Know Where You Come From

Enforcing Program Behavior Through Syscall Sequences and Origins

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Who am I?

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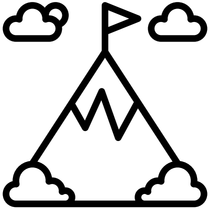
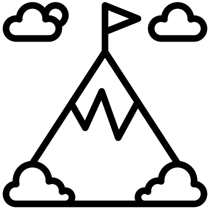
Motivation



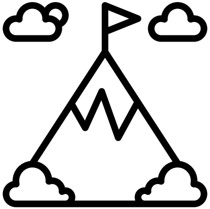
- Memory safety vulnerabilties are common

Motivation

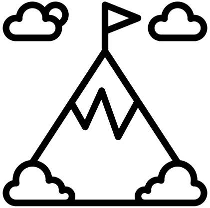


- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact

Motivation

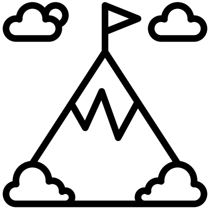


- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact
- Linux seccomp:



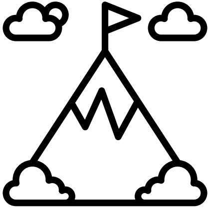
- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact
- Linux seccomp:
    - lot of manual work

Motivation



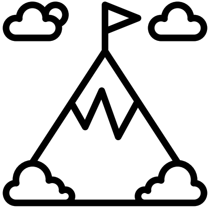
- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact
- Linux seccomp:
  - lot of manual work→ automated [Can+21]

Motivation

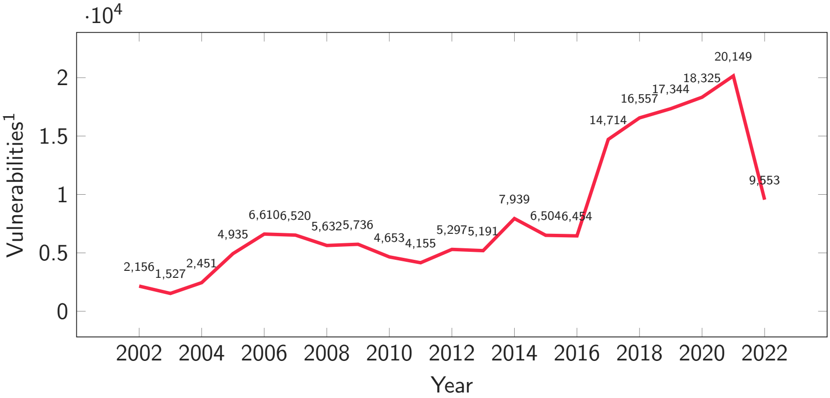


- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact
- Linux seccomp:
  - lot of manual work→ automated [Can+21]
  - stateless

Motivation



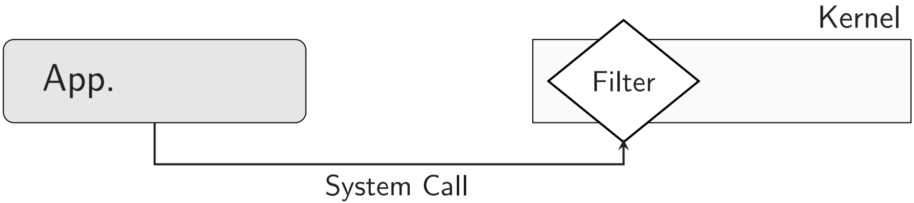
- Memory safety vulnerabilties are common
- Sandboxing helps in limiting their post-exploitation impact
- Linux seccomp:
  - lot of manual work→ automated [Can+21]
  - stateless
- CFI only within one domain

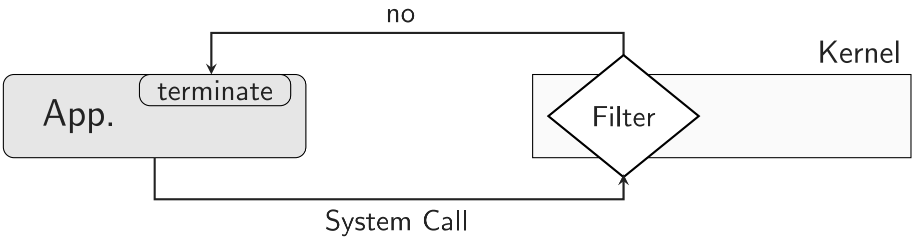


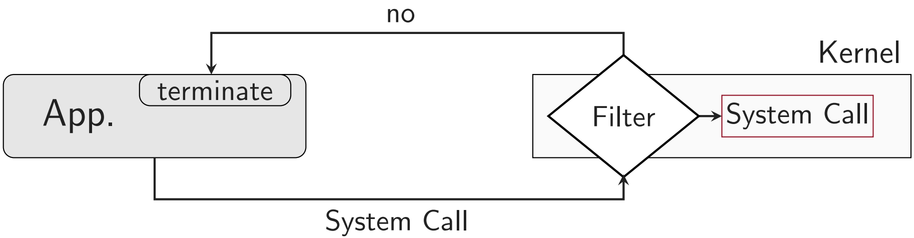
[1]Source: `http://www.cvedetails.com/vulnerabilities-by-types.php`

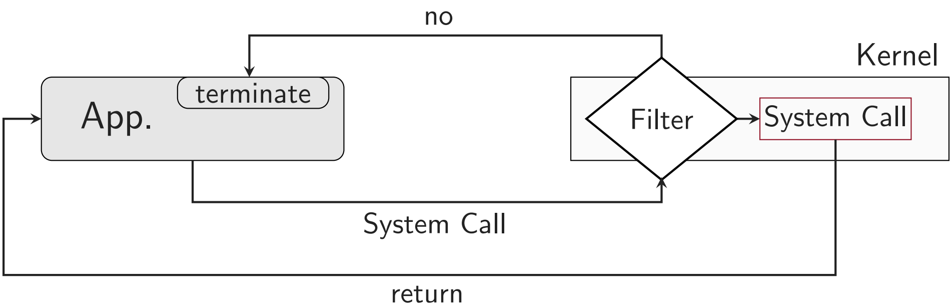

Kernel
App.


