Machine-level programming
Segmentation Fault
&
Buffer overflow

Jinyang Li

What we’ve learnt so far

- A running program’s memory layout: both instructions and data are stored in memory
  - Code, data, stack, heap
- CPU execution
  - control flows: sequential, jumps, call/ret

Today’s lesson plan

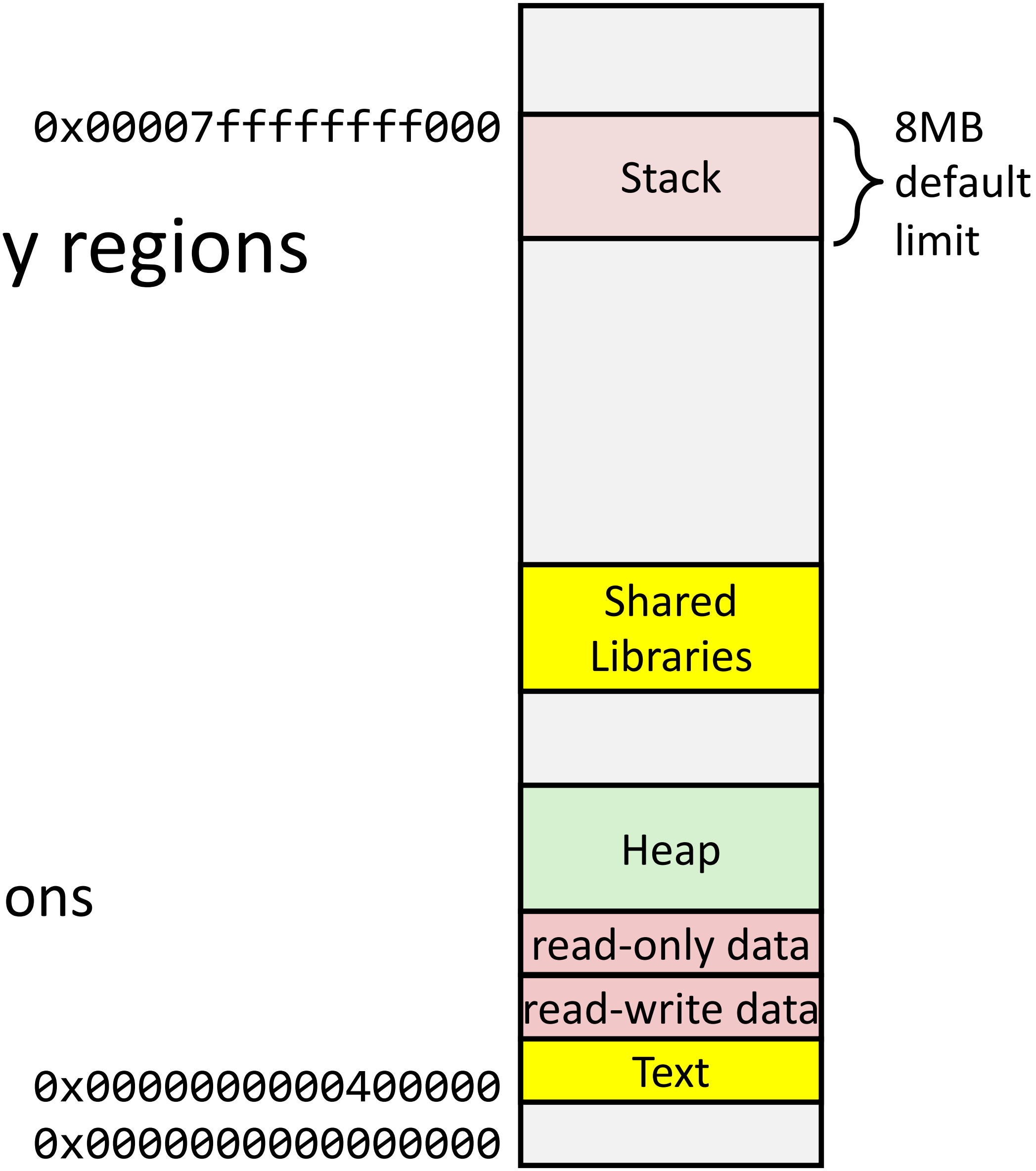
- What’s segmentation fault?
- What’s buffer overflow?

Recap: Linux Memory Layout

- OS allocates memory regions

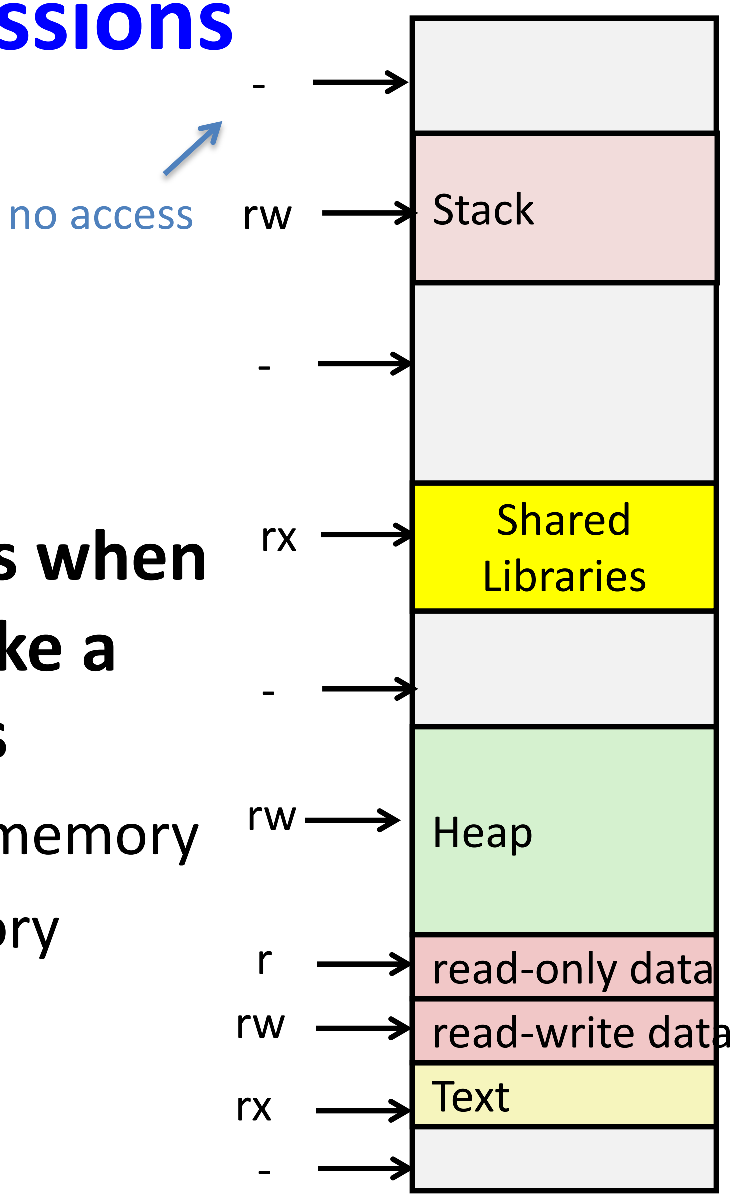
to a running program:

  - Stack
  - Heap
  - Data
  - Code
    - contain x86 instructions



Memory regions have hardware enforced permissions

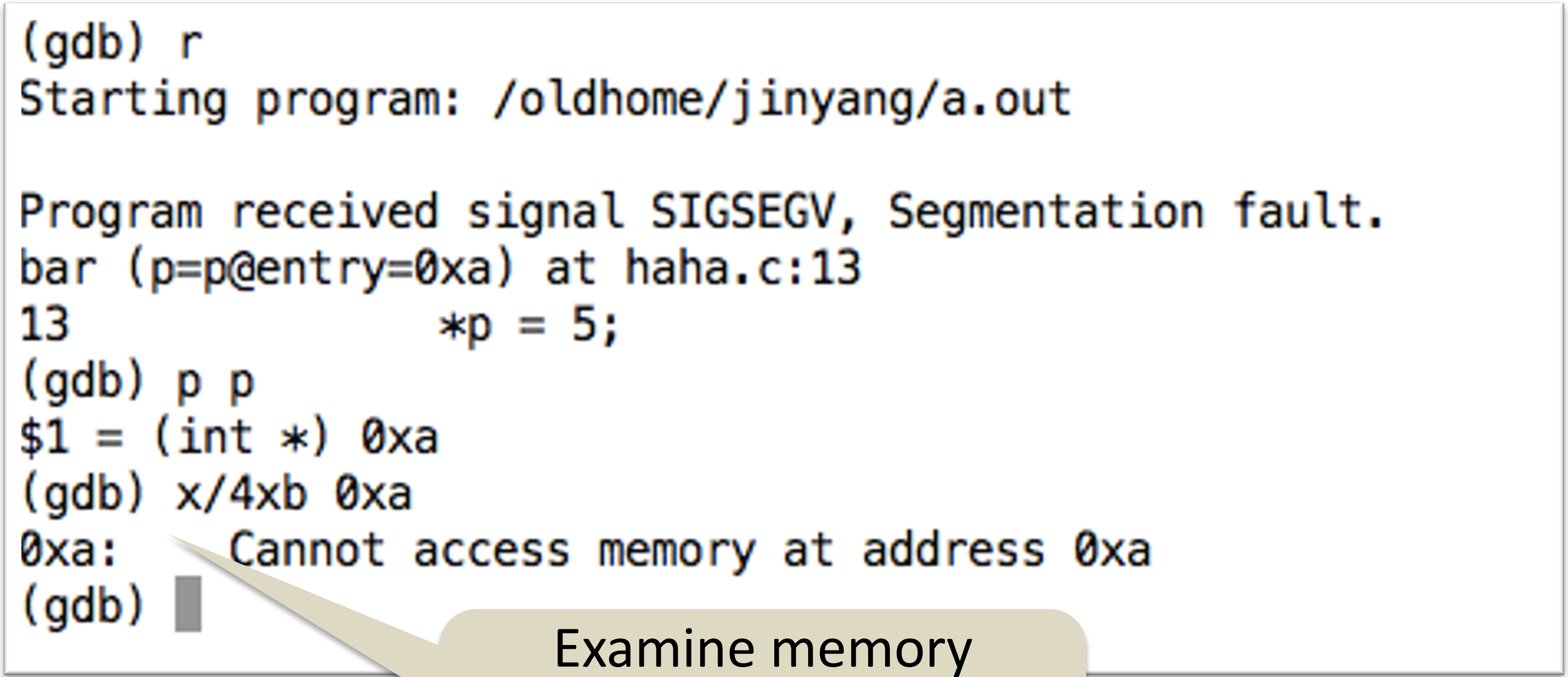
- **Permissions are:**
  - readable (r),
  - executable (x)
  - writable(w)
- **Segmentation fault occurs when an instruction tries to make a forbidden memory access**
  - Read or write “no-access” memory
  - Write to “read-only” memory



Segmentation fault example

```
void foo(int *p) {
   *p = 5;
}
```

```
int main() {
   foo((int *)10);
   printf(“finished\n”);
}
```

