Building an Executable

CSE 351 Summer 2018

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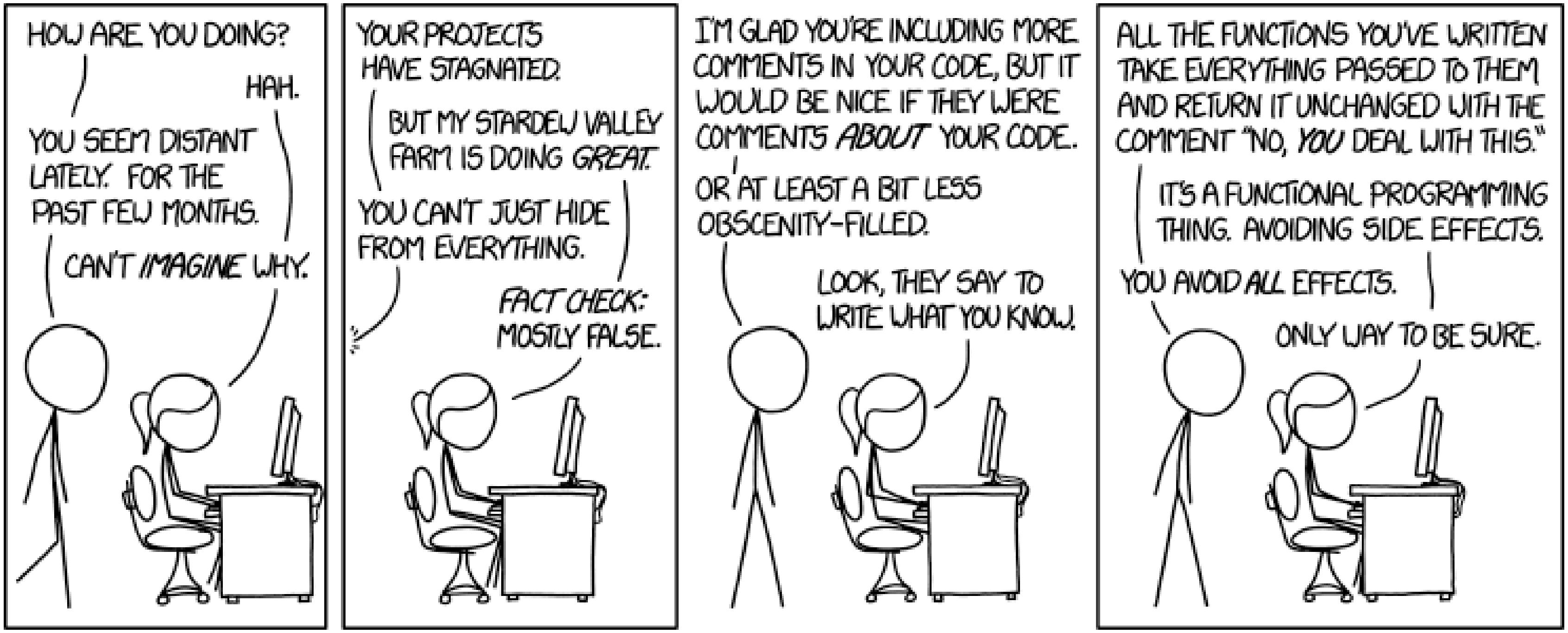

HOW ARE YOU DOING?
HAH.
YOU SEEM DISTANT LATELY. FOR THE PAST FEW MONTHS.
CAN'T IMAGINE WHY.
YOUR PROJECTS HAVE STAGNATED.
BUT MY STARDEW VALLEY FARM IS DOING GREAT.
YOU CAN'T JUST HIDE FROM EVERYTHING.
FACT CHECK: MOSTLY FALSE.
I'M GLAD YOU'RE INCLUDING MORE COMMENTS IN YOUR CODE, BUT IT WOULD BE NICE IF THEY WERE COMMENTS ABOUT YOUR CODE.
OR AT LEAST A BIT LESS OBSCENITY-FILLED.
LOOK, THEY SAY TO WRITE WHAT YOU KNOW.
ALL THE FUNCTIONS YOU'VE WRITTEN TAKE EVERYTHING PASSED TO THEM AND RETURN IT UNCHANGED WITH THE COMMENT "NO, YOU DEAL WITH THIS."
IT'S A FUNCTIONAL PROGRAMMING THING. AVOIDING SIDE EFFECTS.
YOU AVOID ALL EFFECTS.
ONLY WAY TO BE SURE.

http://xkcd.com/1790/

Administrivia

- Lab 2 due Monday (7/16)
- Homework 3 due 7/23

- **Midterm** Wednesday (7/18, in lecture)
  - Make a cheat sheet! – two-sided letter page, *handwritten*
  - Check Piazza for announcements
  - **Review session** 5:00-6:30 pm on Monday (7/16) in EEB 105

Procedures

- Stack Structure
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- **Illustration of Recursion**

Recursive Function

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

logical right shift

stop once all 1's shifted off

value of LSB

shift off LSB and recurse

Compiler Explorer:

https://godbolt.org/g/W8DxeR

- Compiled with `-O1` for brevity instead of `-Og`
- Try `-O2` instead!

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

Recursive Function: Base Case

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

Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

prepare return val of 0

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

jump to .L6 if x & x == 0

(don't worry about it)

