WEIZZ: Automatic Grey-Box Fuzzing for Structured Binary Formats

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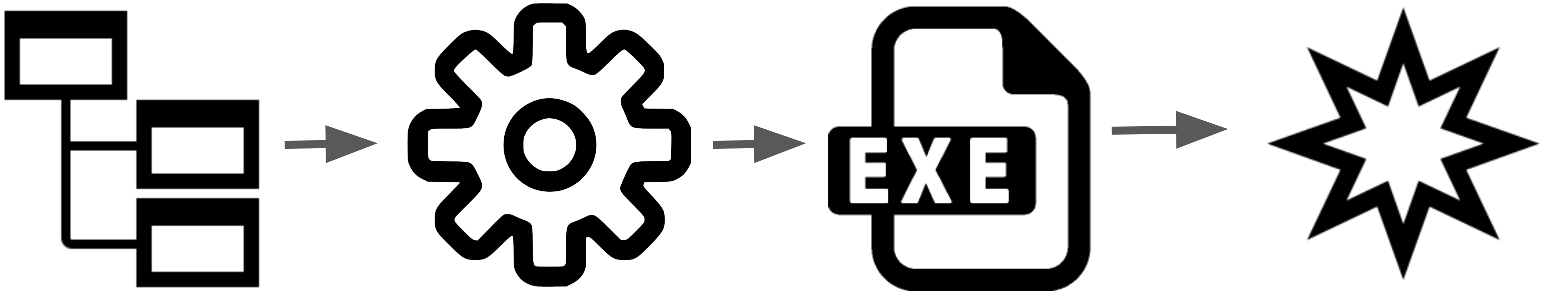
ISSTA
LAX 2020

Format-aware Fuzzing



Input Format Model

Input Generation

Program Under Test

Crashes

Format-aware Fuzzing

- LangFuzz
- Peach
- Spike
- CSmith
- ...

Problems

- Impossible if the input structure is unknown

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- Impossible if the input structure is unknown
- May fail to find bugs related to syntactically invalid inputs in parsers
- Parser implementations do not always closely mirror format specifications
- Models take some time to be written by a human (and contain simplifications)
- Wrong models make fuzzing ineffective

Solutions?

- Automatically learn the model from the actual implementation of the parser

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- Generate not always syntactically valid inputs

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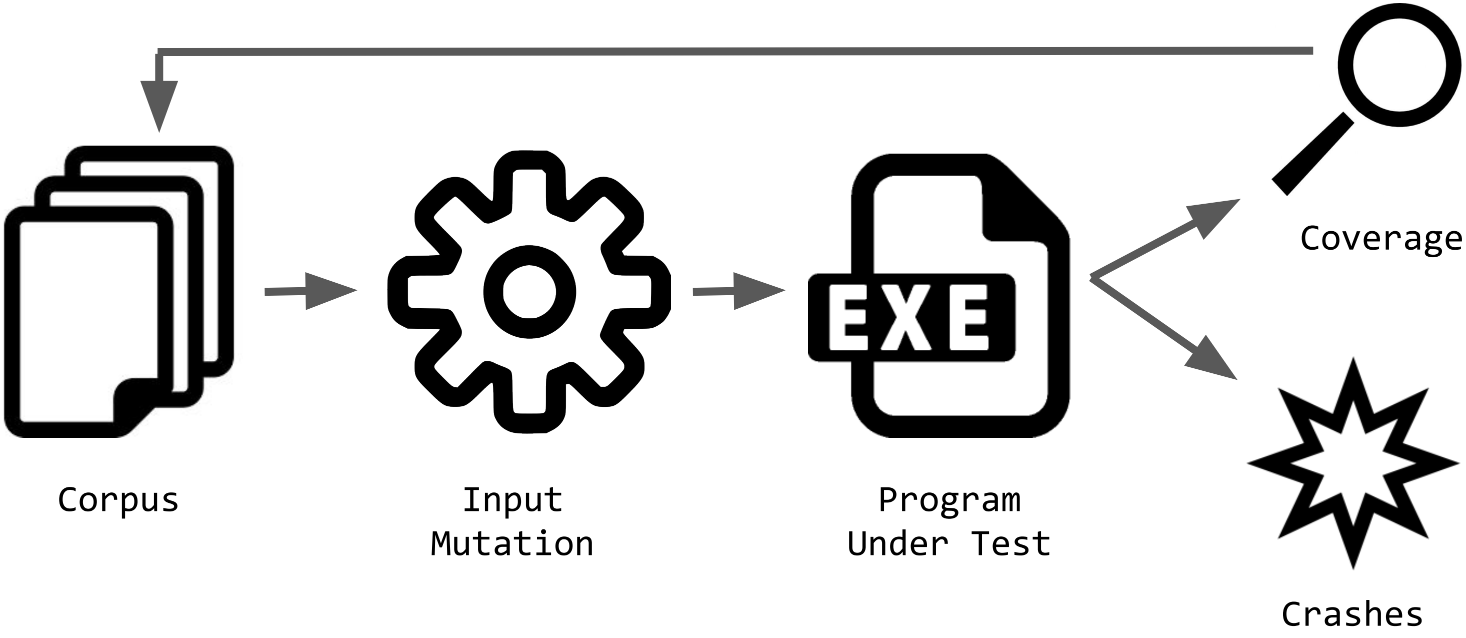
- Automatically learn the model from the actual implementation of the parser
  - (Approximation of) Taint Tracking
    - [Tupni] [Autogram] [Polyglot] [Grimoire]
  - Machine Learning
    - [Learn&Fuzz] [REINAM]
  - Oracle based
    - [GLADE]
- Generate not always syntactically valid inputs

Coverage-guided Fuzzing



Problems

- Fail to explore deep paths behind parsers

Problems

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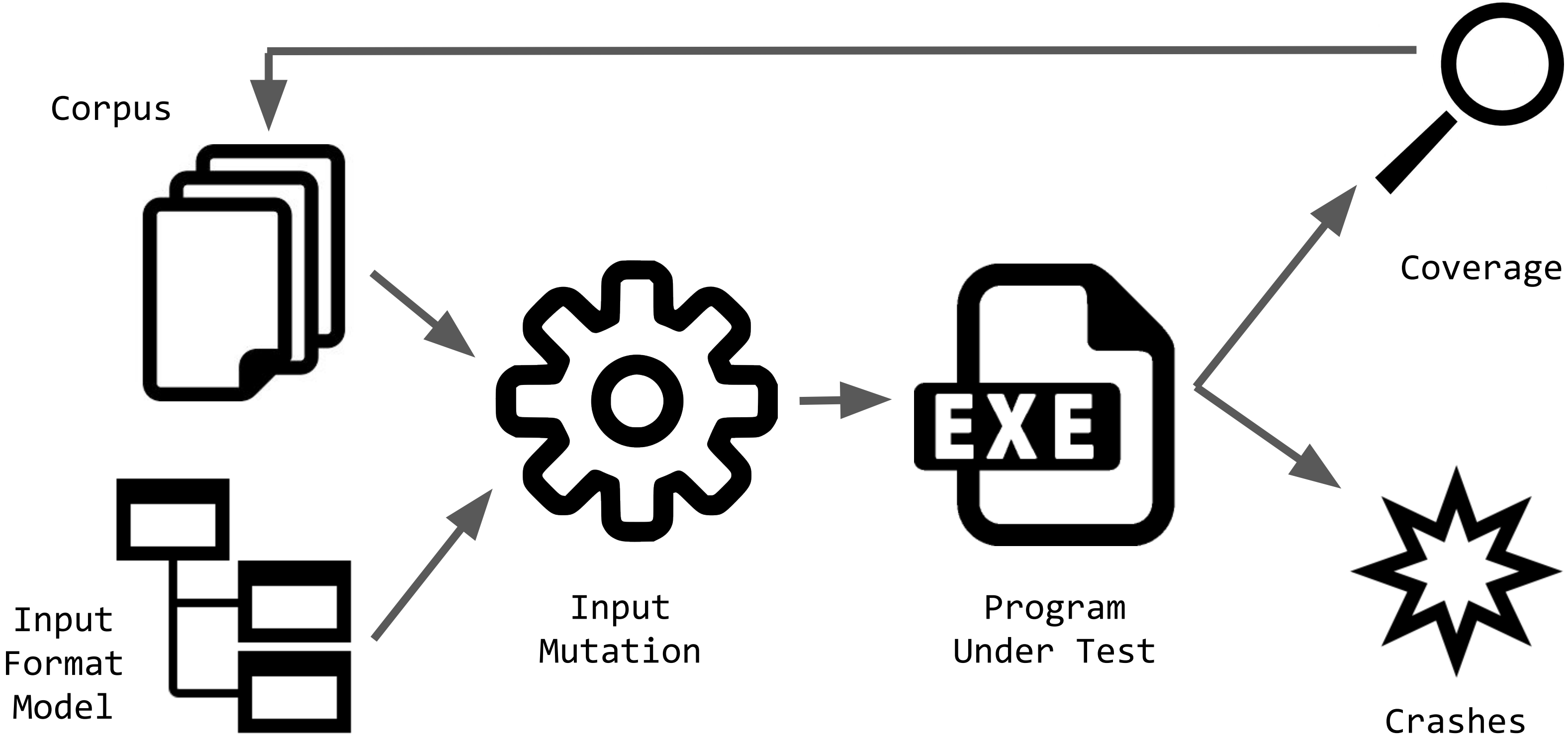
- Affected by roadblocks (multi-byte comparisons, checksums, hashes, …)

```
if (hash(input[0:8]) != input[8:12]) exit(1)

if (input[12:16] == 0xABADCAFE) bug()
```

Structured Fuzzing



Structured Fuzzing

- AFLSmart
- Nautilus
- Superion
- Libprotobuf-Mutator
- Zest
- ...

