Chopping Code for More Modular and Scalable Symbolic Execution

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Joint work with

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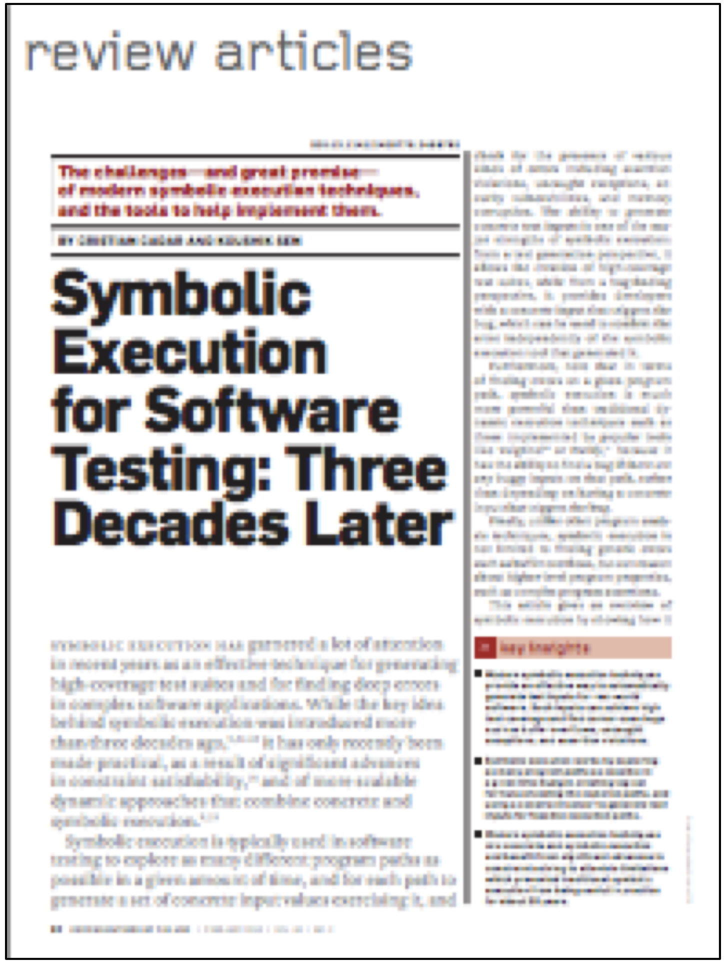
Symbolic Execution
or Dynamic Symbolic Execution (DSE)

Program analysis technique for ***automatically exploring paths*** through a program

Applications in:

- Bug finding
- Test generation
- Vulnerability detection and exploitation
- Equivalence checking
- Debugging
- Program repair
- etc. etc.

Modern Symbolic Execution


review articles

The challenges—and great promise—of modern symbolic execution techniques, and the tools to help implement them.

BY CRISTIAN CADAR AND KOUSHIK SEN

Symbolic Execution for Software Testing: Three Decades Later

[Cadar and Sen, CACM 2013]

- Symbolic execution introduced in 1970s
  - *Boyer, Elspass, Levitt (SRI)*
  - *Clarke (UMass Amherst)*
  - *King (IBM Research)*

- Revived in 2005 in the form of *dynamic symbolic execution:*
  - *DART system (Bell Labs)*
  - *EGT system (Stanford)*

Dynamic Symbolic Execution

PyExZ3 SymDroid KLOVER jCUTE

SAGE The KeY Project Otter PathGrind SymJS

Jalangi2 BinSE CREST Miasm

CUTE

Symbolic PathFinder

angr KLEE DART Kite

LDSE

Pex

Rubyx JDart S^2E

CATG CiVL Mayhem

Webpage: **http://klee.github.io/**

Code: **https://github.com/klee**

Web version: **http://klee.doc.ic.ac.uk/**

- Active user and developer base with over 300 subscribers on the mailing list and over 50 contributors listed on GitHub
- Academic impact:
  - Over 2K citations to original KLEE paper
  - From many different research communities: testing, verification, systems, software engineering, security, etc.
  - Several influential systems using KLEE: AEG, Angelix , BugRedux , Cloud9, GKLEE, KleeNet, KLEE-UC, S2E, SemFix, etc.
- Growing impact in industry:
  - **Fujitsu**: [PPoPP 2012], [CAV 2013], [ICST 2015], [IEEE Software 2017], [KLEE Workshop 2018], **Hitachi**: [CPSNA 2014], [ISPA 2015], [EUC 2016], **Trail of Bits**: https://blog.trailofbits.com/, **Intel**: [WOOT 2015], **NASA Ames**: [NFM 2014], **Baidu**: [KLEE Workshop 2018]

From Whole-Program Analysis… …To More Localized Tasks

- Most work on modern symbolic execution:
  - Whole-program test generation
  - Whole-program bug-finding
- More recently attention shifted to more localized tasks:
  - Patch testing
  - Debugging
  - Bug reproduction
  - Program repair
  - etc.
- Which one is easier?

Opportunity of more localized tasks:

Prune a large part of the search space

Chopped Symbolic Execution

- Some code fragments are unrelated to certain tasks
  - But symbolic execution can spend lots of time unnecessarily analyzing them
- Determining precisely if a part of the code is unrelated is hard
  - Often, most computation in a code fragment is unrelated, but not all

IDEA:

1) Guess unrelated code fragments (manually or via lightweight analysis)
2) Speculatively skip these code fragments
3) If their side effects are ever needed, execute relevant paths only

Chopped Symbolic Execution

```
int j; // symbolic
int k; // symbolic
int x = 0;
int y = 0;
```

```
void main() {
  f();
  if (j > 0) {
    if (y)
      target1;
  }
  else target2;
}
```

```
void f() {
  if (k > 0)
    x = 1;
  else
    if (j > 0)
      y = 1;
    else
      y = 0;
}
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void f() {
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}
```

Ref(main) = **{j, y}**

Mod(f) = **{x, y}**

Chopped Symbolic Execution

```c
int j; // symbolic
int k; // symbolic
int x = 0;
int y = 0;
```

```c
void main() {
  f();
  if (j > 0) {
    if (y)
      target1;
  }
  else target2;
}
```

