Lecture 5: Introduction to Assembly

CS 105

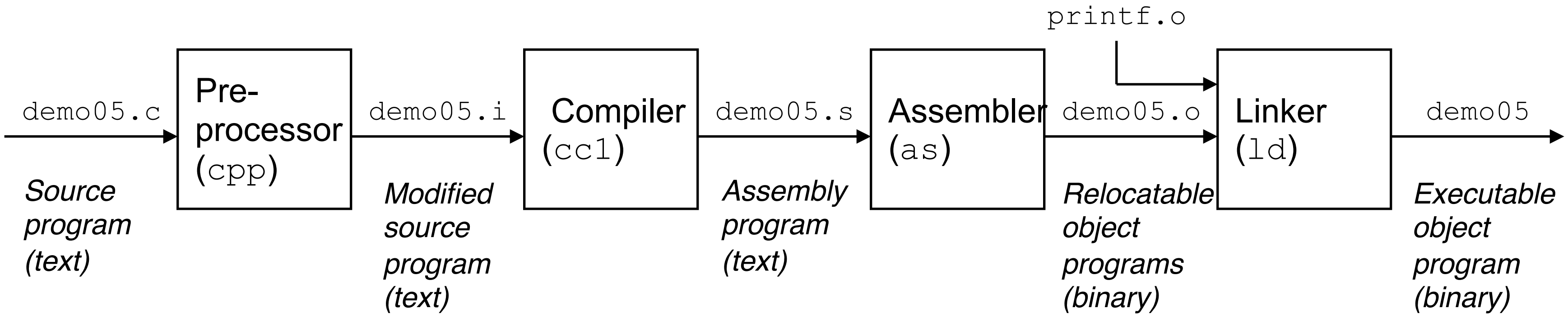
Spring 2024

Programs

```
#include<stdio.h>

int main(int argc,
         char** argv){

  printf("Hello
          world!\n");

  return 0;
}
```

```
55
48 89 e5
48 83 ec 20
48 8d 05 25 00 00 00
c7 45 fc 00 00 00 00
89 7d f8
48 89 75 f0
48 89 c7
b0 00
e8 00 00 00 00
31 c9
89 45 ec
89 c8
48 83 c4 20
5d
c3
```

Compilation



```
#include<stdio.h>

int main(int argc,
         char ** argv){

  printf("Hello
          world!\n");
  return 0;
}
```

```
…
int printf(const char *
           restrict,
           ...)
__attribute__((__format_
_ (__printf__, 1, 2)));
…
int main(int argc,
         char ** argv){

  printf("Hello
          world!\n");
  return 0;
}
```

