Structs and Alignment

CSE 351 Winter 2018

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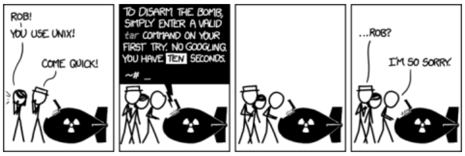
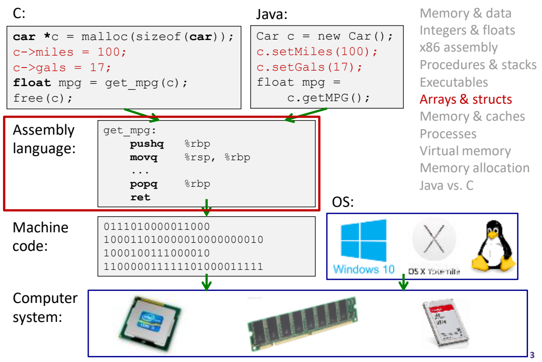

ROB!
YOU USE UNIX!
COME QUICK!
TO DISARM THE BOMB, SIMPLY ENTER A VALID tar COMMAND ON YOUR FIRST TRY. NO GOOGLING. YOU HAVE TEN SECONDS.
~# _
...ROB?
I'M SO SORRY.

http://xkcd.com/1168/

Administrivia

- Mid-quarter survey due by Thursday at 11:59 pm
- Homework 3 due Friday (2/9)
- Lab 3 released today!
  - Due next Friday (2/16)
- Midterm check-in
  - Difficulty?
  - Length?

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
```

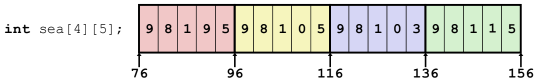
OS:

Computer system:

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

Peer Instruction Question

- Which of the following statements is FALSE?



`int sea[4][5];`

A. `sea[4][-2]` is a *valid* array reference

B. `sea[1][1]` makes *two* memory accesses

C. `sea[2][1]` will *always* be a higher address than `sea[1][2]`

D. `sea[2]` is calculated using *only* `lea`

E. We're lost…

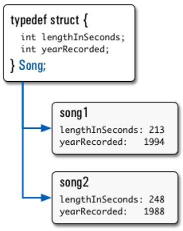
Data Structures in Assembly

- 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

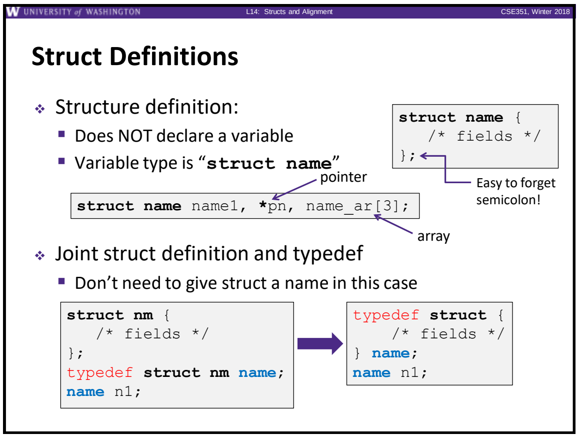
```
typedef struct {
  int lengthInSeconds;
  int yearRecorded;
} Song;

Song song1;

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

Song song2;

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



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

```
song1
lengthInSeconds: 213
yearRecorded:   1994
```

```
song2
lengthInSeconds: 248
yearRecorded:   1988
```



Struct Definitions

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

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

Easy to forget semicolon!

