Finding good bugs in very good code

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Fraser Brown, Dawson Engler, Deian Stefan, Craig Disselkoen

We like finding bugs

0. Write checking tool

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1. Take large codebase that isn’t aggressively checked

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…

We want to find good bugs

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in very good code

This talk: security bugs in Chrome, Firefox, SQLite

Chrome and Firefox browsers run fuzzers

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Testing with ~random inputs

Chrome and Firefox browsers run fuzzers

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- As a result, Chrome testing hits ~75% line coverage of browser
- Firefox has an entire team devoted to fuzzing
- Firefox runs 7+ different fuzzers (2016)

Chrome and Firefox browsers run fuzzers *with sanitizers*

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Look for bugs in code while it executes

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- Chrome's 24/7 fuzzers use:
    - ASAN: heap and stack buffer overflows, etc
    - MSan: uninitialized memory bugs
    - UBSan: undefined behavior bugs

Chrome and Firefox run static checkers

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Check code without running it

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  - Coverity checkers

Chrome and Firefox run static checkers

- Chrome: Clang C++, unix, and core static checkers
- Firefox:
  - Automatic static checkers on every patch
  - Clang checkers
  - Coverity checkers
  - Infer checkers

Chrome and Firefox browsers have bug bounty programs

SQLite:

SQLite:

- Part of Chrome and Firefox

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- 700x more test code than database code

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- 100% branch test coverage

SQLite:

- Part of Chrome and Firefox
- 700x more test code than database code
- 100% branch test coverage
- Re-tests with sanitizers for three different compilers on:
  - 32- and 64-bit builds
  - Big- and little-endian architectures

Few bugs with our existing checking systems

New approach: Static analysis + symbolic execution

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Check code without running it

New approach: Static analysis + symbolic execution

“Run” program over all possible paths and values

New approach: Static analysis + symbolic execution

New approach: Static analysis + symbolic execution

Symbolic: checking:

- UC-Klee
- Woodpecker

Combined static and symbolic:

- Chopper
- Dowser
- Deadline
- ... more!

New approach: Static analysis + symbolic execution

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- Static analysis identifies many potential errorsites ($)
  - Programmer-written static extension (avg. 175 LOC)
- Symbolic execution jumps directly to candidate errorsite and executes ($$$$$)
  - Programmer-written symbolic checkers (avg. 40 LOC)

New approach: Static analysis + symbolic execution

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```
; ModuleID = 'undef.bc'

source_filename = "undef.c"

target datalayout =
"e-m:e-i64:64-f80:128-n8:16:32:64-
S128"
target triple =
"x86_64-pc-linux-gnu"
```

LLVM IR File(s)

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```

LLVM IR File(s)