Bypass Roadblocks

- Concolic Fuzzing
    - [Driller] [QSYM] [Eclipser]
- (Approximation of) Taint Tracking
    - [TaintScope] [Vuzzer] [Angora] [Redqueen]
- Sensitive feedbacks
    - [LAF-Intel] [CompareCoverage] [FuzzFactory] [IJON]

Bypass Roadblocks

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Idea #1

- Reuse expensive analysis to bypass roadblocks previously explored in past works to enable Structure-aware mutations

Bypass Roadblocks [Redqueen]

- Mutations targeting magic byte comparisons (Input-To-State)

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```
input: AAAABBBBCCCCBBBB

cmp eax, FFFF → eax = BBBB
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Bypass Roadblocks [Redqueen]

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  input: AAAABBBBDDCCDDCC (equivalent in coverage)

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- Mutations targeting magic byte comparisons (Input-To-State)

```
input: AAAABBBBDDCCDDCC (equivalent in coverage)

cmp eax, FFFF → eax = BBBB

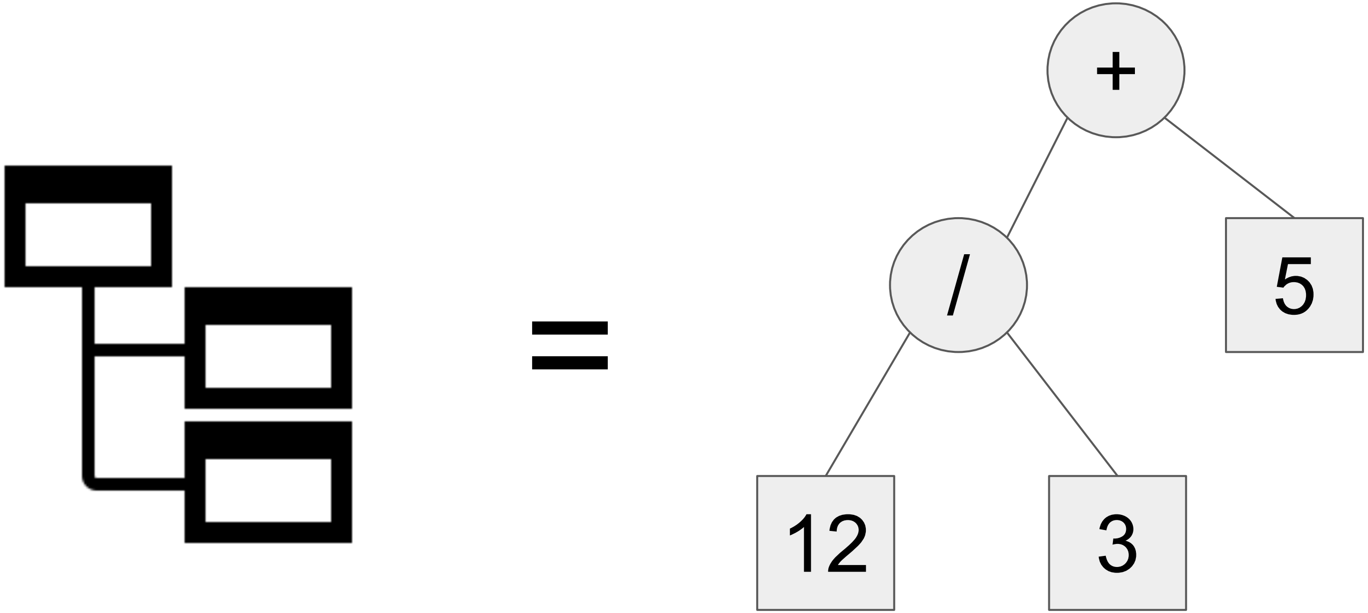
new input: AAAAFFFFDDCCDDCC
```

Bypass Roadblocks [Redqueen]

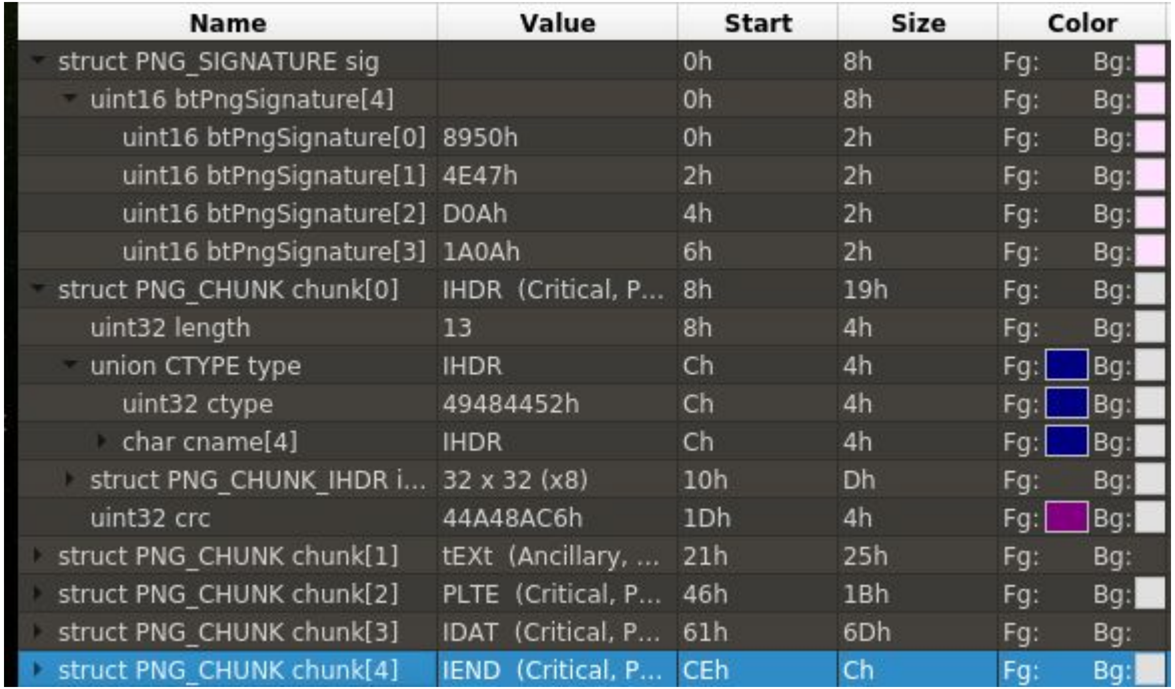
- Mutations targeting magic byte comparisons (Input-To-State)

- Patch out checksum checks

Formats as an AST [Grimoire]



Not all formats are parsed into an AST



Name	Value	Start	Size	Color
struct PNG_SIGNATURE sig		0h	8h	Fg: Bg: □
uint16 btPngSignature[4]		0h	8h	Fg: Bg: □
uint16 btPngSignature[0]	8950h	0h	2h	Fg: Bg: □
uint16 btPngSignature[1]	4E47h	2h	2h	Fg: Bg: □
uint16 btPngSignature[2]	D0Ah	4h	2h	Fg: Bg: □
uint16 btPngSignature[3]	1A0Ah	6h	2h	Fg: Bg: □
struct PNG_CHUNK chunk[0]	IHDR (Critical, P...	8h	19h	Fg: Bg: □
uint32 length	13	8h	4h	Fg: Bg: □
union CTYPE type	IHDR	Ch	4h	Fg: 🟦 Bg: □
uint32 ctype	49484452h	Ch	4h	Fg: 🟦 Bg: □
char cname[4]	IHDR	Ch	4h	Fg: 🟦 Bg: □
struct PNG_CHUNK_IHDR i...	32 x 32 (x8)	10h	Dh	Fg: Bg: □
uint32 crc	44A48AC6h	1Dh	4h	Fg: 🟪 Bg: □
struct PNG_CHUNK chunk[1]	tEXt (Ancillary, ...	21h	25h	Fg: Bg:
struct PNG_CHUNK chunk[2]	PLTE (Critical, P...	46h	1Bh	Fg: Bg: □
struct PNG_CHUNK chunk[3]	IDAT (Critical, P...	61h	6Dh	Fg: Bg:
struct PNG_CHUNK chunk[4]	IEND (Critical, P...	CEh	Ch	Fg: Bg: □

Comparisons for validation

```
if (chunk->size_field > SIZE_MAX)
    error(“Invalid Chunk Size”);
```

