GREYONE: Data Flow Sensitive Fuzzing

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Our previous work

- CollAFL: Path sensitive Fuzzing (IEEE S&P 2018)
  - More precise edge feedback
  - Prioritize seeds with more untouched branches
- Path Sensitivity is not enough to cover complicated branch.

Background

- CheckSum/Magic Bytes checking branches generally existed in popular programs.
- Symbolic-based techniques are applied in fuzzing to alleviate the problem(Driller, QSYM, DigFuzz..),
  - open challenge of constraint solving
- Data flow analysis (e.g., dynamic taint analysis) has proven to be useful for guiding fuzzing（TaintScope，Vuzzer，Anogra..）.

Bottleneck of traditional taint analysis

- ✓ Consume large memory, execute slowly
- ✓ Under-taint by external call
- ✓ Under-taint by implicit control flow
- ✓ Over-taint by specified instructions

```
…
int yy0= 0, yy1=0, yy2, yy3;
String xx=ReadSource();
int point = xx.size()/2;
for(int i = 0; i<point;i++){
   yy0 +=NormalFun0(xx[i]); /*Normal taint*/
   yy2 +=NormalFun1(xx[i]); /*Normal taint*/
}
for(int i = point; i<xx.size();i++){
   yy0 +=ExternalFun(xx[i]);/*Truncate taint*/
   for(int j=0; j<(int) xx[i]; j++){
      yy1 += 1;
   }
}
//br0: yy0's tainting range: [0 , xx.size()/2)
if(yy0 == MagicNumber){
      … //Important code
}
//br1: Implicit contral flow make
//the following branch lose all taints data
if(yy1>Min){
      … //Important code
}
//br2: lose harf of taints data
if(yy1 + yy2> Max){
      … //Important code
}
yy3 = yy2&0xff;
if(yy3 > 20){
   … //Important code
}
```

Leave many questions …

RQ1: How to perform lightweight and accurate taint analysis for efficient fuzzing ?

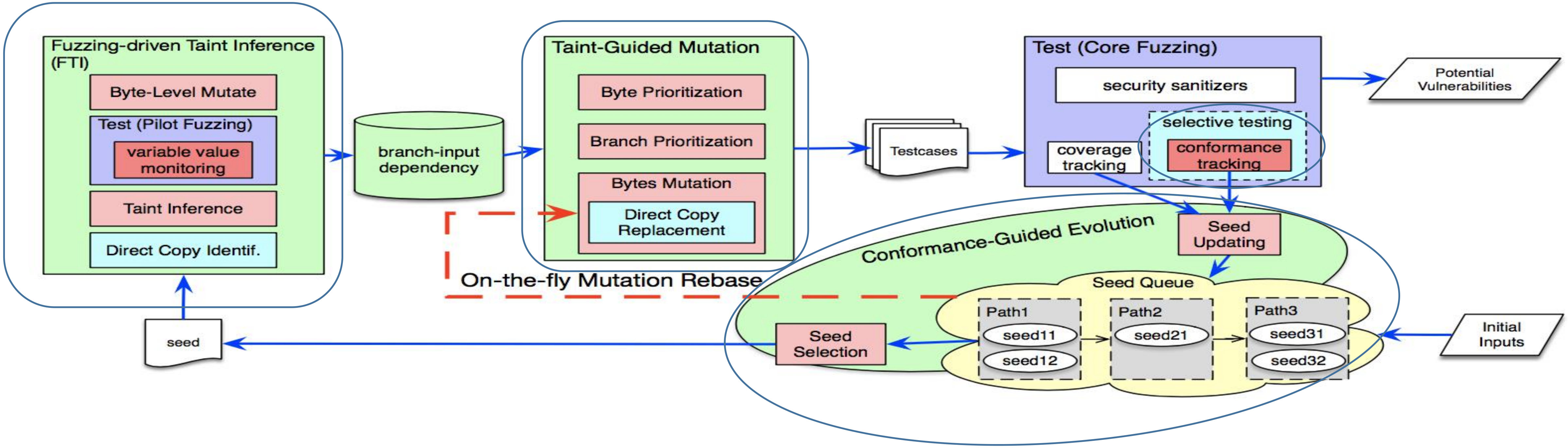
RQ2: How to efficiently guide mutation with taint?

RQ3: How to tune fuzzers' evolution direction with data flow features?

GreyOne: Data Flow Sensitive Fuzzing

Our Solution

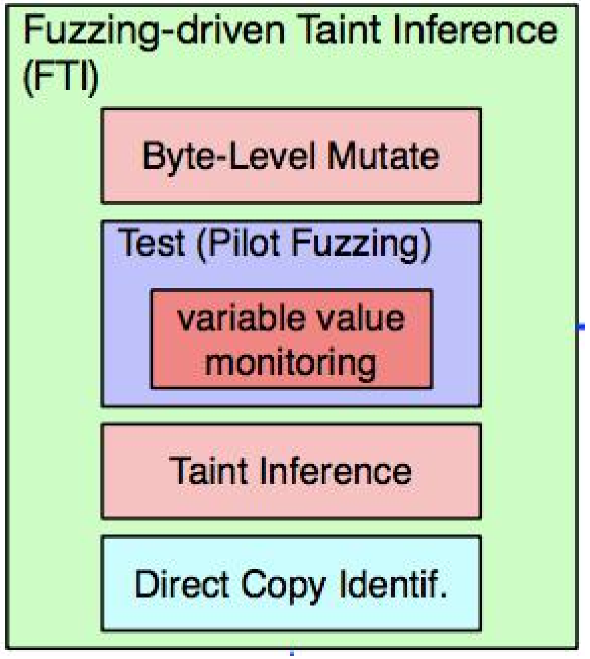
Architecture of GreyOne



- FTI :Fuzzing-driven Taint Inference → Solve RQ1
- Taint-Guided Mutation → Solve RQ2
- Conformance-Guided Evolution → Solve RQ3
- Selective testing → Performance optimization

Part 1: Fuzzing-driven Taint Inference

Fuzzing-driven Taint Inference



Byte-level Mutation

✓ A set of predefined mutation rules
- ◆ Single bit flipping
- ◆ Multiple-bits flipping
- ◆ Arithmetic operations

Variable Value Monitoring

✓ Static instrumentation
- ◆ Variables in constraints with multiple-bits flipping

Taint Inference

✓ Taint rule
- ◆ If the value of a variable var changes, we could infer that var is tainted and depends on the pos-th byte of the input seed S.

