Go With the Flow

Enforcing Program Behavior Through Syscall Sequences and Origins

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Who am I?

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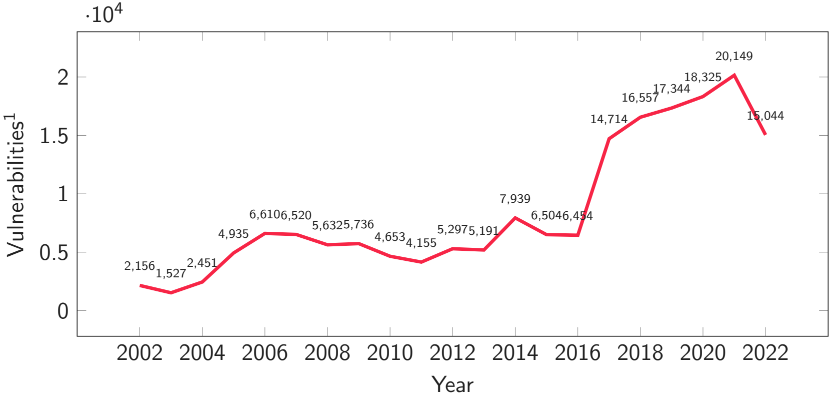

[1] Source: `http://www.cvedetails.com/vulnerabilities-by-types.php`

What to do?

Eliminate bugs

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Eliminate bugs

Limit Post-Exploitation Impact

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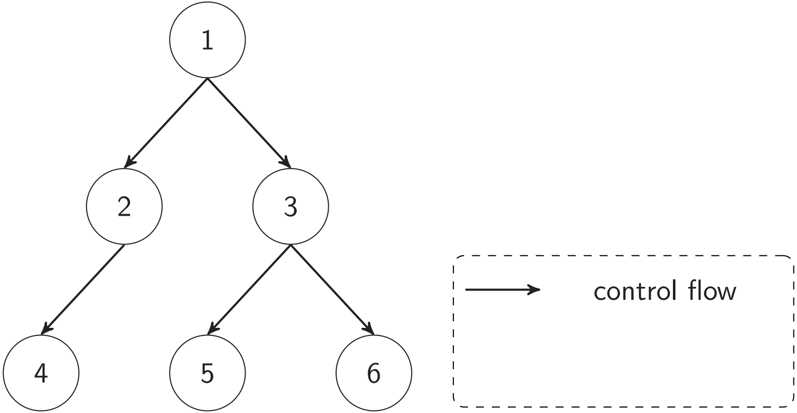
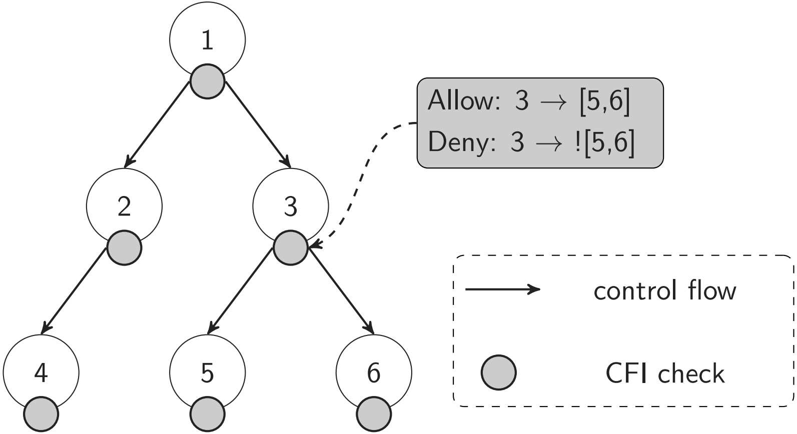
Eliminate bugs

Limit Post-Exploitation Impact

Control-Flow Integrity



Control-Flow Integrity



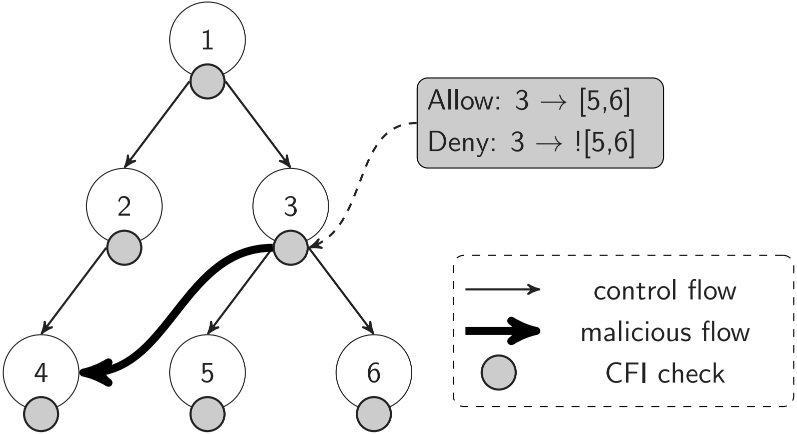
Allow: 3 → [5,6]

Deny: 3 → ![5,6]

→ control flow

● CFI check

Control-Flow Integrity



Allow: 3 → [5,6]
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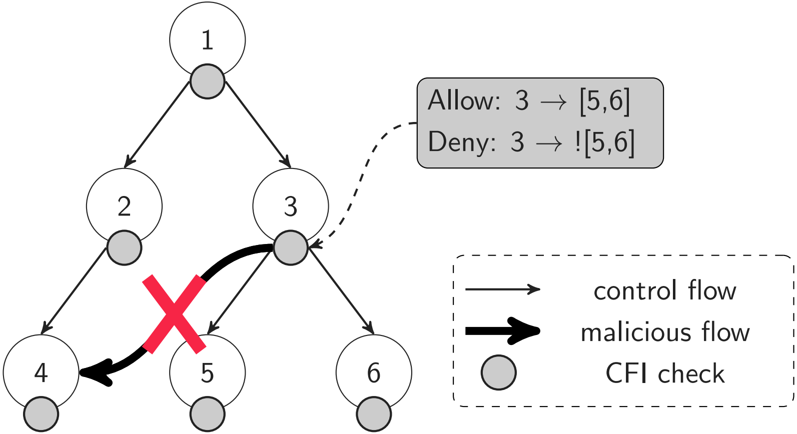
Control-Flow Integrity

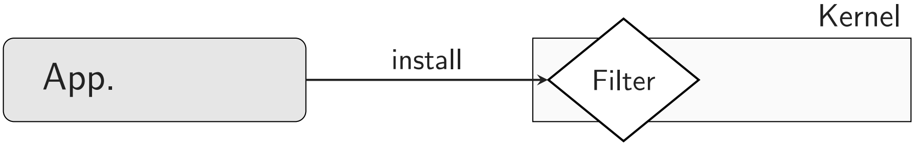


Allow: 3 → [5,6]
Deny: 3 → ![5,6]

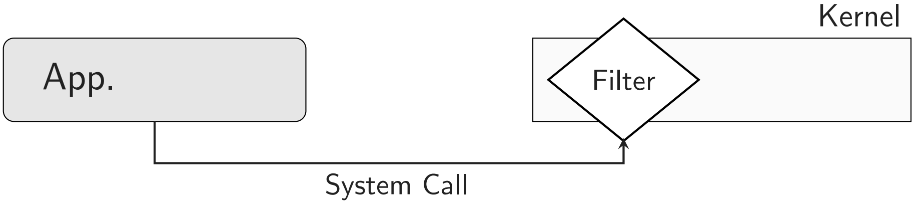
→ control flow
➔ malicious flow
● CFI check

Linux Seccomp

Linux Seccomp



Linux Seccomp



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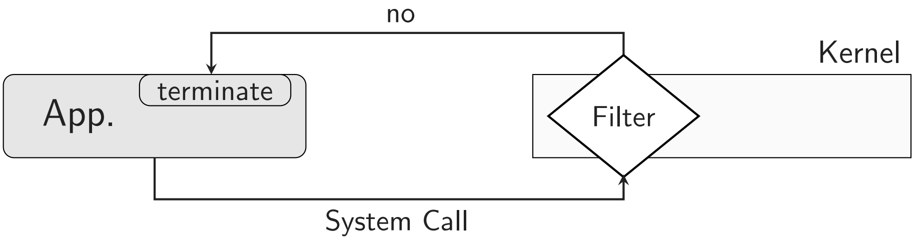

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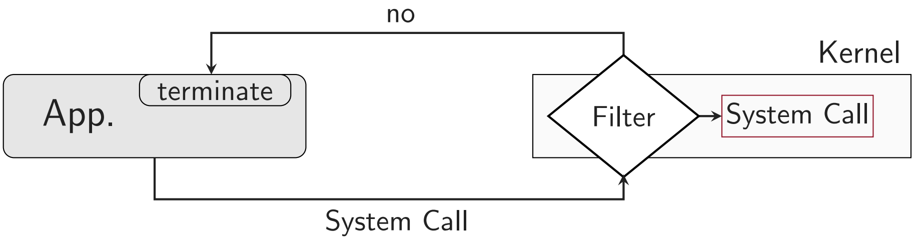

