T-Fuzz: Fuzzing by Program Transformation

Hui Peng[1], Yan Shoshitaishvili[2], Mathias Payer[1]

1 Purdue University

hexhive

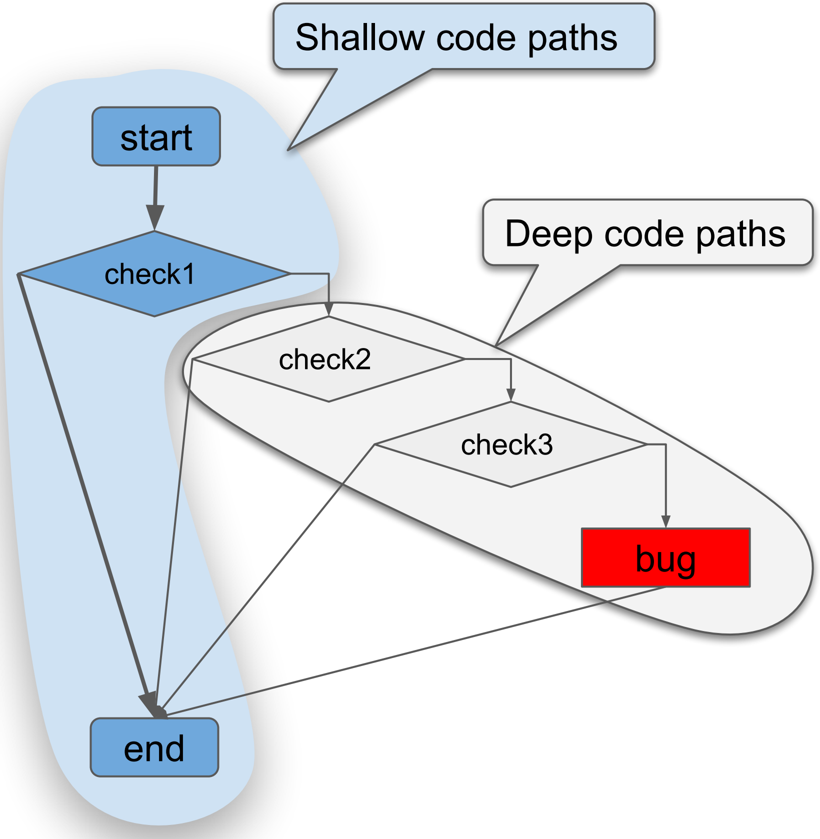
2 Arizona State University

Fuzzing as a bug finding approach

- Fuzzing is highly effective in finding bugs (CVEs)
- Developers use it as proactive defense measure: OSS-Fuzz, MSRD
- Analysts use it as first step in exploit development

Challenges for fuzzers

- Challenges
  - Shallow coverage
  - Hard to find “deep” bugs
- Root cause
  - Fuzzer-generated inputs cannot bypass **complex sanity checks** in the target program



Existing approaches & their limitations

- Existing approaches focus on ***input generation***
  - AFL improvements (searching for constants, corpus generation)
  - Driller (selective concolic execution)
  - VUzzer (taint analysis, data & control flow analysis)
- Limitations
  - High overhead
  - Not scalable
  - Unable to bypass “hard” checks
    - Checksum values
    - Crypto-hash values