pointer

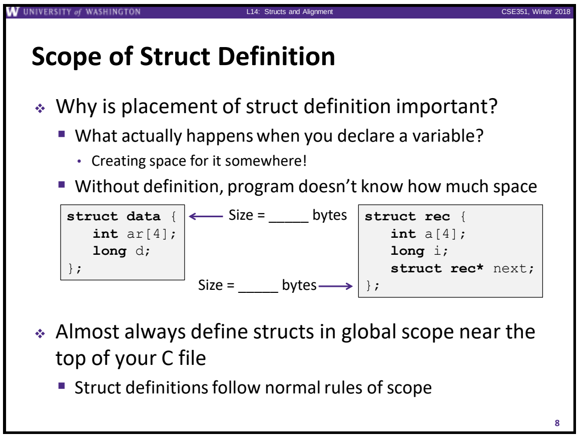
```
struct name name1, *pn, name_ar[3];
```

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

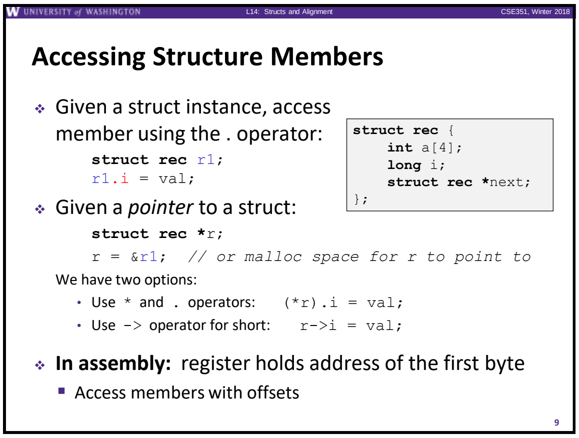
```
struct data {
   int ar[4];
   long d;
};
```

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

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

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

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

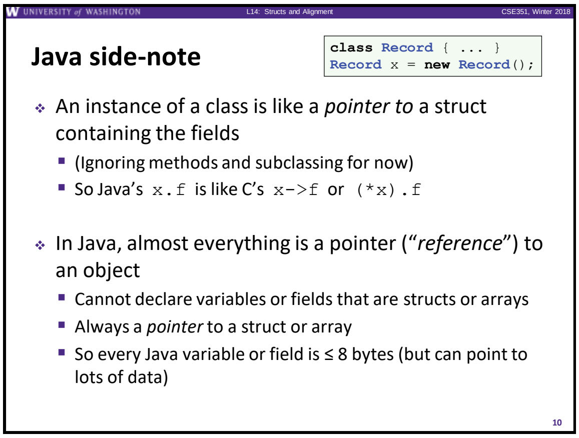
- Given a *pointer* to a struct:

```
    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;`

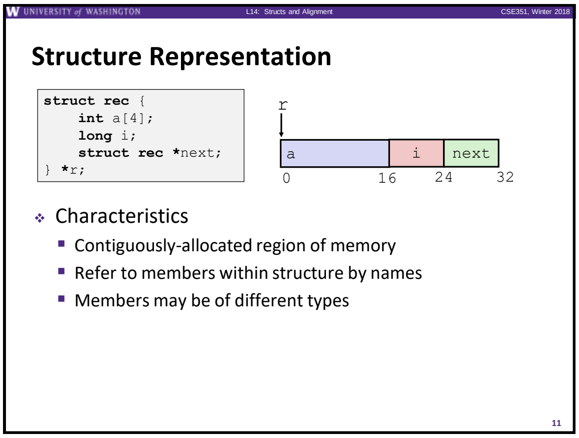
- **In assembly:** register holds address of the first byte
  - Access members with offsets



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)

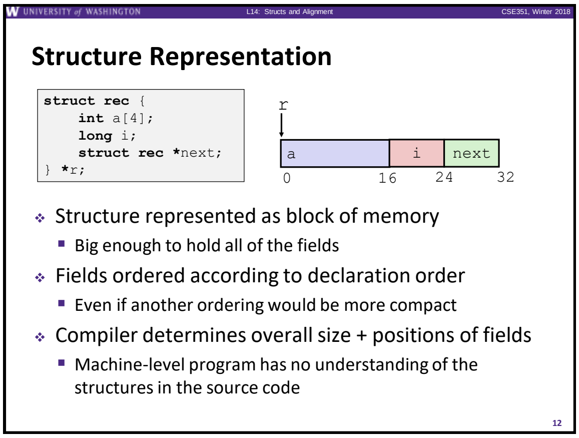


Structure Representation

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

r
a
i
next
0
16
24
32

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

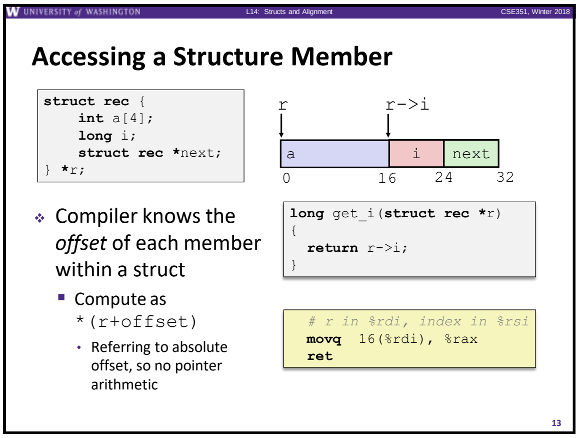


Structure Representation

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

r
a
i
next
0
16
24
32

- 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;
} *r;
```

