



ASIA 2024

APRIL 18-19, 2024

BRIEFINGS

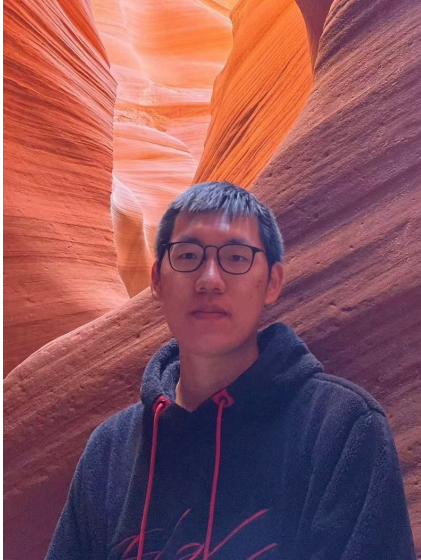
One Flip is All It Takes: Identifying Syscall-Guard Variables for Data-Only Attacks

Speaker: Hengkai Ye

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Other Contributors: Hong Hu, Song Liu, Zhechang Zhang

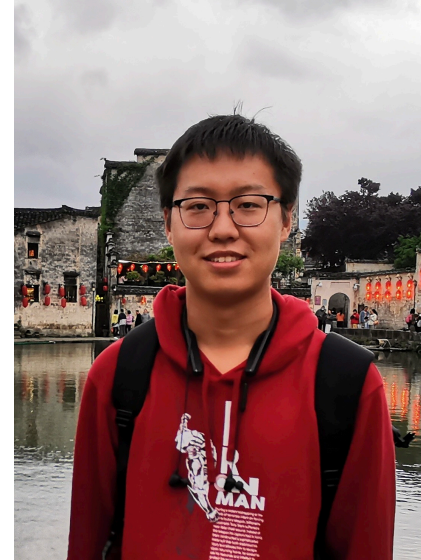
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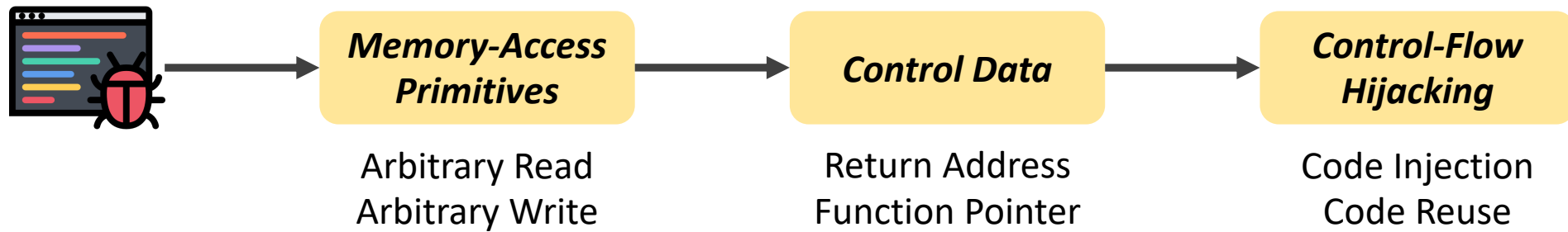


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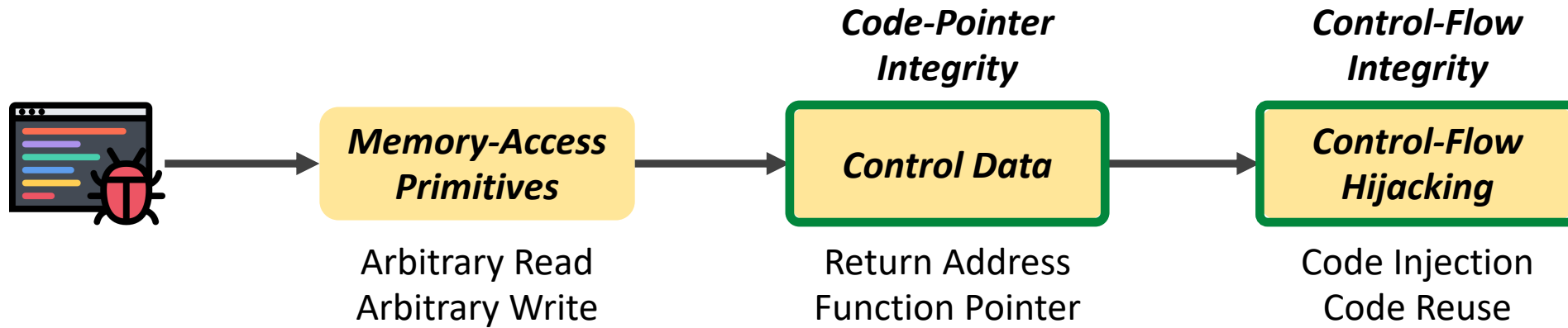