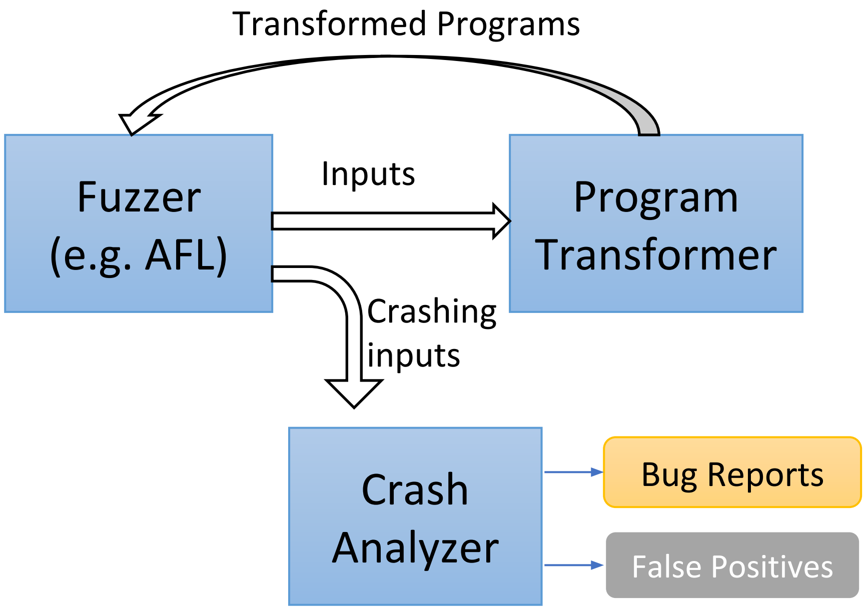
Insight: some checks are non-critical

- Some checks are not intended to prevent bugs
- **Non-Critical Checks (NCC)**
  - E.g., checks on magic values, checksum, hashes
- Removing NCCs won't incur erroneous bugs
- Removal of NCCs simplifies fuzzing

```
void main() {
  int fd  = open(...);
  char *hdr = read_header(fd);
  if (strncmp(hdr, "ELF", 3) == 0) {
    // main program logic
    // ...
  } else {
    error();
  }
}
```

T-Fuzz: fuzzing by program transformation

- Fuzzer generates inputs
- When Fuzzer gets stuck, Program Transformer:
  - Detects NCC candidates
  - Transforms program
- Repeats
- Crash Analyzer verifies crashes in the original program

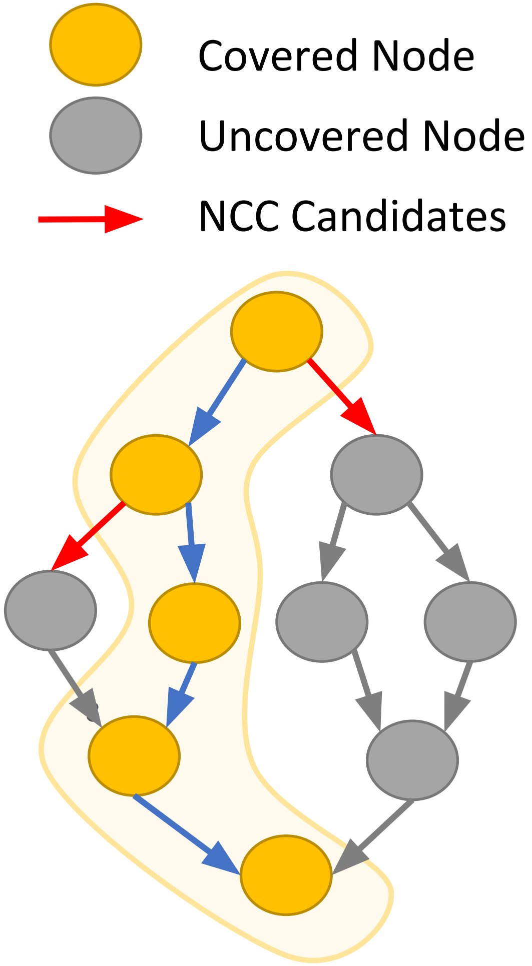


Detecting NCCs (1)

- Precisely detecting NCCs is hard
- Precise approach
  - Leveraging control and data flow analysis techniques
  - Slow and unscalable
- Imprecise approach
  - Approximate NCCs as the checks fuzzer cannot bypass
  - May result in false positives due to imprecision

Detecting NCCs (2)

- Approximate NCCs as edges connecting covered and uncovered nodes in CFG
- Over approximate, *may contain false positive*
- Lightweight and simple to implement
    - Dynamic tracing

