# Structs & Alignment

CSE 351 Summer 2020

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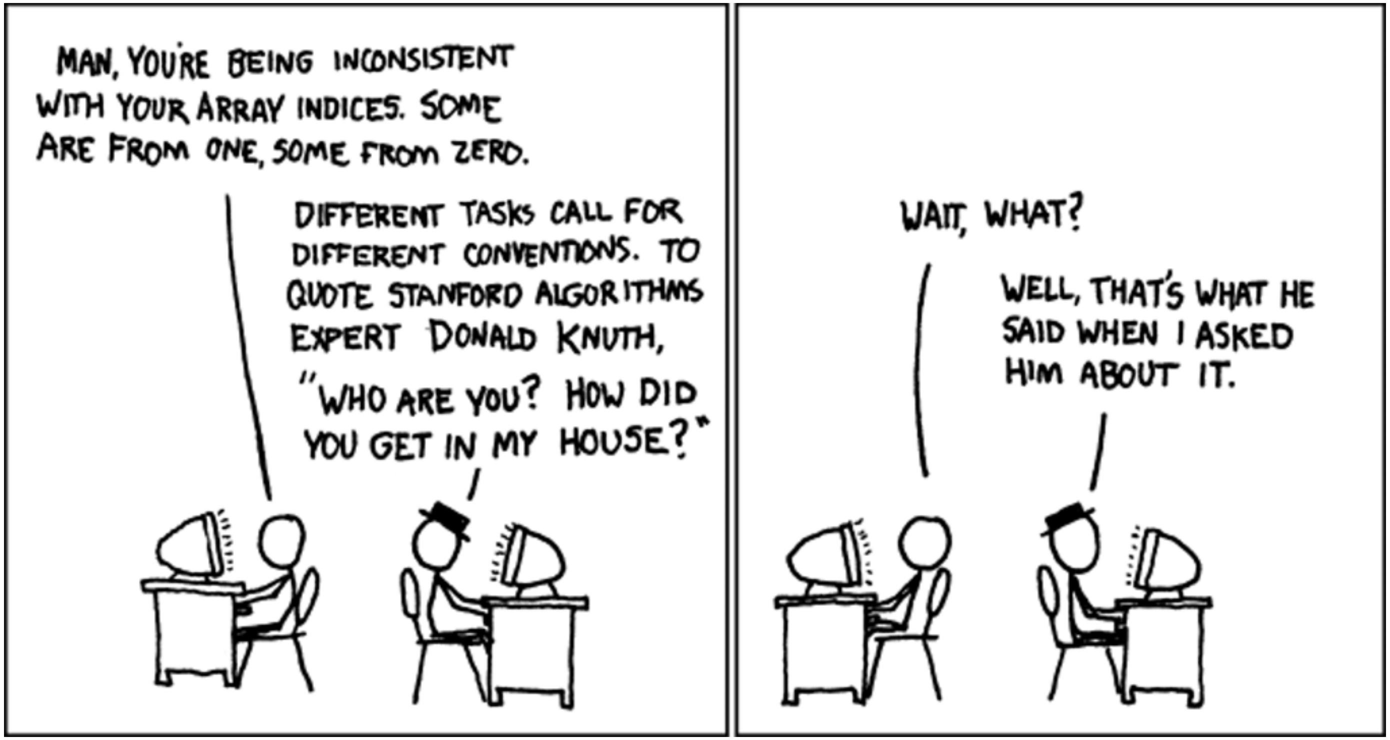



http://xkcd.com/163/

# Administrivia

- Questions doc: https://tinyurl.com/CSE351-7-24

- hw13 due Monday (7/27) – 10:30am
- hw14 due Wednesday (7/29) – 10:30am
  - This one is especially long, please start early

- Lab 3 due next Friday (7/31 ) – 11:59pm
  - You get to write some buffer overflow exploits!

# 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

# Data Structures in Assembly

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

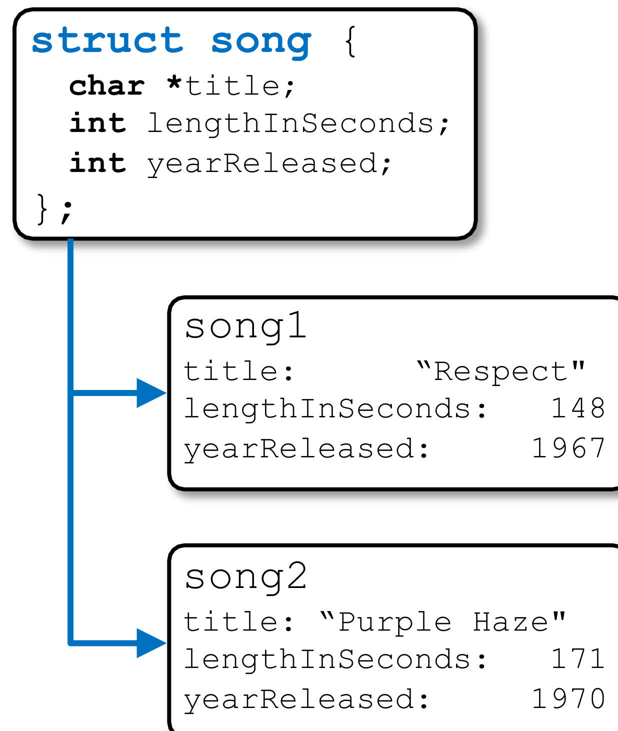
# Structs in C

- A structured group of variables, possibly including other structs
  - Way of defining compound data types

```
struct song {
  char *title;
  int lengthInSeconds;
  int yearReleased;
};

struct song song1;
song1.title = "Respect";
song1.lengthInSeconds = 148;
song1.yearReleased = 1967;

struct song song2;
song2.title = "Purple Haze";
song2.lengthInSeconds = 171;
song2.yearReleased = 1970;
```



# Struct Definitions

- Structure definition:
  - Does NOT declare a variable
  - Variable type is "**`struct name`**"

keyword / your choice

```
struct name {
  /* fields */
};
```

Easy to forget semicolon!

