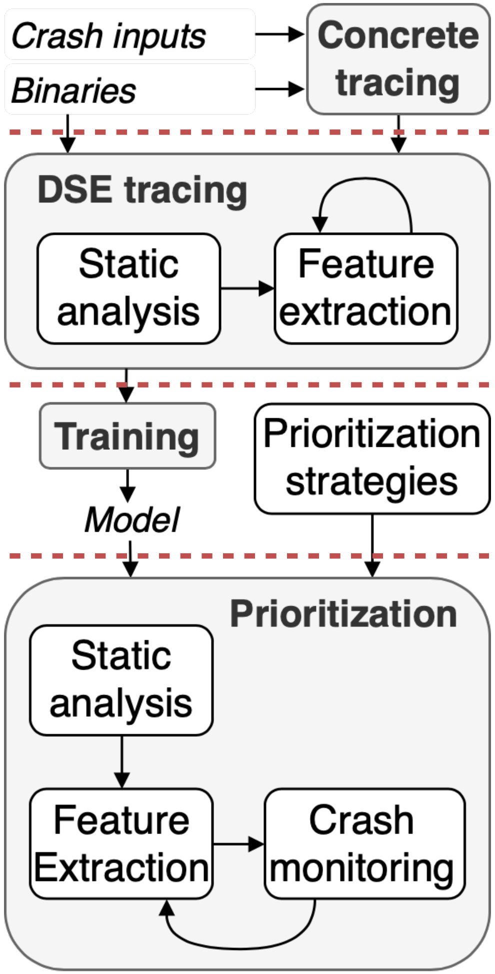
Approach Overview

Stage 1: Concrete Tracing

Stage 2: (Dynamic) Symbolic Tracing

Stage 3: Training

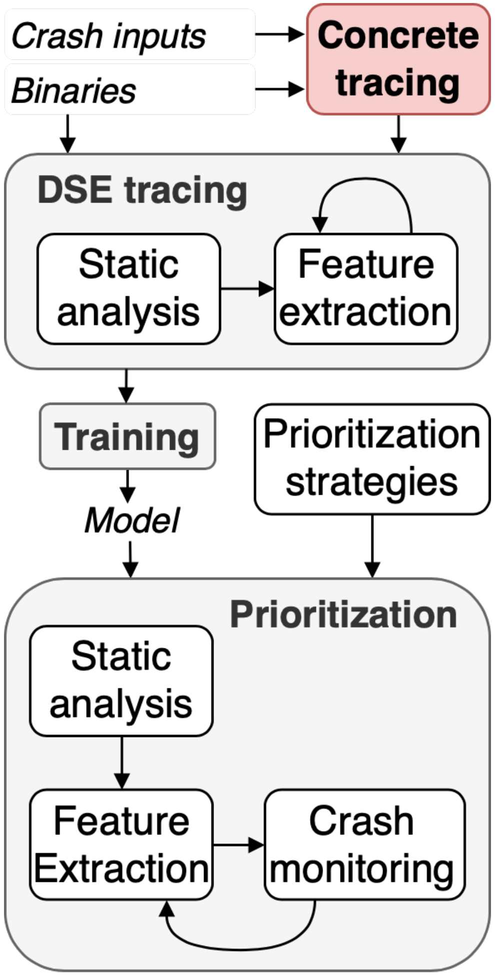
Stage 4: Prioritization



= angr

Stage 1: Concrete Tracing

- Dataset (**binaries** and **known vulnerabilities**)
- Run binary inside the QEMU emulator
- Send crashing input
- Monitor the execution
- Collect **execution traces**

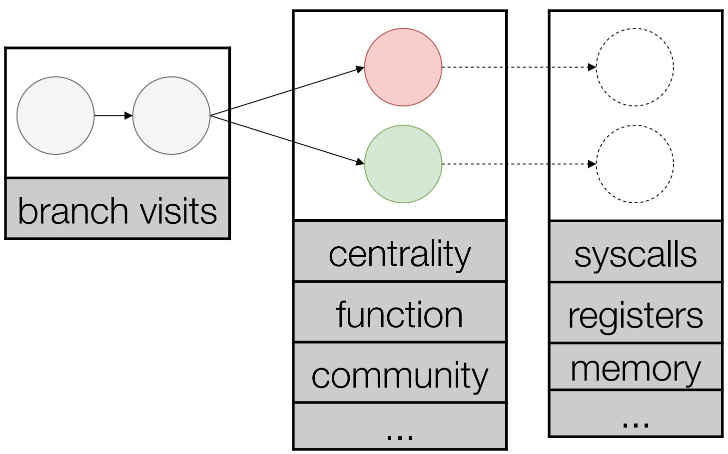


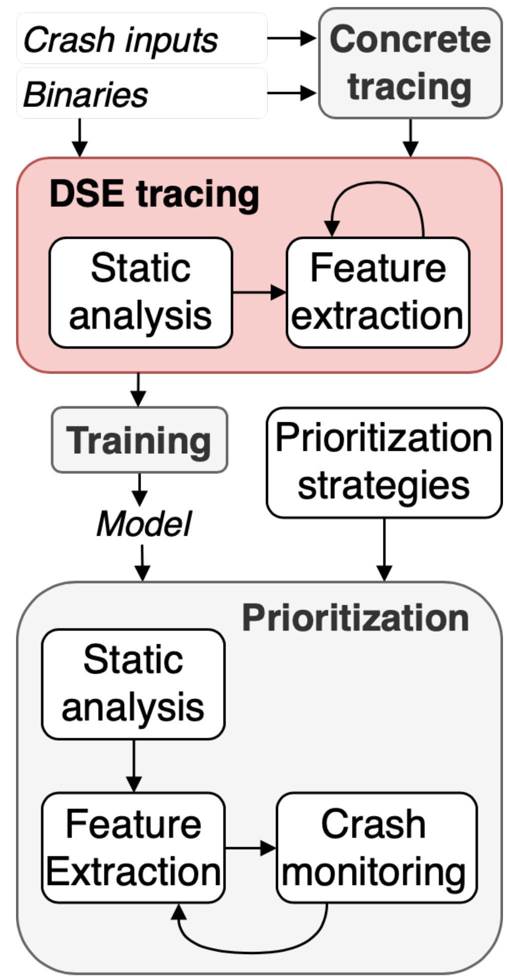
Stage 2: Symbolic Tracing

- **Static analysis** *(CFG, symbols, etc.)*

- Execute in angr
- **Synchronize** execution with recorded trace

- At every conditional node:
  - Create 2 new training points
  - **Extract features**