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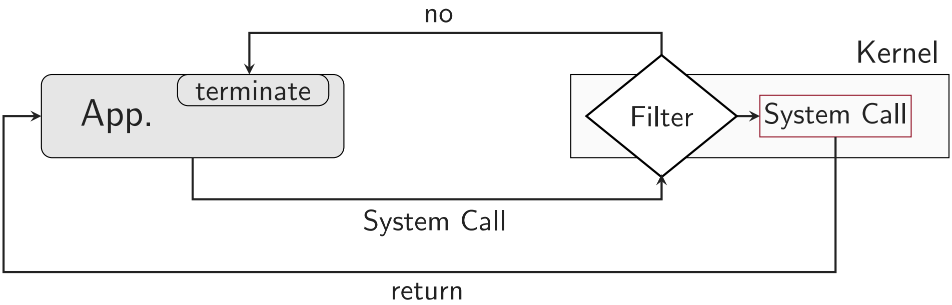
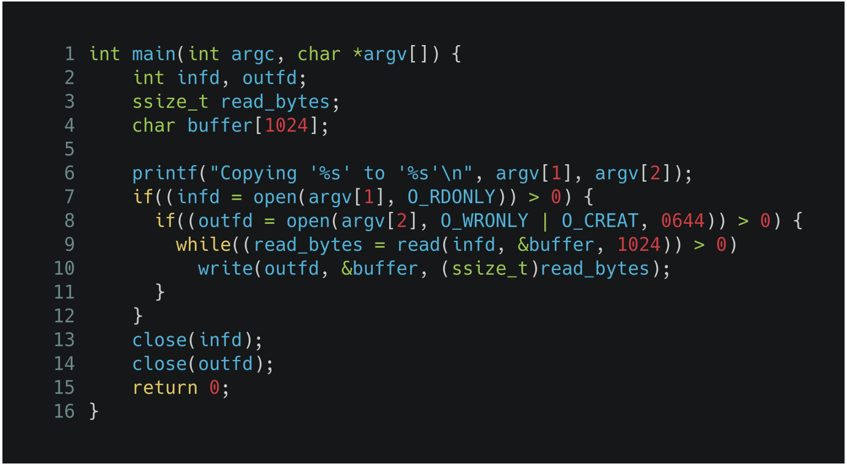


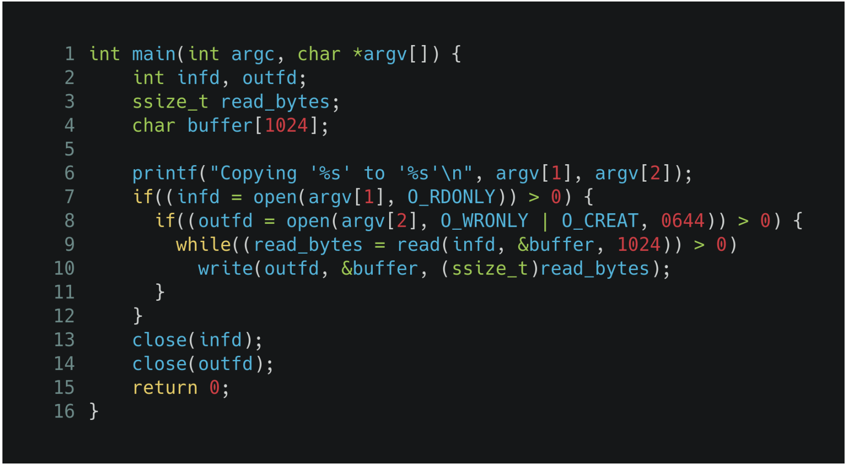
Sample



```c
int main(int argc, char *argv[]) {
    int infd, outfd;
    ssize_t read_bytes;
    char buffer[1024];

    printf("Copying '%s' to '%s'\n", argv[1], argv[2]);
    if((infd = open(argv[1], O_RDONLY)) > 0) {
      if((outfd = open(argv[2], O_WRONLY | O_CREAT, 0644)) > 0) {
        while((read_bytes = read(infd, &buffer, 1024)) > 0)
          write(outfd, &buffer, (ssize_t)read_bytes);
      }
    }
    close(infd);
    close(outfd);
    return 0;
}
```

Sample



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      }
    }
    close(infd);
    close(outfd);
    return 0;
}
```

Syscalls: 0 1 2 3 16 19 20 60 72 202 231

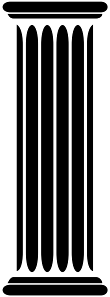
ENTER SANDBOX

https://github.com/chestnut-sandbox/Chestnut

Claudio Canella (@cc0x1f), Mario Werner (we.rner.at), Michael Schwarz (@misc0110)

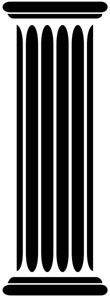
Syscall-Flow-Integrity Protection

Syscall-Flow-Integrity Protection

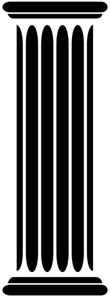


State Machine

Syscall-Flow-Integrity Protection

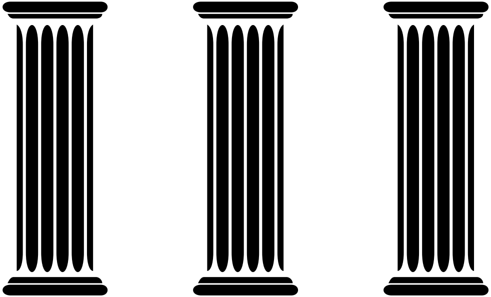


State Machine



Origins

Syscall-Flow-Integrity Protection

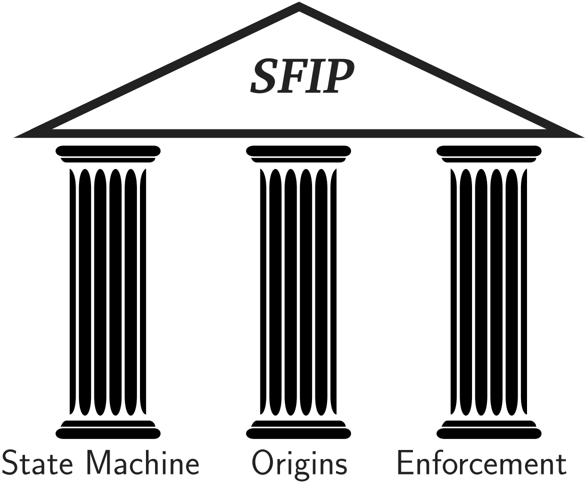


State Machine

Origins

Enforcement

Syscall-Flow-Integrity Protection



SysFlow

Compiler: Extraction

SysFlow

Compiler: Extraction

Library: Setup

SysFlow

Compiler: Extraction

Library: Setup

Kernel: Enforcement

Syscall and CFG Extraction

Source Code

```
L01: void foo(int test) {
L02:   scanf(...);
L03:   if(test)
L04:     printf(...)
L05:   else
L06:     syscall(read, ...);
L07:   int ret = bar(...);
L08:   if(!ret)
L09:       exit(0);
L10:   return ret;
L11: }
```

Syscall and CFG Extraction

Source Code

```
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L07:   int ret = bar(...);
L08:   if(!ret)
L09:       exit(0);
L10:   return ret;
L11: }
```

extract →

Extracted Function Info

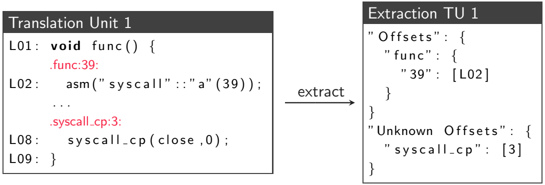
```
{
  "Transitions": {
    "L03": [L04,L06],
    "L04": [L07],
    "L06": [L07]
    "L08": [L09,L10]
  }
  "Call Targets": {
    "L02": ["scanf"],
    "L04": ["printf"],
    "L07": ["bar"],
    "L09": ["exit"],
  }
  "Syscalls": {
    "L06" : [read]
  }
}
```

Syscall Offset Extraction

Translation Unit 1

```
void func() {
.func:39:
  asm("syscall"::"a"(39));
  ...
.syscall_cp:3:
  syscall_cp(close,0);
}
```

Syscall Offset Extraction



Translation Unit 1

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L01: void func() {
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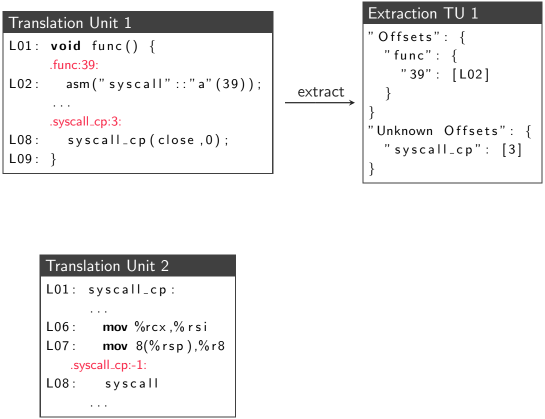
L02:   asm("syscall"::"a"(39));
     ...
     .syscall_cp:3:
L08:   syscall_cp(close,0);
L09: }
```

