Structs & Alignment

CSE 351 Winter 2019

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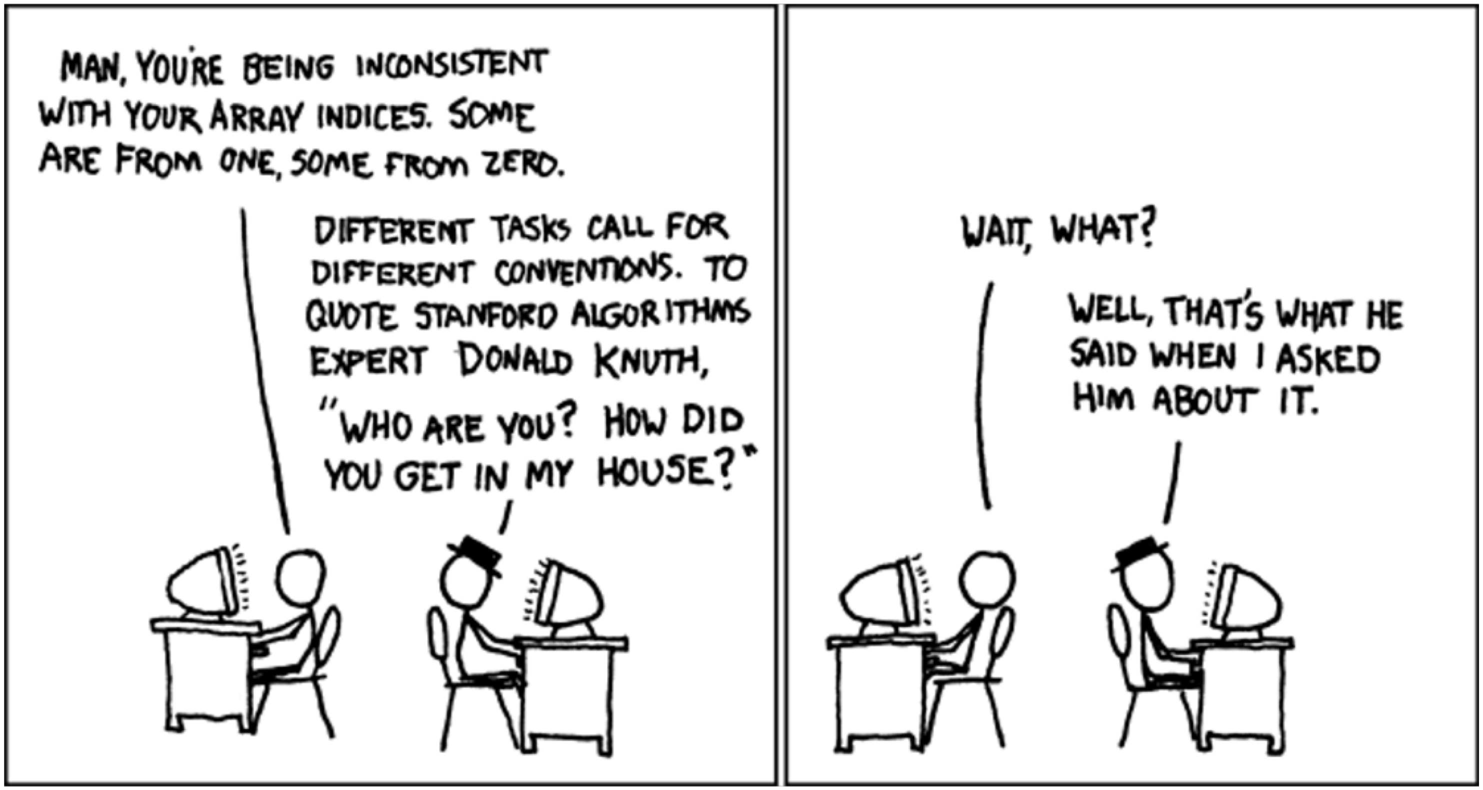

MAN, YOU'RE BEING INCONSISTENT WITH YOUR ARRAY INDICES. SOME ARE FROM ONE, SOME FROM ZERO.
DIFFERENT TASKS CALL FOR DIFFERENT CONVENTIONS. TO QUOTE STANFORD ALGORITHMS EXPERT DONALD KNUTH, "WHO ARE YOU? HOW DID YOU GET IN MY HOUSE?"
WAIT, WHAT?
WELL, THAT'S WHAT HE SAID WHEN I ASKED HIM ABOUT IT.

http://xkcd.com/163/

Administrivia

- Snow Day! Online office hours
- Mid-survey due Thursday (2/14)
- Homework 3 due Friday (2/15)
- **Take Home Midterm** (Thursday 2/14)
  - Due that night!