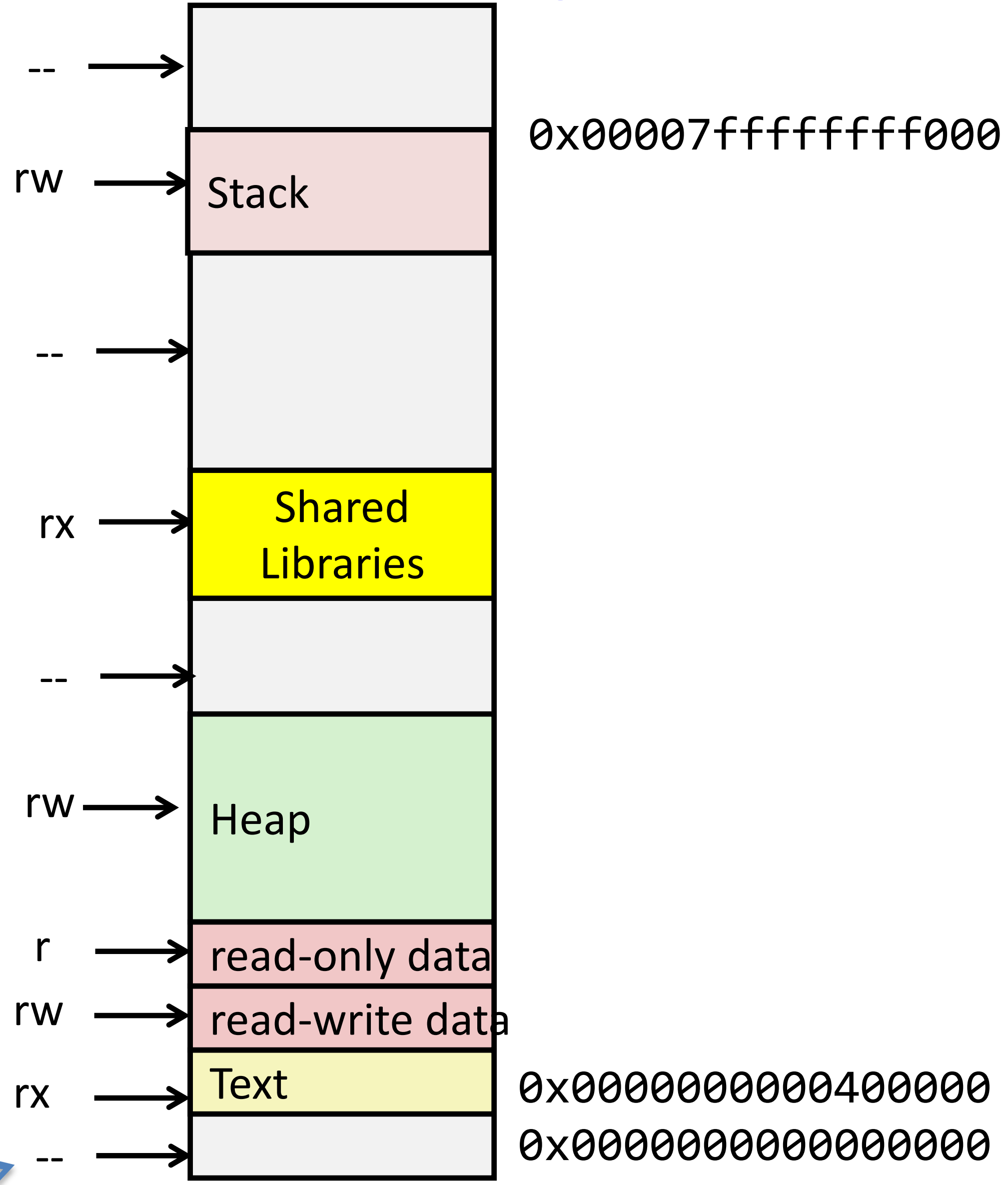


```
(gdb) r
Starting program: /oldhome/jinyang/a.out

Program received signal SIGSEGV, Segmentation fault.
bar (p=p@entry=0xa) at haha.c:13
13              *p = 5;
(gdb) p p
$1 = (int *) 0xa
(gdb) x/4xb 0xa
0xa:    Cannot access memory at address 0xa
(gdb)
```

Examine memory contents at address 0xa
4xb → 4 bytes in hex

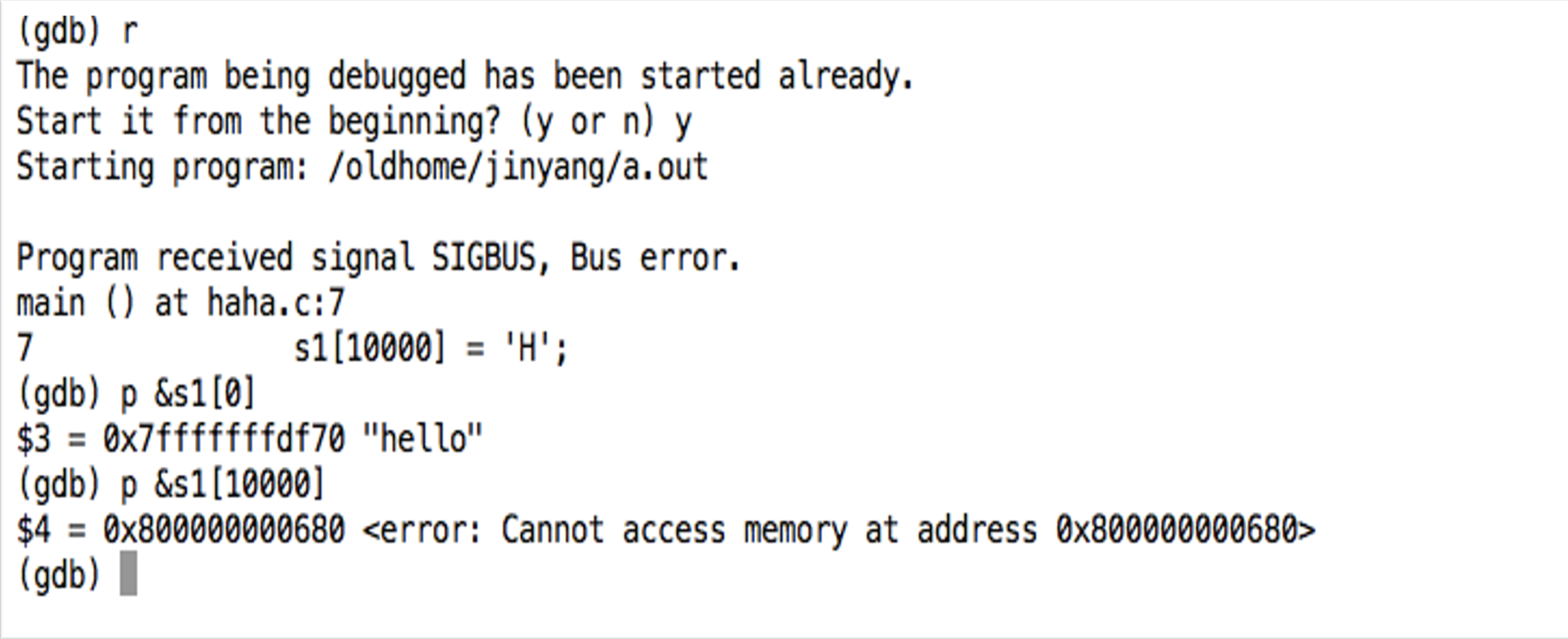
Segmentation fault example

```
void foo(int *p) {
    *p = 5;
}

int main() {
    foo((int *)10);
    printf(“finished\n”);
}
```



Another segmentation fault example

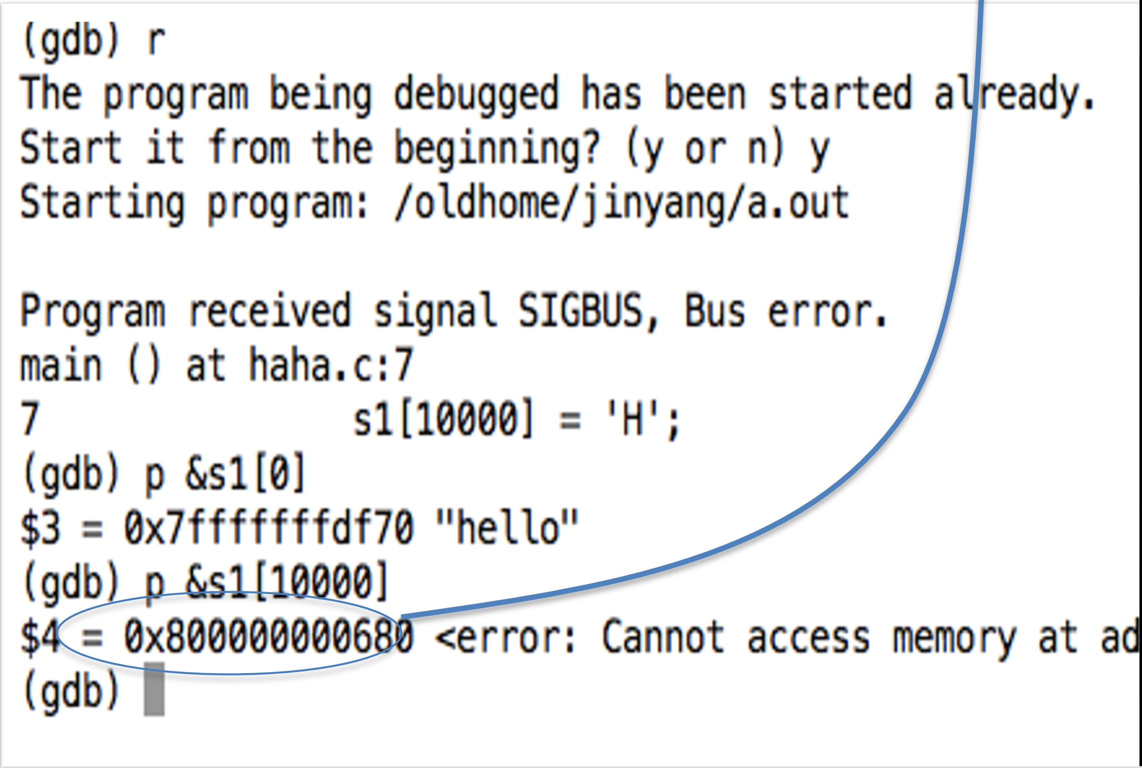
```
int main() {
   char s1[6] = “hello”;
   s1[10000] = ‘H’;
   printf(“finished\n”);
}
```



```
(gdb) r
The program being debugged has been started already.
Start it from the beginning? (y or n) y
Starting program: /oldhome/jinyang/a.out

Program received signal SIGBUS, Bus error.
main () at haha.c:7
7               s1[10000] = 'H';
(gdb) p &s1[0]
$3 = 0x7fffffffdf70 "hello"
(gdb) p &s1[10000]
$4 = 0x800000000680 <error: Cannot access memory at address 0x800000000680>
(gdb) 
```