Comparison with Traditional Taint Analysis

Speed

- ✓ Traditional taint analysis
  - ◆ Slow
  - ◆ Dynamic binary instrumentation
- ✓ FTI
  - ◆ Fast
  - ◆ Based on static code instrumentation

Accuracy

- ✓ Traditional taint analysis
  - ◆ Over-taint
  - ◆ Under-taint
- ✓ FTI
  - ◆ No over-taint
  - ◆ Less under-taint

Manual Efforts

- ✓ Traditional taint analysis
  - ◆ Labor-intensive efforts
  - ◆ Custom specific taint propagation rules for each instruction
- ✓ FTI
  - ◆ Architecture independent
  - ◆ No extra efforts to port to new platforms

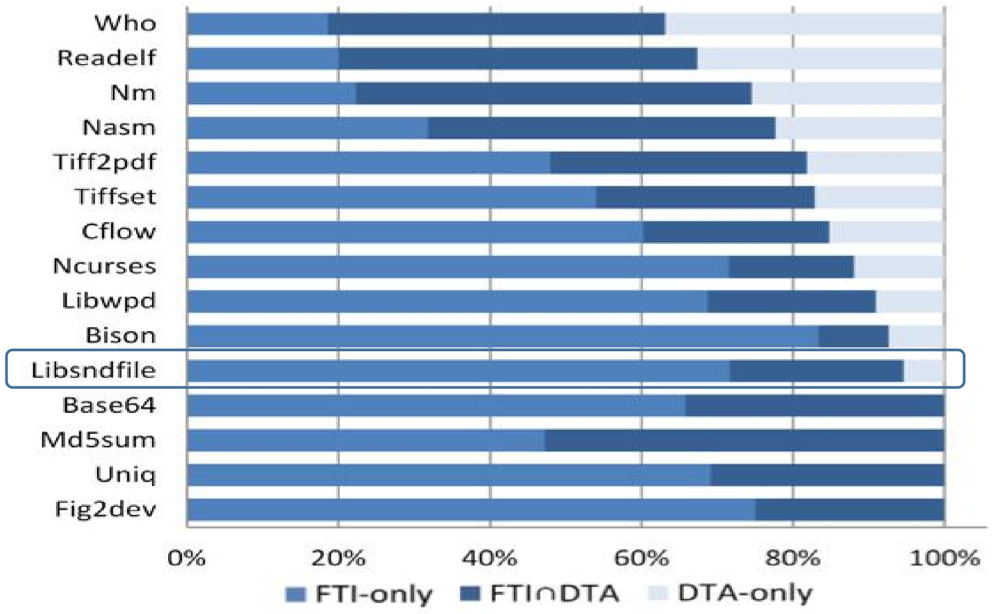
Application : Branch-Input Dependency

```
// magic number: direct copy of input[0:8] vs. constant
if(u64(input) == u64("MAGICHDR")){
    bug1();
}
// checksum: direct copy input[8:16] vs. computed val
if(u64(input+8) == sum(input+16, len-16)){
    bug2();
}
// length: direct copy of input[16:18] vs. constant
if( u16(input+16) > len )) { bug3(); }
// indirect copy of input[18:20]
if(foo(u16(input+18))==...){ bug4(); }
// implicit dependency: var1 depends on input[20:24]
if(u32(input+20) == ...){
    var1 = ...;
}
// var1 may change if input[20:24] changes
// FTI infers: var1 depends on input[20:24]
if(var1 == ...){
    bug5();
}
```

Branch-Input Dependency

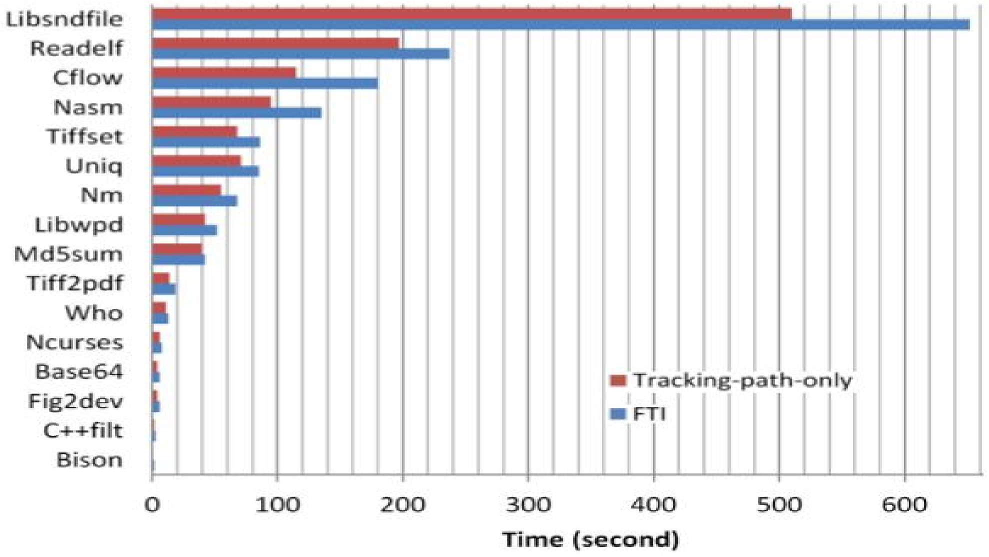
- ✓ Identify Direct Copies of Inputs
- ✓ Identify InDirect Copies of Inputs

Performance of FTI



Proportion of tainted untouched branches reported

- ✓ FTI outperforms the classic taint analysis solution DFSan
- ✓ FTI finds 1.3X more untouched branches that are tainted



Average speed of analyzing one seed by FTI

- ✓ FTI brings 25% overhead on average

Part 2: Taint-guided Mutation

Related work: how to mutate(1)

The most efficient way to make fuzzing smart

- ✓Where to mutate
- ✓What to mutate

Static analysis-based optimization

- ✓ Decomposing long constant comparisons constraint recursively (laf-intel,steelix)
  - ◆ Too many useless branches
  - ◆ Helpless on non-constant comparisons
- ✓ Leverages static symbolic analysis to detect dependencies among input bits, and uses it to compute an optimal mutation ratio
  - ◆ Slowly
  - ◆ The calculated dependency between bits do not show many improvements for mutation.

Learning-based model

- ✓ RNN-based model, predicting best locations to mutate (Rajpal et.al)
  - ◆ Slow training speed
  - ◆ Get too many locations
- ✓ Deep reinforcement learning, mutation actions prioritization
  - ◆ The granularity of mutation actions are too coarse
- ✓ Program smoothing and incremental learning to guide mutation (neuzz)
  - ◆ Lack of accurate input-branches dependence

Related work: how to mutate(2)