Kernel
App.
install
Filter


Kernel
App.
Filter
System Call


no
Kernel
terminate
App.
Filter
System Call


no
Kernel
App.
terminate
Filter
System Call
System Call


no
Kernel
terminate
App.
Filter
System Call
System Call
return

```
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

```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;
}
```

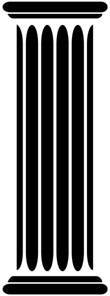
Syscalls: 0 1 2 3 16 19 20 60 72 202 231 blackhat

ENTER SANDBOX

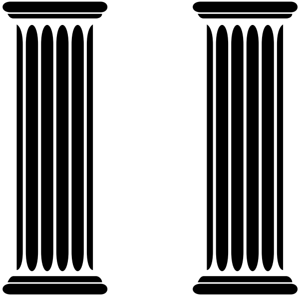
https://github.com/chestnut-sandbox/Chestnut

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

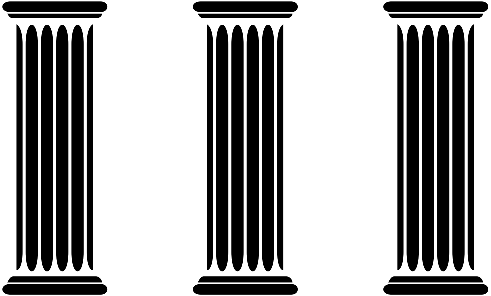
Syscall-Flow-Integrity Protection

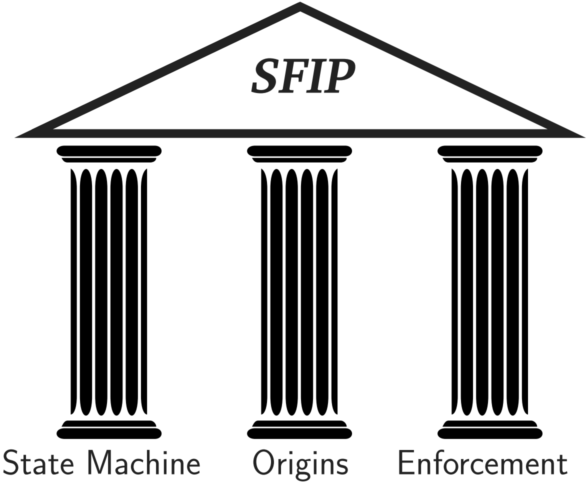


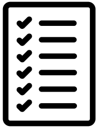
State Machine



State Machine Origins

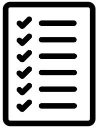

State Machine
Origins
Enforcement


SFIP
State Machine
Origins
Enforcement

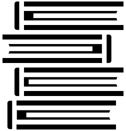


Syscalls from C Functions?

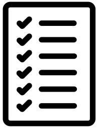
Challenges



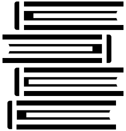
Syscalls from C Functions?



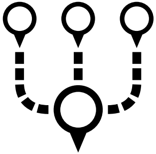
Precise Control-Flow Graph?



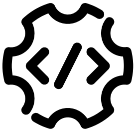
Syscalls from C Functions?



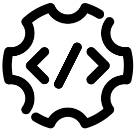
Precise Control-Flow Graph?



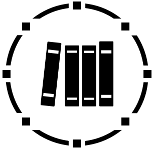
Non-bijective Mappings?



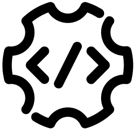
Compiler: Extraction



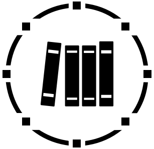
Compiler: Extraction



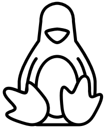
Library: Setup



Compiler: Extraction



Library: Setup



Kernel: Enforcement

Syscall and CFG Extraction

Source Code

```
void foo(int test) {
  scanf(...);
  if(test)
    printf(...)
  else
    syscall(read, ...);
  int ret = bar(...);
  if(!ret)
      exit(0);
  return ret;
}
```

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: }
```

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]
  }
}
```

Translation Unit 1

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

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: }
```

extract →

Extraction TU 1

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

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:  }
```

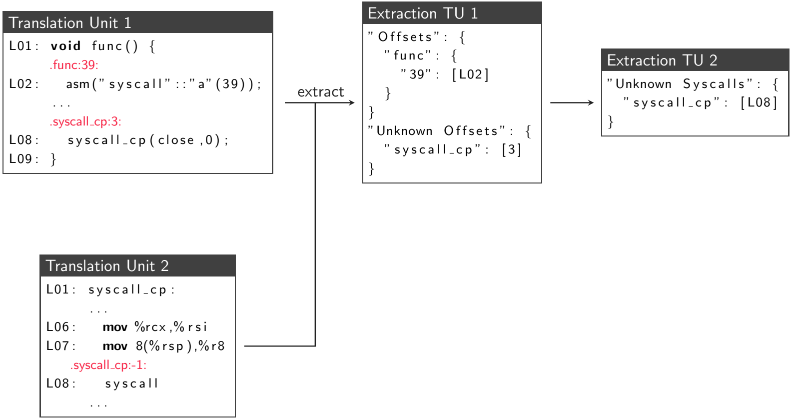
extract →

Extraction TU 1