Extraction TU 1

```
"Offsets": {
  "func": {
    "39": [L02]
  }
}
"Unknown Offsets": {
  "syscall_cp": [3]
}
```

Syscall Offset Extraction



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```
"Offsets": {
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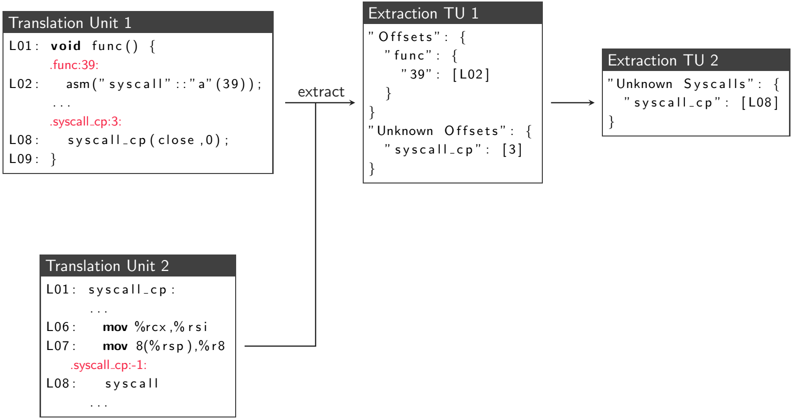
    "39": [L02]
  }
}
"Unknown Offsets": {
  "syscall_cp": [3]
}
```

Translation Unit 2

```
L01: syscall_cp:
       ...
L06:     mov %rcx,%rsi
L07:     mov 8(%rsp),%r8
       .syscall_cp:-1:
L08:     syscall
       ...
```

Syscall Offset Extraction



Translation Unit 1

```
L01: void func() {
     .func:39:
L02:    asm("syscall"::"a"(39));
        ...
     .syscall_cp:3:
L08:    syscall_cp(close,0);
L09: }
```

Translation Unit 2

```
L01: syscall_cp:
        ...
L06:    mov %rcx,%rsi
L07:    mov 8(%rsp),%r8
      .syscall_cp:-1:
L08:    syscall
        ...
```

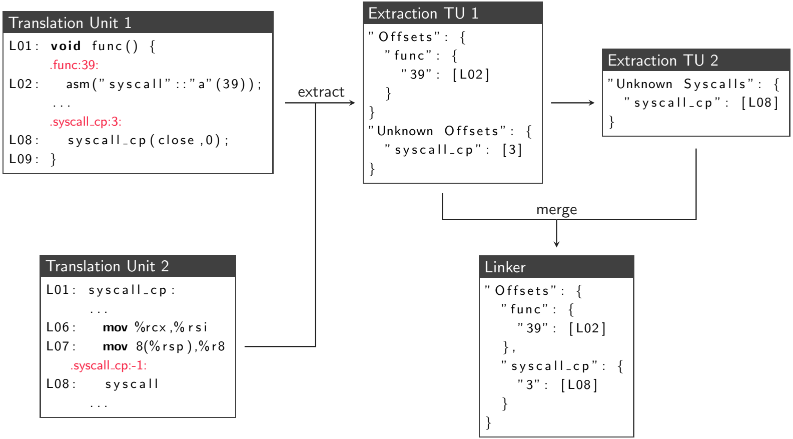
Extraction TU 1

```
"Offsets": {
  "func": {
    "39": [L02]
  }
}
"Unknown Offsets": {
  "syscall_cp": [3]
}
```

Extraction TU 2

```
"Unknown Syscalls": {
  "syscall_cp": [L08]
}
```

Syscall Offset Extraction



Translation Unit 1

```
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     .func:39:
L02:    asm("syscall"::"a"(39));
     ...
     .syscall_cp:3:
L08:    syscall_cp(close,0);
L09: }
```

Translation Unit 2

```
L01: syscall_cp:
       ...
L06:     mov %rcx,%rsi
L07:     mov 8(%rsp),%r8
       .syscall_cp:-1:
L08:     syscall
       ...
```

Extraction TU 1

```
"Offsets": {
  "func": {
    "39": [L02]
  }
}
"Unknown Offsets": {
  "syscall_cp": [3]
}
```

Extraction TU 2

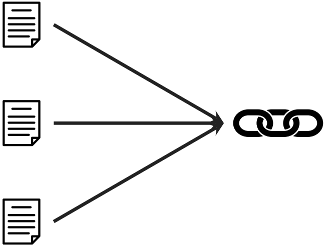
```
"Unknown Syscalls": {
  "syscall_cp": [L08]
}
```

Linker

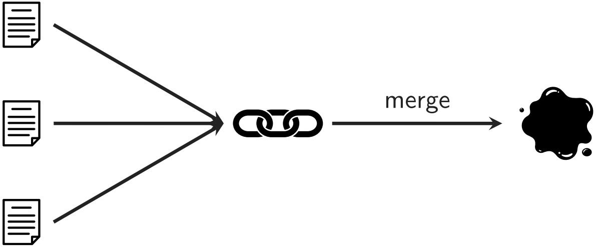
```
"Offsets": {
  "func": {
    "39": [L02]
  },
  "syscall_cp": {
    "3": [L08]
  }
}
```

State Machine Generation

State Machine Generation



State Machine Generation



State Machine Generation

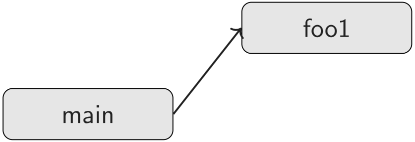
Info main

```
Call Targets: {
  "L56": [foo1],
  "L59": [foo2]
}
```

Last Syscalls

State Machine

State Machine Generation



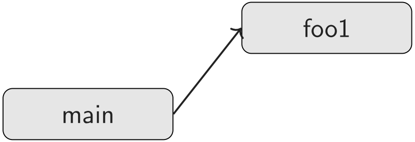
Info foo1

```
Call Targets: {
  "L03": [bar1]
}
Syscalls: {
  "L02": [open]
}
```

Last Syscalls

State Machine

State Machine Generation



Info foo1

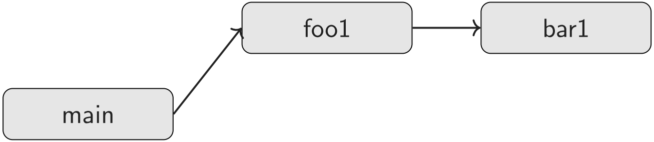
```
Call Targets: {
  "L03": [bar1]
}
Syscalls: {
}
```

Last Syscalls

open

State Machine

State Machine Generation



Info bar1

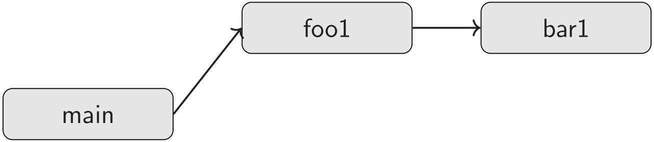
```
Syscalls: {
  "L12": [read]
}
```

Last Syscalls

open

State Machine

State Machine Generation



Info bar1

```
Syscalls: {
  "L12": [read]
}
```

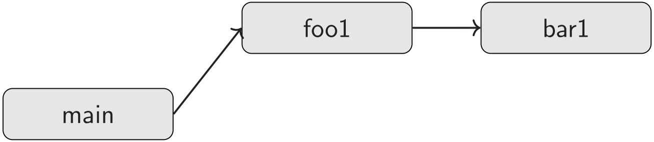
Last Syscalls

open

State Machine

open: [read]

State Machine Generation



Info bar1

Syscalls: {
}

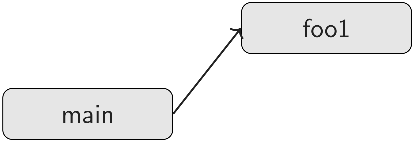
Last Syscalls

read

State Machine

open: [read]

State Machine Generation



Info foo1

```
Call Targets: {
}
Syscalls: {
}
```

Last Syscalls

read

State Machine

open: [read]

State Machine Generation

main

Info main

```
Call Targets: {
  "L59": [foo2]
}
```

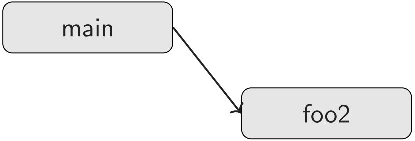
Last Syscalls

read

State Machine

open: [read]

State Machine Generation



Info foo2

```
Call Targets: {
  "L179": [bar2]
}
Syscalls: {
  "L178": [open]
}
```

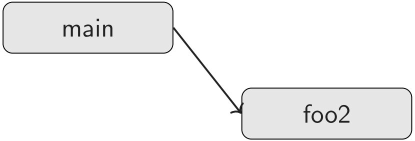
Last Syscalls

read

State Machine

open: [read]

State Machine Generation



Info foo2