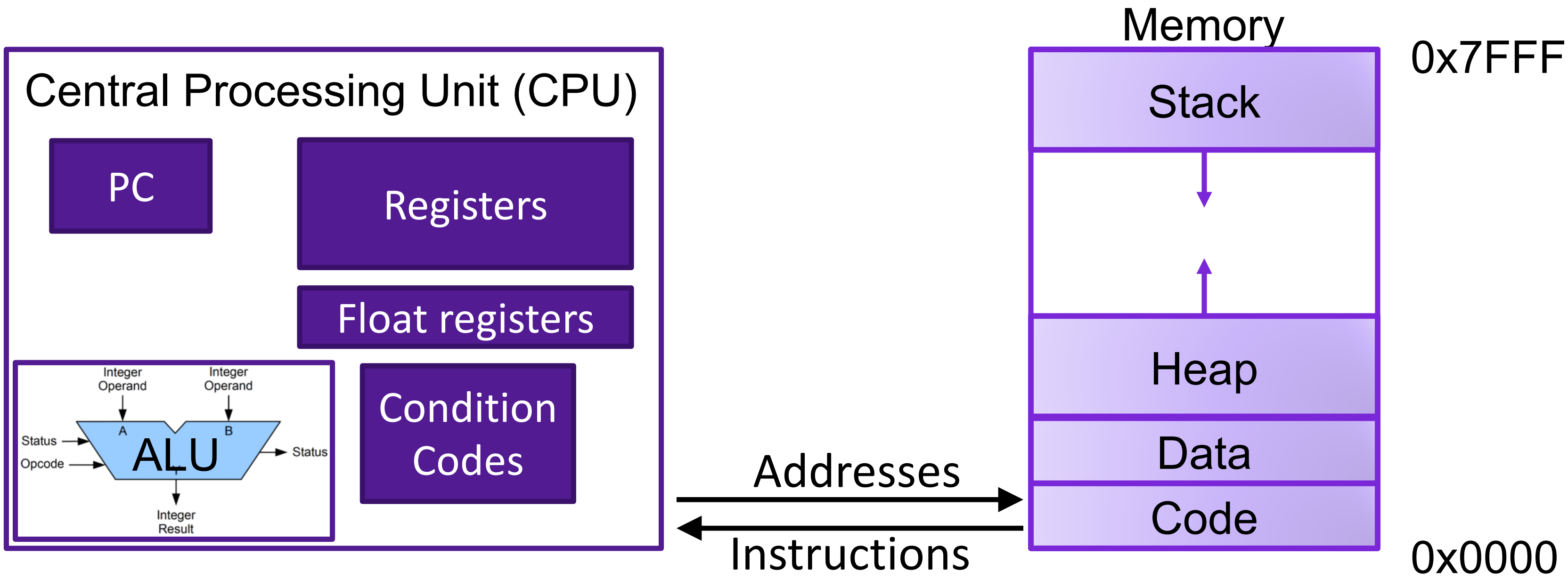
```
pushq    %rbp
movq     %rsp, %rbp
subq  $32, %rsp
leaq  L_.str(%rip), %rax
movl  $0, -4(%rbp)
movl  %edi, -8(%rbp)
movq  %rsi, -16(%rbp)
movq  %rax, %rdi
movb  $0, %al
callq _printf
xorl  %ecx, %ecx
movl  %eax, -20(%rbp)
movl  %ecx, %eax
addq  $32, %rsp
popq  %rbp
retq
```

```
55
48 89 e5
48 83 ec 20
48 8d 05 25 00 00 00
c7 45 fc 00 00 00 00
89 7d f8
48 89 75 f0
48 89 c7
b0 00
e8 00 00 00 00
31 c9
89 45 ec
89 c8
48 83 c4 20
5d
c3
```

x86-64 Assembly Language

- Evolutionary design, going back to 8086 in 1978
  - Basis for original IBM Personal Computer, 16-bits
- Intel Pentium 4E (2004): 64 bit instruction set
- High-level languages are translated into x86 instructions and then executed on the CPU
  - Actual instructions are sequences of bytes
  - We give them mnemonic names

Assembly/Machine Code View



Programmer-Visible State

- PC: Program counter (%rip)
- Register file: 16 Registers
- Float registers
- Condition codes

Memory

- Byte addressable array
- Code and user data
- Stack to support procedures

Assembly Characteristics: Instructions

- Transfer data between memory and register
  - Load data from memory into register
  - Store register data into memory

- Perform arithmetic operations on register or memory data

- Transfer control
  - Conditional branches
  - Unconditional jumps to/from procedures

Data Movement Instructions

- MOV source, dest   Moves data source->dest

  `dest = source`

Operand Forms

- Immediate:
  - Syntax: $c   Ex: $47   Val: c   C Equiv: 47
- Register:
  - Syntax: r   Ex: %rdi   Val: Reg[r]   C Equiv: x
- Memory (Absolute):
  - Syntax: addr   Ex: 0x4050   Val: Mem[addr]   ~~C Equiv: *0x60201a~~
- Memory (Indirect):
  - Syntax: (r)   Ex: (%rsp)   Val: Mem[Reg[r]]   C Equiv: *x