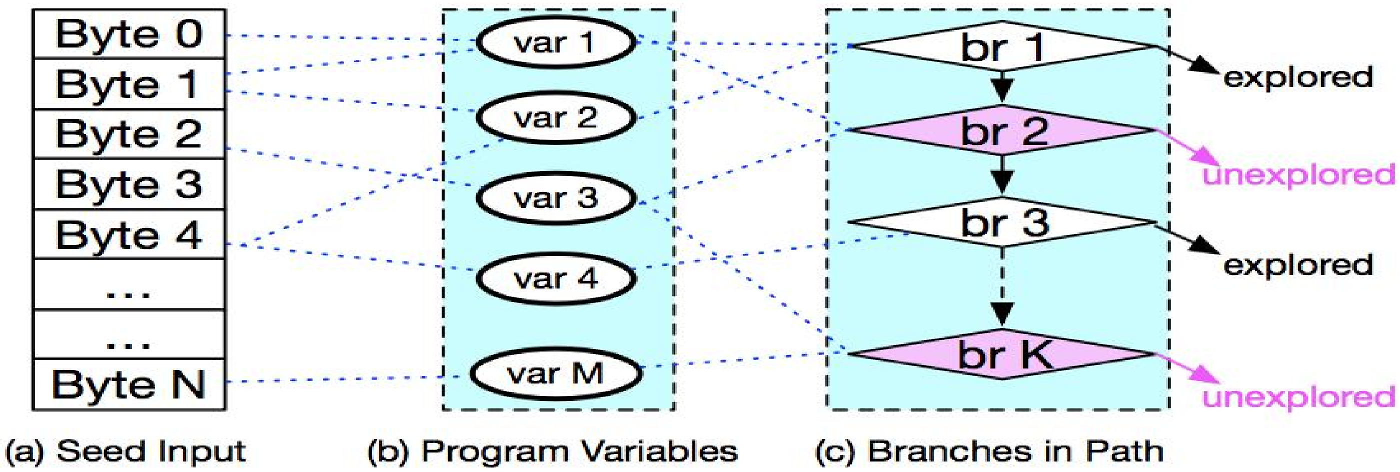
Taint-based mutation

- ✓ Locating buffer boundary violations and buffer over-read vulnerabilities (Dowser, BORG)
- ✓ Tracking the regions of external seed inputs that affect sensitive library or system calls (BuzzFuzz)
- ✓ Identifying checksum branch (TaintScope)
- ✓ Tracking magic bytes related variables (VUzzer)
- ✓ shape inference and gradient descent computation (Angora)
  - ◆ Traditional dynamic taint analysis, many open problems

Our work on taint-guided Mutation

Taint-guided Mutation

- Prioritize Bytes to Mutate
- Prioritize Branches to Explore
- Determine Where and How to Mutate



Prioritize Bytes to Mutate

$$W_{byte}(S, pos) = \sum_{br \in Path(S)} IsUntouched(br) * DepOn(br, pos)$$

- IsUntouched returns 1 if the branch br is not explored by any test case so far, otherwise 0.
- DepOn returns 1 if the branch br depends on the pos-th input byte, according to FTI, otherwise 0.

Prioritize Branches to Explore

$$W_{br}(S,br) = \sum_{pos \in S} DepOn(br,pos) * W_{byte}(S,pos)$$

The weight of an untouched branch br in the according path as the sum of all its dependent input bytes' weight

Determine Where and How to Mutate

Where to mutate

- ✓ Exploring the untouched neighbor branches along this path one by one
  - ◆ Descending order of branch weight
- ✓ For specific untouched neighbor branch
  - ◆ Mutating its dependent input bytes one by one
  - ◆ Descending order of byte weight

Mitigate the under-taint issue

- ✓ Randomly mutating their adjacent bytes with a small probability

How to mutate indirect copies of input

- ✓ Random bit flipping and arithmetic operations on each dependent byte
- ✓ Multiple dependent bytes could be mutated together

How to mutate direct copies of input

- ✓ Executing twice
  - ◆ The first time used to get value
  - ◆ The second time used to cover relevant branch

Part 3: Conformance-Guided Evolution

Related work on selecting and updating seeds

Evolutionary direction control

- ✓Covering more code
- ✓Discovering more vulnerabilities
- ✓Triggering relevant behavior

Related work

- ✓ AFLFast (CCS'16): seeds being picked fewer or exercising less-frequent paths
- ✓ Vuzzer (NDSS'17): seeds exercising deeper paths
- ✓ QTEP (FSE'17): seeds covering more faulty code
- ✓ AFLgo (CCS'17): seeds closer to target vulnerable paths
- ✓ SlowFuzz (CCS'17): seeds consuming more resources

Our previous solution

- ✓Prioritize seeds with more untouched branches(CollAFL-br, s&p 18')
- ✓20% more paths over AFL

Data flow features: conformance of constraints

Conformance of constraints

- ✓ Expressing the distance of tainted variables to the values expected in untouched branches
- ✓ Higher conformance means lower complexity of mutation

Q1: How to evaluate single constraint?
Q2 How to evaluate a set of constraints?

Conformance of one branch

$$C_{br}(br,S) = NumEqualBits(var1, var2)$$

Conformance of a basic block

$$C_{BB}(bb,S) = \underset{br \in Edges(bb)}{MAX} IsUntouched(br) * C_{br}(br,S)$$

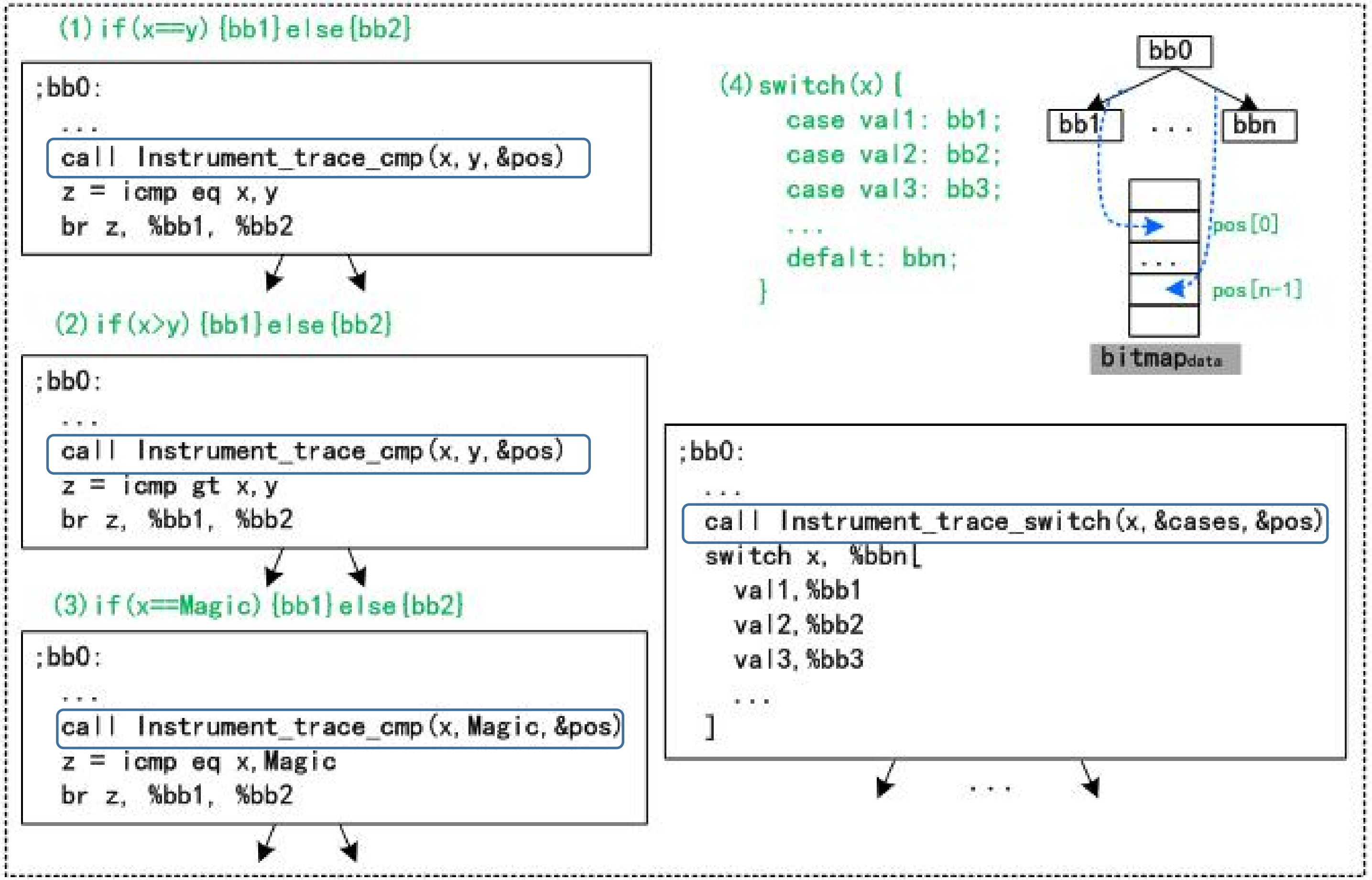
A set of constraints : Conformance of one path