```
Call Targets: {
  "L179": [bar2]
}
Syscalls: {
  "L178": [open]
}
```

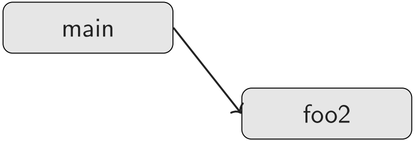
Last Syscalls

read

State Machine

open: [read]
read: [open]

State Machine Generation



Info foo2

```
Call Targets: {
  "L179": [bar2]
}
Syscalls: {
}
```

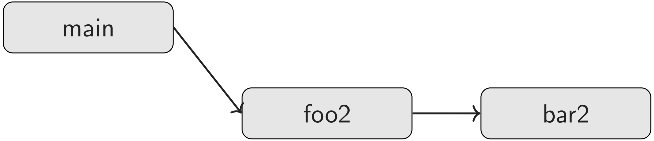
Last Syscalls

open

State Machine

open: [read]
read: [open]

State Machine Generation



Info bar2

```
Syscalls: {
  "L162": [stat]
}
```

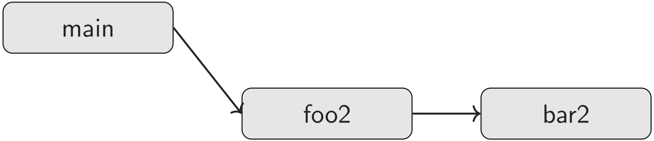
Last Syscalls

open

State Machine

open: [read]
read: [open]

State Machine Generation



Info bar2

```
Syscalls: {
}
```

Last Syscalls

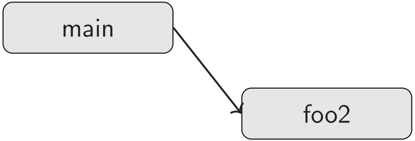
stat

State Machine

open: [read,stat]

read: [open]

State Machine Generation



Info foo2

```
Call Targets: {
}
Syscalls: {
}
```

Last Syscalls

stat

State Machine

open: [read,stat]
read: [open]

State Machine Generation

Info main

```
Call Targets: {
}
```

Last Syscalls

stat

State Machine

open: [read,stat]

read: [open]

Enforcement

Library

- extracts information

Enforcement

Library

- extracts information
- makes offset adjustment

Enforcement

Library

- extracts information
- makes offset adjustment

Kernel

- performs transition check

Enforcement

Library

- extracts information
- makes offset adjustment

Kernel

- performs transition check
- performs independent origin check

Evaluation

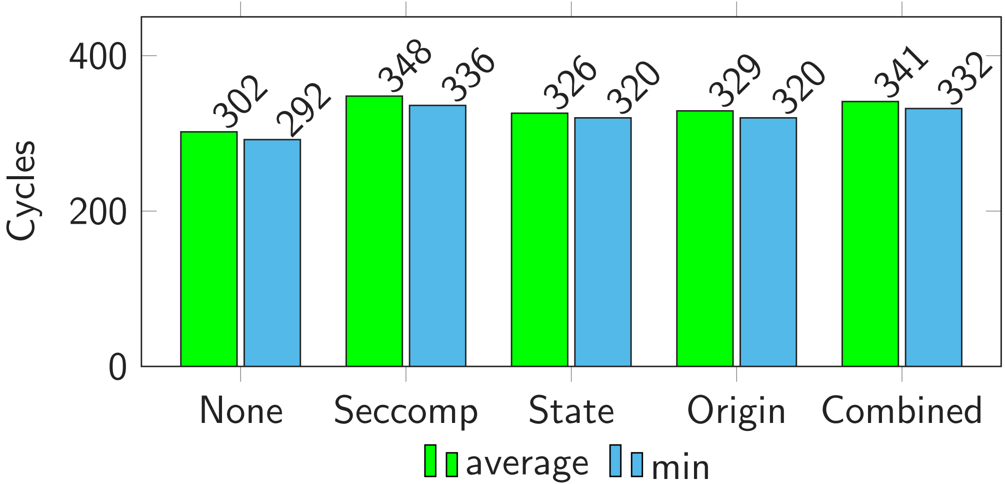
Performance

Evaluation

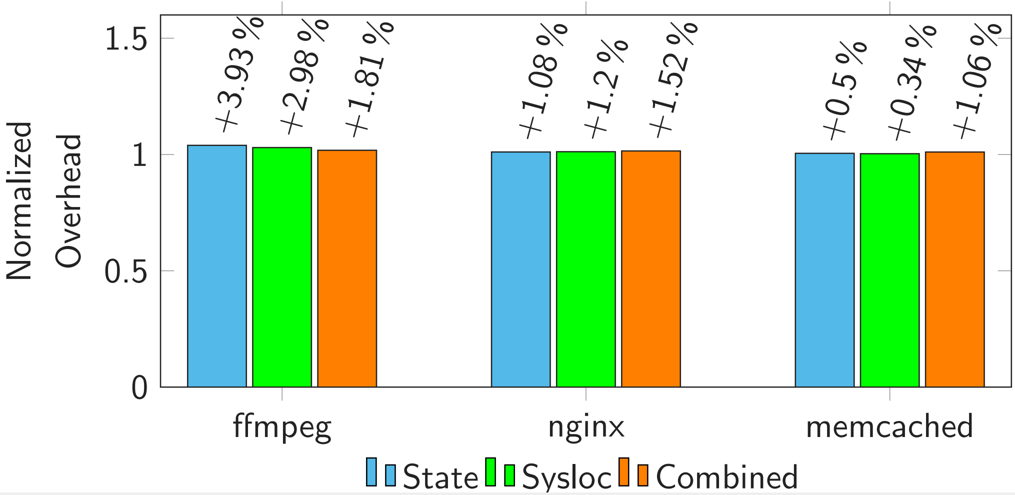
Performance

Security

Microbenchmark



Macrobenchmark



State Machine Analysis

Application	Average Transitions	#States
busybox	15.99	23.52
coreutils	16.66	26.64
pwgen	13.56	18
muraster	18.89	29
nginx	74.05	107
ffmpeg	49.07	55
memcached	43.16	86
mutool	32.26	53

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muraster	18.89	29
nginx	74.05	107
ffmpeg	49.07	55
memcached	43.16	86
mutool	32.26	53

Origin Analysis

Application	Total #Offsets	Avg #Offsets
busybox	102.64	3.75
coreutils	116.71	4.42
pwgen	84	4.42
muraster	193	4.6
nginx	318	3.0
ffmpeg	279	4.98
memcached	317	3.69
mutool	278	4.15

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Return-oriented programming

- Use exisiting code to exploit a program

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  - `syscall; retq`
  - `add RSP, 8; retq`

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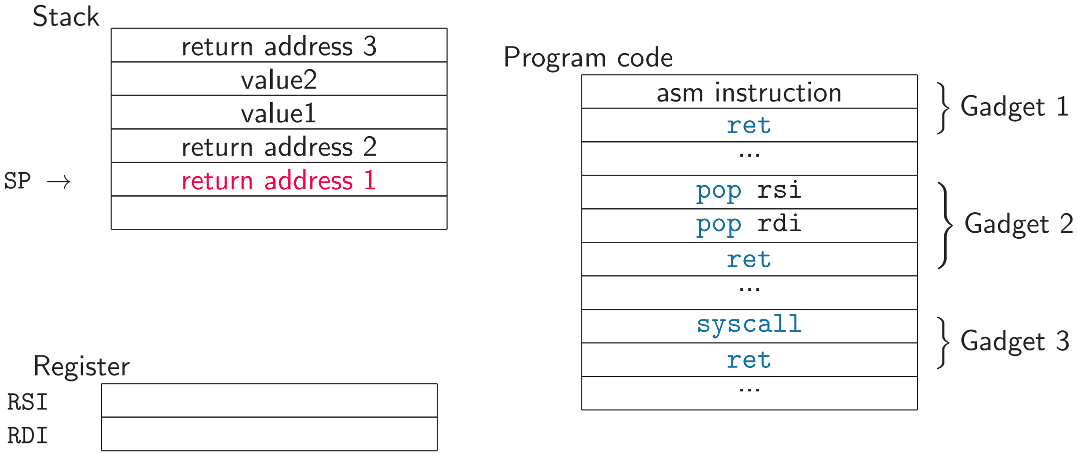
  - `add RSP, 8; retq`
- Gadgets are chained together for an exploit
- Overwrite the stack with gadget addresses and parameters

Return-oriented programming



Stack

- return address 3
- value2
- value1
- return address 2
- return address 1

SP →

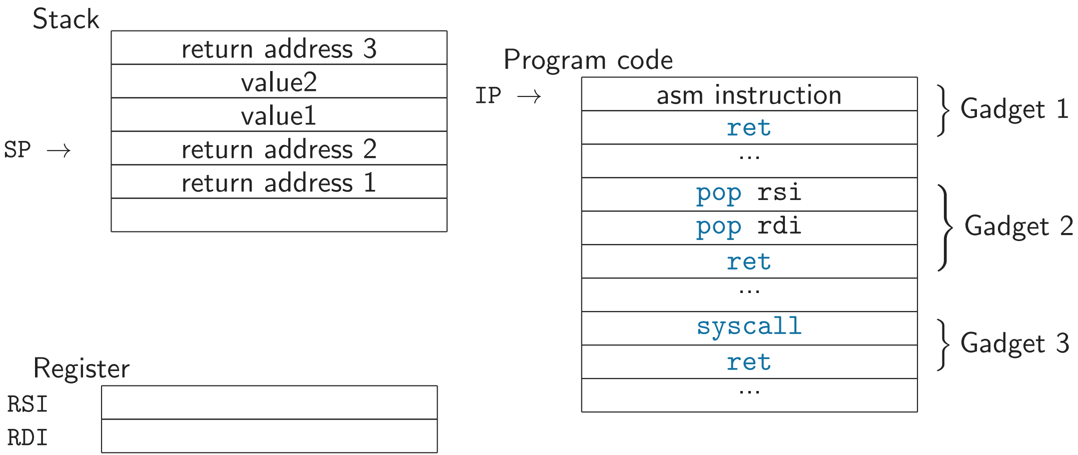
Register

- RSI
- RDI

Program code