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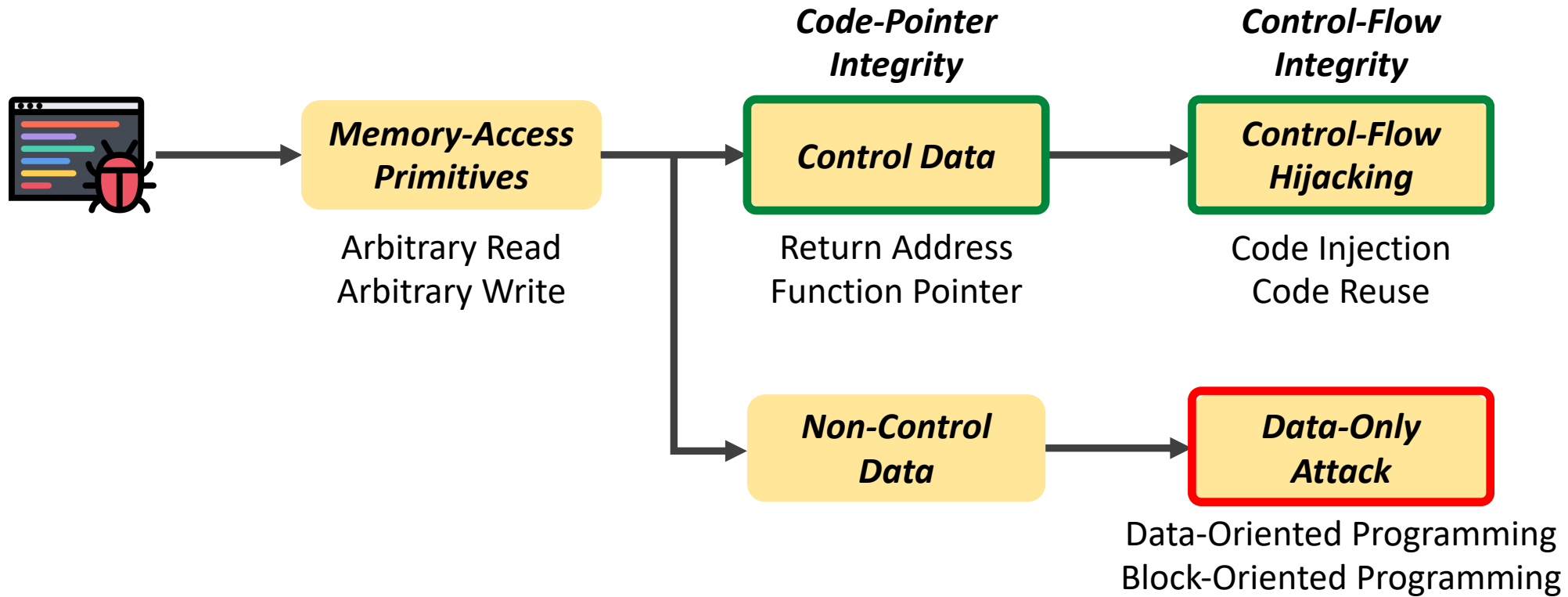
Current Exploit Method: Control-Flow Hijacking



Current Exploit Method: Control-Flow Hijacking



Next Gen Exploit Method: Data-Only Attack

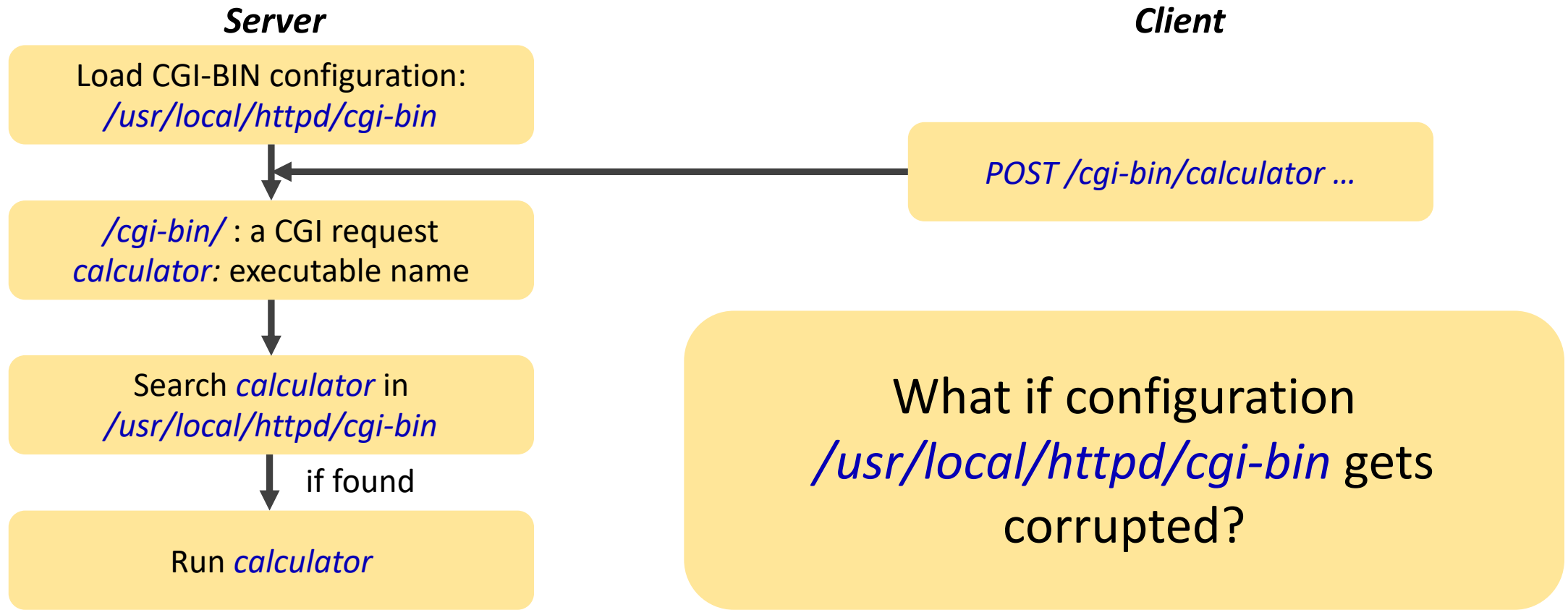




IS SUCH A THING EVEN POSSIBLE?

