Computer Systems Principles

x86-64 Assembly (Part 3)

Annoucement

- HW6 is out (due Mar. 28)

Objectives

- x86-64 Assembly Language
  - To learn about procedure call and return
  - To learn about array

Procedure Overview

Mechanisms in Procedures

```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point

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x86-64 Stack

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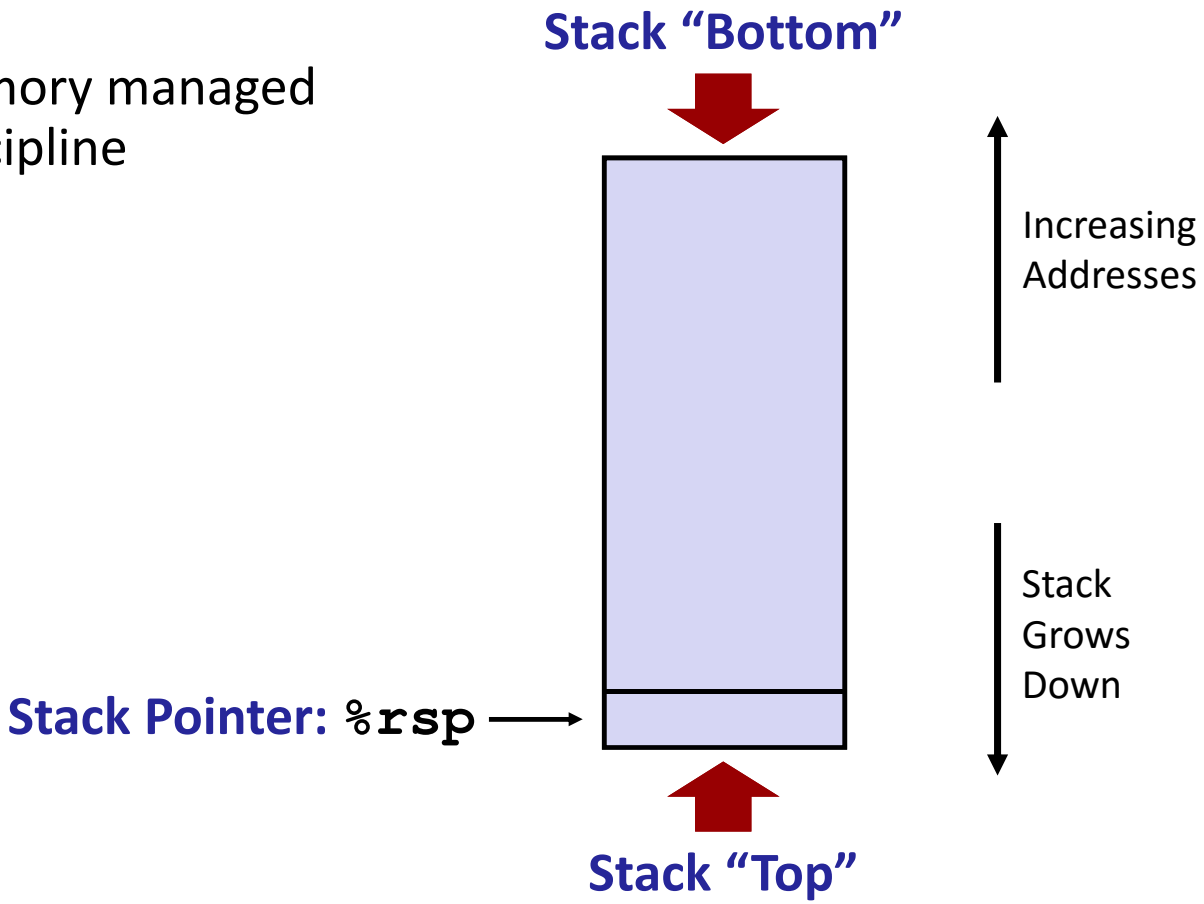
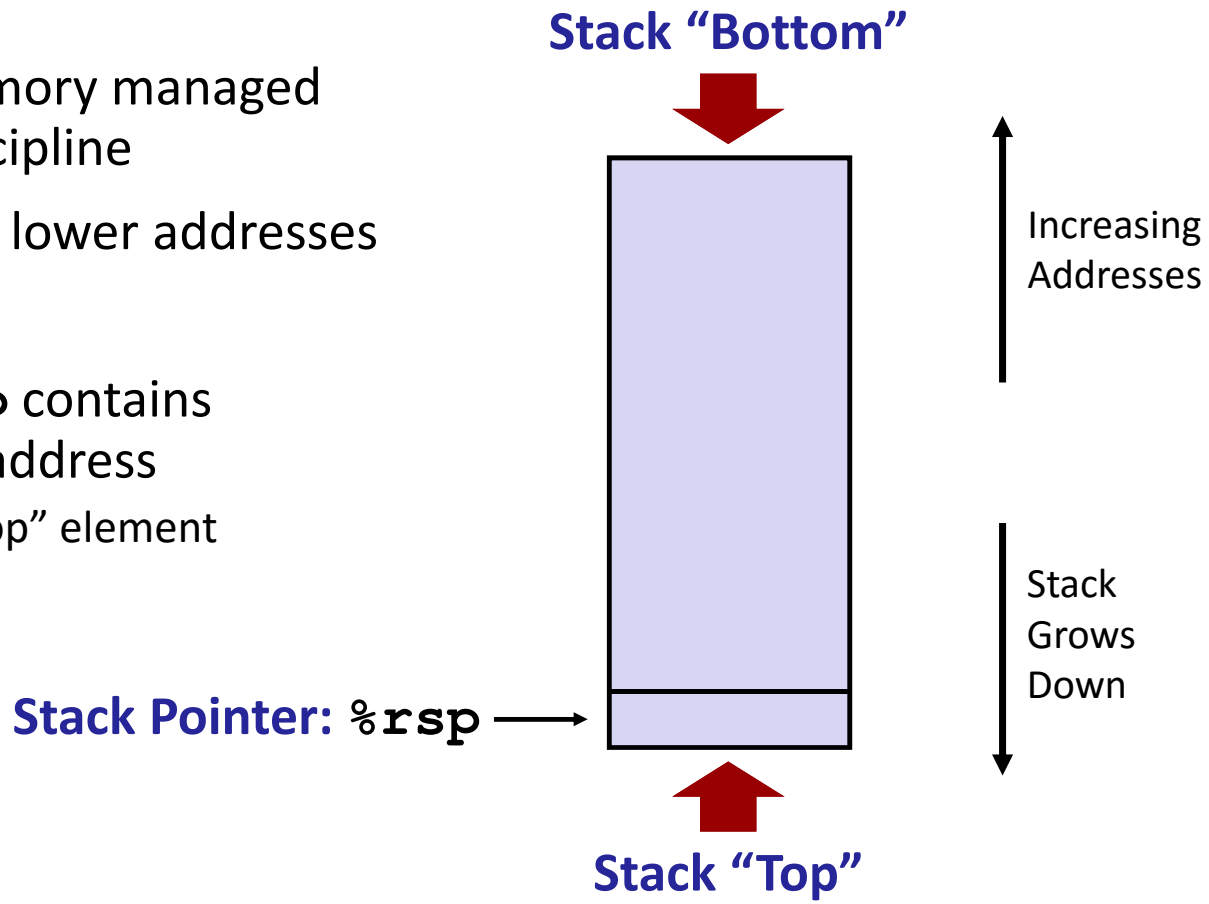
- Region of memory managed with stack discipline



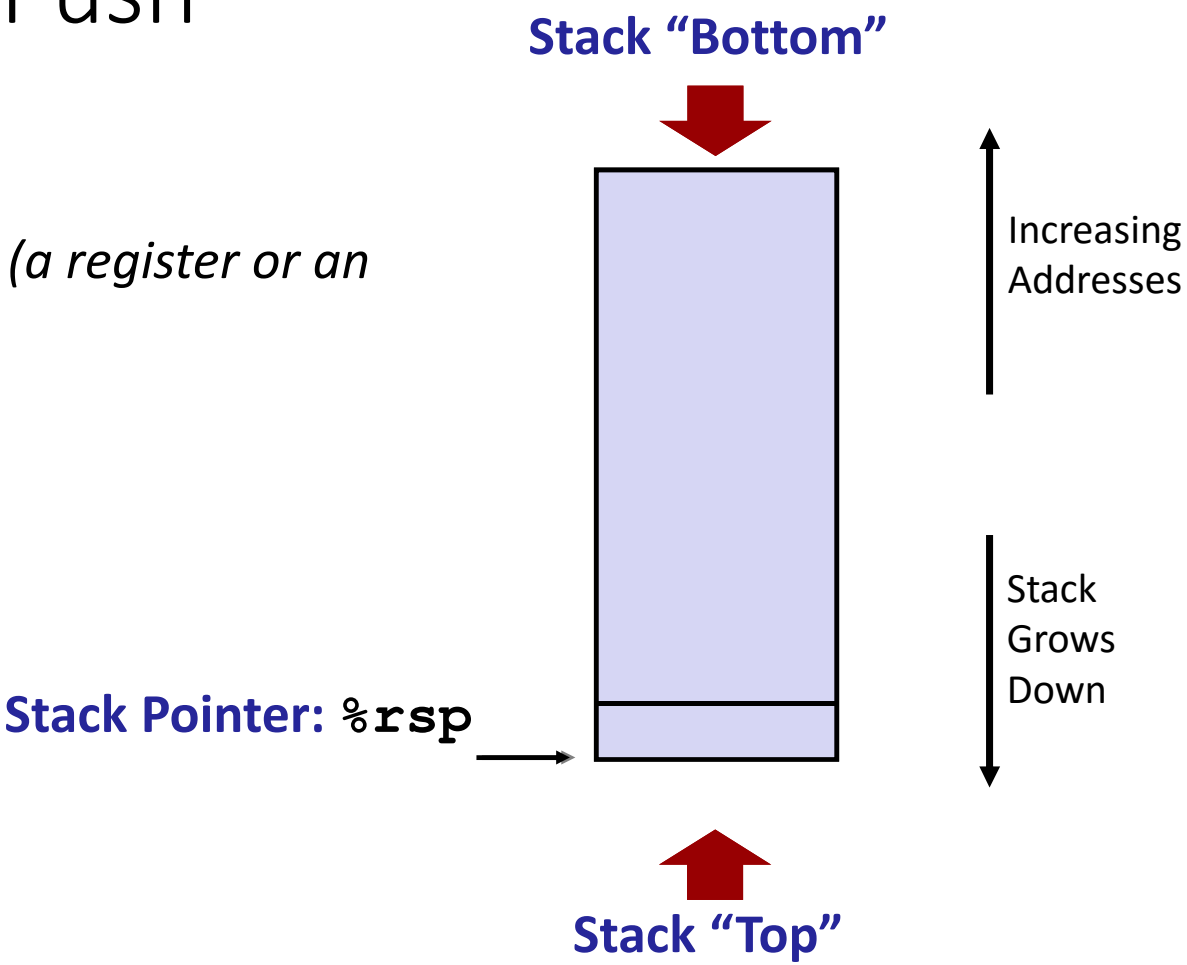
x86-64 Stack

- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register **`%rsp`** contains lowest stack address
  - address of "top" element



x86-64 Stack: Push

- **`pushq` *Src***
  - Fetch operand at *Src (a register or an immediate)*



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- **`pushq` *Src***
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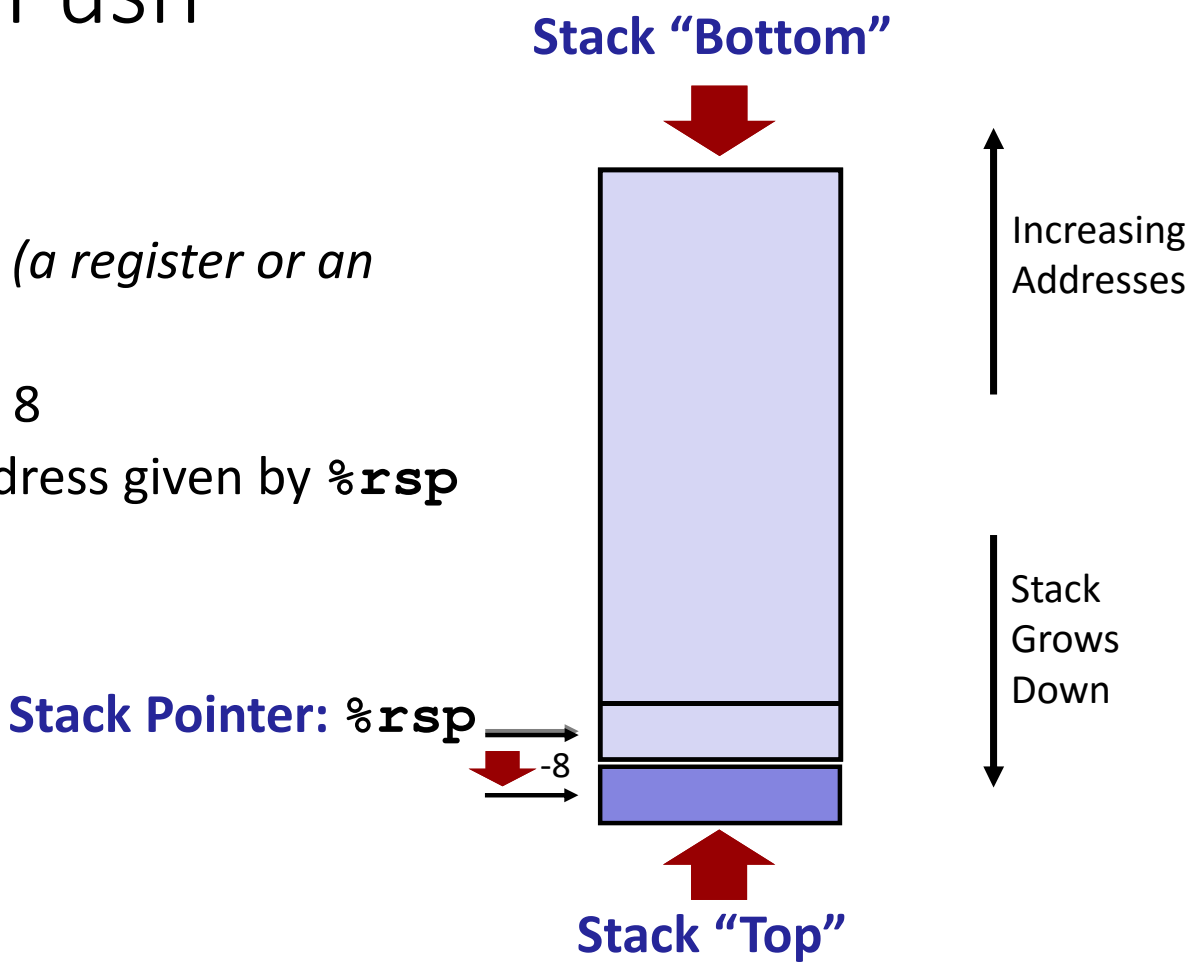

x86-64 Stack: Pop

- **`popq`** ***Dest***
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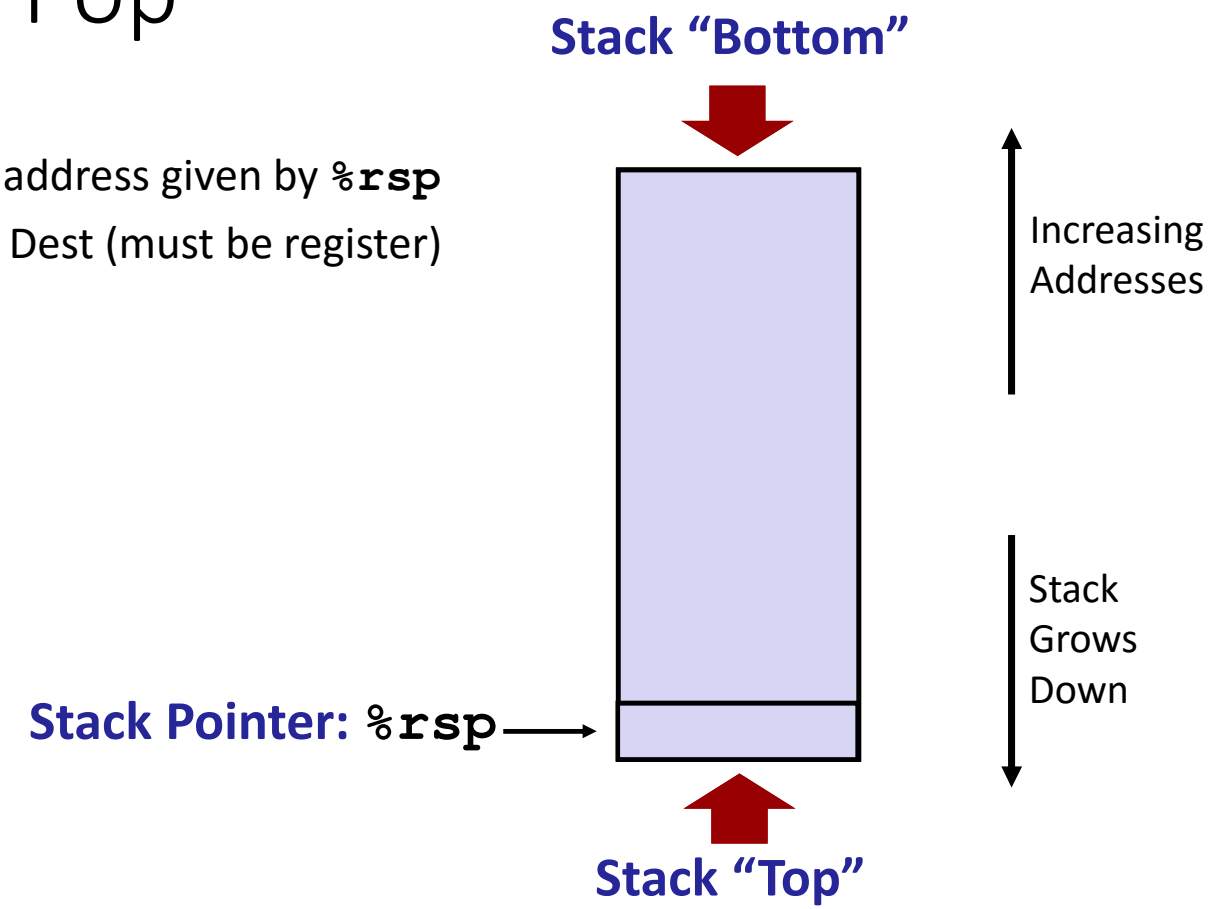

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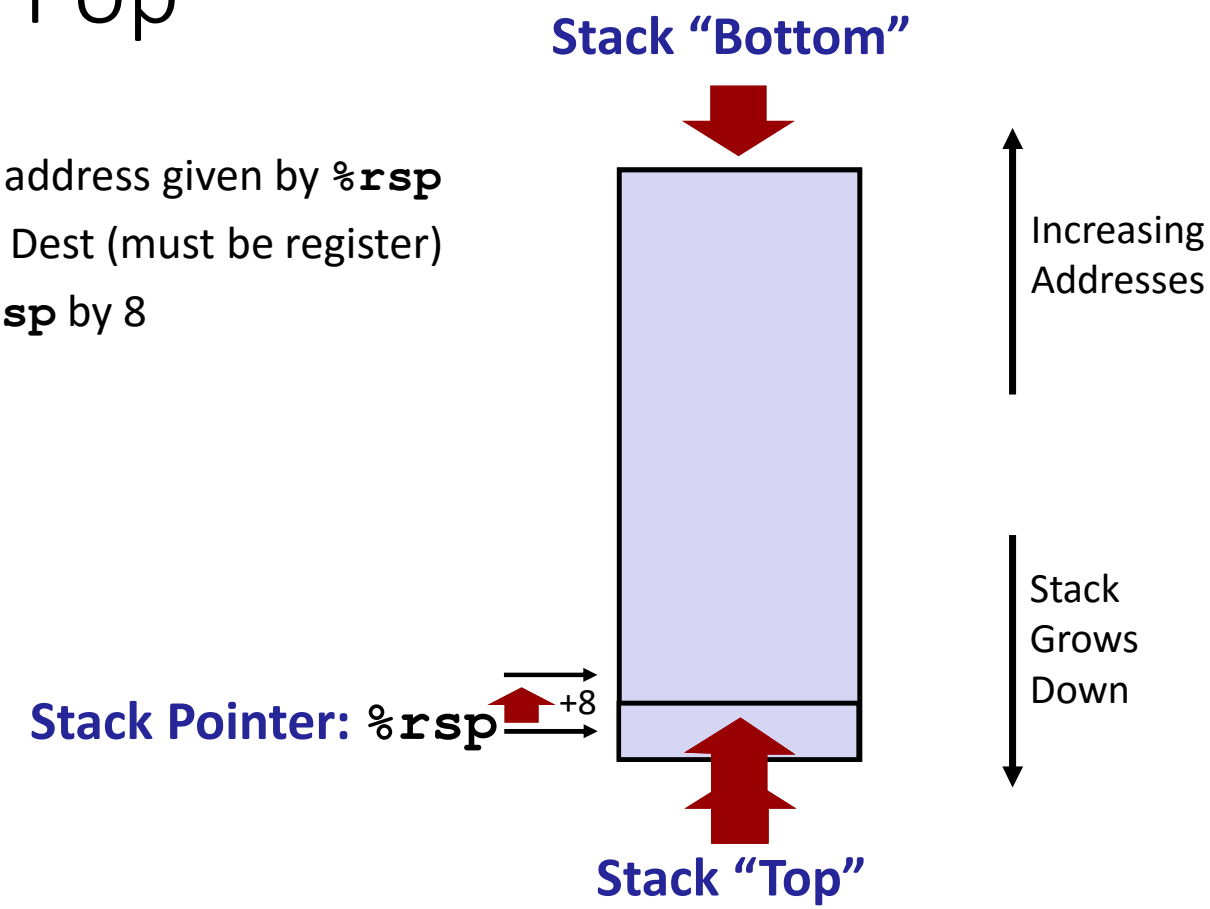

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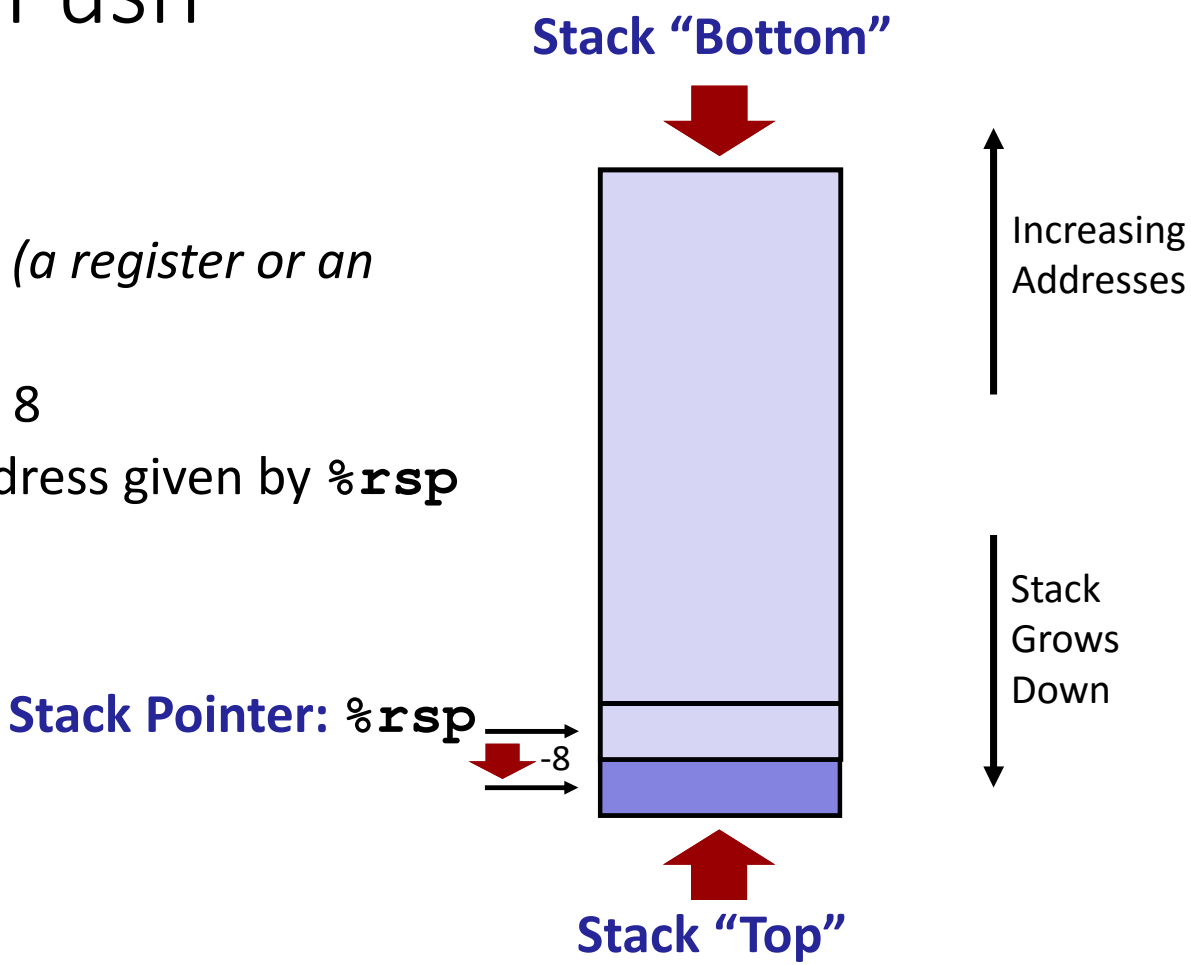

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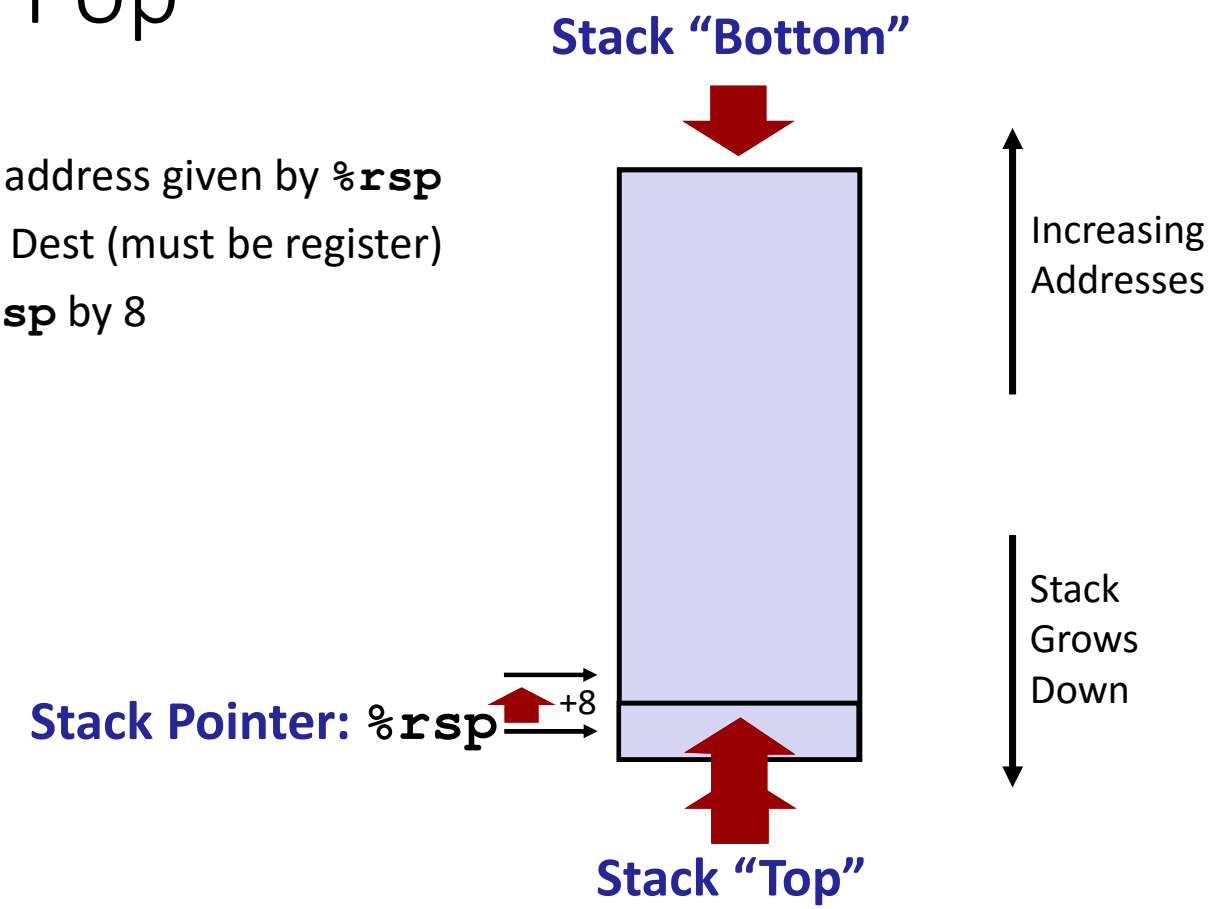

Call and Return

Code Examples