```
"Offsets": {
   "func": {
      "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
        ...
```



Translation Unit 1
L01: void func() {
.func:39:
L02: asm("syscall"::"a"(39));
...
.syscall_cp:3:
L08: syscall_cp(close,0);
L09: }
extract
Extraction TU 1
"Offsets": {
"func": {
"39": [L02]
}
}
"Unknown Offsets": {
"syscall_cp": [3]
}
Extraction TU 2
"Unknown Syscalls": {
"syscall_cp": [L08]
}
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
       ...
```

extract

Extraction TU 1

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

Extraction TU 2

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

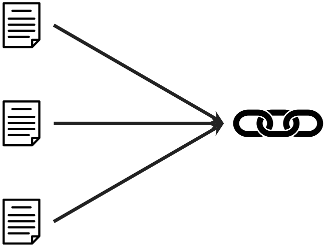
merge

Linker

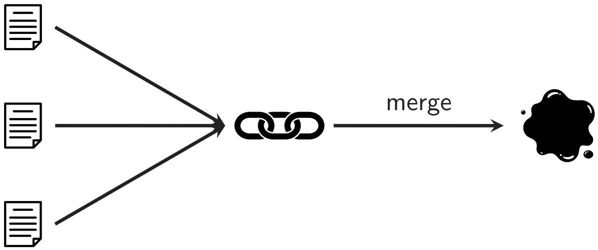
```
"Offsets": {
  "func": {
    "39": [L02]
  },
  "syscall_cp": {
    "3": [L08]
  }
}
```

State Machine Generation

State Machine Generation



State Machine Generation



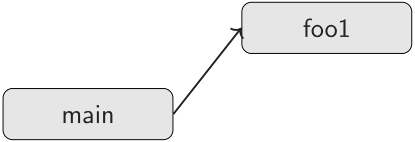
main

Info main

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

Last Syscalls

State Machine



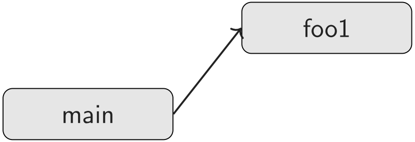
Info foo1

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

Last Syscalls

State Machine

State Machine Generation



Info foo1

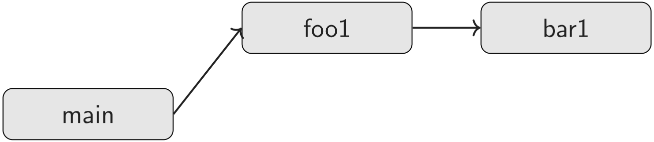
```
Call Targets: {
  "L03": [bar1]
}
Syscalls: {
}
```

Last Syscalls

open

State Machine

State Machine Generation



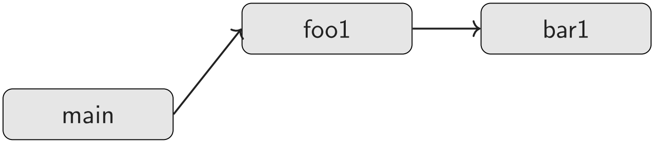
Info bar1

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

Last Syscalls

open

State Machine



Info bar1

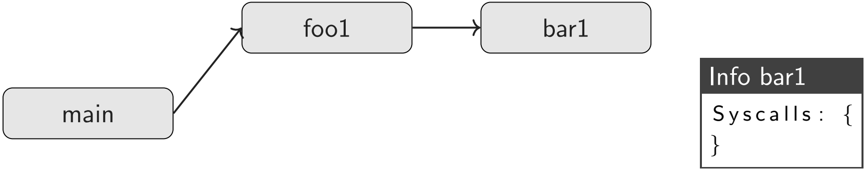
```
Syscalls: {
  "L12": [read]
}
```

Last Syscalls

open

State Machine

open: [read]

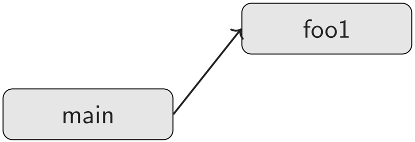


Last Syscalls

read

State Machine

open: [read]



Info foo1

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

Last Syscalls

read

State Machine

open: [read]

main

Info main

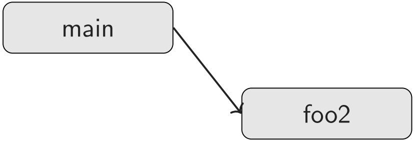
```
Call Targets: {
  "L59": [foo2]
}
```

Last Syscalls

read

State Machine

open: [read]



Info foo2

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

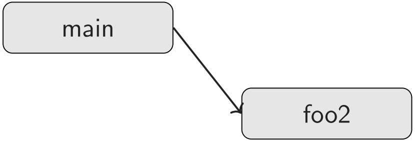
Last Syscalls

read

State Machine

open: [read]

State Machine Generation



Info foo2

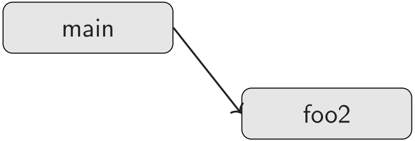
```
Call Targets: {
  "L179": [bar2]
}
Syscalls: {
  "L178": [open]
}
```

Last Syscalls

read

State Machine

open: [read]
read: [open]



Info foo2

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

Last Syscalls

open

State Machine

open: [read]
read: [open]

Info bar2

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

Last Syscalls

open

State Machine

open: [read]
read: [open]

Info bar2

Syscalls : {
}

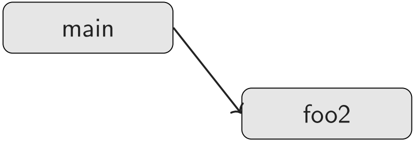
Last Syscalls

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]

main

Info main

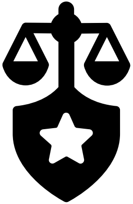
```
Call Targets: {
}
```

Last Syscalls

stat

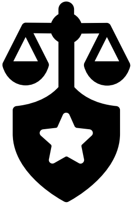
State Machine

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



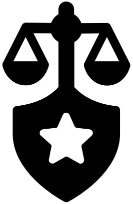
Library

- extracts information



Library

- extracts information
- makes offset adjustment



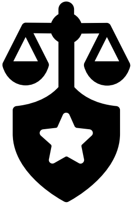
Library

- extracts information
- makes offset adjustment

Kernel

- performs transition check

Enforcement

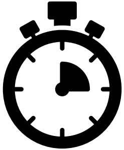


Library

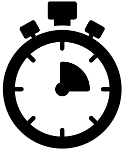
- extracts information
- makes offset adjustment

