Building an Executable

CSE 351 Summer 2018

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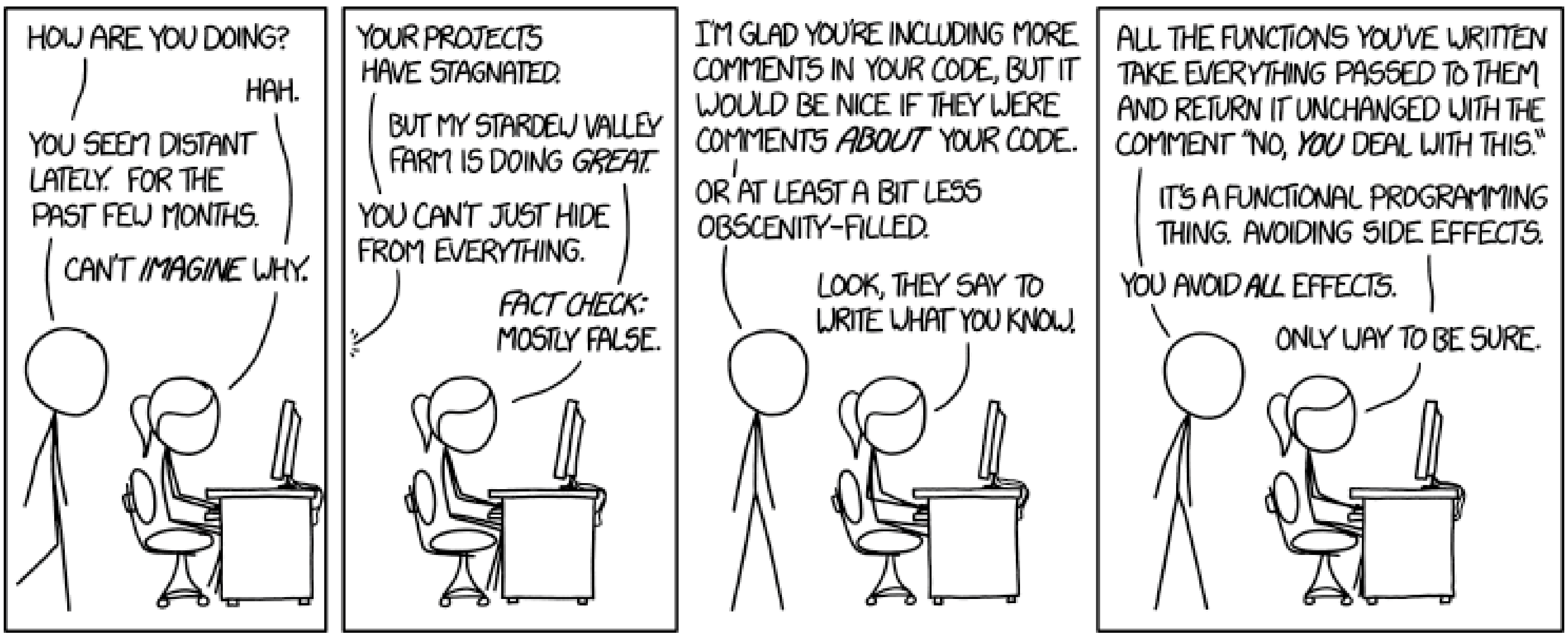


http://xkcd.com/1790/

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);
}
```

```
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
```

Compiler Explorer:

https://godbolt.org/g/W8DxeR

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

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

```
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
```

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

Recursive Function: Callee Register Save

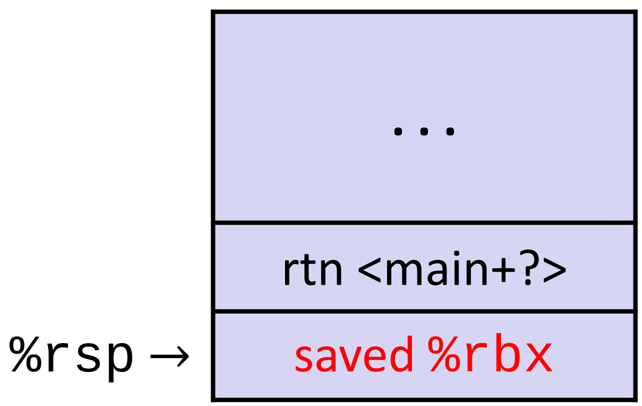
```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

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.

