13 Sep 2019, CROSSING Summer School on Sustainable Security & Privacy, Darmstadt, Germany

From Control-Flow to Data-Oriented Exploits

Hands-On Lab on Runtime Attacks

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University of Duisburg-Essen

Outline

Lecture
15:45 – 16:45

Hands-On Lab
16:45 – 17:45

Hands-On Lab

Download and install the VirtualBox VM:

http://bit.do/secsummer19

Motivating Problem

- Software increasingly sophisticated and complex

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Three Decades of Run-Time Attacks

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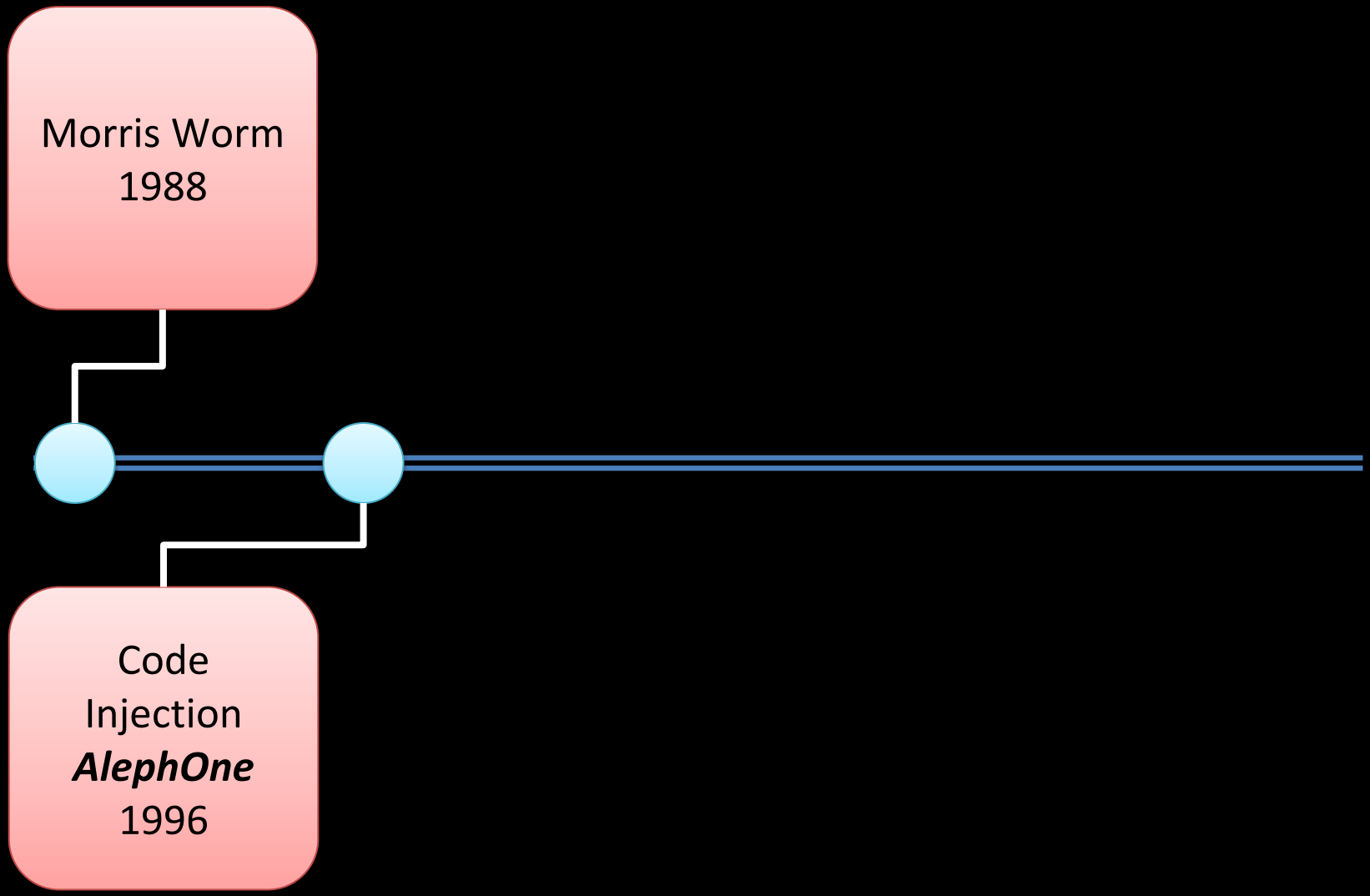

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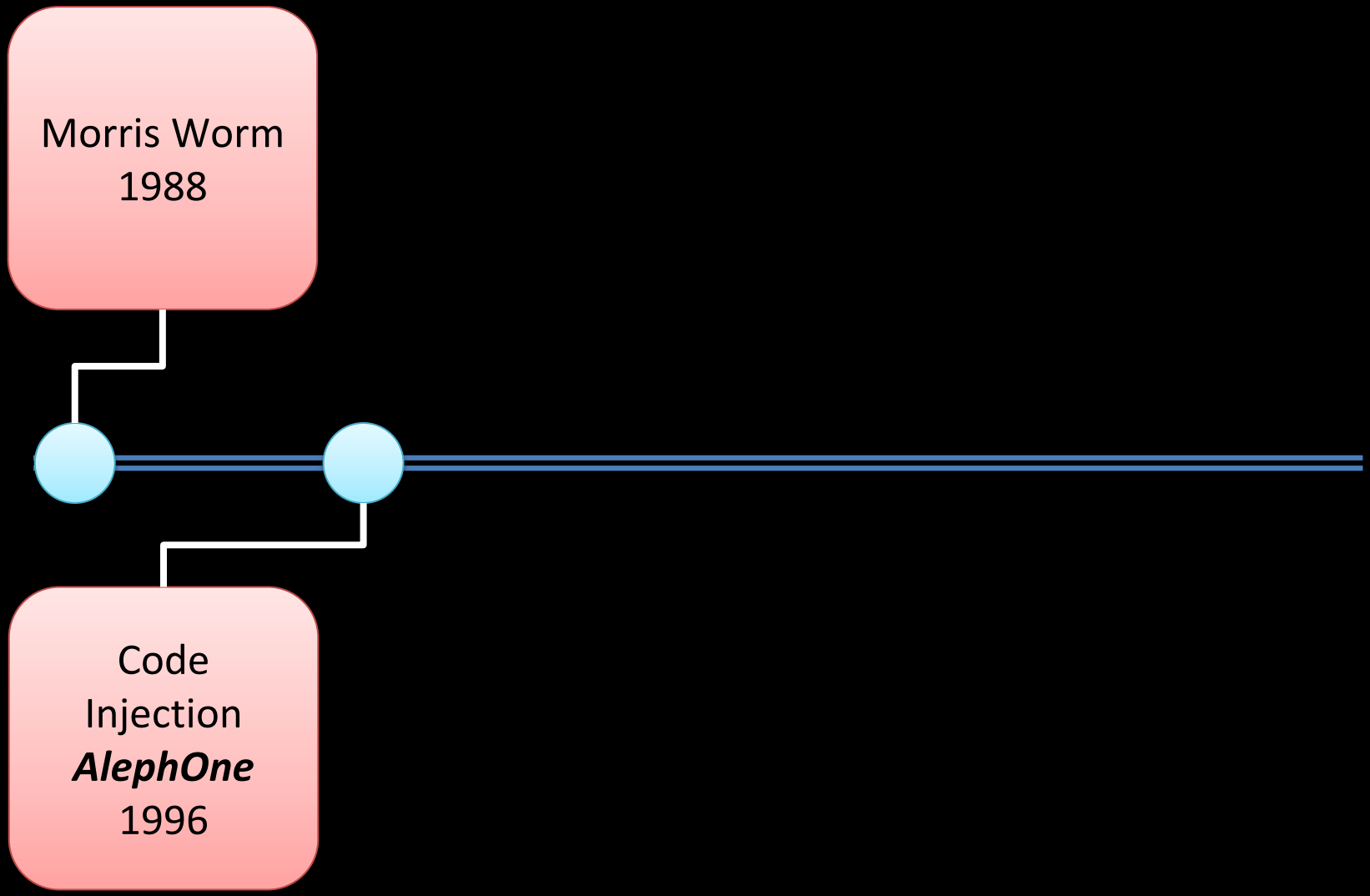

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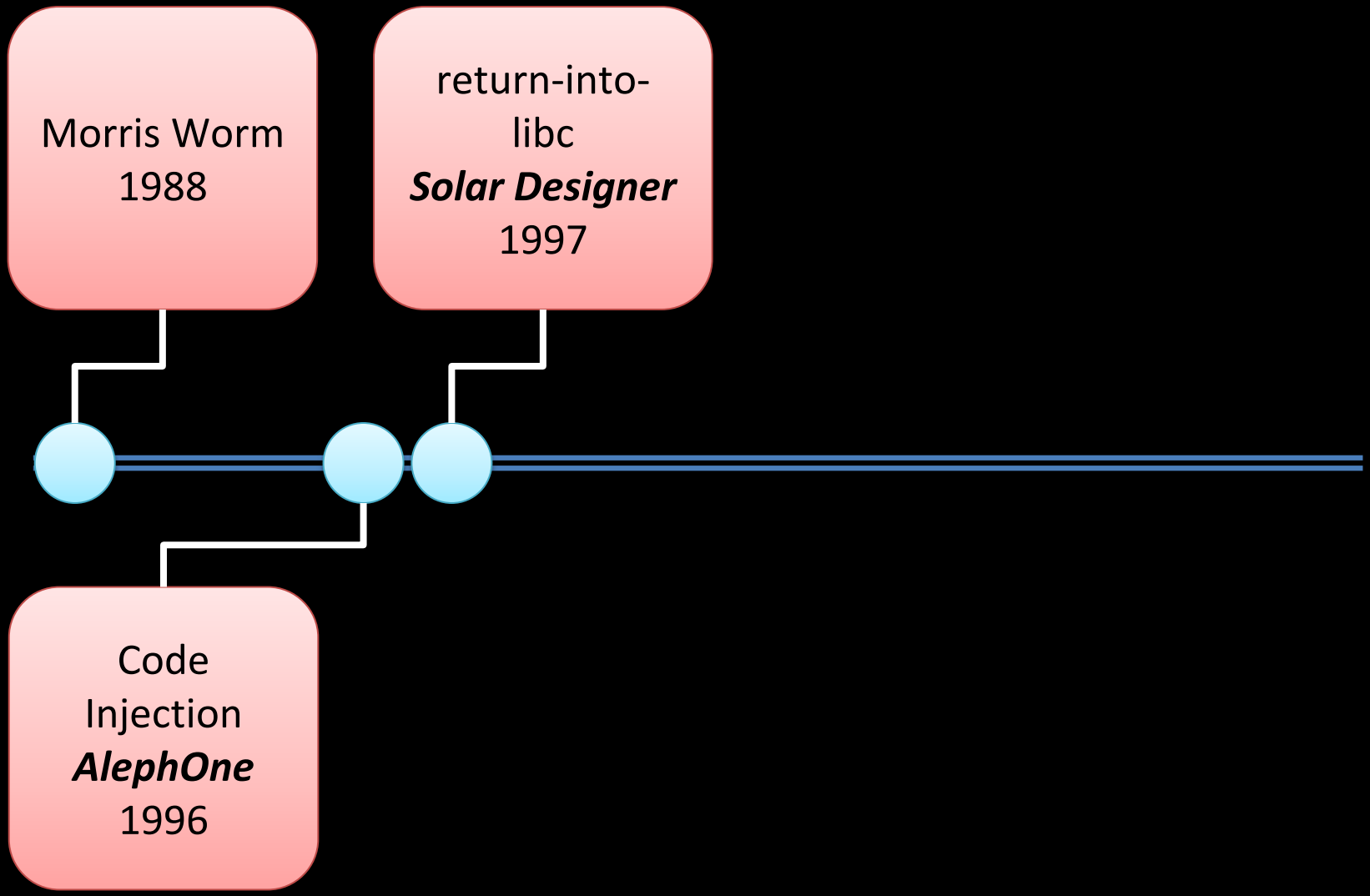

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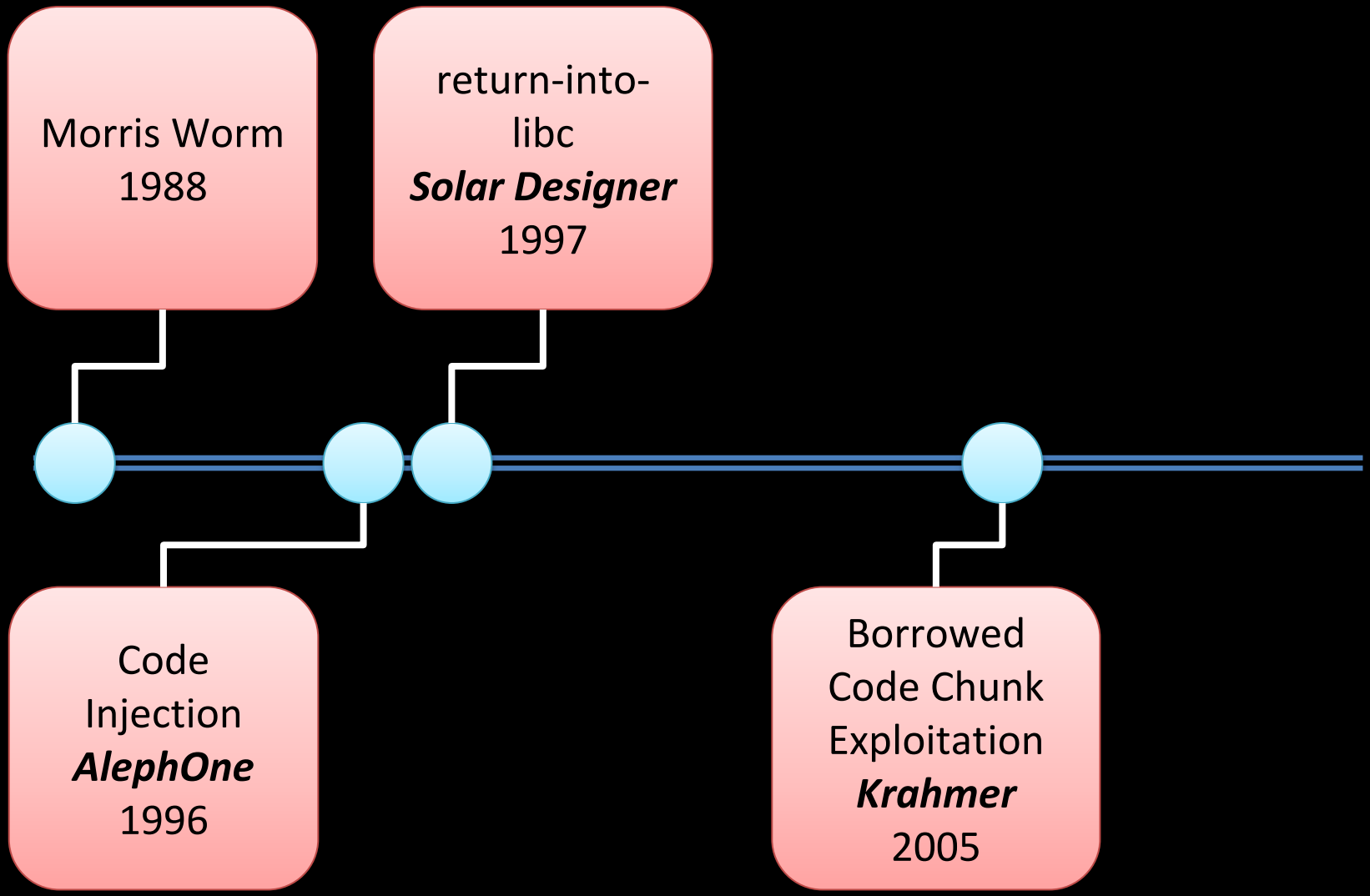

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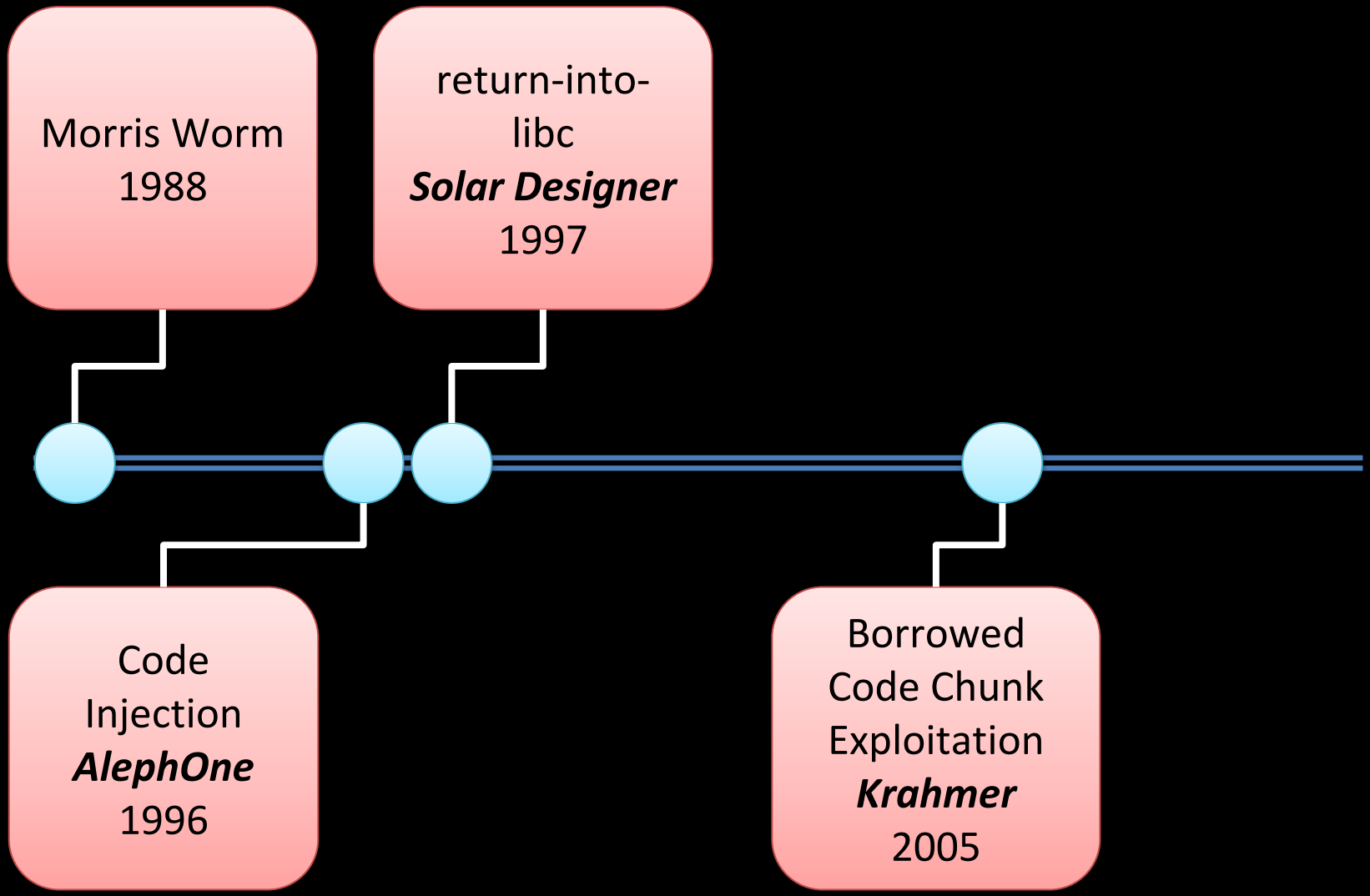

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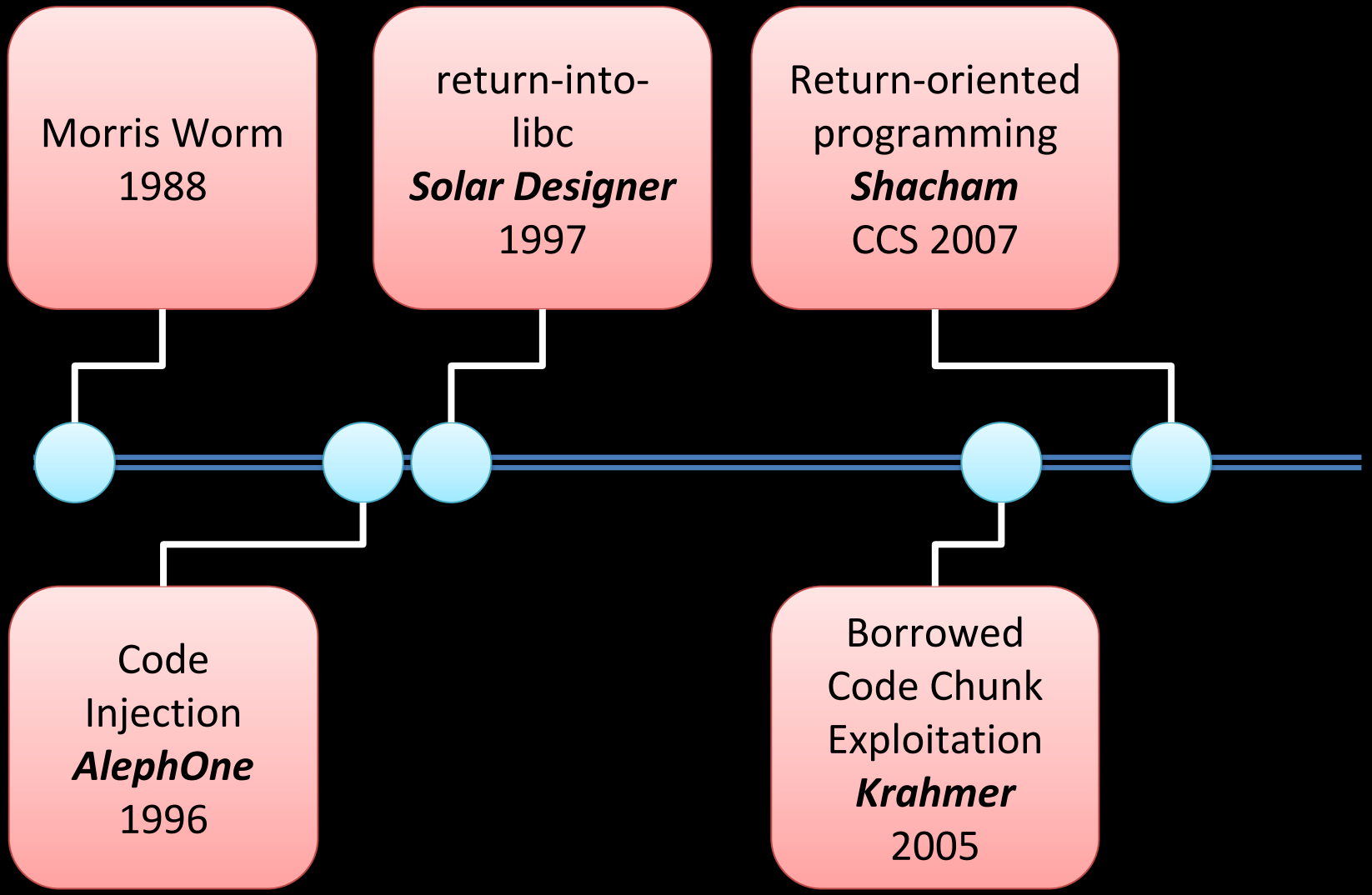

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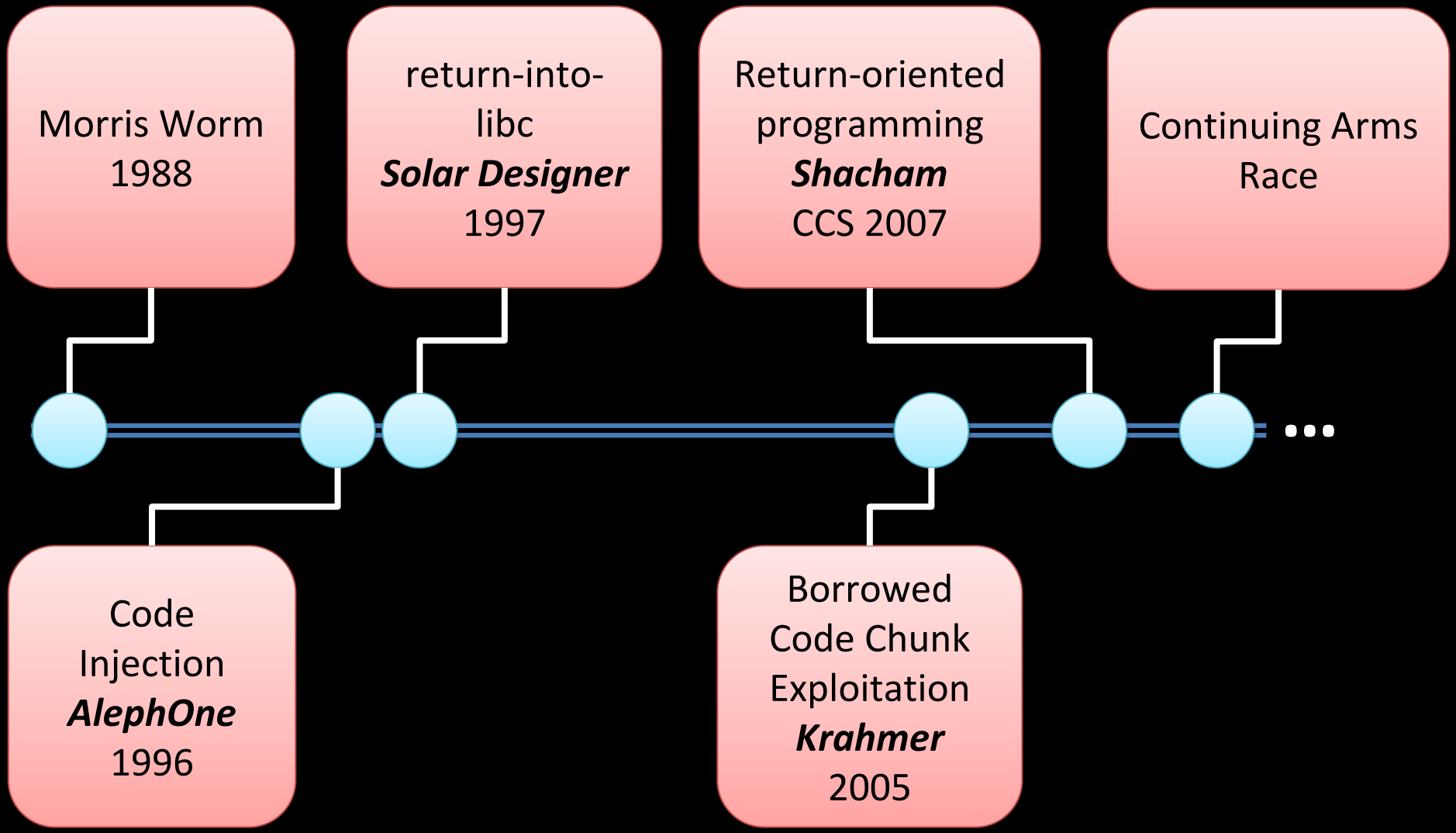

Relevance and Impact

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High Impact of Attacks

- Web browsers repeatedly exploited in pwn2own contests
- Zero-day issues exploited in Stuxnet/Duqu [Microsoft, BH 2012]
- iOS jailbreak

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Industry Efforts on Defenses

- Microsoft EMET (Enhanced Mitigation Experience Toolkit) includes a ROP detection engine
- Microsoft Control Flow Guard (CFG) in Windows 10
- Google‘s compiler extension VTV (virtual table verification)
- Intel Control-flow Enforcement Technology (CET)
- Kernel CFI (kCFI) since Android 9

But runtime exploits have also some “good” side-effects

Apple iPhone Jailbreak

Disable signature verification and escalate privileges to root

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Disable signature verification and escalate privileges to root

Request
http://www.jailbreakme.com/_/iPhone3,1_4.0.pdf

1) Exploit PDF Viewer Vulnerability by means of **Return-Oriented Programming**
2) Start Jailbreak

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1) Exploit PDF Viewer Vulnerability by means of **Return-Oriented Programming**
2) Start Jailbreak
3) Download required system files
4) Jailbreak Done

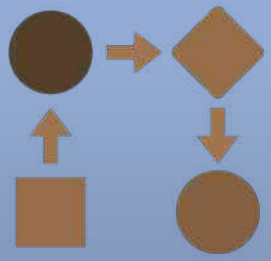
Overview

Background on Run-Time Attacks

Building Code Randomization Defenses

Code-Reuse Attacks

Building Control-Flow Integrity Defenses



Data-Oriented Exploits

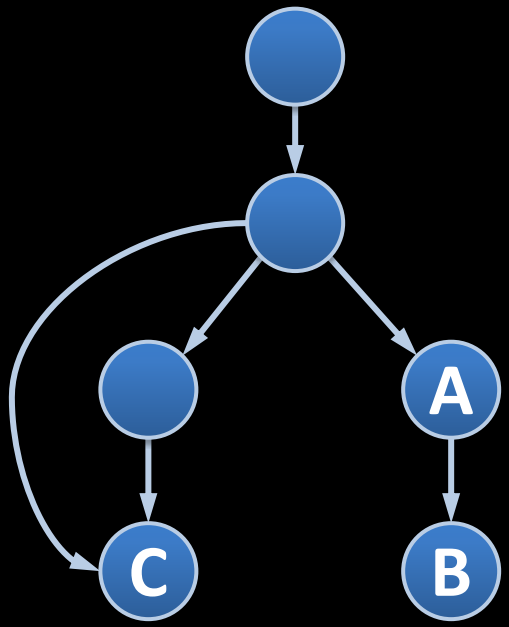
How can an attacker exploit vulnerabilities in a meaningful way?

Code Injection Attacks

Code-Reuse Attacks

General Principle of Code Injection Attacks

Control-Flow Graph (CFG)



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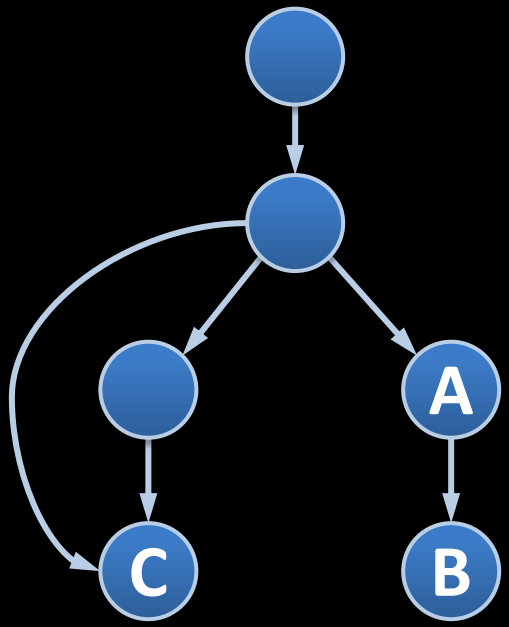

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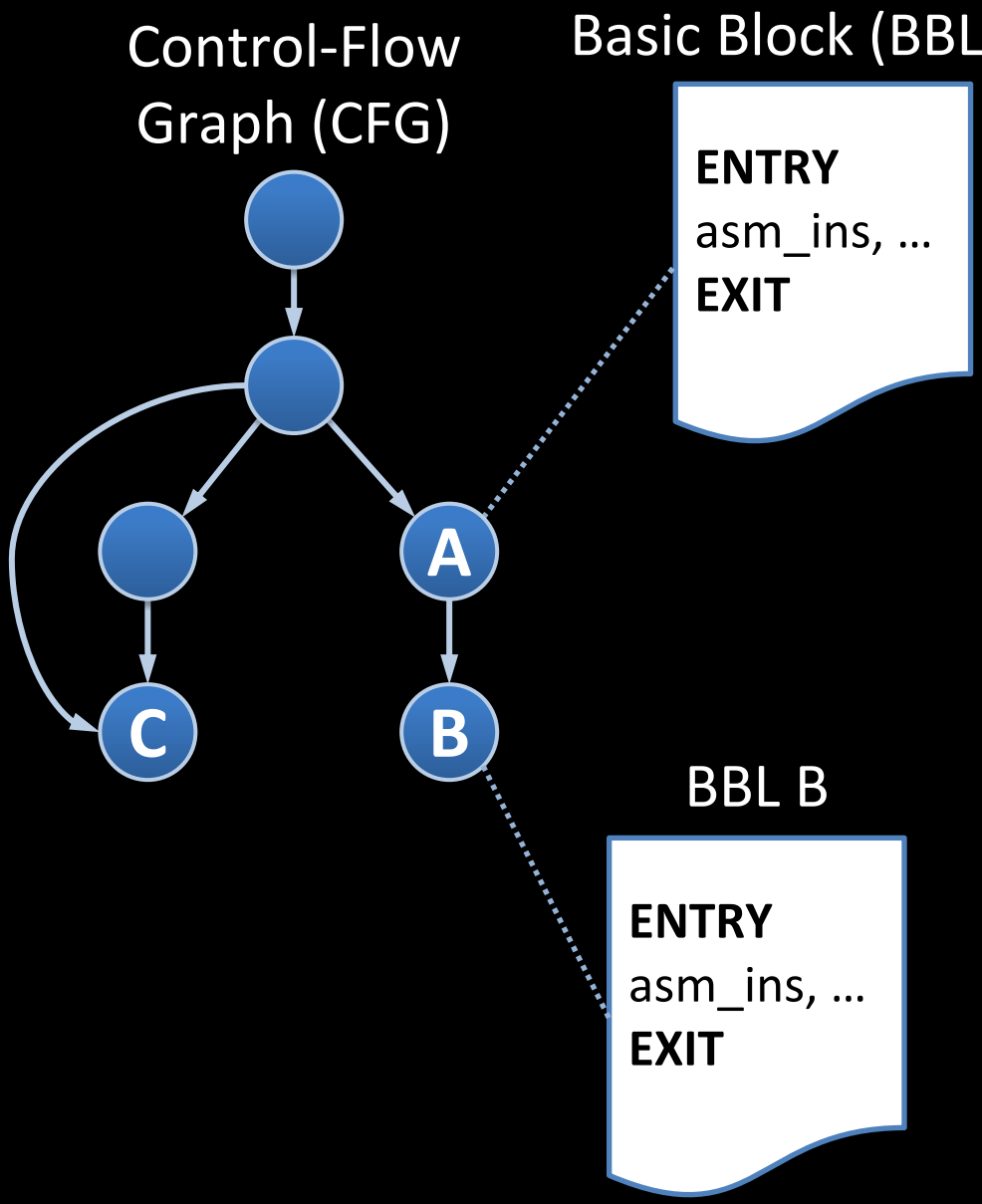

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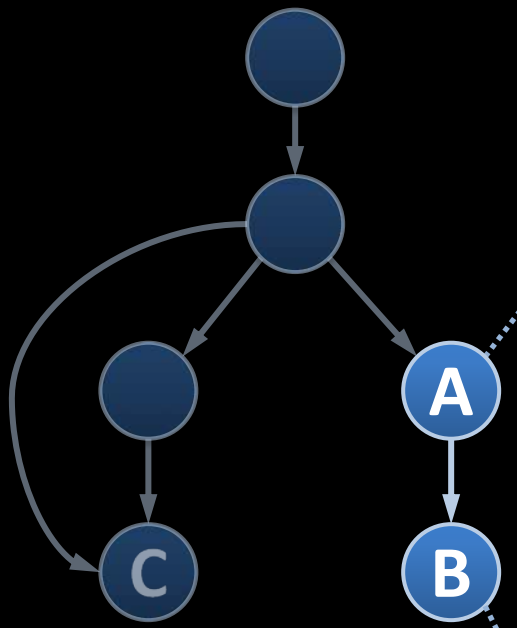

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EXIT

BBL B

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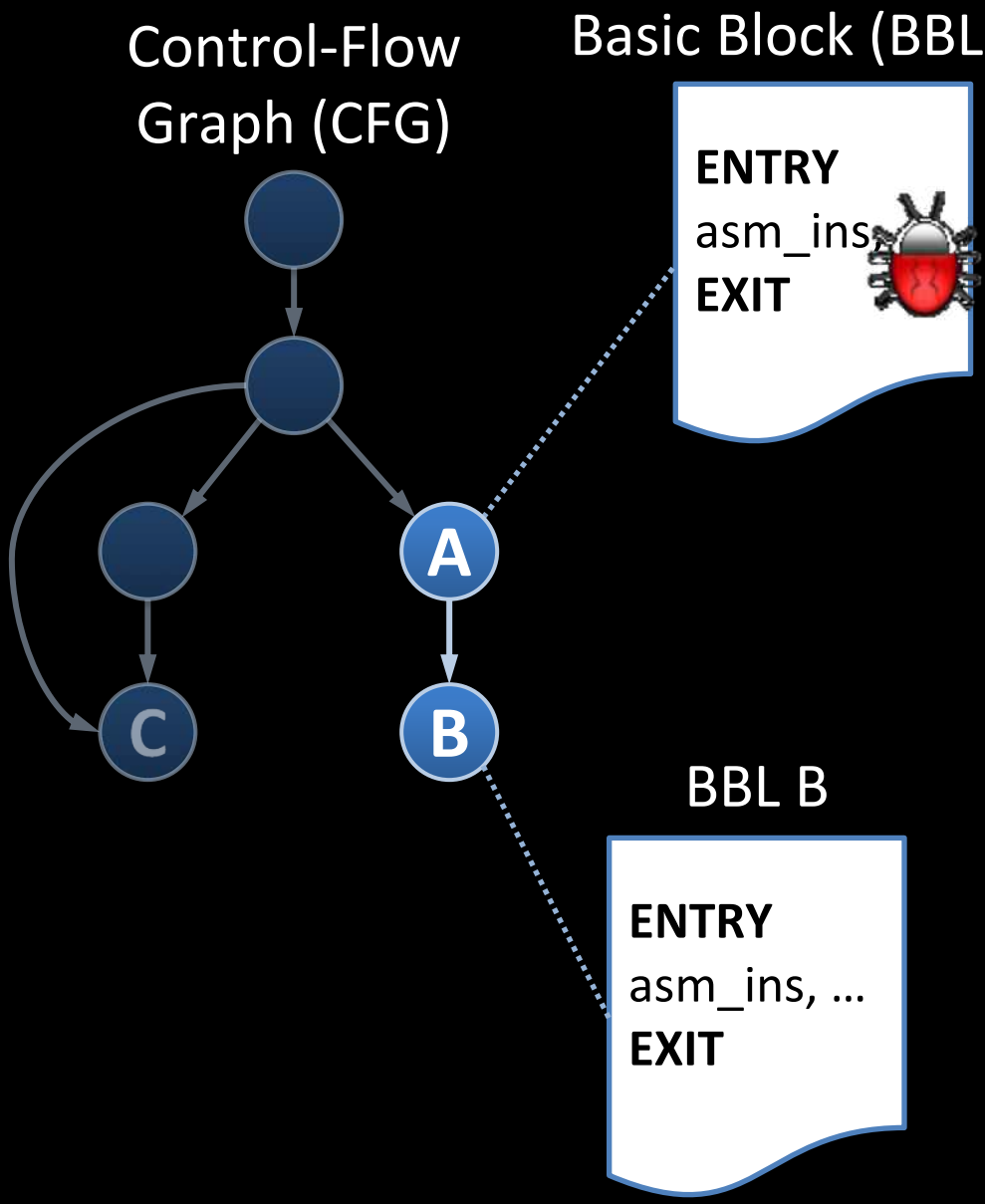

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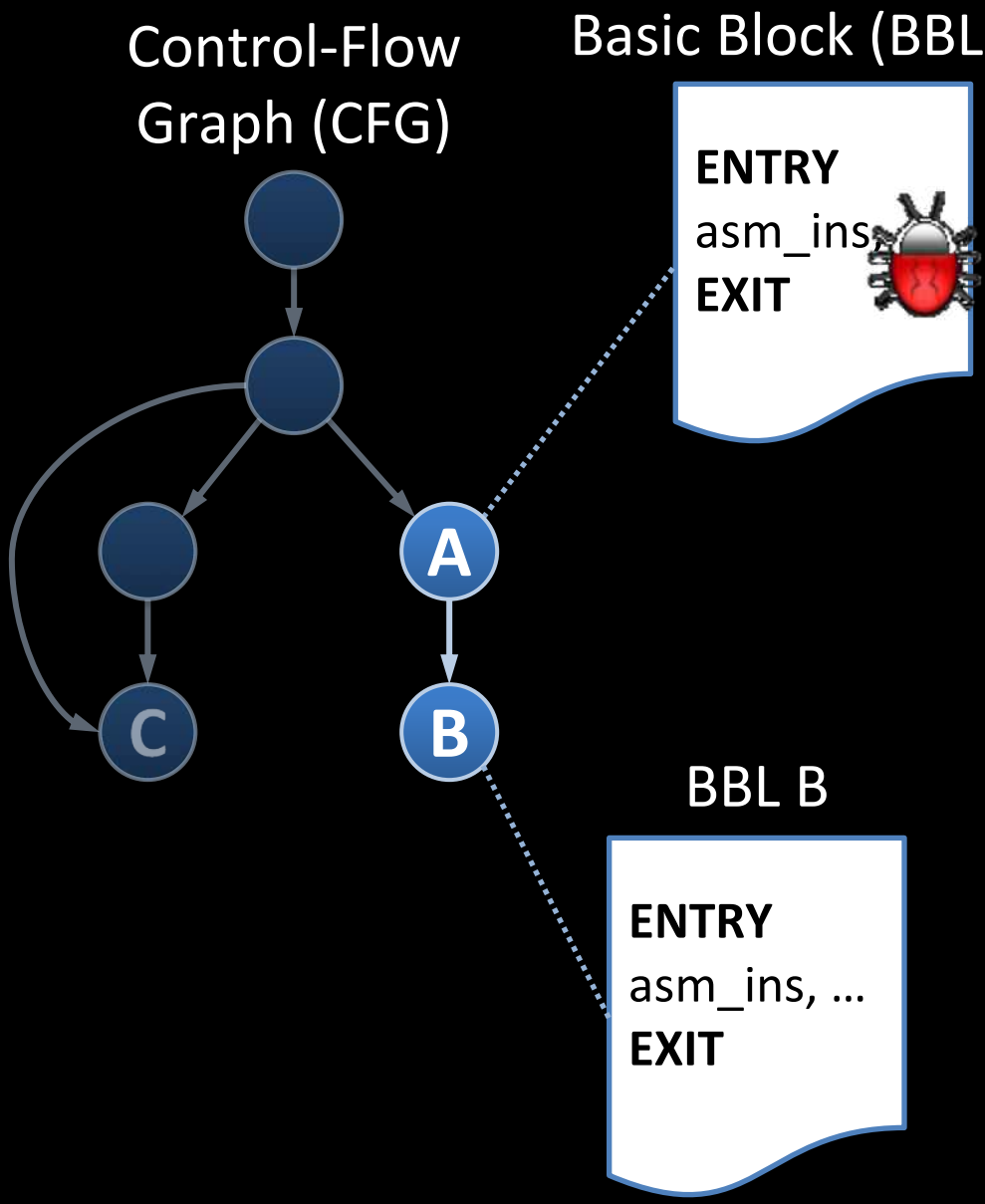

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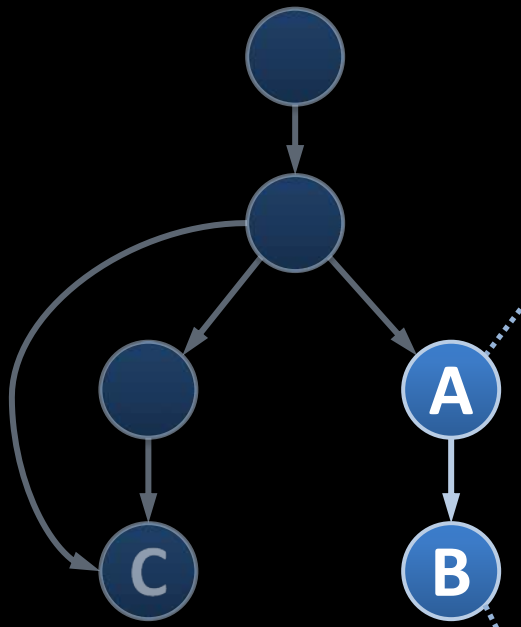

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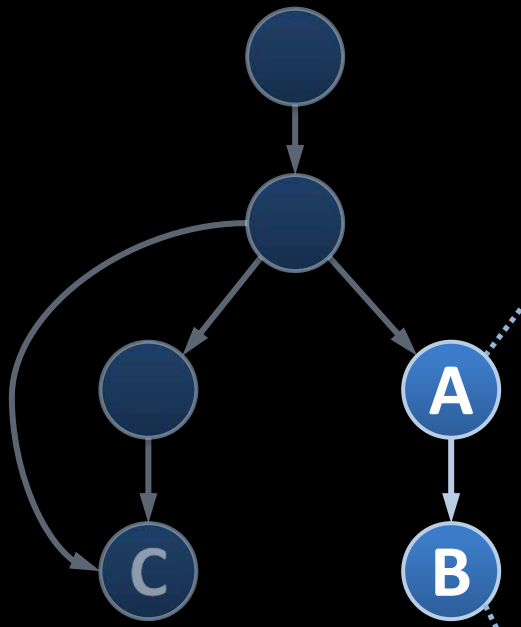

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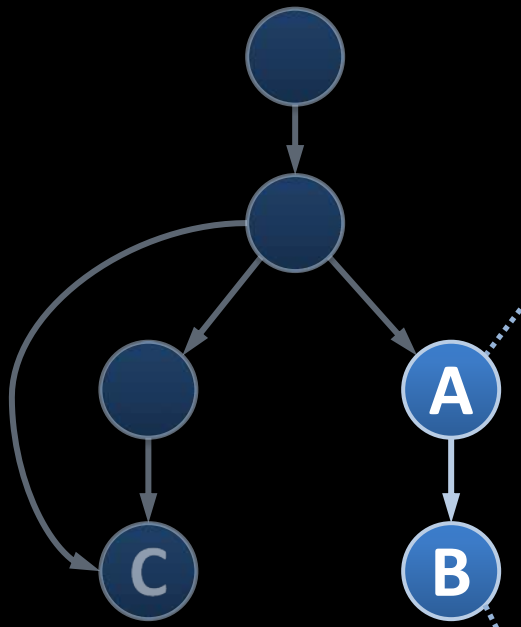

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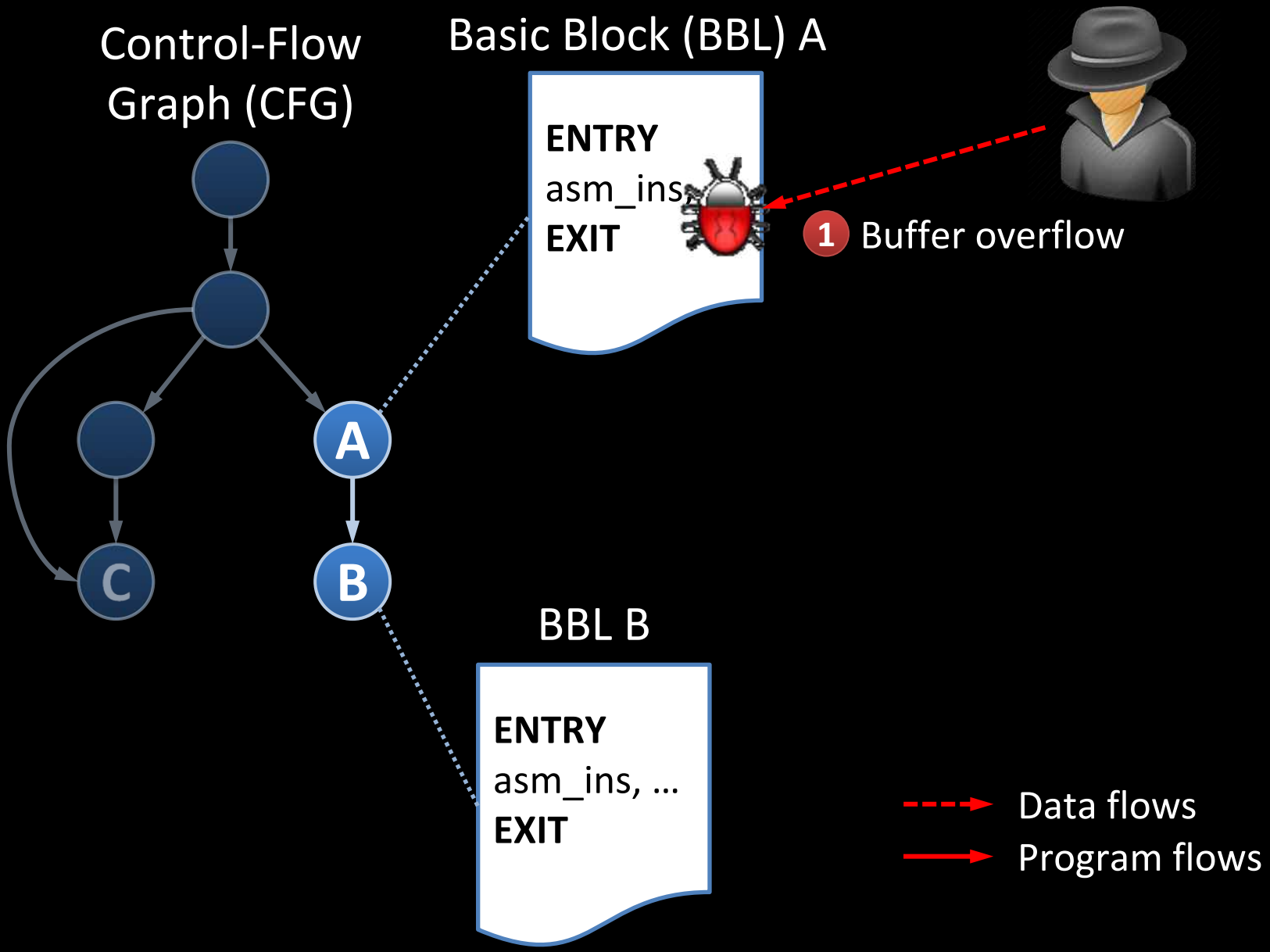

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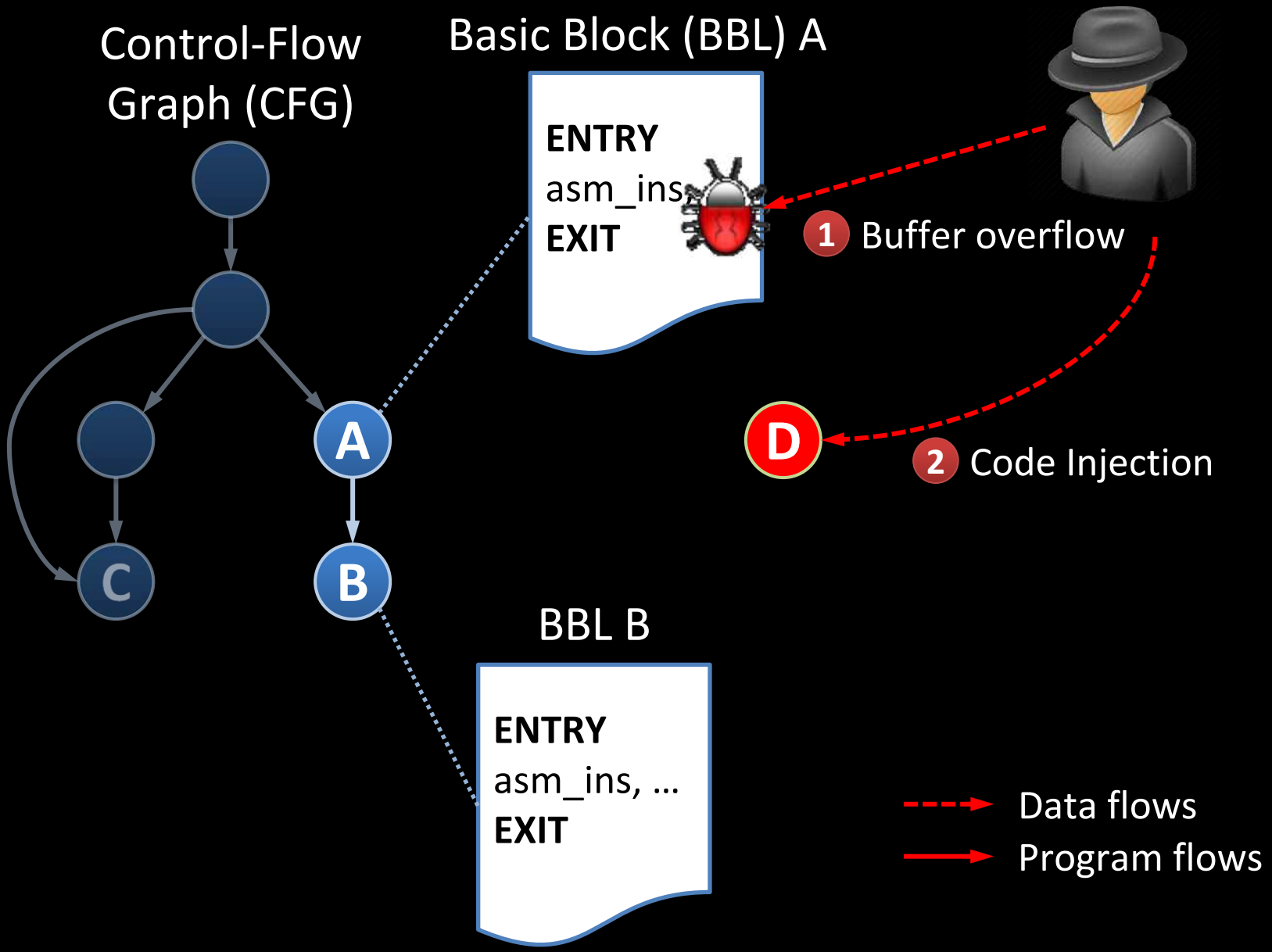

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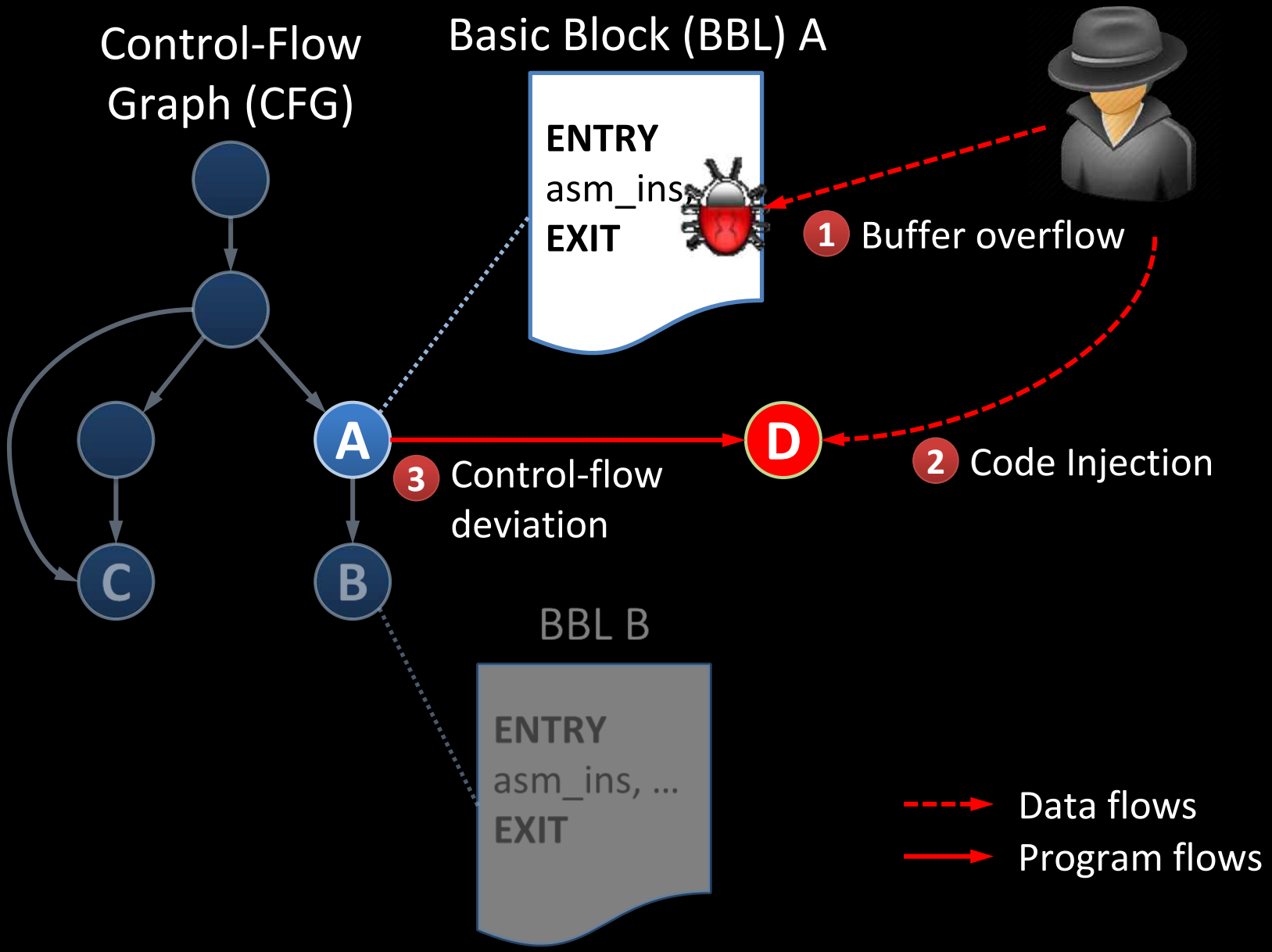

Example: Code Injection Attack

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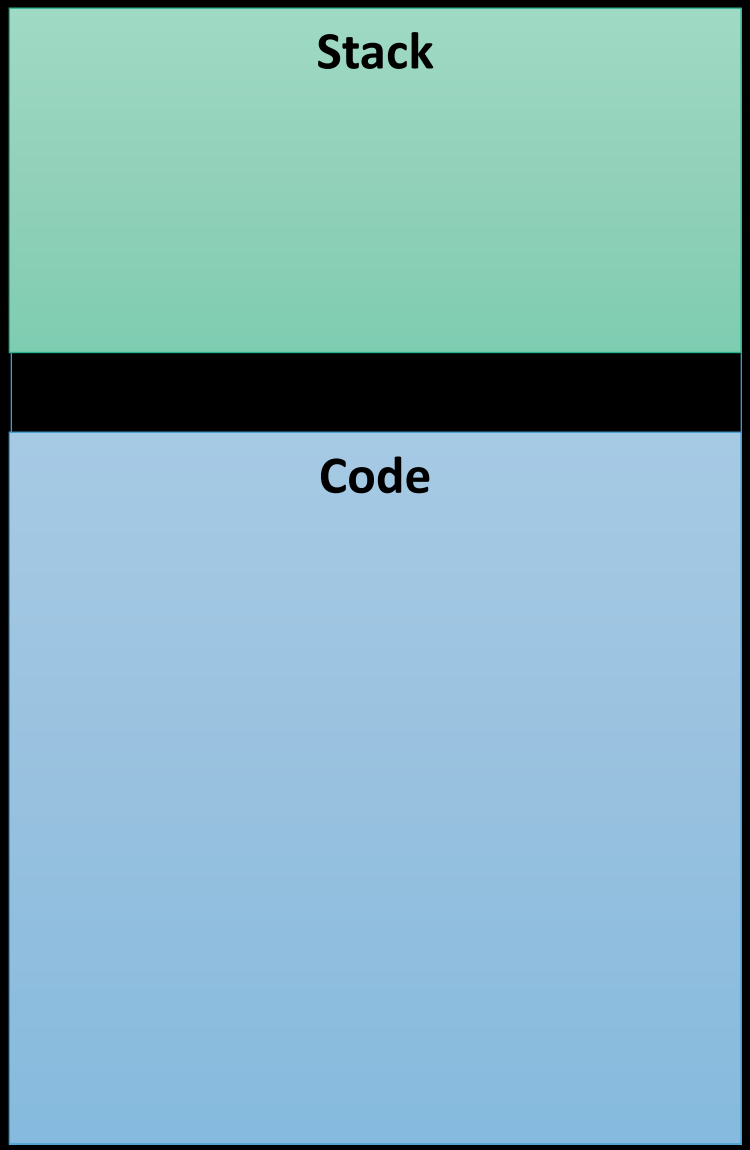
Program Memory



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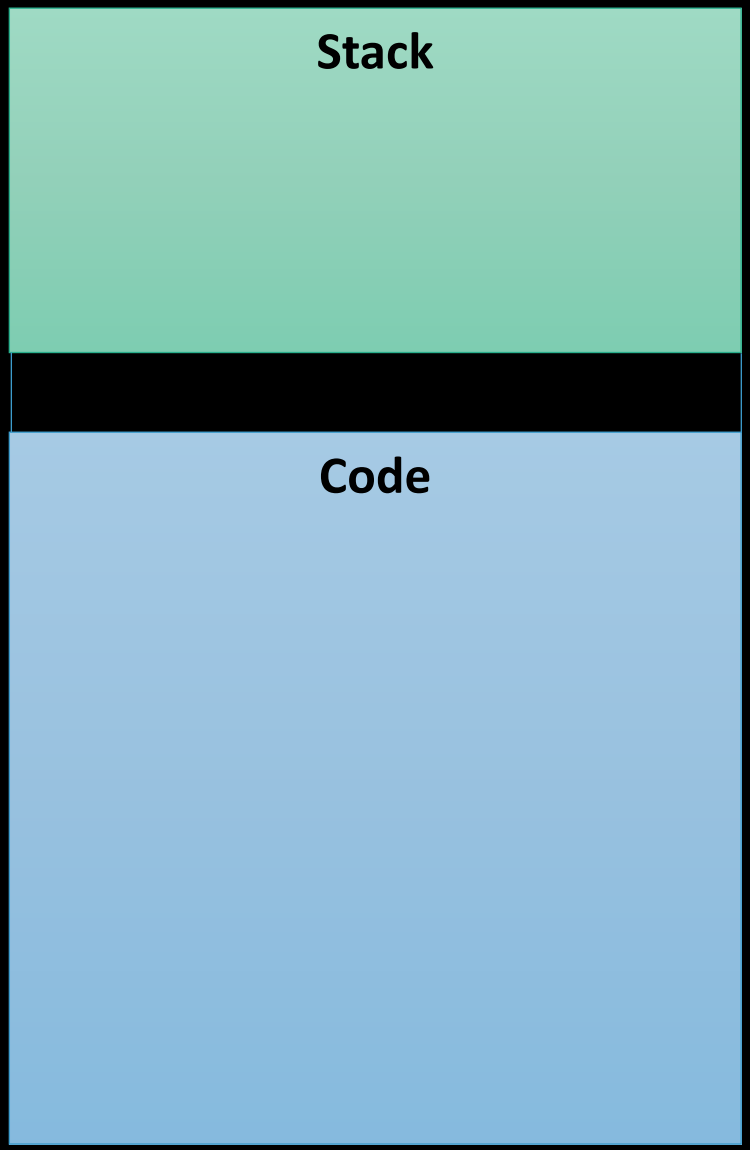

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Program Memory

Stack

Code

<main>:

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x86_ins…
CALL func()
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Return Address ← **ESP**

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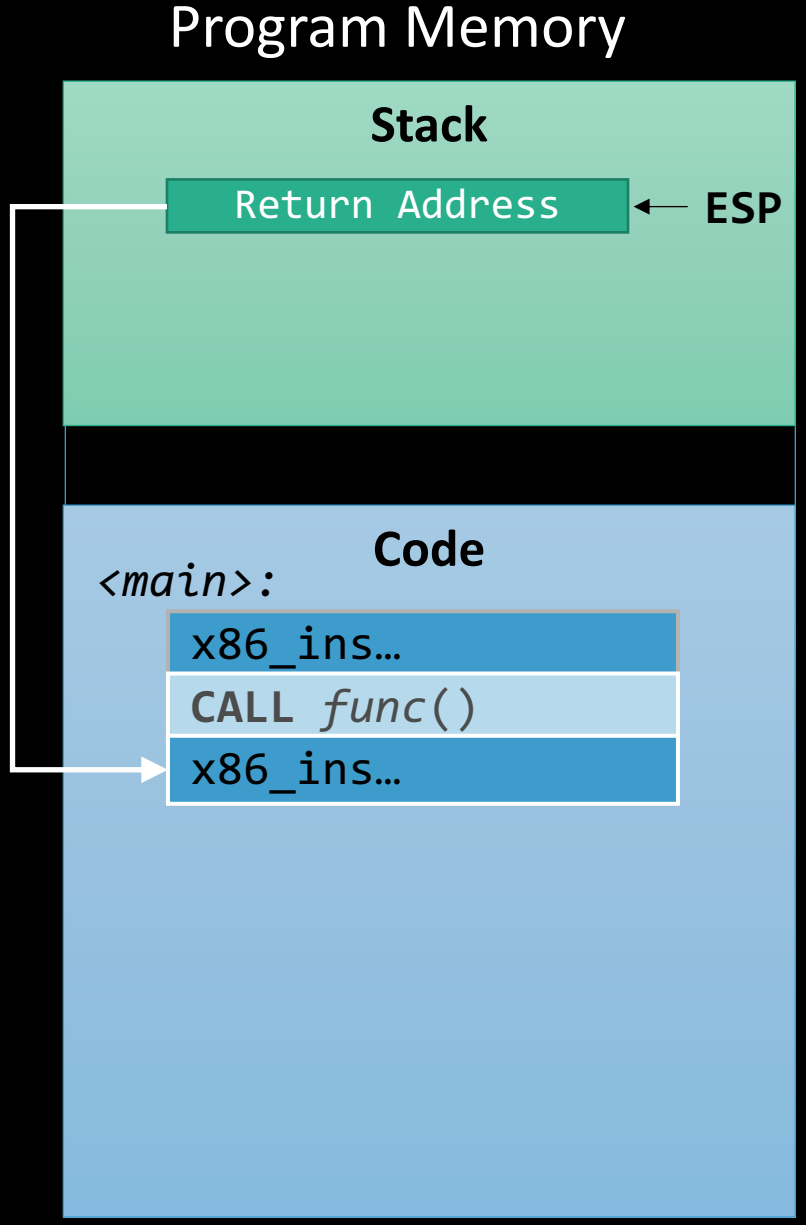

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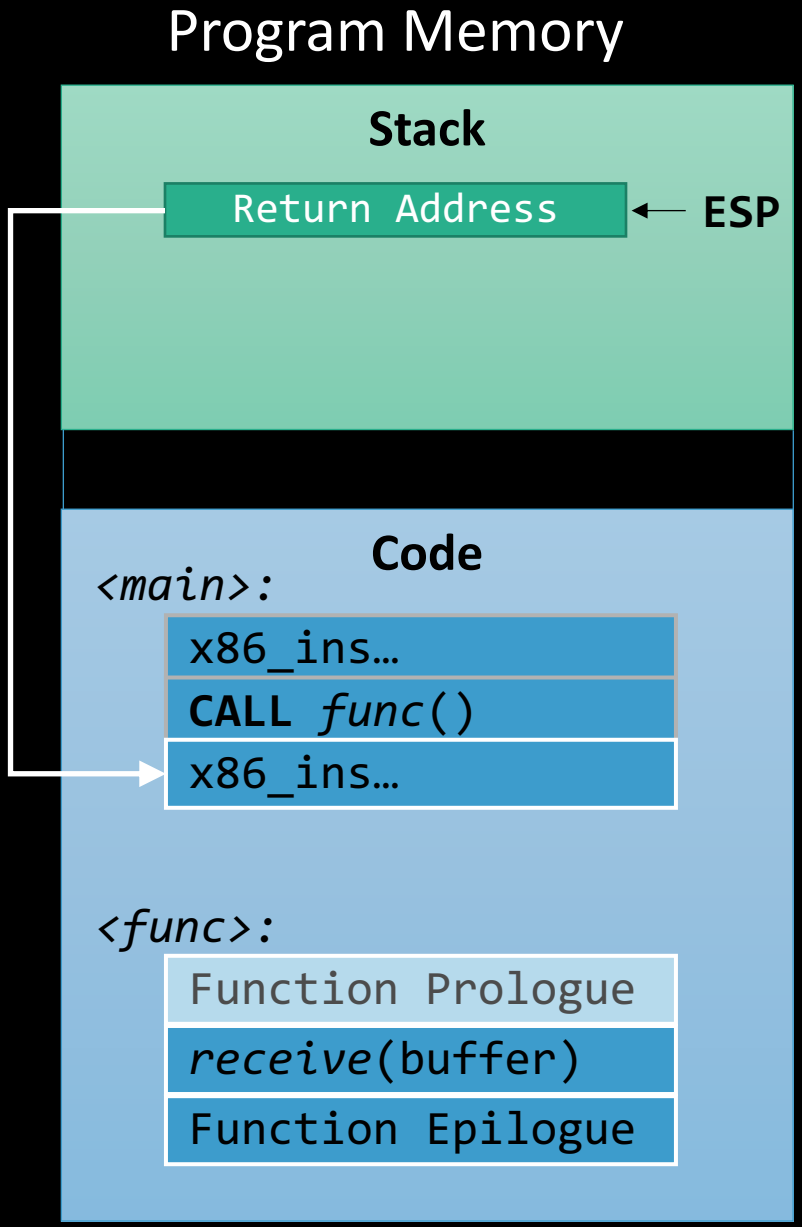

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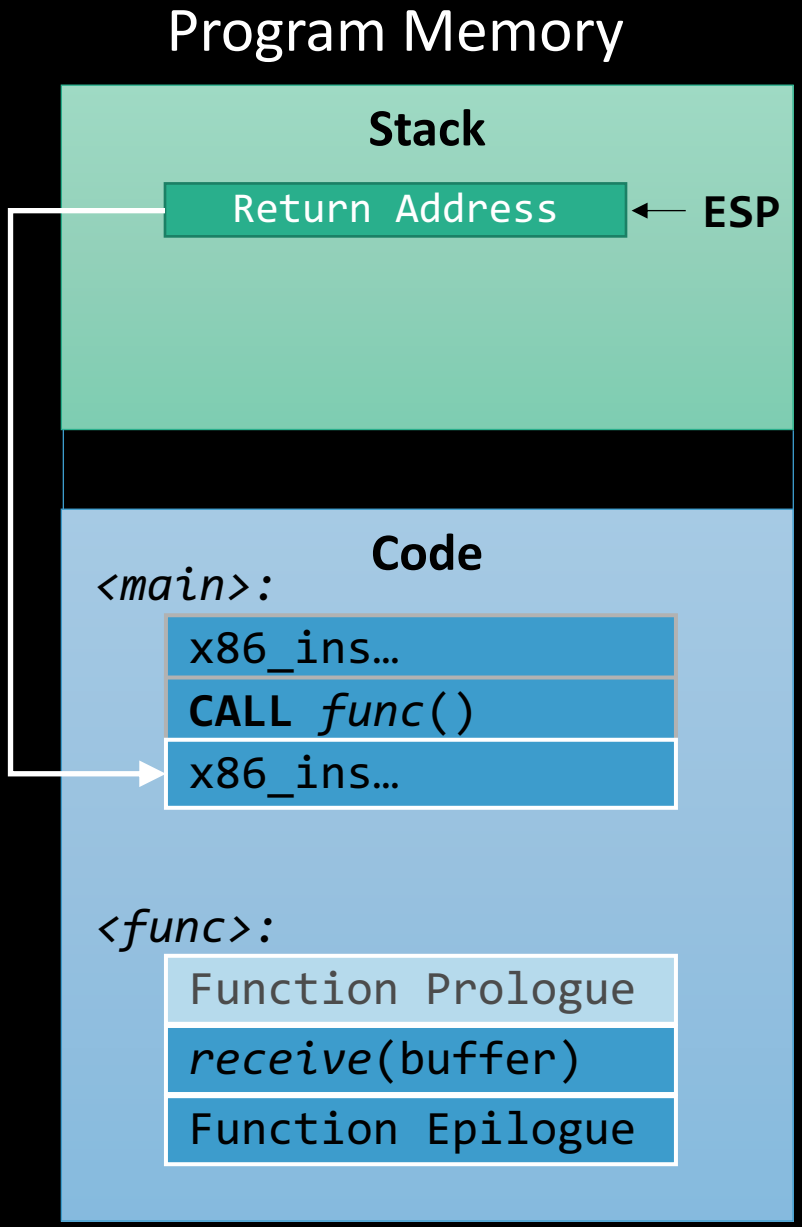