```
asm instruction   } Gadget 1
ret
...
pop rsi           } Gadget 2
pop rdi
ret
...
syscall           } Gadget 3
ret
...
```

Return-oriented programming



Stack

return address 3

value2

value1

SP → return address 2

return address 1

Program code

IP → asm instruction

ret

...

pop rsi

pop rdi

ret

...

syscall

ret

...

Gadget 1

Gadget 2

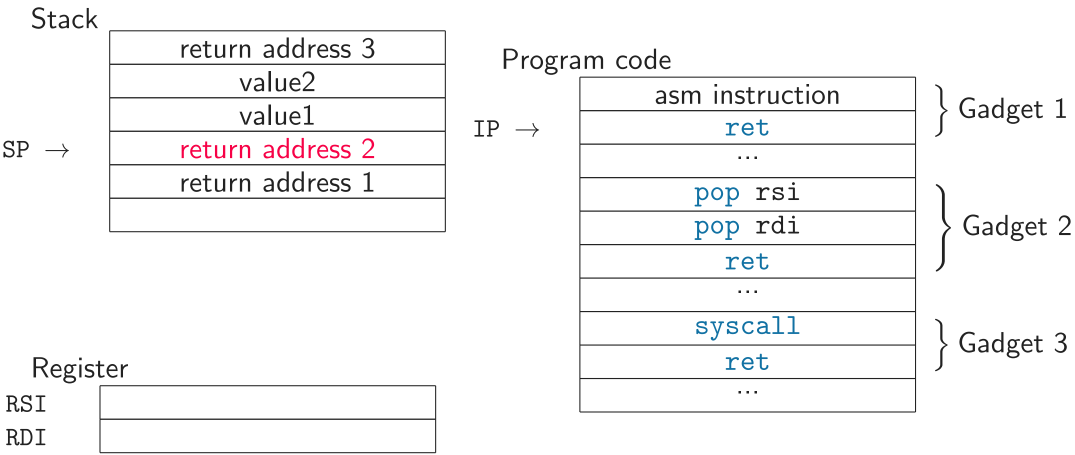
Gadget 3

Register

RSI

RDI

Return-oriented programming



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return address 3

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Program code

IP →

asm instruction

ret

...

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...

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Gadget 2

Gadget 3

Register

RSI

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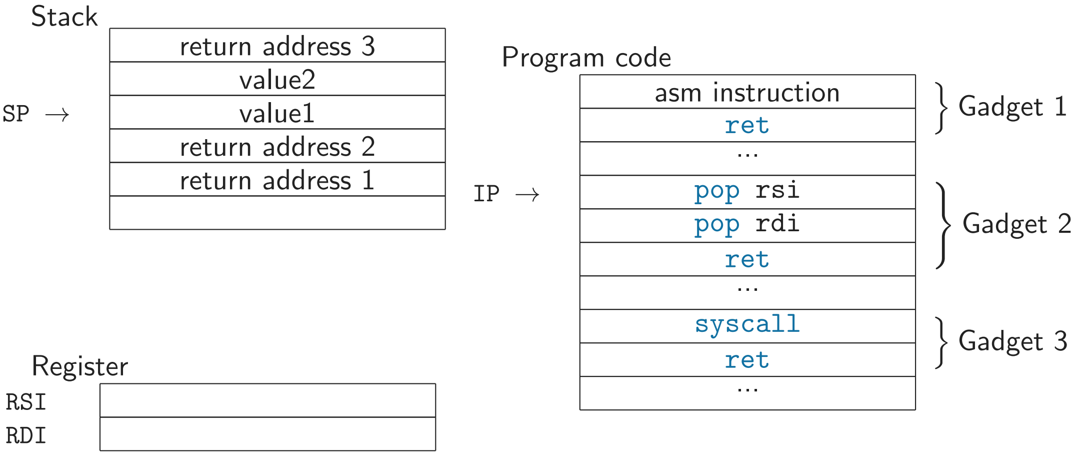

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Register

RSI
RDI

Program code

IP →

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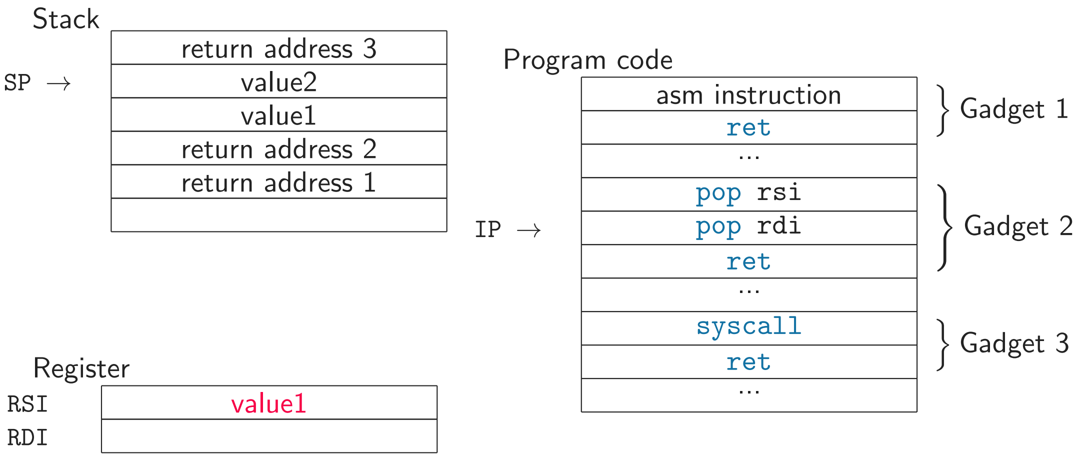
Gadget 1

Gadget 2

Gadget 3

Return-oriented programming



Stack

SP →

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value1
return address 2
return address 1

Program code

IP →

