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;
}
```

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

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

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

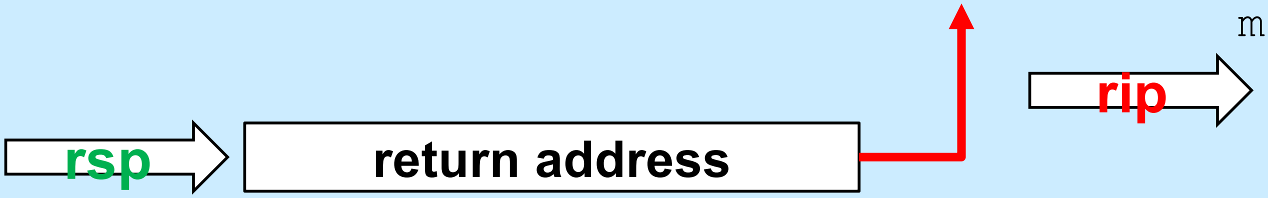
Arguments and Local Variables (1)

```
mainfunc:
   pushq %rbp                 # save old %rbp
   movq %rsp, %rbp            # set %rbp to point to stack frame
   subq $32, %rsp             # alloc. space for locals (array and sum)
   movq $2, -32(%rbp)         # initialize array[0]
   movq $117, -24(%rbp)       # initialize array[1]
   movq $-6, -16(%rbp)        # initialize array[2]
   pushq $3                   # push arg 2
   leaq -32(%rbp), %rax       # array address is put in %rax
   pushq %rax                 # push arg 1
   call ASum
   addq $16, %rsp             # pop args
   movq %rax, -8(%rbp)        # copy return value to sum
   ...
   addq $32, %rsp             # pop locals
   popq %rbp                  # pop and restore old %rbp
   ret
```

Arguments and Local Variables (2)

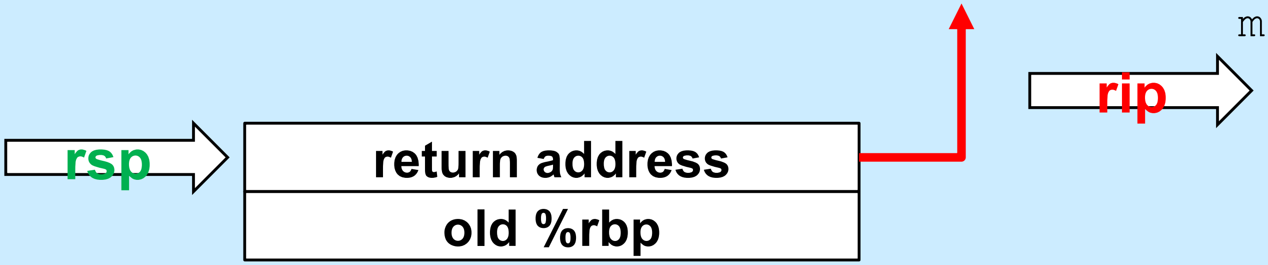
```
ASum:
   pushq %rbp                 # save old %rbp
   movq %rsp, %rbp            # set %rbp to point to stack frame
   movq $0, %rcx              # i in %rcx
   movq $0, %rax              # sum in %rax
   movq 16(%rbp), %rdx        # copy arg 1 (array) into %rdx
loop:
   cmpq 24(%rbp), %rcx        # i < size?
   jge done
   addq (%rdx,%rcx,8), %rax   # sum += a[i]
   incq %rcx                  # i++
   ja loop
done:
   popq %rbp                  # pop and restore %rbp
   ret
```

Enter mainfunc



```
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
```

Enter mainfunc



rsp

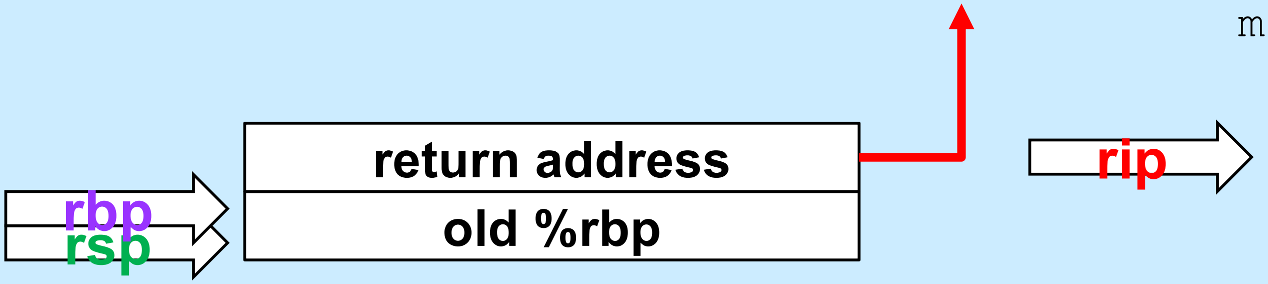
return address

old %rbp

rip

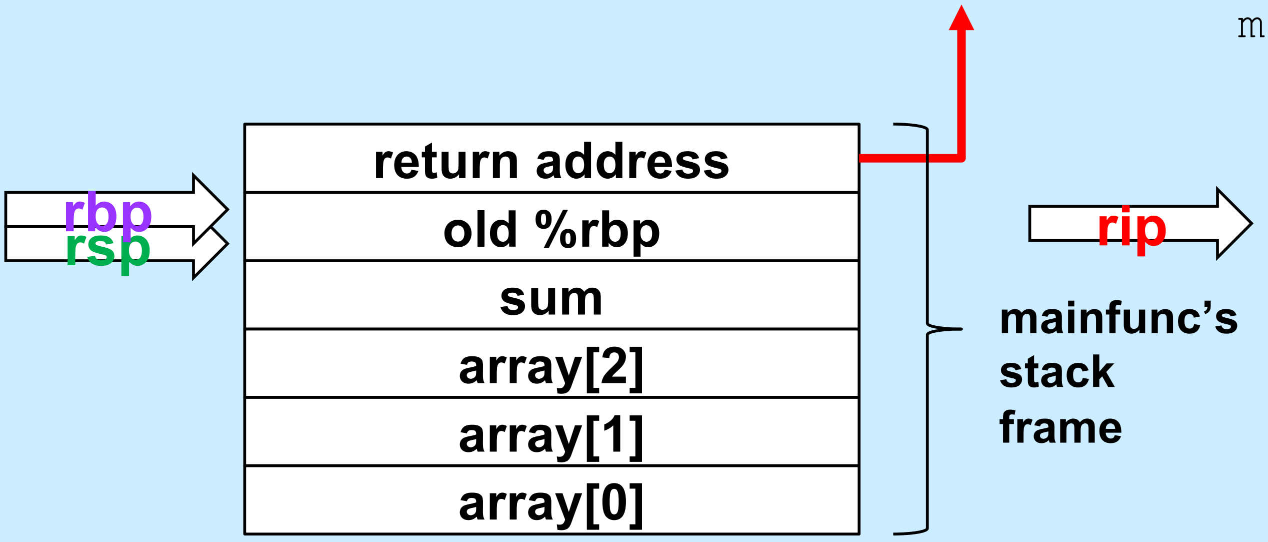
```
mainfunc:
      pushq %rbp
      movq %rsp, %rbp
      subq $32, %rsp
      movq $2, -32(%rbp)
      movq $117, -24(%rbp)
      movq $-6, -16(%rbp)
      pushq $3
      leaq -32(%rbp), %rax
      pushq %rax
      call ASum
      addq $16, %rsp
      movq %rax, -8(%rbp)
      addq $32, %rsp
     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

Setup Frame



```
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
```

Allocate Local Variables



rbp

rsp

return address

old %rbp

sum

array[2]

array[1]

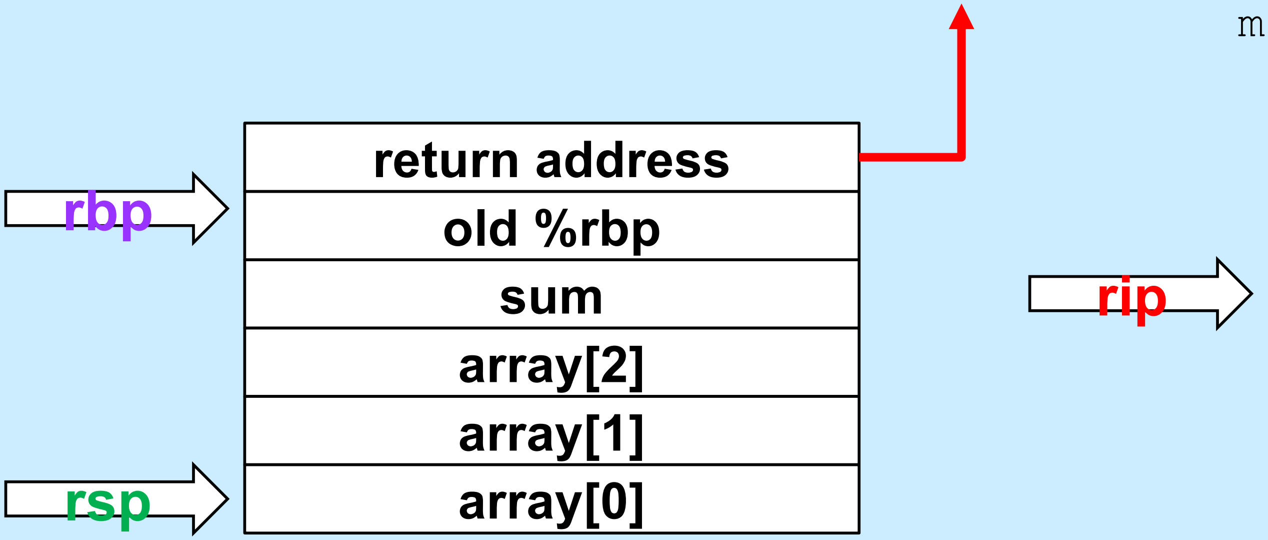
array[0]

mainfunc's stack frame

rip

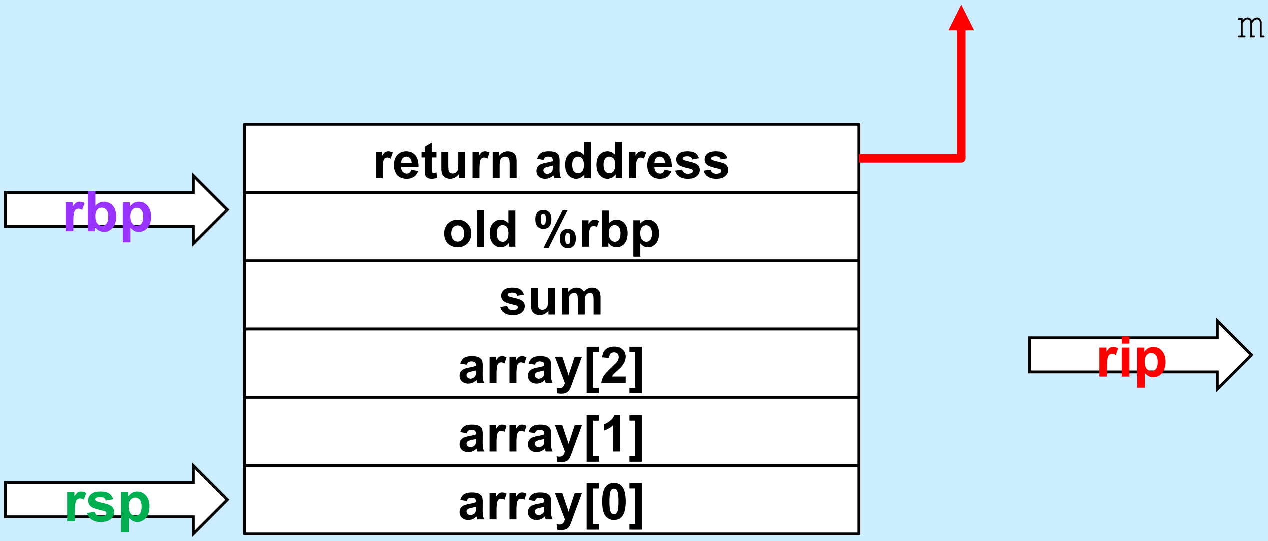
```
mainfunc:
   pushq %rbp
   movq %rsp, %rbp
   subq $32, %rsp
   movq $2, -32(%rbp)
   movq $117, -24(%rbp)
   movq $-6, -16(%rbp)
   pushq $3
   leaq -32(%rbp), %rax
   pushq %rax
   call ASum
   addq $16, %rsp
   movq %rax, -8(%rbp)
   addq $32, %rsp
   popq %rbp
   ret
```