Another segmentation fault example

```
int main() {
   char s1[6] = “hello”;
   s1[10000] = ‘H’;
   printf(“finished\n”);
}
```



```
(gdb) r
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Starting program: /oldhome/jinyang/a.out

Program received signal SIGBUS, Bus error.
main () at haha.c:7
7                s1[10000] = 'H';
(gdb) p &s1[0]
$3 = 0x7fffffffdf70 "hello"
(gdb) p &s1[10000]
$4 = 0x800000000680 <error: Cannot access memory at ad          00000680>
(gdb)
```
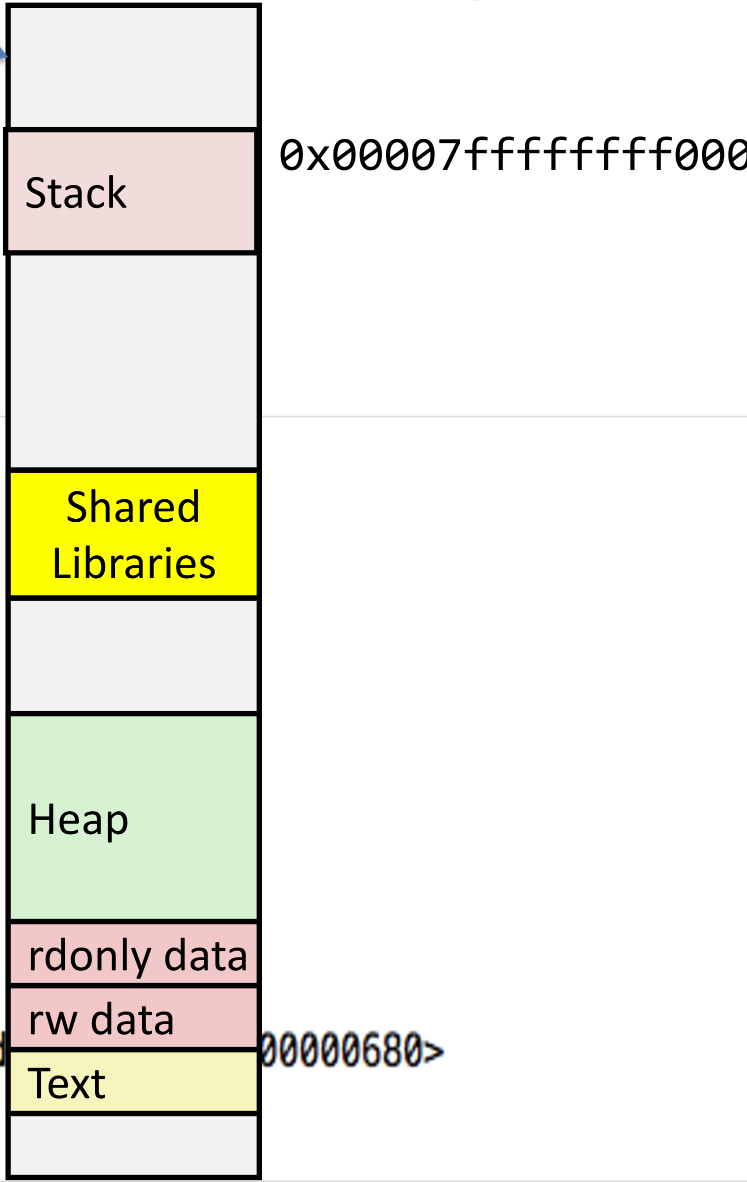



Not all buggy memory references cause forbidden memory access

→ buffer overflow exploits

Buggy code

```
void echo() {
     char buf[4];
     gets(buf);
     puts(buf);
}

void main() {
     echo();
}
```

read a line from stdin until a terminating newline or EOF, which it replaces with a NULL byte.

writes string and a trailing newline to stdout.

buffer overruns,
but things seem ok??

```
$./a.out
Type a string:0123456789012345678912
0123456789012345678912
```

```
$./a.out
Type a string:0123456789012345678912345
Segmentation Fault
```

Buggy code Disassembly

echo:

"allocate " 24 bytes on stack

```
0000000004006cf <echo>:
 4006cf:  48 83 ec 18          sub    $0x18,%rsp
 4006d3:  48 89 e7             mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff       callq  400680 <gets>
 4006db:  48 89 e7             mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff       callq  400520 <puts@plt>
 4006e3:  48 83 c4 18          add    $0x18,%rsp
 4006e7:  c3                   retq
```

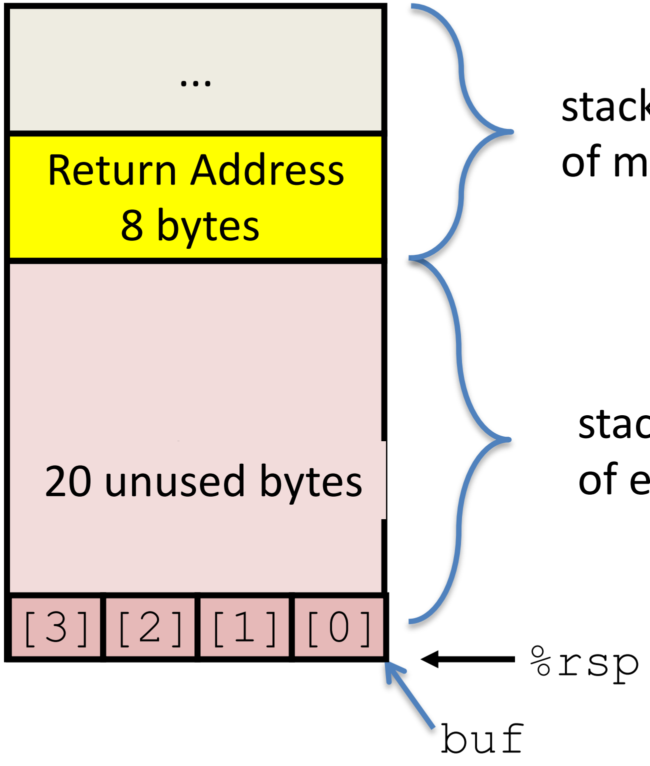
pass address of top of stack as 1st argument to gets

main:

```
4006e8:   48 83 ec 08          sub    $0x8,%rsp
 4006ec:  b8 00 00 00 00       mov    $0x0,%eax
 4006f1:  e8 d9 ff ff ff       callq  4006cf <echo>
 4006f6:  48 83 c4 08          add    $0x8,%rsp
 4006fa:  c3                   retq
```

Buggy code's stack

Before call to gets



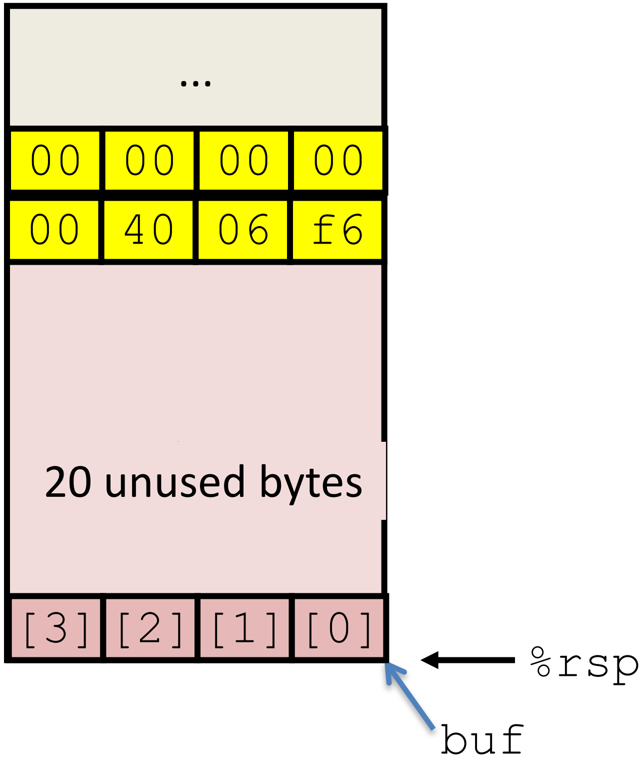
```
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq  $0x18, %rsp
  movq  %rsp, %rdi
  call  gets
  ...
```

```
main:
  ....
  4006f1: callq  4006cf <echo>
  4006f6: add    $0x8,%rsp
  ....
```

Buggy code's stack

Before call to gets



```
void echo()
{
      char buf[4];
      gets(buf);
      puts(buf);
}
```

```
echo:
   subq   $0x18, %rsp
   movq   %rsp, %rdi
   call   gets
   ...
```

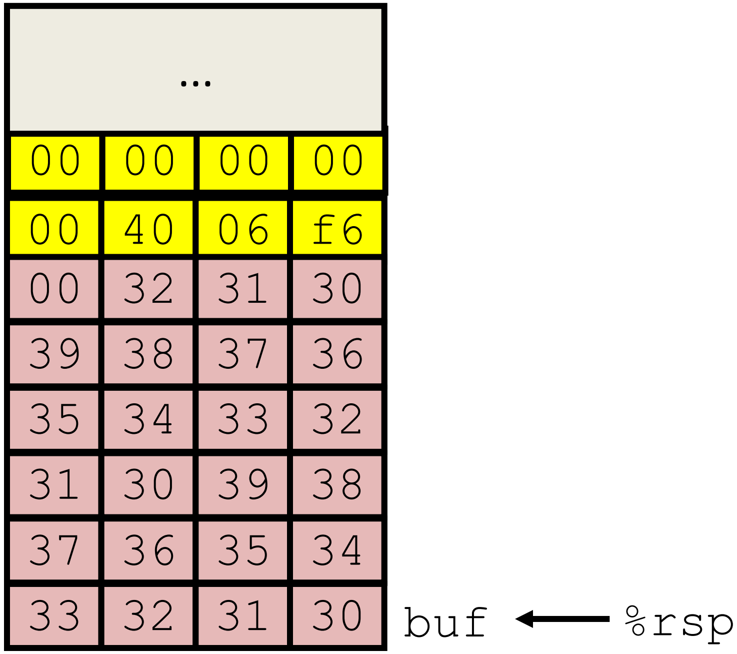
```
main:
   ....
   4006f1: callq   4006cf <echo>
   4006f6: add     $0x8,%rsp
   ....
```

```
$./a.out
Type a string:01234567890123456789012
```

What's the stack like after gets(..) returns?