r r->i

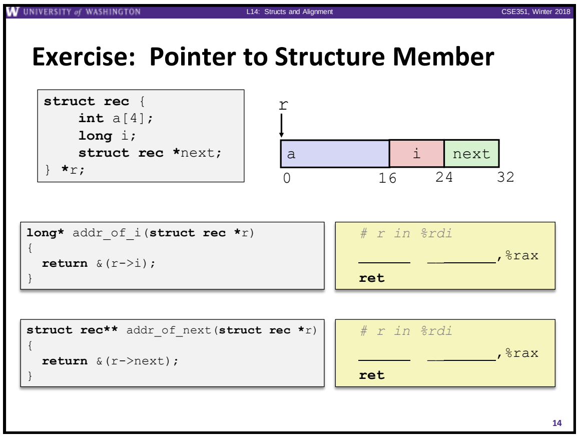
a | i | next

0 16 24 32

- 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;
} *r;
```

r

a | i | next

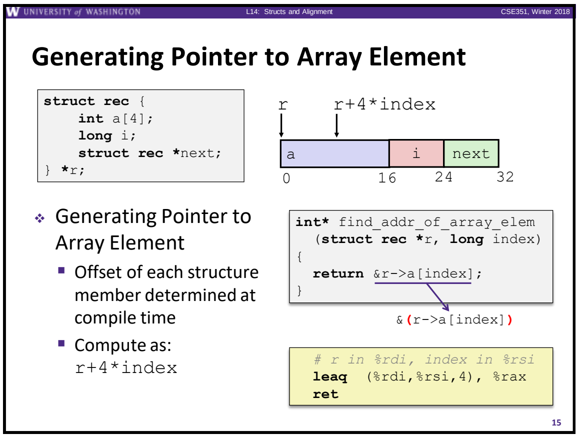
0 16 24 32