Idea #2

- Instead of using memory accesses to reconstruct the format ([Tupni] [Autogram]) use the comparisons instructions that are likely validation checks

Idea #3

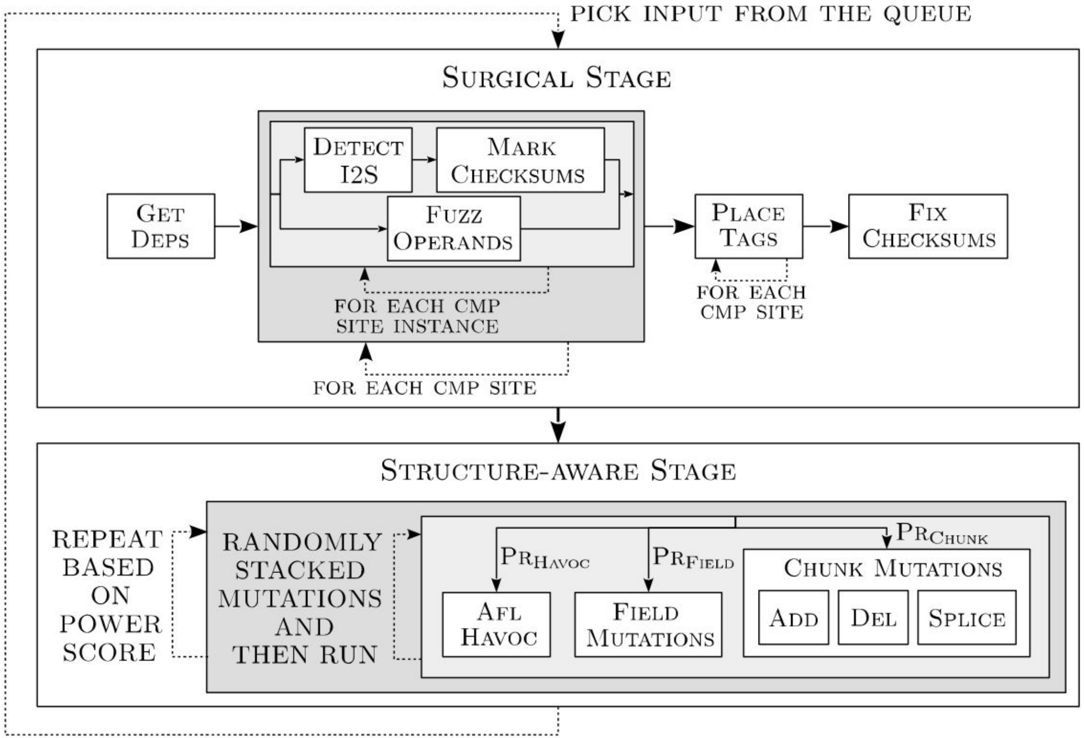
- Don’t learn a model and use it to guide the fuzzer, but reconstruct each time the structure and apply mutations.

  This avoids the problem of having errors in the learning process.

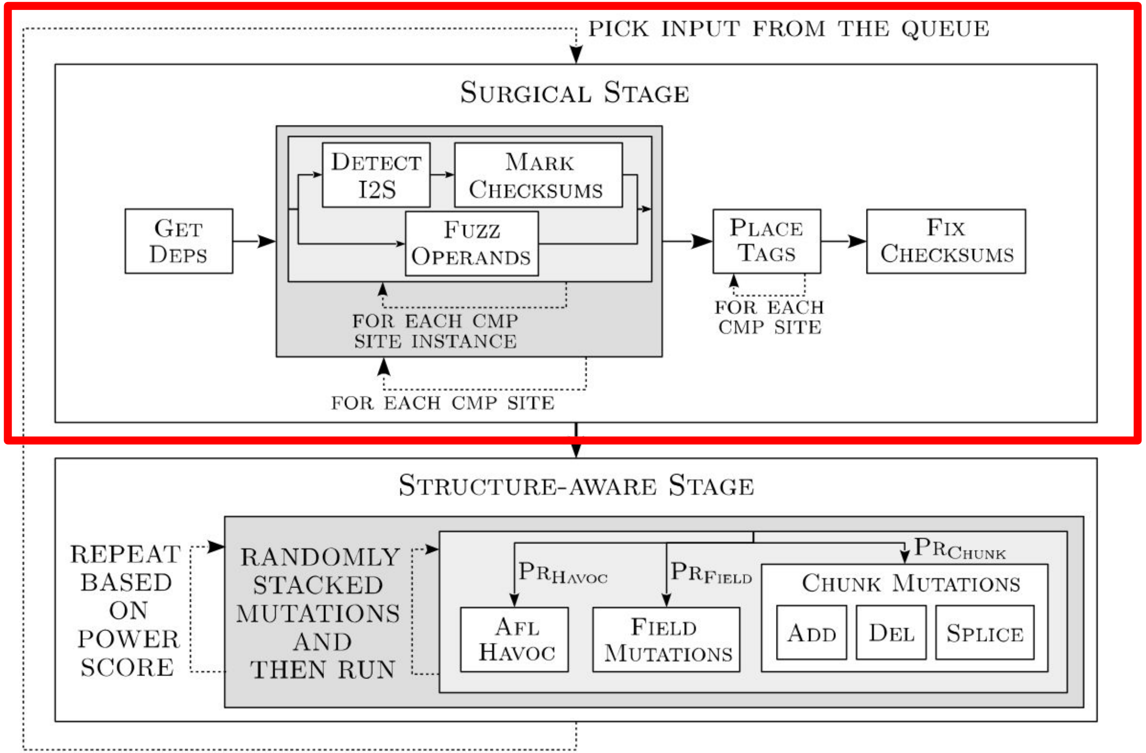
Weizz

- Based on AFL 2.52b
- Binary-only (QEMU)
- Approximate Taint to bypass Roadblocks and learn information about validation checks
- Structural mutations based on that information (inspired by [AFLSmart])

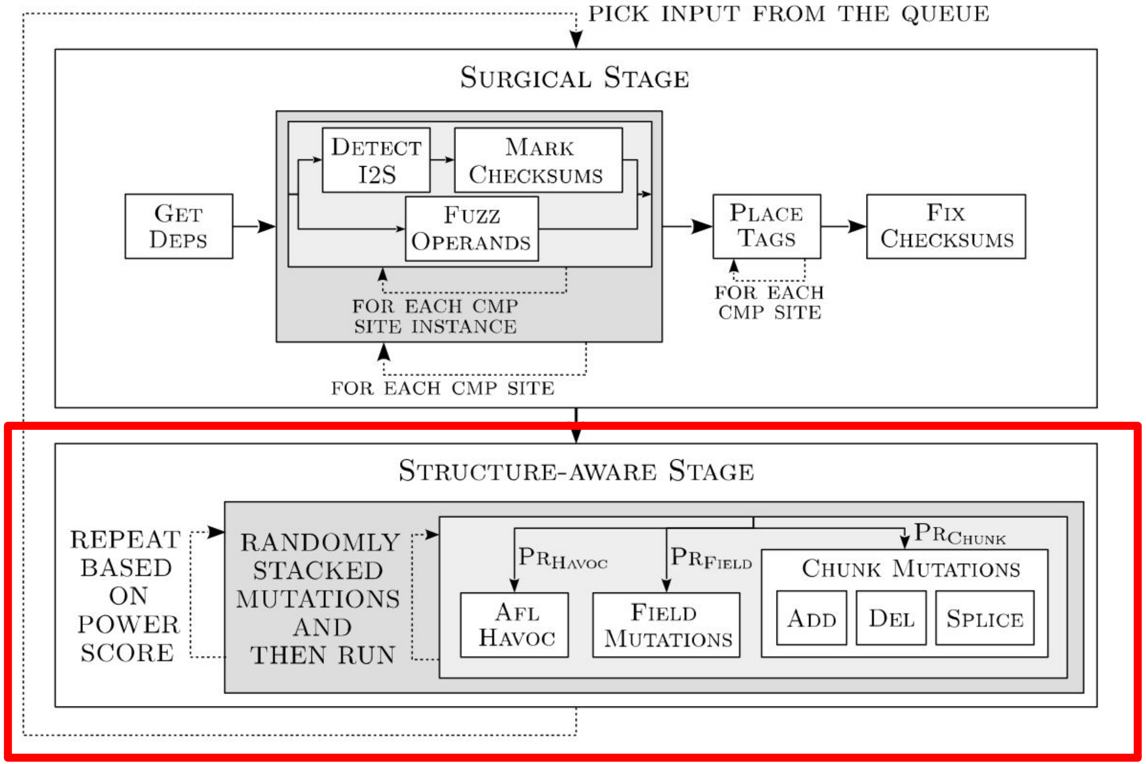
Architecture



Architecture



Architecture



GetDeps: Approximating Taint Tracking

Input: AAAABBBBCCCCDDDD

```
cmp eax, FFFF → eax = AAAA
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Input: AAAABBBBCCCCDDDD
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```
cmp eax, FFFF → eax = AAAA
```

```
Bitflip #1: BAAABBBBCCCCDDDD
```

```
cmp eax, FFFF → eax = BAAA
```