Dependent load

```c
void f() {
  if (k > 0)
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  else
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```

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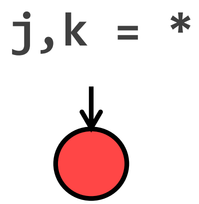


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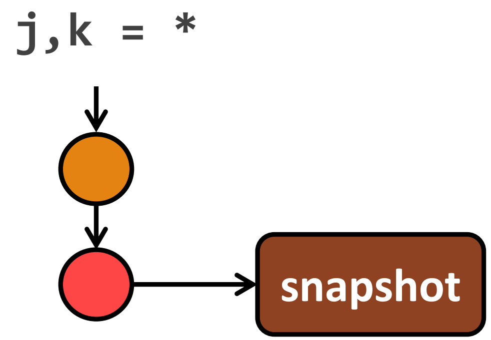


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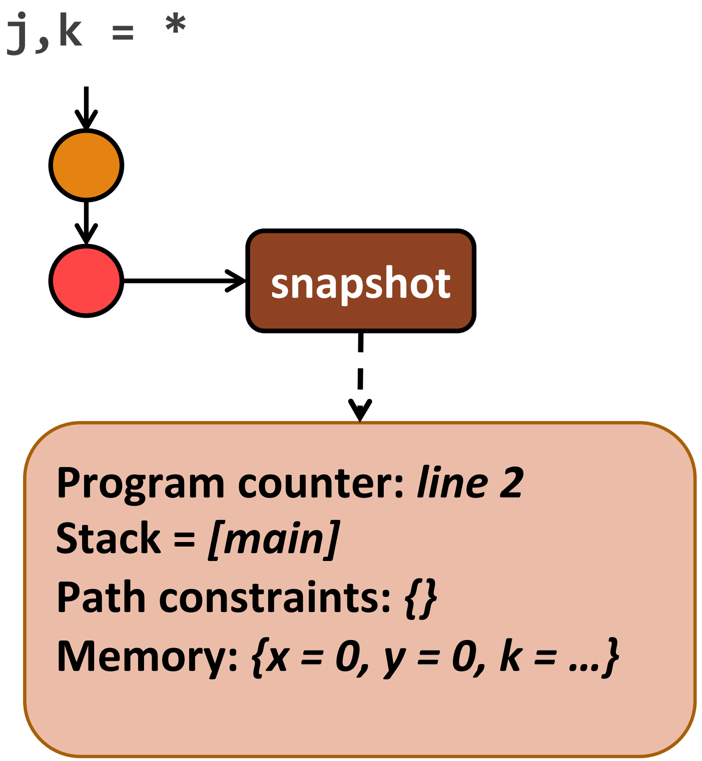


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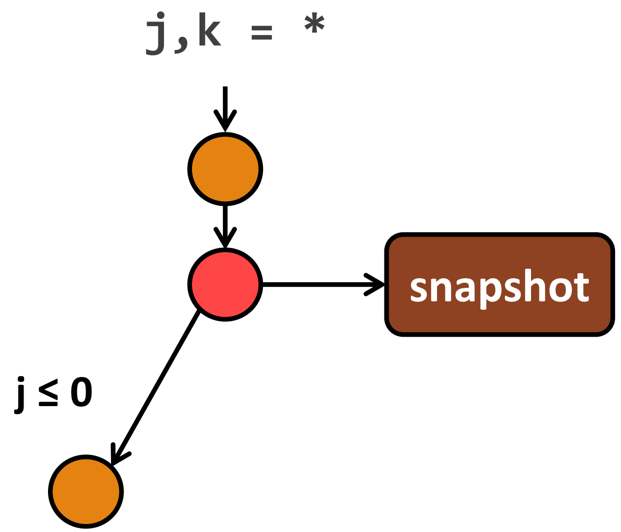