Initialize Local Array



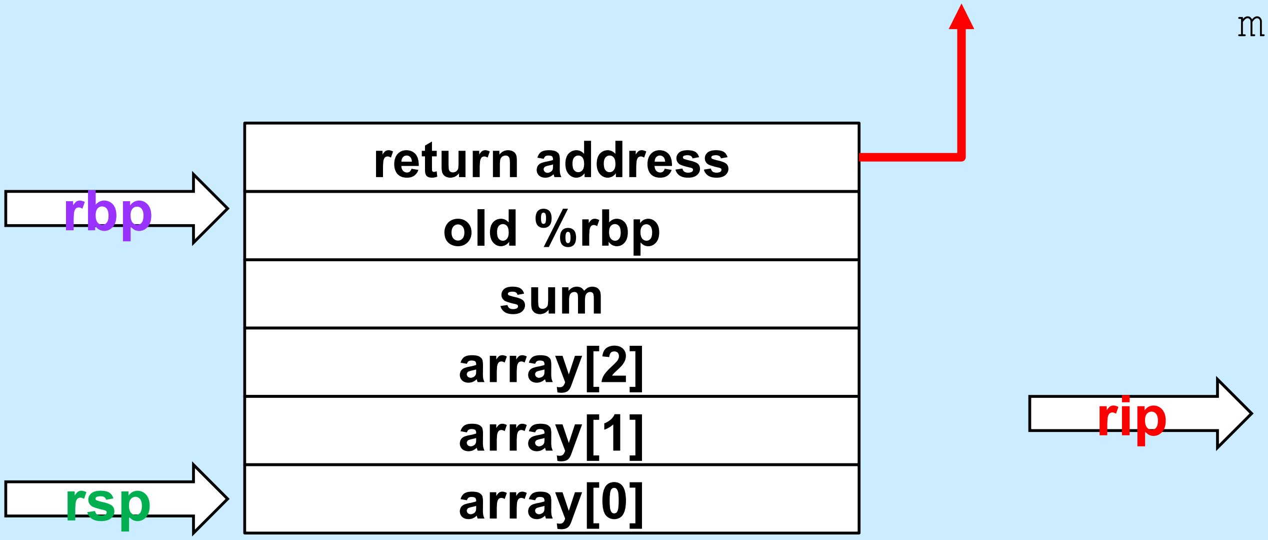
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Initialize Local Array



```
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
```

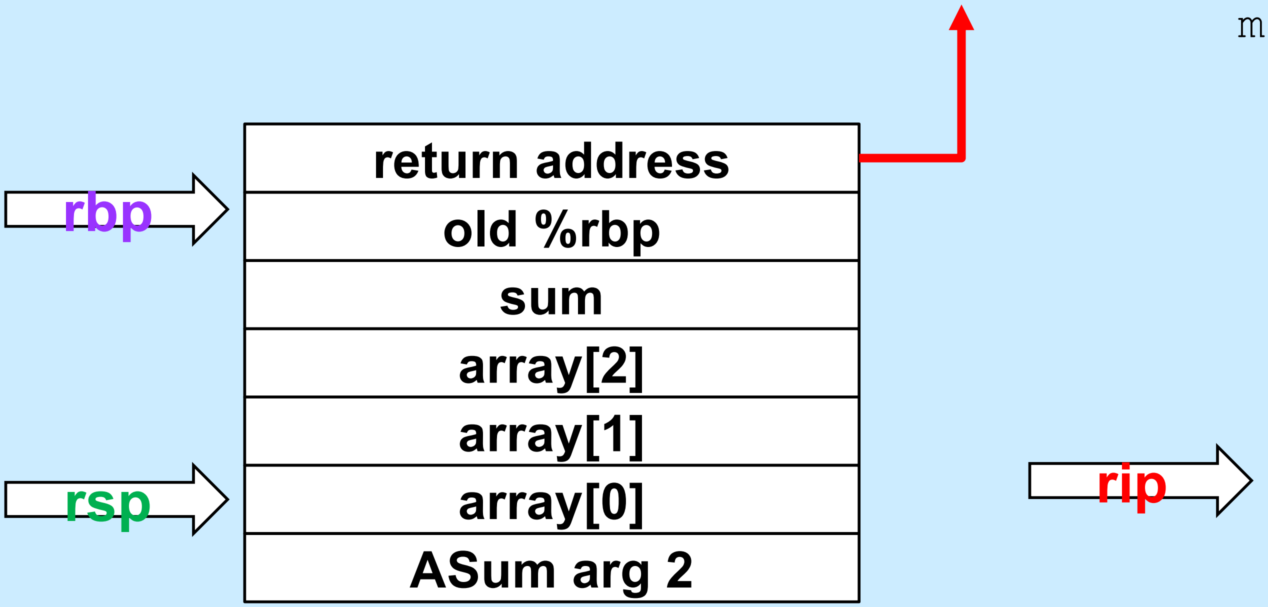
Initialize Local Array



return address
old %rbp
sum
array[2]
array[1]
array[0]

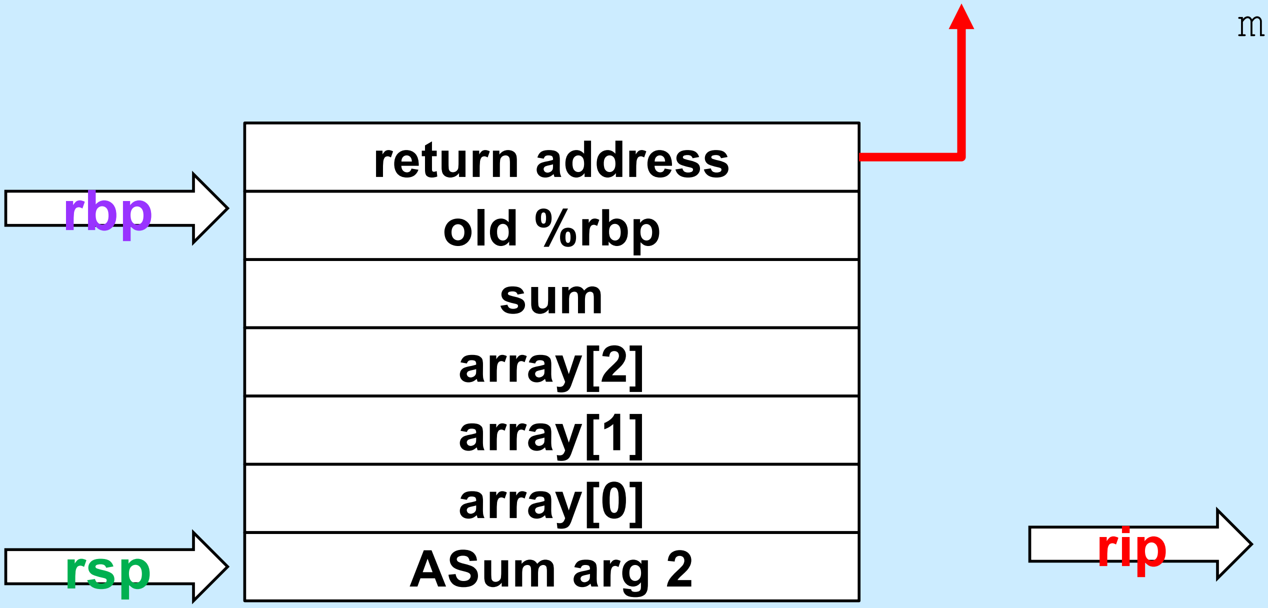
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Push Second Argument



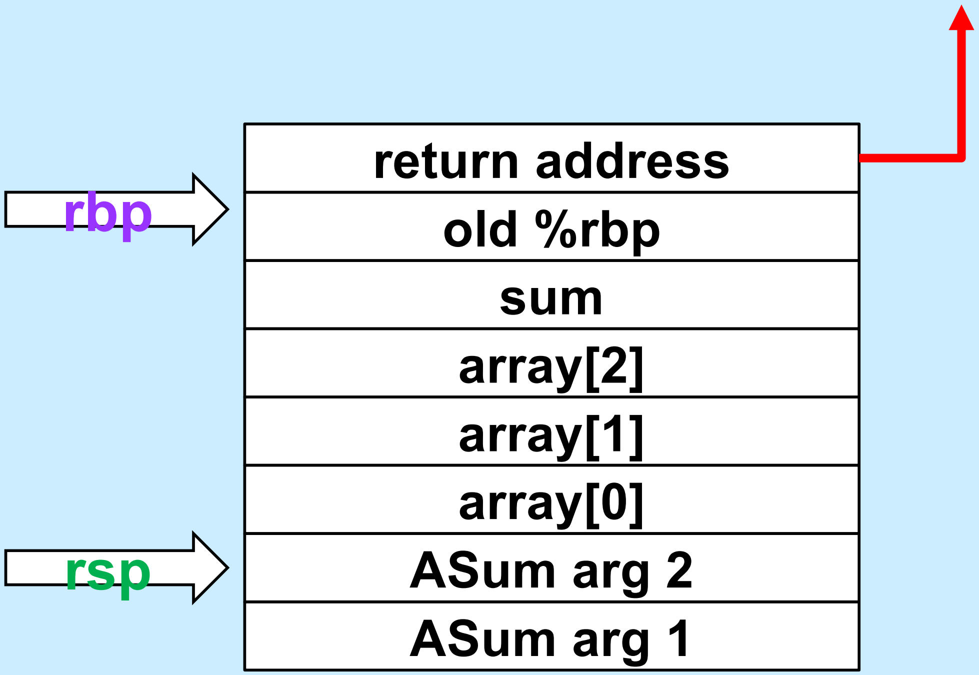
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Get Array Address



```
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
```

