CSC 405
Computer Security

Control-Flow Integrity

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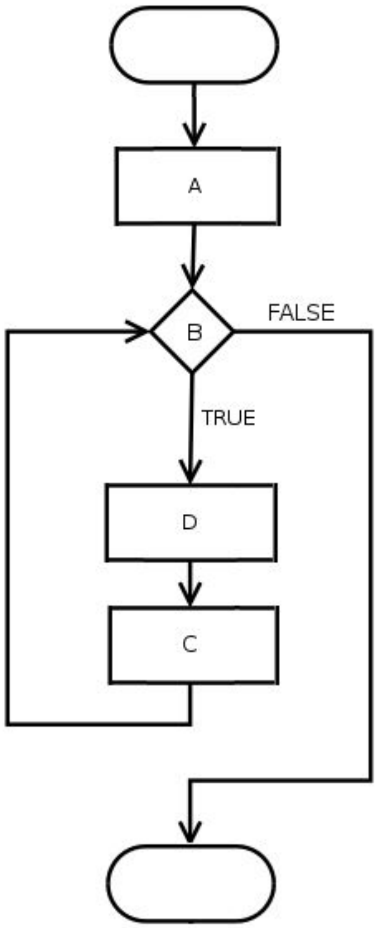
ROP & return-to-libc reuse existing code instead of injecting malicious code. How can we stop this?

Program control flow

- Unconditional jumps
- Conditional jumps
- Loops
- Subroutines
- Unconditional halt

```
for(A;B;C)
  D;
```



vuln.c

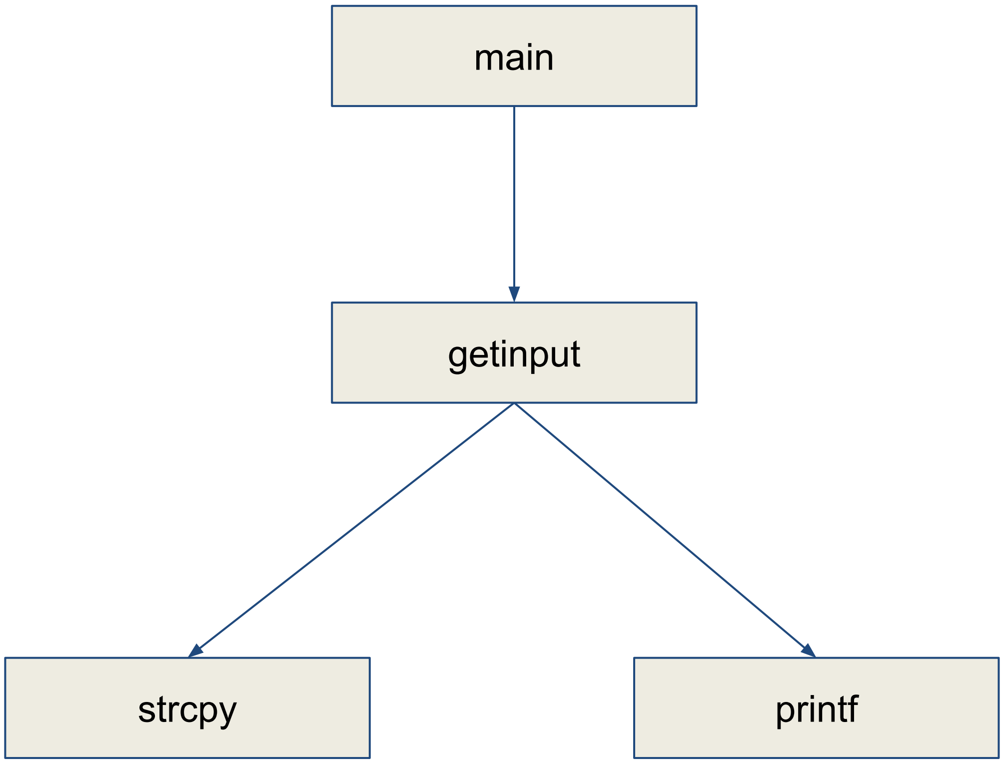
```
#include <stdio.h>
#include <string.h>

void getinput(char *input) {
    char buffer[32];

    strcpy(buffer, input);
    printf("You entered: %s\n", buffer);
}

int main(int argc, char **argv) {
    getinput(argv[1]);
    return(0);
}
```