Kernel

- performs transition check
- performs independent origin check



Performance



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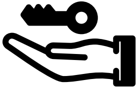
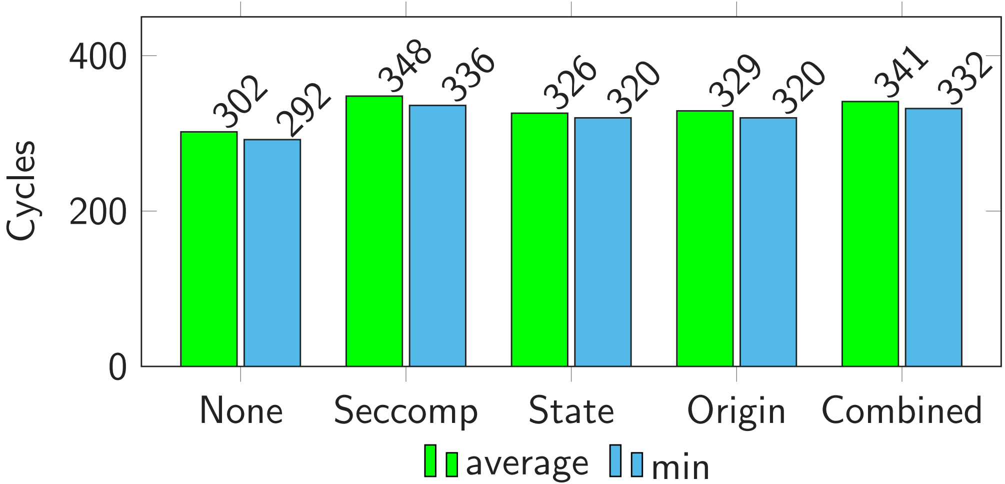
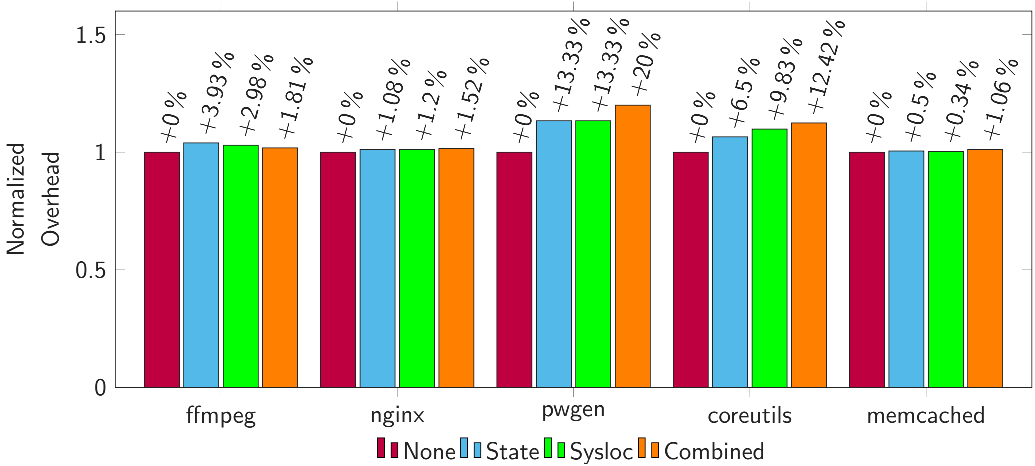


Security

Application	Vanilla	SysFlow
ffmpeg	162.12 s	1783.15 s
mupdf	58.01 s	489.85 s
nginx	8.22 s	226.64 s
busybox	16.09 s	81.33 s
coreutils	5.50 s	14.39 s
memcached	2.90 s	4.59 s
pwgen	0.07 s	0.12 s

Microbenchmark



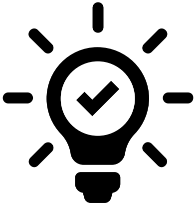

Normalized Overhead
0
0.5
1
1.5
+0 %
+3.93 %
+2.98 %
+1.81 %
+0 %
+1.08 %
+1.2 %
+1.52 %
+0 %
+13.33 %
+13.33 %
+20 %
+0 %
+6.5 %
+9.83 %
+12.42 %
+0 %
+0.5 %
+0.34 %
+1.06 %
ffmpeg
nginx
pwgen
coreutils
memcached
None
State
Sysloc
Combined

Application	Average Transitions	#States
busybox	15.73	24.51
coreutils	15.75	27.11
pwgen	12.42	19
muraster	17.51	41
nginx	65.55	108
ffmpeg	48.48	56
memcached	40.6	87
mutool	32.0	61

Origin Analysis

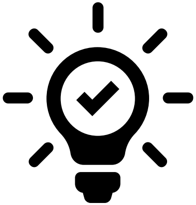
Application	Total #Offsets	Avg #Offsets
busybox	102.64	3.75
coreutils	116.71	4.42
pwgen	84	4.42
muraster	193	4.6
nginx	318	3.0
ffmpeg	279	4.98
memcached	317	3.69
mutool	278	4.15

Return-oriented programming



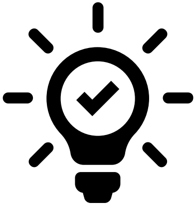
- Use exisiting code to exploit a program

Return-oriented programming



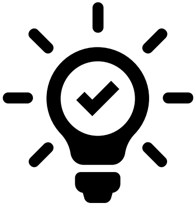
- Use exisiting code to exploit a program
- Jumps to parts of functions (so called gadgets)

Return-oriented programming



- Use exisiting code to exploit a program
- Jumps to parts of functions (so called gadgets)
- These *gadgets* are assembler instructions followed by a `ret`
  - `pop RDI; retq`
  - `syscall; retq`
  - `add RSP, 8; retq`

Return-oriented programming



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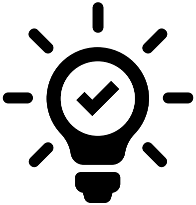

