# FastSpec:
# Scalable Generation and Detection of Spectre Gadgets Using Neural Embeddings

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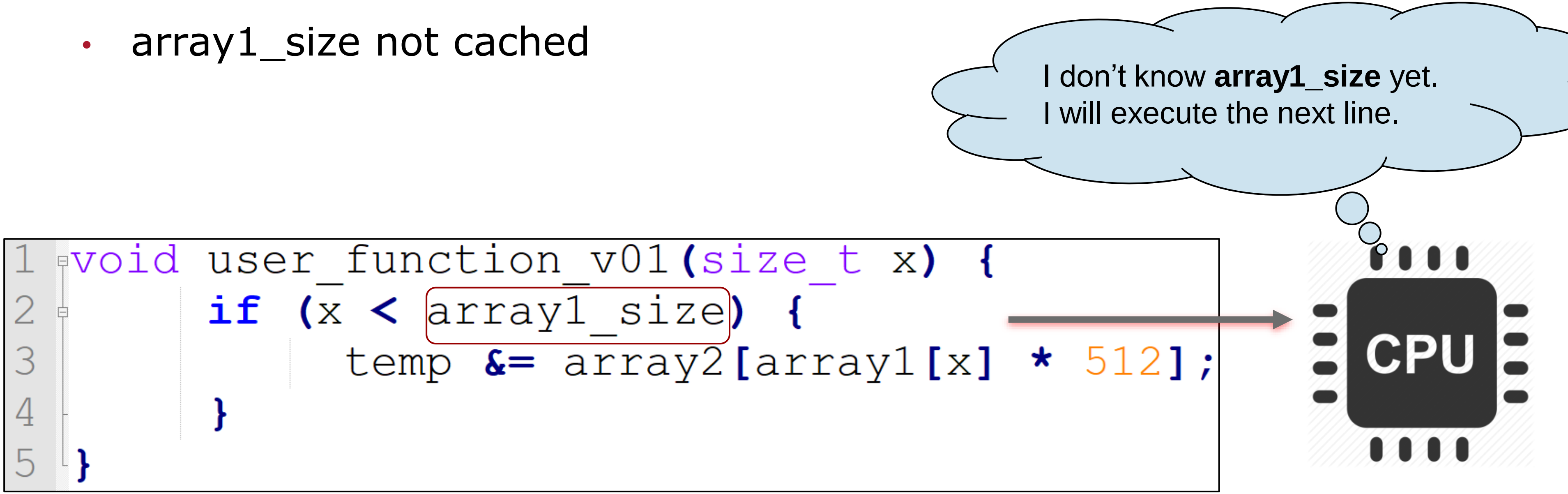
# Speculative Execution

- array1_size not cached



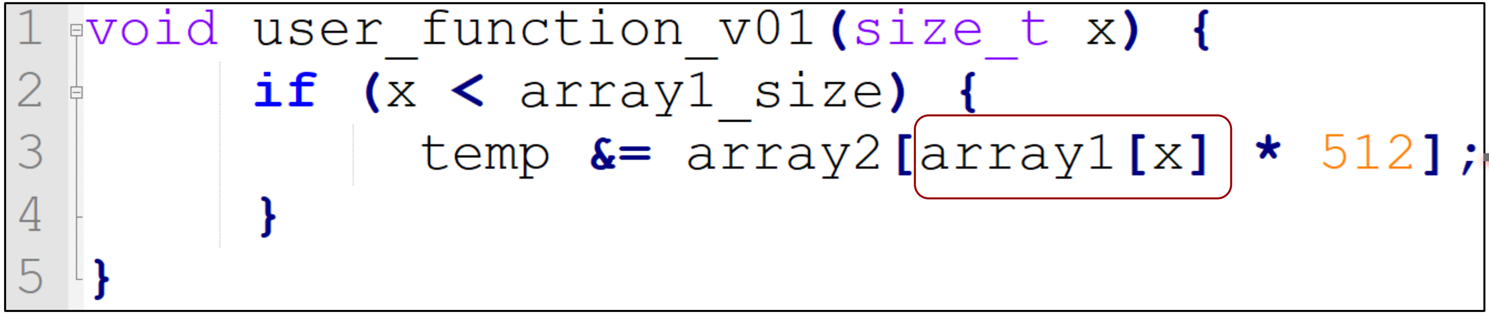
```
void user_function_v01(size_t x) {
        if (x < array1_size) {
                temp &= array2[array1[x] * 512];
        }
}
```

I don't know **array1_size** yet.
I will execute the next line.

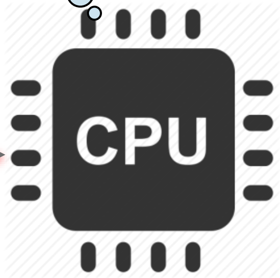
# Spectre Attack (v1)

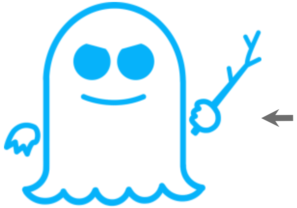
- Kocher et al, *Spectre Attacks: Exploiting Speculative Execution*, S&P ’19
- Mitigation: Software Updates

I don’t know **array1_size** yet.
I will execute the next line.

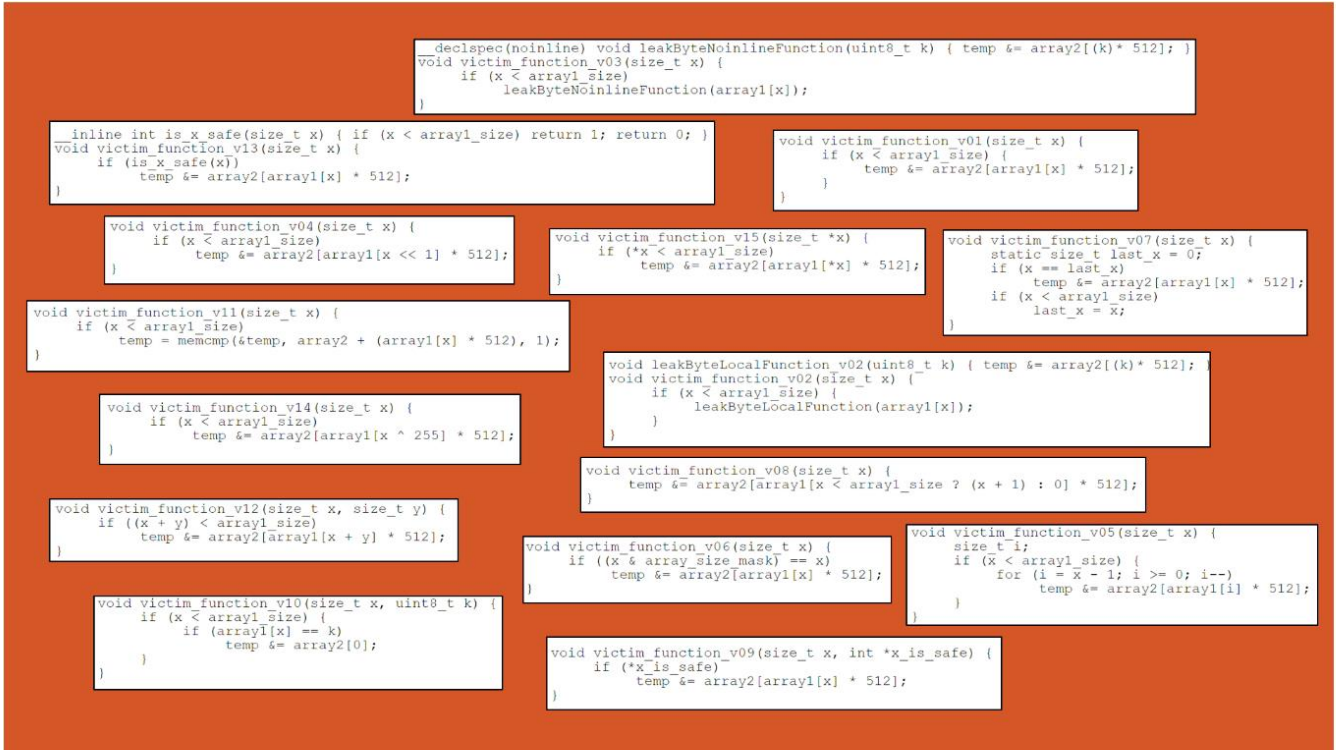


```
void user_function_v01(size_t x) {
        if (x < array1_size) {
                temp &= array2[array1[x] * 512];
        }
}
```





