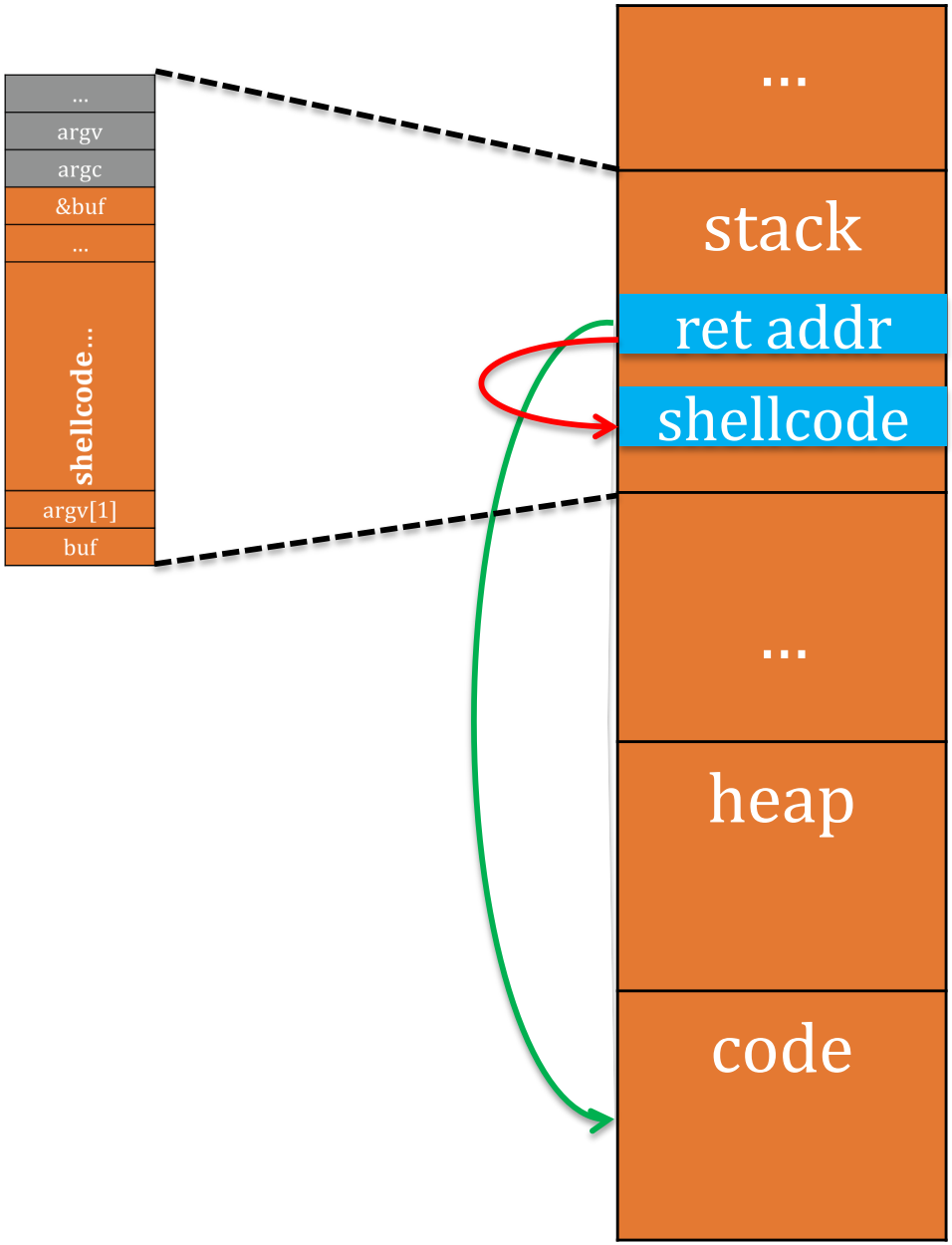
CS165 – Computer Security

Return-Oriented Programming

October 11, 2024

Attacks Injecting Shellcode



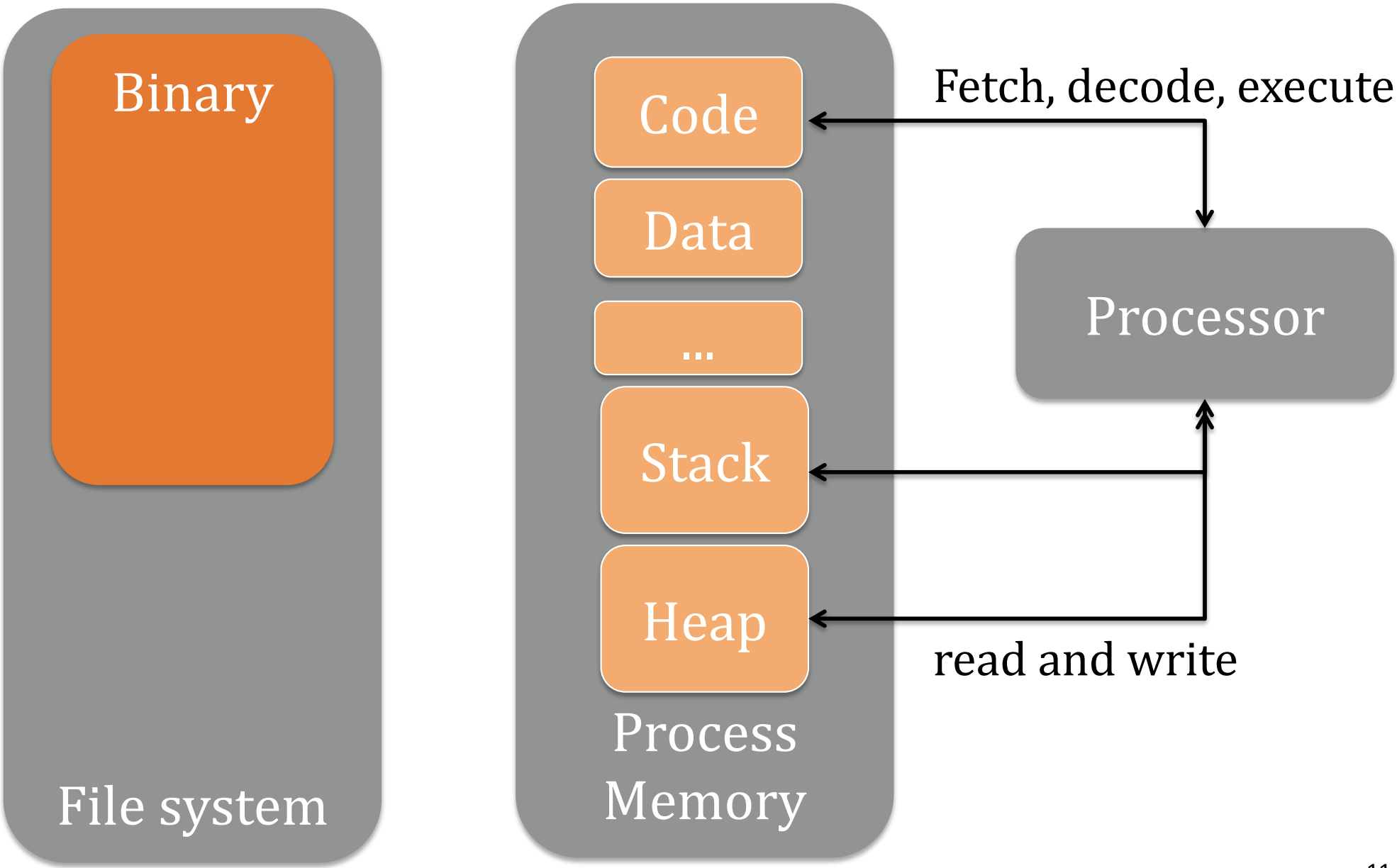
Injection Requirements

- What is required for a code injection attack?
  - Appreciated by the adversary…
  - That is not expected in practice?

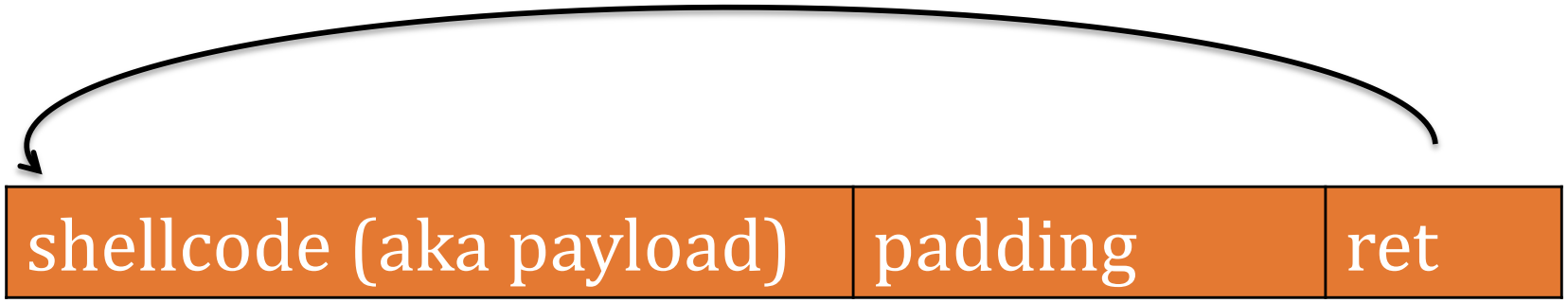
Injection Requirements

- What is required for a code injection attack?
  - Appreciated by the adversary…
  - That is not expected in practice?
- Answer: Execute stack memory
  - Code is injected in stack memory
  - So, we must be able to execute stack memory
- Must all memory be executable?
  - Recall page permissions

Basic Execution



Control Flow Hijack: Always control + computation

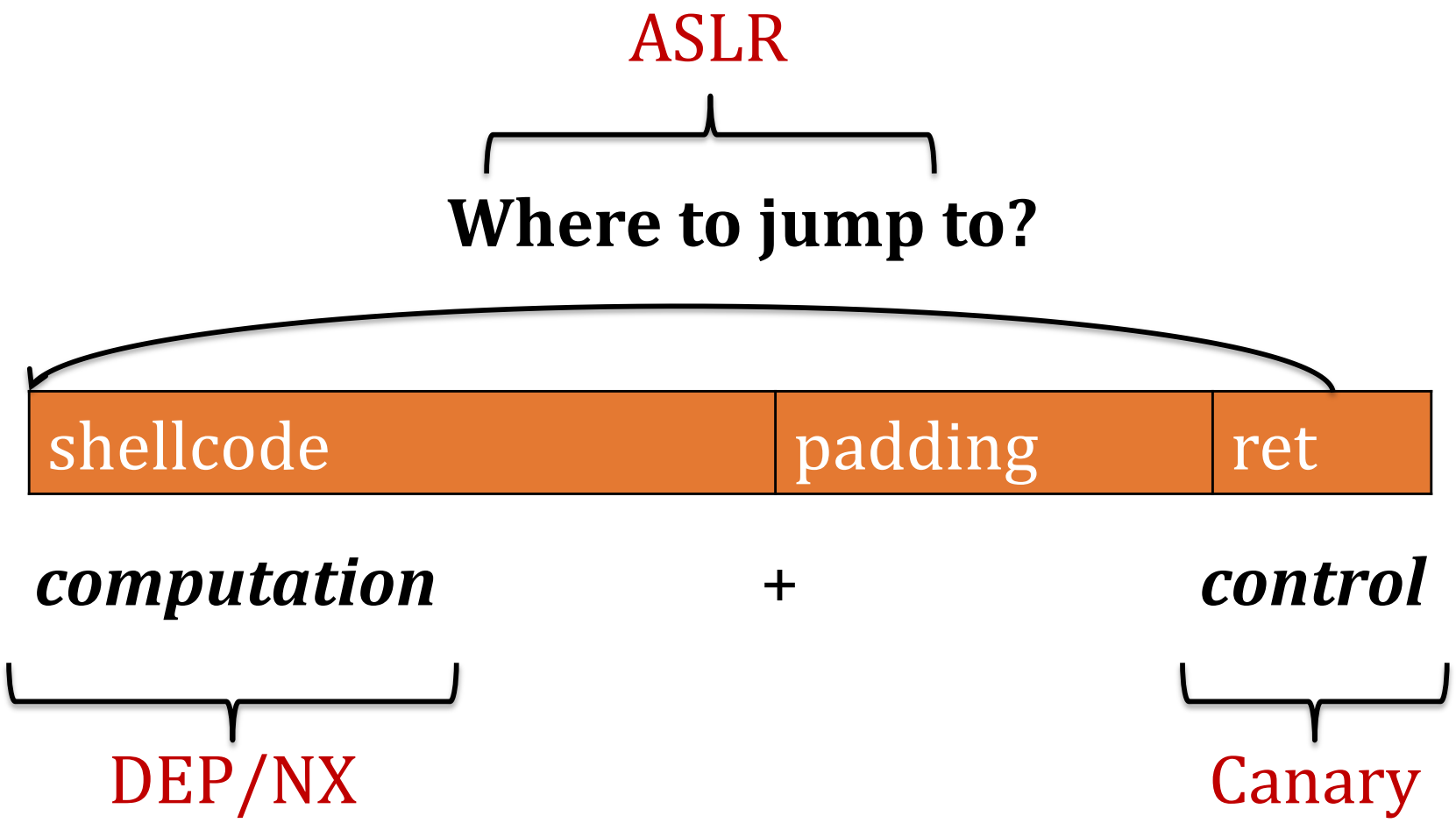


computation + ***control***

Return-oriented programming (ROP): shellcode without code injection

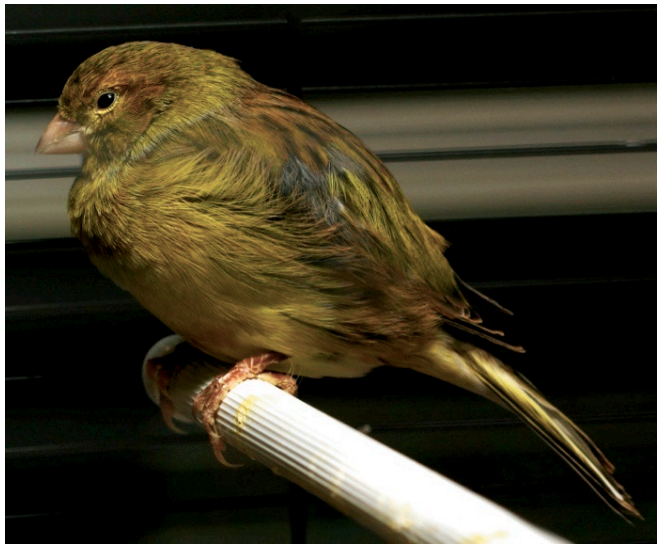
Acknowledgement: Some slides from David Brumley , Ed Schwartz, Kevin Snow, and Lucas Davi

Control-Flow Hijacking Defenses



Wikipedia: “the historic practice of using canaries in coal mines, since they would be affected by toxic gases earlier than the miners, thus providing a biological warning system.”