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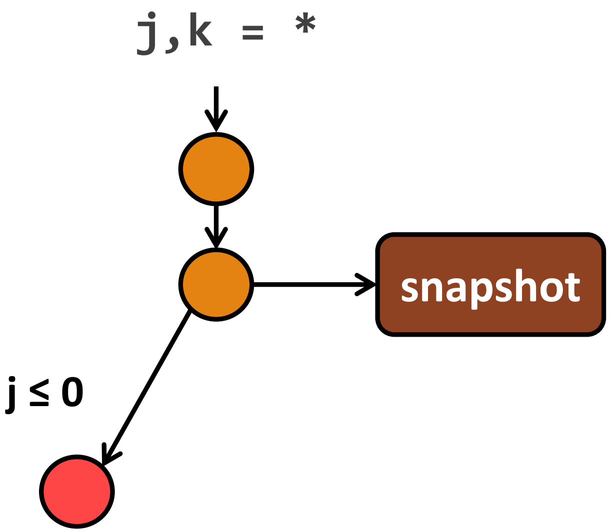


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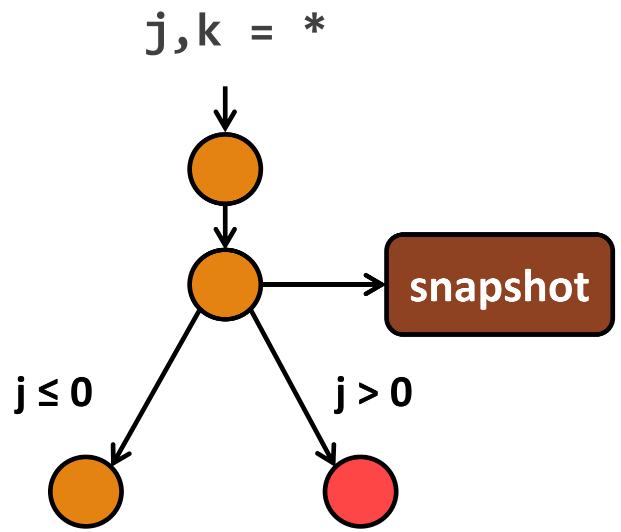

dependent load

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void main() {
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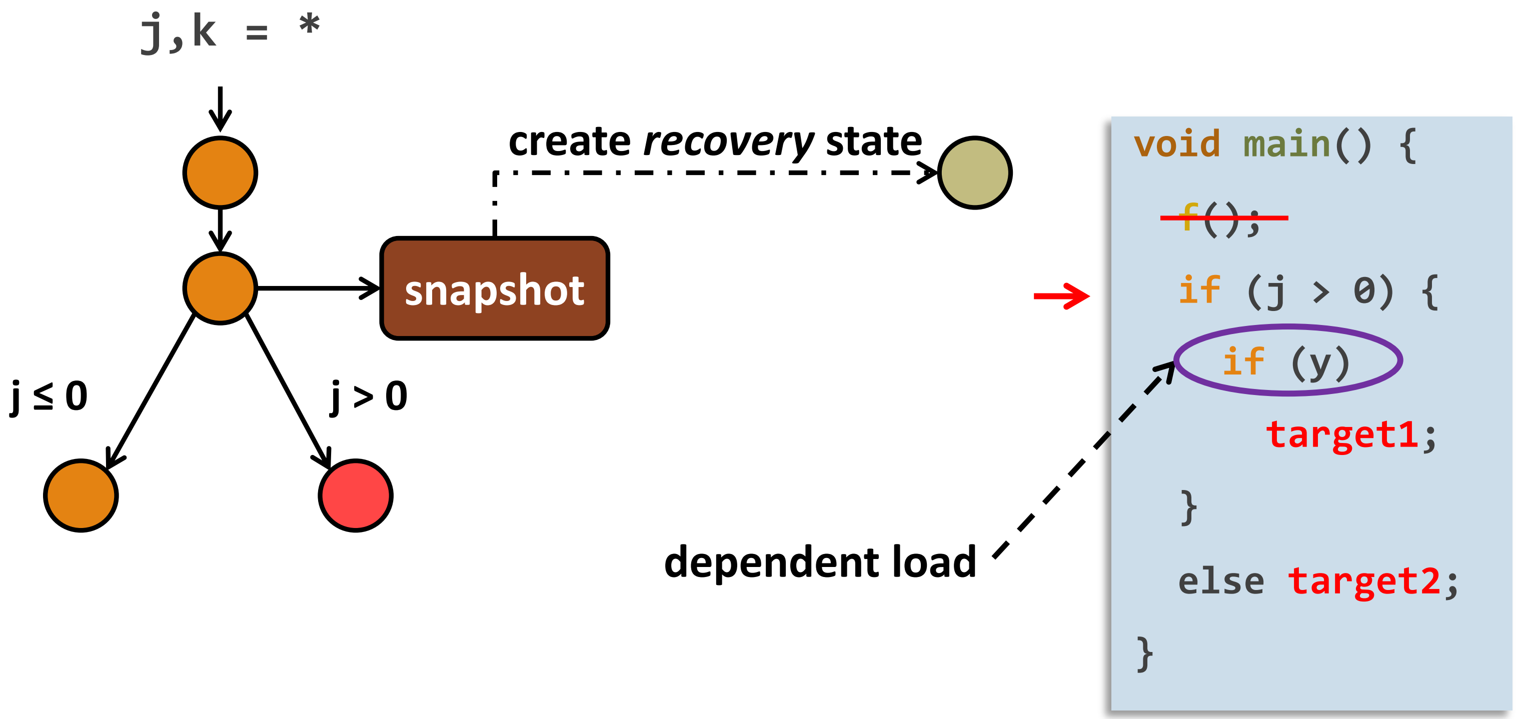
Chopped Symbolic Execution



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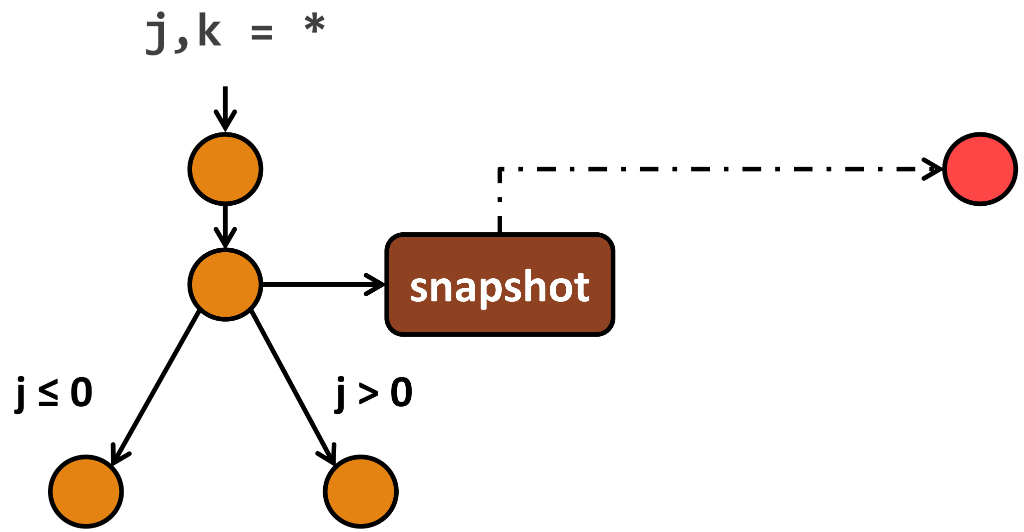