Detect Checksum Checks

- One operand is I2S
- The other operand is not I2S and GetDeps revealed dependencies on some input bytes
- The sets of their byte dependencies are disjoint

Input Tags

- Comparison ID
- Timestamp
- Parent ID
- Number of tags with the same ID
- The Comparison ID of the inner checksum that guard this byte
- Flags (which CMP operand, if this is a checksum field, …)

Many Comparisons affected by the same byte

1. Prioritize Checksum fields

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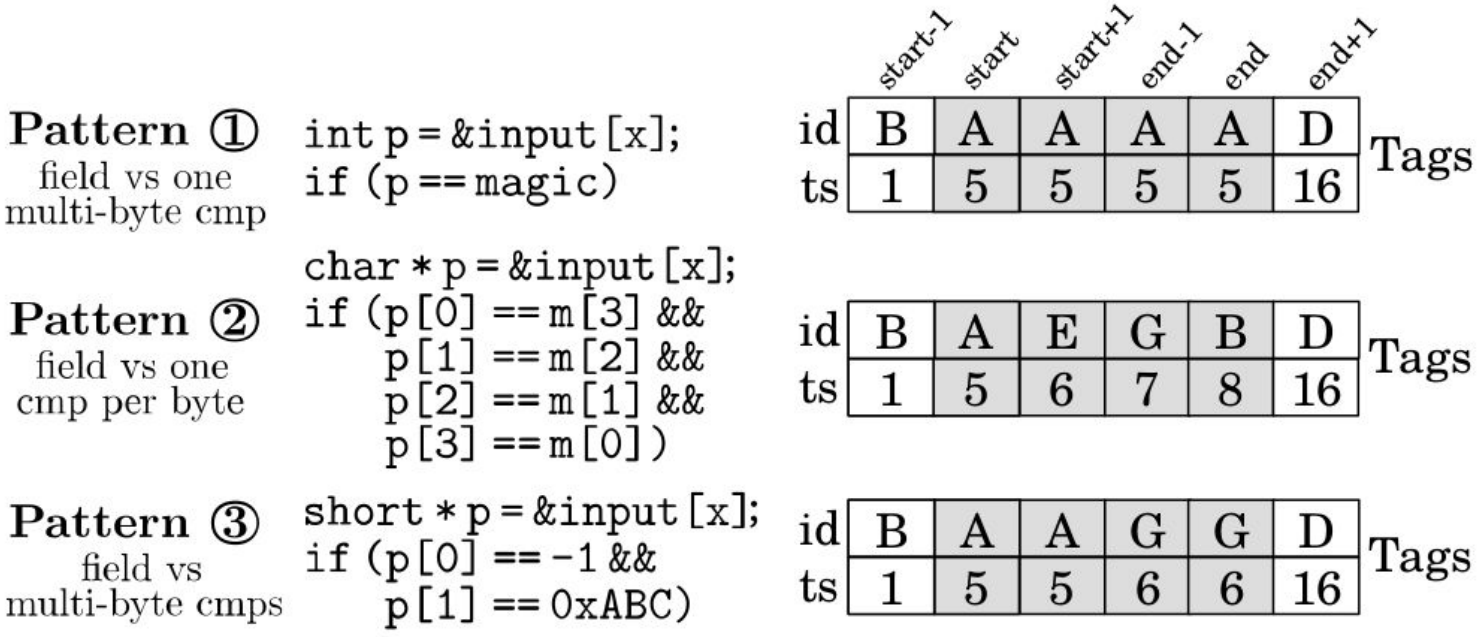
3. Prioritize if the number of bytes influencing the comparison are low

Fixing Checksum

- Late-stage repair
- Topological Sort (Tags have the info for this)
- Unpatch false positives

Locating Fields



Pattern ①
field vs one
multi-byte cmp

```
int p = &input [x];
if (p == magic)
```

	start-1	start	start+1	end-1	end	end+1	
id	B	A	A	A	A	D	Tags
ts	1	5	5	5	5	16	

Pattern ②
field vs one
cmp per byte

```
char * p = &input [x];
if (p[0] == m[3] &&
     p[1] == m[2] &&
     p[2] == m[1] &&
     p[3] == m[0])
```

id	B	A	E	G	B	D	Tags
ts	1	5	6	7	8	16	

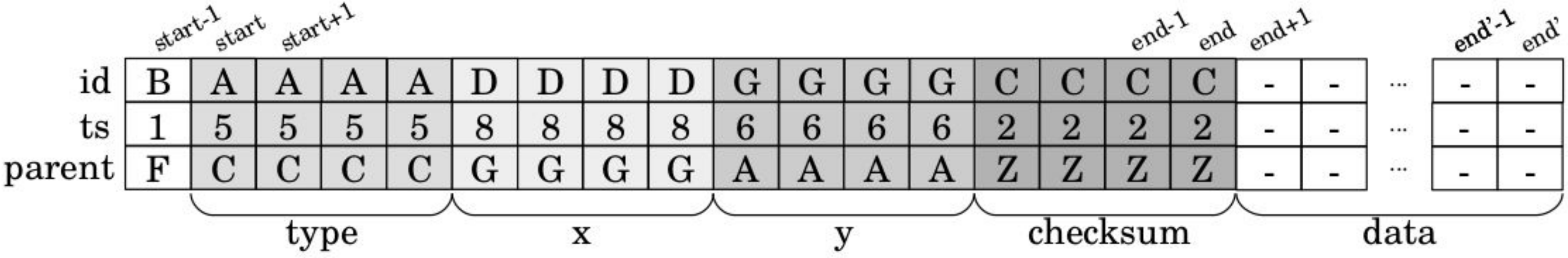
Pattern ③
field vs
multi-byte cmps

```
short * p = &input [x];
if (p[0] == -1 &&
     p[1] == 0xABC)
```

id	B	A	A	G	G	D	Tags
ts	1	5	5	6	6	16	

Locating Chunks

```
struct {
  int type;
  int x , y;
  int cksm;
};
```



	start-1	start	start+1												end-1	end	end+1			end'-1	end'
id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-

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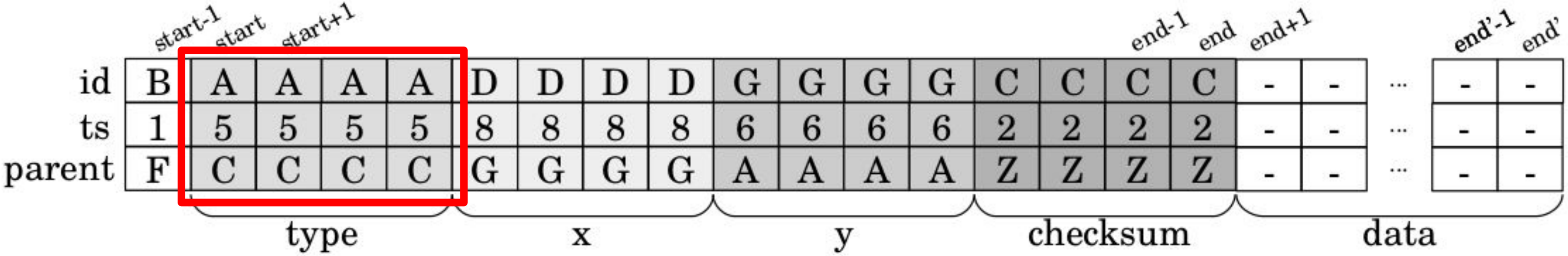
1. Pick a tag type



	start-1	start	start+1													end-1	end	end+1			end'-1	end'
id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-

Locating Chunks

```
struct {
  int type;
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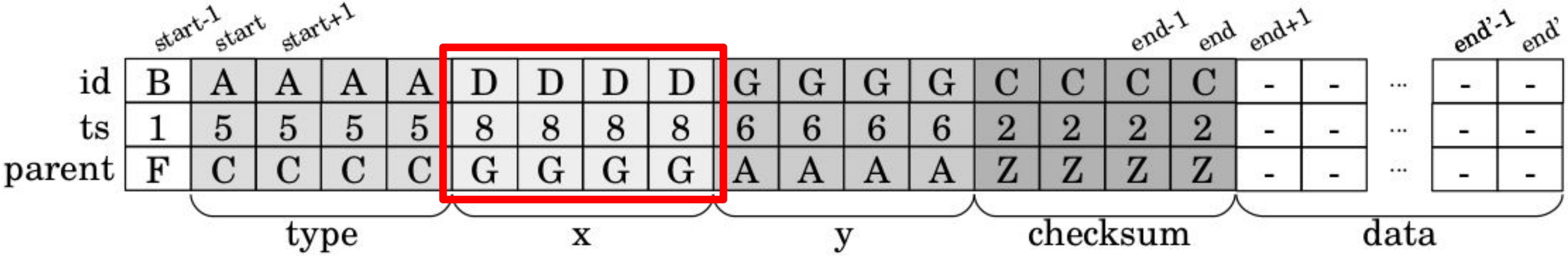
};
```