Push First Argument



rbp

rsp

return address

old %rbp

sum

array[2]

array[1]

array[0]

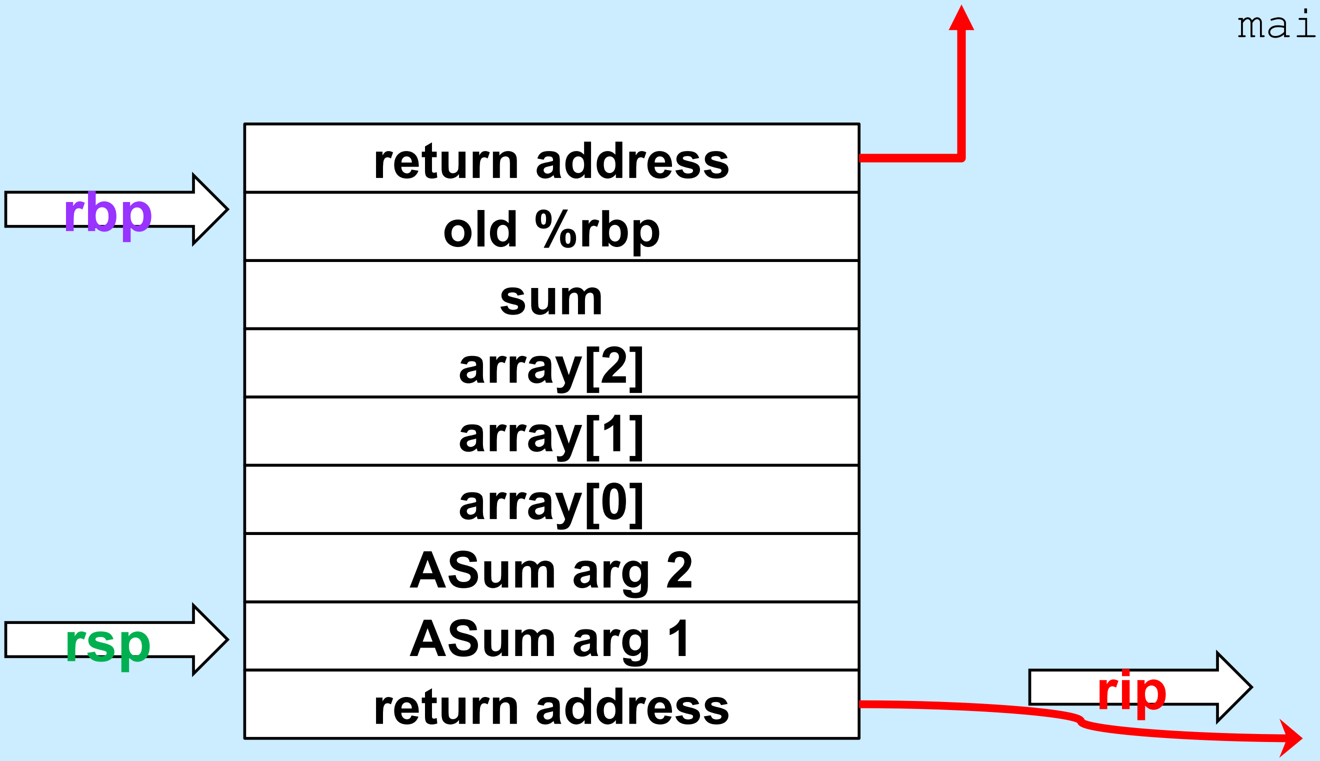
ASum arg 2

ASum arg 1

rip

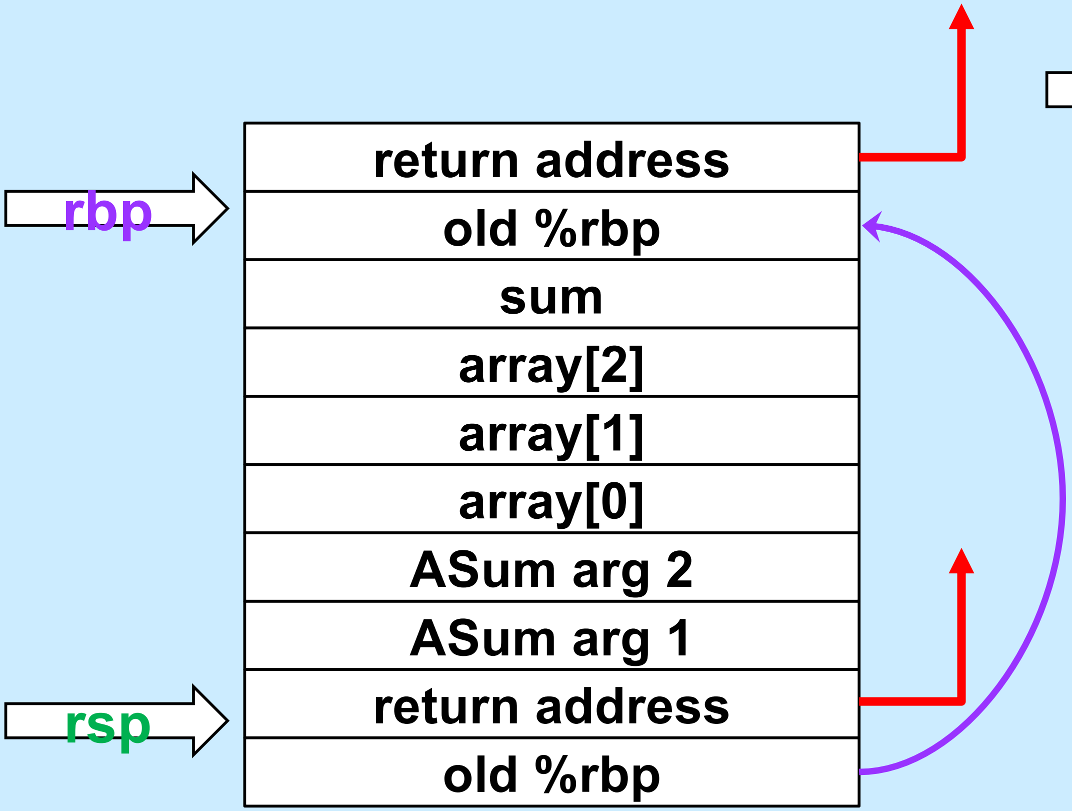
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Call ASum



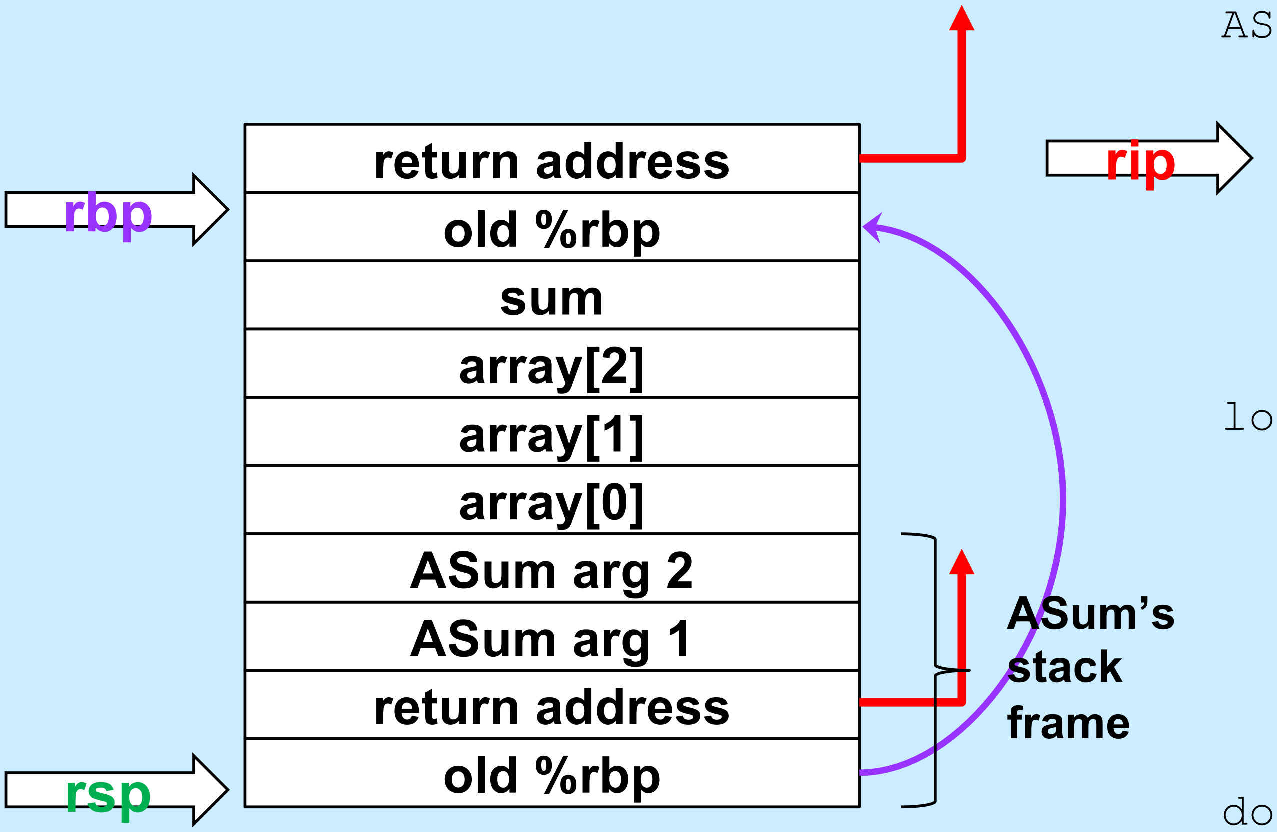
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Enter ASum