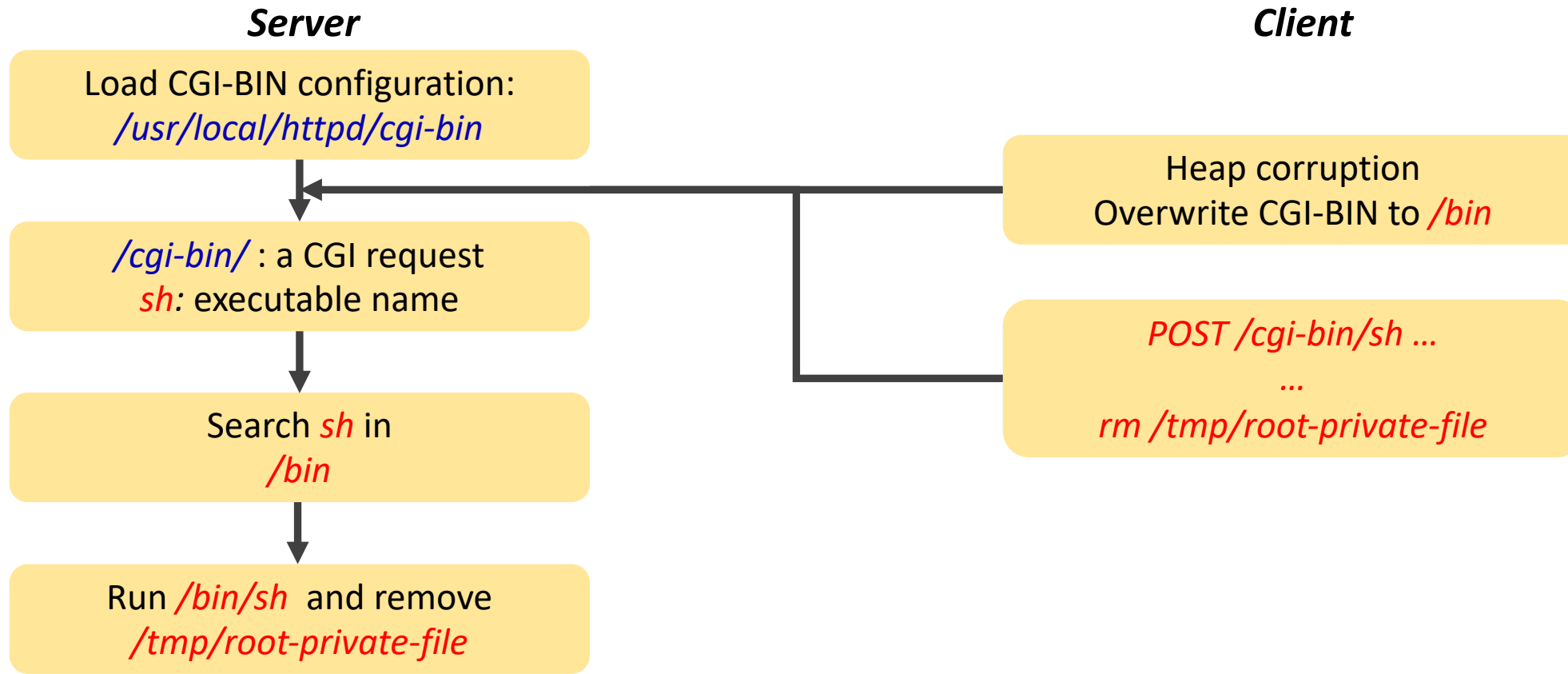
Data-Only Attack

CGI-BIN configuration string in Null Httpd



Data-Only Attack

CGI-BIN configuration string in Null Httpd



Data-Only Attack

Shuo Chen et al. at USENIX Security'05

Attack: Root privilege in WU-FTPD server

Critical Data: *seteuid(pw->pw_uid);*

Yang Yu at BlackHat USA'14

Attack: Code execution in IE browser

Critical Data:
if (safemode & 0xB == 0) { Turn_on_God_Mode(); }

Moritz Jodeit et al. at HITB GSEC'16

Attack: Bypass EMET in Windows

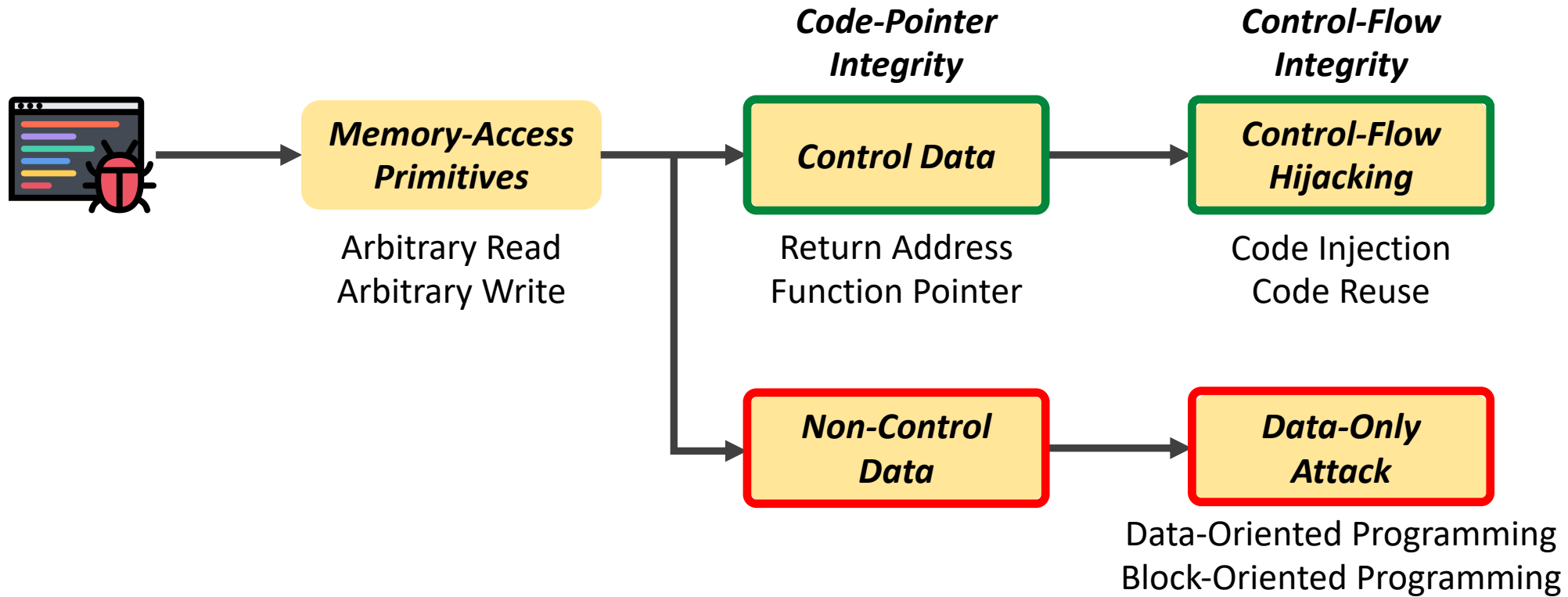
Critical Data: *EnableProtectionPtr*

Bing Sun et al. at BlackHat Asia'17

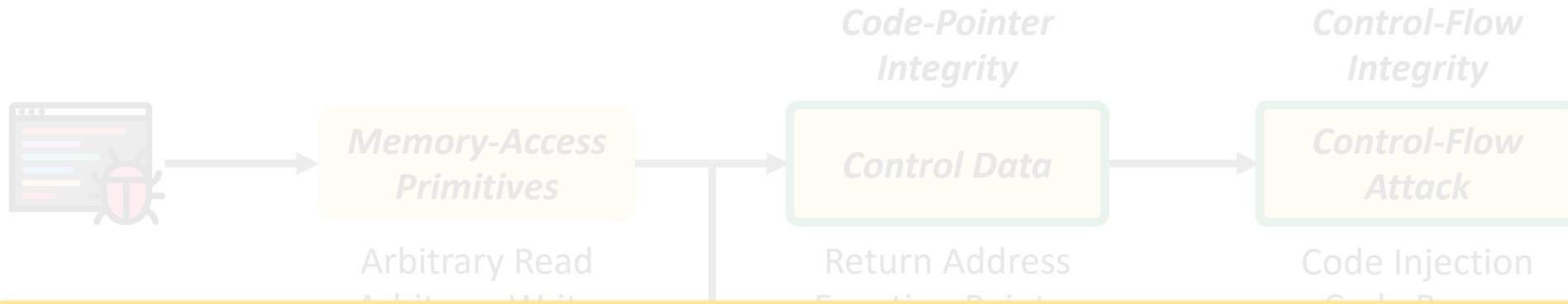
Attack: Bypass Control Flow Guard in Windows

Critical Data: *glsCFGEnabled ...*

Next Gen Exploit Method: Data-Only Attack



Next Gen Exploit Method: Data-Only Attack



***How to Automatically Identify Security-Critical Non-Control Data
(Critical Data)***

?

Data-Oriented Programming
Block-Oriented Programming

Spotting Critical Data is Challenging

Critical data

- No common low-level properties (e.g., data type, memory location)
- Difficult to infer high-level semantics

Previous work

- Manual inspection: tedious human efforts, not scalable
- FlowStitch [Security'15]: rely on explicit sources/sinks
 - e.g., argument of *setuid*
- KENALI [NDSS'16]: rely on error codes in Linux Kernel

Our Contribution

- Automatic identification of syscall-guard variables
 - Branch force
 - Corruptibility assessment
- A framework - *VIPER*
 - 34 unknown syscall-guard variables from 13 programs
 - 4 new data-only attacks on SQLite and V8
- <https://github.com/psu-security-universe/viper>



Motivating Example

How to identify “authenticated”?

```
1 void do_authentication(char *user, ...) {
2   int authenticated = 0;
3   ...
4   while (!authenticated) {
5     /* Get a packet from the client */
6     type = packet_read();
7     ...
8     if (auth_password(user, password))
9       authenticated = 1;
10    ...
11    if (authenticated) break;