Buffer overflow on the stack

After call to gets



00	00	00	00
00	40	06	f6
00	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

```
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

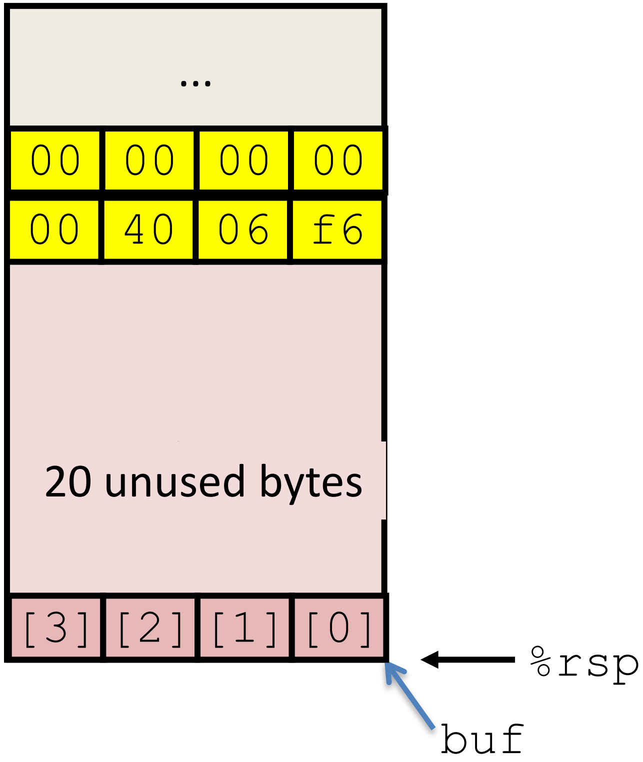
```
echo:
   subq  $0x18, %rsp
   movq  %rsp, %rdi
   call  gets
   ...
```

```
main:
   ....
   4006f1: callq   4006cf <echo>
   4006f6: add     $0x8,%rsp
   ....
```

```
$./a.out
Type a string:01234567890123456789012
01234567890123456789012
```

Buggy code's stack

Before call to gets



```
void echo()
{
     char buf[4];
     gets(buf);
     puts(buf);
}
```

```
echo:
   subq   $0x18, %rsp
   movq   %rsp, %rdi
   call   gets
   ...
```

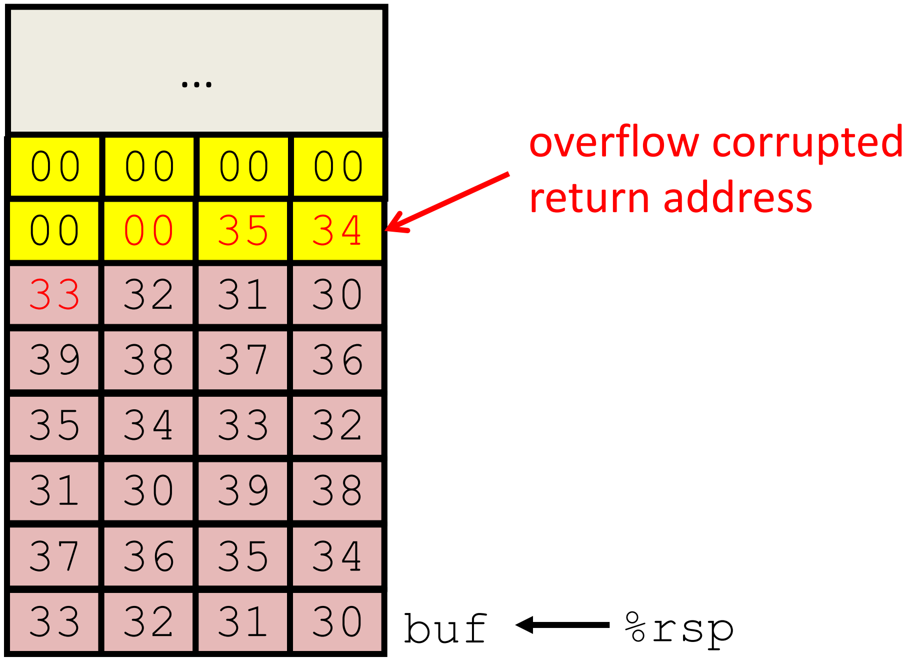
```
main:
   ....
   4006f1: callq   4006cf <echo>
   4006f6: add     $0x8,%rsp
   ....
```

```
$./a.out
Type a string:012345678901234567890123456789012345
```

What's the stack like after gets(..) returns?

Buffer overflow corrupts return address

After call to gets



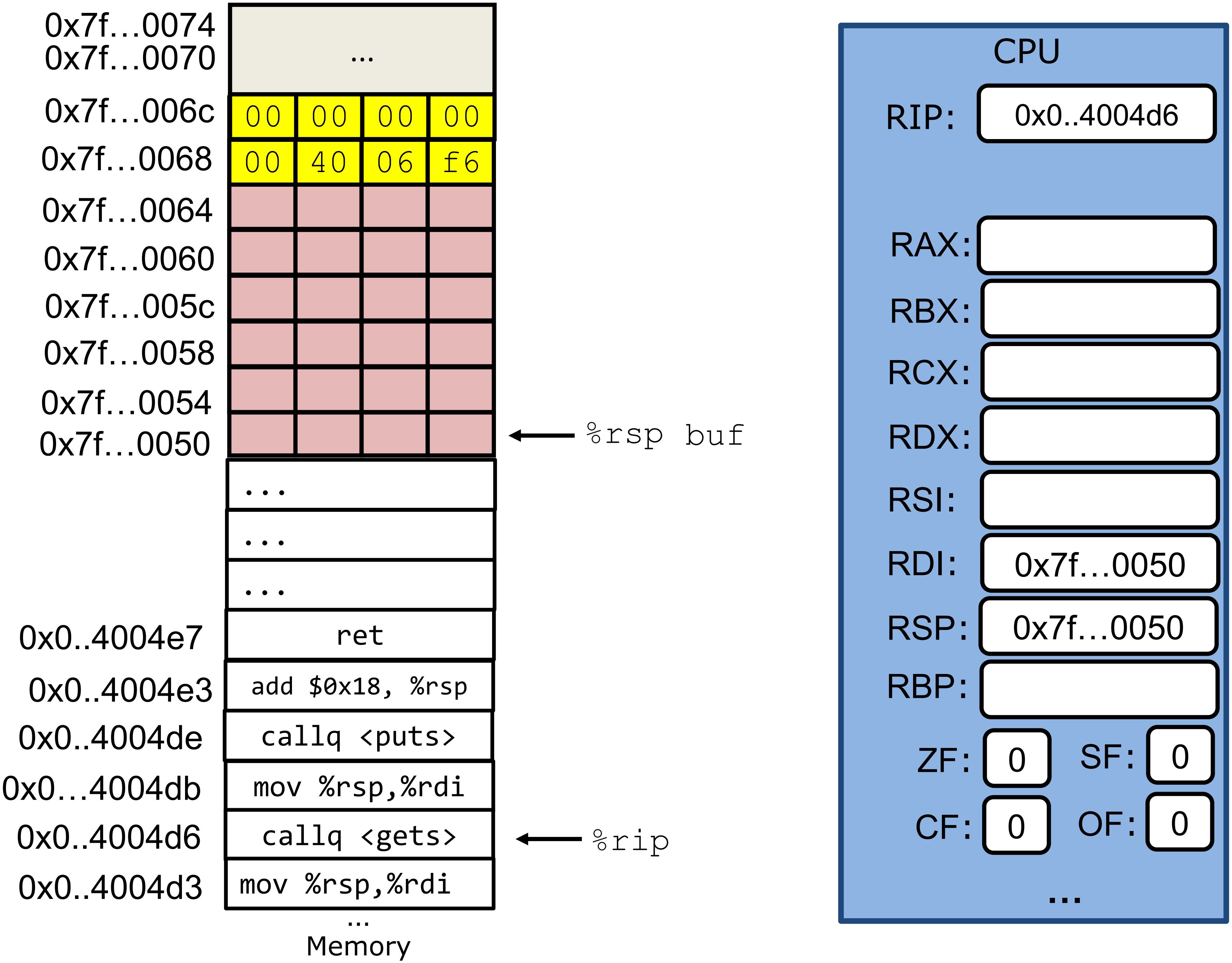
…			
00	00	00	00
00	00	35	34
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

```
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

```
echo:
   subq   $0x18, %rsp
   movq   %rsp, %rdi
   call   gets
   ...
```

```
main:
   ....
   4006f1: callq   4006cf <echo>
   4006f6: add     $0x8,%rsp
   ....
```

```
$./a.out
Type a string:012345678901234567890123456789012345
Segmentation Fault
```



0x7f…0074 0x7f…0070	…				
0x7f…006c	00	00	00	00	
0x7f…0068	00	40	06	f6	
0x7f…0064					
0x7f…0060					
0x7f…005c					
0x7f…0058					
0x7f…0054					
0x7f…0050					← %rsp buf
	...				
	...				
	...				
0x0..4004e7	`ret`				
0x0..4004e3	`add $0x18, %rsp`				
0x0..4004de	`callq <puts>`				
0x0…4004db	`mov %rsp,%rdi`				
0x0..4004d6	`callq <gets>`				← %rip
0x0..4004d3	`mov %rsp,%rdi`				
	…				

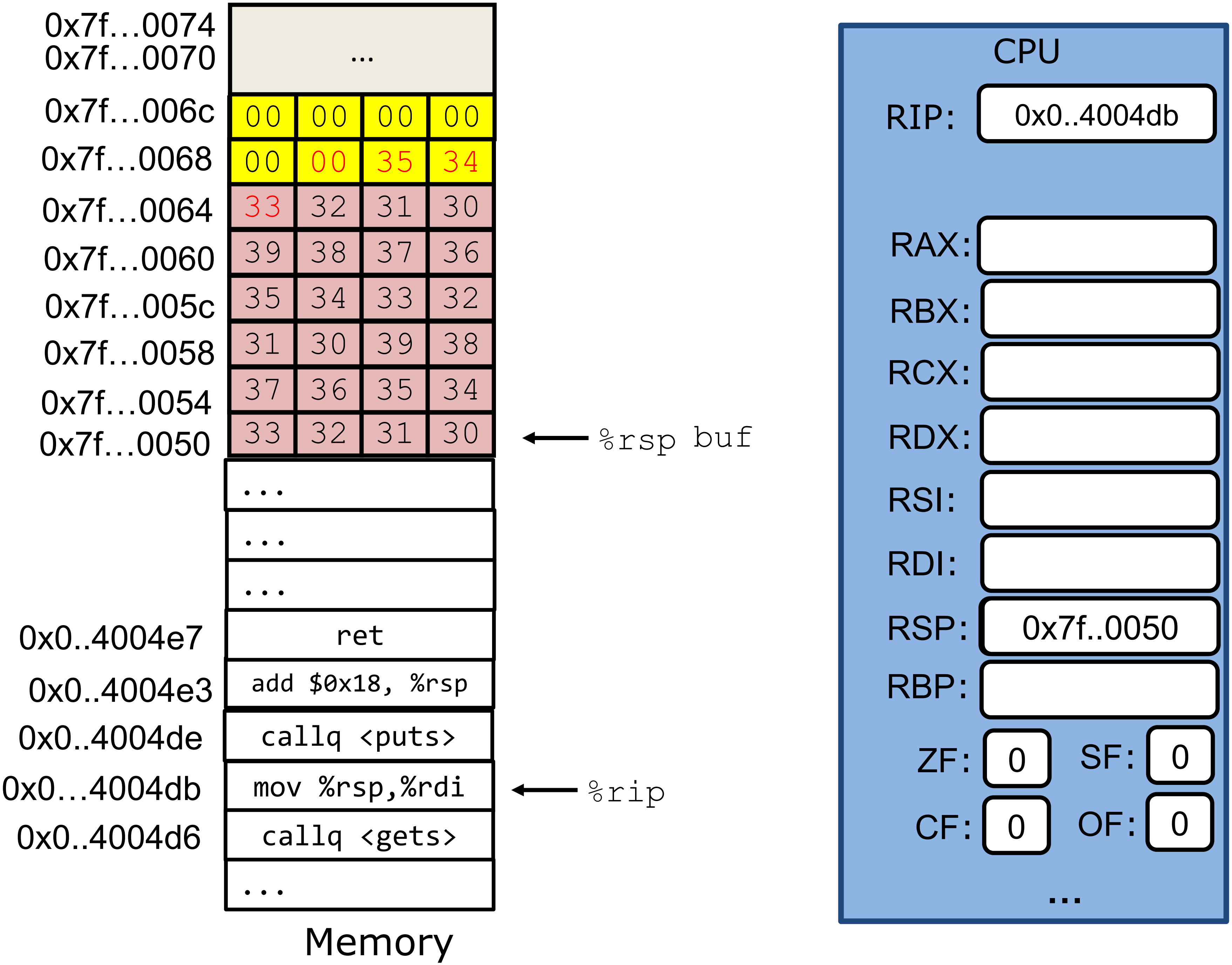
Memory

CPU

RIP:	0x0..4004d6
RAX:	
RBX:	
RCX:	
RDX:	
RSI:	
RDI:	0x7f…0050
RSP:	0x7f…0050
RBP:	