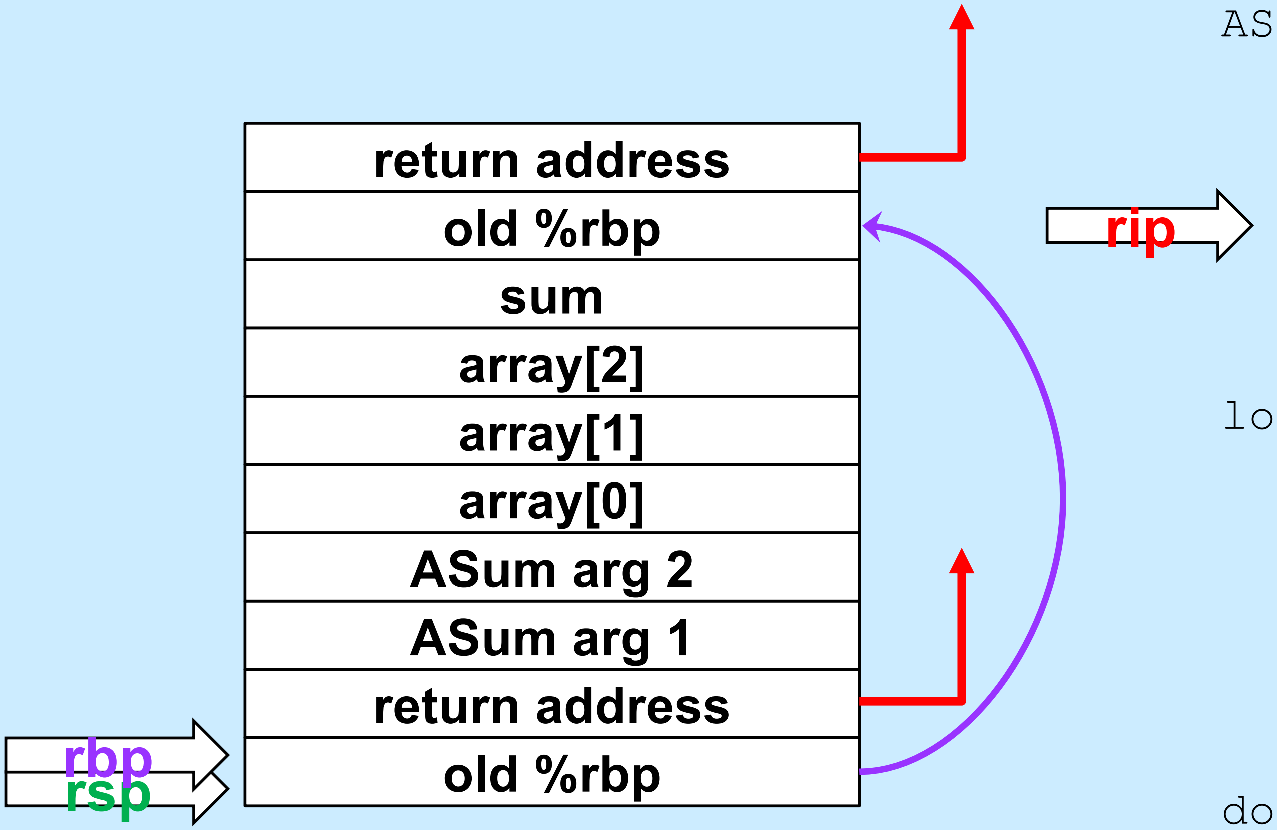
```
ASum:
    pushq %rbp
    movq %rsp, %rbp
    movq $0, %rcx
    movq $0, %rax
    movq 16(%rbp), %rdx
loop:
    cmpq 24(%rbp), %rcx
    jge done
    addq (%rdx,%rcx,8), %rax
    incq  %rcx
    ja loop
done:
    popq %rbp
    ret
```

Setup Frame



```
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
```

Execute the Function



```
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
```

Quiz 1

What's at 16(%rbp) (after the second instruction is executed)?