The Stack




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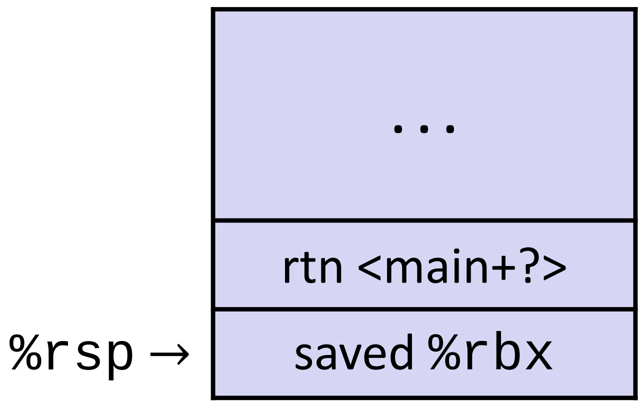
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

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

The Stack




```
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
```

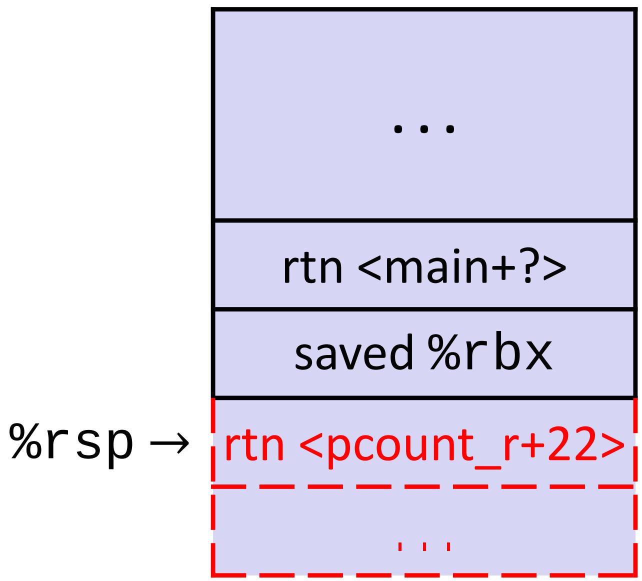
Recursive Function: Call

```
/* 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
```

The Stack

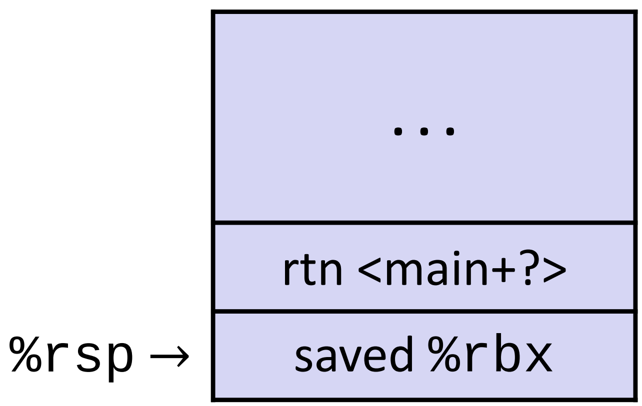


Recursive Function: Result

```
/* 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

The Stack



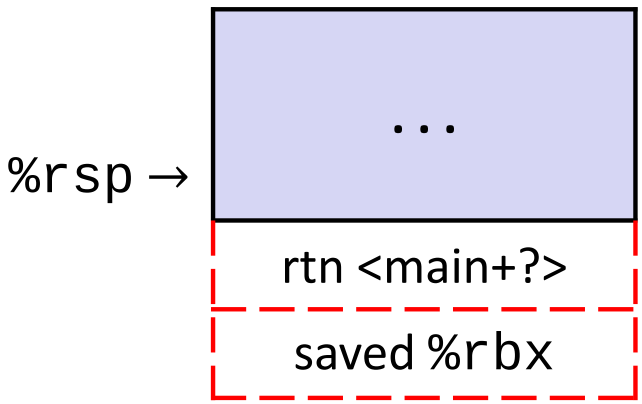

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

Recursive Function: 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

The Stack