1. Pick a tag type
2. Recurse if next Timestamp (ts) > current



id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-

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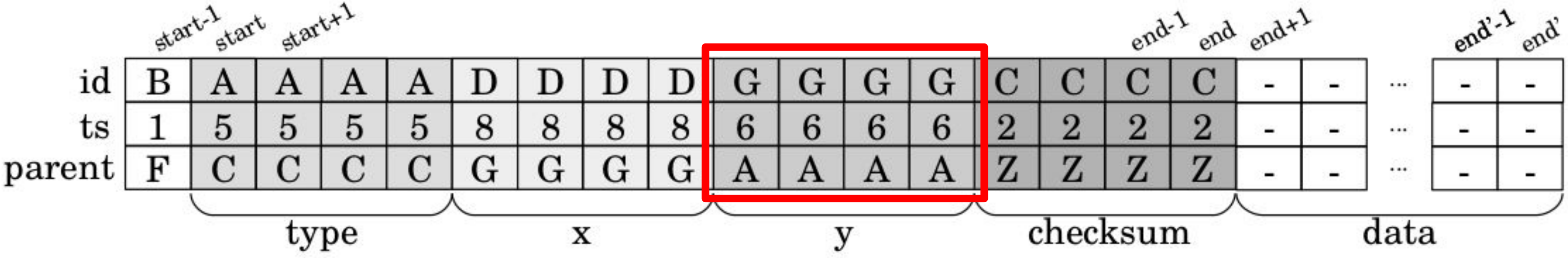

	start-1	start	start+1													end-1	end	end+1			end'-1	end'
id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-
		type				x				y				checksum				data				

Locating Chunks

```
struct {
  int type;
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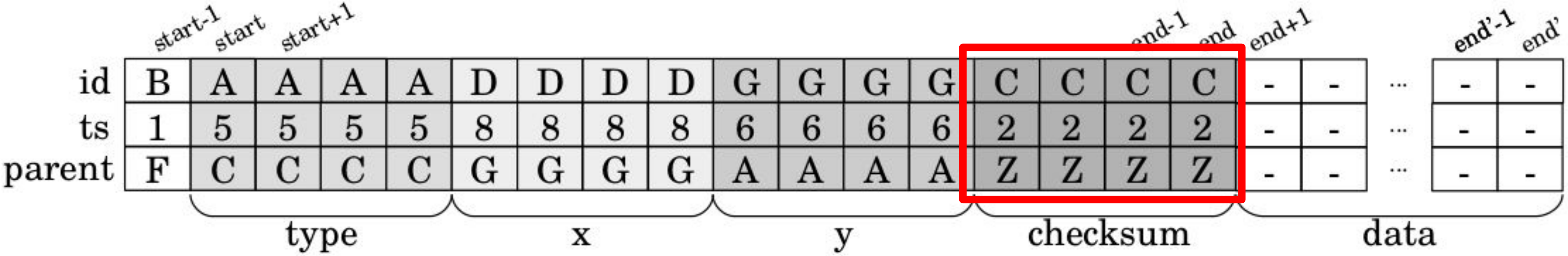
```

1. Pick a tag type
2. Recurse if next Timestamp (ts) > current
3. Go forward if next ID = current Parent



	start-1	start	start+1												end-1	end	end+1				end'-1	end'
id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-
		type				x				y				checksum				data				