12  }
13  /* Perform session preparation. */
14  do_authenticated(pw);    // open access
15 }
```

Chen, Shuo, et al. "Non-control-data attacks are realistic threats." USENIX security symposium. Vol. 5. 2005.

Motivating Example

```
1 void do_authentication(char *user, ...) {
2   int authenticated = 0;    // non-control data
3   ...
4   while (!authenticated) {
5     /* Get a packet from the client */
6     type = packet_read();   // bug -> write primitive
7     ...
8     if (auth_password(user, password))
9       authenticated = 1;
10    ...
11    if (authenticated) break;
12  }
13  /* Perform session preparation. */
14  do_authenticated(pw);     // open access
15 }
```



How to identify “authenticated”?

Most data-only attacks rely on **security-related syscalls**

Security-related syscalls are often guarded by security checks

Syscall-Guard Branch: security checks as conditional branches

Syscall-Guard Variable: variables in syscall-guard branches

VIPER: identify syscall-guard variables

Chen, Shuo, et al. "Non-control-data attacks are realistic threats." USENIX security symposium. Vol. 5. 2005.

Does Syscall-Guard Variable Matter?

Program	Critical Data	Security Impact
nginx ↗	clcf->root.data ctx	access any server file execute arbitrary program
openssh ↗	authenticated original_uid	login w/ wrong password obtain root-user privilege
sudo ↗	user_details.uid	obtain root-user privilege
null httpd ↗	config.server_cgi_dir config.server_htdocs_dir	execute arbitrary program access any server file
ghttpd ↗	ptr	execute arbitrary program
orzhttpd ↗	conn->basedir.path	access any server file
wu-ftpd ↗	pw->pw_uid	obtain root-user privilege
telnet ↗	loginprg	execute arbitrary program
chromium ↗	m_universalAccess	disable same-origin check
httpdx ↗	ftps.i["admin"].pass ftps.i["anon"].flags ftps.i["anon"].root handlers[cgi].cmd	admin login w/o password can delete file or directory access any file on the server execute arbitrary program
IE Browser	safemode	execute arbitrary code