Exercise: Operands

Register	Value
%rax	0x100
%rcx	0x01
%rdx	0x03

Memory Address	Value
0x100	0xFF
0x104	0xAB
0x108	0x13

- What are the values of the following operands (assuming register and memory state shown above)?
  1. `%rax`
  2. `0x104`
  3. `$0x108`
  4. `(%rax)`

`mov` Operand Combinations

	Source	Dest	Src,Dest	C Analog
`mov`	*Imm*	*Reg*	`mov $0x4,%rax`	`x = 4;`
		Mem	`mov $-147,(%rdx)`	`*p = -147;`
	Reg	*Reg*	`mov %rax,%rcx`	`y = x;`
		Mem	`mov %rax,(%rdx)`	`*p = x;`
	Mem	*Reg*	`mov (%rdx),%rax`	`x = *p;`

Cannot do memory-memory transfer with a single instruction

Exercise: Moving Data

- For each of the following move instructions, write an equivalent C assignment
  1. `mov $0x40604a, %rbx`
  2. `mov %rbx, %rax`
  3. `mov $47, (%rax)`

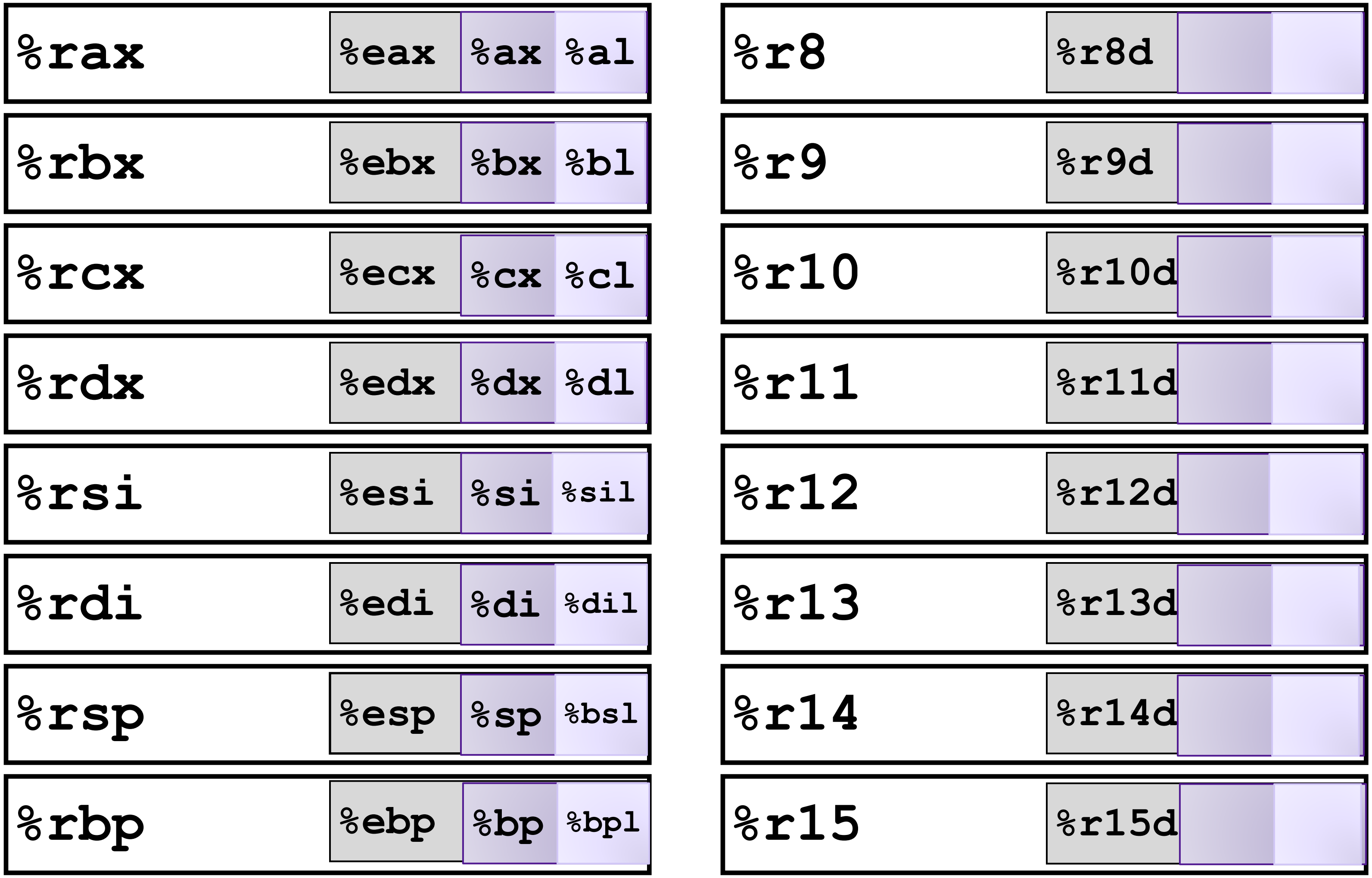
Sizes of C Data Types in x86-64

C declaration	Size (bytes)	Intel data type	Assembly suffix
char	1	Byte	b
short	2	Word	w
int	4	Double word	l