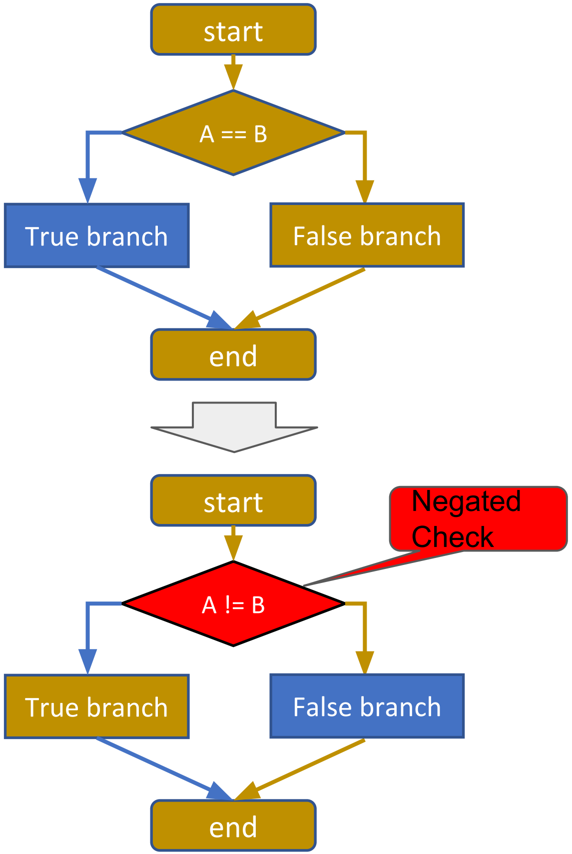


Program Transformation (1)

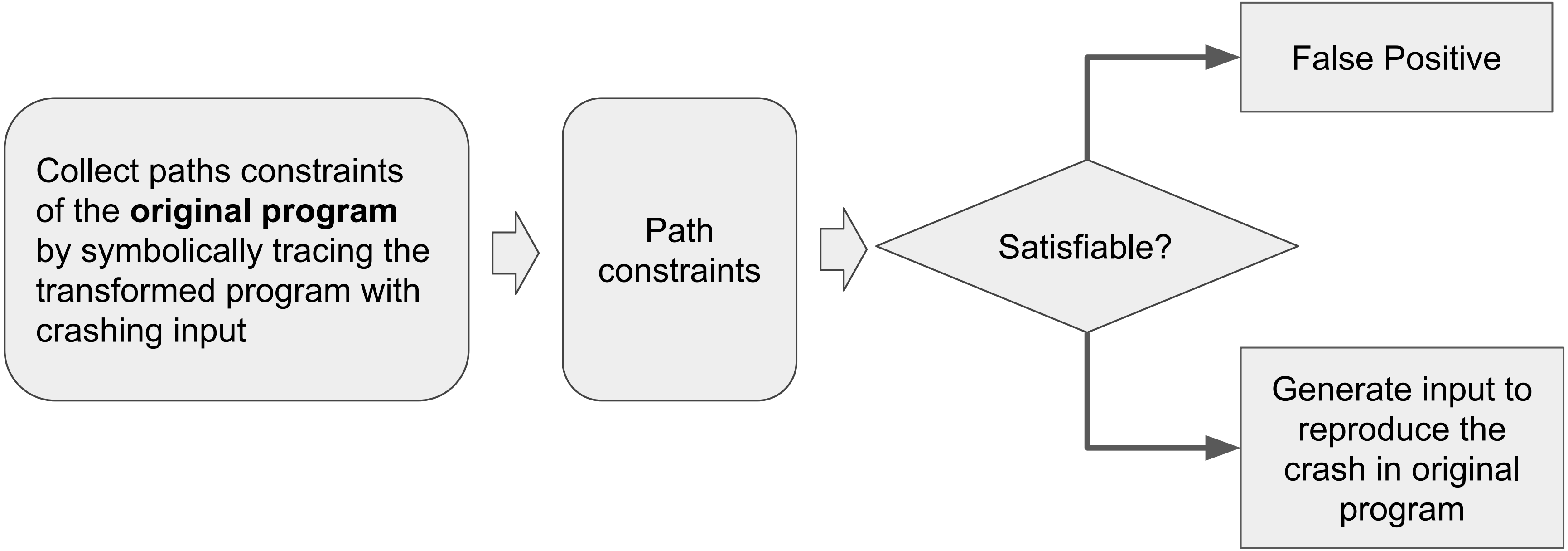
- **Goal**: disable NCCs
- Possible options
    - Source rewriting & recompilation
        - Complexity involved with mapping between binary and source code
        - Compilation results in overhead
    - Static instrumentation
        - Error prone
    - Dynamic instrumentation
        - High overhead

Program Transformation (2)

- Our approach: **negate NCCs**
  - Easy to implement: static binary rewriting
  - Zero runtime overhead in resulting target program
  - The CFG of program stays the same
  - Trace in transformed program maps to original program
  - Path constraints of original program can be recovered



Filtering out false positives & reproducing bugs



Example 1

Collected path constraints

{ x > 0, y == 0xdeadbeef }

SAT

True BUG

un-negating

```
int main (){
  int x = read_input();
  int y = read_input();
  if (x > 0) {
    if (y == 0xdeadbeef)
      bug();
  }
}
```