```
asm instruction   } Gadget 1
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...
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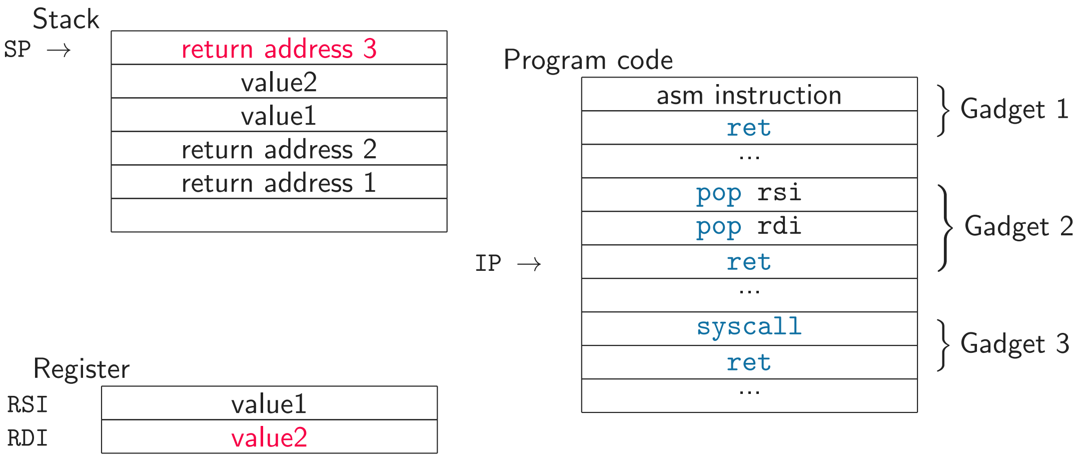
pop rdi
ret
...
syscall           } Gadget 3
ret
...
```

Register

RSI	value1
RDI	

Return-oriented programming



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SP →

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value2

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return address 2

return address 1

Register

RSI value1

RDI value2

Program code

asm instruction

ret

...

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pop rdi

ret

...

syscall

ret

...

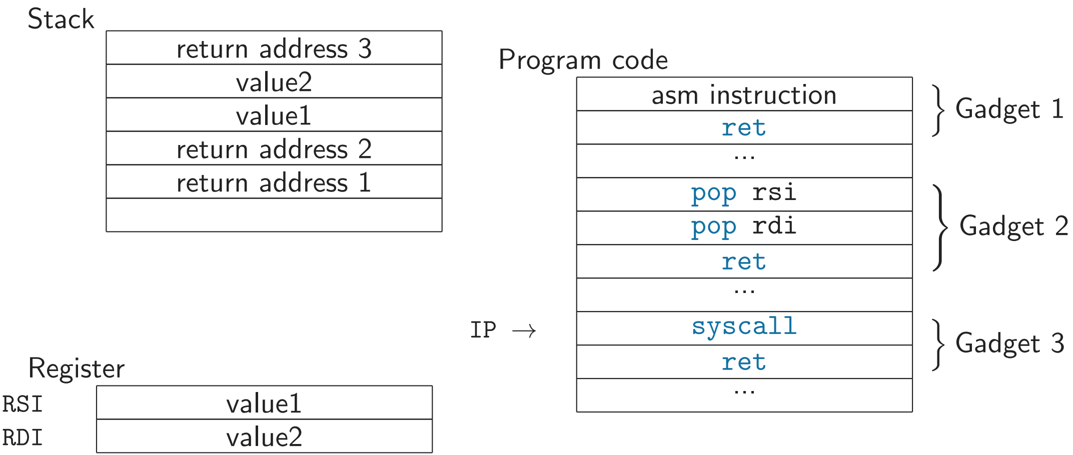
IP →

Gadget 1

Gadget 2

Gadget 3

Return-oriented programming



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Register

RSI	value1
RDI	value2

Program code

asm instruction	Gadget 1
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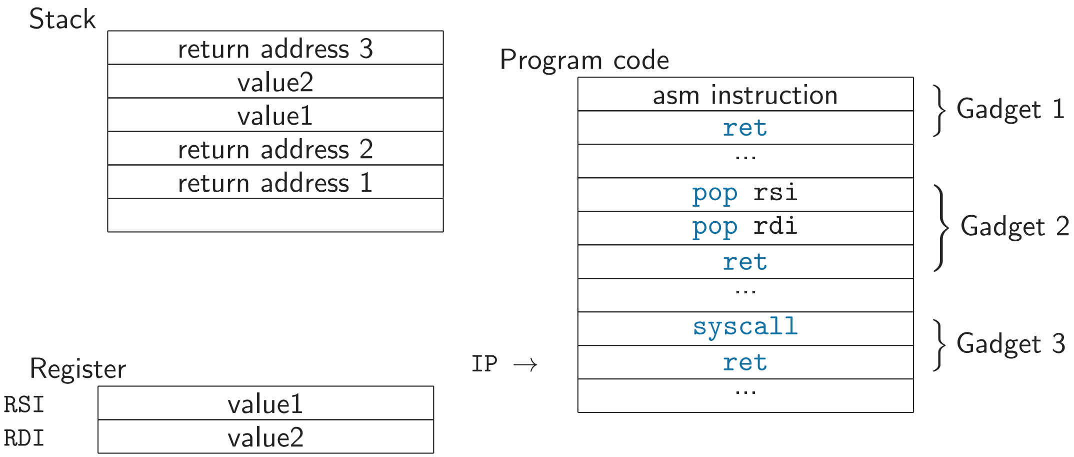
...	
pop rsi	Gadget 2
pop rdi	
ret	
...	
syscall	Gadget 3
ret	
...	

Return-oriented programming



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return address 3

value2

value1

return address 2

return address 1

Program code

asm instruction

ret

...

pop rsi

pop rdi

ret

...

syscall

ret

...

Gadget 1

Gadget 2

Gadget 3

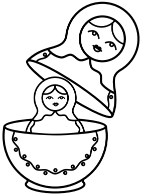
IP →

Register

RSI value1

RDI value2

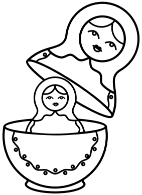
Return-oriented programming



Gadgets are often unintended

- Consider the byte sequence `05 5a 5e 5f c3`

Return-oriented programming



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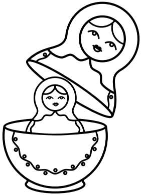
- Consider the byte sequence `05 5a 5e 5f c3`
- It disassembles to

```
add eax, 0xc35f5e5a
```

Return-oriented programming



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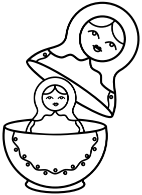
```
add eax, 0xc35f5e5a
```

- However, if we skip the first byte, it disassembles to

```
pop rdx
pop rsi
pop rdi
ret
```

Return-oriented programming



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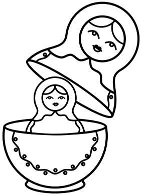
```
add eax, 0xc35f5e5a
```

- However, if we skip the first byte, it disassembles to