long	8	Quad word	q
char *	8	Quad word	q
float	4	Single precision	s
double	8	Double precision	l

Data Movement Instructions

MOV source, dest	Move data source->dest
`movb`	Move 1 byte
`movw`	Move 2 bytes
`movl`	Move 4 bytes
`movq`	Move 8 bytes

X86-64 Integer Registers



%rax	%eax	%ax	%al	%r8	%r8d		
%rbx	%ebx	%bx	%bl	%r9	%r9d		
%rcx	%ecx	%cx	%cl	%r10	%r10d		
%rdx	%edx	%dx	%dl	%r11	%r11d		
%rsi	%esi	%si	%sil	%r12	%r12d		
%rdi	%edi	%di	%dil	%r13	%r13d		
%rsp	%esp	%sp	%bsl	%r14	%r14d		
%rbp	%ebp	%bp	%bpl	%r15	%r15d		

X86-64 Integer Registers

`%rax` (function result)	`%r8` (fifth argument)
`%rbx`	`%r9` (sixth argument)
`%rcx` (fourth argument)	`%r10`
`%rdx` (third argument)	`%r11`
`%rsi` (second argument)	`%r12`
`%rdi` (first argument)	`%r13`
`%rsp` (stack pointer)	`%r14`
`%rbp`	`%r15`

Exercise: Translating Assembly

- Write a C function `void decode1(long* xp, long* yp)` that will do the same thing as the following assembly code:

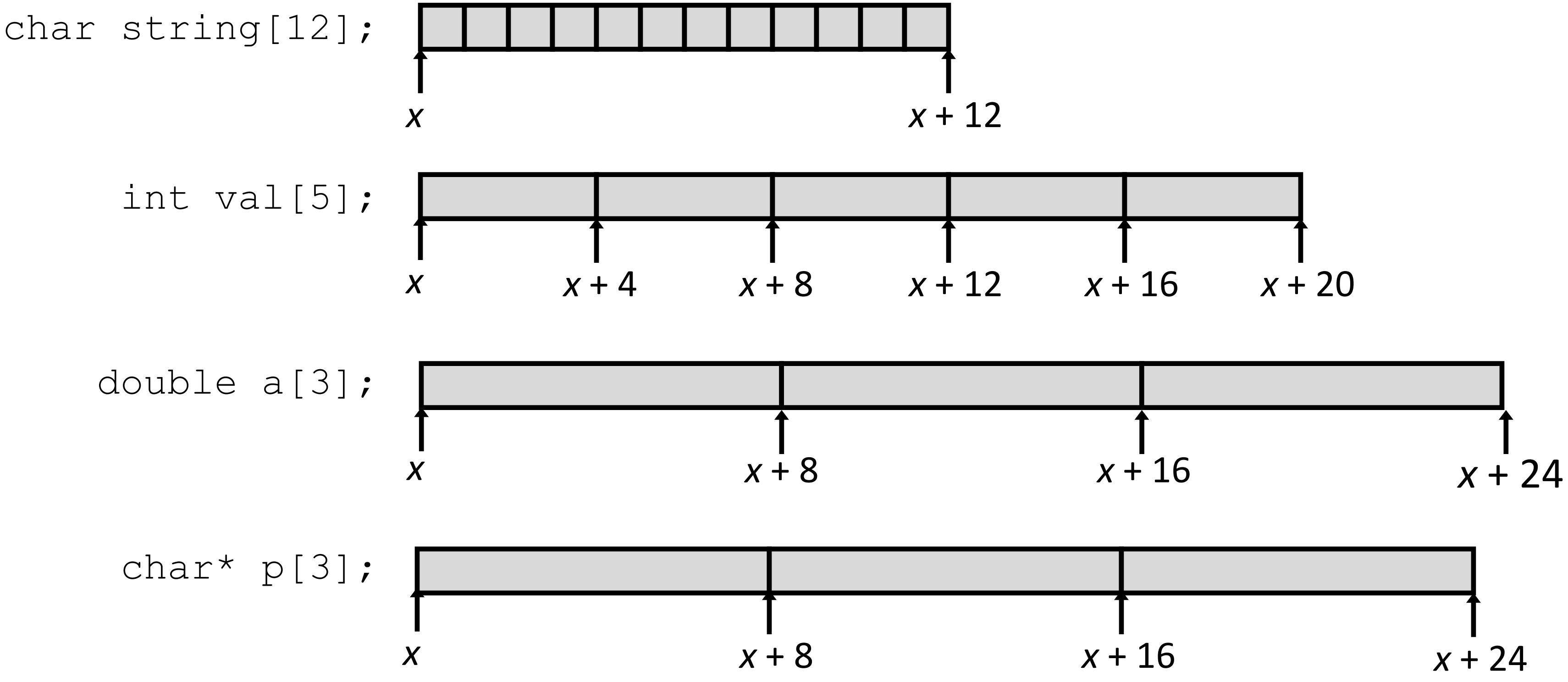
```
decode:

        movq (%rdi), %rax
        movq (%rsi), %rcx
        movq %rax, (%rsi)
        movq %rcx, (%rdi)
        ret
```

```
void decode(long* xp, long* yp){






}
```

Register	Use(s)
`%rdi`	Argument **`xp`**
`%rsi`	Argument **`yp`**

Review: Array Allocation

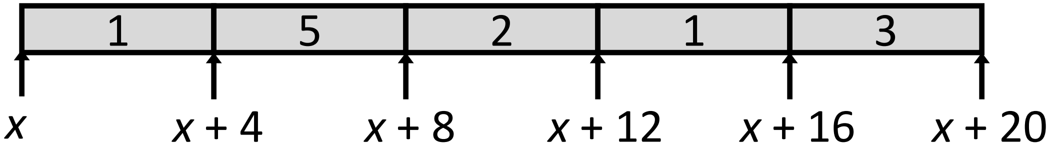
- Basic Principle *T* **A[*L*];**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof**(*T*) bytes in memory
  - Identifier **A** can be used as a pointer to array element 0: Type *T**



Exercise: Array Access

- Basic Principle *T* **`A[`*`L`*`];`**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **`sizeof`**(*T*) bytes in memory
  - Identifier **`A`** can be used as a pointer to array element 0: Type *T**