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();
```

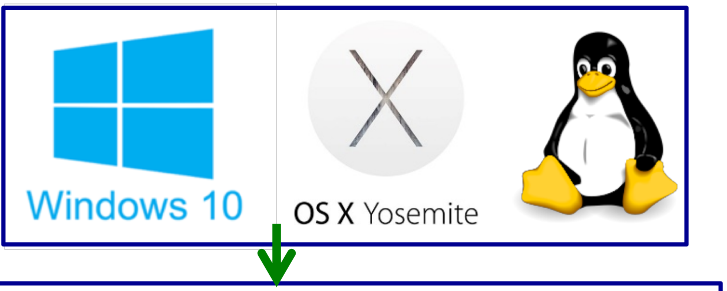
Assembly language:

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

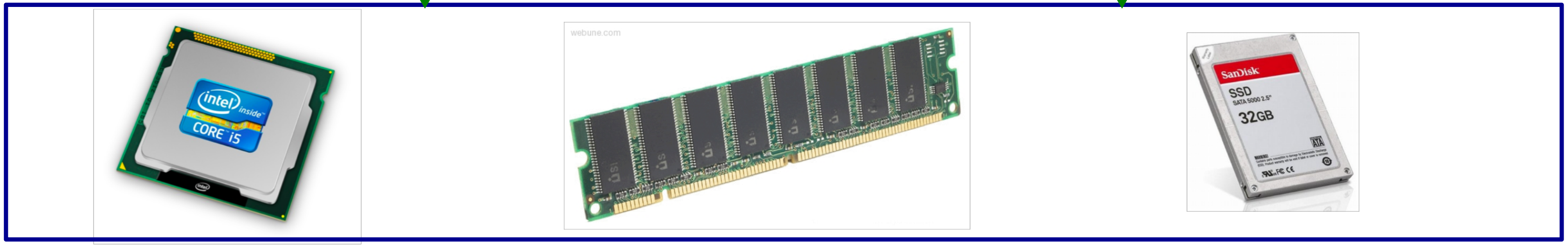
Machine code:

```
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~~

Multi-Level Array Example

Multi-Level Array Declaration(s):

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

```
int* univ[3] = {uw, cmu, ucb};
```

Is a multi-level array the same thing as a 2D array?

NO

2D Array Declaration:

```
zip_dig univ2D[3] = {
  { 9, 8, 1, 9, 5 },
  { 1, 5, 2, 1, 3 },
  { 9, 4, 7, 2, 0 }
};
```

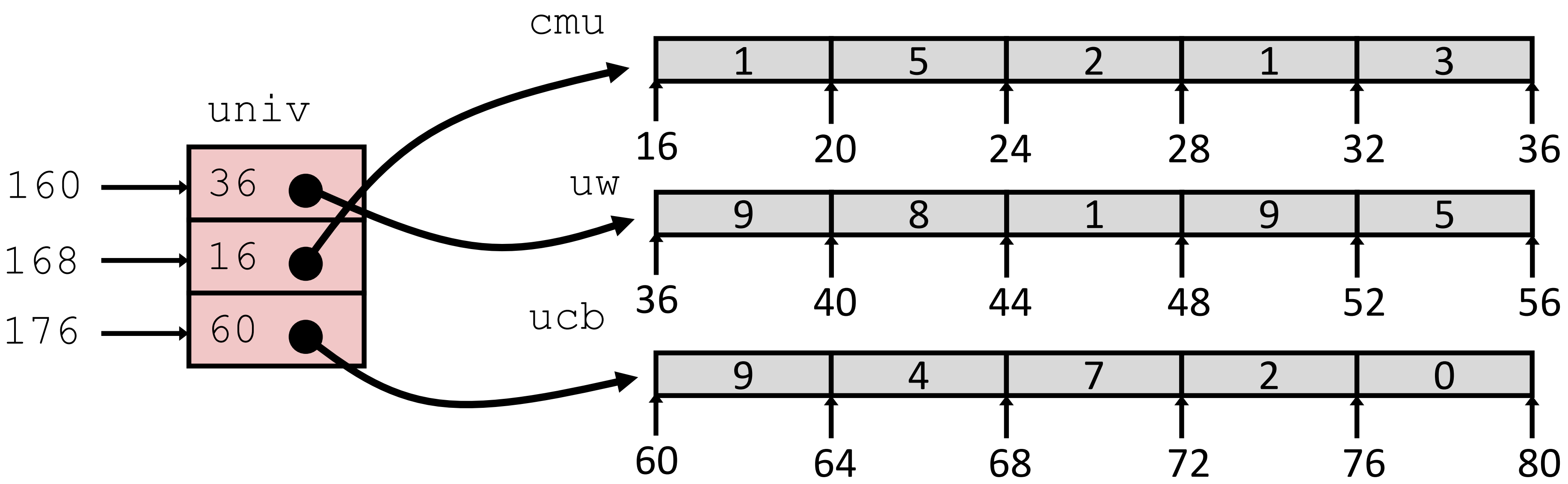
One array declaration = one contiguous block of memory

Multi-Level Array Example

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

```
int* univ[3] = {uw, cmu, ucb};
```