```
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
```

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)

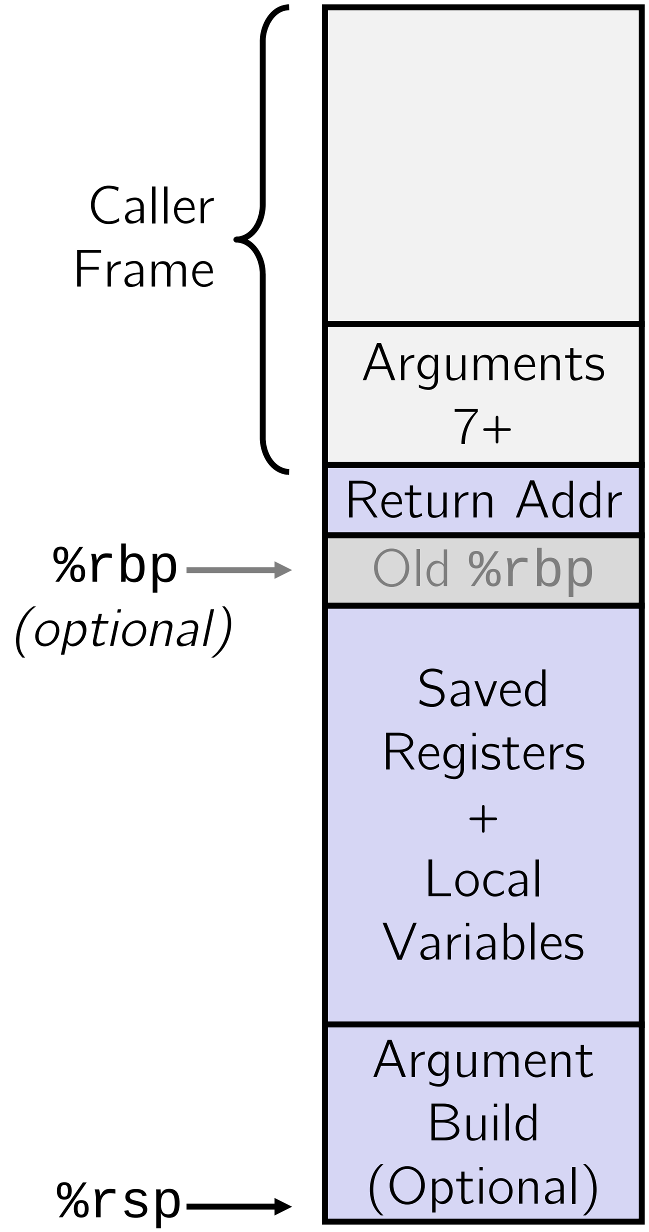
x86-64 Stack Frames

- 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

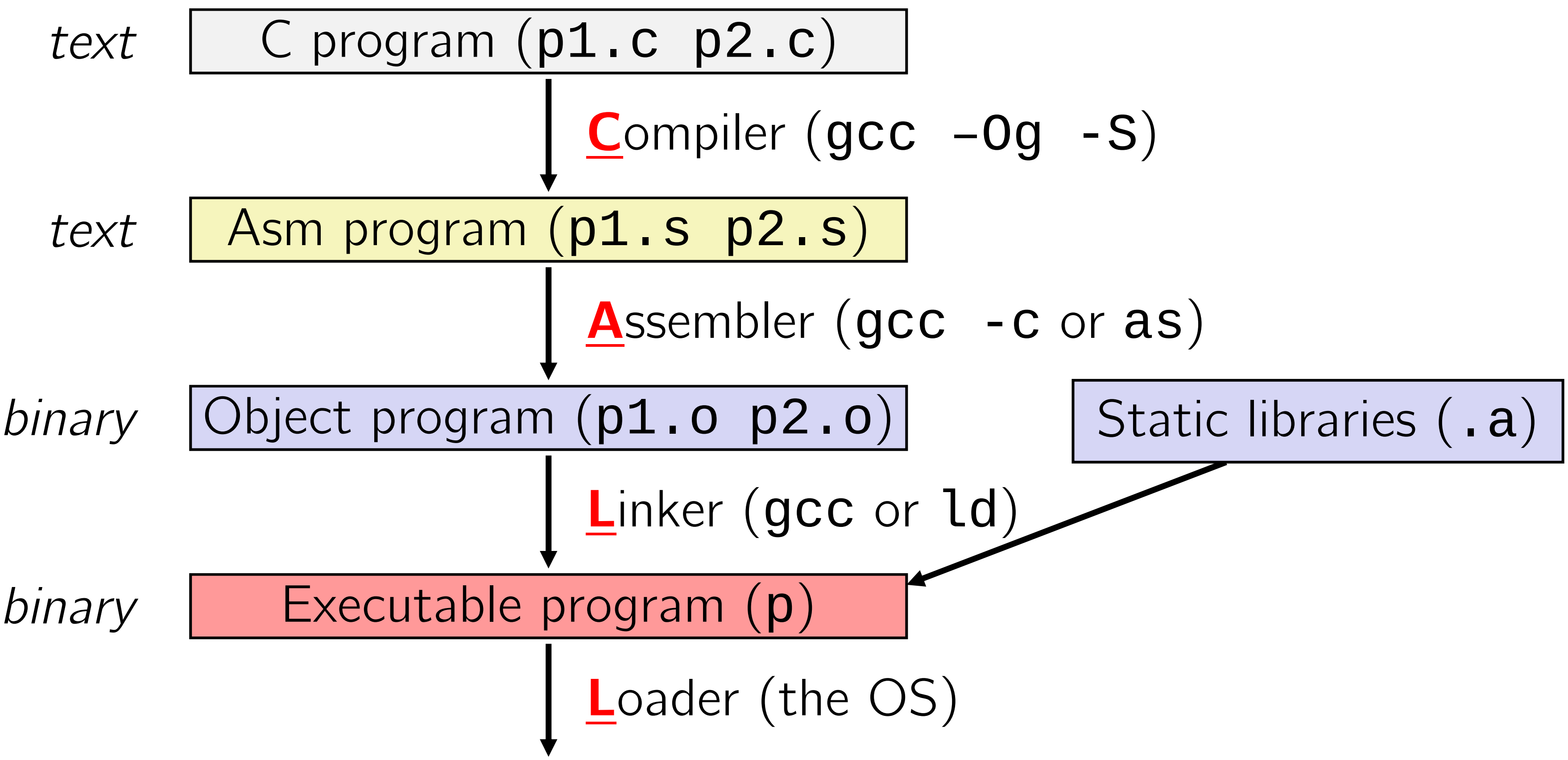
OS X Yosemite

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`



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

- **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`

- 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
2) text segment: the machine code
3) data segment: data in the source file (binary)
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