Locating Chunks

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struct {
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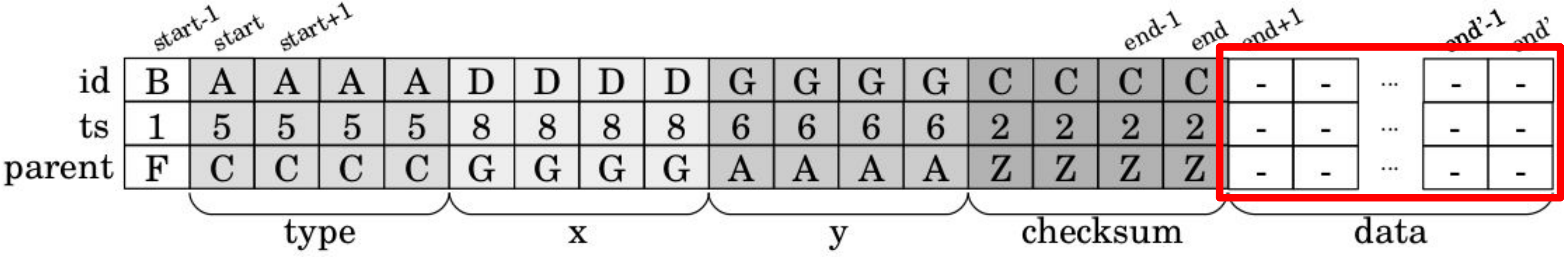
};
```

1. Pick a tag type
2. Recurse if next Timestamp (ts) > current
3. Go forward if next ID = current Parent
4. With a probability take untagged part and recurse again



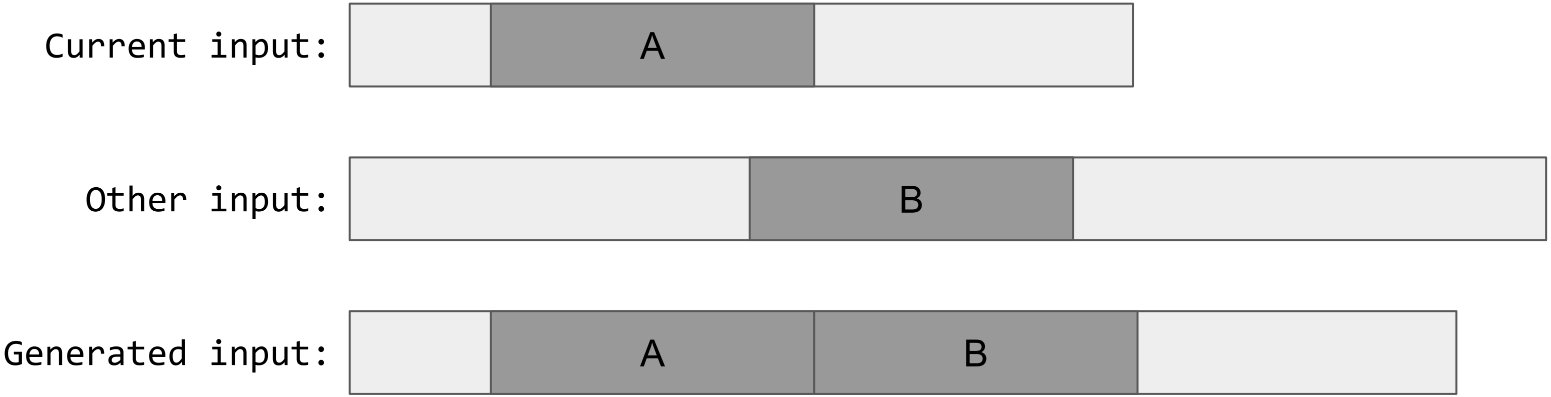
	start-1	start	start+1													end-1	end	end+1			end'-1	end'
id	B	A	A	A	A	D	D	D	D	G	G	G	G	C	C	C	C	-	-	...	-	-
ts	1	5	5	5	5	8	8	8	8	6	6	6	6	2	2	2	2	-	-	...	-	-
parent	F	C	C	C	C	G	G	G	G	A	A	A	A	Z	Z	Z	Z	-	-	...	-	-

Mutating Chunks [AFLSmart]

- Addition
- Deletion
- Splicing

Mutating Chunks [Weizz]

- Addition
    - Select a chunk A and adds a chunk from another input in the queue with the same parent ID in the first tag of A before or after A



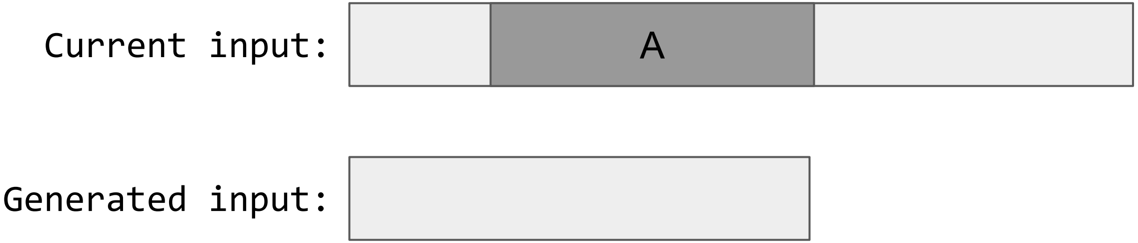
Current input: A

Other input: B

Generated input: A B

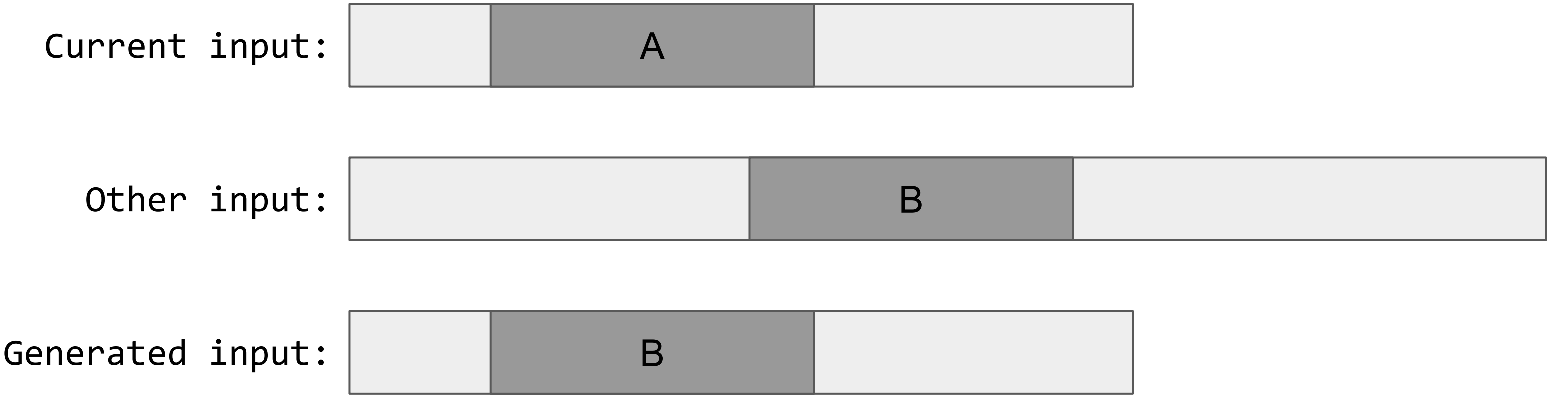
Mutating Chunks [Weizz]

- Deletion
    - Select a chunk and removes it



Mutating Chunks [Weizz]

- Splicing
  - Select a chunk A and replaces it with a chunk from another input in the queue with the same comparison ID in the first tag



Current input: A

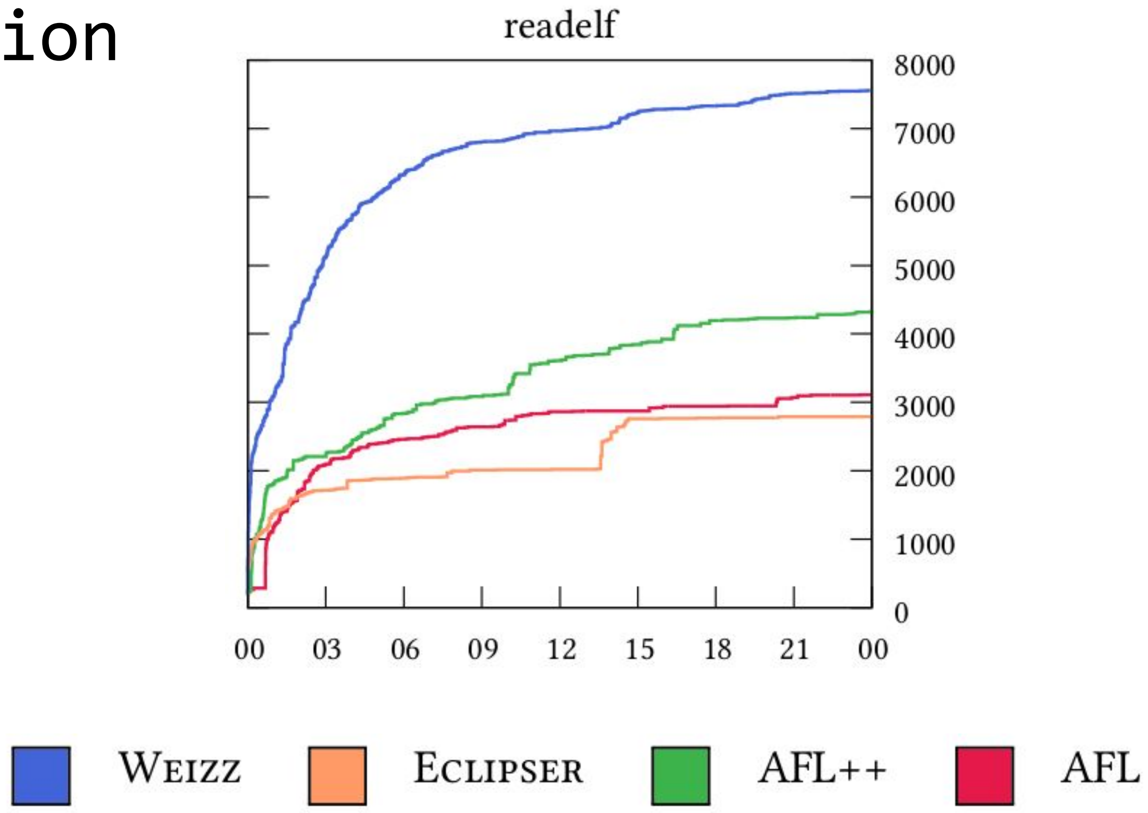
Other input: B

Generated input: B