```
void multstore
 (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  400540: push   %rbx              # Save %rbx
  400541: mov    %rdx,%rbx         # Save dest
  400544: callq  400550 <mult2>    # mult2(x,y)
  400549: mov    %rax,(%rbx)       # Save at dest
  40054c: pop    %rbx              # Restore %rbx
  40054d: retq                     # Return
```

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long mult2
  (long a, long b)
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Procedure Control Flow

- Use stack to support procedure call and return
- Procedure call: **`call label`**
  - Push return address on stack
  - Jump to ***label***
- Return address:
  - Address of the next instruction right after call
  - Example from disassembly
- Procedure return: **`ret`**
  - Pop address from stack
  - Jump to address

Control Flow Example

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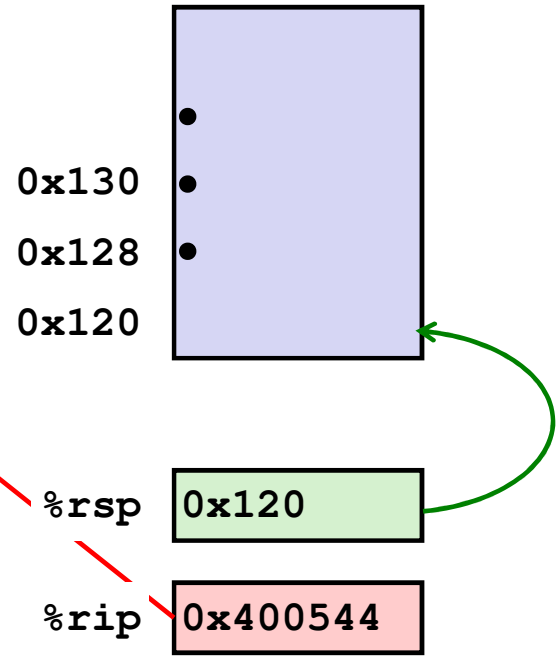

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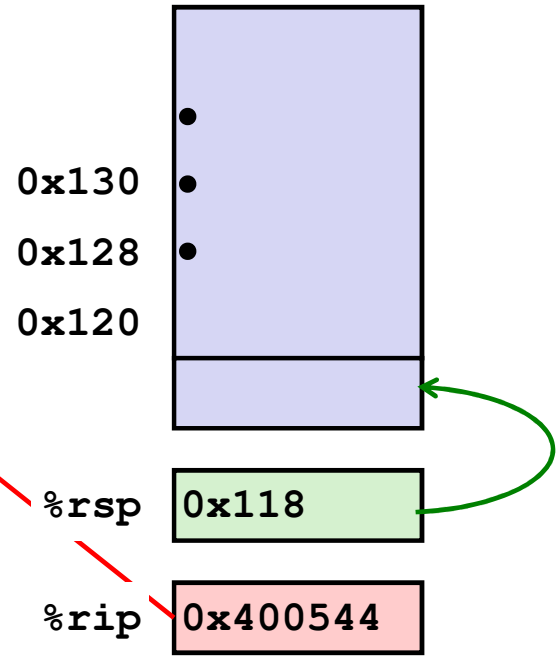

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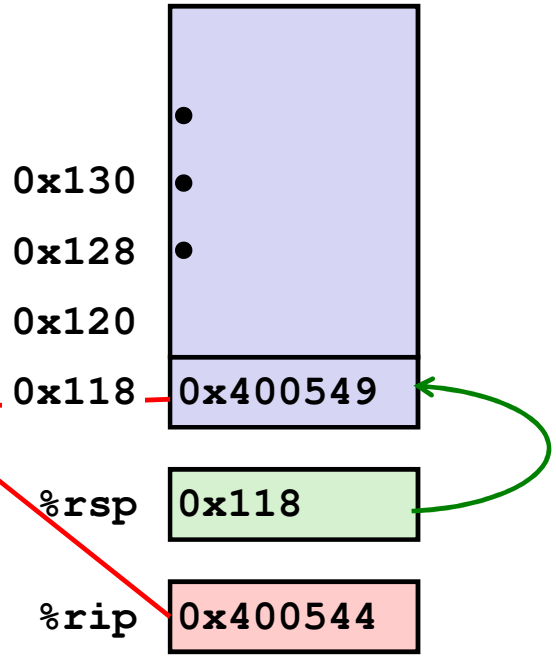

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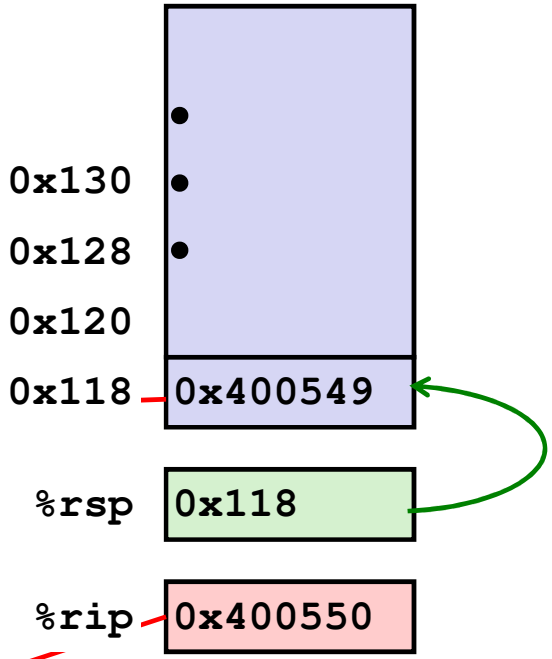

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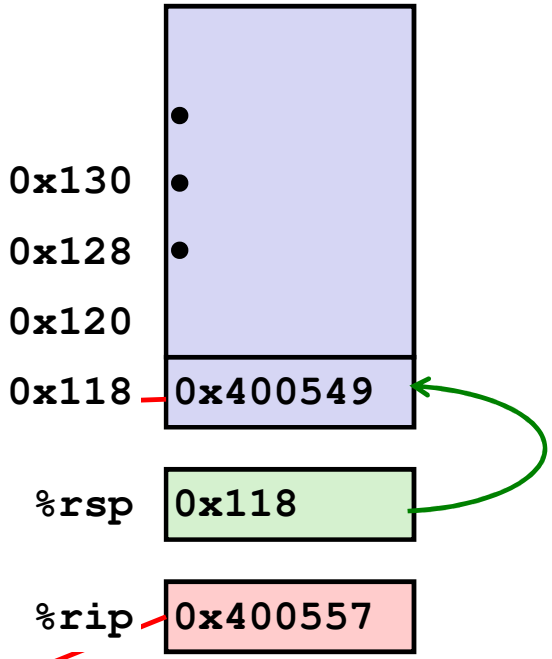

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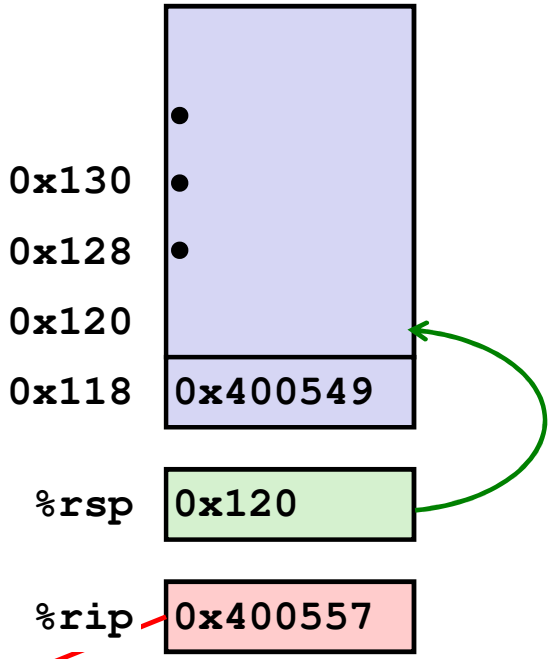

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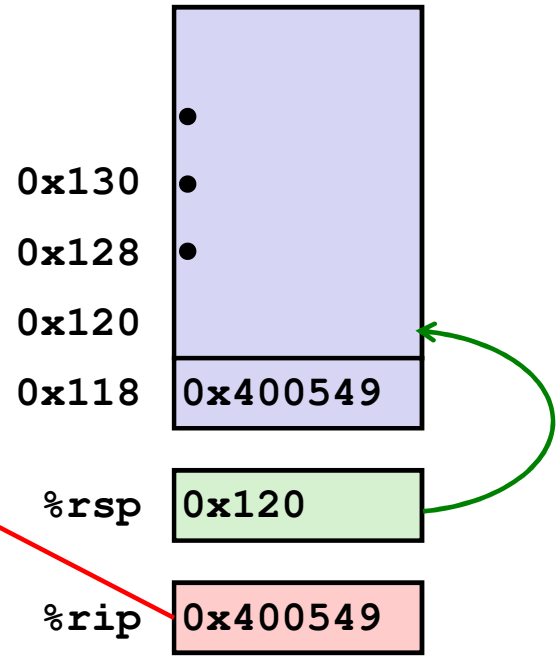

Parameter and Return Value Convention

Procedure Data Flow

Registers

- First 6 arguments

`%rdi`
`%rsi`
`%rdx`
`%rcx`
`%r8`
`%r9`

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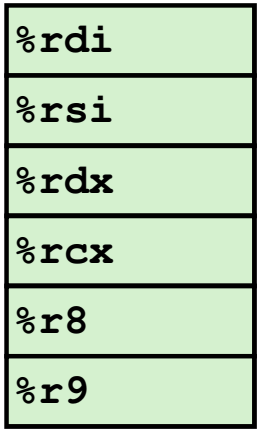
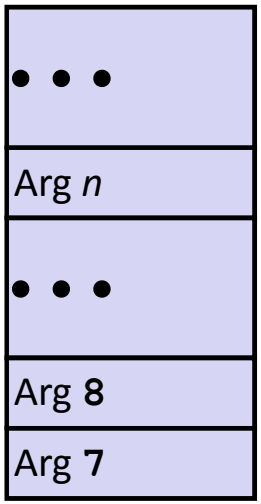


Stack



- Only allocate stack space when needed

Procedure Data Flow

Registers

- First 6 arguments

`%rdi`
`%rsi`
`%rdx`
`%rcx`
`%r8`
`%r9`

- Return value

`%rax`

Stack

• • •
Arg *n*
• • •
Arg **8**
Arg **7**

- Only allocate stack space when needed

Data Flow Examples

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  •••
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Managing Local Data

Stack-Based Languages

- Need some place to store state of each instantiation
  - Arguments
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  - From when called to when return
- Stack allocated in ***Frames***
  - state for single procedure instantiation

Call Chain Example

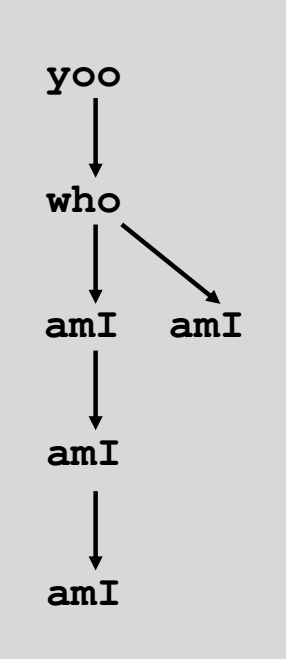
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```

Procedure `amI()` is recursive

Example Call Chain



Stack Frames

- Contents
  - Return information
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  - Temporary storage (if needed)

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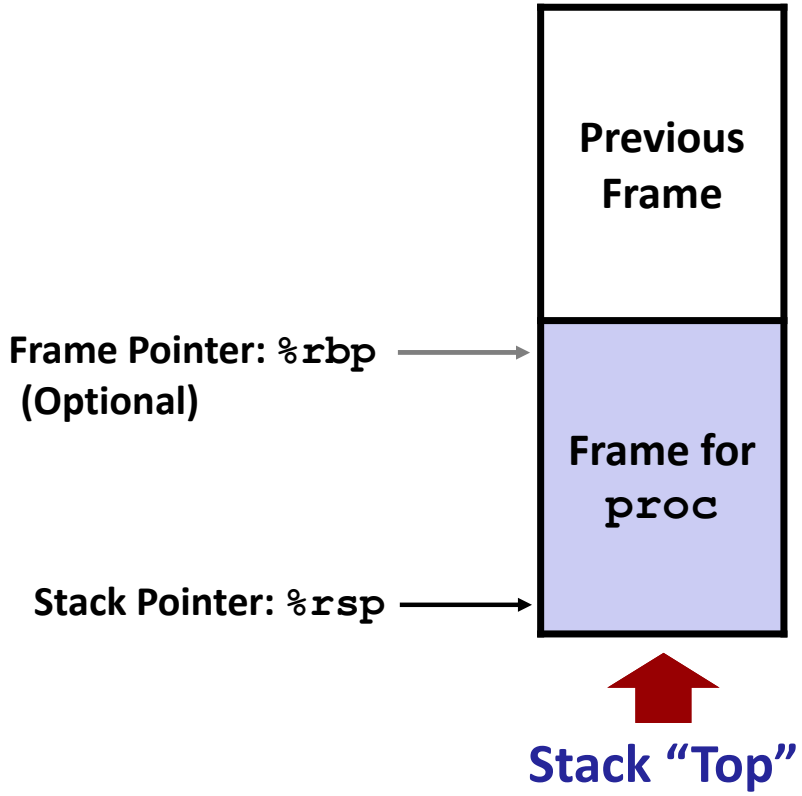

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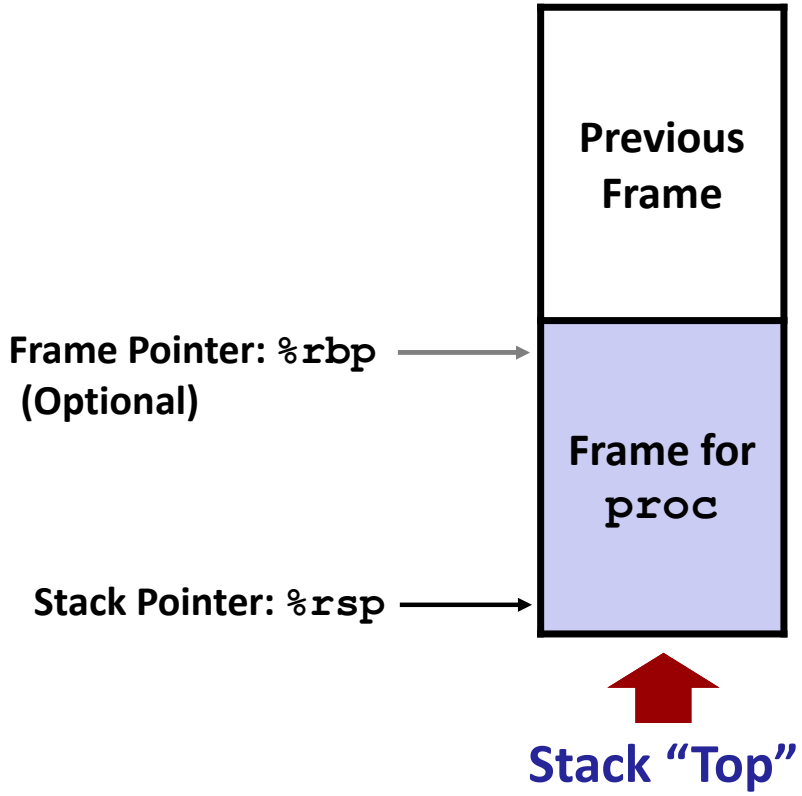

- Management
  - Space allocated when enter procedure
    - "Set-up" code
    - Includes push by **`call`** instruction
  - Deallocated when return
    - "Finish" code
    - Includes pop by **`ret`** instruction

Example

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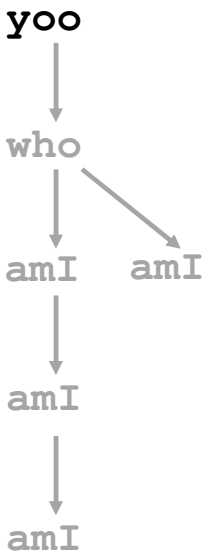
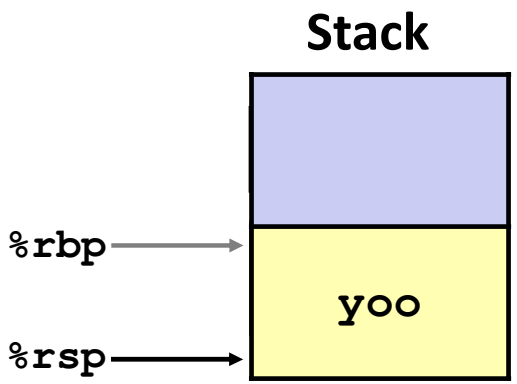
{
   •
   •
   who();
   •
   •
}
```