a) the first argument to ASum

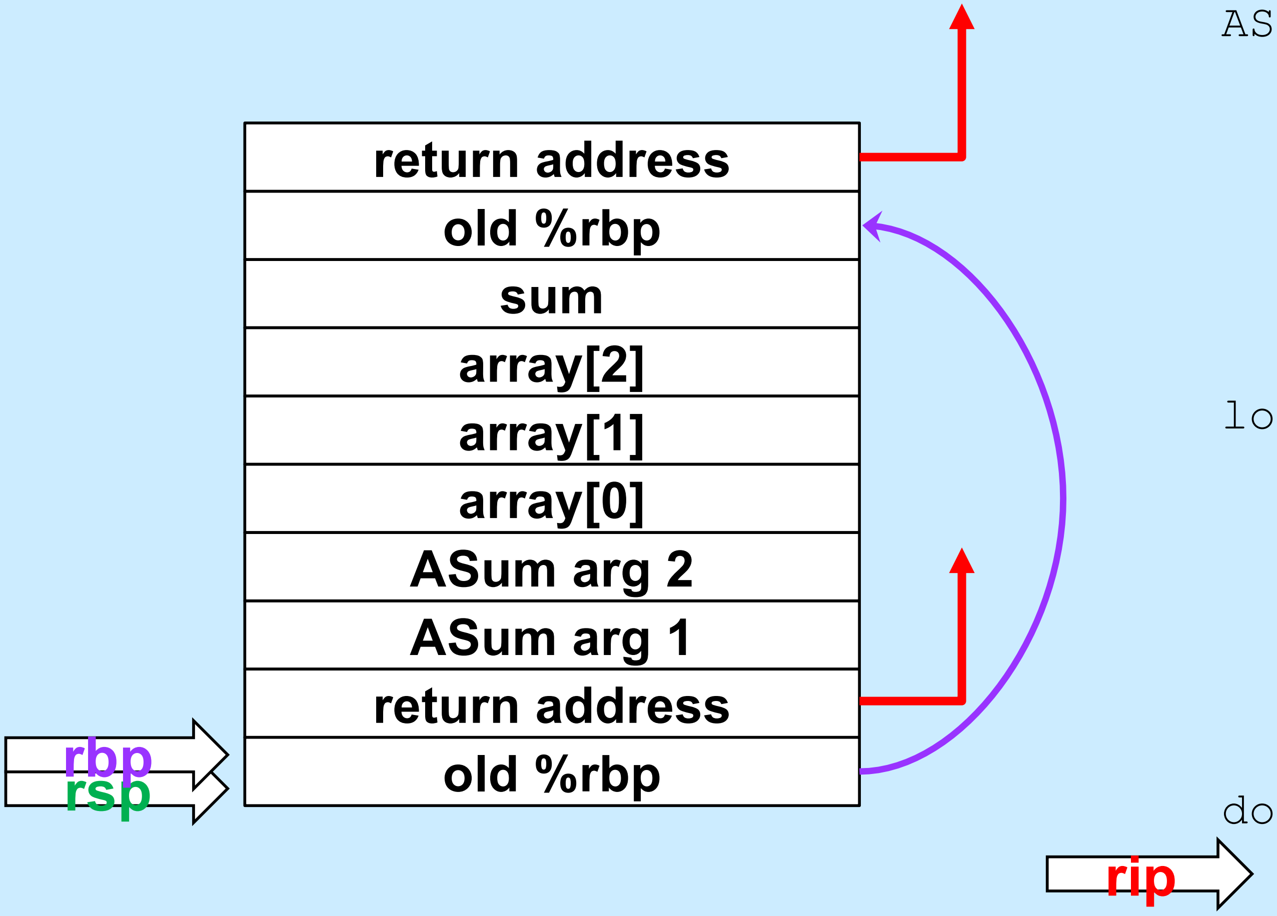
b) the second argument to ASum

c) a local variable

d) something else

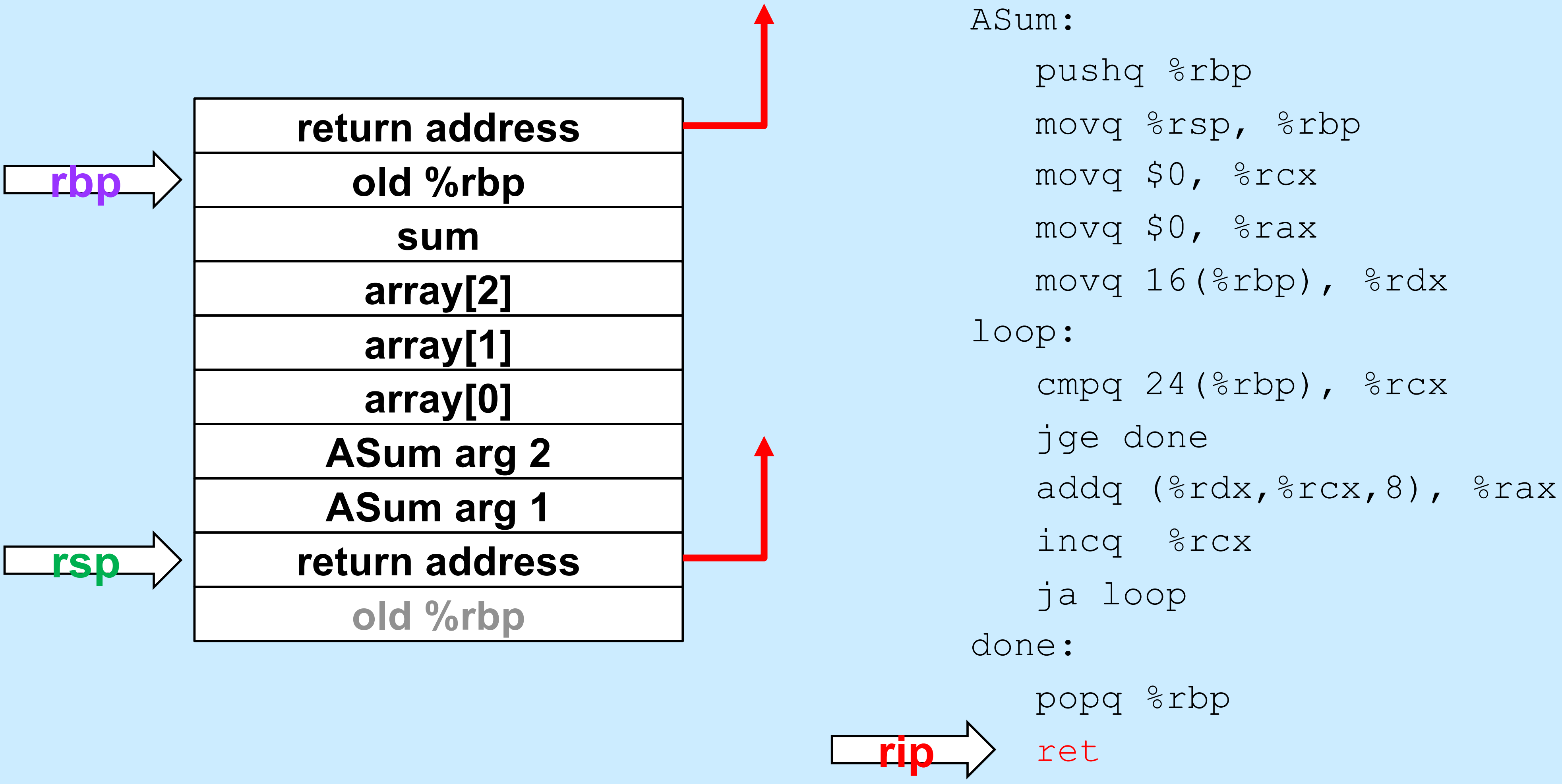
```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

Prepare to Return



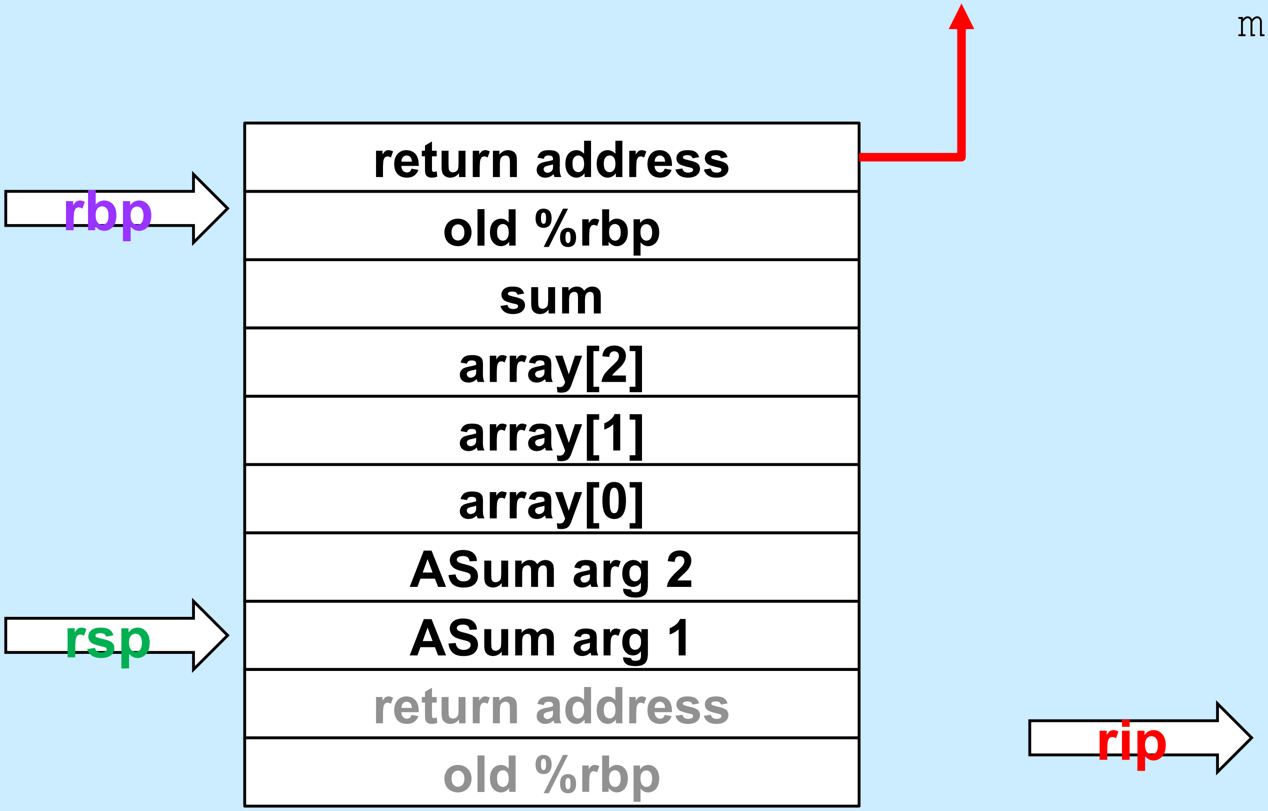
```
ASum:
    pushq %rbp
    movq %rsp, %rbp
    movq $0, %rcx
    movq $0, %rax
    movq 16(%rbp), %rdx
loop:
    cmpq 24(%rbp), %rcx
    jge done
    addq (%rdx,%rcx,8), %rax
    incq  %rcx
    ja loop
done:
    popq %rbp
    ret
```

Return



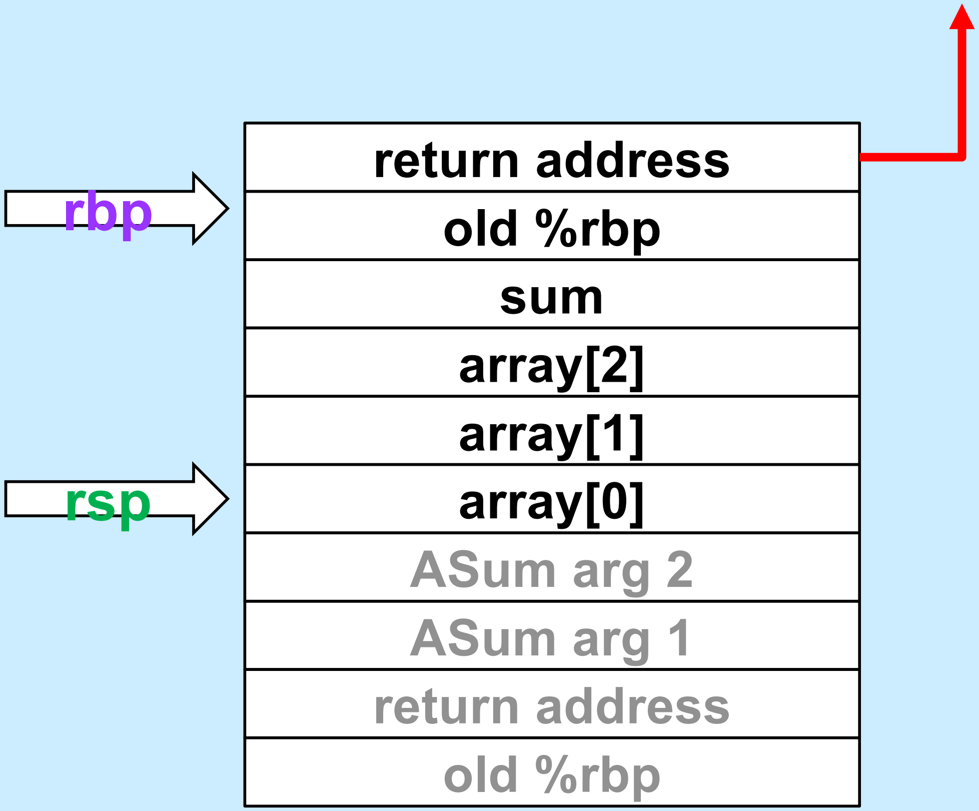
```
ASum:
   pushq %rbp
   movq %rsp, %rbp
   movq $0, %rcx
   movq $0, %rax
   movq 16(%rbp), %rdx
loop:
   cmpq 24(%rbp), %rcx
   jge done
   addq (%rdx,%rcx,8), %rax
   incq  %rcx
   ja loop
done:
   popq %rbp
   ret
```

Pop Arguments



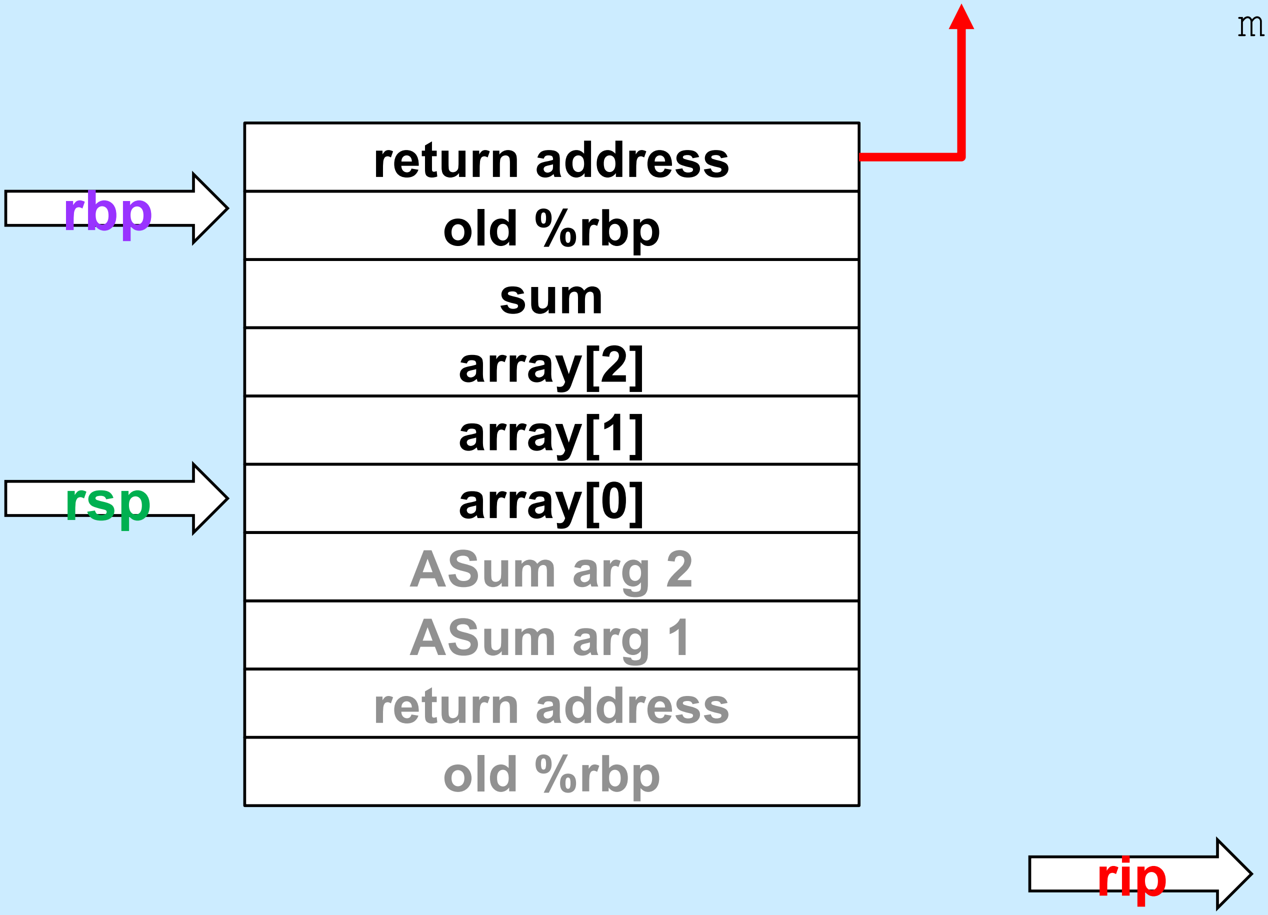
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

Save Return Value



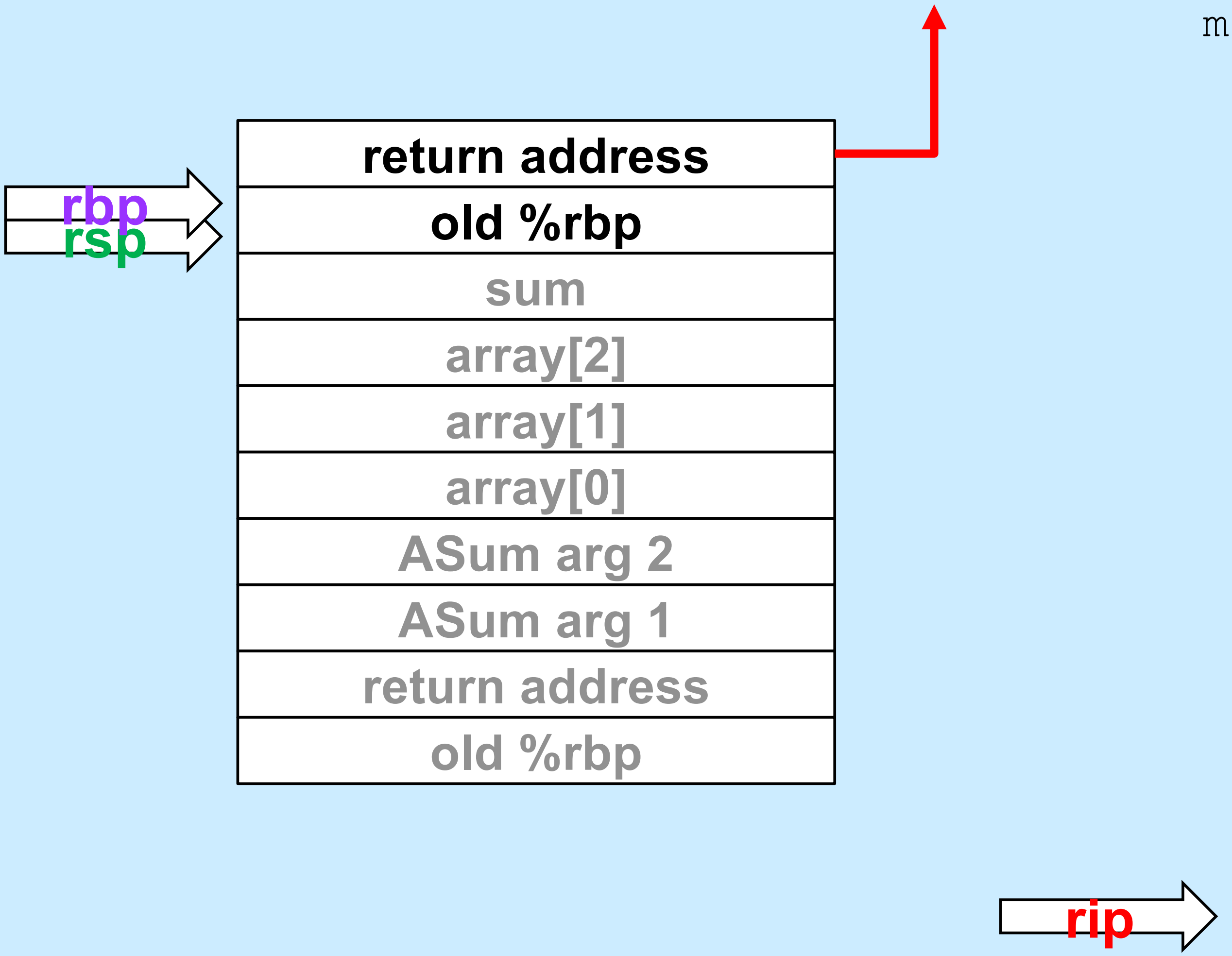
```
mainfunc:
    pushq %rbp
    movq %rsp, %rbp
    subq $32, %rsp
    movq $2, -32(%rbp)
    movq $117, -24(%rbp)
    movq $-6, -16(%rbp)
    pushq $3
    leaq -32(%rbp), %rax
    pushq %rax
    call ASum
    addq $16, %rsp
rip →
    movq %rax, -8(%rbp)
    addq $32, %rsp
    popq %rbp
    ret
```

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)
    addq $32, %rsp
    popq %rbp
    ret
```