Trick because some AMD hardware doesn't like jumping to `ret`

Recursive Function: Callee Register Save

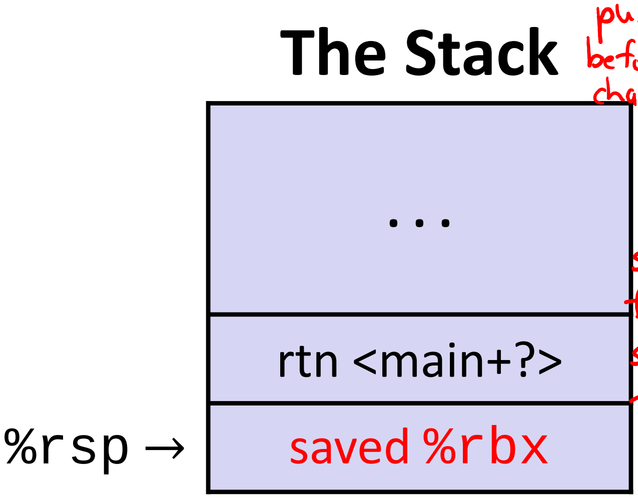
```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

need x across procedure call

Register	Use(s)	Type
%rdi	x	Argument

Need original value of x *after* recursive call to pcount_r.

"Save" by putting in %rbx (**callee** saved), but need to save old value of %rbx before you change it.



push before changing

store "x" for this stack frame

pop/restore before returning

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

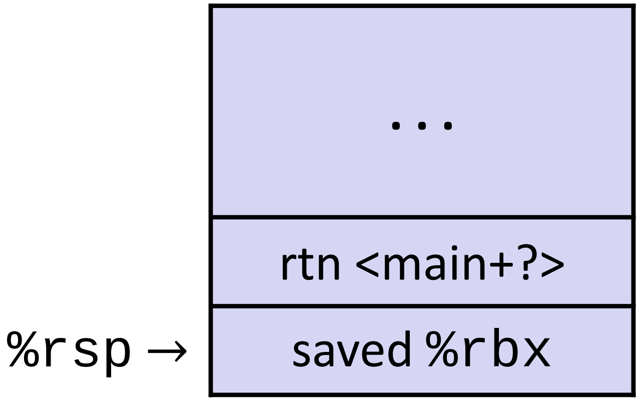
Recursive Function: Call Setup

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

Register	Use(s)	Type
%rdi	x (new)	Argument
%rbx	x (old)	Callee saved

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq  $1, %rdi
       implicit
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

The Stack



...

rtn <main+?>

%rsp →

saved %rbx

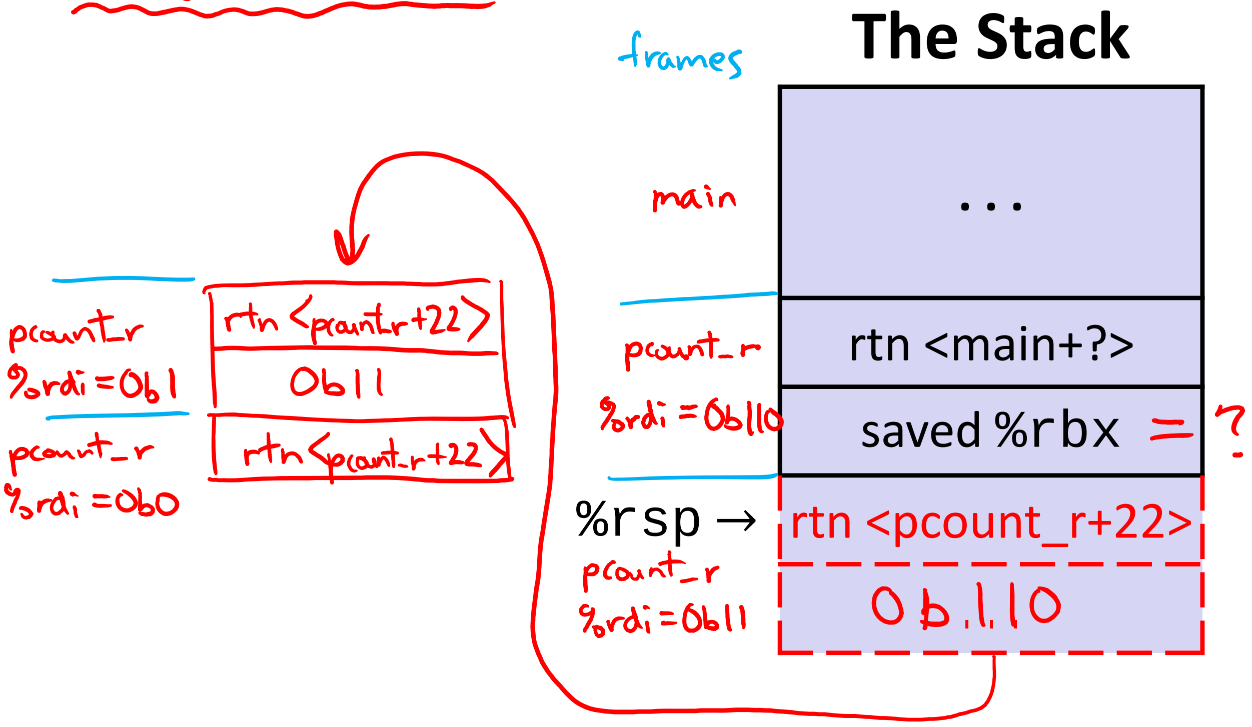
Recursive Function: Call

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

Register	Use(s)	Type
%rax	Recursive call return value	Return value
%rbx	x (old)	Callee saved

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

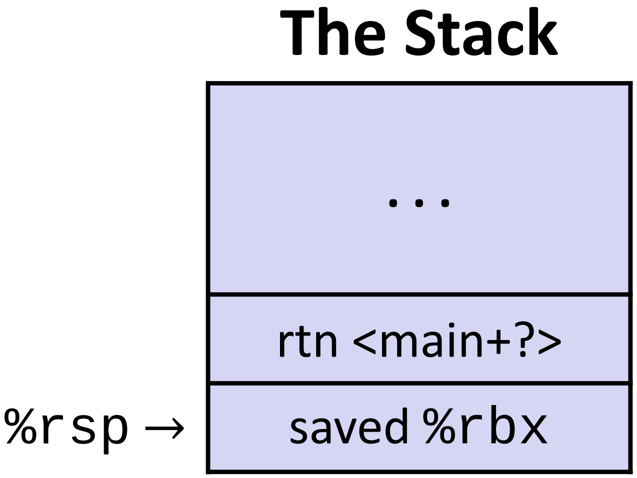
if original x = 0b110 :



Recursive Function: Result

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

Register	Use(s)	Type
%rax	Return value	Return value
%rbx	x&1	Callee saved