11 syscall arguments

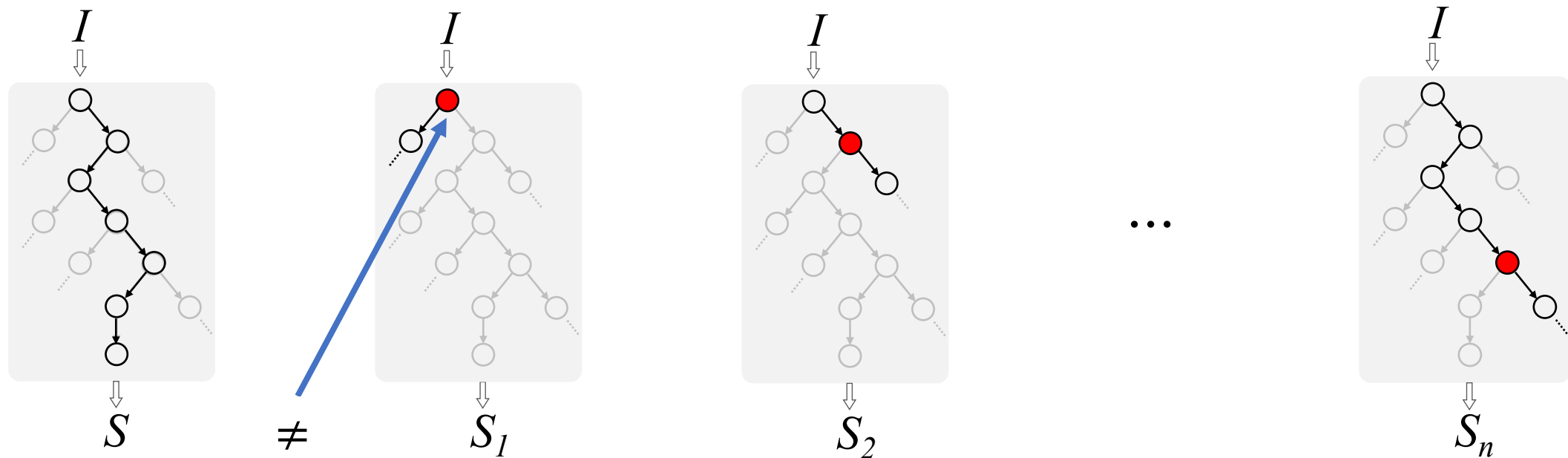
6 syscall-guard variables

Challenges

- Identify *sole* contribution of each variable
 - Symbolic execution can identify a complete path
 - Limitation: cannot tell which variables are more critical
- Efficient and scalable analysis
 - Static analysis
 - Limitations: indirect calls, inter-procedural analysis, etc

Branch Force: Identify Syscall-Guard Branches

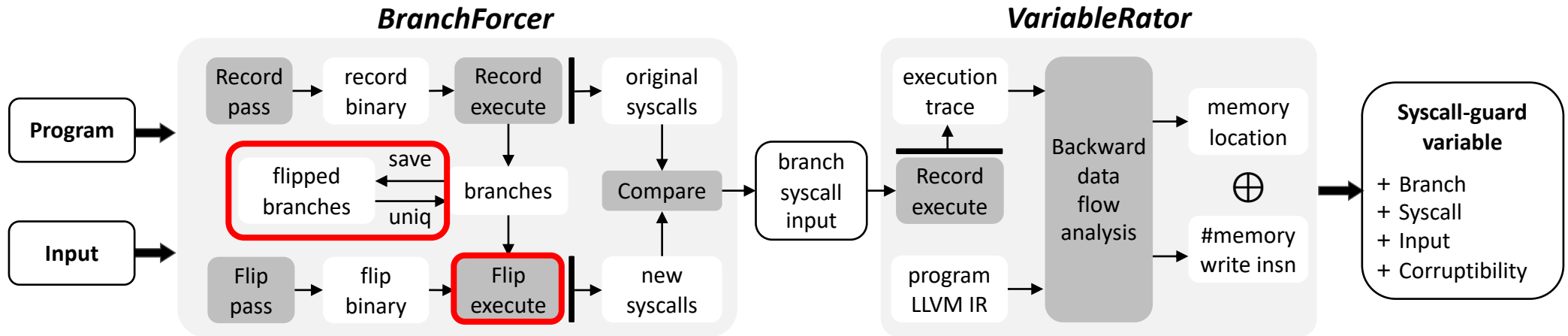
- Flip every branch during execution
- Hook syscalls to find newly invoked ones
- If yes, the flipped is a syscall-guard branch



Corruptibility Assessment

- Backward Data-Flow Analysis
 - Generate data flow of syscall-guard variables
- Assessment (for each memory node in the data flow)
 - Metric 1: memory location
 - ***Global > Heap > Stack***
 - Metric 2: number of memory-write instructions
 - Assumption: every memory-write could be abused

Workflow of VIPER



- Unique Branch Flipping
- Forkserver

- Record execution trace on LLVM IR level
- Simulate execution based on recorded trace

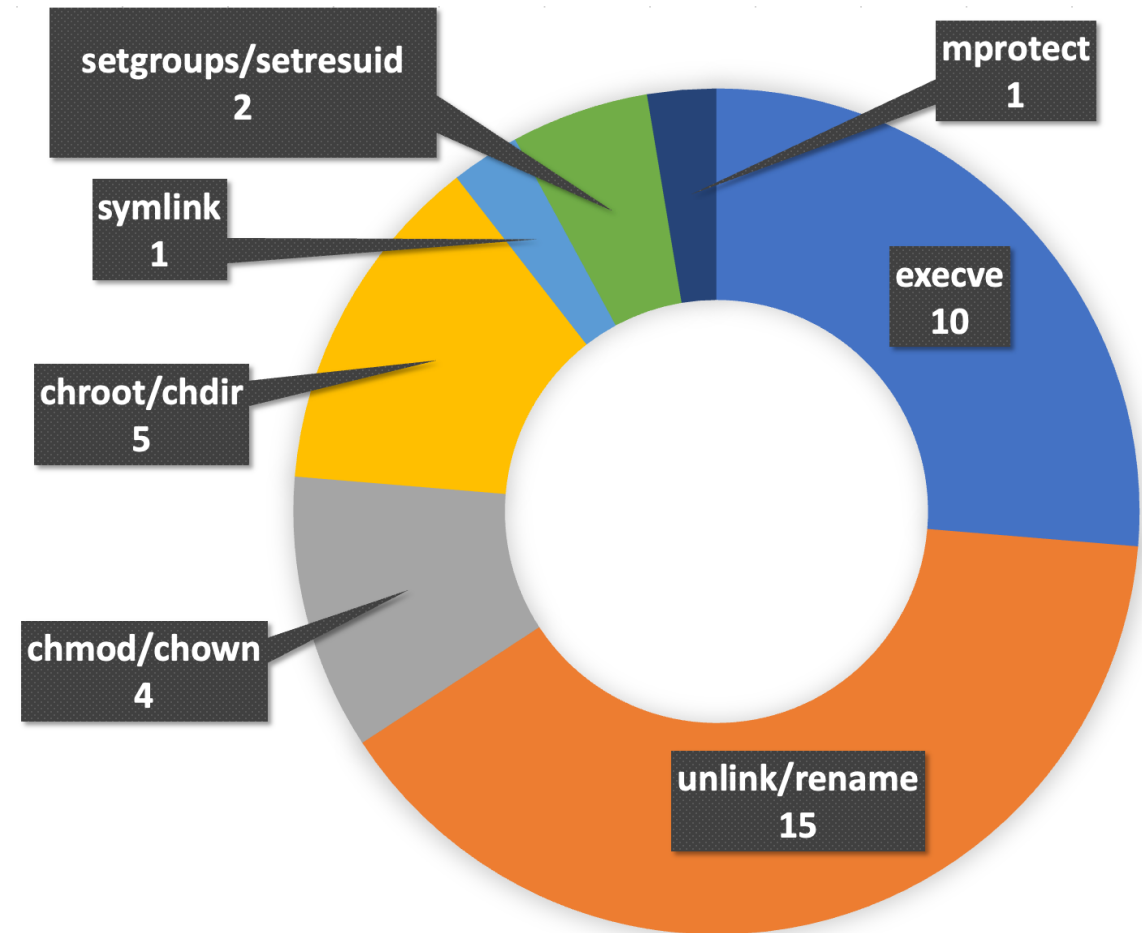
Evaluation (setting)