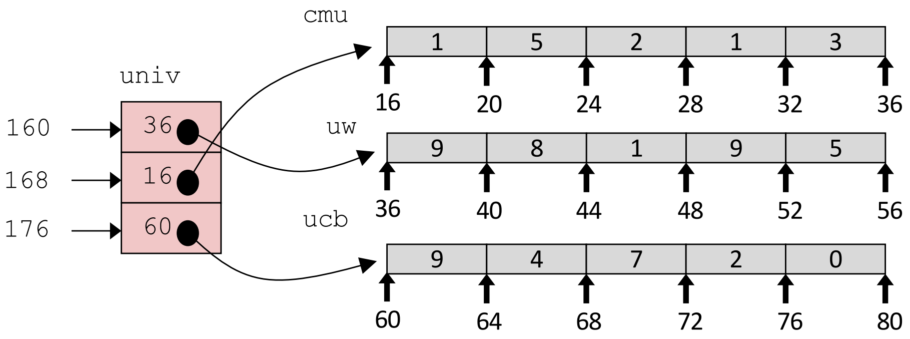
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `int`s



Note: this is how Java represents multi-dimensional arrays

Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int digit)
{
  return univ[index][digit];
}
```



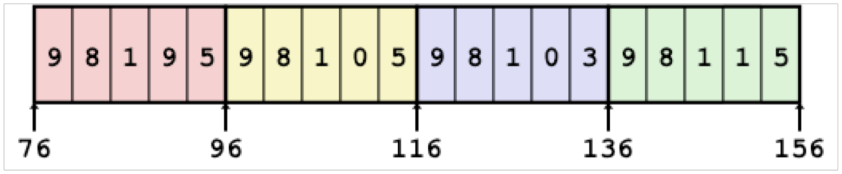
```
salq    $2, %rsi               # rsi = 4*digit
addq    univ(,%rdi,8), %rsi    # p = univ[index] + 4*digit
movl    (%rsi), %eax           # return *p
ret
```

- Computation
  - Element access Mem[Mem[`univ+8*index`]+`4*digit`]
  - Must do **two memory reads**
    - First get pointer to row array
    - Then access element within array
  - But allows inner arrays to be different lengths (not in this example)

Array Element Accesses

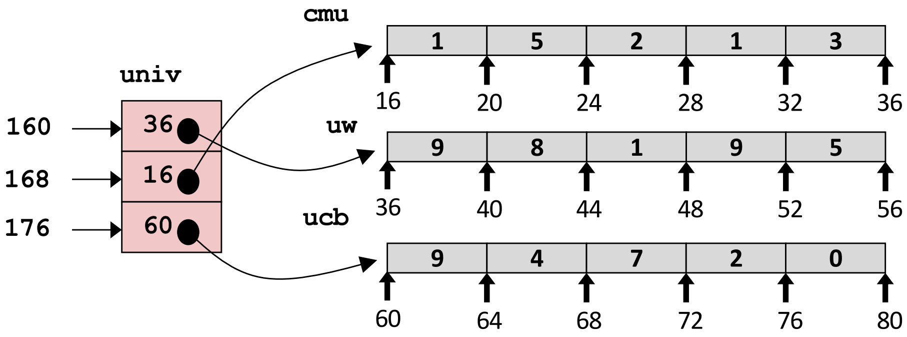
Nested array

```
int get_sea_digit
  (int index, int digit)
{
  return sea[index][digit];
}
```



Multi-level array