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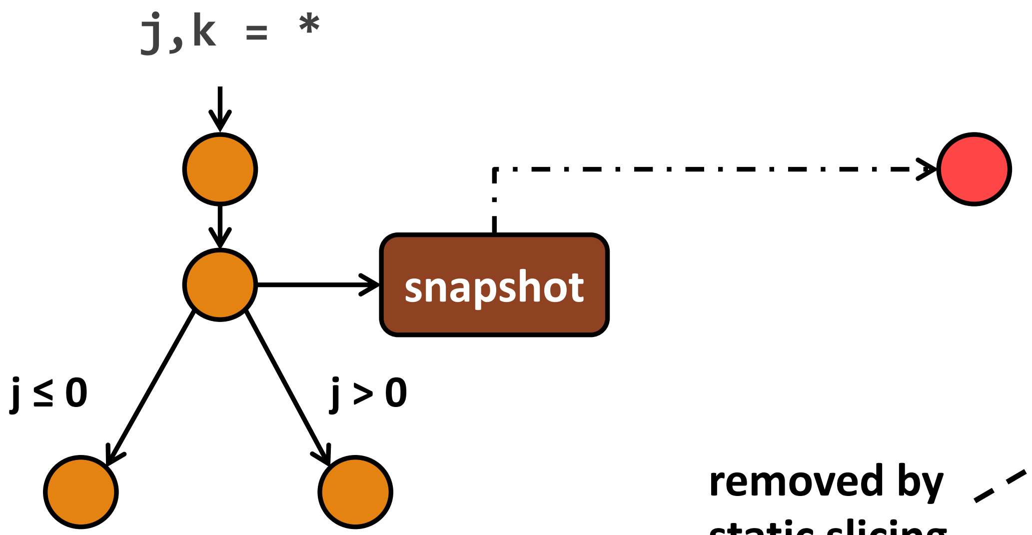

removed by static slicing

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void f() {
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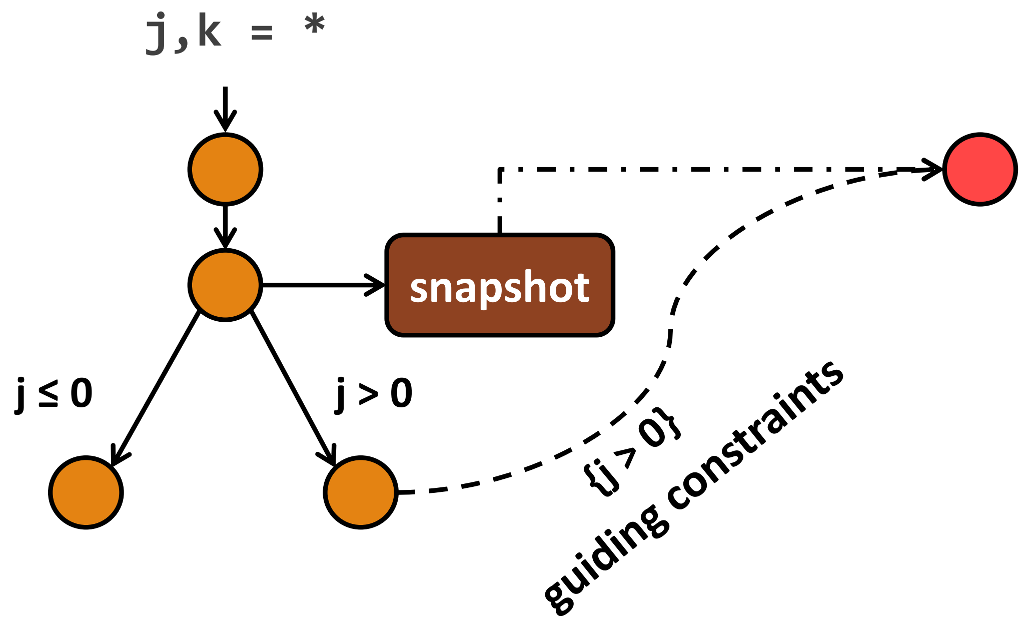
Chopped Symbolic Execution

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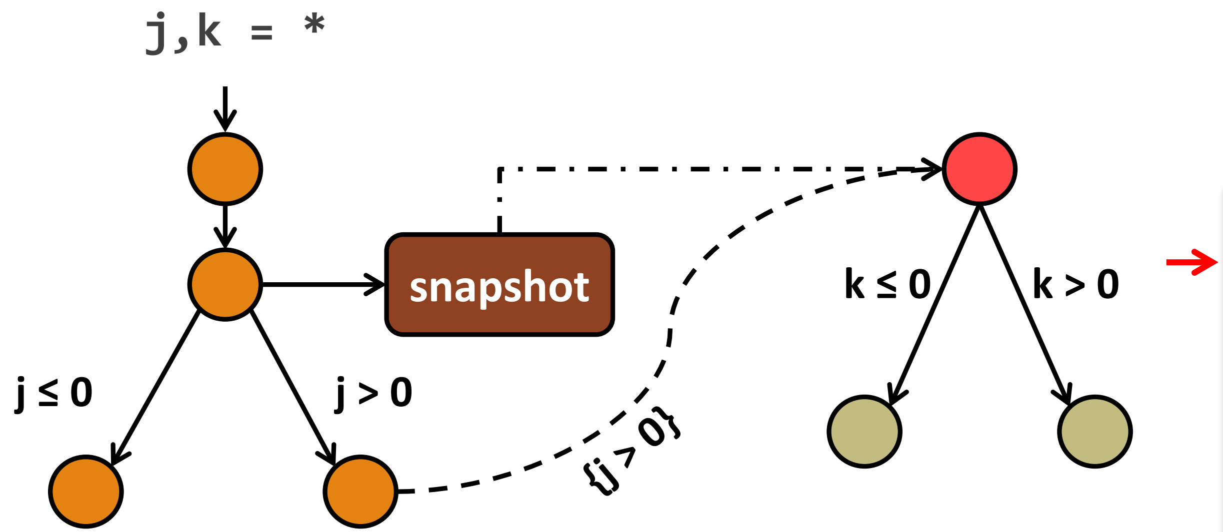


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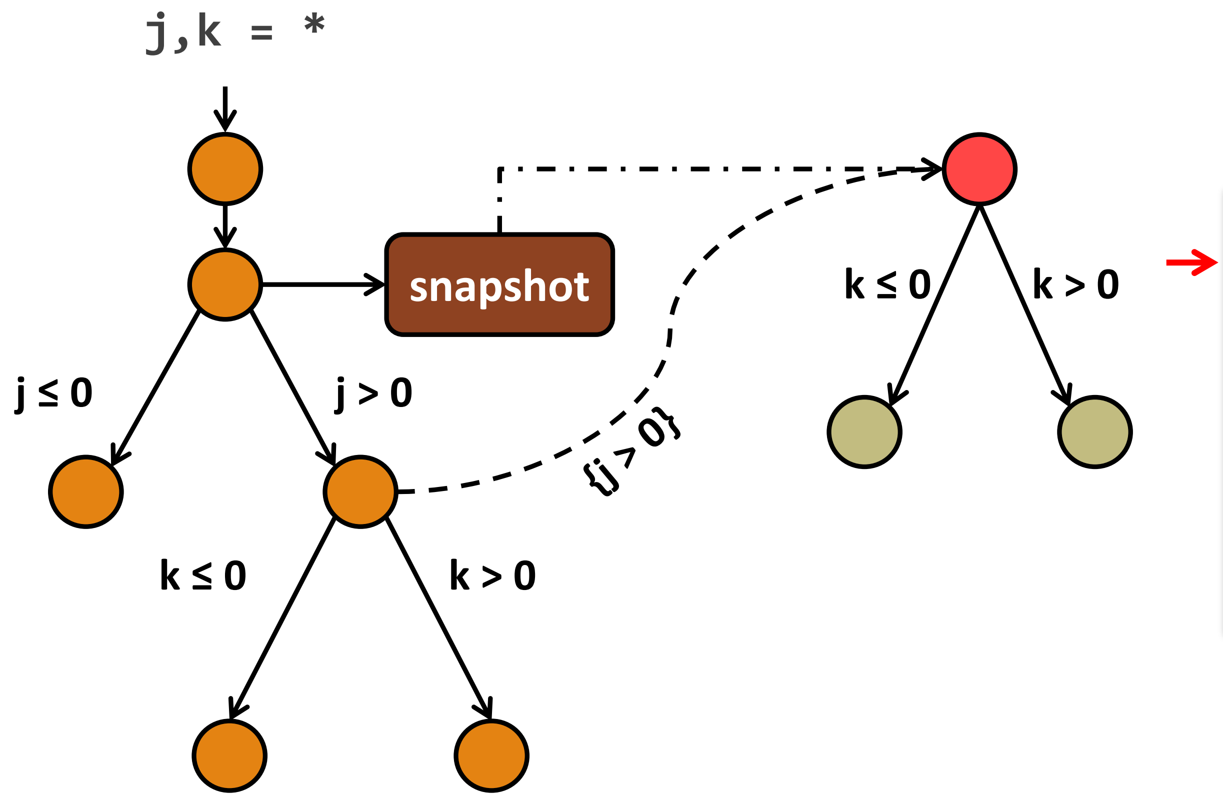