$$C_{seed}(S) = \sum_{bb \in Path(S)} C_{BB}(bb,S)$$

Advantages

- ✓ Few extra instrumented overhead
- ✓ Keep the original construct of program
- ✓ Non-constant variables comparison branch could be calculated

Details of Conformance Calculation

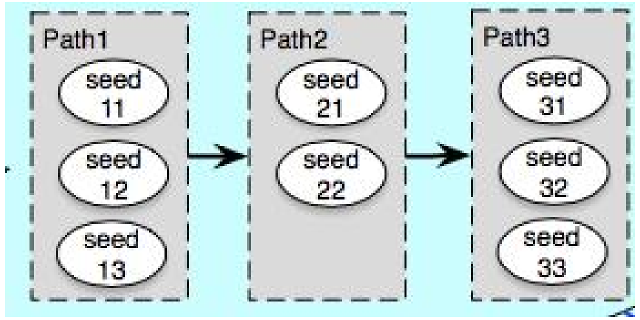


Conformance-Guided Seed Updating

- Two-Dimensional Seed Queue

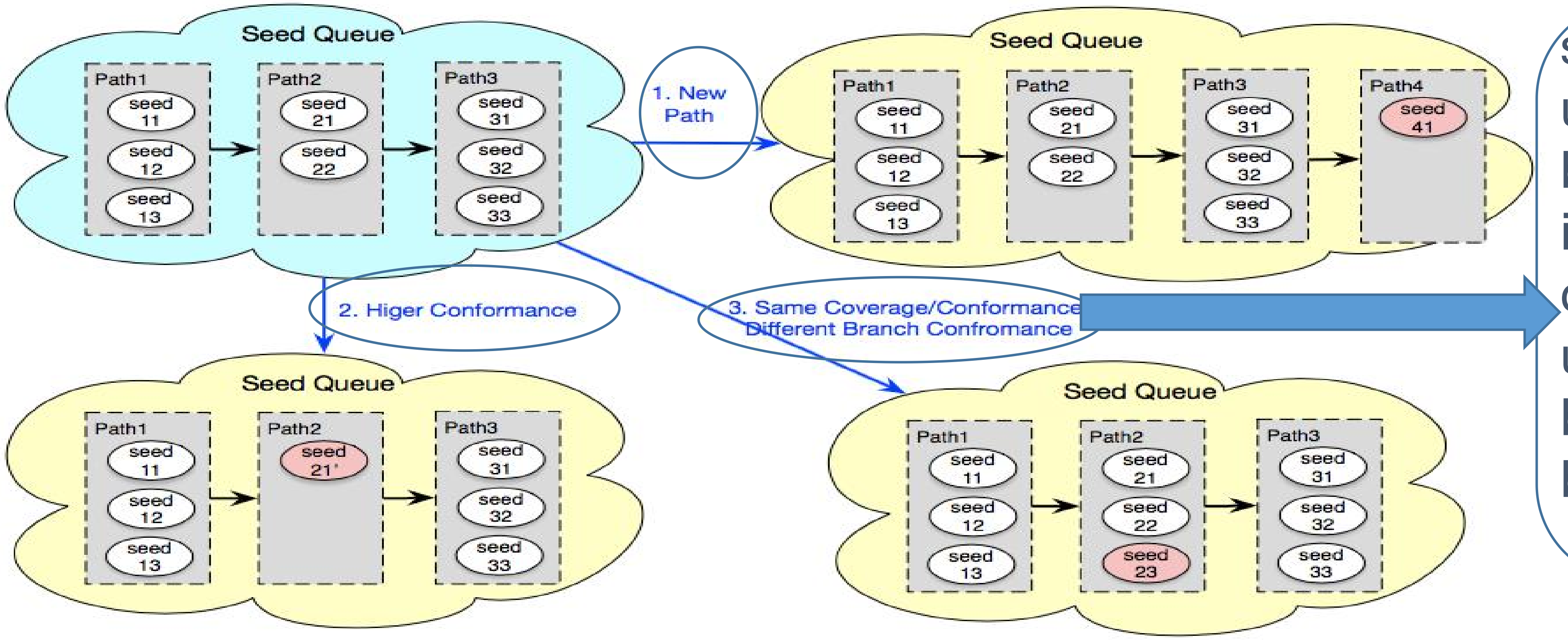
Traditional seed queues are usually kept in a linked list, where each node represents a seed that explores a unique path

GREYONE extend each node to include multiple seeds that explore a same path and have a same conformance but different block conformance, to form a two-dimensional seed queue



Conformance-Guided Seed Updating

- Seed queue Updates



since the test case has a unique distribution of basic block conformance, it could derive new test cases to quickly trigger untouched neighbor branches of some basic blocks

Conformance-Guided Seed Selection

Combining with updating mechanism

Giving priority to seeds with high conformance

Advantages: accelerate the evolution of fuzzing

- ✓ Long-term stable improvements
- ✓ Avoid getting stuck in local minimum like gradient descent algorithm(s&p 2018)
- ✓ The conformance focuses on untouched branches, which is better than the measurement of Honggfuzz and libfuzzer