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

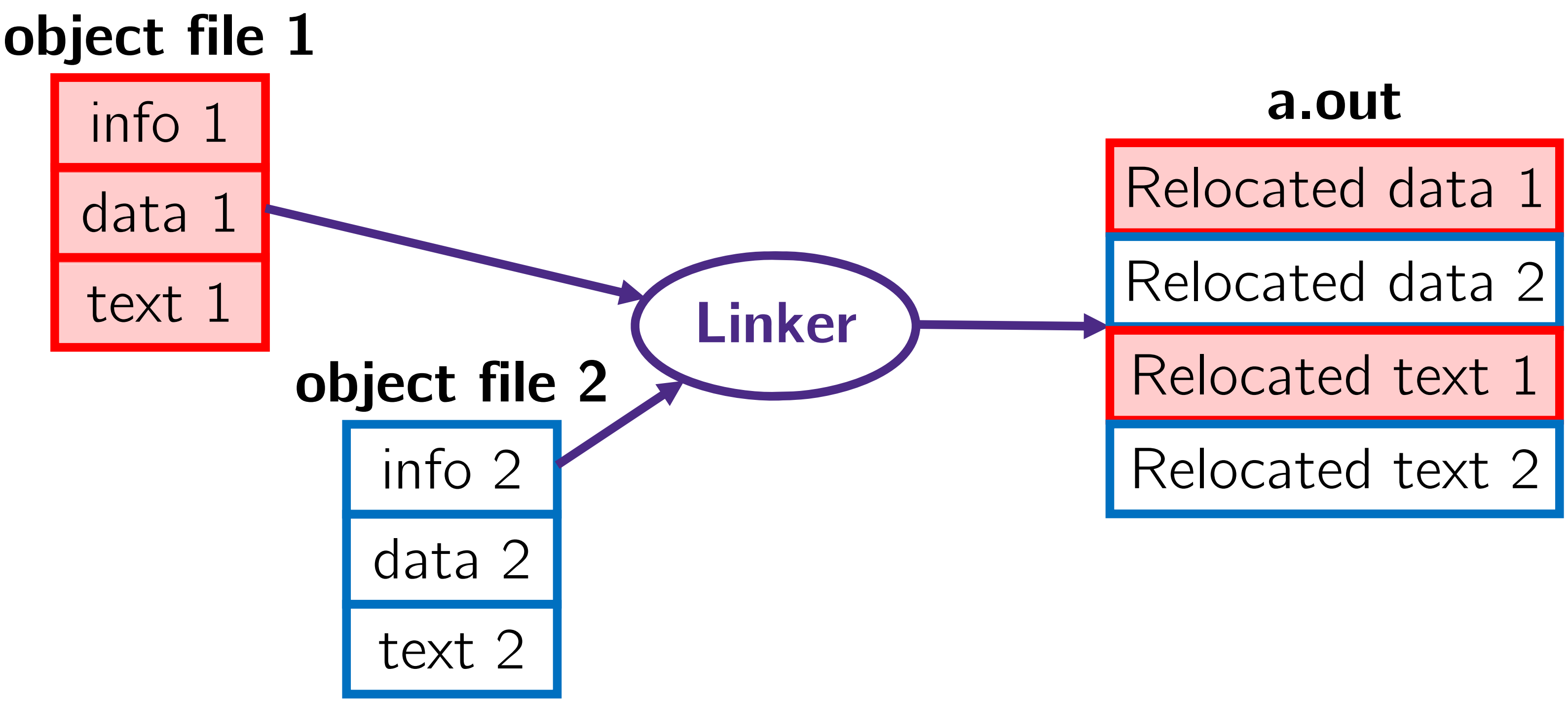
Linker

- **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



Disassembling Object Code

- Disassembled:

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

- **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);
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float mpg =
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Assembly language:

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get_mpg:
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    ...
    popq    %rbp
    ret
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Machine code:

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OS:

Windows 10

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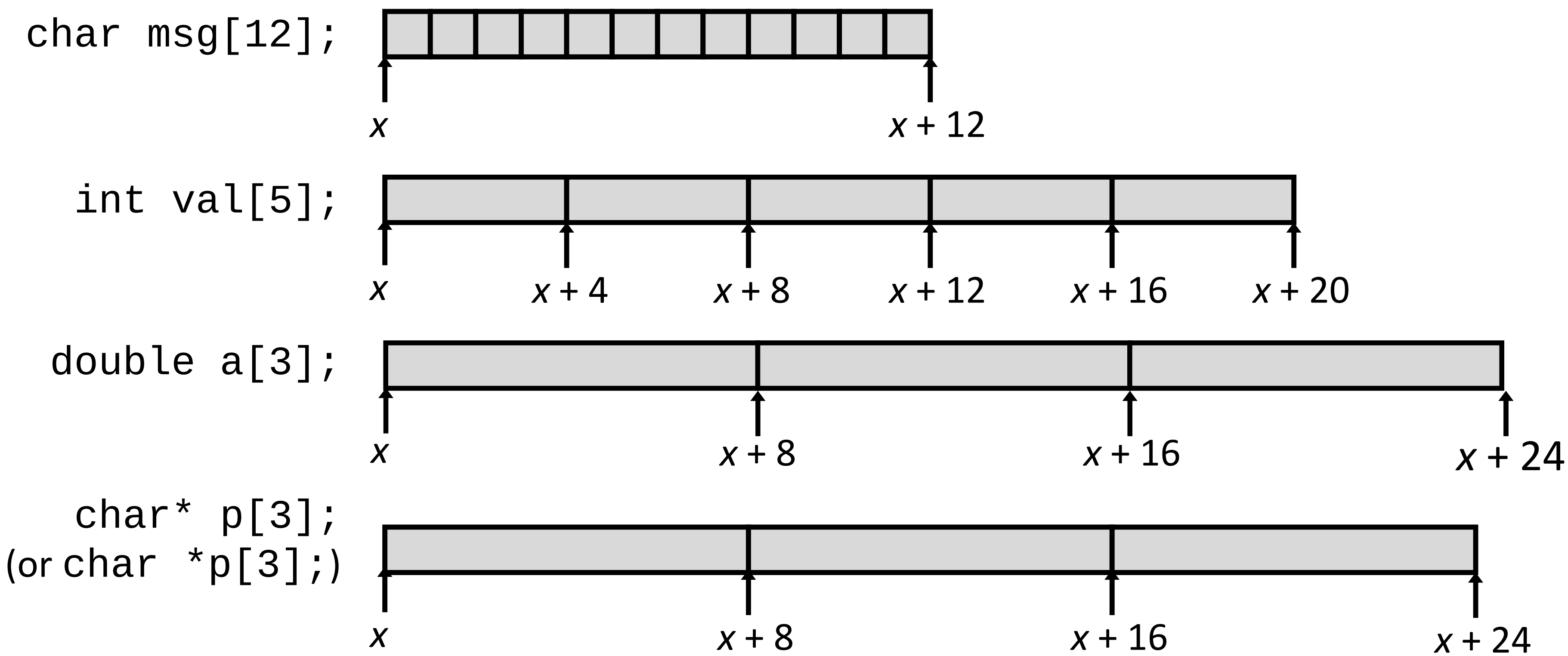
Memory allocation
Java vs. C

Data Structures in Assembly

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

Array Allocation

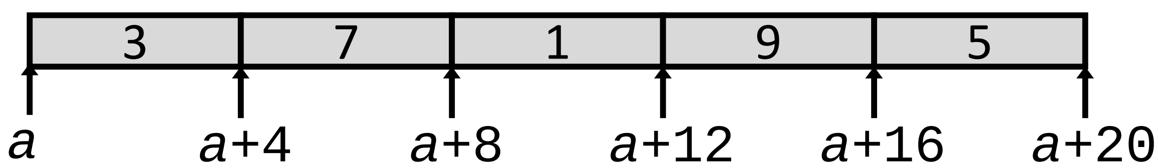
- Basic Principle
  - **`T A[N];`** → array of data type **`T`** and length **`N`**
  - *Contiguously* allocated region of `N*sizeof(T)` bytes
  - Identifier **`A`** returns address of array (type **`T*`**)



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`	**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 };
```