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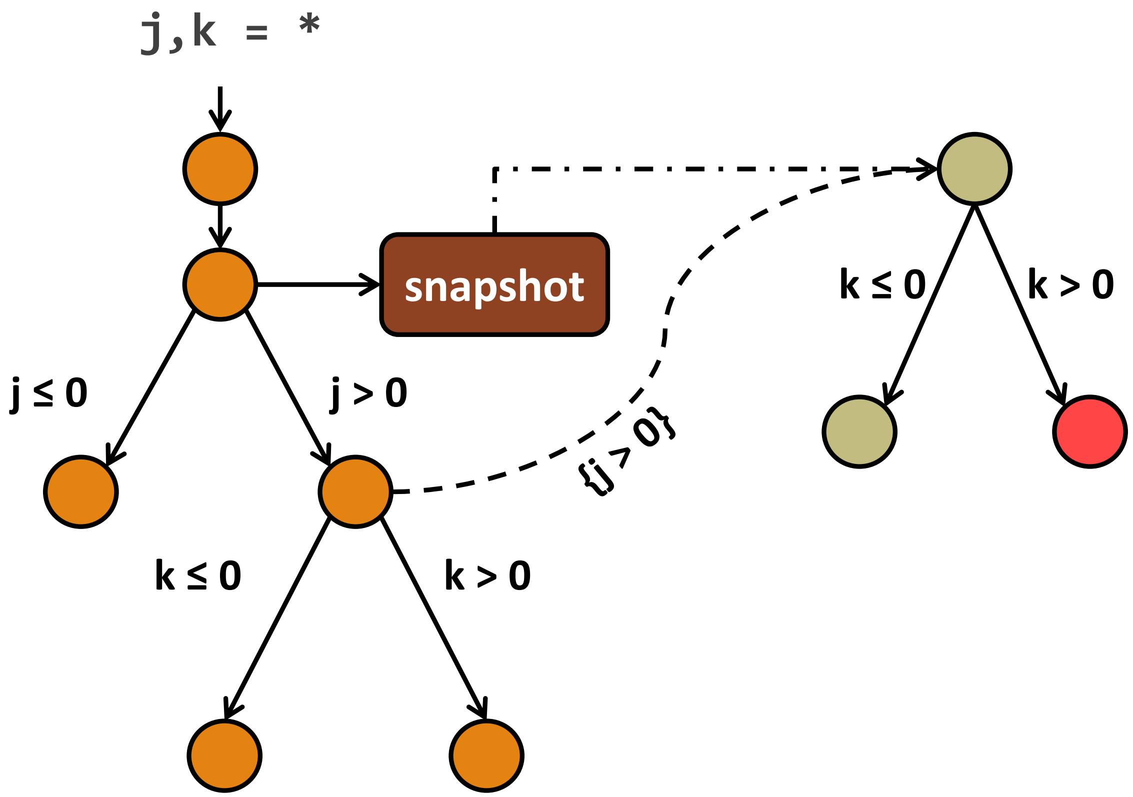


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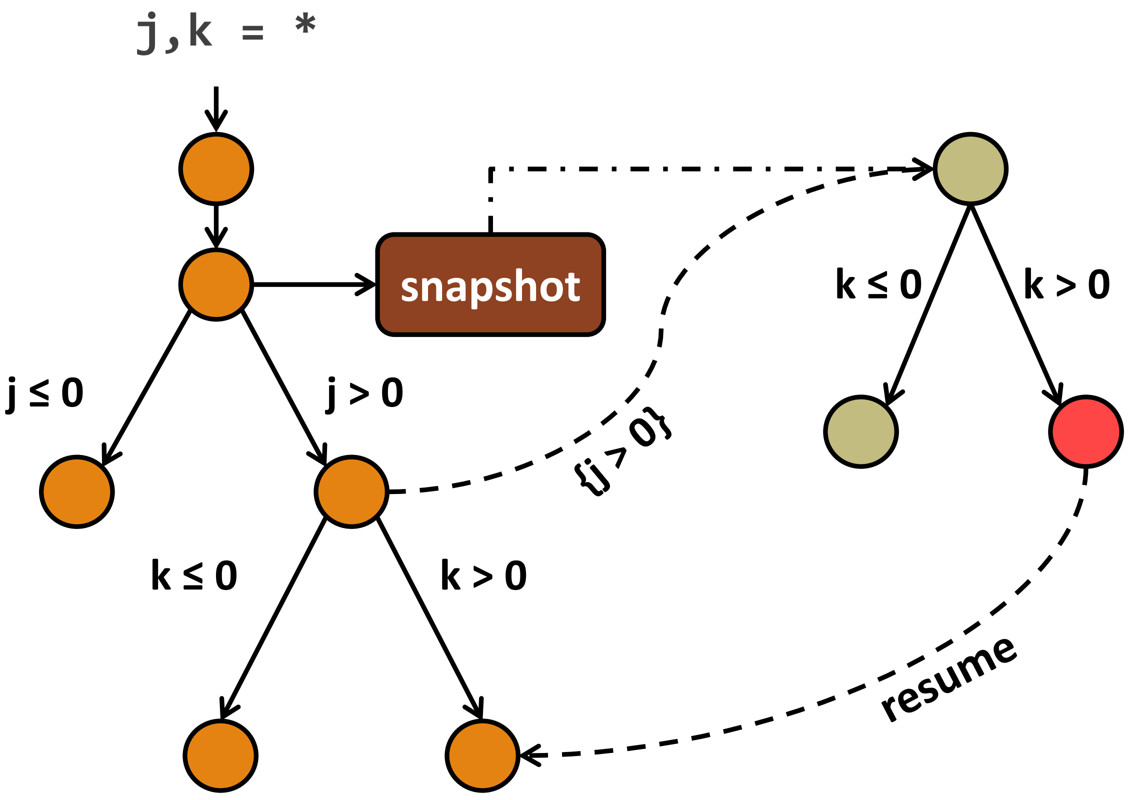


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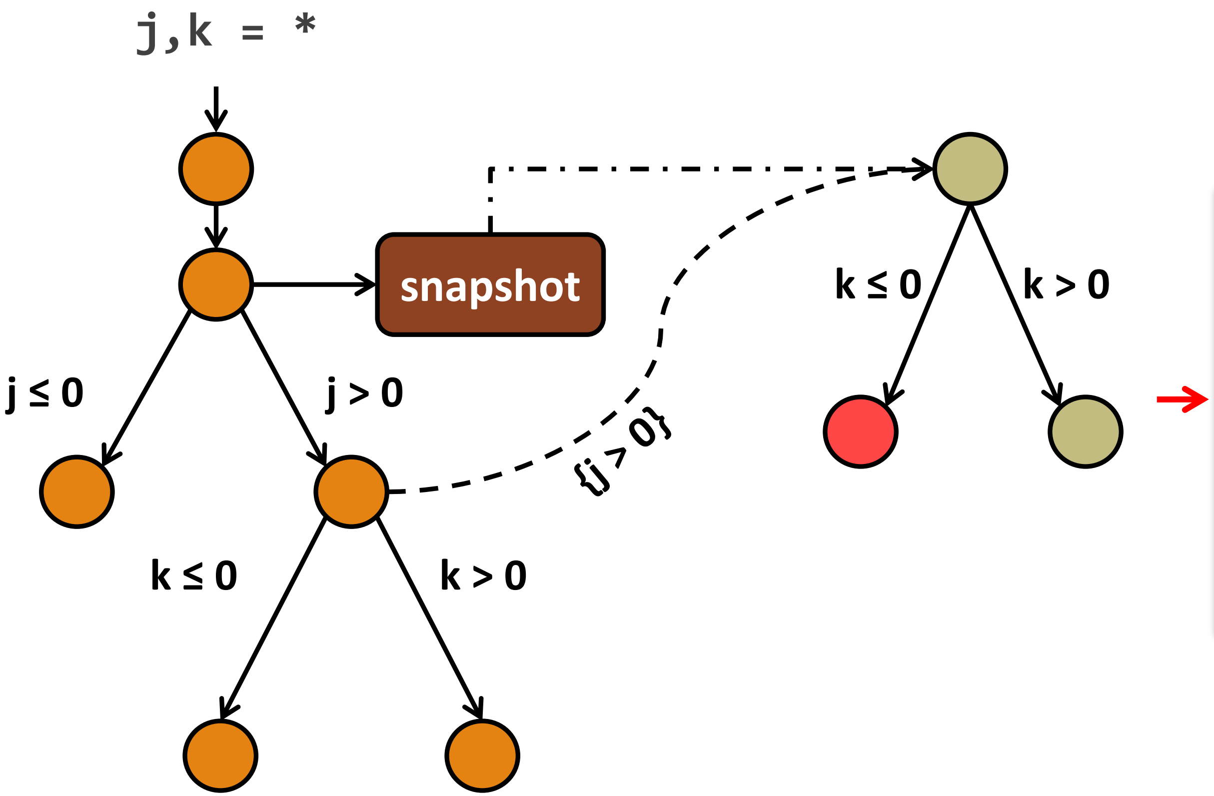


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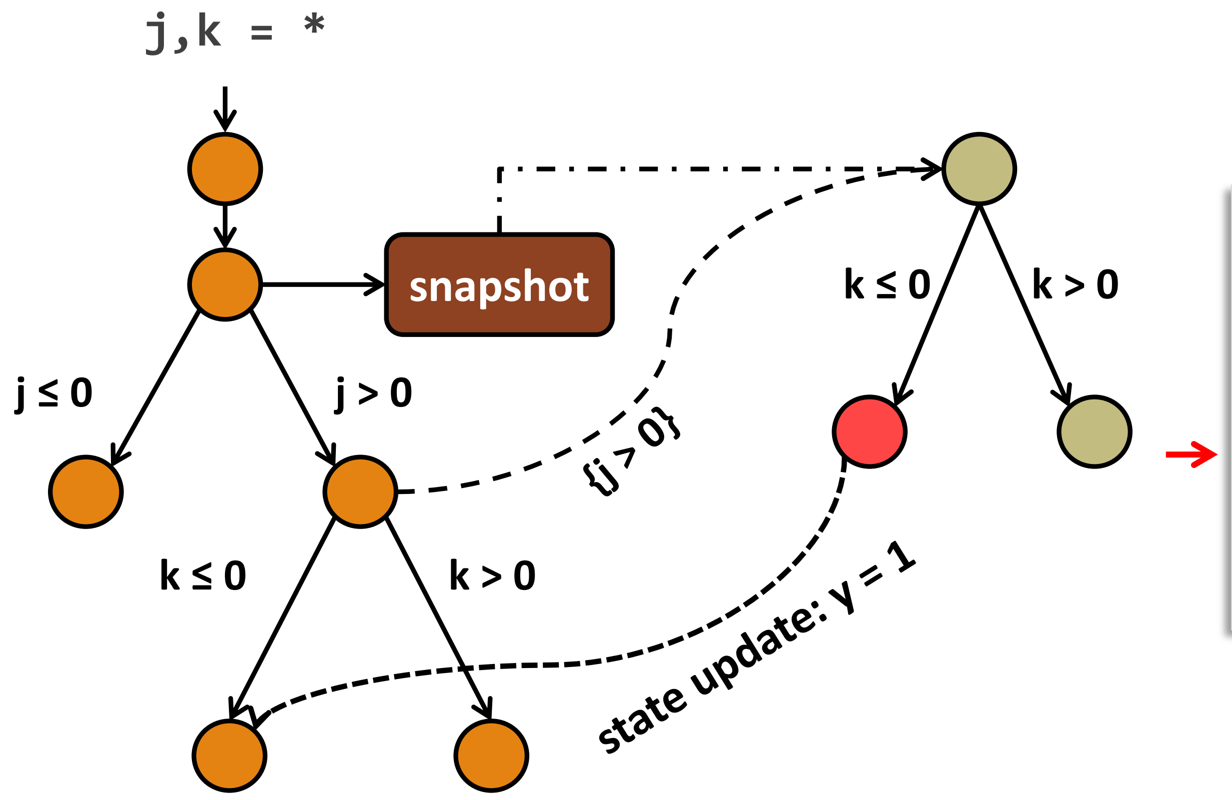


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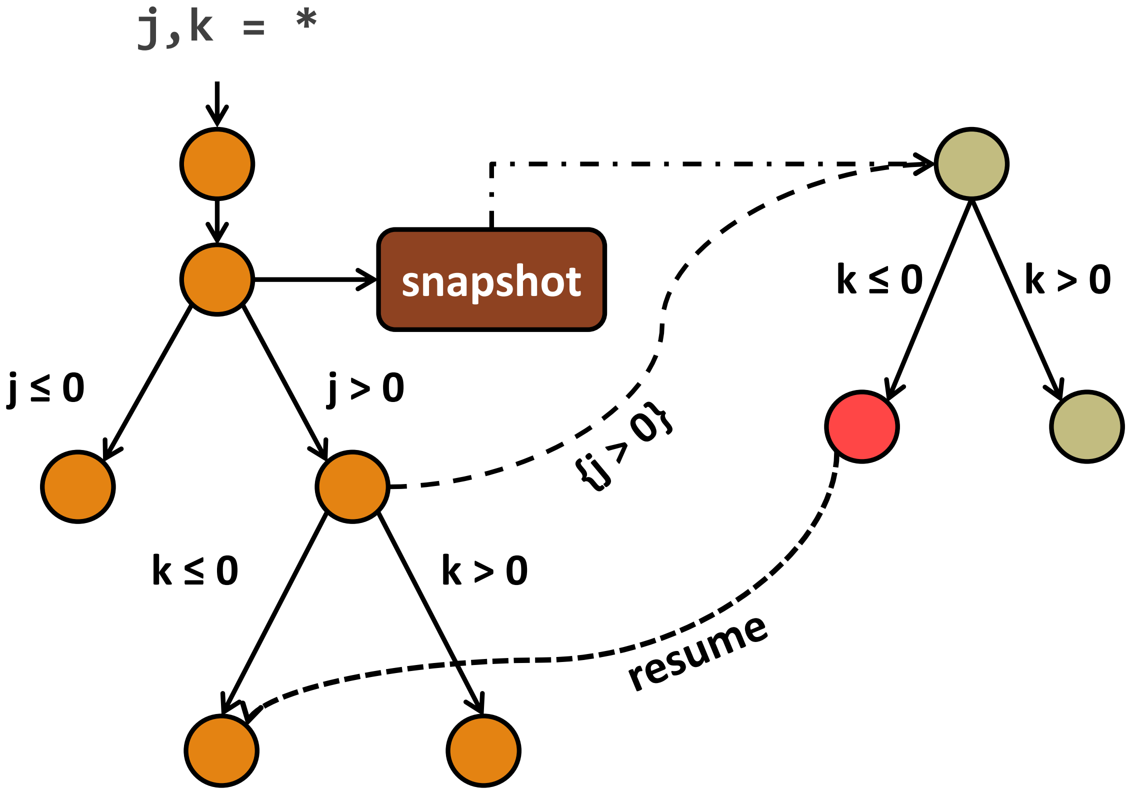


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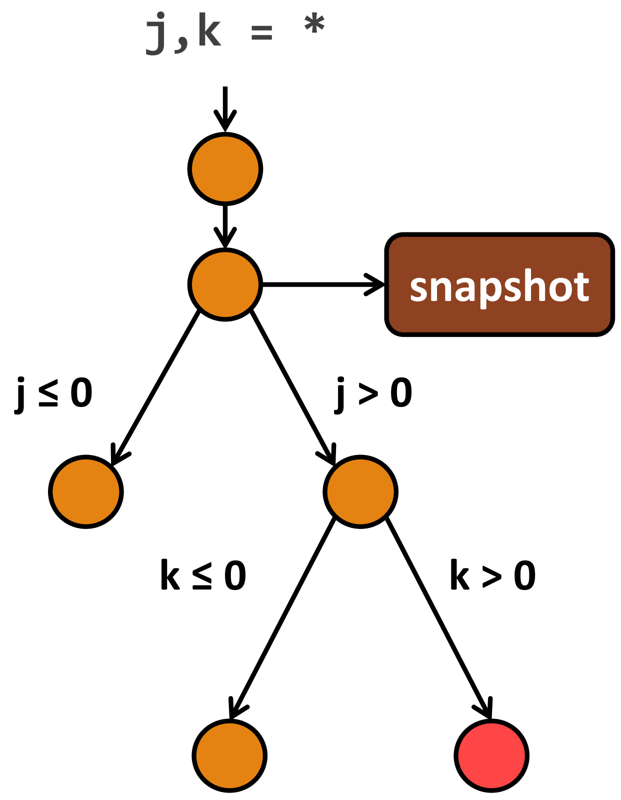