- Use exisiting code to exploit a program
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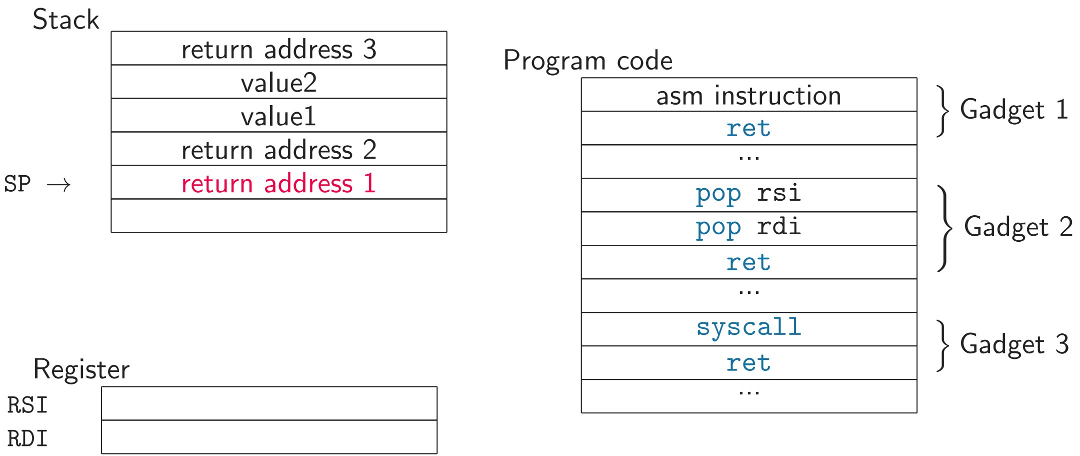
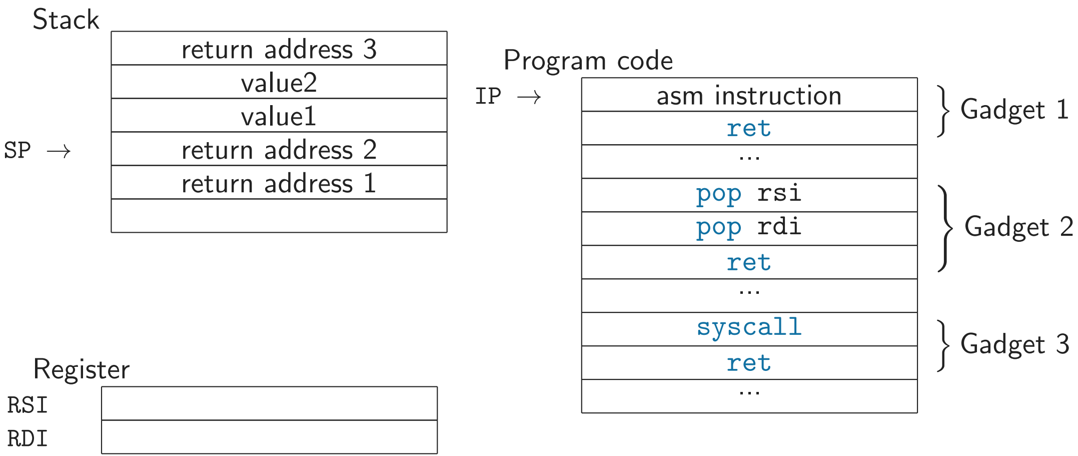
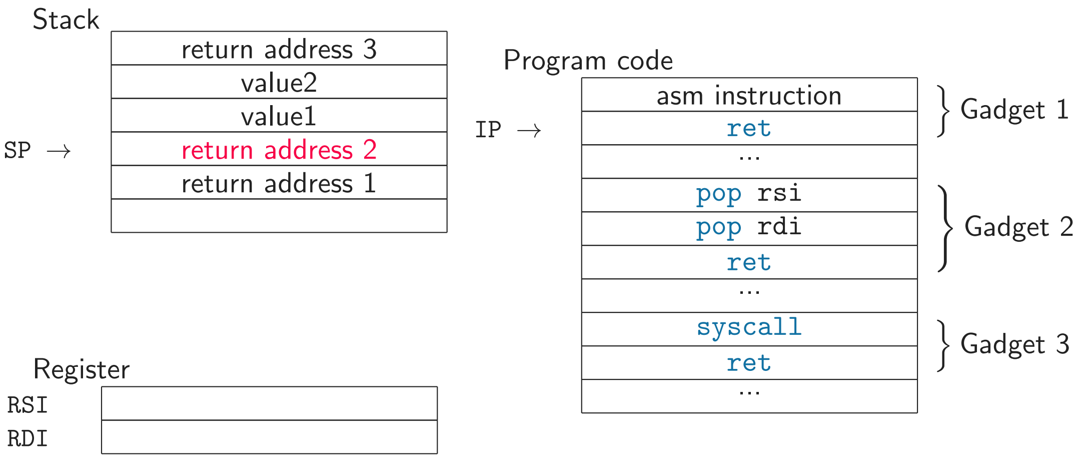
- These *gadgets* are assembler instructions followed by a `ret`
  - `pop RDI; retq`
  - `syscall; retq`
  - `add RSP, 8; retq`
- Gadgets are chained together for an exploit
- Overwrite the stack with gadget addresses and parameters


Stack
return address 3
value2
value1
return address 2
SP
return address 1
Register
RSI
RDI
Program code
asm instruction
ret
...
pop rsi
pop rdi
ret
...
syscall
ret
...
Gadget 1
Gadget 2
Gadget 3


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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value1
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return address 2
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Program code
IP →
asm instruction
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...
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pop rdi
ret
...
syscall
ret
...
Gadget 1
Gadget 2
Gadget 3
Register
RSI
RDI