Original Program

```
int main (){
  int x = read_input();
  int y = read_input();
  if (x > 0) {
    if (y != 0xdeadbeef)
      bug();
  }
}
```

Negated check

Transformed Program

Example 2

Collected path constraints

{ i > 0, i <= 0}

un-negating

UN SAT

False BUG

```
int main (){
  int i = read_input();
  if (i > 0) {
    func(i);
  }
}

void func(int i) {
  if (i <= 0) {
    bug();
  }
  //...
}
```

Original Program

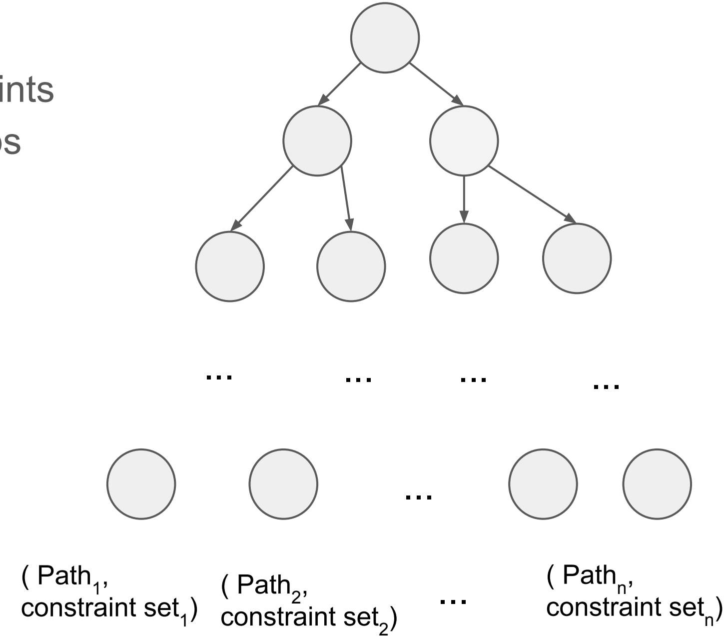
```
int main (){
  int i = read_input();
  if (i > 0) {
    func(i);
  }
}

void func(int i) {
  if (i > 0) {
    bug();
  }
  //...
}
```

Negated check

Transformed Program

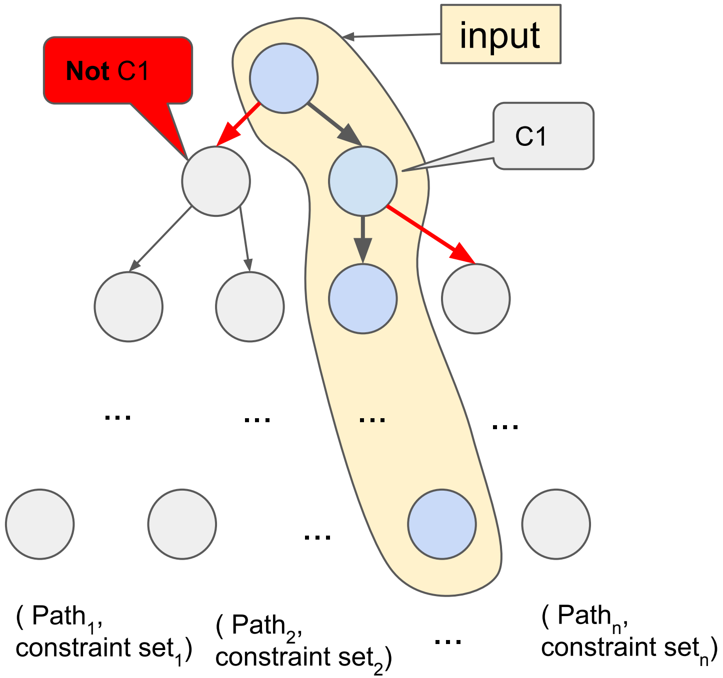
Comparison with other SE based approaches (1)

- Pure symbolic execution, e.g., KLEE
  - Explores all possible code paths, tracking input constraints
  - Path explosion issue, especially in the presence of loops
    - Each branch doubles the number of code paths
  - Very high resource requirement
  - Theoretically beautiful, limited practical use