```
void main() {
  f();
  if (j > 0) {
    if (y)
      target1;
  }
  else target2;
}
```

Execution Trees

```
void main() {
  f();
  if (j > 0) {
    if (y)
      bug1();
 }
 else bug2();
}
```

```
void f() {
  if (k > 0)
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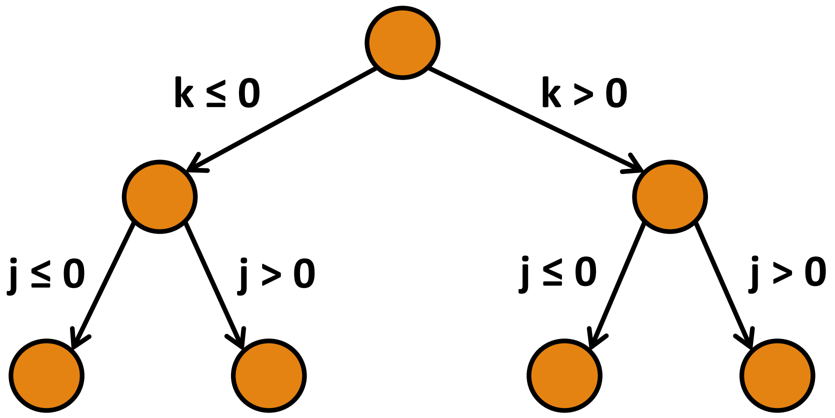
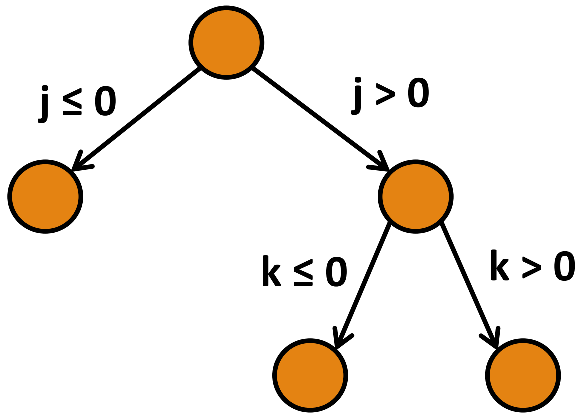