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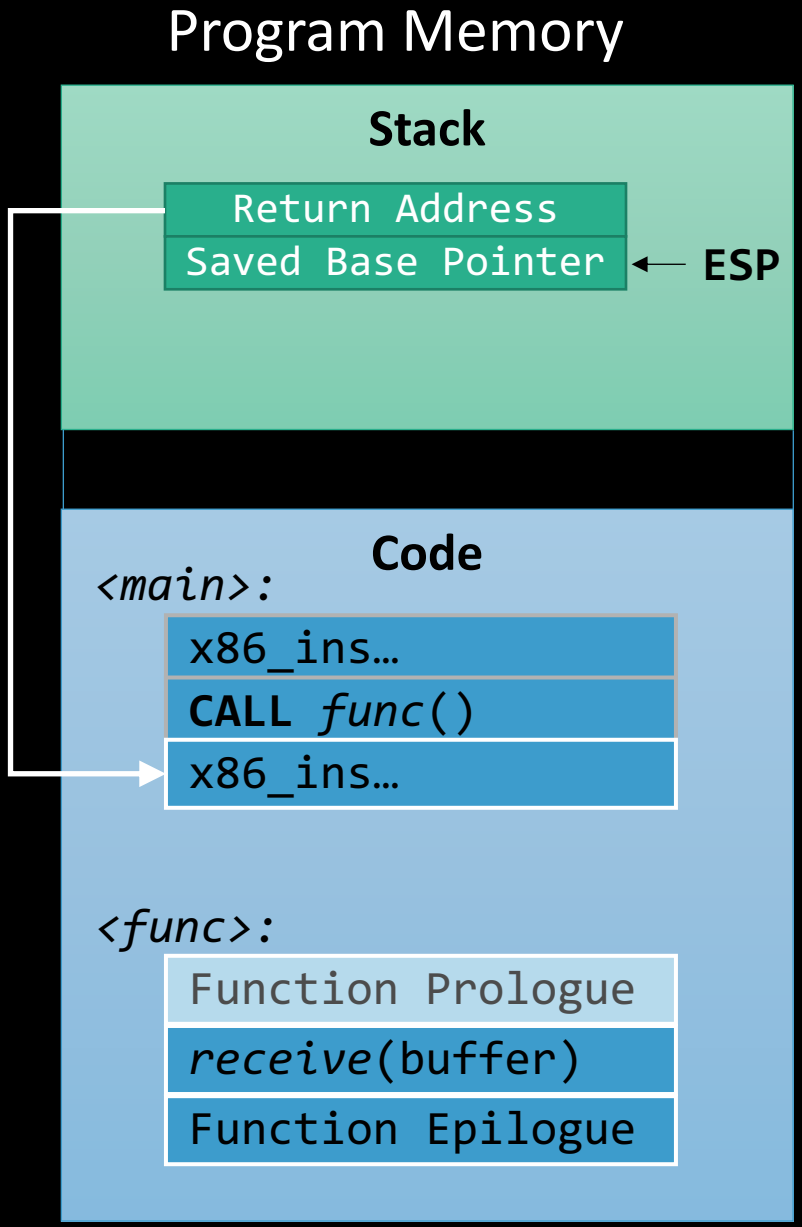

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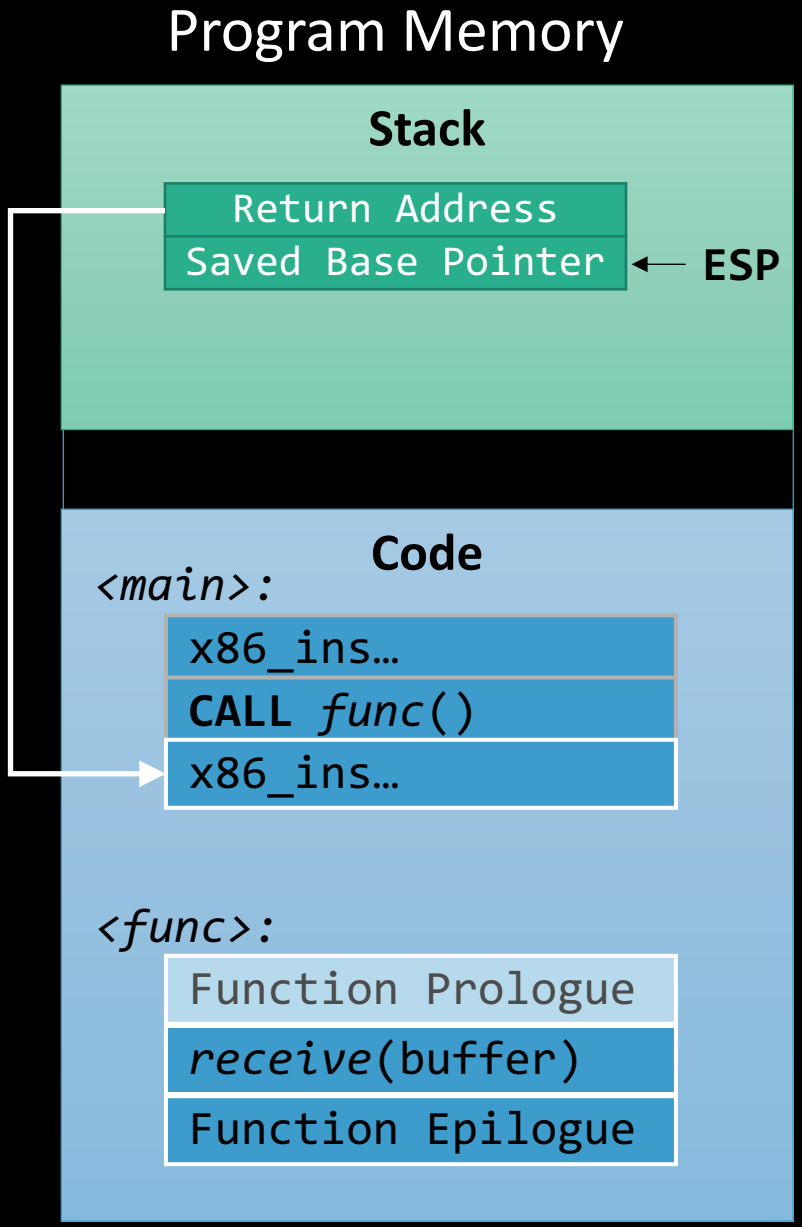

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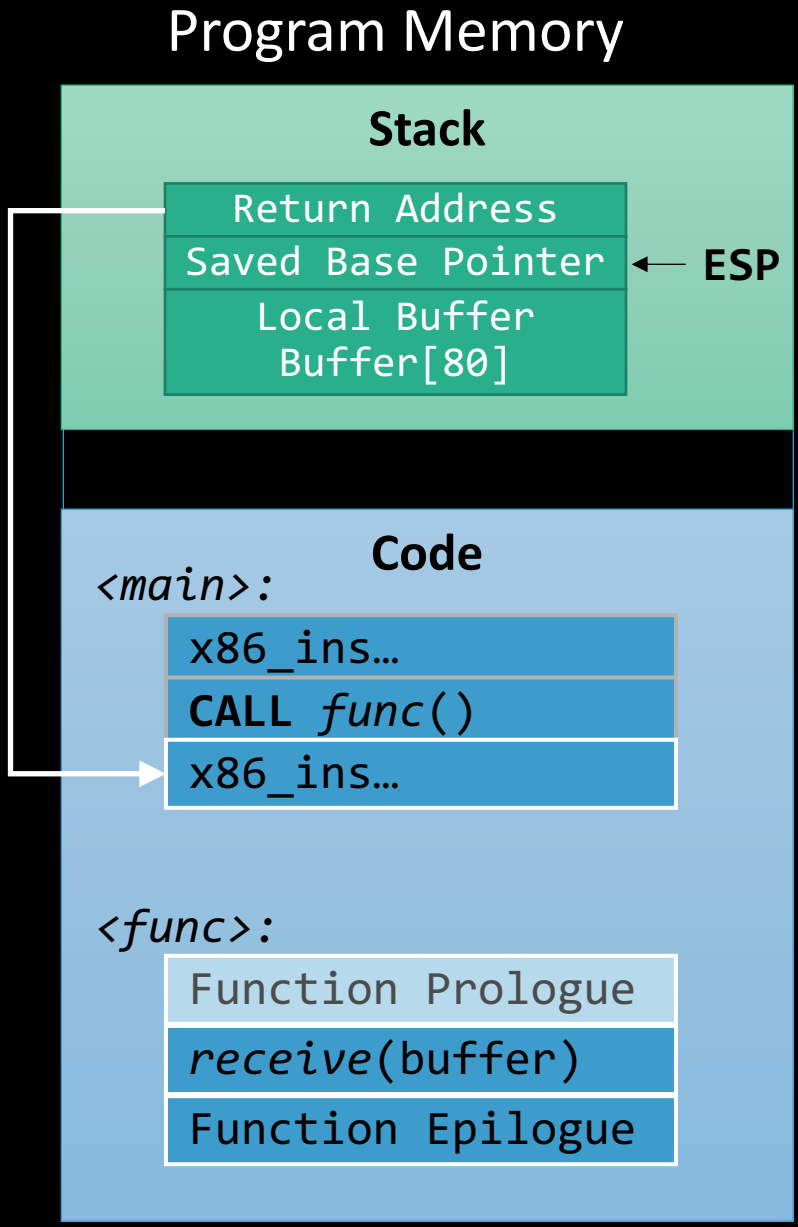

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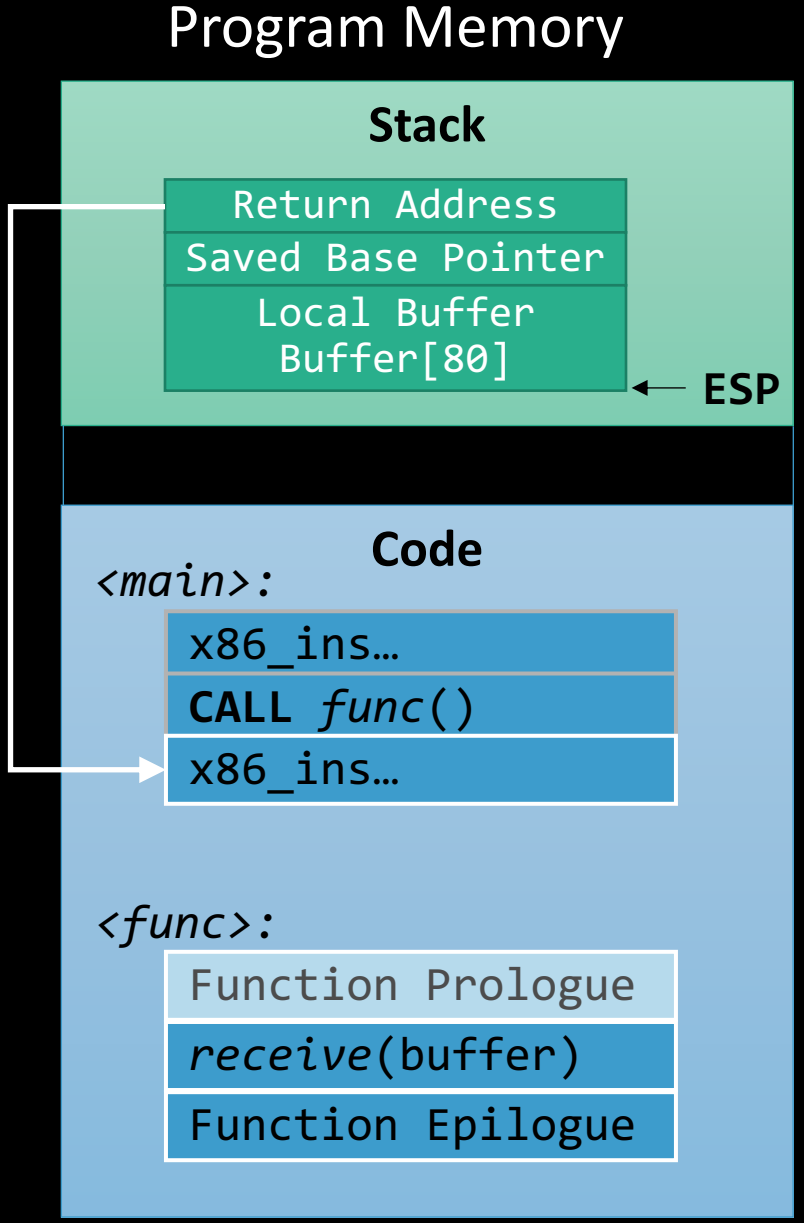
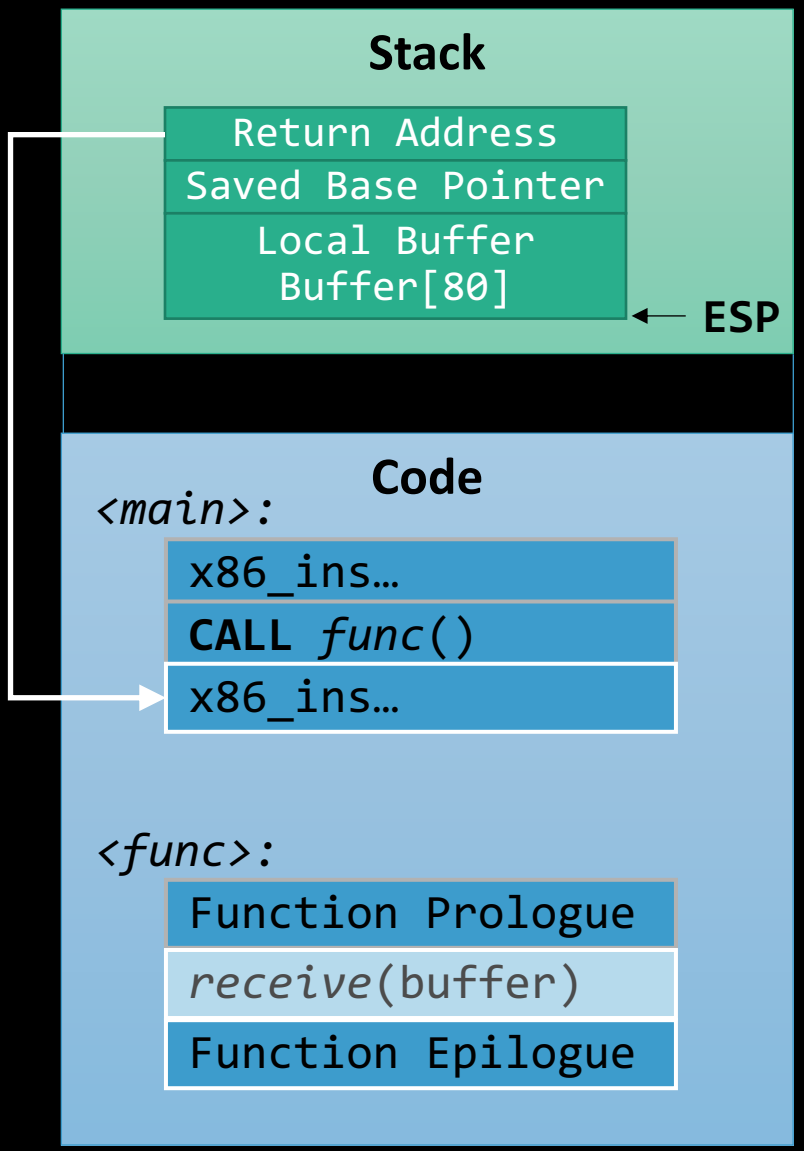


Example: Code Injection Attack

Corrupt Control Structures

Program Memory



Example: Code Injection Attack

Program Memory

Stack

Return Address
Saved Base Pointer
Local Buffer
Buffer[80]

← **ESP**

Corrupt Control Structures

Code

<main>:

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CALL *func*()
x86_ins…

<func>:

Function Prologue
receive(buffer)
Function Epilogue

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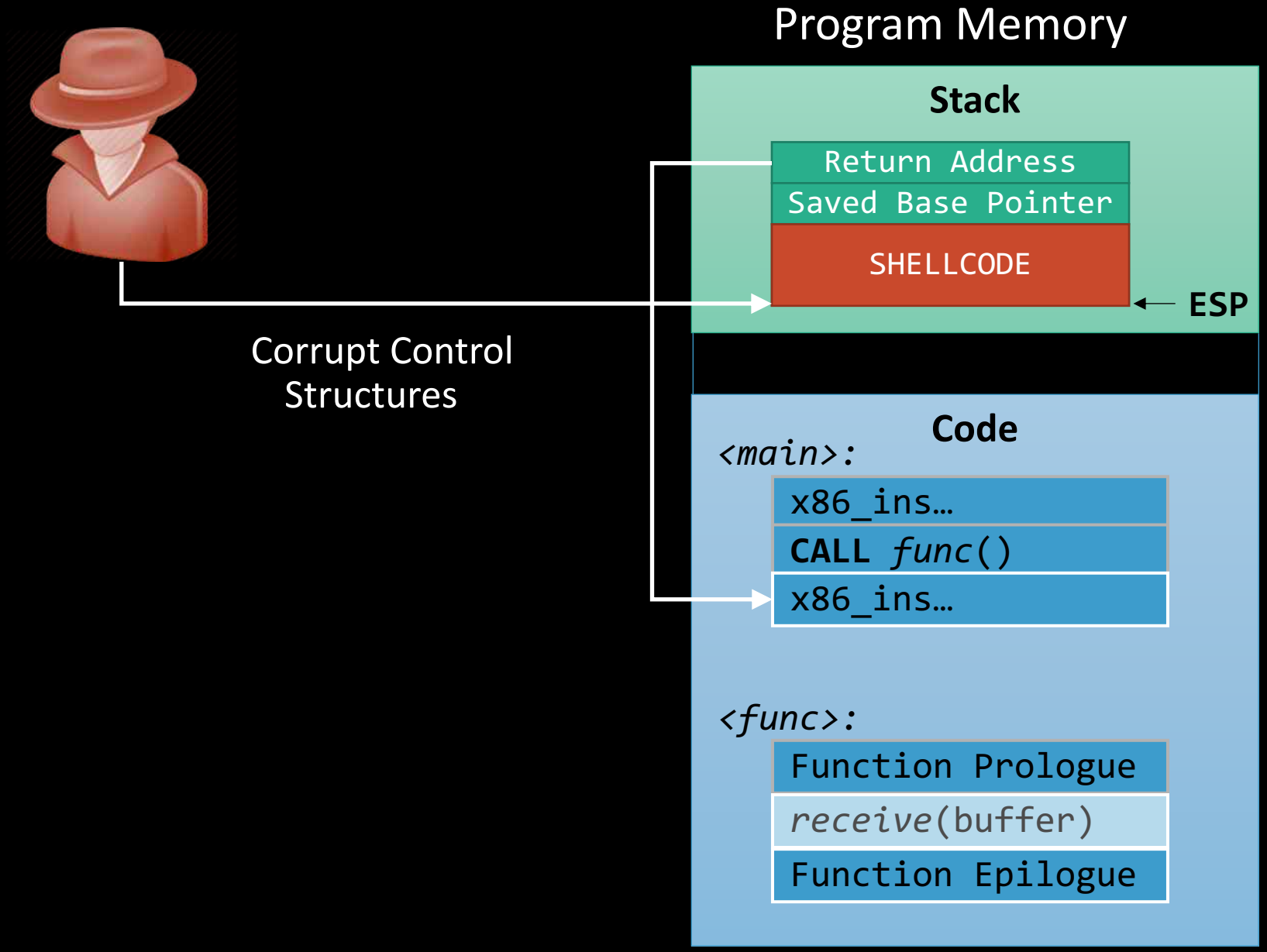

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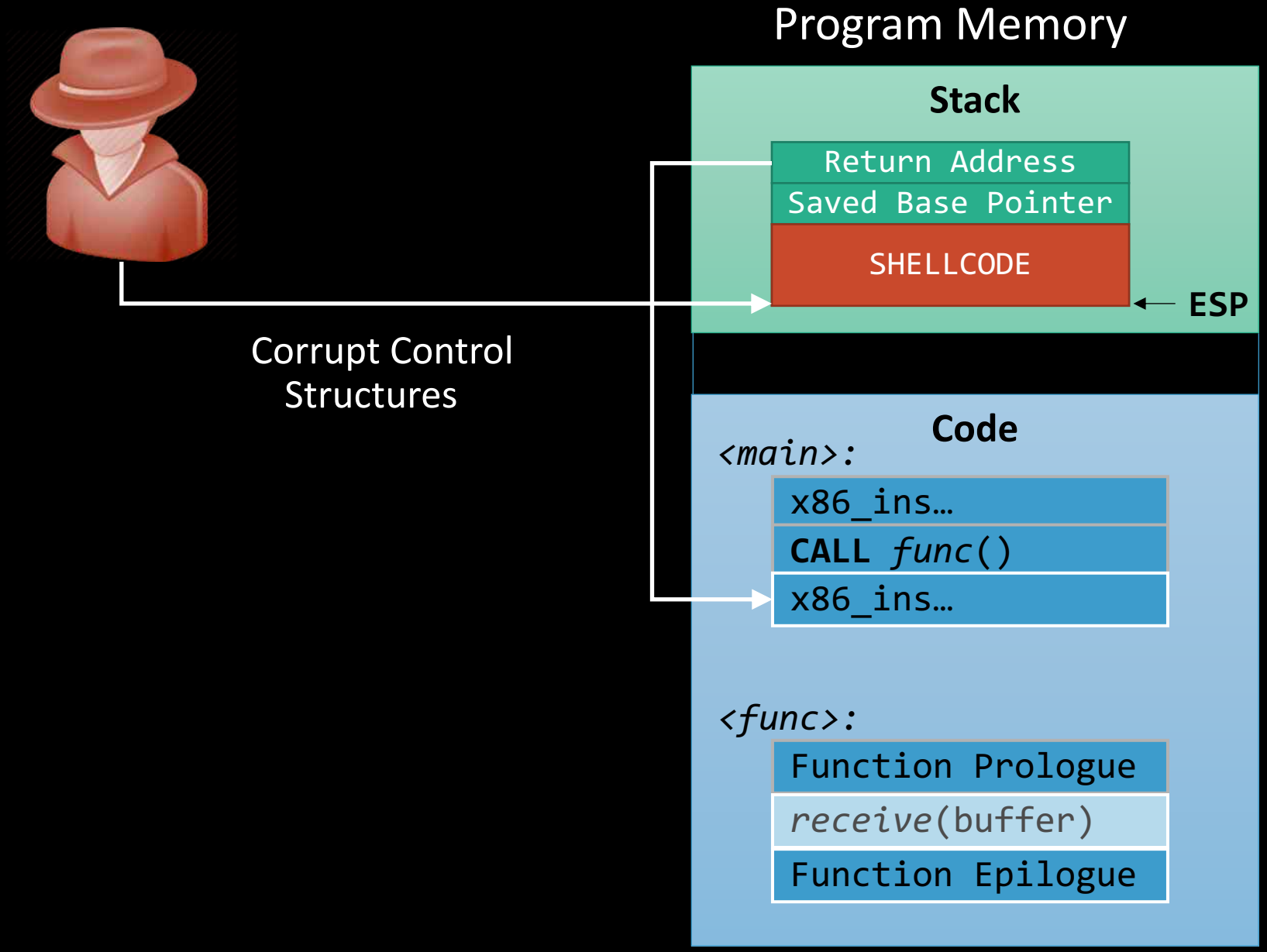

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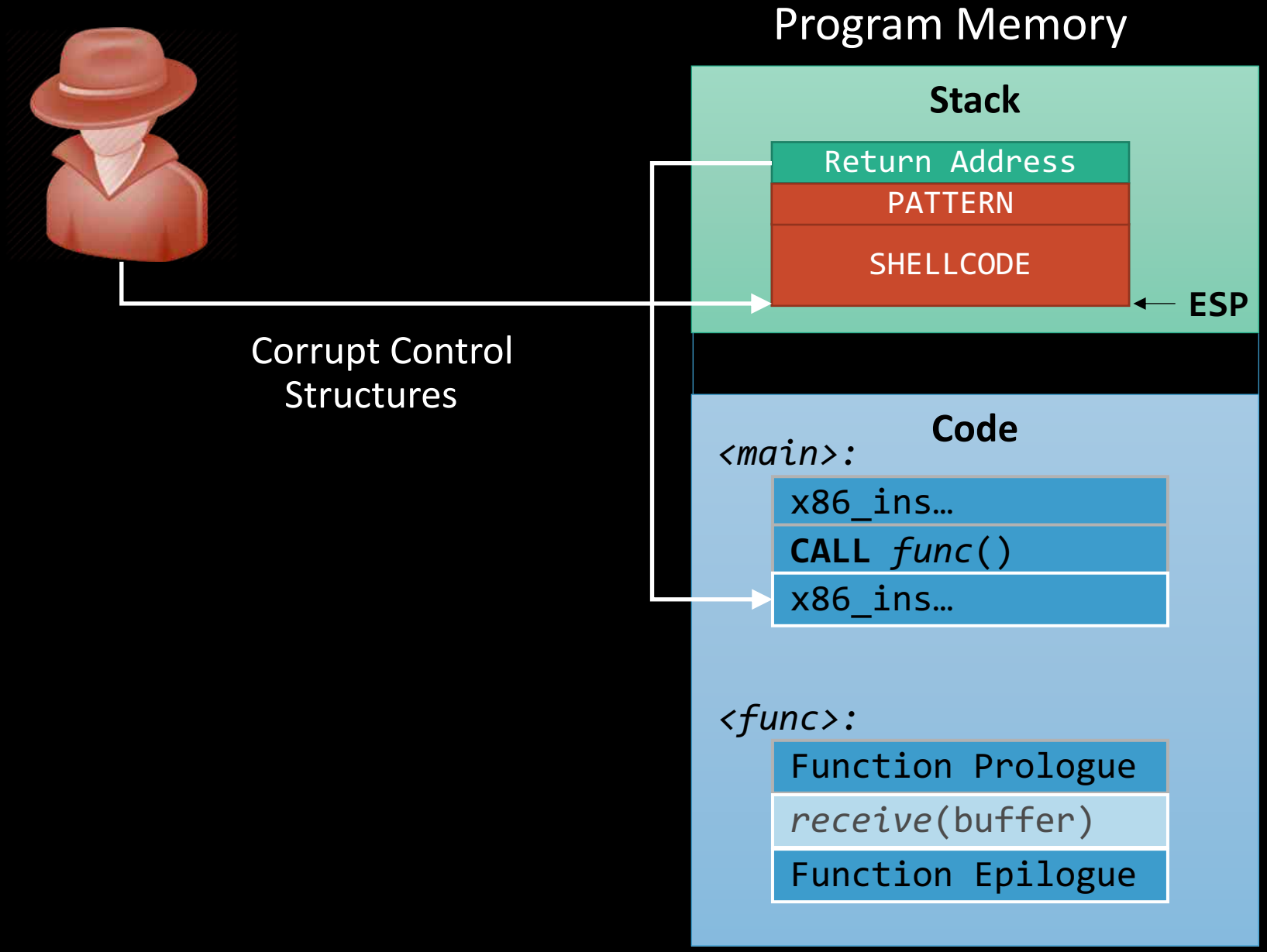

Example: Code Injection Attack

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NEW RETURN ADDR

PATTERN

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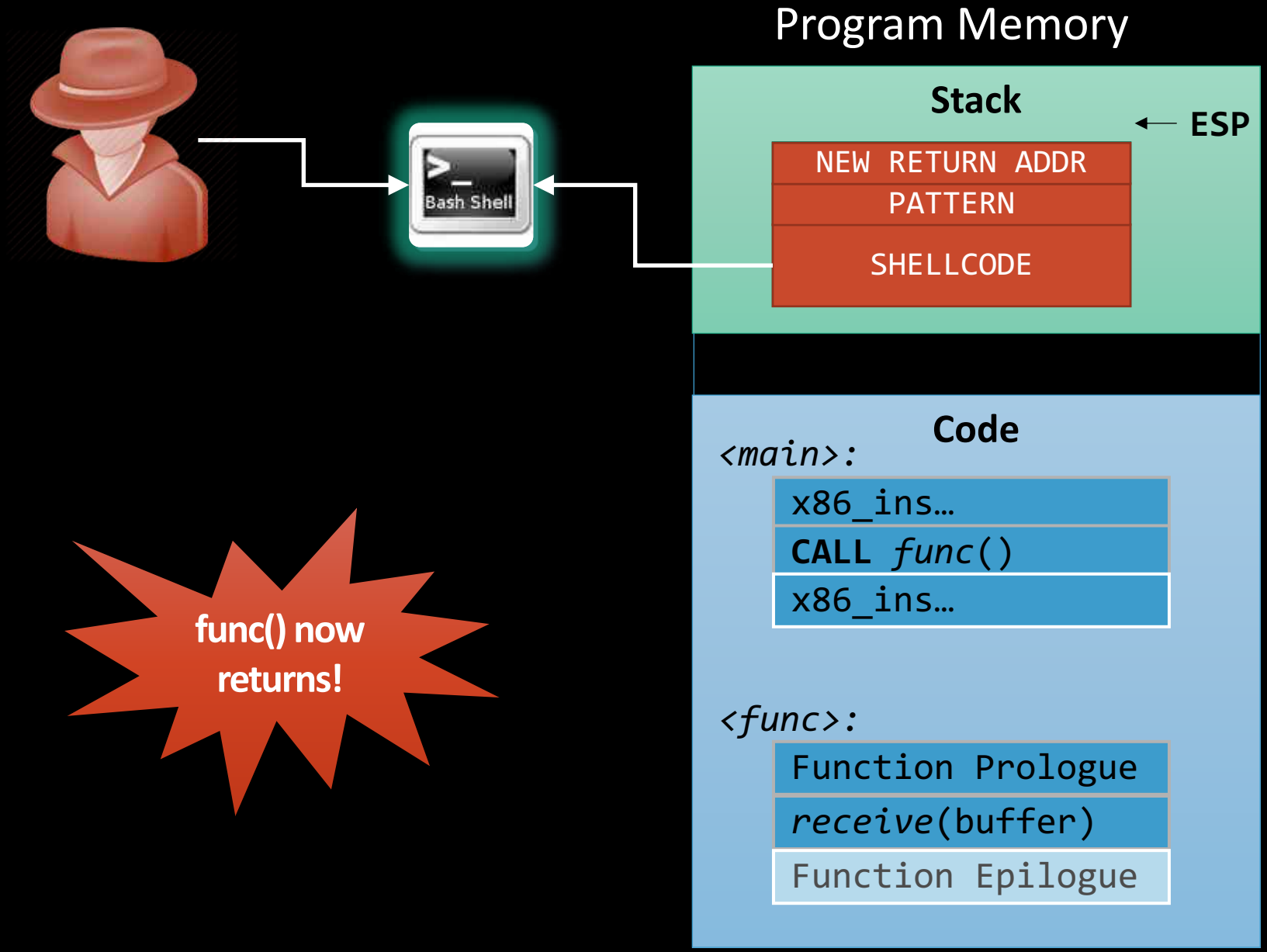
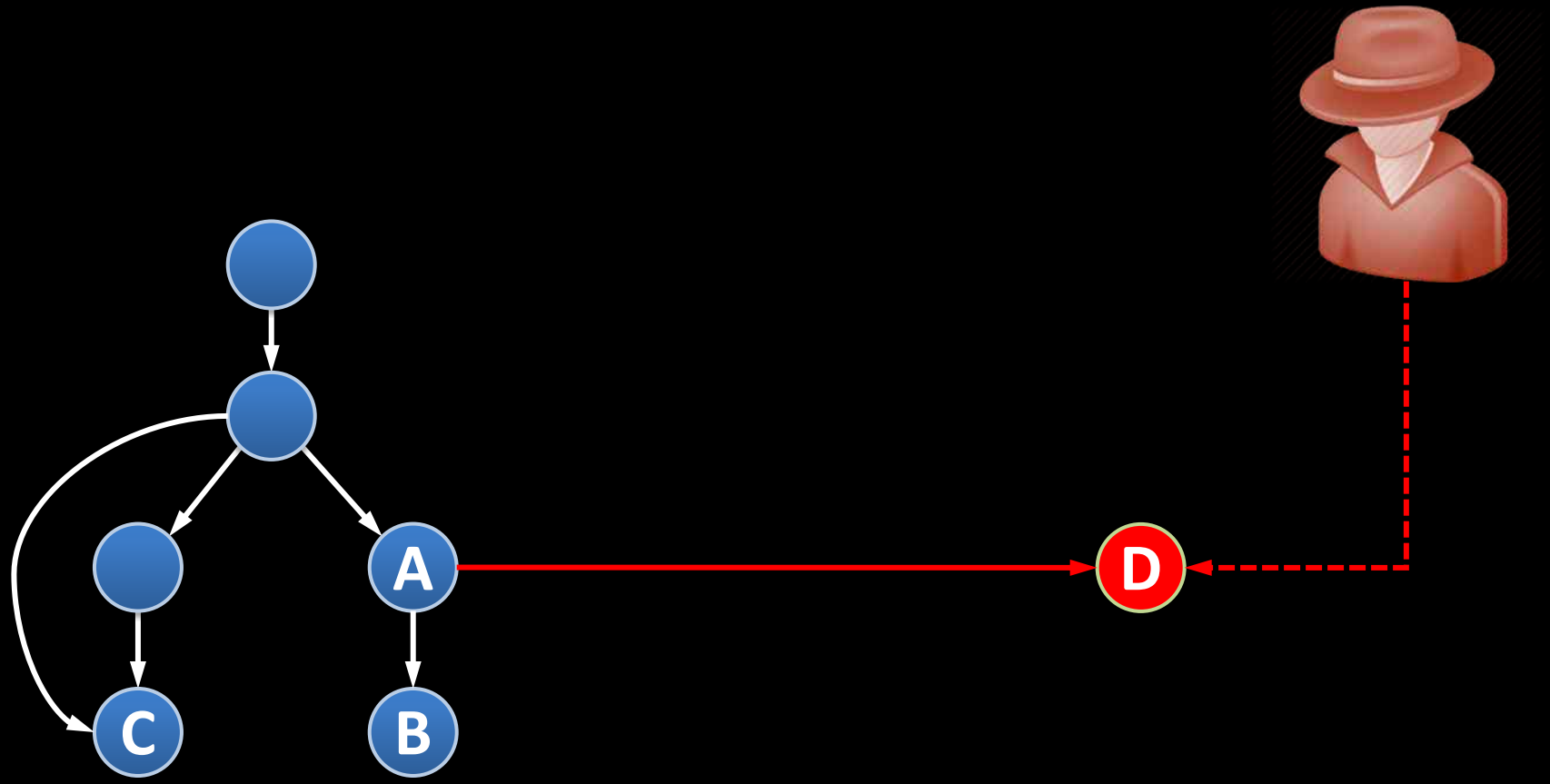


Data Execution Prevention (DEP)

- Prevent execution from a writeable memory (data) area



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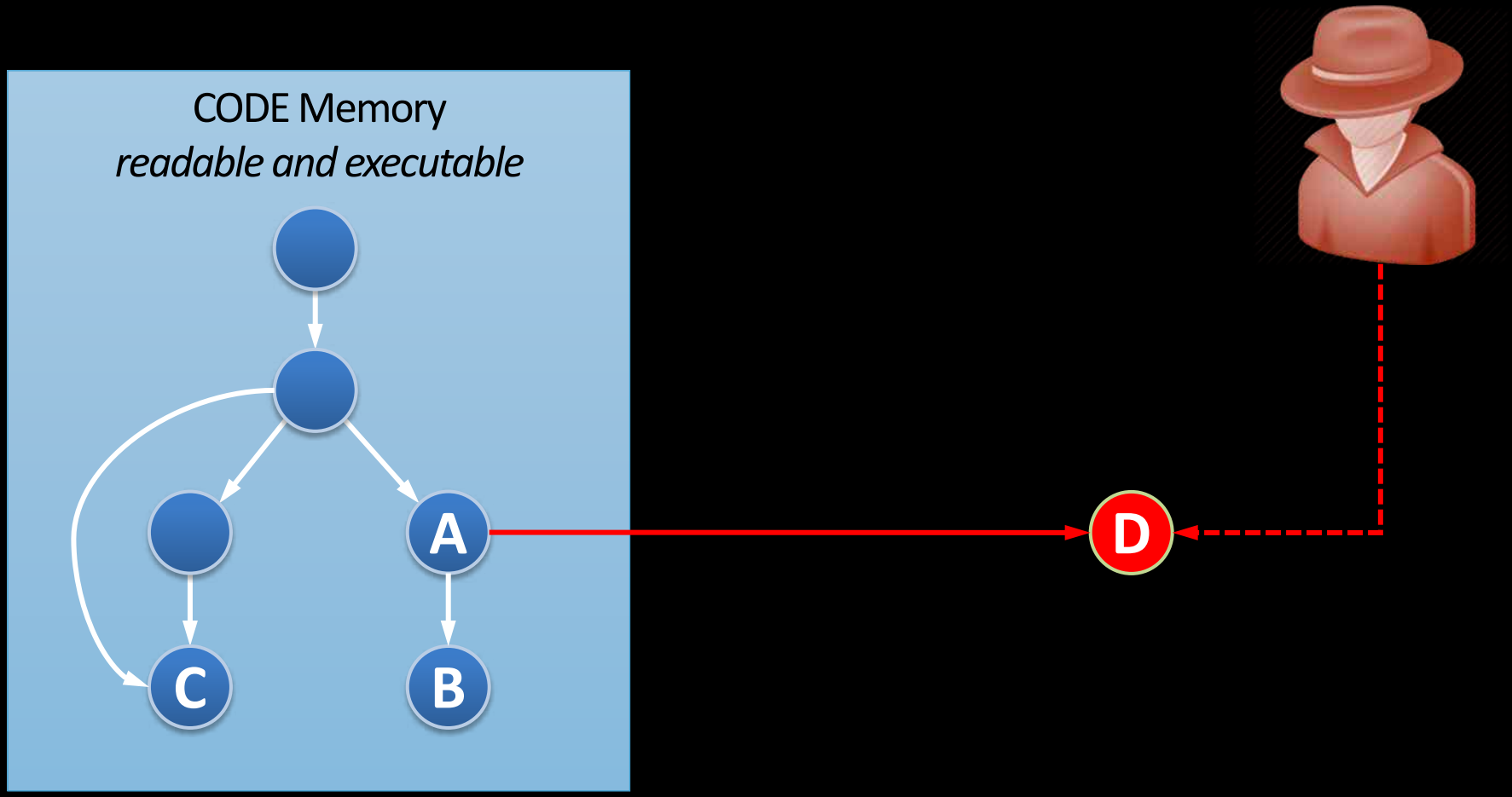

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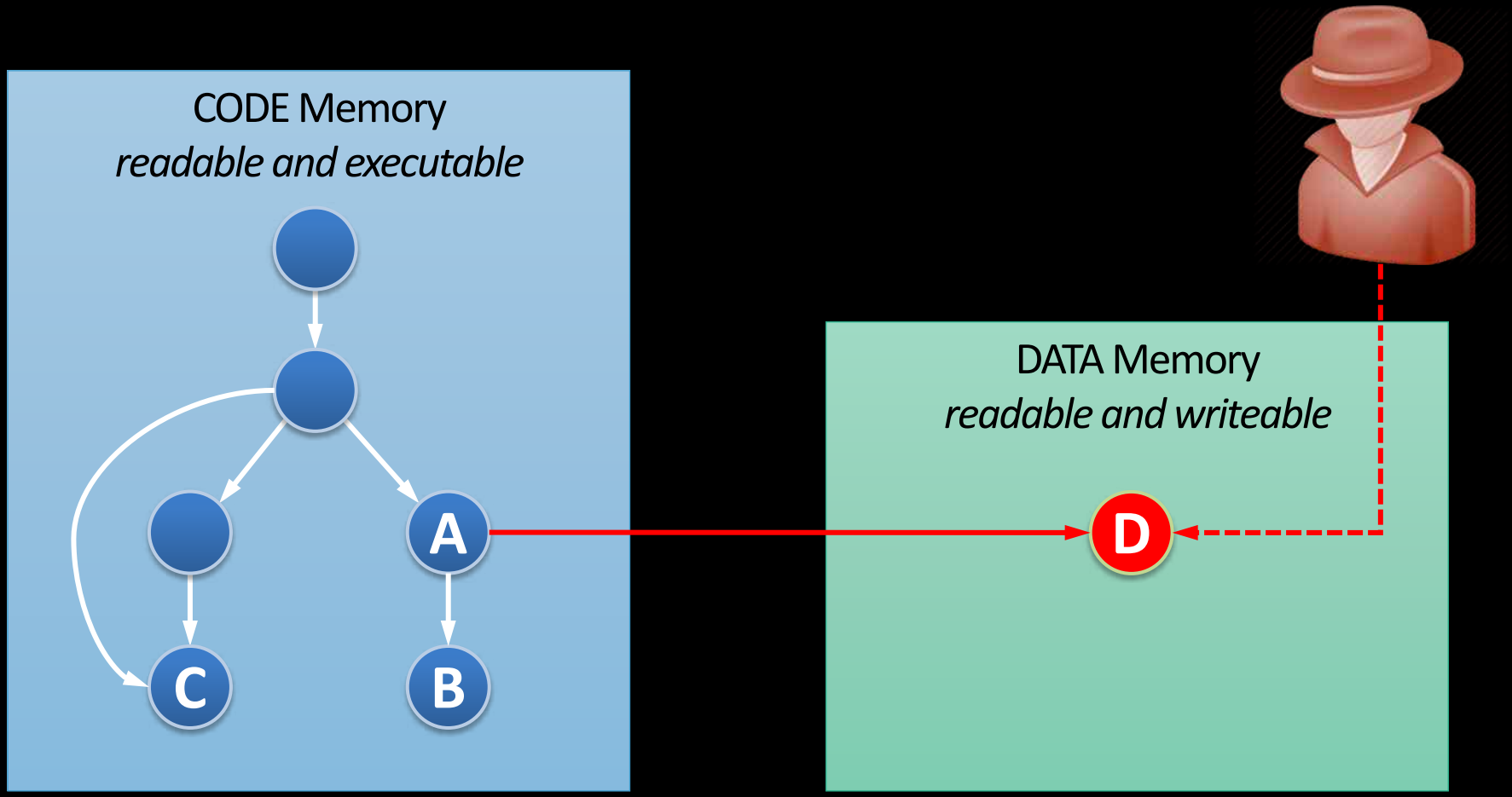

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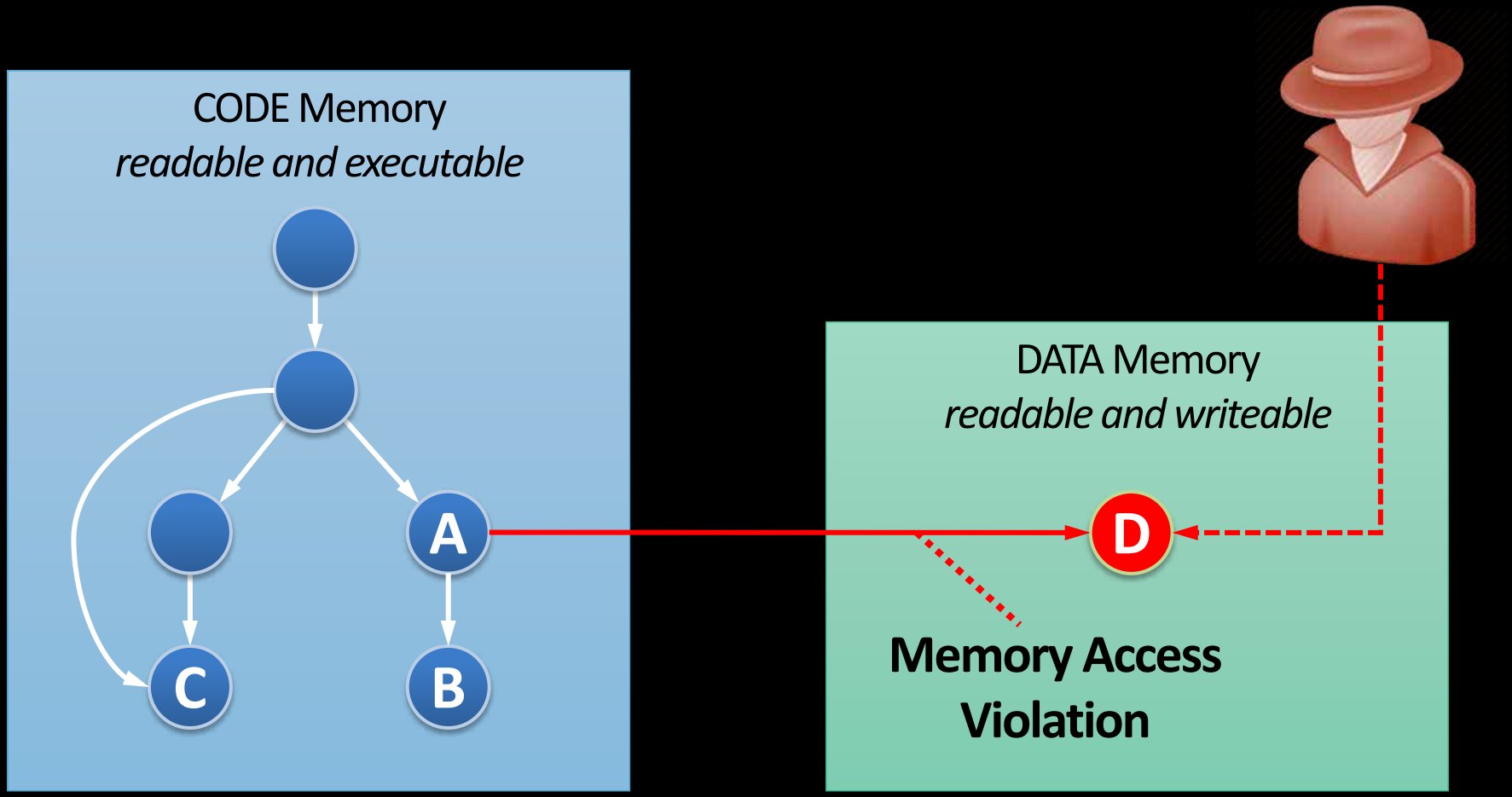
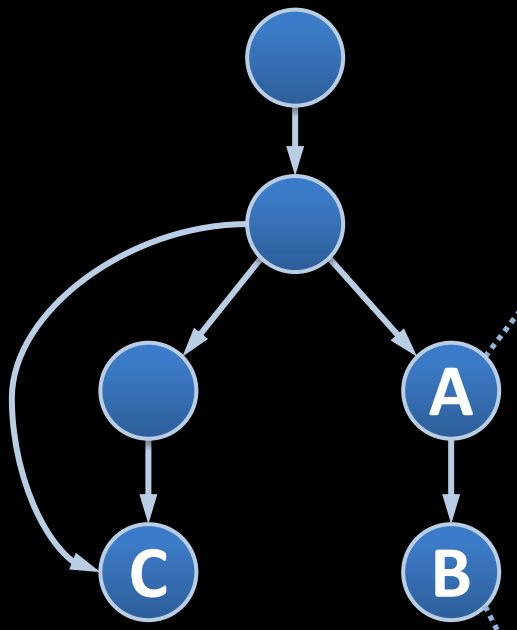


General Principle of Code-Reuse Attacks

Control-Flow Graph (CFG)



Basic Block (BBL) A

ENTRY
asm_ins,
EXIT

BBL B

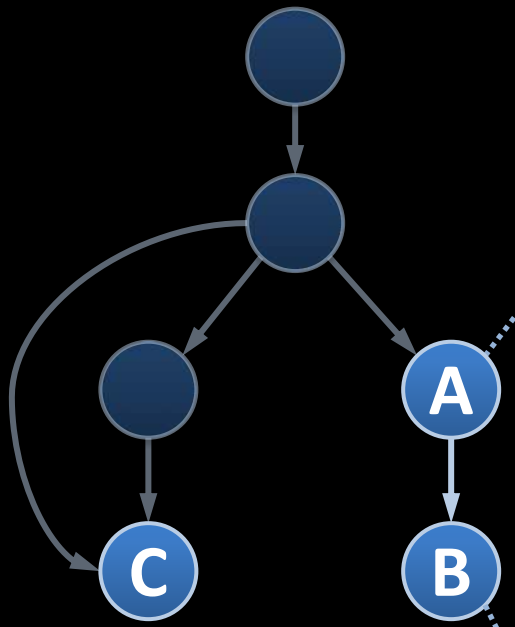
ENTRY
asm_ins, …
EXIT

Data flows

Program flows

General Principle of Code-Reuse Attacks

Control-Flow Graph (CFG)



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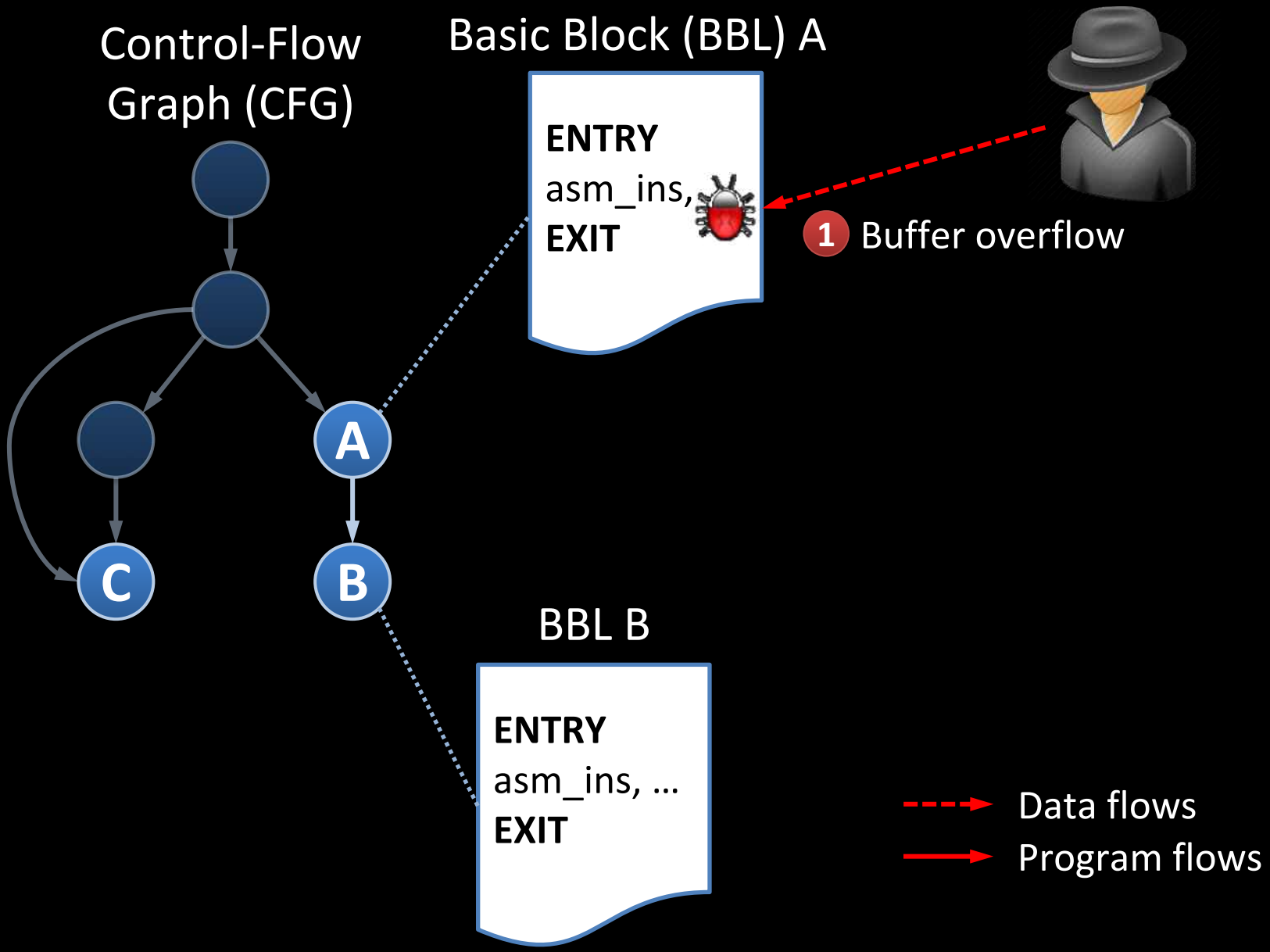
Data flows

Program flows

General Principle of Code-Reuse Attacks



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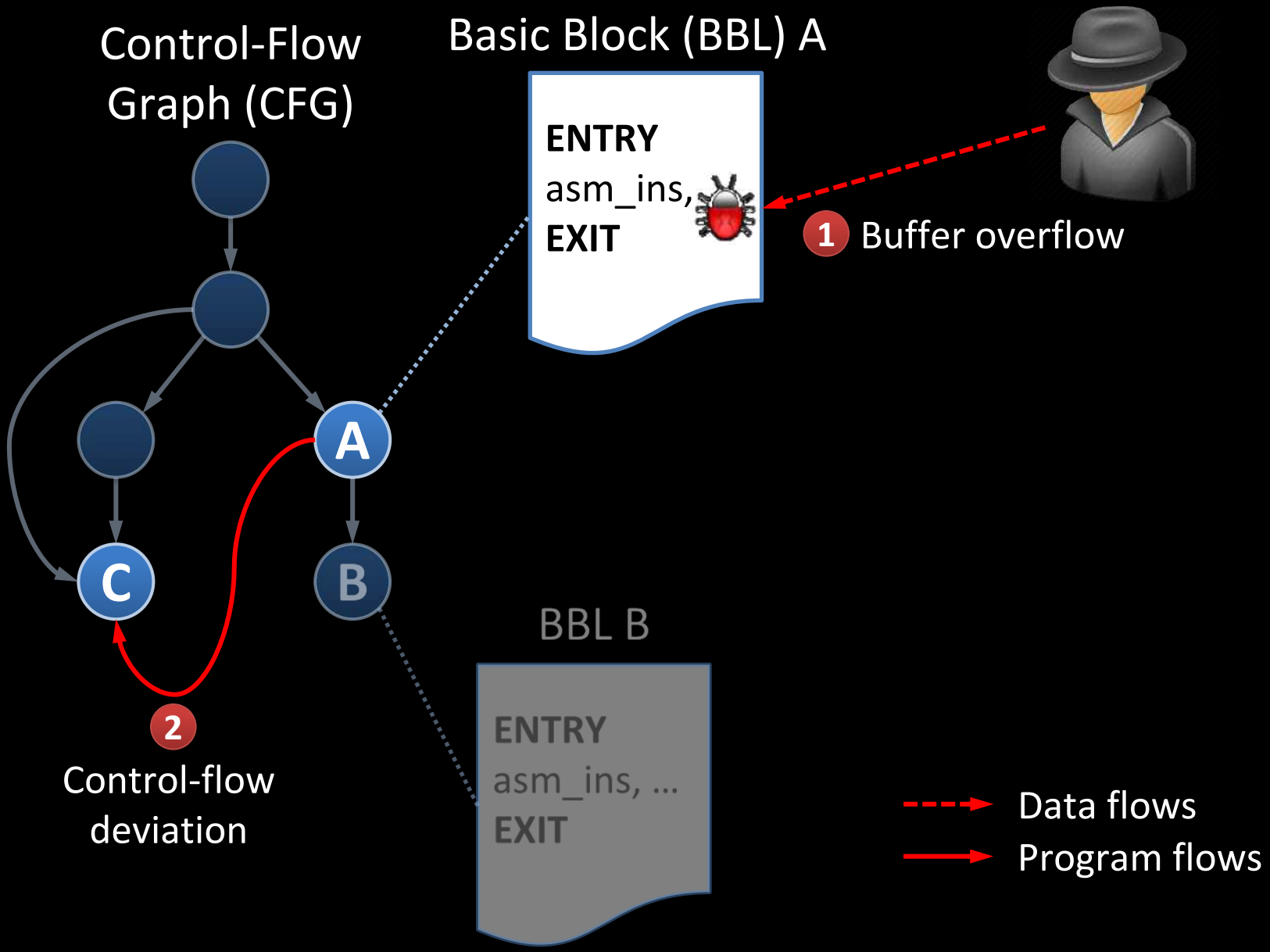

Generalization of return-into-libc attacks: return-oriented programming [Shacham, ACM CCS 2007]

Big Picture

The New Y

Saturday, January 6, 2007

Daily Blog Tips awarded th

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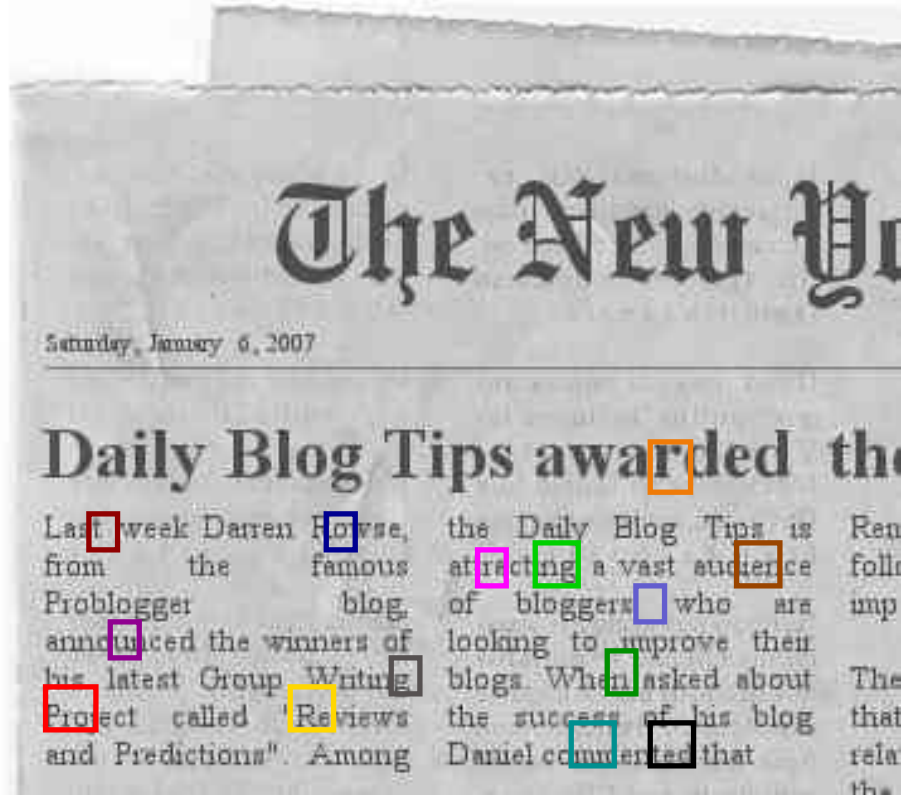

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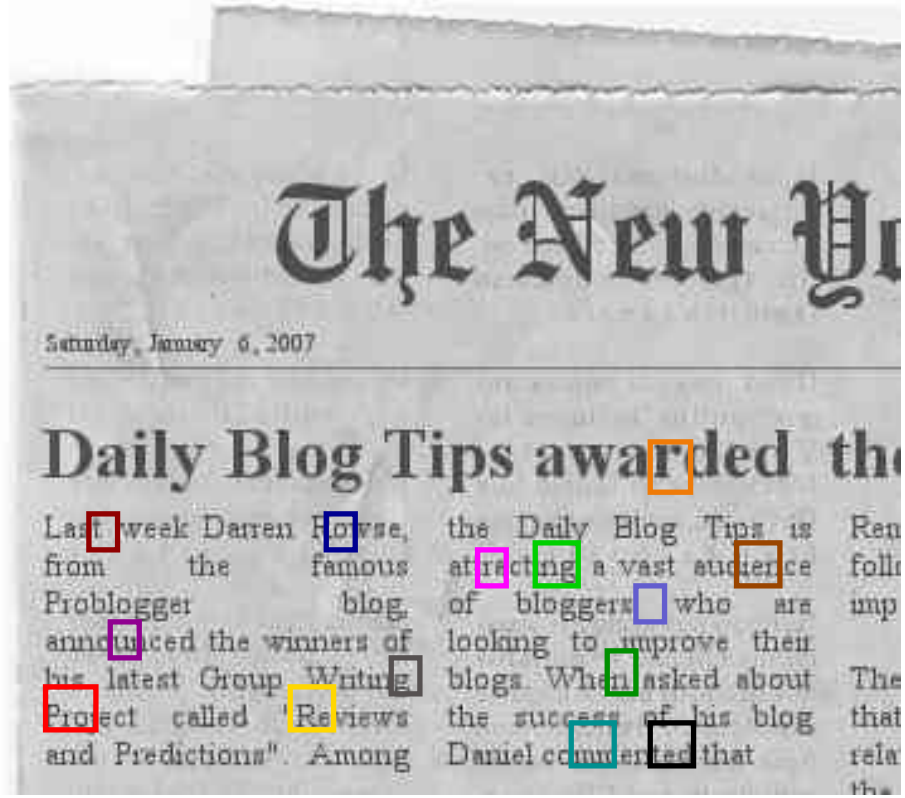

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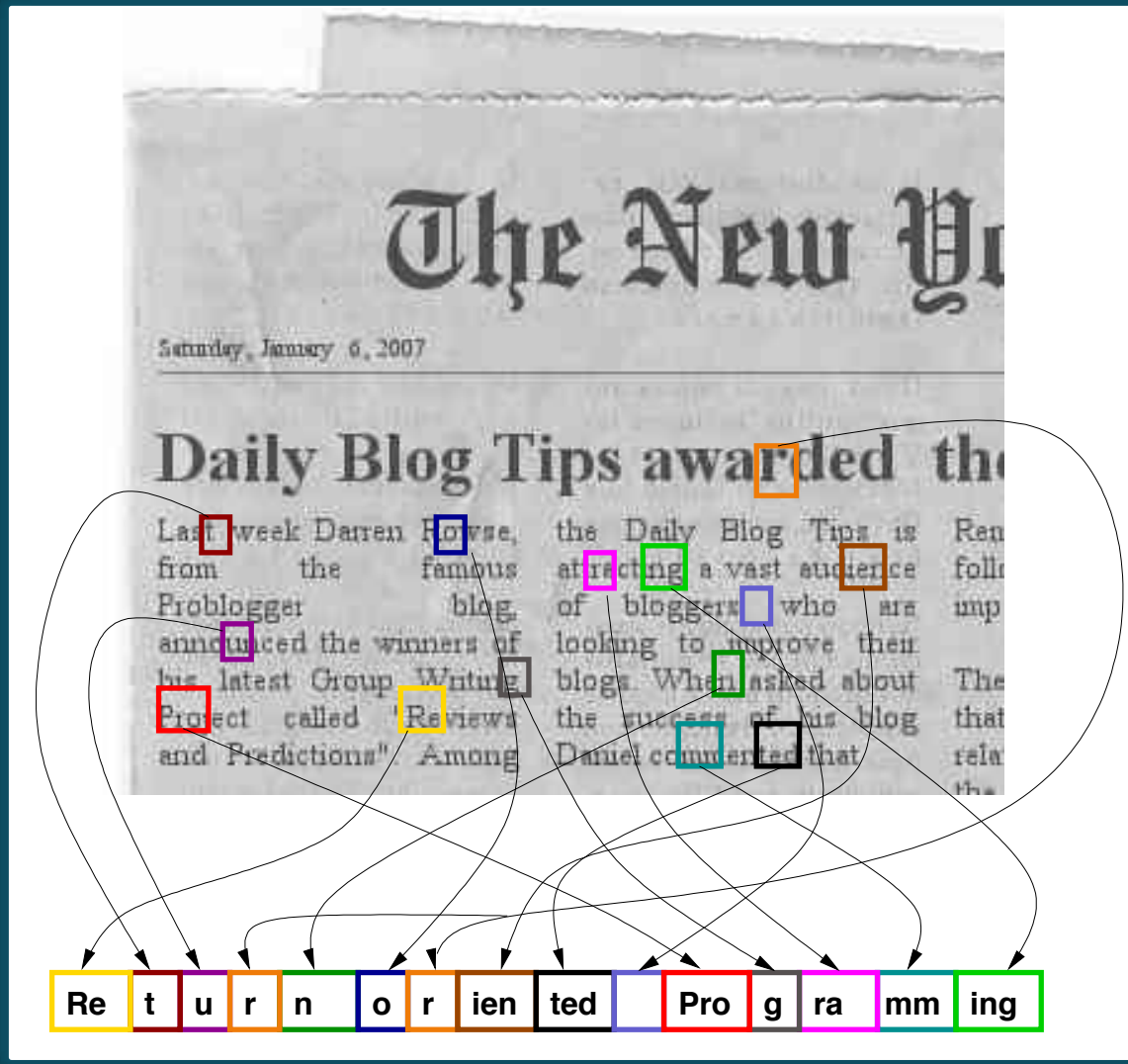
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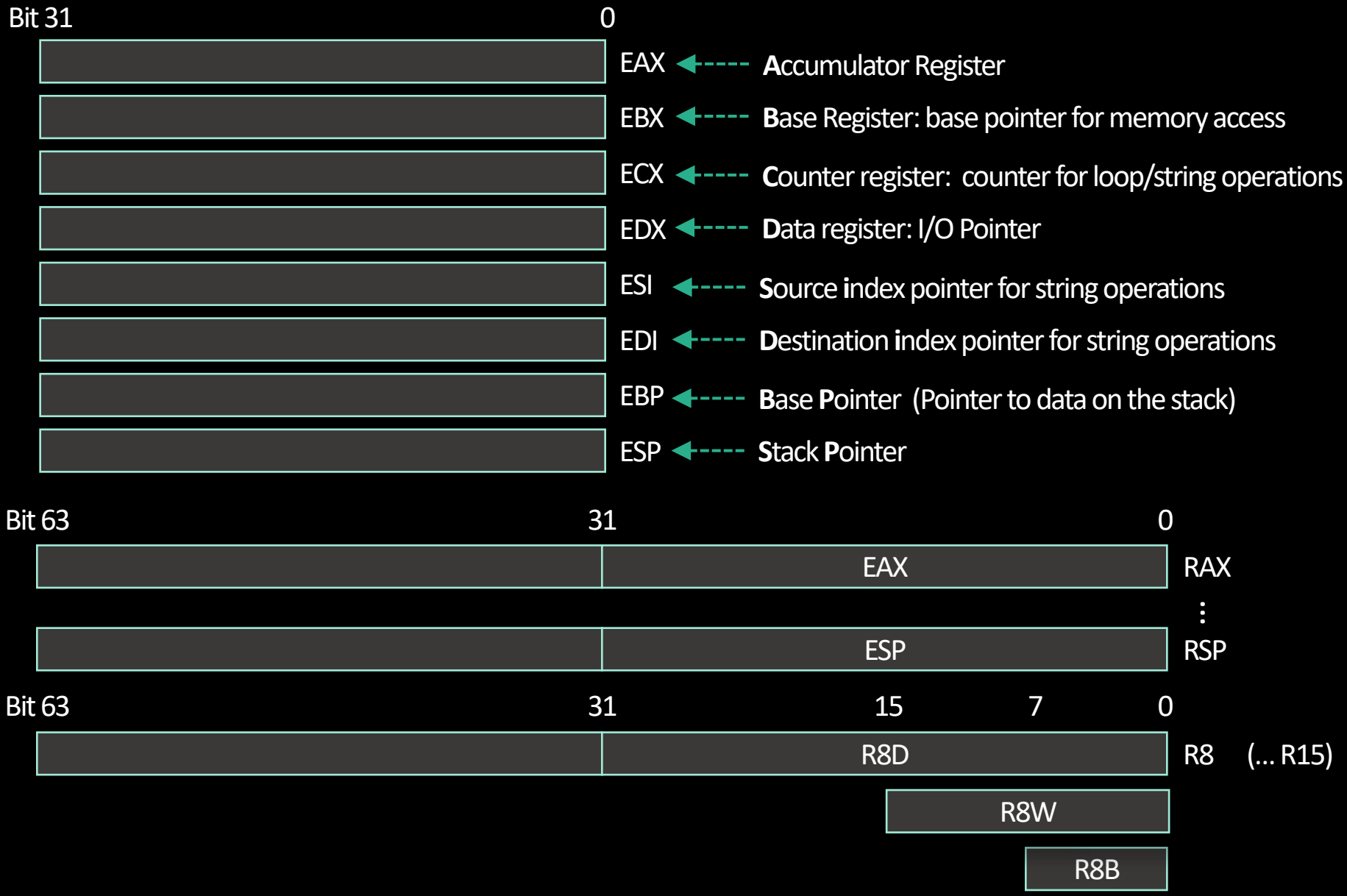
x86 and x64 CPU registers



Attack Technique: Overview on x86

Attack Technique: Overview on x86

Program Stack

Attack Technique: Overview on x86

Program Code

Sequence 1

Sequence 2

Sequence 3

Program Stack

Attack Technique: Overview on x86

Program Code

Sequence 1

Sequence 2

Sequence 3

Program Stack

Attack Technique: Overview on x86

Program Stack

Program Code

Sequence 1

```
x86_ins
ret
```

Sequence 2

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pop eax
pop ebx
ret
```

Sequence 3

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Attack Technique: Overview on x86

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EAX:

EBX:

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EAX:

EBX:

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Program Stack

Return Address 3

0xAABBCCDD

0X80102030

Return Address 2

Return Address 1

Program Code

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Sequence 2

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Program Stack

```
Return Address 3
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Return Address 1
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ESP →

EAX:

EBX:

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Sequence 3

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Program Stack

ESP → Return Address 3

0xAABBCCDD

0X80102030

Return Address 2

Return Address 1

EAX:	0x80102030
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Program Stack

ESP → Return Address 3

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Sequence 2

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Sequence 3

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x86_ins
ret
```

Program Stack

ESP

```
Return Address 3
0xAABBCCDD
0X80102030
Return Address 2
Return Address 1
```

EAX:	0x80102030
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Program Code

Sequence 1

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Sequence 2

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Sequence 3

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x86_ins
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...

ESP

Program Stack

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Return Address 3
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EAX:	0x80102030
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Memory Load Gadget on x86

Memory Load Gadget on x86

Program Stack

Memory Load Gadget on x86

Program Stack

Data Area

0x80102030: 0xDEADBEEF

Memory Load Gadget on x86

Program Stack

Data Area

0x80102030: 0xDEADBEEF

Memory Load Gadget on x86

Program Stack

Program Code

Sequence 2