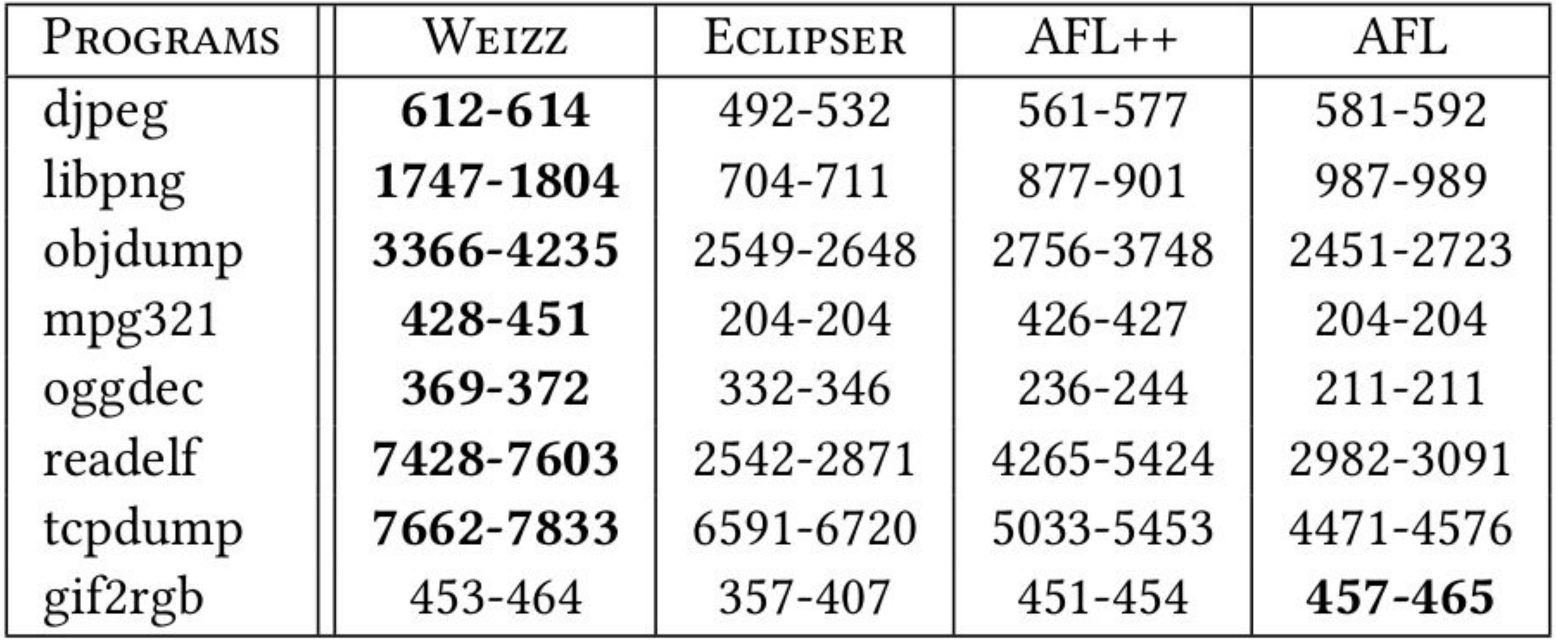
Evaluation

1. Comparison with popular fuzzers over chunk-oriented programs
2. New bugs found by Weizz
3. Role of structural mutations and roadblock bypassing?

Evaluation

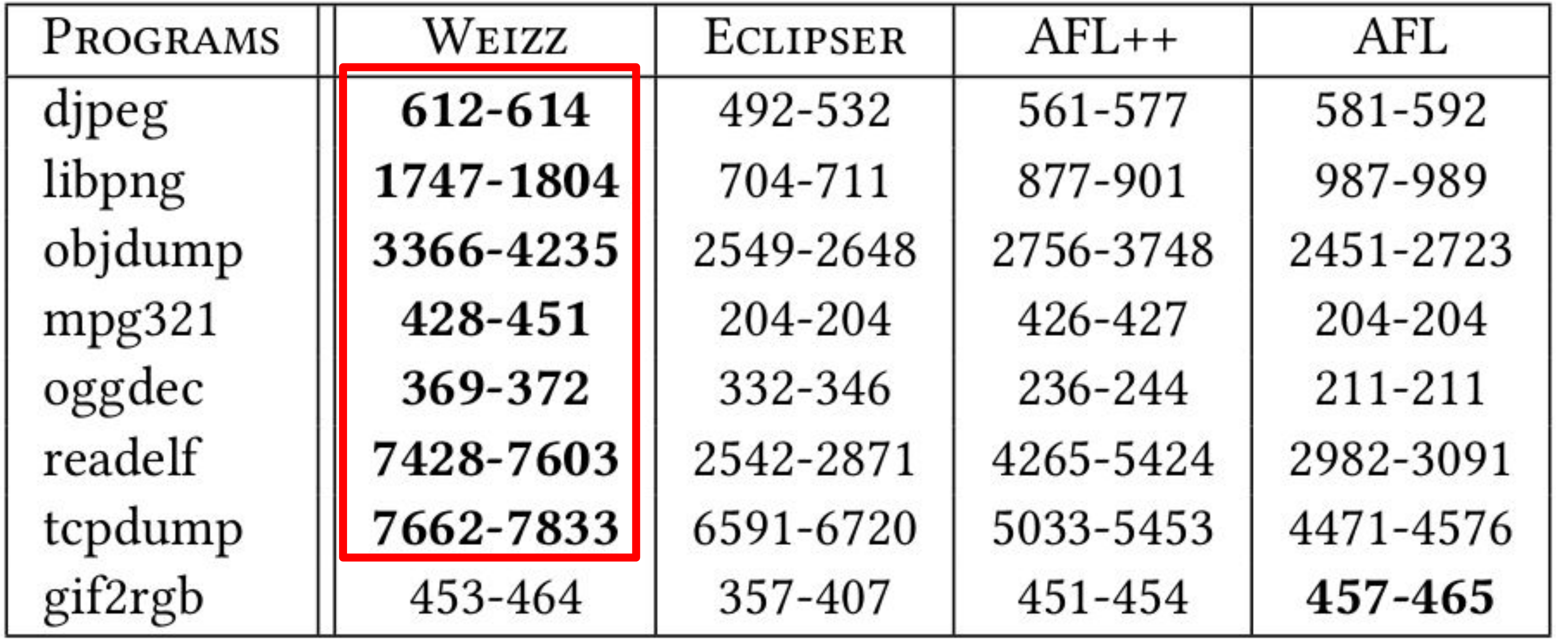

readelf
8000
7000
6000
5000
4000
3000
2000
1000
0
00
03
06
09
12
15
18
21
00
WEIZZ
ECLIPSER
AFL++
AFL

Evaluation (60% conf. intervals)



Programs	Weizz	Eclipser	AFL++	AFL
djpeg	**612-614**	492-532	561-577	581-592
libpng	**1747-1804**	704-711	877-901	987-989
objdump	**3366-4235**	2549-2648	2756-3748	2451-2723
mpg321	**428-451**	204-204	426-427	204-204
oggdec	**369-372**	332-346	236-244	211-211
readelf	**7428-7603**	2542-2871	4265-5424	2982-3091
tcpdump	**7662-7833**	6591-6720	5033-5453	4471-4576
gif2rgb	453-464	357-407	451-454	**457-465**

Evaluation (60% conf. intervals)



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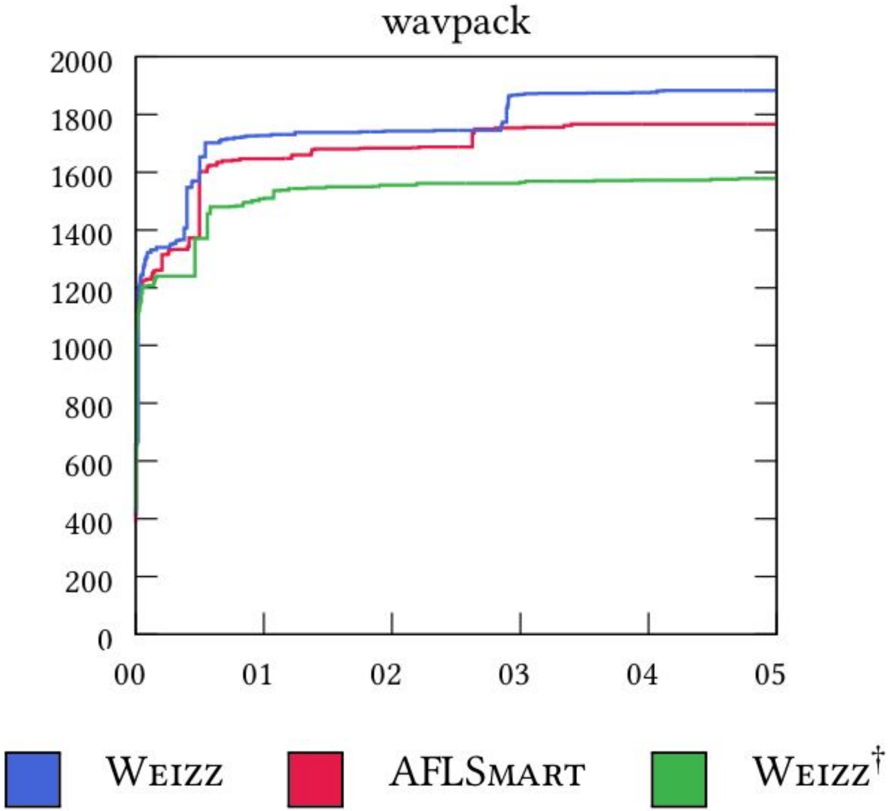
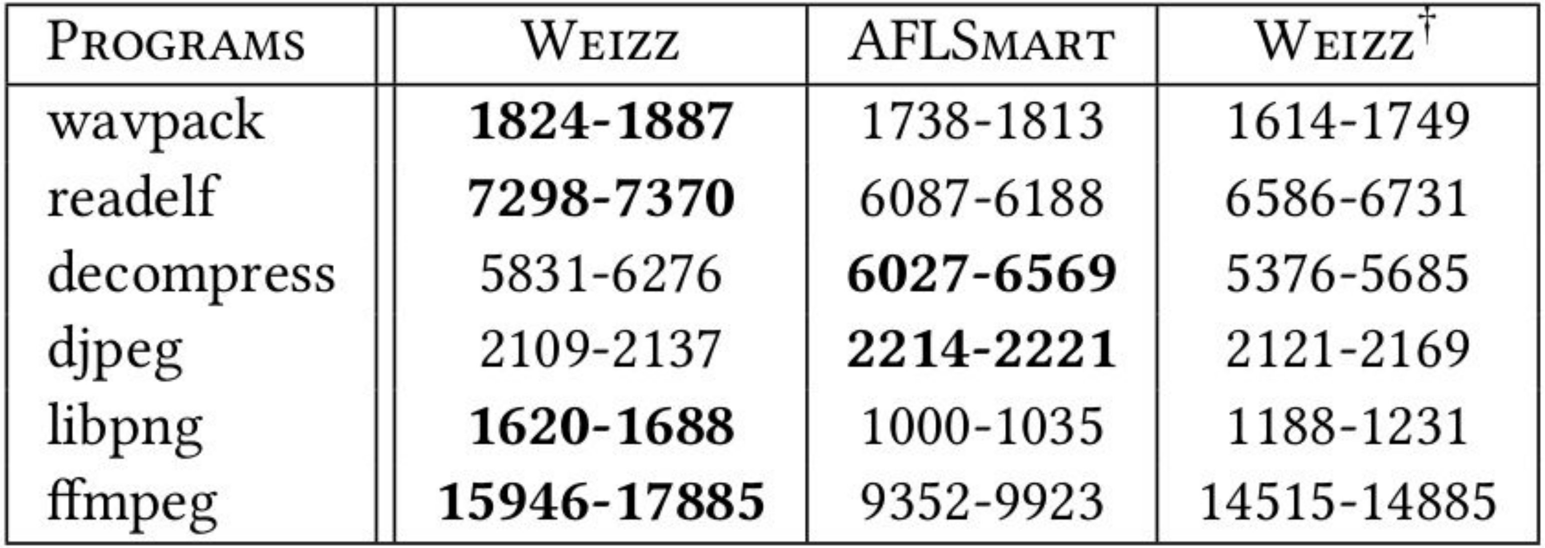


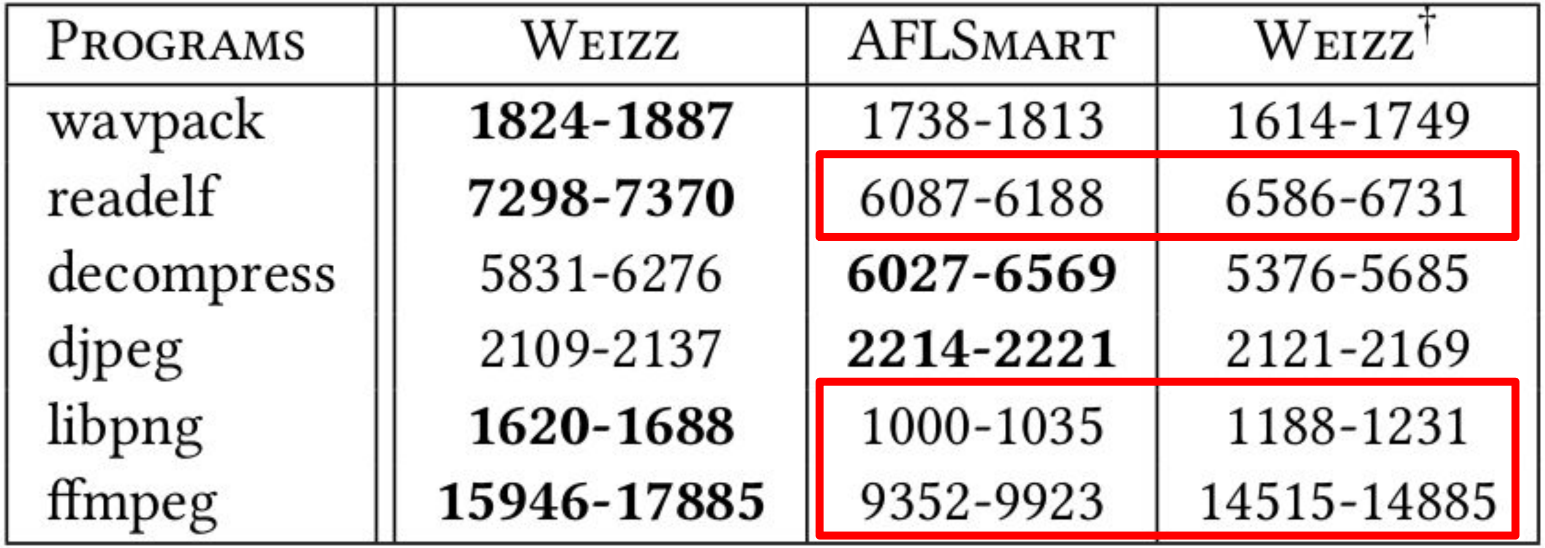
w/o I2S

Evaluation (60% conf. intervals)



Programs	Weizz	AFLSmart	Weizz†
wavpack	**1824-1887**	1738-1813	1614-1749
readelf	**7298-7370**	6087-6188	6586-6731
decompress	5831-6276	**6027-6569**	5376-5685
djpeg	2109-2137	**2214-2221**	2121-2169
libpng	**1620-1688**	1000-1035	1188-1231