```
int get_univ_digit
  (int index, int digit)
{
  return univ[index][digit];
}
```

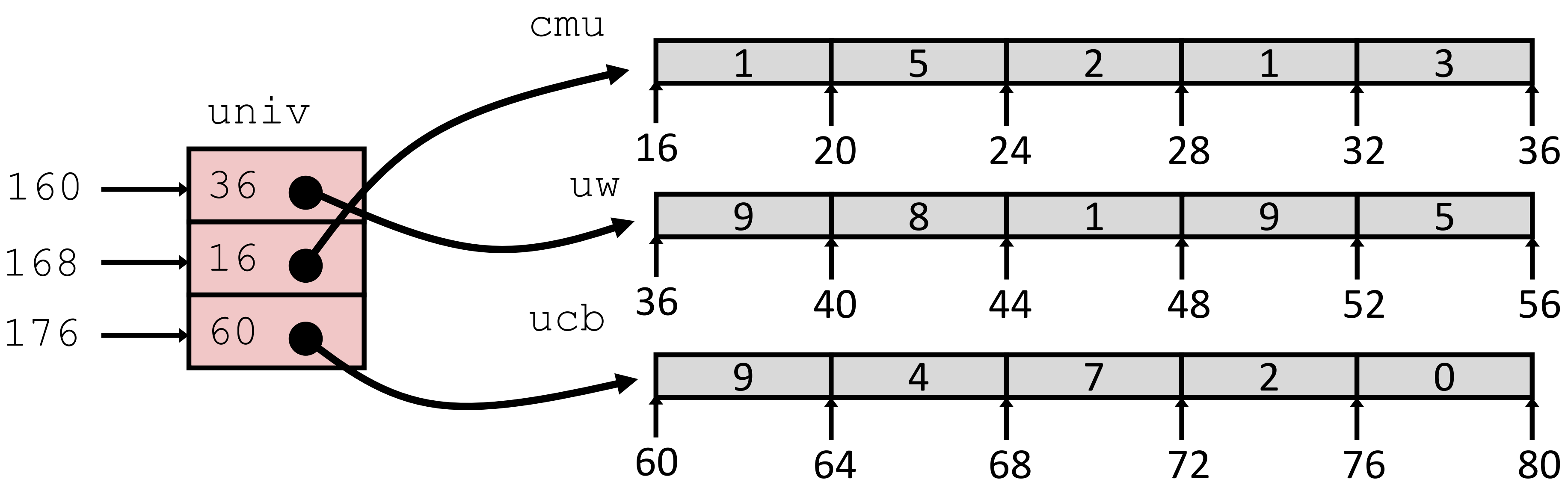


Access *looks* the same, but it isn't:

Mem[sea+20*index+4*digit]

Mem[Mem[univ+8*index]+4*digit]

Multi-Level Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`			
`univ[1][5]`			
`univ[2][-2]`			
`univ[3][-1]`			
`univ[1][12]`			

- C code does not do any bounds checking
- Location of each lower-level array in memory is *not* guaranteed

Summary

- Contiguous allocations of memory
- No bounds checking (and no default initialization)
- Can usually be treated like a pointer to first element
- `int a[4][5];` → array of arrays
  - all levels in one contiguous block of memory
- `int* b[4];` → array of pointers (to arrays)
  - First level in one contiguous block of memory
  - Each element in the first level points to another “sub” array
  - Parts anywhere in memory

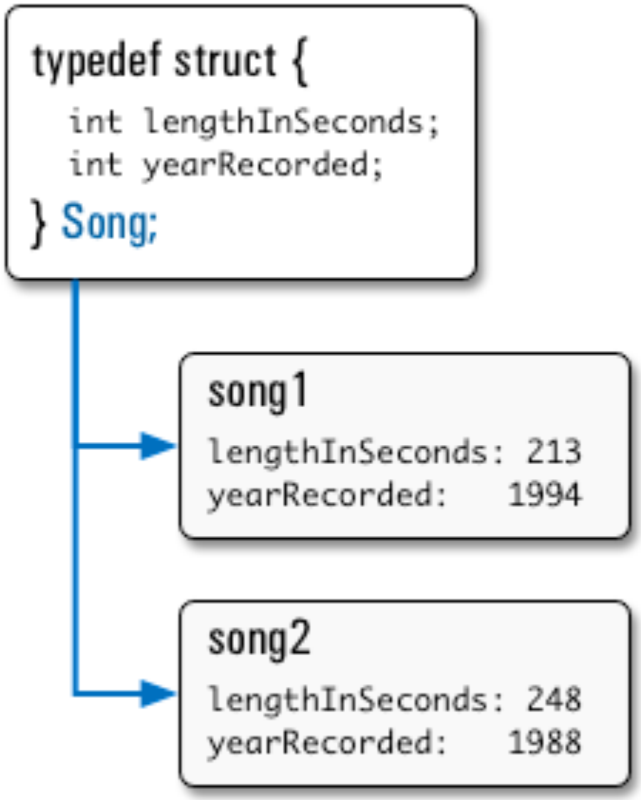
Data Structures in Assembly

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

Structs in C

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

```
typedef struct {
  int lengthInSeconds;
  int yearRecorded;
} Song;

Song song1;

song1.lengthInSeconds =  213;
song1.yearRecorded    = 1994;

Song song2;

song2.lengthInSeconds =  248;
song2.yearRecorded    = 1988;
```



```
typedef struct {
  int lengthInSeconds;
  int yearRecorded;
} Song;
```

Struct Definitions

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

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

Easy to forget semicolon!

pointer

```
struct name name1, *pn, name_ar[3];
```

array

- Joint struct definition and typedef
  - Don't need to give struct a name in this case

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

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

Scope of Struct Definition

- Why is 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;
};
```