```
mov eax,[eax+0x20]
ret
```

Sequence 1

```
pop eax
ret
```

Data Area

0x80102030: 0xDEADBEEF

Memory Load Gadget on x86

Program Code

Sequence 2

```
mov eax,[eax+0x20]
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Sequence 1

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Program Stack

Data Area

0x80102030: 0xDEADBEEF

EAX:

Memory Load Gadget on x86

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Program Stack

Data Area

0x80102030: 0xDEADBEEF

EAX:

Memory Load Gadget on x86

Program Code

Sequence 2

```
mov eax,[eax+0x20]
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Sequence 1

```
pop eax
ret
```

Program Stack

…

Return Address 2

0x80102010

ESP → Return Address 1

Data Area

0x80102030: 0xDEADBEEF

EAX:

Memory Load Gadget on x86

Program Code

Sequence 2

```
mov eax,[eax+0x20]
ret
```

Sequence 1

```
pop eax
ret
```

Program Stack

```
...
Return Address 2
0x80102010
Return Address 1
```

ESP

Data Area

0x80102030: `0xDEADBEEF`

EAX:

Memory Load Gadget on x86

Program Code

Sequence 2

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ret
```

Sequence 1

```
pop eax
ret
```

Program Stack

…

Return Address 2

ESP → 0x80102010

Return Address 1

Data Area

0x80102030: 0xDEADBEEF

EAX:

Memory Load Gadget on x86

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Sequence 1

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pop eax
ret
```

Program Stack

```
...
Return Address 2
0x80102010
Return Address 1
```

ESP

Data Area

0x80102030: 0xDEADBEEF

EAX: 0x80102010

Memory Load Gadget on x86

Program Code

Sequence 2

```
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Program Stack

ESP →

…
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Data Area

0x80102030:

0xDEADBEEF

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Data Area

0x80102030:

0xDEADBEEF

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ESP →

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EAX: `0xDEADBEEF`

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Program Stack

ESP →

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Return Address 1
```

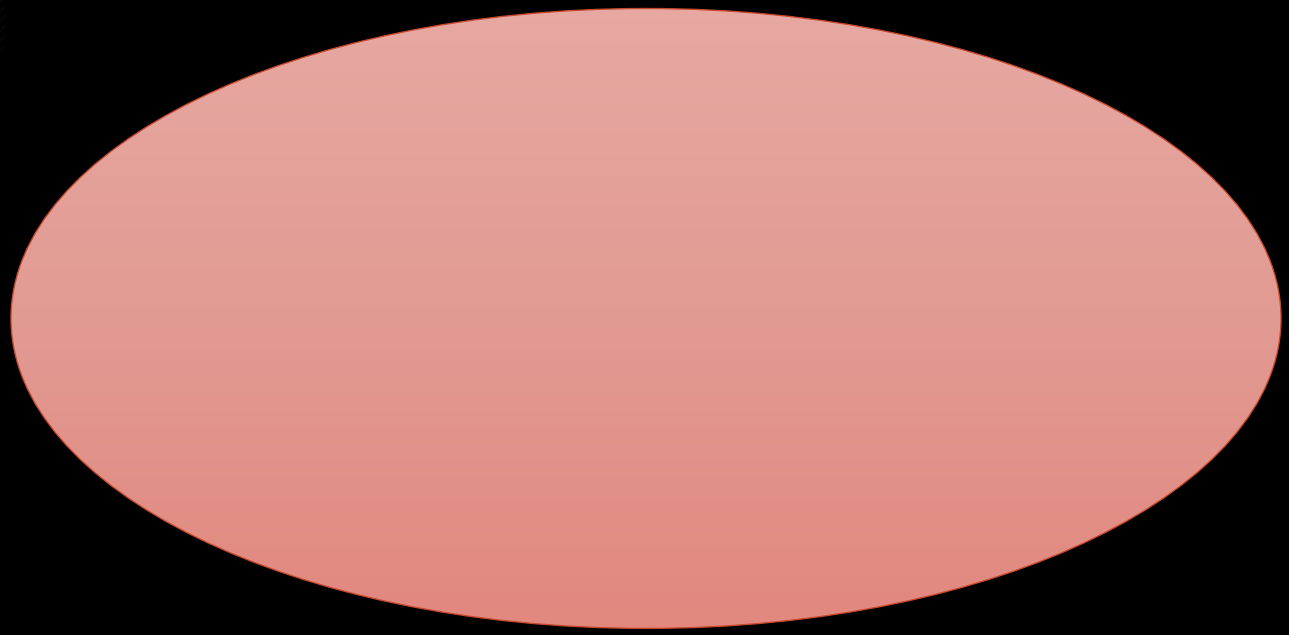
Data Area

0x80102030:

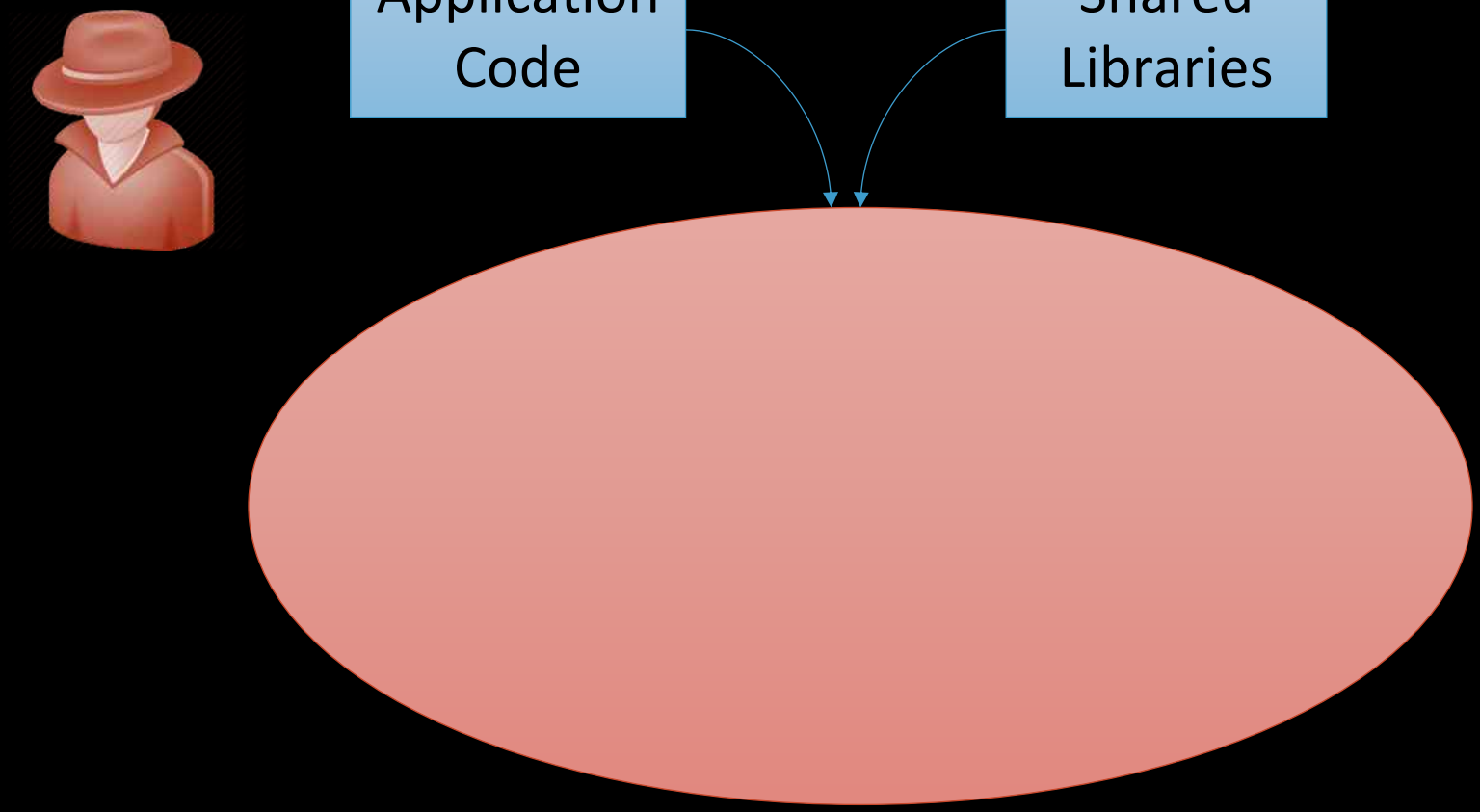
```
0xDEADBEEF
```

EAX: `0xDEADBEEF`

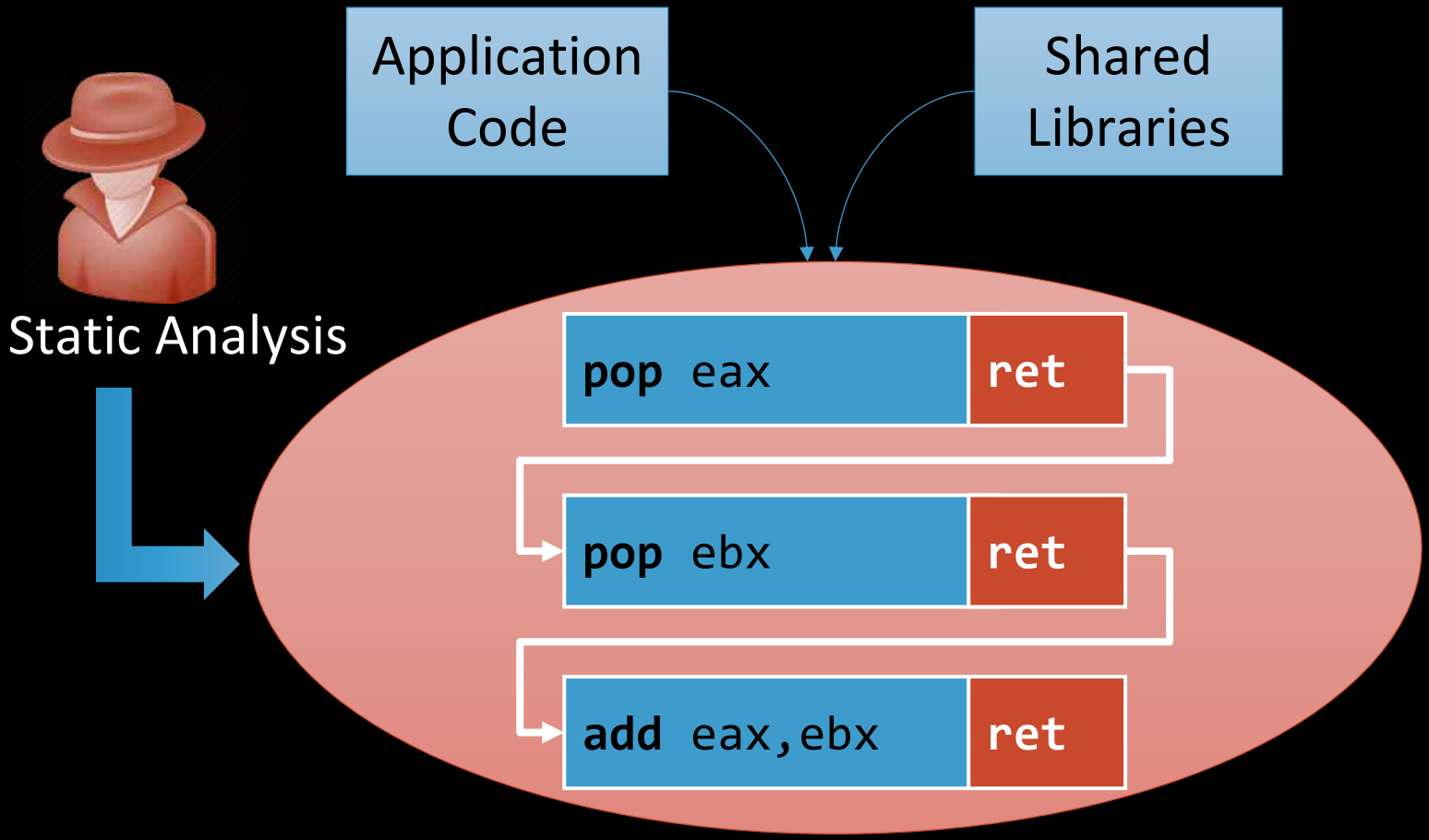
Code Base and Turing-Completeness



Code Base and Turing-Completeness



Code Base and Turing-Completeness



Code Base and Turing-Completeness

Static Analysis

Application Code

Shared Libraries

Cond. JMP

STORE

LOAD

GADGET SPACE

Turing-complete language

Mandatory

Code Base and Turing-Completeness

Static Analysis

Application Code

Shared Libraries

MOV

CALL

Uncond. JMP

Logic.

Cond. JMP

STORE

LOAD

Arith.

GADGET SPACE

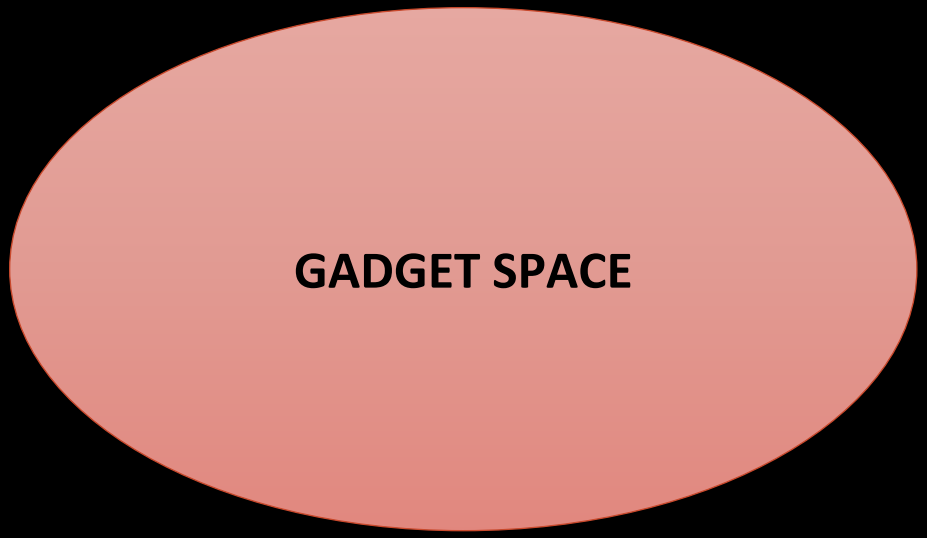
Optional

Mandatory

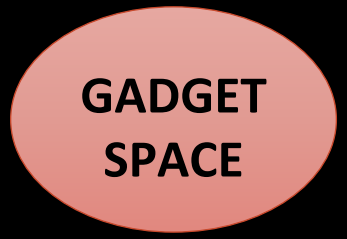
Turing-complete language

Gadget Space on Different Architectures

Architectures with no memory alignment, e.g., Intel x86



Architectures with memory alignment, e.g., SPARC, ARM



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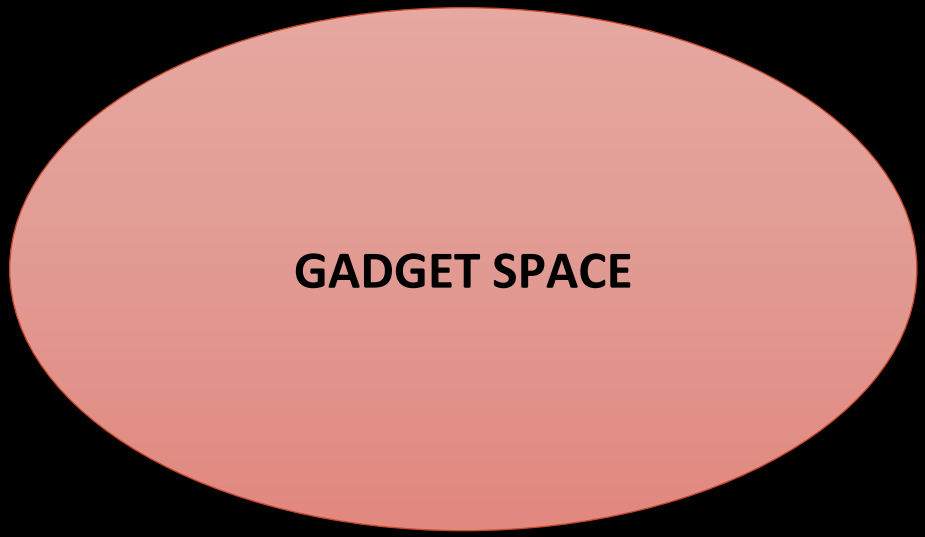

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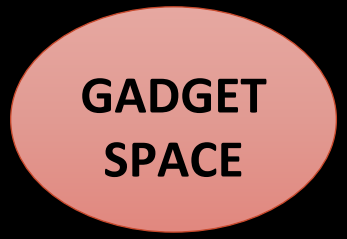

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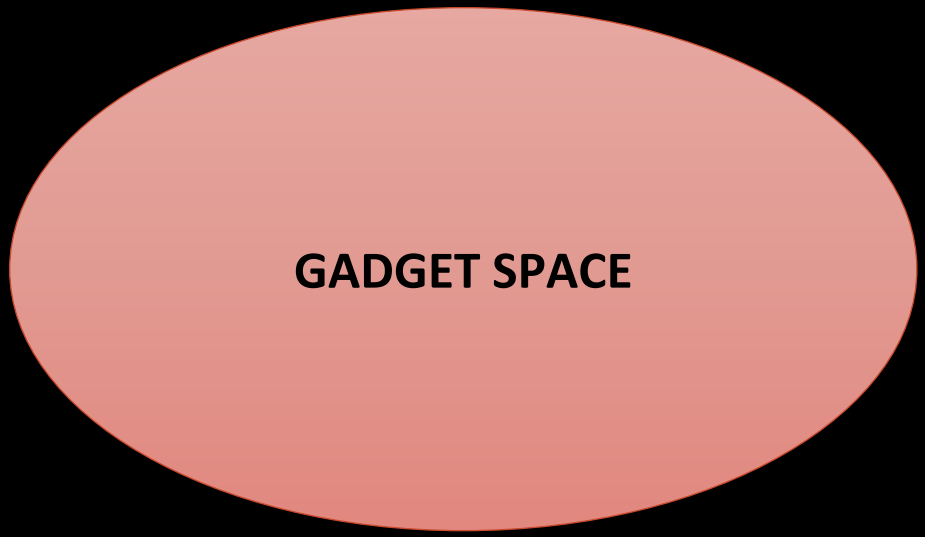

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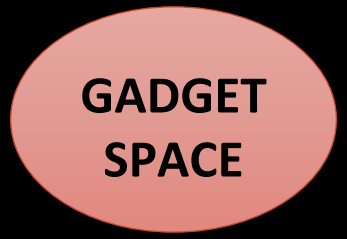

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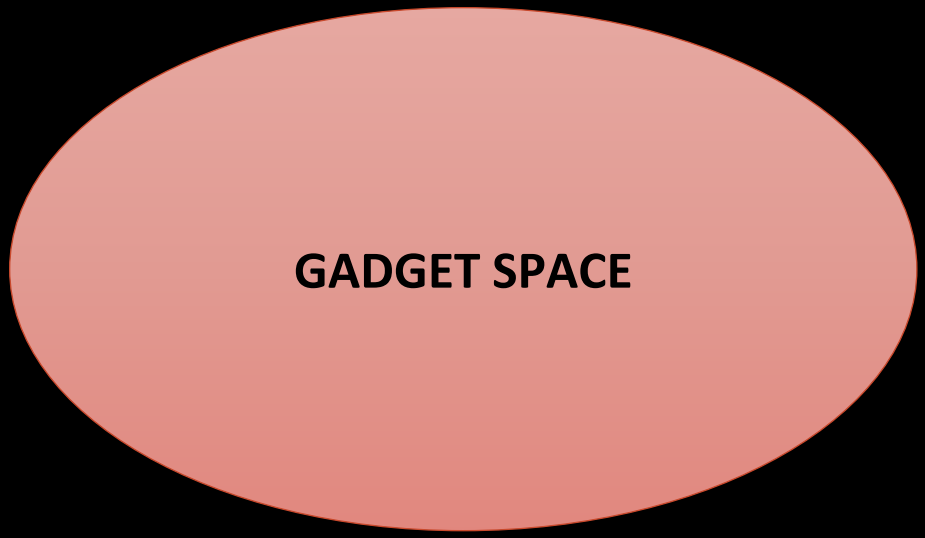

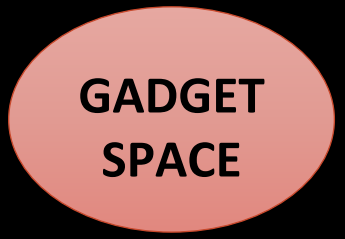

Intended Code

```
mov eax,0x13
jmp 3aae9
```

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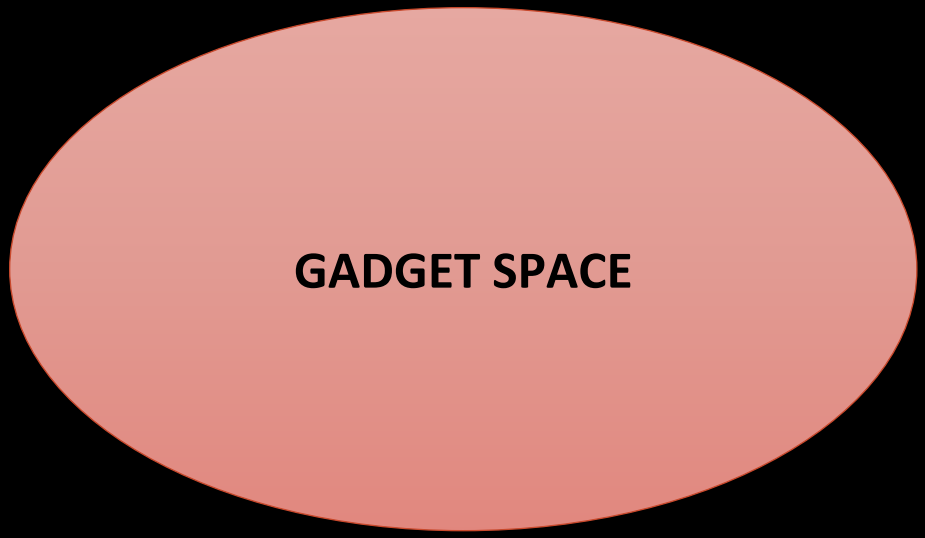

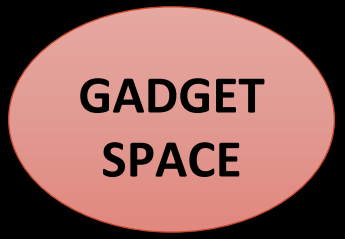

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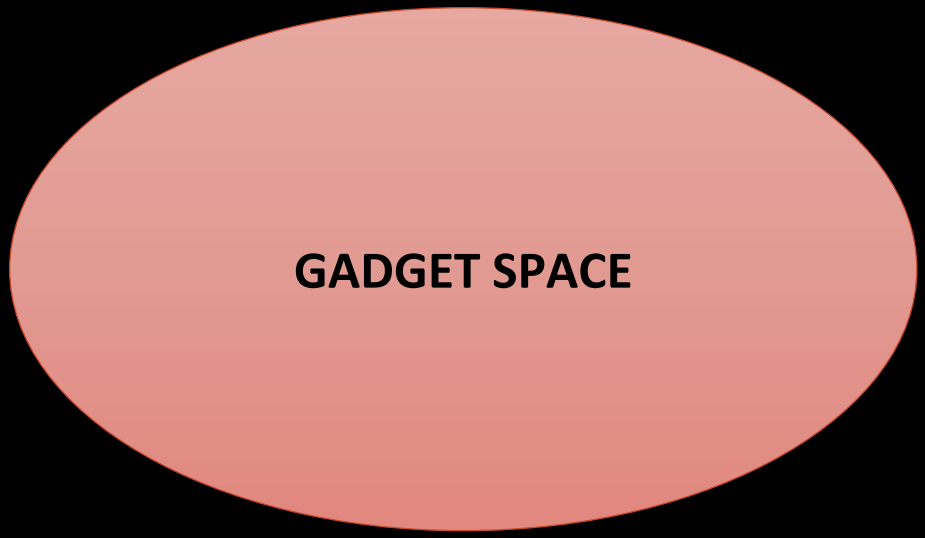
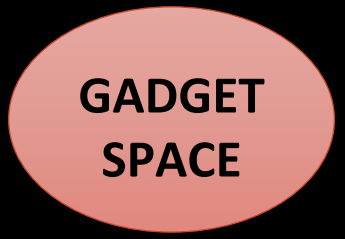
Architectures with memory alignment, e.g., SPARC, ARM





Intended Code