```
pop rdx
pop rsi
pop rdi
ret
```

- This property is due to non-aligned, variable-width opcodes

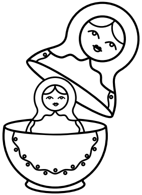
Return-oriented programming



Syscall instruction has byte sequence `0f 05`

→ easy to find unaligned syscall instructions

Return-oriented programming



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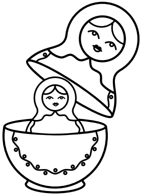
→ easy to find unaligned syscall instructions

SFIP restricts ROP chains via

Return-oriented programming



Syscall instruction has byte sequence `0f 05`

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SFIP restricts ROP chains via

- syscall origins → unaligned instructions not possible

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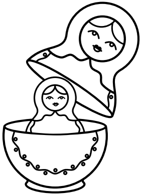

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- syscall origins → unaligned instructions not possible
- syscall transitions → not every sequence is possible

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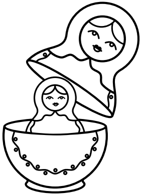

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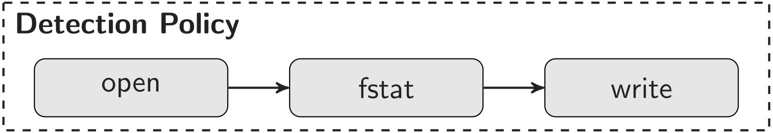
SFIP restricts ROP chains via

- syscall origins → unaligned instructions not possible
- syscall transitions → not every sequence is possible

Conclusion

SFIP imposes significant constraints on control-flow-hijacking attacks

Mimicry Attacks

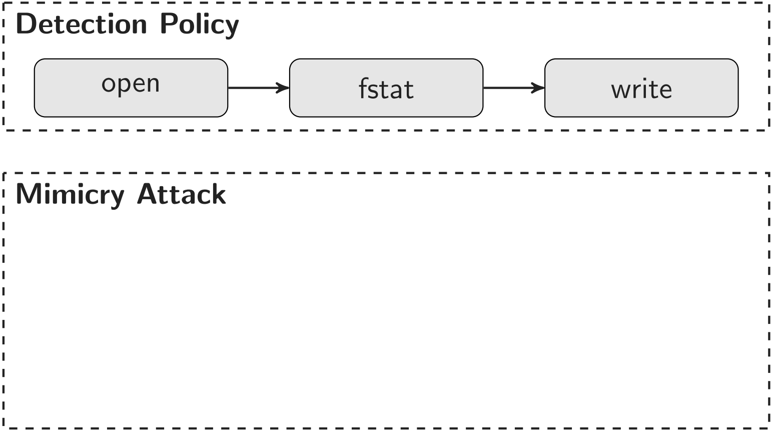

Detection Policy

open

fstat

write

Mimicry Attacks

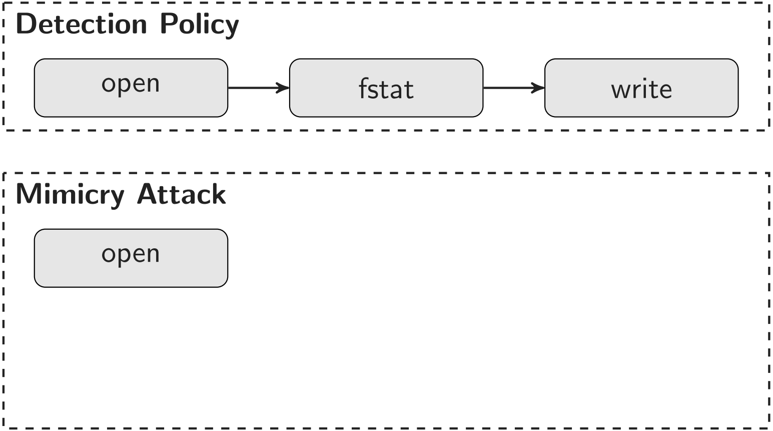


Detection Policy

open → fstat → write

Mimicry Attack

Mimicry Attacks



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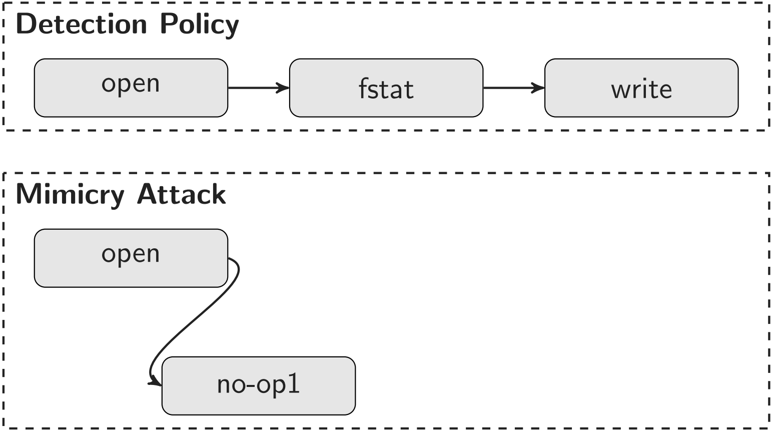

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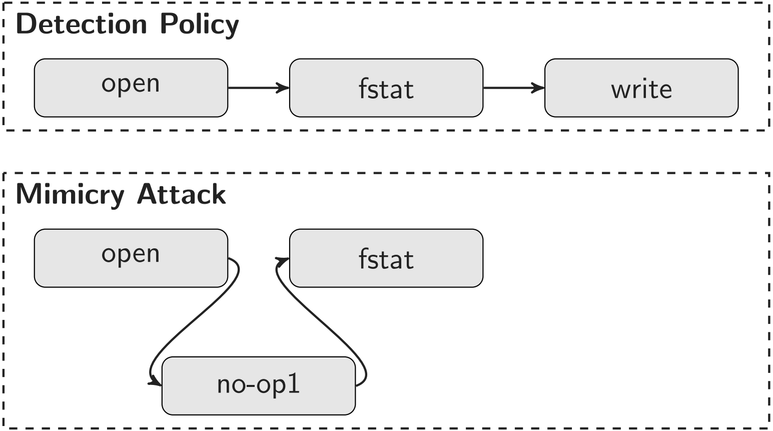

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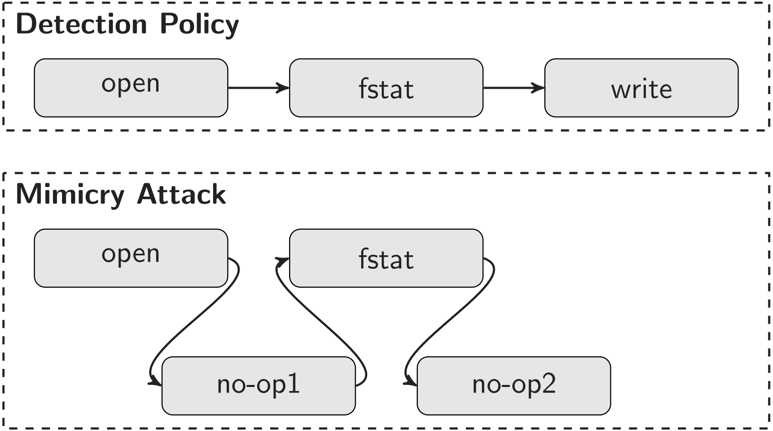

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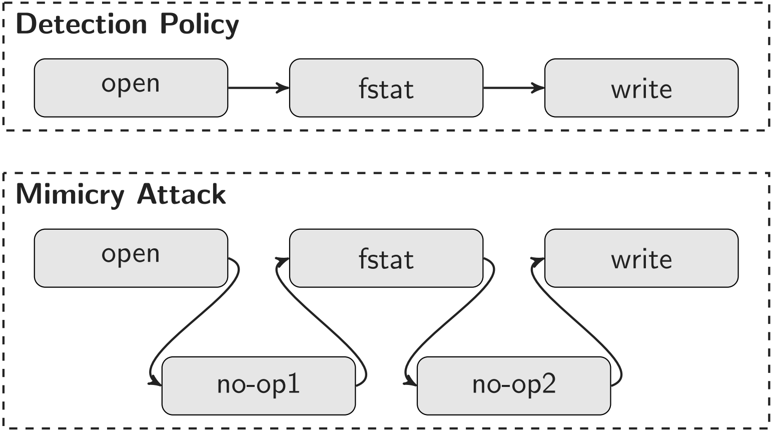

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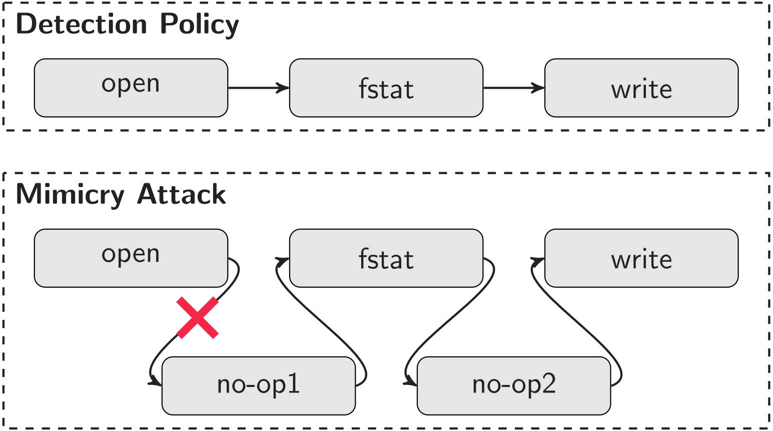

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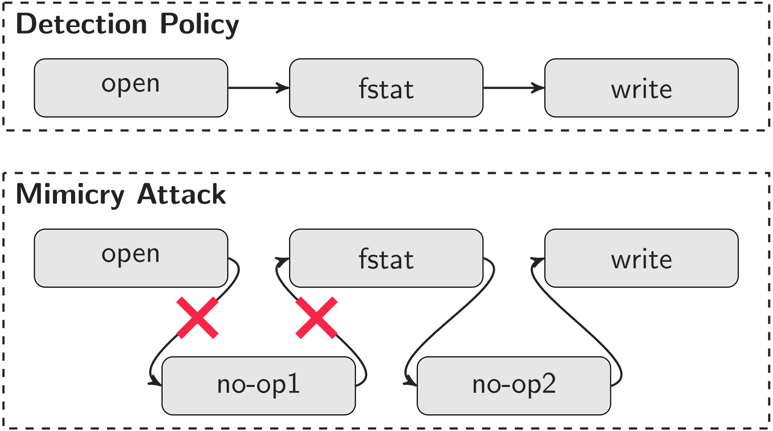

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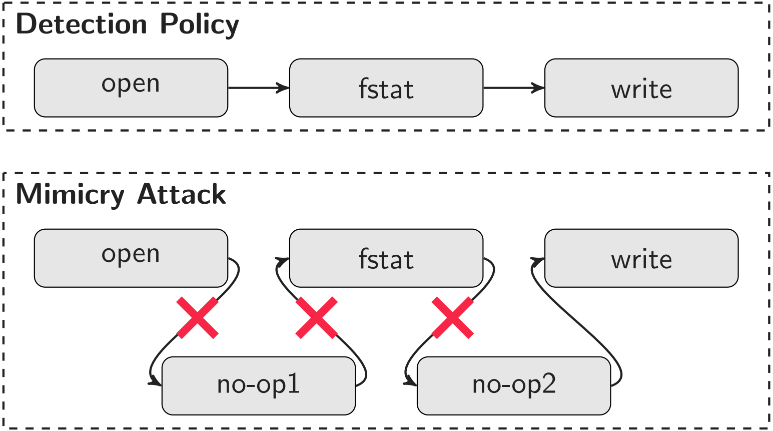


Detection Policy

open → fstat → write

Mimicry Attack

open

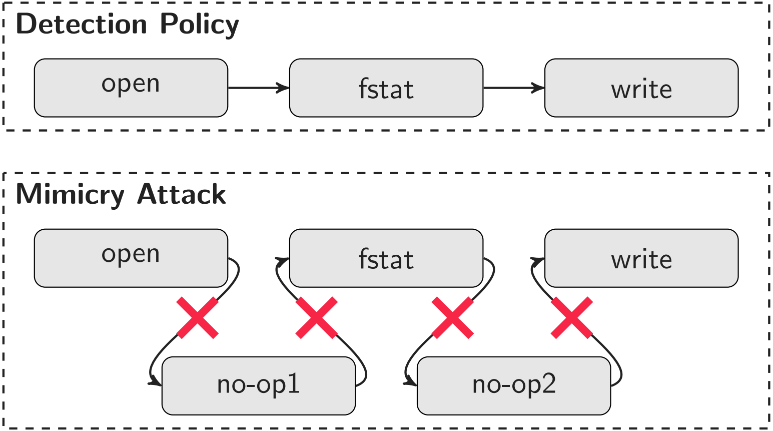
fstat

write

no-op1

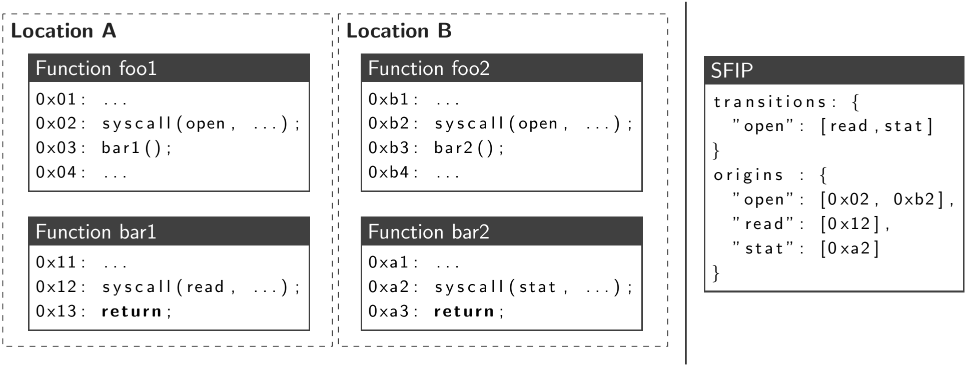
no-op2

Mimicry Attacks



In the near future…

Coarse- to Fine-Grained SFIP



Location A

Function foo1