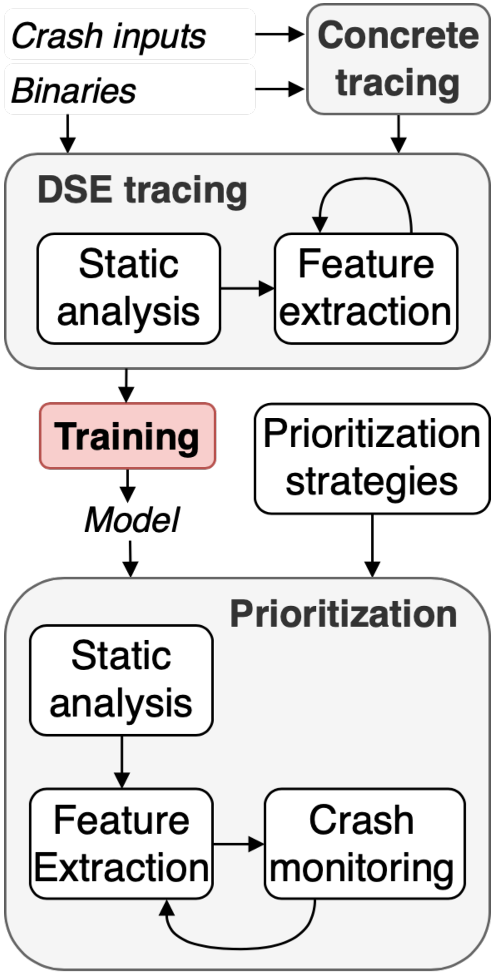




Stage 3: Training

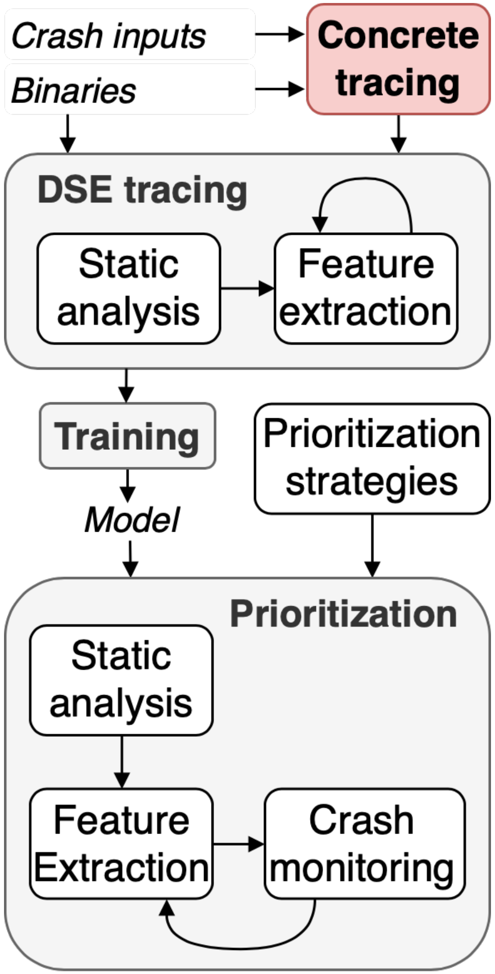
Clean Dataset:
- Numerical features
- Categorical features

Models: Log. Regression, SVM, Dec. Tree, etc.
Metrics: Accuracy, Coverage, F-1, etc.
Cross Validation: Leave-One-Out



Example

Stage 1: Concrete Tracing



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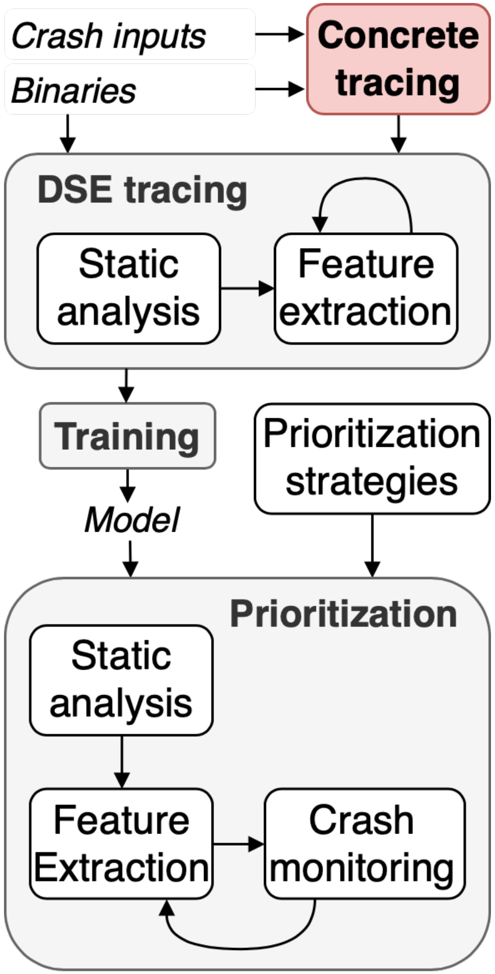
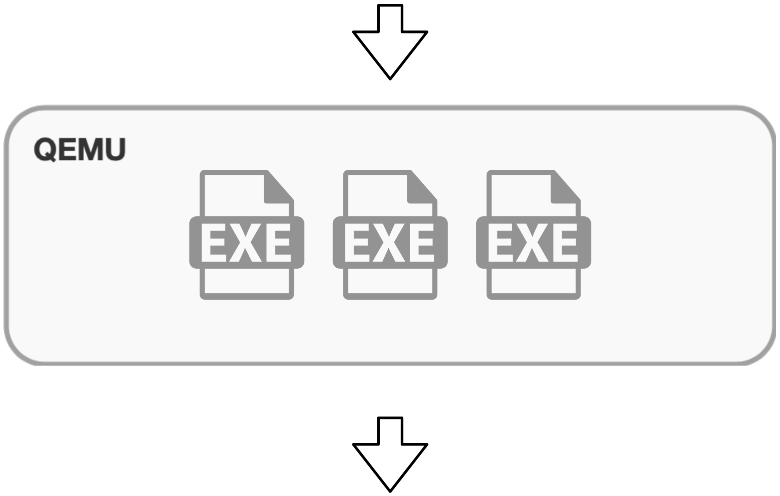
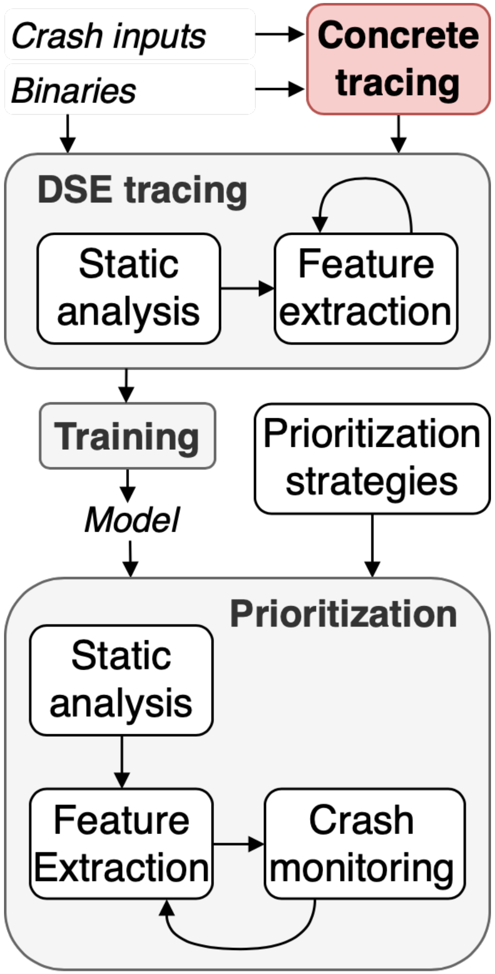