- 20 programs for evaluation
 - 9 programs with known data-only attacks (e.g., OpenSSH)
 - 7 programs from FuzzBench (e.g., SQLite)
 - 4 other well-tested programs (e.g., V8)
- Corpus
 - Testcases in source code repository
 - Online corpus (e.g., FuzzBench Dataset)
 - Fuzz with AFL++

Evaluation (identified syscall-guard variables)

Program	Guard Variable	Branch Location	Syscall	Malicious Goal
sqlite	mode	shell.c:5002	symlink	create symlinks to any file
		shell.c:5038	chmod	change any file to any mode
	p->doXdgOpen	shell.c:20270	execve	execute arbitrary program
	p->zTempFile	shell.c:20560	unlink	delete any file
	isDelete	sqlite3.c:42939	unlink	delete any file
	zPath	sqlite3.c:43094	unlink	delete any file
	exists	sqlite3.c:60294	unlink	delete any file
	isWal	sqlite3.c:58492	unlink	delete any file
curl	tempstore	cookie.c:1732	rename	overwrite any file
	tempstore	hsts.c:386	rename	overwrite any file
	tempstore	altsvc.c:359	rename	overwrite any file
harfbuzz	blob->mode	hb-blob.cc:453	mprotect	make RO memory writable
nginx	sa_family	\$_connection.c:631	chmod	change file mode
	ngx_terminate	\$_process_cycle.c:305	unlink	delete any file
	ngx_quit	\$_process_cycle.c:305	unlink	delete any file
	ft.st_uid	(\$: ngx) \$_file.c:631	chown	change owner of any file
	ft.st_mode	\$_file.c:640	chmod	change file mode
openssh	result*	auth-passwd.c:128	execve	login without password
	received_sigterm	sshd.c:1163	unlink	delete any file
	received_sighup	sshd.c:1177	execve	execute arbitrary program
sudo	details->chroot	exec.c:173	chroot	change root path
	info	sudo.c:697	chdir	change directory path
null httpd	in_RequestURI	main.c:39	execve	enable CGI to run programs
ghttpd	filename*	protocol.c:127	execve	enable CGI to run programs
wu-ftpd	RootDirectory	ftpd.c:1029	chroot	change root path of current user
	anonymous	ftpd.c:2527	setgroups	obtain root privilege
		ftpd.c:2893	chroot	change root path of anonymous
	guest	ftpd.c:2893	chroot	change root path of guest
	rval	ftpd.c:2708	setresuid	login without password
jhead	RegenThumbnail	jhead.c:978	execve	execute arbitrary program
	EditComment	jhead.c:1003	execve	edit any file using vi
	CommentInsertfileName	jhead.c:1003	execve	edit any file using vi
	CommentInsertLiteral	jhead.c:1003	execve	edit any file using vi
jasper	fileobj->flags	jas_stream.c:1392	unlink	delete any file
pdfalto	first	XRef.cc:240	unlink	delete files in specific folders
	offsets[0]	XRef.cc:240	unlink	delete files in specific folders
gzip	fd	gzip.c:2111	unlink	delete any file
v8	enable_os_system	d8-posix.cc:762	execve	execute any program

36 syscall-guard variables from 14 programs



Evaluation (exploitability investigation)

Program	Guard Variable	Branch Location	Rate (S, H, G)	CK	CVE	Type	Cap
sqlite	mode	shell.c:5002	(55, 0, 0)	🟡			
		shell.c:5038	(75, 0, 0)	🟡			
	p->doXdgOpen	shell.c:20270	(181770, 0, 0)	🟢	2017-6983	TC	AW
	p->zTempFile	shell.c:20560	(86907, 0, 0)	🟢	2017-6983	TC	AW
	isDelete	sqlite3.c:42939	(8353, 29276, 0)	🟢	2017-6983	TC	AW
	zPath	sqlite3.c:43094	(57, 15036, 0)	🟡			
	exists	sqlite3.c:60294	(58, 15036, 0)	🟡			
	isWal	sqlite3.c:58492	(61, 15046, 0)	🟡			
curl	tempstore	cookie.c:1732	(15, 0, 0)	🟢	2019-3822	H/SBoF	AW
	tempstore	hsts.c:386	(15, 0, 0)	🟢	2019-3822	H/SBoF	AW
	tempstore	altsvc.c:359	(15, 0, 0)	🟢	2019-3822	H/SBoF	AW
harfbuzz	blob->mode	hb-blob.cc:453	(31, 352, 0)	🟢	2015-8947	HBoF	AW
nginx	sa_family	\$_connection.c:631	(0, 84831, 0)	🟡			
	ngx_terminate	\$_process_cycle.c:305	(0, 0, 208640)	🟢	2013-2028	SBoF	AW
	ngx_quit	\$_process_cycle.c:305	(0, 0, 208640)	🟢	2013-2028	SBoF	AW
	ft.st_uid	(\$: ngx) \$_file.c:631	(350832, 0, 0)	🟡			
	ft.st_mode	\$_file.c:640	(175218, 0, 0)	🟡			
openssh	result*	auth-passwd.c:128	(5, 48153980, 0)	🟡			
	received_sigterm	sshd.c:1163	(0, 0, 1463147)	🟡			
	received_sighup	sshd.c:1177	(0, 0, 1470603)	🟡			
sudo	details->chroot	exec.c:173	(0, 0, 2039)	🟢	2012-0809	FS	AW
	info	sudo.c:697	(1702, 253382, 1982)	🟢	2012-0809	FS	AW
null httpd	in_RequestURI	main.c:39	(0, 525, 0)	🟢	2002-1496	HBoF	AW
ghttpd	filename*	protocol.c:127	(9, 0, 5912)	🟢	2002-1904	SBoF	AW
wu-ftpd	RootDirectory	ftpd.c:1029	(0, 0, 7322)	🟡			
		anonymous	ftpd.c:2527	(0, 0, 7432)	🟡		
		ftpd.c:2893	(0, 0, 8341)	🟡			
	guest	ftpd.c:2893	(0, 0, 37715)	🟡			
	rval	ftpd.c:2708	(8, 0, 0)	🟡			
jhead	RegenThumbnail	jhead.c:978	(0, 0, 2856)	🟢	2016-3822	IO	AW
	EditComment	jhead.c:1003	(0, 0, 2856)	🟢	2016-3822	IO	AW
	CommentInsertfileName	jhead.c:1003	(0, 0, 2856)	🟢	2016-3822	IO	AW
	CommentInsertLiteral	jhead.c:1003	(0, 0, 2856)	🟢	2016-3822	IO	AW
jasper	fileobj->flags	jas_stream.c:1392	(0, 219062, 0)	🟢	2020-27828	HBoF	AW
pdfalto	first	XRef.cc:240	(1952, 214, 0)	🟡			
	offsets[0]	XRef.cc:240	(92, 117, 0)	🟡			
gzip	fd	gzip.c:2111	(0, 0, 11886)	🟢	2010-0001	IO	AW
v8	enable_os_system	d8-posix.cc:762	(0, 0, 93512607)	🟢	2021-30632	TC	AW