Prepare to Return



return address

old %rbp

sum

array[2]

array[1]

array[0]

ASum arg 2

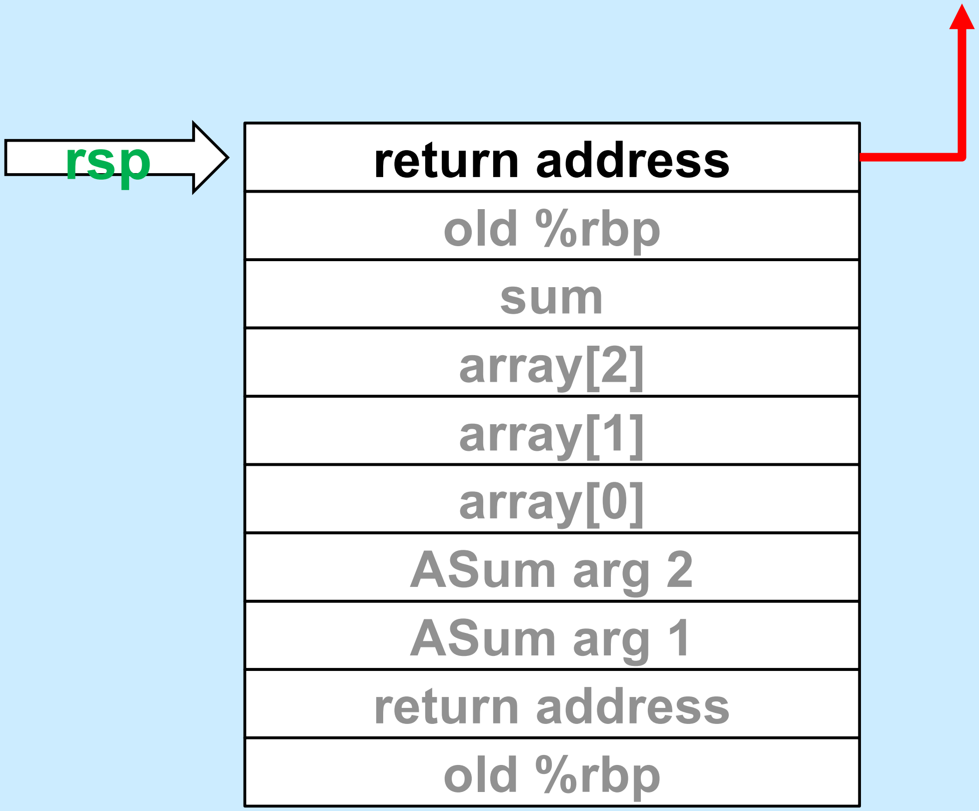
ASum arg 1

return address

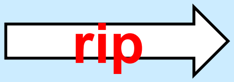
old %rbp

```
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

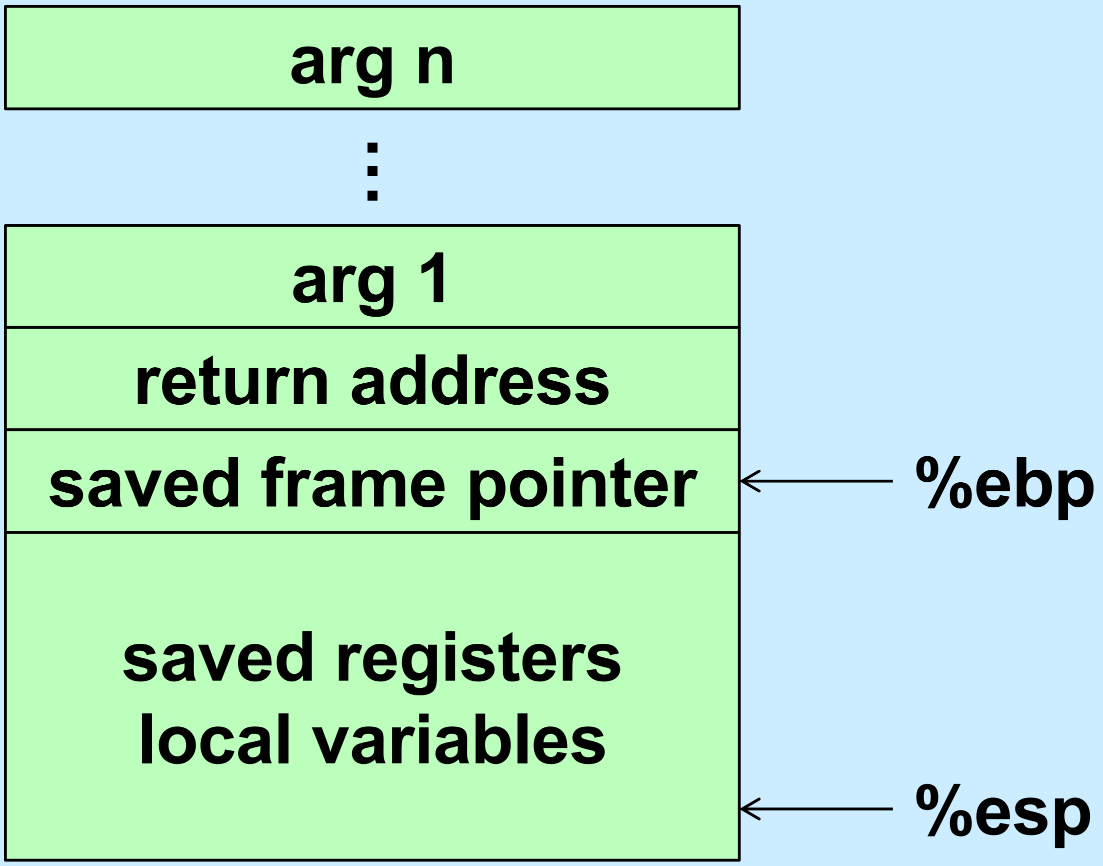
Why Bother with a Base Pointer?

- 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

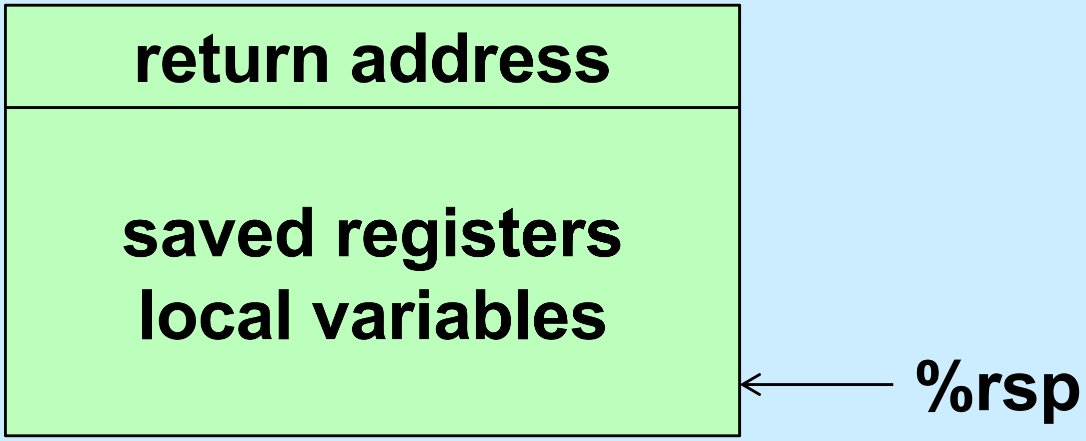
x86-64 General-Purpose Registers: Updated Usage Conventions

`%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

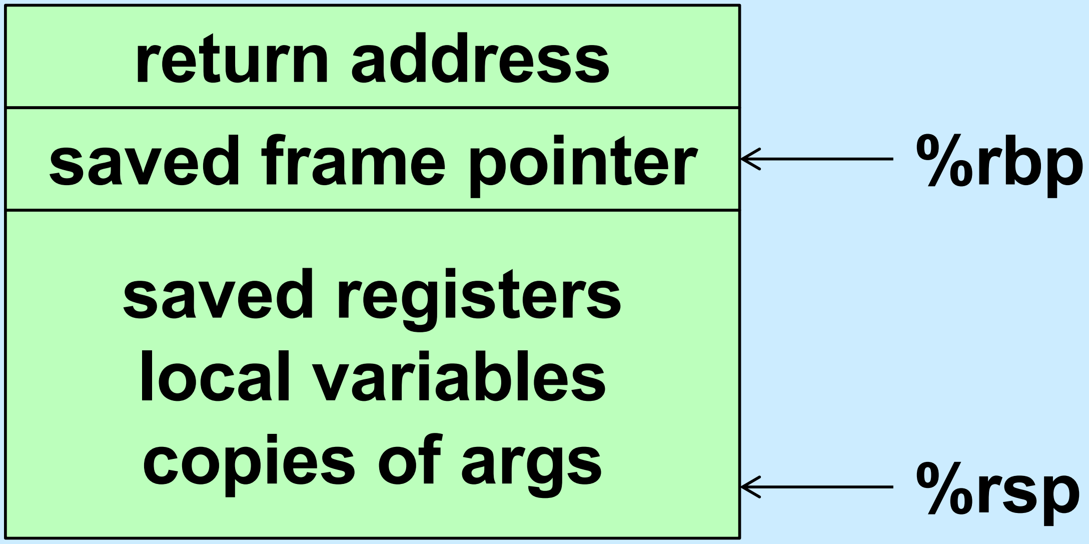
The IA32 Stack Frame



The x86-64 Stack Frame



The -O0 x86-64 Stack Frame (Buffer)



return address

saved frame pointer

saved registers
local variables
copies of args

%rbp

%rsp

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 2

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) Both work

b) Neither case will work

c) A calling B works, but B calling A doesn’t

d) B calling A works, but A calling B doesn’t

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:

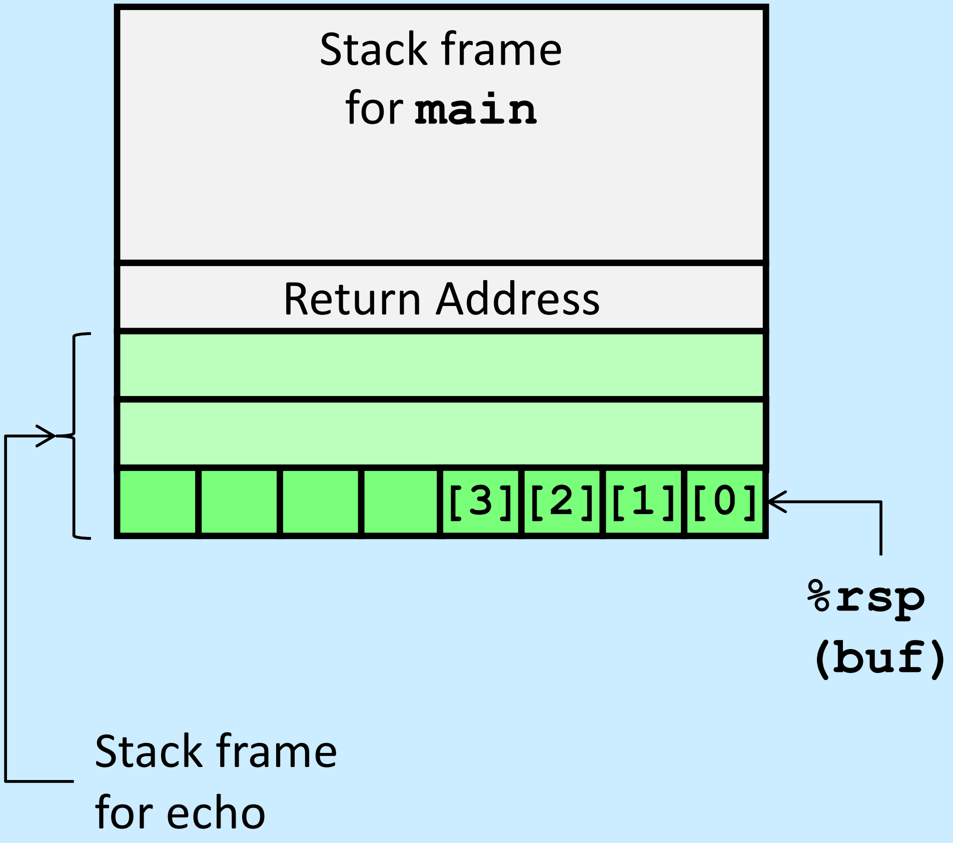
```
000000000040054c <echo>:
  40054c:       48 83 ec 18       sub    $0x18,%rsp
  400550:       48 89 e7          mov    %rsp,%rdi
  400553:       e8 d8 fe ff ff    callq  400430 <gets@plt>
  400558:       48 89 e7          mov    %rsp,%rdi
  40055b:       e8 b0 fe ff ff    callq  400410 <puts@plt>
  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