← Size = _____ bytes

Size = _____ bytes →

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

- 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

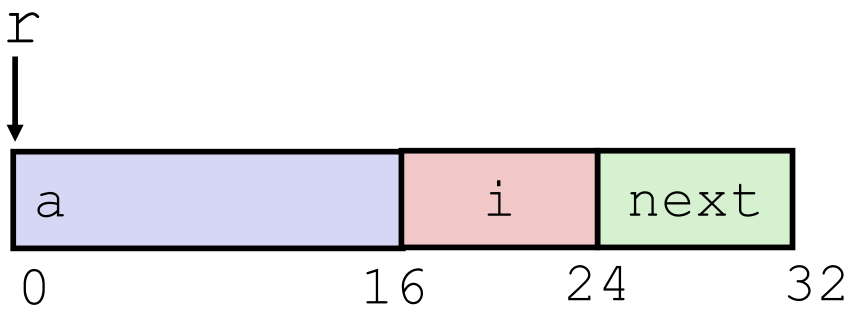
Java side-note

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

- 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

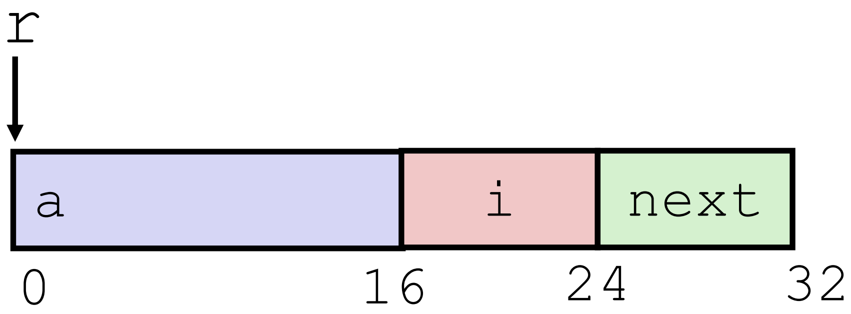
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};

struct rec *r;
```



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

Structure Representation

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

struct rec *r;
```

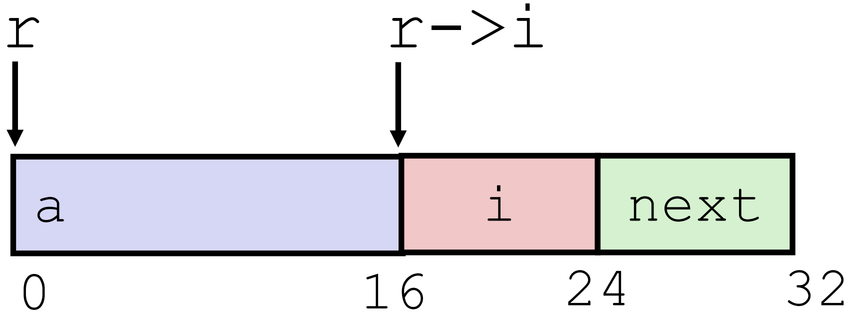


- Structure represented as block of memory
  - Big enough to hold all of the fields
- Fields ordered according to declaration order
  - Even if another ordering would be more compact
- Compiler determines overall size + positions of fields
  - Machine-level program has no understanding of the structures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

Accessing a Structure Member

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

struct rec *r;
```

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

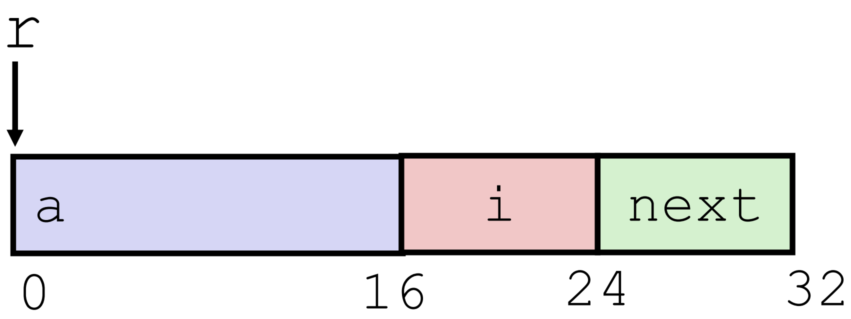


```
long get_i(struct rec *r)
{
  return r->i;
}
```

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

Exercise: Pointer to Structure Member

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

struct rec *r;
```



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

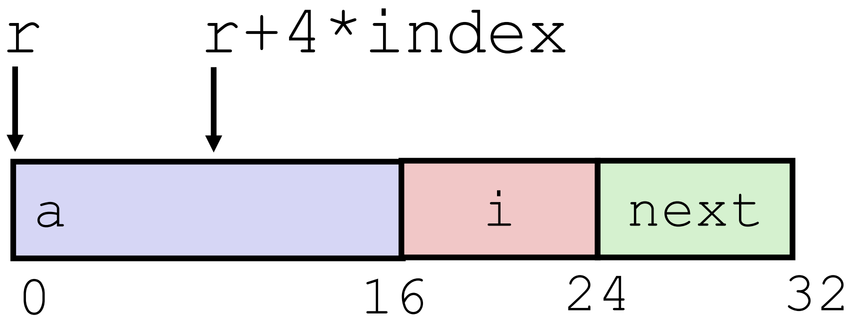
```
  # r in %rdi
  _______   _________,%rax
  ret
```

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

```
  # r in %rdi
  _______   _________,%rax
  ret
```