Part 4: Performance Optimization

Related work

Execution enviroment

- ✓ Fork
- ✓ Forkserver
- ✓ Persistent
- ✓ IPT

Boosting

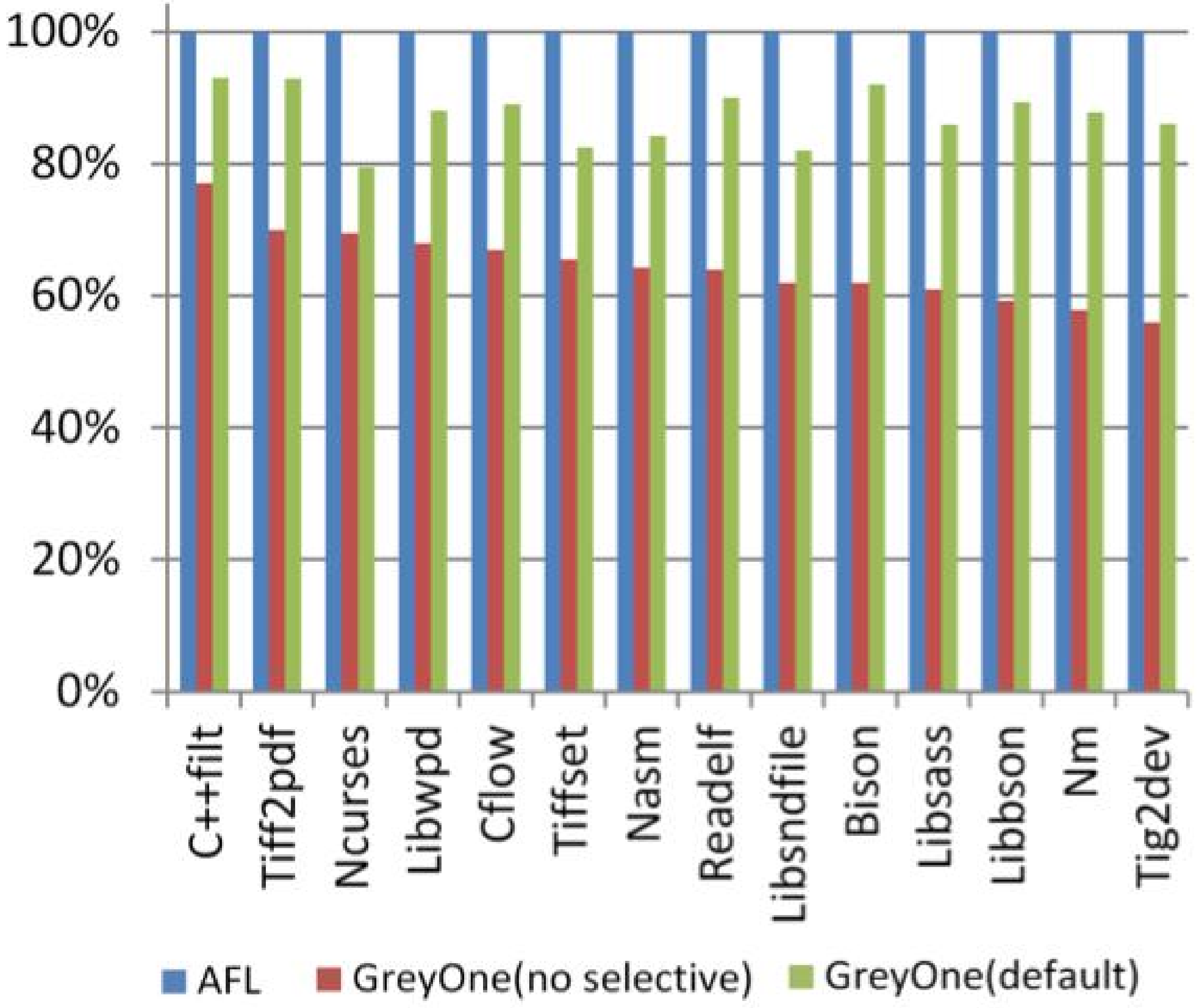
- ✓ Parallel execution(Wen Xu,ccs17)
- ✓ Instrumentation (Instrim NDSS 18,Untracer s&p19)
  - ◆ Removing unnecessary instrumentation

Our work

Selective execution mechanism

- ✓ GREYONE has two more modes during testing
  - ◆ Variable value monitoring mode used for FTI
  - ◆ Conformance-guided tracking mode for evolution tuning
- ✓ Extending the fork server used by AFL to switch between them on demand
  - ◆ When conformance tracking mode brought few conformance promotion, switching to normal tracking mode

Performance Optimization



Selective execution mechanism

✓ By comparing these two mode with AFL

- The mode without selective mechanism will slow down to less than 65%
- GREYONE's could keep execution speed more than 80%

Evaluation

Vulnerabilities Discovery

Applications	Version	AFL	CollAFL- br	Honggfuzz	VUzzer	Angora	GREYONE	Vulnerabilities		
								Unknown	Known	CVE
readelf	2.31	1	1	0	0	3	4	2	2	-
nm	2.31	0	0	0	0	0	2	1	1	*
c++filt	2.31	1	1	1	0	0	4	2	2	*
tiff2pdf	v4.0.9	0	0	0	0	0	2	1	1	0
tiffset	v4.0.9	1	2	0	0	0	2	1	1	1
fig2dev	3.2.7a	1	3	2	0	0	10	8	2	0
libwpd	0.1	0	1	0	0	0	2	2	0	2
ncurses	6.1	1	1	0	0	0	4	2	2	2
nasm	2.14rc15	1	2	2	1	2	12	11	1	8
bison	3.05	0	0	1	0	2	4	2	2	0
cflow	1.5	2	3	1	0	0	8	4	4	0
libsass	3.5-stable	0	0	0	0	0	3	2	1	2
libbson	1.8.0	1	1	1	0	0	2	1	1	1
libsndfile	1.0.28	1	2	2	1	0	2	2	0	1
libconfuse	3.2.2	1	2	0	0	0	3	2	1	1
libwebm	1.0.0.27	1	1	0	0	0	1	1	0	1
libsolv	2.4	0	0	3	2	2	3	3	0	3
libcaca	0.99beta19	2	4	1	0	0	10	8	2	6
liblas	2.4	1	2	0	0	0	6	6	0	4
libslax	20180901	3	5	0	0	0	10	9	1	*
libsixl	v1.8.2	2	2	2	2	3	6	6	0	6
libxsmm	release-1.10	1	1	2	0	0	5	4	1	3
Total	-	21	34	18	6	12	105 (+209%)	80	25	41

Testing 19 popular applications

GREYONE detected 209% more vulnerabilities (41 CVEs)

Number of vulnerabilities (accumulated in 5 runs) detected by 6 fuzzers, including AFL, CollAFL-br, VUzzer, Honggfuzz,Angora, and GREYONE, after testing each application for 60 hours