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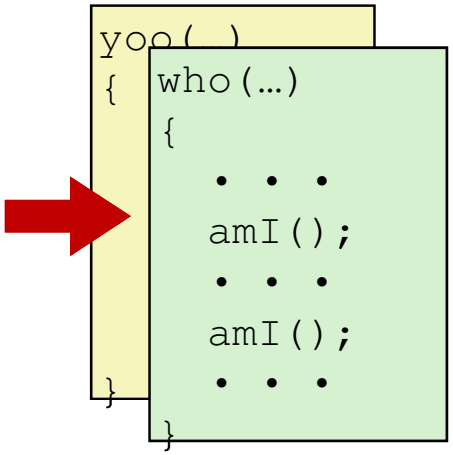

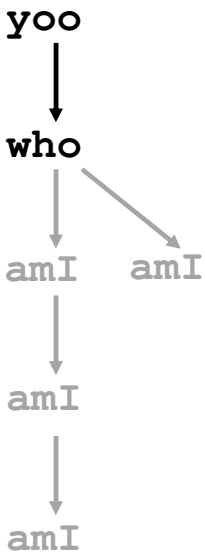

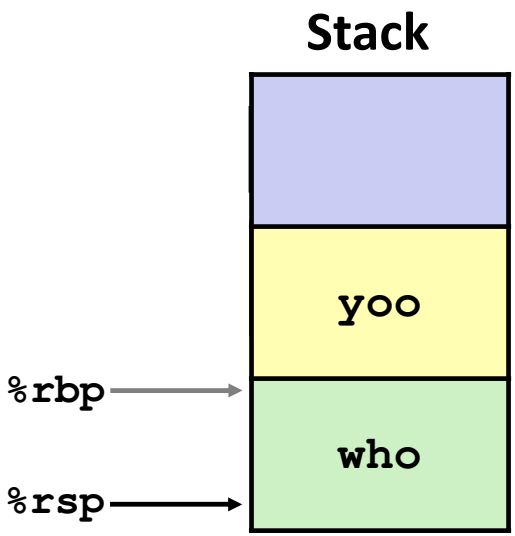

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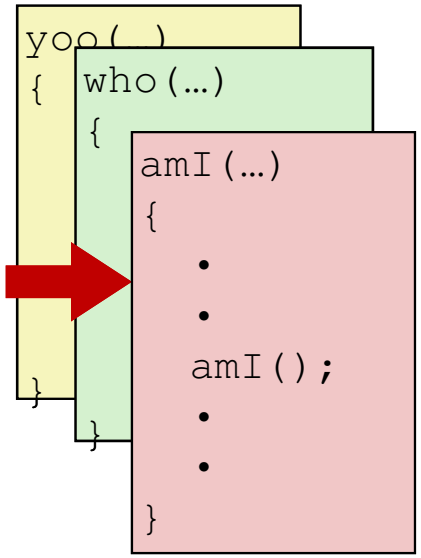
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who(…)
{
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amI(…)
{
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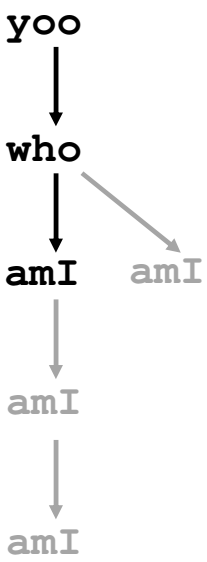
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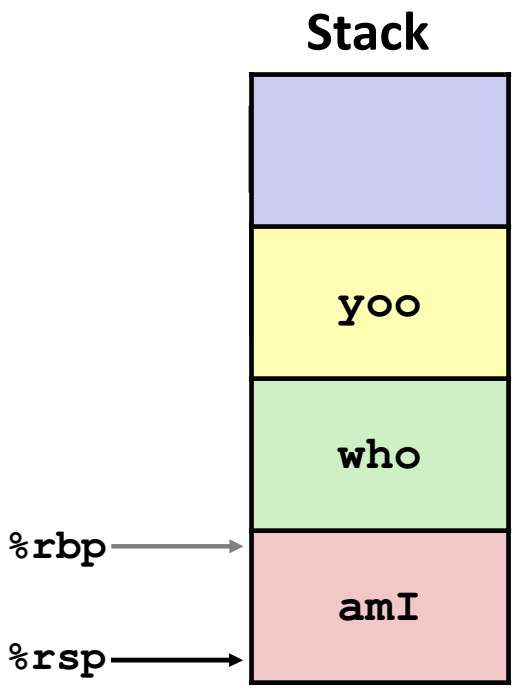
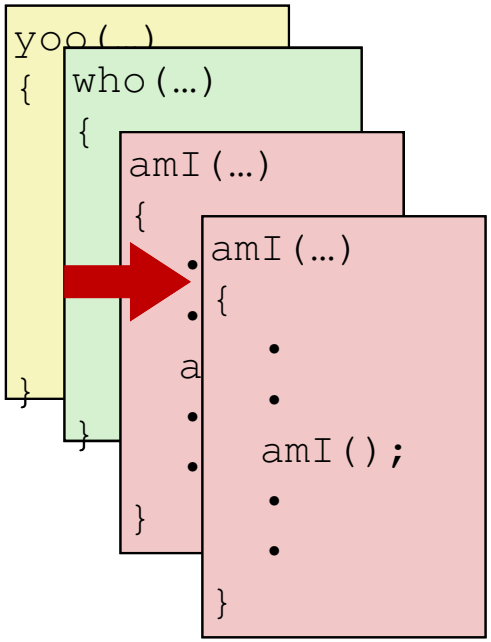