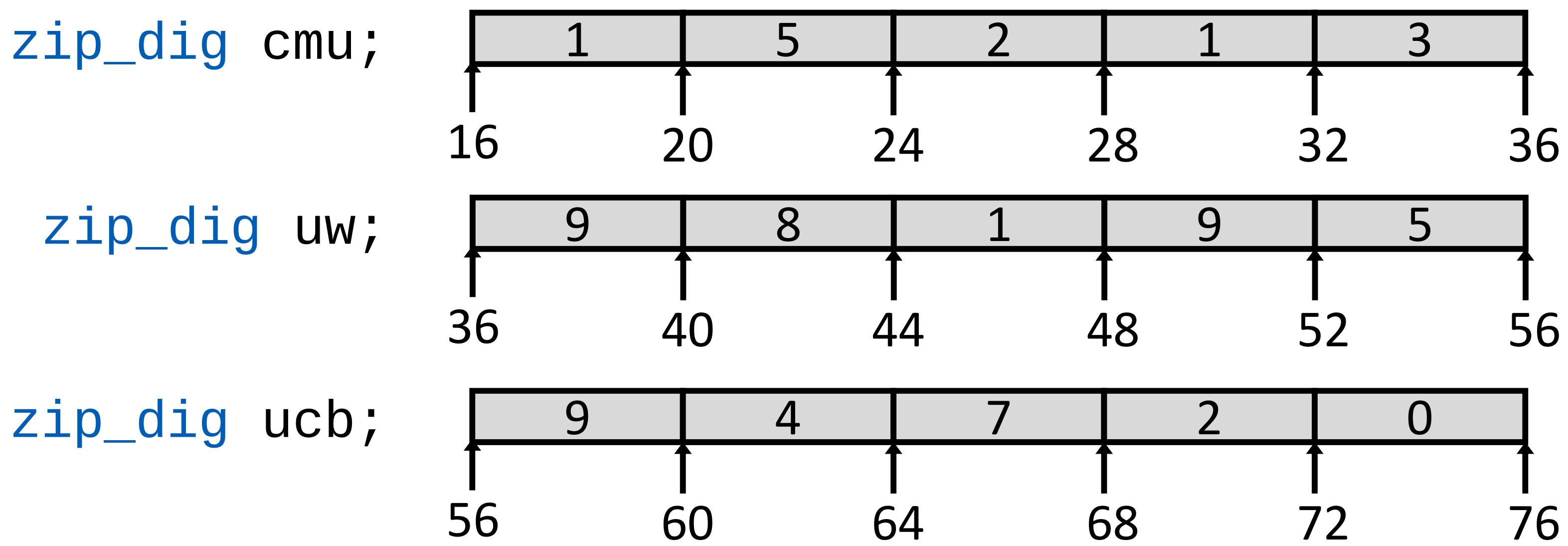
initialization

- `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 };
```

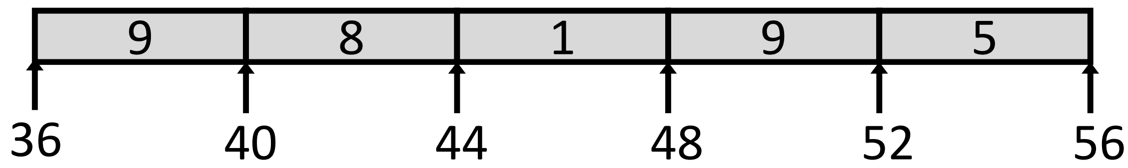


- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

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

Array Accessing Example