CVEs

libwpd	CVE-2017-14226, CVE-2018-19208
libtiff	CVE-2018-19210
libbson	CVE-2017-14227,
libncurses	CVE-2018-19217, CVE-2018-19211
libsass	CVE-2018-19218, CVE-2018-19218
libsndfile	CVE-2018-19758
nasm	CVE-2018-19213, CVE-2018-19215, CVE-2018-19216, CVE-2018-20535, CVE-2018-20538, CVE-2018-19755
libwebm	CVE-2018-19212
libconfuse	CVE-2018-19760
libsixel	CVE-2018-19757, CVE-2018-19756, CVE-2018-19762, CVE-2018-19761, CVE-2018-19763, CVE-2018-19763
libsolv	CVE-2018-20533, CVE-2018-20534, CVE-2018-20532
libLAS	CVE-2018-20539, CVE-2018-20536, CVE-2018-20537, CVE-2018-20540
libxsmm	CVE-2018-20541, CVE-2018-

Libxsmm: CVE-2018-20541

```
There is a  heap-buffer-overflow in libxsmm_sparse_csc_reader  at src/generator_spgemm_csc_reader.c:174
src/generator_spgemm_csc_reader.c:122) in libxsmm.

Description:

The asan debug is as follows:

$./libxsmm_gemm_generator sparse b a 10 10 10 1 1 1 1 1 1 0 wsm nopf SP POC0

=================================================================
==51909==ERROR: AddressSanitizer: heap-buffer-overflow on address 0x60200000eff0 at pc 0x000000444875 b
WRITE of size 4 at 0x60200000eff0 thread T0
    #0 0x444874 in libxsmm_sparse_csc_reader src/generator_spgemm_csc_reader.c:174
    #1 0x405751 in libxsmm_generator_spgemm src/generator_spgemm.c:279
    #2 0x40225a in main src/libxsmm_generator_gemm_driver.c:318
    #3 0x7f73105a0a3f in __libc_start_main (/lib/x86_64-linux-gnu/libc.so.6+0x20a3f)
    #4 0x402ea8 in _start (/home/company/real_sanitize/poc_check/libxsmm/libxsmm_gemm_generator_asan+0x

0x60200000eff1 is located 0 bytes to the right of 1-byte region [0x60200000eff0,0x60200000eff1)
allocated by thread T0 here:
    #0 0x7f7310c009aa in malloc (/usr/lib/x86_64-linux-gnu/libasan.so.2+0x989aa)
    #1 0x443f78 in libxsmm_sparse_csc_reader src/generator_spgemm_csc_reader.c:122
    #2 0x7ffc367e92bf  (<unknown module>)
    #3 0x439  (<unknown module>)
```

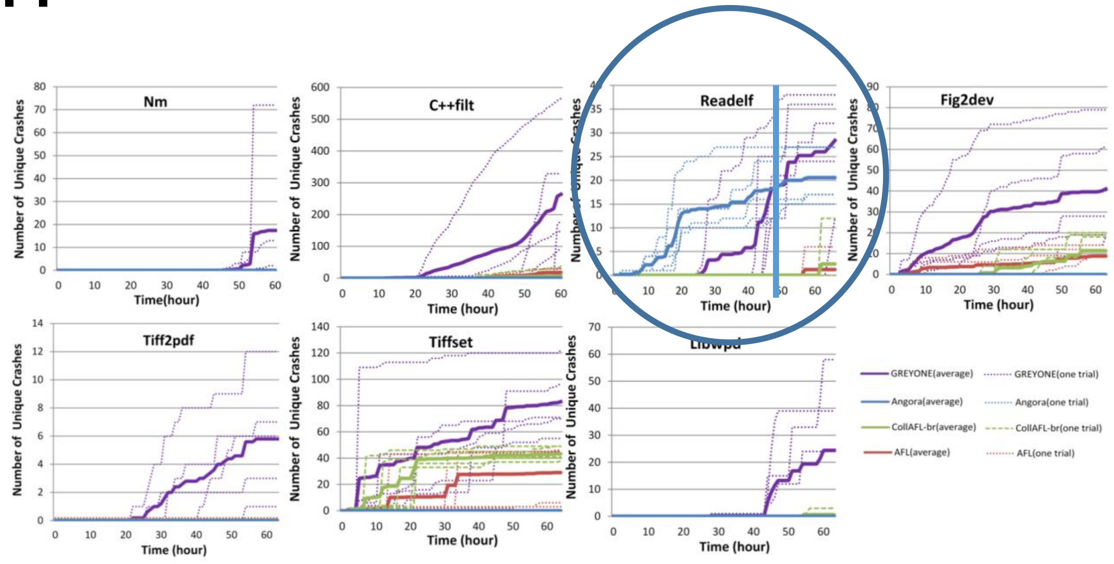
Libsixel:CVE-2018-19757

```
$./img2sixel   POC2
=================================================================
==624==ERROR: AddressSanitizer: heap-buffer-overflow on address 0x60200000a7b1 at pc 0x7fcd853aa04c bp 0x7ffd2dcd54d0 sp
0x7ffd2dcd4c78
WRITE of size 67108863 at 0x60200000a7b1 thread T0
    #0 0x7fcd853aa04b in __asan_memset (/usr/lib/x86_64-linux-gnu/libasan.so.2+0x8d04b)
    #1 0x7fcd8508bf10 in memset /usr/include/x86_64-linux-gnu/bits/string3.h:90
    #2 0x7fcd8508bf10 in image_buffer_resize /home/company/real_sanitize/libsixel-master/src/fromsixel.c:311
    #3 0x7fcd8508d5d4 in sixel_decode_raw_impl /home/company/real_sanitize/libsixel-master/src/fromsixel.c:565
    #4 0x7fcd8508e8b1 in sixel_decode_raw /home/company/real_sanitize/libsixel-master/src/fromsixel.c:881
    #5 0x7fcd850c042c in load_sixel /home/company/real_sanitize/libsixel-master/src/loader.c:613
    #6 0x7fcd850c042c in load_with_builtin /home/company/real_sanitize/libsixel-master/src/loader.c:782
    #7 0x7fcd850c43d9 in sixel_helper_load_image_file /home/company/real_sanitize/libsixel-master/src/loader.c:1352
    #8 0x7fcd850cf283 in sixel_encoder_encode /home/company/real_sanitize/libsixel-master/src/encoder.c:1737
    #9 0x4017f8 in main /home/company/real_sanitize/libsixel-master/converters/img2sixel.c:457
    #10 0x7fcd84a88a3f in __libc_start_main (/lib/x86_64-linux-gnu/libc.so.6+0x20a3f)
    #11 0x401918 in _start (/home/company/real_sanitize/poc_check/libsixel/img2sixel+0x401918)

0x60200000a7b1 is located 0 bytes to the right of 1-byte region [0x60200000a7b0,0x60200000a7b1)
allocated by thread T0 here:
    #0 0x7fcd853b59aa in malloc (/usr/lib/x86_64-linux-gnu/libasan.so.2+0x989aa)
    #1 0x7fcd8508be1f in image_buffer_resize /home/company/real_sanitize/libsixel-master/src/fromsixel.c:292
```