Return-oriented programming

Stack

	return address 3
	value2
SP →	value1
	return address 2
	return address 1

Program code

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

Register

RSI	
RDI	

Return-oriented programming

Stack

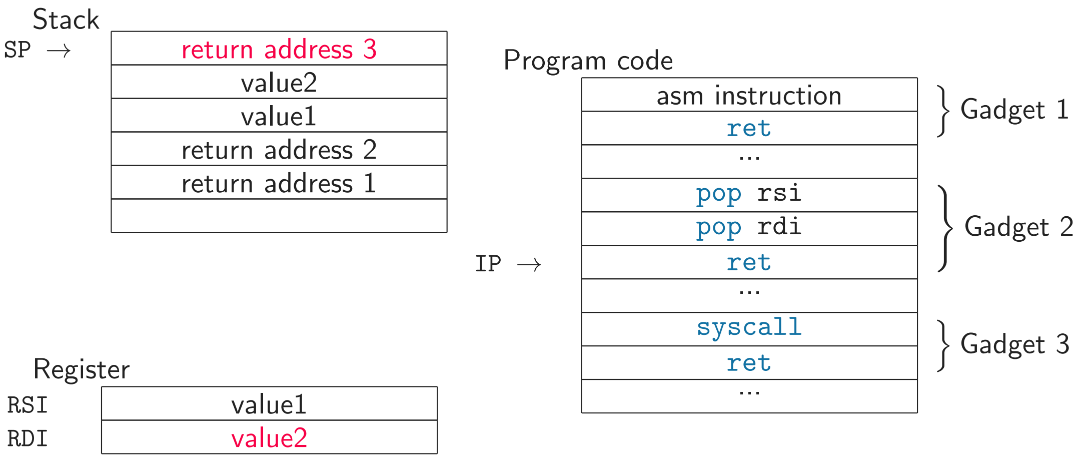
	return address 3
SP →	value2
	value1
	return address 2
	return address 1

Program code

	asm instruction	Gadget 1
	`ret`	
	…	
	`pop rsi`	Gadget 2
IP →	`pop rdi`	
	`ret`	
	…	
	`syscall`	Gadget 3
	`ret`	
	…	

Register

RSI	value1
RDI	


Stack
SP →
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pop rdi
ret
...
syscall
ret
...
Gadget 1
Gadget 2
Gadget 3
IP →
Register
RSI
value1
RDI
value2

Return-oriented programming

Stack

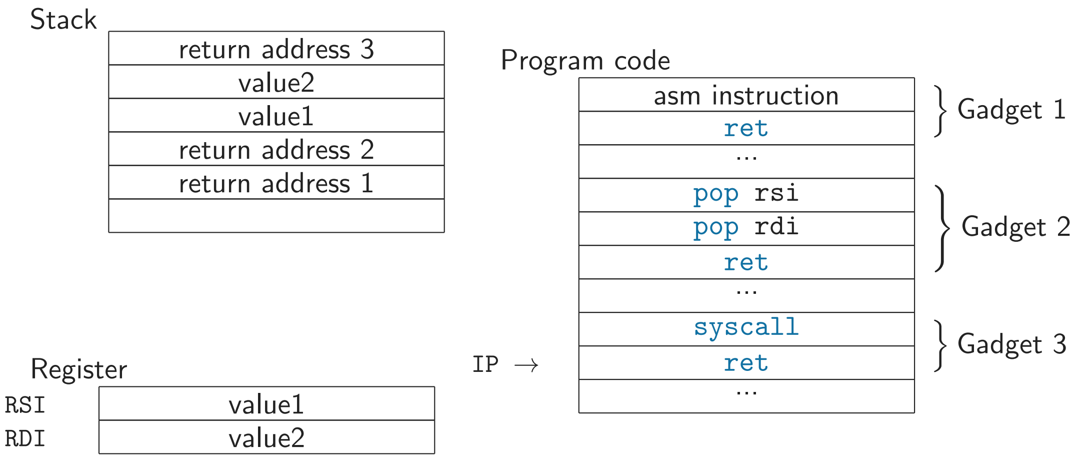
return address 3
value2
value1
return address 2
return address 1

Register

RSI	value1
RDI	value2

Program code

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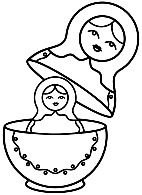
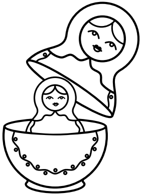
IP →



Gadgets are often unintended

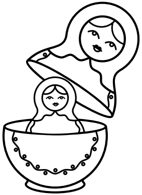
- Consider the byte sequence `05 5a 5e 5f c3`



Gadgets are often unintended

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

```
add eax, 0xc35f5e5a
```



Gadgets are often unintended

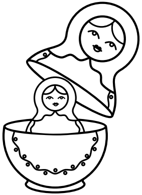
- Consider the byte sequence `05 5a 5e 5f c3`
- It disassembles to

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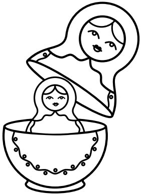
- However, if we skip the first byte, it disassembles to

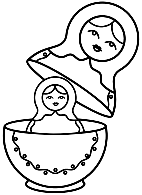
```
pop rdx
pop rsi
pop rdi
ret
```

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



Syscall instruction has byte sequence `0f 05`

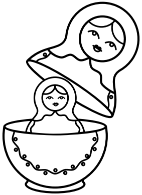
→ easy to find unaligned syscall instructions



Syscall instruction has byte sequence `0f 05`

→ easy to find unaligned syscall instructions

SFIP restricts ROP chains via



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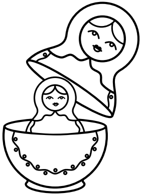
SFIP restricts ROP chains via

- syscall origins → unaligned instructions not possible



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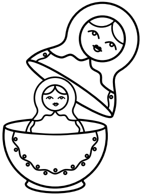
SFIP restricts ROP chains via