Generating Pointer to Array Element

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

struct rec *r;
```



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

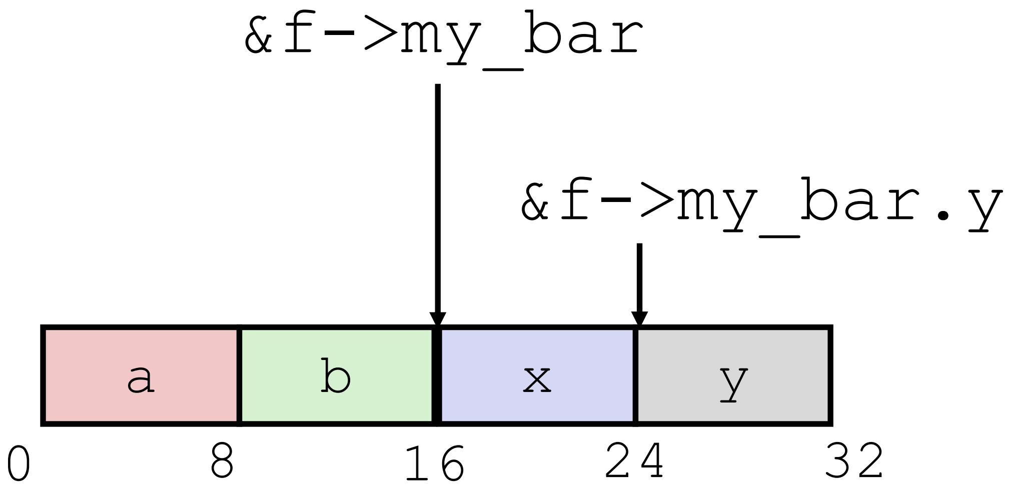
```
int* find_addr_of_array_elem
   (struct rec *r, long index)
{
  return &r->a[index];
}
```

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

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

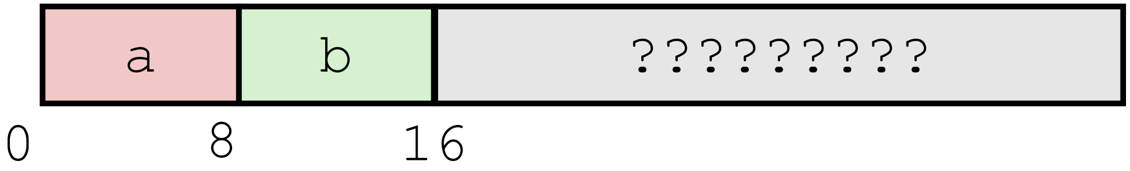
Nested Struct

```
struct foo {
    long a;
    long b;
    struct bar my_bar;
};

struct bar {
    long x;
    long y;
};