ZF:	0	SF:	0
CF:	0	OF:	0

…



0x7f…0074 0x7f…0070	…			
0x7f…006c	00	00	00	00
0x7f…0068	00	00	35	34
0x7f…0064	33	32	31	30
0x7f…0060	39	38	37	36
0x7f…005c	35	34	33	32
0x7f…0058	31	30	39	38
0x7f…0054	37	36	35	34
0x7f…0050	33	32	31	30

← `%rsp buf`

```
...
...
...
0x0..4004e7   ret
0x0..4004e3   add $0x18, %rsp
0x0..4004de   callq <puts>
0x0…4004db    mov %rsp,%rdi      ← %rip
0x0..4004d6   callq <gets>
...
```

Memory

CPU

RIP: 0x0..4004db

RAX:

RBX:

RCX:

RDX:

RSI:

RDI:

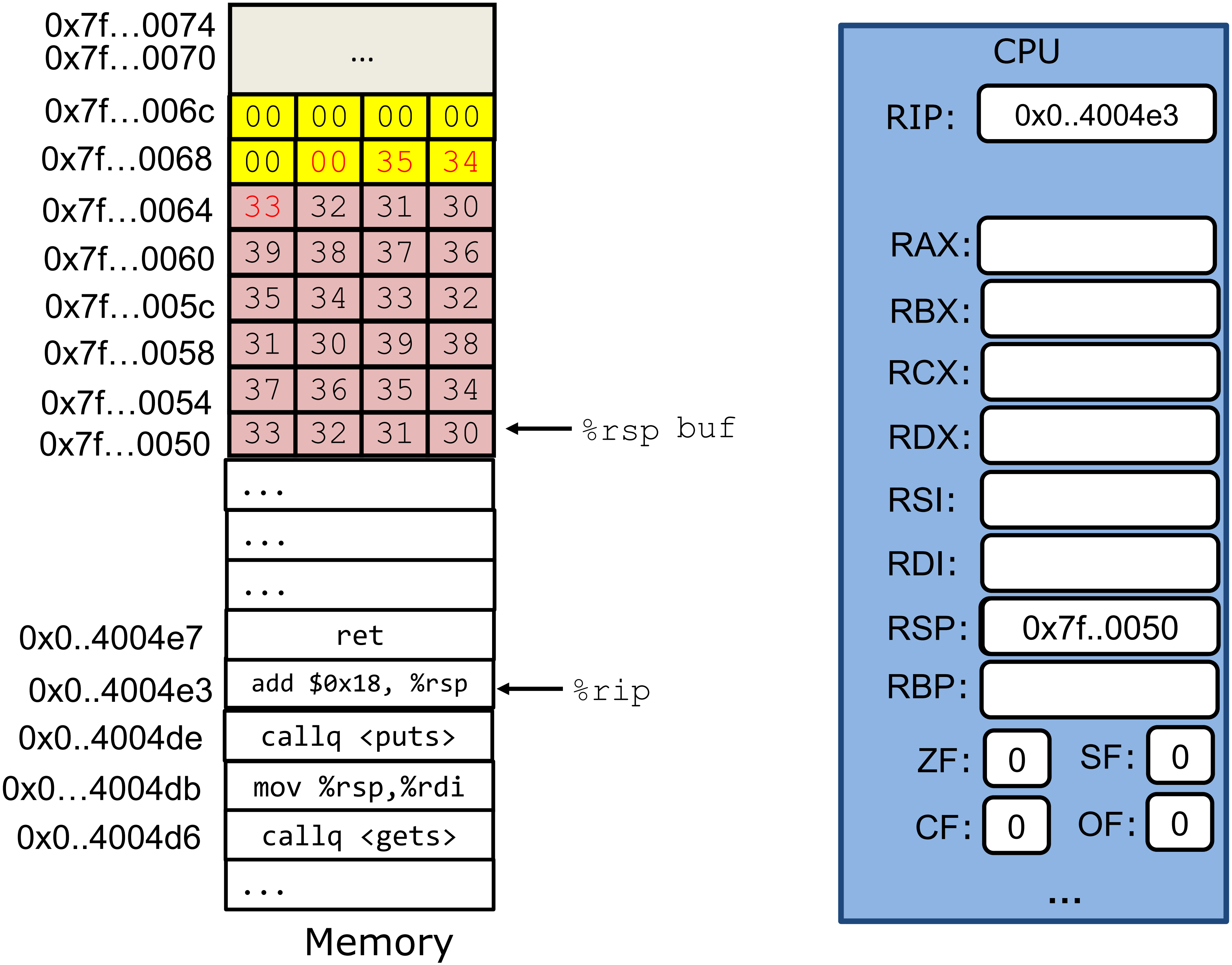
RSP: 0x7f..0050

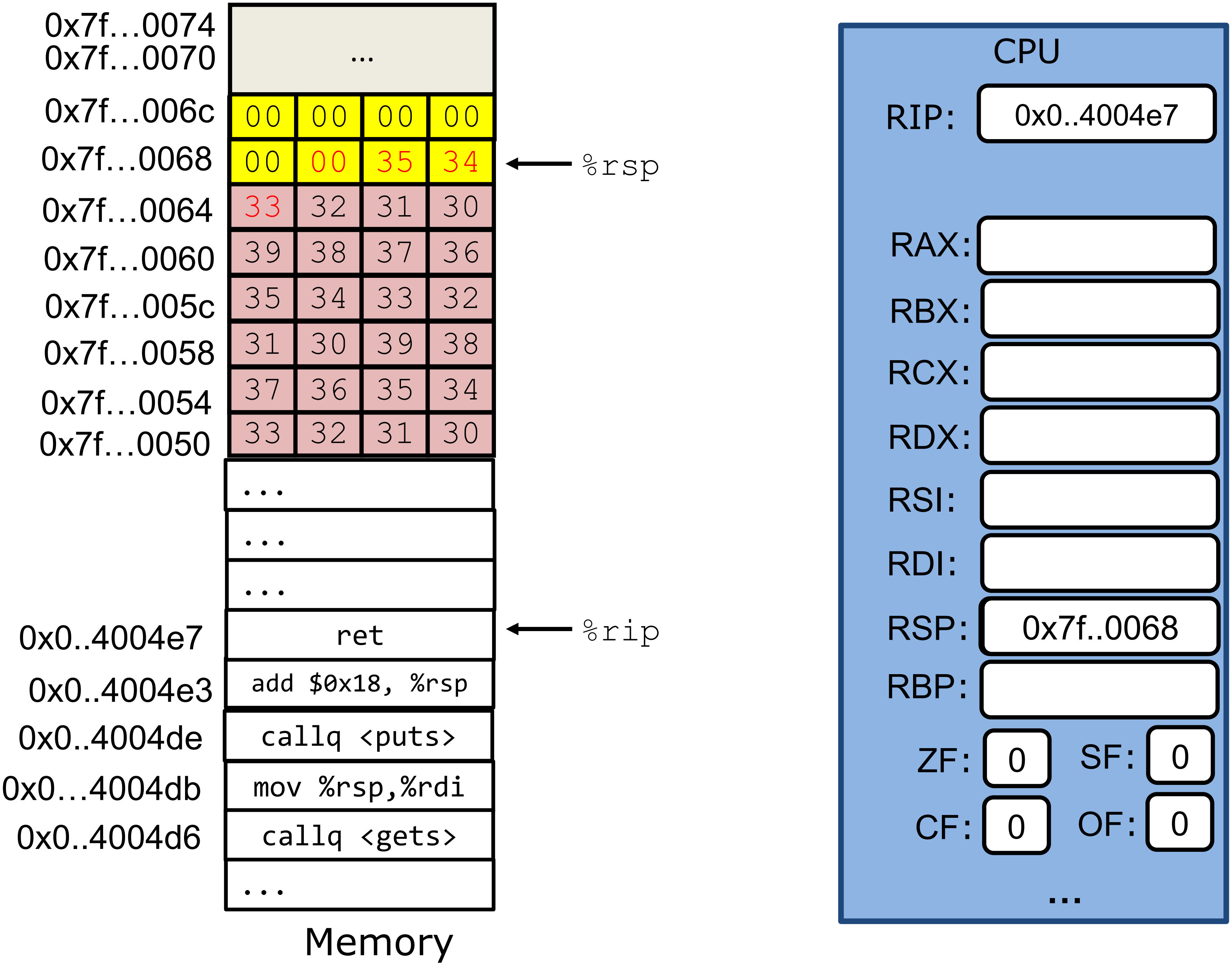
RBP:

ZF: 0 SF: 0

CF: 0 OF: 0

...


0x7f…0074
0x7f…0070
…
0x7f…006c
00 00 00 00
0x7f…0068
00 00 35 34
0x7f…0064
33 32 31 30
0x7f…0060
39 38 37 36
0x7f…005c
35 34 33 32
0x7f…0058
31 30 39 38
0x7f…0054
37 36 35 34
0x7f…0050
33 32 31 30
%rsp buf
...
...
...
0x0..4004e7
ret
0x0..4004e3
add $0x18, %rsp
%rip
0x0..4004de
callq <puts>
0x0…4004db
mov %rsp,%rdi
0x0..4004d6
callq <gets>
...
Memory
CPU
RIP:
0x0..4004e3
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
RSP:
0x7f..0050
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…



0x7f…0074 0x7f…0070	…			
0x7f…006c	00	00	00	00
0x7f…0068	00	00	35	34
0x7f…0064	33	32	31	30
0x7f…0060	39	38	37	36
0x7f…005c	35	34	33	32
0x7f…0058	31	30	39	38
0x7f…0054	37	36	35	34
0x7f…0050	33	32	31	30
	...			
	...			
	...			
0x0..4004e7	`ret`			
0x0..4004e3	`add $0x18, %rsp`			
0x0..4004de	`callq <puts>`			
0x0…4004db	`mov %rsp,%rdi`			
0x0..4004d6	`callq <gets>`			
	...			