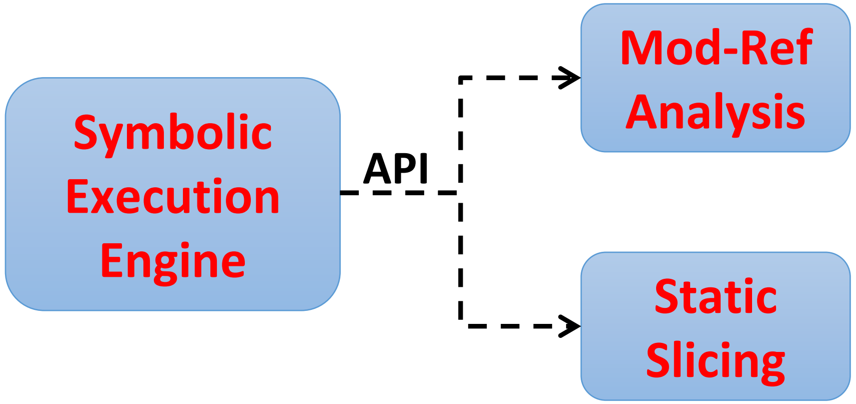
Standard SE



Chopped SE

Implementation: Chopper

- Symbolic execution based on KLEE
- Mod-ref analysis based on SVF
- Static slicing based on DG