```
zip_dig uw;
```




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

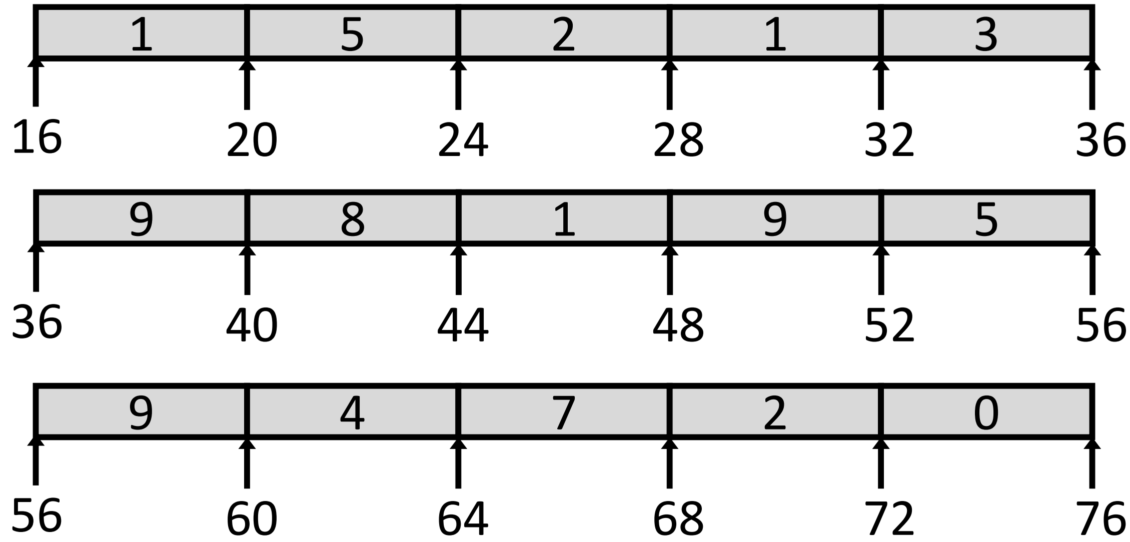
```
get_digit:
  movl (%rdi,%rsi,4), %eax  # z[digit]
```

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

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

Referencing Examples

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



Reference	Address	Value	Guaranteed?
`uw[3]`			
`uw[6]`			
`uw[-1]`			
`cmu[15]`			

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

Array Loop Example

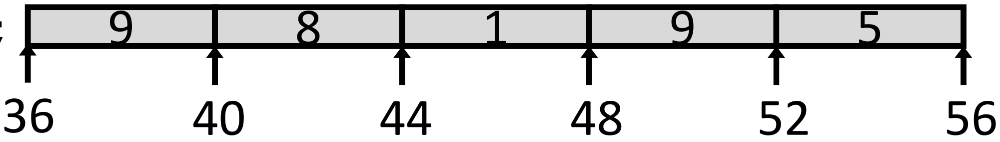
```
typedef int zip_dig[5];
```

```
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

`zip_dig uw;`



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;
}
```

`z + 5;` — address just past 5th digit

`z++;` — Increments by 4 (size of int)

Array Loop Implementation

gcc with -O1

- Registers:
  `%rdi  z`
  `%rax  zi`
  `%rcx  zend`
- Computations
  -
  -

```c
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       #
   movl $0,%eax             #
.L17:
   leal (%rax,%rax,4),%edx  #
   movl (%rdi),%eax         #
   leal (%rax,%rdx,2),%eax  #
   addq $4,%rdi             #
   cmpq %rdi,%rcx           #
   jne .L17                 #
```

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 (0^{th}) 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

- Declared arrays only allocated while the scope is valid:

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

BAD!

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

Really int *ar

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

Must explicitly pass the size!