Before call to gets

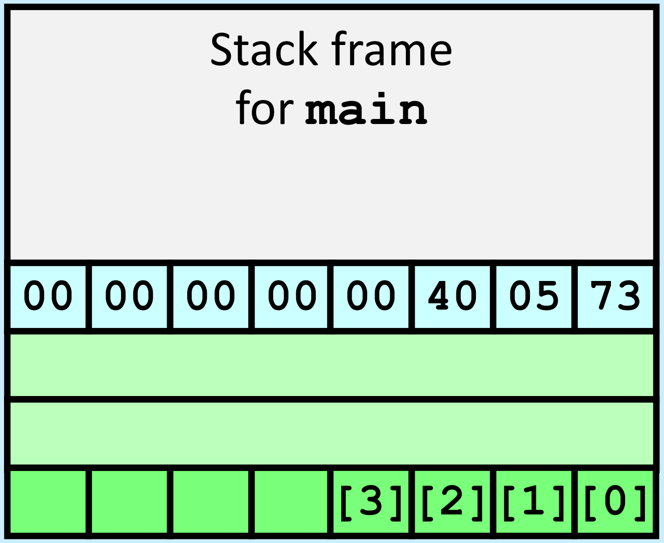


```
/* Echo Line */
void echo()
{
    char buf[4];  /* Too small! */
    gets(buf);
    puts(buf);
}
```

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

Buffer Overflow Stack Example

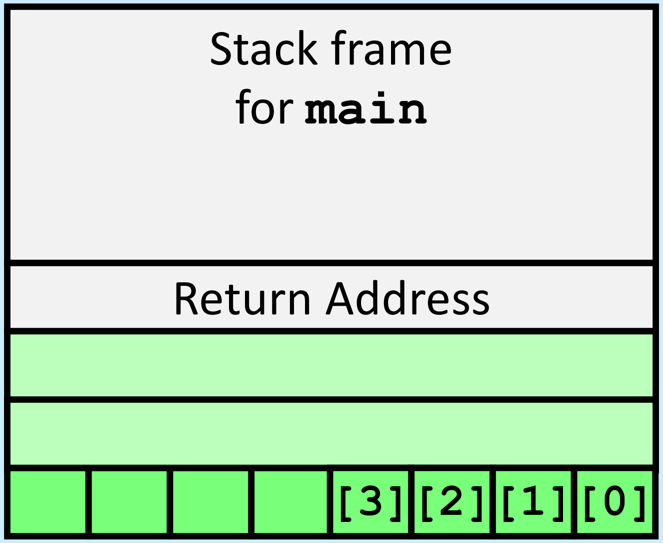
```
unix> gdb echo
(gdb) break echo
Breakpoint 1 at 0x40054c
(gdb) run
Breakpoint 1, 0x000000000040054c in echo ()
(gdb) print /x $rsp
$1 = 0x7fffffffe988
(gdb) print /x *(unsigned *)$rsp
$2 = 0x400573
```



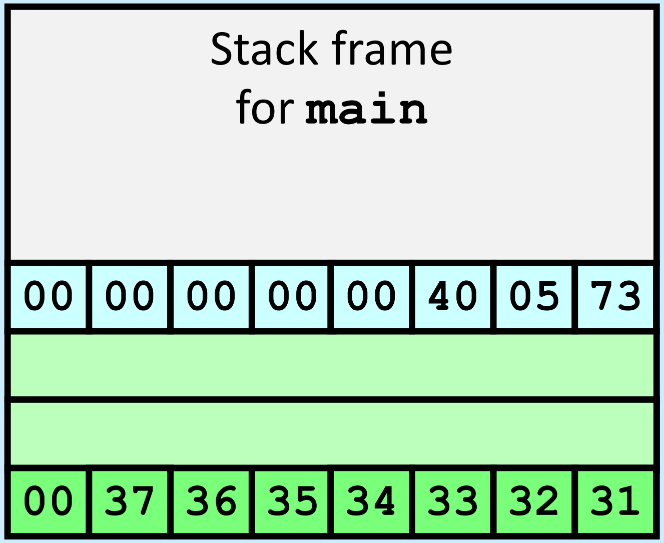
```
40056e:       e8 d9 ff ff ff    callq  40054c <echo>
400573:       b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #1

Before call to gets



Input 1234567

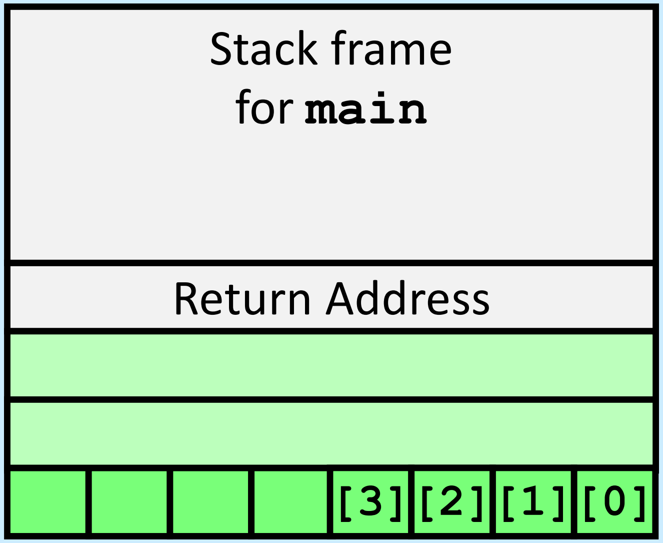


Overflow buf, but no problem

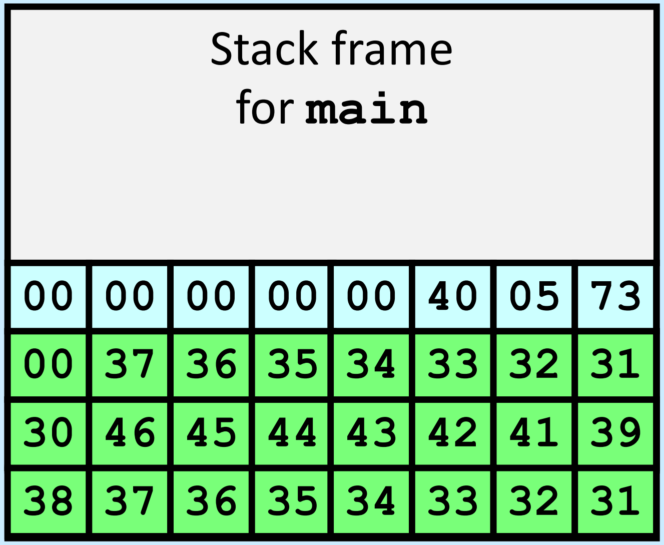
```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #2