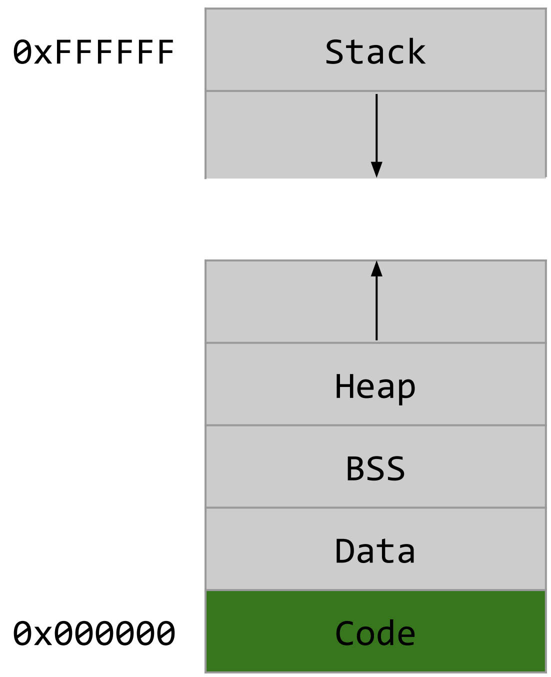
Simple call graph

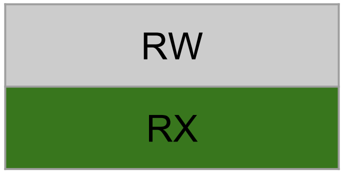


Functions locations

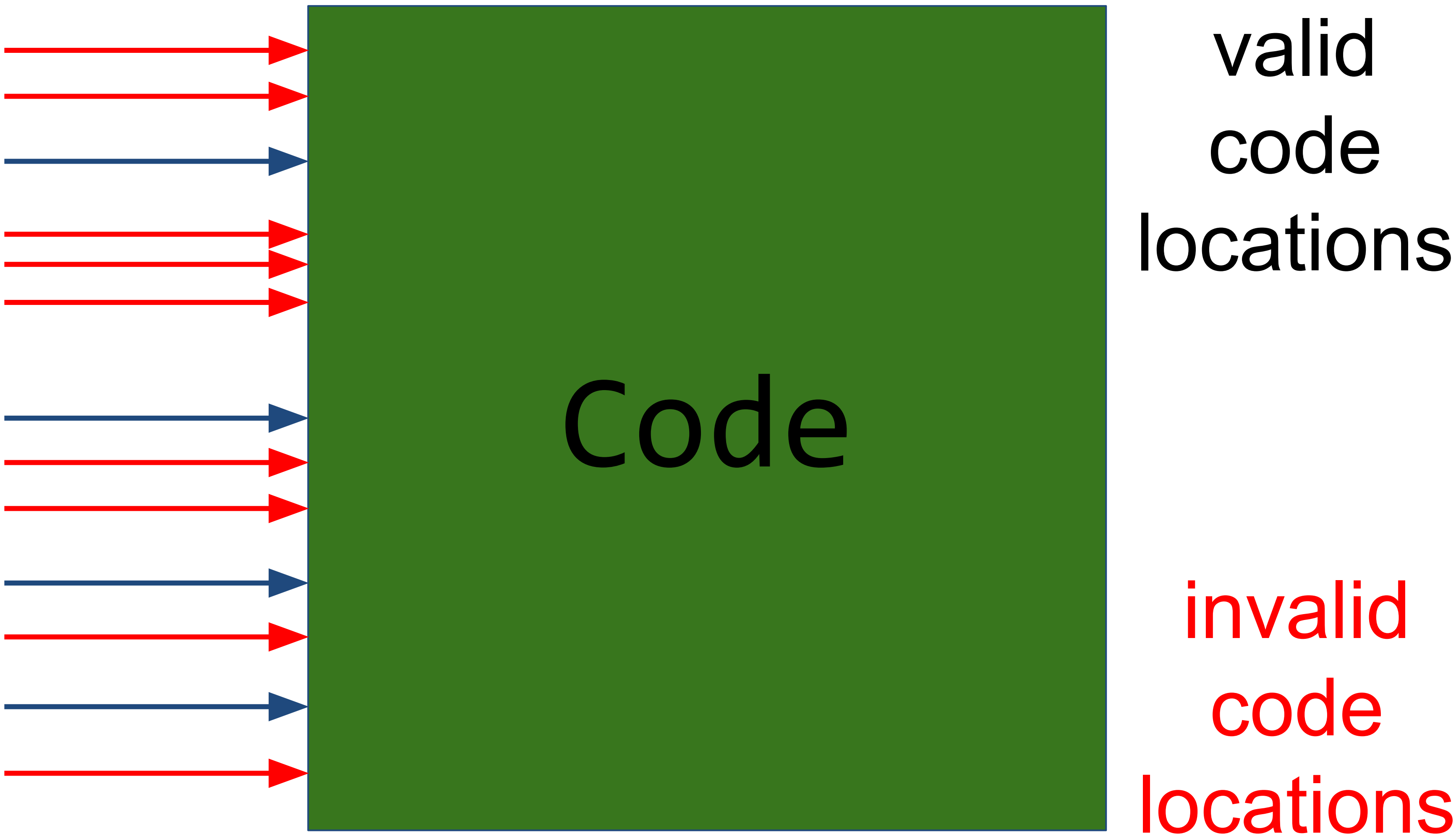
```
$ gcc vuln.c -o vuln
$ radare2 -A ./vuln
[0x004004e0]> afl
0x004004e0 42   1   sym._start
0x004004c0 6    1   sym.imp.__libc_start_main
0x00400631 41   1   sym.main
0x004005d6 91   3   sym.getinput
0x00400490 6    1   sym.imp.strcpy
0x004004b0 6    1   sym.imp.printf
0x004004a0 6    1   sym.imp.__stack_chk_fail
[0x004004e0]>
```

NOEXEC (W^X)





NOEXEC (W^X)



Fundamental problem with this execution model?

Code is not executed in the intended way!