- Variable declarations like any other data type:

```
struct name name1;       ← instance
struct name *pn;         ← pointer
struct name name_ar[3];  ← array
```

just like
int x;
int *p;
int ar[3];

# Scope of Struct Definition

- Why is the placement of struct definition important?
  - What actually happens when you declare a variable?
    - Creating space for it somewhere!
  - Without definition, program doesn't know how much space

```
struct data {
 int ar[4];
 long d;
};
```

16+8 = Size = 24 bytes

```
struct rec {
 int a[4];
 long i;
 struct rec* next;
};
```

16+8+8= Size = 32 bytes

- Almost always define structs in global scope near the top of your C file
  - Struct definitions follow normal rules of scope

# Accessing Structure Members

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
```

- Given a struct instance, access member using the `.` operator:

```
struct rec r1;
r1.i = val;
```

- Given a *pointer* to a struct:

```
struct rec *r;
r = &r1;  // or malloc space for r to point to
```

  We have two options:
  - Use `*` and `.` operators: `(*r).i = val;`
  - Use `->` operator for short: `r->i = val;`

- **In assembly:** register holds address of the first byte
  - Access members with offsets

# Java connection

```
class Record { ... }
Record x = new Record();
```

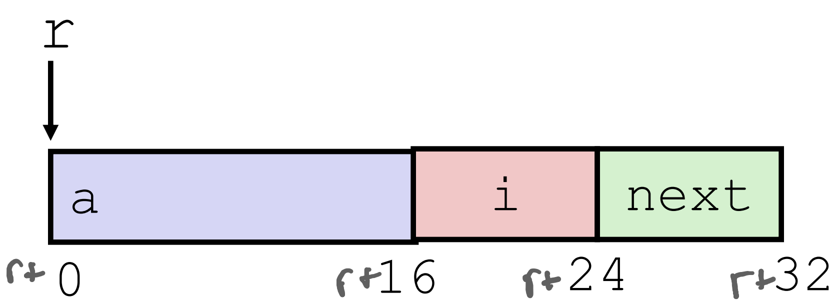
← stores an address

- An instance of a class is like a *pointer to* a struct containing the fields
  - (Ignoring methods and subclassing for now)
  - So Java's `x.f` is like C's `x->f` or `(*x).f`

- In Java, almost everything is a pointer ("*reference*") to an object
  - Cannot declare variables or fields that are structs or arrays
  - Always a *pointer* to a struct or array
  - So every Java variable or field is ≤ 8 bytes (but can point to lots of data)

# Structure Representation

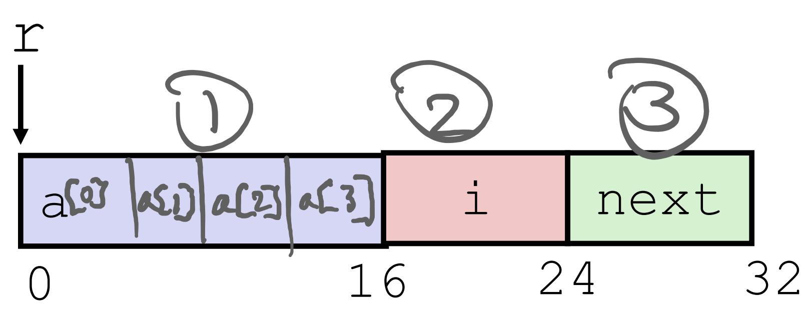
```
struct rec {
  16 int a[4];
   8 long i;
   8 struct rec *next;
};
struct rec st;
struct rec *r = &st;
```




- Characteristics
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Fields may be of different types

# Structure Representation

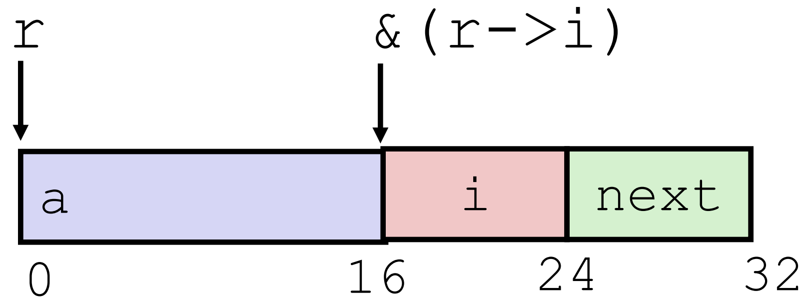
```
struct rec {
  int a[4];
  long i;
  struct rec *next;
};
struct rec st;
struct rec *r = &st;
```




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

# Accessing a Structure Member

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
struct rec st;
struct rec *r = &st;
```



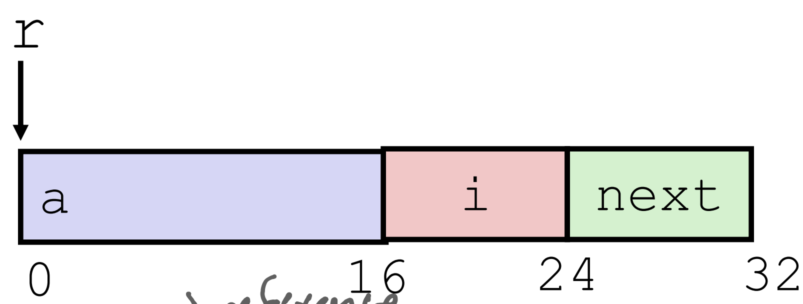

```
long get_i(struct rec *r)
{
  return r->i;
}
```

```
# r in %rdi, index in %rsi
  movq  16(%rdi), %rax
  ret
```

- Compiler knows the *offset* of each member within a struct
  - Compute as
    `*(r+offset)`
    - Referring to absolute offset, so no pointer arithmetic

# Exercise: Pointer to Structure Member

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
struct rec st;
struct rec *r = &st;
```




no dereference needed to calculate address

```
long* addr_of_i(struct rec *r)
{
  return &(r->i); // r + 16
}
```

```
# r in %rdi
leaq  16(%rdi), %rax
ret
```

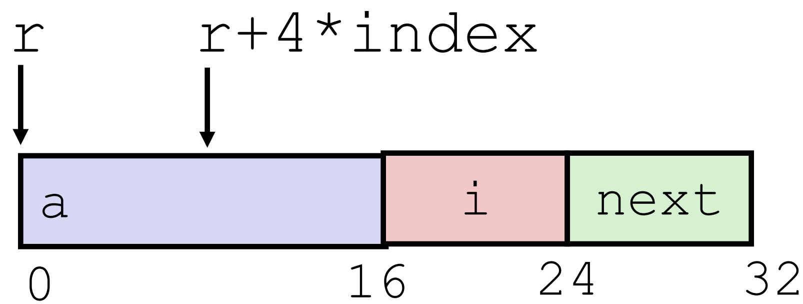
returning address of fields