# Problem 1: What do they look like?



```
__declspec(noinline) void leakByteNoinlineFunction(uint8_t k) { temp &= array2[(k)* 512]; }
void victim_function_v03(size_t x) {
     if (x < array1_size)
          leakByteNoinlineFunction(array1[x]);
}
```

```
__inline int is_x_safe(size_t x) { if (x < array1_size) return 1; return 0; }
void victim_function_v13(size_t x) {
     if (is_x_safe(x))
          temp &= array2[array1[x] * 512];
}
```

```
void victim_function_v01(size_t x) {
     if (x < array1_size) {
          temp &= array2[array1[x] * 512];
     }
}
```

```
void victim_function_v04(size_t x) {
     if (x < array1_size)
          temp &= array2[array1[x << 1] * 512];
}
```

```
void victim_function_v15(size_t *x) {
     if (*x < array1_size)
          temp &= array2[array1[*x] * 512];
}
```

```
void victim_function_v07(size_t x) {
     static size_t last_x = 0;
     if (x == last_x)
          temp &= array2[array1[x] * 512];
     if (x < array1_size)
          last_x = x;
}
```

```
void victim_function_v11(size_t x) {
     if (x < array1_size)
          temp = memcmp(&temp, array2 + (array1[x] * 512), 1);
}
```

```
void leakByteLocalFunction_v02(uint8_t k) { temp &= array2[(k)* 512]; }
void victim_function_v02(size_t x) {
     if (x < array1_size) {
          leakByteLocalFunction(array1[x]);
     }
}
```

```
void victim_function_v14(size_t x) {
     if (x < array1_size)
          temp &= array2[array1[x ^ 255] * 512];
}
```

```
void victim_function_v08(size_t x) {
     temp &= array2[array1[x < array1_size ? (x + 1) : 0] * 512];
}
```

```
void victim_function_v12(size_t x, size_t y) {
     if ((x + y) < array1_size)
          temp &= array2[array1[x + y] * 512];
}
```

```
void victim_function_v06(size_t x) {
     if ((x & array_size_mask) == x)
          temp &= array2[array1[x] * 512];
}
```

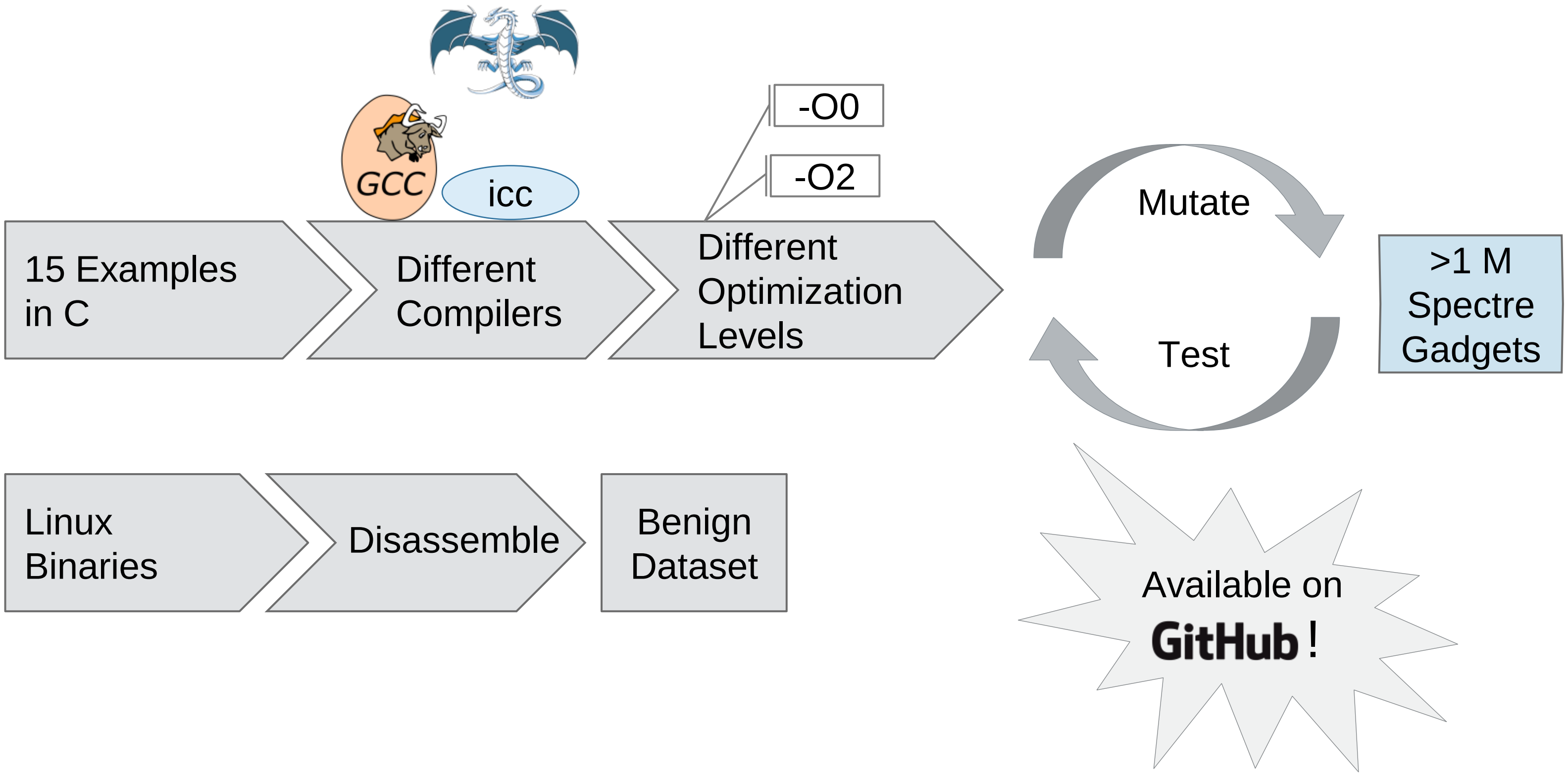
```
void victim_function_v05(size_t x) {
     size_t i;
     if (x < array1_size) {
          for (i = x - 1; i >= 0; i--)
               temp &= array2[array1[i] * 512];
     }
}
```

```
void victim_function_v10(size_t x, uint8_t k) {
     if (x < array1_size) {
          if (array1[x] == k)
               temp &= array2[0];
     }
}
```

```
void victim_function_v09(size_t x, int *x_is_safe) {
     if (*x_is_safe)
          temp &= array2[array1[x] * 512];
}
```