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



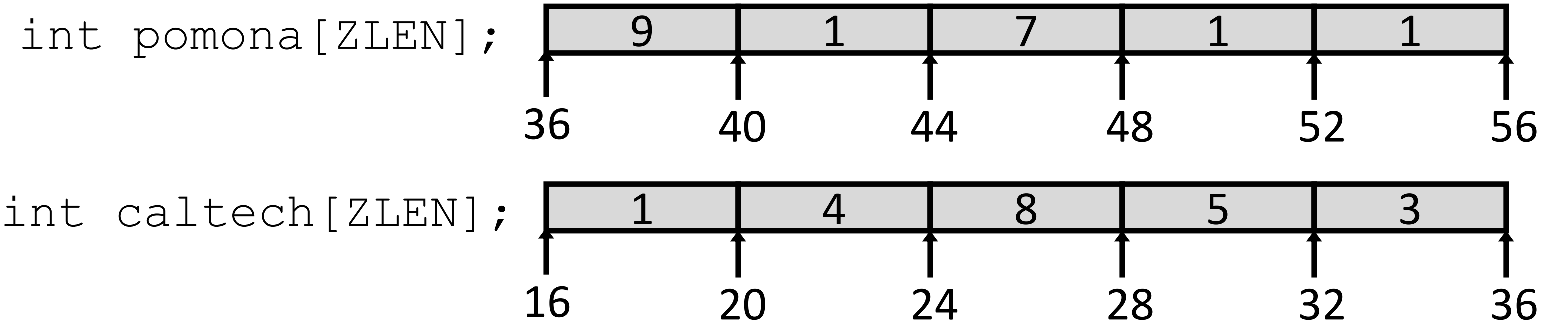
Reference	Type	Value
`val[4]`		
`val`		
`val+1`		
`&(val[2])`		
`val[5]`		
`*(val+1)`		

Register	Use(s)
%rdi	z

Array Example

```
#define ZLEN 5

int pomona[ZLEN]  = { 9, 1, 7, 1, 1 };
int caltech[ZLEN] = { 9, 1, 1, 2, 5 };

void cycle_digits(int* zipcode){
    int temp = zipcode[0];
    zipcode[0] = zipcode[1];
    zipcode[1] = zipcode[2];
    zipcode[2] = zipcode[3];
    zipcode[3] = zipcode[4];
    zipcode[4] = temp;
}
```

???



Operand Forms

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  - Syntax: $c   Ex: $47   Val: c   C Equiv: 47
- Register:
  - Syntax: r   Ex: %rbp   Val: Reg[r]   C Equiv: x
- Memory (Absolute):
  - Syntax: addr   Ex: 0x4050   Val: Mem[addr]   C Equiv: *0x60201a
- Memory (Indirect):
  - Syntax: (r)   Ex: (%rsp)   Val: Mem[Reg[r]]   C Equiv: *x
- Memory (Base+displacement):
  - Syntax: c(r)   Ex: 12(%rsp)   Val: Mem[Reg[r]+c]   C Equiv: *(x+12)

Exercise: Operands

Register	Value
%rax	0x100
%rcx	0x01
%rdx	0x03

Memory Address	Value
0x100	0xFF
0x104	0xAB
0x108	0x13
0x10C	0x47

- What are the values of the following operands (assuming register and memory state shown above)?
  1. `4(%rax)`
  2. `8(%rax)`
  3. `12(%rax)`