```
Alloca x => Uninit x

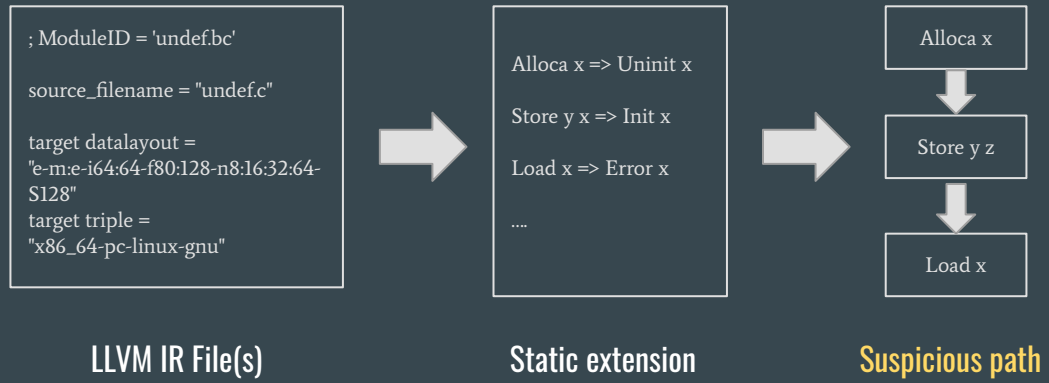
Store y x => Init x

Load x => Error x

....
```

Static extension

New approach: Static analysis + symbolic execution



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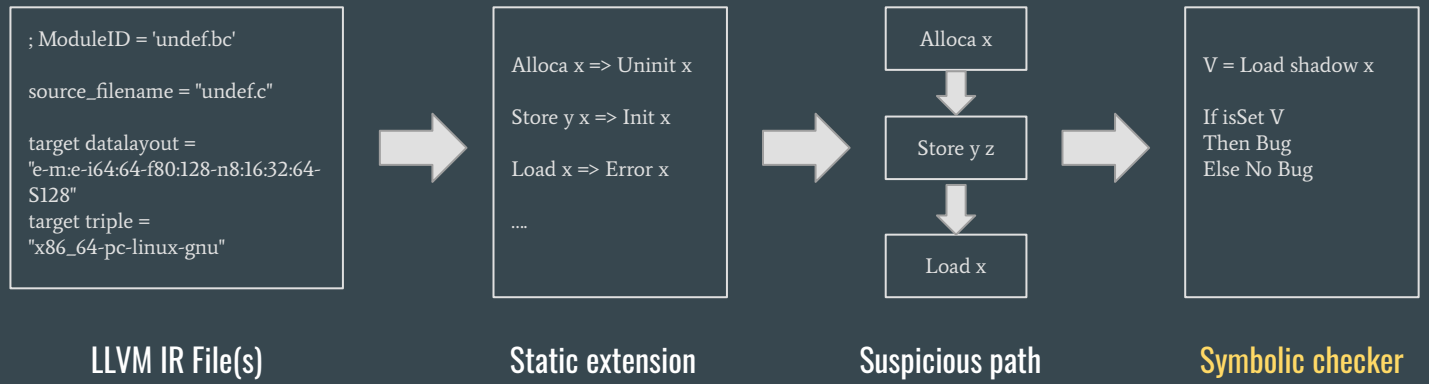

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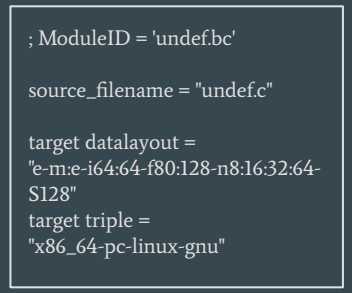

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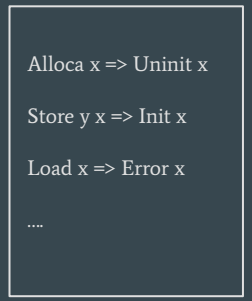
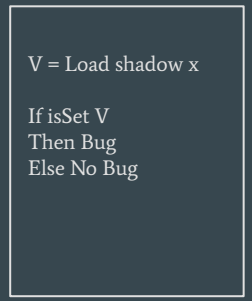


Static extension

Suspicious path



Symbolic checker

Heap out-of-bounds bug, CVE 2019-XXXX

Heap out-of-bounds bug, CVE 2019-XXXX

```
const int stride = input + 1;
...
a = my_malloc( (sizeof(int)+12)*stride );

if( a==0 ){
 return -1;
}
...
memset(a, 0, sizeof(int)*(stride) );
```

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32-bit multiplication

64-bit multiplication

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32-bit multiplication WRAPS TO SMALL

64-bit multiplication STAYS BIG

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Small allocation

Very large out-of-bounds write

Static extension (heap out-of-bounds)

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```
x = malloc (y);

x[y - 1] = 0;
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Dependency between y and y - 1 => mark suspicious path

Static extension (heap out-of-bounds)

```
x = malloc (y);

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```

Static extension (heap out-of-bounds)

```
x = malloc (y);
```

Save sizeof (x) = y

```
x[y - 1] = 0;
```

Static extension (heap out-of-bounds)

```
x = malloc (y);

x[y - 1] = 0;
```

Save indexSize(x) = y - 1

Static extension (heap out-of-bounds)

```
x = malloc (y);

x[y - 1] = 0;
```

indexSize(x) = y - 1
sizeOf(x) = y

Symbolic checker (heap out-of-bounds)

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```
x = malloc (y);

x[y - 1] = 0;
```

Symbolic checker (heap out-of-bounds)

```
x = malloc (y);

x[y - 1] = 0;
```

y - 1 > y => report bug

Symbolic checker (heap out-of-bounds)