Memory

CPU

RIP: 0x0..4004e7

RAX:

RBX:

RCX:

RDX:

RSI:

RDI:

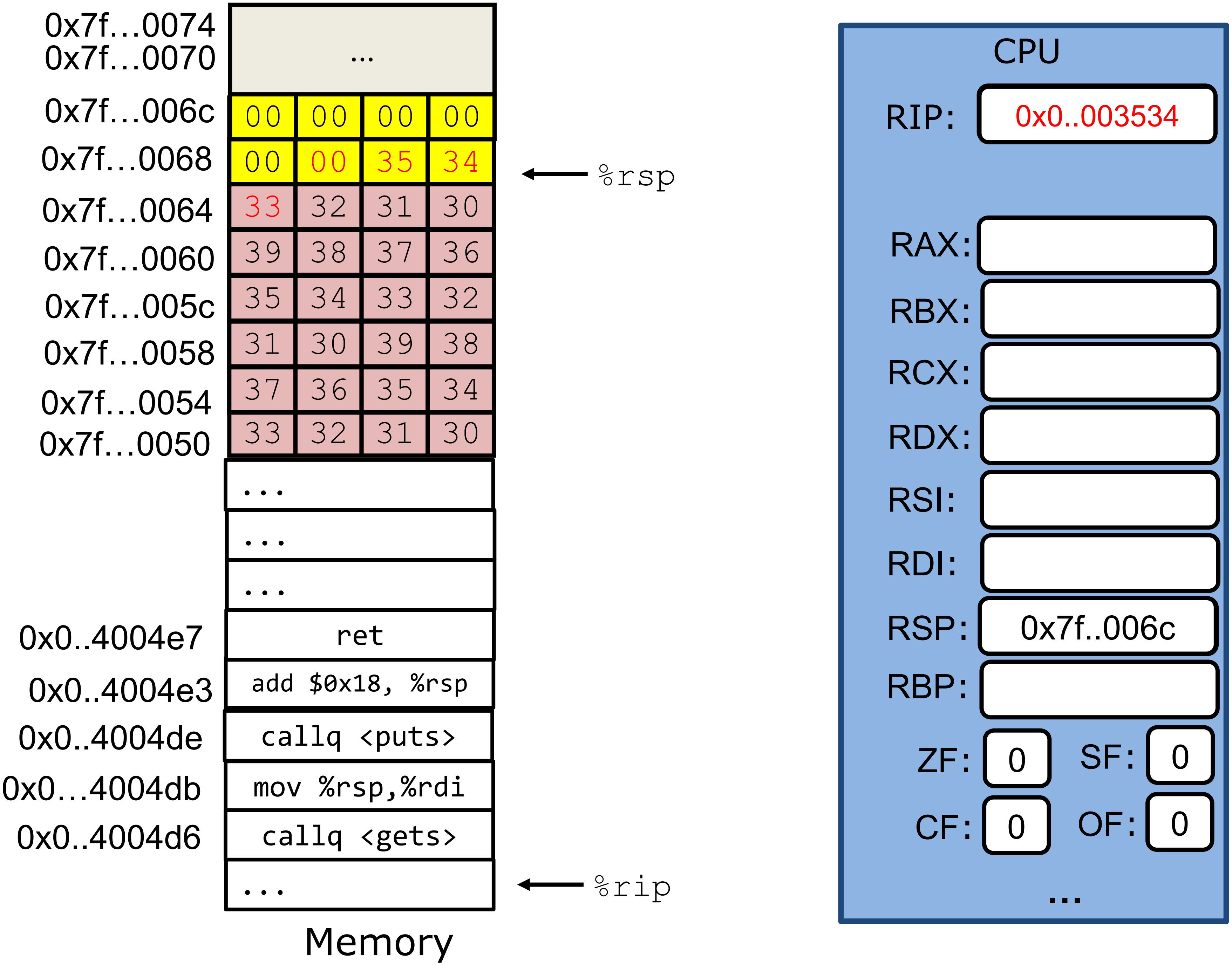
RSP: 0x7f..0068

RBP:

ZF: 0 SF: 0

CF: 0 OF: 0

...



0x7f…0074 0x7f…0070	…			
0x7f…006c	00	00	00	00
0x7f…0068	00	00	35	34
0x7f…0064	33	32	31	30
0x7f…0060	39	38	37	36
0x7f…005c	35	34	33	32
0x7f…0058	31	30	39	38
0x7f…0054	37	36	35	34
0x7f…0050	33	32	31	30
	...			
	...			
	...			
0x0..4004e7	ret			
0x0..4004e3	add $0x18, %rsp			
0x0..4004de	callq <puts>			
0x0…4004db	mov %rsp,%rdi			
0x0..4004d6	callq <gets>			
	...			

CPU

RIP: 0x0..003534

RAX:

RBX:

RCX:

RDX:

RSI:

RDI:

RSP: 0x7f..006c

RBP:

ZF: 0

SF: 0

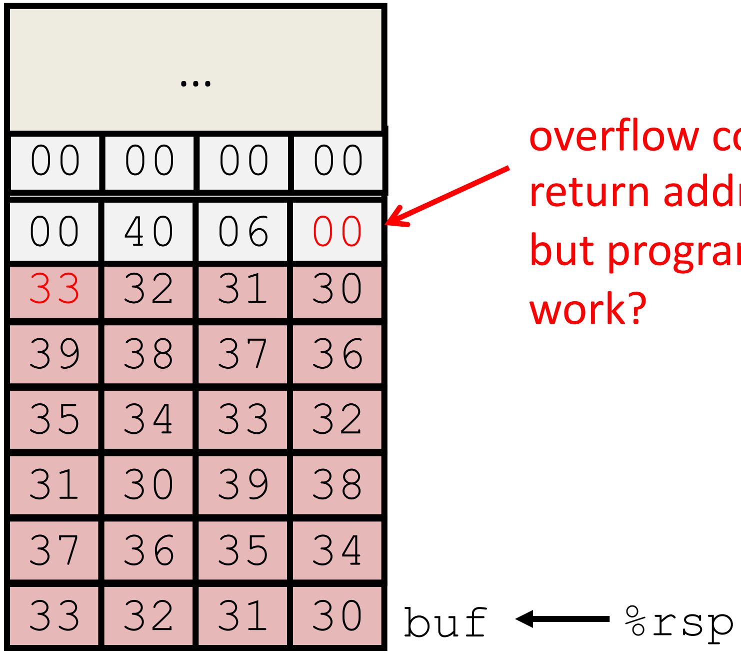
CF: 0

OF: 0

…

Buffer Overflow corrupts return address

After call to gets



overflow corrupted return address, but program seems to work?

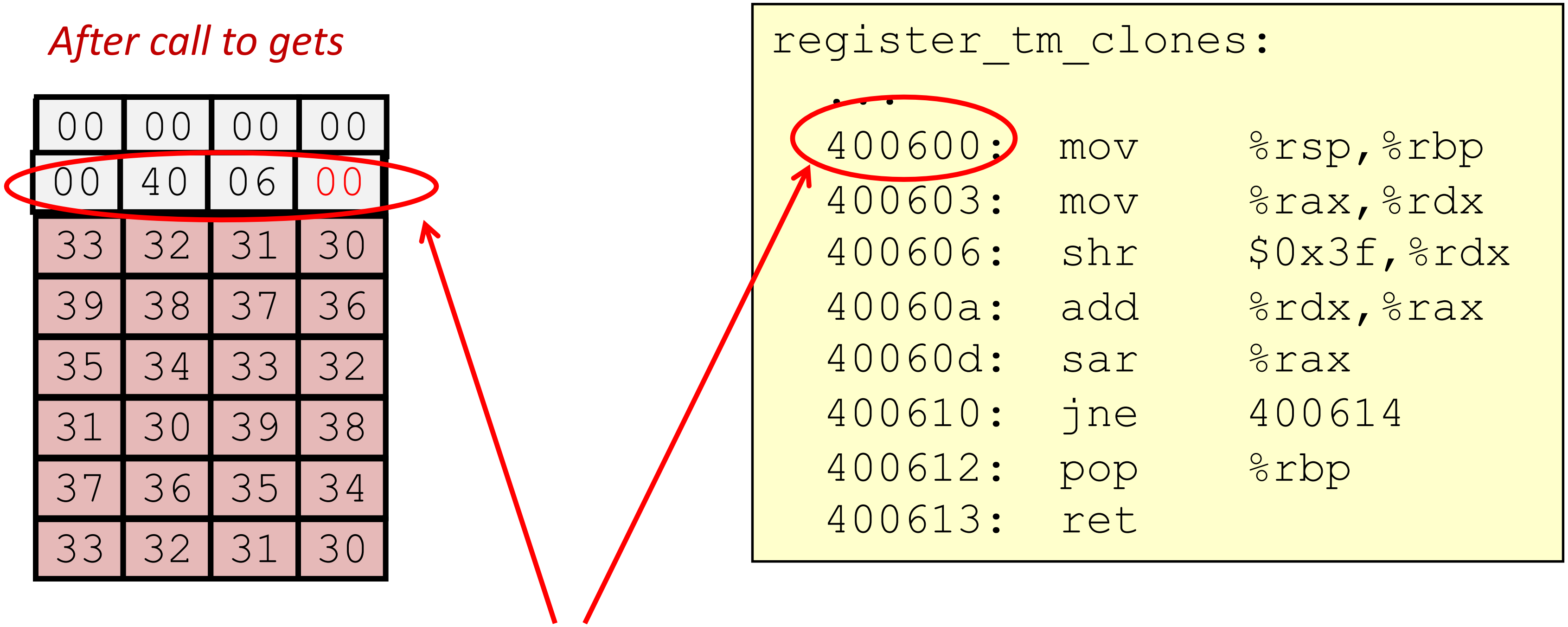
```
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq   $0x18, %rsp
  movq   %rsp, %rdi
  call   gets
  ...
```

```
main:
  ....
  4006f1: callq   4006cf <echo>
  4006f6: add     $0x8,%rsp
  ....
```

```
$./a.out
Type a string:012345678901234567890123
012345678901234567890123
```

Buffer overflow corrupts return address, program jumps to random code



After call to gets

00	00	00	00
00	40	06	00
33	32	31	30
39	38	37	36
35	34	33	32
31	30	39	38
37	36	35	34
33	32	31	30

```
register_tm_clones:
  . . .
  400600:  mov    %rsp,%rbp
  400603:  mov    %rax,%rdx
  400606:  shr    $0x3f,%rdx
  40060a:  add    %rdx,%rax
  40060d:  sar    %rax
  400610:  jne    400614
  400612:  pop    %rbp
  400613:  ret
```

"Returns" to unrelated code
Lots of things happen
(luckily no critical state modified)

How do attackers exploit buffer overflow?

1. Hijack control flow
   - overwrite buffer with a carefully chosen return address
   - executes malicious code (injected by attacker or elsewhere in the running program)
2. Gain broad access on host machine:
   - e.g. execute a shell
   - Take advantage of permissions granted to the hacked process
     - if the process is running as “root”....
     - read user database, send spam, steal bitcoin!