```
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;
} *r;
```

r r+4*index

a | i | next

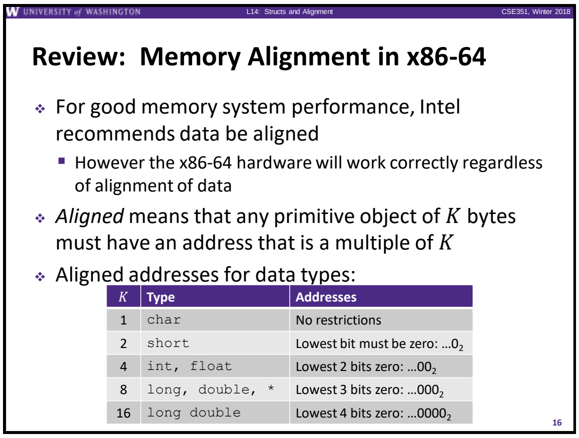
0 16 24 32

- 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])

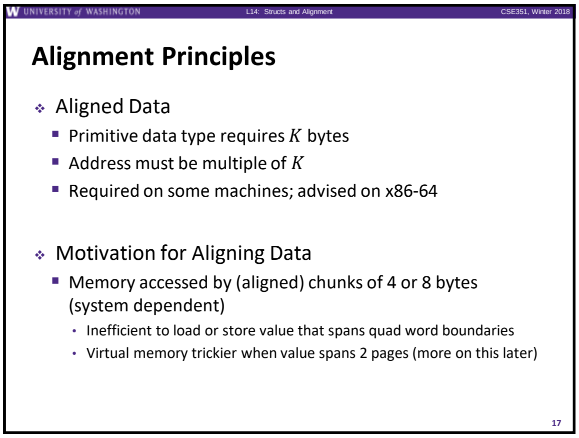
```
  # r in %rdi, index in %rsi
  leaq   (%rdi,%rsi,4), %rax
  ret
```



Review: Memory Alignment in x86-64

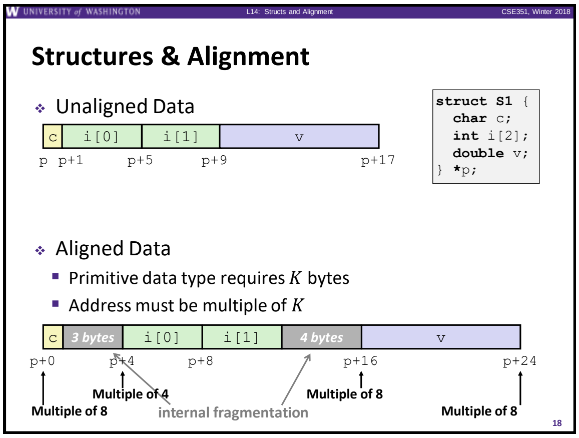
- For good memory system performance, Intel recommends data be aligned
  - However the x86-64 hardware will work correctly regardless of alignment of data
- *Aligned* means that any primitive object of K bytes must have an address that is a multiple of K
- Aligned addresses for data types:

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



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 4 or 8 bytes (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)



Structures & Alignment

- Unaligned Data

c | i[0] | i[1] | v

p p+1 p+5 p+9 p+17

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