Stage 1: Concrete Tracing

INPUT: A!@^F^J%$#@!~(

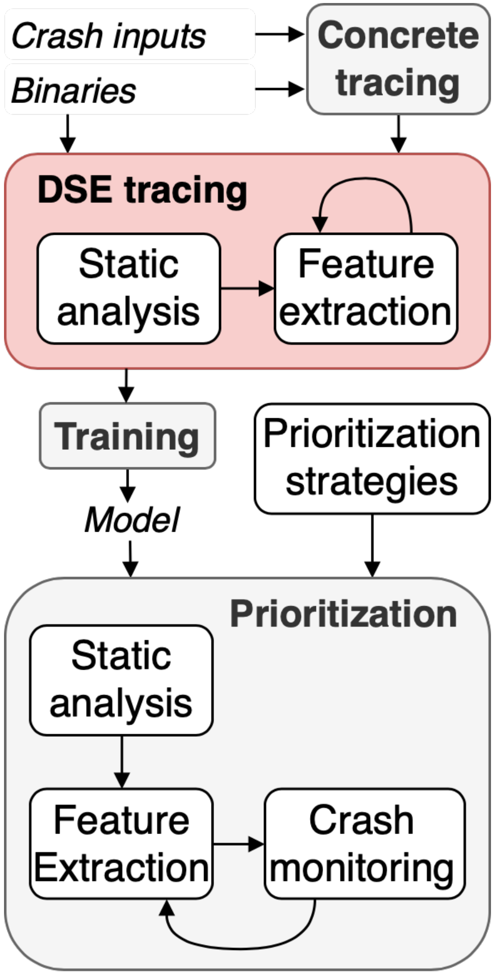


TRACE: 1, 2, 5, 6, 8, 5, 6, 8, 13 ..



Stage 2: Symbolic Tracing

1, 2, 5, 6, 8, 5, 6, 8, 13 ..



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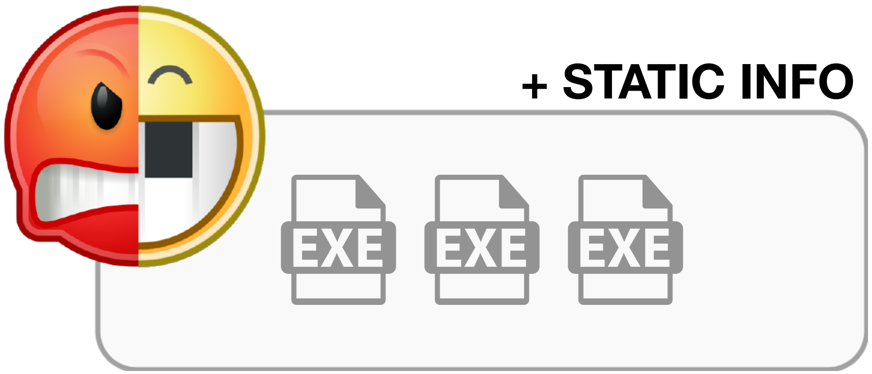