```
x = malloc (y);

x[y - 1] = 0;
```

Symbolic execution engine examines all possible values along path

```
x = malloc (y);

x[y - 1] = 0;
```

Can y - 1 > y ?

“Constraints” express lines of code as logical formulas

a && b && c || d || e ....

“Constraints” express lines of code as logical formulas

a && b && c || d || e ....

a = true
b = true
c = true
d = false
e = true

“Constraints” express lines of code as logical formulas

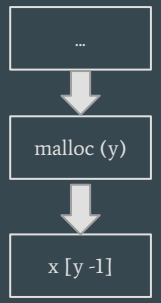
a && not a && b && c || d || e ....

“Constraints” express lines of code as logical formulas

a && not a && b && c || d || e ....

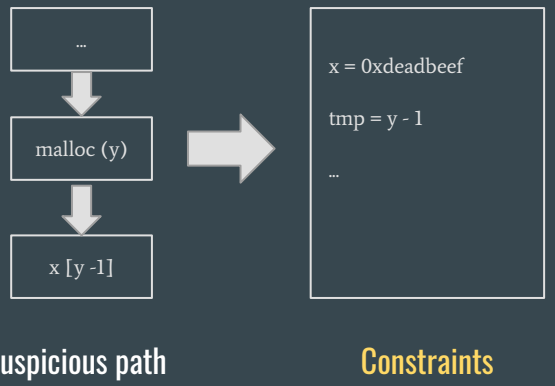
UNSAT

“Constraints” express lines of code as logical formulas



Suspicious path

“Constraints” express lines of code as logical formulas



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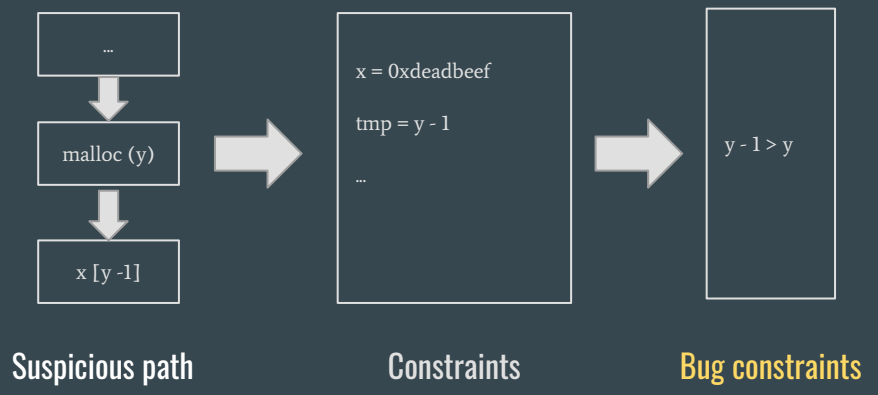

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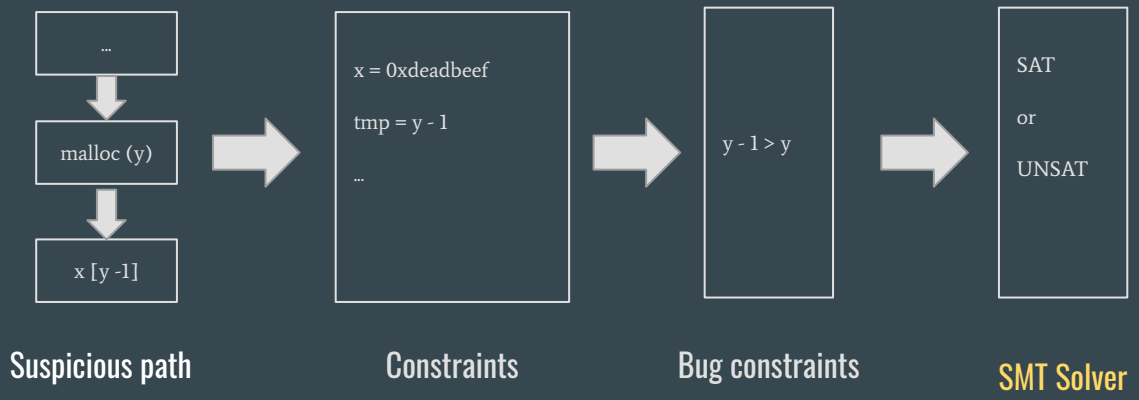

Symbolic checker for heap out-of-bounds