Exploit Construction

4

CVE Investigation

16

GDB Emulation

36

Evaluation (time costs)

Program	Version	kLoC	Time Cost					Stitch
			Record	Flip	Rate	Total	Total/A	
sqlite	3.40.1	273	288"	112"	378"	778"	87"	
curl	97f7f66	160	23"	32"	689"	744"	248"	
harfbuzz	1.3.2	41	17"	8"	8"	33"	33"	
systemd	v252	543	69"	40"	-	>109"	>109"	
mbedtls	10ada35	128	2"	6"	-	>8"	>8"	
openssl	3.0.7	483	13"	61"	-	>74"	>74"	
freetype2	cd02d35	119	18"	26"	-	>44"	>44"	
nginx	1.20.2	141	238"	22"	329"	589"	118"	121"
openssh	36b00d3	119	1"	4722"	10624"	15347"	5116"	1110"
sudo	1.9.9	110	16"	16"	260"	292"	18"	393"
null httpd	0.5.1	2	1"	10"	31"	42"	42"	358"
ghttpd	1.4.4	1	1"	36"	72"	109"	55"	48"
orzhttpd	0.0.6	3	1"	32"	-	>33"	>33"	93"
wu-ftp	2.6.2	18	1"	533"	189"	723"	91"	200"
telnet	3f35287	11	1"	144"	-	>145"	>145"	
jhead	3.04	4	1"	2"	288"	291"	25"	
jasper	4.0.0	34	37"	16"	84"	137"	137"	
pdfalto	0.4	76	342"	116"	107"	565"	282"	
gzip	1.12	6	6"	1"	19"	26"	26"	
v8	8.5.188	3,586	1"	5833"	874"	6708"	6708"	

We can combine VIPER
with other tools for
automatic exploit generation

Case Study: Attacks on SQLite

SQLite: Most widely deployed database engine

- Used in Android, iOS, Chrome, Safari, Opera ...

VIPER result

- 7 syscall-guard variables
- 3 new data-only attacks on top 3 syscall-guard variables
 - (demo 1) p->doXdgOpen: arbitrary command execution
 - (demo 2) p->zTempFile: arbitrary file deletion
 - isDelete: arbitrary file deletion

Case Study 1: Command Execution on SQLite

How SQLite handles query results

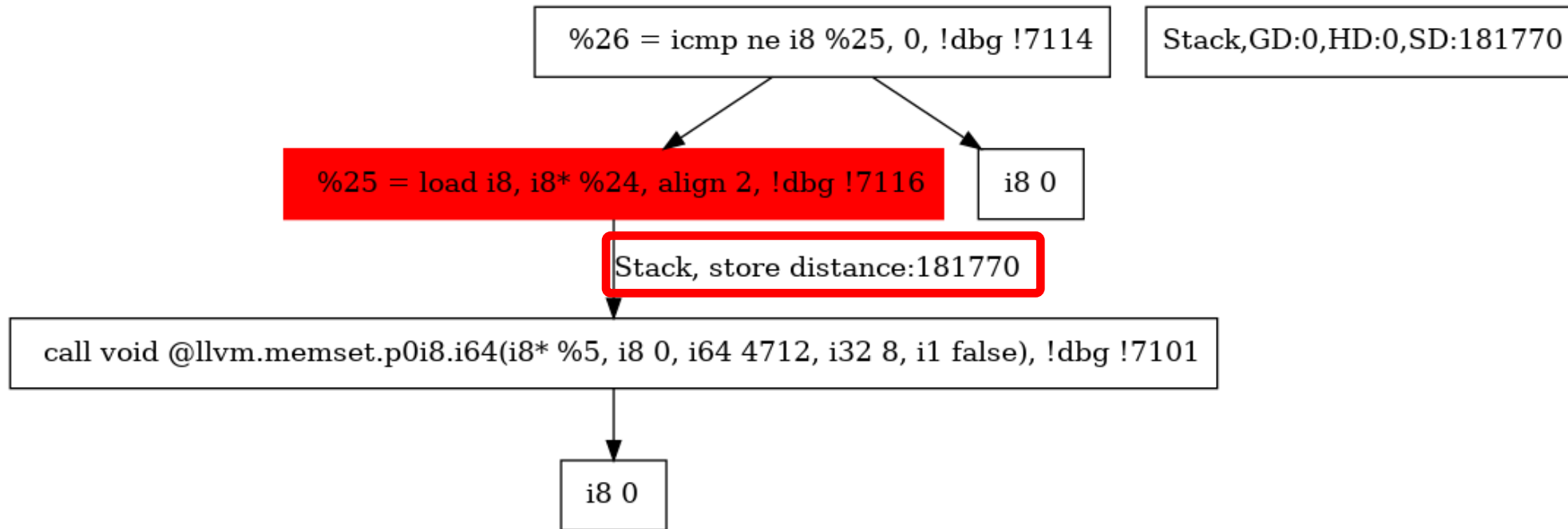
- Print on stdout
- Save to a file (.output filename)
- **Edit before saving (.once -e / .once -x)**

```
void output_reset(ShellState *p) {  
    if (p->doXdgOpen) {  
        char *zCmd = mprintf("xdg-open %s",  
                             p->zTempFile);  
        system(zCmd);      // invoke execve  
    } ... }  
}
```