```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

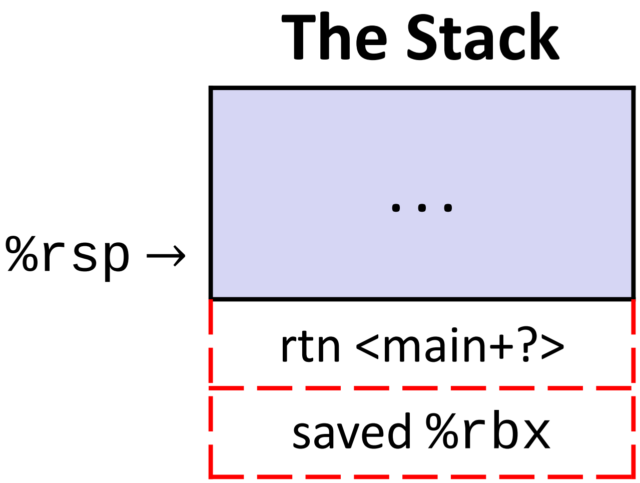
across

assumed the same

Recursive Function: Completion

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

Register	Use(s)	Type
%rax	Return value	Return value
%rbx	Previous %rbx value	Callee restored



```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

restore before returning

Observations About Recursion

- Works without any special consideration
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
    - Unless the code explicitly does so (*e.g.* buffer overflow)
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out (LIFO)
- Also works for mutual recursion (P calls Q; Q calls P)

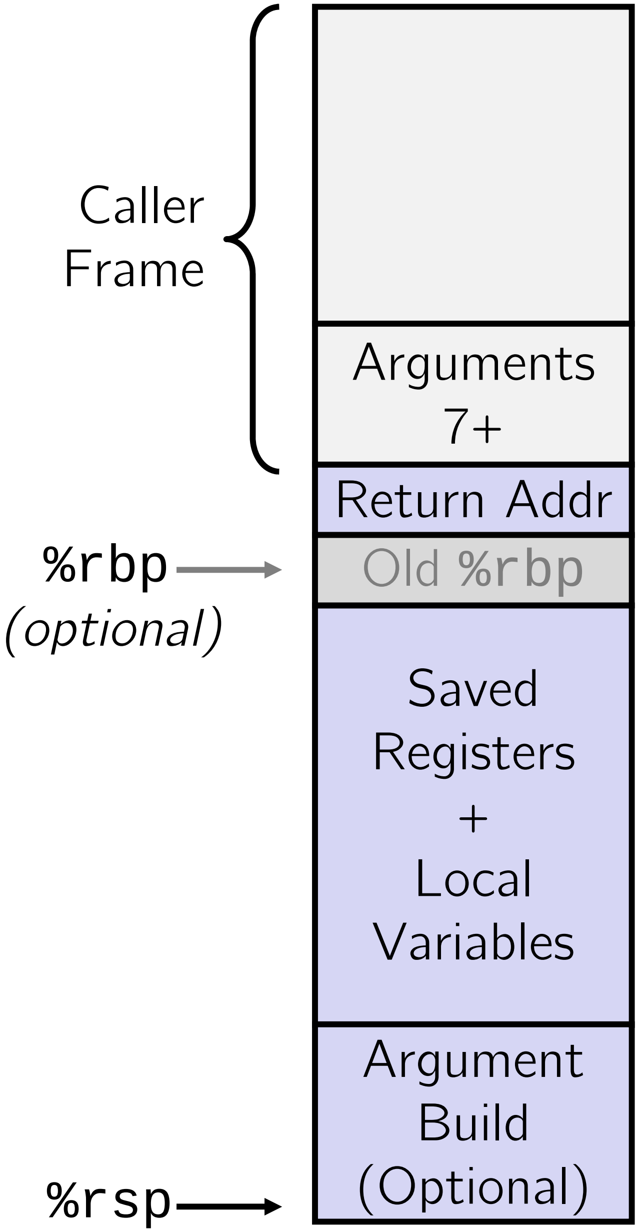
x86-64 Stack Frames

- Many x86-64 procedures have a minimal stack frame
  - Only return address is pushed onto the stack when procedure is called

- A procedure *needs* to grow its stack frame when it:
  - Has too many local variables to hold in **caller**-saved registers
  - Has local variables that are arrays or structs
  - Uses & to compute the address of a local variable
  - Calls another function that takes more than six arguments
  - Is using **caller**-saved registers and then calls a procedure
  - Modifies/uses **callee**-saved registers

x86-64 Procedure Summary

- Important Points
  - Procedures are a combination of *instructions and conventions*
    - Conventions prevent functions from disrupting each other