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

c | *3 bytes* | i[0] | i[1] | *4 bytes* | v

p+0 p+4 p+8 p+16 p+24

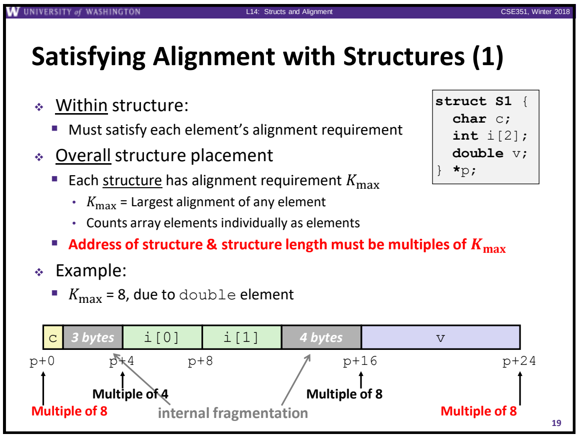
Multiple of 8

Multiple of 4

internal fragmentation

Multiple of 8

Multiple of 8



Satisfying Alignment with Structures (1)

- 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
  - Address of structure & structure length must be multiples of $K_{\max}$
- Example:
  - $K_{\max}$ = 8, due to double element

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

c	3 bytes	i[0]	i[1]	4 bytes	v

p+0 p+4 p+8 p+16 p+24

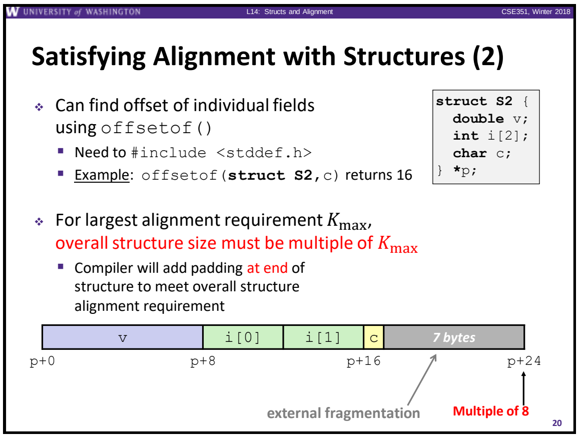
Multiple of 8

Multiple of 4

internal fragmentation

Multiple of 8

Multiple of 8



Satisfying Alignment with Structures (2)

- 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

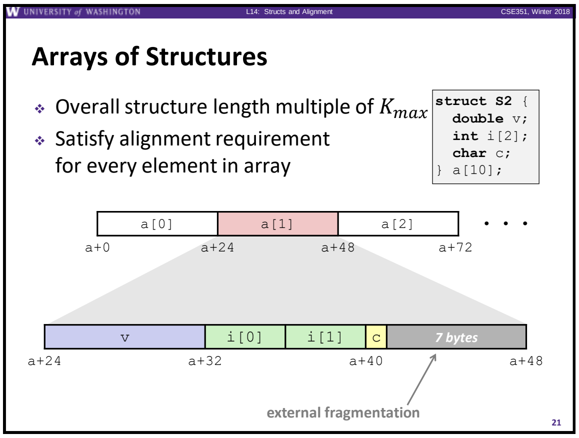
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```

v	i[0]	i[1]	c	7 bytes

p+0 p+8 p+16 p+24

external fragmentation

Multiple of 8



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];
```