ffmpeg	**15946-17885**	9352-9923	14515-14885

Evaluation (60% conf. intervals)



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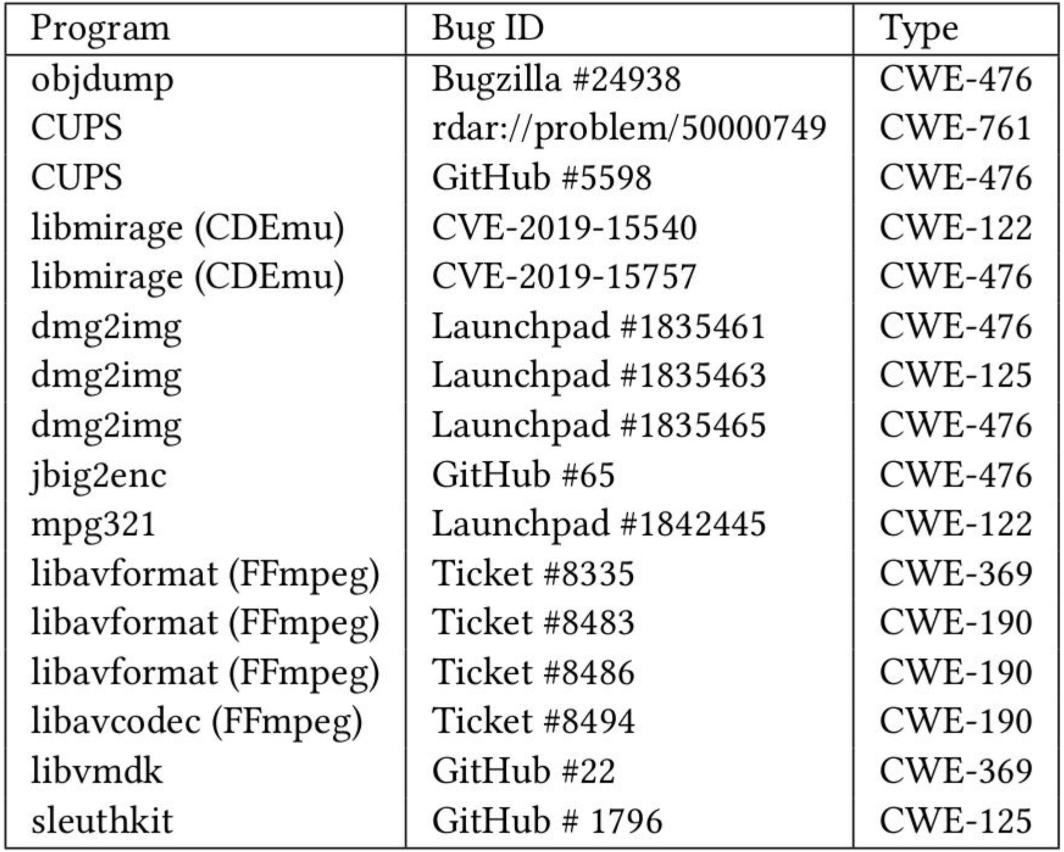
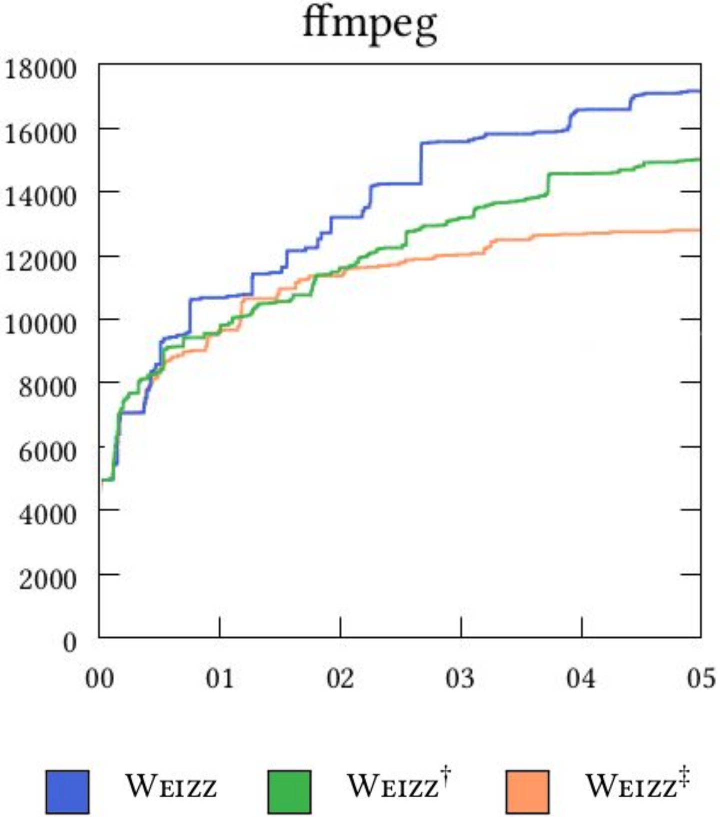
djpeg	2109-2137	**2214-2221**	2121-2169
libpng	**1620-1688**	1000-1035	1188-1231
ffmpeg	**15946-17885**	9352-9923	14515-14885

Bugs



Program	Bug ID	Type
objdump	Bugzilla #24938	CWE-476
CUPS	rdar://problem/50000749	CWE-761
CUPS	GitHub #5598	CWE-476
libmirage (CDEmu)	CVE-2019-15540	CWE-122
libmirage (CDEmu)	CVE-2019-15757	CWE-476
dmg2img	Launchpad #1835461	CWE-476
dmg2img	Launchpad #1835463	CWE-125
dmg2img	Launchpad #1835465	CWE-476
jbig2enc	GitHub #65	CWE-476
mpg321	Launchpad #1842445	CWE-122
libavformat (FFmpeg)	Ticket #8335	CWE-369
libavformat (FFmpeg)	Ticket #8483	CWE-190
libavformat (FFmpeg)	Ticket #8486	CWE-190
libavcodec (FFmpeg)	Ticket #8494	CWE-190
libvmdk	GitHub #22	CWE-369
sleuthkit	GitHub # 1796	CWE-125

Evaluation



w/o I2S

w/o struct. mut.

Future Directions

- Taint Tracking for large inputs
- More chunk location heuristics
  - Exclude types of tags as starting point for a chunk
  - Apply traditional file-format reverse engineering algorithms based on memory accesses to tags
- Port to other OSes

Thank You

https://github.com/andreafioraldi/weizz-fuzzer