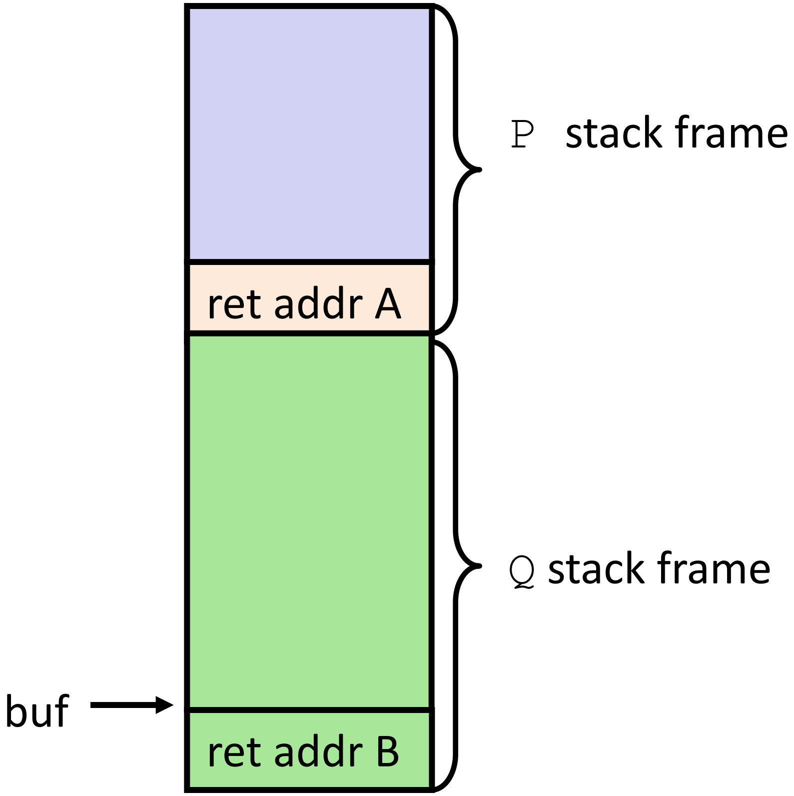
Example exploit: Code Injection Attacks

```
void P(){
  Q();
  ...
}
```

return address A

```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return;
}
```

return address B



Stack upon entering `gets()`

Example exploit: Code Injection Attacks

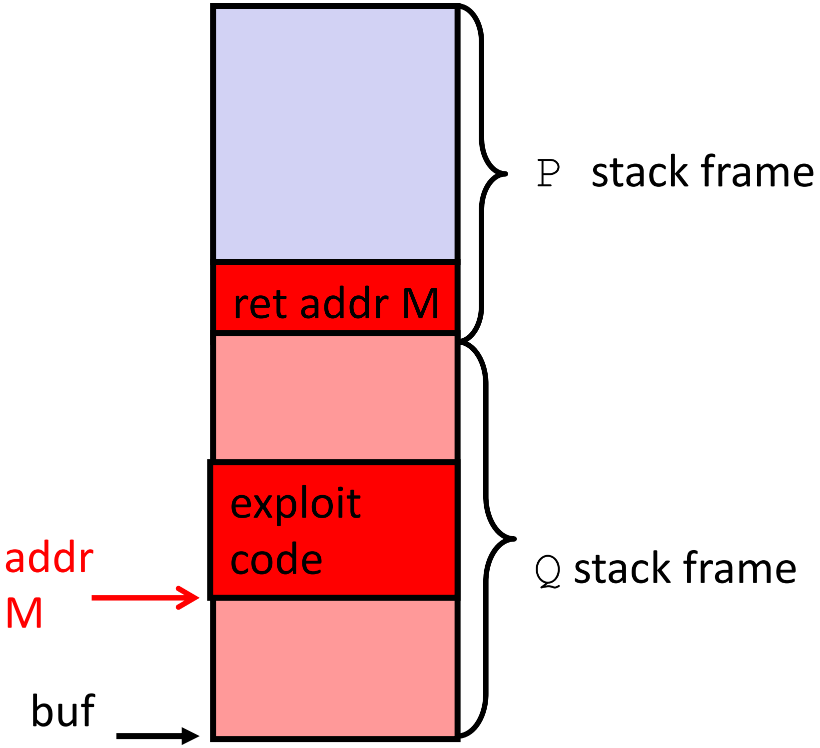
```
void P(){
  Q();
  ...
}
```

return address A

```
int Q() {
  char buf[64];
  gets(buf);
  ...
  return;
}
```

return address B

Upon executing this ret,
control is hijacked by exploit code



P stack frame

ret addr M

exploit
code

addr
M

Q stack frame

buf

Stack after returning from `gets()`

Past Code-Injection Buffer Overflow attacks

- It all started with “Internet worm” (1988)
  - A common network daemon used **`gets()`** to read inputs:
    - **`whois`** [**`student123@nyu.edu`**](mailto:student123@nyu.edu)
  - Worm attacked server by sending phony input:
    - **`whois`** ***`“exploit-code...new-return-address”`***
  - Exploit-code executes a shell (with root permission) with inputs from a network connection to attacker.
  - Worm scans other machines to launch the same attack
- Recent measures make code-injection much more difficult

Defenses against buffer overflow

- Write correct code: avoid overflow vulnerabilities

- Mitigate attacks despite buggy code

Avoid Overflow Vulnerabilities in Code

```
void echo() {
    char buf[4];
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- Better coding practices
  - e.g. use safe library APIs that limit buffer lengths, **fgets** instead of **gets, strncpy** instead of **strcpy**
- Use a memory-safe language instead of C
  - Java programs do not have buffer overflow problems, except in
    - naive methods (e.g. awt image library)
    - JVM itself
- heuristic-based bug finding tools
  - valgrind’s SGCheck

Mitigate BO attacks despite buggy code

- A buffer overflow attack needs two components:
  1. Control-flow hijacking
     - overwrite a code pointer (e.g. return address)
  2. Call to “useful” code
     - Inject executable code in buffer
     - Re-use existing code in the running process (easy if code is in a predictable location)
- How to mitigate attacks? make #1 or #2 hard

Prevent control flow hijacking

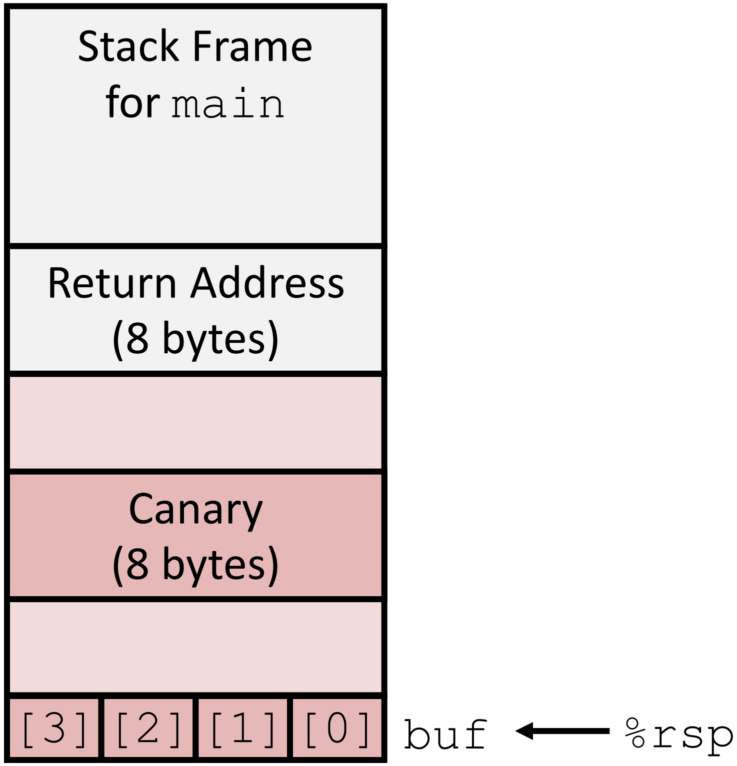
- Idea: Catch over-written return address before invocation!
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - **`-fstack-protector`**
  - Now the default

```
unix>./a.out
Type a string:0123456
0123456
```

```
unix>./a.out
Type a string:01234567
*** stack smashing detected ***
```

Setting Up Canary

Before call to gets



```
/* Echo Line */
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

- Where should canary go?
- When should canary checking happen?
- What should canary contain?

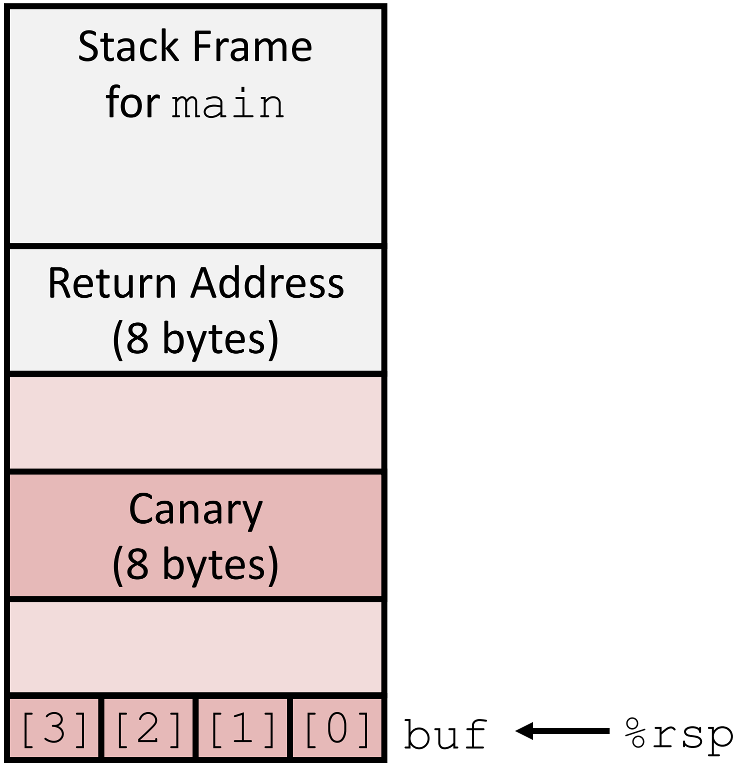
Stack canaries

echo:

```
40072f:  sub     $0x18,%rsp
400733:  mov     %fs:0x28,%rax
40073c:  mov     %rax,0x8(%rsp)
400741:  xor     %eax,%eax
400743:  mov     %rsp,%rdi
400746:  callq   4006e0 <gets>
40074b:  mov     %rsp,%rdi
40074e:  callq   400570 <puts@plt>
400753:  mov     0x8(%rsp),%rax
400758:  xor     %fs:0x28,%rax
400761:  je      400768 <echo+0x39>
400763:  callq   400580 <__stack_chk_fail@plt>
400768:  add     $0x18,%rsp
40076c:  retq
```