Before call to gets



Input 123456789ABCDEF01234567



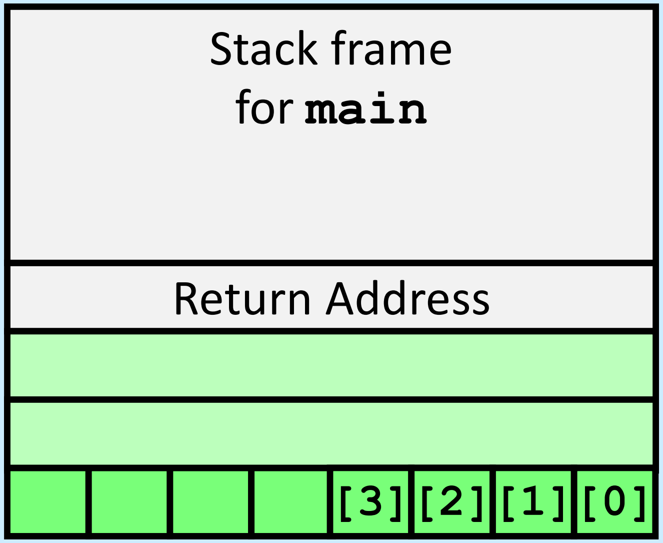
```
00 00 00 00 00 40 05 73
00 37 36 35 34 33 32 31
30 46 45 44 43 42 41 39
38 37 36 35 34 33 32 31
```

Still no problem

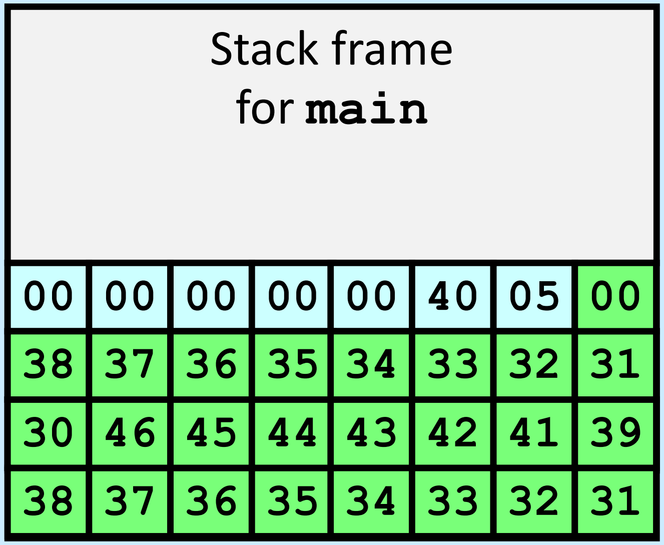
```
40056e:      e8 d9 ff ff ff    callq  40054c <echo>
400573:      b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #3

Before call to gets



Input 123456789ABCDEF012345678



00	00	00	00	00	40	05	00
38	37	36	35	34	33	32	31
30	46	45	44	43	42	41	39
38	37	36	35	34	33	32	31

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**

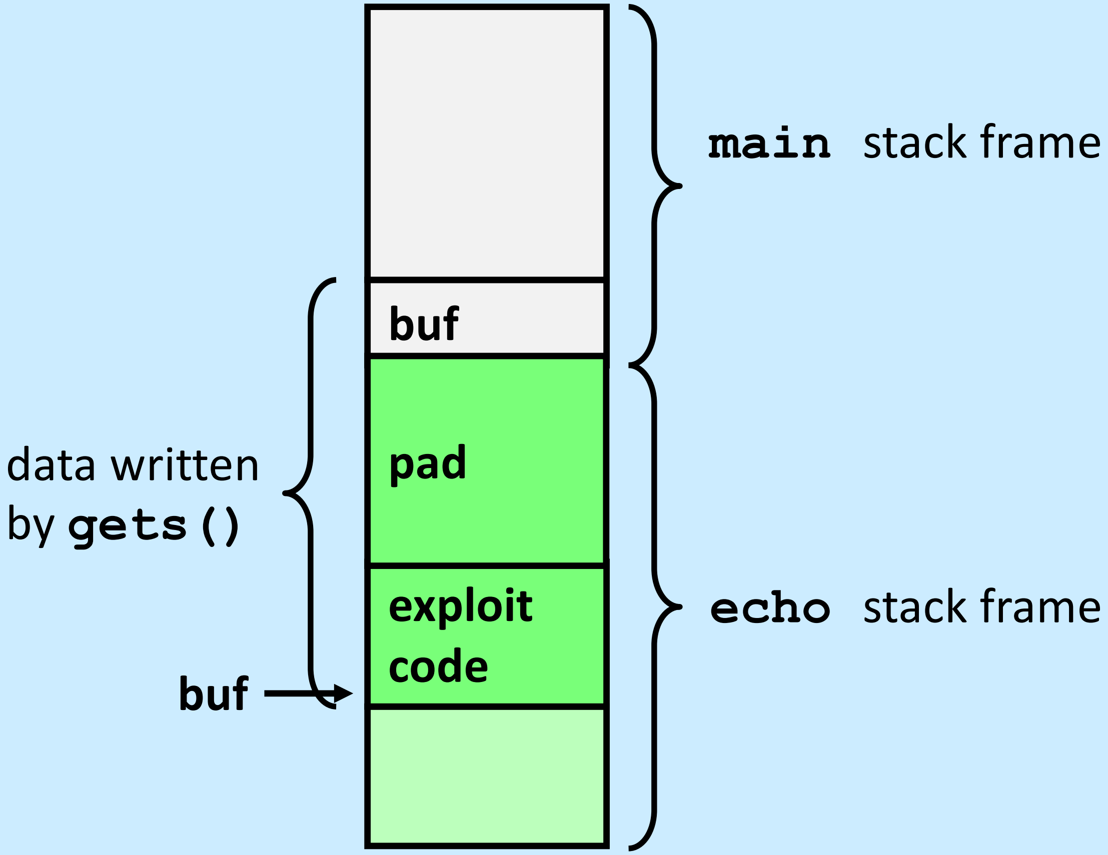
Malicious Use of Buffer Overflow

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

return
address
A

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

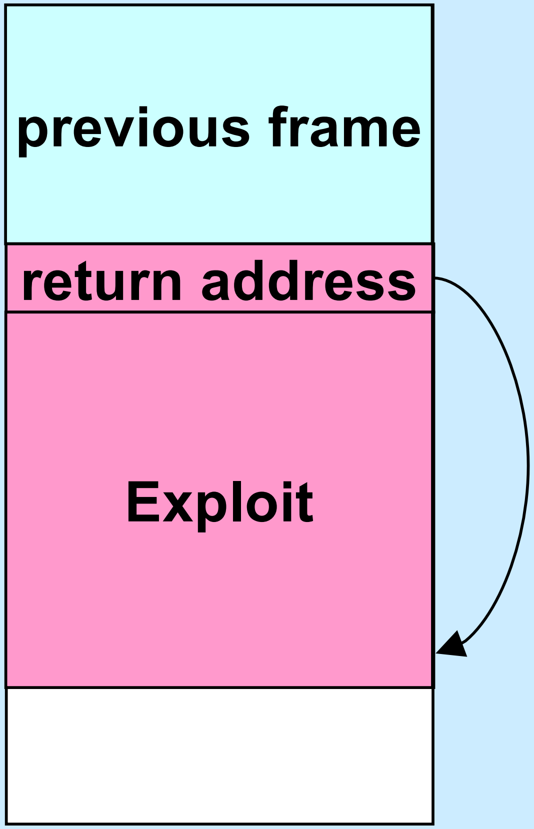
Stack after call to **gets()**



- **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**

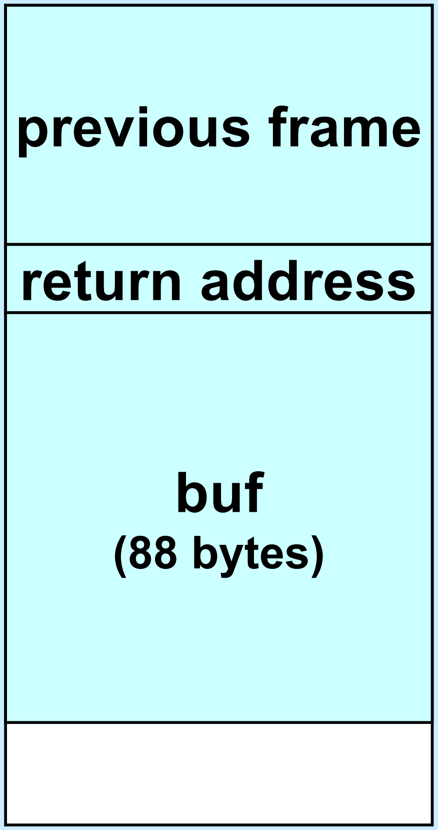
```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
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",
       strlen("hacked by twd"));
  exit(0);
}
```

Quiz 3

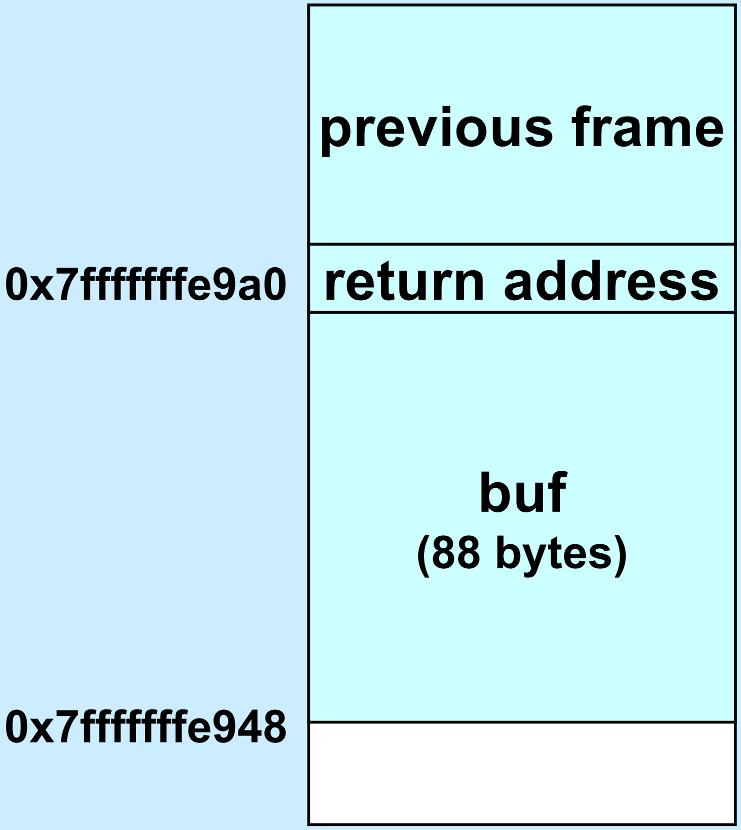
The exploit code will be read into memory starting at location 0x7fffffffe948. What value should be put into the return-address portion of the stack frame?

a) 0

b) 0x7fffffffe948

c) 0x7fffffffe9a0

d) it doesn’t matter what value goes there



previous frame

0x7fffffffe9a0 return address

buf
(88 bytes)

0x7fffffffe948