Paul Kocher, *Spectre Mitigations in Microsoft's C/C++ Compiler*, 2018

# Creating Spectre Gadget Dataset in Assembly



15 Examples in C

GCC

icc

Different Compilers

-O0

-O2

Different Optimization Levels

Mutate

Test

>1 M Spectre Gadgets

Linux Binaries

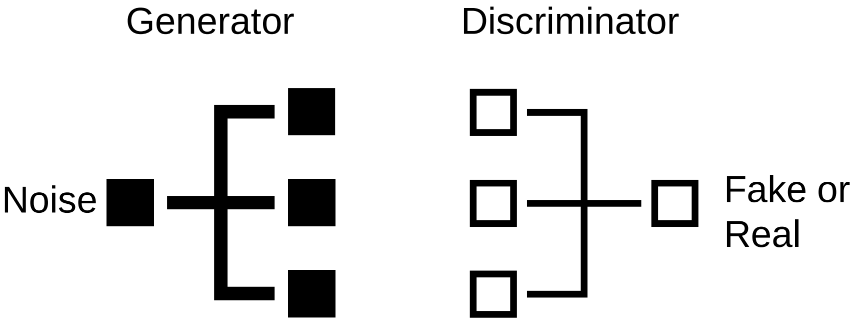
Disassemble

Benign Dataset

Available on GitHub!

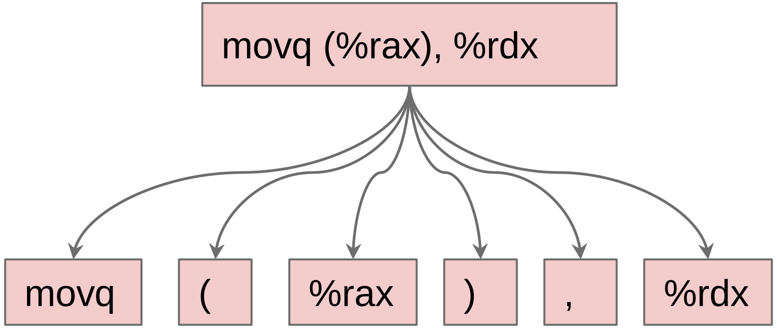
# SpectreGAN

- Spectre gadget generator using Generative Adversarial Networks (Goodfellow et al, NIPS14)
- MaskGAN (Fedus et al, ICLR18)