```
struct rec** addr_of_next(struct rec *r)
{
  return &(r->next); // r + 24
}
```

```
# r in %rdi
leaq  24(%rdi), %rax
ret
```

# Generating Pointer to Array Element

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
struct rec st;
struct rec *r = &st;
```




- Generating Pointer to Array Element
  - Offset of each structure member determined at compile time
  - Compute as: `r+4*index`

really r + offset of a + 4*index

this is 0!

```
int* find_addr_of_array_elem
   (struct rec *r, long index)
{
  return &r->a[index];
}
```

`&(r->a[index])`

```
  # r in %rdi, index in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

r + index*4

# Review: Memory Alignment in x86-64

- *Aligned* means that any primitive object of $K$ bytes must have an address that is a multiple of $K$
- Aligned addresses for data types:

| $K$ | Type | Addresses |
|---|---|---|
| 1 | `char` | No restrictions |
| 2 | `short` | Lowest bit must be zero: $...0_2$ |
| 4 | `int, float` | Lowest 2 bits zero: $...00_2$ |
| 8 | `long, double, *` | Lowest 3 bits zero: $...000_2$ |
| 16 | `long double` | Lowest 4 bits zero: $...0000_2$ |

address must be multiple of 2

lowest $\log_2(K)$ bits should be 0

"multiple of" means no remainder when you divide by.
Since K is a power of 2, dividing by K is equivalent to >> $\log_2(K)$.
No remainder means no weight is "lost" during the shift → all zeros in lowest $\log_2(K)$ bits.

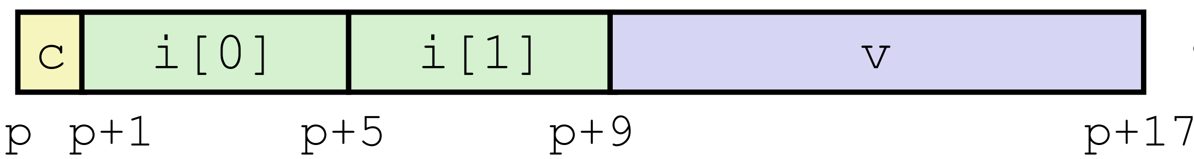
# Alignment Principles

- Aligned Data
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$
  - Required on some machines; advised on x86-64
- Motivation for Aligning Data
  - Memory accessed by (aligned) chunks of bytes (width is system dependent)
    - Inefficient to load or store value that spans quad word boundaries
    - Virtual memory trickier when value spans 2 pages (more on this later)
  - Though x86-64 hardware will work regardless of alignment of data

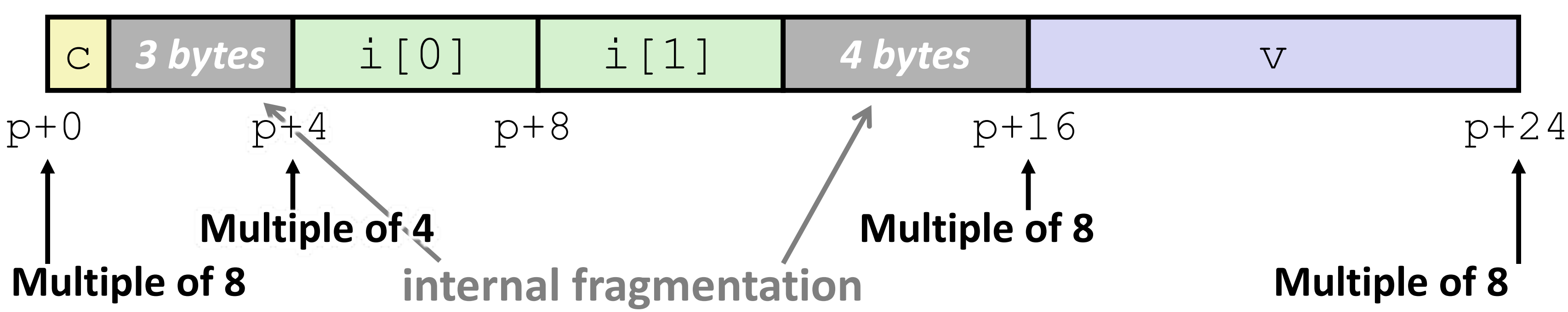
# Structures & Alignment

```
struct S1 {
  char c;
  int i[2];
  double v;
};
struct S1 st;
struct S1 *p = &st;
```

- Unaligned Data



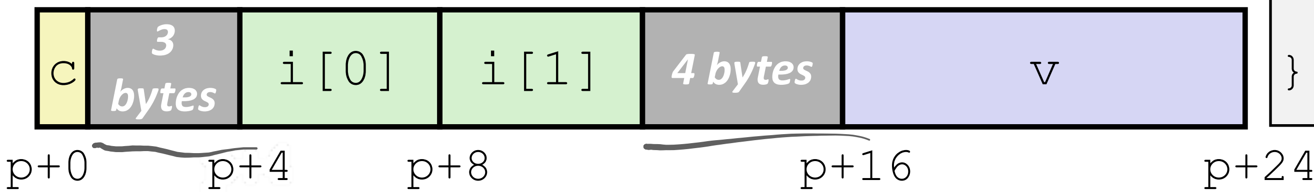

- Aligned Data
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$



# Structures & Alignment: Fragmentation

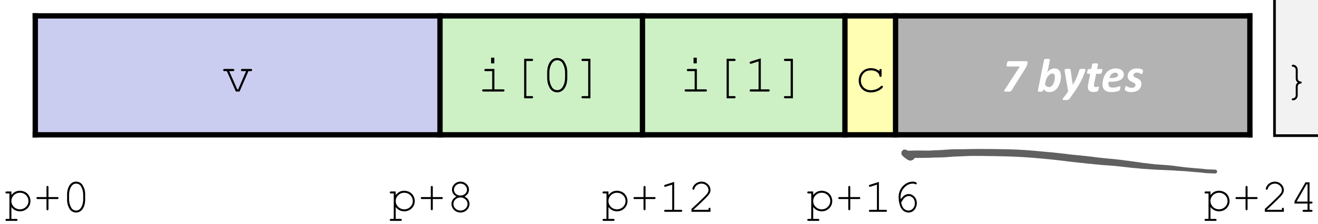
- Fragmentation occurs when there are unused portions of a struct
- Internal Fragmentation
  - Unused portion(s) occur *between* fields