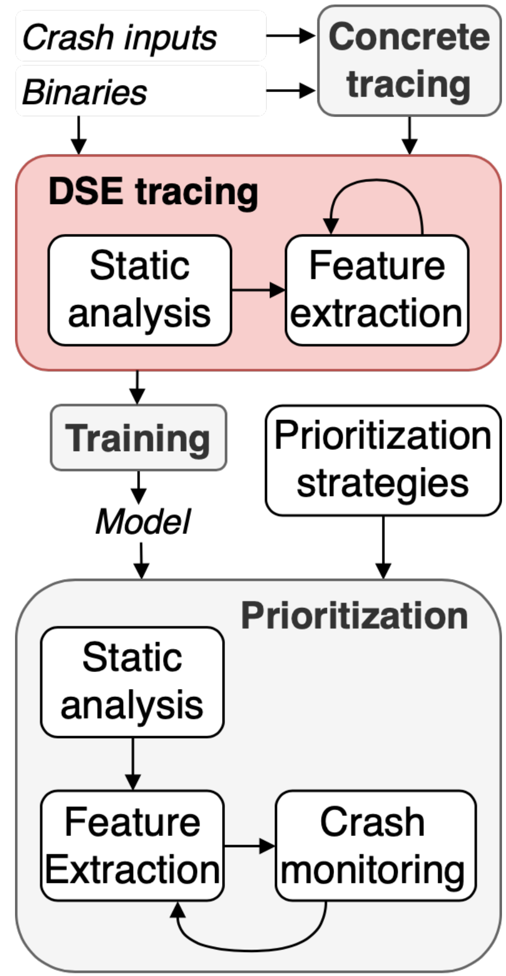

Stage 2: Symbolic Tracing

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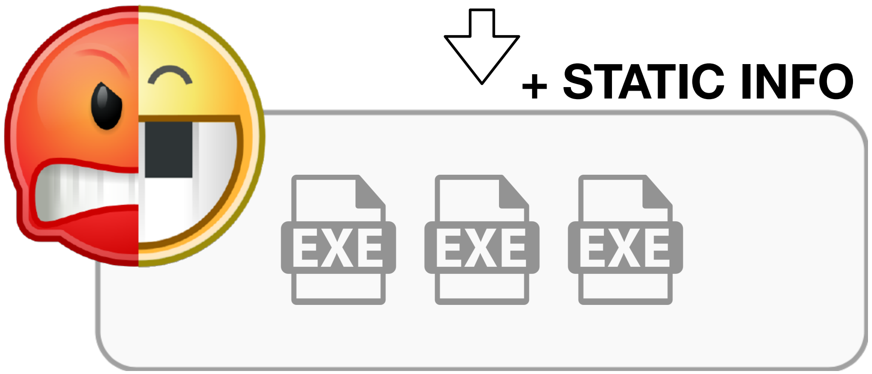
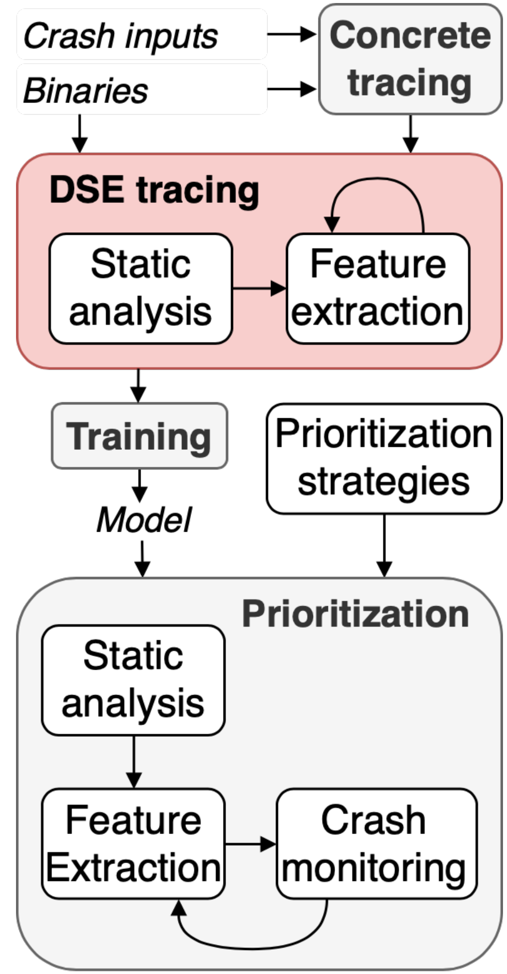


FALSE	111	12	0.0929	{'transmit', '_terminate'}	{'__ne__(SYM,CONCR)'}
TRUE	117	13	0.0112	{'_terminate', 'receive'}	{'CONCR'}



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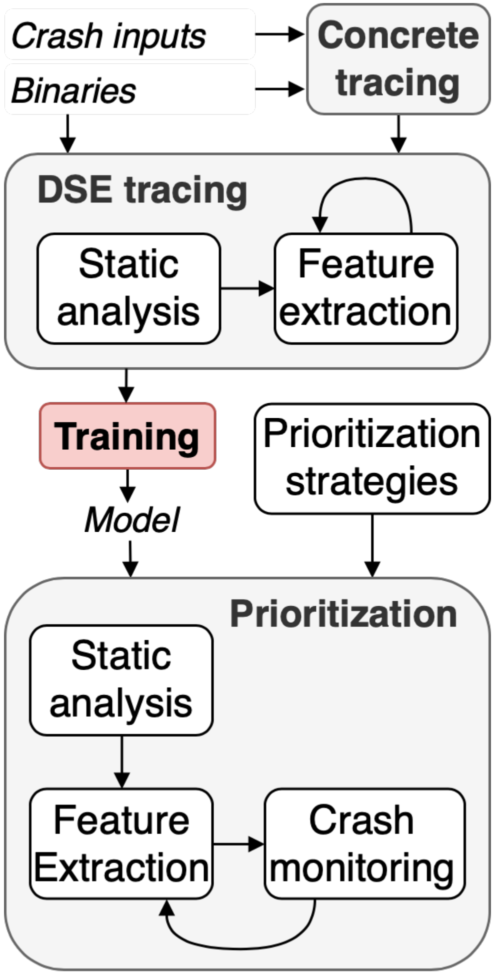

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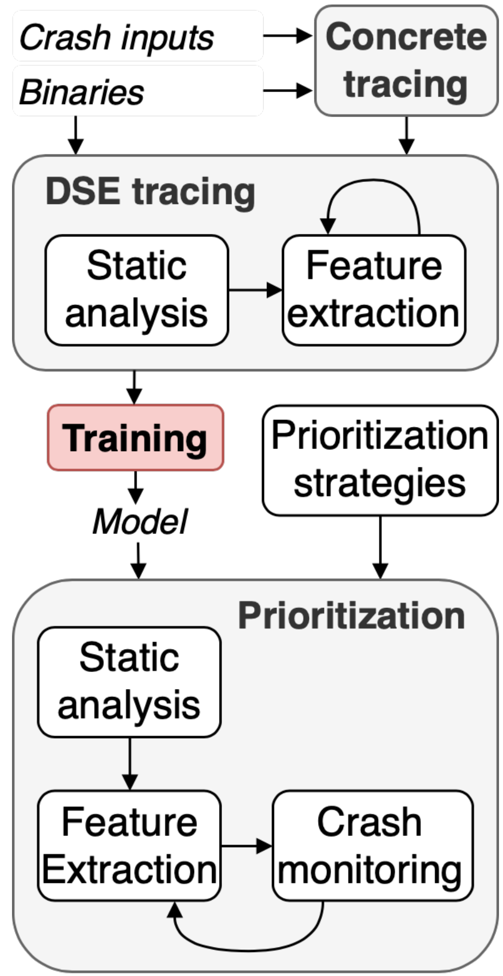
0	111	12	0.0929
1	117	13	0.0112

Numerical

1	1	0	1	0
0	1	1	0	1

Categorical



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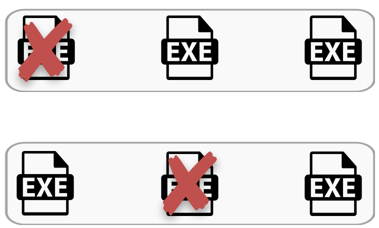
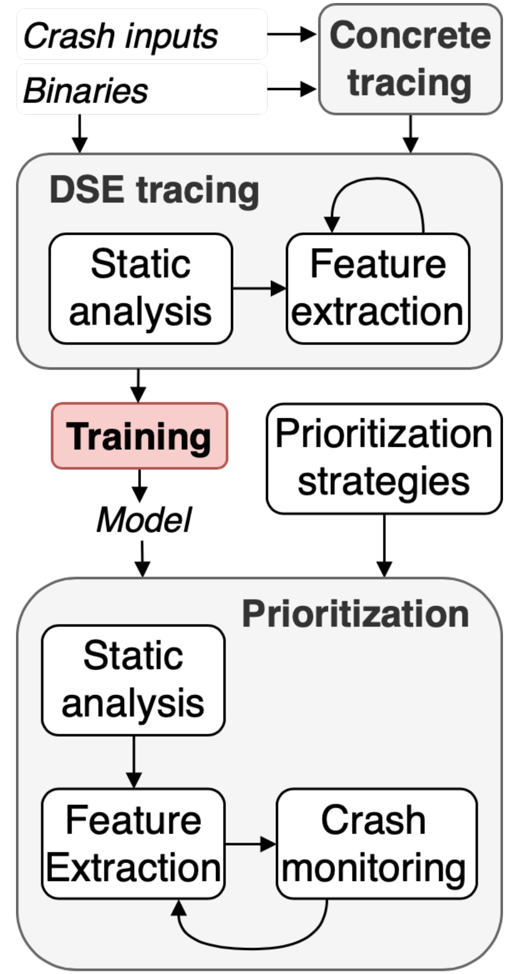


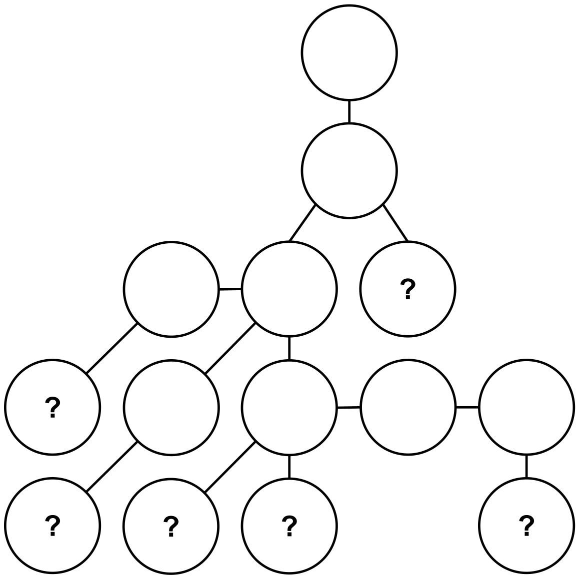
Accuracy?
Coverage?
Time-to-Score?

XGBoost model



Stage 4: Prioritization

XGBoost model

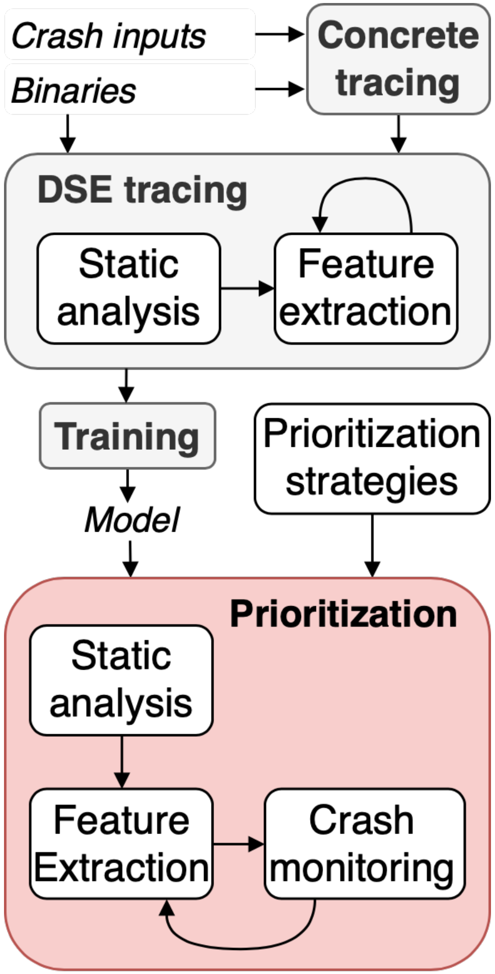


Fast strategy

$$next = \arg\max_{p \in active} \{\overline{score}(p)\}$$

Balanced strategy

$$\Pr(next = p) = \overline{score}(p)$$



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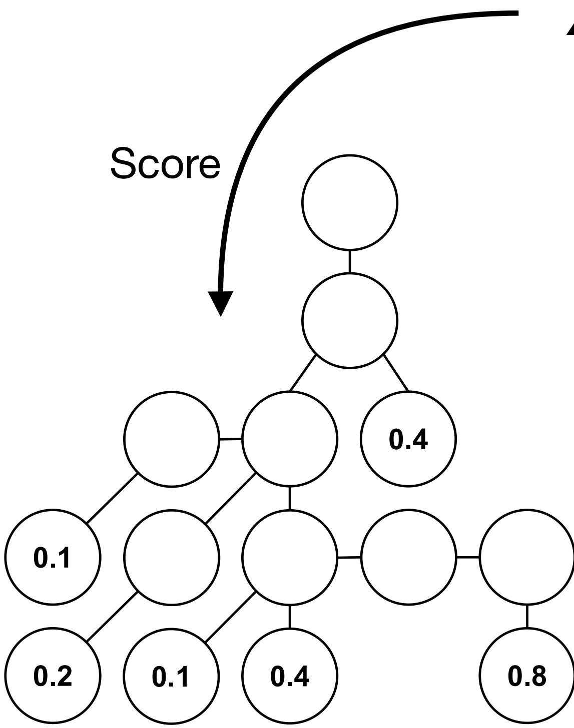

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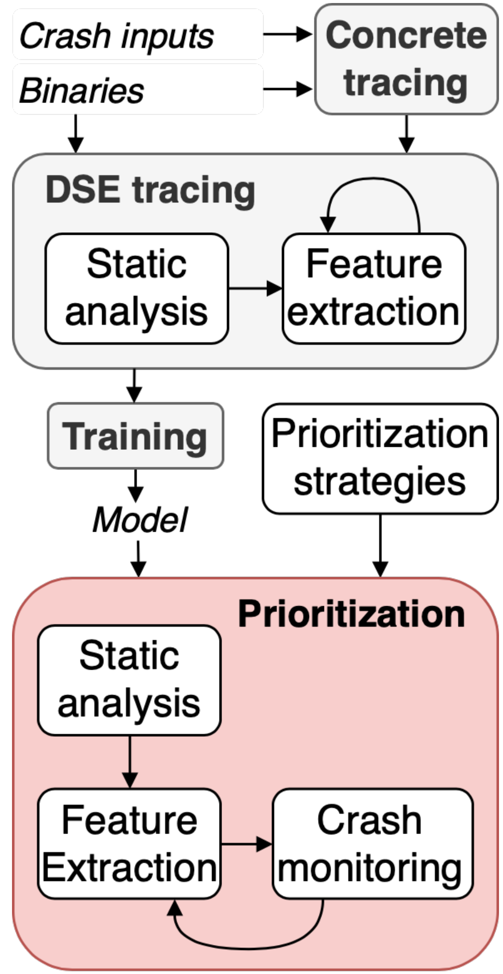

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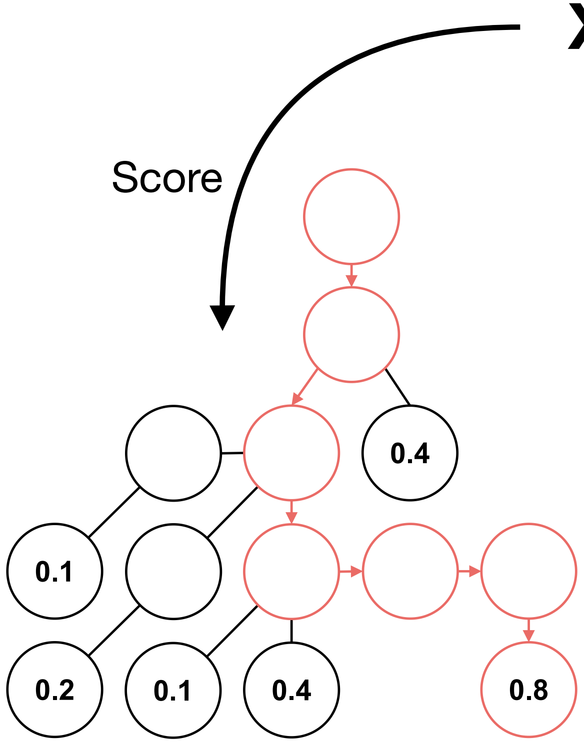

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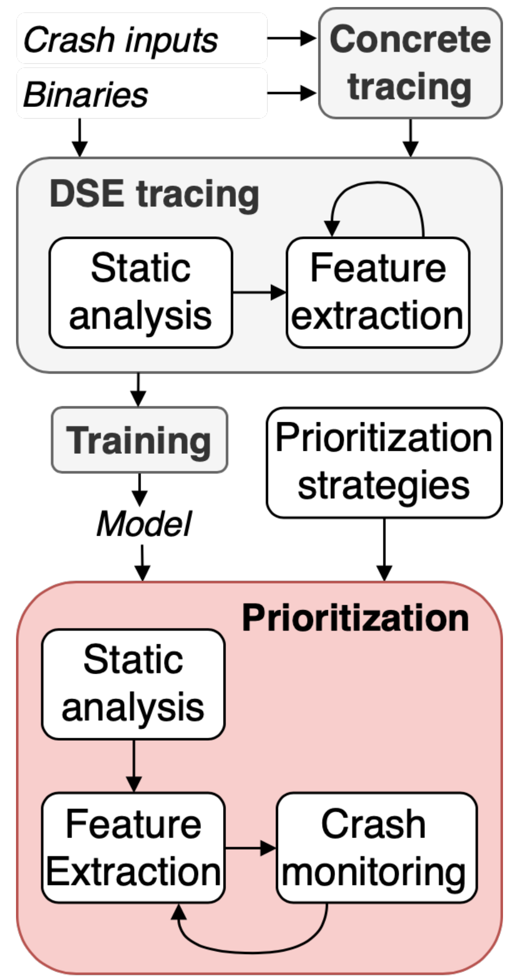

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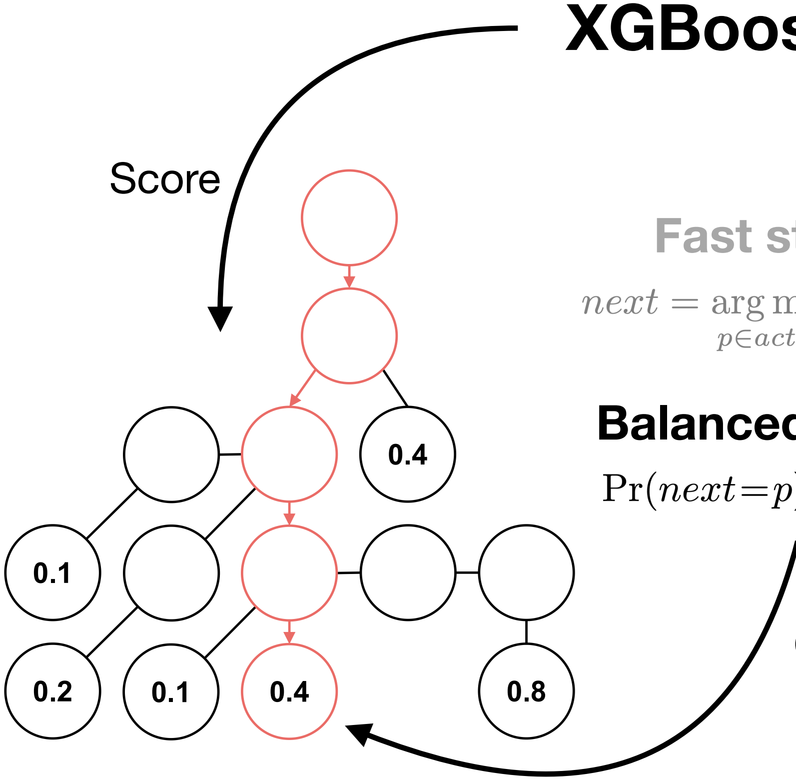

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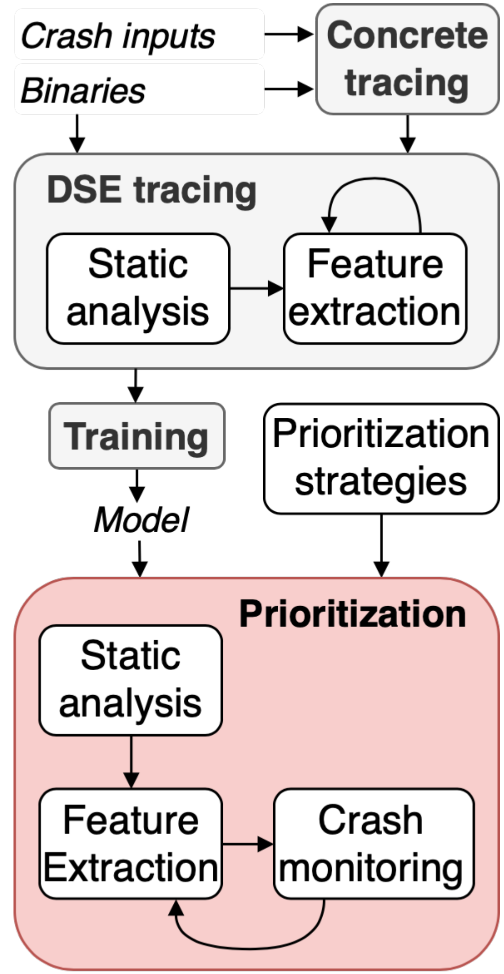