Unique Crashes Evaluation

Applications	AFL		CollAFL-br		Angora		GREYONE	
	Average	Max	Average	Max	Average	Max	Average	Max
tiff2pdf	0	0	0	0	0	0	6	12
libwpd	0	0	1	3	0	0	21	58
fig2dev	8	12	11	20	0	0	40	79
readelf	0	0	0	0	21	27	28	38
nm	0	0	0	0	0	0	16	72
c++filt	18	30	7	32	0	0	268	575
ncurses	7	18	12	23	0	0	28	37
libsndfile	4	13	8	20	0	0	23	33
libbson	0	0	0	0	0	0	6	12
tiffset	22	46	43	49	0	0	83	122
libsass	0	0	0	0	0	0	8	12
cflow	9	47	17	35	0	0	32	185
nasm	5	15	20	42	6	12	157	212
Total	73	181	119	229	27	39	716 (+501%)	1447 (+631%)



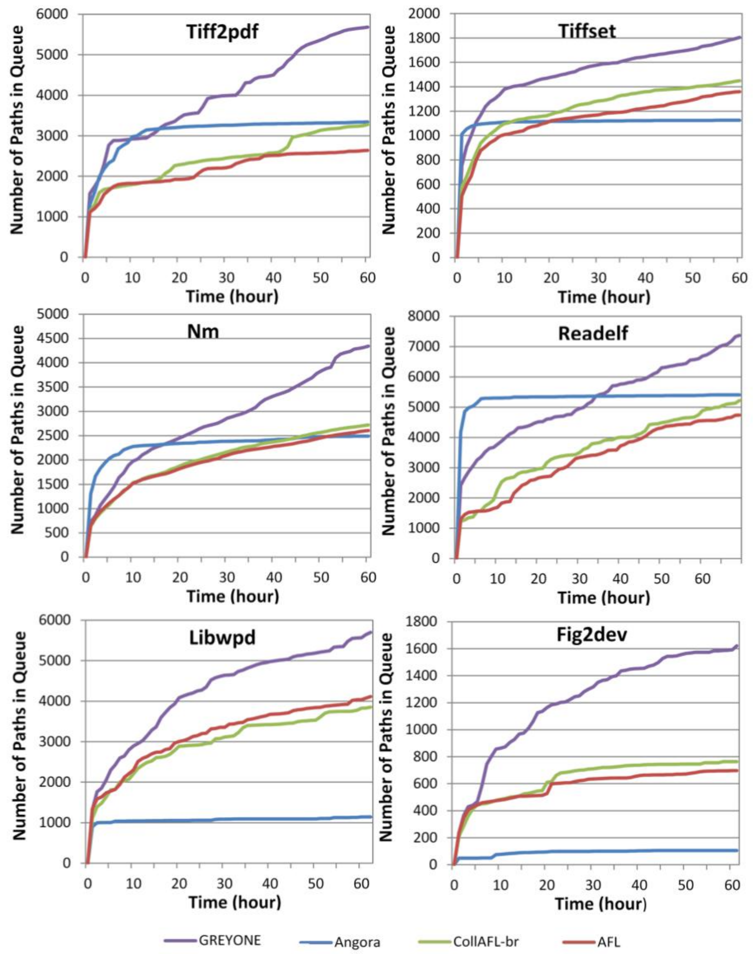
Number of unique crashes (average and maximum count in 5 runs) found in real world programs by various fuzzers

The growth trend of number of unique crashes (average and each of 5 runs) detected by AFL, CollAFL-br, Angora and GREYONE

Code Coverage Evaluation

Applications	Path Coverage				Edge Coverage			
	AFL	CollAFL-br	Angora	GREYONE (INC)	AFL	CollAFL-br	Angora	GREYONE (INC)
tiff2pdf	2638	3278	3344	5681(+69.9%)	6261	6776	6820	8250(+20.9%)
readelf	4519	4782	5212	6834(+32%)	6729	6955	7395	8618(+14.5%)
fig2dev	697	764	105	1622(+112%)	934	1754	489	2460(+40.2%)
ncurses	1985	2241	1024	2926(+30.6%)	2082	2151	1736	2787(+28.2%)
libwpd	4113	3856	1145	5644(+37.2%)	5906	5839	4034	7978(+35.1%)
c++filt	9791	9746	1157	10523(+8%)	6387	6578	3684	7101(+8%)
nasm	7506	7354	3364	9443(+25.8%)	6553	6616	4766	8108(+22.5%)
tiffset	1373	1390	1126	1757(+26%)	3856	3900	3760	4361(+11.8%)
nm	2605	2725	2493	4342(+59%)	5387	5526	5235	8482(+53.5%)
libsndfile	911	848	942	1185(+25.8%)	2486	2392	2525	2975(+17.8%)

Number of unique crashes (average and maximum count in 5 runs) found in real world programs by various fuzzers



The growth trend of number of unique paths (average in 5 runs) detected by AFL, CollAFL-br, Angora and GREYONE

Further evaluation

Heuristic Constraints Solving

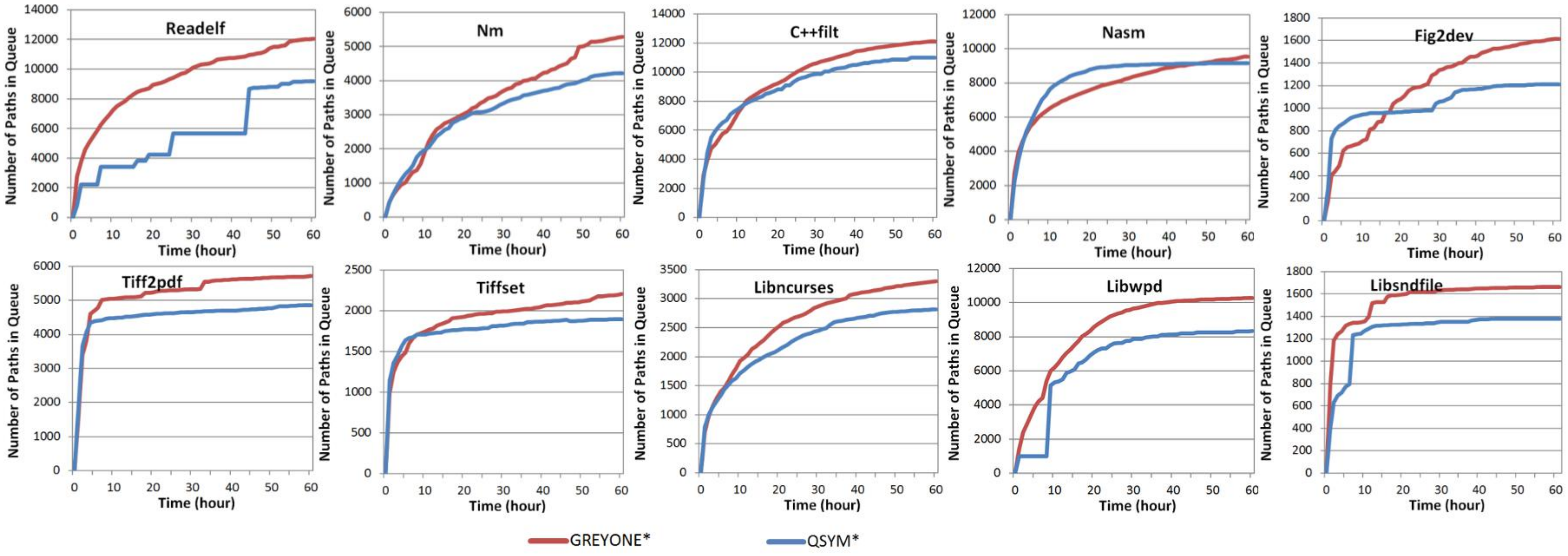


Figure 6: The growth trend of number of unique paths (average of 5 runs) detected by QSYM-* and GREYONE-*.