Canary / Stack Cookies



http://en.wikipedia.org/wiki/File:Domestic_Canary_-_Serinus_canaria.jpg

“A”x68 . “\xEF\xBE\xAD\xDE”

```
#include<string.h>
int main(int argc, char **argv) {
    char buf[64];
    strcpy(buf, argv[1]);
}

Dump of assembler code for function main:
   0x080483e4 <+0>:  push   %ebp
   0x080483e5 <+1>:  mov    %esp,%ebp
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   0x080483ea <+6>:  mov    12(%ebp),%eax
   0x080483ed <+9>:  mov    4(%eax),%eax
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   0x080483f4 <+16>: lea    -64(%ebp),%eax
   0x080483f7 <+19>: mov    %eax,(%esp)
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   0x08048400 <+28>: ret
```

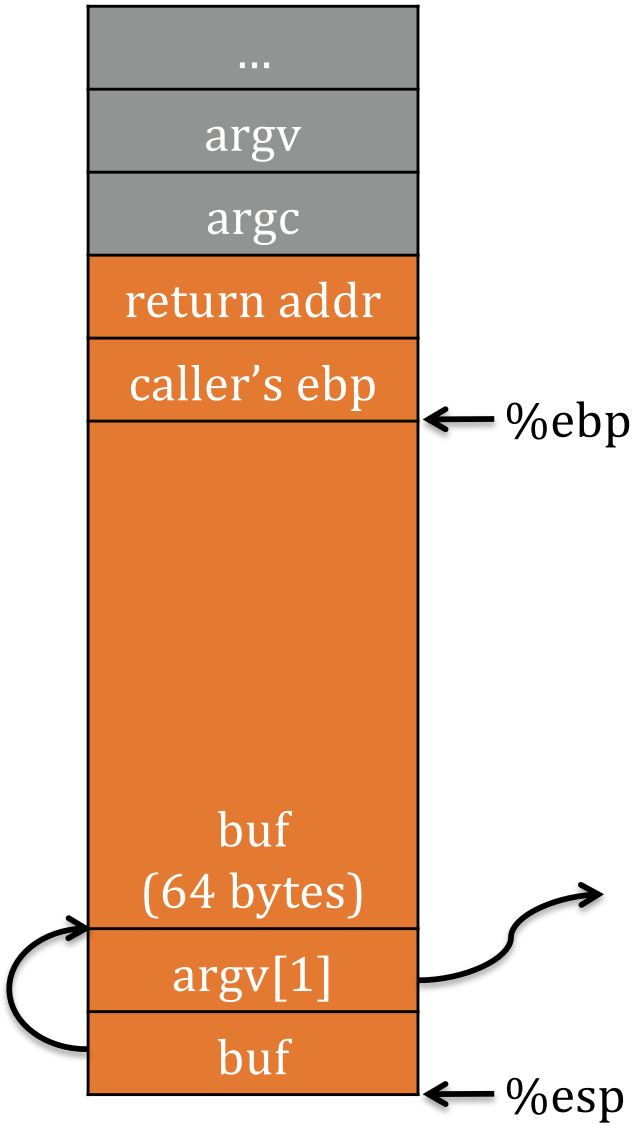

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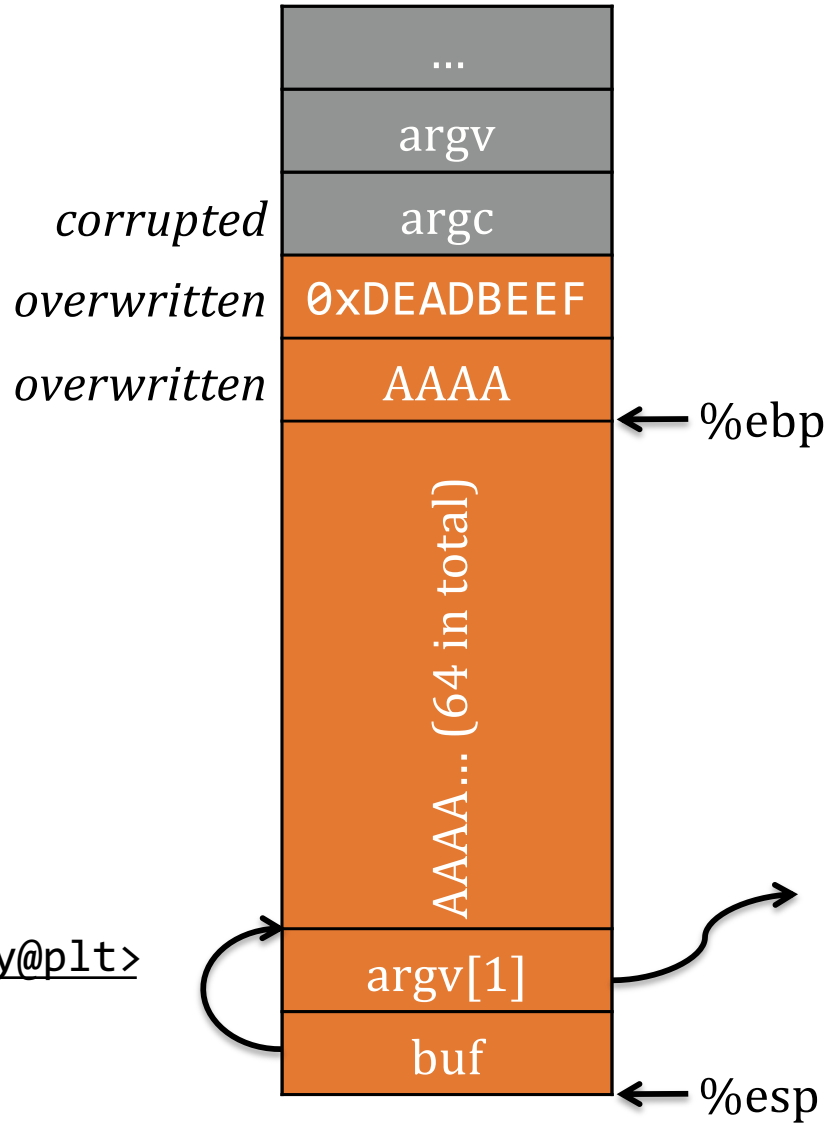

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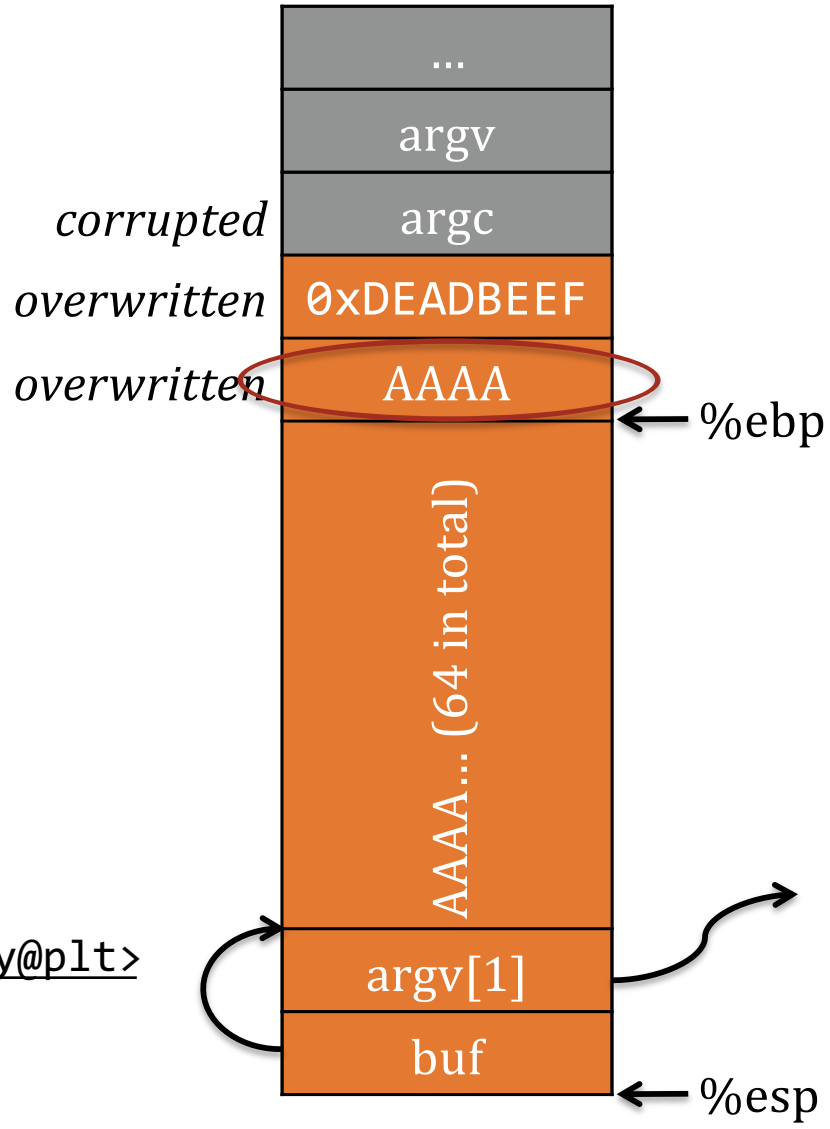
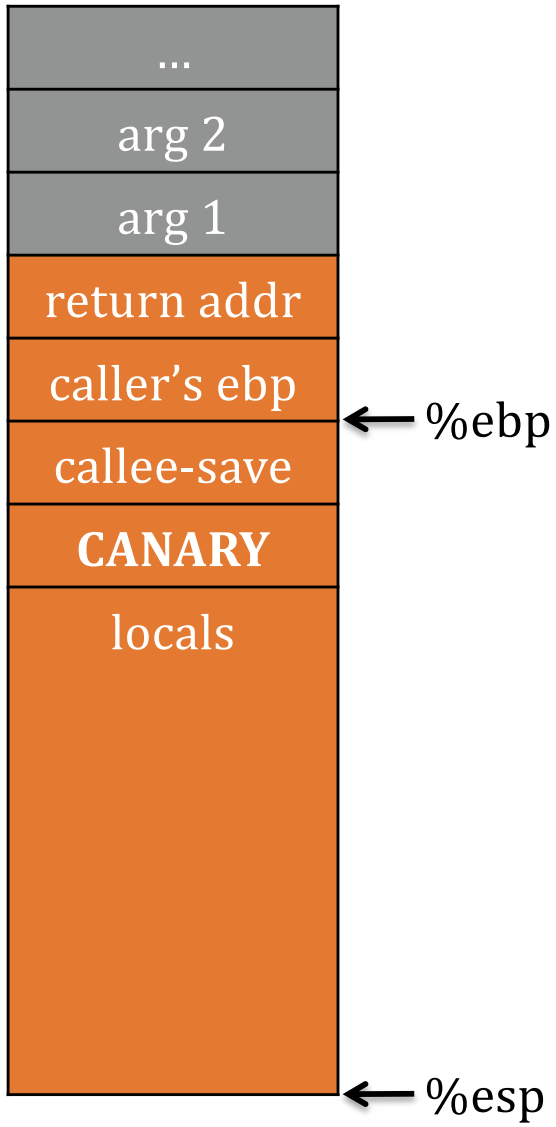


StackGuard [Cowen etal. 1998]

Idea:

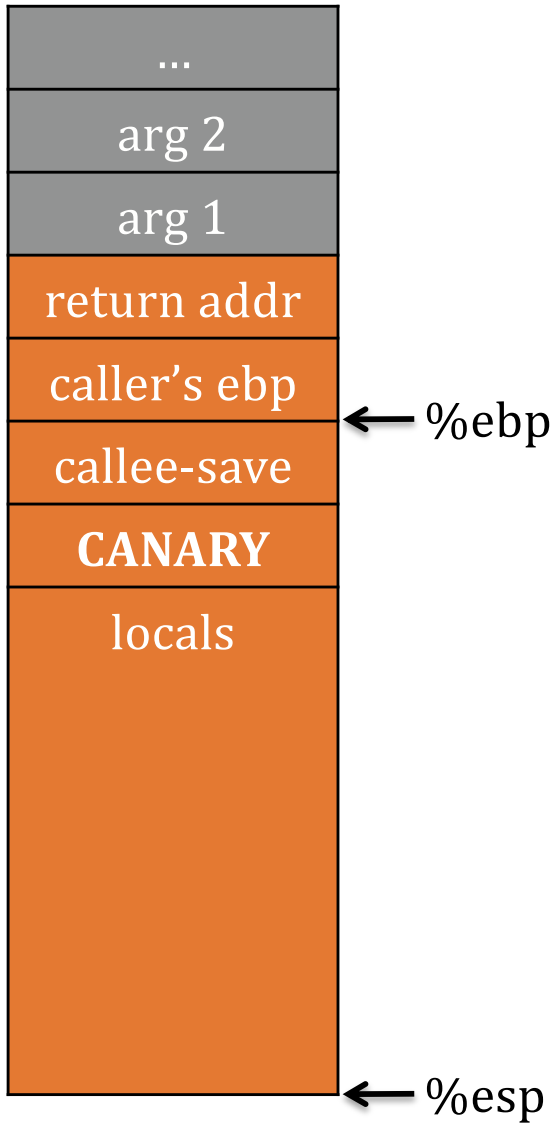
- prologue introduces a ***canary word*** between return addr and locals



StackGuard [Cowen etal. 1998]

Idea:

- prologue introduces a ***canary word*** between return addr and locals
- epilogue checks canary before function returns



Canary Scorecard

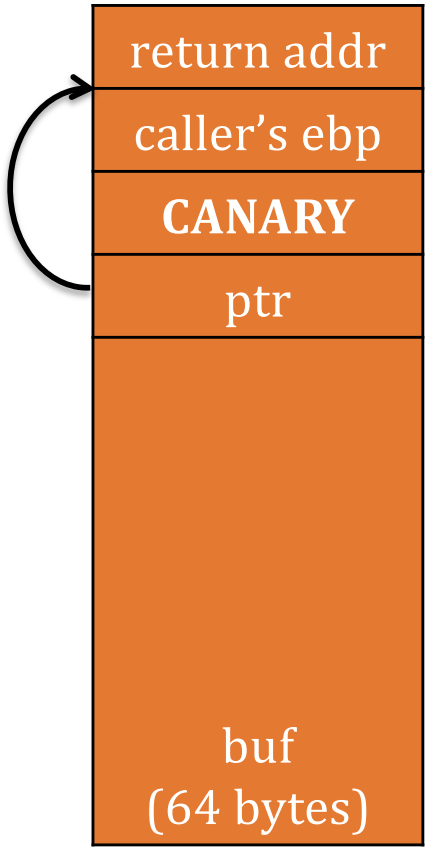
Aspect	Canary
Performance	• Some add'l instructions per function • time: a few percent on average • size: can optimize away in safe functions (but see MS08-067 *)
Deployment	• recompile suffices; no code change
Compatibility	• perfect—invisible to outside
Safety Guarantee	• *not really…*

* http://blogs.technet.com/b/srd/archive/2009/03/16/gs-cookie-protection-effectiveness-and-limitations.aspx