Experiments

Security Vulnerability Reproduction

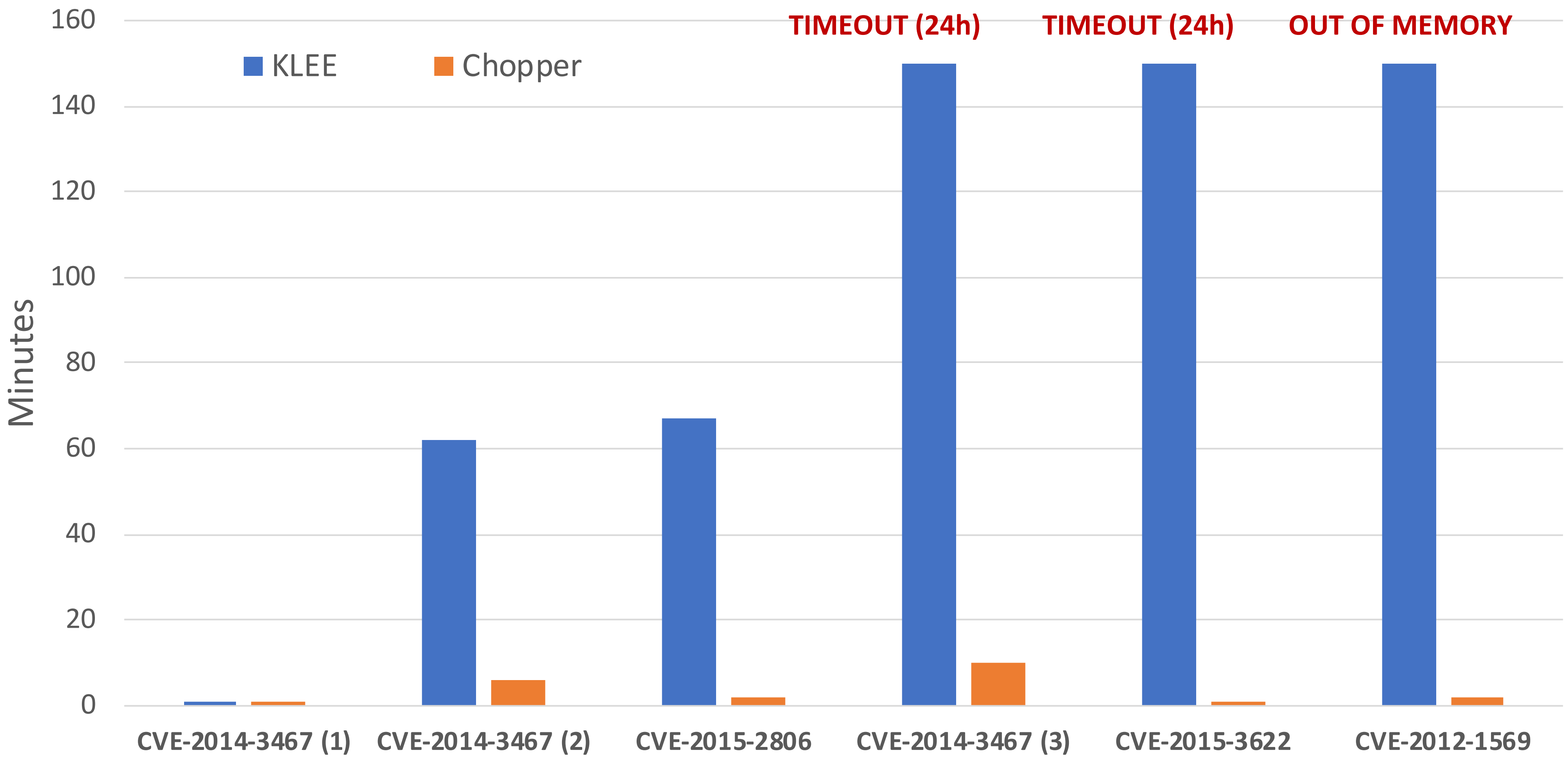
Test Suite Augmentation

Patch Testing

Reproducing Security Vulnerabilities

- Benchmark: GNU libtasn1
  - ASN.1 protocol used in many networking and cryptographic applications, such as for public key certificates and e-mail
  - Considered 4 CVE security vulnerabilities, with a total of 6 vulnerable locations (out-of-bounds accesses)
- Goal:
  - Starting from the CVE report, generate inputs that trigger out-of-bounds accesses at the vulnerable locations
- Methodology:
  - Manually identified the irrelevant functions to skip
  - Time limit 24 hours, memory limit 4 GB

Reproducing Security Vulnerabilities



Effectiveness of Chopped Symbolic Execution

- Choice of code to skip
  - Application-specific, still work in progress
  - Some scenarios are easier to automate than others
  - Can always make different guesses and try them in parallel

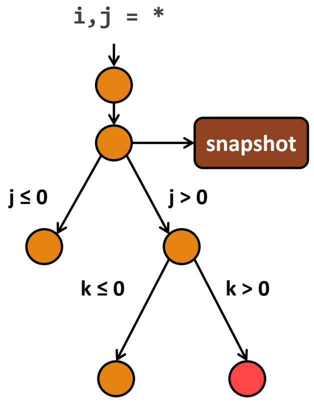
- Precision of points-to analysis
  - Currently we use a flow-insensitive, context-insensitive and field-sensitive points-to analysis
  - Currently a single points-to analysis, in the beginning

From Whole-Program Analysis…
…To More Localized Tasks

- Most work on modern symbolic execution:
  - Whole-program test generation
  - Whole-program bug-finding
- More recently attention shifted to more localized tasks:
  - Patch testing
  - Debugging
  - Bug reproduction
  - Program repair
  - etc.

> - Which one is easier?
> - Opportunities of more localized tasks:
>   - Prune a large part of the search space
>   - Perform incremental reasoning/analysis
>   - Use previous/correct version as an oracle
>   - etc.

Chopped Symbolic Execution

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Experiments

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Chopped Symbolic Execution [ICSE 2018]

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Noam Rinetzky, Tel Aviv University, Israel, maon@cs.tau.ac.il
Cristian Cadar, Imperial College London, United Kingdom, c.cadar@imperial.ac.uk

ABSTRACT

Symbolic execution is a powerful program analysis technique that systematically explores multiple program paths. However, despite important technical advances, symbolic execution often struggles to reach deep parts of the code due to the well-known path explosion problem and constraint solving limitations.

In this paper, we propose *chopped symbolic execution*, a novel form of symbolic execution that allows users to specify uninteresting parts of the code to exclude during the analysis, thus only targeting the exploration to paths of importance. However, the excluded parts are not summarily ignored, as this may lead to both false positives and false negatives. Instead, they are executed lazily, when their effect may be observable by code under analysis. Chopped symbolic execution leverages various on-demand static analyses at runtime to automatically exclude code fragments

the code with symbolic values instead of concrete ones. Symbolic execution engines thus replace concrete program operations with ones that manipulate symbols, and add appropriate constraints on the symbolic values. In particular, whenever the symbolic executor reaches a branch condition that depends on the symbolic inputs, it determines the feasibility of both sides of the branch, and creates two new independent *symbolic states* which are added to a worklist to follow each feasible side separately. This process, referred to as *forking*, refines the conditions on the symbolic values by adding appropriate constraints on each path according to the conditions on the branch. Test cases are generated by finding concrete values for the symbolic inputs that satisfy the *path conditions*. To both determine the feasibility of path conditions and generate concrete solutions that satisfies them, symbolic execution engines employ *satisfiability-modulo theory* (SMT) constraint solvers [19].