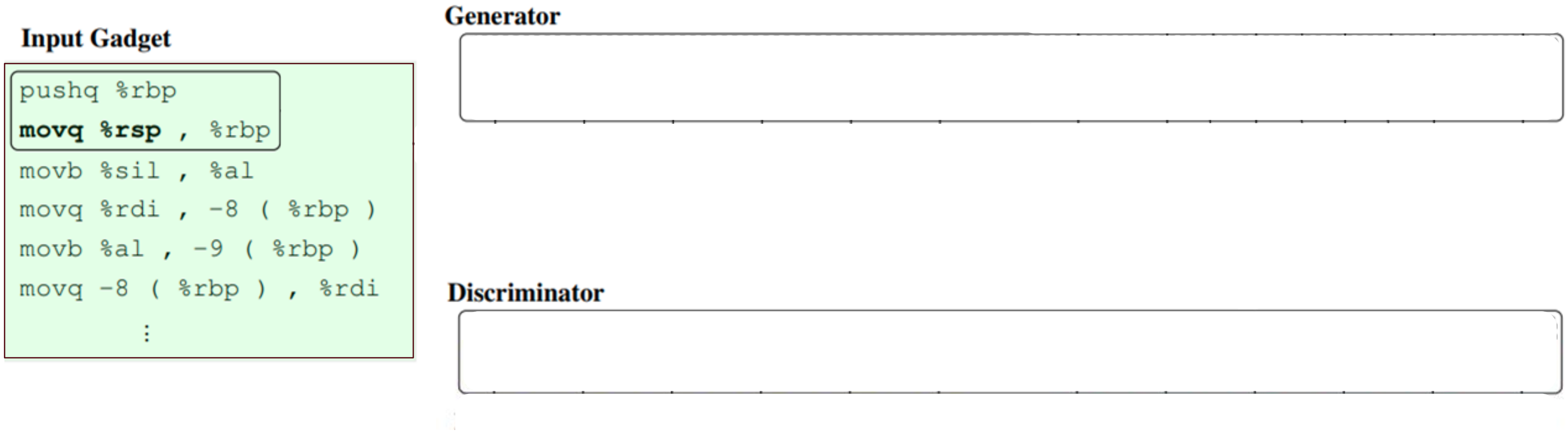


# Tokenization

- <imm> Immediate
- <label> Label
- <UNK> Unknown label



# SpectreGAN



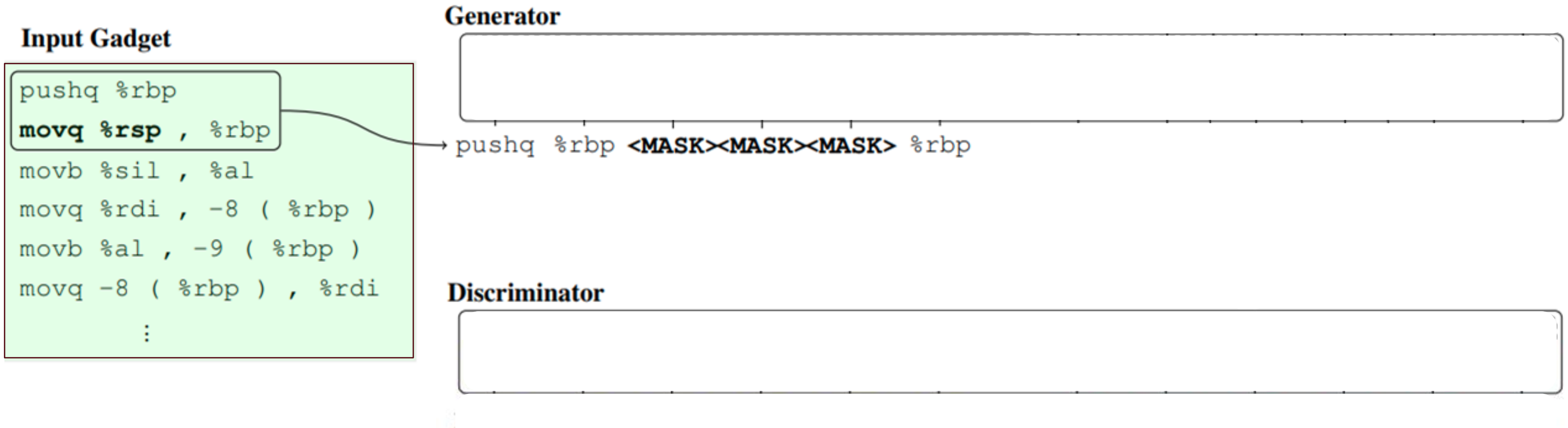
Input Gadget

```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

Generator

Discriminator

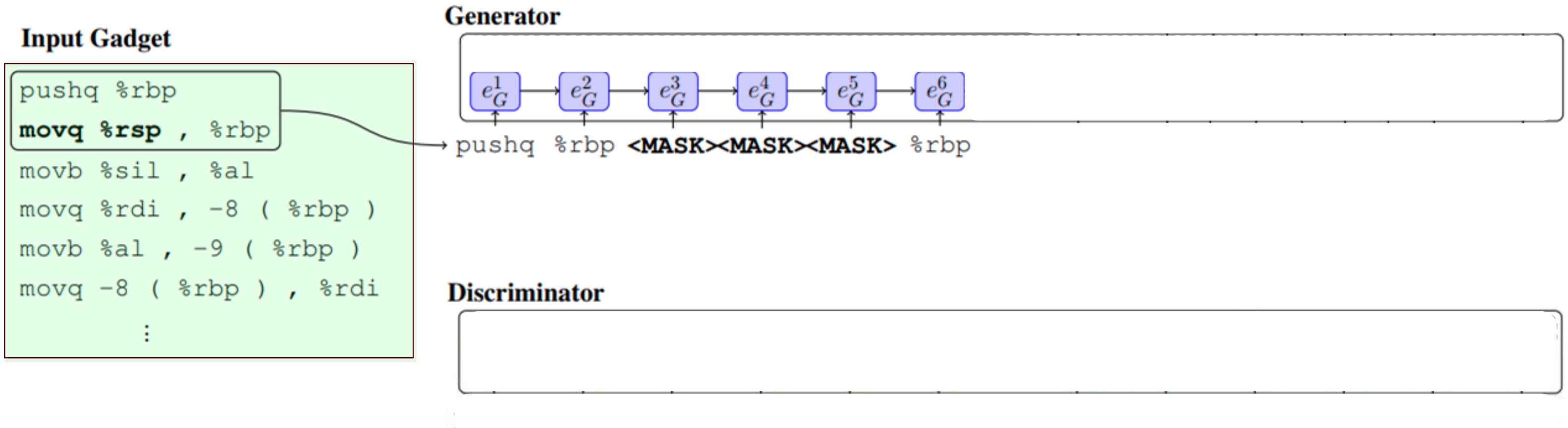
# SpectreGAN



```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

```
pushq %rbp <MASK><MASK><MASK> %rbp
```

# SpectreGAN



Input Gadget

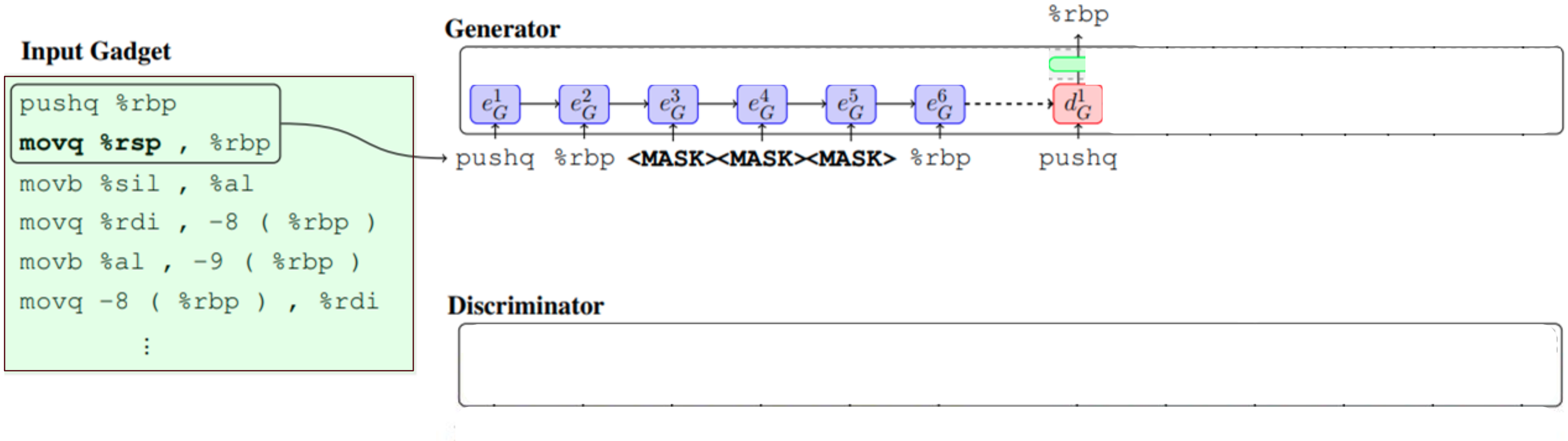
```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

Generator

pushq %rbp **<MASK><MASK><MASK>** %rbp

Discriminator

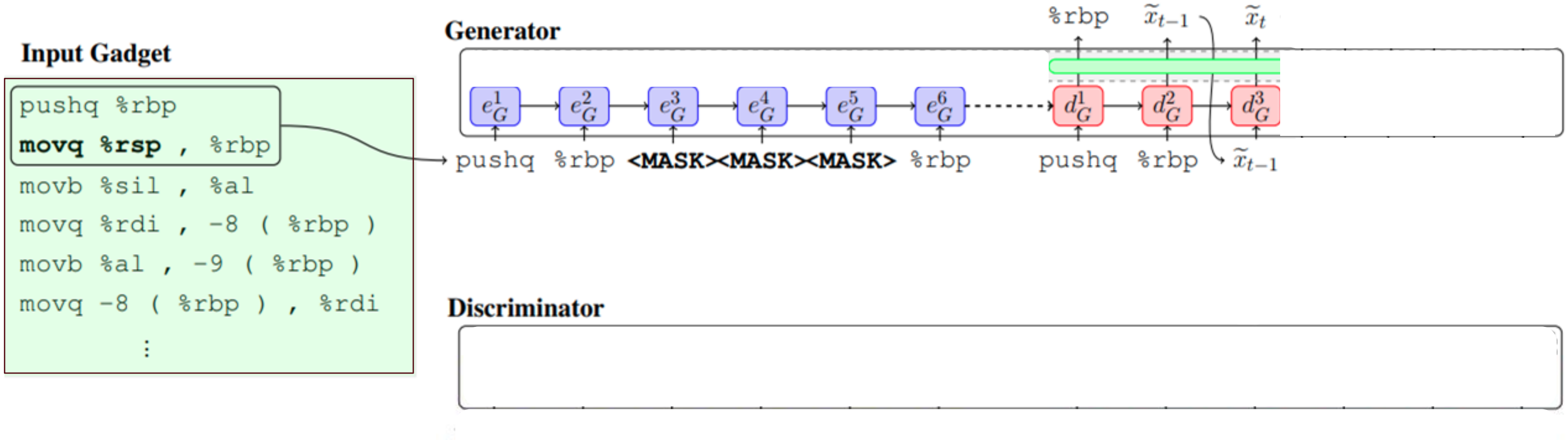
# SpectreGAN



Input Gadget