  - Stack is the right data structure for procedure call/return
    - If P calls Q, then Q returns before P
  - Recursion handled by normal calling conventions
- Heavy use of registers
  - Faster than using memory
  - Use limited by data size and conventions
- Minimize use of the Stack



Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

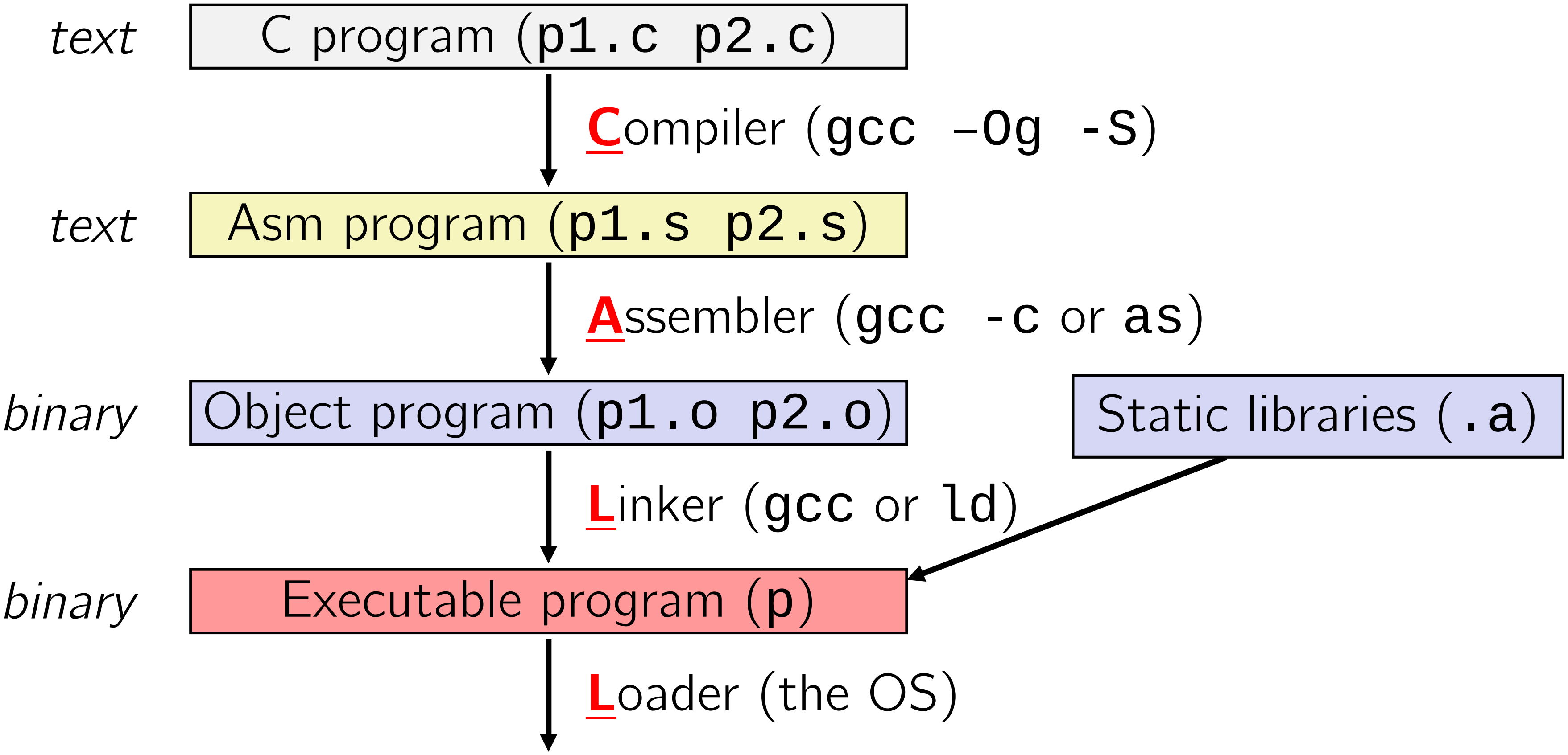
Windows 10 OS X Yosemite

Computer system:

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Building an Executable from a C File

- Code in files `p1.c p2.c`
- Compile with command: `gcc -Og p1.c p2.c -o p`
  - Put resulting machine code in file `p`
- Run with command: `./p`



text C program (`p1.c p2.c`)

Compiler (`gcc –Og -S`)

text Asm program (`p1.s p2.s`)

Assembler (`gcc -c` or `as`)

binary Object program (`p1.o p2.o`)

Static libraries (`.a`)

Linker (`gcc` or `ld`)

binary Executable program (`p`)

Loader (the OS)

Compiler

- **Input:** Higher-level language code (*e.g.* C, Java)
  - `foo.c`
- **Output:** Assembly language code (*e.g.* x86, ARM, MIPS)
  - `foo.s`

- First there's a preprocessor step to handle #directives
  - Macro substitution, plus other specialty directives
  - If curious/interested: http://tigcc.ticalc.org/doc/cpp.html
- Super complex, whole courses devoted to these!
- Compiler optimizations
  - "Level" of optimization specified by capital '`O`' flag (*e.g.* `-Og`, `-O3`)
  - Options: https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

Compiling Into Assembly

- C Code (sum.c)