Register	Use(s)
%rdi	z

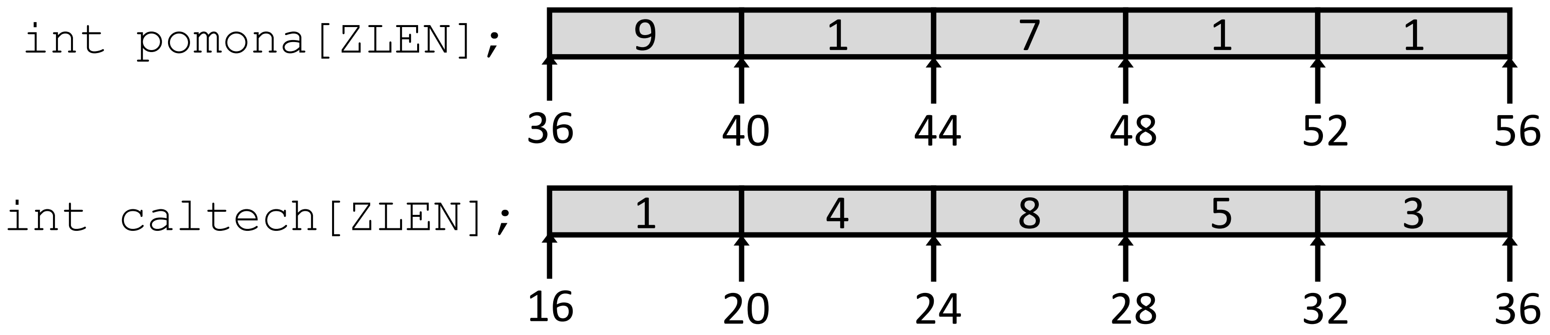
Array Example

```
#define ZLEN 5

int pomona[ZLEN]  = { 9, 1, 7, 1, 1 };
int caltech[ZLEN] = { 9, 1, 1, 2, 5 };

void cycle_digits(int* zipcode){
    int temp = zipcode[0];
    zipcode[0] = zipcode[1];
    zipcode[1] = zipcode[2];
    zipcode[2] = zipcode[3];
    zipcode[3] = zipcode[4];
    zipcode[4] = temp;
}
```

```
movl  (%rdi), %rdx
movl 4(%rdi), %rcx
movl %rcx, (%rdi)
movl 8(%rdi), %rcx
movl %rcx, 4(%rdi)
movl 12(%rdi), %rcx
movl %rcx, 8(%rdi)
movl 16(%rdi), %rcx
movl %rcx, 12(%rdi)
movl %rdx, (rdi)
```



int pomona[ZLEN];

9	1	7	1	1

36 40 44 48 52 56

int caltech[ZLEN];

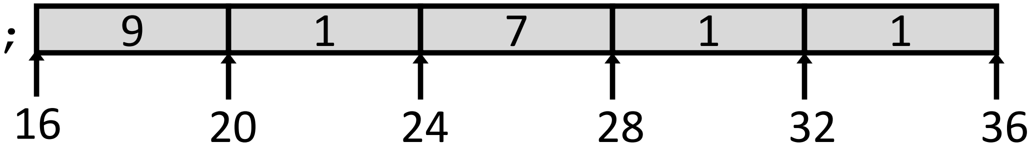
1	4	8	5	3

16 20 24 28 32 36

Array Accessing Example

Register	Use(s)
`%rdi`	`z`
`%rsi`	`digit`
`%rax`	`return val`

```
zip_code pomona;
```



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

???

Operand Forms

- Immediate:
  - Syntax: $c   Ex: $47   Val: c   C Equiv: 47
- Register:
  - Syntax: r   Ex: %rbp   Val: Reg[r]   C Equiv: x
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- Memory (Indirect):
  - Syntax: (r)   Ex: (%rsp)   Val: Mem[Reg[r]]   C Equiv: *x
- Memory (Base+displacement):
  - Syntax: c(r)   Ex: 12(%rsp)   Val: Mem[Reg[r]+c]   C Equiv: *(x+12)
- Memory (Scaled indexed):
  - Syntax: (r1,r2,s)   Ex: (%rdx,%rsi,4)   Val: Mem[Reg[r1]+Reg[r2]*s]   C: r1[r2]
- Memory (Scaled indexed w/ displacement):
  - Syntax: c(r1,r2,s)   Ex: 8(%rdx,%rsi,4)   Val: Mem[Reg[r1]+Reg[r2]*s+c] C: (r1+8)[r2]