Bypass: Data Pointer Corruption

Overwrite a data pointer *first*…

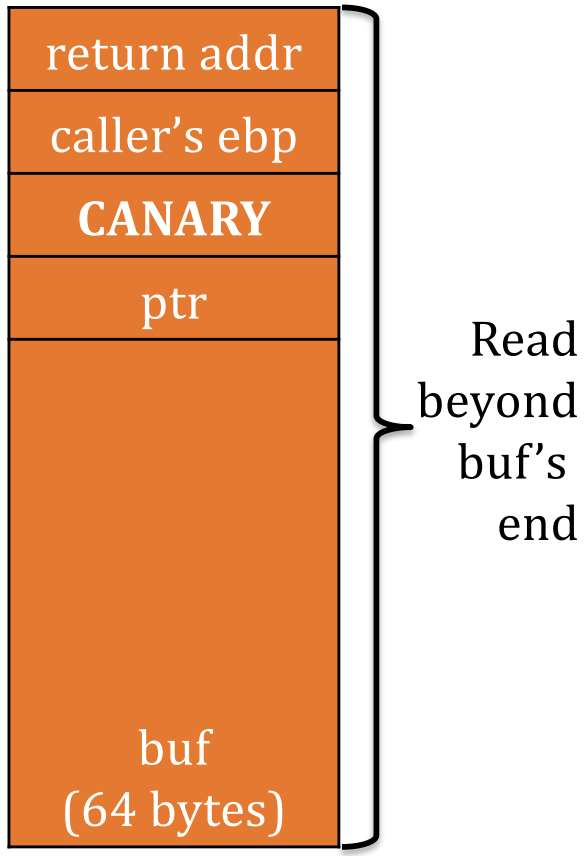
```
int *ptr;
char buf[64];
n = strlen(user1);
memcpy(buf, user1, n);
*ptr = user2;
```



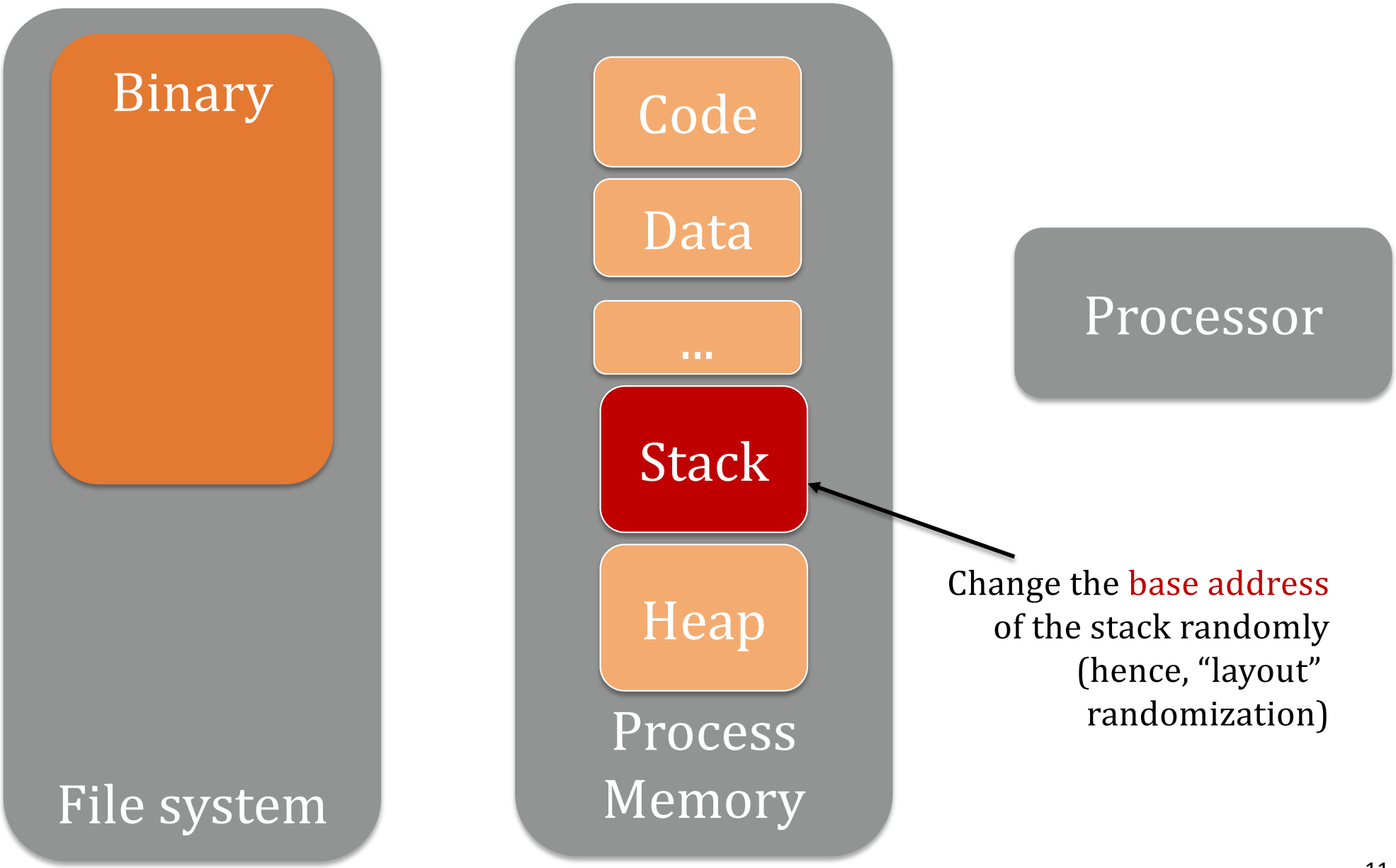
Bypass: Buffer Over-Read (Disclosure)

Read beyond the end of buf to find the canary value

```
char user1[user2];
char buf[64];
memcpy(user1, buf, user2);
printf(”%s”, user1);
```



Address Space Layout Randomization



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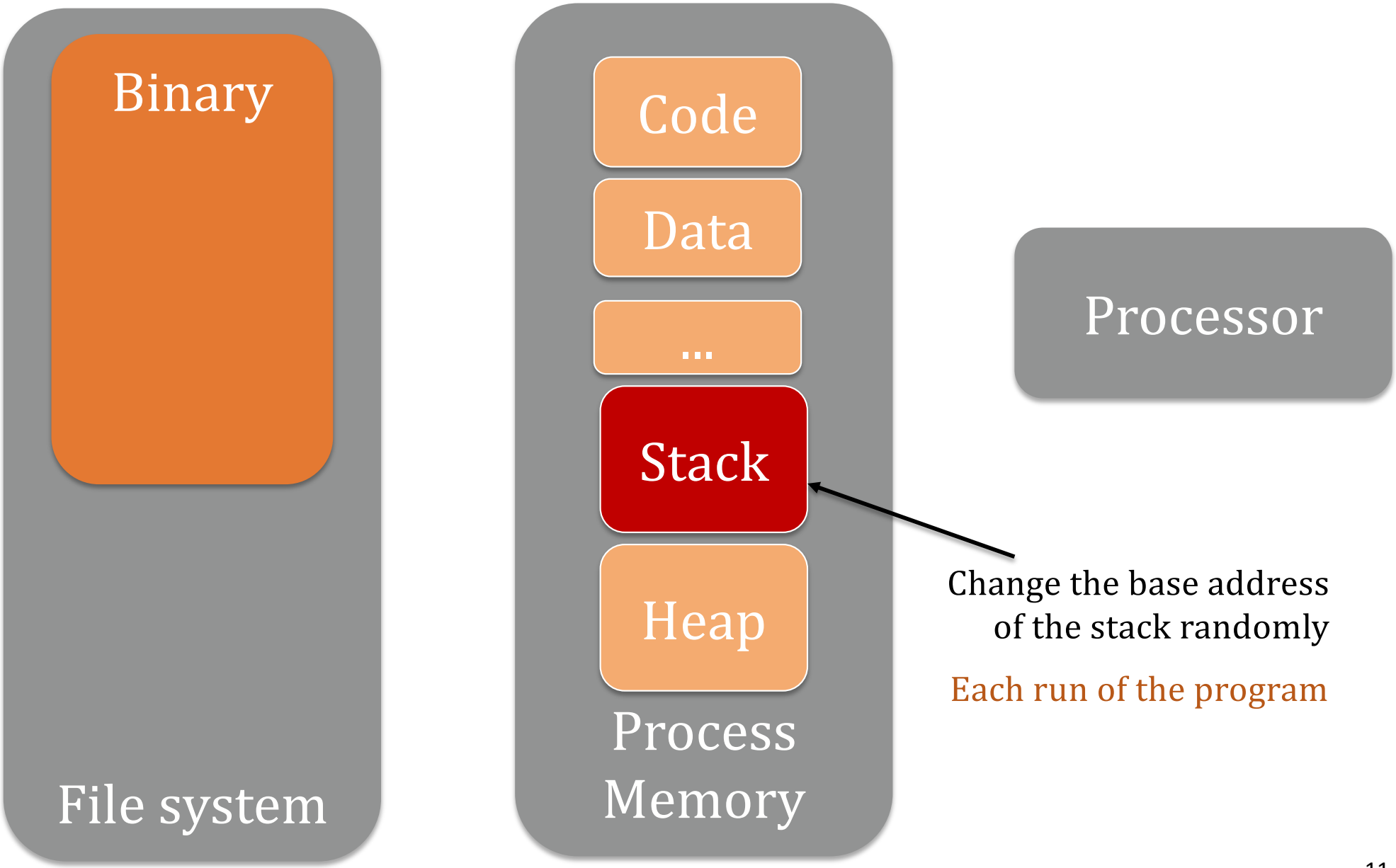
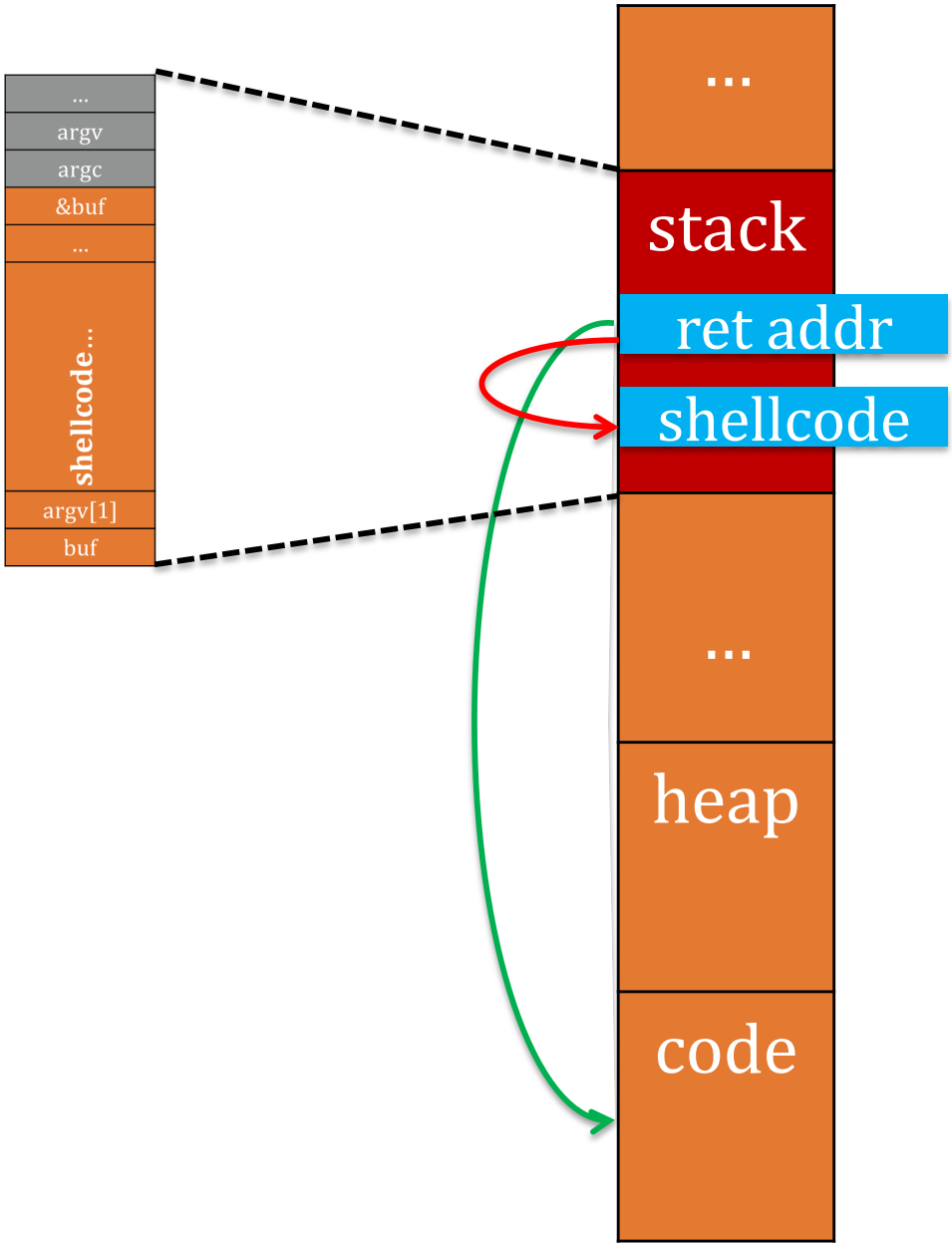


Thwarts Finding Shellcode



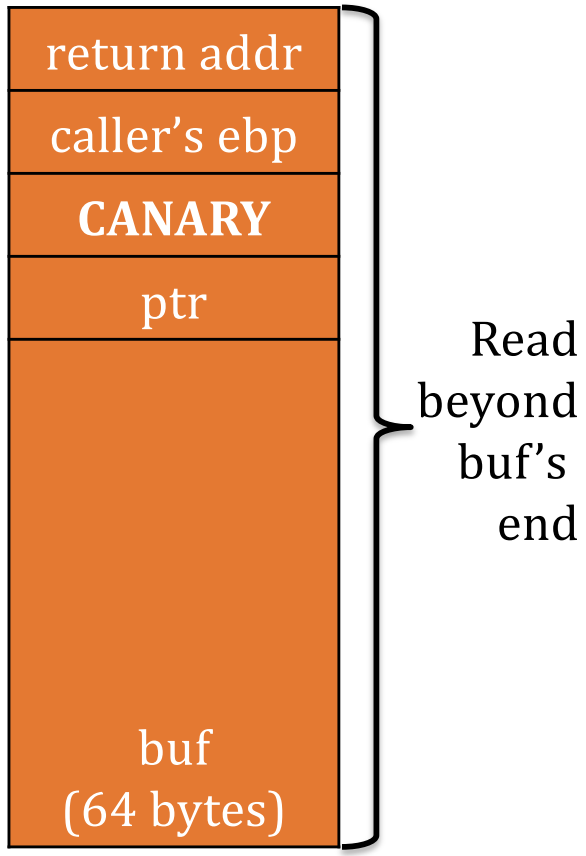
ASLR Scorecard

Aspect	ASLR
Performance	• few instructions when allocating stack • time: very little overhead • size: use more space for stack, but not that large in general (and 64-bit addrs)
Deployment	• recompile suffices; no code change
Compatibility	• perfect—invisible to outside
Safety Guarantee	• *not really…*