```
struct S1 {
  char c;
  int i[2];
  double v;
};
```




- External Fragmentation
  - Unused portion at the end of the struct

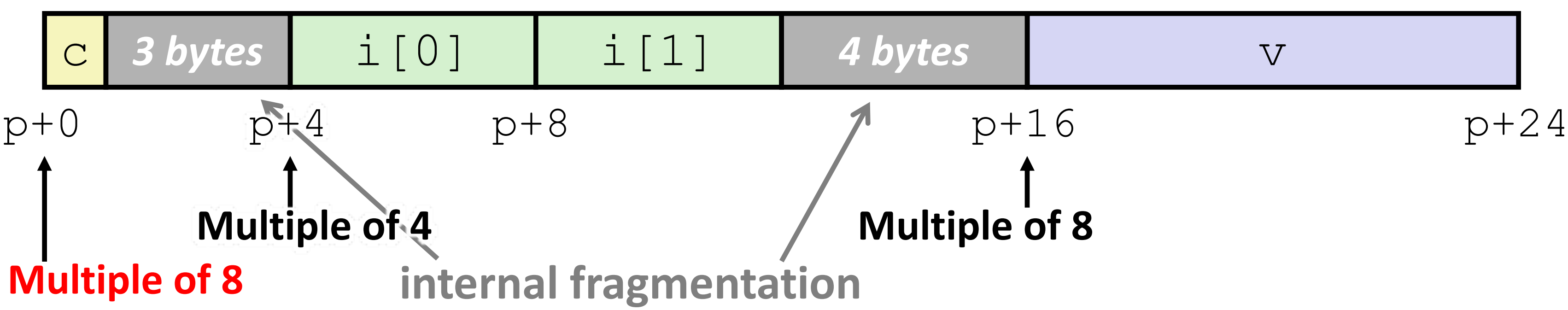
```
struct S2 {
  double v;
  int i[2];
  char c;
};
```



# Satisfying Alignment with Structures (1)

```
struct S1 {
  char c;
  int i[2];
  double v;
};
struct S1 st;
struct S1 *p = &st;
```

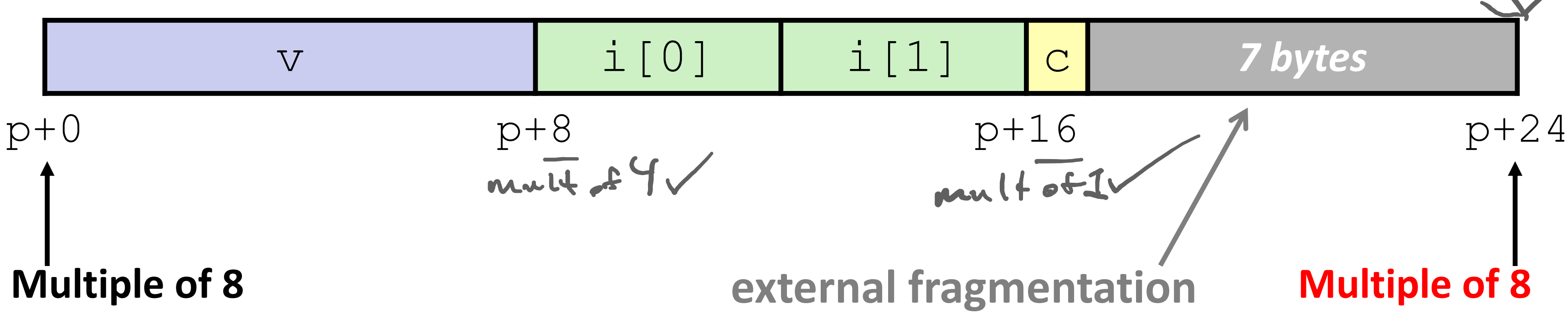
- Within structure:
  - Must satisfy each element's alignment requirement
- Overall structure placement
  - Each structure has alignment requirement $K_{max}$
    - $K_{max}$ = Largest alignment of any element
    - Counts array elements individually as elements
- Example:
  - $K_{max}$ = 8, due to `double` element



# Satisfying Alignment with Structures (2)