```
mov eax,0x13
jmp 3aae9
```

Unintended Code

```
add eax,[al]
add cl,ch
ret
```

Research on Code-Reuse Attacks

SELECTED

1997 — ret2libc *Solar Designer*

2001 — Advanced ret2libc *Nergal*

2005 — Borrowed Code Chunk Exploitation *Krahmer*

2007 — ROP on x86 *Shacham (CCS)*

2008 — ROP on SPARC *Buchanan et al (CCS)*; ROP on Atmel AVR *Francillon et al (CCS)*

2009 — ROP Rootkits *Hund et al (USENIX)*; ROP on PowerPC *FX Lindner (BlackHat)*; ROP on ARM/iOS *Miller et al (BlackHat)*

2010 — ROP without Returns *Checkoway et al (CCS)*; Practical ROP *Zovi (RSA Conference)*; Pwn2Own (iOS/IE) *Iozzo et al / Nils*

2011/2012 — Real-World Exploits





2013 — JIT-ROP *Snow et al (IEEE S&P)*

2014 — Blind ROP *Bittau et al (IEEE S&P)*; Out-Of-Control *Göktas et al (IEEE S&P)*; Stitching Gadgets *Davi et al (USENIX)*; Flushing Attacks *Schuster et al (RAID)*; ROP is Dangerous *Carlini et al (USENIX)*

2015 — COOP *Schuster et al (IEEE S&P)*; Losing Control *Liebchen et al (CCS)*; Control-Flow Bending *Carlini et al (USENIX)*

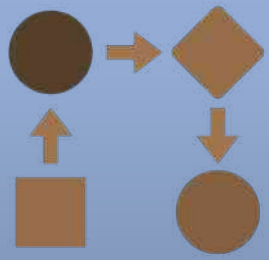
Overview

Background on Run-Time Attacks

Building Code Randomization Defenses

Code-Reuse Attacks

Building Control-Flow Integrity Defenses



Data-Oriented Exploits

Probabilistic vs Enforcement-Based Defense Approach

(Fine-grained) Code Randomization

[Cohen 1993 & Larsen et al., SoK IEEE S&P 2014]

Control-Flow Integrity (CFI)

[Abadi et al., CCS 2005 & TISSEC 2009]

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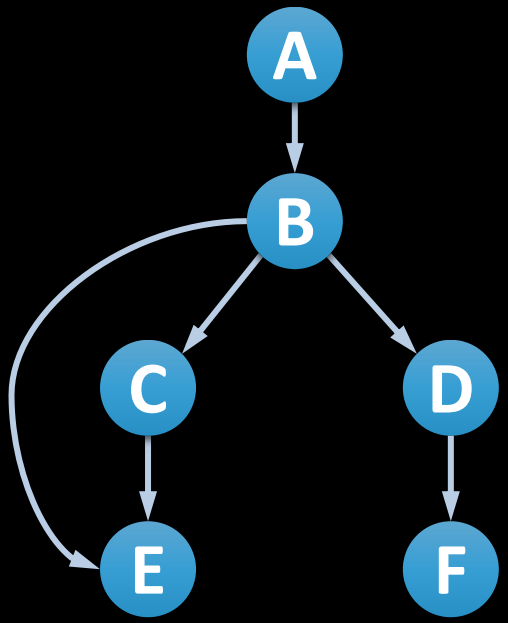

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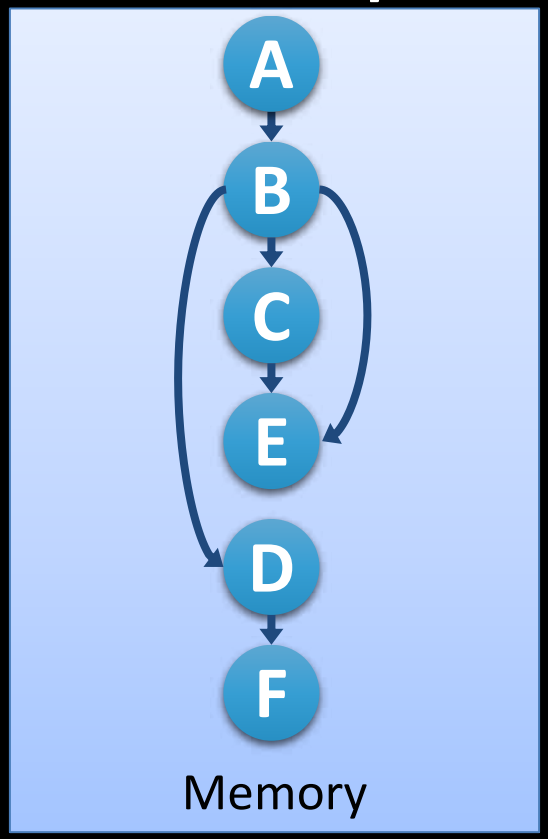

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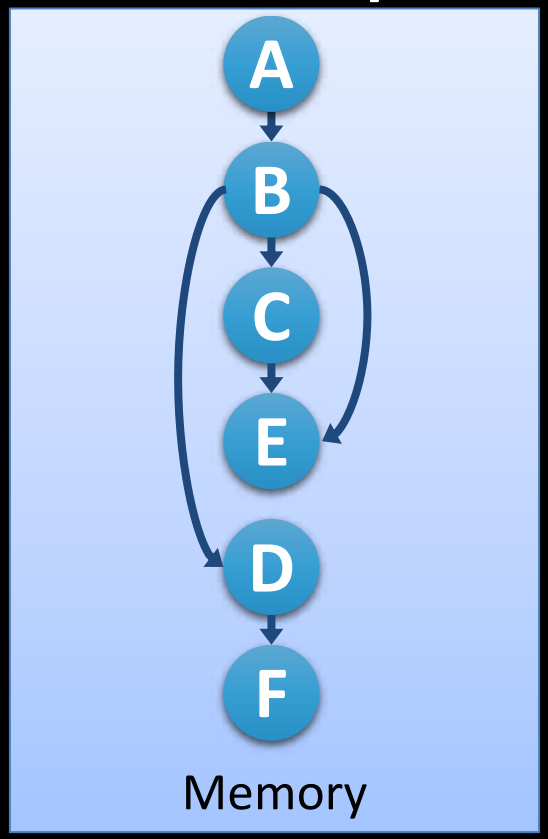

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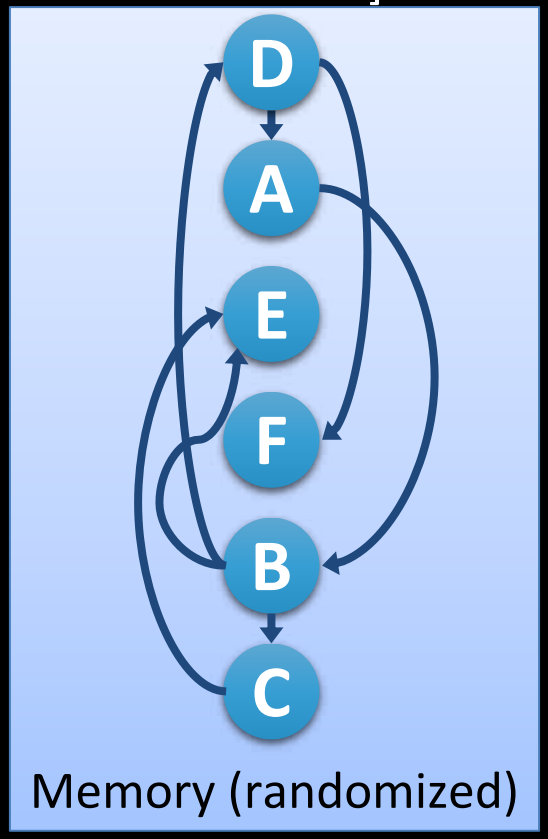

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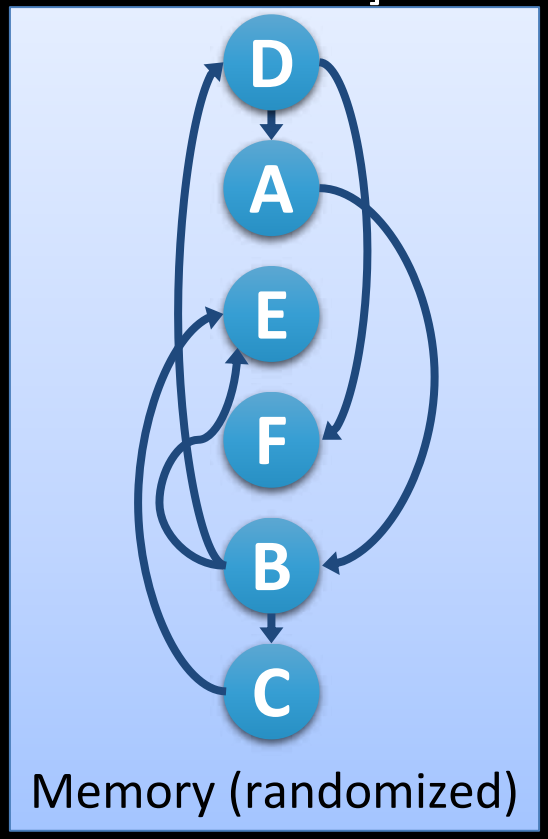

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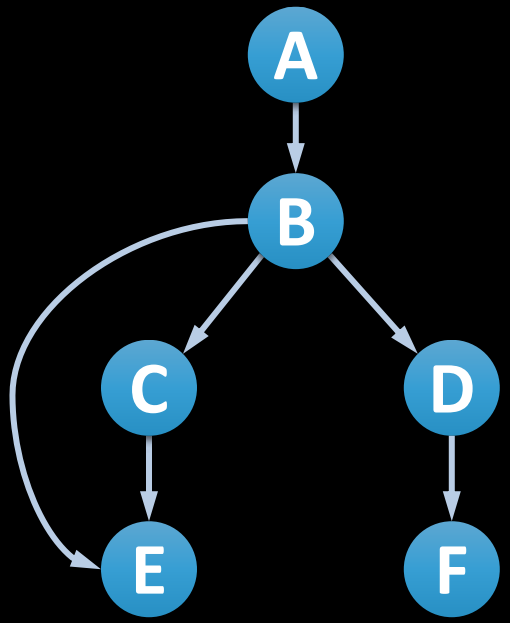

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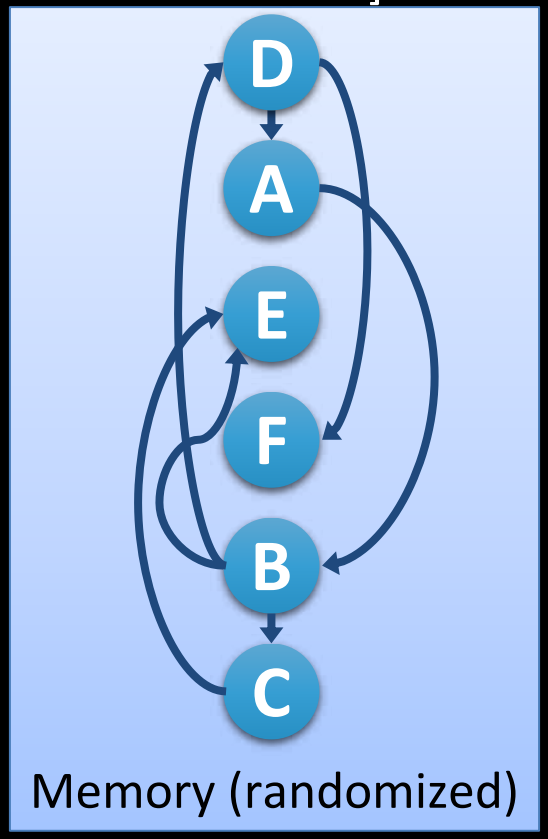

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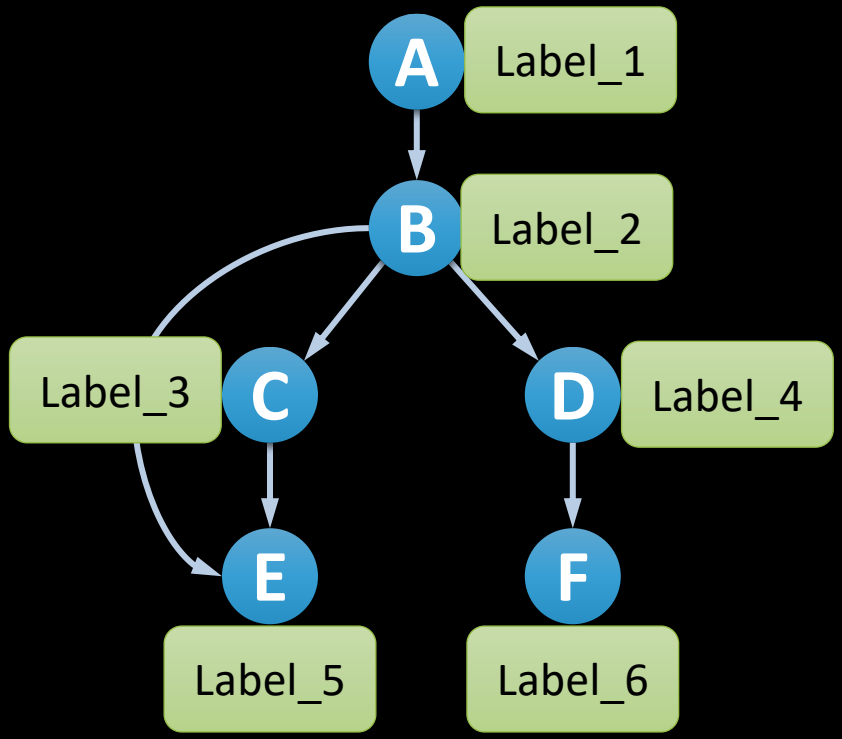

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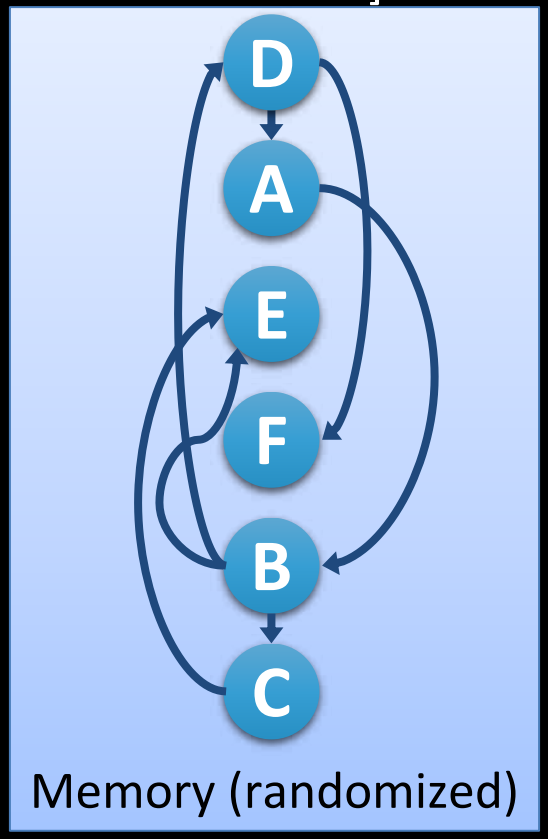

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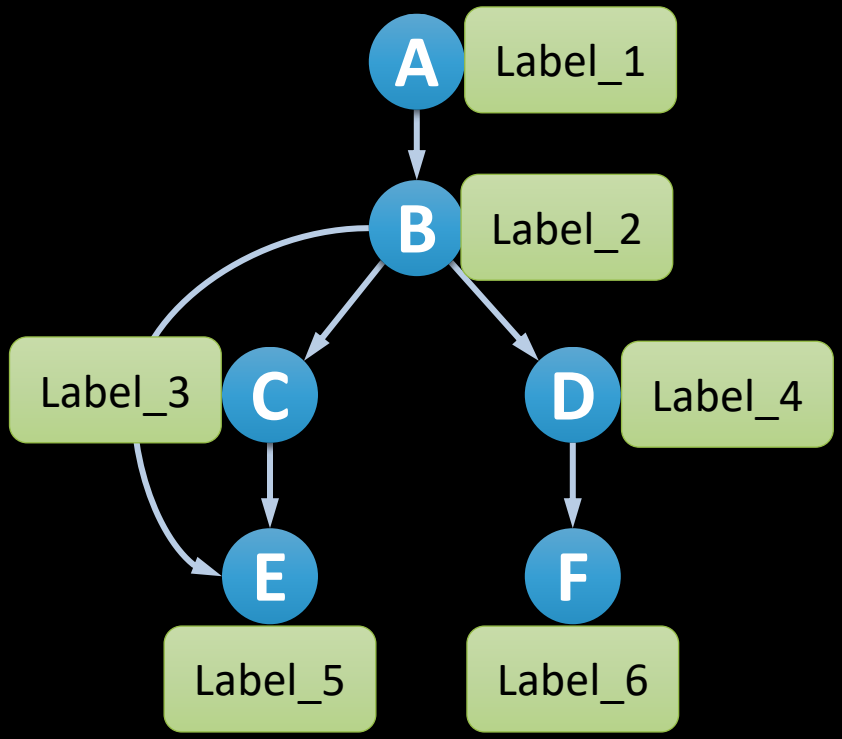

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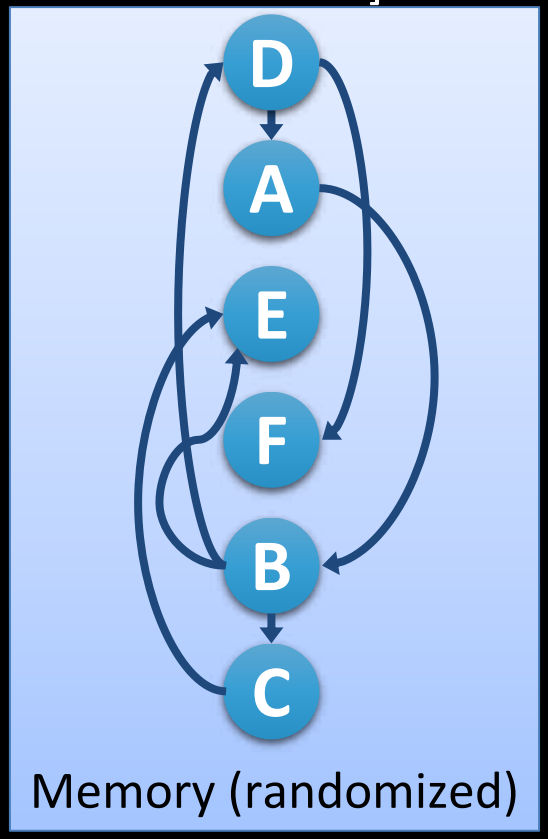

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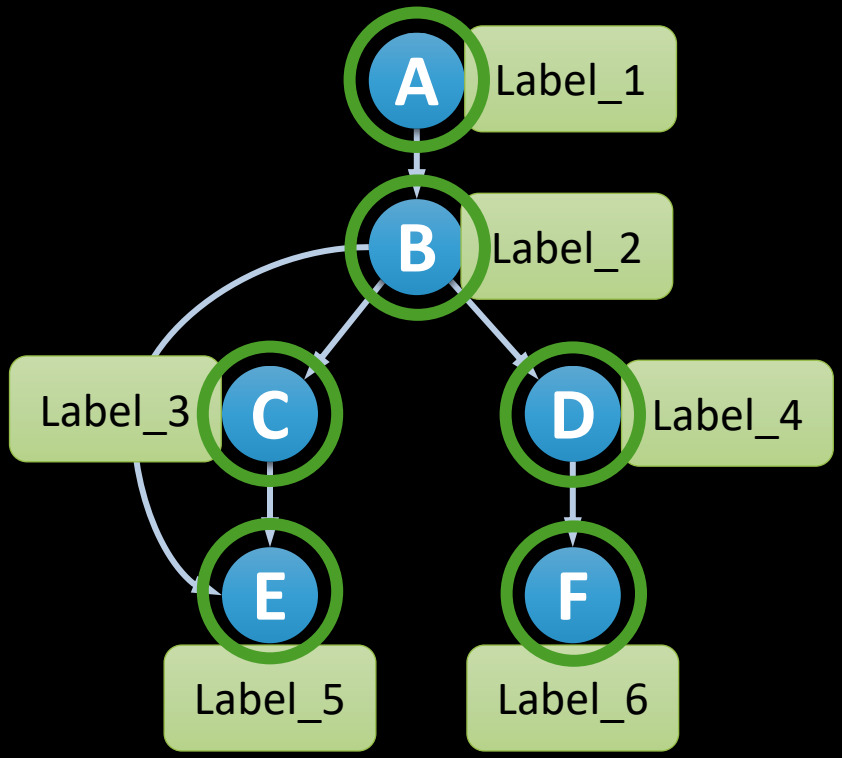

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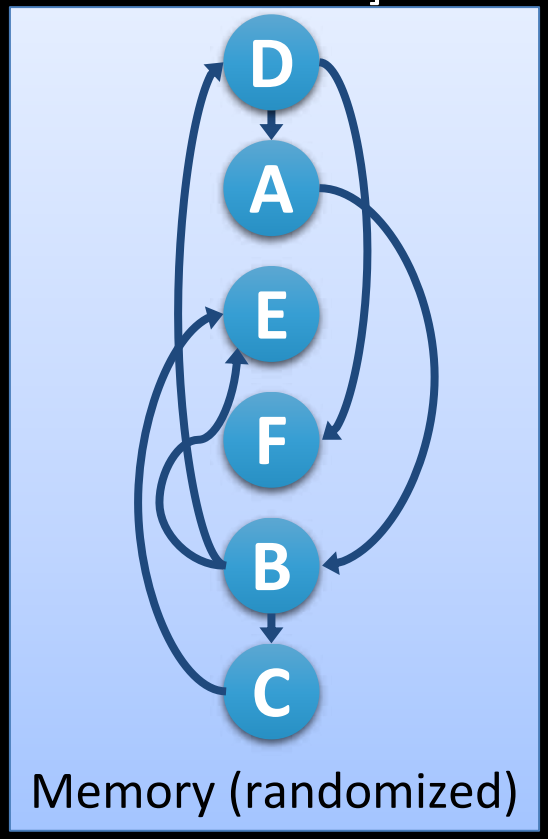

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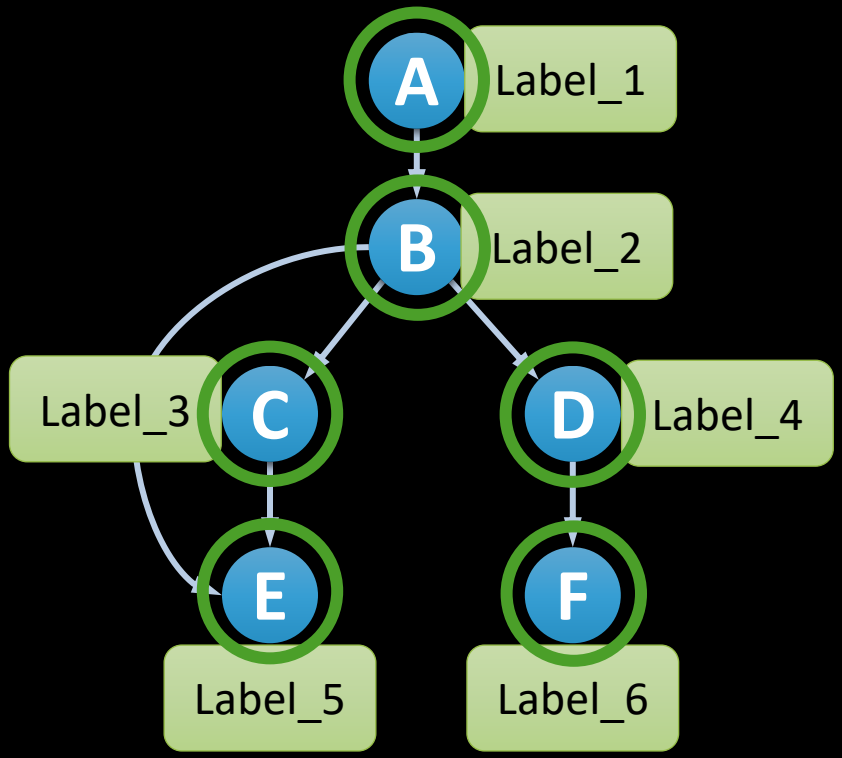

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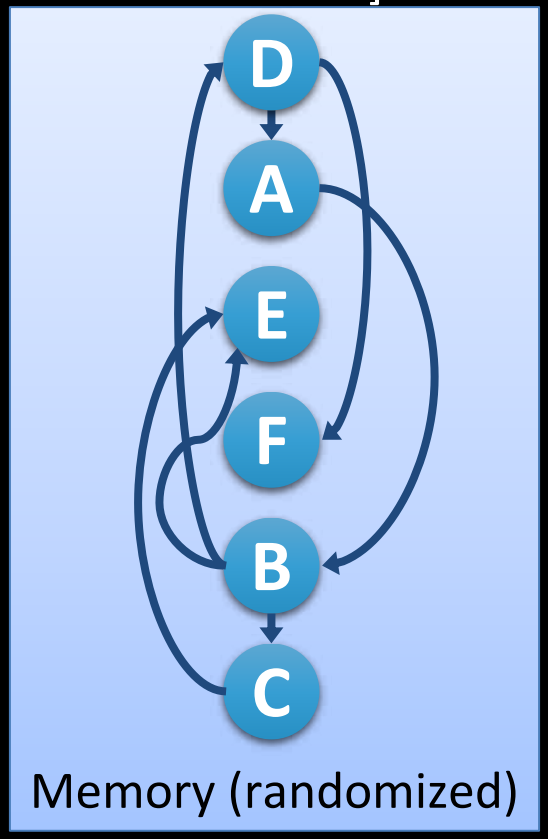

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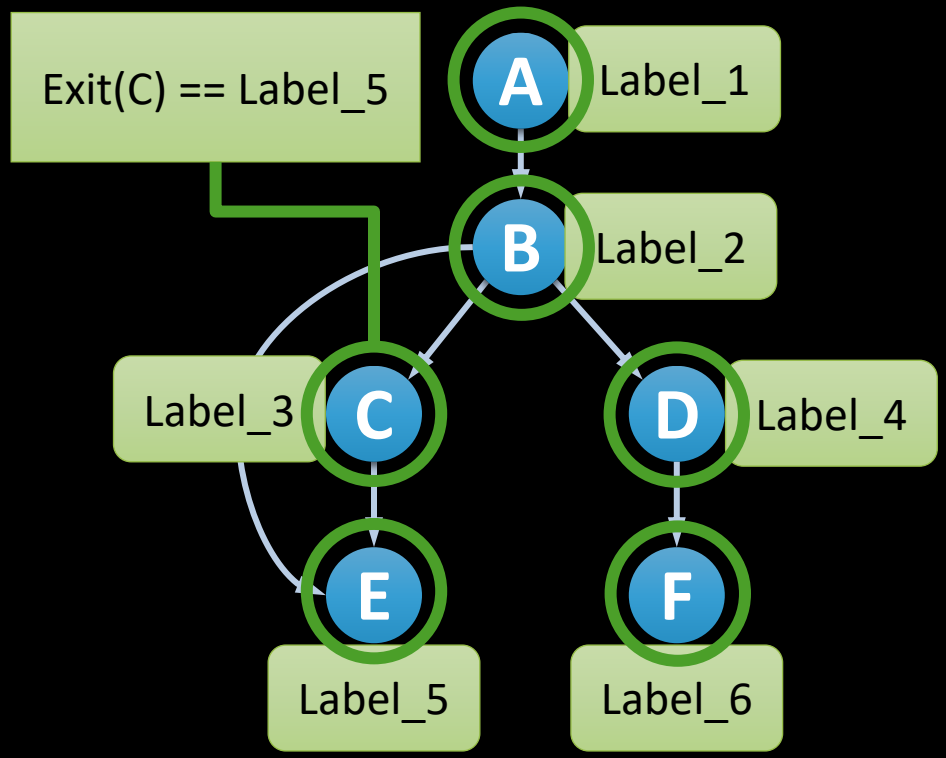

Basics of Code Randomization

- ASLR randomizes the base address of code/data segments

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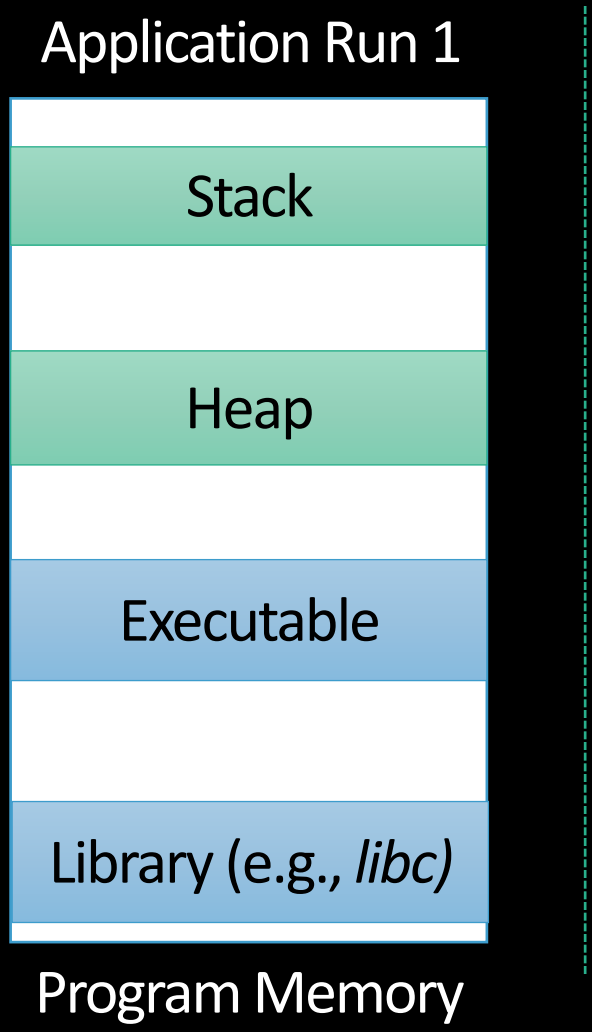

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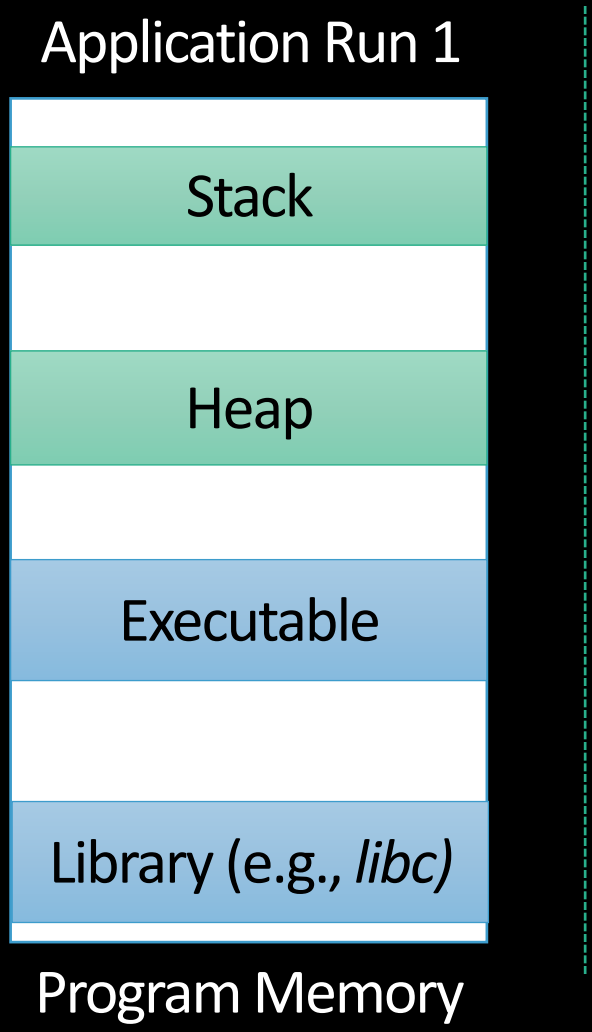

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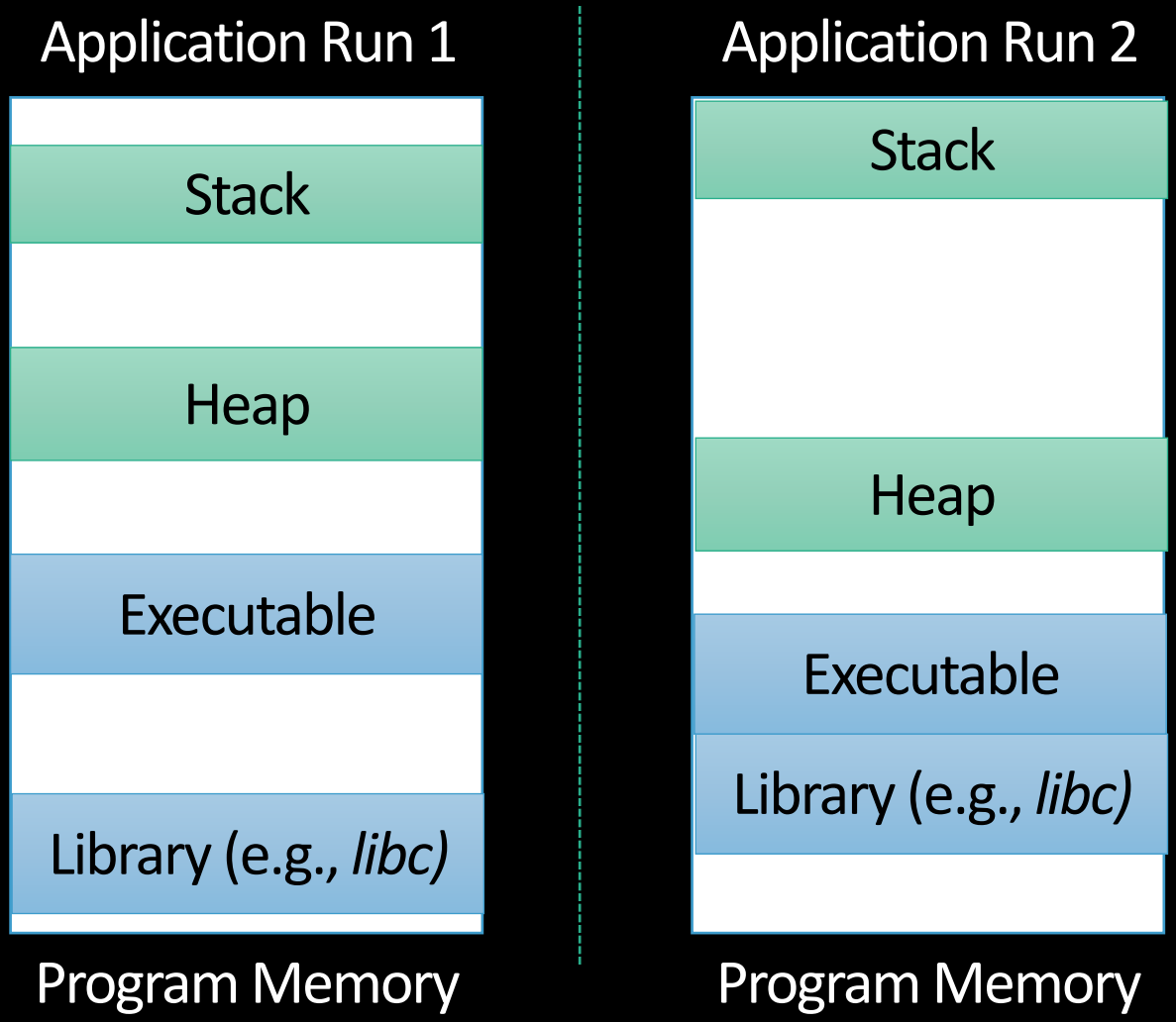

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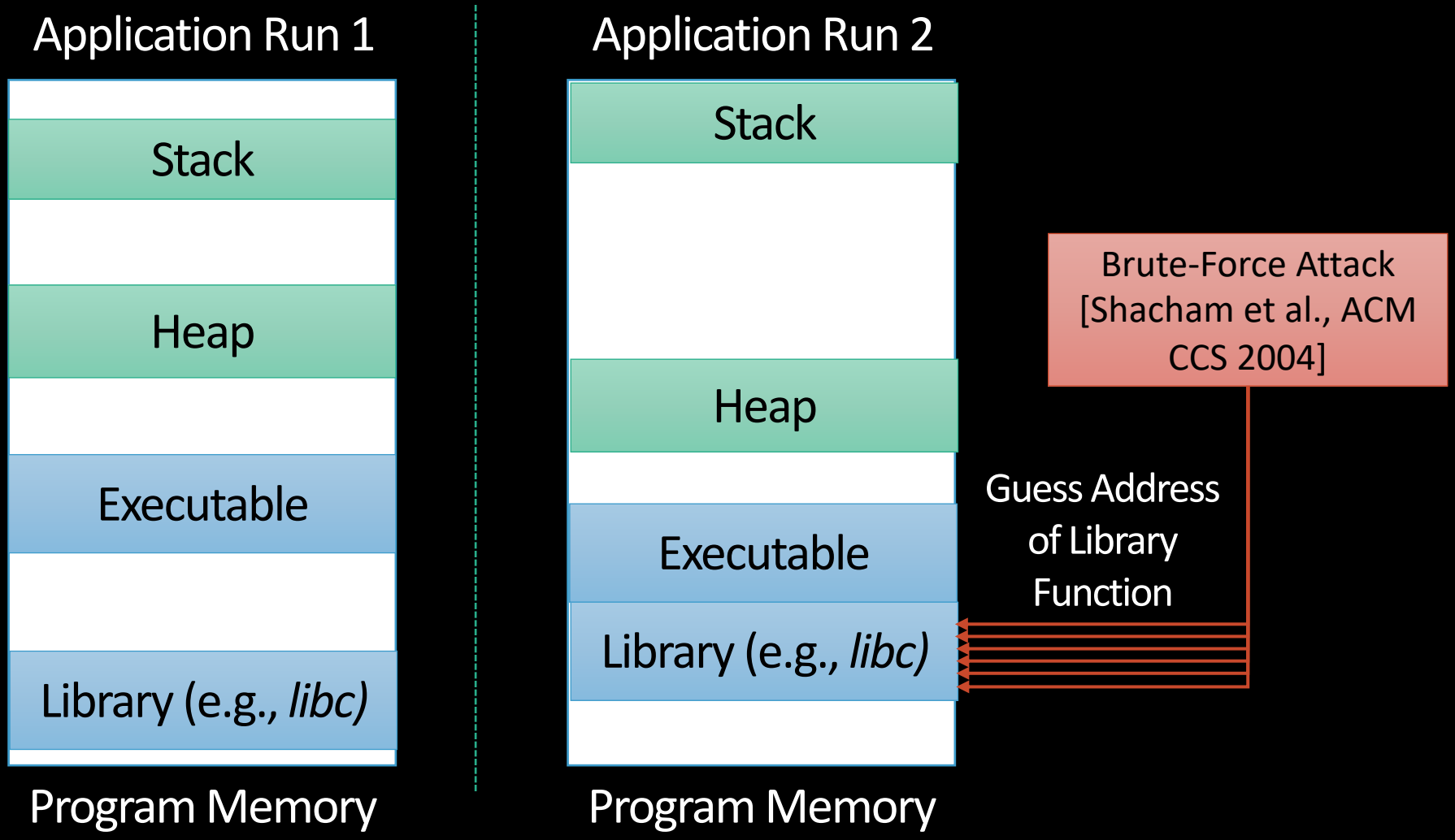
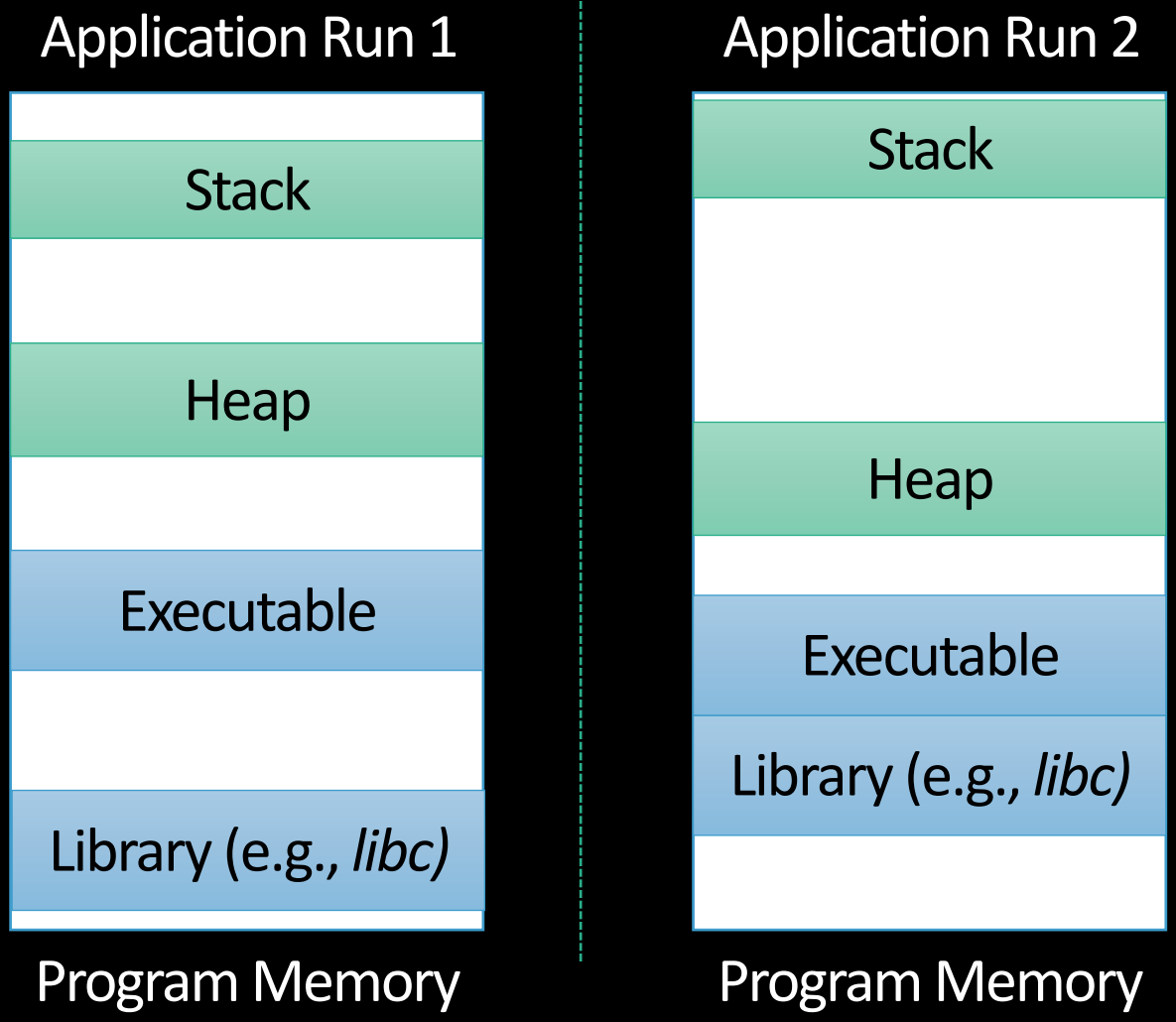
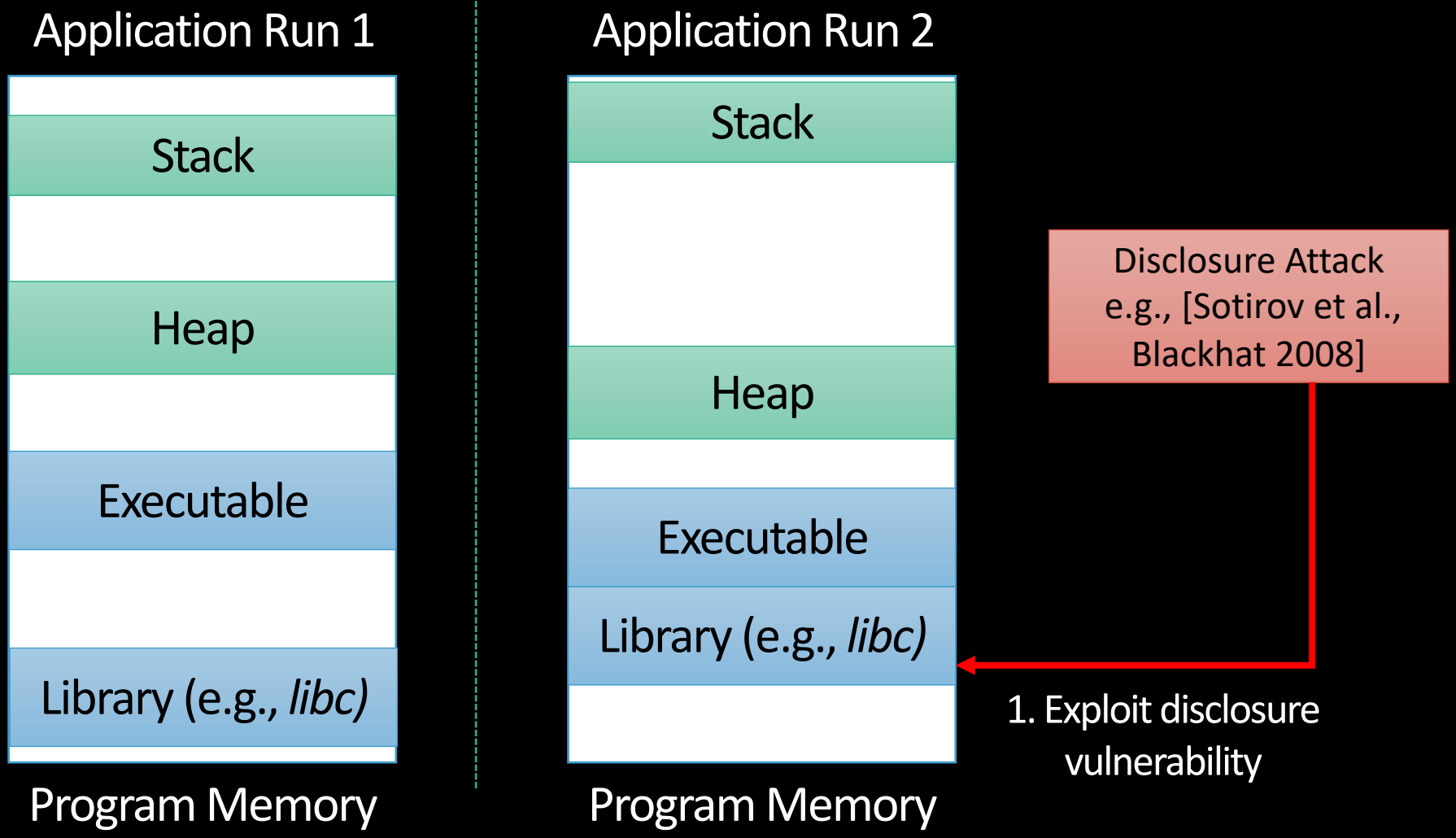


Big Picture


Application Run 1
Stack
Heap
Executable
Library (e.g., *libc)*
Program Memory
Application Run 2
Stack
Heap
Executable
Library (e.g., *libc)*
Program Memory

Big Picture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Disclosure Attack
e.g., [Sotirov et al., Blackhat 2008]
1. Exploit disclosure vulnerability

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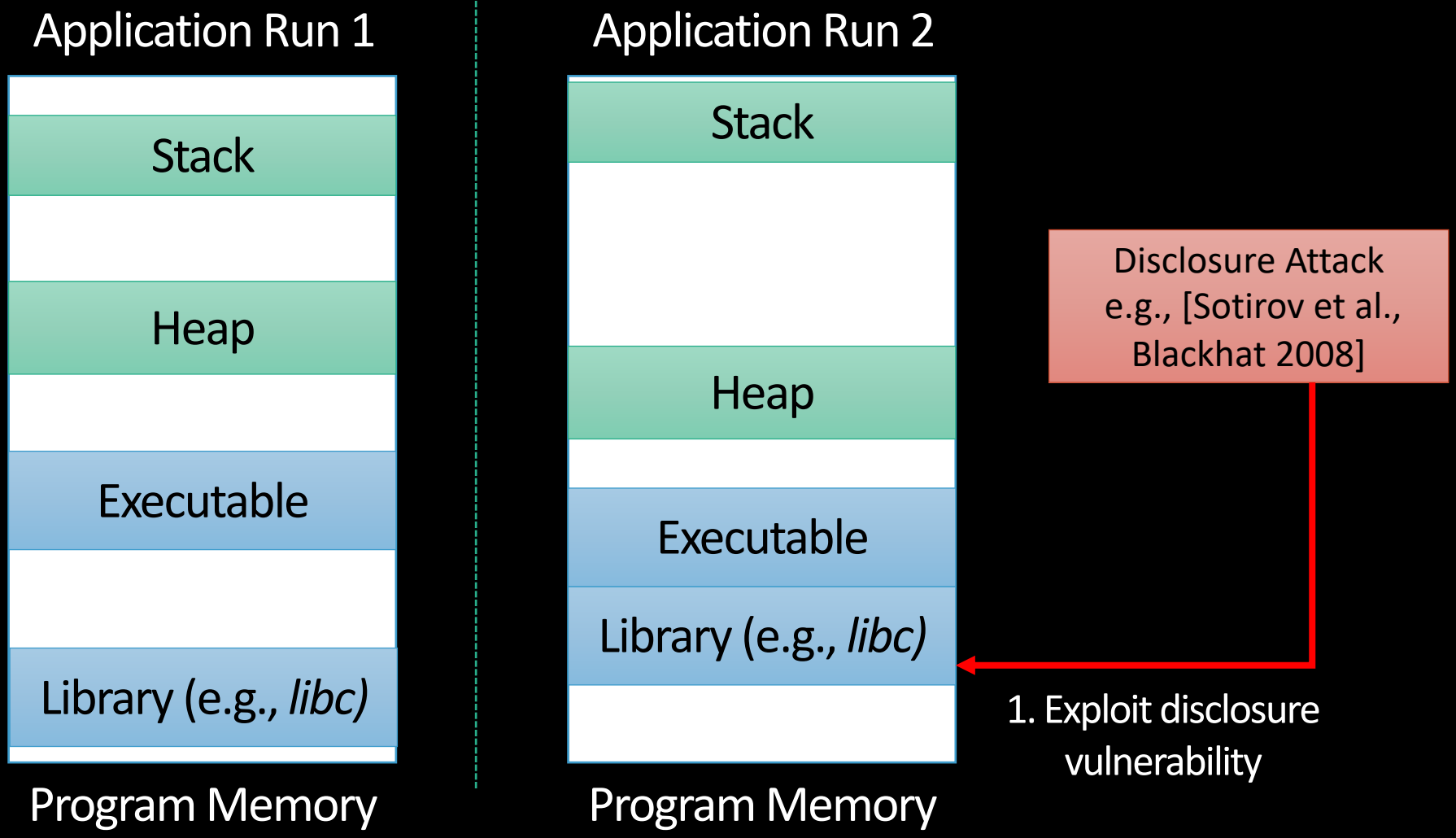
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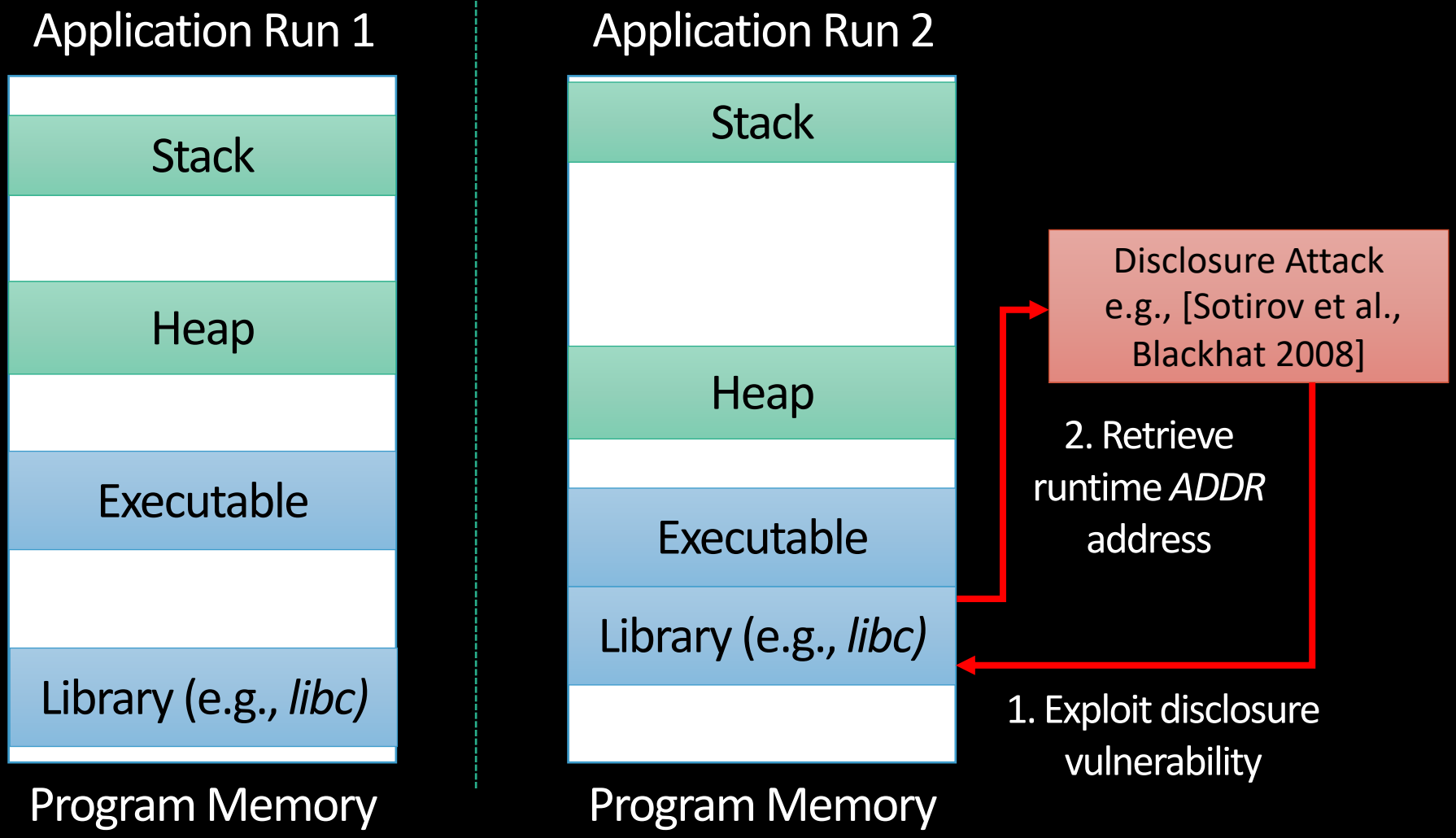
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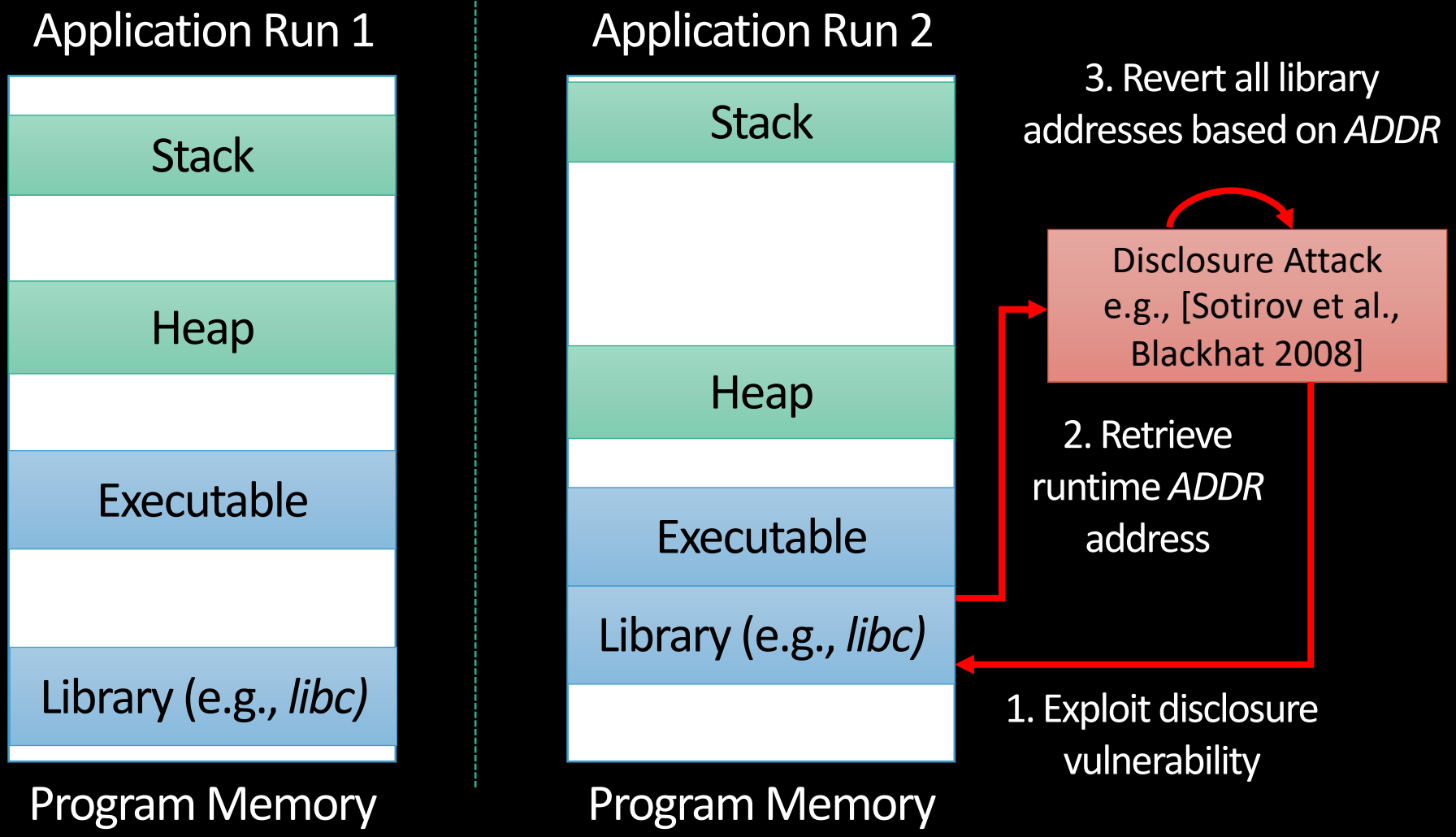
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Program Memory
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Program Memory
3. Revert all library addresses based on ADDR
Disclosure Attack e.g., [Sotirov et al., Blackhat 2008]
2. Retrieve runtime ADDR address
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Making exploitation harder with fine-grained code randomization

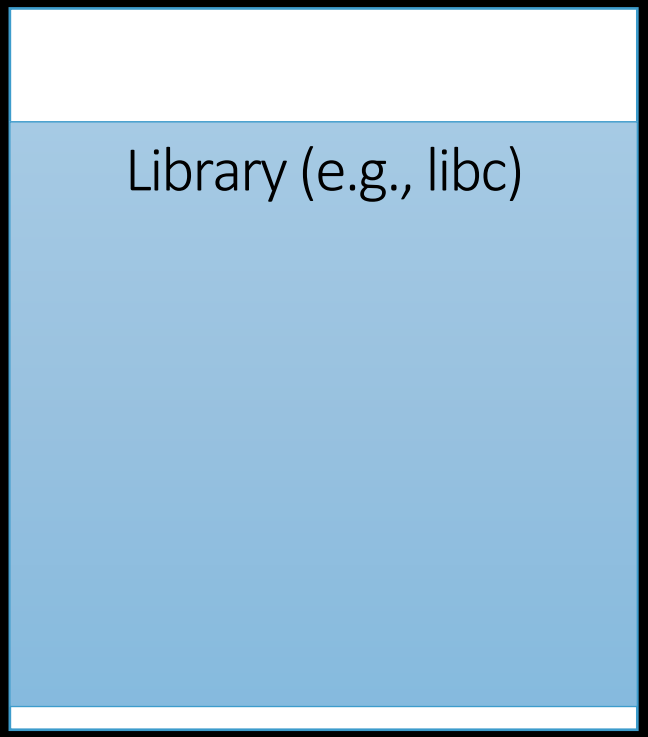
Fine-Grained ASLR

Fine-Grained ASLR

Application Run 1

Fine-Grained ASLR

Application Run 1



Fine-Grained ASLR

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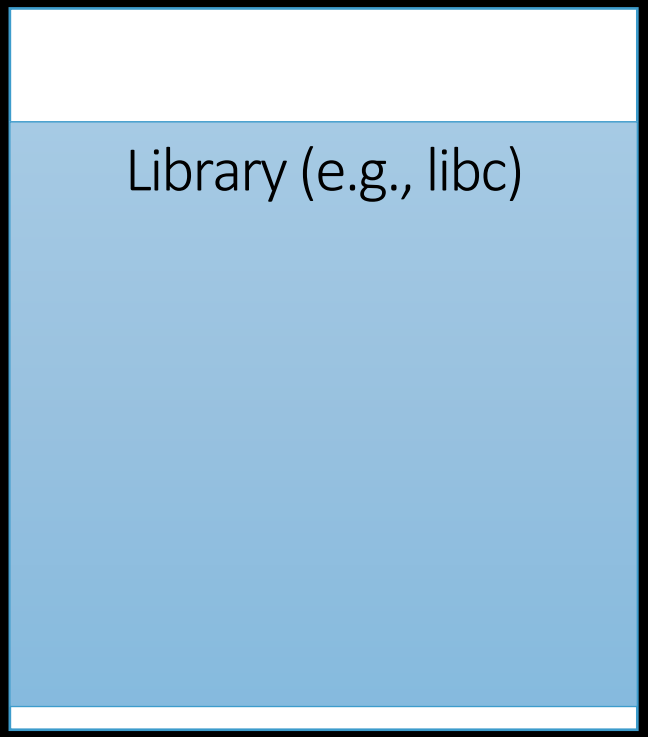

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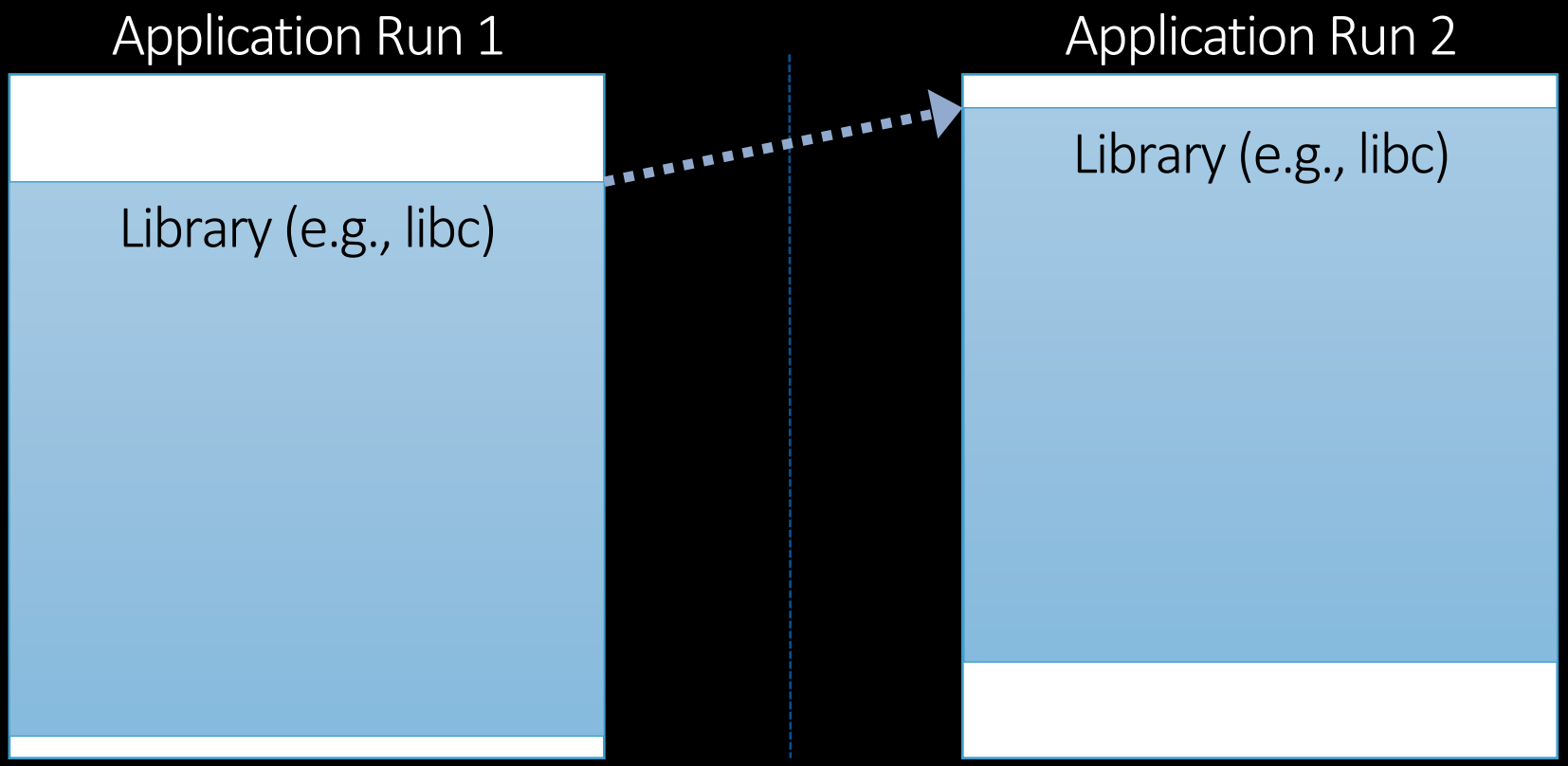

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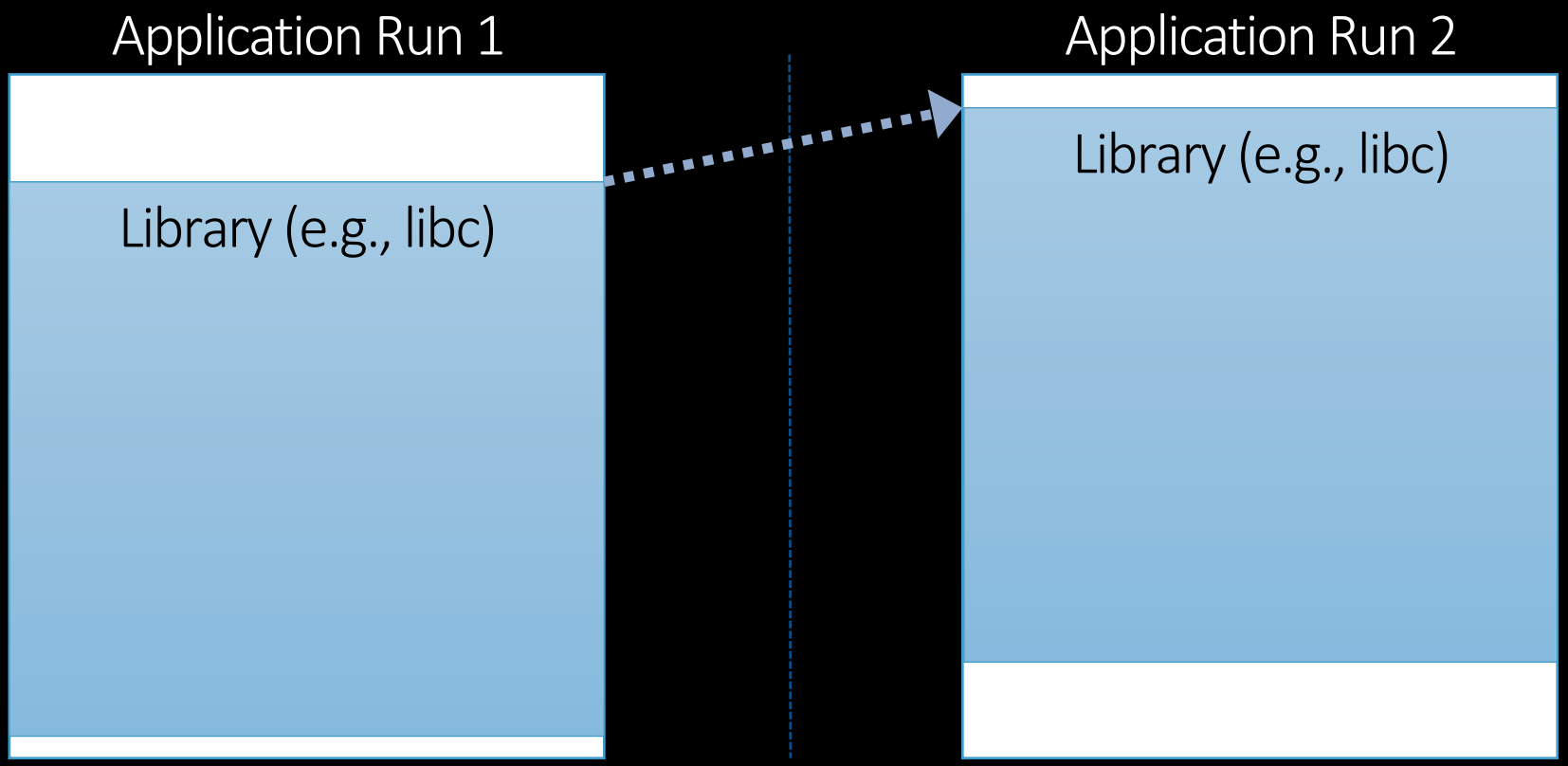

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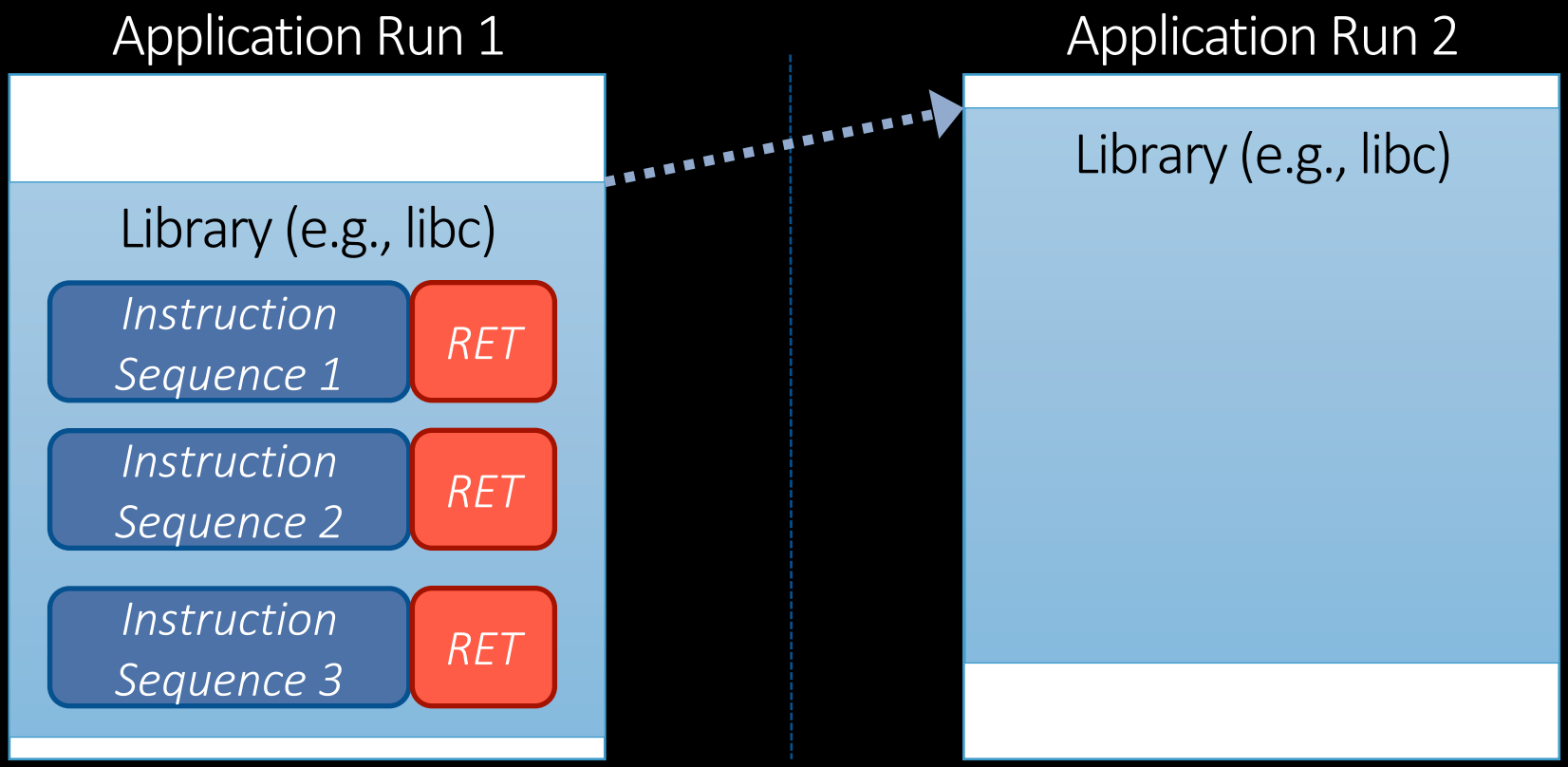

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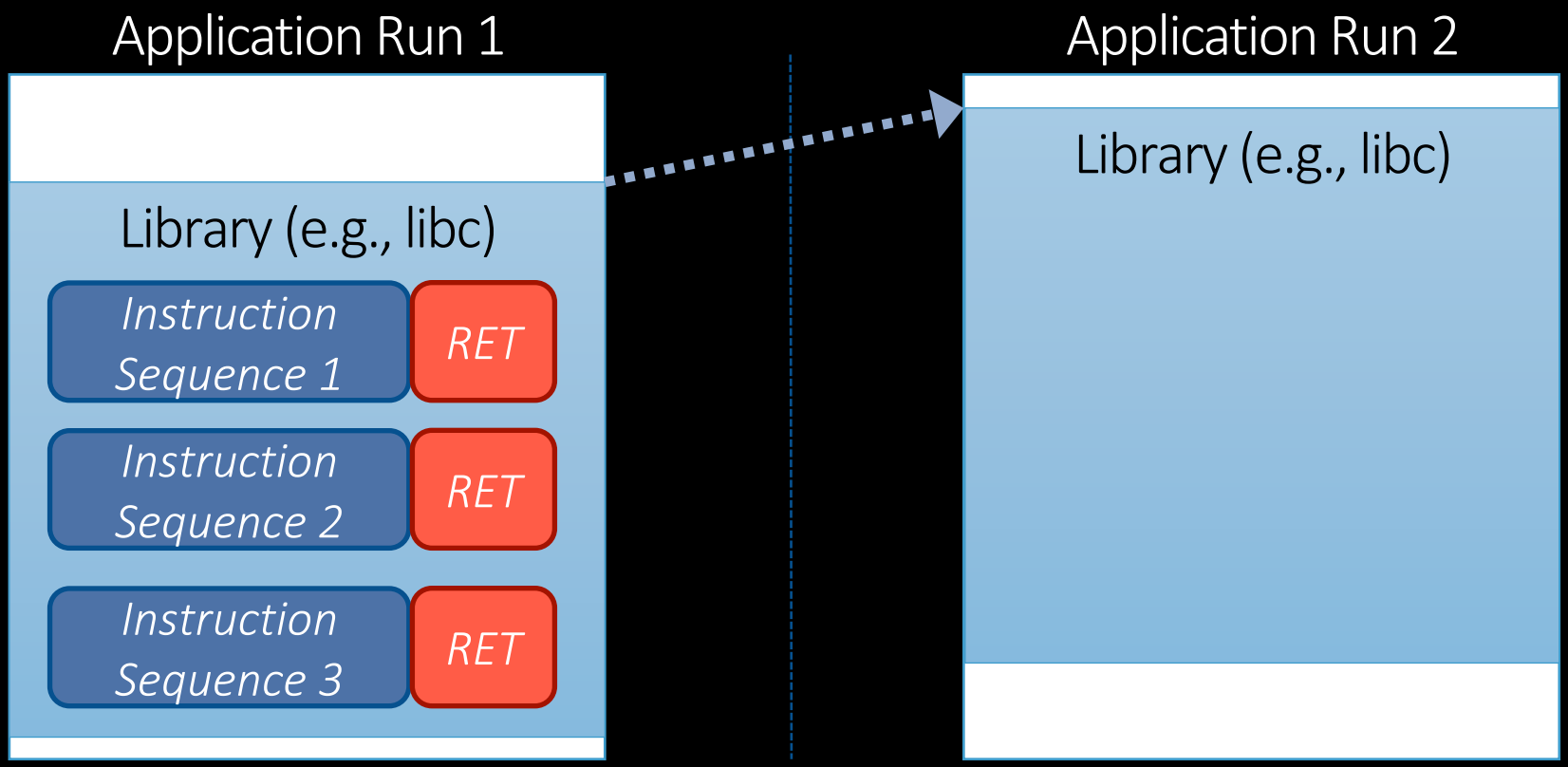

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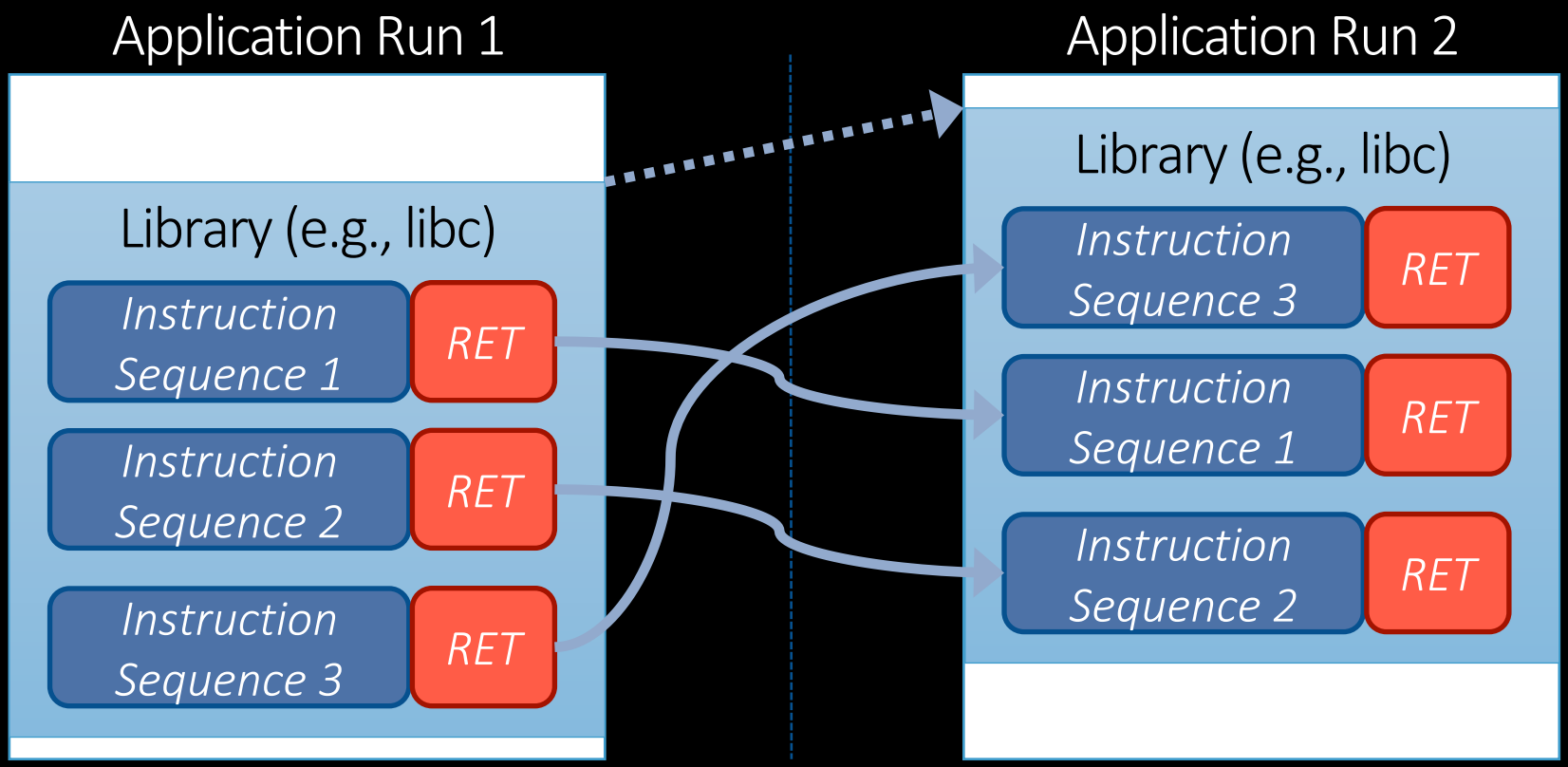

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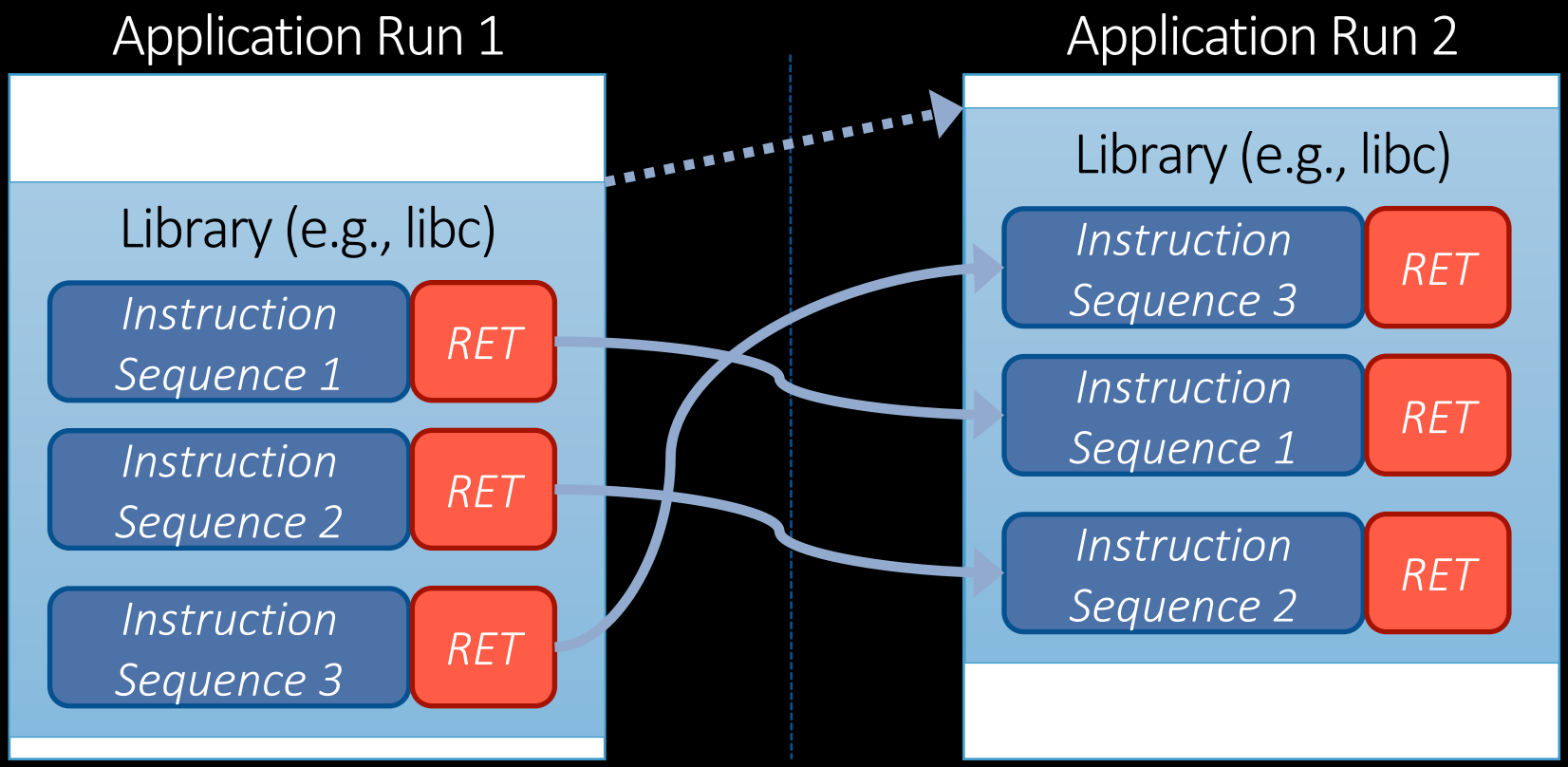


- **ORP** [Pappas et al., IEEE S&P 2012]: Instruction reordering/substitution within a BBL

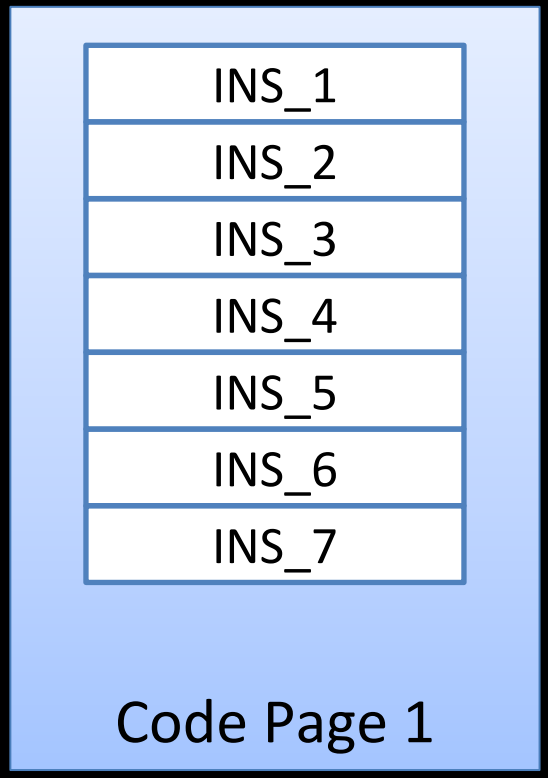
  ILR [Hiser et al., IEEE S&P 2012]: Randomizing each instruction‘s location
- **STIR** [Wartell et al., ACM CCS 2012] & **XIFER** [with Davi et al., AsiaCCS 2013]: Permutation of BBLs

Does Fine-Grained ASLR Provide a Viable Defense in the Long Run?

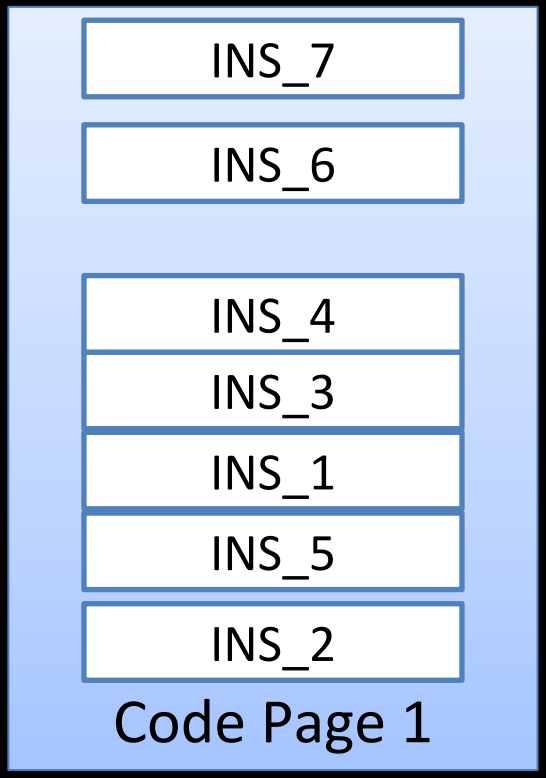
Just-In-Time Code Reuse: On the Effectiveness of Fine-Grained Address Space Layout Randomization

[Kevin Snow, Lucas Davi, Alexandra Dmitrienko, Christopher Liebchen, Fabian Monrose, Ahmad-Reza Sadeghi, Best Student Paper at IEEE S&P 2013]

High-Level Idea



High-Level Idea



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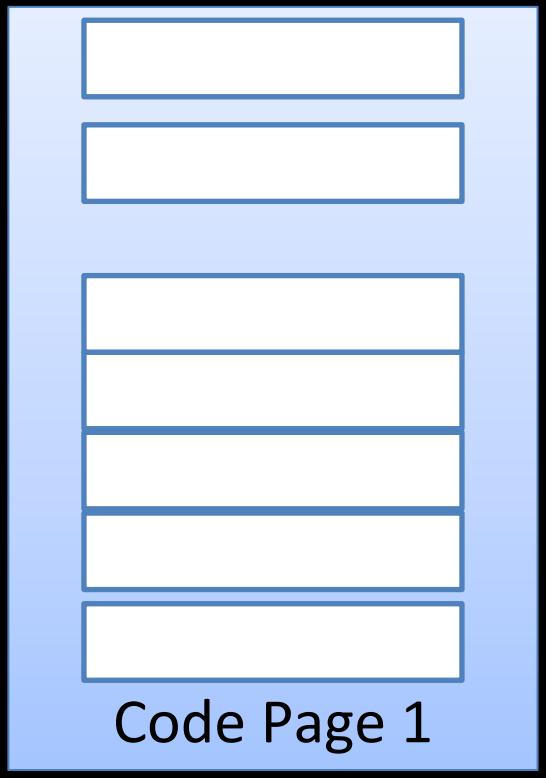

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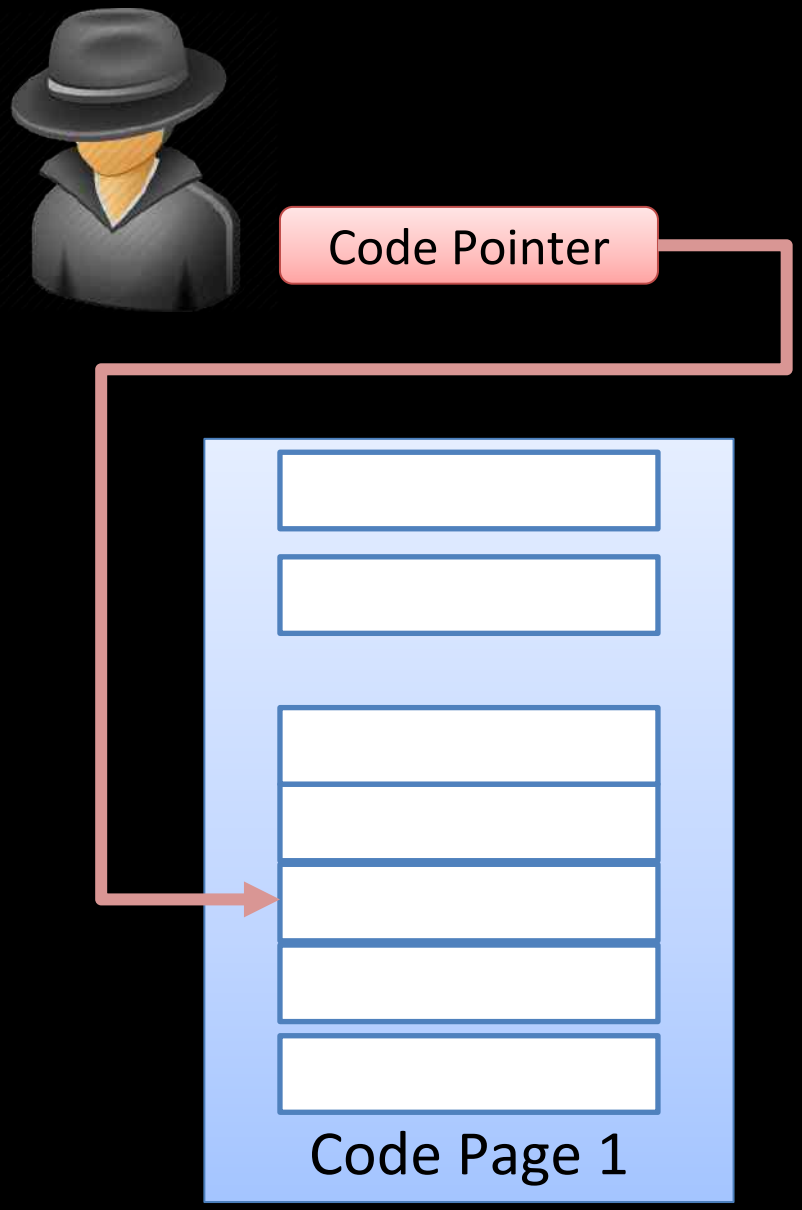

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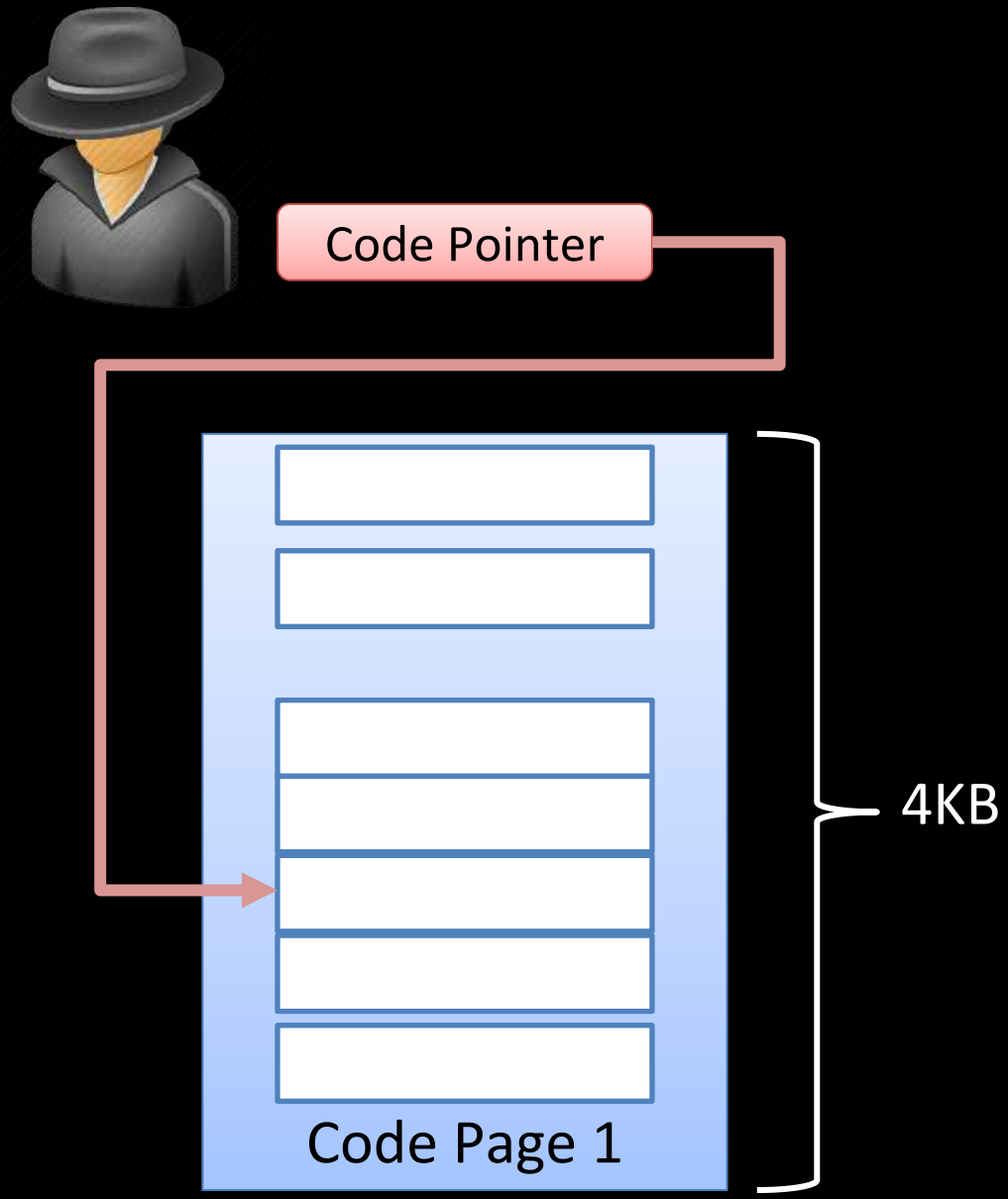
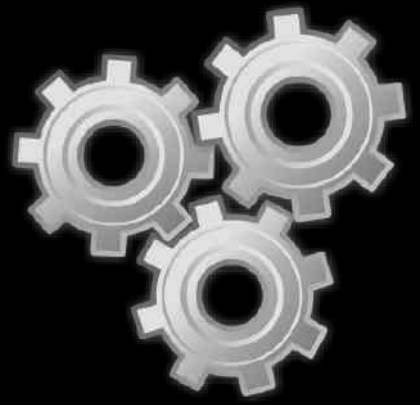


High-Level Idea

Scripting Engine



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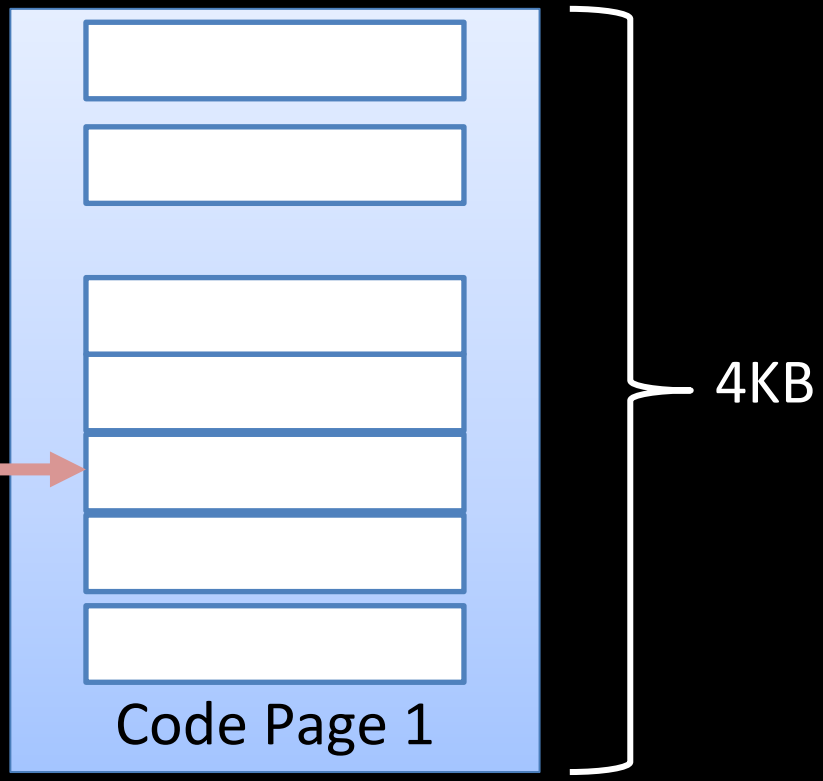

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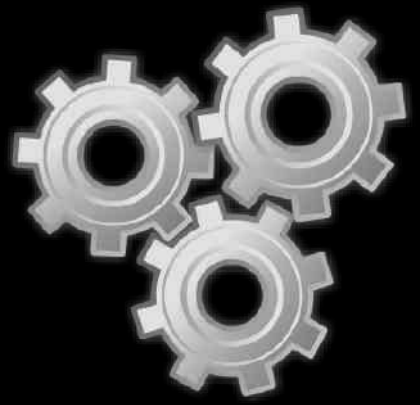

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Disassemble

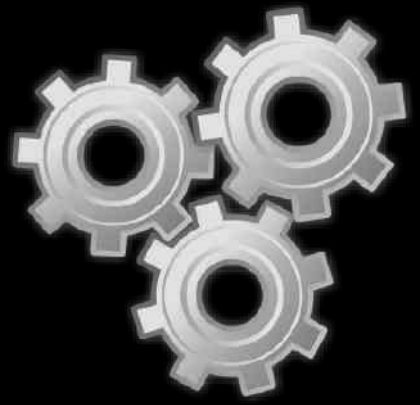
4KB

Code Page 1

Page End

High-Level Idea

Scripting Engine



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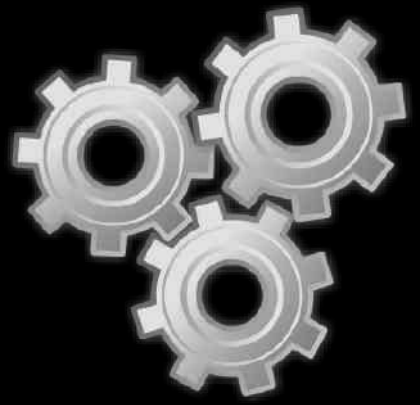

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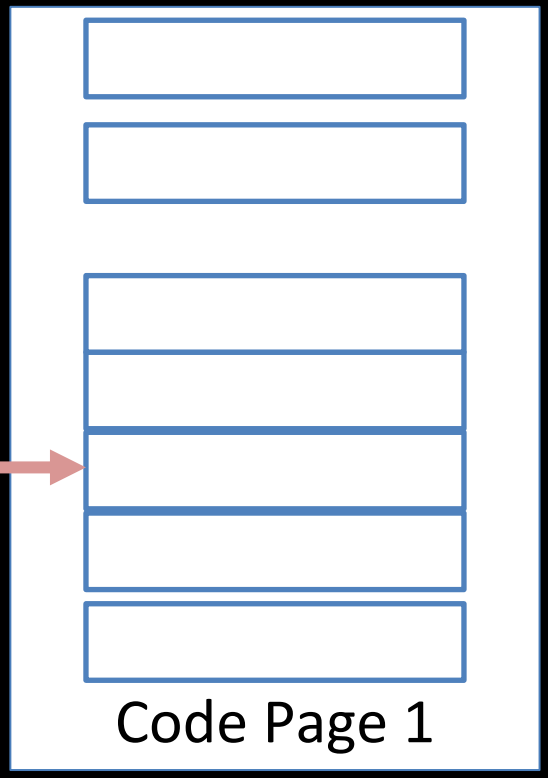

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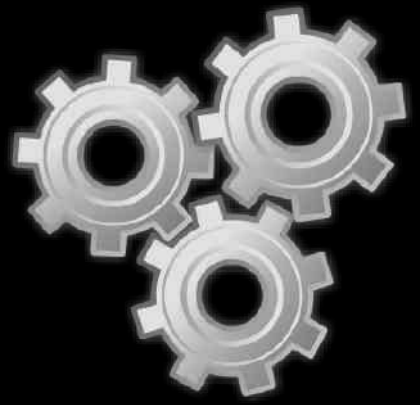

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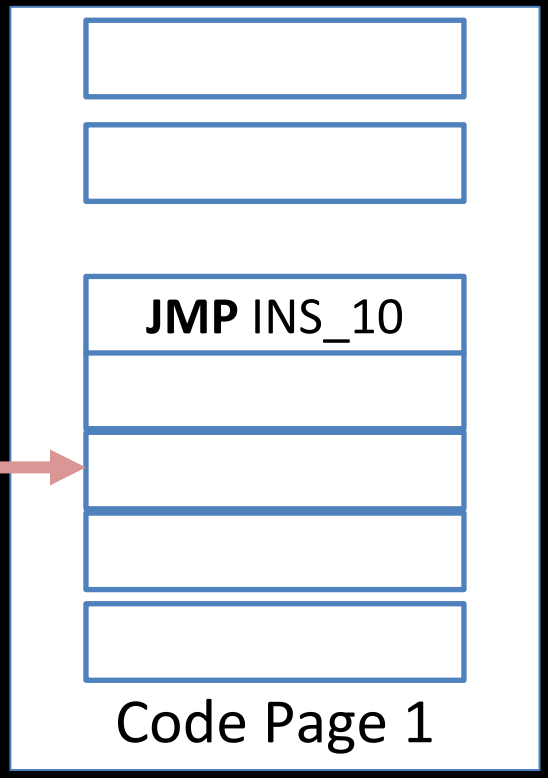

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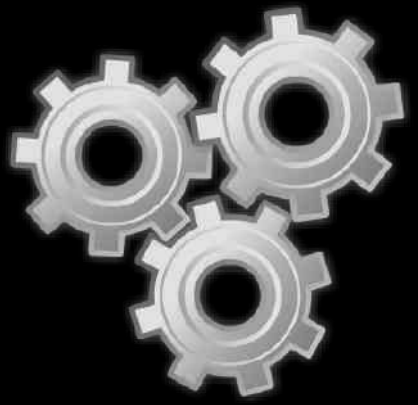

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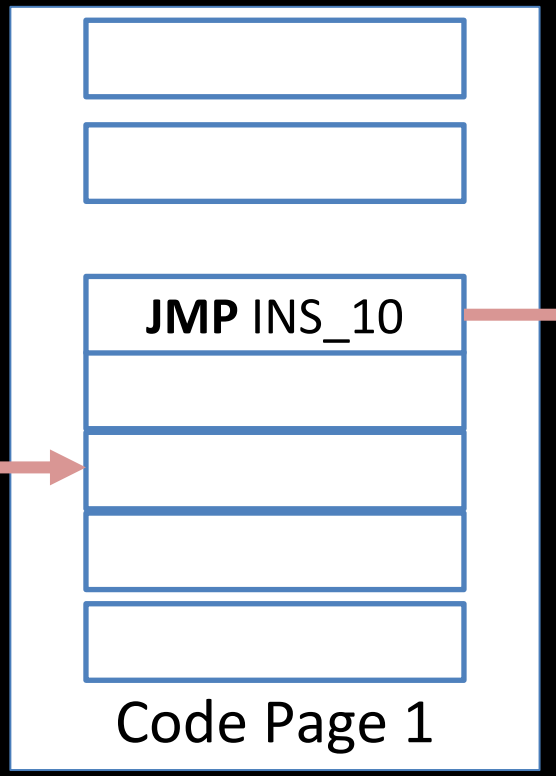

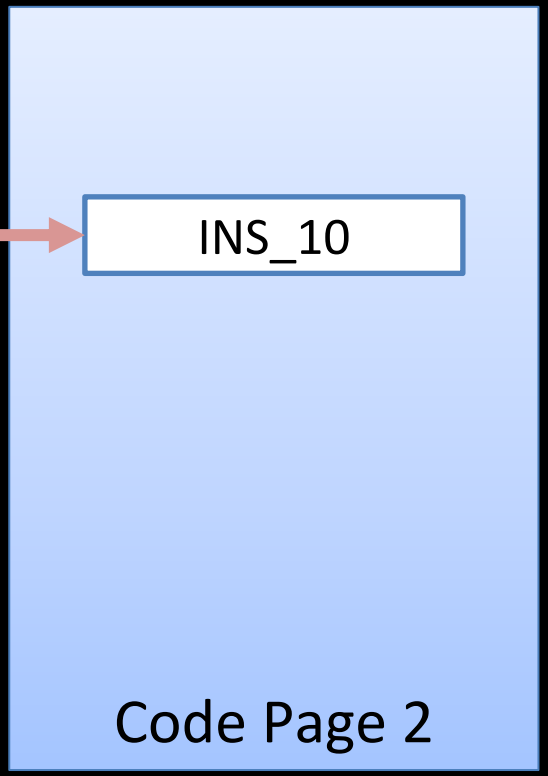

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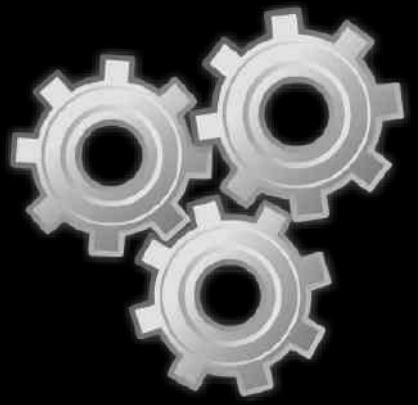

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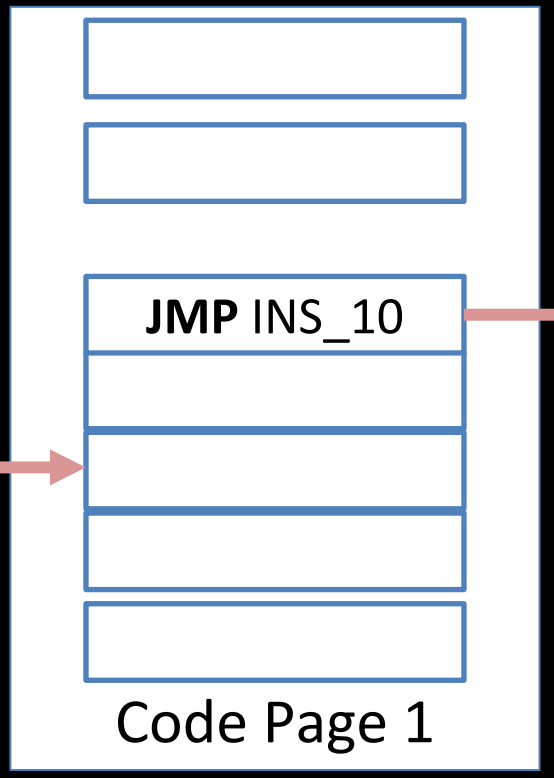

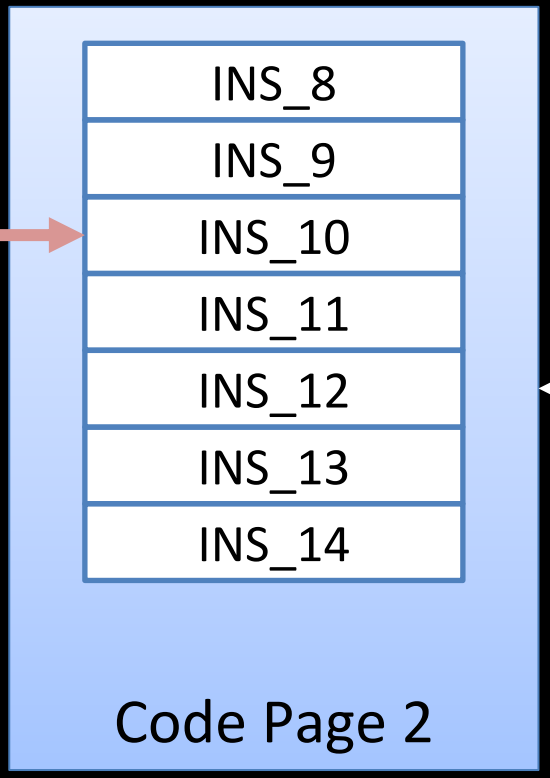

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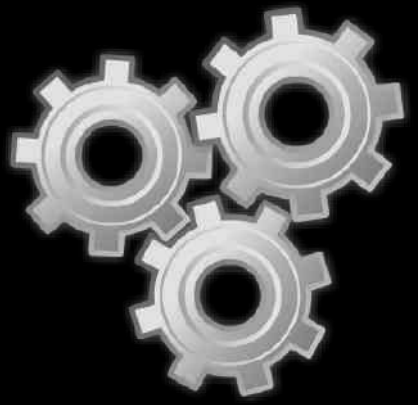

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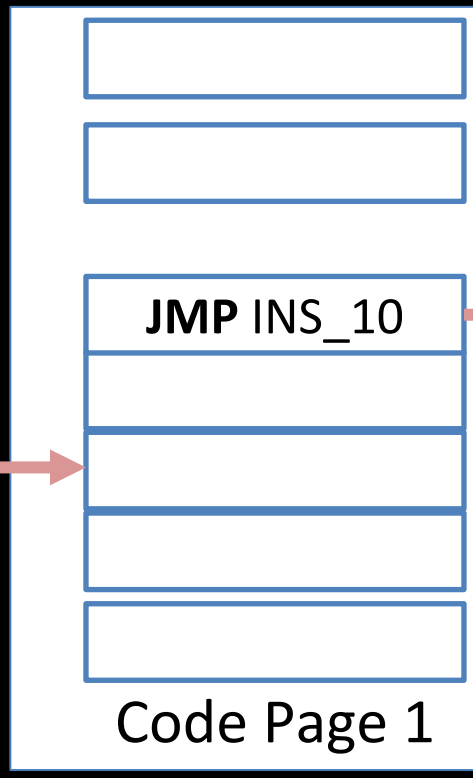
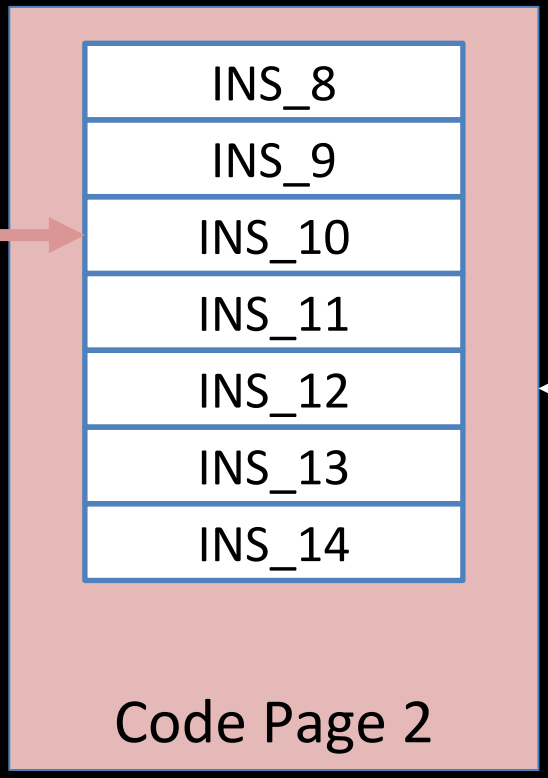




Execute-Only Memory

Remove the read permission from code pages

see e.g., Readactor [IEEE S&P 2015]

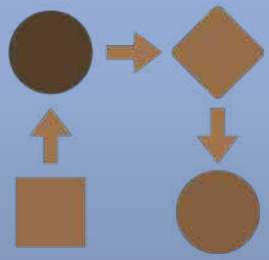
Overview

Background on Run-Time Attacks

Building Code Randomization Defenses

Code-Reuse Attacks

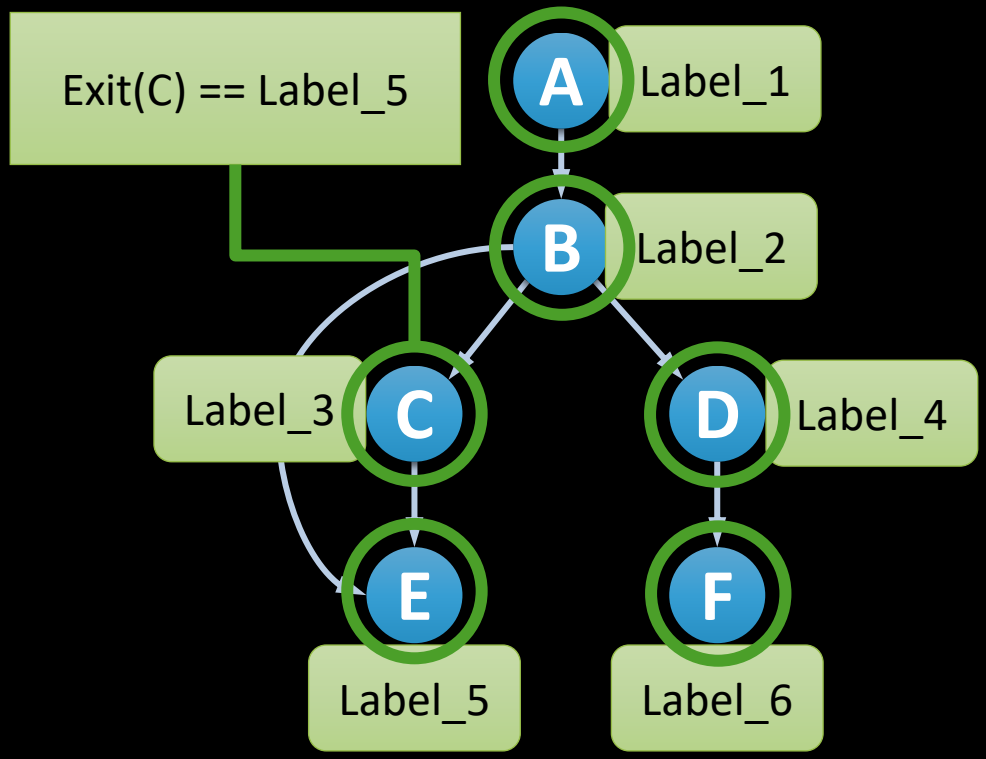
Building Control-Flow Integrity Defenses



Data-Oriented Exploits

Control-Flow Integrity (CFI)

[Abadi et al., CCS 2005 & TISSEC 2009]



Label Problem for Returns

- Static CFI label checking leads to coarse-grained protection for returns

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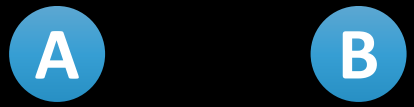

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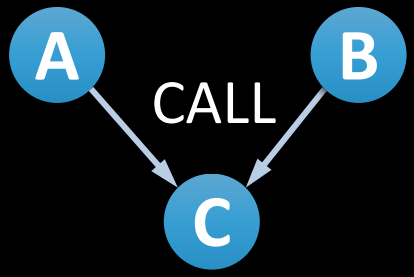

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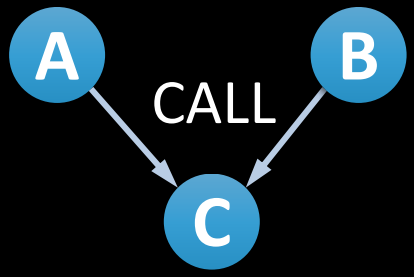