Stack
yoo
who
amI
%rbp
%rsp

Example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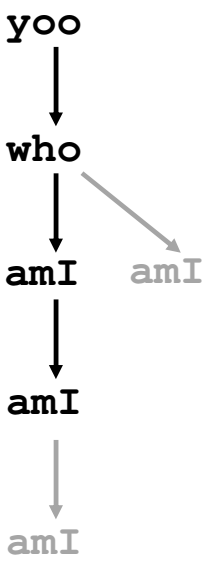
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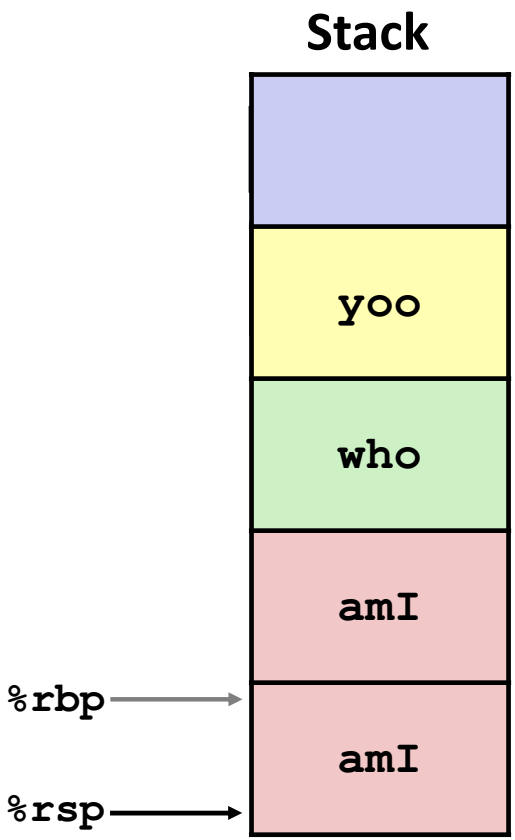
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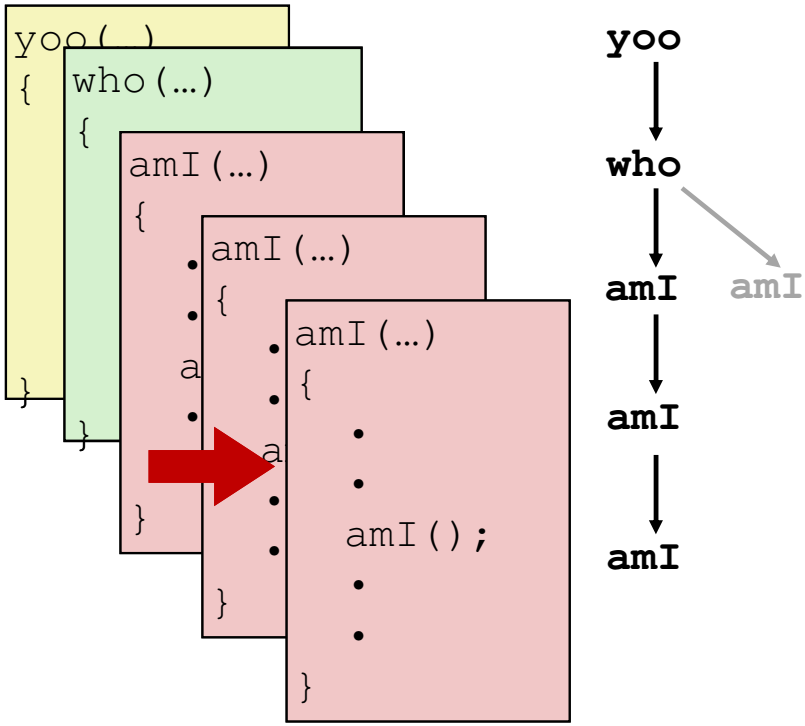
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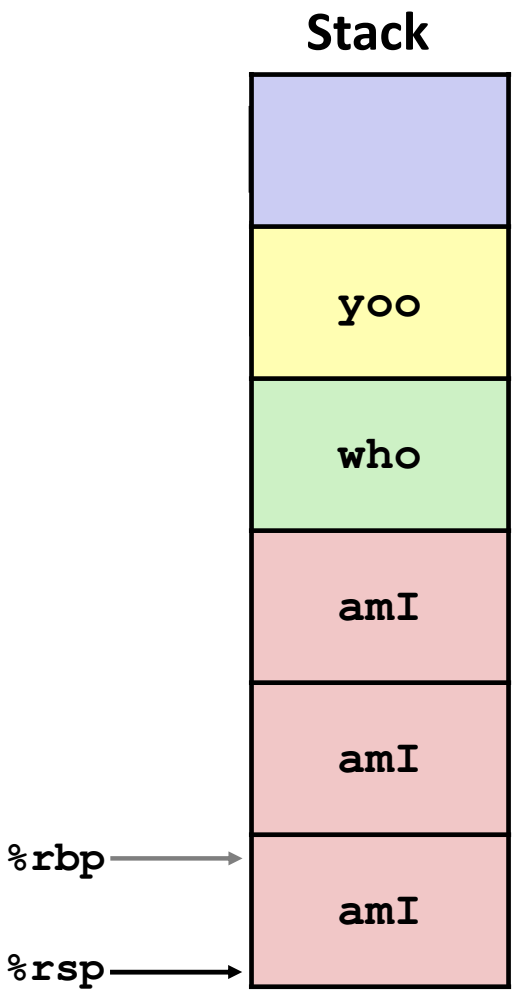
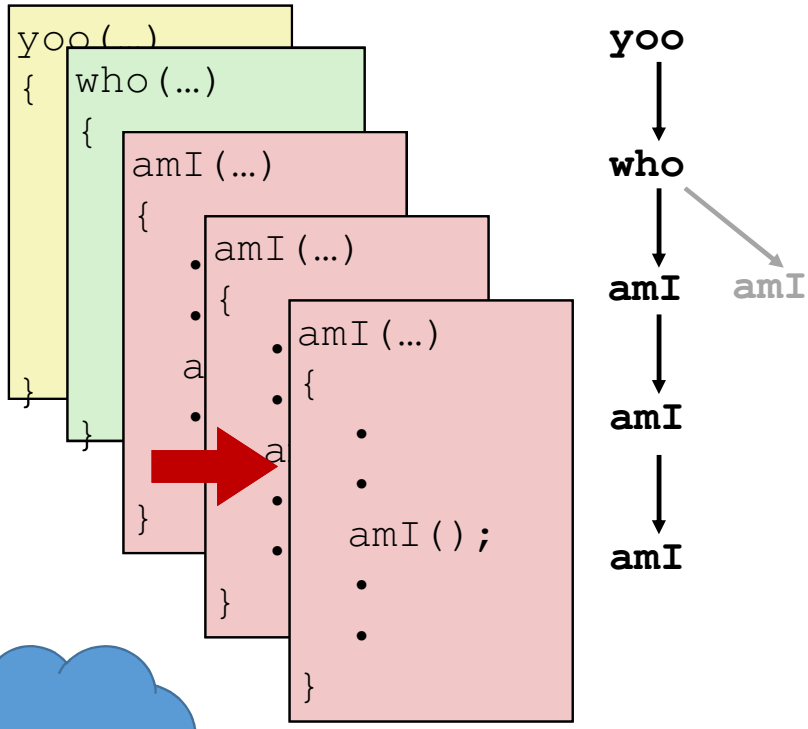
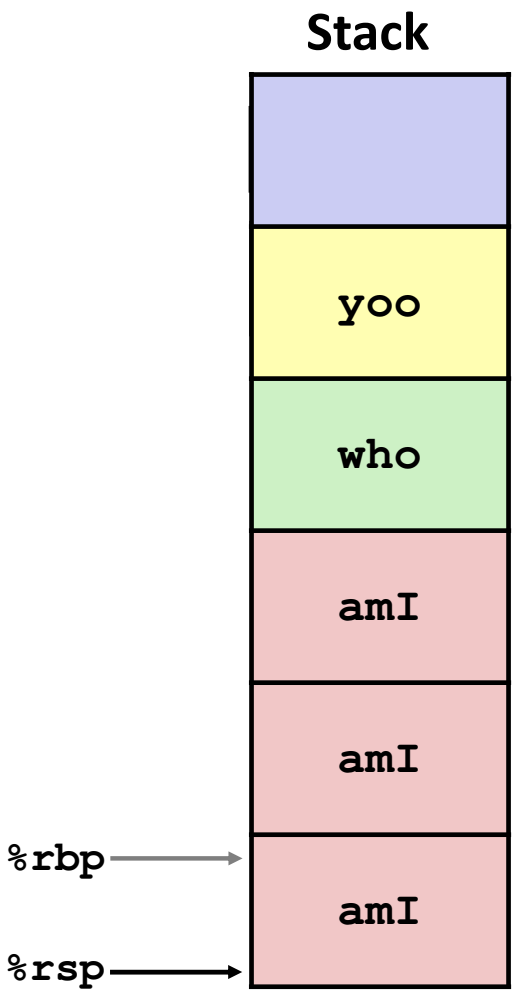
}
amI(…)
{
}
amI(…)
{
amI();
}

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
amI
%rbp
%rsp

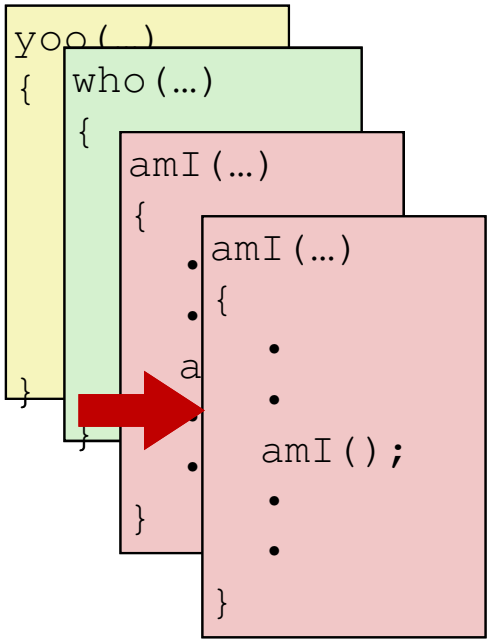
Example





Recursion can be risky!

Example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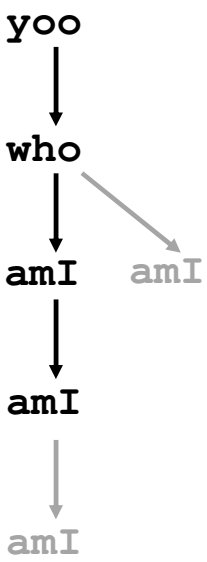
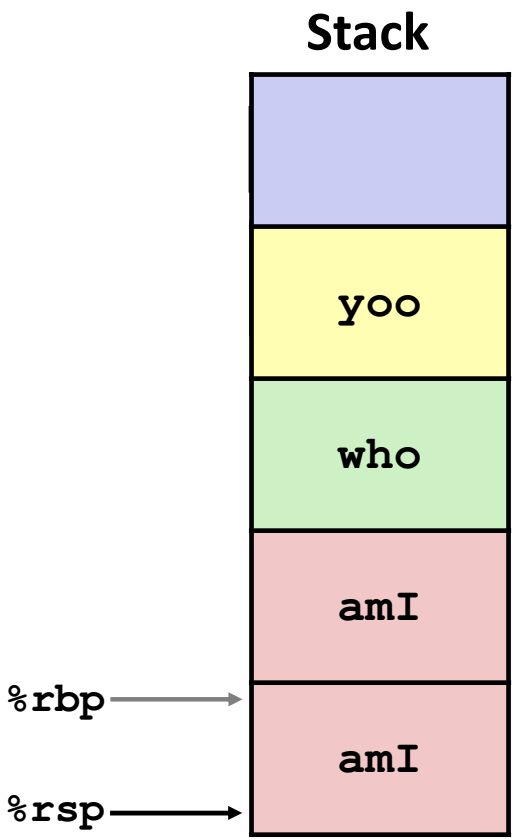
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}


yoo
who
amI
amI
amI
amI


Stack
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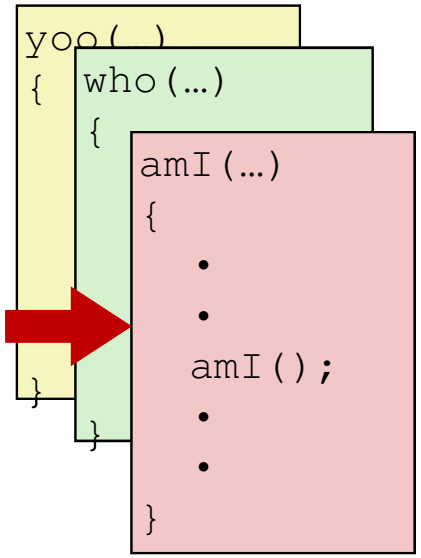
Example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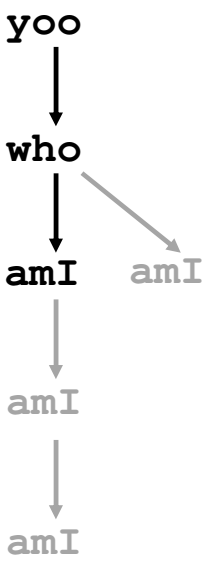
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amI
amI
amI
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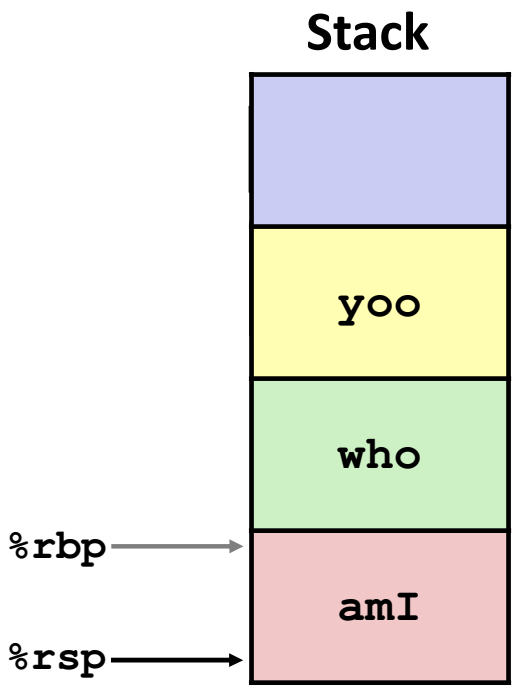
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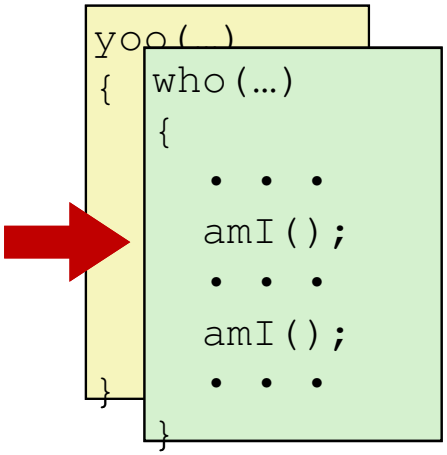
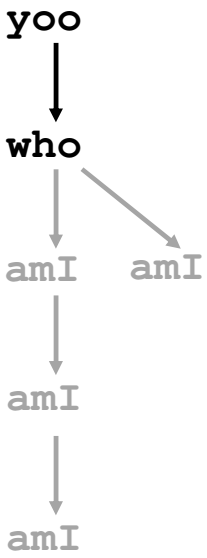
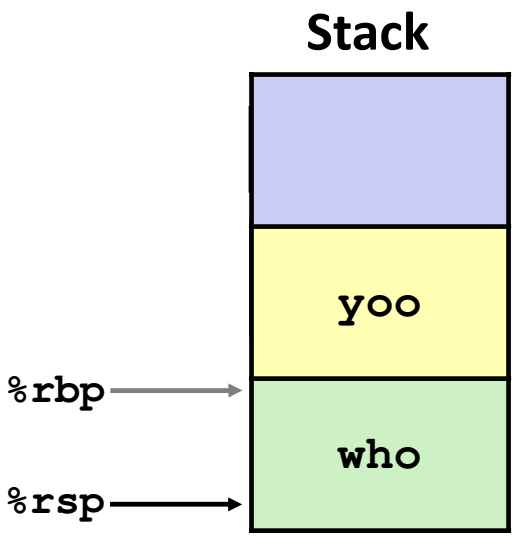
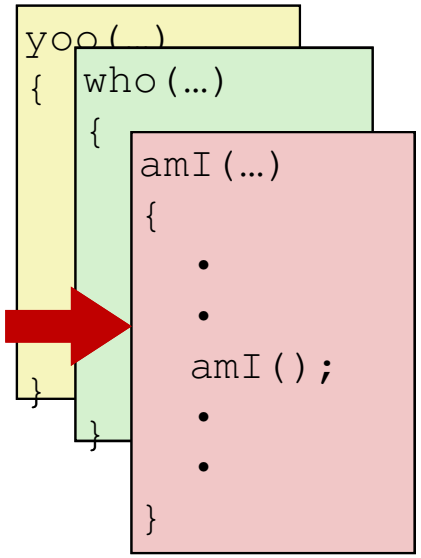