How VIPER identified p->doXdgOpen

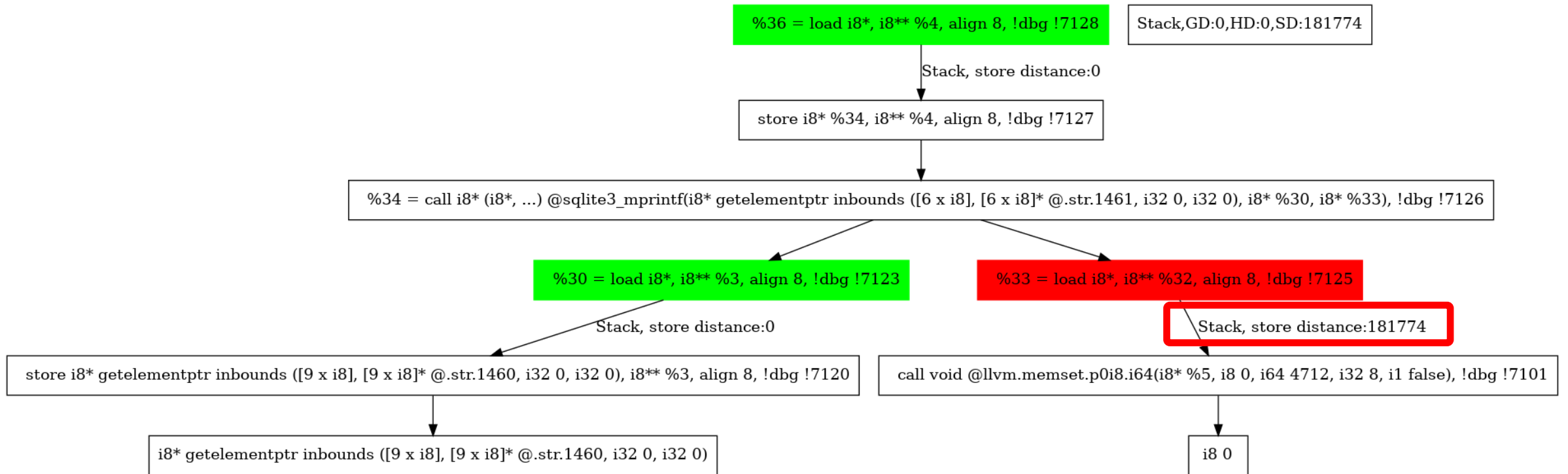
- BranchForce flips *if (p->doXdgOpen)* and catches *execve*
- VariableRator generates data flow graph for p->doXdgOpen and p->zTempFile

Case Study 1: Command Execution on SQLite



Data-flow Graph of p->doXdgOpen

Case Study 1: Command Execution on SQLite



Data-flow Graph of p->zTempFile

Case Study 1: Command Execution on SQLite

One memory bug to corrupt p->doXdgOpen and p->zTempFile

- CVE 2017-6983 ([Kun Yang at BlackHat USA'17](#))
 - Arbitrary write primitive
 - Bypass ASLR is feasible

Demo 1

```
hfy5130 in 🌐 I4-GL-HQH5357-4 in sqlite (1fdaa9d) [!?] via C v10.0.0-4ubuntu1-clang via 🐍 v2  
.7.18  
> □
```

Case Study 2: File Deletion on SQLite

zTempFile is also used in other places

```
void clearTempFile(ShellState *p){
    if (p->zTempFile == 0) return;
    // shellDeleteFile invokes unlink
    if (shellDeleteFile(p->zTempFile))
        return;
}
```

- Flip *if (p->zTempFile == 0)* and *catches* unlink
- Both syscall-guard variable and syscall argument are zTempFile
- One shot exploit

Demo 2

```
hfy5130 in 🌐 I4-GL-HQH5357-4 in sqlite (1fdaa9d) [!?] via C v10.0.0-4ubuntu1-clang via 🐍 v2  
.7.18  
> 
```

Case Study 3: New Attack on V8

V8: Chromium JavaScript engine

- Used in Google Chrome, Microsoft Edge, Opera, Node.js ...
- 3,586 KLoC in the latest version

VIPER result

- 2 potential syscall-guard variables
- 1 highly corruptible variable
 - Location: global variable
 - Memory-Write instructions: 93,512,607

Case Study 3: New Attack on V8

```
1 void Shell::AddOSMethods(Isolate* isolate,  
2                           Local<ObjectTemplate> os_tmpl) {  
3   if (options.enable_os_system) {  
4     os_tmpl->Set(isolate, "system",  
5       FunctionTemplate::New(isolate, System));  
6   } ...  
7 }
```

Our Attack (CVE-2021-30632)

- Arbitrary read privilege
 - Bypass ASLR
- Arbitrary write privilege
 - Set `options.enable_os_system` to 1

Demo



Conclusion

- *VIPER*: automatically spotting syscall-guard variables for data-only attacks
 - Design branch force and corruptibility assessment
 - Find 34 previous unknown syscall-guard variables
 - Build 4 new data-only attacks on SQLite and V8
- Open Source
 - VIPER: <https://github.com/psu-security-universe/viper>
 - Exploits: <https://github.com/psu-security-universe/data-only-attacks>

Thank You

Question?

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