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



Syscall instruction has byte sequence `0f 05`

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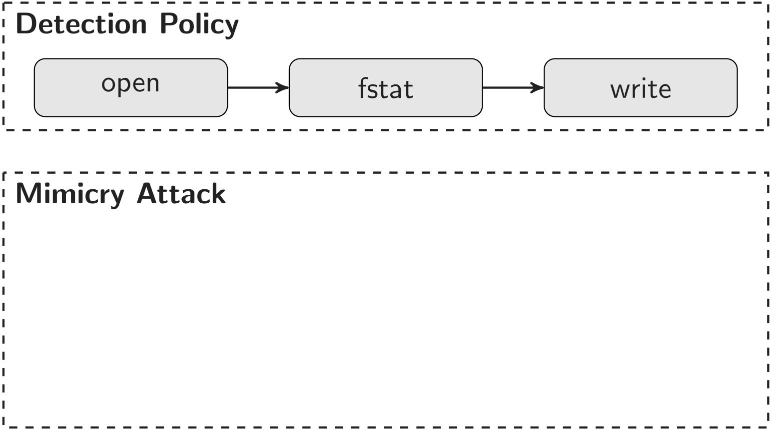
SFIP restricts ROP chains via

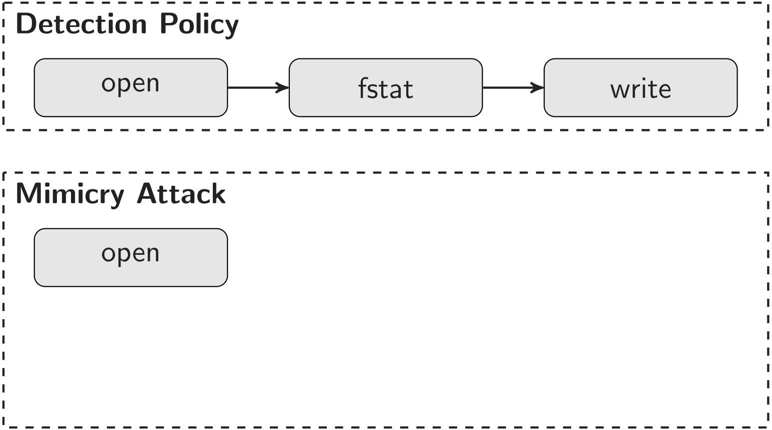
- syscall origins → unaligned instructions not possible
- syscall transitions → not every sequence is possible

Conclusion

SFIP imposes significant constraints on control-flow-hijacking attacks


Detection Policy
open
fstat
write


Detection Policy
open
fstat
write
Mimicry Attack


Detection Policy
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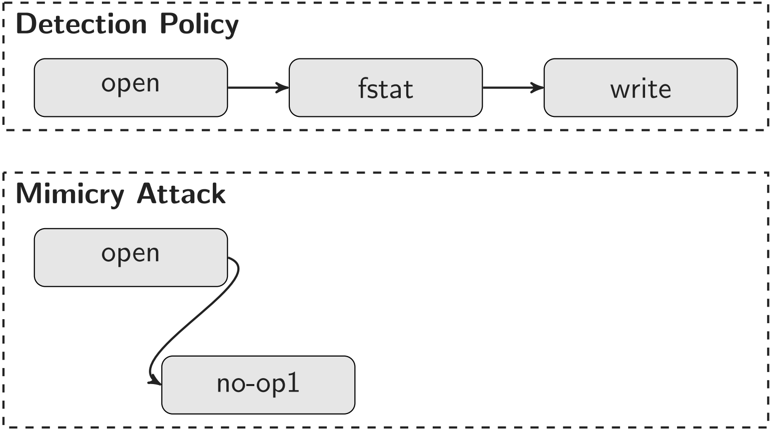
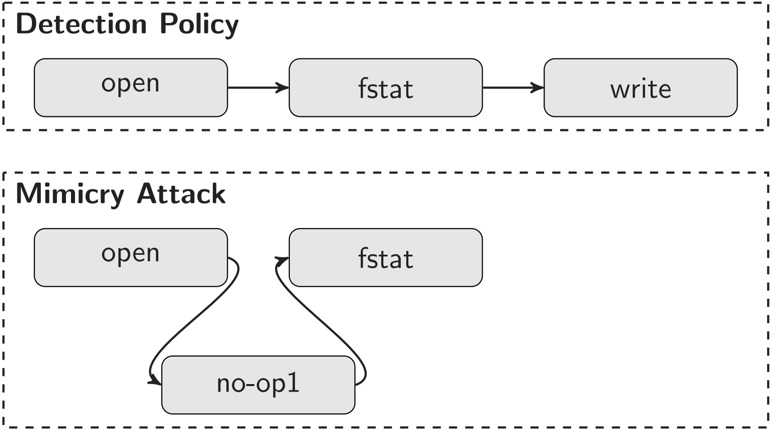

Detection Policy
open
fstat
write
Mimicry Attack
open
no-op1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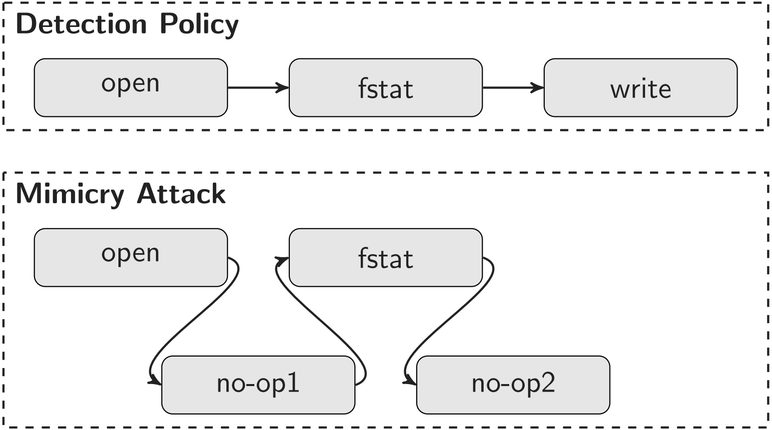
Detection Policy
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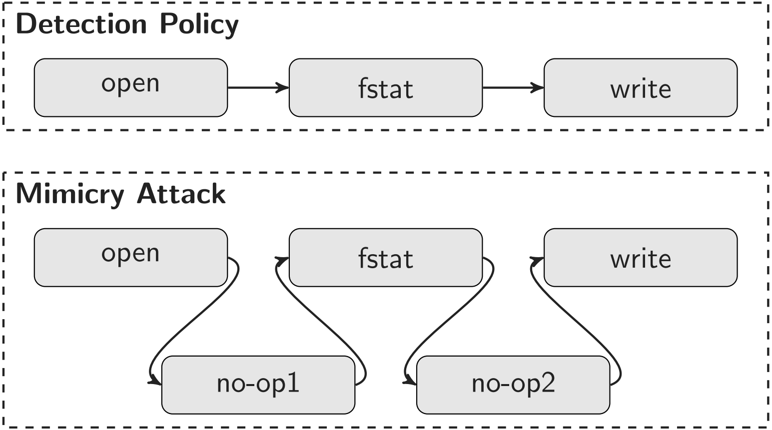