How can we make sure that the program is executed in the intended way?
Control-Flow Integrity (CFI)

Control-flow integrity

- CFI is a security policy
- Execution must follow a path of a Control-Flow Graph
- CFG can be pre-computed
  - source-code analysis
  - binary analysis
  - execution profiling

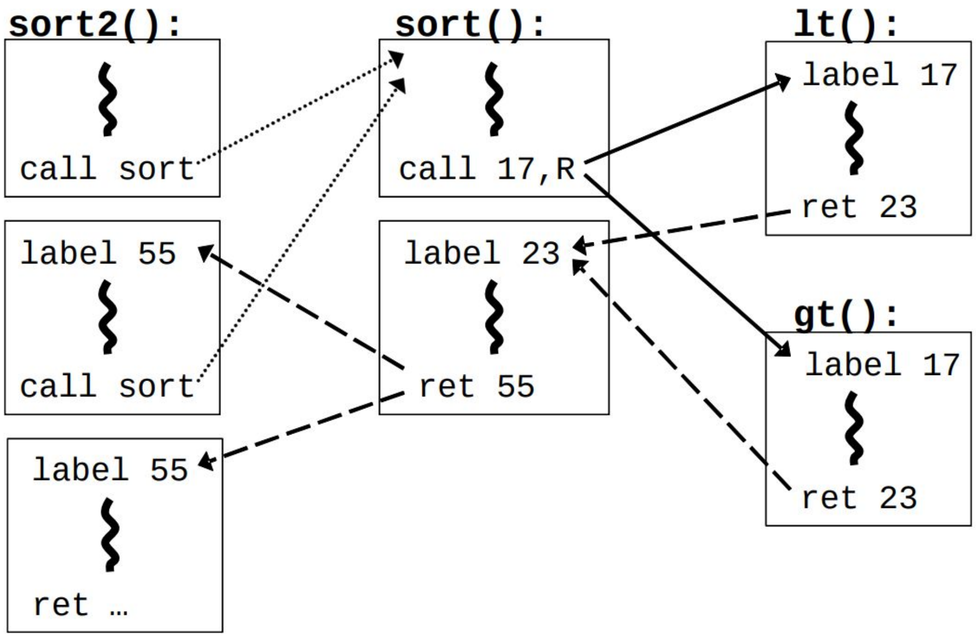
- But how can we enforce this extracted control-flow?

Enforcing CFI by Instrumentation

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



- LABEL ID
- CALL ID, DST
- RET ID

source: Control-Flow Integrity (link)

CFI Instrumentation Code

Source / **Destination**

```
Source                                                               Destination
Opcode bytes          Instructions                                   Opcode bytes   Instructions
FF E1                 jmp  ecx                ; computed jump        8B 44 24 04    mov  eax, [esp+4]   ; dst
                                                                     ...

                              can be instrumented as (a):

81 39 78 56 34 12     cmp  [ecx], 12345678h   ; comp ID & dst        78 56 34 12    ; data 12345678h    ; ID
75 13                 jne  error_label        ; if != fail           8B 44 24 04    mov  eax, [esp+4]   ; dst
8D 49 04              lea  ecx, [ecx+4]       ; skip ID at dst       ...
FF E1                 jmp  ecx                ; jump to dst

                         or, alternatively, instrumented as (b):

B8 77 56 34 12        mov  eax, 12345677h     ; load ID-1            3E 0F 18 05    prefetchnta         ; label
40                    inc  eax                ; add 1 for ID         78 56 34 12       [12345678h]      ;    ID
39 41 04              cmp  [ecx+4], eax       ; compare w/dst        8B 44 24 04    mov  eax, [esp+4]   ; dst
75 13                 jne  error_label        ; if != fail           ...
FF E1                 jmp  ecx                ; jump to label
```

- The extra code checks that the destination code is the intended jump location

source: Control-Flow Integrity (link)

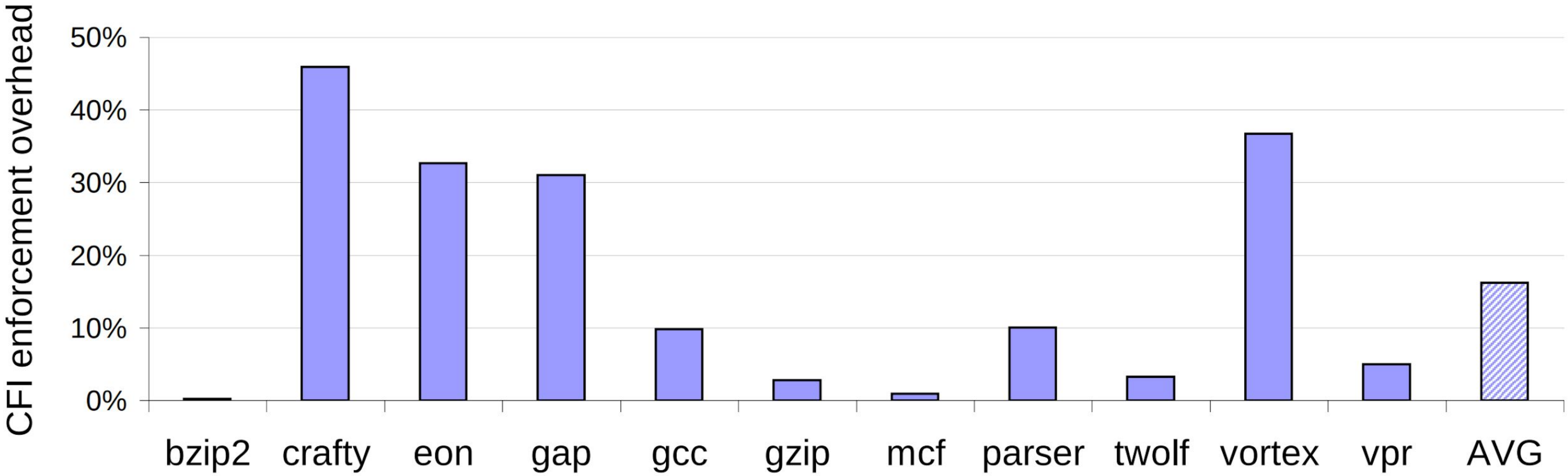
CFI assumptions

- Unique IDs
- Non-writable Code (NWC)
- Non-executable Data (NXD)
- Jumps cannot go into the middle of instructions