```
struct S2 {
  double v;
  int i[2];
  char c;
};
struct S2 st;
struct S2 *p = &st;
```

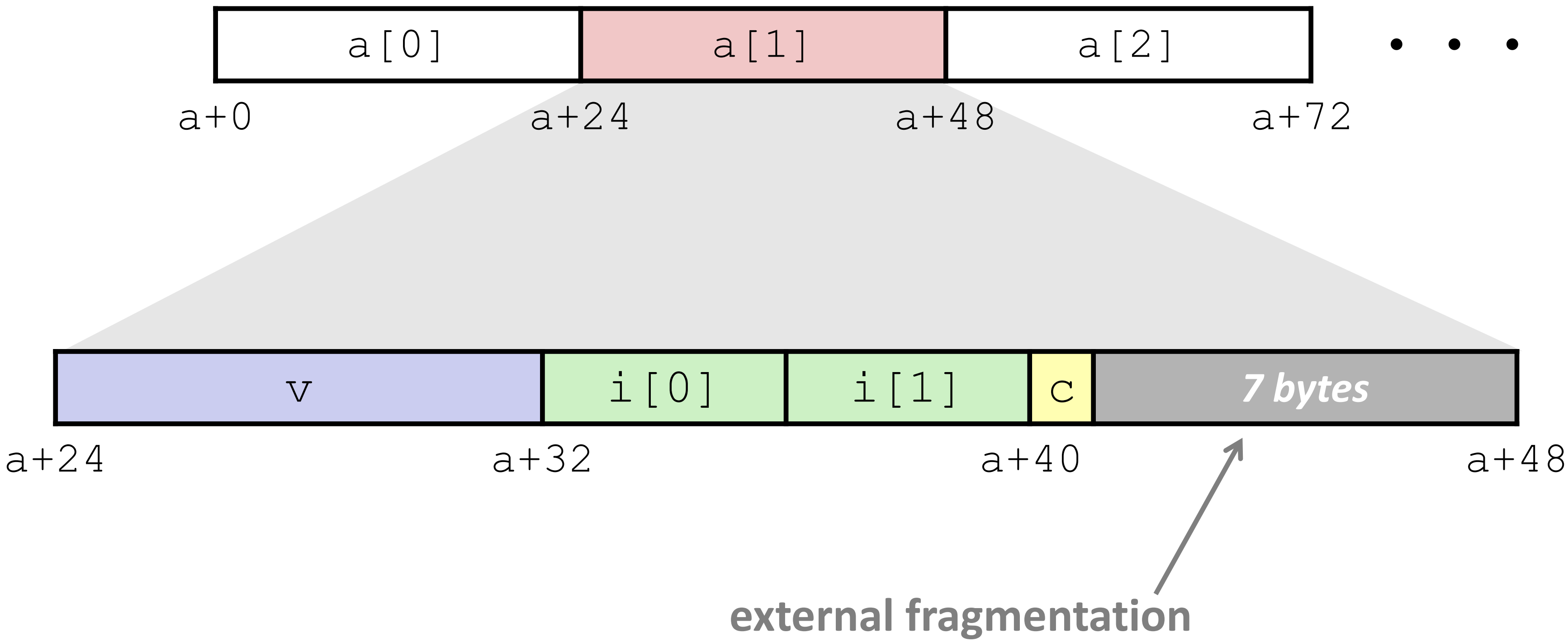
- Can find offset of individual fields using `offsetof()`
  - Need to `#include <stddef.h>`
  - *e.g.* `offsetof(struct S2,c)` returns 16
- For largest alignment requirement $K_{\text{max}}$, overall structure size must be multiple of $K_{\text{max}}$
  - Compiler will add padding at end of structure to meet overall structure alignment requirement



# Arrays of Structures

- Overall structure size multiple of $K_{max}$
- Satisfy alignment requirement for every element in array

```
struct S2 {
  double v;
  int i[2];
  char c;
};
struct S2 a[10];
```



# Alignment of Structs

- Compiler will do the following:
  - Maintains declared *ordering* of fields in struct
  - Each ***field*** must be aligned *within* the struct *(may insert padding)*
    - `offsetof` can be used to get actual field offset
  - Overall struct must be ***aligned*** according to largest field
  - Total struct ***size*** must be multiple of its alignment *(may insert padding)*
    - `sizeof` should be used to get true size of structs

# How the Programmer Can Save Space

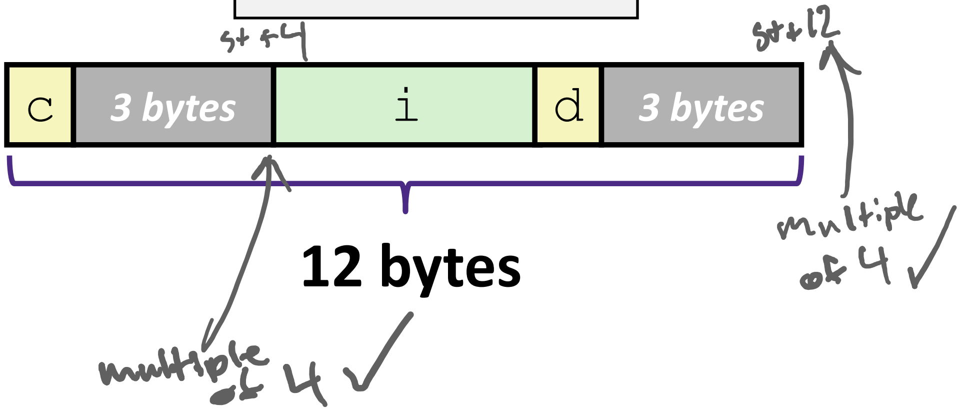
- Compiler must respect order elements are declared in
  - Sometimes the programmer can save space by declaring large data types first

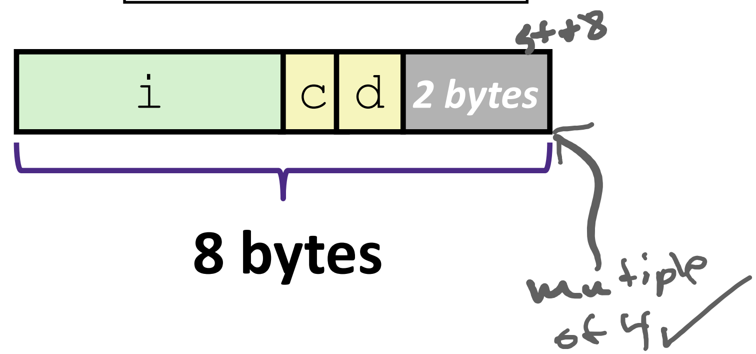
$K_{max} = 4$!

Same data, more efficient

```
struct S4 {
  char c;
  int i;
  char d;
};
struct S4 st;
```

```
struct S5 {
  int i;
  char c;
  char d;
};
struct S5 st;
```



# Polling Question [Structs]

Vote on `sizeof(struct old)`:
http://pollev.com/pbjones

- Minimize the size of the struct by re-ordering the vars

```
struct old {
  int i;

  short s[3];

  char *c;