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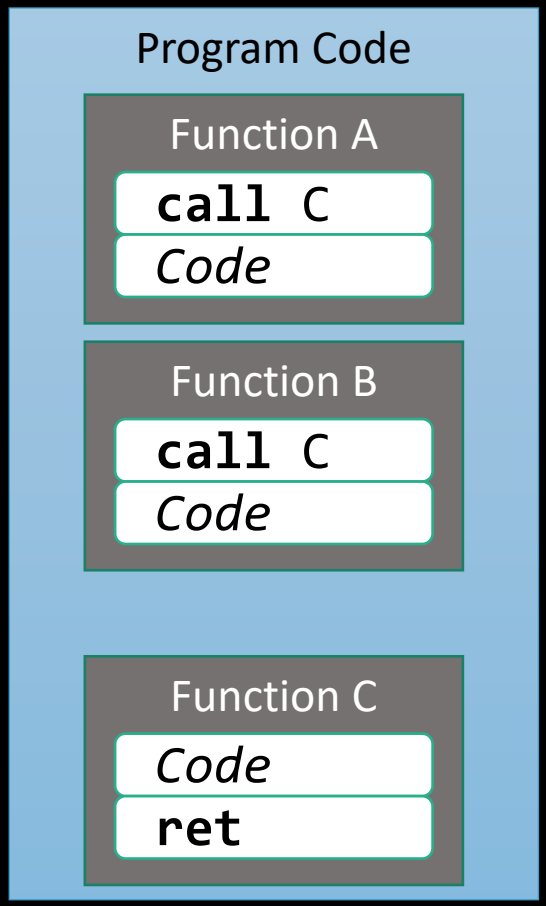

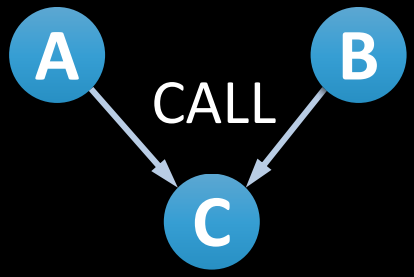

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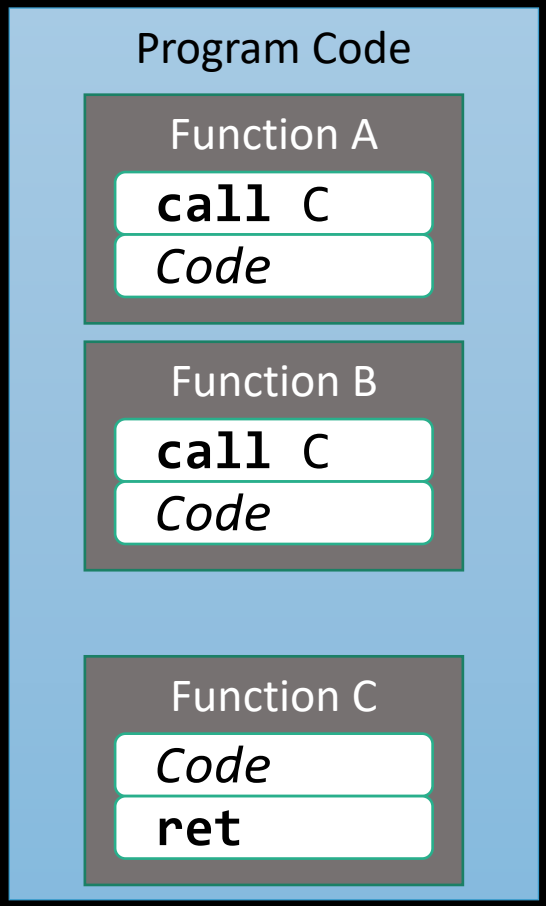

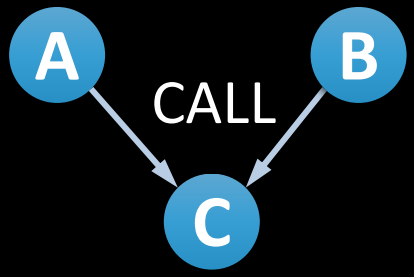

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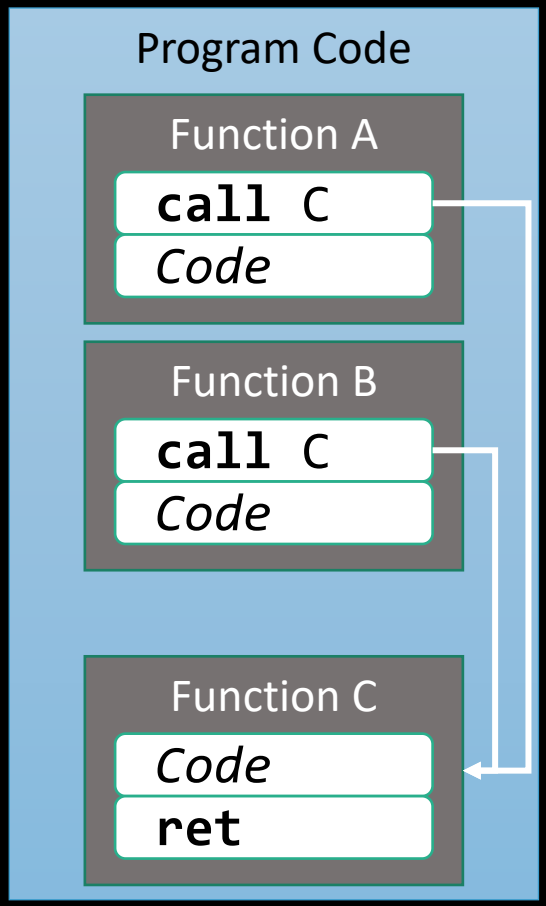

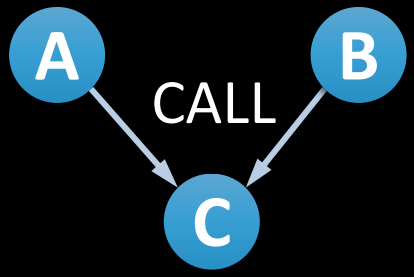

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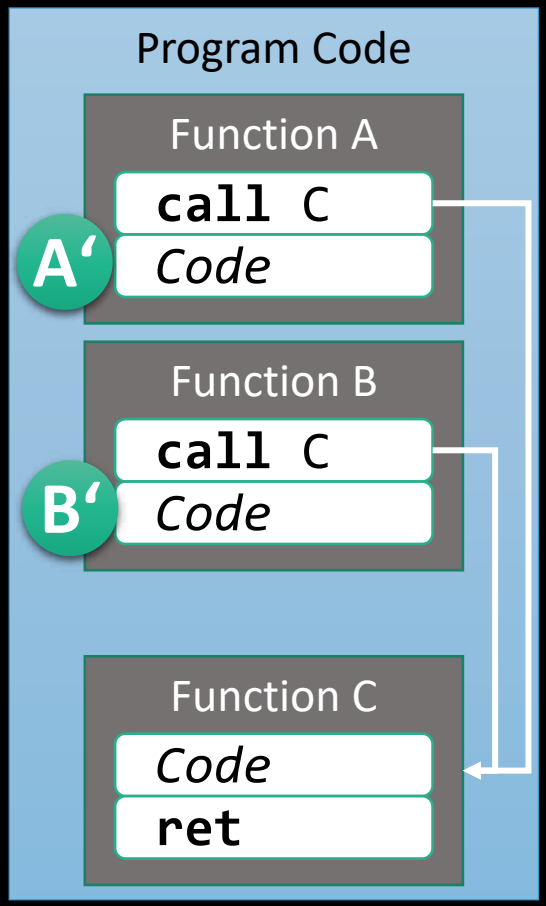

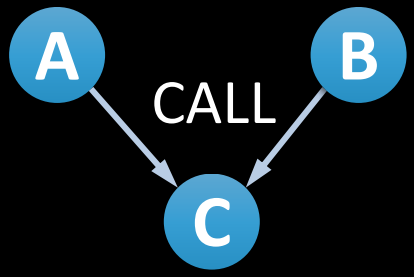

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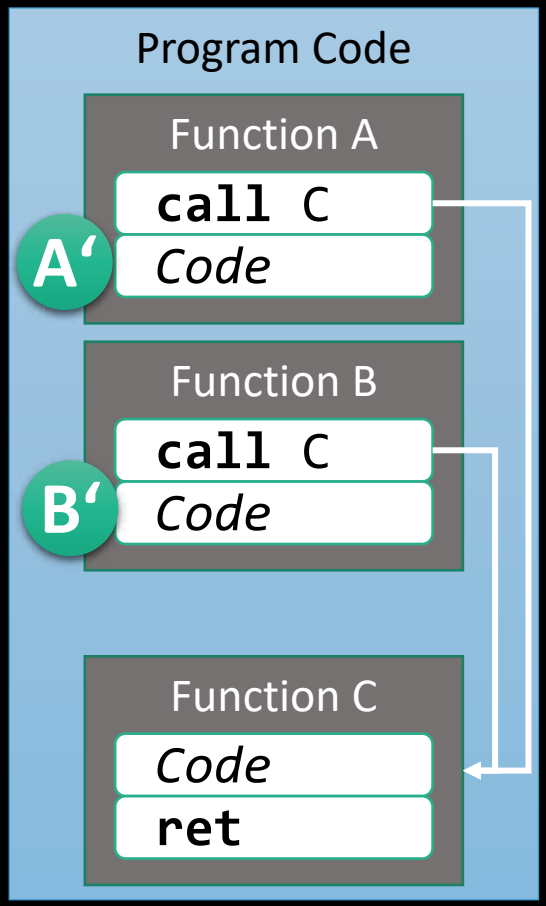

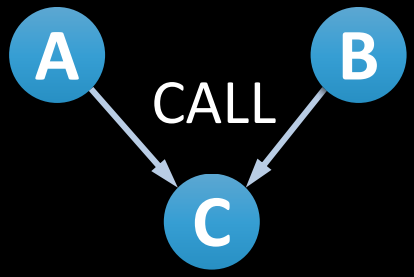

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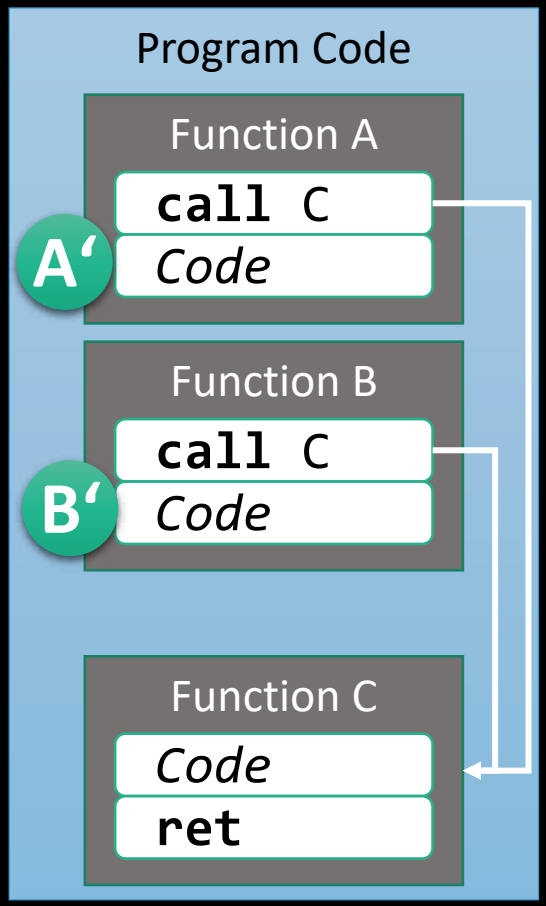

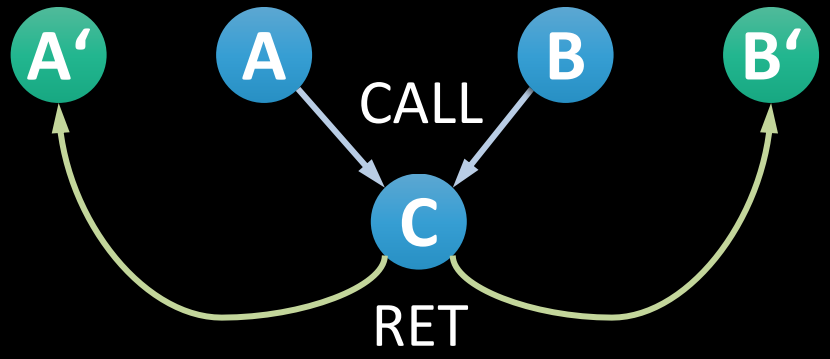

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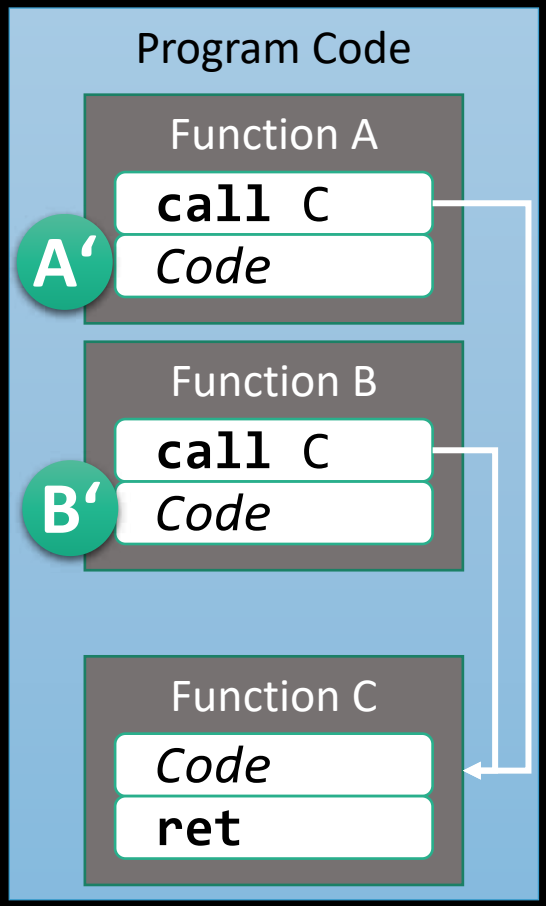

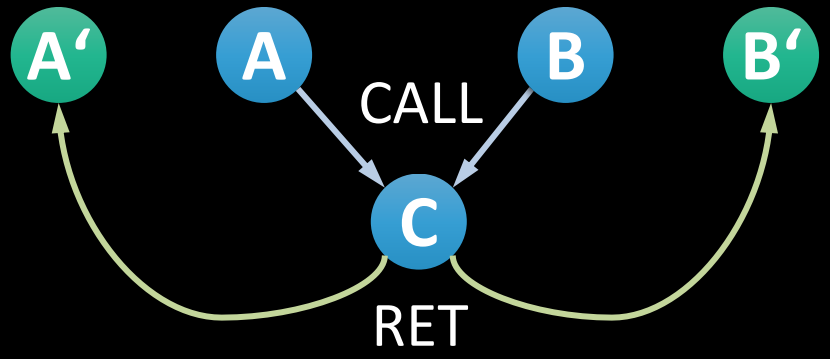

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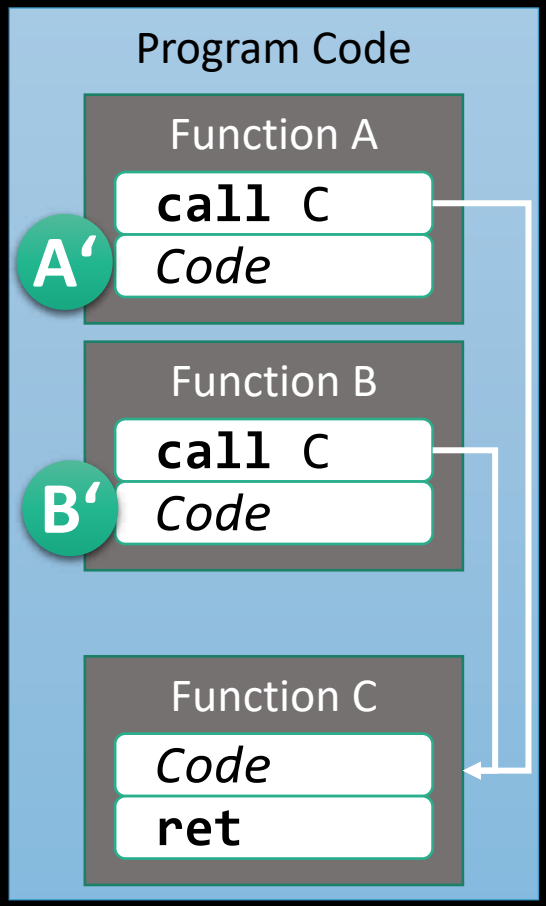

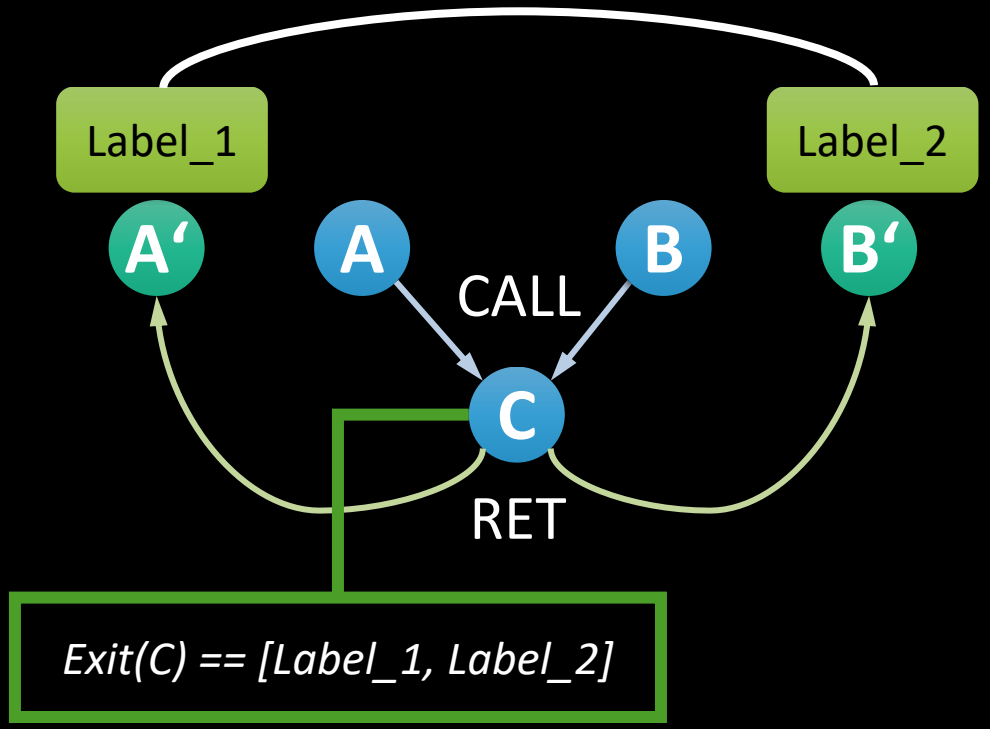

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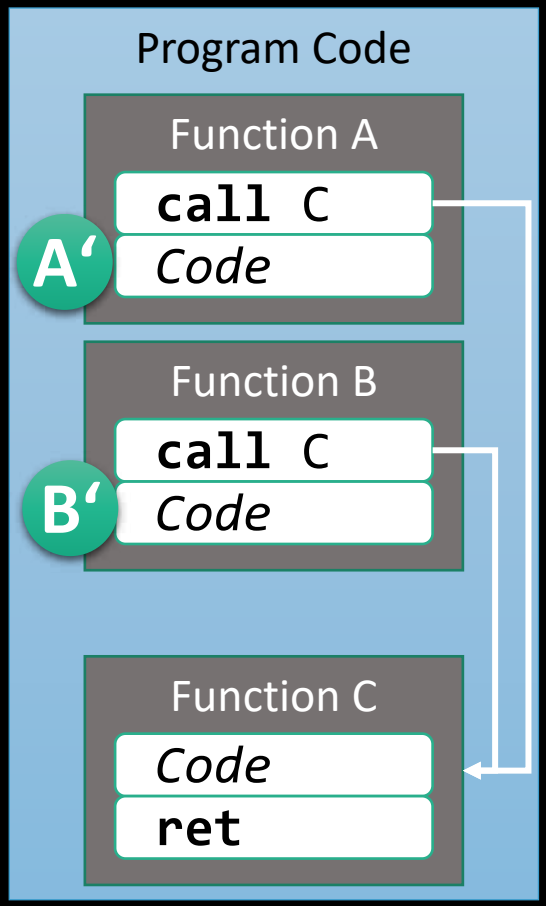

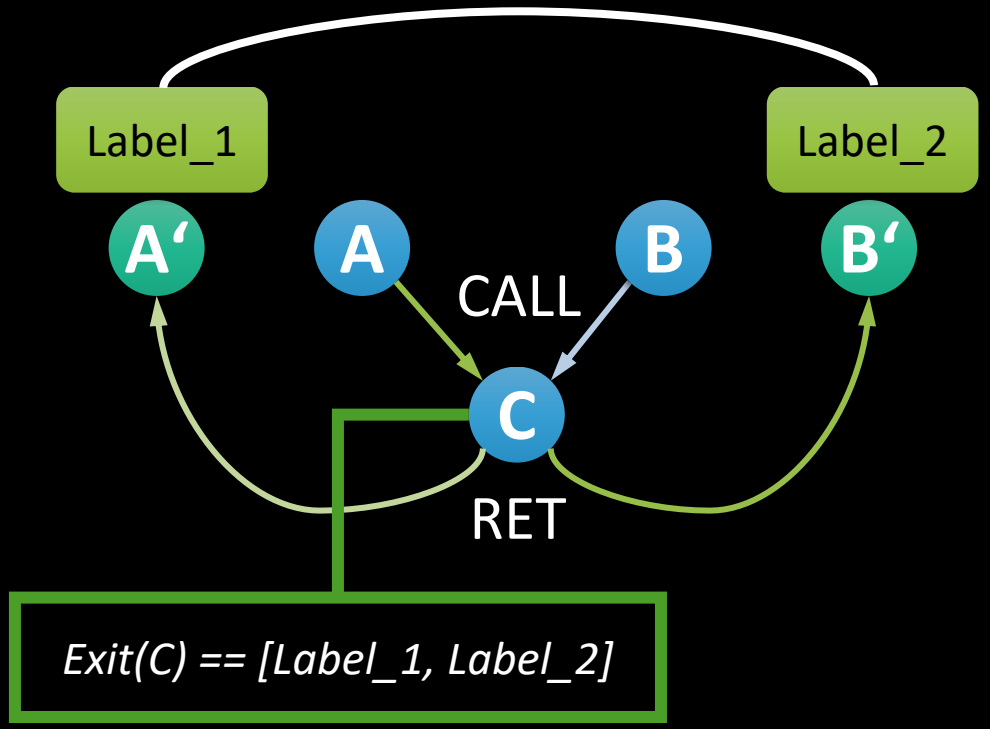

Shadow Stack / Return Address Stack

- Shadow stack allows for fine-grained return address protection but incurs higher overhead

Shadow Stack

Backup storage for return addresses

Shadow Stack / Return Address Stack

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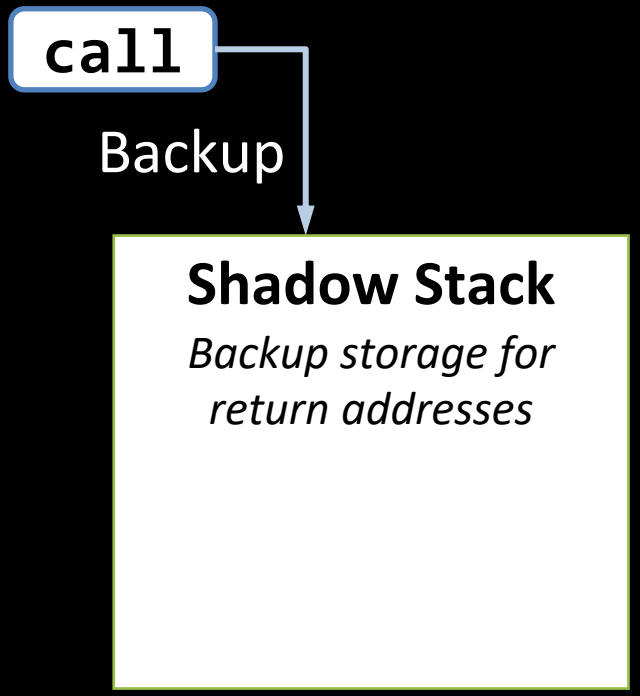

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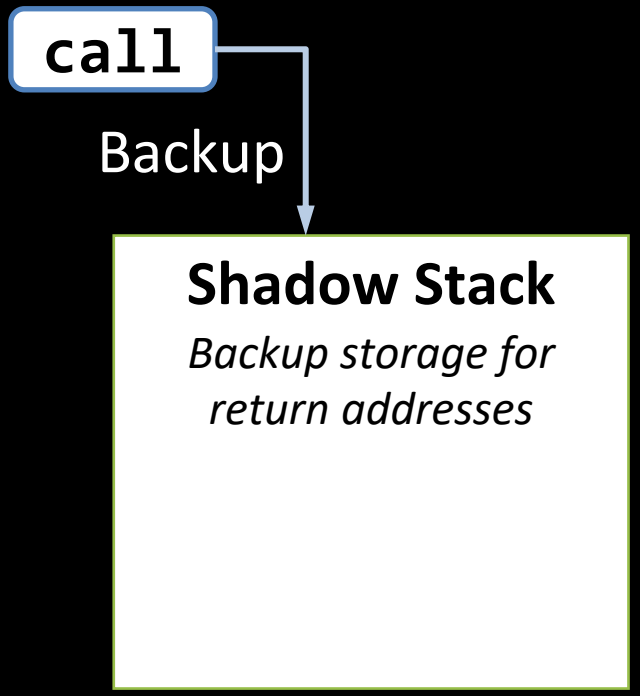

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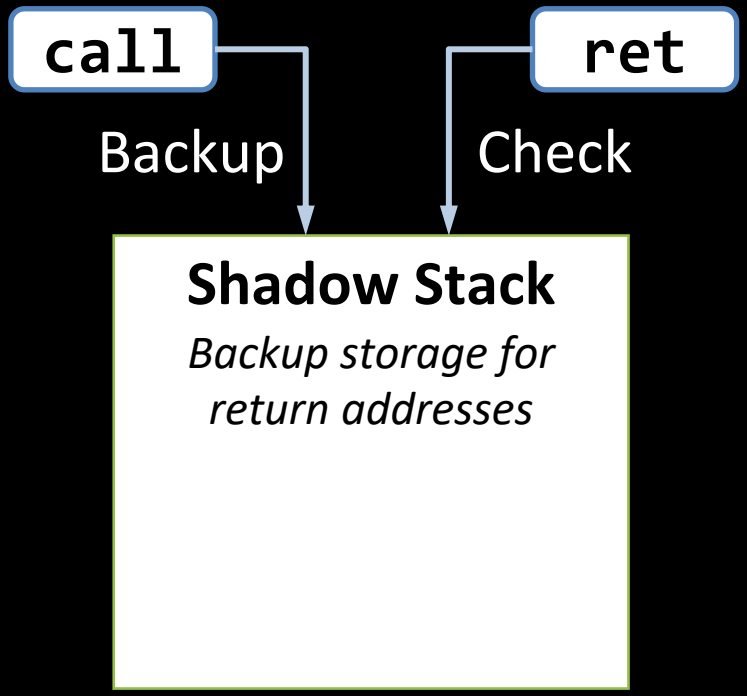

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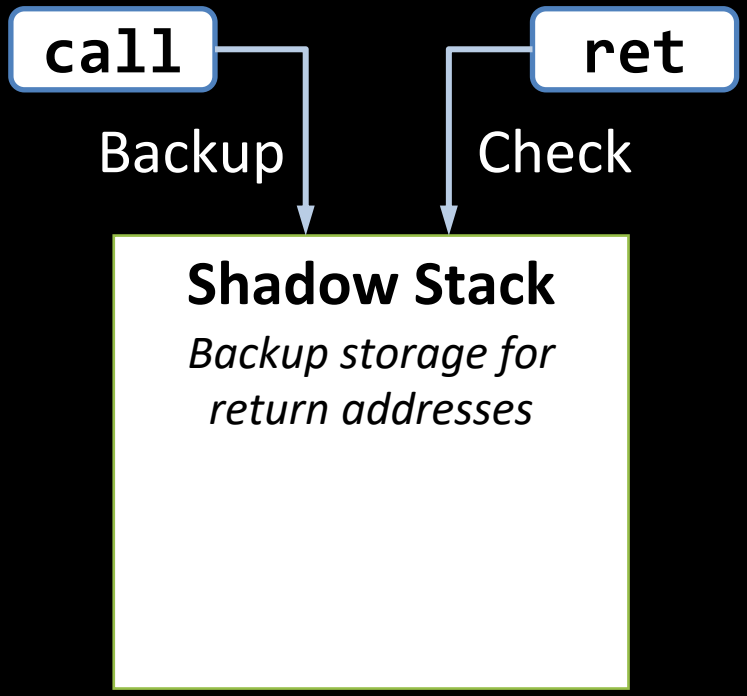

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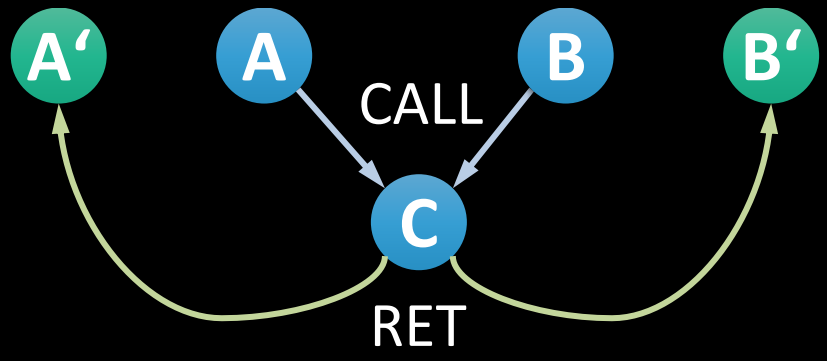

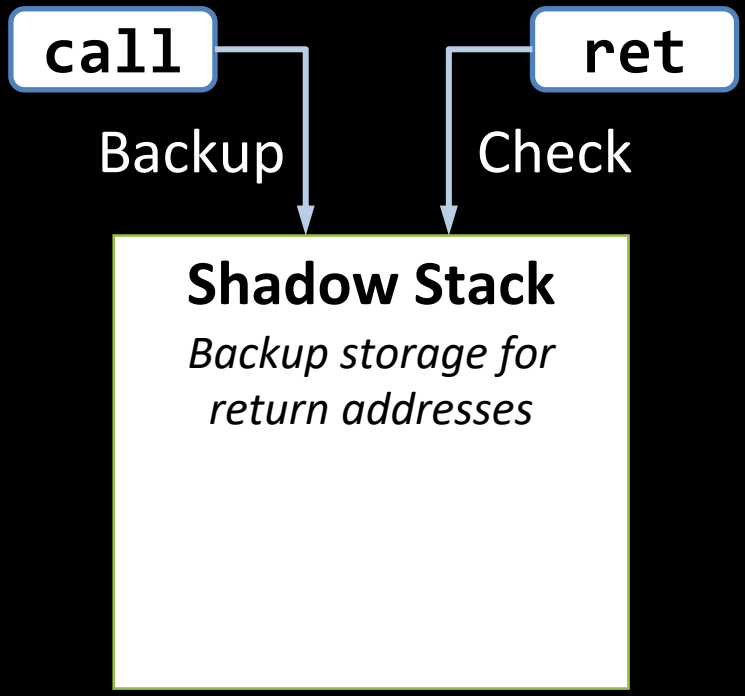

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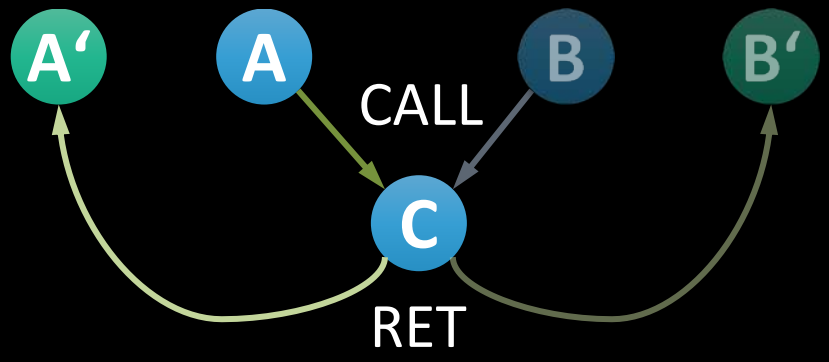

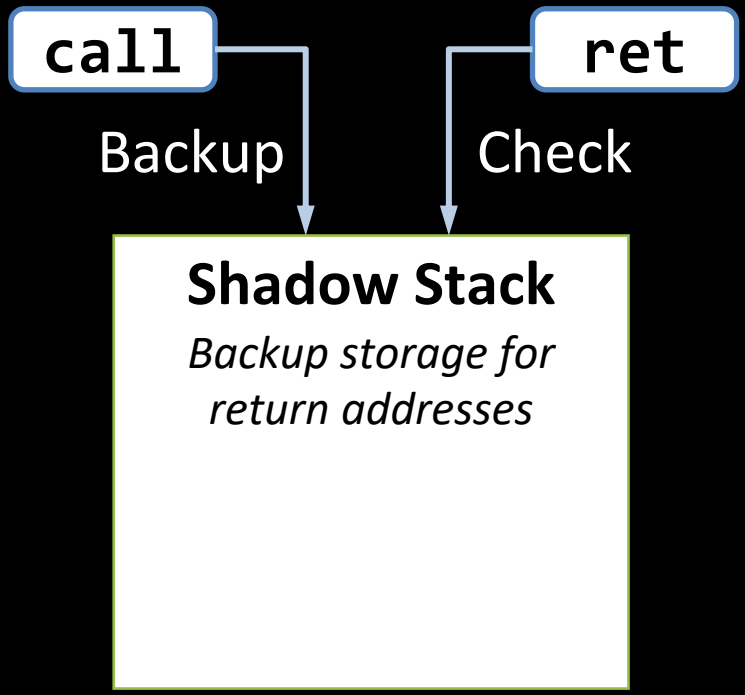

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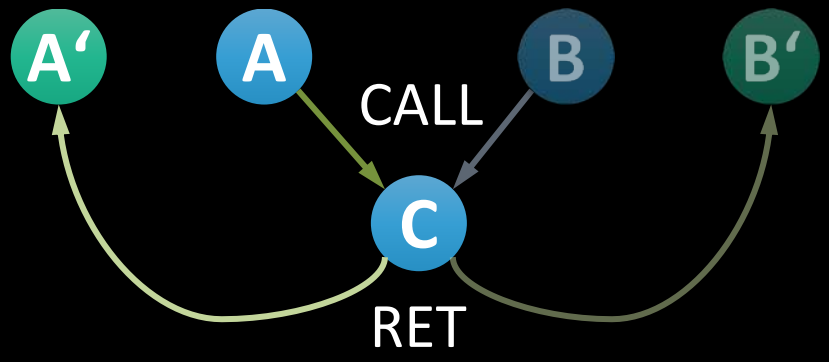

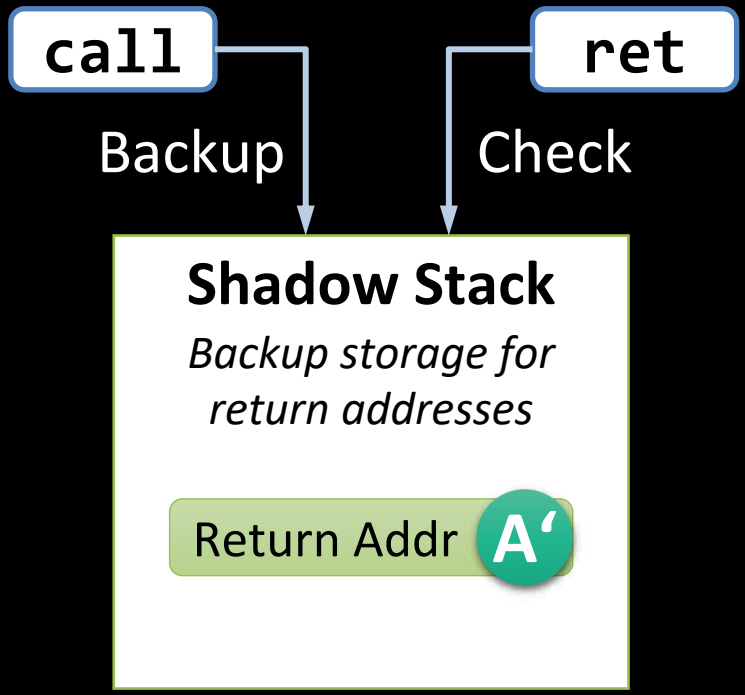

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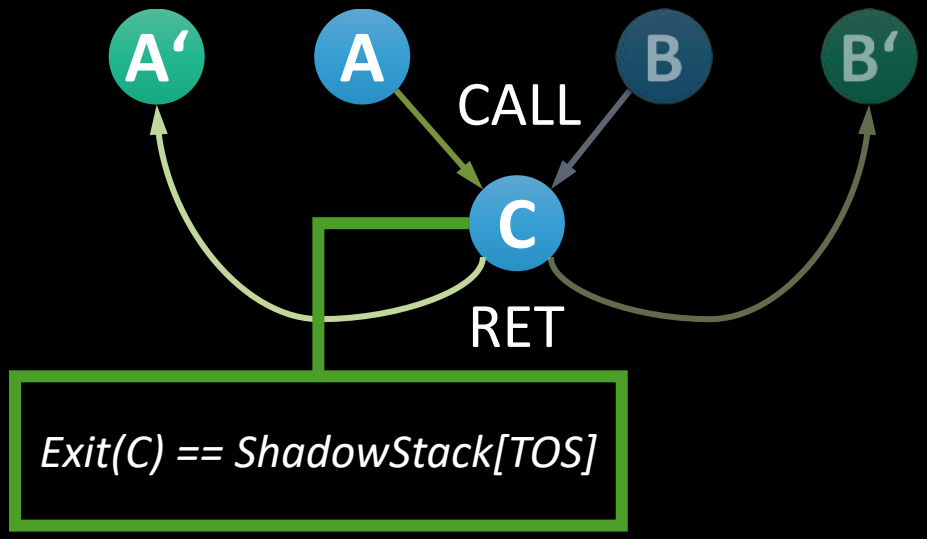

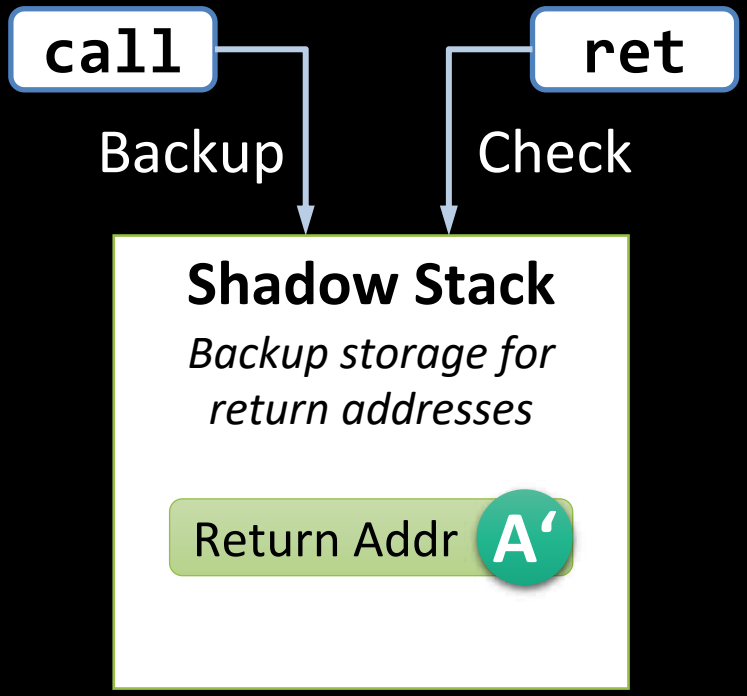

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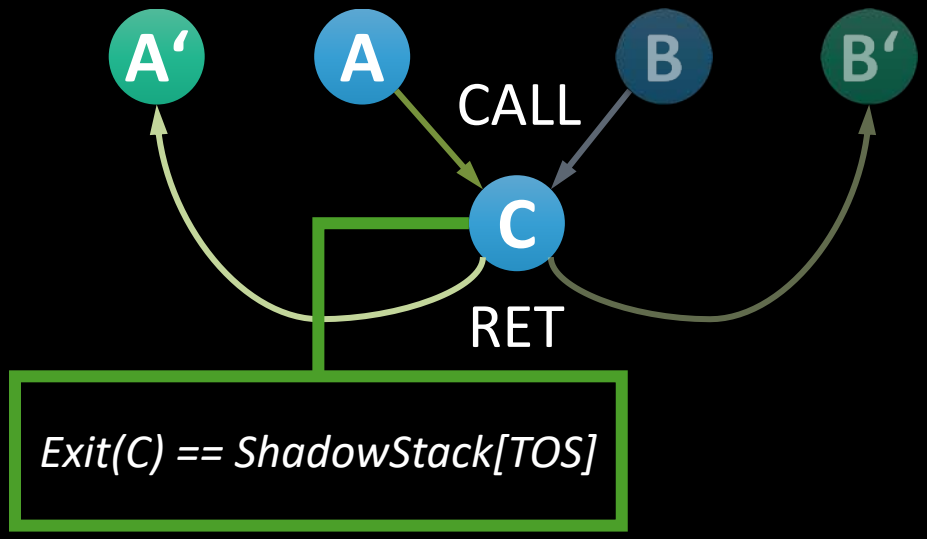

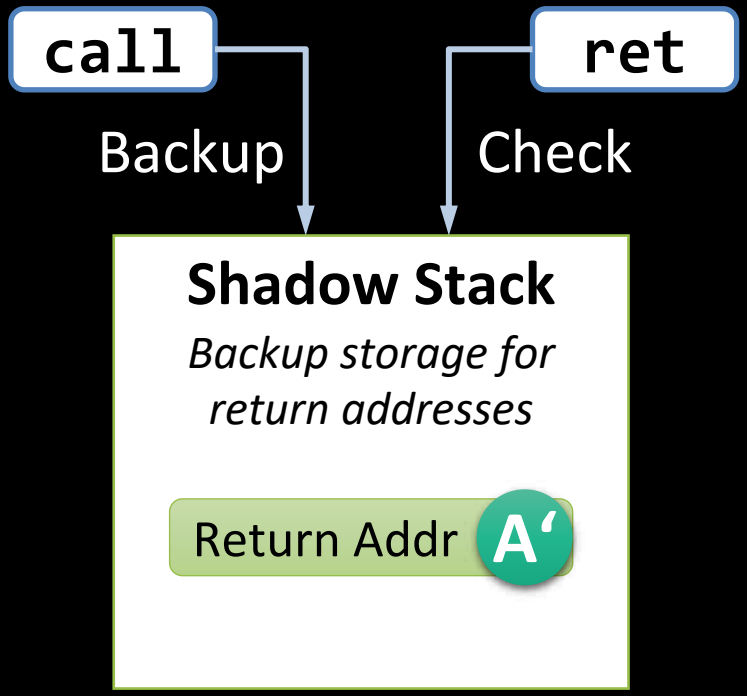

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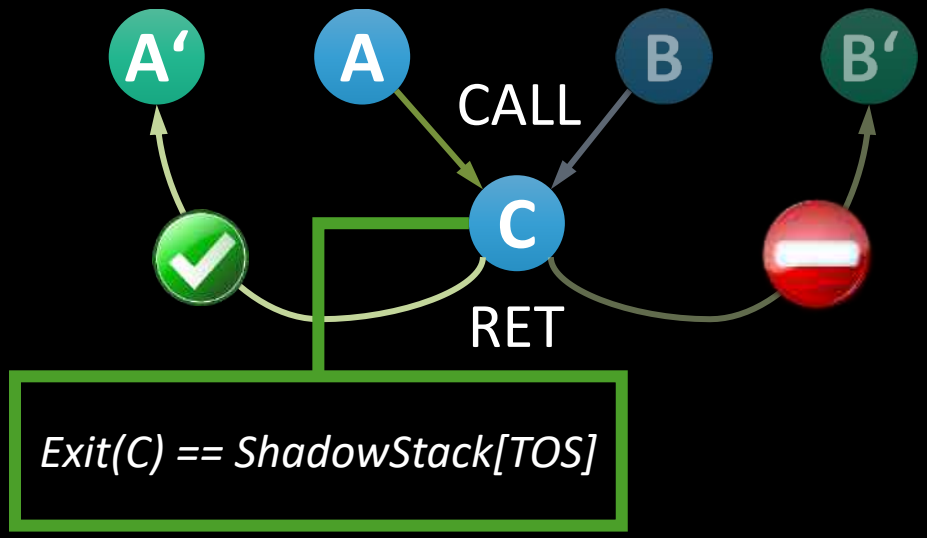
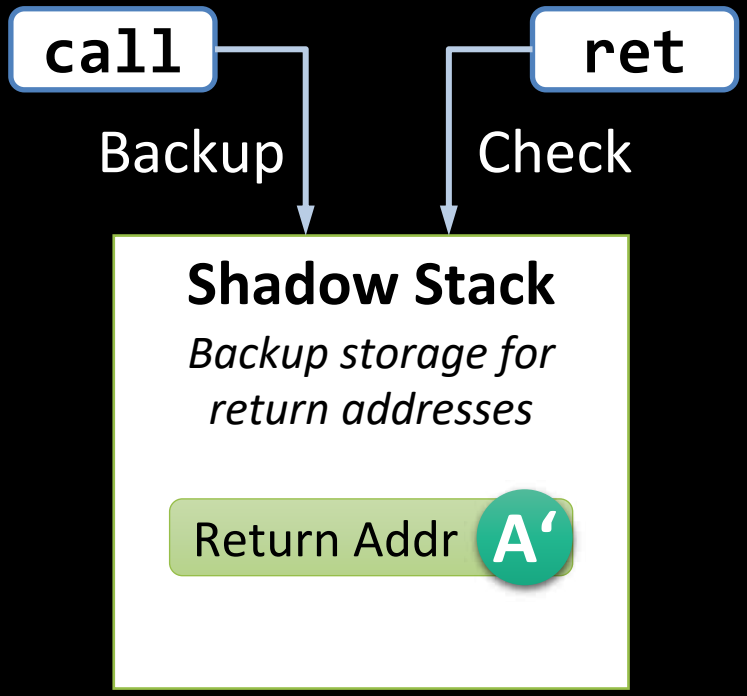
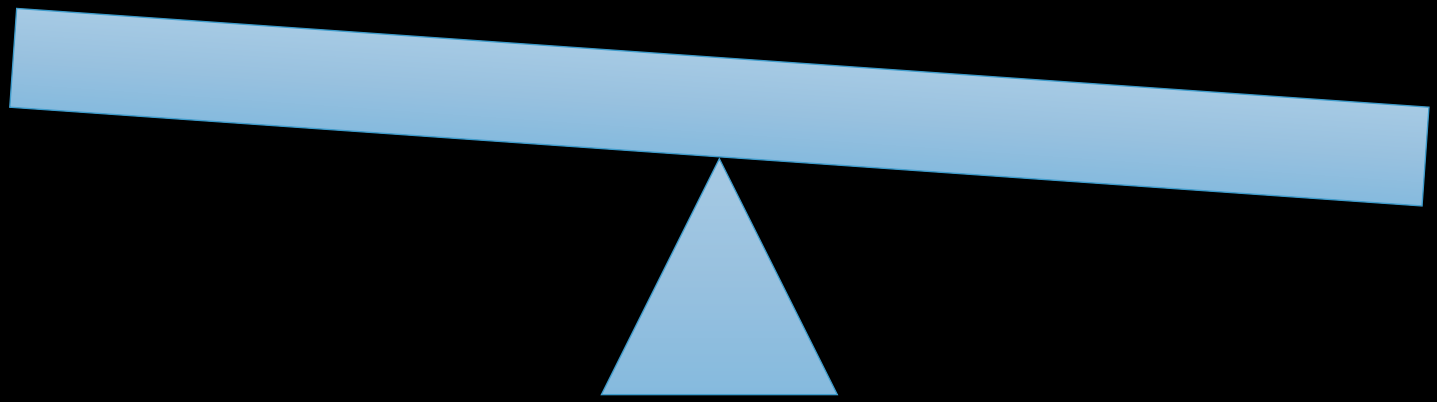




CFI: Benefits and Limitations



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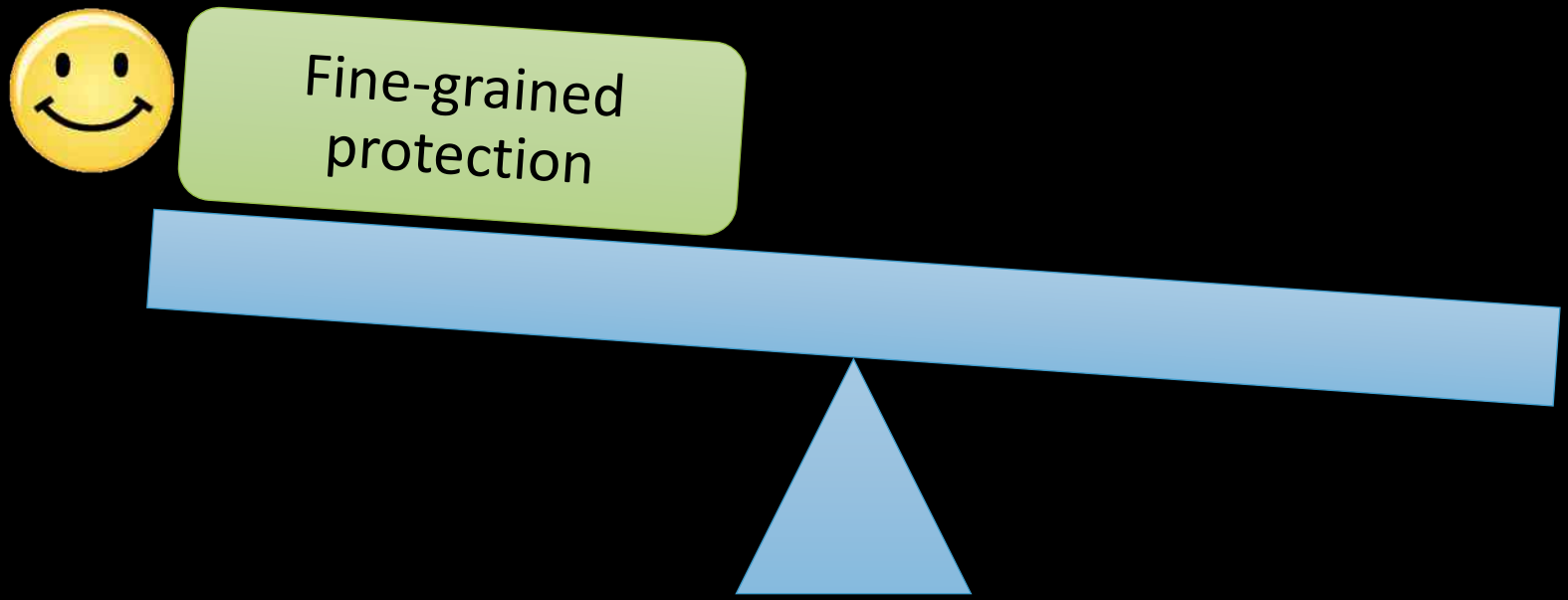

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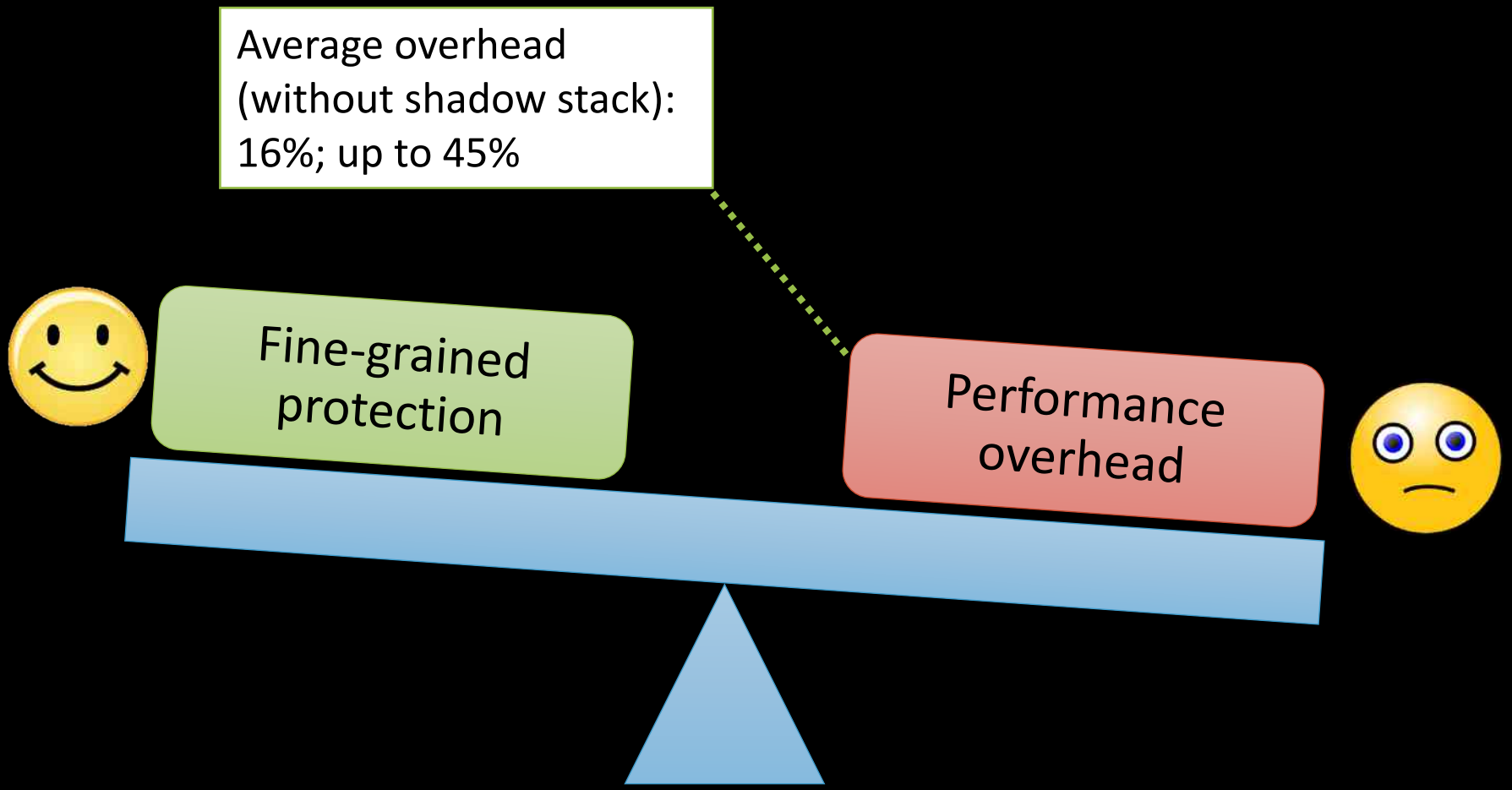

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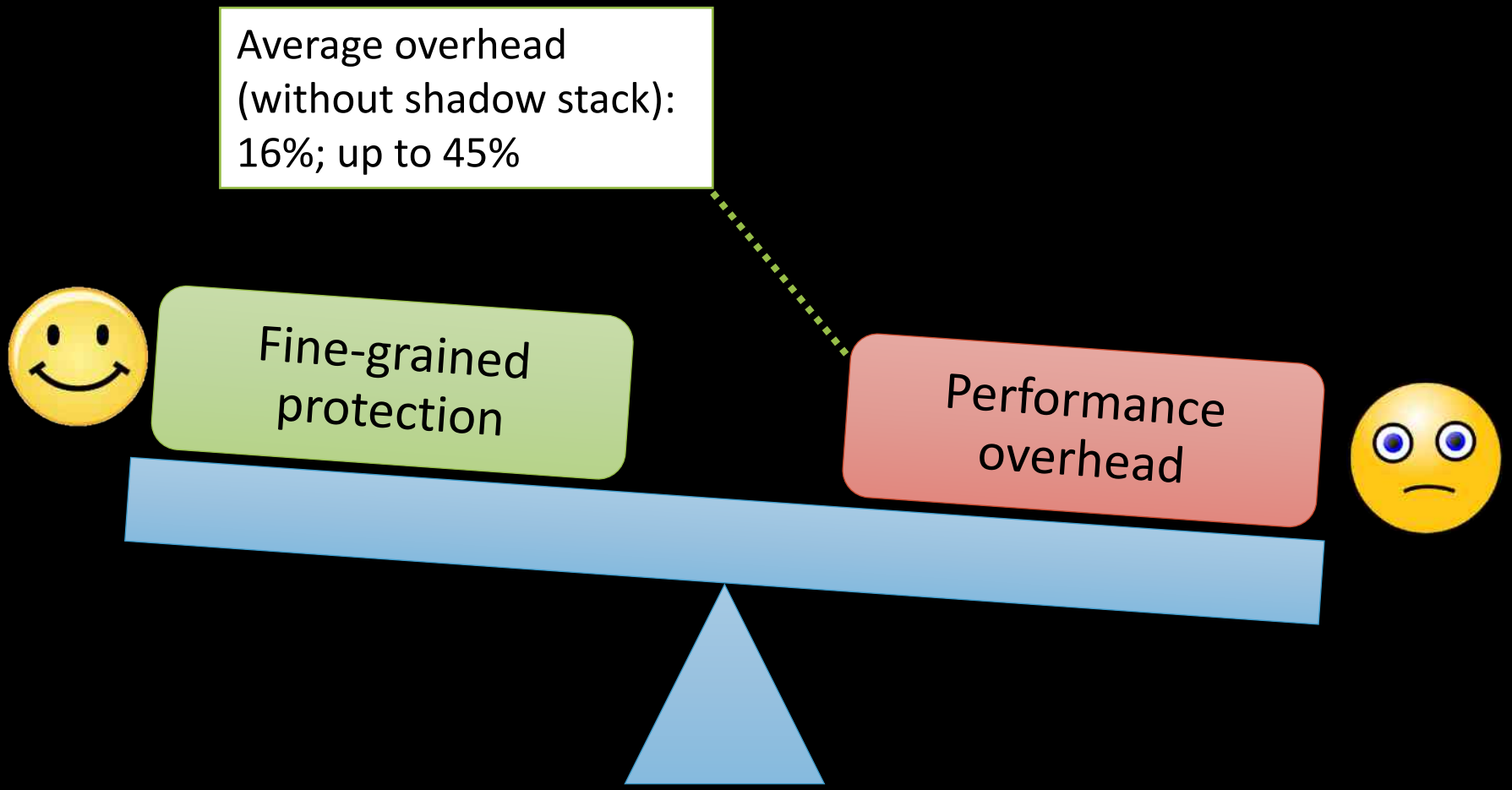

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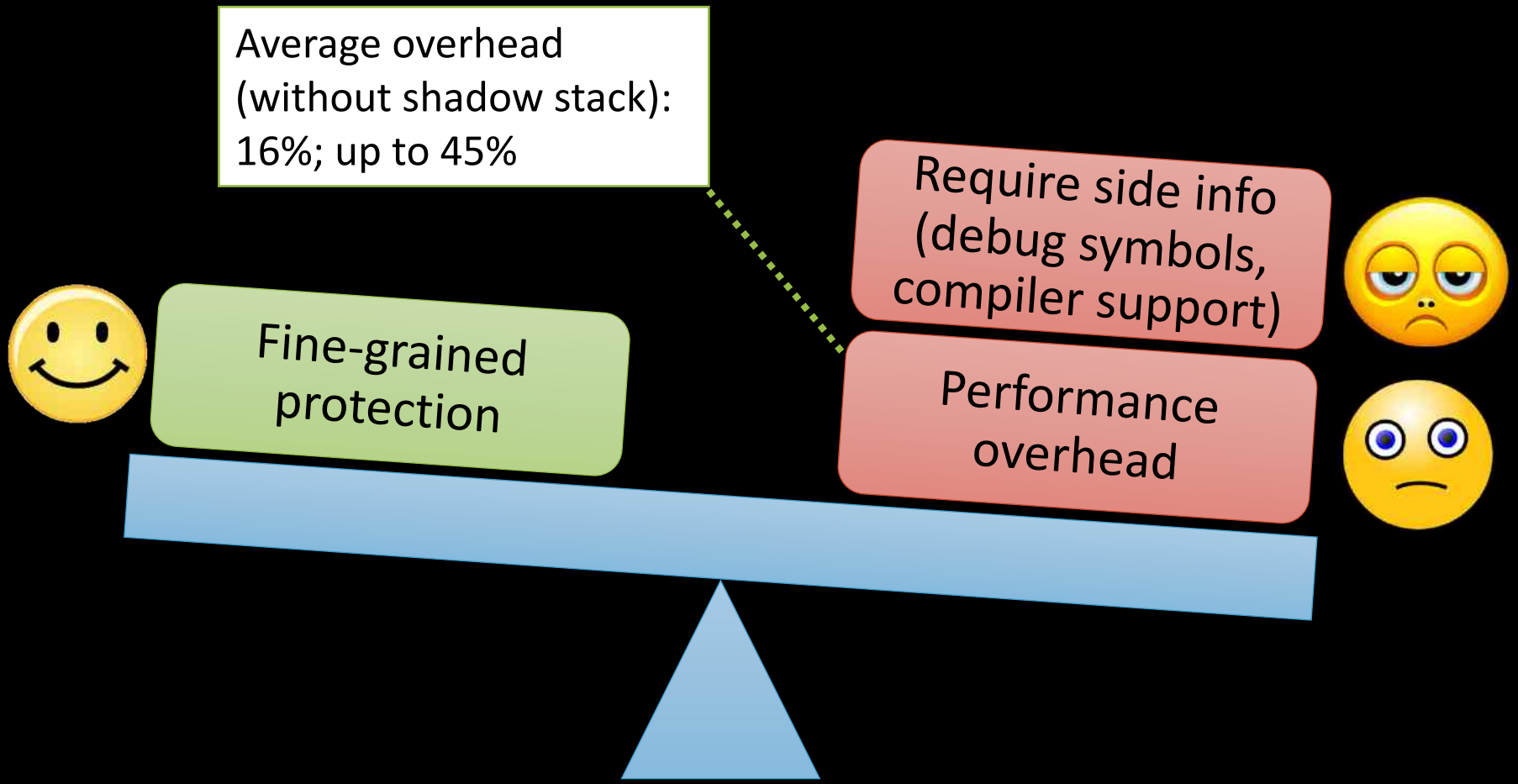

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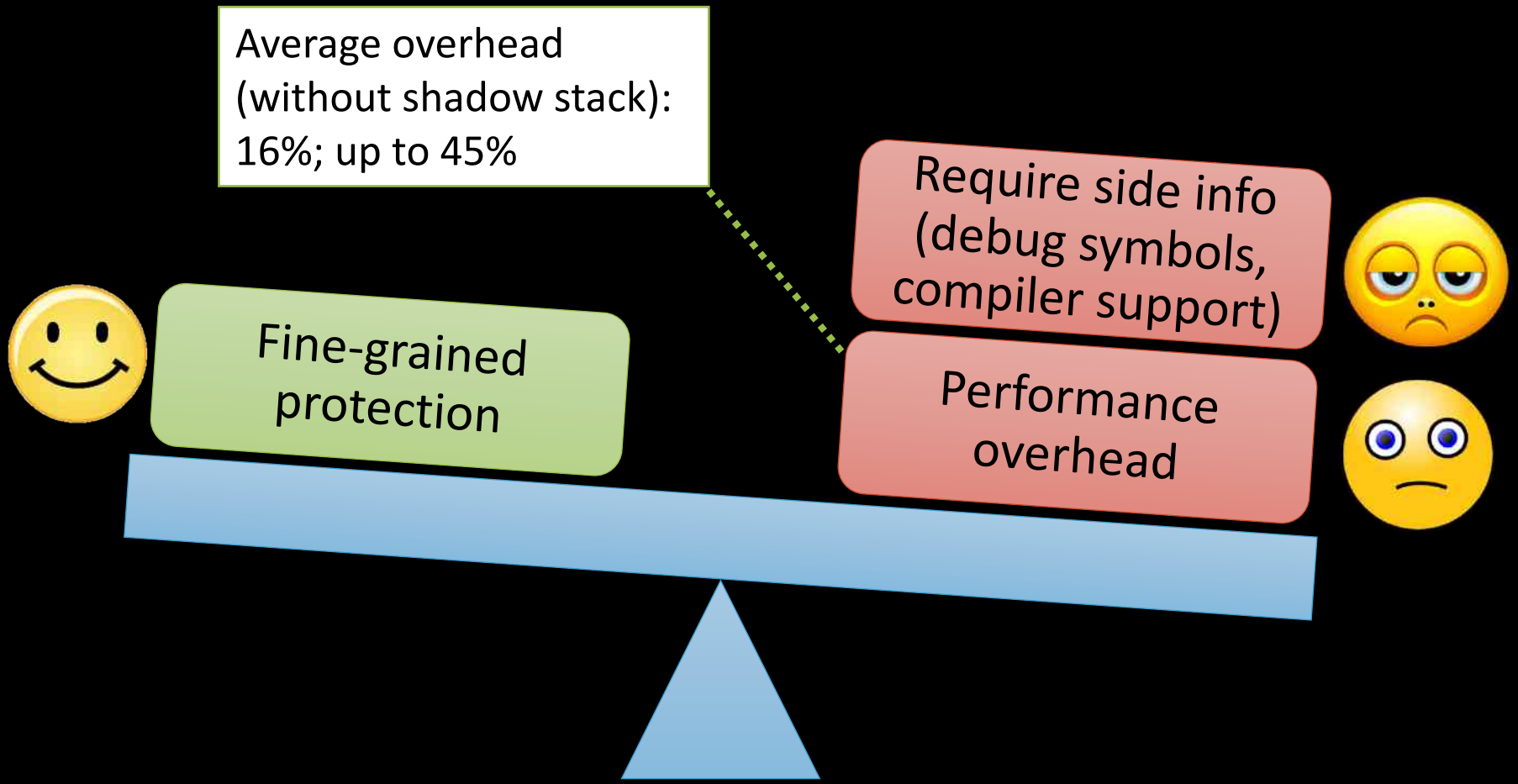

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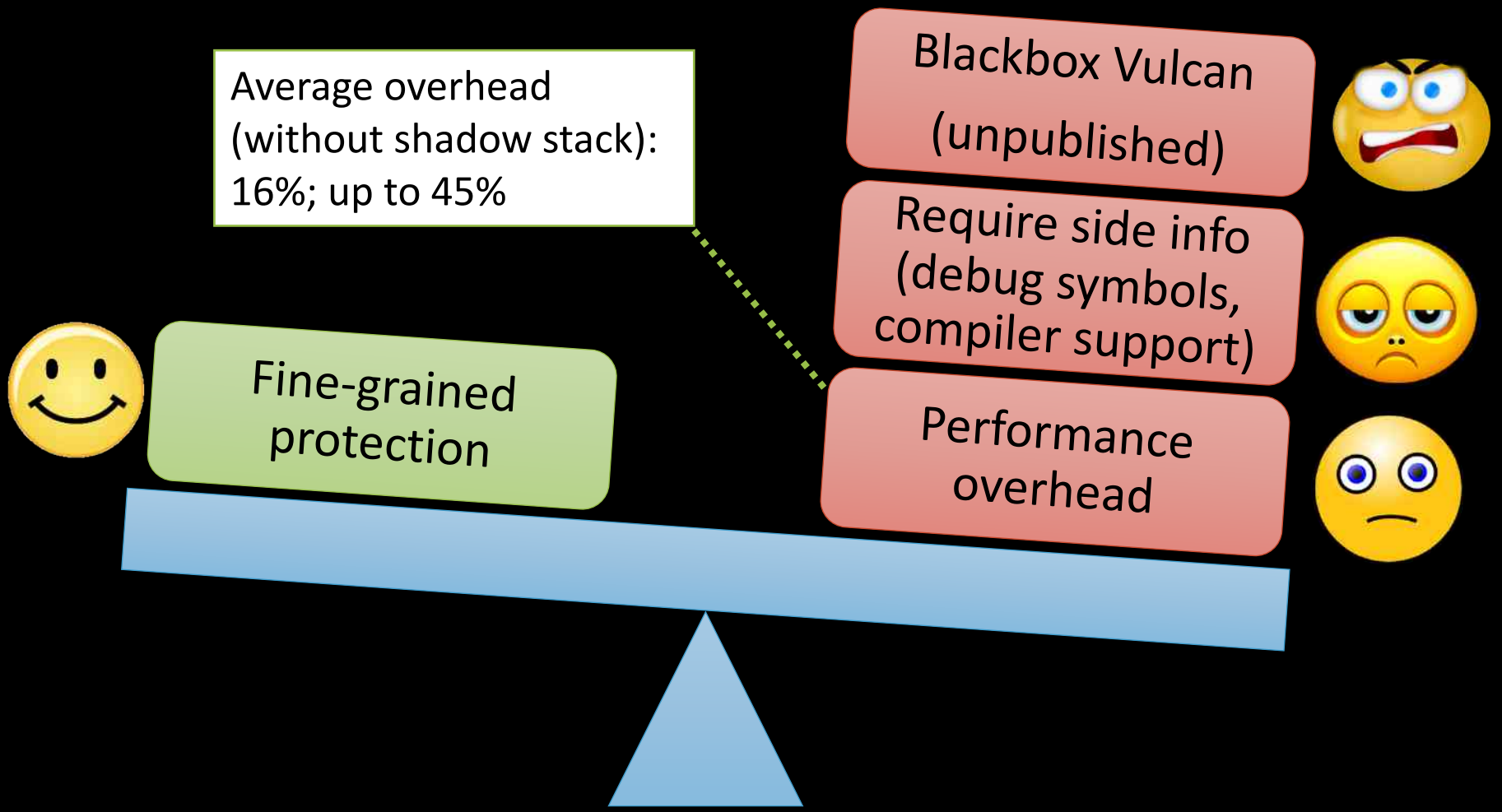

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"Practical" (coarse-grained)

Control Flow Integrity (CFI)

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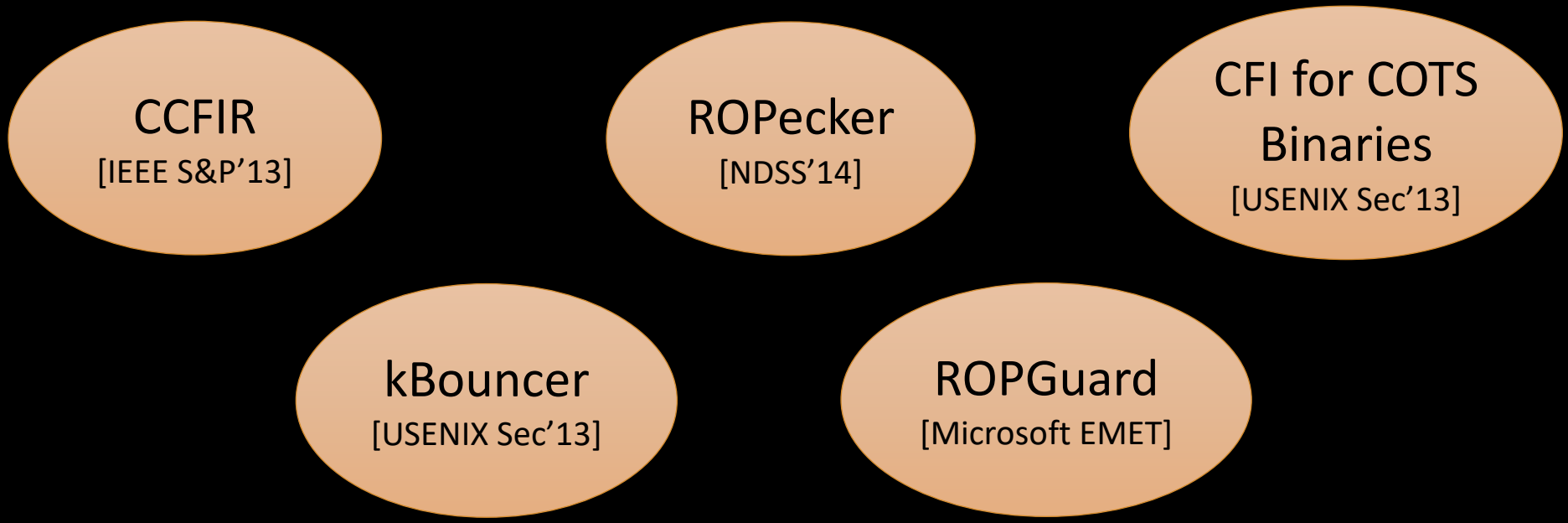

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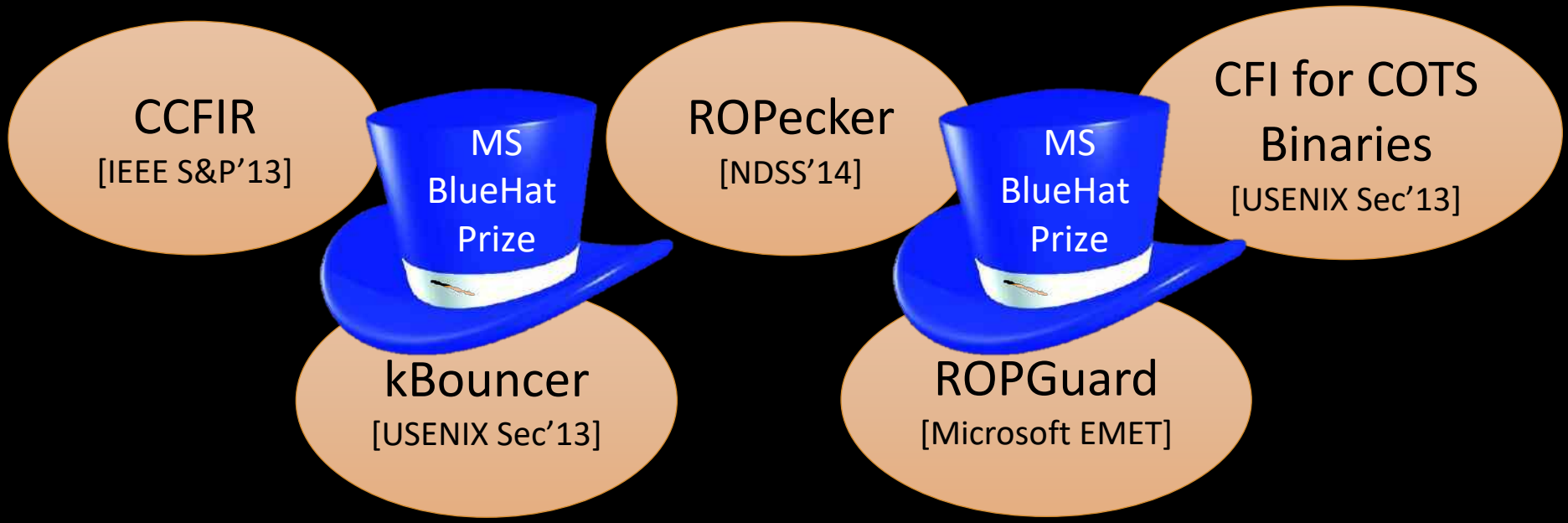

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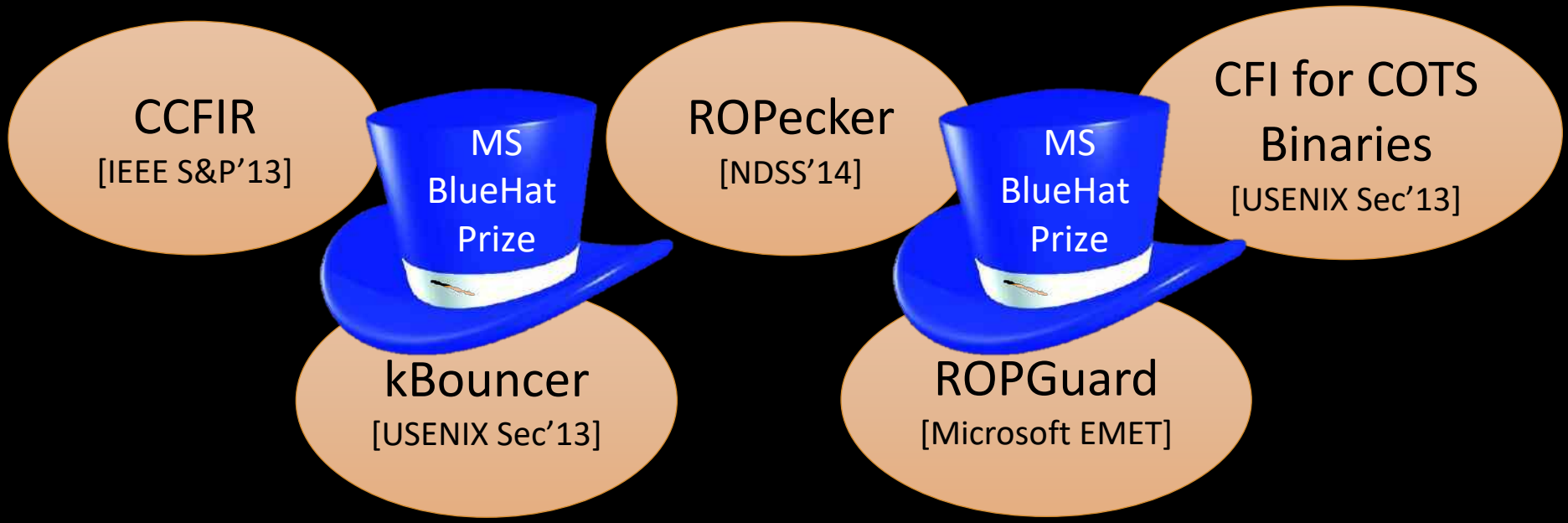

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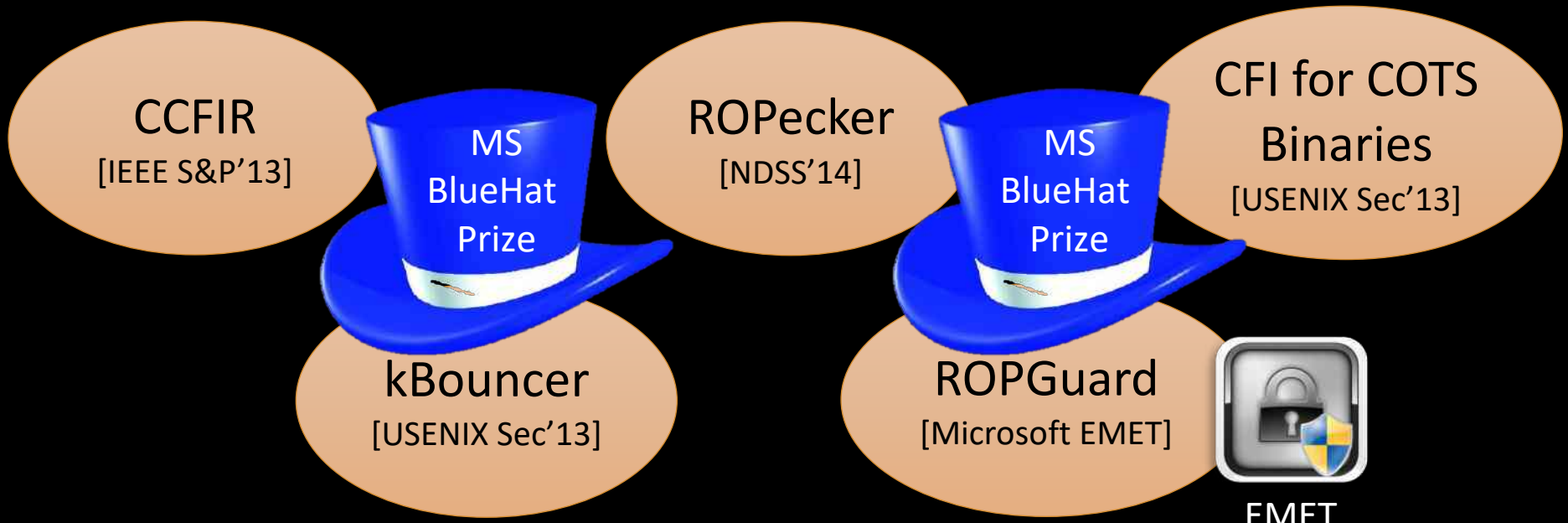
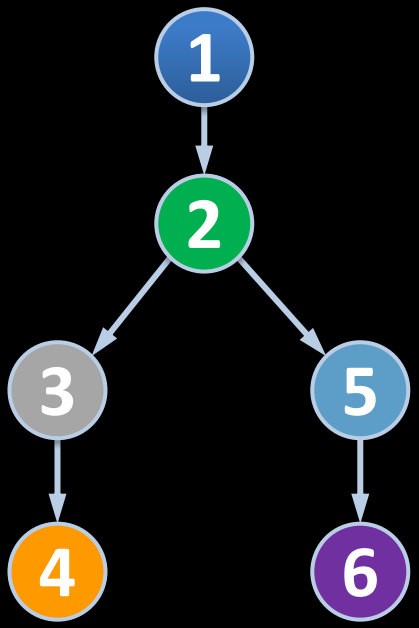


http://technet.microsoft.com/en-us/security/jj653751

Coarse-grained CFI leads to CFG imprecision



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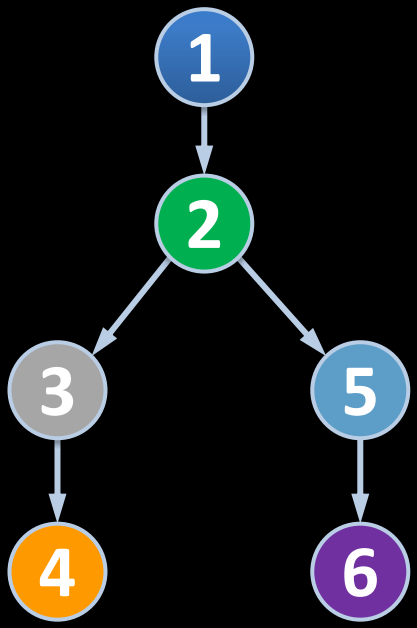

Reducing number of labels

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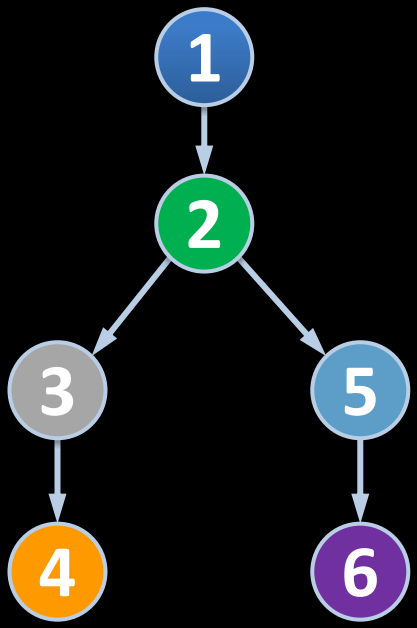

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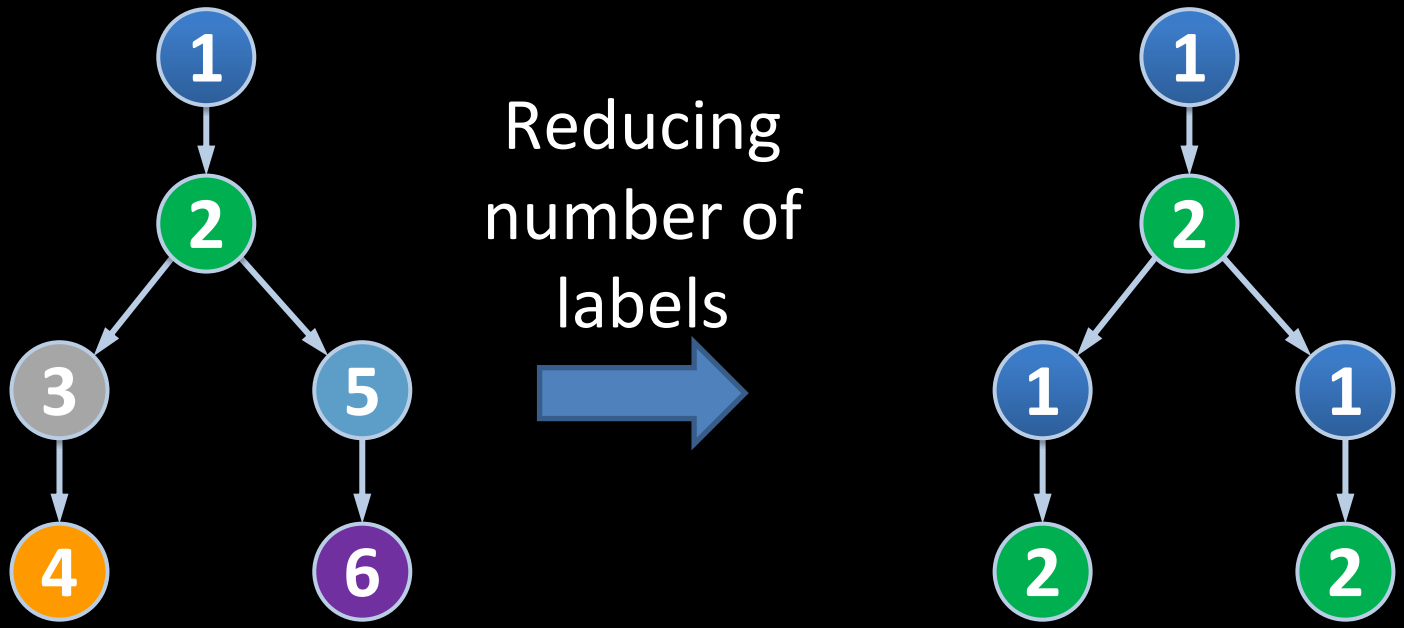
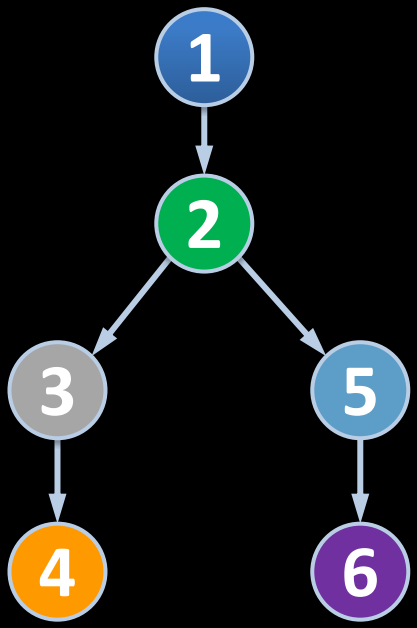


Coarse-grained CFI leads to CFG imprecision

Allowed paths: 1→2 and 2→1



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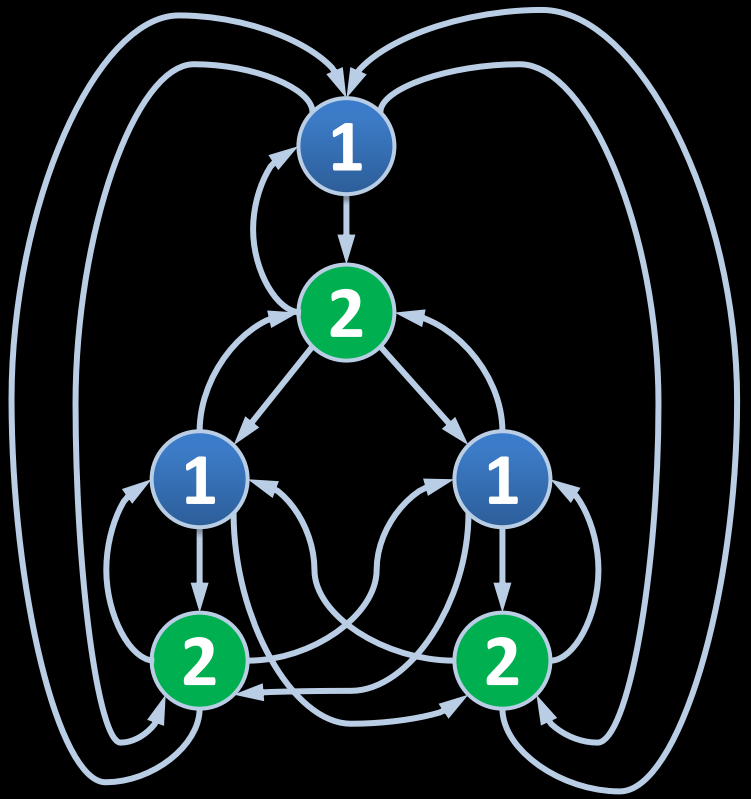

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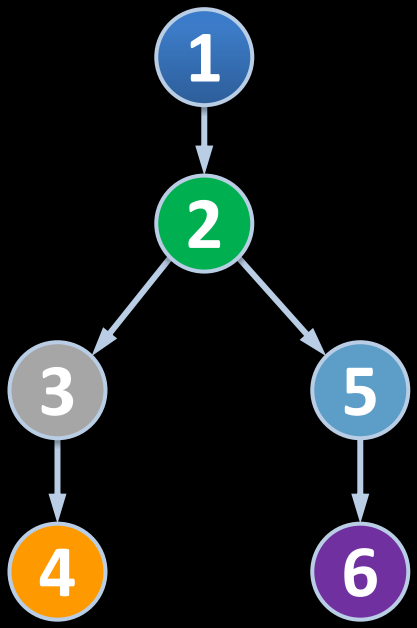

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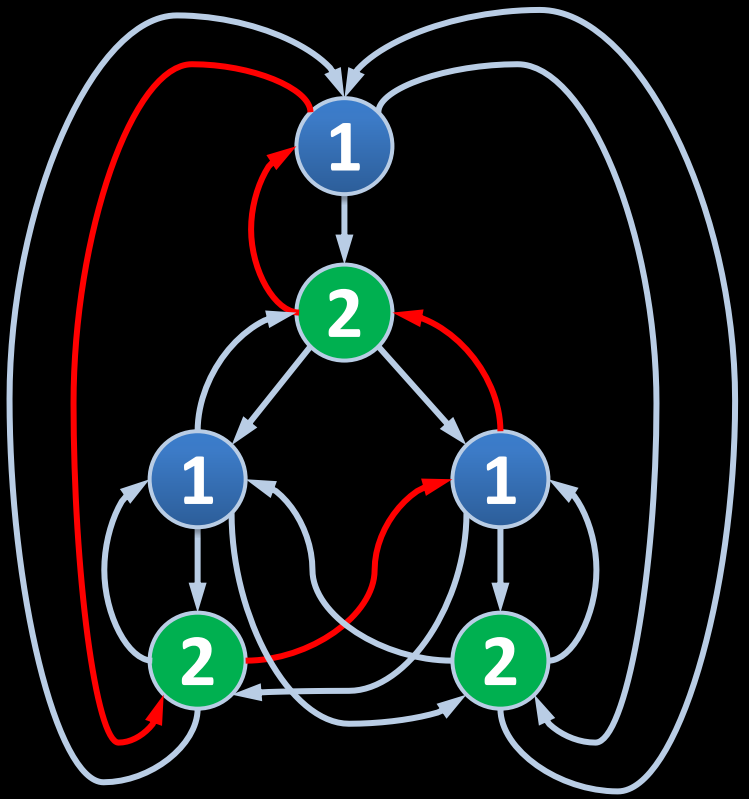

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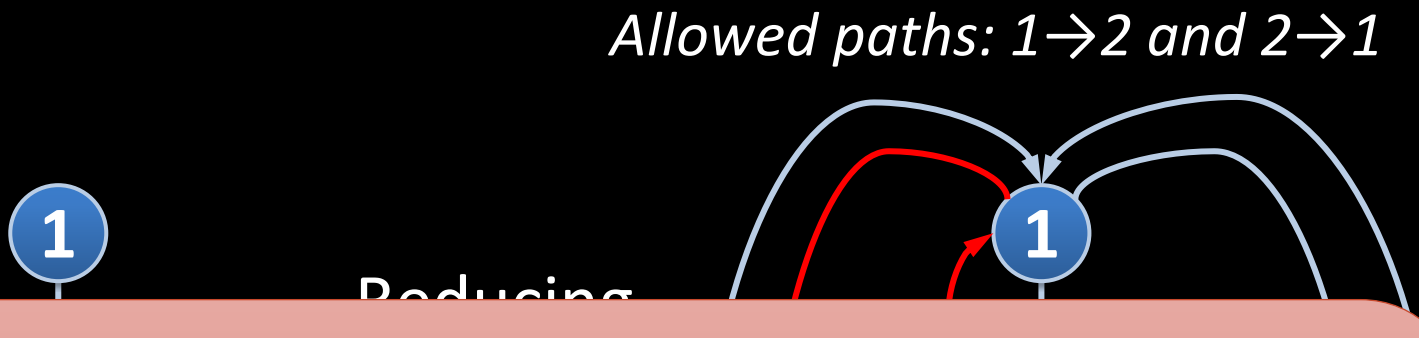
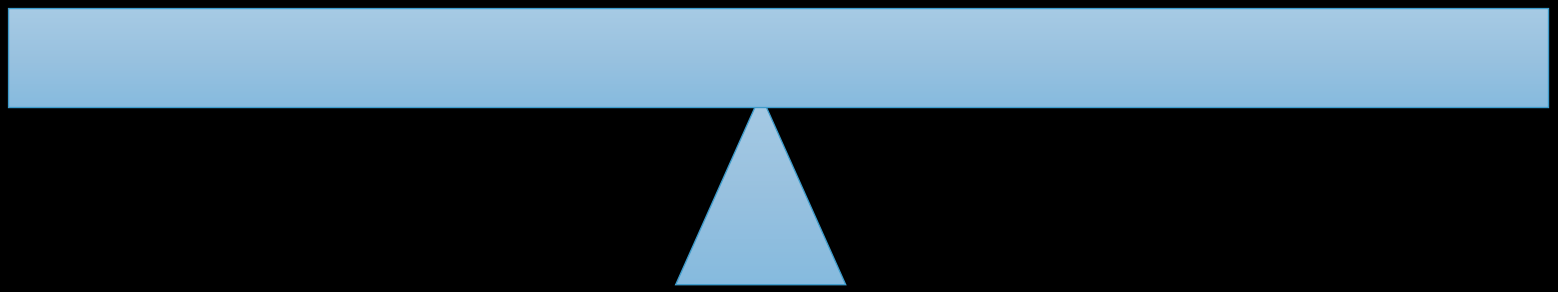


Many attacks have been proposed that exploit the coarse-grained checks of these CFI schemes

Out-of-Control [Goktas et al., IEEE S&P 2014]
Stitching the Gadgets [Davi et al., USENIX Sec. 2014]
ROP is still dangerous [Carlini and Wagner, USENIX Sec. 2014]

Randomization vs. CFI



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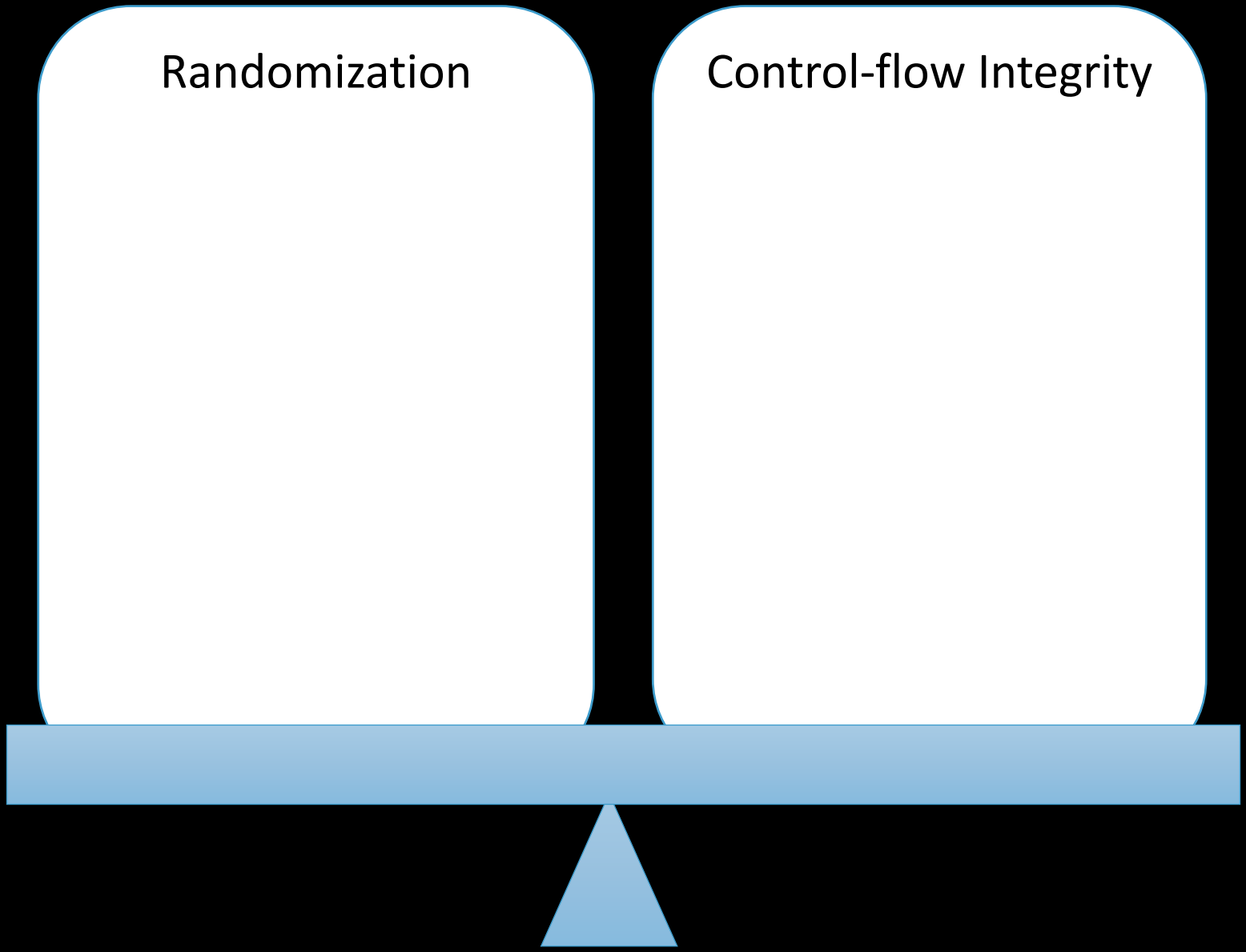

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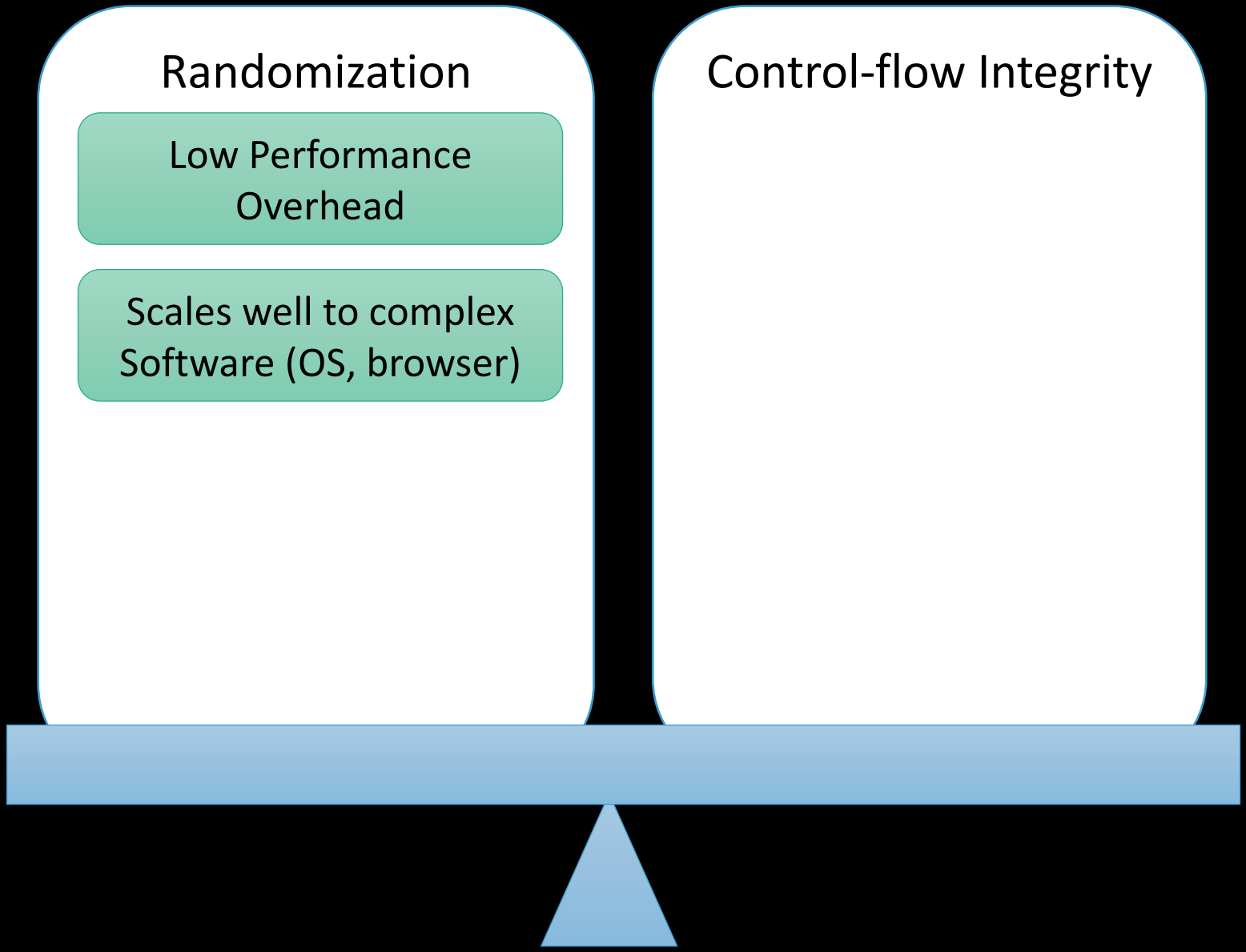

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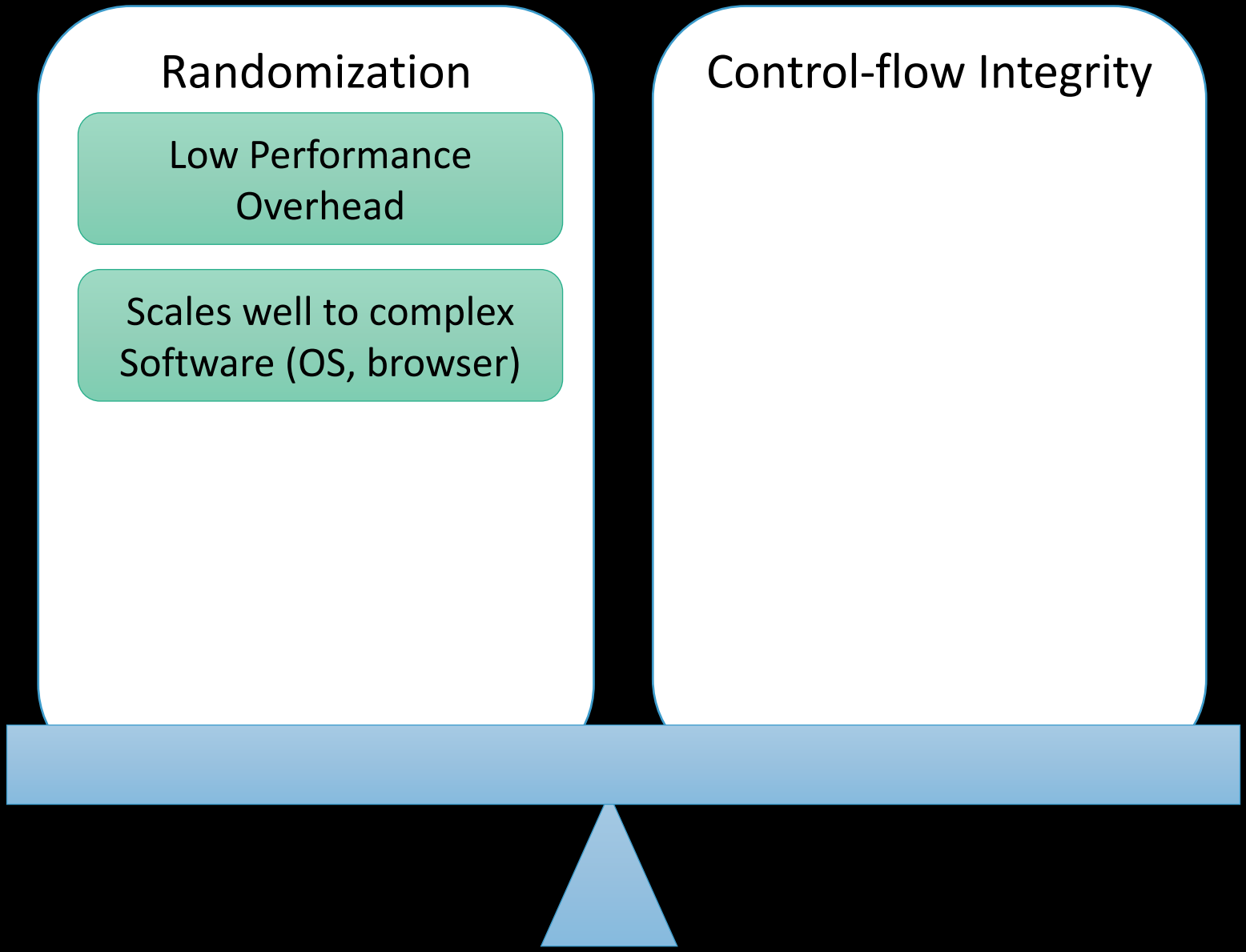

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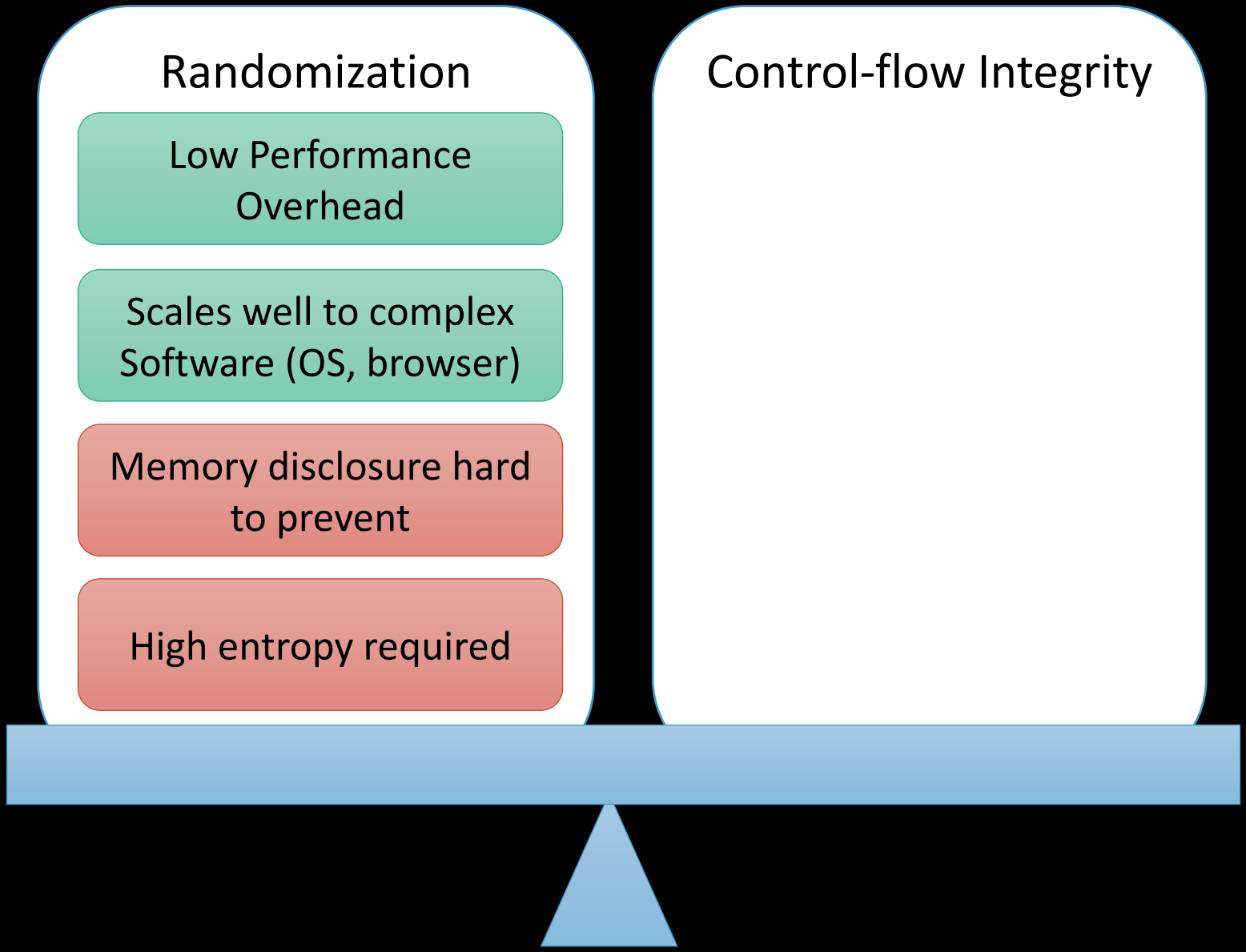

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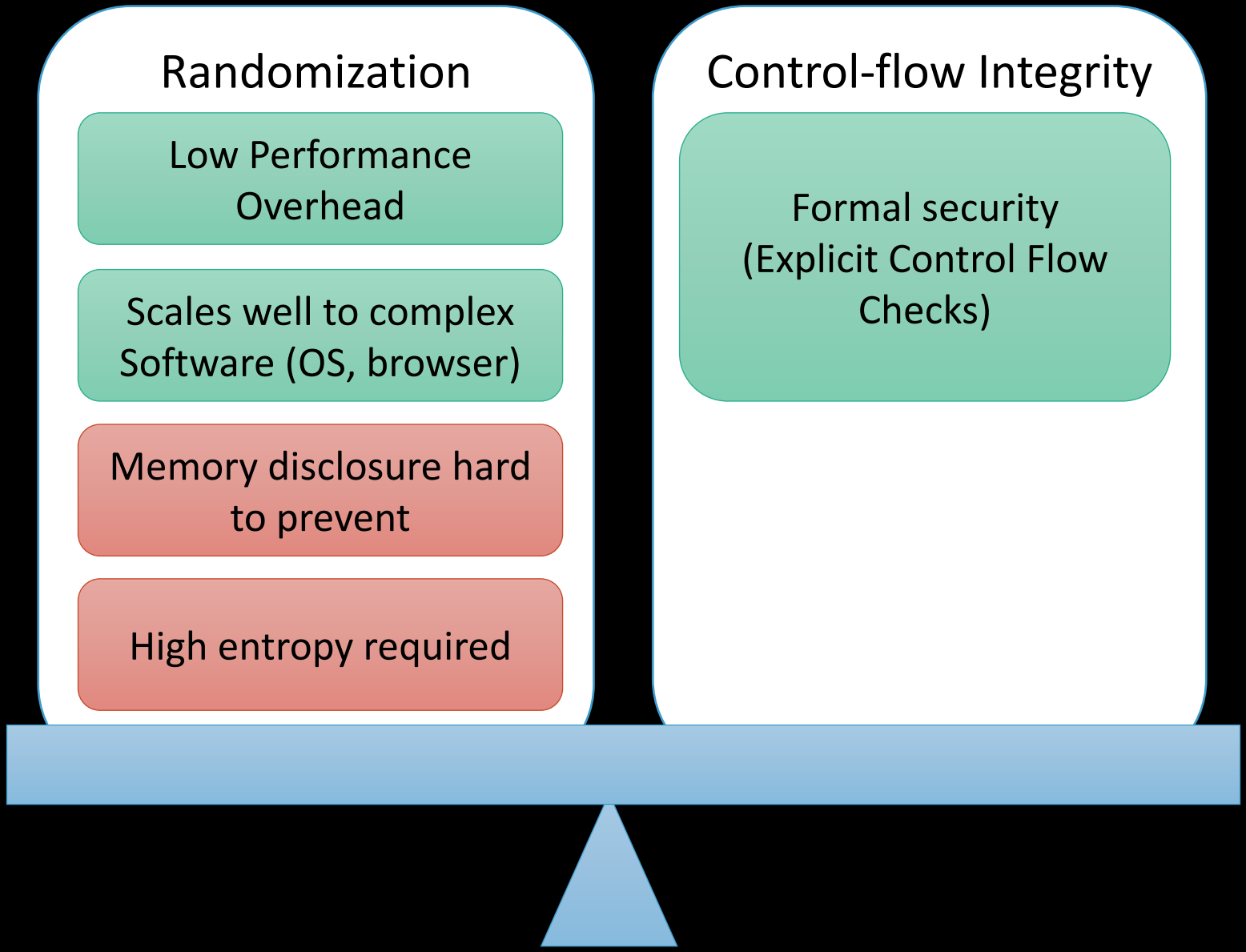

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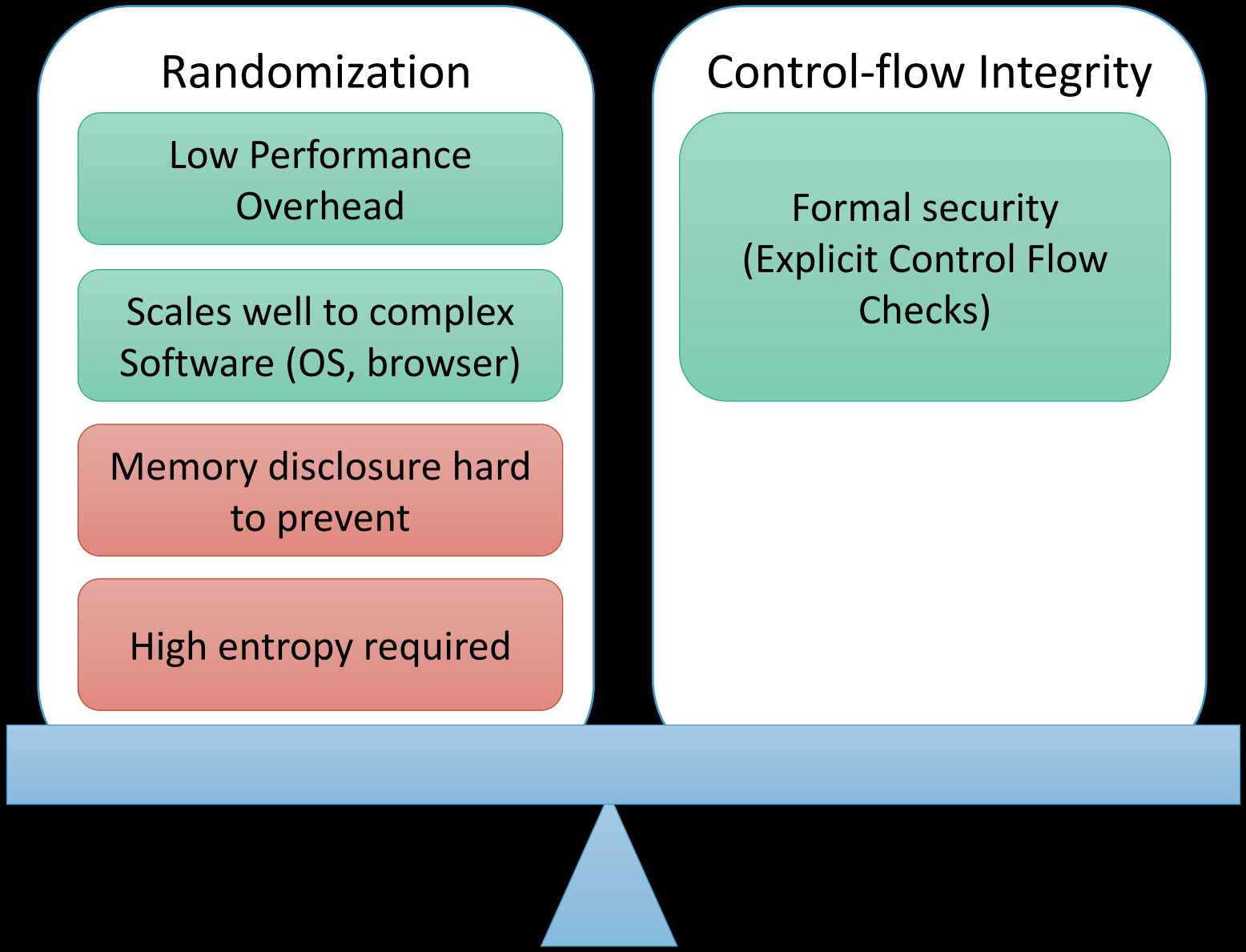

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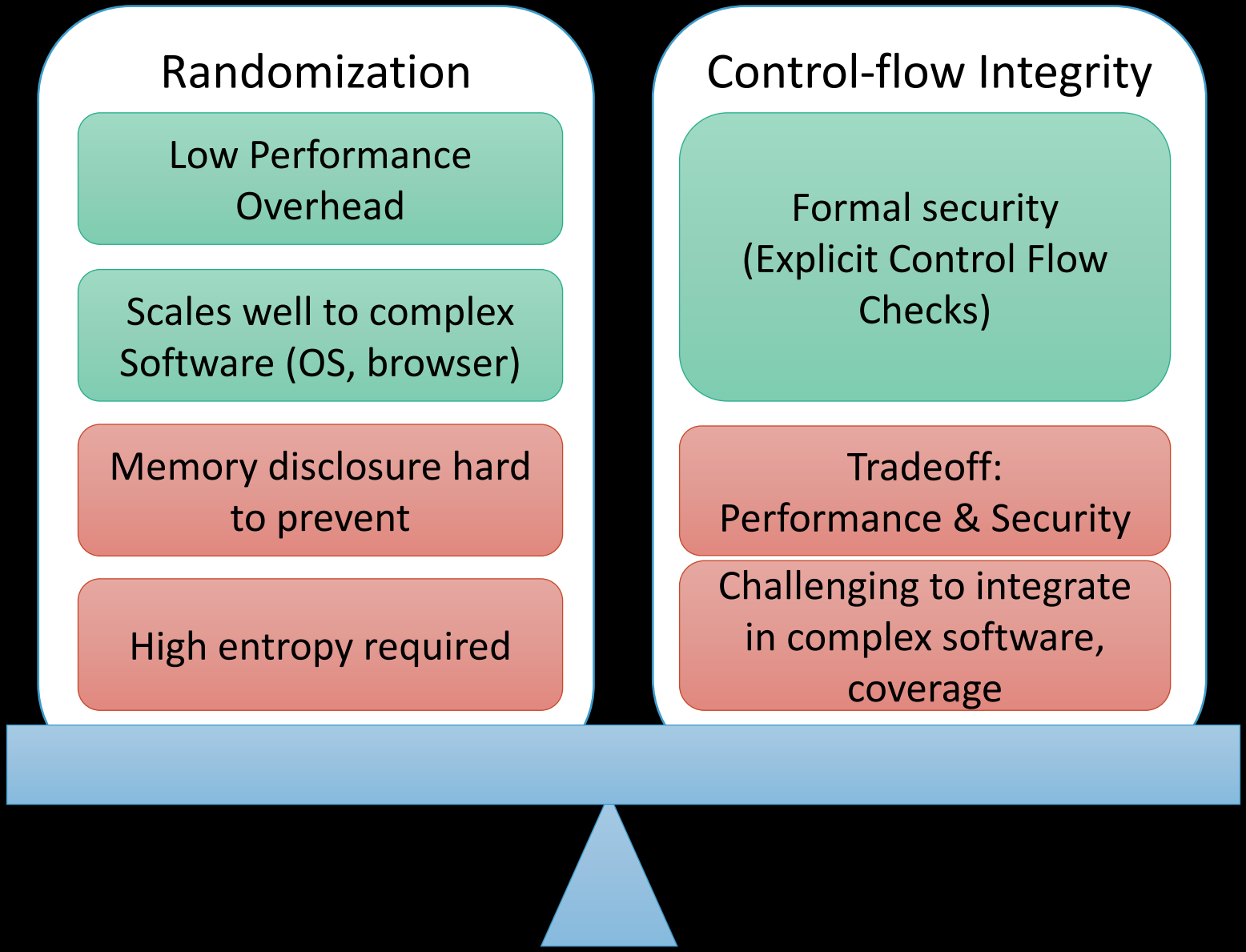


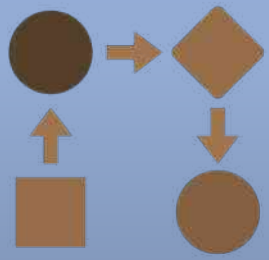
Overview

Background on Run-Time Attacks

Building Code Randomization Defenses

Code-Reuse Attacks

Building Control-Flow Integrity Defenses



Data-Oriented Exploits

Problem Space of Zero-Day Exploits

Control-Flow Attack

[Shacham, ACM CCS 2007]
[Schuster et al., IEEE S&P 2015]

Non-Control-Data Attack

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Adversary

Memory write
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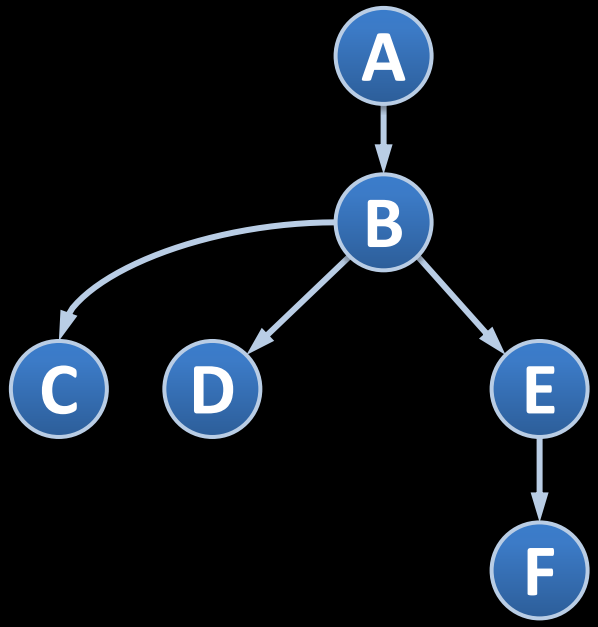

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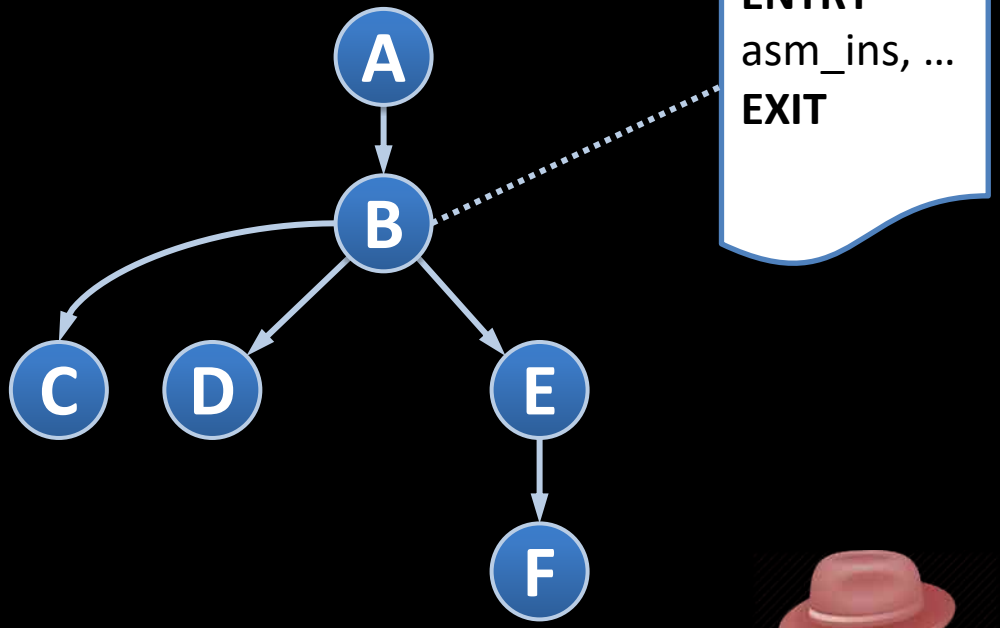

Basic Block

ENTRY
asm_ins, …
EXIT

Adversary

Memory write
Program flow

Problem Space of Zero-Day Exploits

Control-Flow Attack

[Shacham, ACM CCS 2007]
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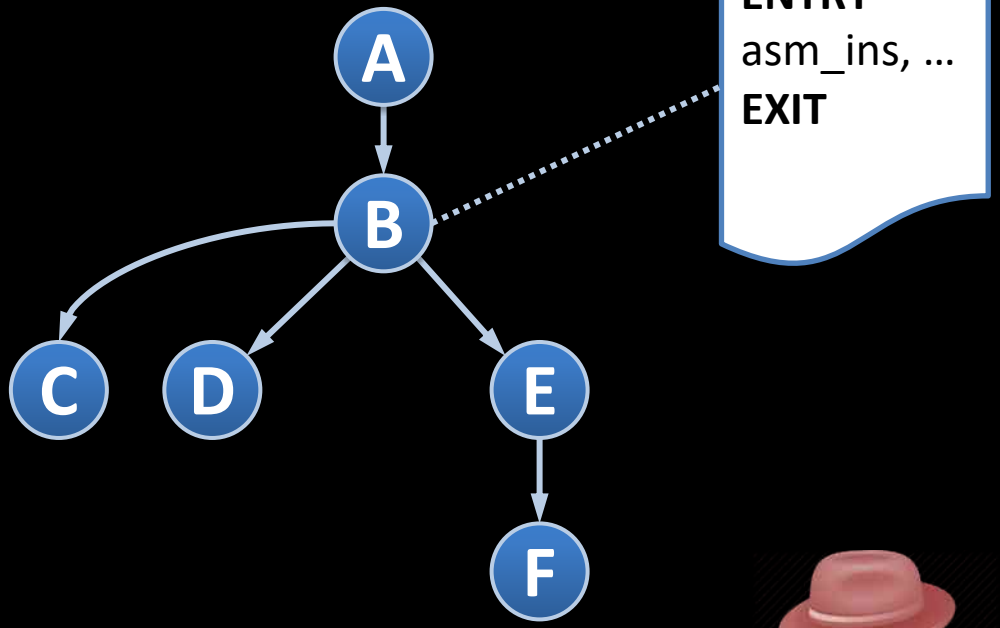

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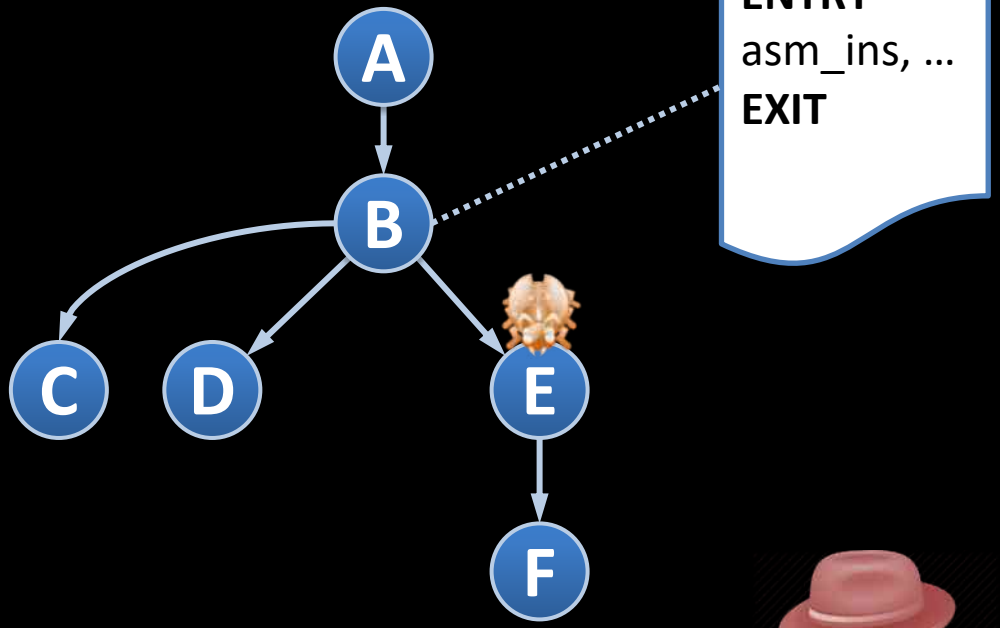

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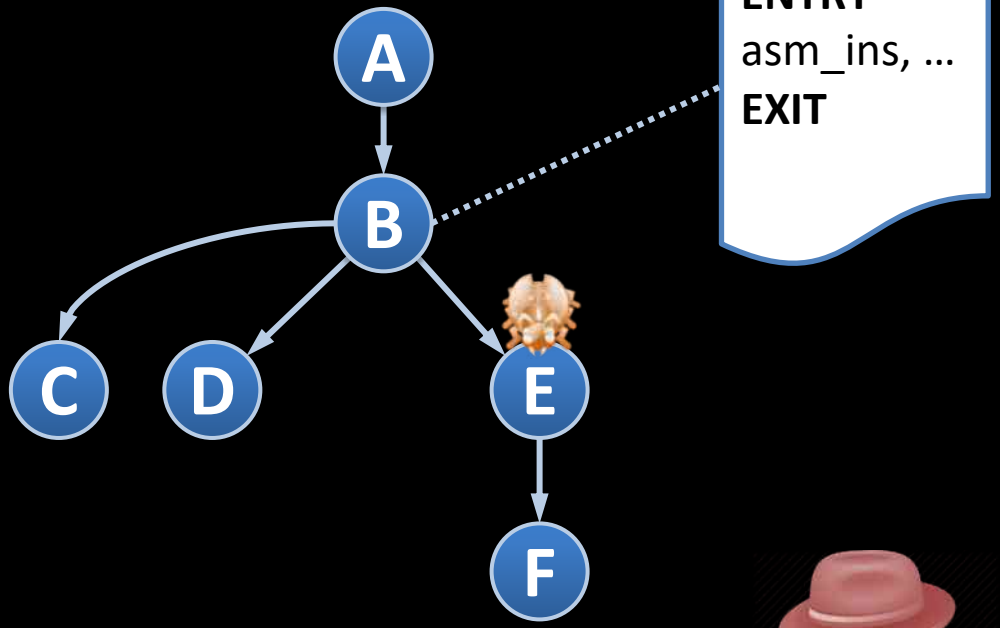

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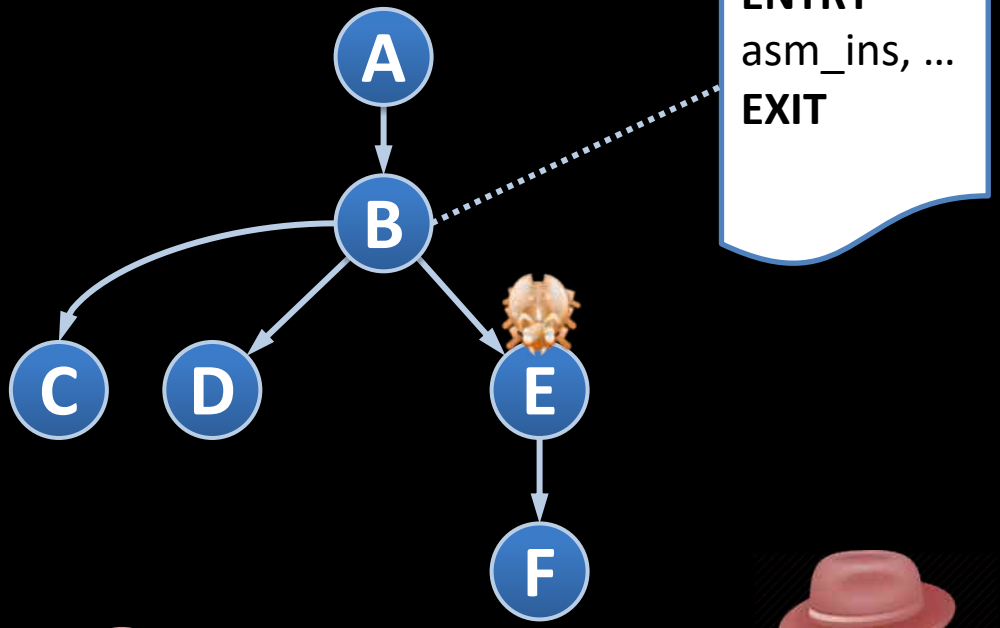

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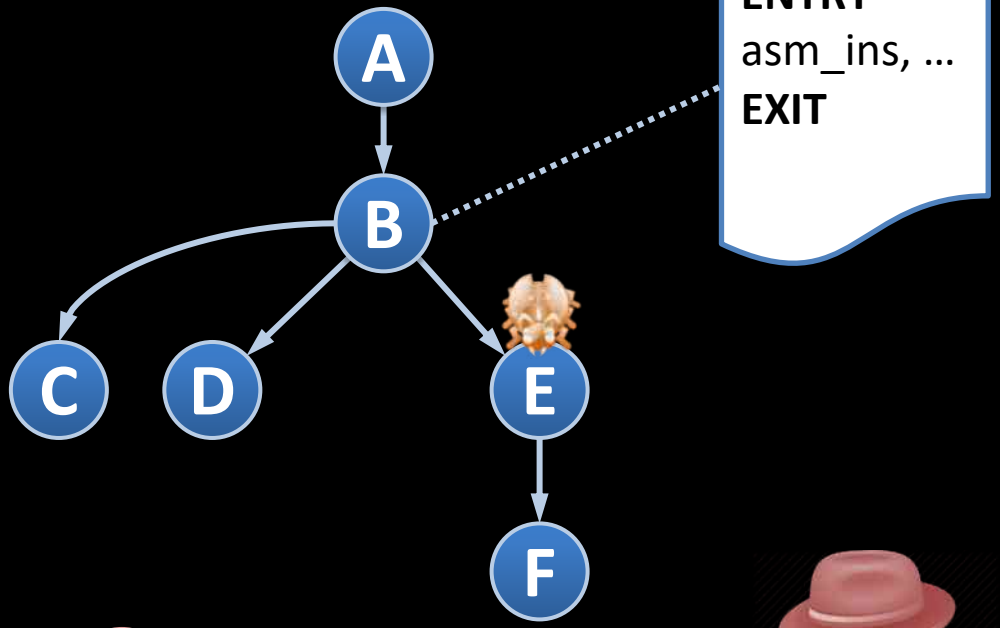

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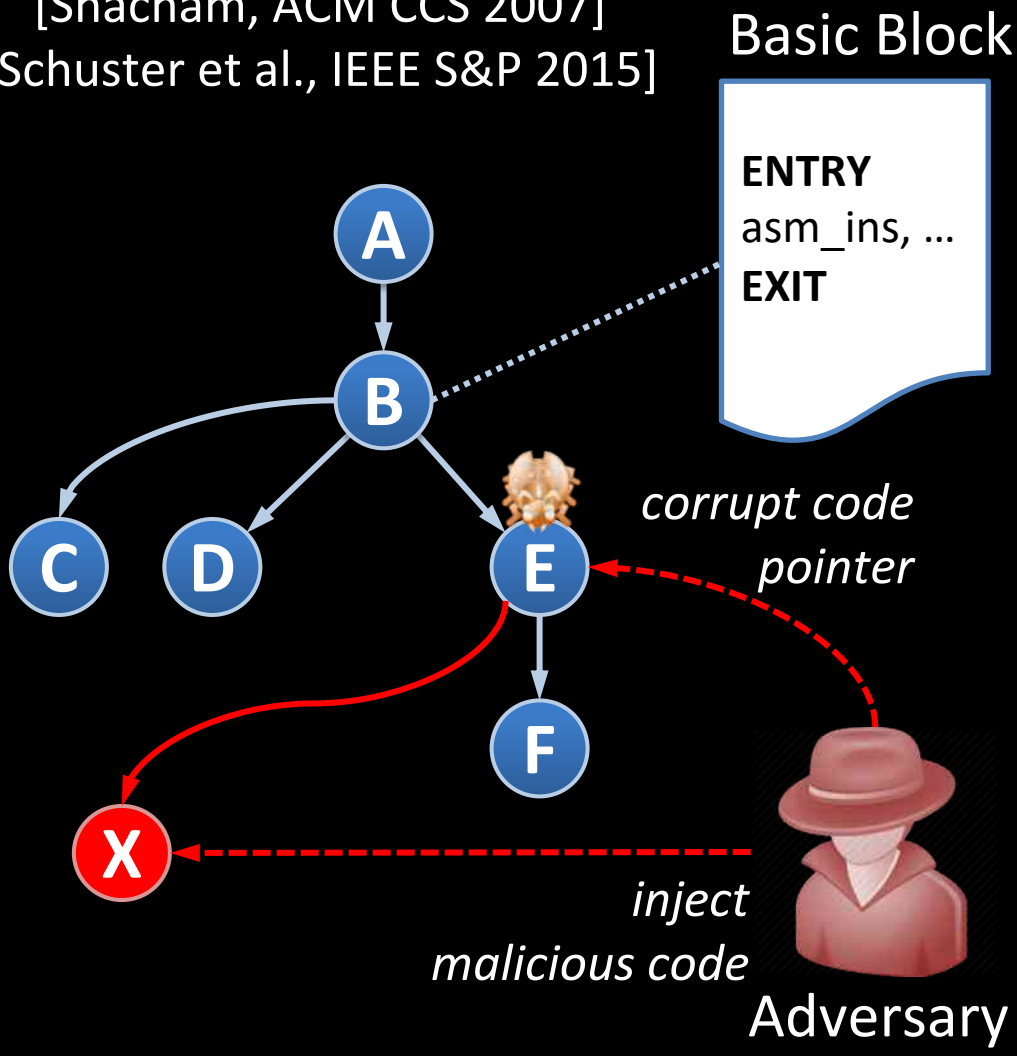

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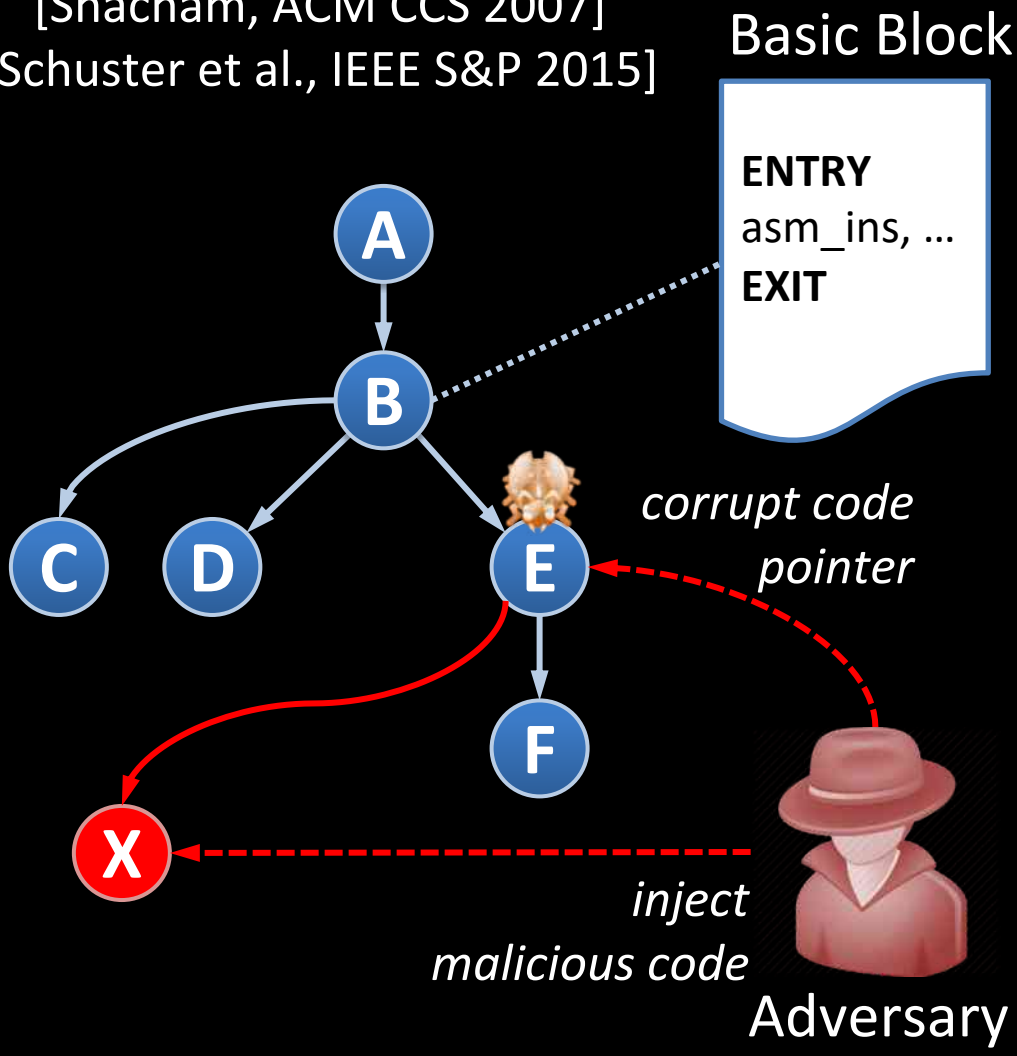

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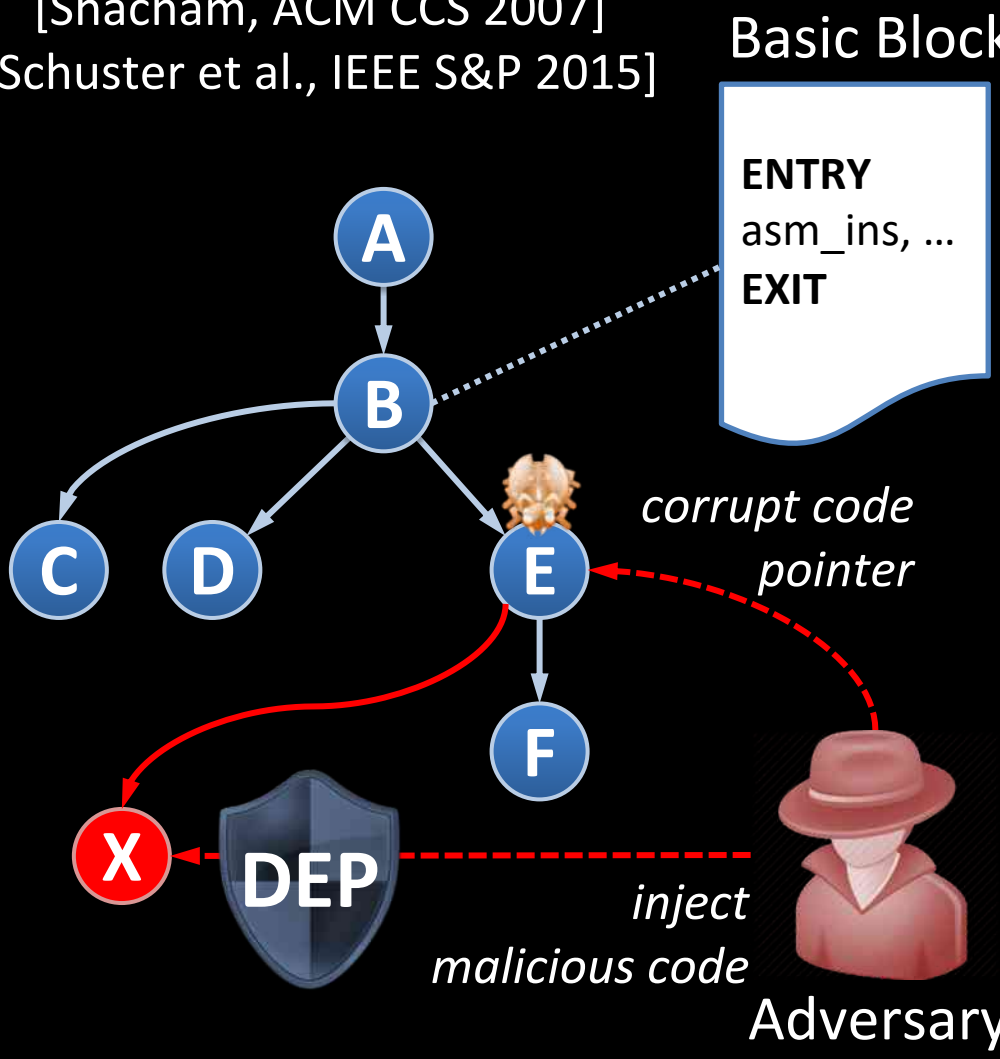

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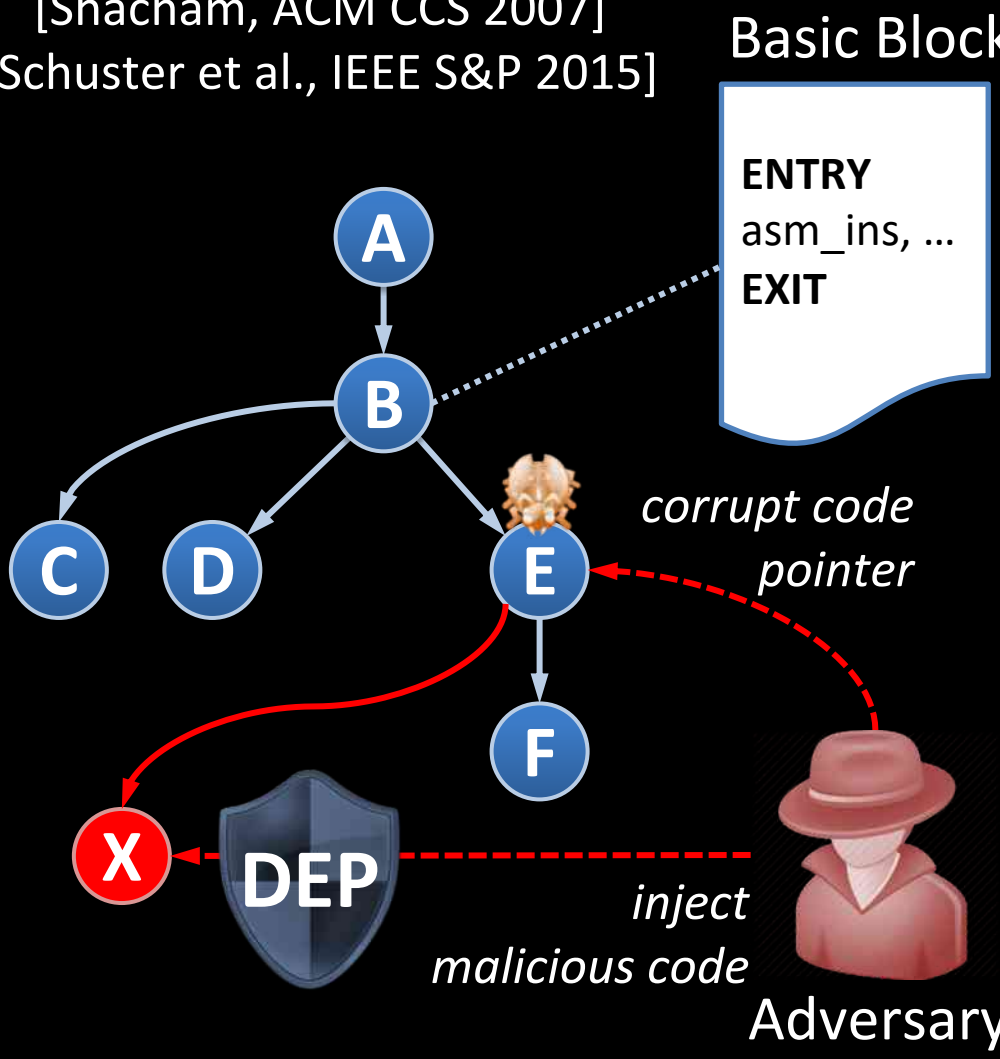

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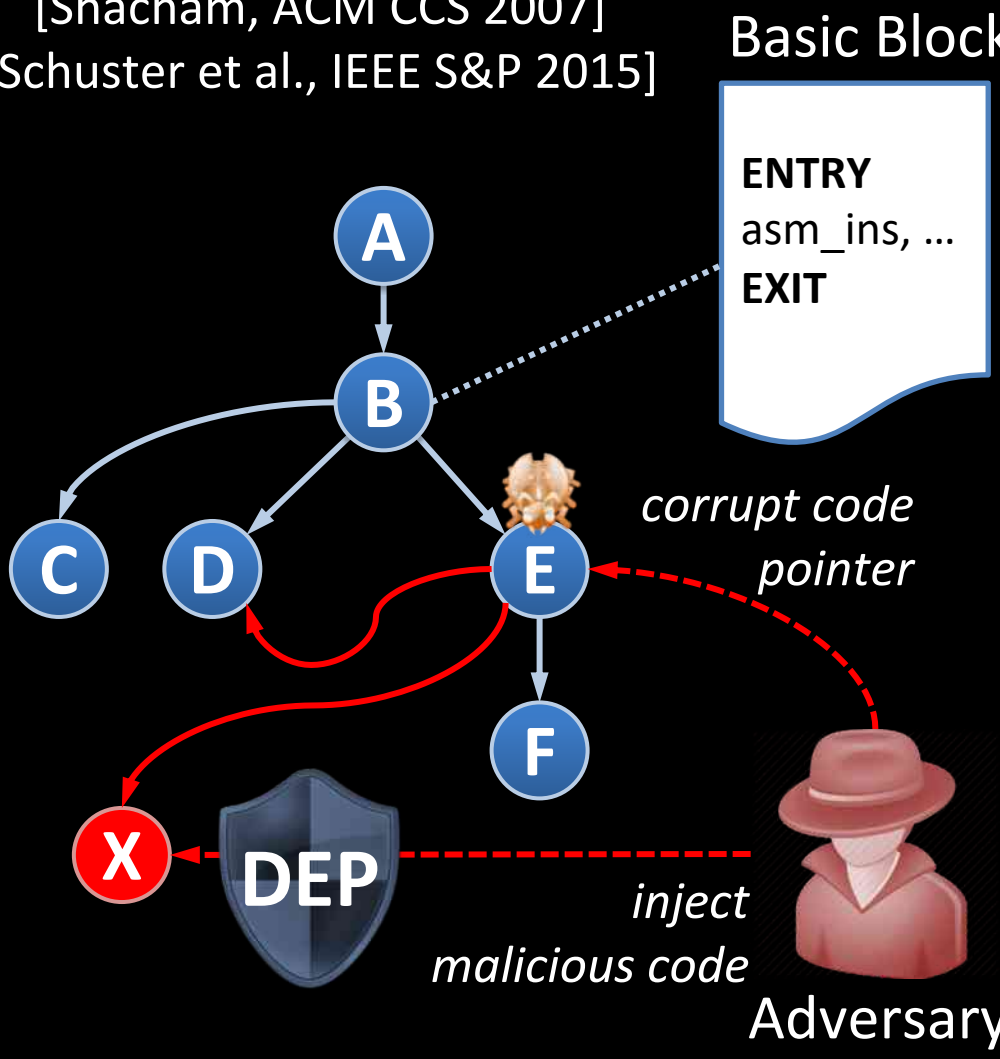

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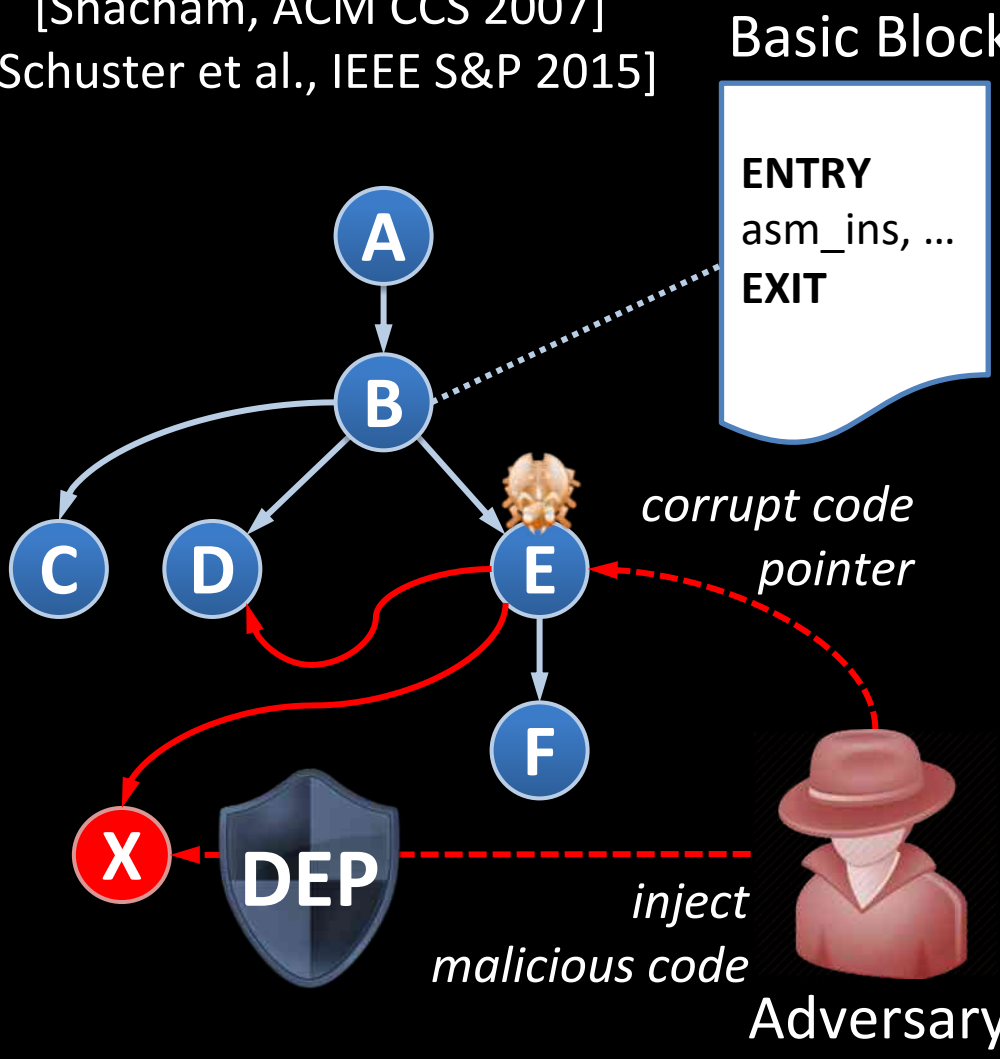

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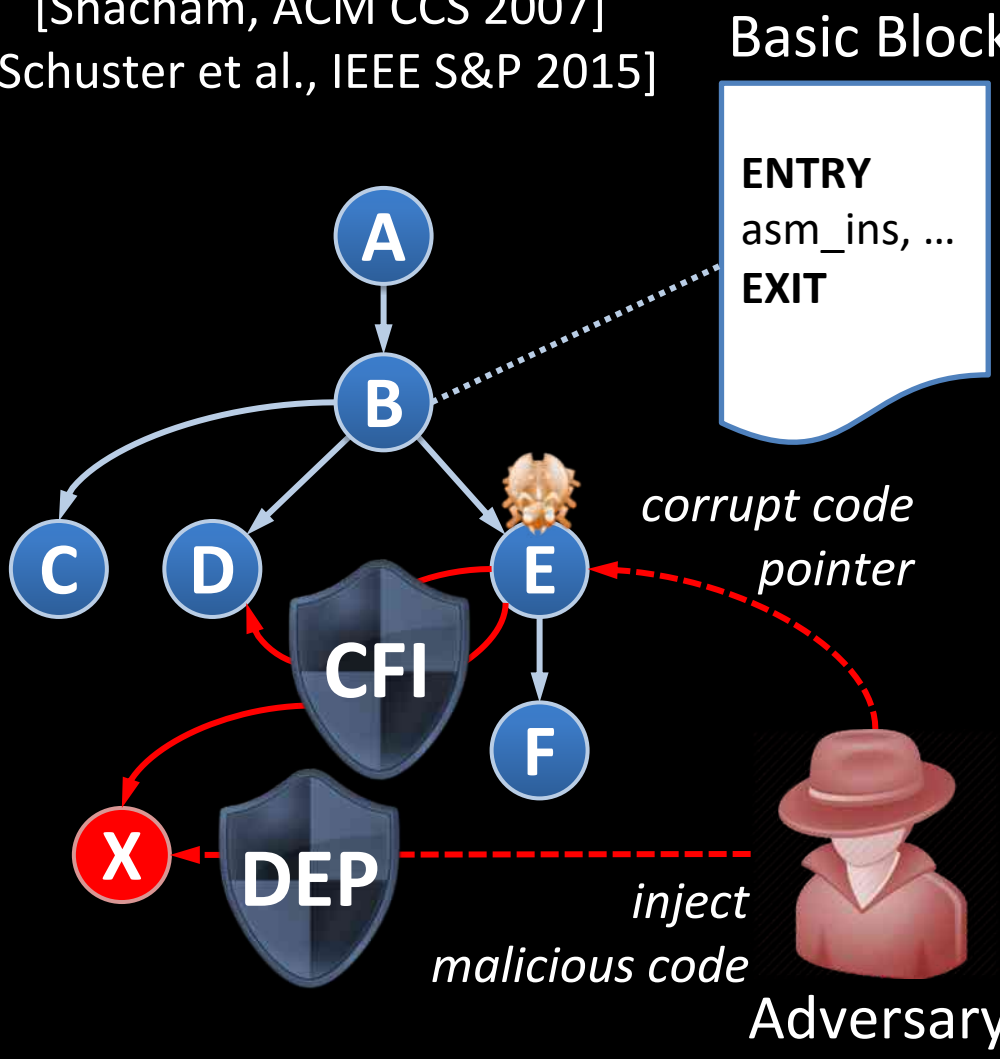

Memory write
Program flow

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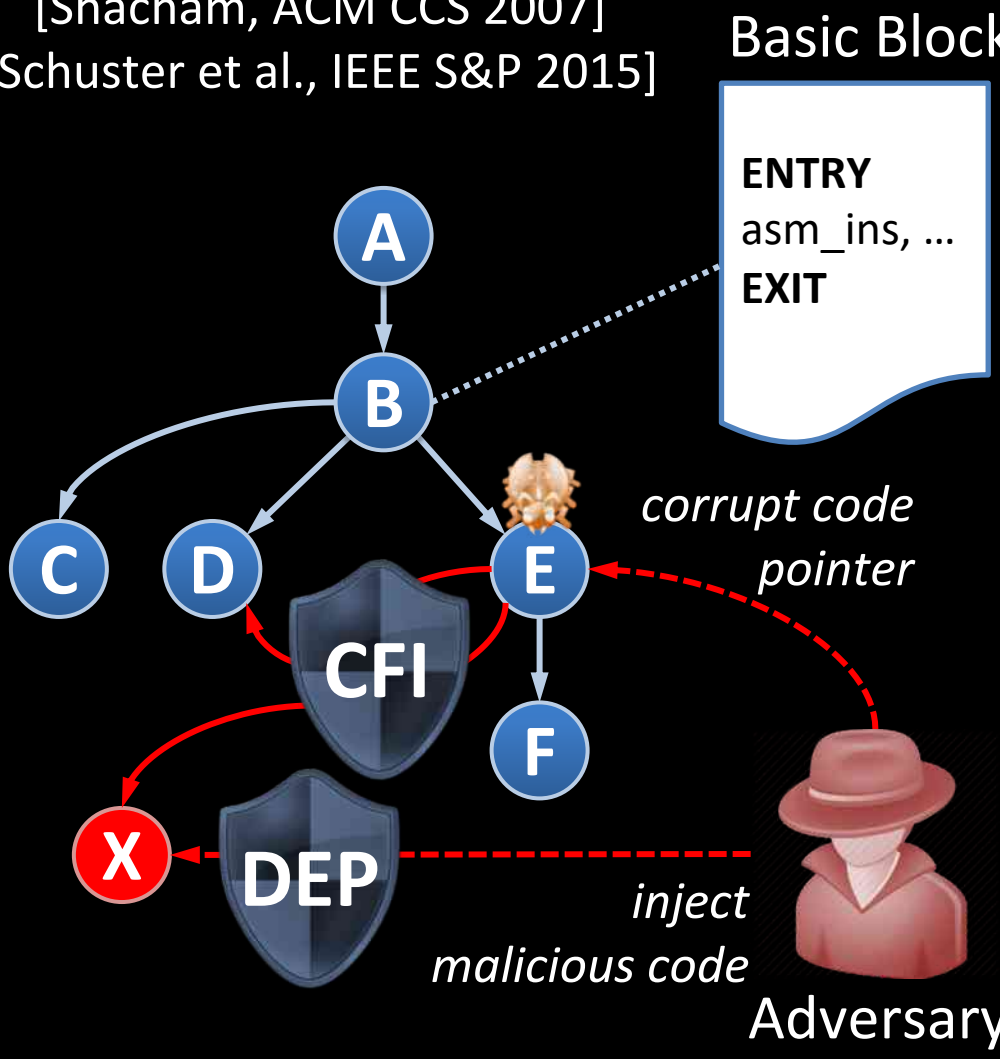

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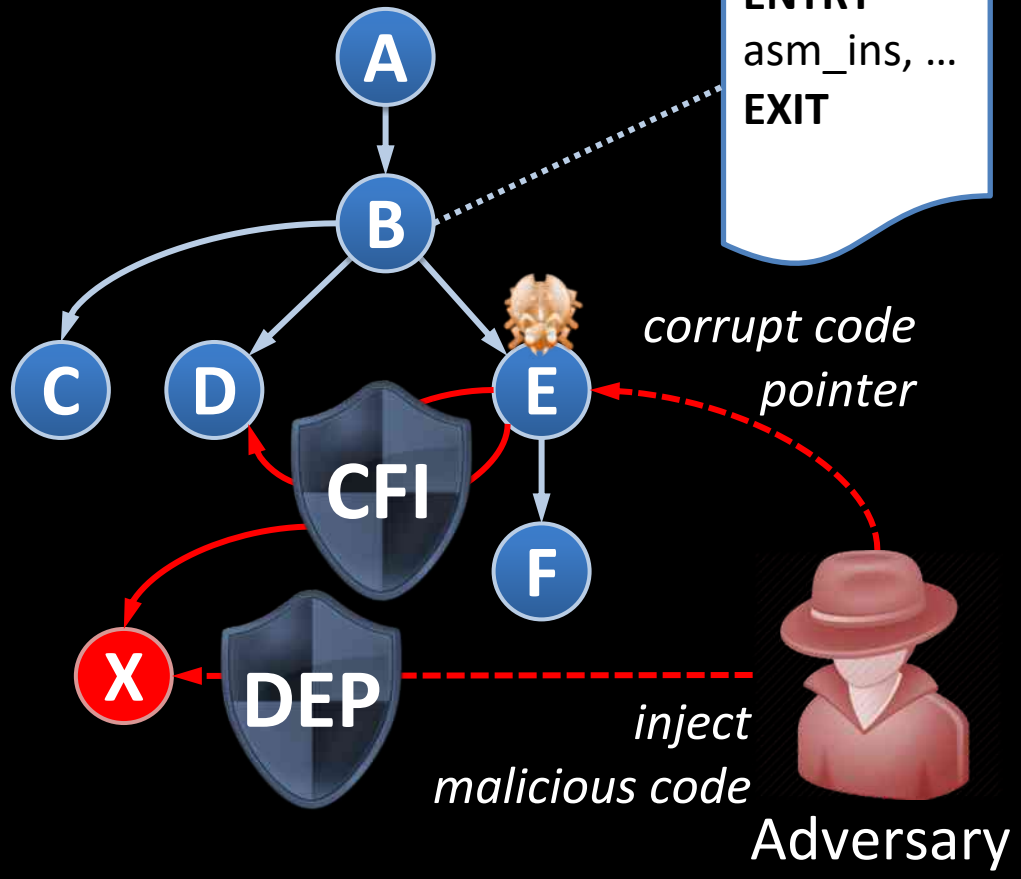

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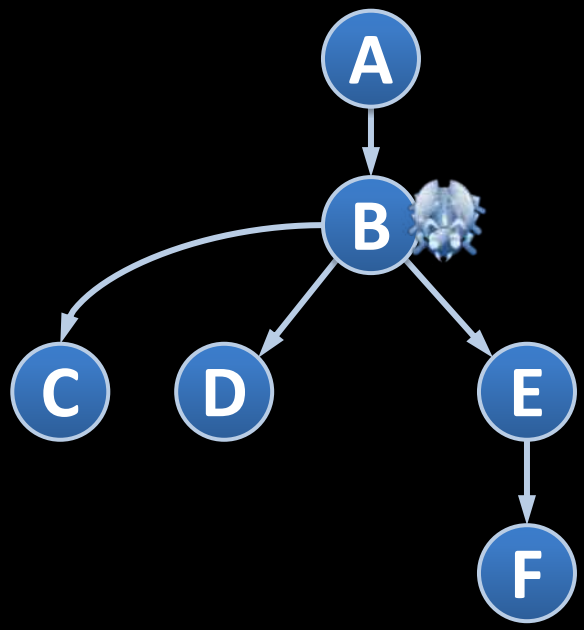

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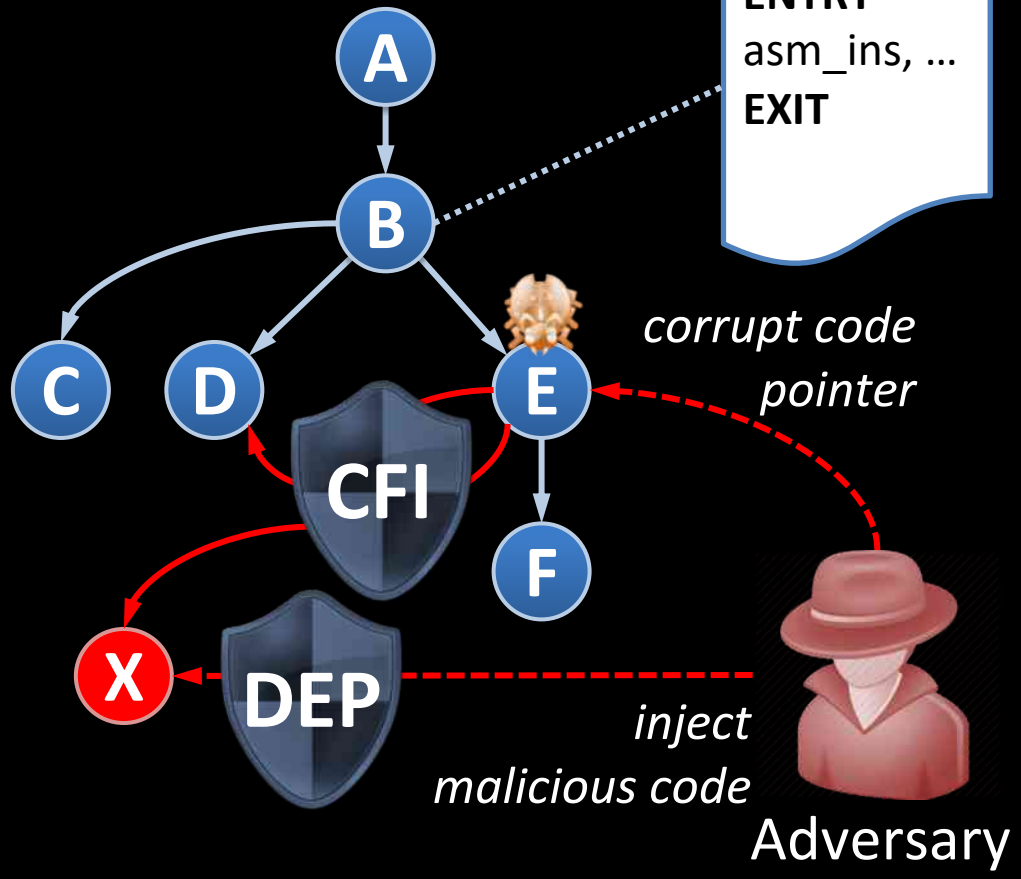

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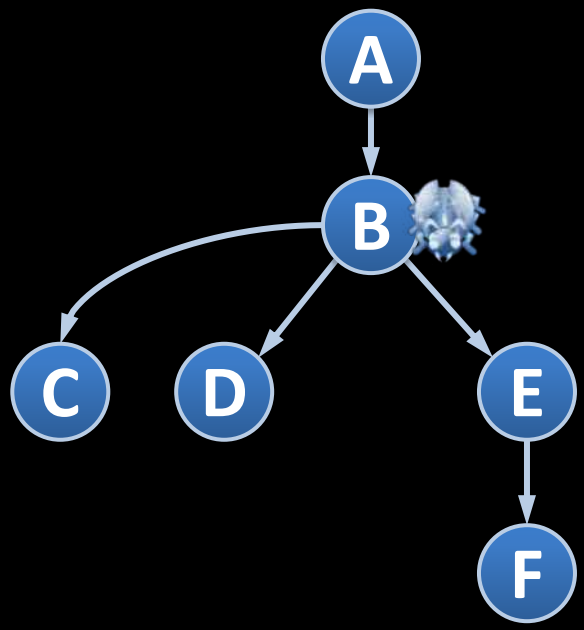

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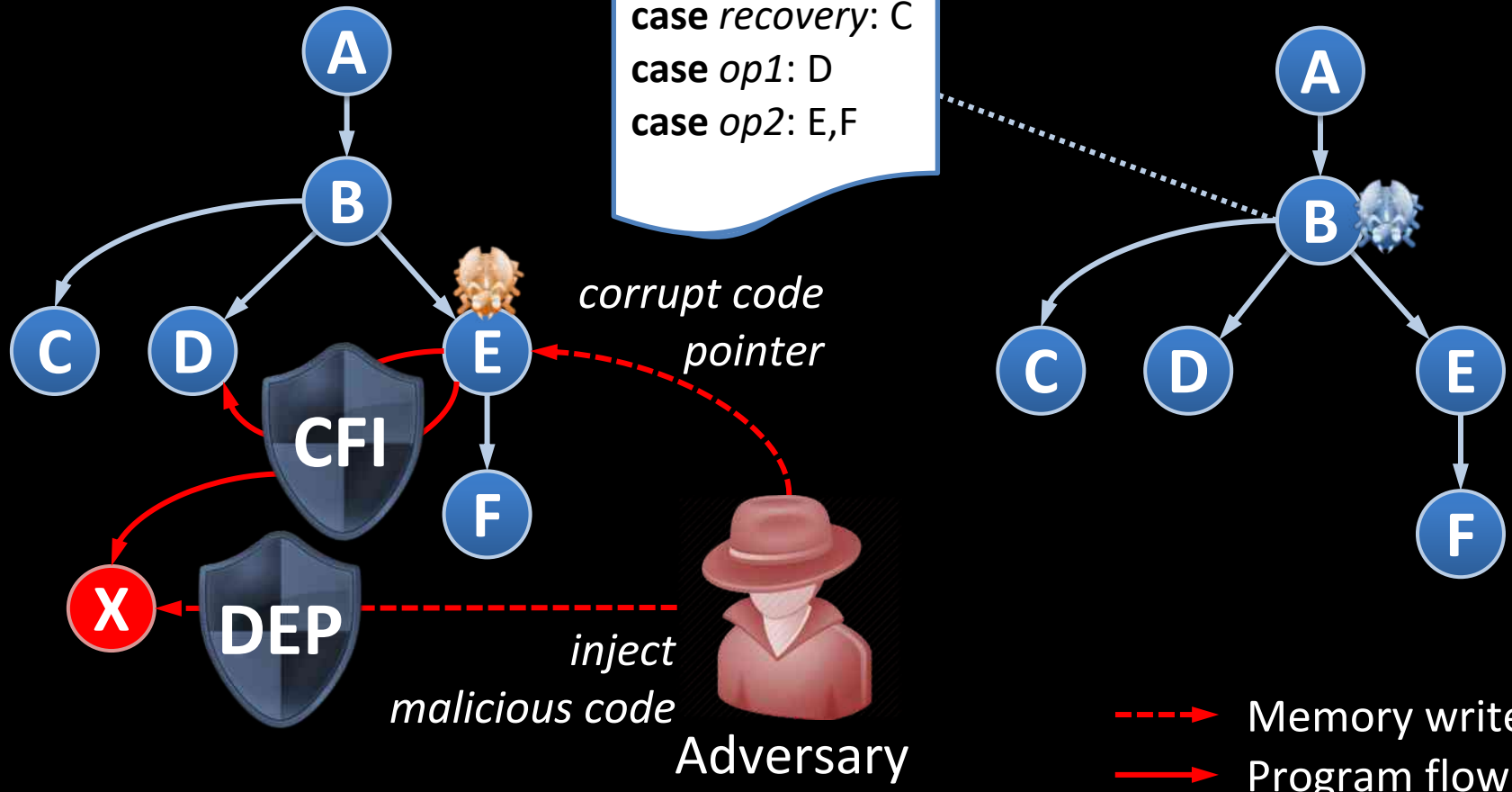

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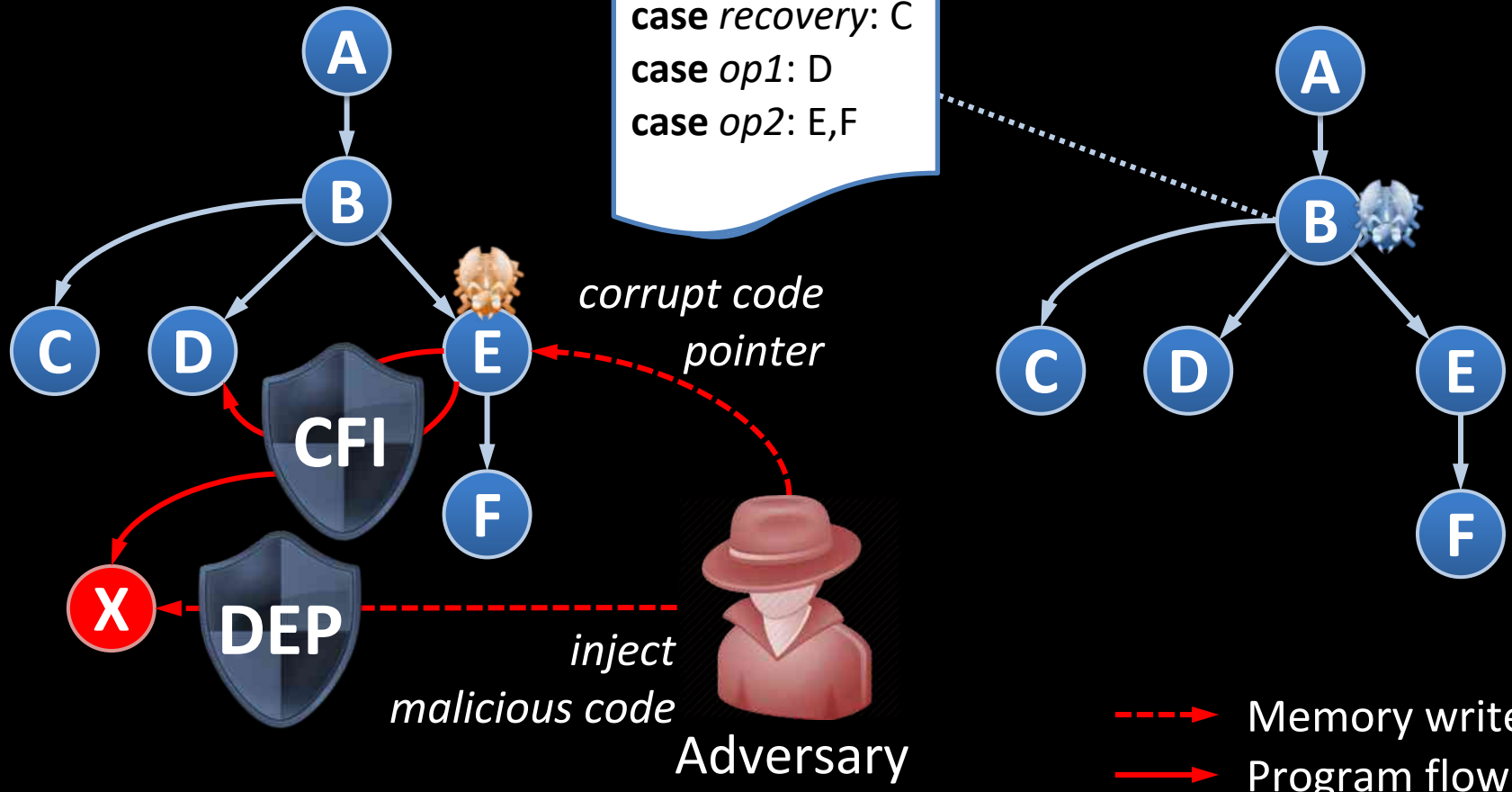

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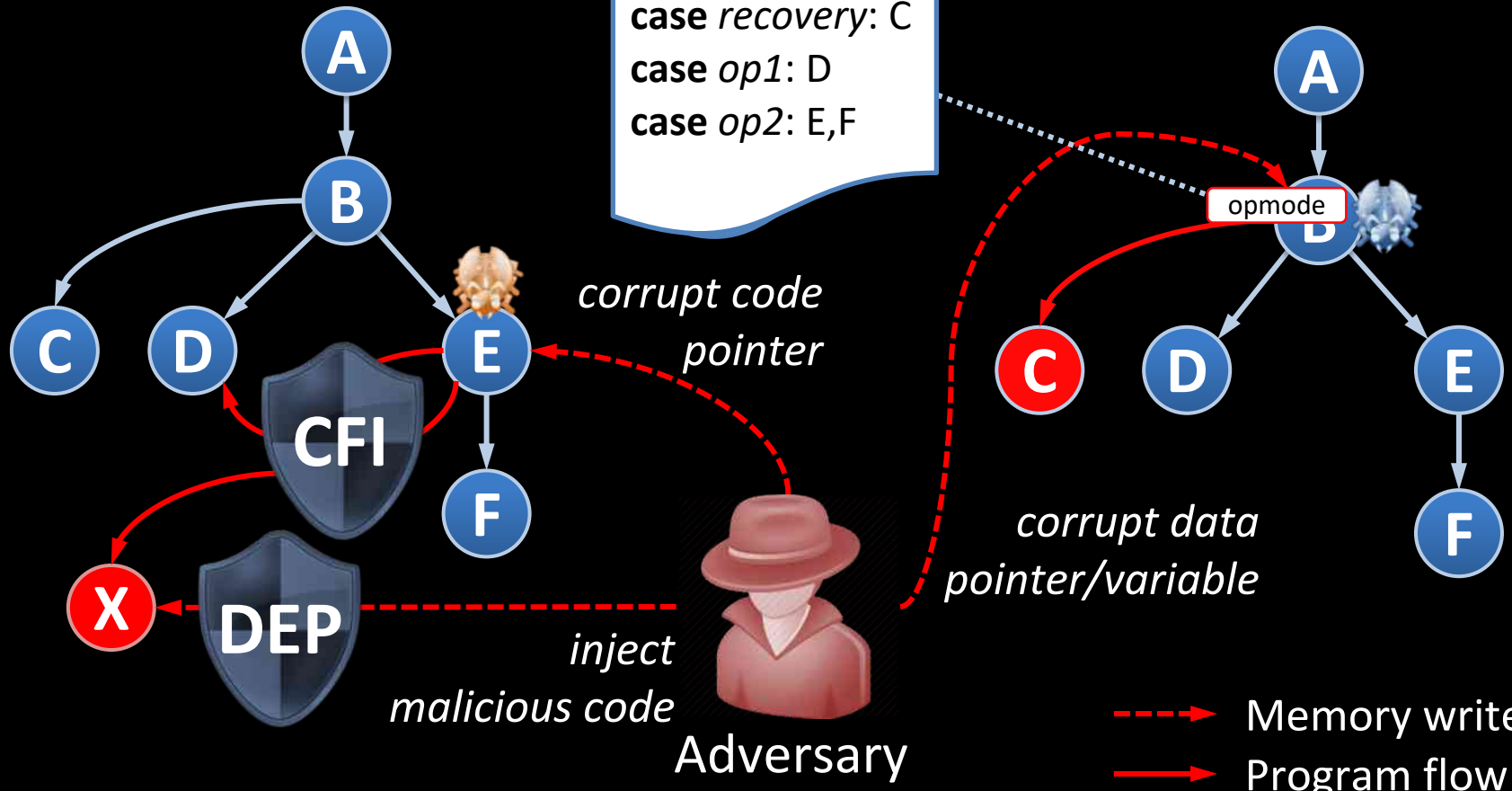

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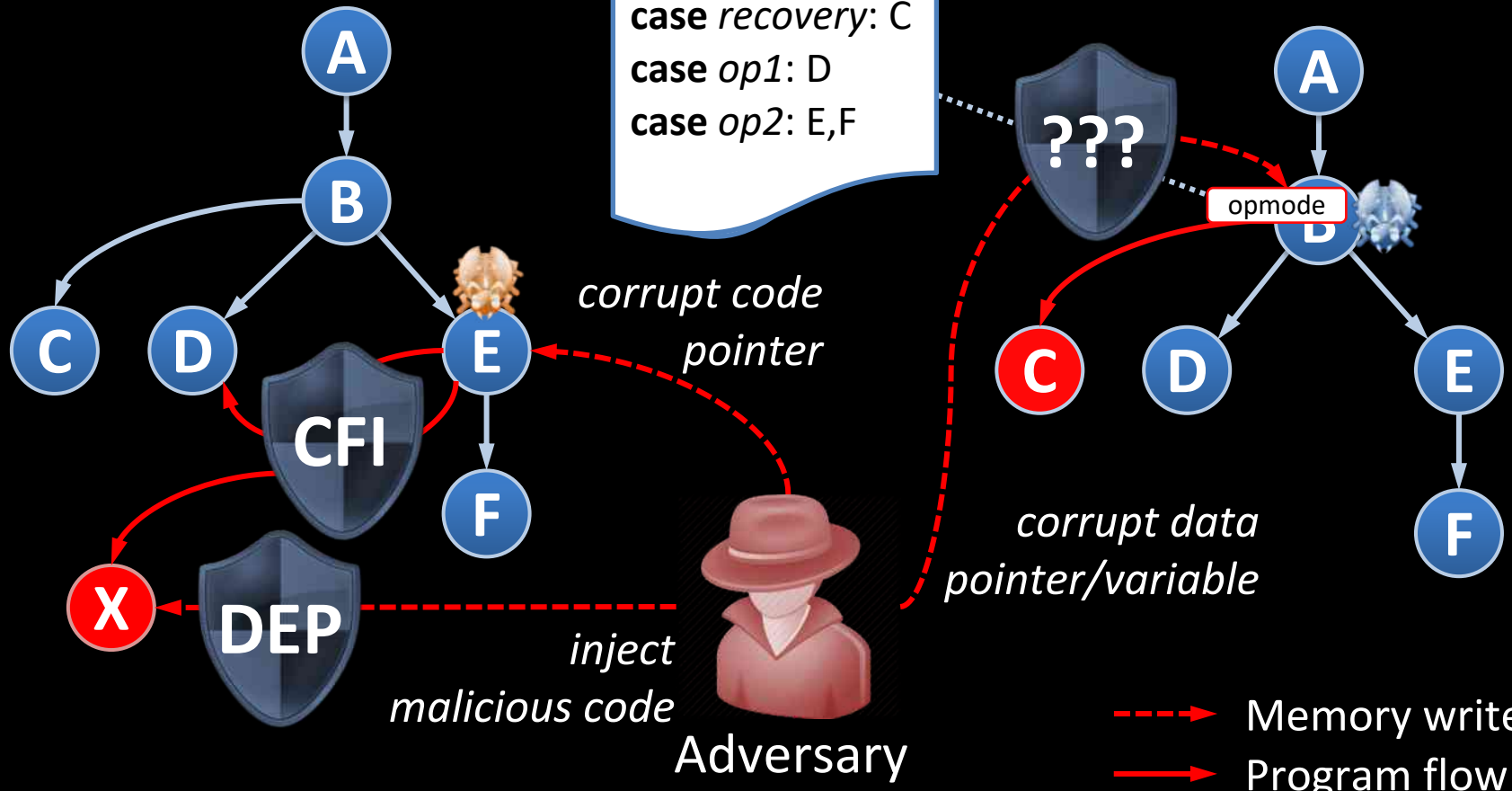
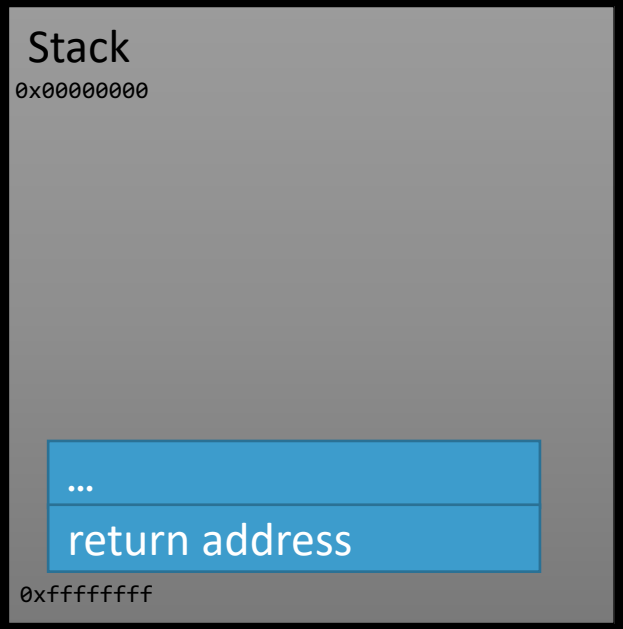


Control-Flow Hijacking on Example Code