```
void sumstore(long x, long y, long *dest) {
    long t = x + y;
    *dest = t;
}
```

- x86-64 assembly (gcc -Og -S sum.c)
  - Generates file sum.s (see https://godbolt.org/g/o34FHp)

```
sumstore(long, long, long*):
  addq    %rdi, %rsi
  movq    %rsi, (%rdx)
  ret
```

Warning: You may get different results with other versions of gcc and different compiler settings

Assembler

- **Input:** Assembly language code (*e.g.* x86, ARM, MIPS)
  - `foo.s`
- **Output:** Object files (*e.g.* ELF, COFF)
  - `foo.o`
  - Contains *object code* and *information tables*
- Reads and uses *assembly directives*
  - *e.g.* `.text`, `.data`, `.quad`
  - x86: https://docs.oracle.com/cd/E26502_01/html/E28388/eoiyg.html
- Produces "machine language"
  - Does its best, but object file is *not* a completed binary
- Example: `gcc -c foo.s`

Producing Machine Language

addq %rdi, %rsi

- **Simple cases:** arithmetic and logical operations, shifts, etc.
  - All necessary information is contained in the instruction itself

- What about the following?
  - Conditional jump
  - Accessing static data (*e.g.* global var or jump table)
  - `call` addr/label

- Addresses and labels are problematic because final executable hasn't been constructed yet!
  - So how do we deal with these in the meantime?

Object File Information Tables

- **Symbol Table** holds list of "items" that may be used by other files
  - *Non-local labels* – function names for `call`
  - *Static Data* – variables & literals that might be accessed across files

- **Relocation Table** holds list of "items" that this file needs the address of later (currently undetermined)
  - Any *label* or piece of *static data* referenced in an instruction in this file
    - Both internal and external

- Each file has its own symbol and relocation tables

Object File Format

1) object file header: size and position of the other pieces of the object file "table of contents"
2) text segment: the machine code (Instructions)
3) data segment: data in the source file (binary) (Static Data & Literals)
4) relocation table: identifies lines of code that need to be "handled"
5) symbol table: list of this file's labels and data that can be referenced
6) debugging information (info for GDB)

- More info: ELF format
  - http://www.skyfree.org/linux/references/ELF_Format.pdf

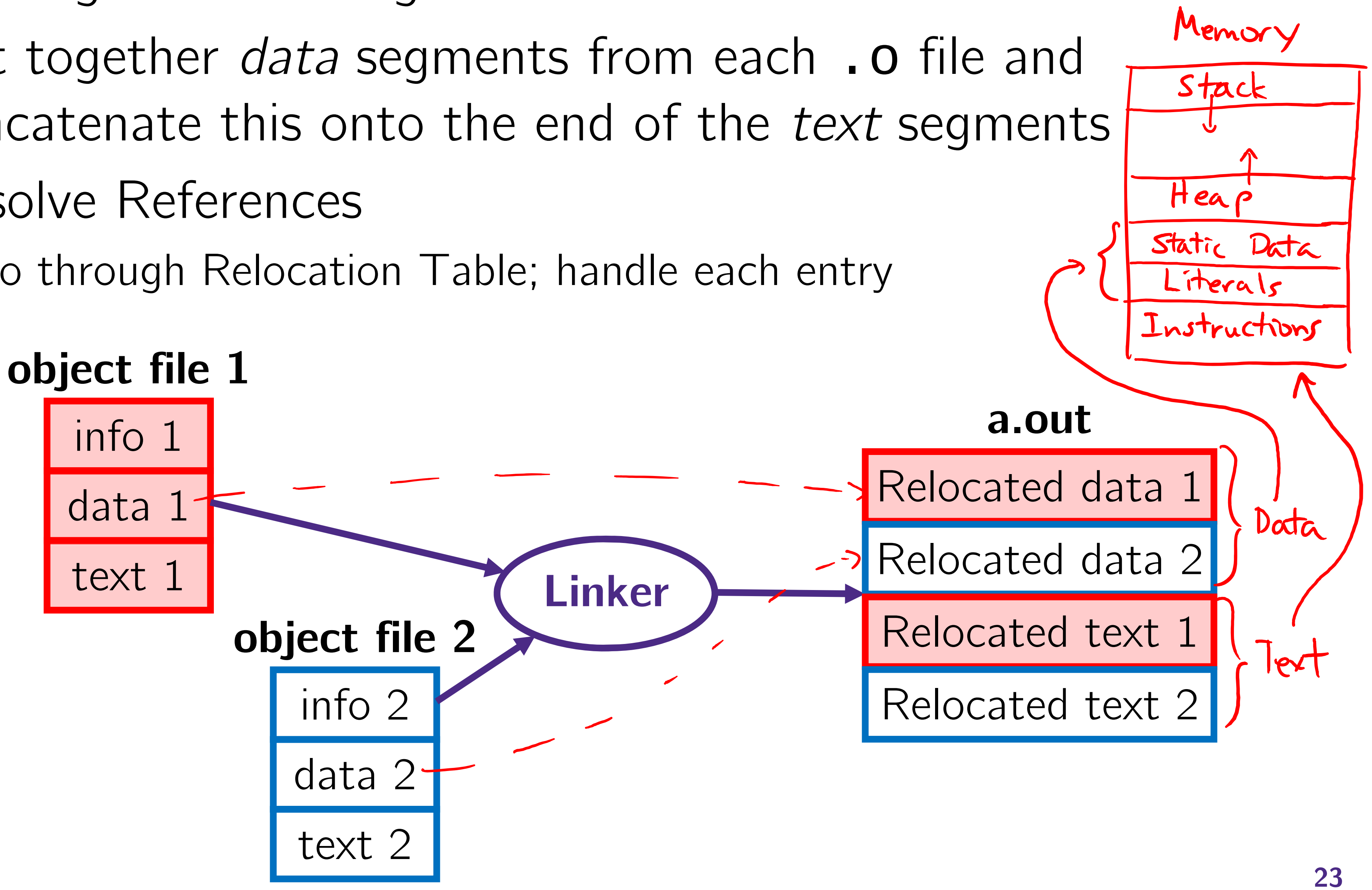
Linker

- **Input:** Object files (e.g. ELF, COFF)
  - `foo.o`
- **Output:** executable binary program
  - `a.out`

- Combines several object files into a single executable (*linking*)
- Enables separate compilation/assembling of files
  - Changes to one file do not require recompiling of whole program

Linking

1) Put together *text* segments from each `.o` file
2) Put together *data* segments from each `.o` file and concatenate this onto the end of the *text* segments
3) Resolve References
   - Go through Relocation Table; handle each entry



object file 1

info 1

data 1

text 1

object file 2

info 2

data 2

text 2

Linker

a.out

Relocated data 1

Relocated data 2

Relocated text 1

Relocated text 2

Disassembling Object Code

- Disassembled:

```
0000000000400536 <sumstore>:
  400536:   48 01 fe       add    %rdi,%rsi
  400539:   48 89 32       mov    %rsi,(%rdx)
  40053c:   c3             retq
```

36 37 38

39 3a 3b

3c

address of instruction

object code bytes (hex)

interpreted assembly instructions

- **Disassembler** (`objdump -d sum`)
  - Useful tool for examining object code (`man 1 objdump`)
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code
  - Can run on either `a.out` (complete executable) or `.o` file

What Can be Disassembled?

```
% objdump -d WINWORD.EXE

WINWORD.EXE:   file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:
30001001:
30001003:
30001005:
3000100a:
```

Reverse engineering forbidden by
Microsoft End User License Agreement

- Anything that can be interpreted as executable code
- Disassembler examines bytes and attempts to reconstruct assembly source

Loader

- **Input:** executable binary program, command-line arguments
  - `./a.out arg1 arg2`
- **Output:** <program is run>

- Loader duties primarily handled by OS/kernel
  - More about this when we learn about processes
- Memory sections (Instructions, Static Data, Literals, Stack) are set up
- Registers are initialized

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

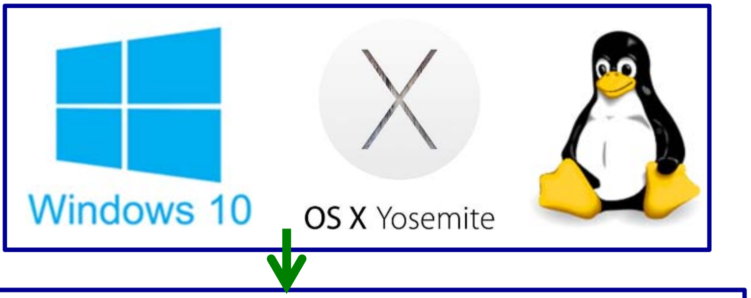
Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

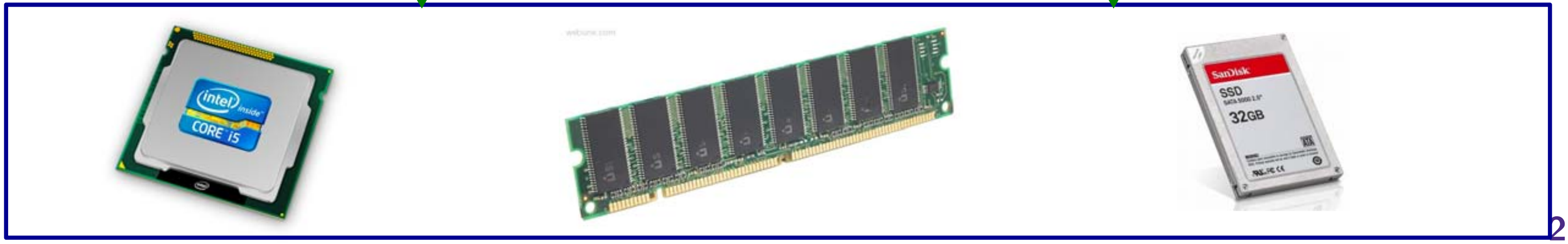
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:



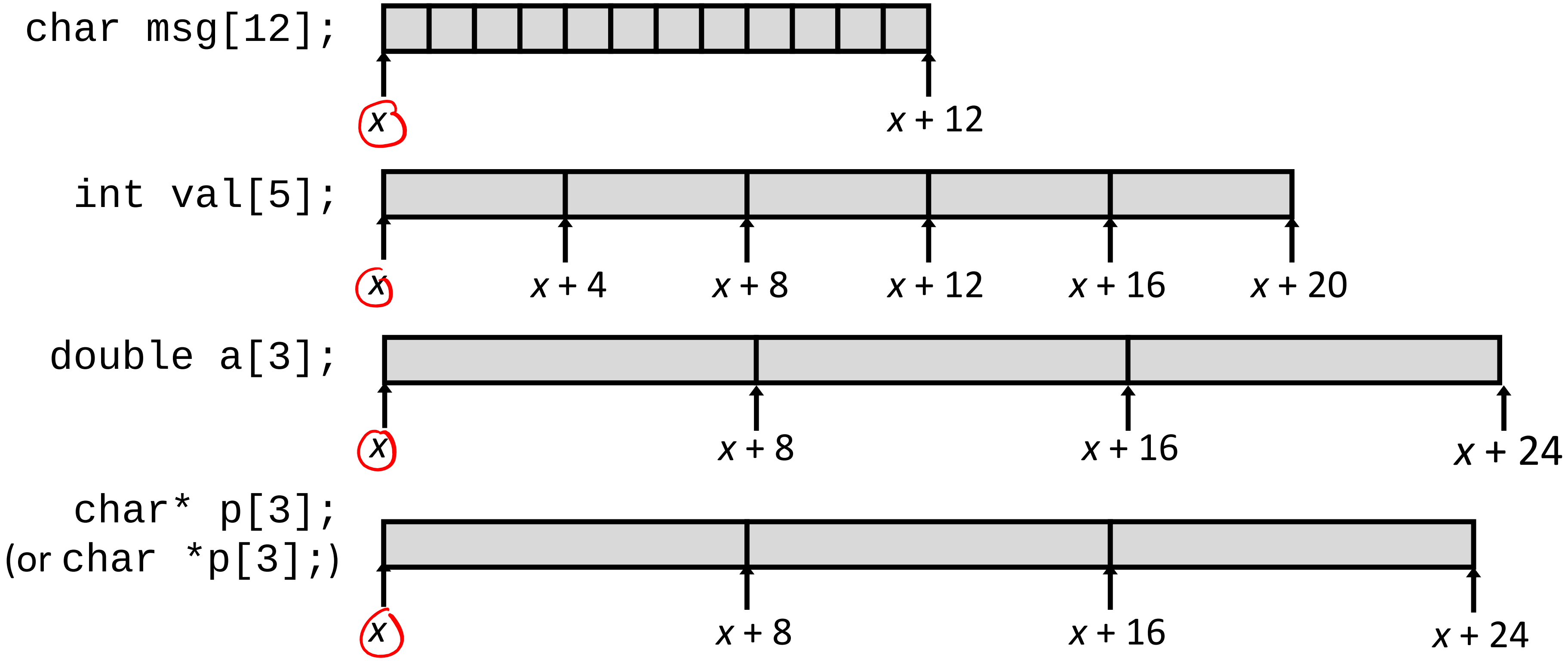
- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Data Structures in Assembly

- **Arrays**
  - **One-dimensional**
  - Multi-dimensional (nested)
  - Multi-level
- Structs
  - Alignment
- Unions

Array Allocation

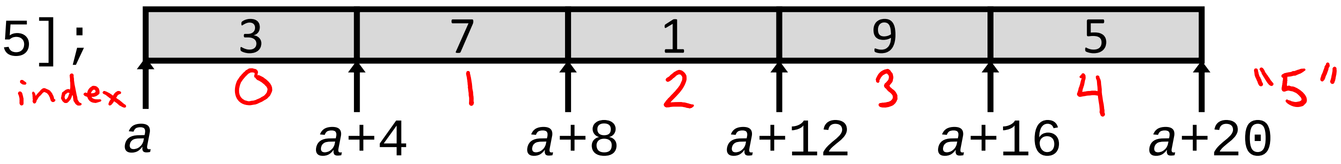
- Basic Principle
  - **`T A[N];`** → array of data type **`T`** and length `N`
  - *Contiguously* allocated region of `N*sizeof(T)` bytes
  - Identifier **A** returns address of array (type **`T*`**)



Array Access

- Basic Principle
  - `T A[N];` → array of data type **`T`** and length **`N`**
  - Identifier **`A`** returns address of array (type **`T*`**)