struct foo *f;
```



Nested Struct

```
struct foo {
    long a;
    long b;
    struct foo my_foo;
};
```



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

Alignment Principles

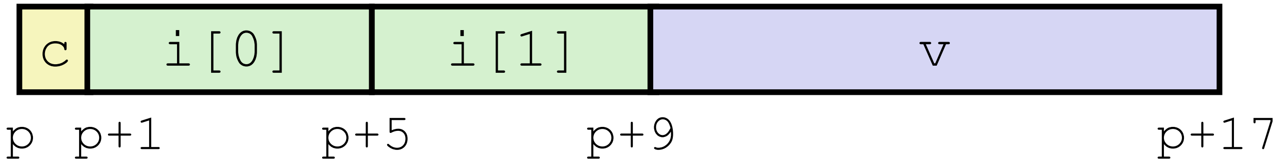
- Aligned Data
  - Primitive data type requires K bytes
  - Address must be multiple of K
  - Required on some machines; advised on x86-64

- 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

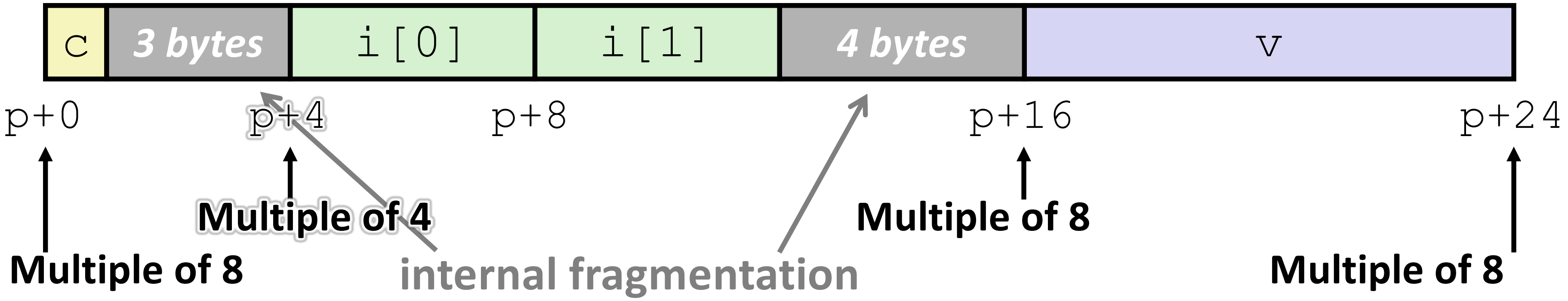
Structures & Alignment

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

- Unaligned Data



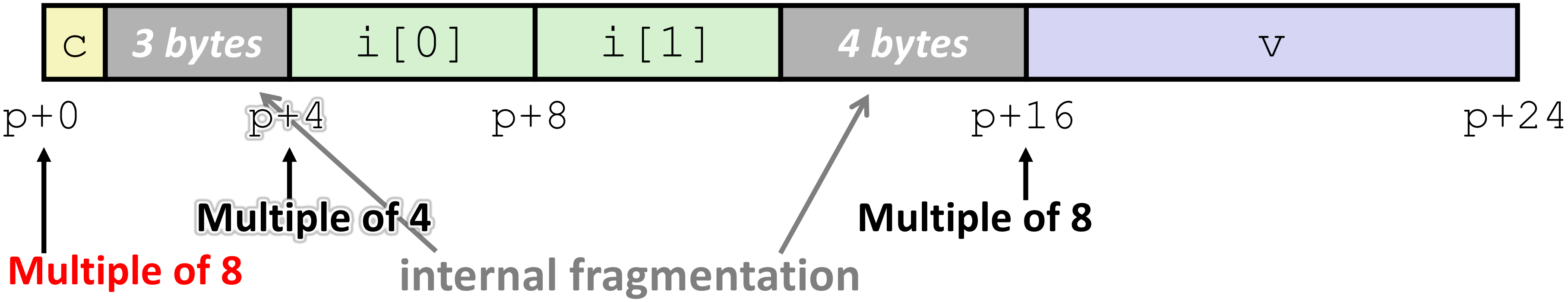
- Aligned Data
  - Primitive data type requires K bytes
  - Address must be multiple of K



Satisfying Alignment with Structures (1)

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

- 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
    - Inner structs are aligned to *their* largest alignment
- Example:
  - $K_{\max}$ = 8, due to `double` element

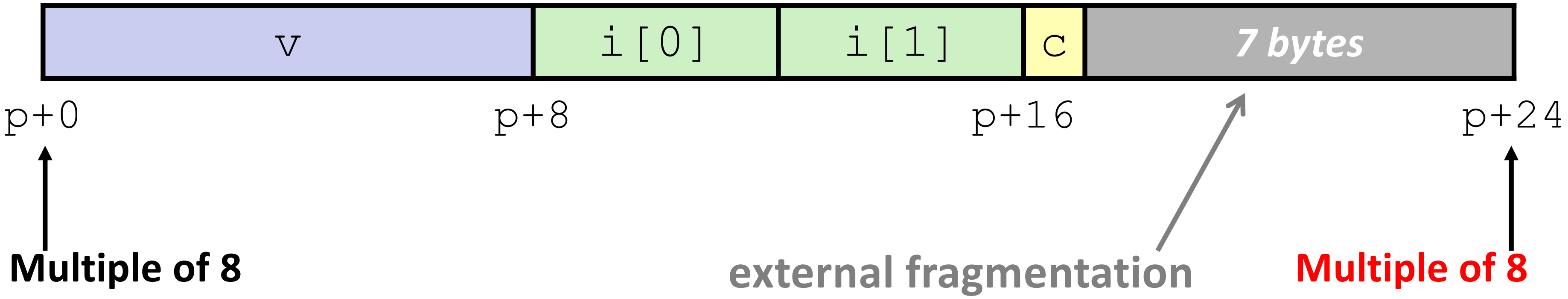


Satisfying Alignment with Structures (2)

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

- Can find offset of individual fields using `offsetof()`
  - Need to `#include <stddef.h>`
  - Example: `offsetof(struct S2,c)` returns 16

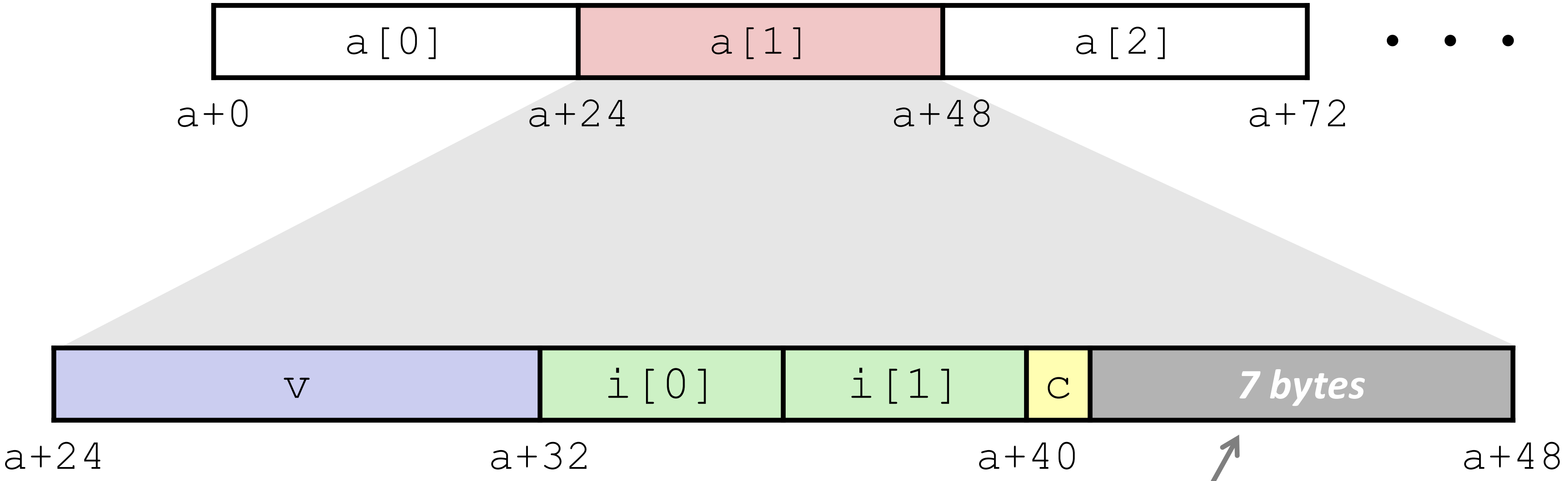
- For largest alignment requirement K_{max}, overall structure size must be multiple of K_{max}
  - Compiler will add padding at end of structure to meet overall structure alignment requirement



Arrays of Structures

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

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

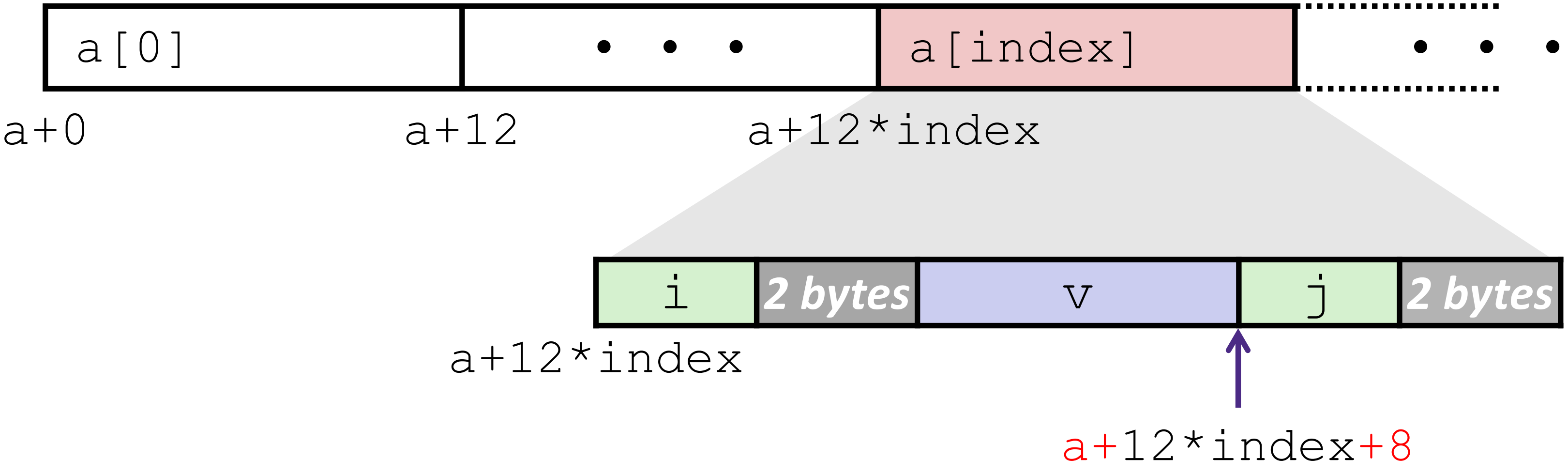


external fragmentation

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
```