Attacker

- Powerful attacker model
  - Arbitrary control of all data in memory
  - Even hijack the execution flow of the program
- With CFI, execution will always follow the CFG

Overhead


CFI enforcement overhead
50%
40%
30%
20%
10%
0%
bzip2
crafty
eon
gap
gcc
gzip
mcf
parser
twolf
vortex
vpr
AVG

Control Flow Guard

- Windows 10 and Windows 8.1
- Microsoft Visual Studio 2015+
- Adds lightweight security checks to the compiled code
- Identifies the set of functions in the application that are valid targets for indirect calls
- The runtime support, provided by the Windows kernel:
  - Efficiently maintains state that identifies valid indirect call targets
  - Implements the logic that verifies that an indirect call target is valid

Control-flow enforcement technology

- Shadow stack
  - CALL instruction pushes the return address on both the data and shadow stack
  - RET instruction pops the return address from both stacks and compares them
  - if the return addresses from the two stacks do not match, the processor signals a control protection exception (#CP)
- Indirect branch tracking
  - `ENDBRANCH` -> new CPU instruction
  - marks valid indirect call/jmp targets in the program
  - the CPU implements a state machine that tracks indirect jmp and call instructions
  - when one of these instructions is seen, the state machine moves from IDLE to WAIT_FOR_ENDBRANCH state
  - if an `ENDBRANCH` is not seen the processor causes a control protection fault

Limitations of CFI?

Fine-grained CFI

- Precise monitoring of indirect control-flow changes
- caller-callee must match
- High performance overhead (~21%)
- Highest security

Coarse-grained CFI

- Trades security for better performance
- Any valid call location is accepted

[1] N. Carlini and D. Wagner, "ROP is still dangerous: Breaking modern defenses"

[2] L. Davi, A.-R. Sadeghi, D. Lehmann, and F. Monrose, "Stitching the gadgets: On the ineffectiveness of coarse grained control-flow integrity protection"

[3] E. Goktas, E. Athanasopoulos, H. Bos, and G. Portokalidis, "Out of control: Overcoming control-flow integrity"

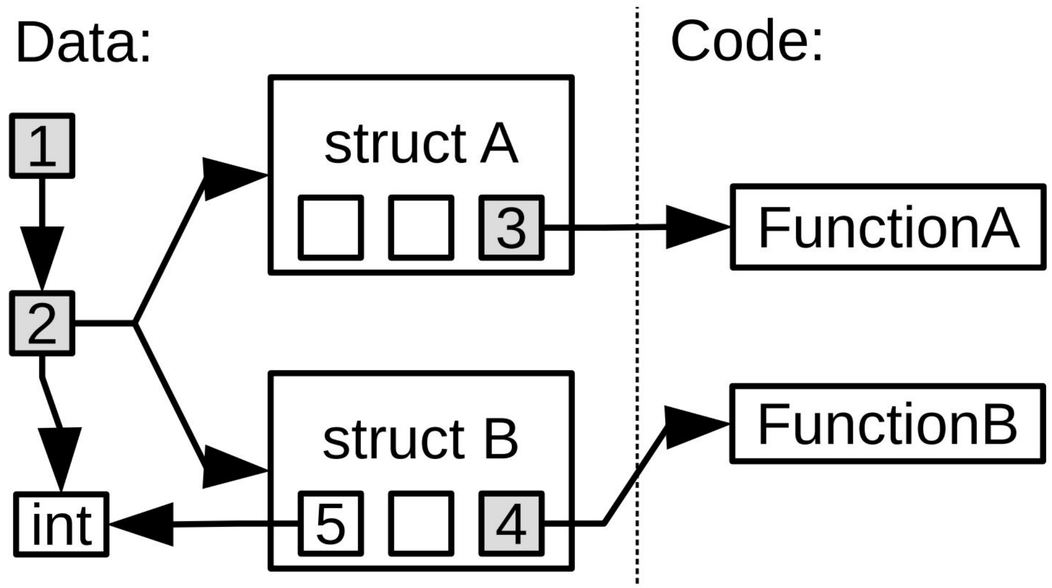
[4] E. Goktas, E. Athanasopoulos, M. Polychronakis, H. Bos, and G. Portokalidis, "Size does matter: Why using gadget chain length to prevent code-reuse attacks is hard"

Which type of CFI did Intel choose to implement in hardware?

Coarse-grained CFI...