On average, GREYONE found 1.2X unique paths, 1.12X edges, 2.15X unique crashes and 1.52X vulnerabilities than QSYM.

Improvements Breakdown (FTI)

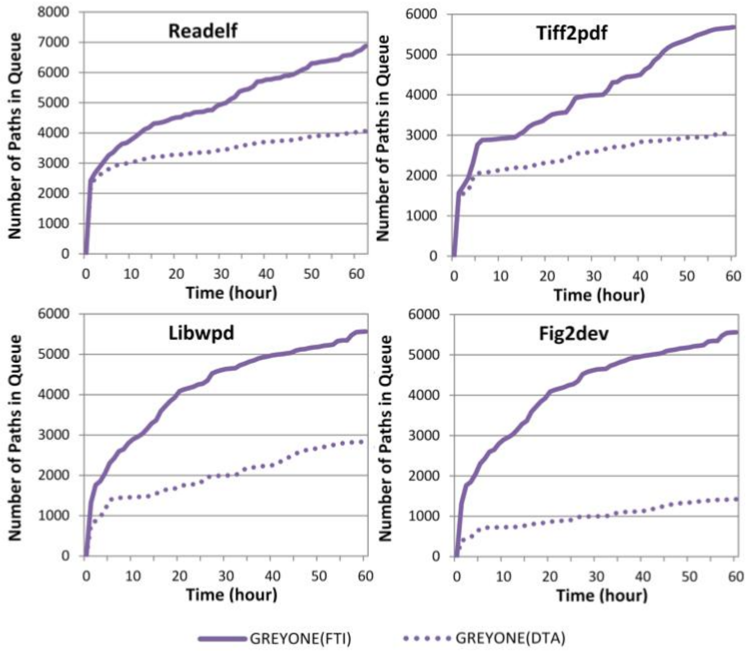


Figure 10: Code coverage improvement brought by FTI.

FTI could double the code coverage on all targets, comparing to GREYONE-DTA.

Improvements Breakdown
(byte prioritization and conformance-guided evolution)

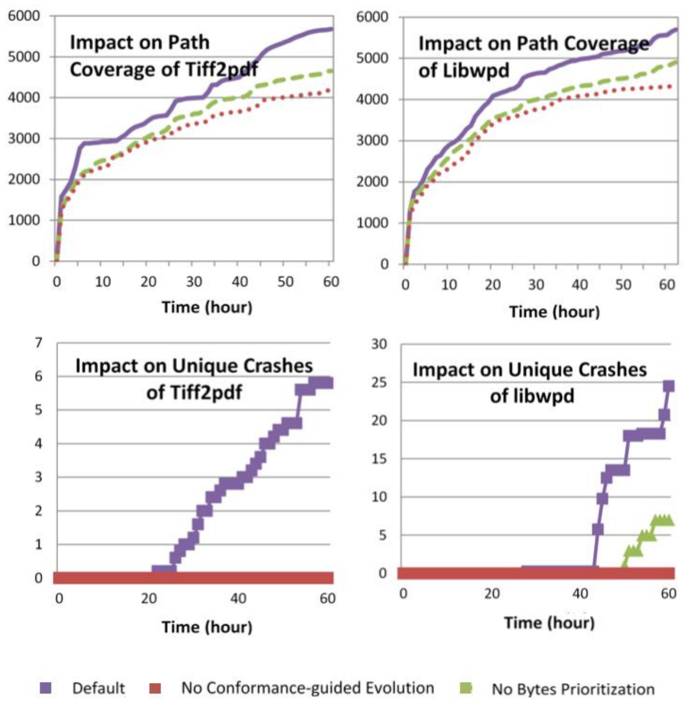


Figure 11: Improvements brought by *byte prioritization* and *conformance-guided evolution*, in terms of code coverage and unique crashes found in two applications.

Table 6: Number of unique paths and crashes (average in 5 runs with 60 hours one run) found in real world programs by GREYONE, GREYONE-CE and GREYONE-BP, where GREYONE-CE is the mode of GREYONE disabling conformance-guided evolution and GREYONE-BP is the mode of GREYONE disabling bytes prioritization.

Applications	Unique Paths			Unique Crashes		
	GREYONE	GREYONE-CE	GREYONE-BP	GREYONE	GREYONE-CE	GREYONE-BP
Readelf	6834	6222(-9%)	5757(-15.8%)	28	21(-25%)	25(-10.7%)
Nm	4342	3432(-21%)	3886(-10.5%)	16	4(-75%)	7(-56.3%)
C++filt	10523	9870(-6.2%)	9932(-5.6%)	268	127(-52.6%)	225(-16%)
Tiff2pdf	5681	4107(-27.8%)	4598(-19%)	6	0(-100%)	0(-100%)
Tiffset	1757	1345(-23.4%)	1434(-18.4%)	83	28(-66.3%)	49(-41%)
Libwpd	5644	4220(-25.2%)	4982(-11.7%)	21	0(-100%)	7(-66%)
libsndfile	1185	1069(-10%)	1081(-8.2%)	23	7(-69.6%)	9(-60.9%)
Fig2dev	1622	999(-38.4%)	1211(-25.3%)	40	24(-40%)	33(-17.5%)
Nasm	9443	6578(-30.3%)	7979(-15.5%)	157	28(-82.2%)	79(-49.7%)
libncurses	2926	2112(-27.8%)	2543(-13%)	28	22(-21.4%)	25(-10.7%)
Average Reduction	-	-21.9%	-14.3%	-	-63.2%	-42.9%

Conclusion

We propose a novel data flow sensitive fuzzing solution GREYONE

- ✓ where Fuzzing-driven taint inference is further more efficient than traditional dynamic taint inference
- ✓ It performs better performance than many popular fuzzing tools including AFL, CollAFL, Honggfuzz in terms of code coverage and vulnerabilities discovery
- ✓ It detected 105 unknown vulnerabilities with 41 CVEs

Thanks!

Q&A