Example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}
who(…)
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}
amI(…)
{
amI();
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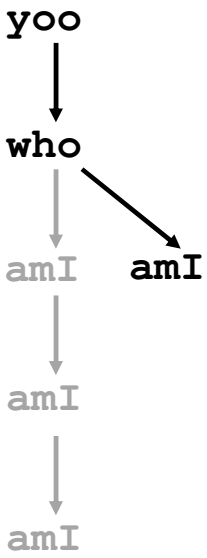
yoo
who
amI
amI
amI
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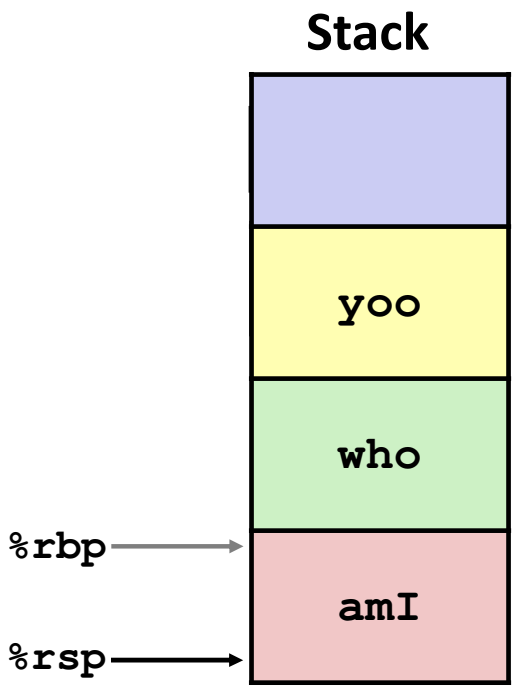
Stack
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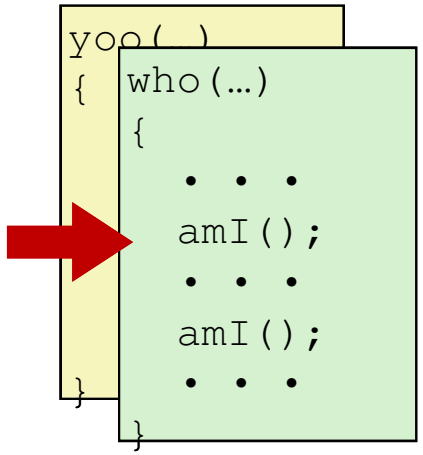
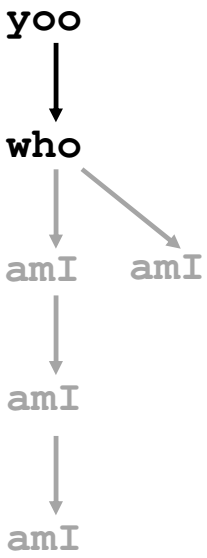
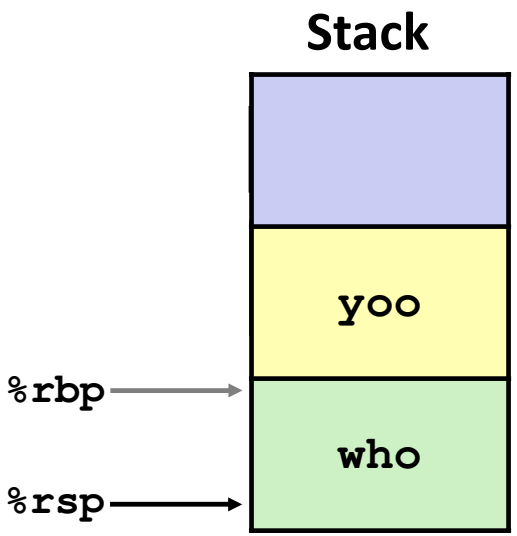
Example

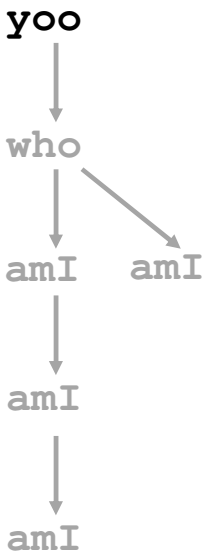


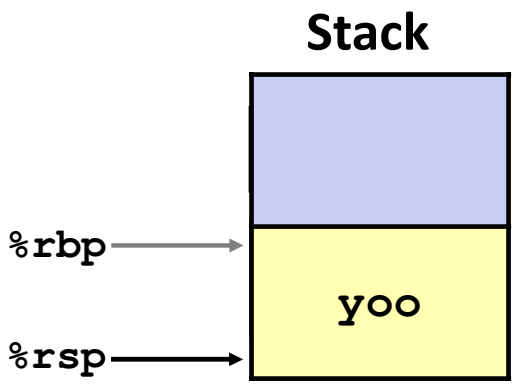




Example

```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

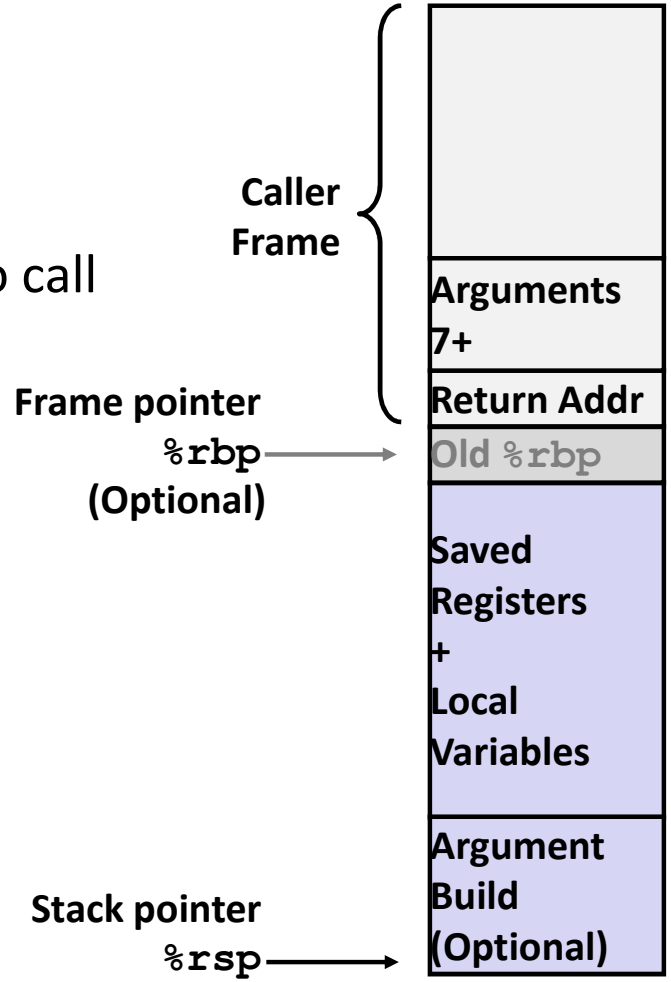




x86-64/Linux Stack Frame

- Current Stack Frame ("Top" to Bottom)
  - "Argument build:"
    Parameters for function about to call
  - Local variables
    If can't keep in registers
  - Saved register context
  - Old frame pointer (optional)

- Caller Stack Frame
  - Return address
    - Pushed by **`call`** instruction
  - Arguments for this call



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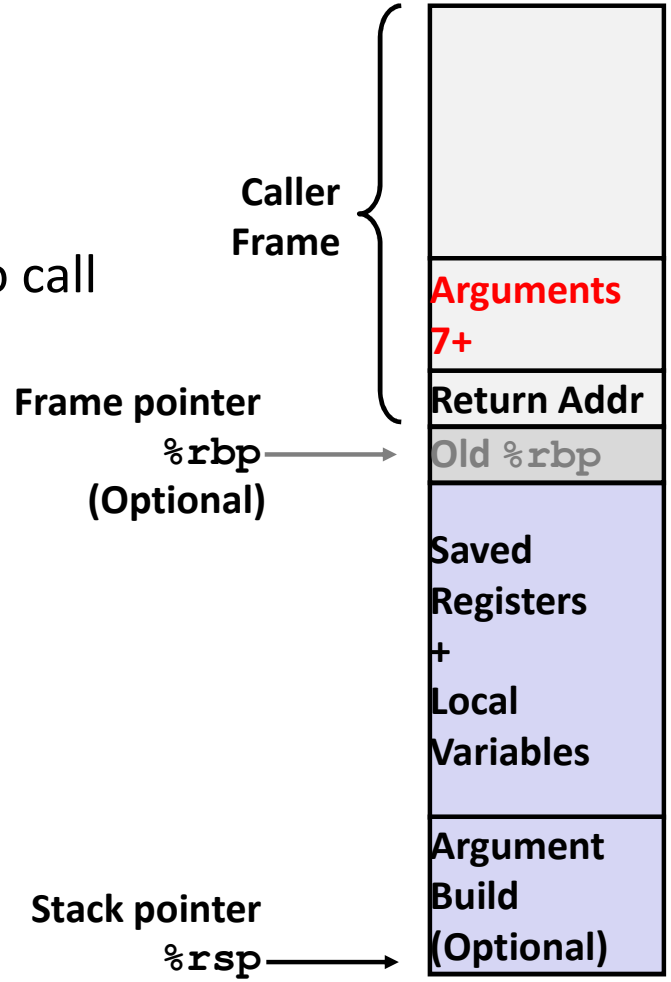

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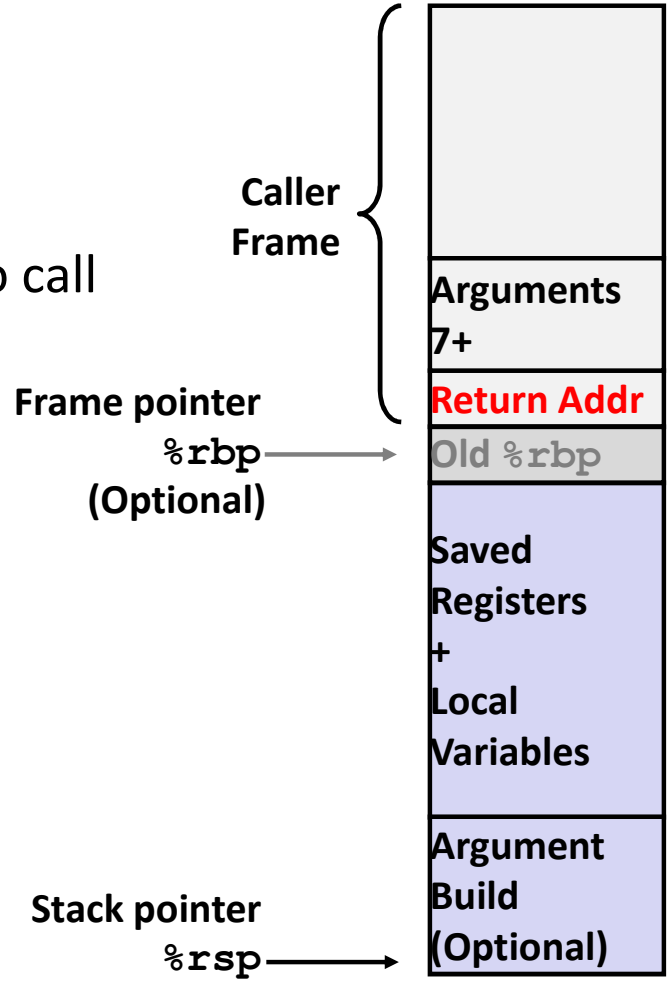

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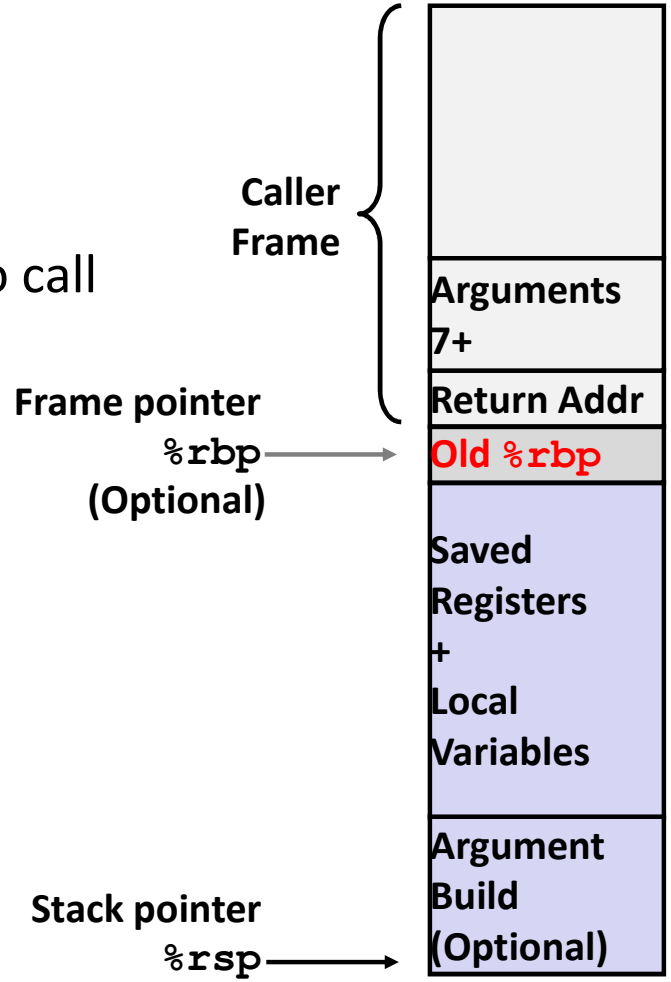

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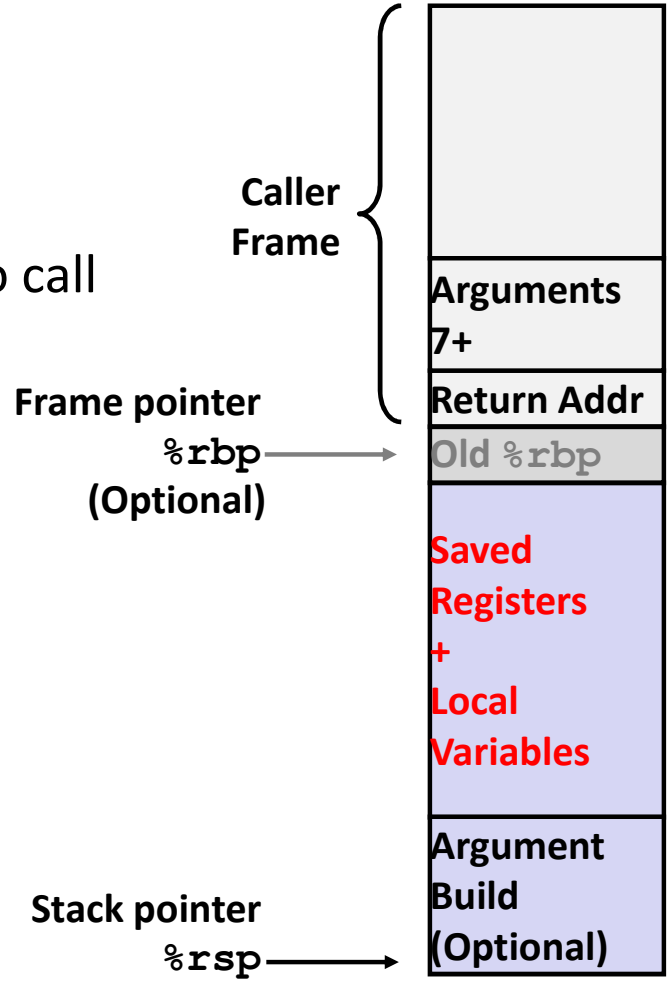

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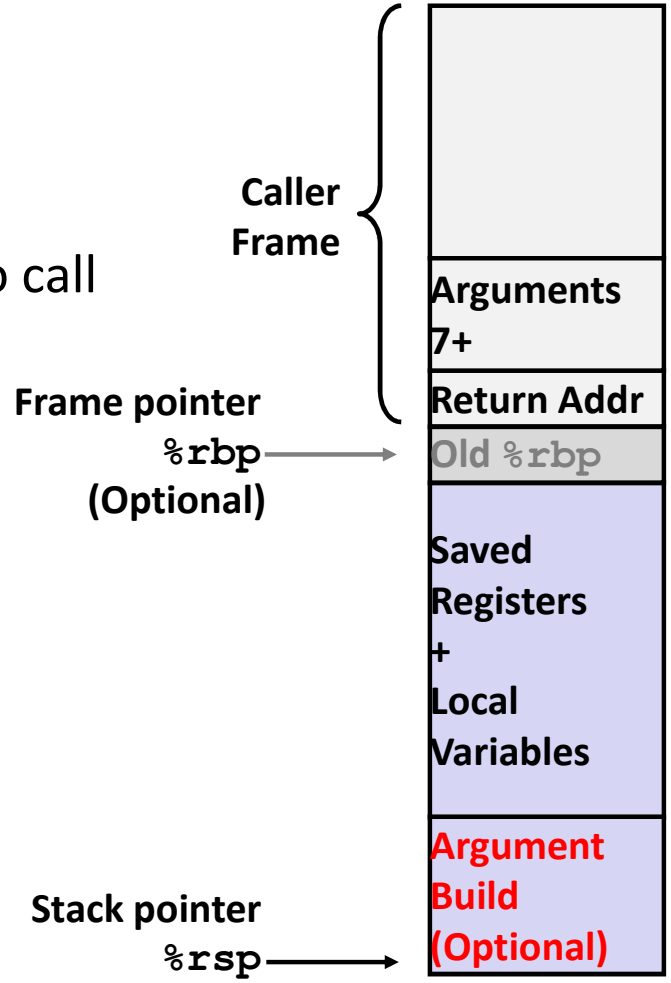

Example: **incr**