  float f;
};
```

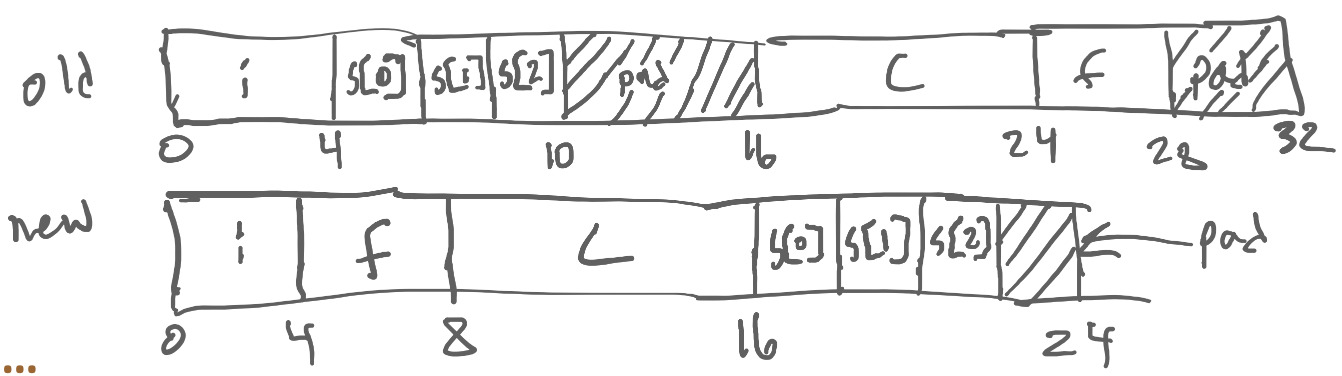
```
struct new {
  int     i;
  float   f     ;
  char*   c     ;
  short   s[3]  ;
};
```

(could switch these (internal vs. external frag))

- What are the old and new sizes of the struct?

`sizeof(struct old) =` 32 `sizeof(struct new) =` 24

A. 16 bytes
B. 22 bytes
C. 28 bytes
D. 32 bytes
E. We're lost…



# Aside: More Struct Definitions

- Can combine struct and instance definitions:

```
struct name {
  /* fields */
};
struct name st;
struct name *p = &st;
```

```
struct name {
  /* fields */
} st, *p = &st;
```

These parts do the same thing

- Defines a struct type (`struct name`), an instance of that type (`st`), and a pointer to that type (`p`)
- This syntax is difficult to read
  - Porter doesn't like it in *most* situations because it conflates a type definition with an instance definition. But that's just his opinion…
  - We are showing it because you may see it in code in the future (and on the homework ☺)

# Aside: Typedef in C

- A way to create an *alias* for another data type: `typedef <data type> <alias>;`
  - After typedef, the alias can be used interchangeably with the original data type
  - *e.g.* `typedef unsigned long int uli;`

    can now use uli; instead of unsigned long int
- Joint struct definition and typedef
  - Don't need to give struct a name in this case
  - `typedef` alone doesn't create an instance of the struct!

```
struct nm {
  /* fields */
};
typedef struct nm name;
name n1;
```

type definition

creates instance

→

```
typedef struct {
  /* fields */
} name;
name n1;
```

type definition

creates instance

# Summary

- Arrays in C
  - Aligned to satisfy every element's alignment requirement
- Structures
  - Allocate bytes for fields in order declared by programmer
  - Pad in middle to satisfy individual element alignment requirements
  - Pad at end to satisfy overall struct alignment requirement

# Data Structures in Assembly

This is extra (non-testable) material

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

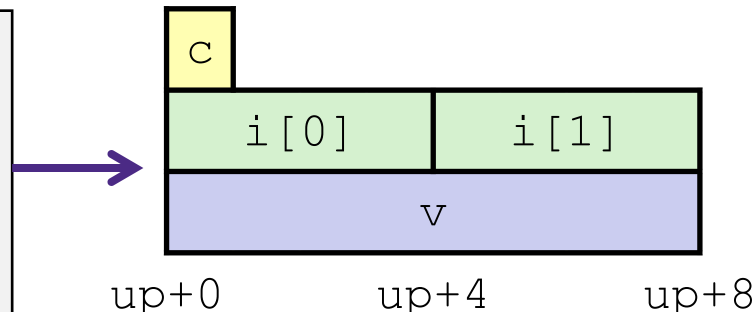
# Unions

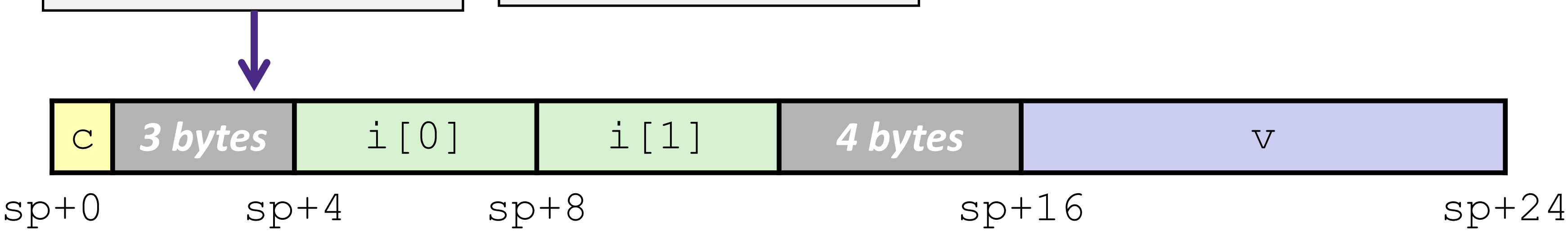
This is extra (non-testable) material

- Only allocates enough space for the largest element in union
- Can only use one member at a time

```
struct S {
  char c;
  int i[2];
  double v;
} s, *sp = &s;
```

```
union U {
  char c;
  int i[2];
  double v;
} u, *up = &u;
```

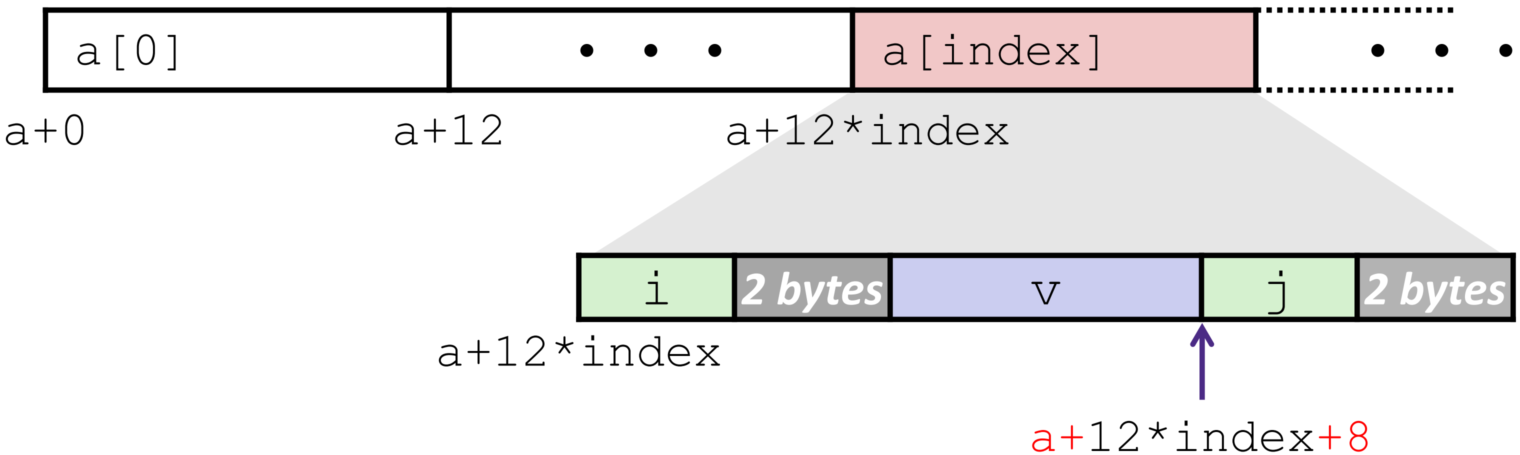


# Accessing Array Elements

- Compute start of array element as: `12*index`
  - `sizeof(S3) = 12`, including alignment padding
- Element `j` is at offset 8 within structure
- Assembler gives offset `a+8`

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```