Evaluation

Experimental Setup

- Reimplement the state-of-the-art in a **unified framework** (angr)
  - AEG Loop Exhaustion
  - KLEE Coverage Optimization
  - KLEE Random

- Binaries and crashing inputs
  - **CGC Dataset**
  - 3 real-world **Linux CVEs** (transfer learning)

- 1 Binary per CPU Core (3,6GHz)
- Run and monitor for 24 hours
- **Check and classify crashes**

Dataset

- **CGC** dataset (**binaries** and **known vulnerabilities**)
  - Statically compiled x86 binaries
  - Semantics equivalent to Linux binaries
  - Running on DECREE—a different OS with a smaller set of system calls

- **Linux CVEs**
  - CVE-2004-1261 (asp2php)
  - CVE-2004-1288 (o3read)
  - CVE-2004-1292 (ringtonetools)

Model Choice

Model	F1	Accuracy	Trace Coverage	Time-to-Score
LogRegr	77%	66%	73%	0.01s
LinDiscr	76%	68%	75%	0.01s
KNN	79%	63%	70%	0.1s
SVM	82%	76%	72%	0.04s
MLP	81%	80%	68%	0.04s
DecisionTree	85%	80%	78%	0.02s
RandomForest	92%	90%	90%	0.32s
AdaBoost	93%	91%	83%	0.02s
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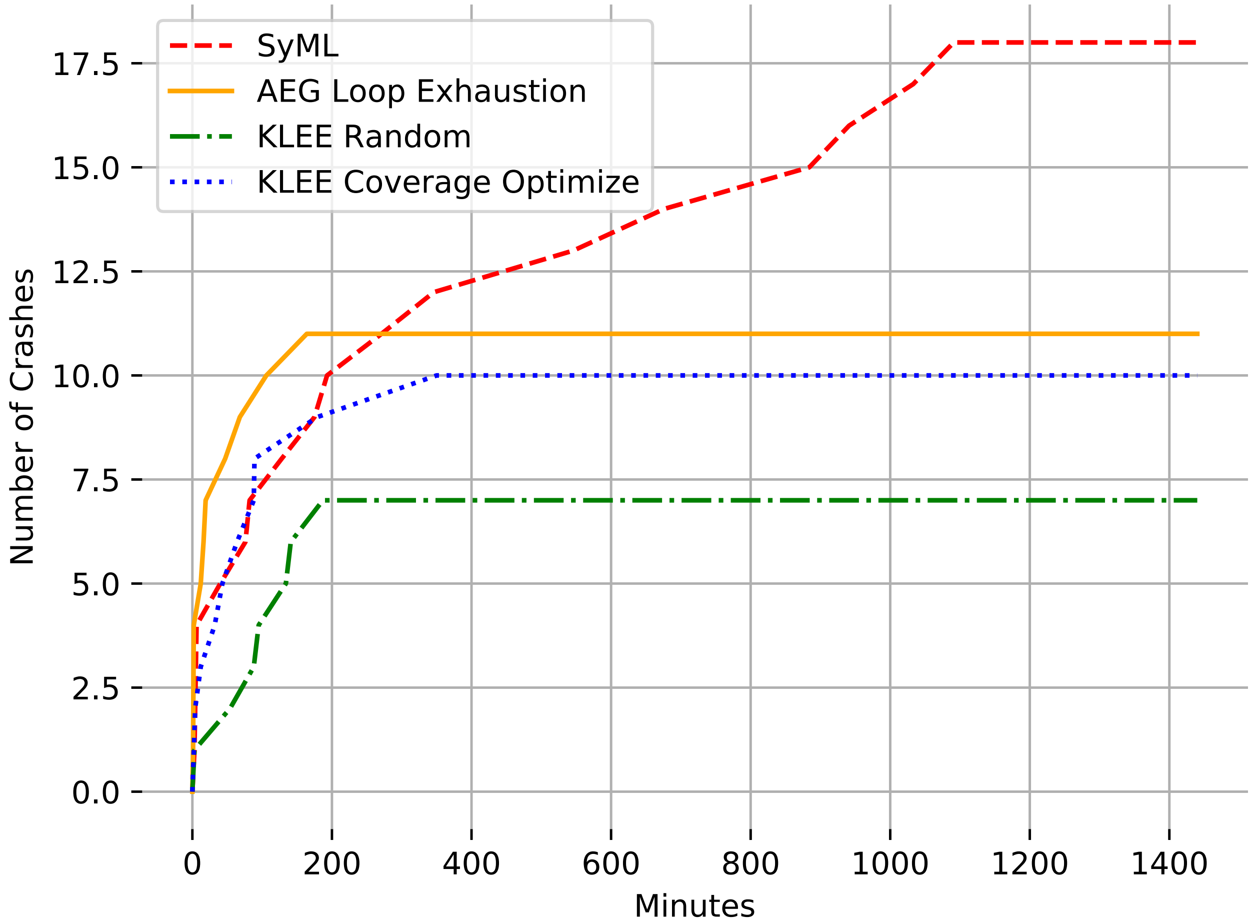
Comparison Results