```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

Register	Use(s)
`%rdi`	Argument **`p`**
`%rsi`	Argument **`val`**, **`y`**
`%rax`	**`x`**, Return value

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`%rsi`	Argument **`val`**, **`y`**
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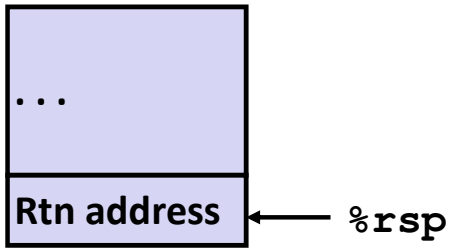
Example: Calling **incr**

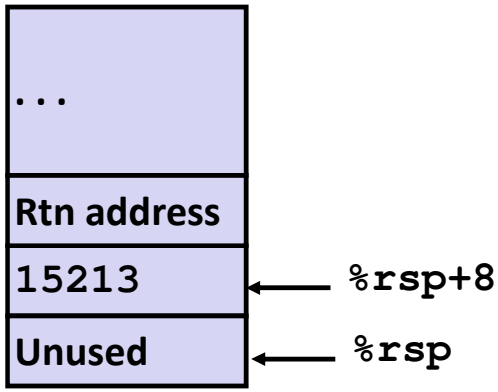
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Initial Stack Structure



Resulting Stack Structure



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  leaq    8(%rsp), %rdi
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  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```
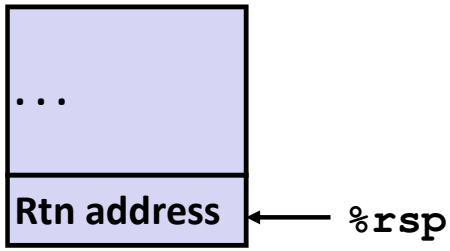
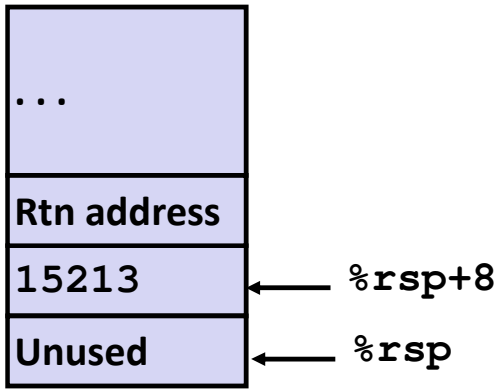

Initial Stack Structure



Resulting Stack Structure



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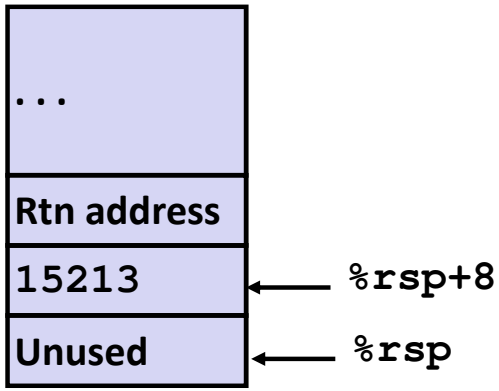
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rdi	&v1
%rsi	3000

Example: **incr**

```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

Register	Use(s)
`%rdi`	Argument **`p`**
`%rsi`	Argument **`val`**, **`y`**
`%rax`	**`x`**, Return value

Example: Calling **incr**

```
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```

```
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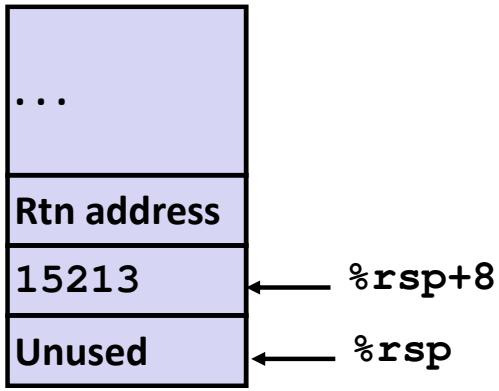
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rdi	&v1
%rsi	3000

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```
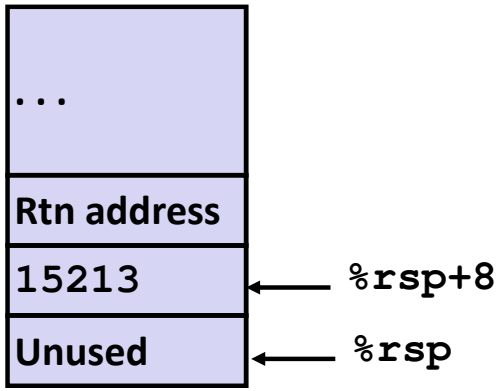

Stack Structure



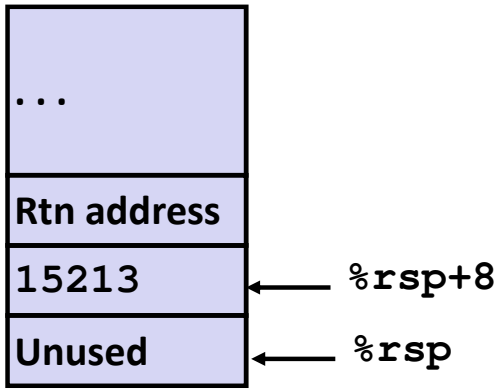
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling **incr**

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



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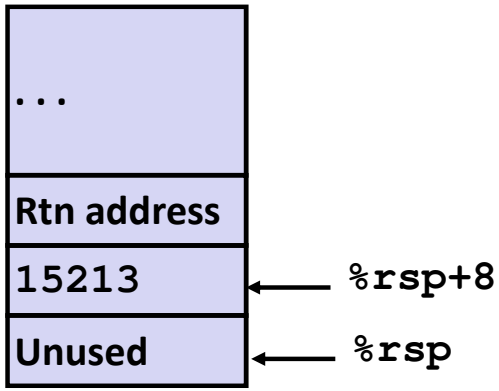
Stack Structure



Register	Use(s)
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%rsi	3000

Example: **incr**

```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

Register	Use(s)
`%rdi`	Argument **`p`**
`%rsi`	Argument **`val`**, **`y`**
`%rax`	**`x`**, Return value

Example: Calling **incr**

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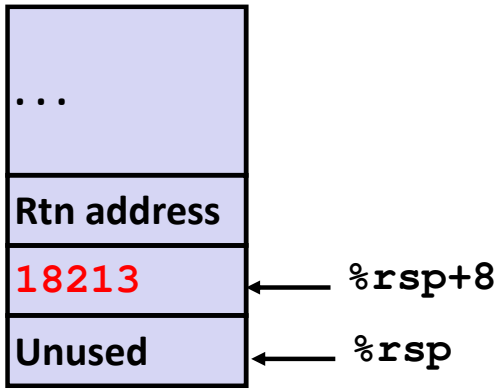
Stack Structure



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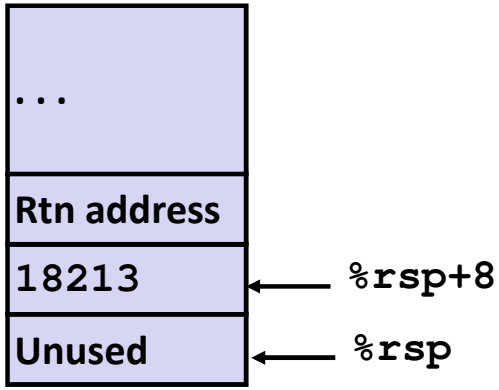
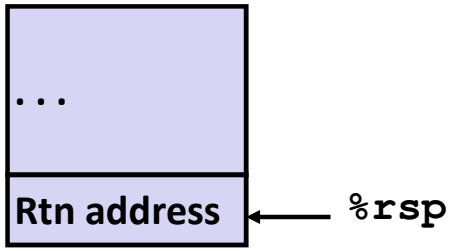
Stack Structure



Register	Use(s)
%rax	Return value

Updated Stack Structure



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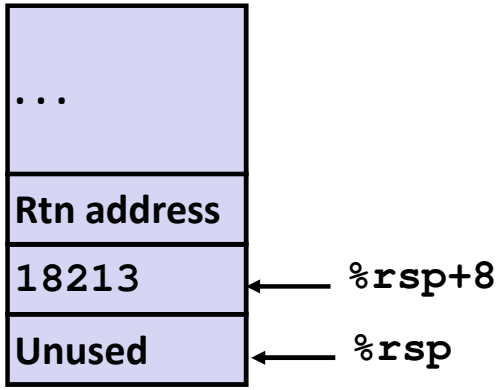

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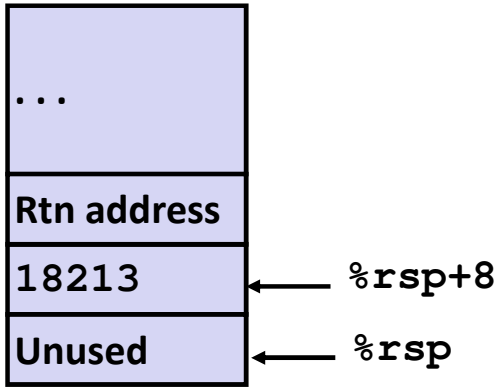
Stack Structure



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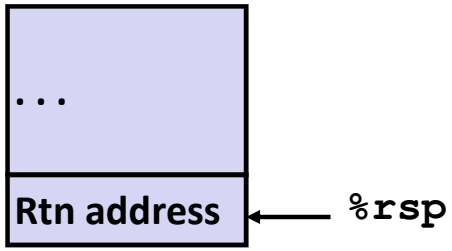

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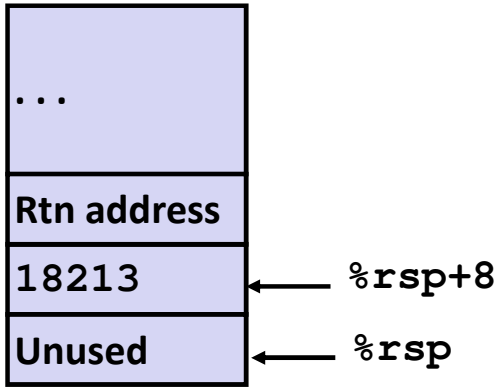
  ret
```

Stack Structure



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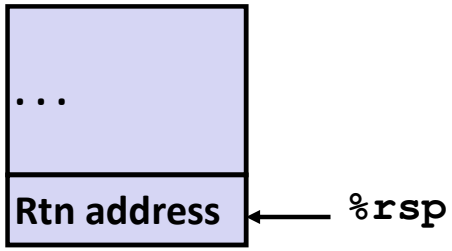
Updated Stack Structure



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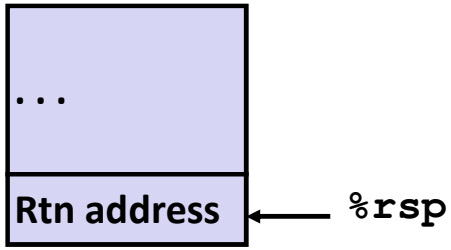


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  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Register	Use(s)
%rax	Return value

Final Stack Structure

Example: Calling **incr**

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
  subq    $16, %rsp
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  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```
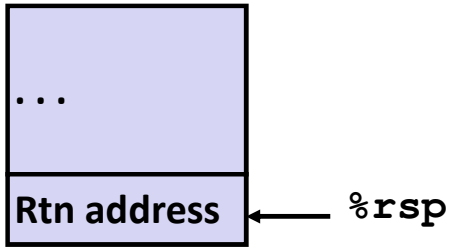

Updated Stack Structure



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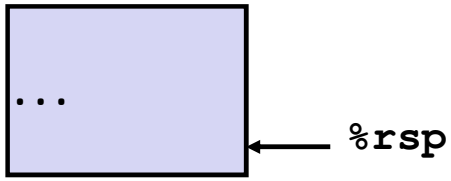
%rax	Return value

Final Stack Structure



i-clicker question

- How many stack frame will be created during the function call pcount_r(4)?

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

A.1

B.2

C.4

D.8

i-clicker question

- How many stack frame will be created during the function call pcount_r(4)? Sol. C

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A.1

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Register Saving Conventions

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- When procedure **`yoo`** calls **`who`**:
  - **`yoo`** is the ***caller***
  - **`who`** is the ***callee***

Register Saving Conventions

- When procedure **`yoo`** calls **`who`**:
  - **`yoo`** is the ***caller***
  - **`who`** is the ***callee***
- Can register be used for temporary storage?