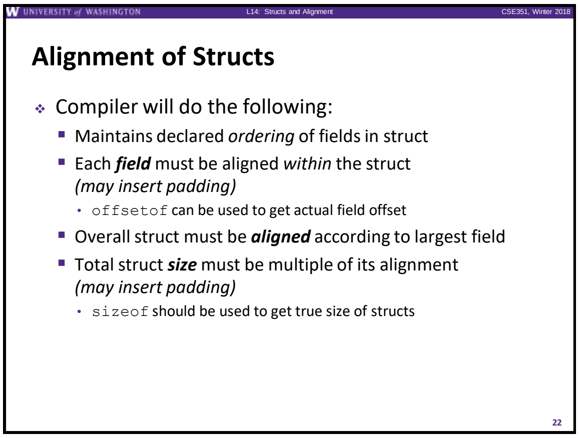
a[0]	a[1]	a[2]	• • •

a+0 a+24 a+48 a+72

v	i[0]	i[1]	c	7 bytes

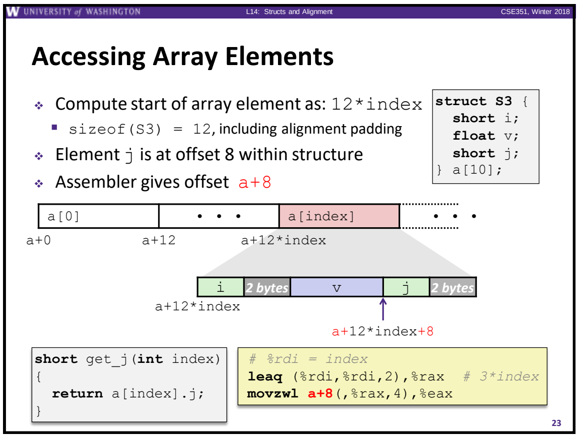
a+24 a+32 a+40 a+48

external fragmentation



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



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];
```

a[0]	• • •	a[index]	• • •

a+0 a+12 a+12*index

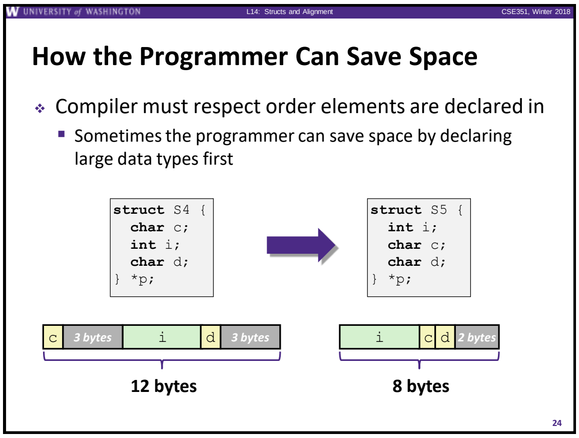
i	2 bytes	v	j	2 bytes

a+12*index

a+12*index+8

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

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



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;
```

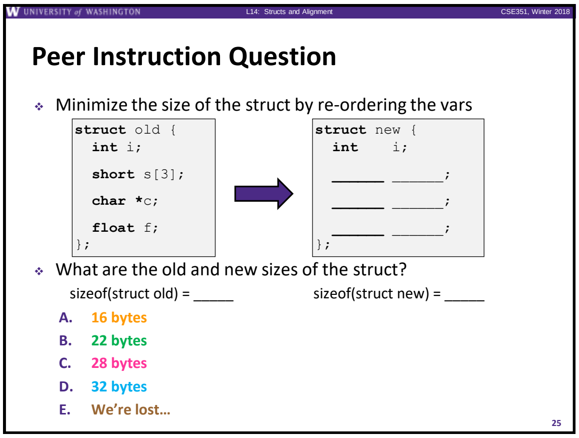
```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```

c	3 bytes	i	d	3 bytes

12 bytes

i	c	d	2 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) = _____

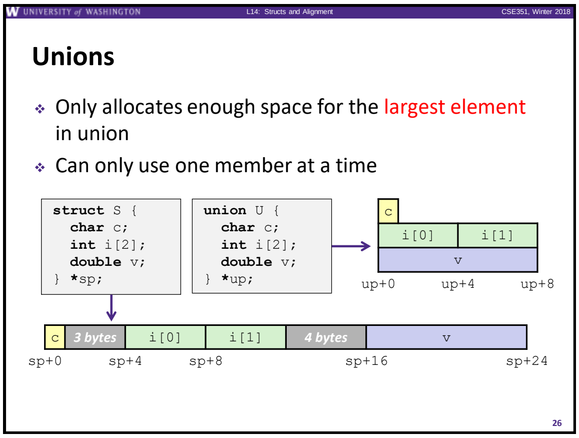
A. 16 bytes

B. 22 bytes

C. 28 bytes

D. 32 bytes

E. We're lost…

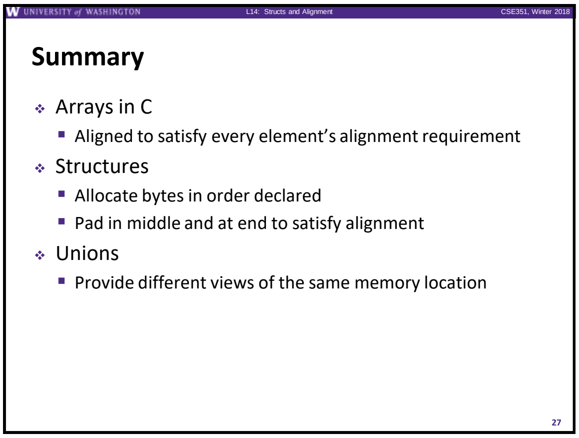


Unions

- 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;
} *sp;
```

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



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
- Unions
  - Provide different views of the same memory location