```
short get_j(int index)
{
  return a[index].j;
}
```

```
# %rdi = index
leaq (%rdi,%rdi,2),%rax   # 3*index
movzwl a+8(,%rax,4),%eax
```

# 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();
```

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

Assembly language:

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

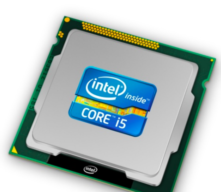
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

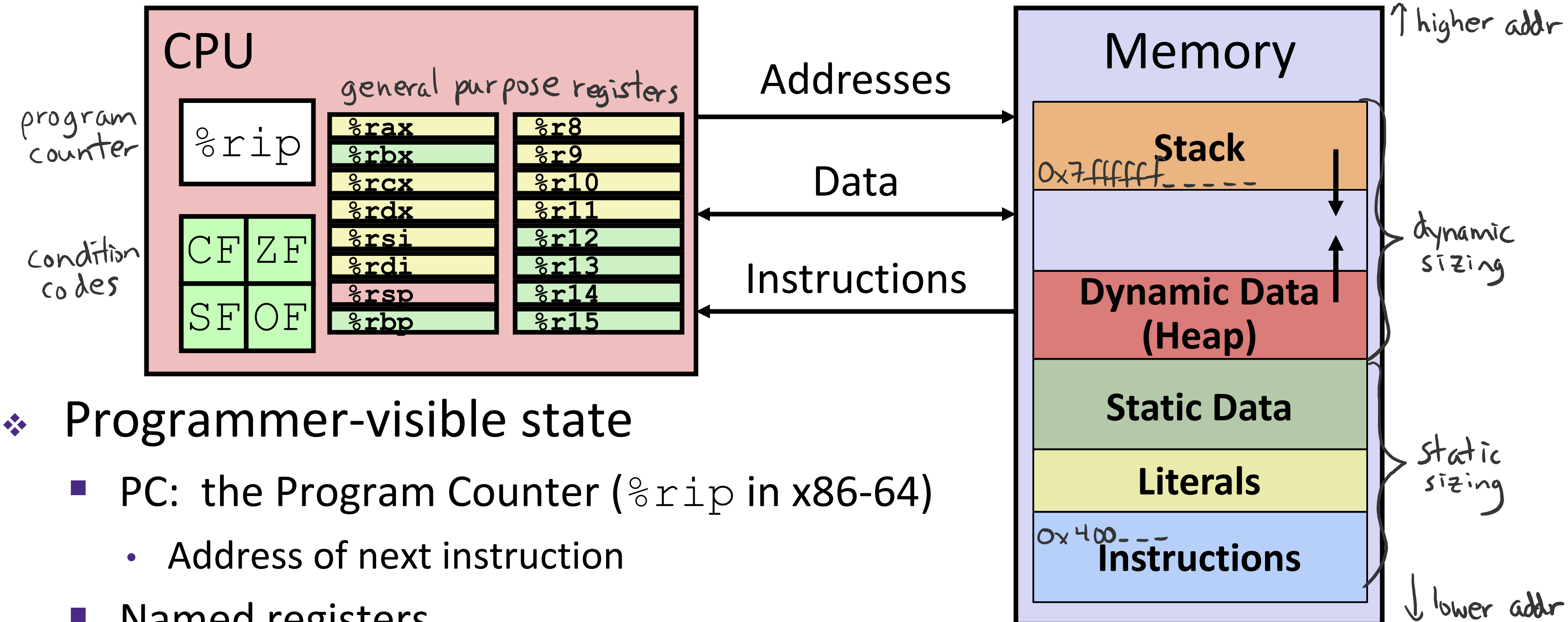
OS:

Windows 10  OS X Yosemite

Computer system:



# Assembly Programmer's View




- Programmer-visible state
  - PC: the Program Counter (`%rip` in x86-64)
    - Address of next instruction
  - Named registers
    - Together in "register file"
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching

- Memory
  - Byte-addressable array
  - Code and user data
  - Includes *the Stack* (for supporting procedures)

# x86-64 Instructions

size specifiers: b, w, l, q
1, 2, 4, 8 bytes

- (1) Data movement
  - `mov, movs, movz, ...`

operand types:
Imm $
Reg %
Mem ( )