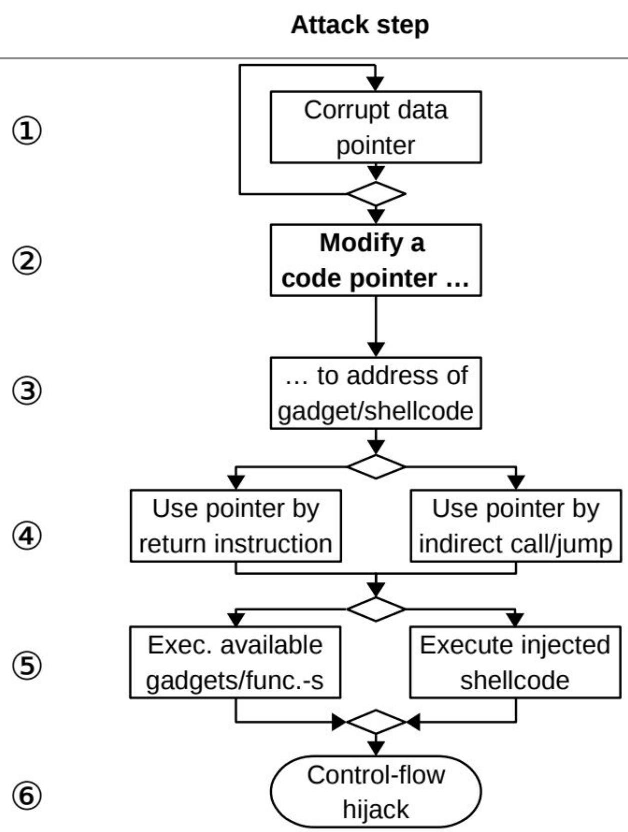
Code-Pointer Integrity

- Static analysis
  - all sensitive pointers
  - all instructions that operate on them
- Instrumentation
  - store them in a separate, safe memory region
- Instruction-level isolation mechanism
  - prevents non-protected memory operations from accessing the safe region



source: https://www.usenix.org/system/files/conference/osdi14/osdi14-paper-kuznetsov.pdf

Defenses overview and overheads



Property	Mechanism	Stops all control-flow hijacks?	Avg. overhead
Memory Safety	SoftBound+CETS [34, 35]	**Yes**	116%
	BBC [4],	No: sub-objects, reads not protected	110%
	LBC [20], ASAN [43],	No: protects red zones only	23%
	WIT [3]	No: over-approximate valid sets	7%
Code-Pointer Integrity (this work)	CPI	**Yes**	8.4%
	CPS	No: valid code ptrs. interchangeable	1.9%
	Safe Stack	No: precise return protection only	~0%
Randomization	ASLR [40], ASLP [26]	No: vulnerable to information leaks	~10%
	PointGuard [13]	No: vulnerable to information leaks	10%
	DSR [6]	No: vulnerable to information leaks	20%
	NOP insertion [21]	No: vulnerable to information leaks	2%
Control-Flow Integrity	Stack cookies	No: probabilistic return protection only	~2%
	CFI [1]	No: over-approximate valid sets	20%
	WIT (CFI part) [3]	No: over-approximate valid sets	7%
	DFI [10]	No: over-approximate valid sets	104%
Non-Executable Data	HW (NX bit)	No: code reuse attacks	0%
	SW (Exec Shield, PaX)	No: code reuse attacks	few %
High-level policies	Sandboxing (SFI)	Isolation only	varies
	ACLs	Isolation only	varies
	Capabilities	Isolation only	varies

kBouncer

- Detection of abnormal control transfers that take place during ROP code execution

- *Transparent*
  - Applicable on third-party applications
  - Compatible with code signing, self-modifying code, JIT, …

- *Lightweight*
  - Up to 4% overhead when artificially stressed, practically zero

- *Effective*
  - Prevents real-world exploits

source: http://www.cs.columbia.edu/~vpappas/papers/kbouncer.sec13.pdf

ROP Code Runtime Properties

- Illegal ret instructions that target locations not preceded by call sites
  - Abnormal condition for legitimate program code
- Sequences of relatively short code fragments “chained” through any kind of indirect branch
  - Always holds for any kind of ROP code

Illegal Returns

- Legitimate code:
  - ret transfers control to the instruction right after the corresponding call ➔ legitimate call site
- ROP code:
  - ret transfers control to the first instruction of the next gadget ➔ arbitrary locations
- Main idea:
  - Runtime monitoring of ret instructions' targets

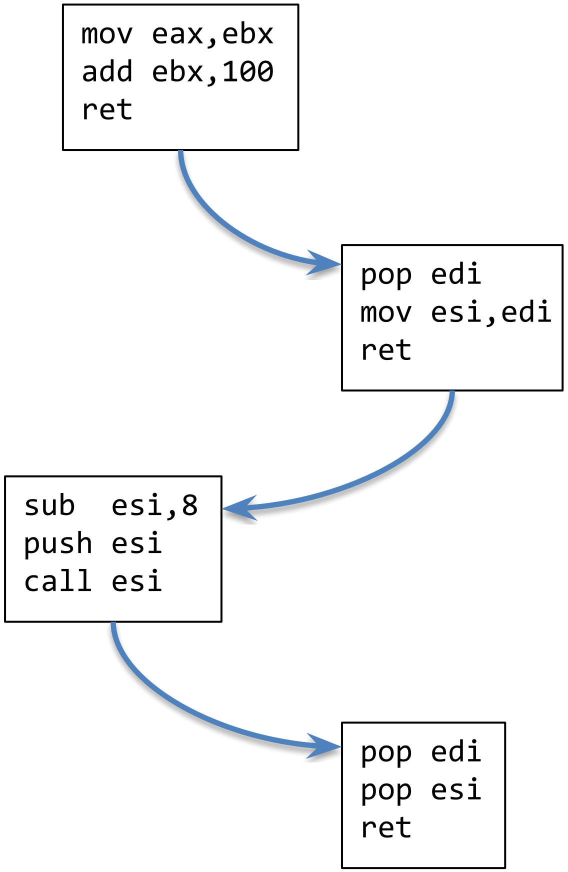
Gadget Chaining

- Advanced ROP code may avoid illegal returns
  - Rely only on call-preceded gadgets (just 6% of all ret gadgets in our experiments)
  - "Jump-Oriented" Programming (non-ret gadgets)

- Look for a second ROP attribute: Several short instruction sequences chained through (any kind of) indirect branches

Gadget Chaining

- Look for consecutive indirect branch targets that point to gadget locations
- Conservative gadget definition: up to 20 instructions
  - Typically 1-5



Last Branch Record (LBR)

- Introduced in the Intel Nehalem architecture

- Stores the last 16 executed branches in a set of model-specific registers (MSR)
  - Can filter certain types of branches (relative/indirect calls/jumps, returns, ...)