```
int x[5];
```



Reference	Type	Value
`x[4]`	**`int`**	`5`
`x`	**`int*`**	`a`
`x+1` ← ptr arithmetic	**`int*`**	`a + 4`
`&x[2]`	**`int*`**	`a + 8`
`x[5]`	**`int`**	`??` (whatever's in memory at addr `x+20`)
`*(x+1)`	**`int`**	`7`
`x+i`	**`int*`**	`a + 4*i`

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

array of size 5 ints

typedef unsigned long int uli

old data type

new, equivalent data type

initialization

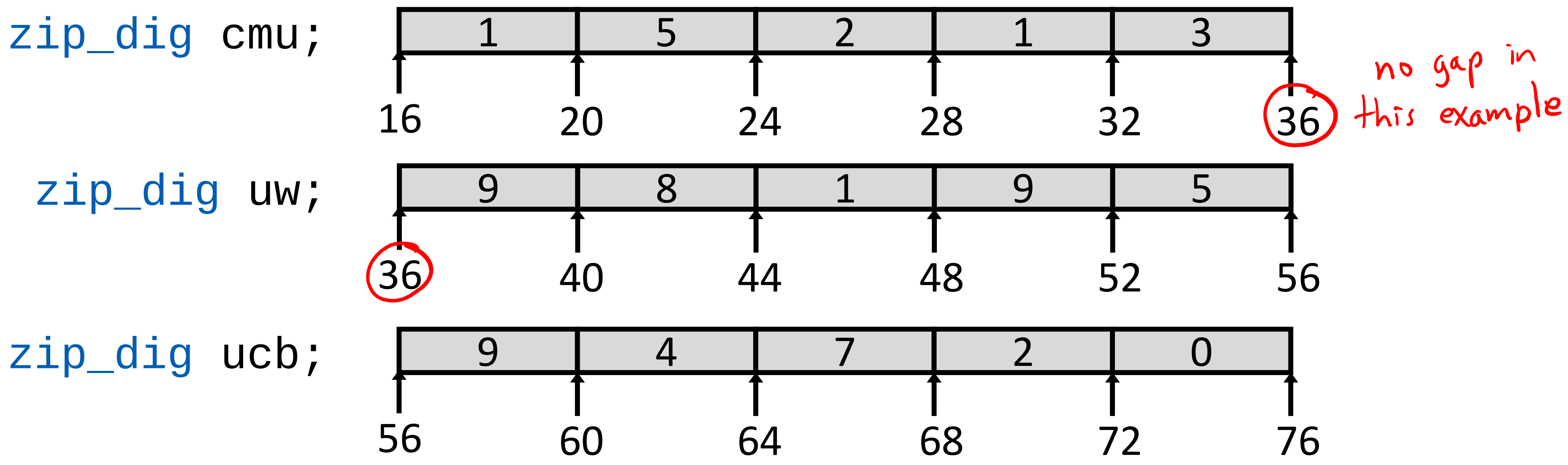
- `typedef`: Declaration "**zip_dig** `uw`" equivalent to "**int** `uw[5]`"

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

20 B each



zip_dig cmu;

1	5	2	1	3

16 20 24 28 32 36

no gap in this example

zip_dig uw;

9	8	1	9	5

36 40 44 48 52 56

zip_dig ucb;

9	4	7	2	0

56 60 64 68 72 76

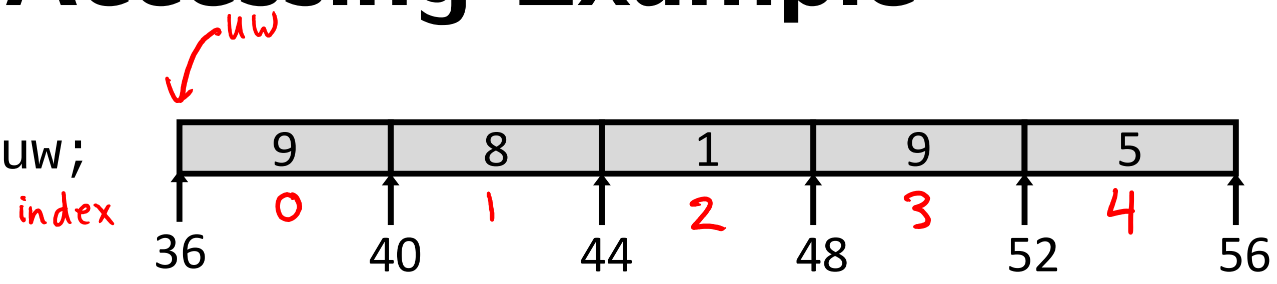
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

(could have allocated variables in-between)

Array Accessing Example

```
typedef int zip_dig[5];
```

```
zip_dig uw;
```



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

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

base reg Rb

index reg Ri

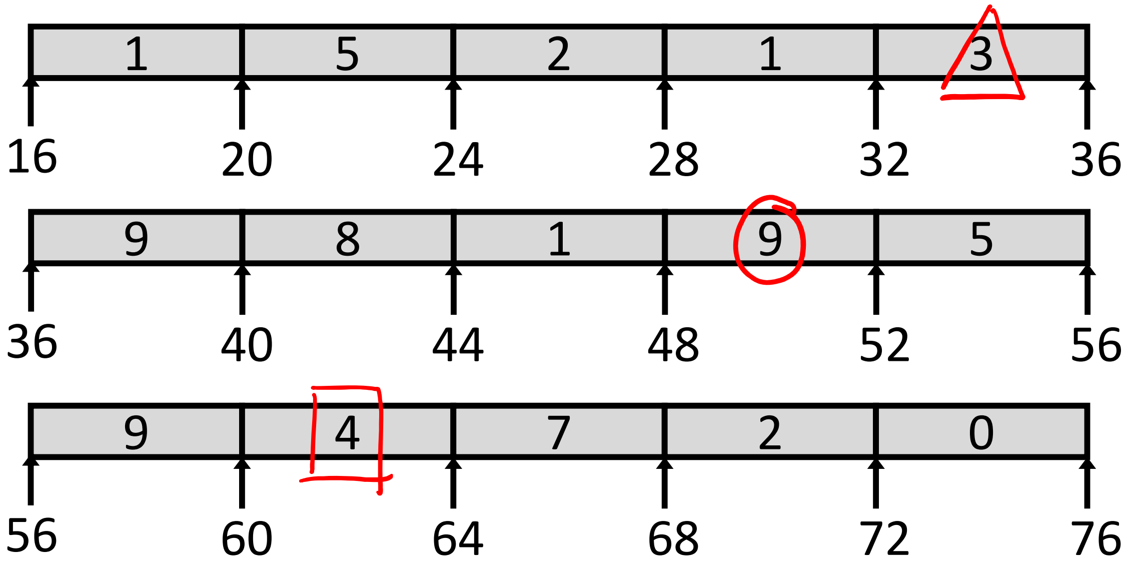
S: scale factor (sizeof)

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