```
0x01:  ...
0x02:  syscall(open,  ...);
0x03:  bar1();
0x04:  ...
```

Function bar1

```
0x11:  ...
0x12:  syscall(read,  ...);
0x13:  return;
```

Location B

Function foo2

```
0xb1:  ...
0xb2:  syscall(open,  ...);
0xb3:  bar2();
0xb4:  ...
```

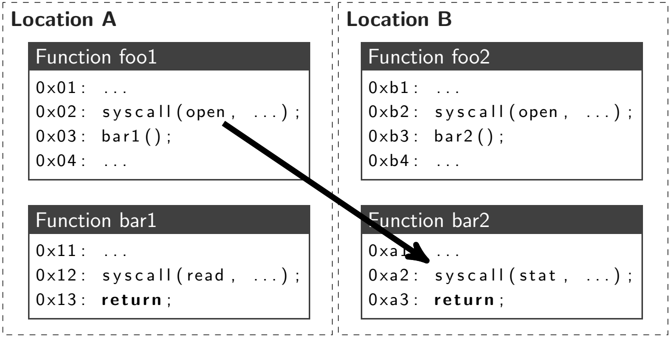
Function bar2

```
0xa1:  ...
0xa2:  syscall(stat,  ...);
0xa3:  return;
```

SFIP

```
transitions: {
  "open": [read,stat]
}
origins : {
  "open": [0x02, 0xb2],
  "read": [0x12],
  "stat": [0xa2]
}
```

Coarse- to Fine-Grained SFIP



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Function foo2

```
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0xb3:  bar2();
0xb4:  ...
```

Function bar2

```
0xa1:  ...
0xa2:  syscall(stat, ...);
0xa3:  return;
```

SFIP

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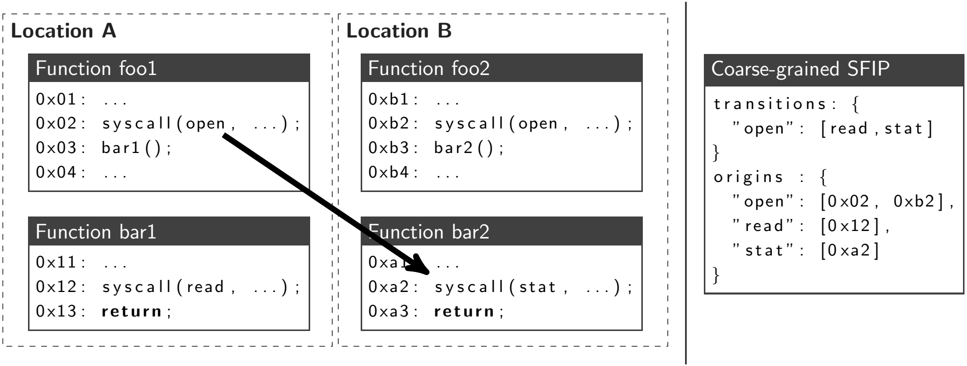

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0xb4: ...
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Function bar2

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0xa1: ...
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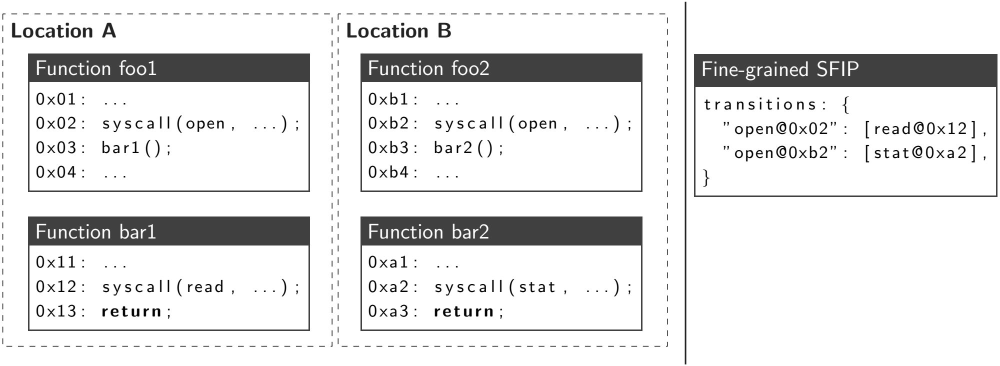

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Function bar2

```
0xa1:  ...
0xa2:  syscall(stat, ...);
0xa3:  return;
```

Fine-grained SFIP

```
transitions: {
  "open@0x02": [read@0x12],
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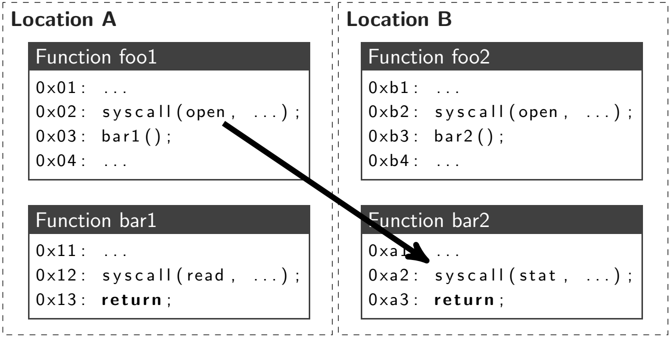
}
```

Coarse- to Fine-Grained SFIP



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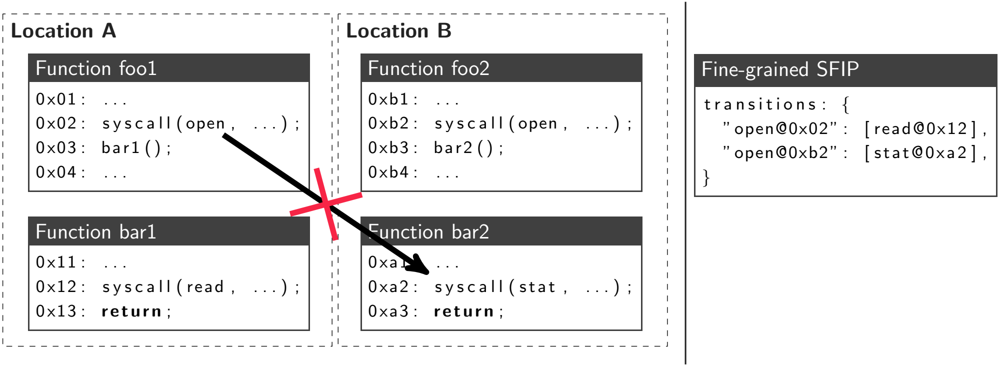
Coarse- to Fine-Grained SFIP



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Fine-grained SFIP

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}
```

Proof-of-Concept

You can find our proof-of-concept implementation of SysFlow on:

- `https://github.com/SFIP/SFIP`

More Details

More details in the paper

- More implementation details
- More extensive security discussion
- . . .

[Can+22]

Claudio Canella, Sebastian Dorn, Daniel Gruss, Michael Schwarz.
SFIP: Coarse-Grained Syscall-Flow-Integrity Protection in Modern Systems.

Recap

SFIP provides

- integrity to user-kernel transitions

Recap

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- security via syscall transition and origin checks

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and

- is fully automatized

Recap

SFIP provides

- integrity to user-kernel transitions
- security via syscall transition and origin checks

and

- is fully automatized
- has minimal runtime overhead

Go With the Flow

Enforcing Program Behavior Through Syscall Sequences and Origins

Claudio Canella (🐦@cc0x1f)

August 11, 2022

Graz University of Technology

References

[Can+22] C. Canella, S. Dorn, D. Gruss, and M. Schwarz. SFIP: Coarse-Grained Syscall-Flow-Integrity Protection in Modern Systems. In: arXiv:2202.13716 (2022).