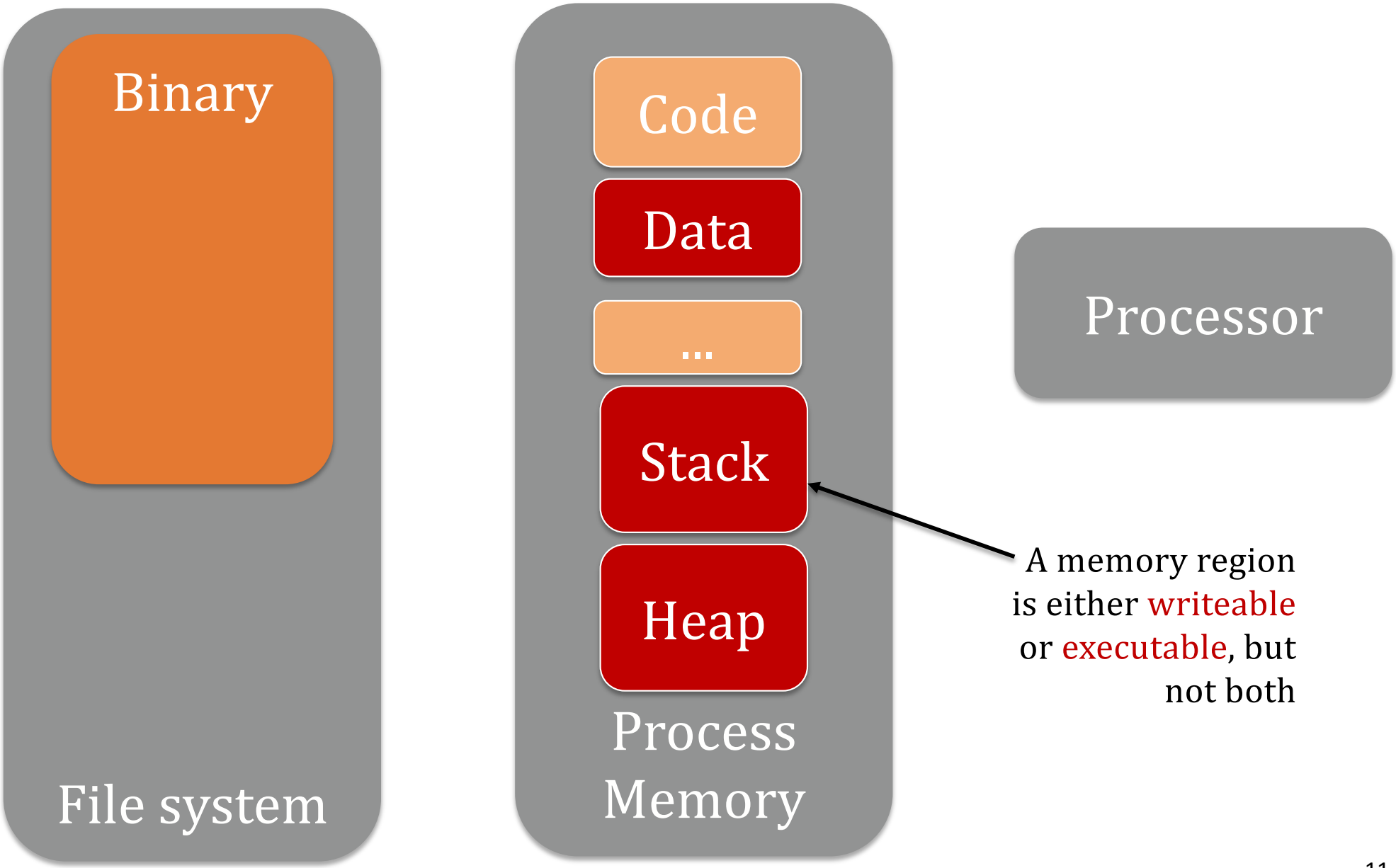
Bypass: Disclose Stack Pointer

Overread to read stack addresses to determine base address

```
char user1[user2];
char buf[64];
memcpy(user1, buf, user2);
offset = &user1[64]-expect;
```



Data Execution Protection



DEP Scorecard

Aspect	DEP
Performance	• already check page permissions • time: essentially none • size: one bit per page in page table
Deployment	• recompile suffices; no code change
Compatibility	• perfect—invisible to outside
Safety Guarantee	• *Better, but…*

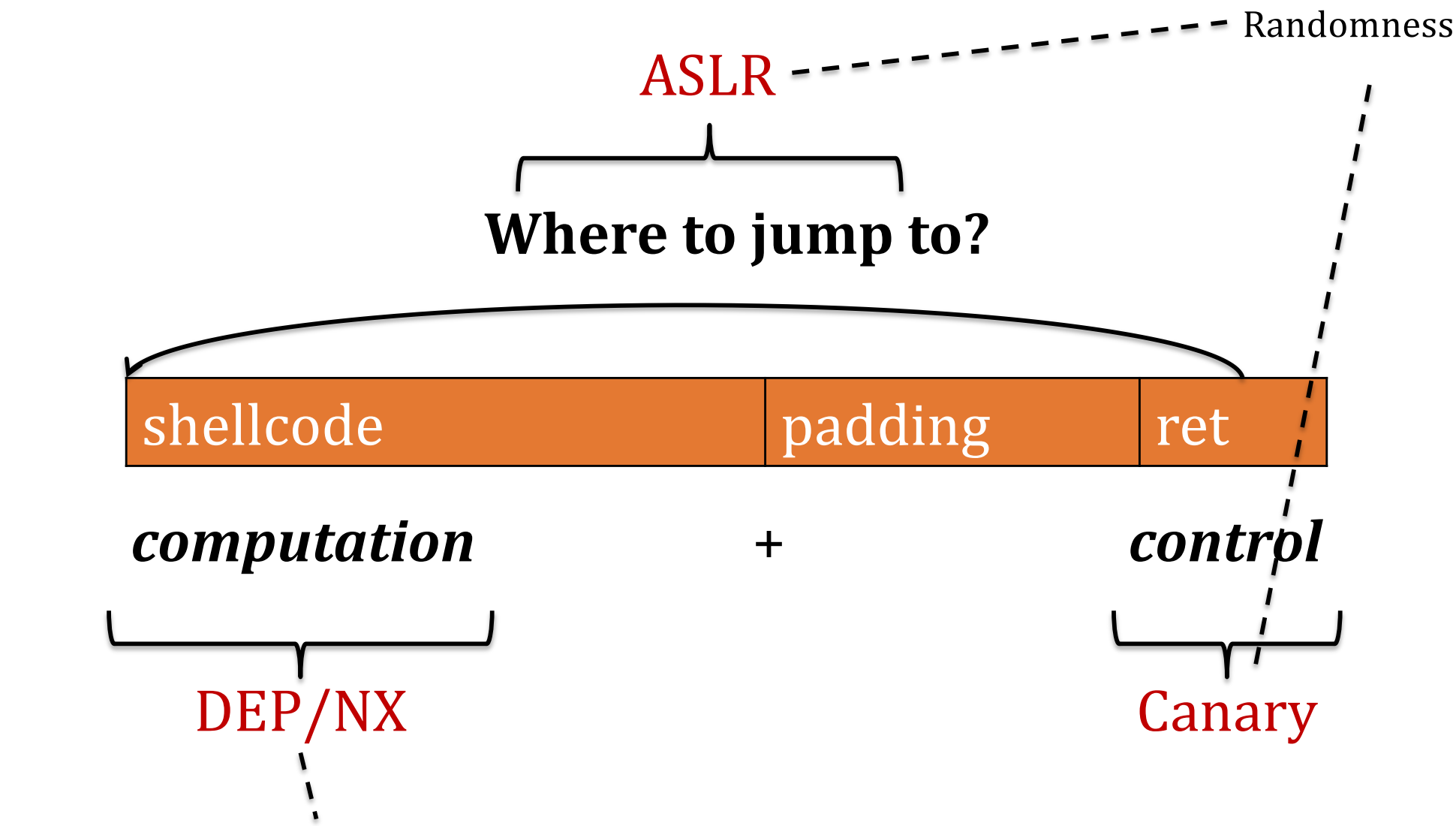
Disable DEP

- Can disable DEP
  - There's a system call to change page protections

```
int mprotect(void *addr, size_t len, int prot);
```

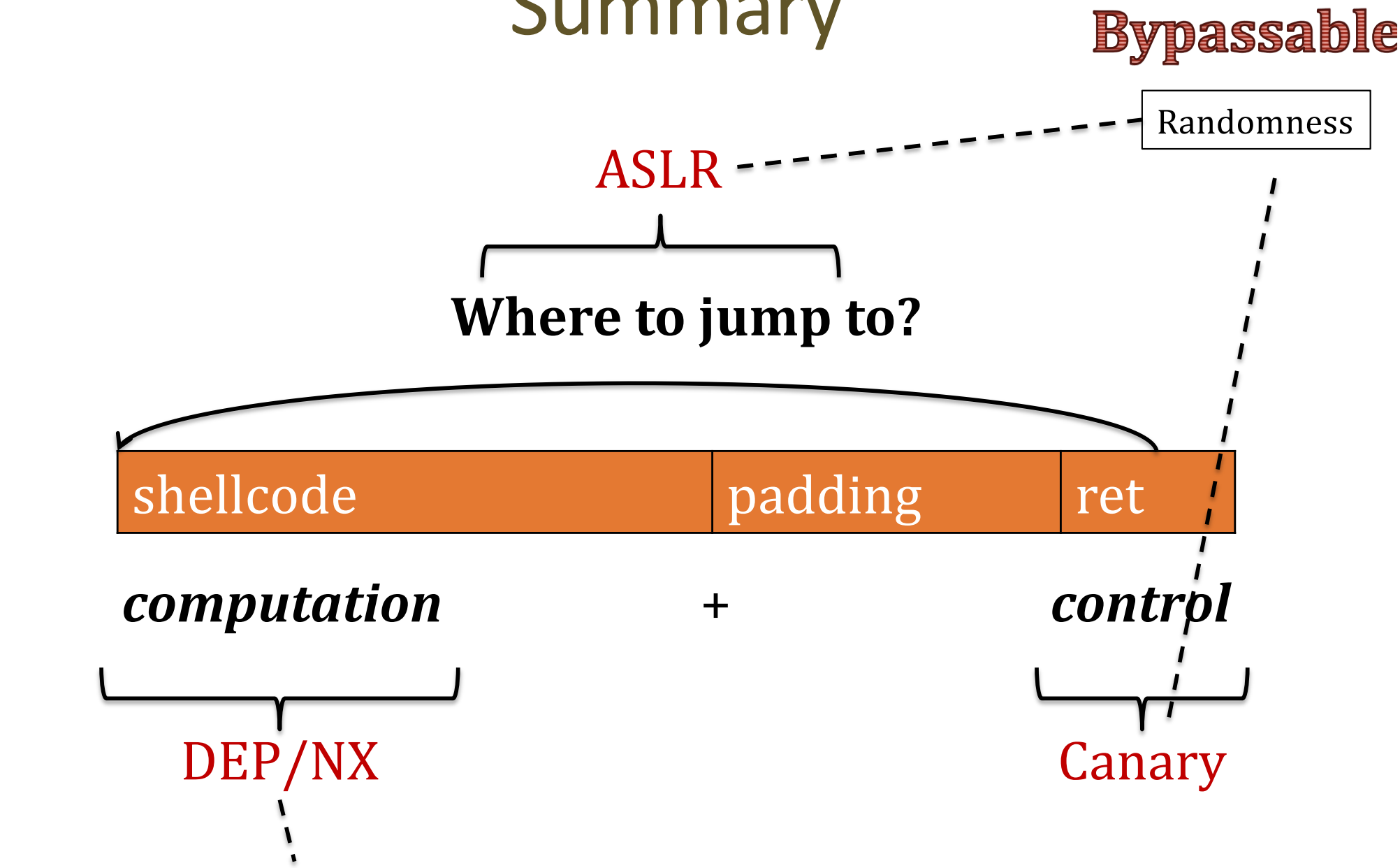
  - Sets protection for region of memory starting at address
  - Invoke this system call to allow execution on stack and then start executing from the injected code
- But, need to get shellcode running to do this

Summary



Eliminating “Mixing of data and code”

Summary



Eliminating "Mixing of data and code"