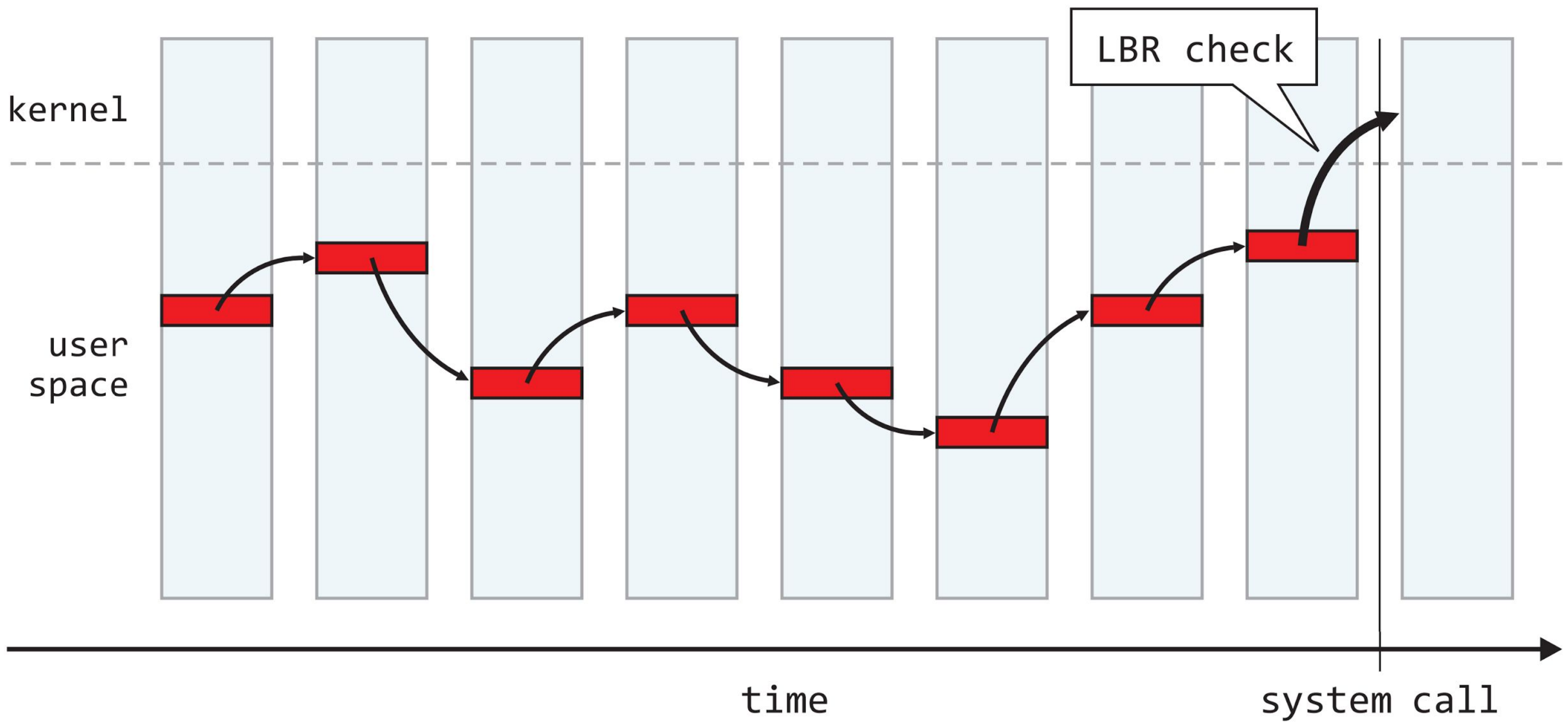
- Multiple advantages
  - Zero overhead for recording the branches
  - Fully transparent to the running application
  - Does not require source code or debug symbols
  - Can be dynamically enabled for any running application