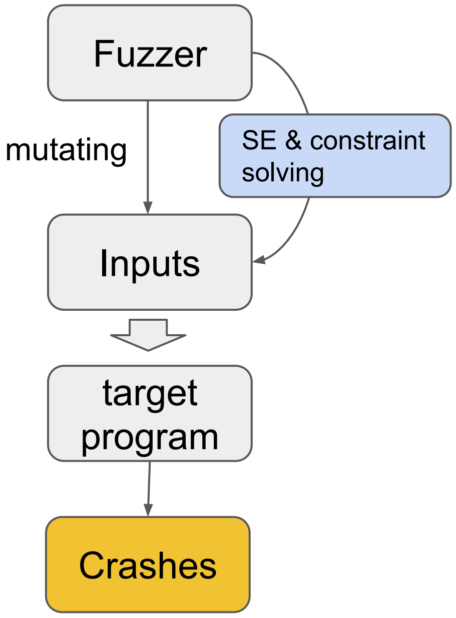
Comparison with other SE based approaches (2)

➢ Concolic execution, e.g., CUTE
- Guided by concrete inputs
- Following a single code path, collects constraints for new code paths by flipping conditions
- Reduced resource requirements
- Total number of explored **symbolic** code paths remains exponential



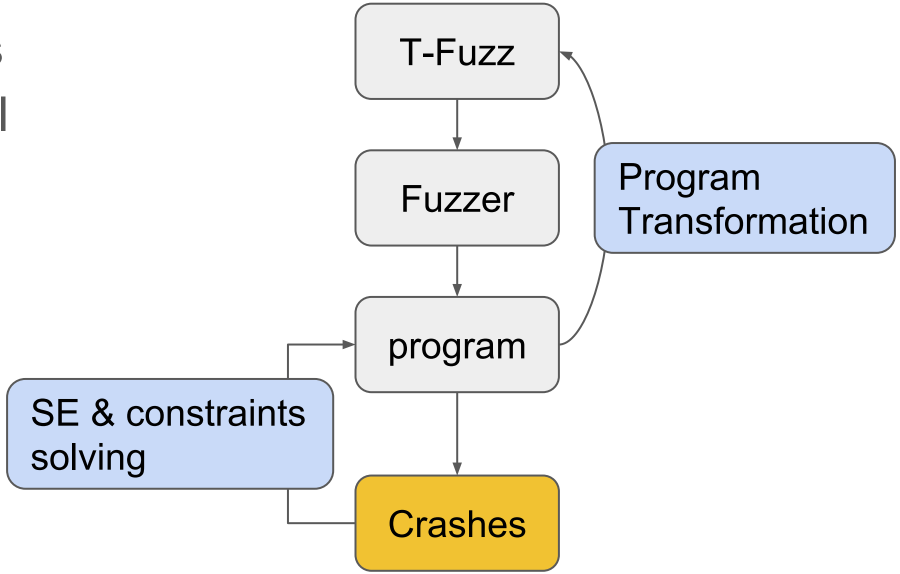
Comparison with other SE based approaches (3)

- Combining fuzzing with concolic execution (Driller)
  - Fuzzing explores code paths as much as possible
  - When fuzzing gets "stuck", concolic execution explores new code paths using fuzzer generated inputs
  - Limitations
    - "SE & constraints solving" slows down fuzzing
    - Not able to bypass "hard" checks



Comparison with other SE based approaches (4)

- SE is decoupled from fuzzing
- SE only applied to detected crashes
- In case of “hard” checks, T-Fuzz still detects the guarded bug, though cannot verify it



Usage of SE in T-Fuzz

T-Fuzz limitation: false crashes (L1)