```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

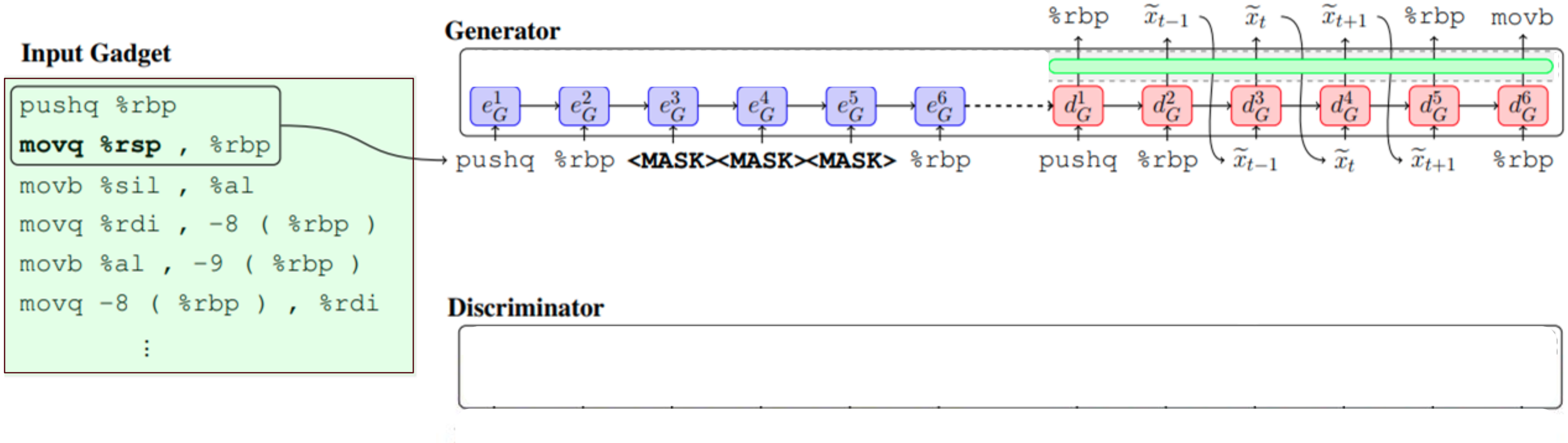
# SpectreGAN



Input Gadget

```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

# SpectreGAN

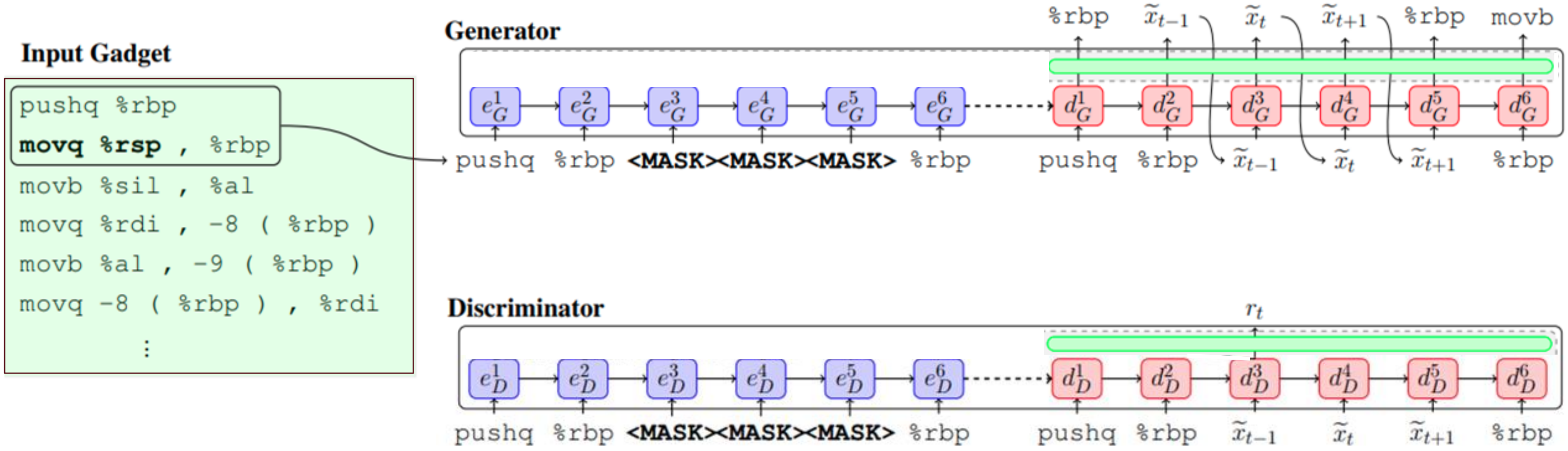


Input Gadget

```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

Generator
$e_G^1$ $e_G^2$ $e_G^3$ $e_G^4$ $e_G^5$ $e_G^6$
$d_G^1$ $d_G^2$ $d_G^3$ $d_G^4$ $d_G^5$ $d_G^6$
pushq %rbp <MASK><MASK><MASK> %rbp
pushq %rbp $\widetilde{x}_{t-1}$ $\widetilde{x}_t$ $\widetilde{x}_{t+1}$ %rbp
%rbp $\widetilde{x}_{t-1}$ $\widetilde{x}_t$ $\widetilde{x}_{t+1}$ %rbp movb
Discriminator

# SpectreGAN



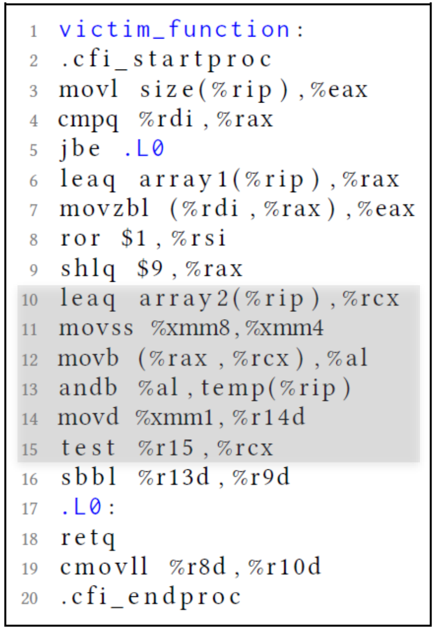
Input Gadget

```
pushq %rbp
movq %rsp , %rbp
movb %sil , %al
movq %rdi , -8 ( %rbp )
movb %al , -9 ( %rbp )
movq -8 ( %rbp ) , %rdi
        ⋮
```