```
typedef int zip_dig[5];
```

Referencing Examples

```
zip_dig cmu;
zip_dig uw;
zip_dig ucb;
```



Rb	Ri	S
uw	3	4

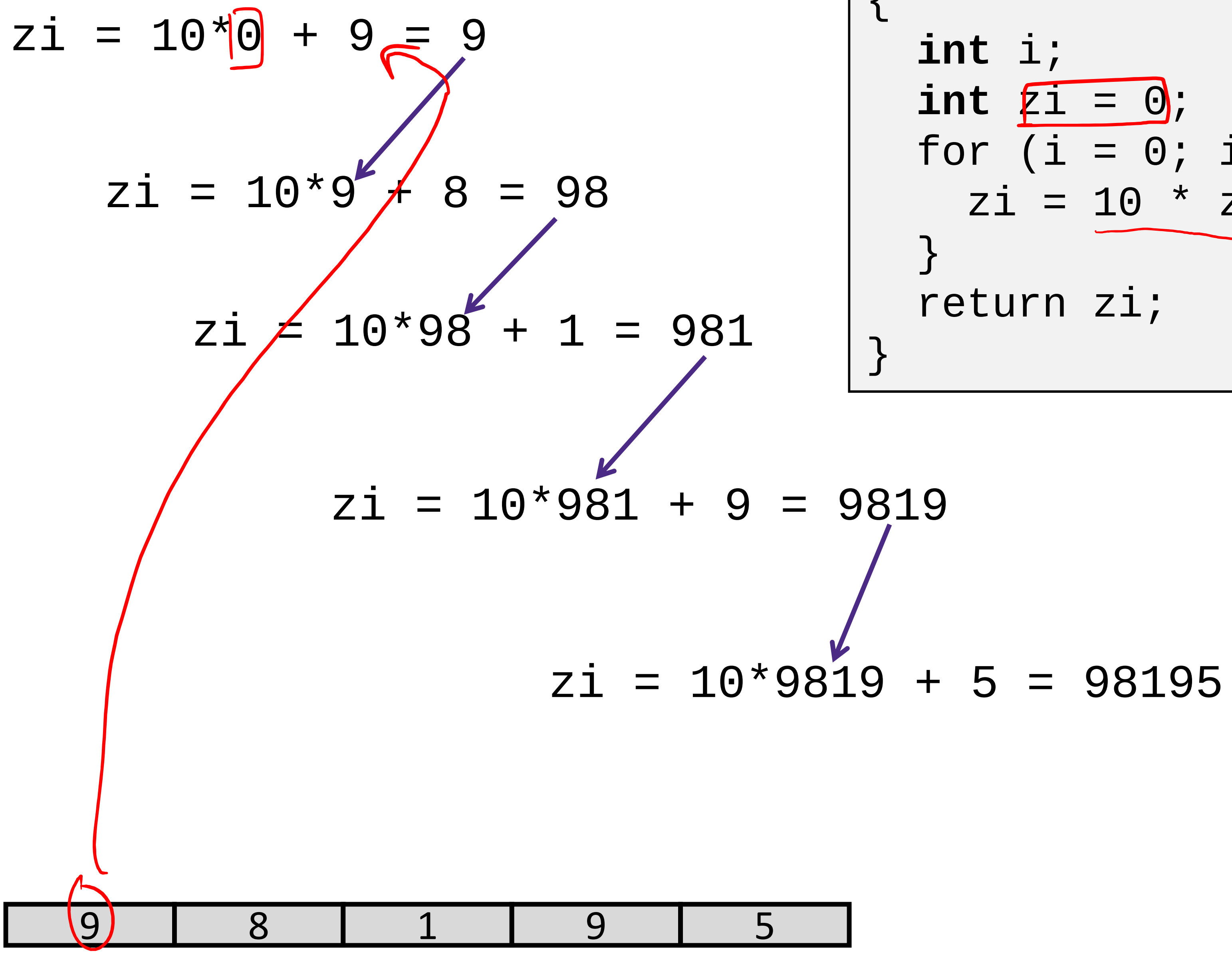
Reference	Address	Value	Guaranteed?
uw[3]	36+3*4=48	9	Yes
uw[6]	36+6*4=$\boxed{60}$	4	No
uw[-1]	36+(-1)*4=32	3	No
cmu[15]	16+15*4=76	?	No

- No bounds checking
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Loop Example

```
typedef int zip_dig[5];
```

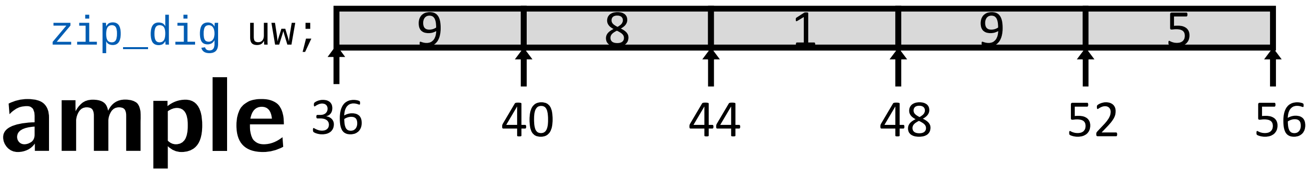
```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```



```
zi = 10*0 + 9 = 9
    zi = 10*9 + 8 = 98
        zi = 10*98 + 1 = 981
              zi = 10*981 + 9 = 9819
                       zi = 10*9819 + 5 = 98195
```

9	8	1	9	5

Array Loop Example



- Original:

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- Transformed:
  - Eliminate loop variable `i`, **use pointer `zend` instead**
  - Convert array code to pointer code
    - Pointer arithmetic on `z`
  - Express in do-while form (no test at entrance)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 5;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z < zend);
  return zi;
}
```

address just past 5th digit

Increments by 4 (size of int)

Array Loop Implementation

`gcc with -O1`

- Registers:
  ```
  %rdi  z
  %rax  zi
  %rcx  zend
  ```
- Computations
  - 10zi + *z implemented as *z + 2(5zi)
  - z++ increments by 4 bytes (size of int)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 5;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z < zend);
  return zi;
}
```

```
   # %rdi = z
   leaq 20(%rdi),%rcx          # rcx = zend = z+5 (scale by 4)
   movl $0,%eax                # rax = zi = 0
.L17:
   leal (%rax,%rax,4),%edx     # rdx = zi+4*zi = 5zi
   movl (%rdi),%eax            # rax = *z
   leal (%rax,%rdx,2),%eax     # rax = *z + 2(5zi) = *z +10zi
   addq $4,%rdi                # z++
   cmpq %rdi,%rcx              # zend - z
   jne .L17                    # if != 0, goto Loop
```

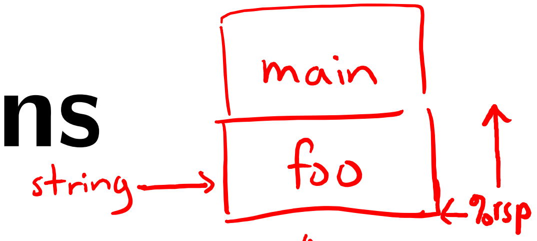
C Details: Arrays and Pointers

- Arrays are (almost) identical to pointers
  - **`char *string`** and **`char string[]`** are nearly identical declarations
  - Differ in subtle ways: initialization, `sizeof()`, etc.

- An array name looks like a pointer to the first (0th) element
  - `ar[0]` same as `*ar`; `ar[2]` same as `*(ar+2)`

- An array variable is read-only (no assignment)
  - Cannot use `"ar = <anything>"`

C Details: Arrays and Functions



data will get overwritten by future stack frames

- Declared arrays only allocated while the scope is valid:

array is allocated on stack

```
char* foo() {
    char string[32]; ...;
    return string;
}
```

BAD!

returns stack addr that is < %rsp

- An array is passed to a function as a pointer:
  - Array size gets lost!

Really `int *ar` (%rdi can only fit 8 bytes)

```
int foo(int ar[], unsigned int size) {
    ... ar[size-1] ...
}
```

Must explicitly pass the size!