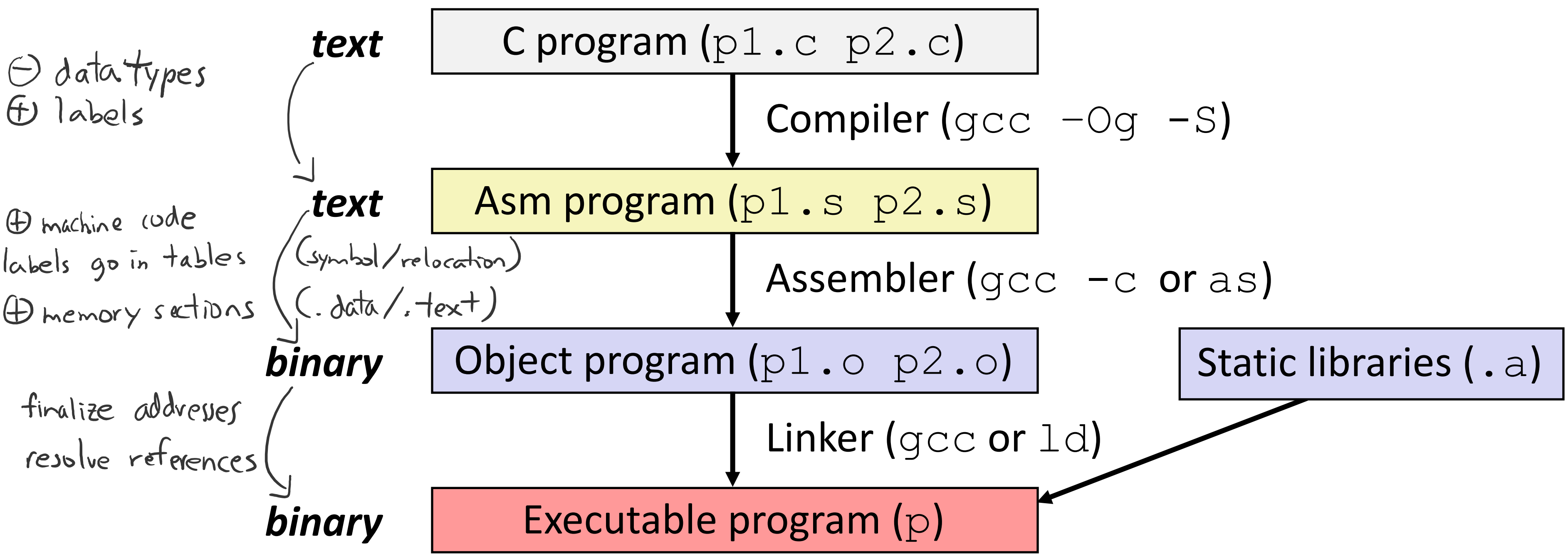
- (2) Arithmetic
  - `add, sub, shl, sar, lea, ...`

Labels are addresses

- (3) Control flow
  - `cmp, test, j*, set*, ...`
- (3) Stack/procedures
  - `push, pop, call, ret, ...`

# Turning C into Object Code

- Code in files `p1.c p2.c`
- Compile with command: `gcc -Og p1.c p2.c -o p`
  - Use basic optimizations (`-Og`)
  - Put resulting machine code in file `p`



# Assembling

- Executable has **addresses** (no more labels)

assembler

```
00000000004004f6 <pcount_r>:
  4004f6:  b8 00 00 00 00    mov    $0x0,%eax
  4004fb:  48 85 ff          test   %rdi,%rdi
  4004fe:  74 13             je     400513 <pcount_r+0x1d>
  400500:  53                push   %rbx
  400501:  48 89 fb          mov    %rdi,%rbx
  400504:  48 d1 ef          shr    %rdi
  400507:  e8 ea ff ff ff    callq  4004f6 <pcount_r>
  40050c:  83 e3 01          and    $0x1,%ebx
  40050f:  48 01 d8          add    %rbx,%rax
  400512:  5b                pop    %rbx
  400513:  f3 c3             rep ret
```

used to be a label (Exit: or .L6:) → 400513

pcount_r + 0x1d = 30 bytes after start of pcount_r

  - `gcc -g pcount.c -o pcount`
  - `objdump -d pcount`

# A Picture of Memory (64-bit view)

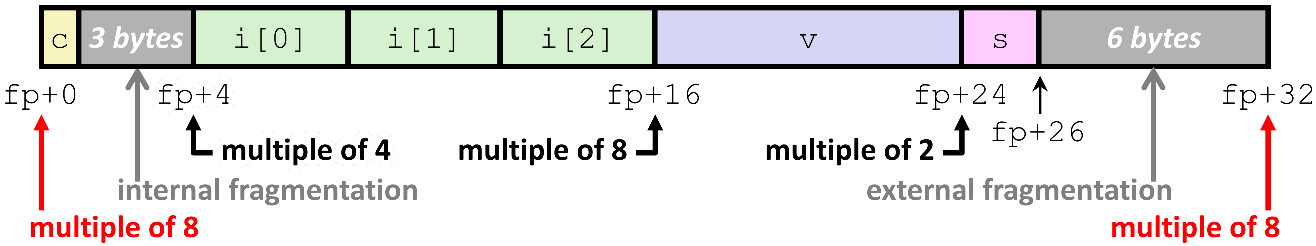
```
00000000004004f6 <pcount_r>:
  4004f6:  b8 00 00 00 00       mov    $0x0,%eax
  4004fb:  48 85 ff             test   %rdi,%rdi
  4004fe:  74 13                je     400513 <pcount_r+0x1d>
  400500:  53                   push   %rbx
  400501:  48 89 fb             mov    %rdi,%rbx
  400504:  48 d1 ef             shr    %rdi
  400507:  e8 ea ff ff ff       callq  4004f6 <pcount_r>
  40050c:  83 e3 01             and    $0x1,%ebx
  40050f:  48 01 d8             add    %rbx,%rax
  400512:  5b                   pop    %rbx
  400513:  f3 c3                rep ret
```

instruction addresses

stored bytes

| 0\|8 | 1\|9 | 2\|a | 3\|b | 4\|c | 5\|d | 6\|e | 7\|f | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0x00 |
| | | | | | | | | 0x08 |
| | | | | | | | | 0x10 |
| ... | | | | | | | | ... |
| | | | | | | b8 | 00 | 0x4004f0 |
| 00 | 00 | 00 | 48 | 85 | ff | 74 | 13 | 0x4004f8 |
| 53 | 48 | 89 | fb | 48 | d1 | ef | e8 | 0x400500 |
| ea | ff | ff | ff | 83 | e3 | 01 | 48 | 0x400508 |
| 01 | d8 | 5b | f3 | c3 | | | | 0x400510 |

unaligned, but more compact


c
3 bytes
i[0]
i[1]
i[2]
v
s
6 bytes
fp+0
fp+4
fp+16
fp+24
fp+26
fp+32
multiple of 4
multiple of 8
multiple of 2
internal fragmentation
external fragmentation
multiple of 8
multiple of 8