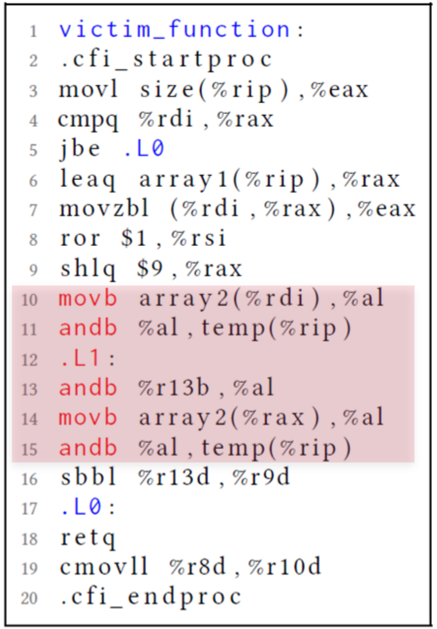
Generator
$e_G^1$ $e_G^2$ $e_G^3$ $e_G^4$ $e_G^5$ $e_G^6$
$d_G^1$ $d_G^2$ $d_G^3$ $d_G^4$ $d_G^5$ $d_G^6$
%rbp $\widetilde{x}_{t-1}$ $\widetilde{x}_t$ $\widetilde{x}_{t+1}$ %rbp movb
pushq %rbp <MASK><MASK><MASK> %rbp pushq %rbp $\widetilde{x}_{t-1}$ $\widetilde{x}_t$ $\widetilde{x}_{t+1}$ %rbp
Discriminator
$r_t$
$e_D^1$ $e_D^2$ $e_D^3$ $e_D^4$ $e_D^5$ $e_D^6$
$d_D^1$ $d_D^2$ $d_D^3$ $d_D^4$ $d_D^5$ $d_D^6$
pushq %rbp <MASK><MASK><MASK> %rbp pushq %rbp $\widetilde{x}_{t-1}$ $\widetilde{x}_t$ $\widetilde{x}_{t+1}$ %rbp

# SpectreGAN

- ~3 days of training
- Assembly function syntax without any supervision
- 70% success rate in the compiled samples compare to 5% in fuzzing.



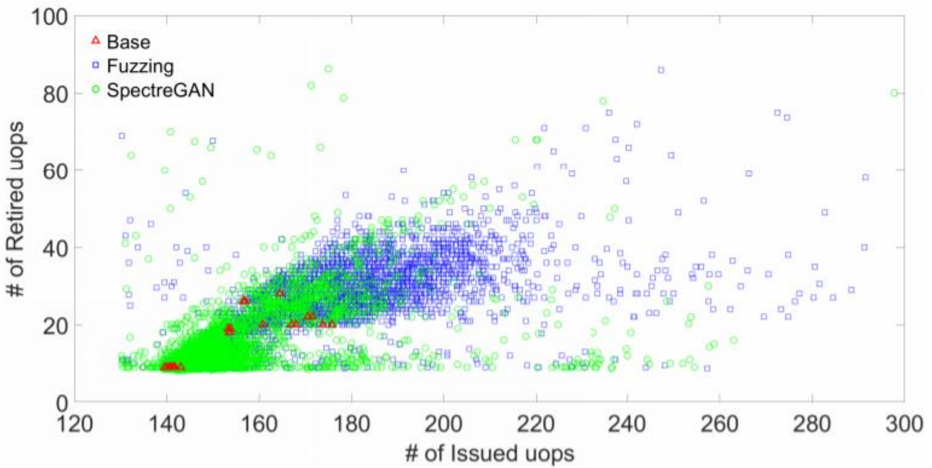
```
victim_function:
.cfi_startproc
movl size(%rip),%eax
cmpq %rdi,%rax
jbe .L0
leaq array1(%rip),%rax
movzbl (%rdi,%rax),%eax
ror $1,%rsi
shlq $9,%rax
leaq array2(%rip),%rcx
movss %xmm8,%xmm4
movb (%rax,%rcx),%al
andb %al,temp(%rip)
movd %xmm1,%r14d
test %r15,%rcx
sbbl %r13d,%r9d
.L0:
retq
cmovll %r8d,%r10d
.cfi_endproc
```



```
victim_function:
.cfi_startproc
movl size(%rip),%eax
cmpq %rdi,%rax
jbe .L0
leaq array1(%rip),%rax
movzbl (%rdi,%rax),%eax
ror $1,%rsi
shlq $9,%rax
movb array2(%rdi),%al
andb %al,temp(%rip)
.L1:
andb %r13b,%al
movb array2(%rax),%al
andb %al,temp(%rip)
sbbl %r13d,%r9d
.L0:
retq
cmovll %r8d,%r10d
.cfi_endproc
```

# SpectreGAN

- Unique n-gram analysis (n=5)
  - Base 4.7K
  - Fuzzing ~1M
  - SpectreGAN ~1M
  - ~2M in total
- Microarchitectural analysis
  - uops_issued vs uops_retired
- Detection analysis
  - oo7 and Spectector tools



# Problem 2: Where are they?

- We can blindly put lfence after every branch.
  - With 62-74.8% performance overhead (Carruth, 2018)

Or…

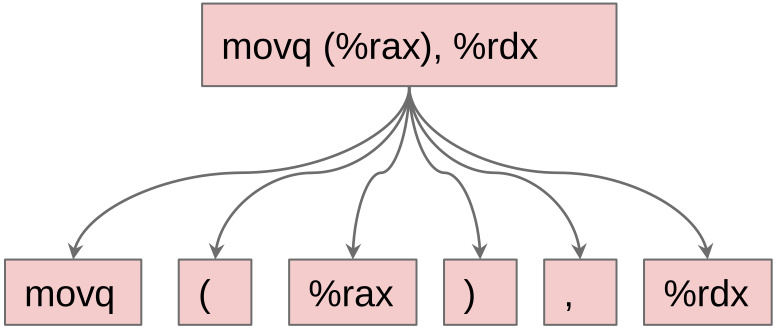
- We can build a ___________ tool to find the Spectre gadgets.
  - automated
  - scalable
  - accurate

# FastSpec

- BERT-based vulnerability detector

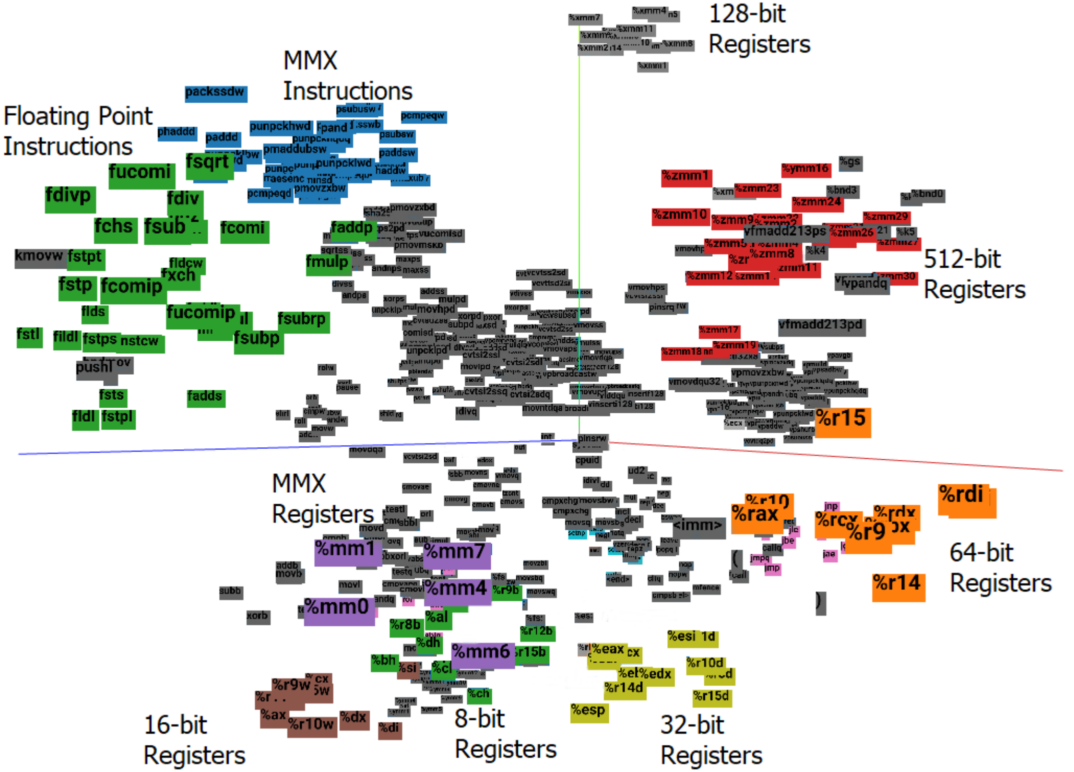
  (Devlin et al, NAACL18)