Exercise: Operands

Register	Value
%rax	0x100
%rcx	0x01
%rdx	0x03

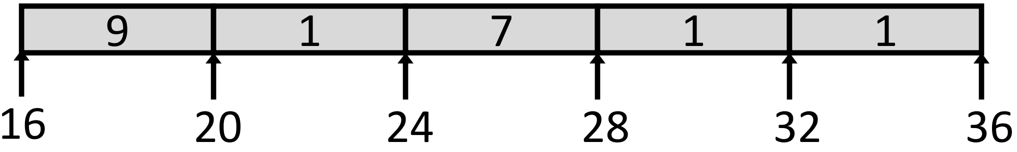
Memory Address	Value
0x100	0xFF
0x104	0xAB
0x108	0x13
0x10C	0x47

- What are the values of the following operands (assuming register and memory state shown above)?
  1. `(%rax,%rcx,4)`
  2. `(%rax,%rdx,4)`
  3. `8(%rax,%rcx,4)`

Array Accessing Example

Register	Use(s)
`%rdi`	`z`
`%rsi`	`digit`
`%rax`	`return val`

`zip_code pomona;`



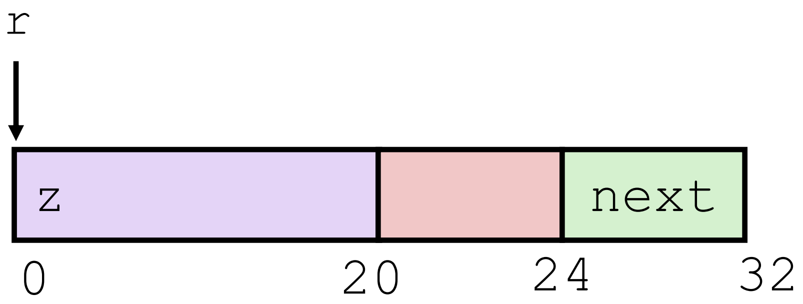
```
int get_digit(int* zipcode, int digit){
  return z[digit];
}
```

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

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

Structure Representation

```
struct node {
  int z[5];
  struct node* next;
};
```

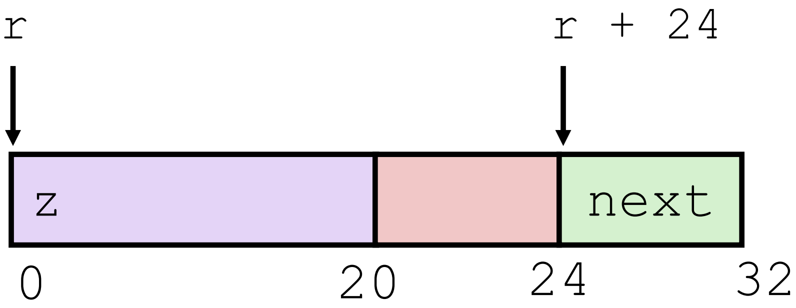


- Structure represented as block of memory
  - **Big enough to hold all of the fields**
- Fields ordered according to declaration
  - **Even if another ordering could yield a more compact representation**
- Compiler determines overall size + positions of fields
  - **Machine-level program has no understanding of the structures in the source code**

Register	Use(s)
%rdi	n
%rax	return val

Accessing Fields

```
struct node {
  int z[5];
  struct node* next;
};
```



- Accessing a field in a struct
    - Offset of each structure member determined at compile time

```
struct node* get_next(struct rec* n){
  return n->next;
}
```

```
  # n in %rdi
  movq  24(%rdi), %rax
  ret
```

C is close to Machine Language

```
*dest = t;
```

- C Code
  - Store value **`t`** where designated by **`dest`**

```
movq %rax, (%rbx)
```

- Assembly
  - Move 8-byte value to memory
    - Quad words in x86-64 parlance
  - Operands:

`t`:	Register	**`%rax`**
`dest`:	Register	**`%rbx`**
`*dest`:	Memory	**M[`%rbx`]**

```
0x40059e:   48 89 03
```

- Object Code
  - 3-byte instruction
  - at address **`0x40059e`**