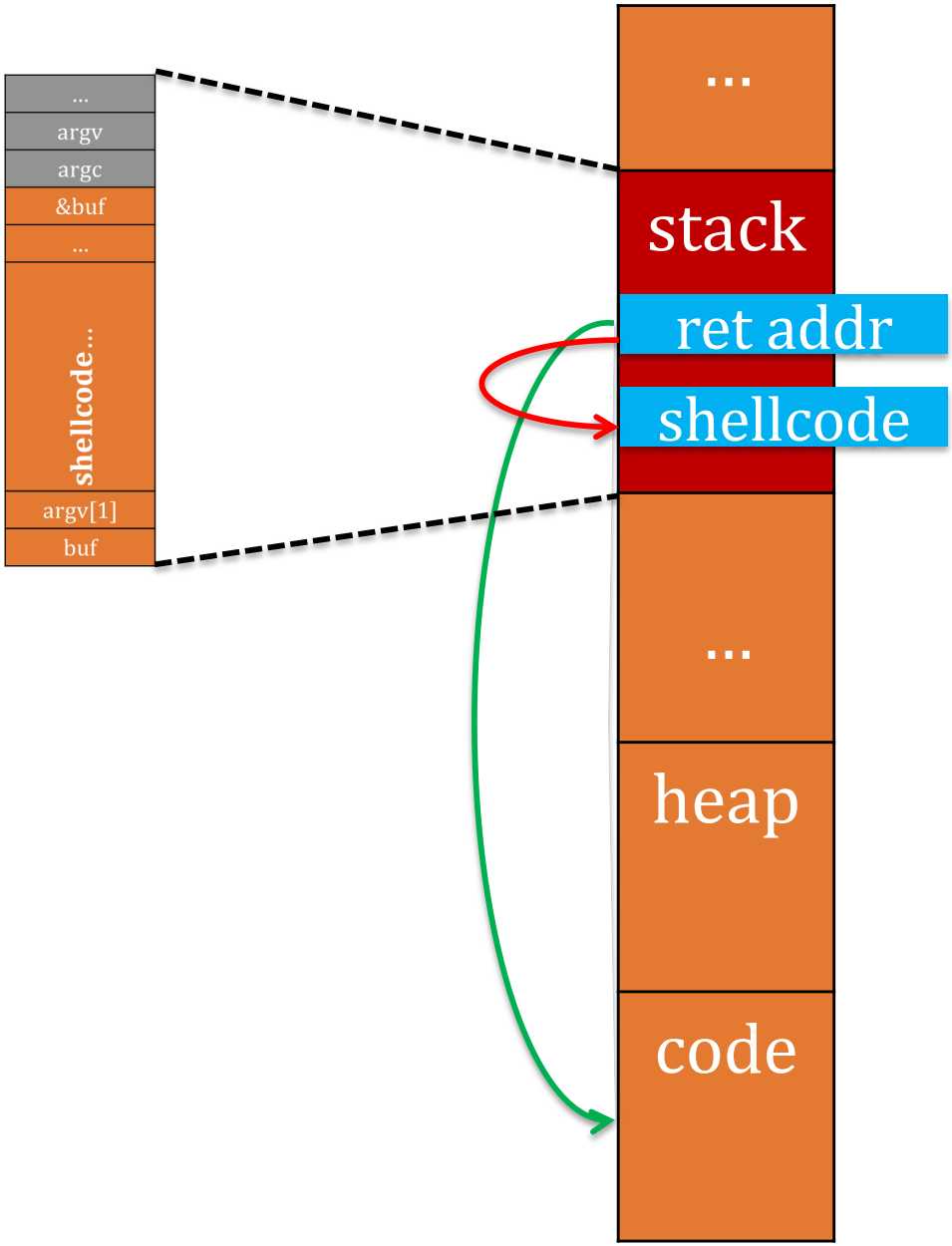
Agenda

ROP Overview

Gadgets

Disassembling code

Thwarts Finding Shellcode



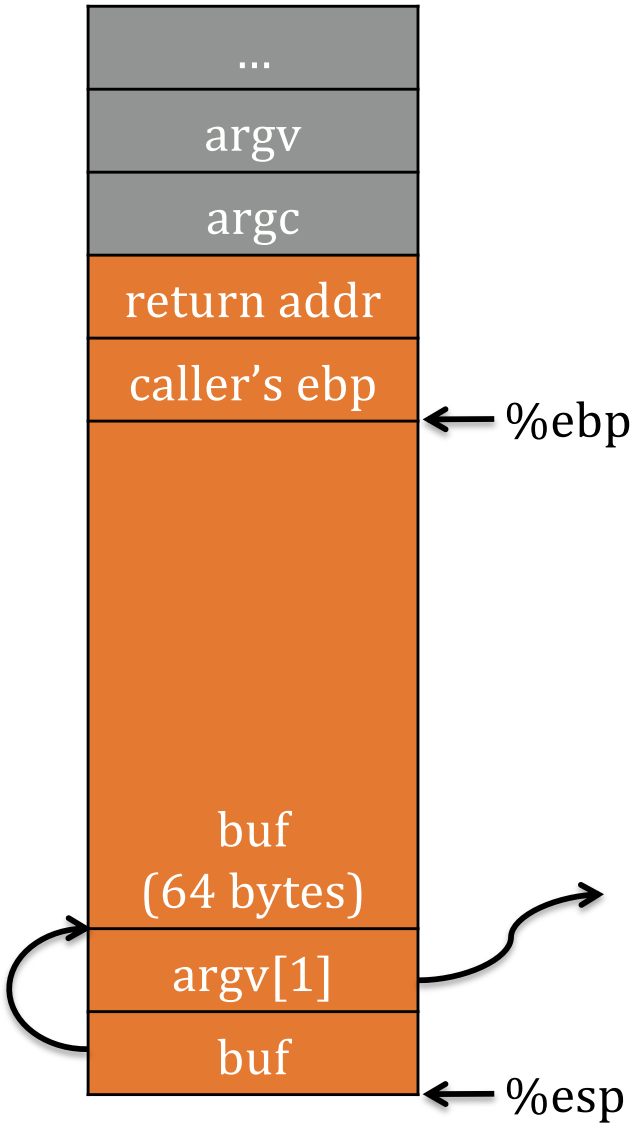
Motivation: Return-to-libc Attack

Bypassing DEP!

Overwrite return address with address of libc function

- setup fake return address and argument(s)
- `ret` will "call" libc function

No injected code!



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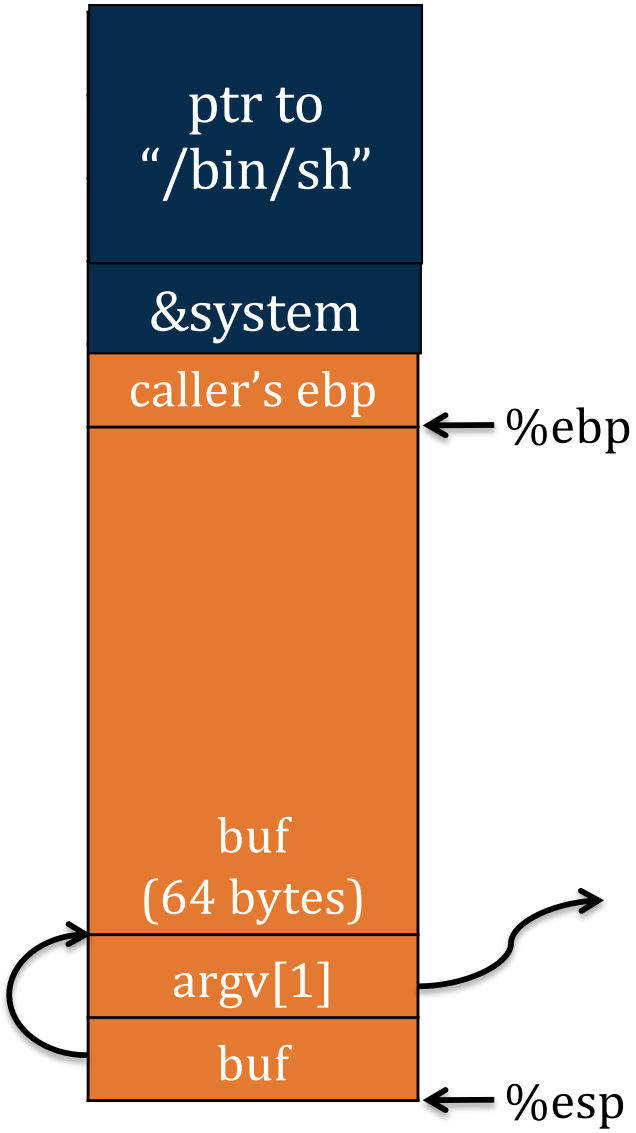
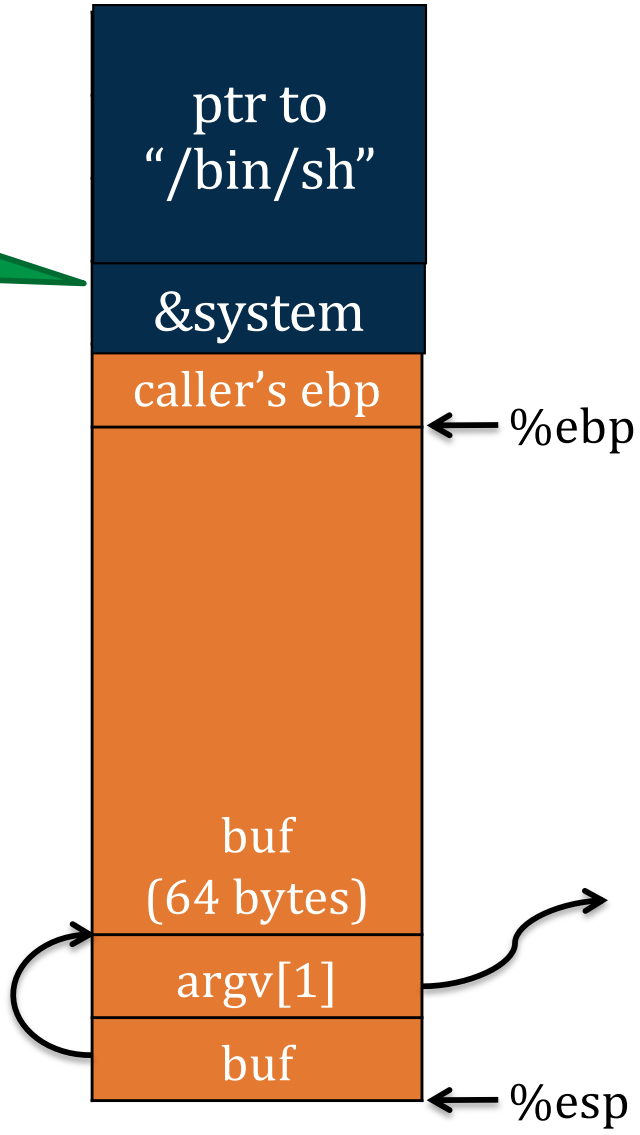


Motivation: Return-to-libc Attack

ret transfers control to `system`, which finds arguments on stack



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No injected code!

Return Oriented Programming Techniques

Geometry of Innocent Flesh on the Bone

Shacham et al, ACM CCS 2007

The New Yo

Saturday, January 6, 2007

Daily Blog Tips awarded the

Last week Darren Rowse, from the famous Problogger blog, announced the winners of his latest Group Writing Project called "Reviews and Predictions". Among the Daily Blog Tips is attracting a vast audience of bloggers who are looking to improve their blogs. When asked about the success of his blog Daniel commented that

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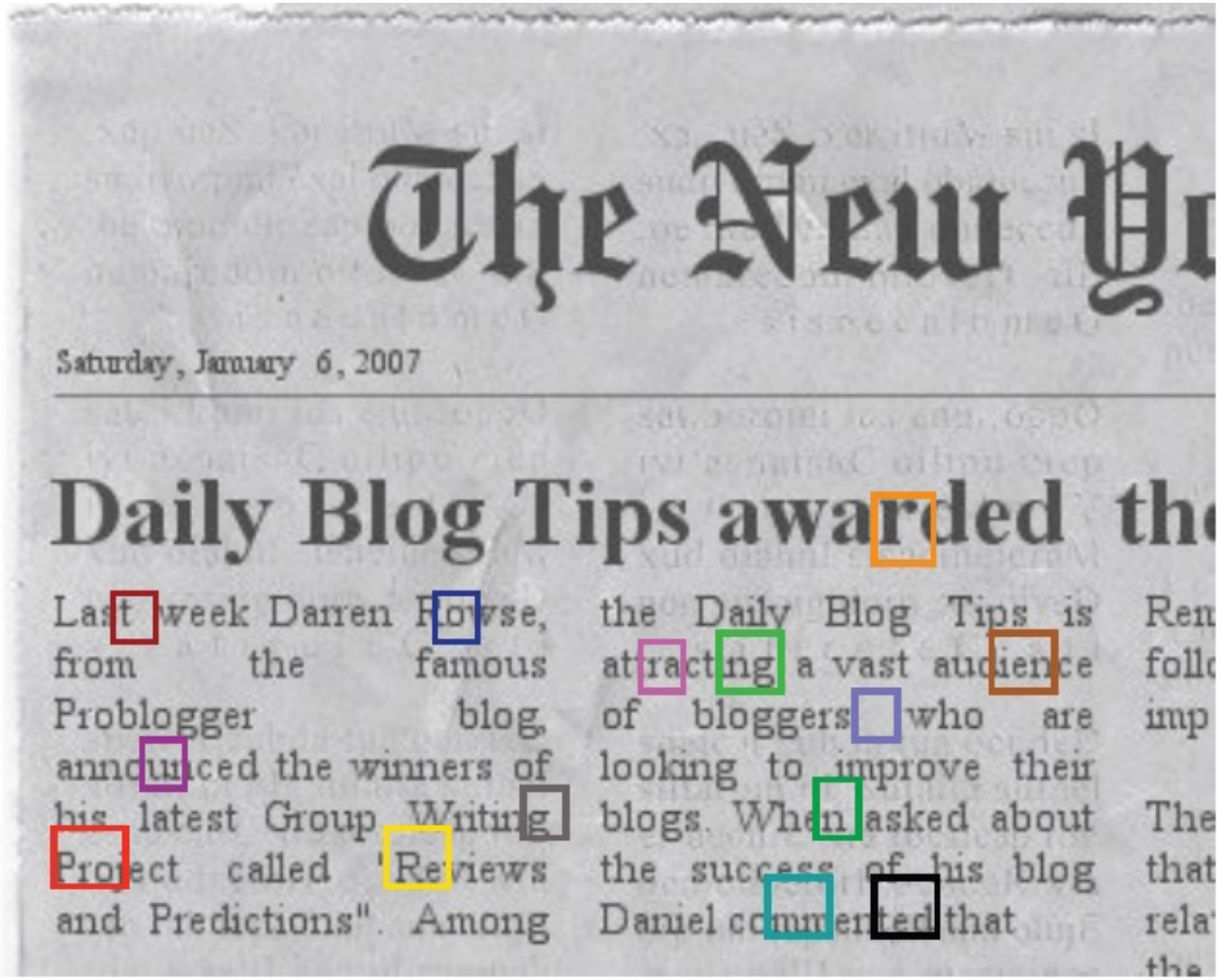