```
int main() {
  /* ... */
  user_t user;
  /* ... */
  update_name(&user);
  /* ... */
}
```



Control-Flow Hijacking on Example Code

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int main() {
  /* ... */
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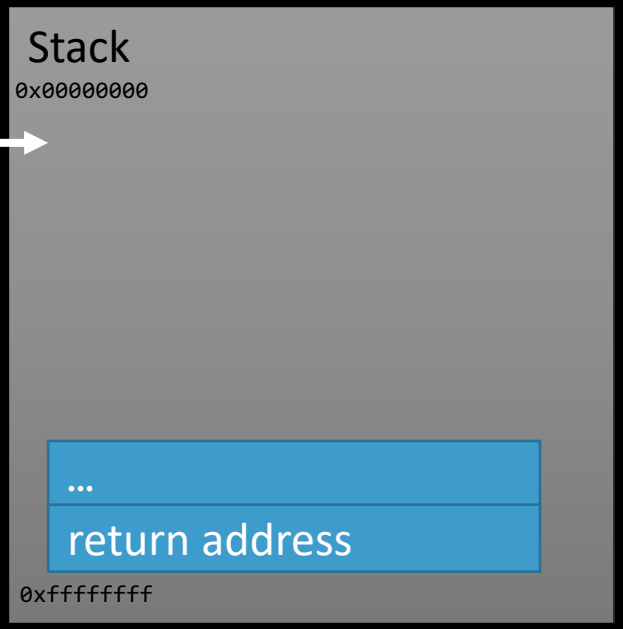
}
```