- Scans binaries with linear complexity

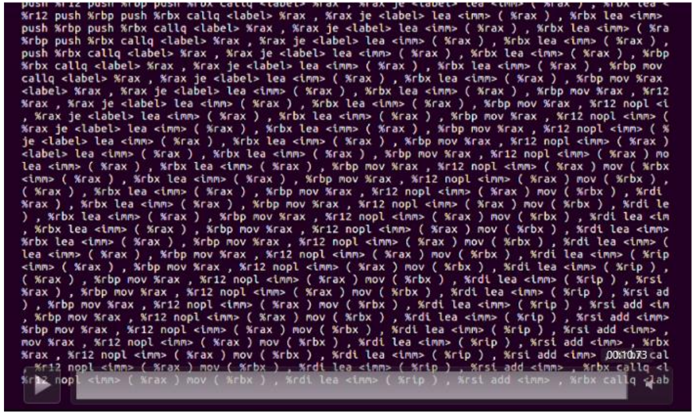


# FastSpec

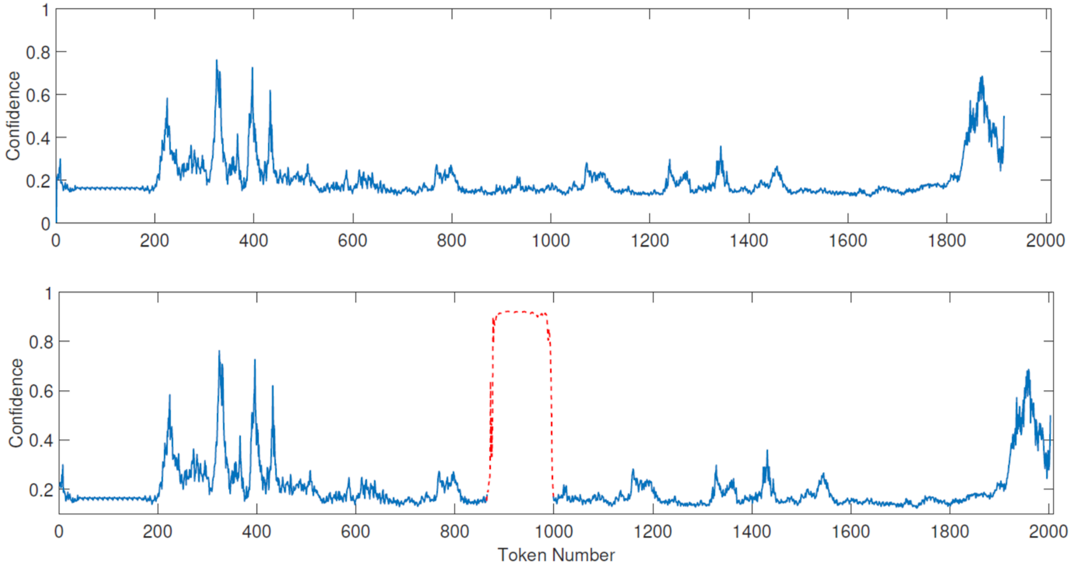
- Vector representations
- t-SNE visualization



# FastSpec



```
push %r12 push %rbp push %rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <
%r12 push %rbp push %rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm>
push %rbp push %rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %ra
%rbp push %rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) ,
push %rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp
%rbx callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov
callq <label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax
<label> %rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12
%rax , %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <i
, %rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> (
%rax je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %
je <label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax )
<label> lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mo
lea <imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx
<imm> ( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) ,
( %rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi
%rax ) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi le
) , %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <im
, %rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm>
%rbx lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> (
lea <imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip
<imm> ( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) ,
( %rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi
%rax ) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi ad
) , %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <im
, %rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm>
%rbp mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm> ,
mov %rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm> , %rbx
%rax , %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm>          cal
, %r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm> , %rbx callq <l
%r12 nopl <imm> ( %rax ) mov ( %rbx ) , %rdi lea <imm> ( %rip ) , %rsi add <imm> , %rbx callq <lab
```



# Case Study 1: OpenSSL

- OpenSSL v3 "*speed*" benchmark
- SpecFuzz (Oleksenko et al, USENIX '20)

- Sliding window of size 80 tokens
- AUC=0.998
- FP=0.04%, FN=2%

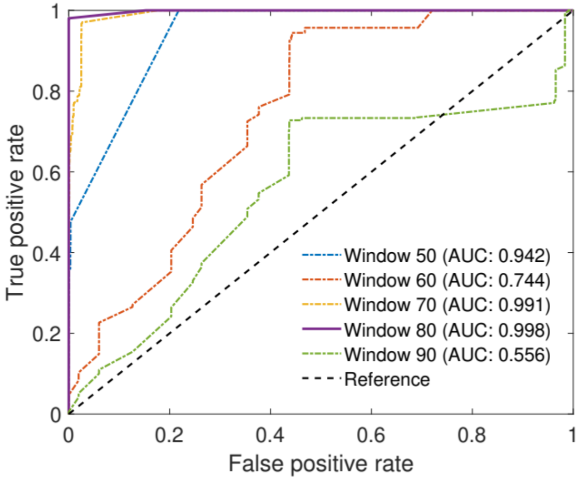
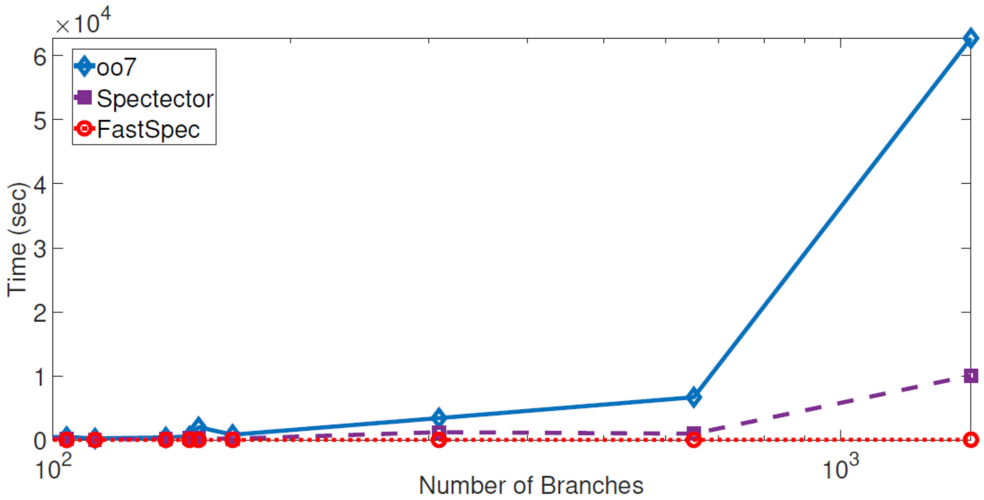


Figure 5: Solid line stands for the ROC curve of FastSpec for Spectre gadget class. Dashed line represents the reference line.