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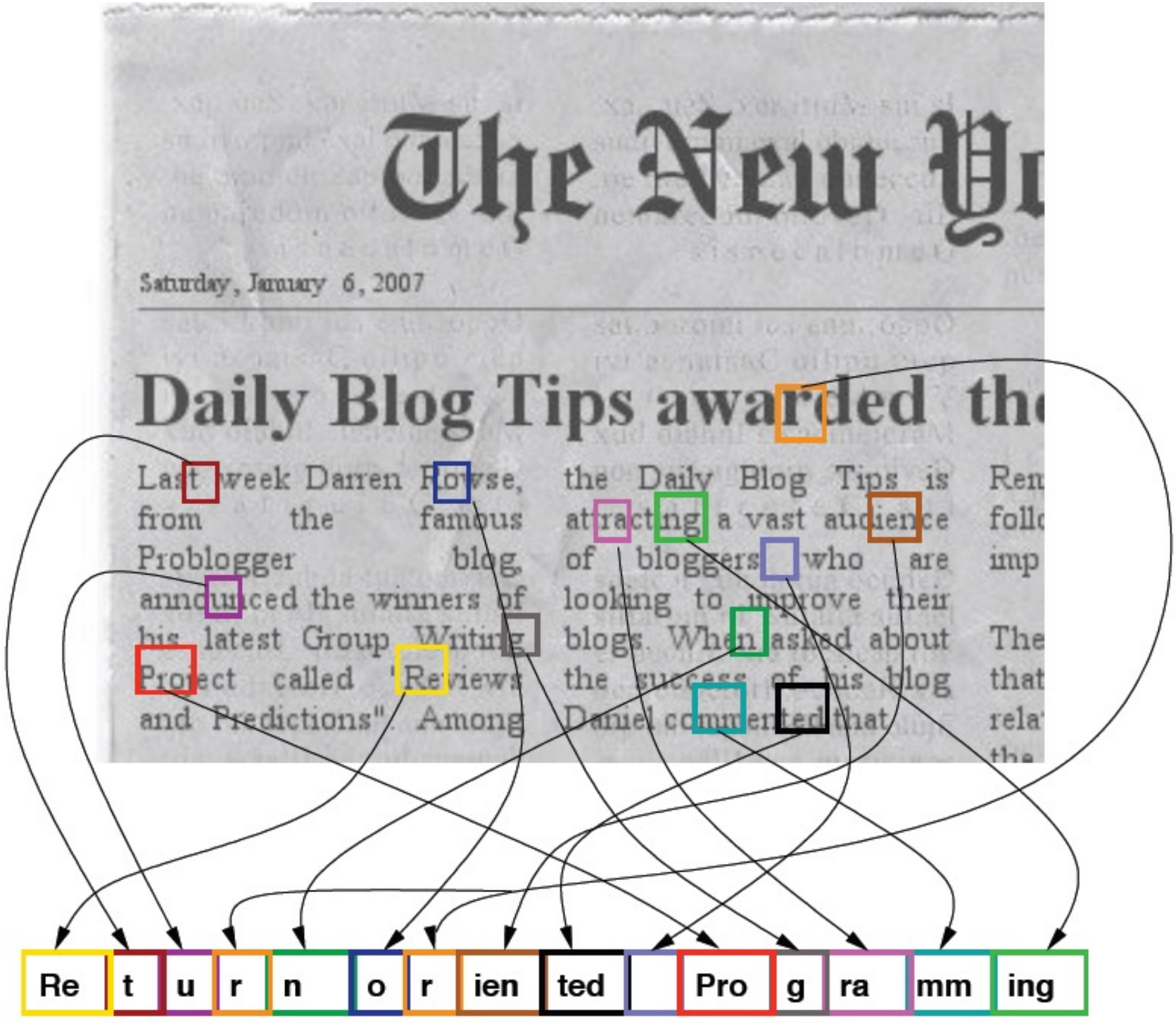
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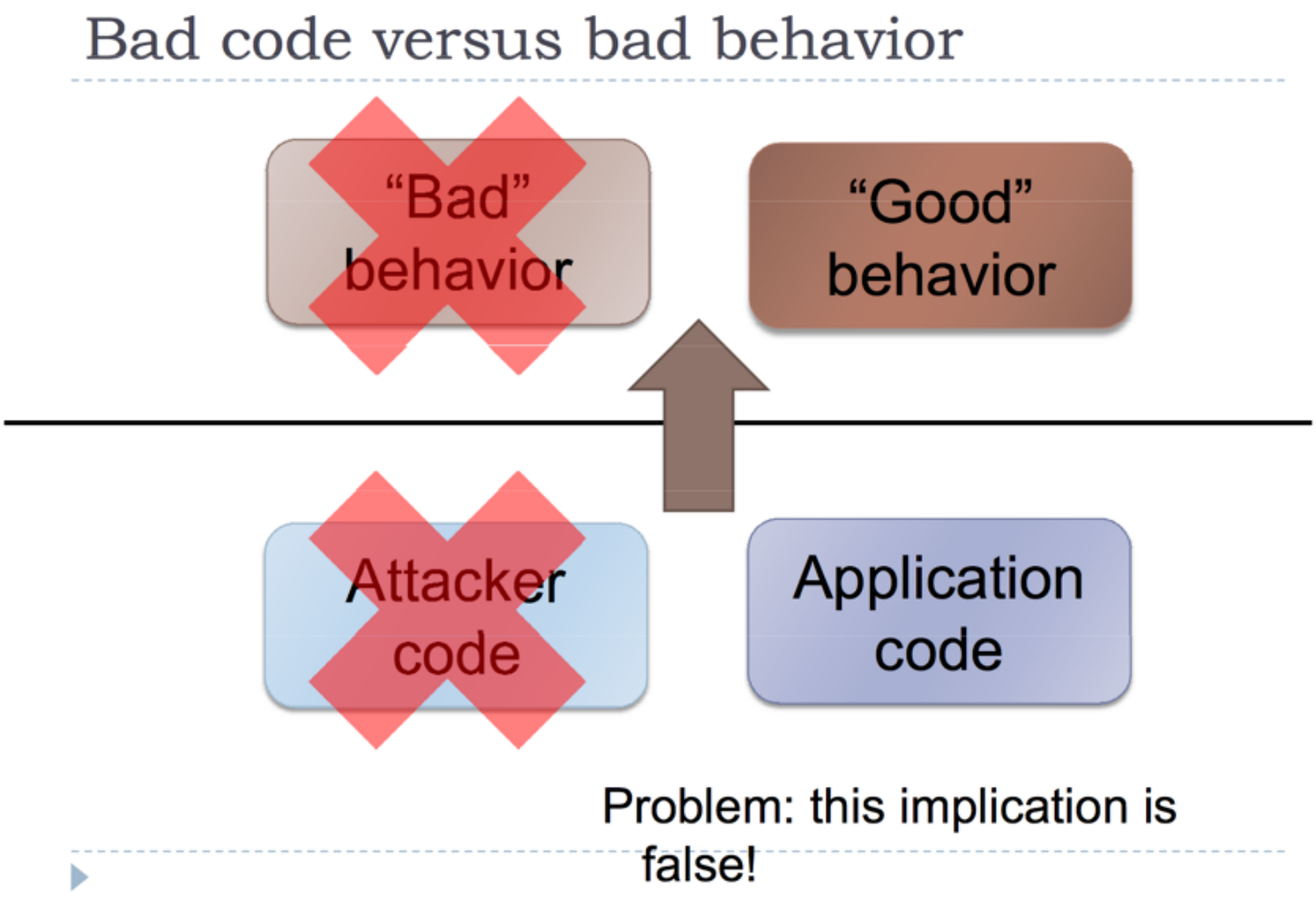
ROP Programming



ROP Programming

attacker control of stack

arbitrary attacker computation and behavior
via return-into-libc techniques

(given any sufficiently large codebase to draw on)

ROP Programming: Key Steps

1. Disassemble code
2. Identify *useful* code sequences as gadgets
3. Assemble gadgets into desired shellcode

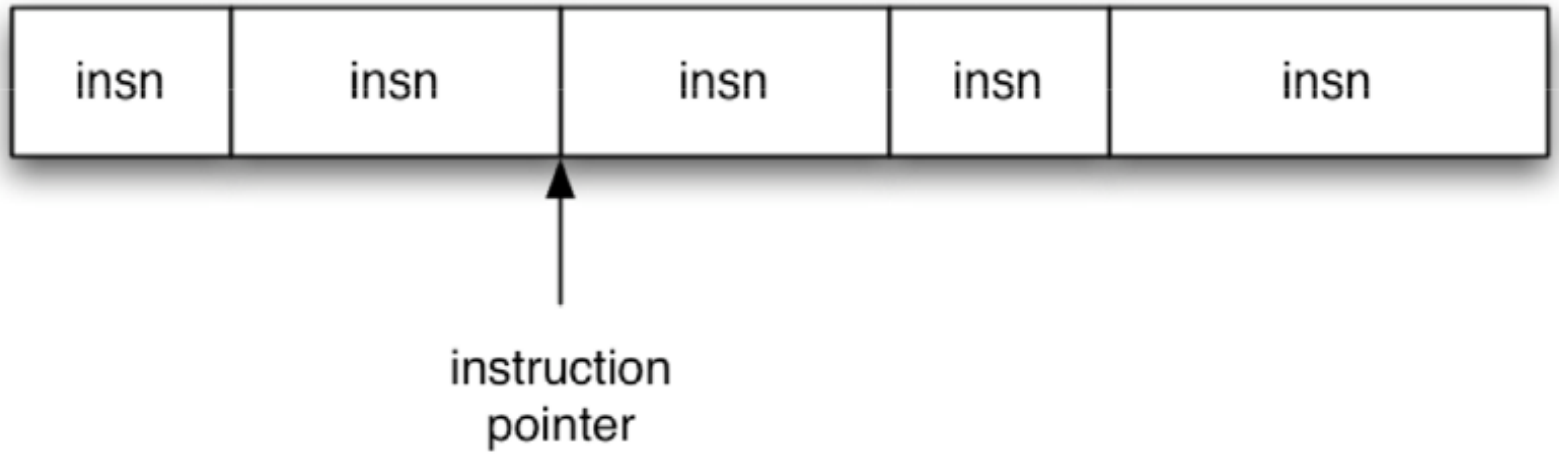
Agenda

ROP Overview

Gadgets

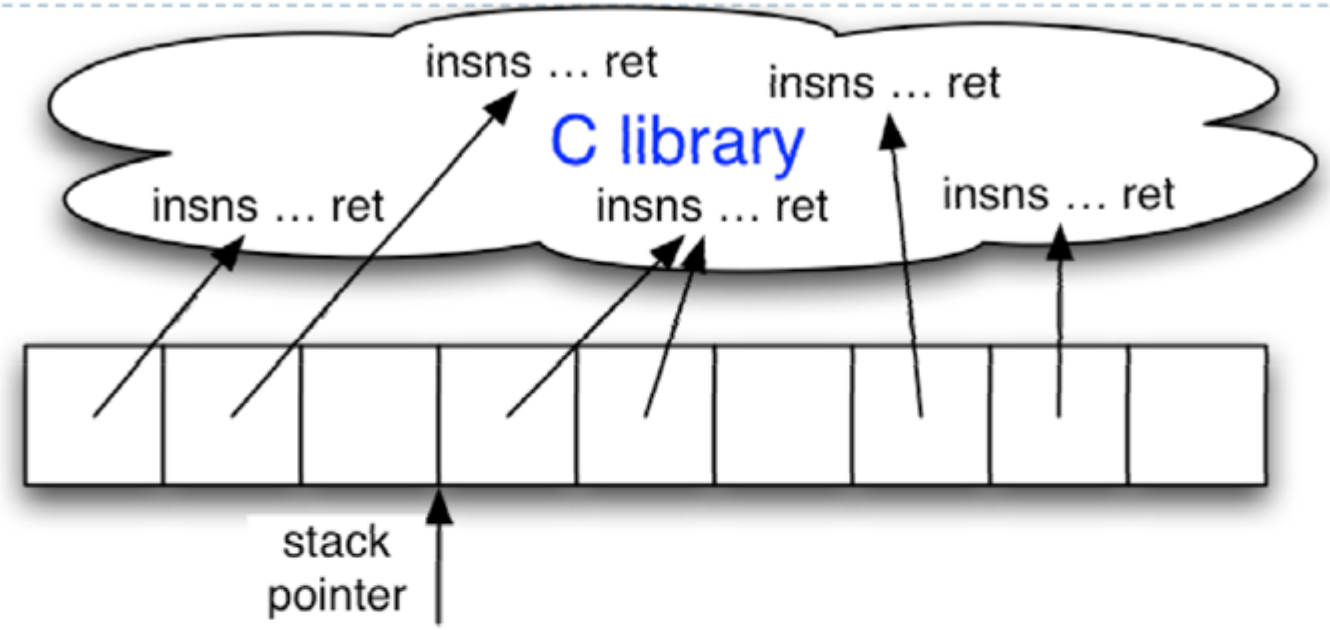
Disassembling code

Normal Execution



- The instruction pointer (%eip) determines which instruction to fetch and execute
- Once an instruction has executed, the processor automatically increments %eip to the next instruction

ROP Execution (On the Stack)

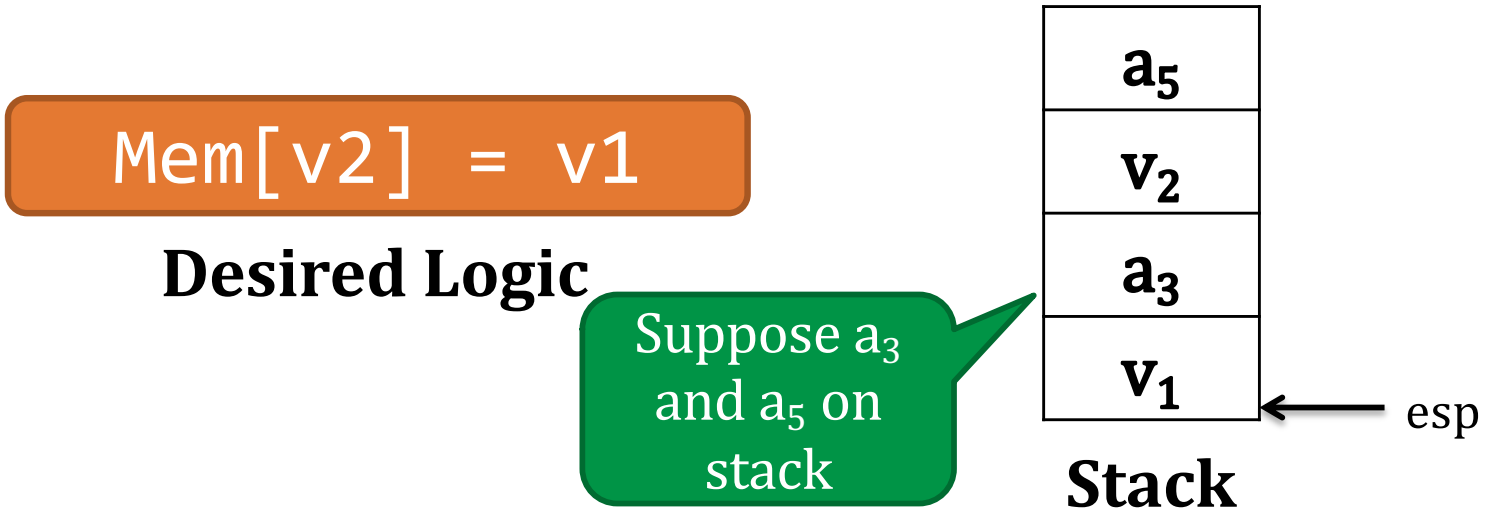


- The stack pointer (%esp) determines which instruction sequence to fetch and execute
- Once a sequence returns (executes ”ret”), the processor increments %esp to the next instruction sequence

Gadgets

A gadget is any instruction sequence ending with `ret`

Gadgets



eax	
ebx	
eip	a_1

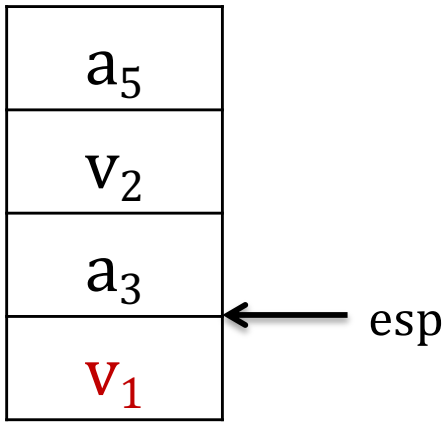
Suppose ret address was set to a_1

```
a1: pop eax;
    ret
a3: pop ebx;
    ret
a5: mov [ebx], eax
    ret
```