Stack allocated




```
typedef struct {
  char name[32];
  unsigned id;
} user_t;
```

Control-Flow Hijacking on Example Code

```
int main() {
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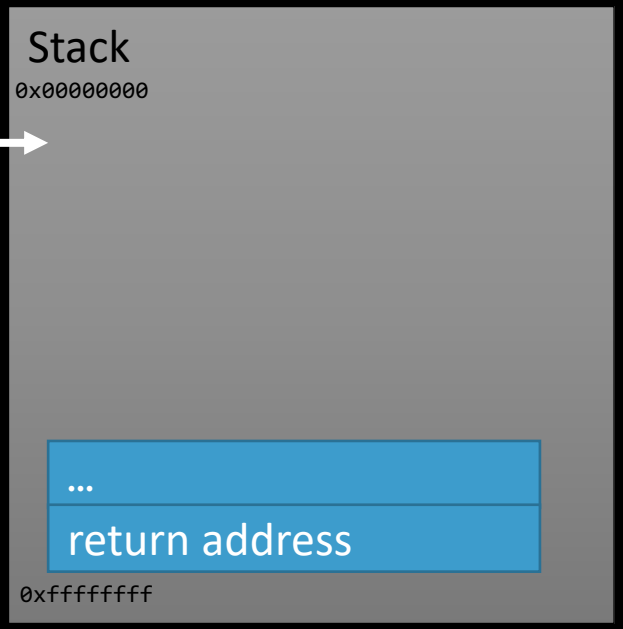
Stack allocated

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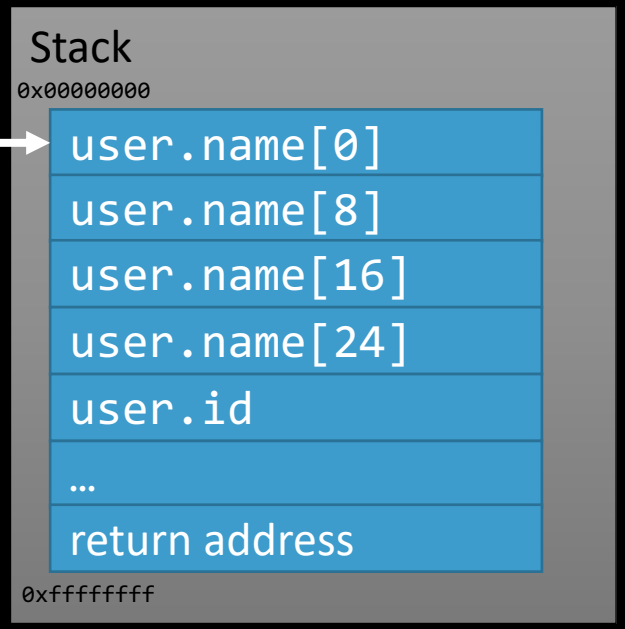
Control-Flow Hijacking on Example Code

```c
int main() {
  /* ... */
  user_t user;
  /* ... */
  update_name(&user);
  /* ... */
}
```

Stack allocated

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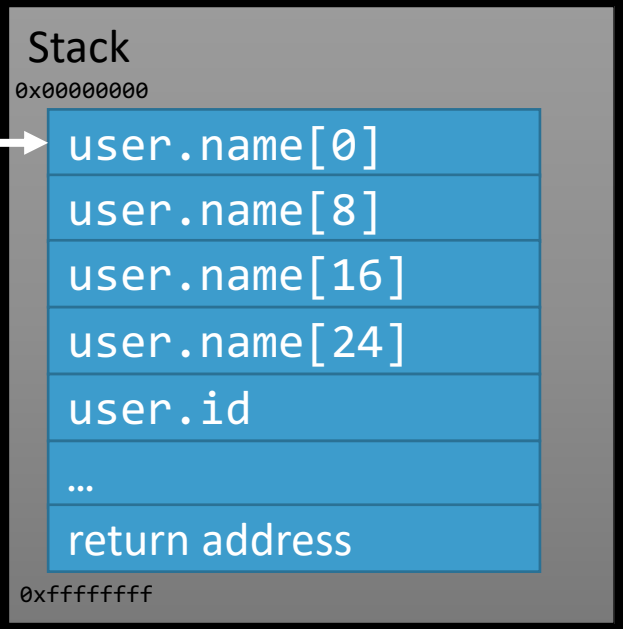
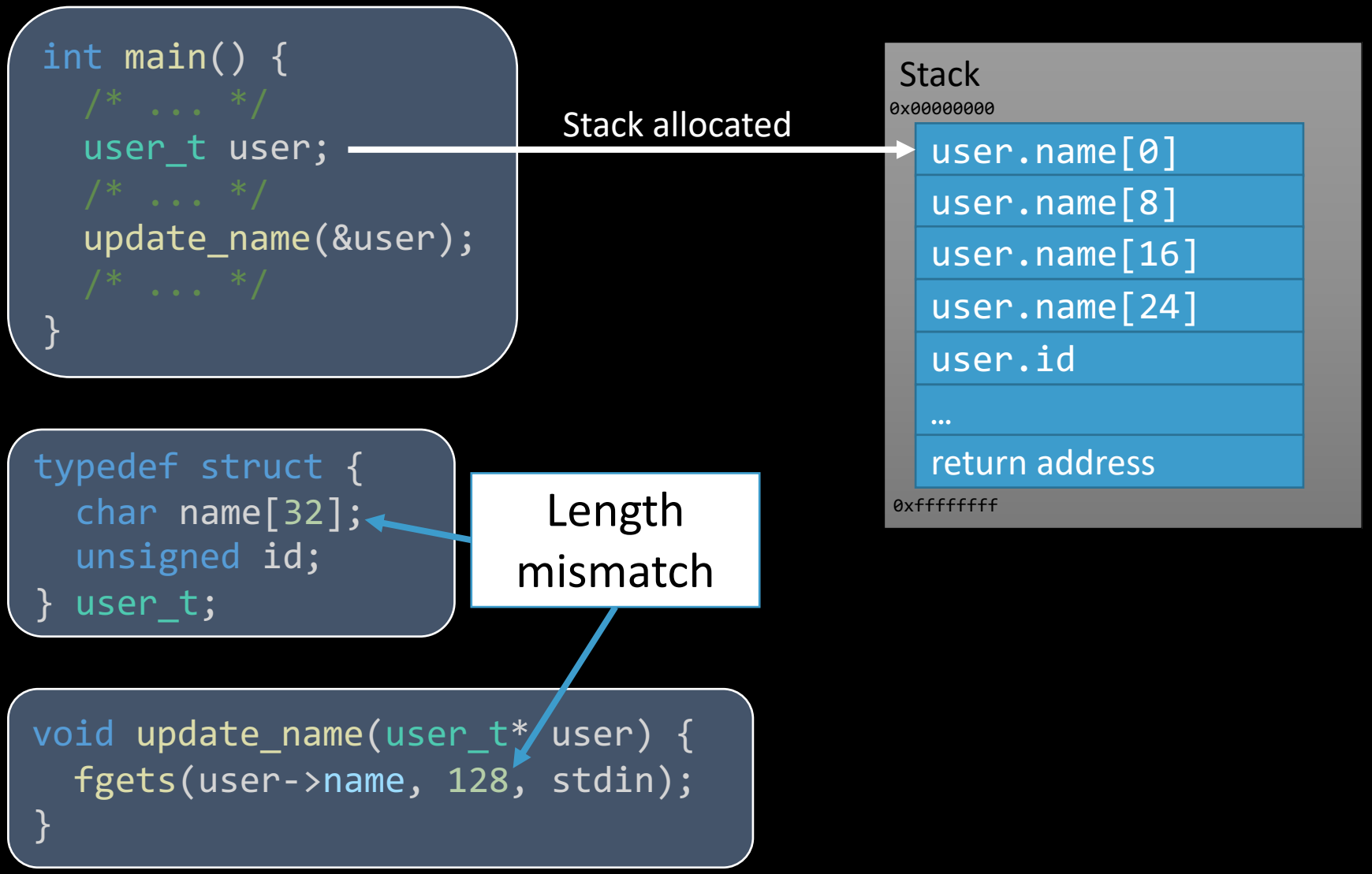



```
typedef struct {
  char name[32];
  unsigned id;
} user_t;
```

```
void update_name(user_t* user) {
  fgets(user->name, 128, stdin);
}
```

Control-Flow Hijacking on Example Code



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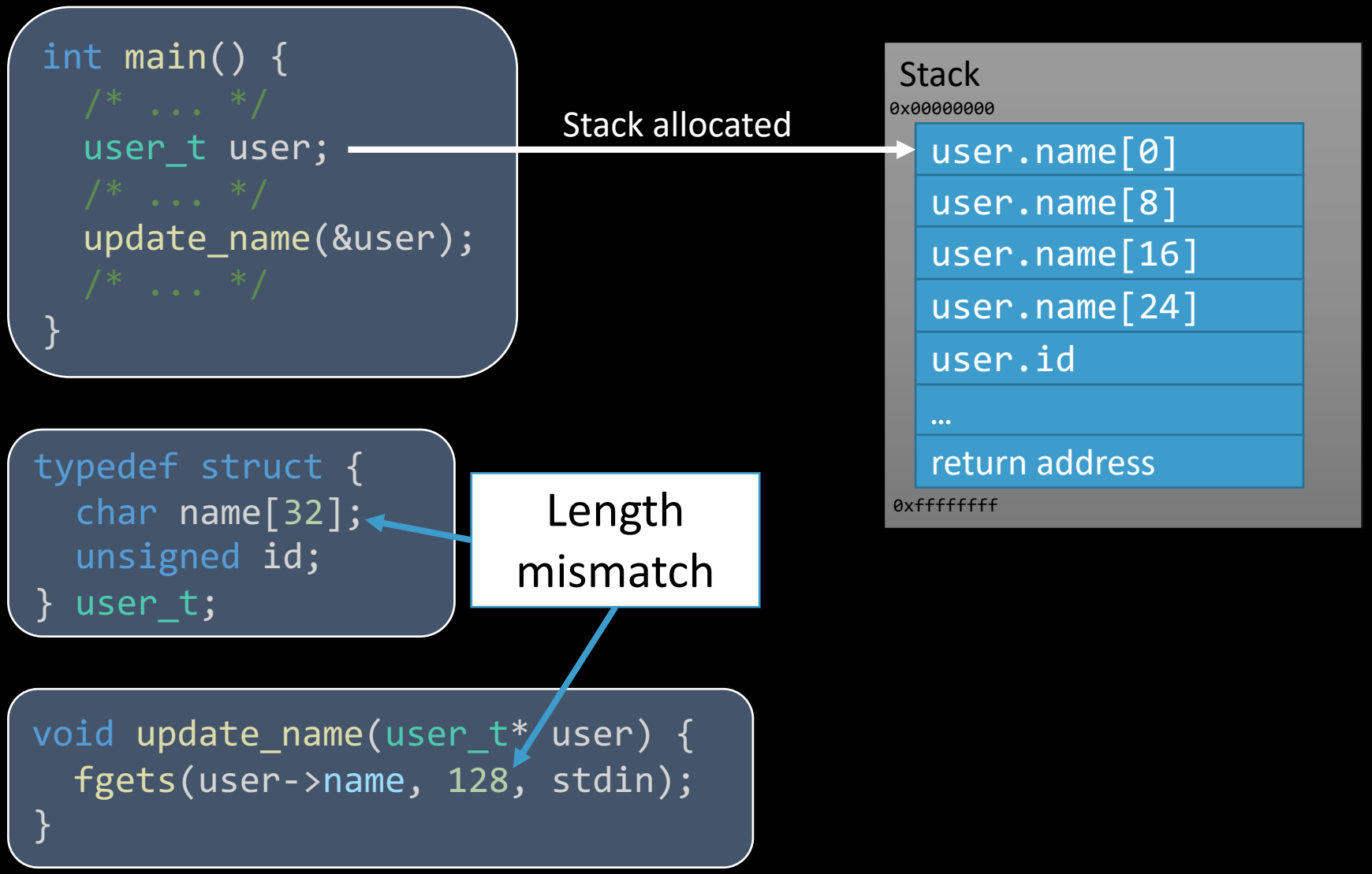

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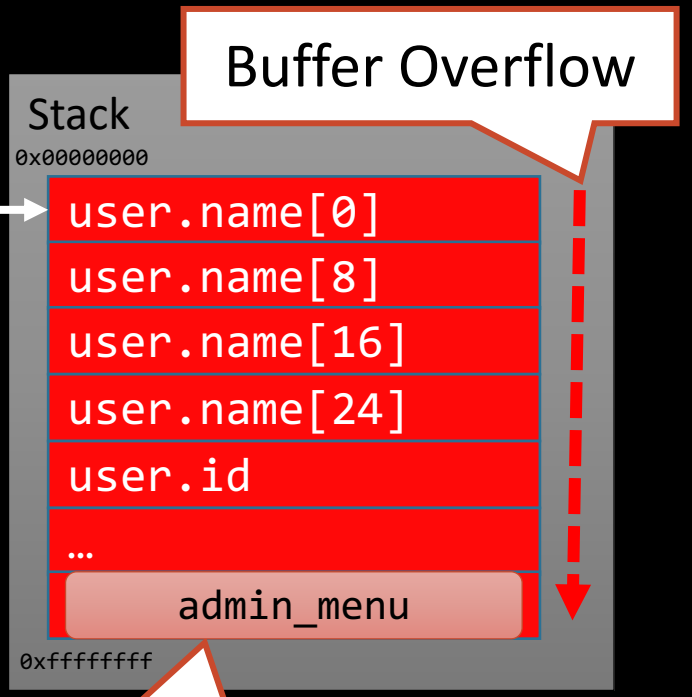


```
typedef struct {
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```

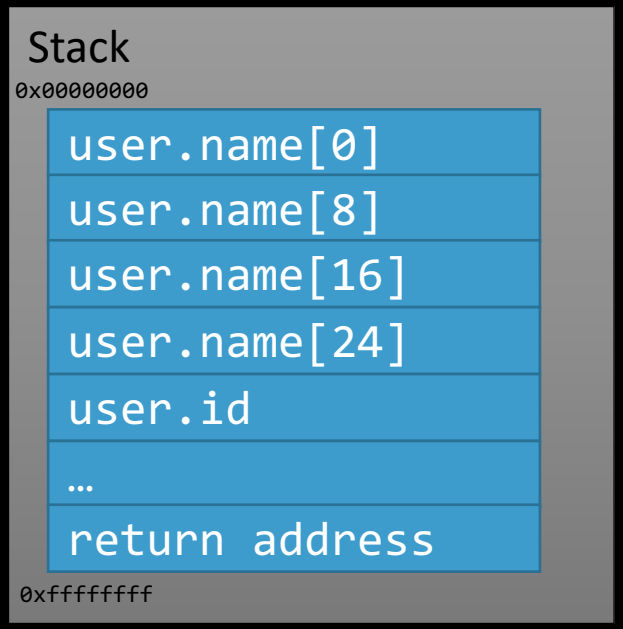
Length mismatch

```
void update_name(user_t* user) {
  fgets(user->name, 128, stdin);
}
```

Return to a different address.
Attacker redirects to target function.

Data-Only Exploit on Example Code

```
int main() {
  /* ... */
  update_name(&user);
  /* ... */
  admin_access(&user);
  /* ... */
}
```



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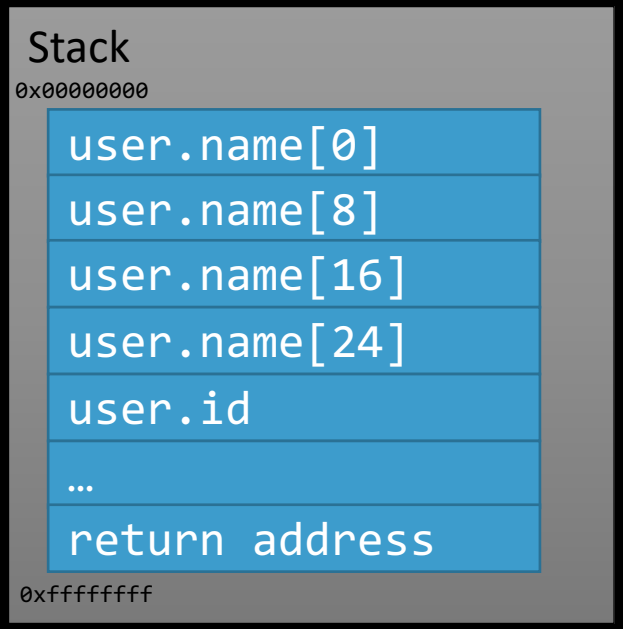

Data-Only Exploit on Example Code

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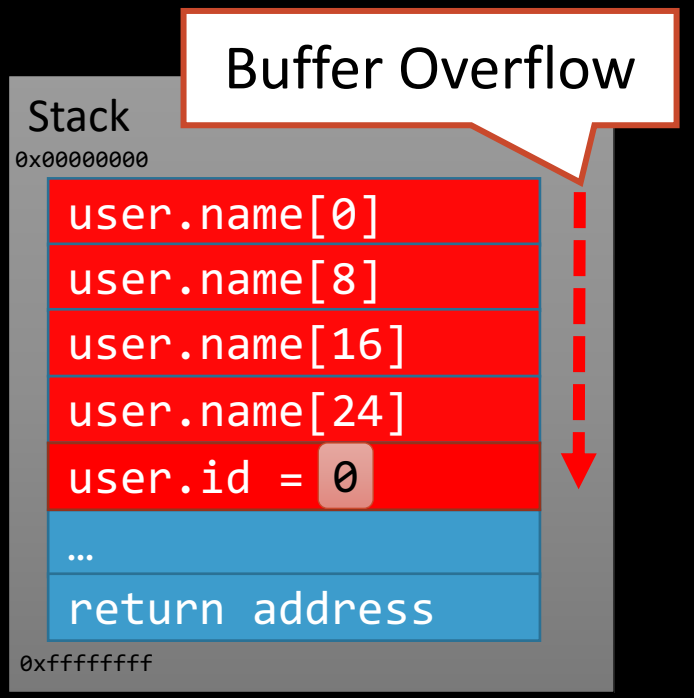
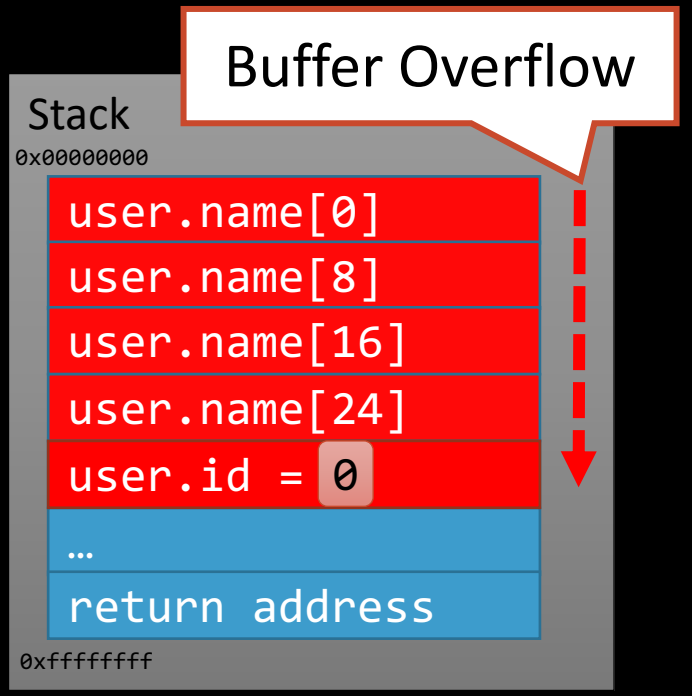


Data-Only Exploit on Example Code

```
int main() {
  /* ... */
  update_name(&user);
  /* ... */
  admin_access(&user);
  /* ... */
}
```

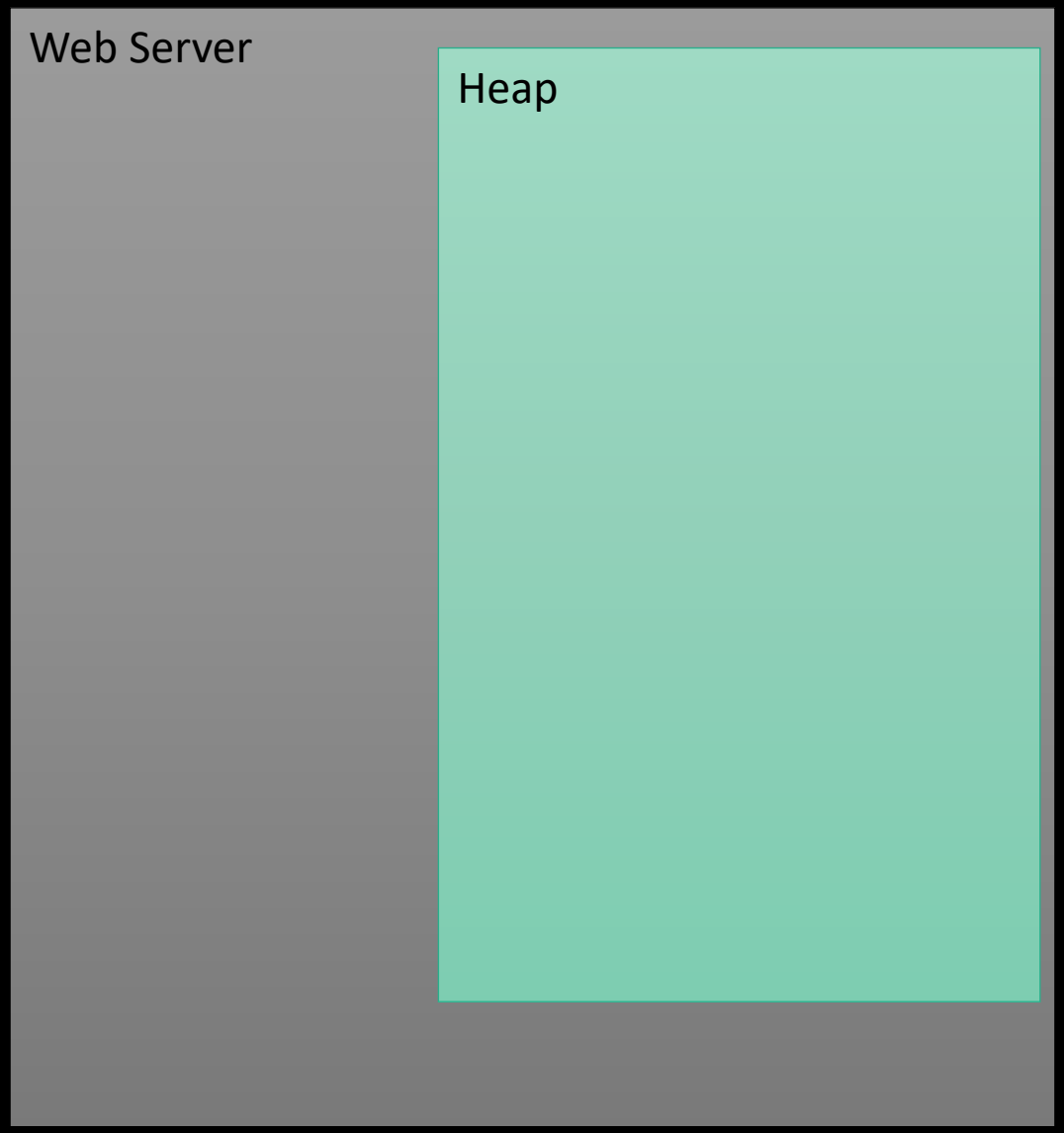
```
void update_name(user_t* user) {
  fgets(user->name, 128, stdin);
}
```

```
void admin_access(user_t* user) {
  if (user->id == 0) {
    admin_menu();
  } else {
    error(); }}
```