```
x = malloc (y);

x[y - 1] = 0;
```

1. Symbolic engine translates line

```
x = malloc (y);

x[y - 1] = 0;
```

1. Symbolic engine translates line

```
x = malloc (y);
```

X = new concrete location (e.g., 0xdeadbeef)

```
x[y - 1] = 0;
```

2. Symbolic checker examines line

```
x = malloc (y);
```

NOOP

```
x[y - 1] = 0;
```

1. Symbolic engine translates line

```
x = malloc (y);

x[y - 1] = 0;
```

1. Symbolic engine translates line

x = malloc (y);

x[y - 1] = 0;

1. tmp = y - 1

1. Symbolic engine translates line

```
x = malloc (y);

x[y - 1] = 0;
```

1. tmp = y - 1
2. ptr = x + sizeof(x) * tmp

1. Symbolic engine translates line

```
x = malloc (y);

x[y - 1] = 0;
```

1. tmp = y - 1
2. ptr = x + sizeof(x) * tmp
3. mem[ptr] = 0

2. Symbolic checker examines line

```
x = malloc (y);

x[y - 1] = 0;
```

2. Symbolic checker examines line

```
x = malloc (y);

x[y - 1] = 0;
```

know sizeOf(x) = y
know indexSize(x) = y - 1

2. Symbolic checker examines line

```
x = malloc (y);

x[y - 1] = 0;
```

know sizeOf(x) = y
know indexSize(x) = y - 1
assert y-1 > y

3. Query SMT solver

```
x = malloc (y);

x[y - 1] = 0;
```

3. Query SMT solver

```
x = malloc (y);

x[y - 1] = 0;
```

SAT

y = 0
x = 0xdeadbeef

Results of the heap out-of-bounds checker

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- 22 bugs

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- 22 bugs
- High-severity pattern in SQLite
  - Patched within 7hrs
  - Backported
  - Bounty
  - CVE

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Results of the heap out-of-bounds checker

- 22 bugs
- High-severity pattern in SQLite
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- 3 security audits
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- 4 false positives

Three checkers

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- Heap out-of-bounds

Three checkers

- Heap out-of-bounds
- Uninitialized memory

Three checkers

- Heap out-of-bounds
- Uninitialized memory

```
int x;
int y = x + 5;
```

Three checkers

- Heap out-of-bounds
- Uninitialized memory
- Simple stack out-of-bounds

Three checkers

- Heap out-of-bounds
- Uninitialized memory
- Simple stack out-of-bounds

```
int x[5];
return x[6];
```

Challenges

Challenge: Unknown state

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```
int foo (int * buff, int x) {

  int val = buff[x];

}
```

Challenge: Unknown state

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Challenge: Unknown state

Solutions: Unknown state

1. Target specific errors instead of general correctness

Ask bad questions get bad answers

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int foo (int * buff, int x) {

  int val = buff[x];

}
```

Solutions: Unknown state

1. Target specific errors instead of general correctness

Target error; ignore all else

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const int stride = input + 1;
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a = my_malloc( (sizeof(int)+12)*stride );

if( a==0 ){
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memset(a, 0, sizeof(int)*(stride) );
```

Target error; ignore all else

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Solutions: Unknown state

1. Target specific errors instead of general correctness
2. All paths are internally consistent

Constraint solver rejects infeasible paths

```
if (p) ....

if (!p) ....
```

Constraint solver rejects infeasible paths

```
if (p) ....

if (!p) ....
```

Solutions: Unknown state

1. Target specific errors instead of general correctness
2. All paths are internally consistent
3. Tool is simple to support checker-specific tricks

Results so far (3mos, 1 person):

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- 3 checkers (2 out-of-bounds, 1 uninitialized memory)
- Every checker has found at least one bountied browser bug
- 2 CVEs
- High severity, exploitable Chrome pattern (~13 instances)
- 4 medium-severity bugs
- 4 low-severity bugs
- 12+ patches (+3 already patched, +5 mystery patches)
- 22+ patched functions
- 2 security audits
- 48 reported bugs, 38+ confirmed bugs, 18 false positives