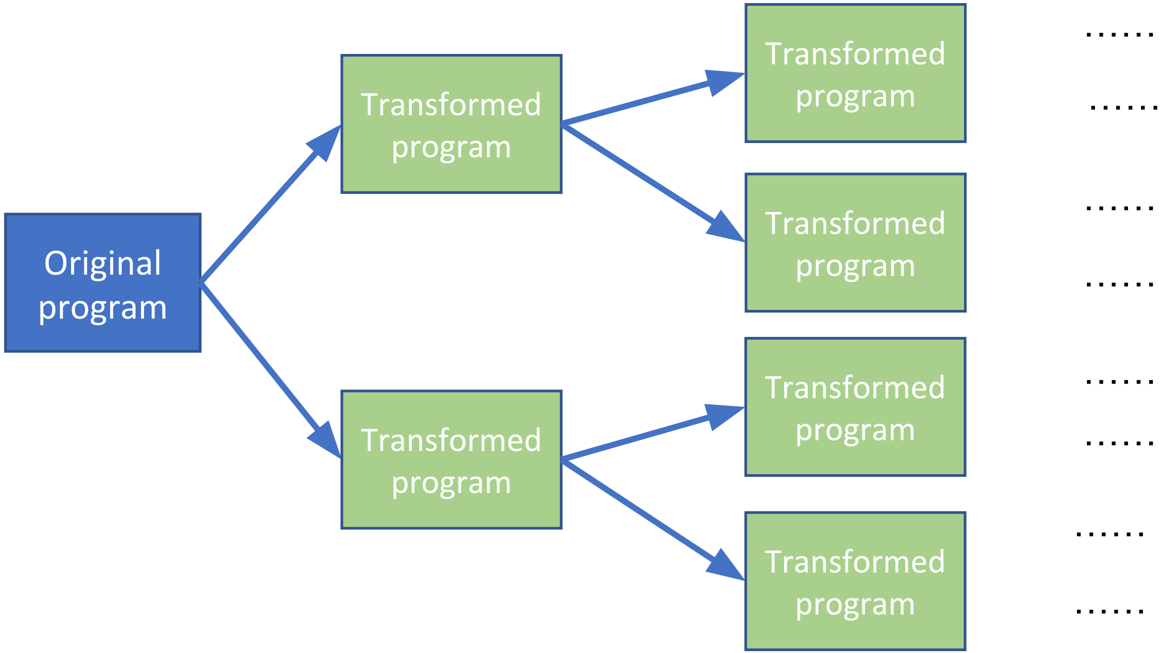
➢ False crashes may hinder true bug discovery

```
FILE *fp = fopen(...);
if (fp != NULL) {
    // False crash
    fread(fp, ...);
    // ...
    // true bug
    bug();
}
```

Example: false crash hindering discovery of true bug

T-Fuzz limitation: transformation explosion (L2)

- Analogous to path explosion issue in symbolic execution



T-Fuzz limitation: Crash Analyzer (1)

Collected path constraints

{ lava_123 == 0x12345678,
lava_123 != 0x12345678 }

➢ Conflicting constraints result from checks on the same input cause FN

Negated check

un-negating

```
FILE *fp = fopen(...);
// injected bug in lava-m dataset
fread(fp + lava_get(123) *
      (lava_get(123) == 0x12345678), ...);
```

```
int lava_get(int bug_num) {
 if (lava_vals[bug_num] == 0x12345678) {
   printf("triggered bug %d\n", bug_num);
 }
 return lava_vals[bug_num];
}
```

Original Program

```
FILE *fp = fopen(...);
// injected bug in lava-m dataset
fread(fp + lava_get(123) *
      (lava_get(123) != 0x12345678), ...);
```

```
int lava_get(int bug_num) {
 if (lava_vals[bug_num] == 0x12345678) {
   printf("triggered bug %d\n", bug_num);
 }
 return lava_vals[bug_num];
}
```

Transformed Program

UN SAT

True BUG

T-Fuzz limitation: Crash Analyzer (2)

- Unable to verify non-termination (endless loop) detections
  - Tracing won’t terminate
- Overhead is still high
  - Size of program trace (collecting constraints)
  - Size of collected path constraints set (constraints solving)

Implementation

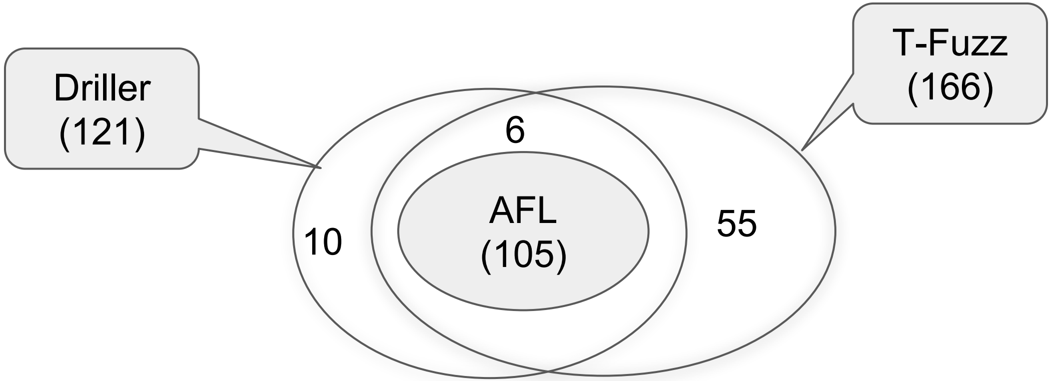
- Fuzzer: shellphish fuzzer (python wrapper of AFL)
- Program Transformer
    - angr tracer
    - radare2
- Crash Analyzer
    - angr
- 2K LOC (python) + a lot of hackery in angr