Setting Up Canary

Before call to gets

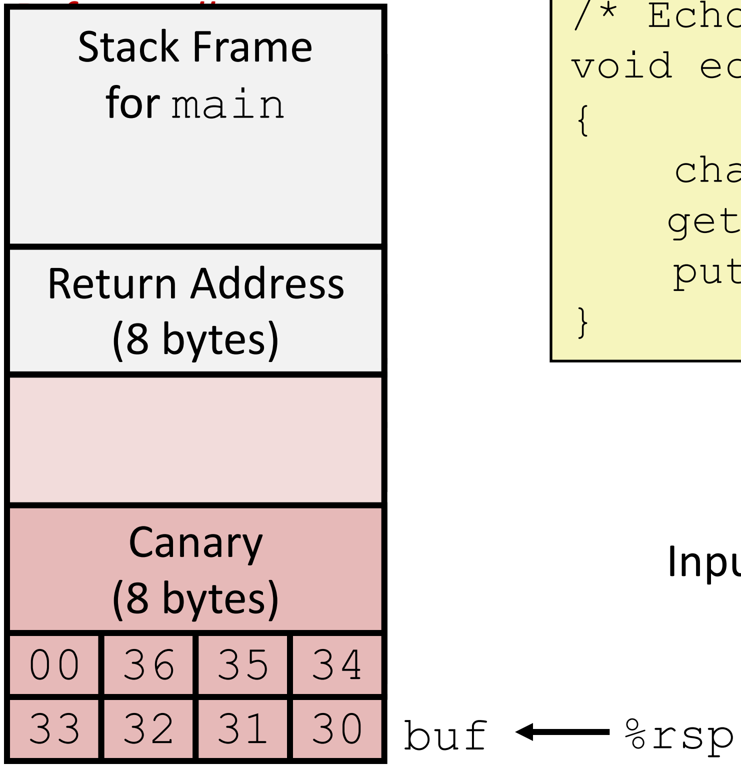


```
/* Echo Line */
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq     %fs:0x28, %rax  # Get canary
    movq     %rax, 8(%rsp) # Place on stack
    xorl     %eax, %eax    # Erase canary
    . . .
```

Checking Canary

After call to gets



Stack Frame
for `main`

Return Address
(8 bytes)

Canary
(8 bytes)

00	36	35	34
33	32	31	30

`buf` ← `%rsp`

```
/* Echo Line */
void echo()
{
    char buf[4];
    gets(buf);
    puts(buf);
}
```

Input: *0123456*

```
echo:
    . . .
    movq    8(%rsp), %rax        # Retrieve from stack
    xorq    %fs:0x28, %rax         # Compare to canary
    je      .L6                  # If same, OK
    call    __stack_chk_fail     # FAIL
.L6:. . .
```

What isn’t caught by canaries?

```
void myFunc(char *s) {
...
}
void echo()
{
    void (*f)(char *);
    f = myFunc;
    char buf[8];
    gets(buf);
    f();
}
```

```
void echo()
{
    char *msg; //stored on stack
    char buf[8];
    gets(buf);
    strcpy(msg, buf);
}
```

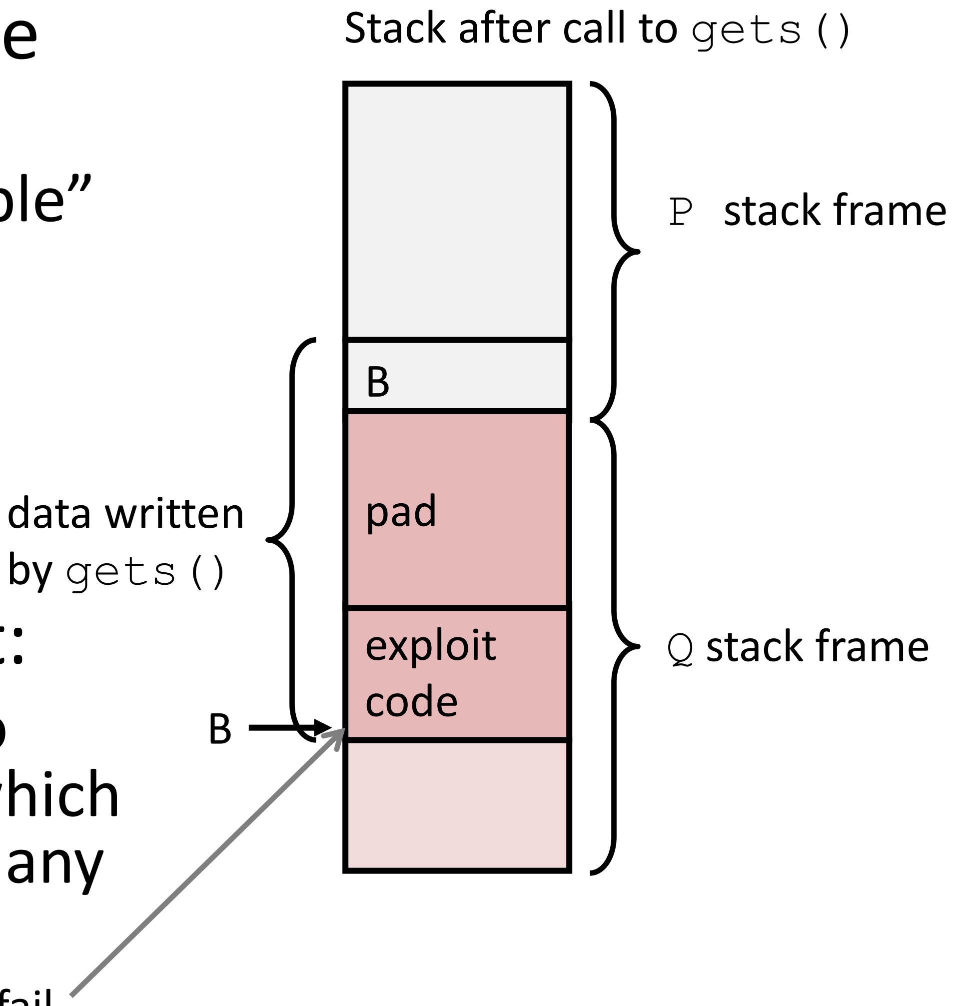
ptr contains an address determined by attacker

f contains an address determined by attacker

- Overwrite a code pointer before canary
- Overwrite a data pointer before canary

Prevent code injection

- NX: Non-executable code segments
  - Old x86 has no “executable” permission bit, X86-64 added explicit “execute” permission
  - Stack marked as non-executable
- Does not defend against:
  - Modify return address to point to code in stdlib (which has functions to execute any programs e.g. shell)



Any attempt to execute this code will fail

Prevent attempts to inject “useful” return addresses

- Insight: attacks often use hard-coded address → make it difficult for attackers to figure out the address to use
- Address Space Layout Randomization
  - Stack randomization
    - Makes it difficult to determine where the return addresses are located
  - Randomize the heap, location of dynamically loaded libraries etc.

Summary

- Why buffer overflow poses security risk
  - Allows attack to change control flow by returning to arbitrary address
- Gcc stack protector
  - Set up canary behind a stack-allocated buffer
- Make stack not executable
- Randomize stack, heap, shared library addresses

The rest of the slides are optional

Return-Oriented Programming Attacks

- Challenge (for hackers)
  - Stack randomization makes it hard to predict buffer location
  - Non-executable stack makes it hard to insert arbitrary binary code
- Alternative Strategy
  - Use existing code
    - E.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
- How to concoct an arbitrary mix of instructions from the current running program?
  - Gadgets: A short sequence of instructions ending in **`ret`**
    - Encoded by single byte **`0xc3`**

Gadget Example #1

```
long ab_plus_c
   (long a, long b, long c)
{
    return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0:   48 0f af fe   imul %rsi,%rdi
  4004d4:   48 8d 04 17   lea (%rdi,%rdx,1),%rax
  4004d8:   c3            retq
```

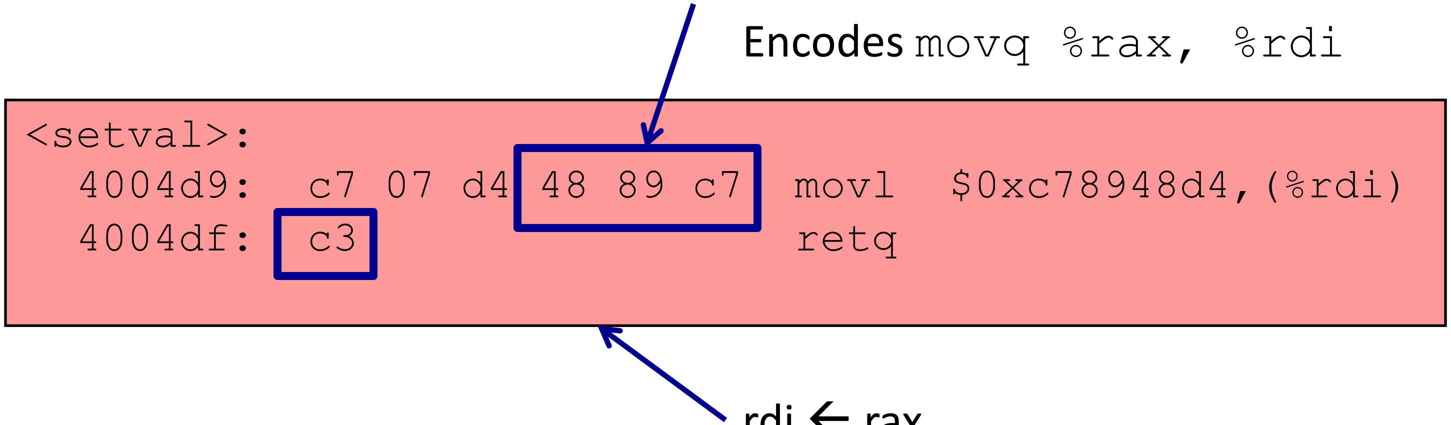
rax ← rdi + rdx

Gadget address = `0x4004d4`

- Use tail end of existing functions

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```



Encodes `movq %rax, %rdi`

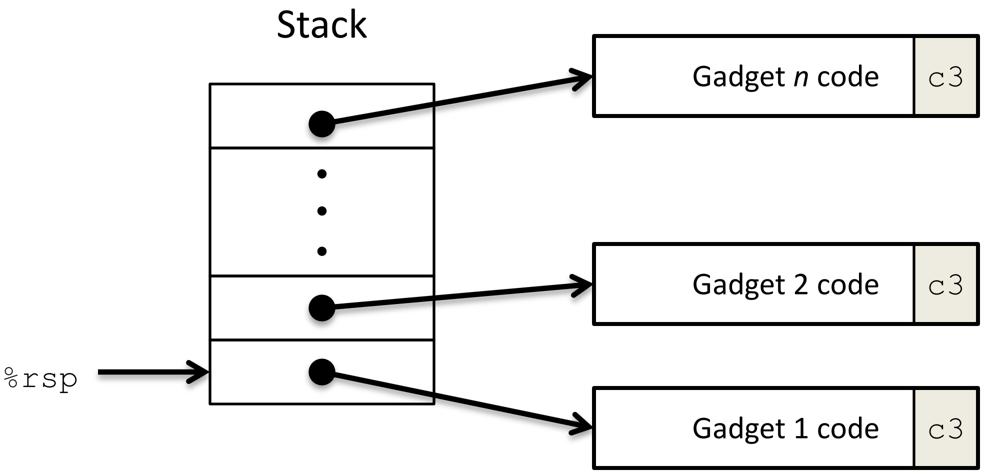
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7  movl  $0xc78948d4,(%rdi)
  4004df:  c3                 retq
```

rdi ← rax

Gadget address = `0x4004dc`

- Repurpose byte codes

ROP Execution



- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one