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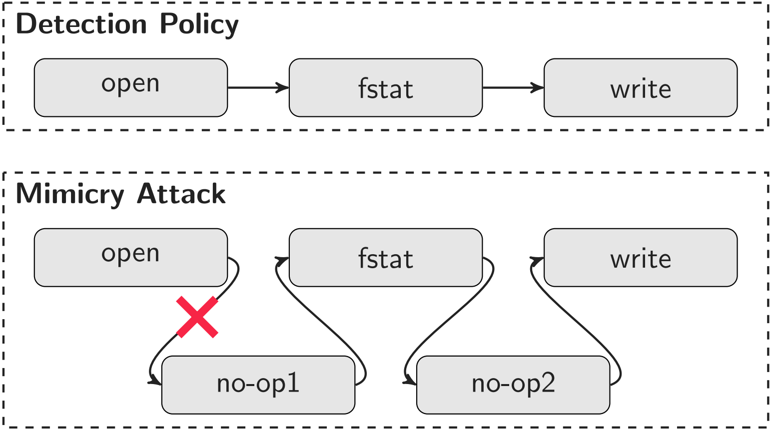
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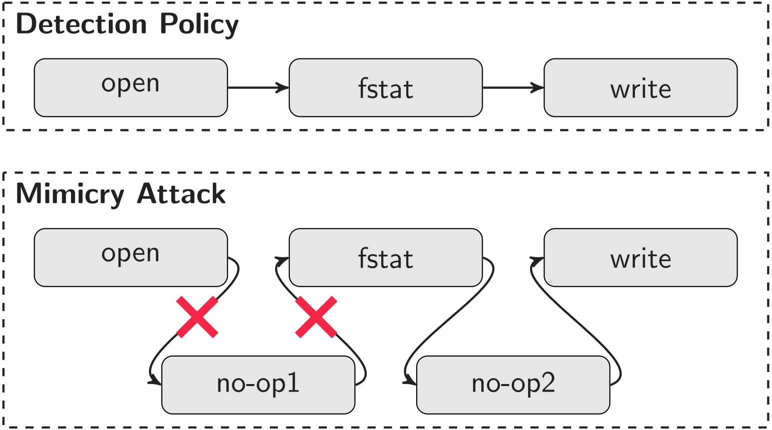
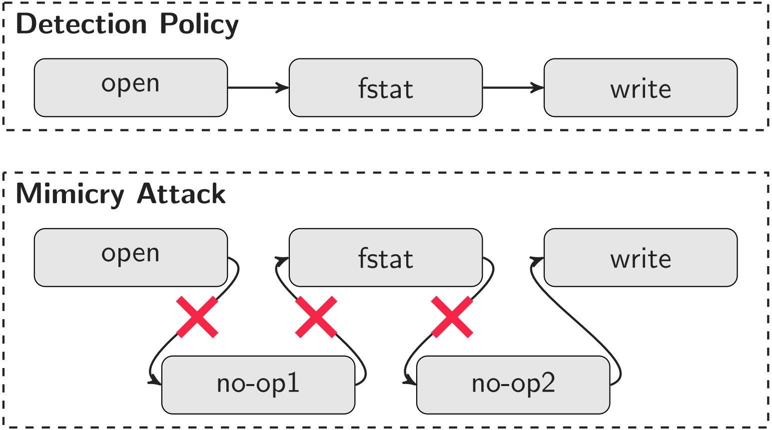
Mimicry Attacks

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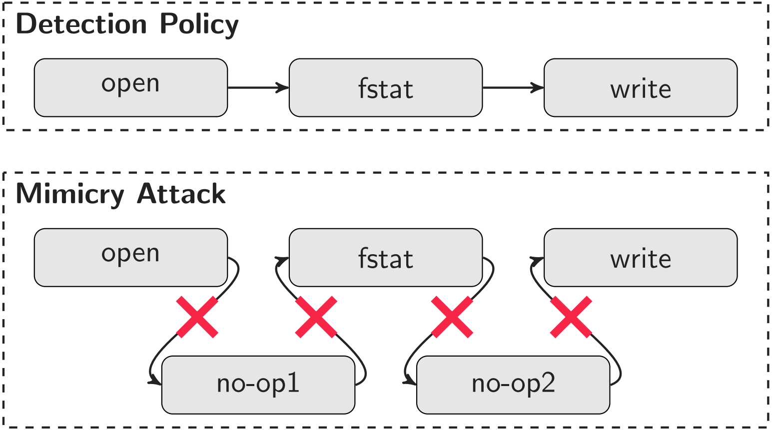

In the near future...

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]
}
```

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;
```

Coarse-grained SFIP

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

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;
```

Fine-grained SFIP

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

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.

SFIP provides

- integrity to user-kernel transitions

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

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

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

Know Where You Come From

Enforcing Program Behavior Through Syscall Sequences and Origins

Claudio Canella

May 19, 2022

Graz University of Technology

References

[Can+21] C. Canella, M. Werner, D. Gruss, and M. Schwarz. Automating Seccomp Filter Generation for Linux Applications. In: CCSW. 2021.

[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).