Evaluation

- ➢ DARPA CGC dataset
- ➢ LAVA-M dataset
- ➢ 4 real-world programs

DARPA CGC dataset

- Improvement over Driller/AFL: 55 (45%) / 61 (58%)
- T-Fuzz defeated by Driller in 10
  - 3 due to false crashes (L1)
  - 7 due to transformation explosion (L2)



Method	# bugs
AFL	105
Driller	121
T-Fuzz	166
Driller - AFL	16
T-Fuzz - AFL	61
T-Fuzz - Driller	55
Driller - T-Fuzz	10

LAVA-M dataset

- ➢ T-Fuzz performs well given favorable conditions for VUzzer and Steelix
- ➢ T-Fuzz outperforms VUzzer and Steelix for “hard” checks
- ➢ T-Fuzz defeated by Steelix due to transformation explosion in who, but still found more bugs than VUzzer
- ➢ T-Fuzz found 1 unintended bug in who

Program	Total # of bugs	VUzzer	Steelix	T-Fuzz
base64	44	17	43	43
unique	28	27	24	26
md5sum	57	1	28	49
who	2136	50	194	95*

Real-world programs

- Widely used in related work
- T-Fuzz detected far more (verified) crashes than AFL
- T-Fuzz found 3 new bugs

Program + library	AFL	T-Fuzz
pngfix + libpng (1.7.0)	0	11
tiffinfo + libtiff (3.8.2)	53	124
magick + ImageMagicK (7.0.7)	0	2
pdftohtml + libpoppler (0.62.0)	0	1

Case study: CROMU_00030 (from CGC dataset)

```
void main() {
  int step = 0;
  Packet packet;
  while (1) {
    memset(packet, 0, sizeof(packet));
    if (step >= 9) {
       char name[5];
       int len = read(stdin, name, 128);
       printf("Well done, %s\n", name);
       return SUCCESS;
    }
    read(stdin, &packet, sizeof(packet));
    if(strcmp((char *)&packet, "1212") == 0) {
       return FAIL;
    }
    if (compute_checksum(&packet) != packet.checksum) {
       return FAIL;
    }
    if (handle_packet(&packet) != 0) {
       return FAIL;
    }
    step ++;
  }
}
```