Monitoring Granularity

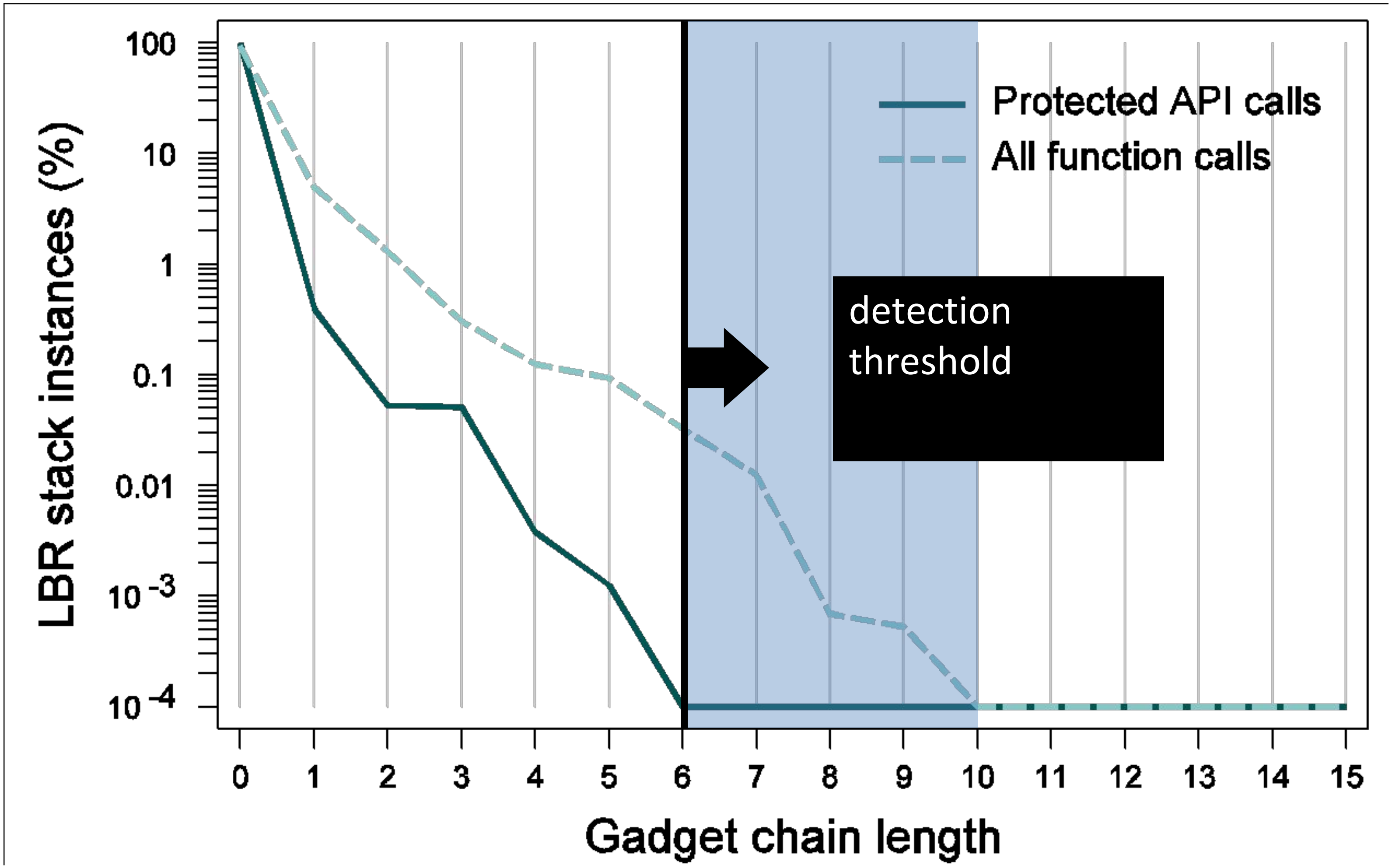
- Non-zero overhead for reading the LBR stack (accessible only from kernel level)
  - Lower frequency ➔ lower overhead
- ROP code can run at any point
  - Higher frequency ➔ higher accuracy

Monitoring Granularity

- Meaningful ROP code will eventually interact with the OS through system calls
  - Check for abnormal control transfers on system call entry