```
yoo:
    • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    • • •
    ret
```

```
who:
    • • •
    subq $18213, %rdx
    • • •
    ret
```

  - Contents of register **`%rdx`** overwritten by **`who`**
  - This could be trouble → something should be done!
    - Need some coordination

Register Saving Conventions

- ***Caller Saved Register***
  - Function P calling function Q
  - Function P has some local data in such a register
  - P should save the data in the register before the call

Register Saving Conventions

- ***Caller Saved Register***
  - Function P calling function Q
  - Function P has some local data in such a register
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- ***Callee Saved Register***
  - Function P calling function Q
  - Function Q wants to alter such a register
  - Q must perverse the values of the register

x86-64 Linux Register Usage

- **`%rax`**
  - Return value
  - Also caller-saved
  - Can be modified by procedure

Return value	`%rax`
	`%rdi`
	`%rsi`
	`%rdx`
	`%rcx`
	`%r8`
	`%r9`
	`%r10`
	`%r11`

x86-64 Linux Register Usage

- **`%rax`**
  - Return value
  - Also caller-saved
  - Can be modified by procedure
- **`%rdi, ..., %r9`**
  - Arguments
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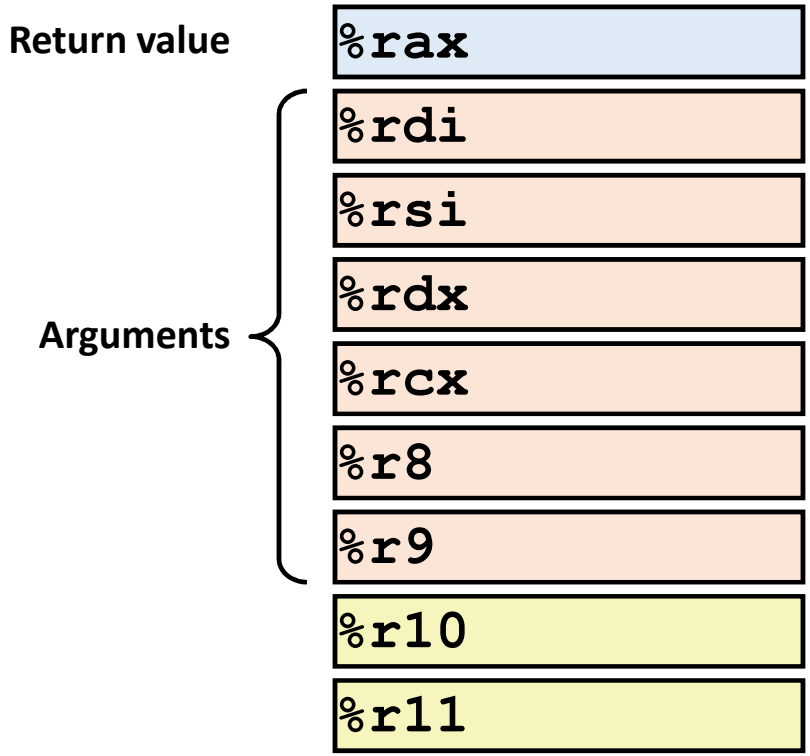
  - Can be modified by procedure



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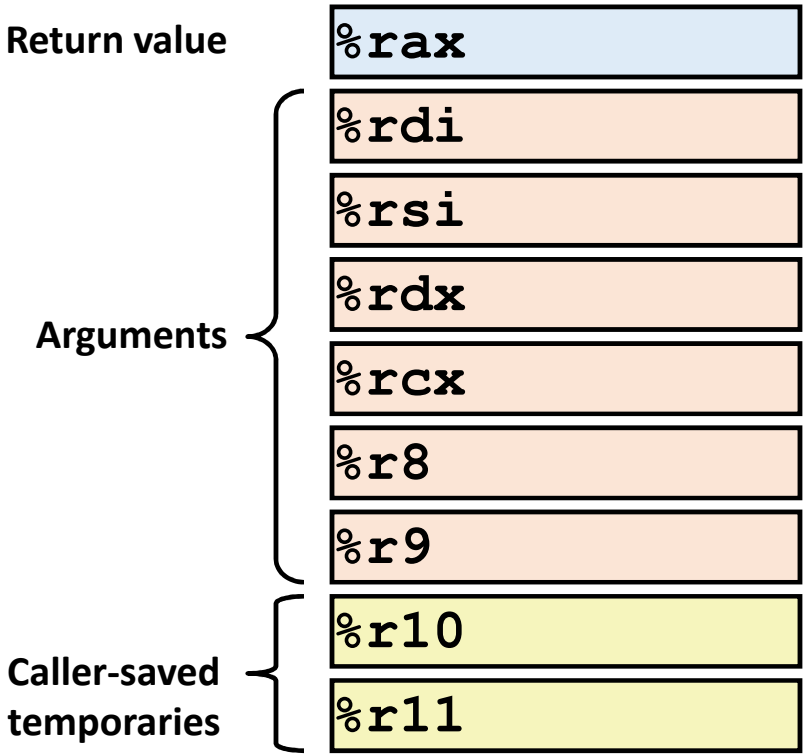
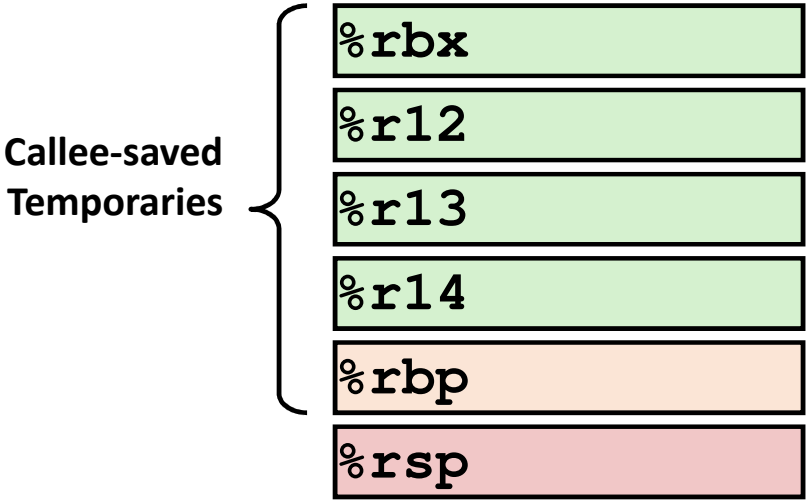


x86-64 Linux Register Usage

- **`%rbx, %r12, %r13, %r14`**
  - Callee-saved
  - Callee must save & restore



x86-64 Linux Register Usage

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  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
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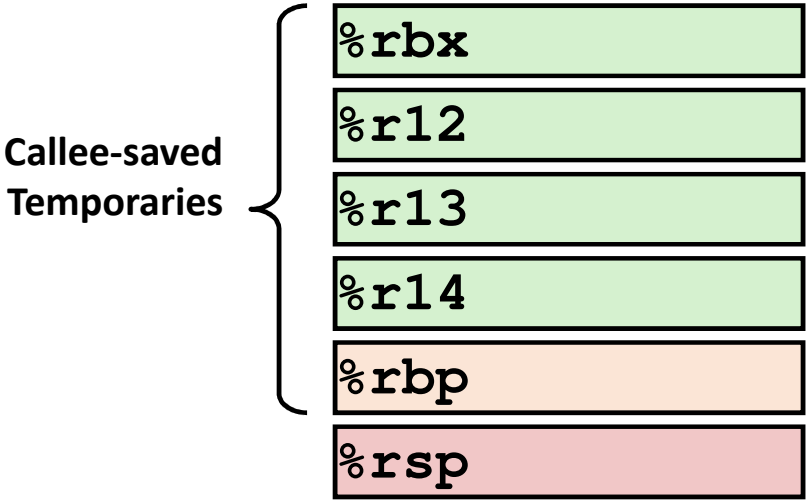
  - May be used as frame pointer
  - Can mix & match



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- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
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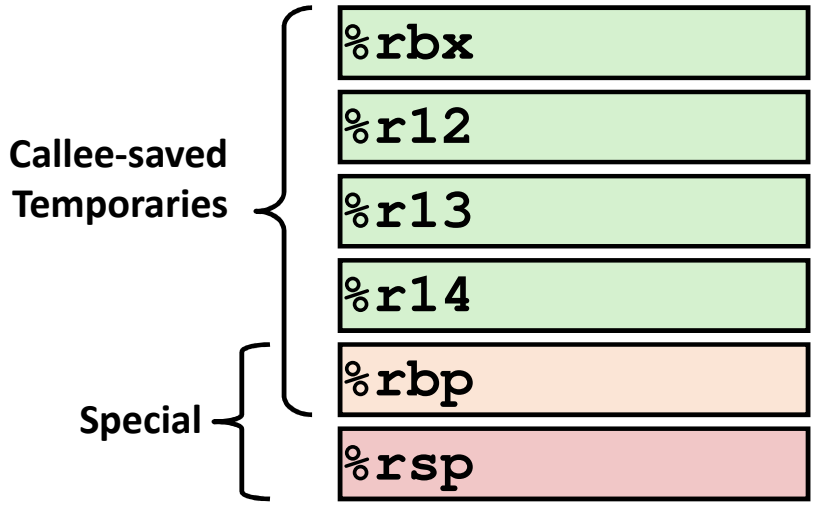
  - Can mix & match
- **`%rsp`**
  - Special form of callee save
  - Restored to original value upon exit from procedure



Callee-Saved Example

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    return x+v2;
}
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  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
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Arrays

Array Allocation

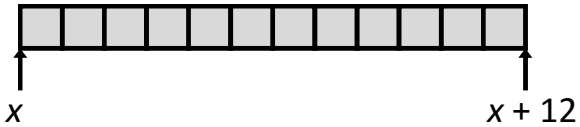
Array Allocation

- Basic Principle

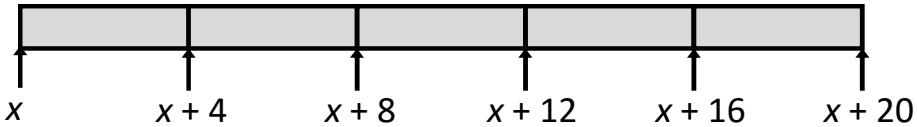
  T **A[***L***];**

  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof**(*T*) bytes in memory

```
char string[12];
```

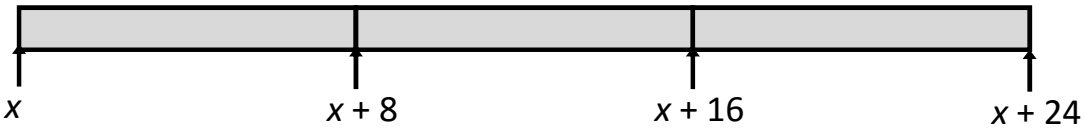



```
int val[5];
```




```
double a[3];
```


```
char *p[3];
```



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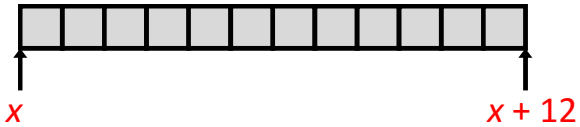


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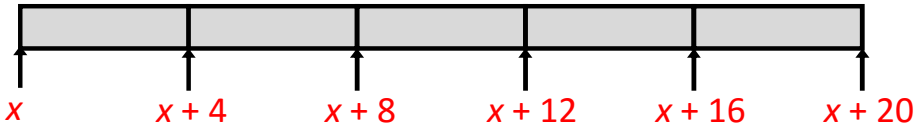


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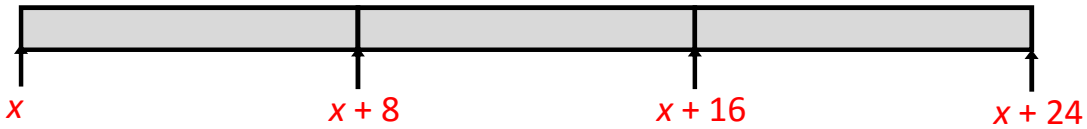

Array Access

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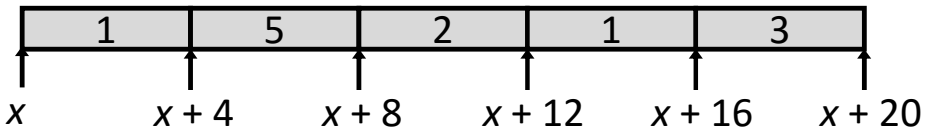

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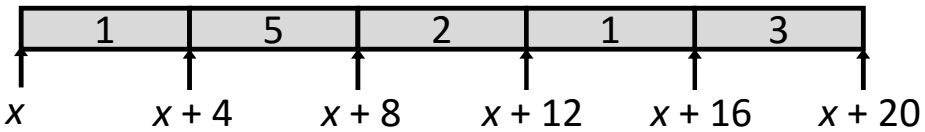

- Reference Type Value

  `val[4]` **`int`** 3

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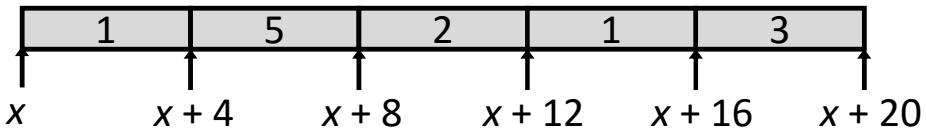
int val[5];
```



- Reference

Reference	Type	Value
`val[4]`	**`int`**	3
`val`	**`int *`**	*x*

Array Access

- Basic Principle

  T **`A[`***L***`];`**

  - Array of data type *T* and length *L*
  - Identifier **`A`** can be used as a pointer to array element 0: Type *T**

```
int val[5];
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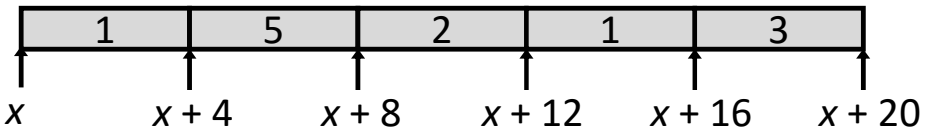
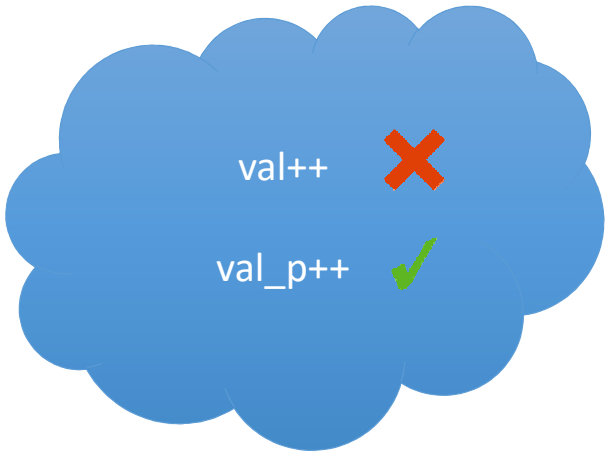


- Reference

Reference	Type	Value
`val[4]`	**`int`**	3
`val`	**`int *`**	*x*
`val+1`	**`int *`**	*x* + 4



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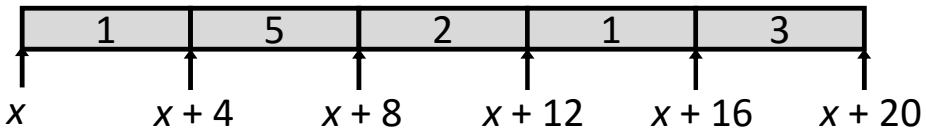

- Reference

Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8

*(val+2) == val[2]

Array Access

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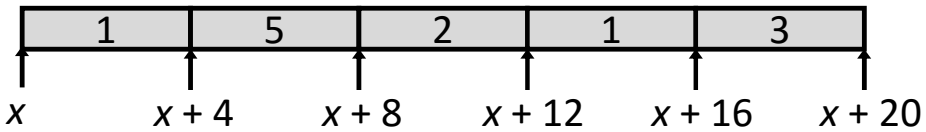

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`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8

address:
&val[i] = x+4*i

Array Access

- Basic Principle

  T **A[***L***];**

  - Array of data type *T* and length *L*
  - Identifier **A** can be used as a pointer to array element 0: Type *T**

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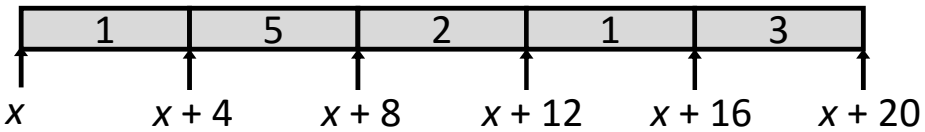
int val[5];
```



- Reference

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val[4]	**int**	3
val	**int ***	*x*
val+1	**int ***	*x* + 4
&val[2]	**int ***	*x* + 8
val[5]	**int**	??