Stack Buffer overflow bug

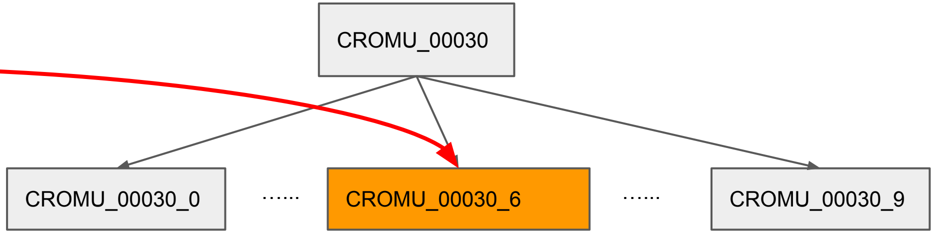
C1: check on magic values

C2: check on checksum

C3: authenticate user info

How the bug was found by T-Fuzz

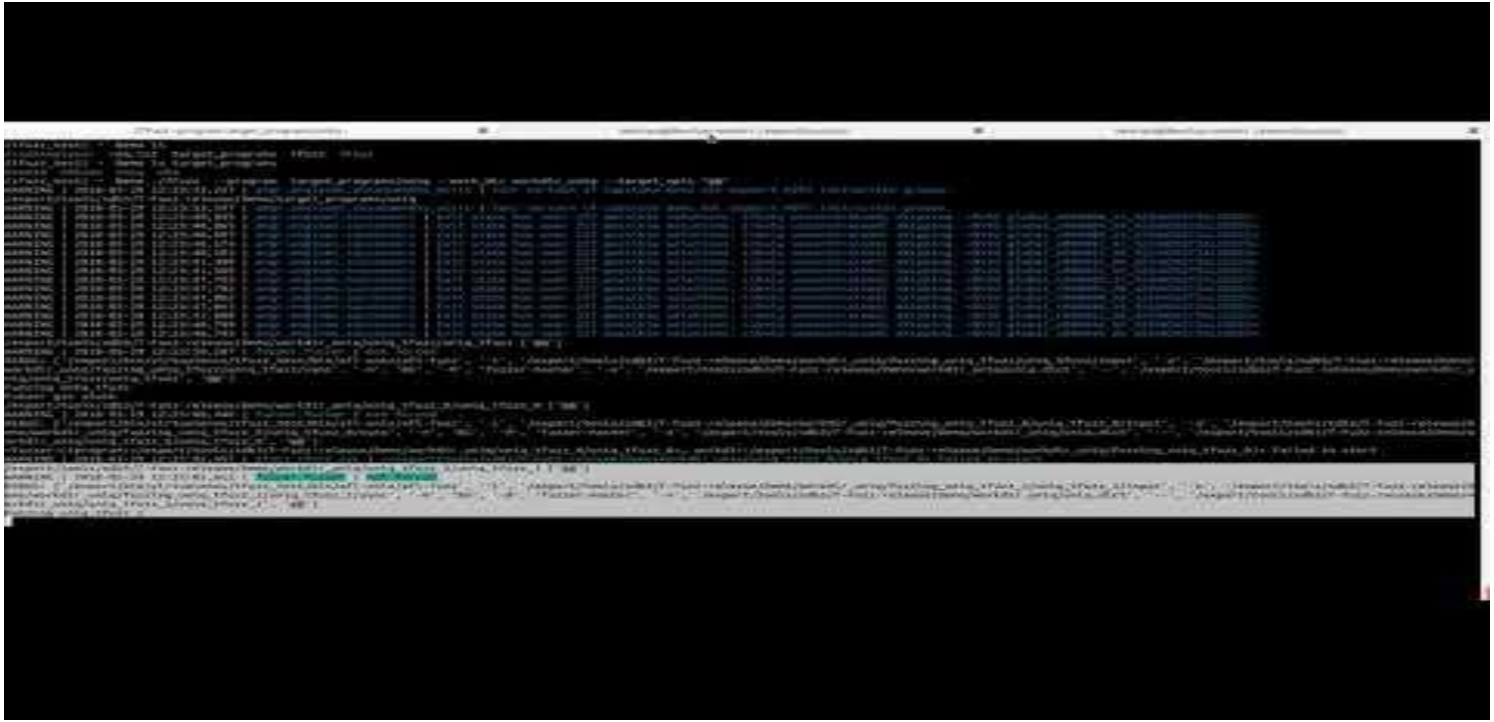
```
void main() {
  int step = 0;
  Packet packet;
  while (1) {
    memset(packet, 0, sizeof(packet));
    if (step >= 9) {
      char name[5];
      int len = read(stdin, name, 128);
      printf("Well done, %s\n", name);
      return SUCCESS;
    }
    read(stdin, &packet, sizeof(packet));
    if(strcmp((char *)&packet, "1212") == 0) {
      return FAIL;
    }
    if (compute_checksum(&packet) != packet.checksum) {
      return FAIL;
    }
    if (handle_packet(&packet) != 0) {
      return FAIL;
    }
    step ++;
  }
}
```



Total time to find the bug: ~4h

Manually verified

Demo - T-Fuzz finding bugs in LAVA-M’s uniq



Current status

- Program transformation
  - No support to transform shared libraries
  - Jump tables are not supported
    - switch … case statements, complex if … else if … statements
- Crash Analyzer
  - Scalability issues for large programs
  - Lack of environmental modelling (syscall, libc functions) in angr

Future work

- Improve precision of NCCs
  - Use some static analysis to, e.g., underestimate NCCs
- Improve mutation of target program
  - Add support for mutating jump tables
  - Add support for mutating shared libraries
- Improve Crash Analyzer
  - Add environmental modelling to better support real-world programs
  - Crash Analyzer
    - Reduce tracing time: eager concolic execution
    - Reduce memory consumption: keep track of only one program state
    - rewrite the core of angr using C/C++ (?)

Conclusion

- Fuzzers are limited by coverage and unable to find “deep” bugs
- T-Fuzz extends fuzzing by mutating both inputs and target program
- ***T-Fuzz outperforms state-of-art fuzzers***
    - T-Fuzz had improvement over Driller/AFL by 45%/58%
    - T-Fuzz triggered bugs guarded by “hard” checks
    - T-Fuzz found new bugs: 1 in LAVA-M dataset and 3 in real-world programs

https://github.com/HexHive/T-Fuzz