Gadgets

```
Mem[v2] = v1
```

Desired Logic



Stack

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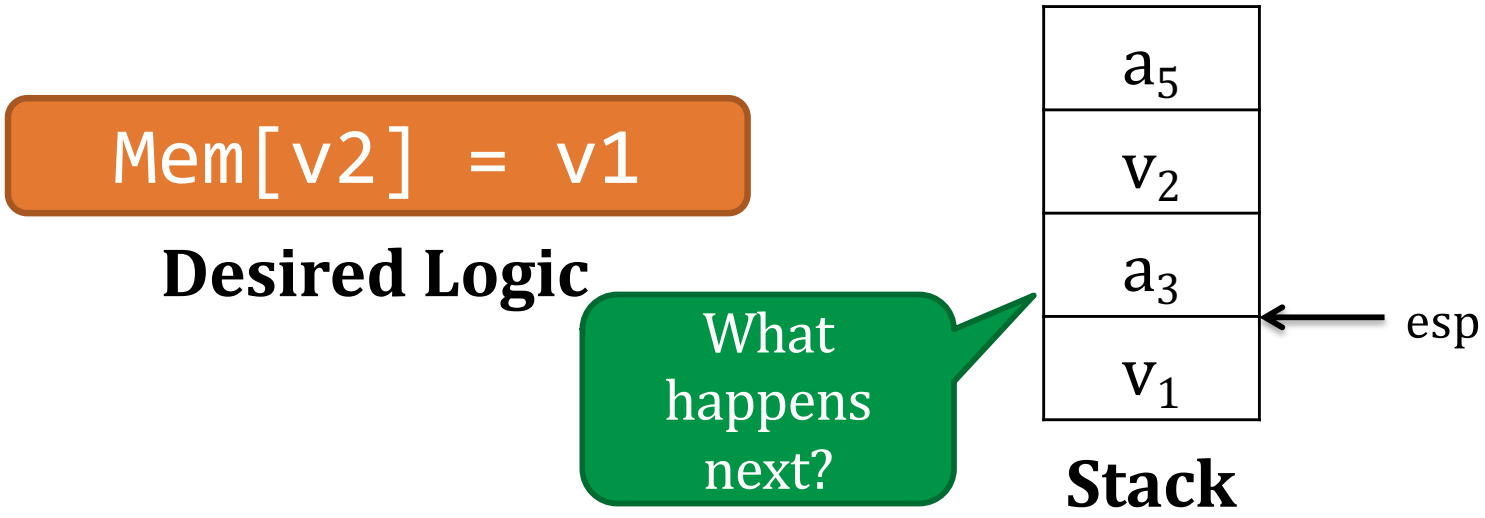

eax	v_1
ebx	
eip	a_2

```
a1: pop eax;
a2: ret
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```

Gadgets

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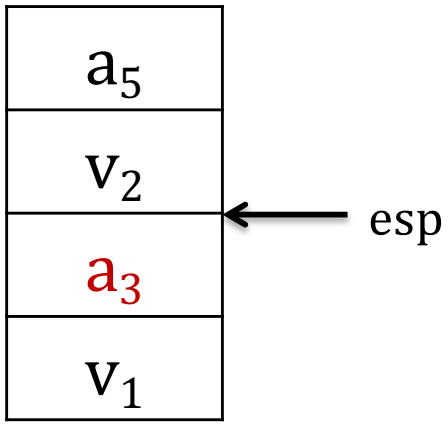

Stack

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ebx	
eip	a_3

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Gadgets

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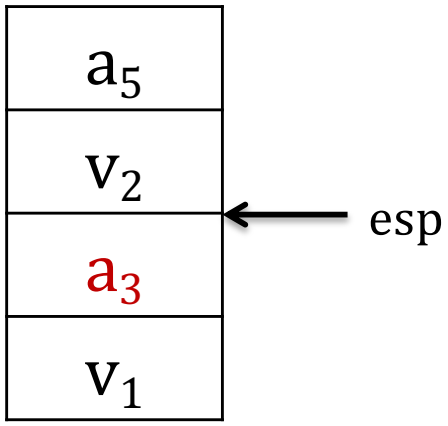

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Gadgets

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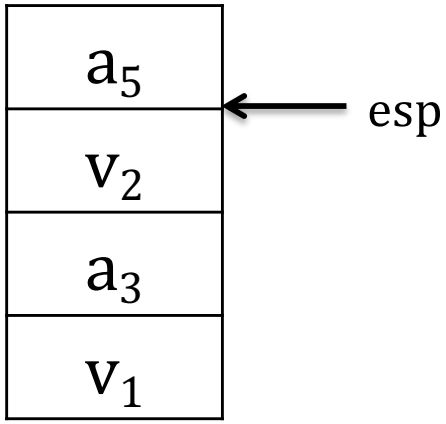

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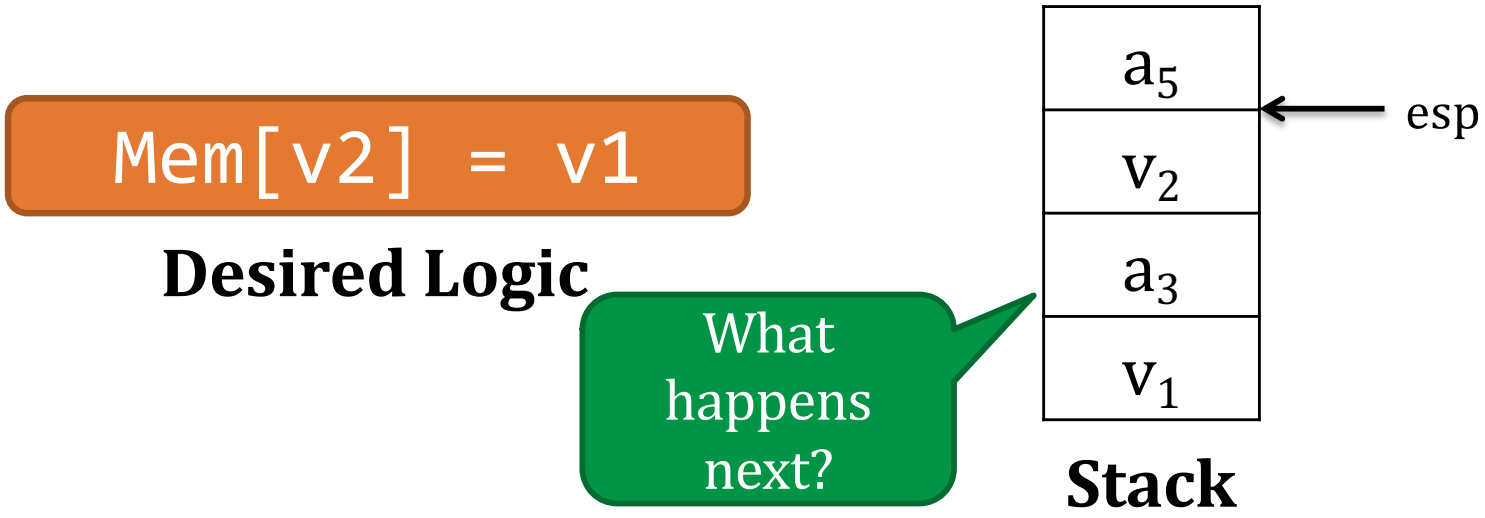

eax	v_1
ebx	v_2
eip	a_4

```
a1: pop eax;
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a4: ret
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    ret
```
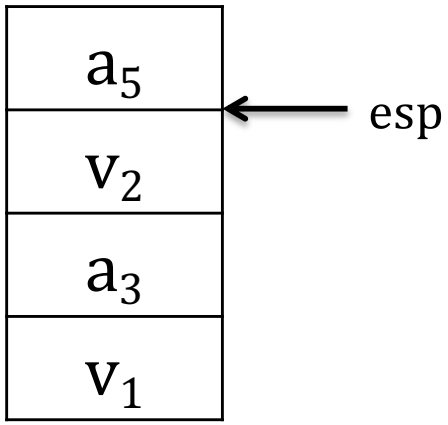

Gadgets

`Mem[v2] = v1`

Desired Logic



Stack

eax	v_1
ebx	v_2
eip	a_5

```
a1: pop eax;
    ret
a3: pop ebx;
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a5: mov [ebx], eax
    ret
```
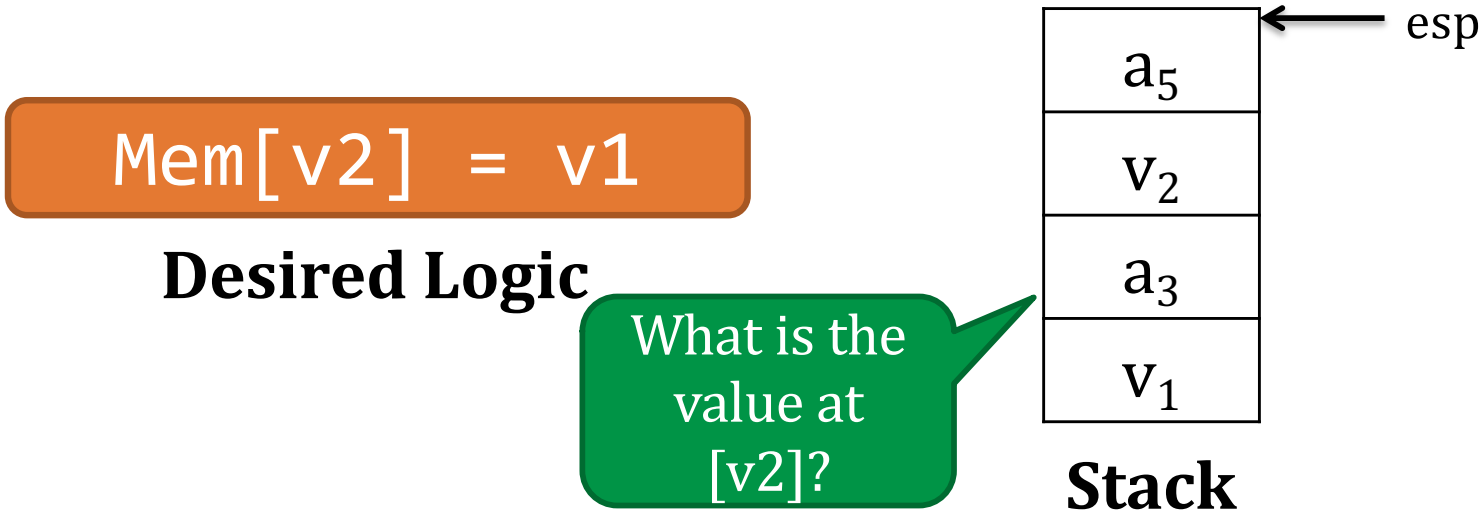

Gadgets



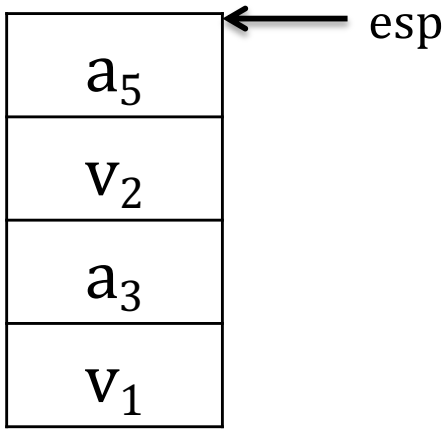
eax	v_1
ebx	v_2
eip	a_5

```
a1: pop eax;
    ret
a3: pop ebx;
    ret
a5: mov [ebx], eax
    ret
```

Gadgets

`Mem[v2] = v1`

Desired Logic



Stack

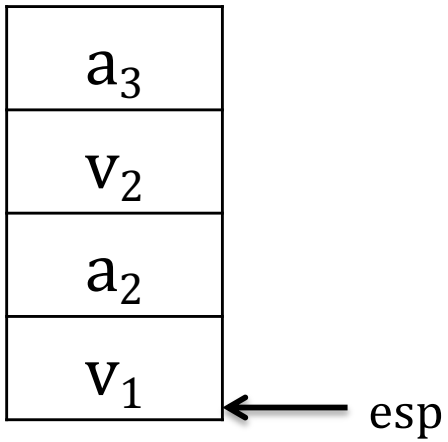
eax	v_1
ebx	v_2
eip	a_5

```
a1: pop eax;
    ret
a3: pop ebx;
    ret
a5: mov [ebx], eax
    ret
```

Equivalence

```
Mem[v2] = v1
```

Desired Logic



Stack

"Gadgets"

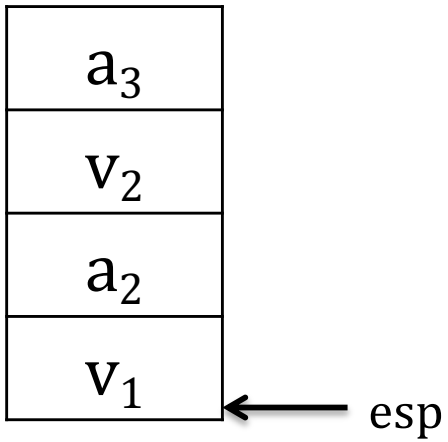
```
a1: pop eax; ret
a2: pop ebx; ret
a3: mov [ebx], eax; ret
```

Implementation 2

Equivalence

```
Mem[v2] = v1
```

Desired Logic



Stack

semantically equivalent

"Gadgets"

```
a1: mov eax, [esp]; ret      <-->  a1: pop eax; ret
a2: mov ebx, [esp+8]; ret    <-->  a2: pop ebx; ret
a3: mov [ebx], eax; ret      <-->  a3: mov [ebx], eax; ret
```

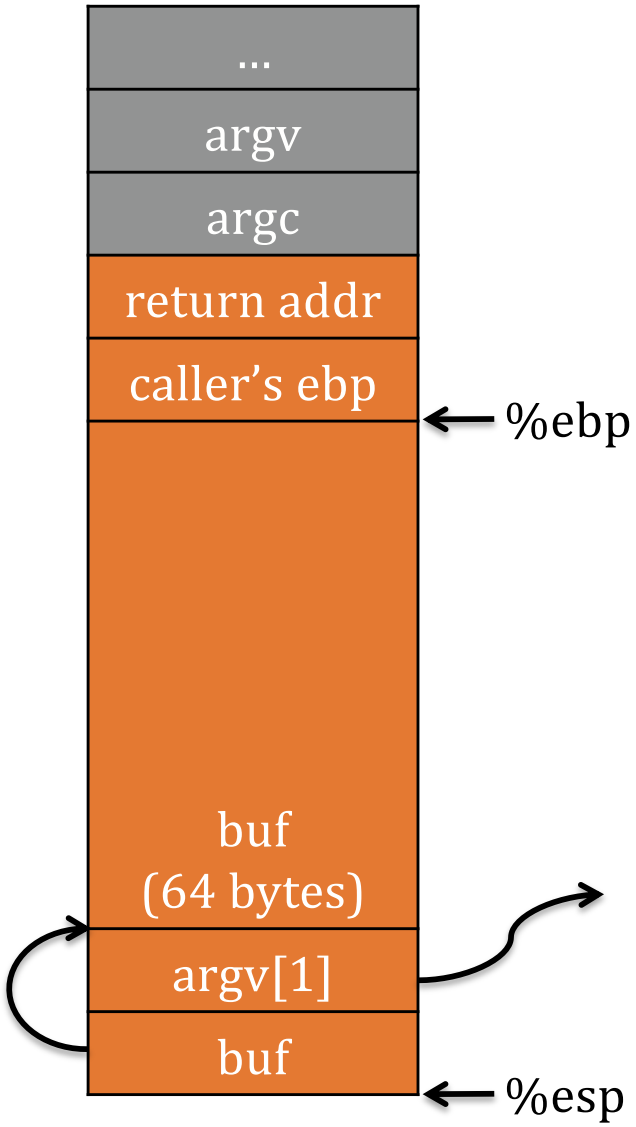
Implementation 1 **Implementation 2**

Return-Oriented Programming (ROP)