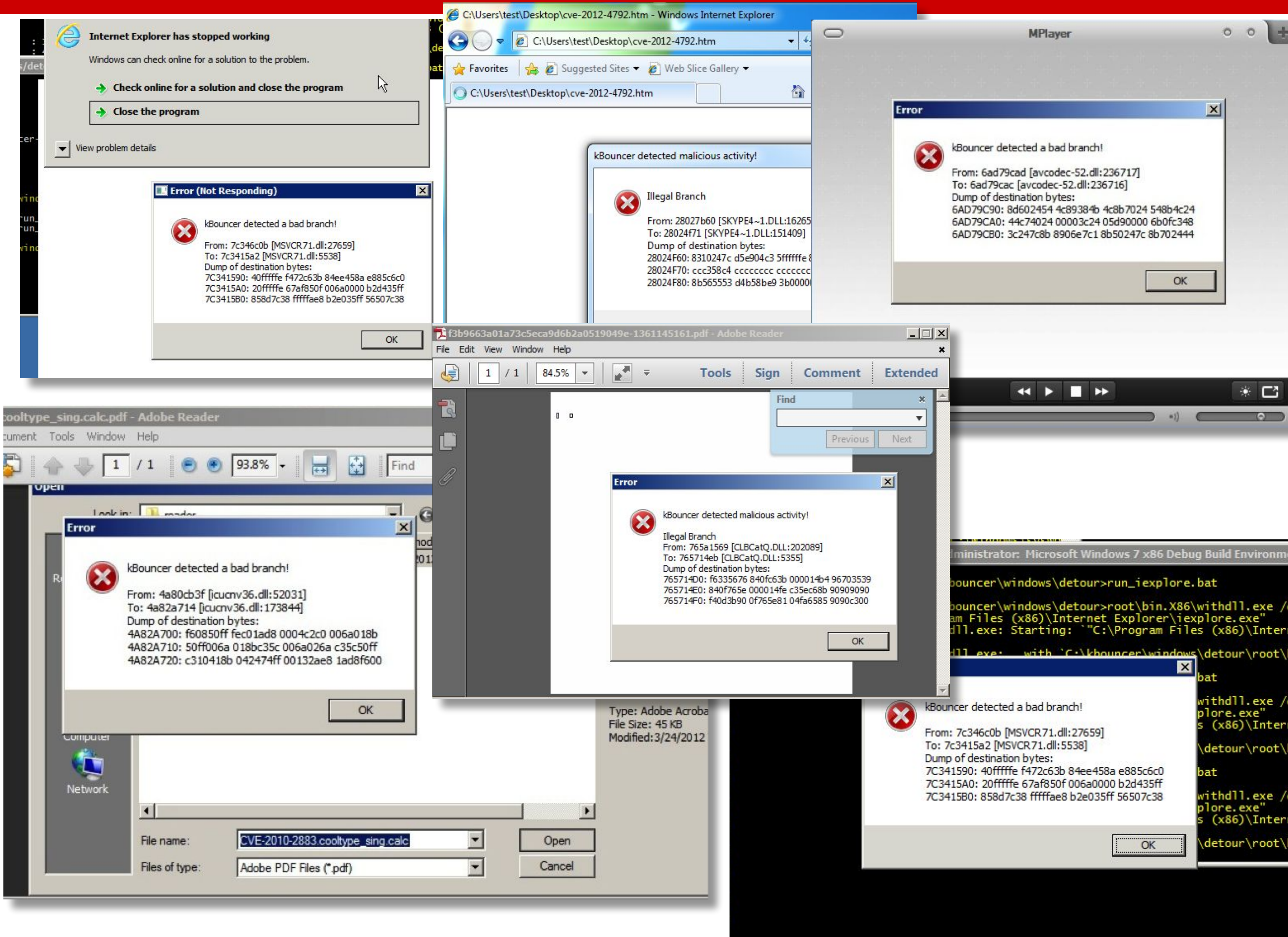
Gadget Chaining: Legitimate Code



* Dataset from: Internet Explorer, Adobe Reader, Flash Player, Microsoft Office (Word, Excel and PowerPoint)

Effectiveness

- Successfully prevented real-world exploits in
  - Adobe Reader XI (zero-day!)
  - Adobe Reader 9
  - Mplayer Lite
  - Internet Explorer 9
  - Adobe Flash 11.3
  - …


Internet Explorer has stopped working
Windows can check online for a solution to the problem.
Check online for a solution and close the program
Close the program
View problem details
Error (Not Responding)
kBouncer detected a bad branch!
From: 7c346c0b [MSVCR71.dll:27659]
To: 7c3415a2 [MSVCR71.dll:5538]
Dump of destination bytes:
7C341590: 40ffffe f472c63b 84ee458a e885c6c0
7C3415A0: 20fffffe 67af850f 006a0000 b2d435ff
7C3415B0: 858d7c38 ffffae8 b2e035ff 56507c38
OK
C:\Users\test\Desktop\cve-2012-4792.htm - Windows Internet Explorer
Favorites
Suggested Sites
Web Slice Gallery
kBouncer detected malicious activity!
Illegal Branch
From: 28027b60 [SKYPE4~1.DLL:16265
To: 28024f71 [SKYPE4~1.DLL:151409]
Dump of destination bytes:
MPlayer
Error
kBouncer detected a bad branch!
From: 6ad79cad [avcodec-52.dll:236717]
To: 6ad79cac [avcodec-52.dll:236716]
Dump of destination bytes:
6AD79C90: 8d602454 4c89384b 4c8b7024 548b4c24
6AD79CA0: 44c74024 00003c24 05d90000 6b0fc348
6AD79CB0: 3c247c8b 8906e7c1 8b50247c 8b702444
OK
f3b9663a01a73c5eca9d6b2a0519049e-1361145161.pdf - Adobe Reader
File Edit View Window Help
Tools Sign Comment Extended
Find
Previous Next
Error
kBouncer detected malicious activity!
Illegal Branch
From: 765a1569 [CLBCatQ.DLL:202089]
To: 765714eb [CLBCatQ.DLL:5355]
Dump of destination bytes:
765714D0: f6335676 840fc63b 000014b4 96703539
765714E0: 840f765e 000014fe c35ec68b 90909090
765714F0: f40d3b90 0f765e81 04fa6585 9090c300
OK
cooltype_sing.calc.pdf - Adobe Reader
Error
kBouncer detected a bad branch!
From: 4a80cb3f [icucnv36.dll:52031]
To: 4a82a714 [icucnv36.dll:173844]
Dump of destination bytes:
4A82A700: f60850ff fec01ad8 0004c2c0 006a018b
4A82A710: 50ff006a 018bc35c 006a026a c35c50ff
4A82A720: c310418b 042474ff 00132ae8 1ad8f600
OK
Type: Adobe Acroba
File Size: 45 KB
Modified: 3/24/2012
Network
File name: CVE-2010-2883.cooltype_sing.calc
Files of type: Adobe PDF Files (*.pdf)
Open
Cancel
ministrator: Microsoft Windows 7 x86 Debug Build Environme
bouncer\windows\detour>run_iexplore.bat
kBouncer detected a bad branch!
From: 7c346c0b [MSVCR71.dll:27659]
To: 7c3415a2 [MSVCR71.dll:5538]
Dump of destination bytes:
7C341590: 40ffffe f472c63b 84ee458a e885c6c0
7C3415A0: 20fffffe 67af850f 006a0000 b2d435ff
7C3415B0: 858d7c38 ffffae8 b2e035ff 56507c38
OK

Limitations

- Indirect branch tracing only checks the last 16 gadgets, up to 20 instructions
  - Still possible to find longer call-preceded or non-return gadgets

kBouncer