Array Access

- Basic Principle

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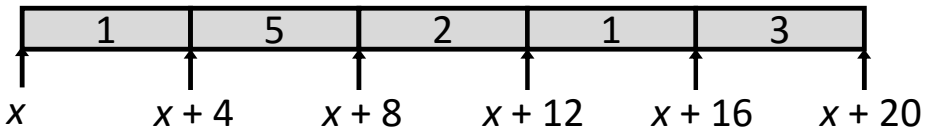

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`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5

*(val+2) == val[2]

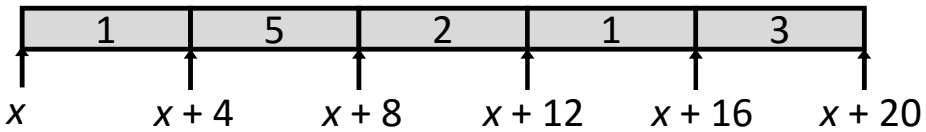
Array Access

- Basic Principle

  T **A[***L***];**

  - Array of data type *T* and length *L*
  - Identifier **A** can be used as a pointer to array element 0: Type *T**

```
int val[5];
```



- Reference

Reference	Type	Value
val[4]	**int**	3
val	**int ***	*x*
val+1	**int ***	*x* + 4
&val[2]	**int ***	*x* + 8
val[5]	**int**	??
***(val+1)**	**int**	5
val + *i*	**int ***	*x* + 4 *i*

*(val+2) == val[2]

Array Example

```
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig uma = { 0, 1, 0, 0, 3 };
```

- Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"

Array Example

```
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig uma = { 0, 1, 0, 0, 3 };
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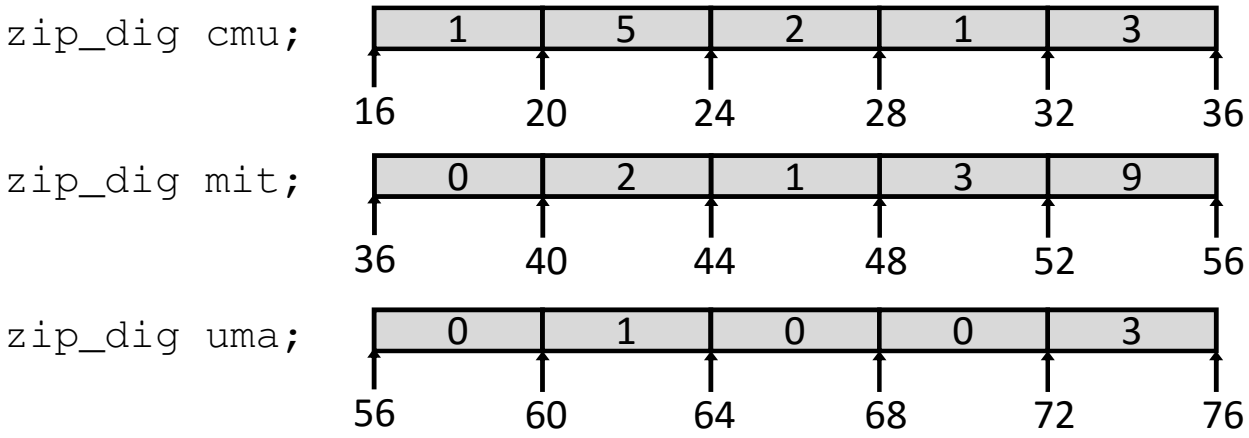
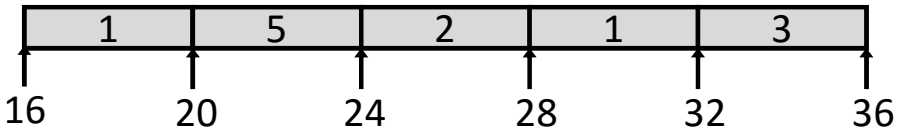


- Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Accessing Example

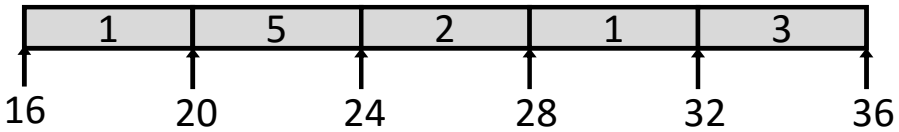
```
zip_dig cmu;
```




```
int get_digit
  (zip_dig z, int digit)
{
  return z[digit];
}
```

Array Accessing Example

```
zip_dig cmu;
```




```
int get_digit
  (zip_dig z, int digit)
{
  return z[digit];
}
```

```
  # %rdi = z
  # %rsi = digit
movl (%rdi,%rsi,4), %eax  # z[digit]
```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi + 4*%rsi`
- Use memory reference `(%rdi,%rsi,4)`

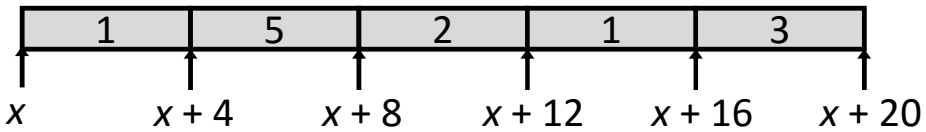
Array Access

- Basic Principle

  T **`A[`***L***`];`**

  - Array of data type *T* and length *L*
  - Identifier **`A`** can be used as a pointer to array element 0: Type *T**

```
int val[5];
```



- Reference

Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8

address:
&val[i] = x+4*i

Array Accessing Example

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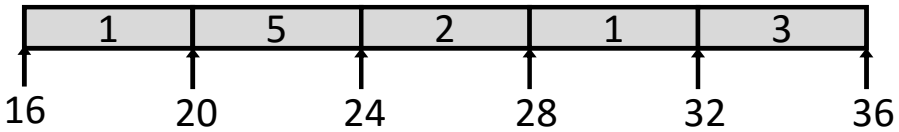
zip_dig cmu;
```

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  (zip_dig z, int digit)
{
  return z[digit];
}
```

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  # %rdi = z
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```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi + 4*%rsi`
- Use memory reference `(%rdi,%rsi,4)`

Array Loop Example

```
void zincr(zip_dig z) {
  unsigned i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # %rdi = z
  movl    $0, %eax          #   i = 0
  jmp     .L3               #   goto middle
.L4:                        # loop:
  addl    $1, (%rdi,%rax,4) #   z[i]++
  addq    $1, %rax          #   i++
.L3:                        # middle
  cmpq    $4, %rax          #   i:4
  jbe     .L4               #   if <=, goto loop
  ret
```

Array Loop Example

```
void zincr(zip_dig z) {
  unsigned i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # %rdi = z
  movl    $0, %eax            #   i = 0
  jmp     .L3                 #   goto middle
.L4:                          # loop:
  addl    $1, (%rdi,%rax,4)   #   z[i]++
  addq    $1, %rax            #   i++
.L3:                          # middle
  cmpq    $4, %rax            #   i:4
  jbe     .L4                 #   if <=, goto loop
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```

Array Loop Example

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void zincr(zip_dig z) {
  unsigned i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # %rdi = z
  movl    $0, %eax          #   i = 0
  jmp     .L3               #   goto middle
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  addl    $1, (%rdi,%rax,4) #   z[i]++
  addq    $1, %rax          #   i++
.L3:                        # middle
  cmpq    $4, %rax          #   i:4
  jbe     .L4               #   if <=, goto loop
  ret
```
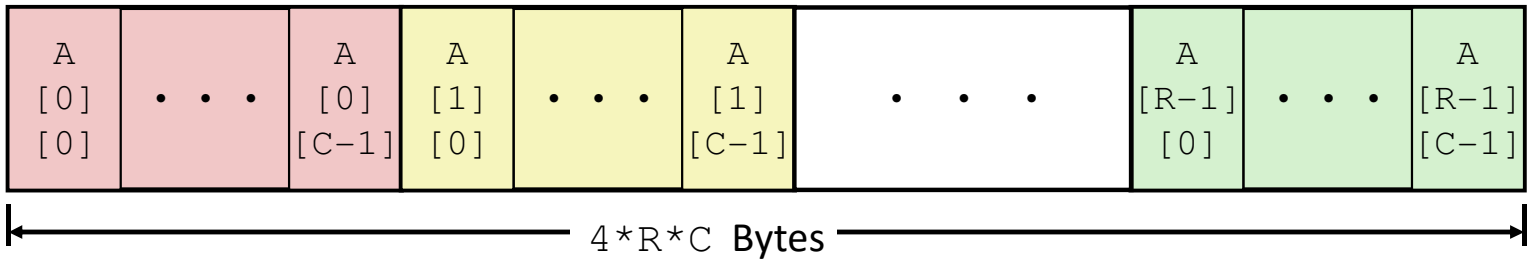

Multidimensional (Nested) Arrays

- Declaration
  - *T* **A**[*R*][*C*];
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Type *T* element requires *K* bytes
- Array Size
  - R * C * K bytes
- Arrangement
  - Row-Major Ordering

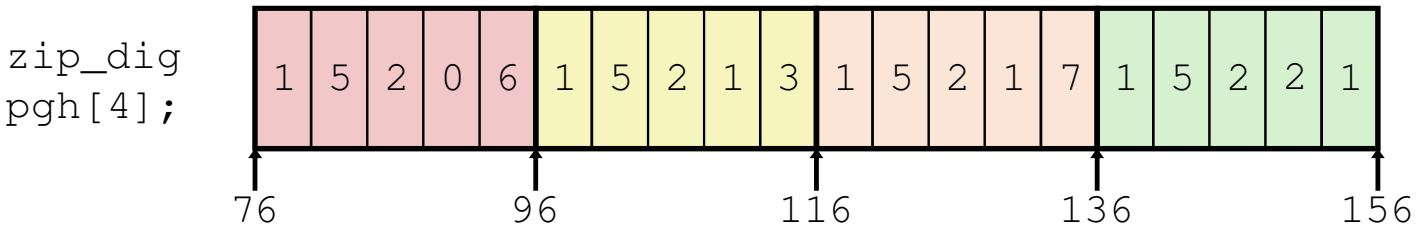
$$\begin{bmatrix} A[0][0] & \cdots & A[0][C-1] \\ \vdots & & \vdots \\ A[R-1][0] & \cdots & A[R-1][C-1] \end{bmatrix}$$

```
int A[R][C];
```



Nested Array Example

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

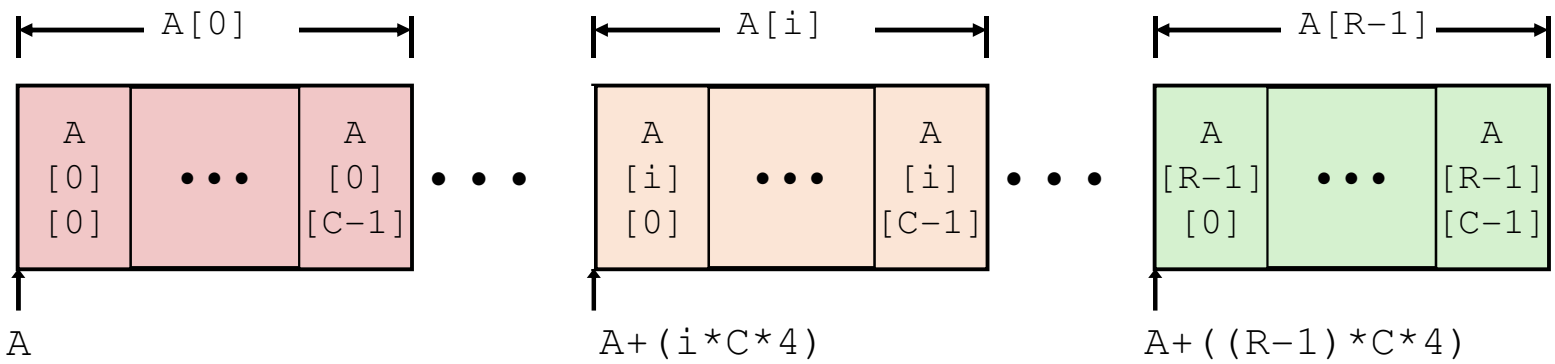


- "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable **`pgh`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**'s, allocated contiguously
- "Row-Major" ordering of all elements in memory

Nested Array Row Access

- Row Vectors
  - **`A[i]`** is array of *C* elements
  - Each element of type *T* requires *K* bytes
  - Starting address **`A +`** *i* * (*C* * *K*)

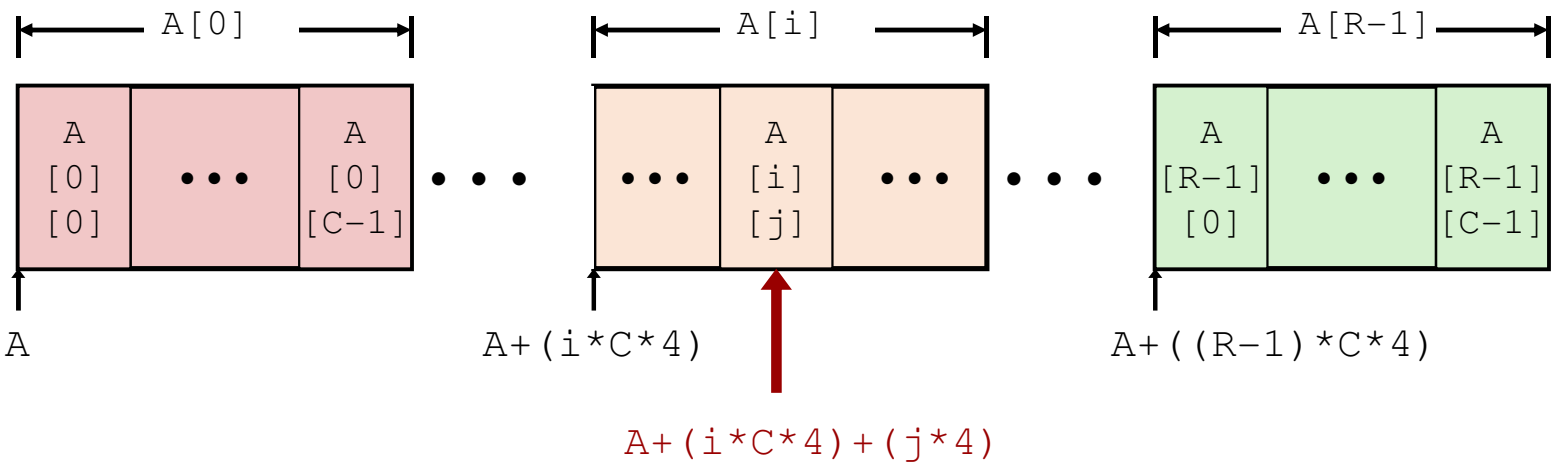
```
int A[R][C];
```



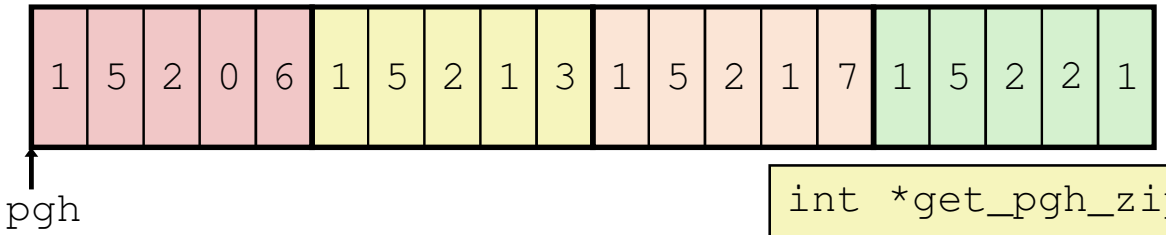
Nested Array Element Access

- Array Elements
  - **`A[i][j]`** is element of type *T,* which requires *K* bytes
  - Address **`A +`** $i * (C * K) + j * K = A + (i * C + j) * K$

```
int A[R][C];
```



Nested Array Row Access Code

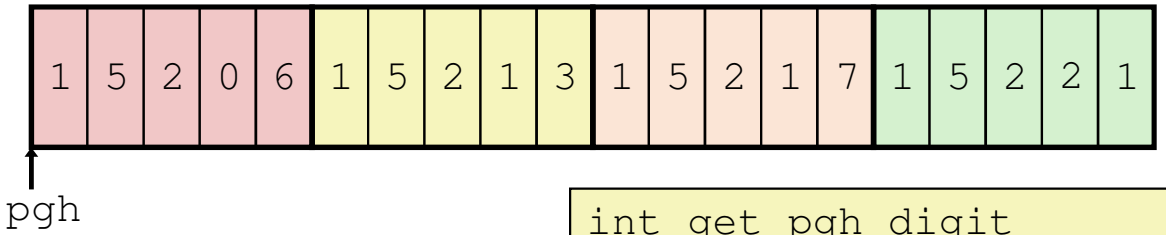



```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
  # %rdi = index
   leaq (%rdi,%rdi,4),%rax  # 5 * index
   leaq pgh(,%rax,4),%rax   # pgh + (20 * index)
```

- Row Vector
  - **`pgh[index]`** is array of 5 **`int`**'s
  - Starting address **`pgh+20*index`**
- Machine Code
  - Computes and returns address
  - Compute as **`pgh + 4*(index+4*index)`**

Nested Array Element Access Code




```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

```
leaq   (%rdi,%rdi,4), %rax    # 5*index
addl   %rax, %rsi             # 5*index+dig
movl   pgh(,%rsi,4), %eax     # M[pgh + 4*(5*index+dig)]
```

- Array Elements
  - **`pgh[index][dig]`** is **`int`**
  - Address: **`pgh + 20*index + 4*dig`**
    - = **`pgh + 4*(5*index + dig)`**