# Case Study 2: Phoronix Test Suite

- State of the art tools are not scalable.
- Crafty benchmark
  - 10K branches
  - 0.6 MB
- Spectector: 2 days
- oo7: 10+ days
- FastSpec: **<6 mins**



# Case Study 2: Phoronix Test Suite

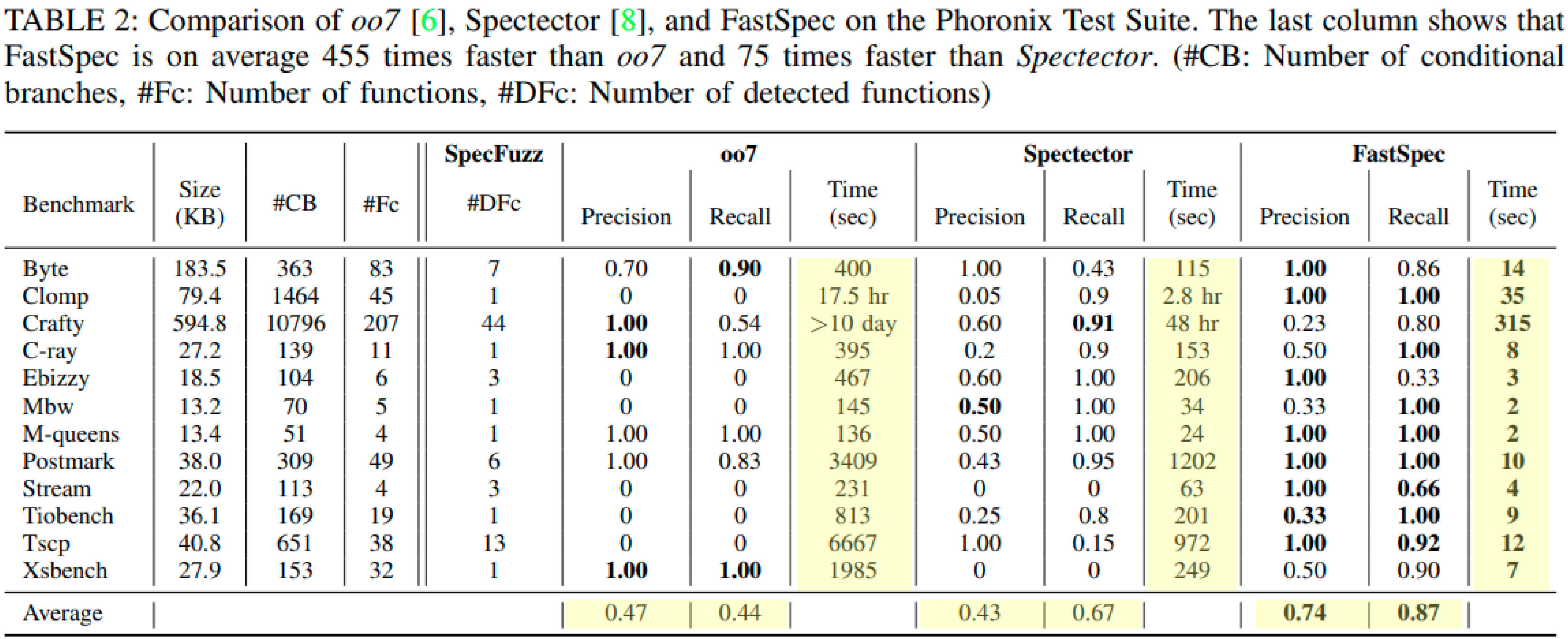


TABLE 2: Comparison of *oo7* [6], Spectector [8], and FastSpec on the Phoronix Test Suite. The last column shows that FastSpec is on average 455 times faster than *oo7* and 75 times faster than *Spectector*. (#CB: Number of conditional branches, #Fc: Number of functions, #DFc: Number of detected functions)

| | | | | **SpecFuzz** | **oo7** | | | **Spectector** | | | **FastSpec** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | Size (KB) | #CB | #Fc | #DFc | Precision | Recall | Time (sec) | Precision | Recall | Time (sec) | Precision | Recall | Time (sec) |
| Byte | 183.5 | 363 | 83 | 7 | 0.70 | **0.90** | 400 | 1.00 | 0.43 | 115 | **1.00** | 0.86 | **14** |
| Clomp | 79.4 | 1464 | 45 | 1 | 0 | 0 | 17.5 hr | 0.05 | 0.9 | 2.8 hr | **1.00** | **1.00** | **35** |
| Crafty | 594.8 | 10796 | 207 | 44 | **1.00** | 0.54 | >10 day | 0.60 | **0.91** | 48 hr | 0.23 | 0.80 | **315** |
| C-ray | 27.2 | 139 | 11 | 1 | **1.00** | 1.00 | 395 | 0.2 | 0.9 | 153 | 0.50 | **1.00** | **8** |
| Ebizzy | 18.5 | 104 | 6 | 3 | 0 | 0 | 467 | 0.60 | 1.00 | 206 | **1.00** | 0.33 | **3** |
| Mbw | 13.2 | 70 | 5 | 1 | 0 | 0 | 145 | **0.50** | 1.00 | 34 | 0.33 | **1.00** | **2** |
| M-queens | 13.4 | 51 | 4 | 1 | 1.00 | 1.00 | 136 | 0.50 | 1.00 | 24 | **1.00** | **1.00** | **2** |
| Postmark | 38.0 | 309 | 49 | 6 | 1.00 | 0.83 | 3409 | 0.43 | 0.95 | 1202 | **1.00** | **1.00** | **10** |
| Stream | 22.0 | 113 | 4 | 3 | 0 | 0 | 231 | 0 | 0 | 63 | **1.00** | **0.66** | **4** |
| Tiobench | 36.1 | 169 | 19 | 1 | 0 | 0 | 813 | 0.25 | 0.8 | 201 | **0.33** | **1.00** | **9** |
| Tscp | 40.8 | 651 | 38 | 13 | 0 | 0 | 6667 | 1.00 | 0.15 | 972 | **1.00** | **0.92** | **12** |
| Xsbench | 27.9 | 153 | 32 | 1 | **1.00** | **1.00** | 1985 | 0 | 0 | 249 | 0.50 | 0.90 | **7** |
| Average | | | | | 0.47 | 0.44 | | 0.43 | 0.67 | | **0.74** | **0.87** | |

# Conclusion

- New Spectre gadget dataset with 1+ million samples
- Task specific assembly code generation
- New DL-based Spectre v1 detection tool

Reproduce results: **vernamlab/FastSpec**

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