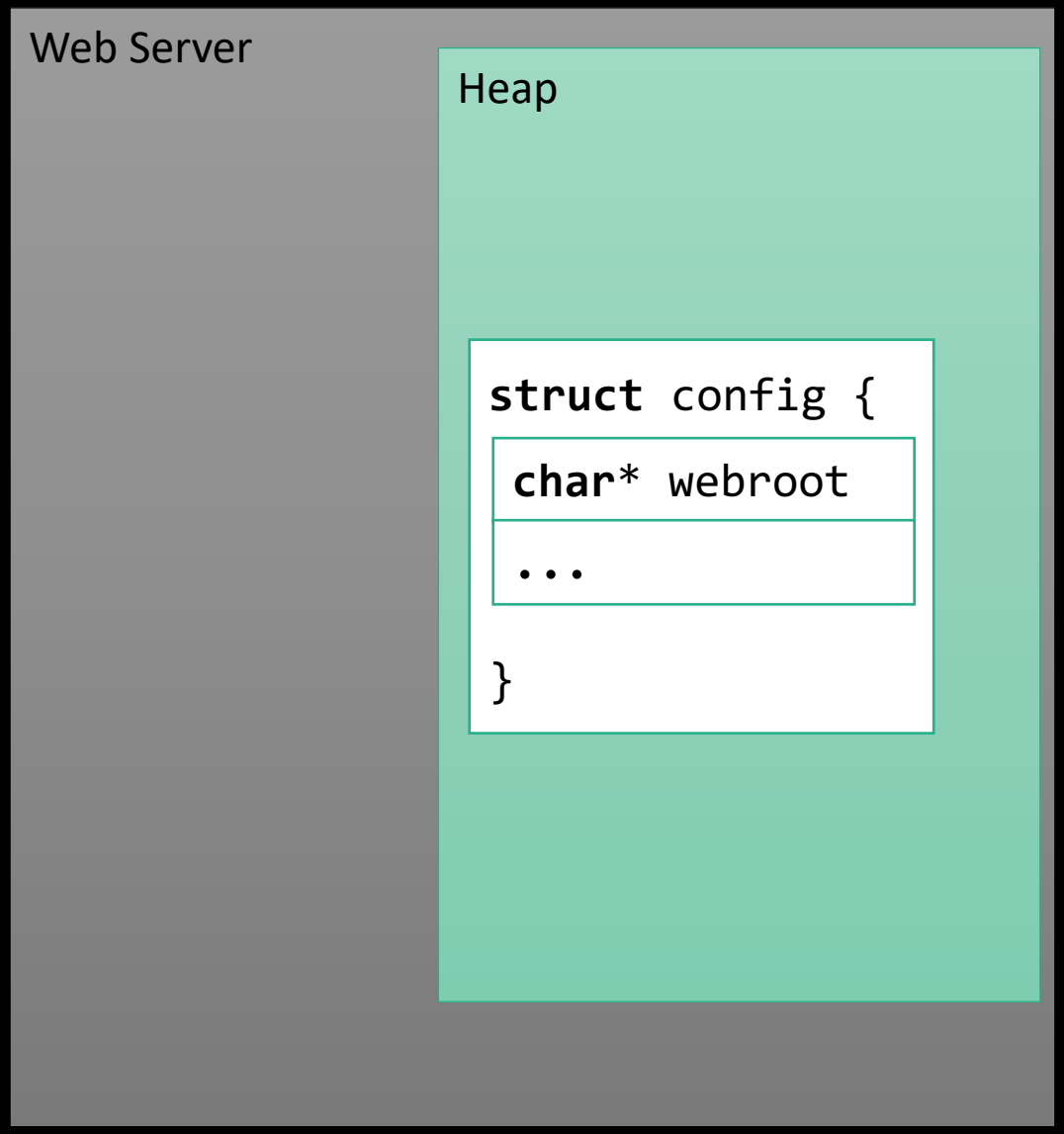


Same effect – control-data left untouched

Corrupt Configuration Data



Corrupt Configuration Data



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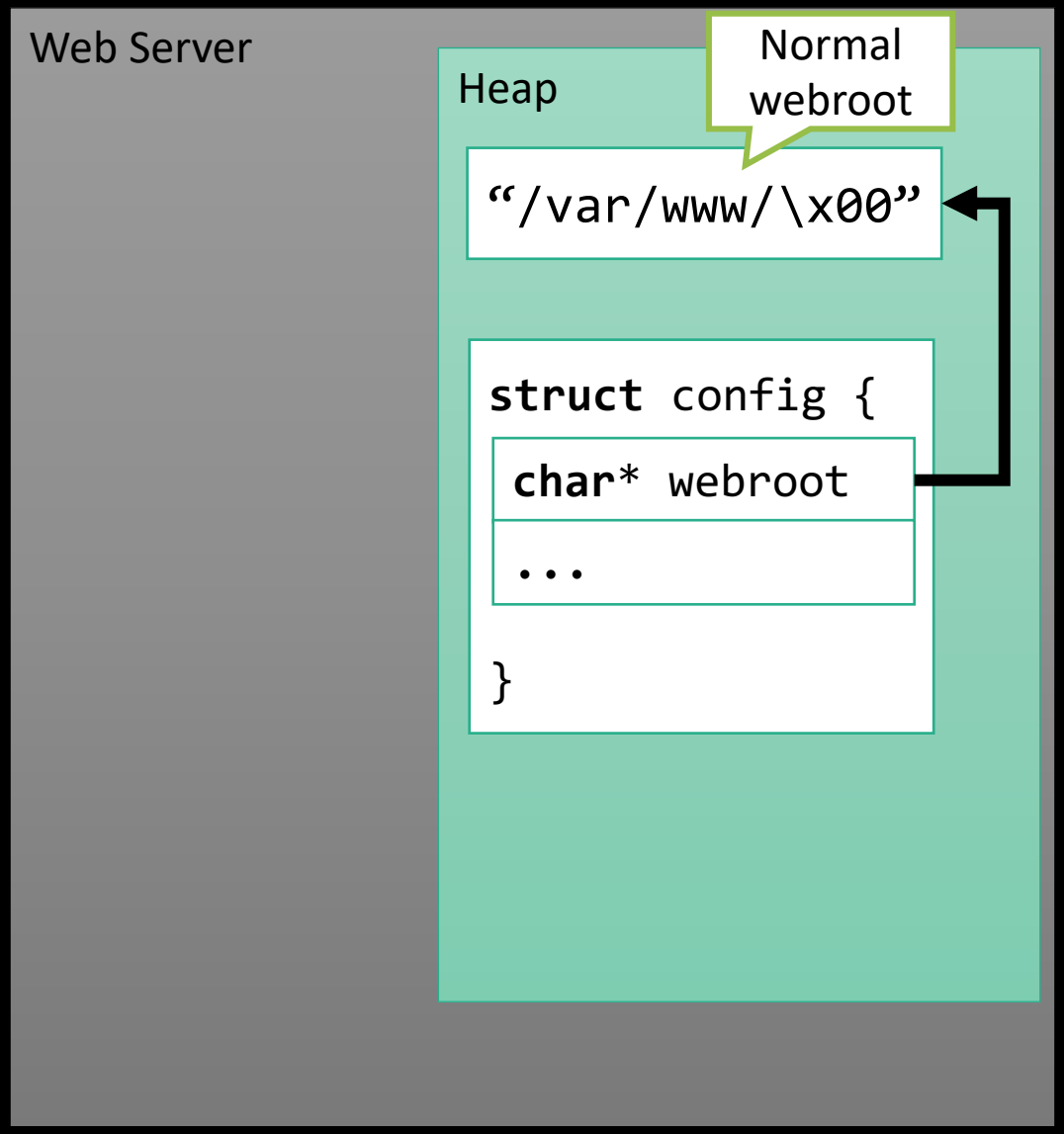
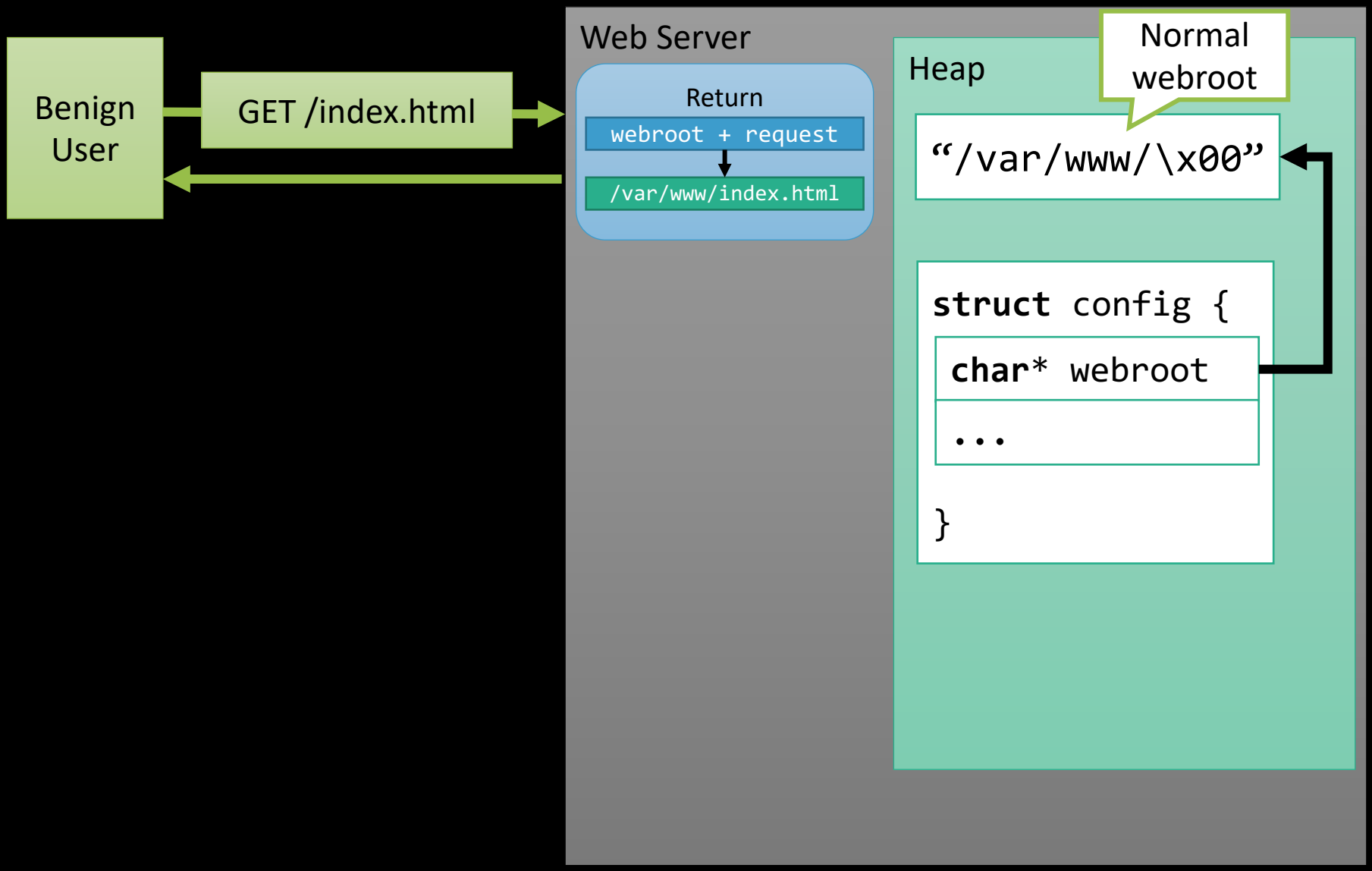


Corrupt Configuration Data

Corrupt Configuration Data



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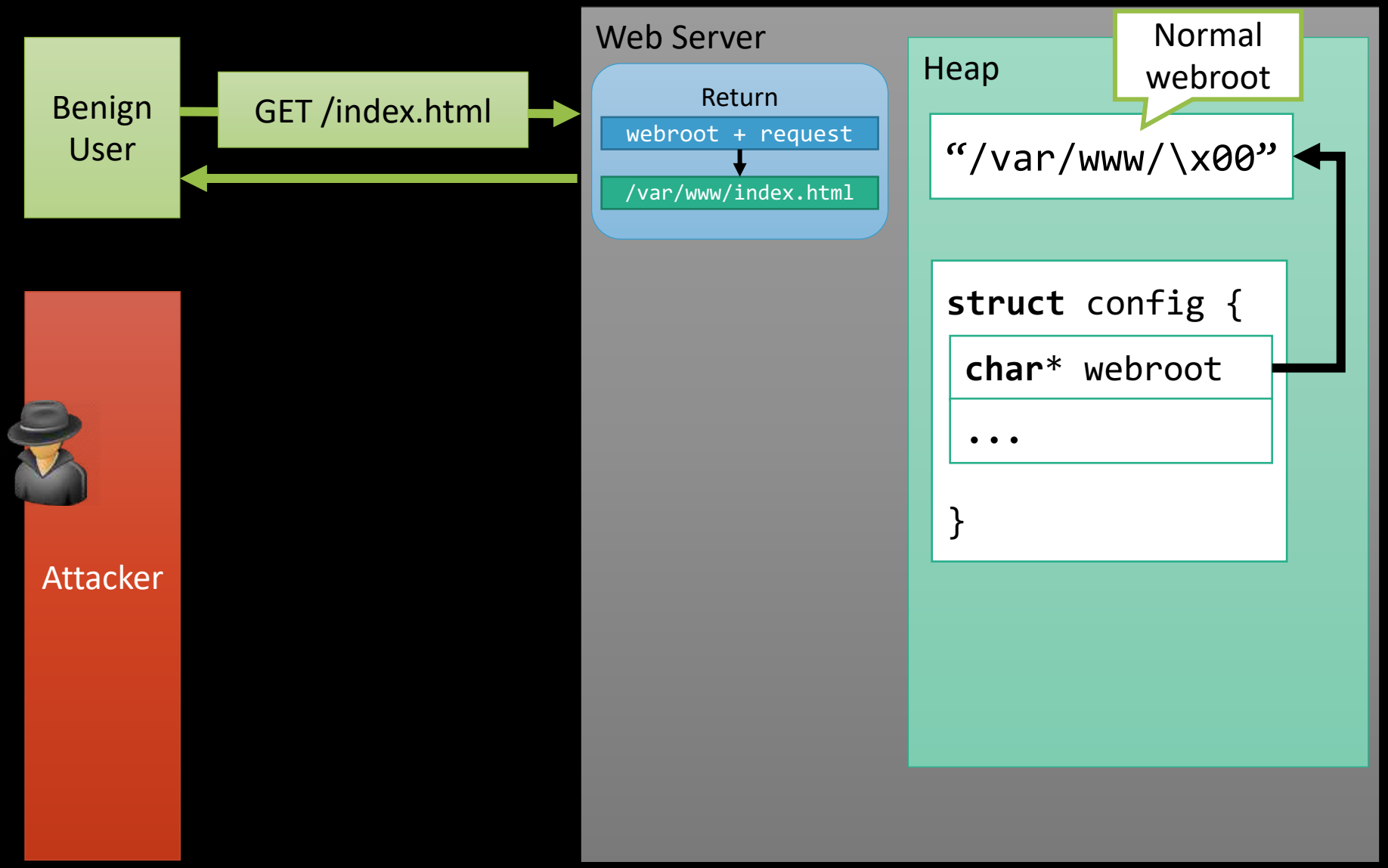

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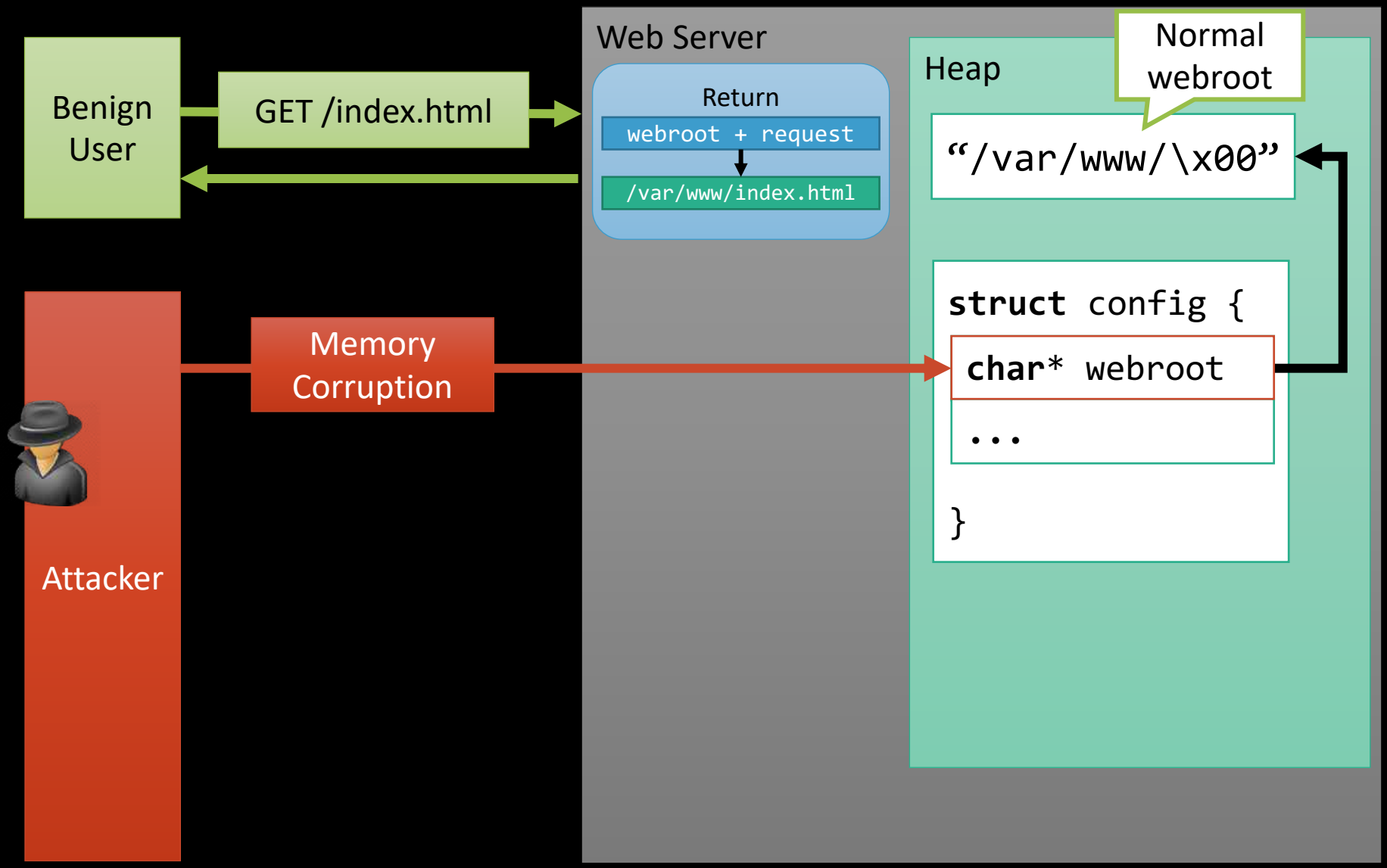

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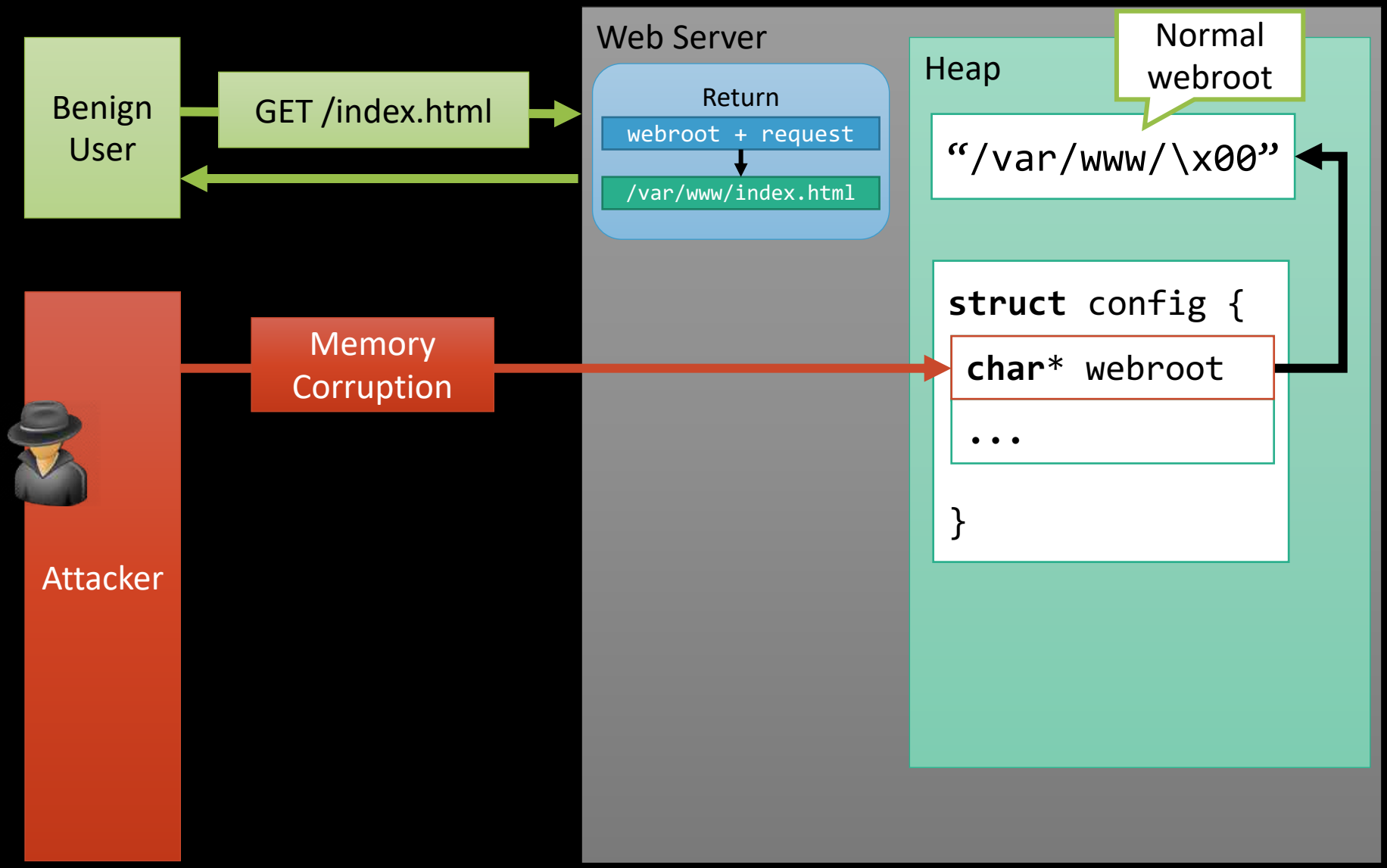

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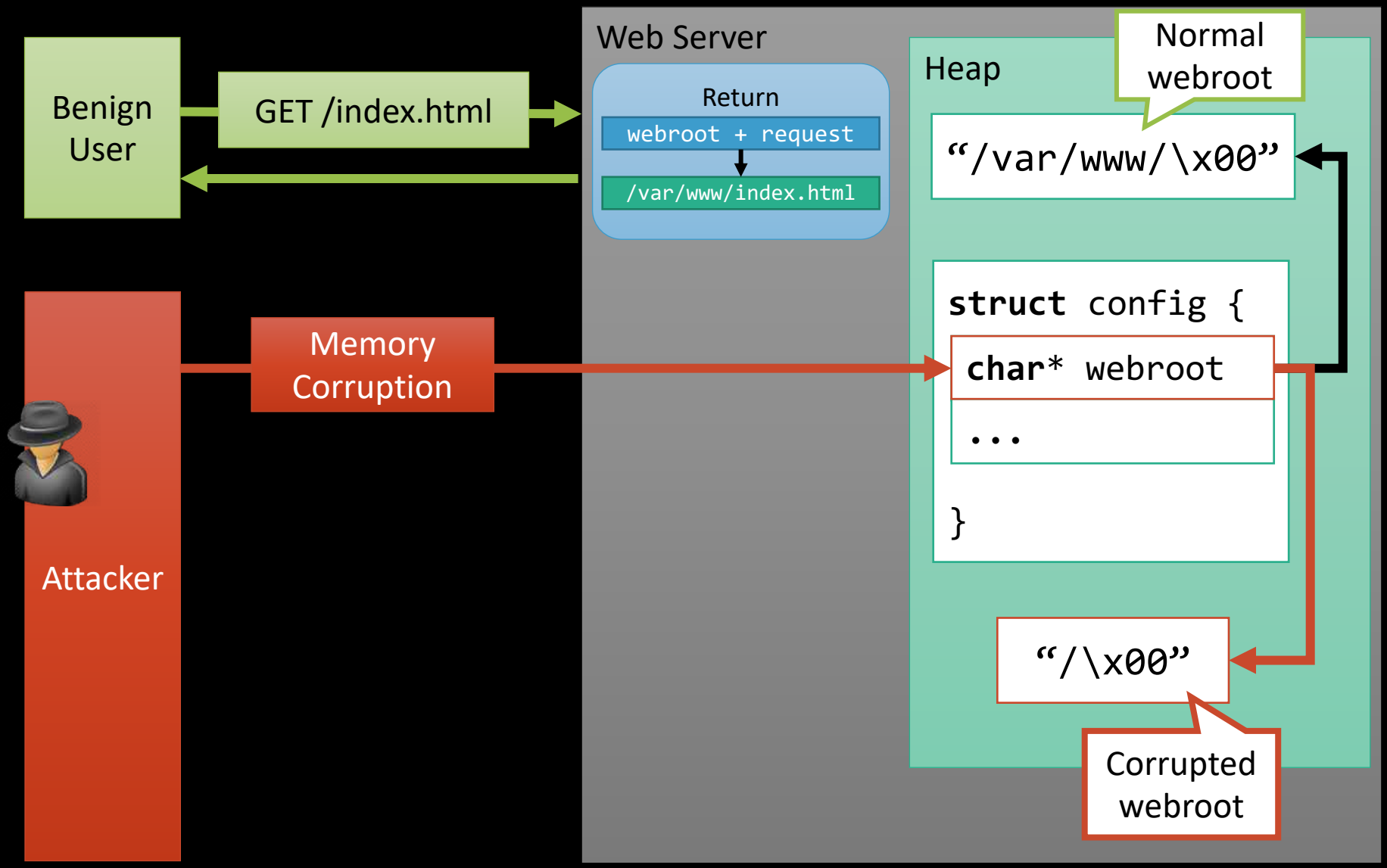

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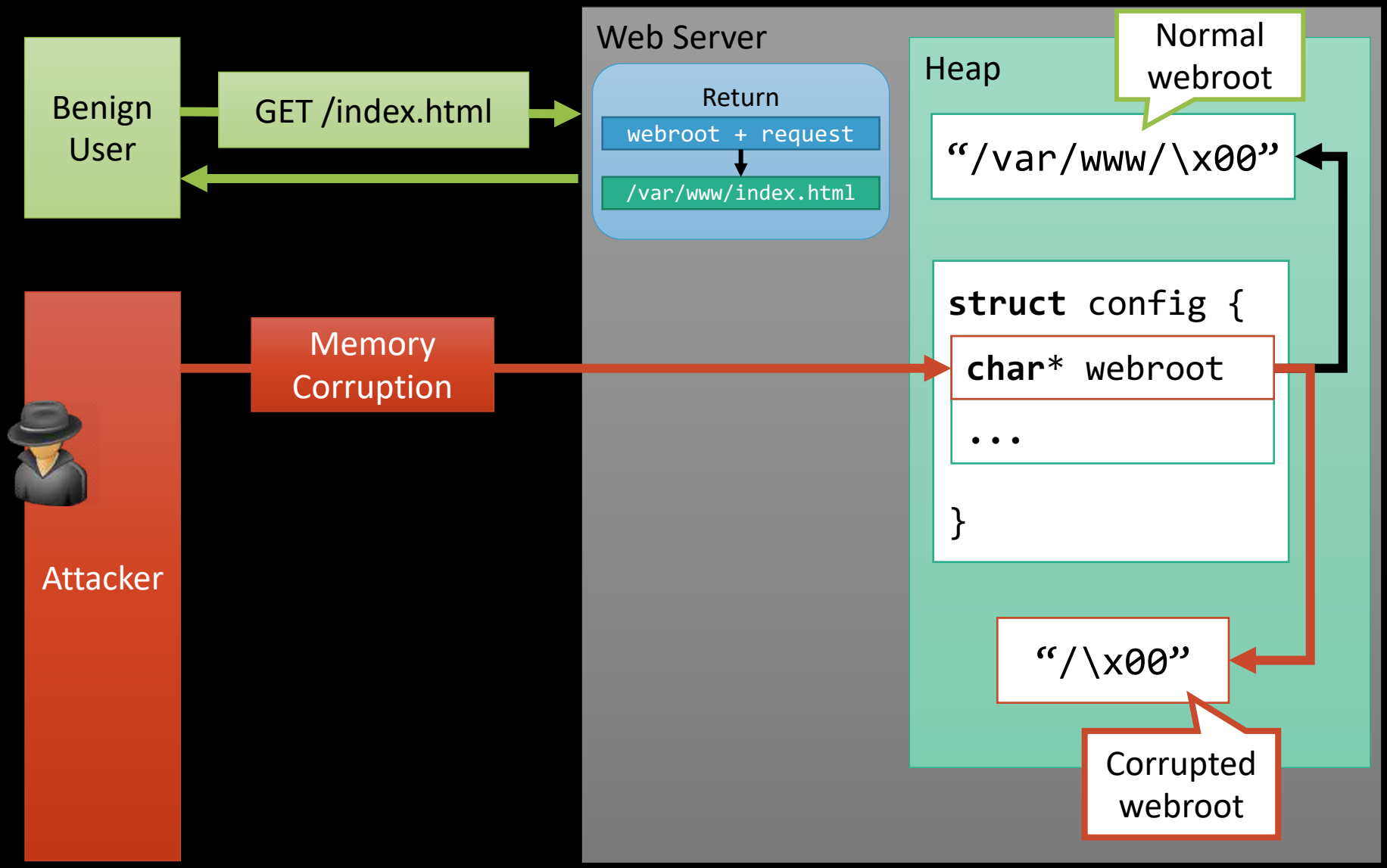

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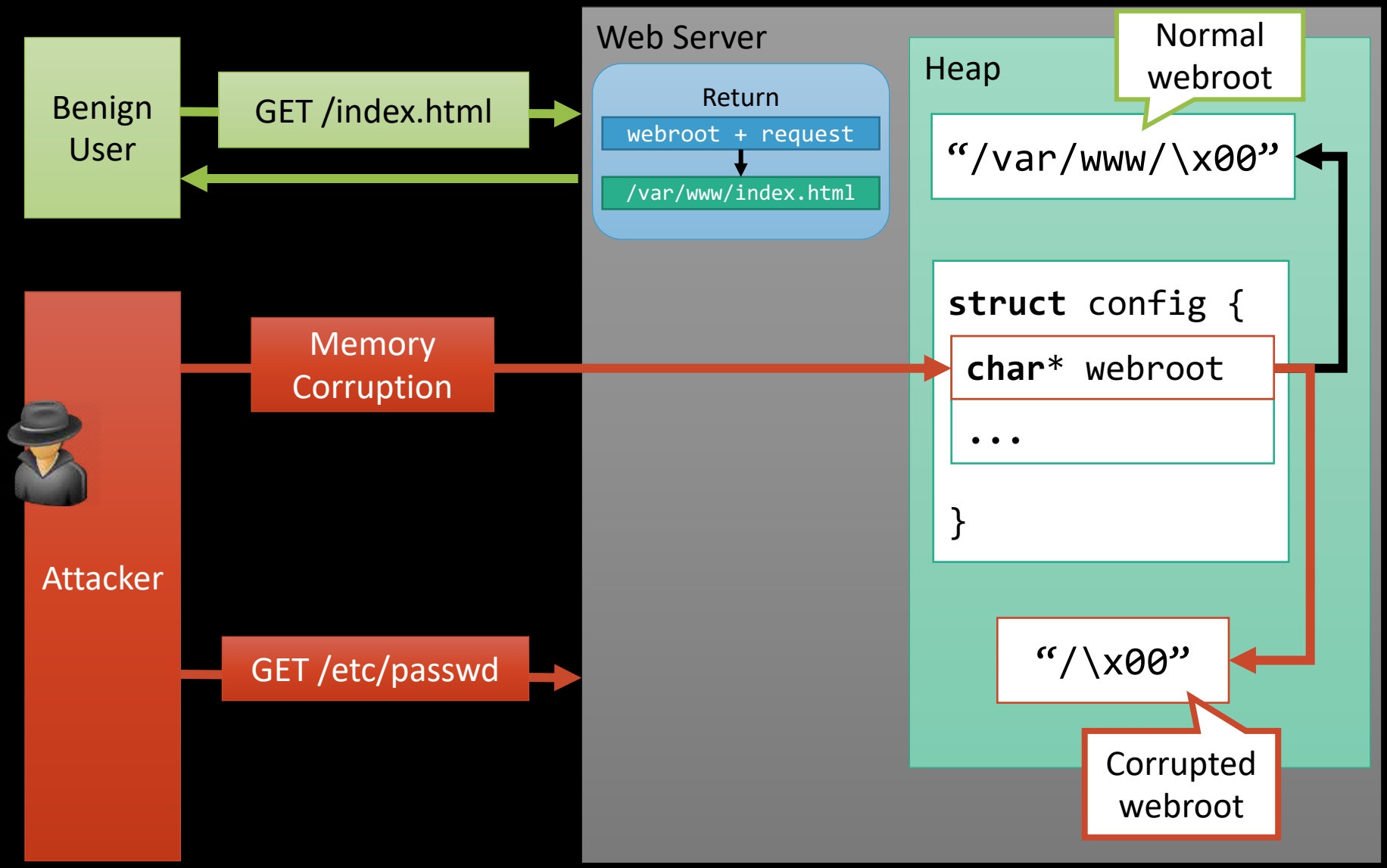

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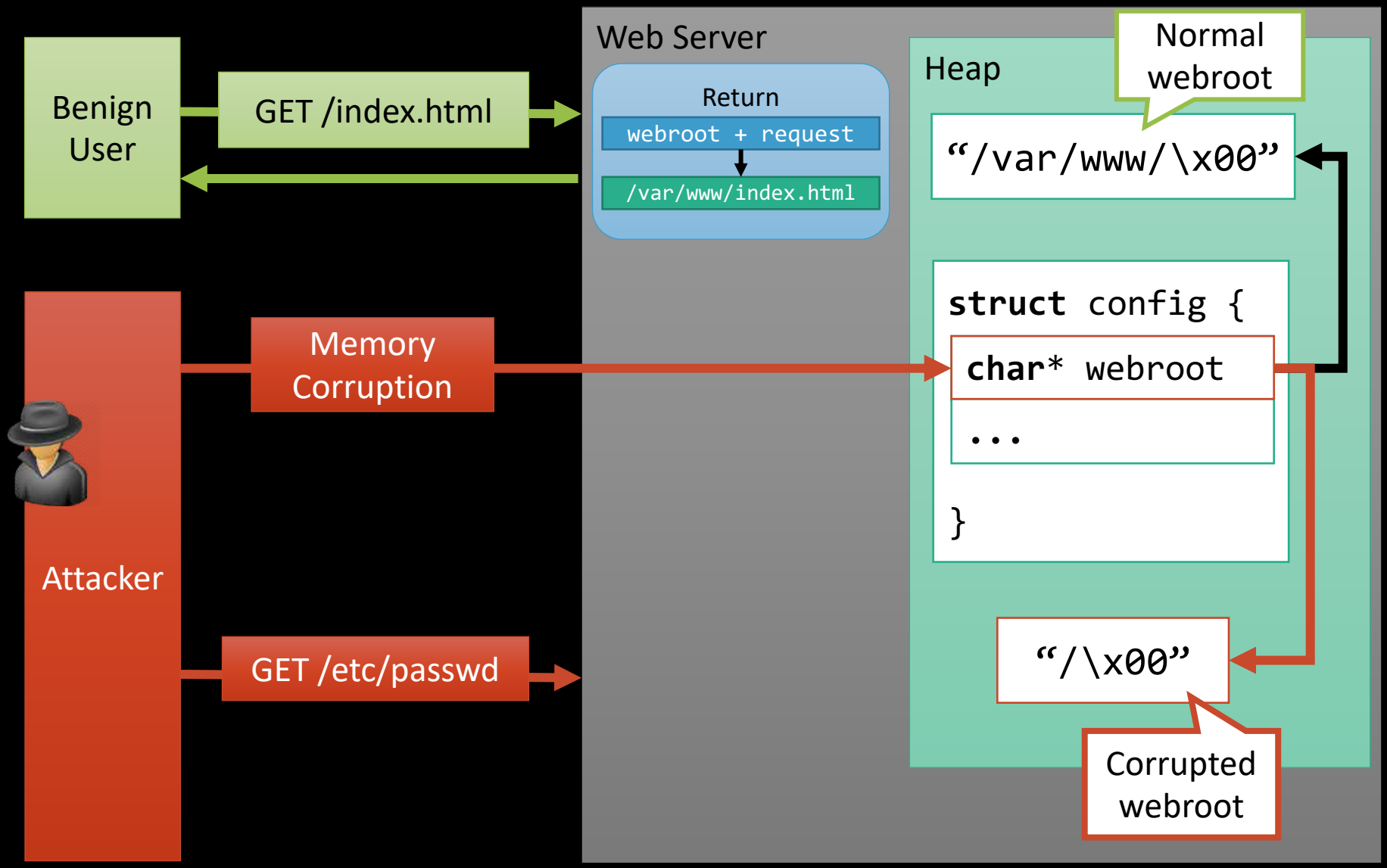

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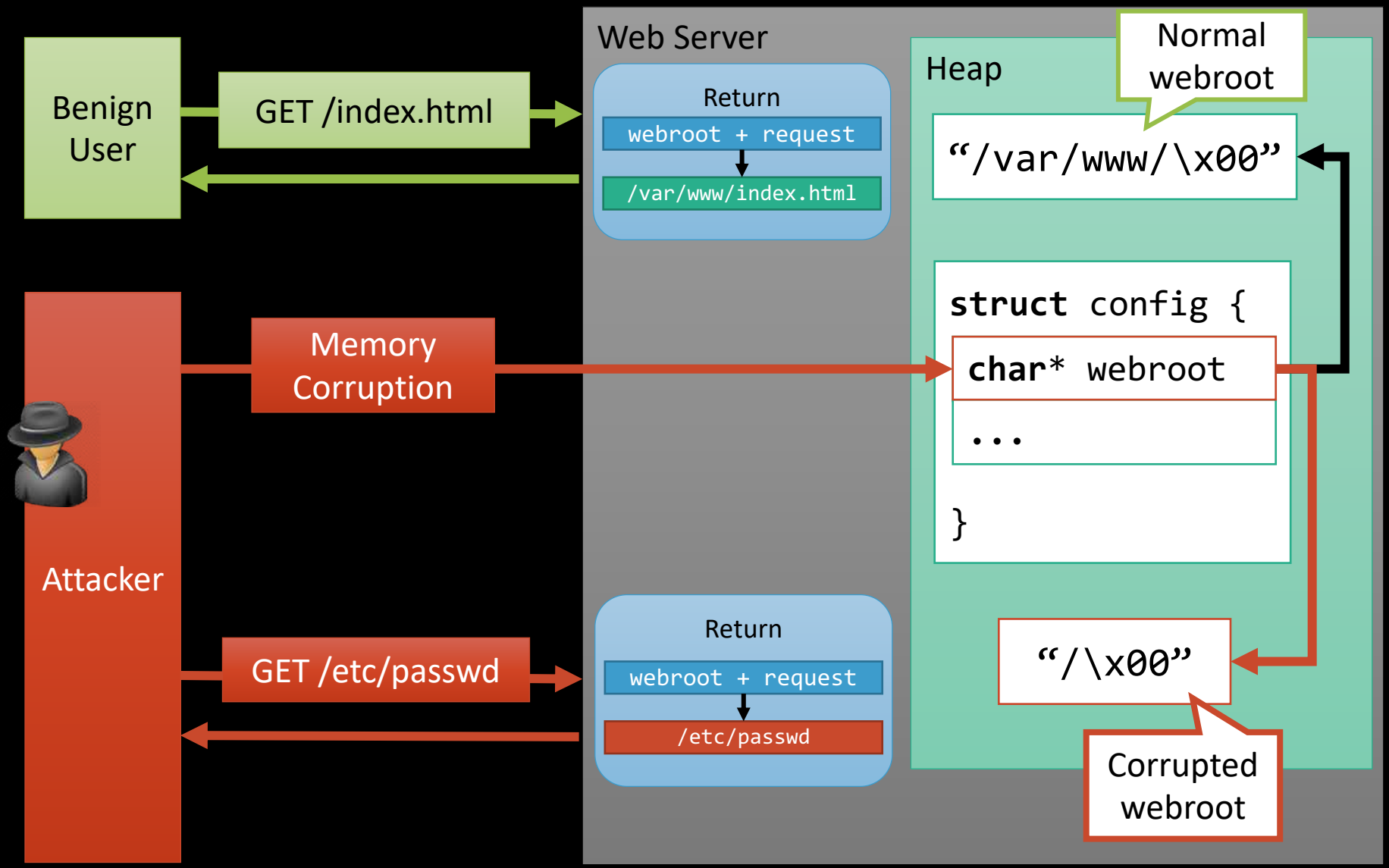

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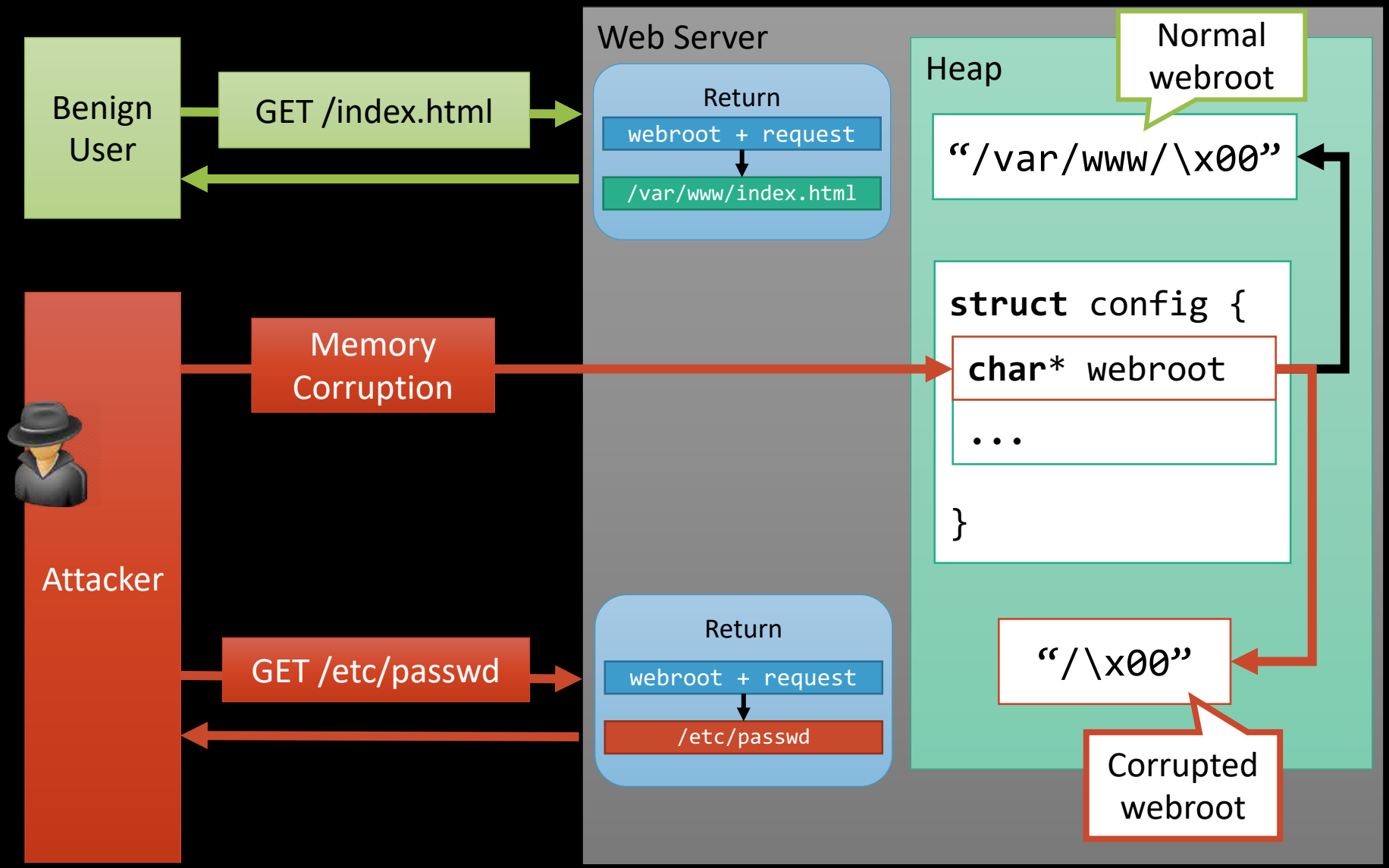

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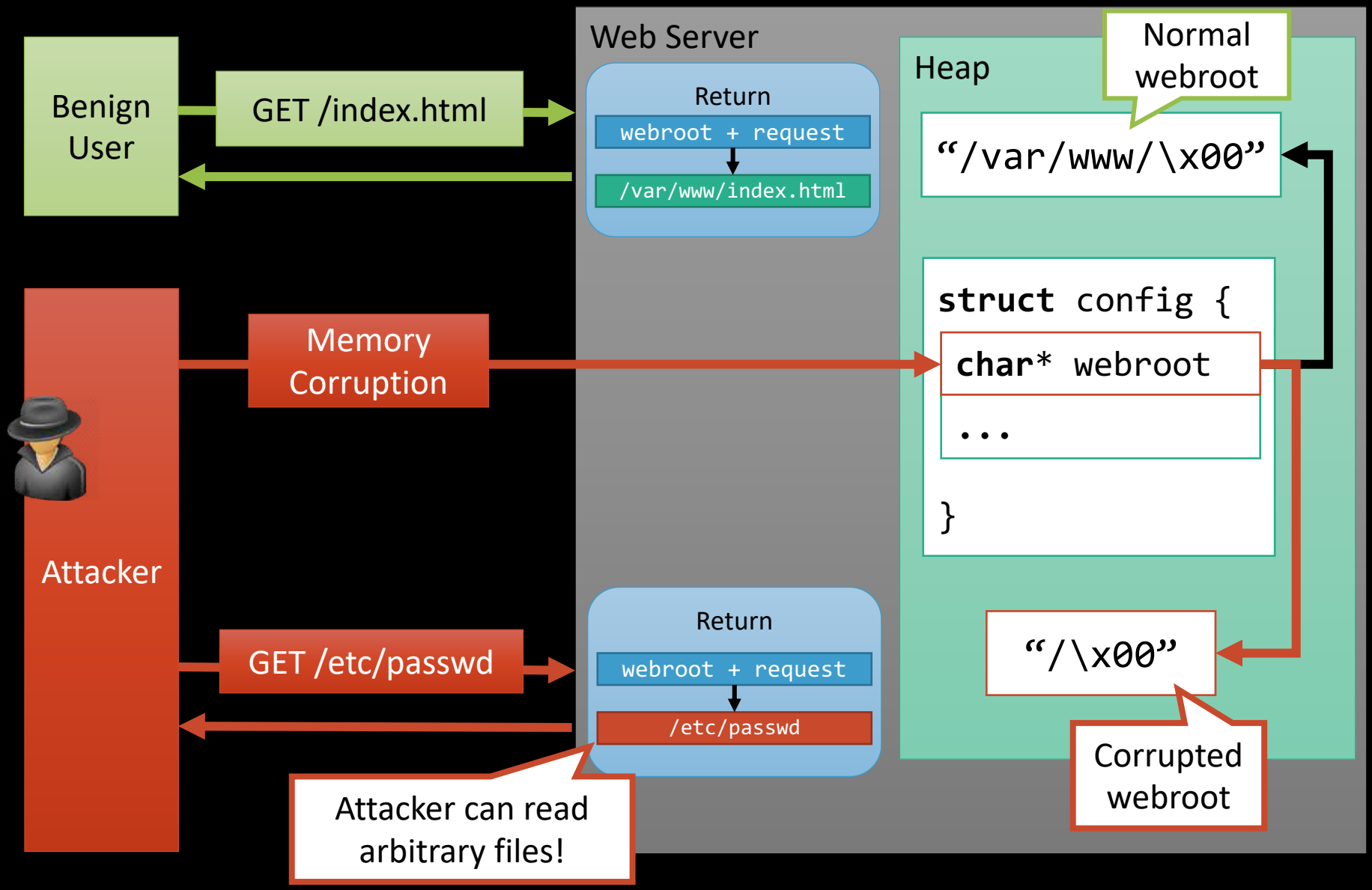

Generalization of data-only attacks: data-oriented programming [Hu et al., IEEE S&P 2016]

DOP Add Gadget Example

[Hu et al., IEEE S&P 2016]

Add Gadget

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Add Gadget

```
r0 = r0 + r1
```

DOP Virtual Registers

DOP Add Gadget Example

[Hu et al., IEEE S&P 2016]

Add Gadget

```
r0 = r0 + r1
```

Stored in target program memory.

DOP Virtual Registers

r0	r1	…

DOP Add Gadget Example

[Hu et al., IEEE S&P 2016]

Add Gadget

```
r0 = r0 + r1
```

C code	`srv->total += *size;`

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DOP Add Gadget Example

[Hu et al., IEEE S&P 2016]

Add Gadget

`r0 = r0 + r1`

Pointer dereference

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DOP Add Gadget Example

[Hu et al., IEEE S&P 2016]

Add Gadget

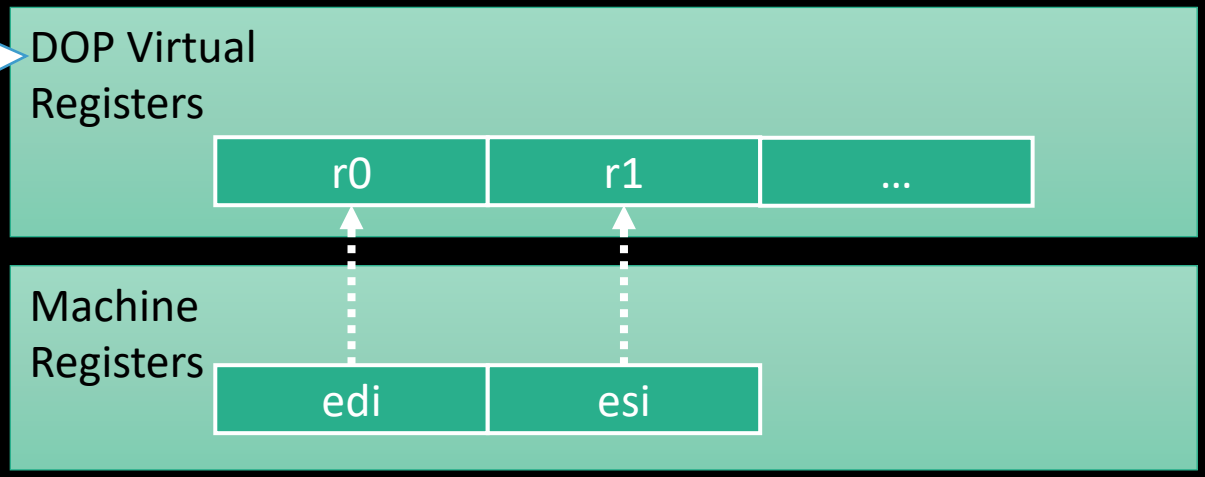
`r0 = r0 + r1`

Pointer dereference

C code	`srv->total += *size;`

ASM code	`mov eax, [edi]`
	`mov ebx, [esi]`
	`add eax, ebx`
	`mov [edi], eax`

Stored in target program memory.



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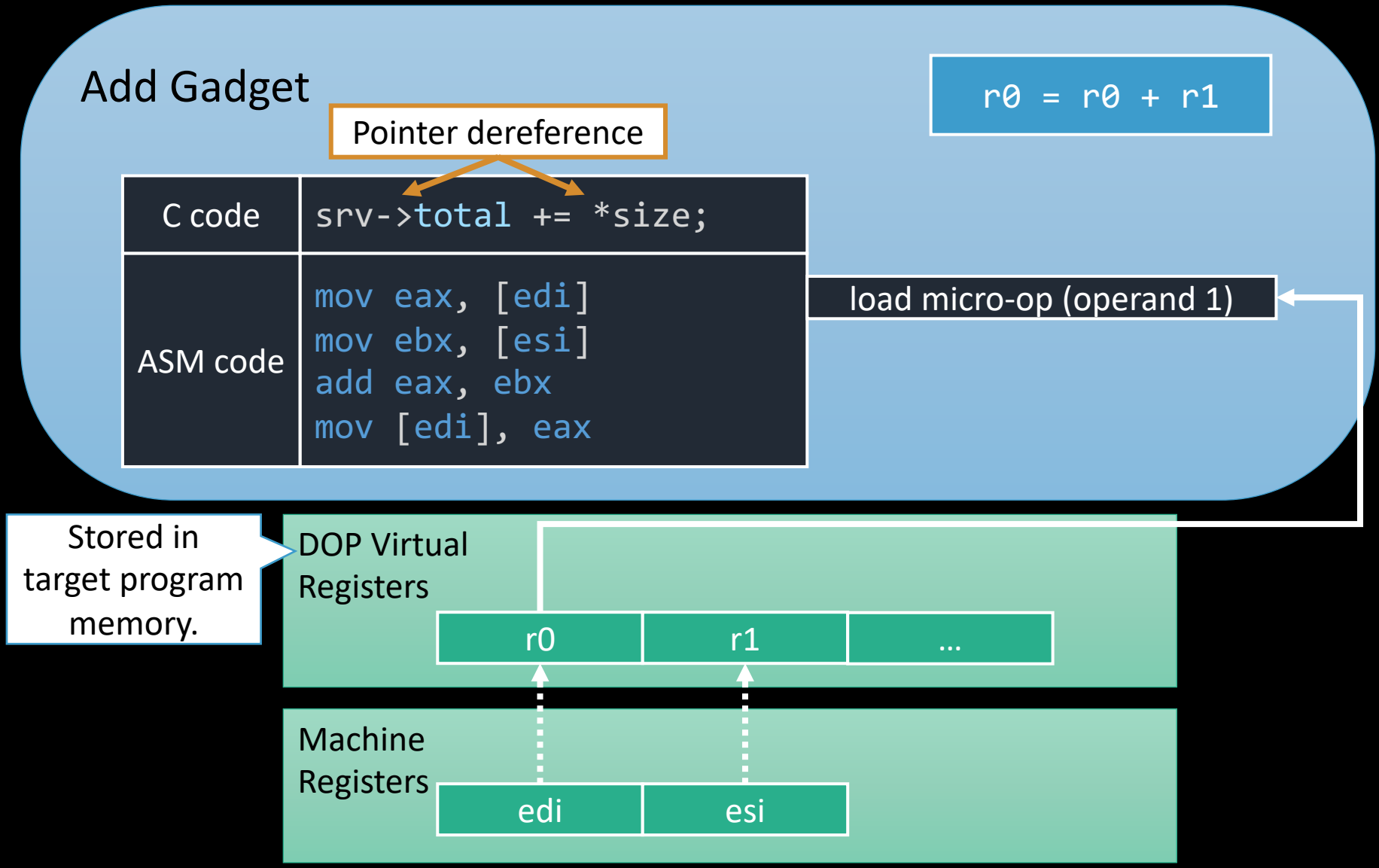

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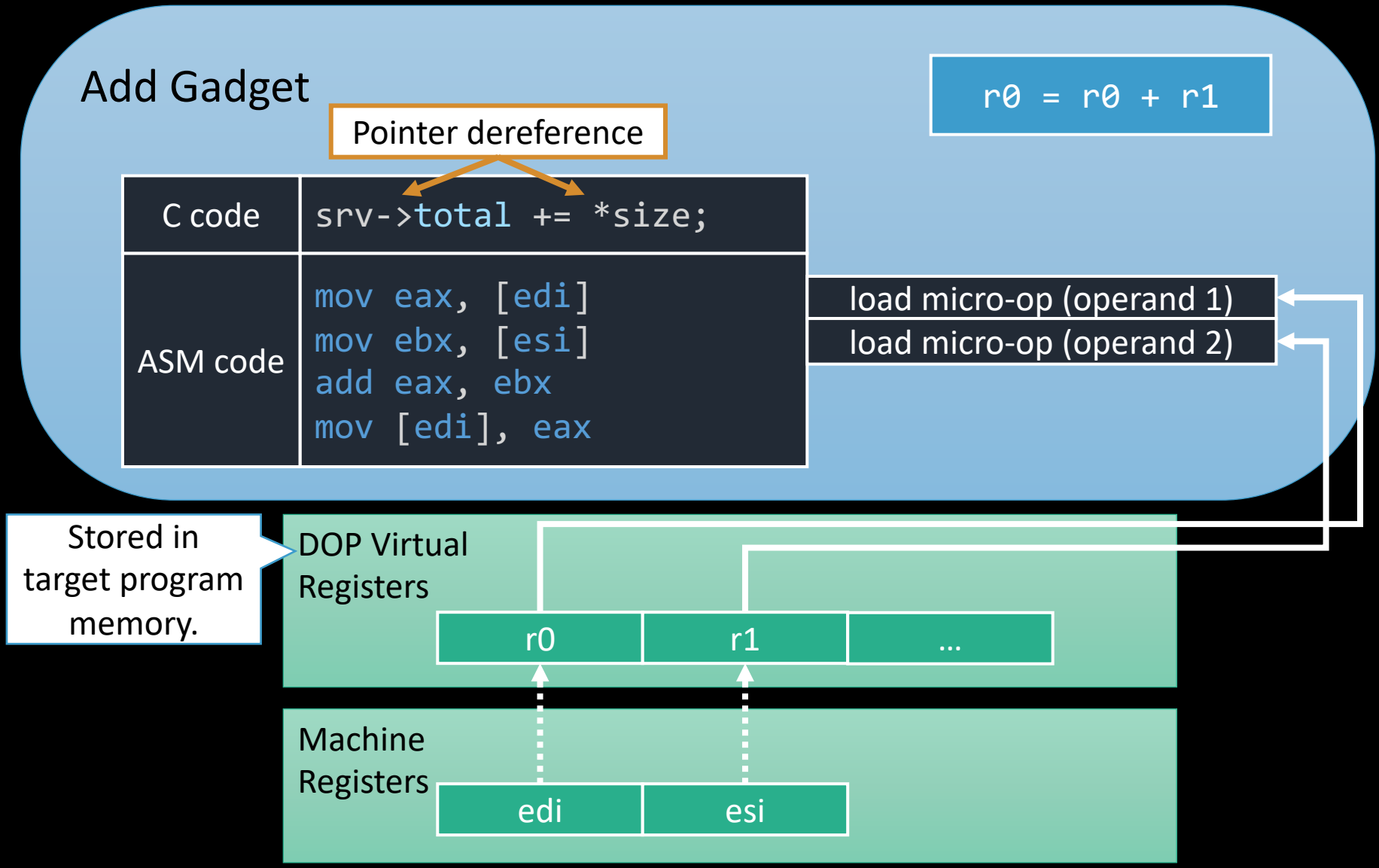

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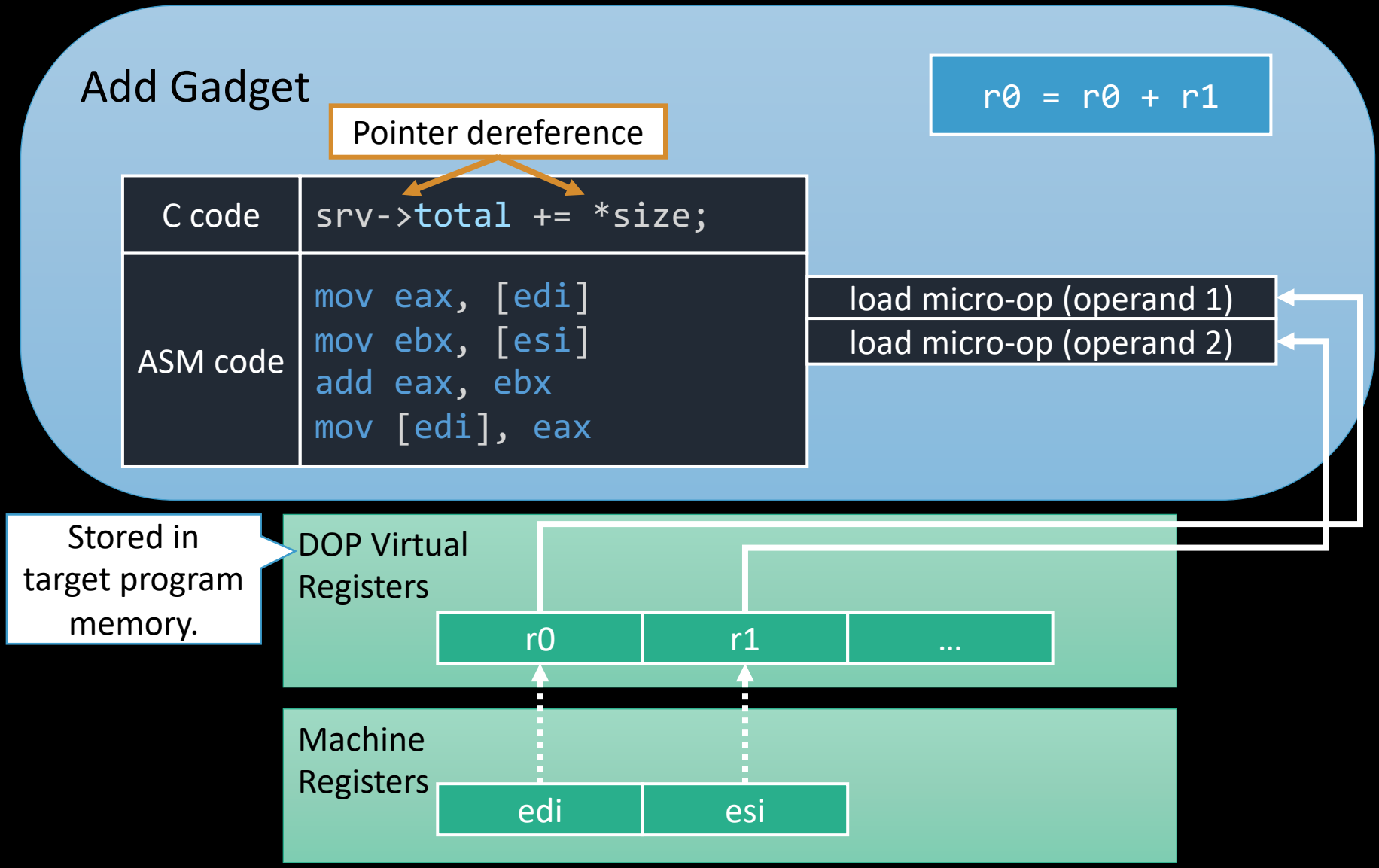
[Hu et al., IEEE S&P 2016]



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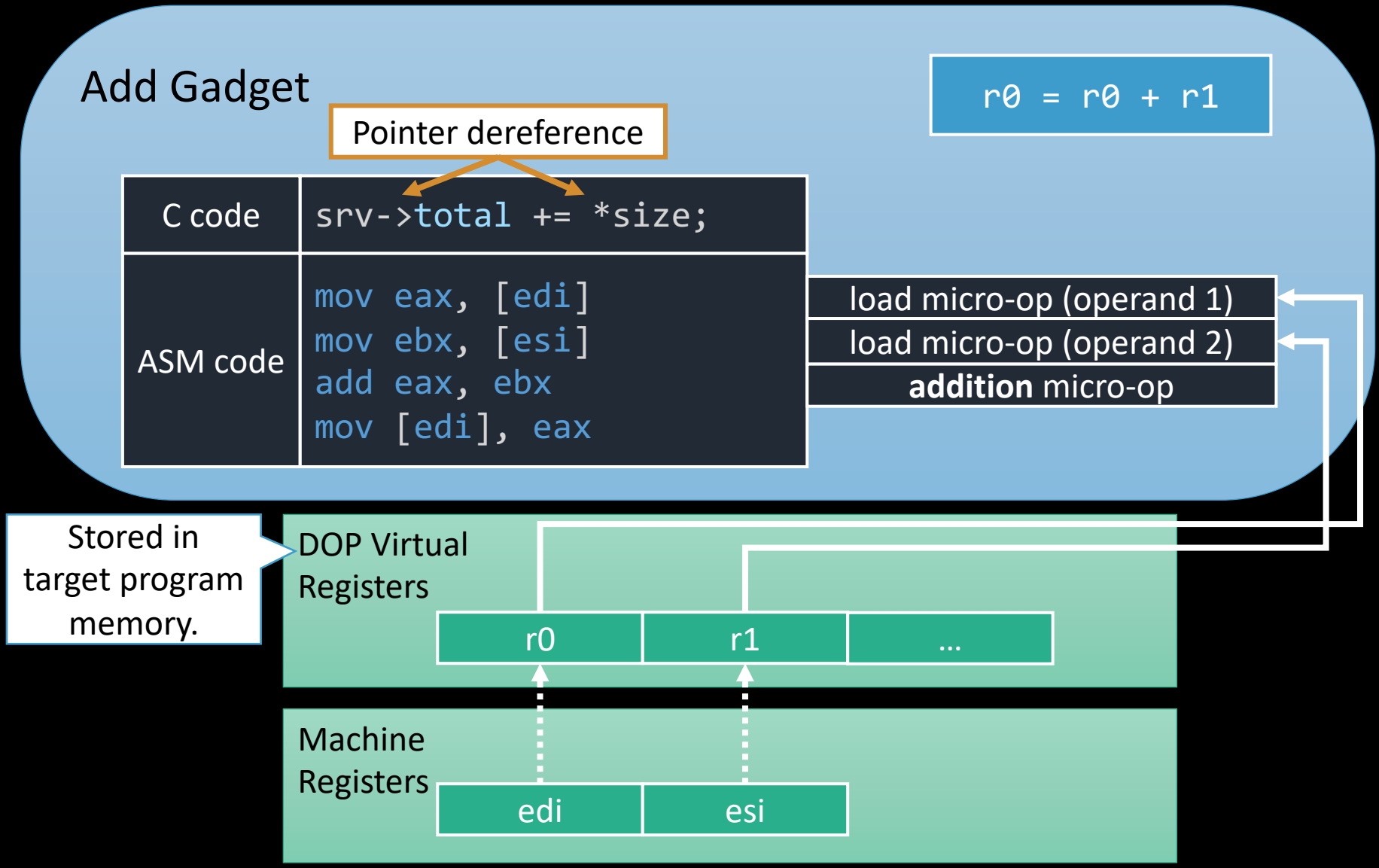

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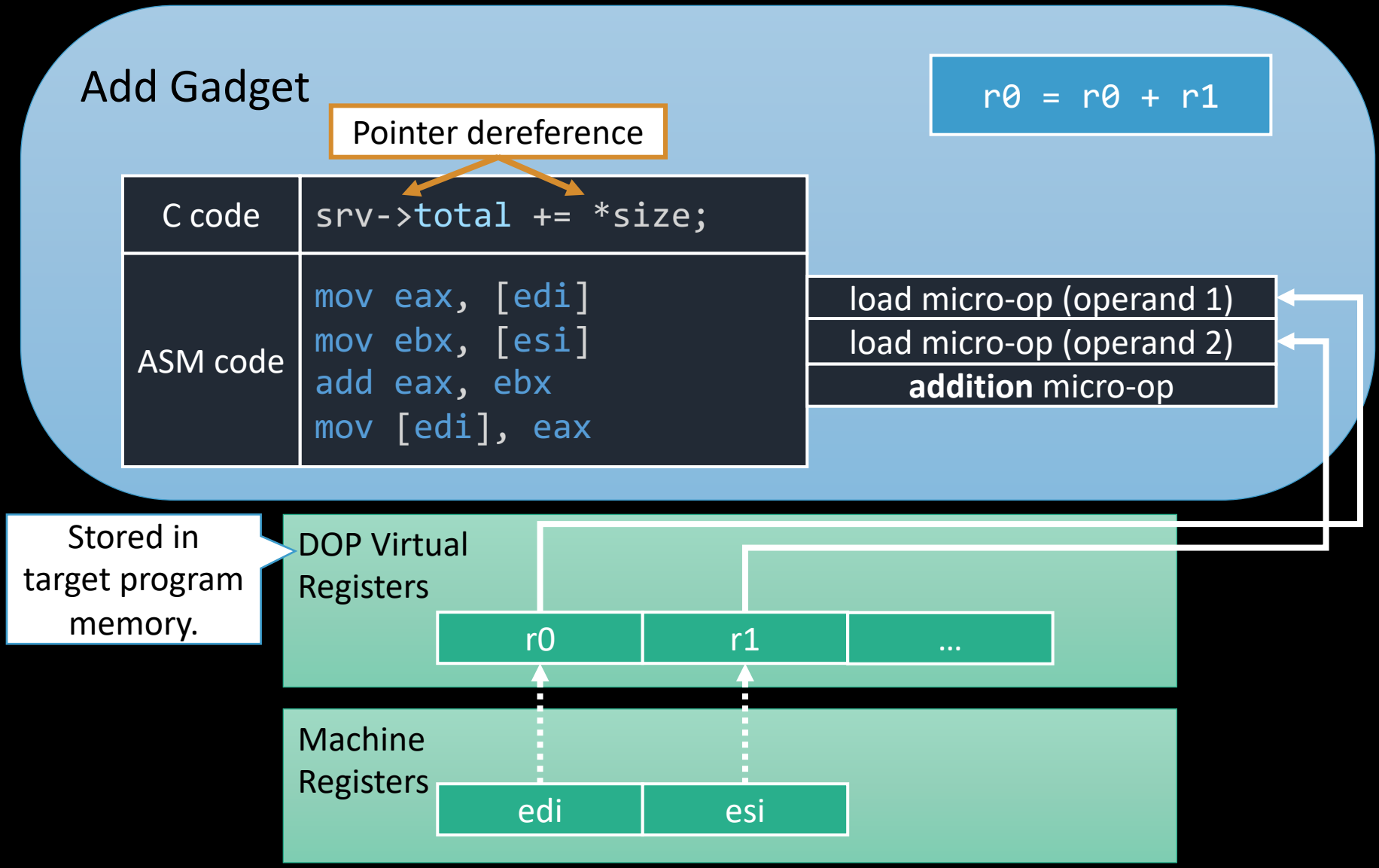

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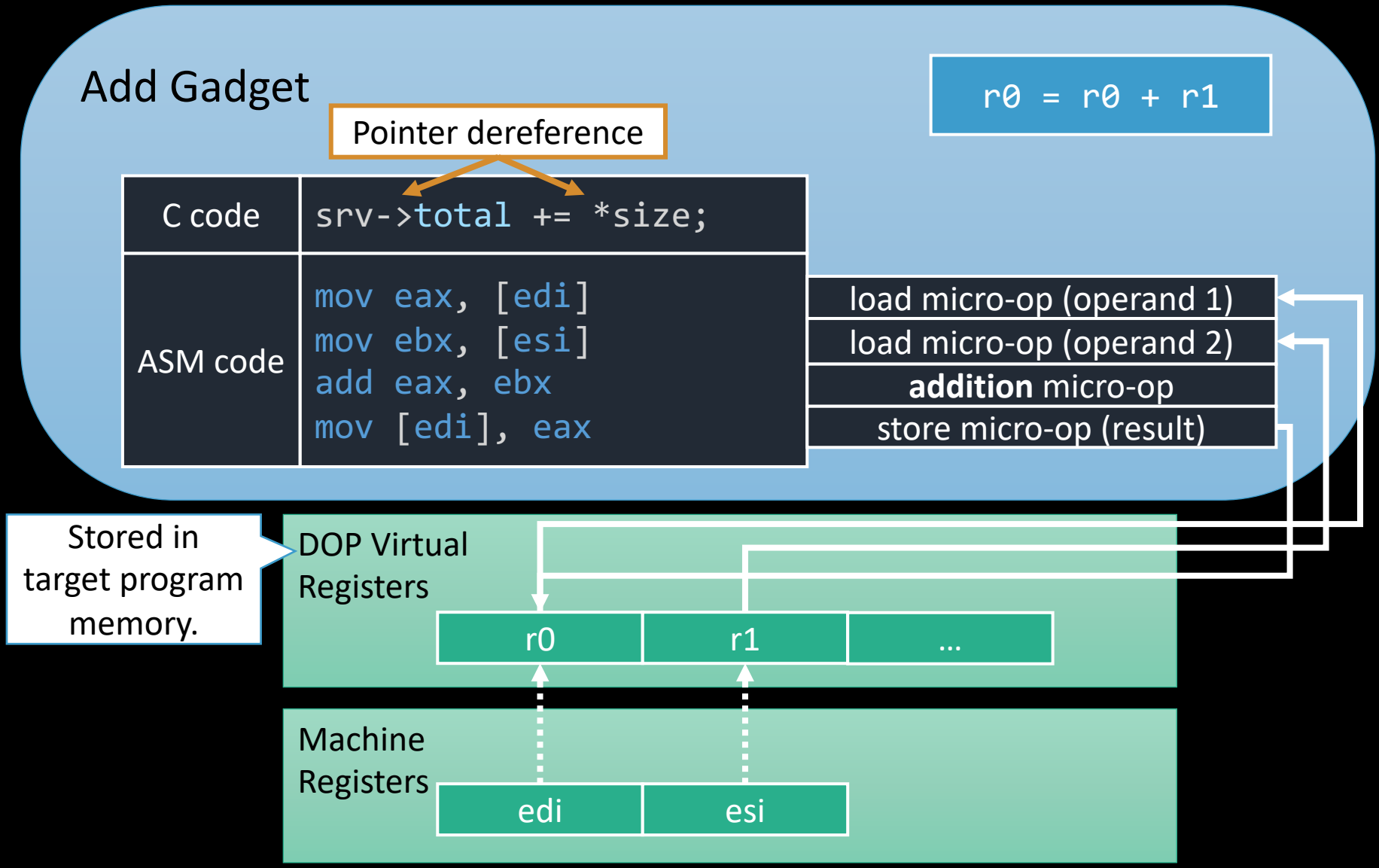

Discussion on Defenses

- Possible defense techniques:
  - Data-Flow Integrity (DFI) [Castro et al., OSDI 2006]
  - Write-Integrity Testing (WIT) [Akritidis et al., IEEE S&P 2008]
- DFI and WIT suffer from similar issues as CFI
  - High performance overhead
  - Depends on the precision of the data-flow graph

Hands-On Lab

Download and install the VirtualBox VM:

http://bit.do/secsummer19

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