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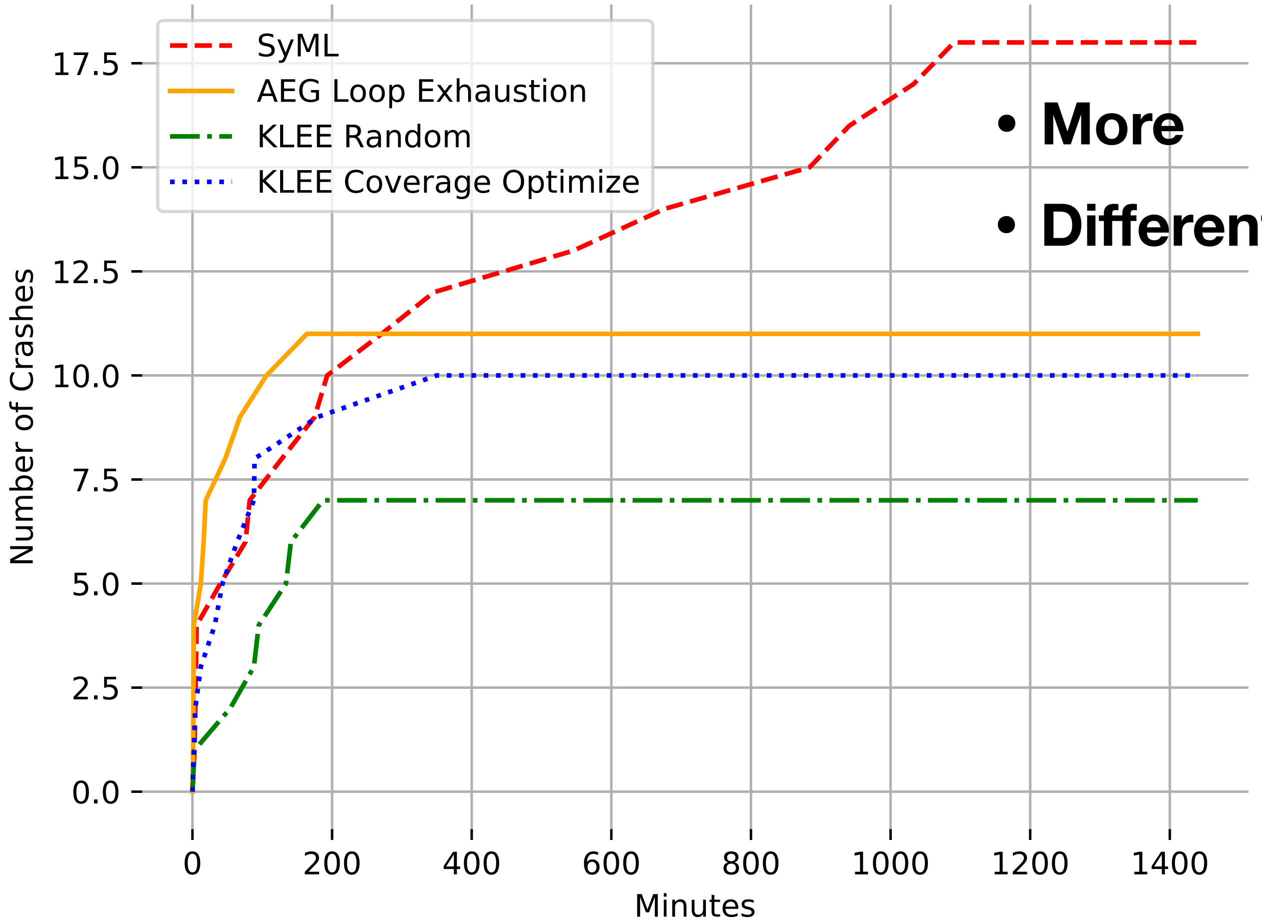


- **More**
- **Different**

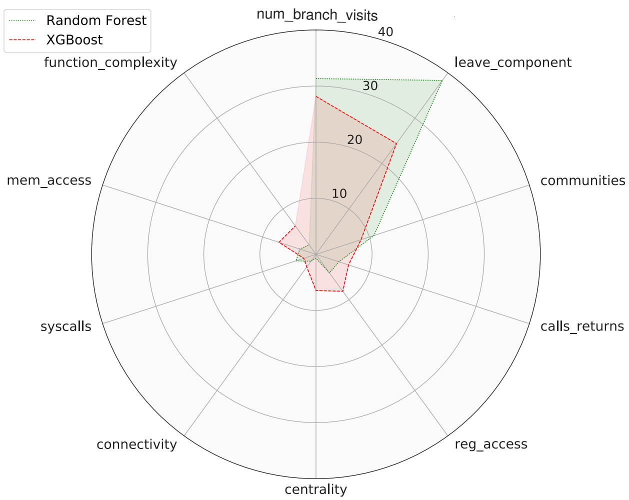
Model Analysis

Features Importance

Prediction Scores Distribution

Model Analysis

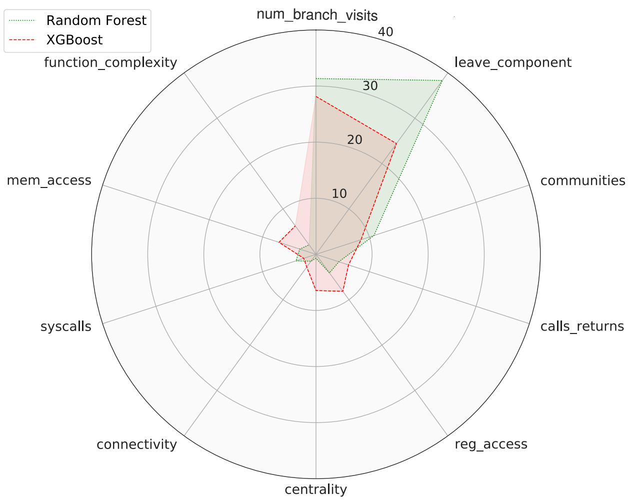
Features Importance

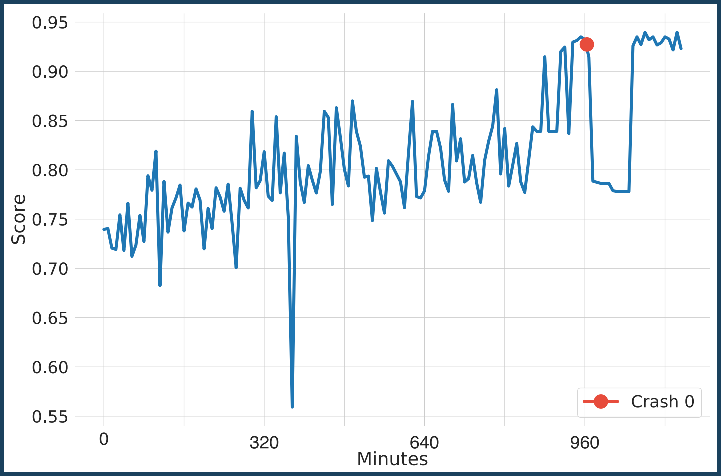


Prediction Scores Distribution

Model Analysis

Features Importance





Prediction Scores Distribution

Transfer Learning

- DSE inaccuracies make it hard to re-trace Linux binaries
- CGC semantics are analogous to the Linux x86 semantics
  - This allows us to transfer some of the knowledge learned from the larger CGC dataset to the Linux dataset

Model	F1	Accuracy
RandomForest (Linux)	63%	70%
AdaBoost (Linux)	63%	63%
XGBoost (Linux)	51%	56%
XGBoost (CGC)	69%	54%
XGBoost (CGC+Linux)	77%	66%

Conclusion

- We propose a **novel path prioritization** approach, leveraging supervised learning algorithms to steer DSE and reach interesting paths
- We evaluate our approach on the CGC dataset, **outperforming prior work** with more (and different) vulnerabilities
- We effectively **transfer the models learned** on the CGC dataset to achieve a better prediction accuracy on 3 real-world CVEs affecting Linux

Future Work

- Train on a **large dataset of Linux binaries** using a different re-tracing framework
- Adapt and apply to guide **hybrid fuzzing**

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Thank You!

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