```
Mem[v2] = v1
```

Desired *Shellcode*

- Find needed instruction gadgets at addresses a_1, a_2, and a_3 in *existing* code
- Overwrite stack to execute a_1, a_2, and then a_3

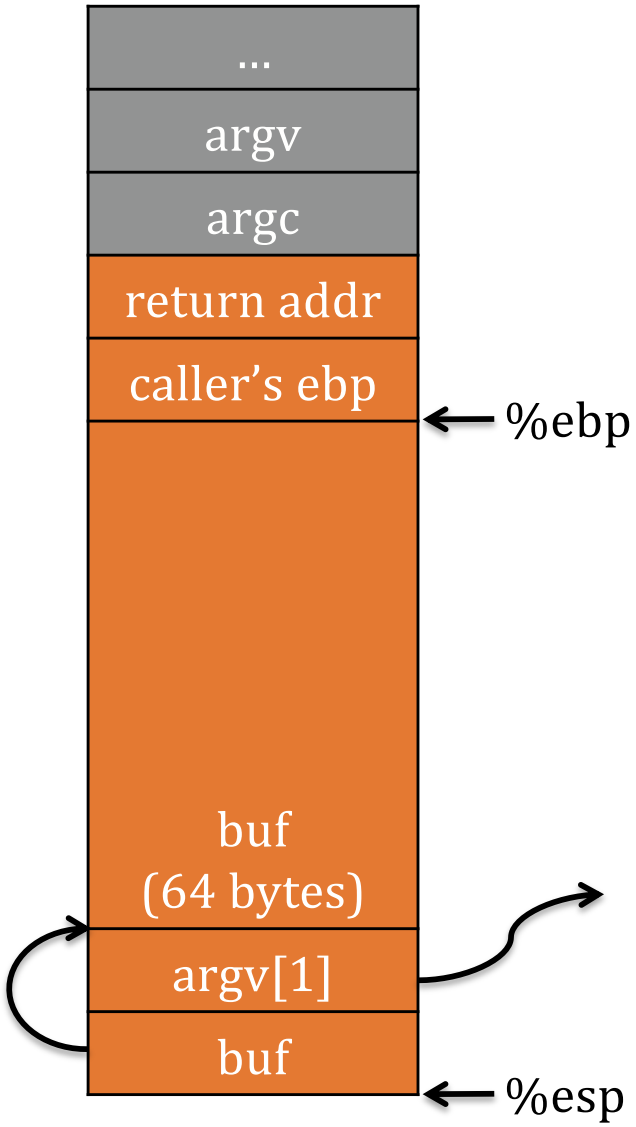


Return-Oriented Programming (ROP)

```
Mem[v2] = v1
```

Desired *Shellcode*

```
a1: pop eax; ret
a2: pop ebx; ret
a3: mov [ebx], eax; ret
```

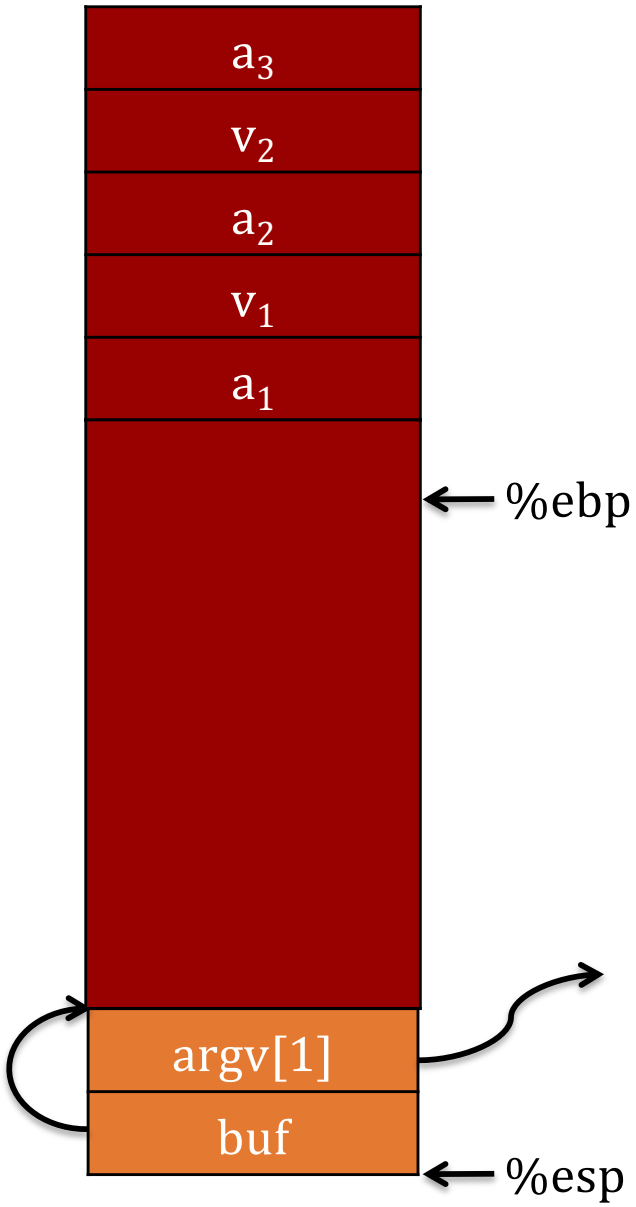


Return-Oriented Programming (ROP)

```
Mem[v2] = v1
```

Desired *Shellcode*

```
a1: pop eax; ret
a2: pop ebx; ret
a3: mov [ebx], eax; ret
```



Return-Oriented Programming (ROP)

`Mem[v2] = v1`

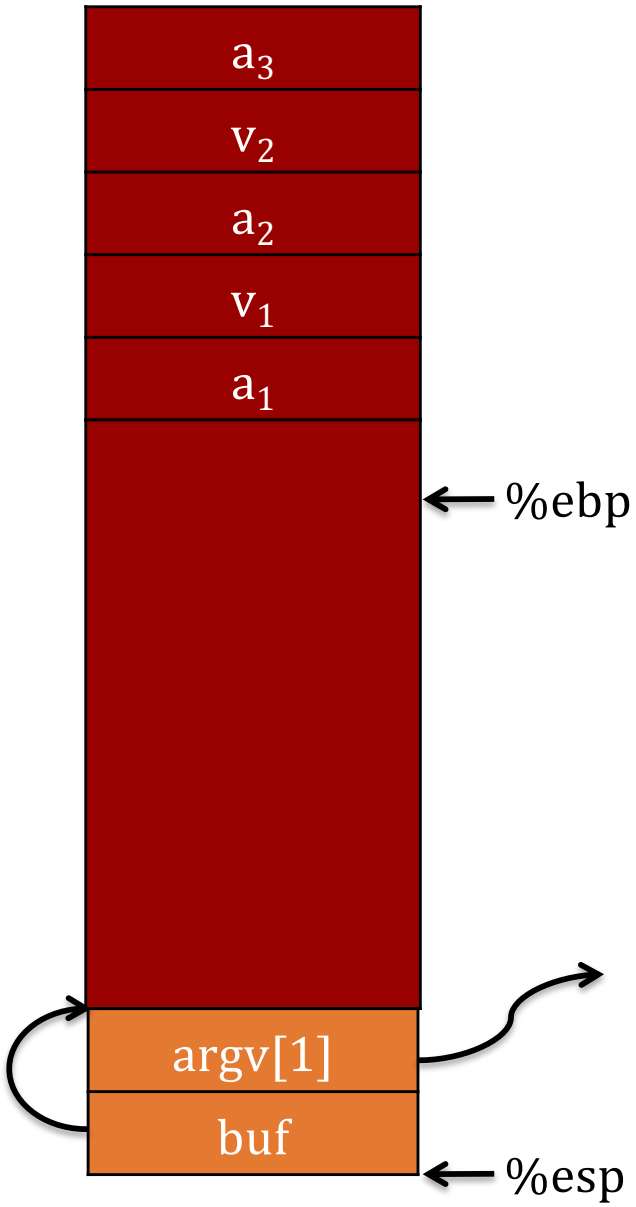
Desired *Shellcode*

a_1: `pop eax; ret`

a_2: `pop ebx; ret`

a_3: `mov [ebx], eax; ret`

Desired store executed!



Finding Gadgets

- How do we build a complete exploit from available code?
  - Must find gadgets in that code
- How do you think one finds ***all*** the gadgets in a code region?

Finding Gadgets

- How do we build a complete exploit from available code?
  - Must find gadgets in that code
- How do you think one finds ***all*** the gadgets in a code region?
  - Find sequence of instructions until a ”ret” is reached
    - Find “a, b, c, ret” – where a, b, and c are other instructions

Finding Gadgets

- How do we build a complete exploit from available code?
  - Must find the gadgets that are available in that code
- How do you think one finds ***all*** the gadgets in a code region?
  - Start from a "ret" byte "0xc3" at any memory location and work backwards to find the longest useful sequence of instructions for a gadget
    - Find "a, b, c, ret" – find "c, ret", then "b, c, ret", then…

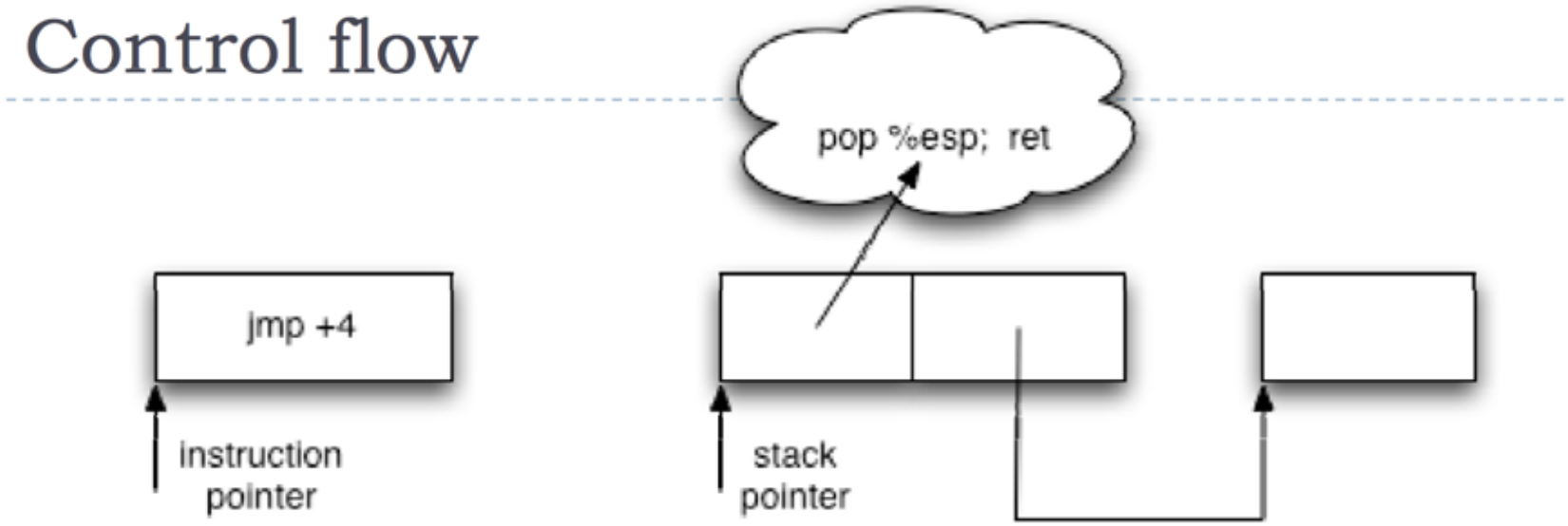
Expressability

- What can we do with return-oriented programming?
  - Anything any other program can do
  - How do we know?

Expressability

- What can we do with return-oriented programming?
  - Anything any other program can do
  - How do we know? Turing completeness
- A language is Turing complete if it has (loosely)
  - Conditional branching
  - Can change memory arbitrarily
- Both are possible with ROP

Expressability



- Cause a control flow change by popping a value from the stack into %esp
  - Executing from that location going forward

Conclusions

- New defenses make code injection impractical
  - Especially DEP/NX (e.g., non-executable stack)
- Another attack option for adversaries
  - Return-oriented programming: Use the code that is already there rather than injecting new code
- If there is enough code, ROP is just as powerful as code injection attacks
  - Turing complete computation
- More defenses are needed (later)

Quiz

```
void foo(char *input){
    char buf[512];
    ...
    strcpy (buf, input);
    return;
}
```

Draw a stack diagram for a ROP exploit to **pop a value 0xBBBBBBBB into eax and add 80.**

a_1: add eax, 0x80; pop ebp; ret

a_2: pop eax; ret

Known Gadgets

Quiz

```
void foo(char *input){
    char buf[512];
    ...
    strcpy (buf, input);
    return;
}
```

Draw a stack diagram for a ROP exploit to **pop a value 0xBBBBBBBB into eax and add 80.**

a_1: add eax, 0x80; pop ebp; ret

a_2: pop eax; ret

Stack: a_2; 0xBBBBBBBB; a_1

Known Gadgets

Quiz

a_1: pop ebx; ret

a_2: pop eax; ret

a_3: mov eax, (ebx); ret

a_4: mov ebx, (eax); ret

a_5: add eax, (ebx); ret

a_6: push ebx; ret

a_7: pop esp; ret

Known Gadgets

Draw a stack diagram for a ROP exploit to **store the value `0xBBBBBBB` into address `0xAAAAAAA`.**

Quiz

a_1: pop ebx; ret

a_2: pop eax; ret

a_3: mov eax, (ebx); ret

a_4: mov ebx, (eax); ret

a_5: add eax, (ebx); ret

a_6: push ebx; ret

a_7: pop esp; ret

Known Gadgets

Draw a stack diagram for a ROP exploit to **store the value `0xBBBBBBB+1` into address `0xAAAAAAA`**

Quiz

a_1: pop ebx; ret

a_2: pop eax; ret

a_3: mov eax, (ebx); ret

a_4: mov ebx, (eax); ret

a_5: add eax, (ebx); ret

a_6: push ebx; ret

a_7: pop esp; ret

Known Gadgets

Draw a stack diagram for a ROP exploit to **store the value `0xBBBBBBB+1` into address `0xAAAAAAA` – then execute from `0xBBBBBBB+1`**

Questions