Alignment of Structs

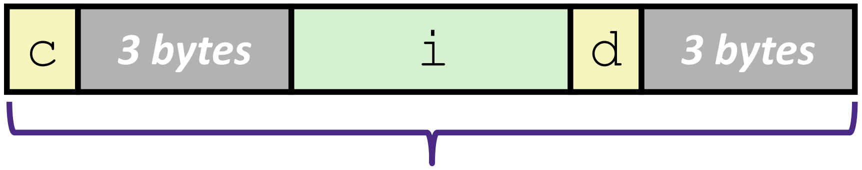
- Compiler will do the following:
  - Maintains declared *ordering* of fields in struct
  - Each ***field*** must be aligned *within* the struct *(may insert padding)*
    - `offsetof` can be used to get actual field offset
  - Overall struct must be ***aligned*** according to largest field
  - Total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

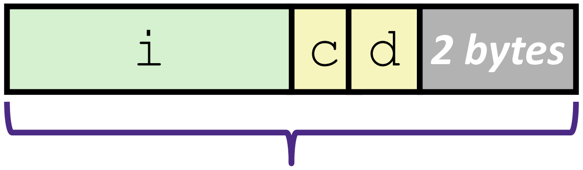
- Compiler must respect order elements are declared in
  - Sometimes the programmer can save space by declaring large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```



12 bytes



8 bytes

Peer Instruction Question

- 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;

  ______ ______;

  ______ ______;

  ______ ______;
};
```

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

sizeof(struct old) = _____ sizeof(struct new) = _____

Summary

- Arrays in C
  - Aligned to satisfy every element’s alignment requirement
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment