

Structs & Alignment

CSE 351 Autumn 2019

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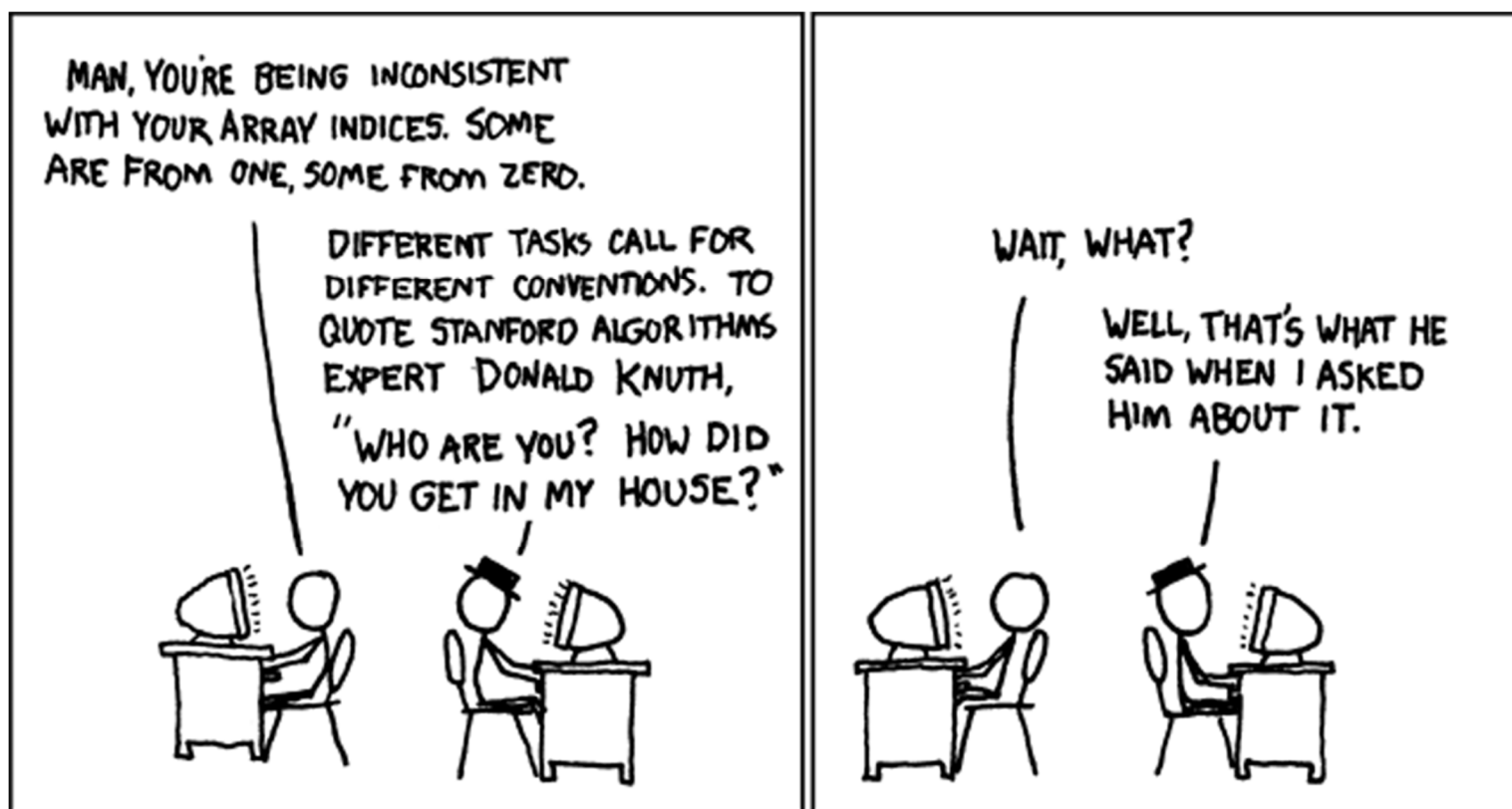
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Administrivia

- ❖ Lab 2 due tonight
- ❖ Lab 3 released next Wednesday (10/30)
- ❖ Mid-quarter survey due Thursday (10/31)
- ❖ hw13 due next Friday (11/1)

- ❖ **Midterm** (10/28, 5:30-6:40 pm, KNE 130)
 - Come early to get exam and settle in
 - Make a cheat sheet! – two-sided letter page, *handwritten*

- ❖ Extra office hours
 - Many over the weekend and on Monday (see Piazza @314)

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

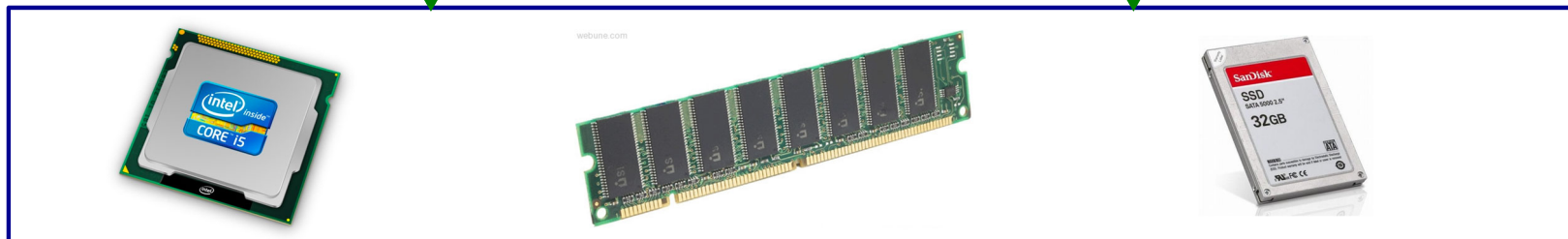
Assembly language:

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

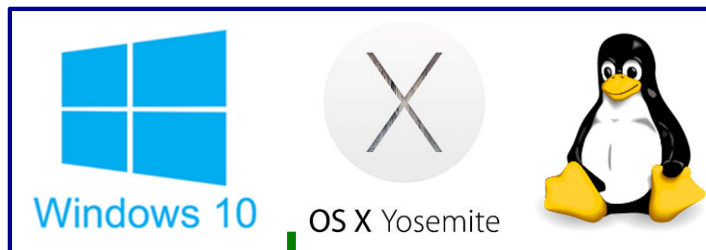
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

Computer system:



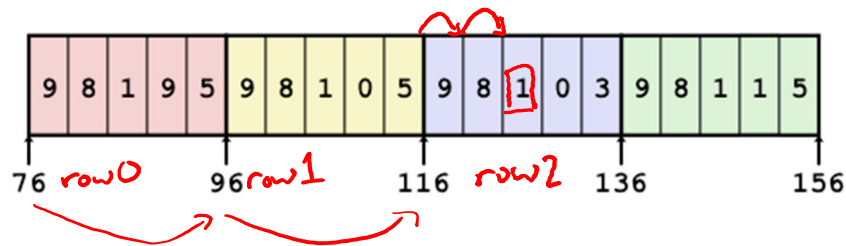
OS:



Array Element Accesses

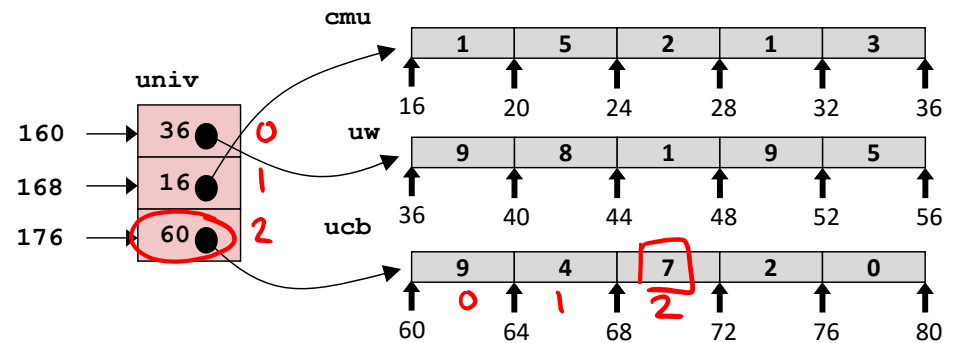
Multidimensional array

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



Multilevel 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]

more efficient:

- less overall memory
- faster to access

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

more flexible:

- easier to "fit" smaller arrays in memory
- can swap out rows (and resize)
- can have rows of different lengths

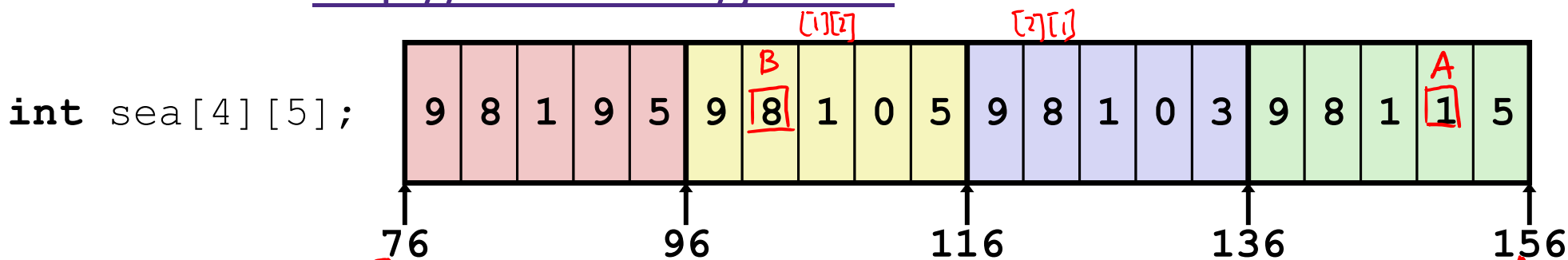
Polling Question

row-major: $\begin{bmatrix} 0 & 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 & 9 \\ 10 & 11 & 12 & 13 & 14 \\ 15 & 16 & 17 & 18 & 19 \end{bmatrix}$

column-major: $\begin{bmatrix} 0 & 4 & 8 & 12 & 16 \\ 1 & 5 & 9 & 13 & 17 \\ 2 & 6 & 10 & 14 & 18 \\ 3 & 7 & 11 & 15 & 19 \end{bmatrix}$

❖ Which of the following statements is FALSE?

▪ Vote at <http://PollEv.com/justinh>



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

Yes, returns 1

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

No, only single memory access

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

Yes, because C is row-major

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

Yes, **sea[2]** returns address of array row

E. We're lost...

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 = "Señorita";
song1.lengthInSeconds = 191;
song1.yearReleased = 2019;

struct song song2;
song2.title = "Call Me Maybe";
song2.lengthInSeconds = 193;
song2.yearReleased = 2011;
```

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

```
song1
title:      "Señorita"
lengthInSeconds: 191
yearReleased: 2019
```

```
song2
title: "Call Me Maybe"
lengthInSeconds: 193
yearReleased: 2011
```

Struct Definitions

❖ Structure definition:

- Does NOT declare a variable
- Variable type is "struct name"

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

your choice

Easy to forget semicolon!

❖ Variable declarations like any other data type:

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

instance

pointer

array

❖ Can also combine struct and instance definitions:

- This syntax can be difficult to parse, though

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

this is the data type (like int)

Typedef in C

- ❖ A way to create an *alias* for another data type:

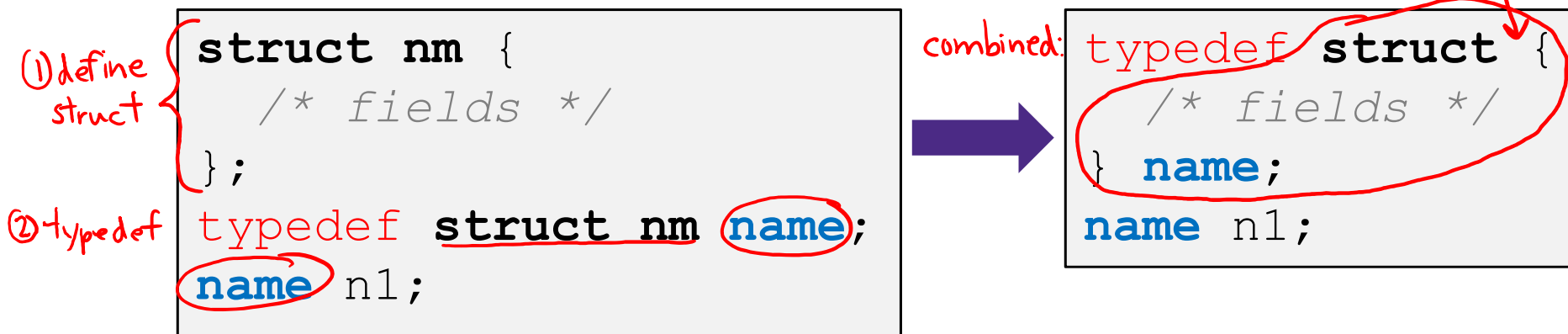
```
typedef <data type> <alias>;
```

- After typedef, the alias can be used interchangeably with the original data type

- e.g. `typedef unsigned long int uli;`
data type alias

- ❖ Joint struct definition and typedef

- Don't need to give struct a name in this case



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;  
};
```

4B x 4
8B

← Size = 24 bytes

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

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

- ❖ 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;`

① dereference (get instance)
 ② access field
 equivalent

- ❖ **In assembly:** register holds address of the first byte

- Access members with offsets

$D(Rb, Ri, S)$

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

Java side-note

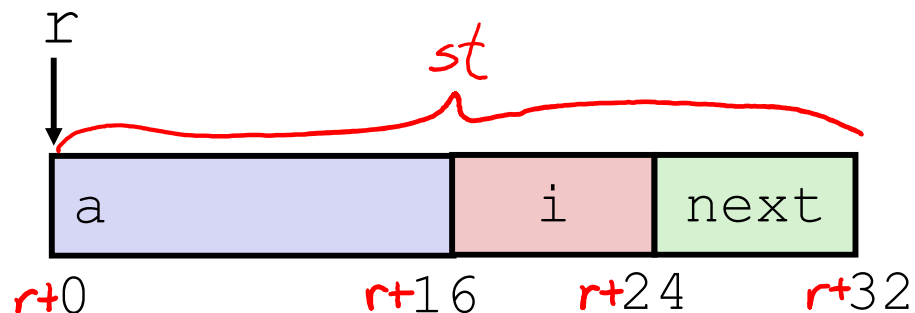
```
class Record { ... }  
Record x = new Record();
```

- ❖ 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 $x \rightarrow f$ 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;  
} st, *r = &st;
```

↑ instance
↑ pointer

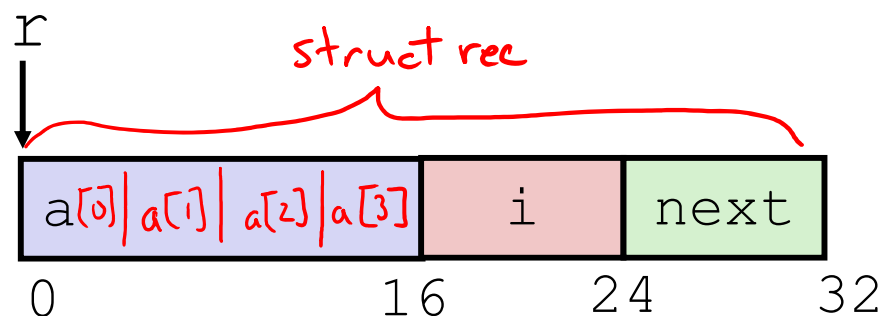


❖ Characteristics

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

Structure Representation

```
struct rec {  
  ① int a[4];  
  ② long i;  
  ③ struct rec *next;  
} st, *r = &st;
```

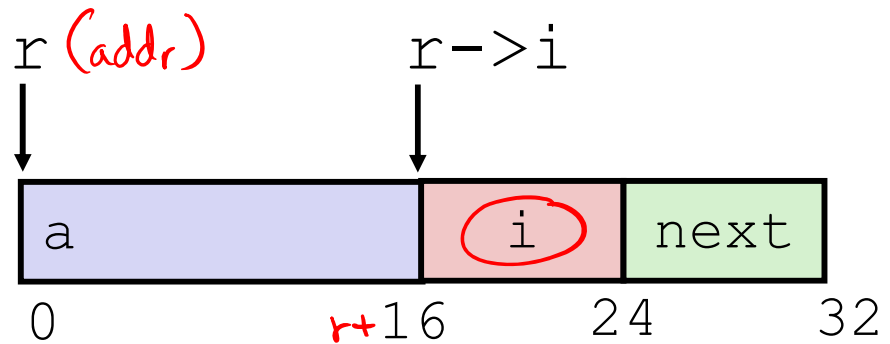


- ❖ Structure represented as block of memory
 - Big enough to hold all of the fields
- ❖ Fields ordered according to declaration order
 - Even if another ordering would be more compact
- ❖ Compiler determines overall size + positions of fields
 - Machine-level program has no understanding of the structures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

Accessing a Structure Member

```

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



❖ Compiler knows the *offset* of each member within a struct

- Compute as `*(r+offset)`
 - Referring to absolute offset, so no pointer arithmetic

```

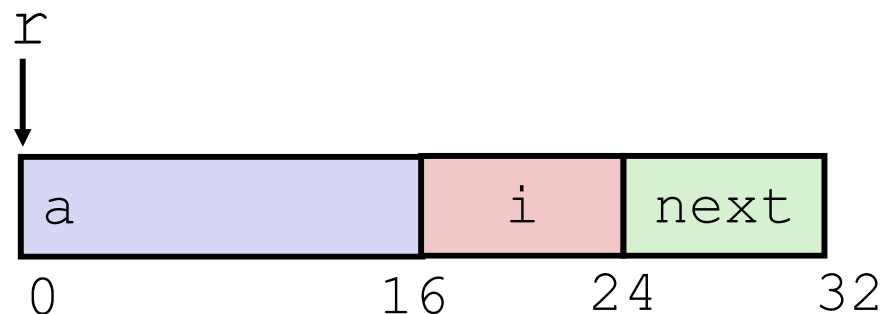
long get_i(struct rec *r)
{
    return r->i;
}
    
```

```

# 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;
} st, *r = &st;
```



pointer

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

want address

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

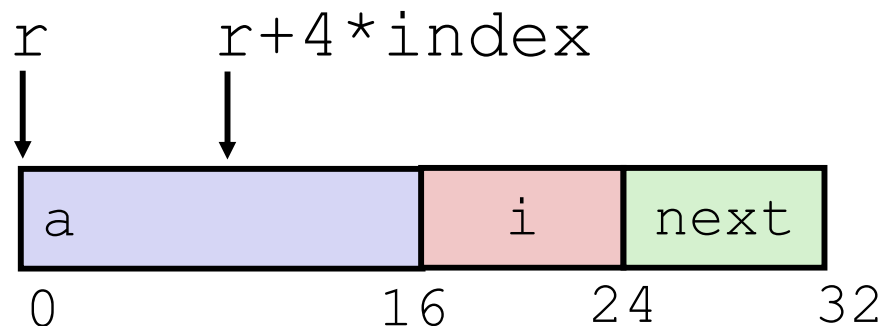
```
# r in %rdi
leaq 16(%rdi), %rax
ret
```

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


Generating Pointer to Array Element

```

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



❖ 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

- ❖ *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: $\dots 0_2$
4	int, float	Lowest 2 bits zero: $\dots 00_2$
8	long, double, *	Lowest 3 bits zero: $\dots 000_2$
16	long double	Lowest 4 bits zero: $\dots 0000_2$

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 $\gg \log_2(K)$.
 No remainder means no weight is "lost" during the shift \rightarrow all zeros in lowest $\log_2(K)$ bits.

Alignment Principles

❖ Aligned Data

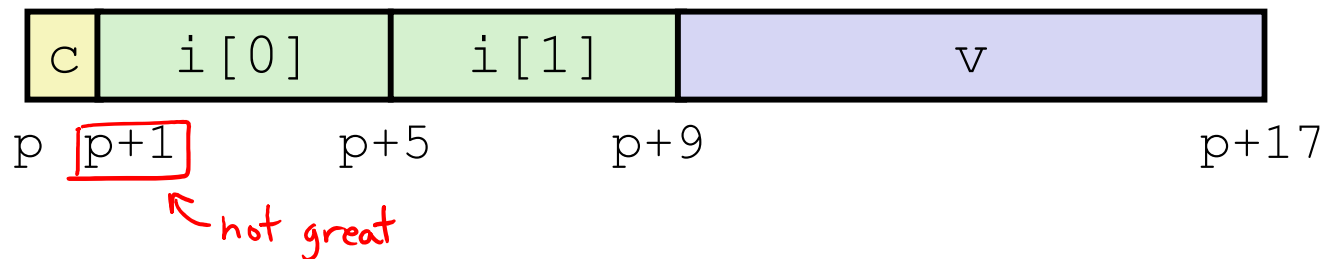
- Primitive data type requires K bytes
- Address must be multiple of K
- Required on some machines; advised on x86-64

❖ 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

❖ Unaligned Data



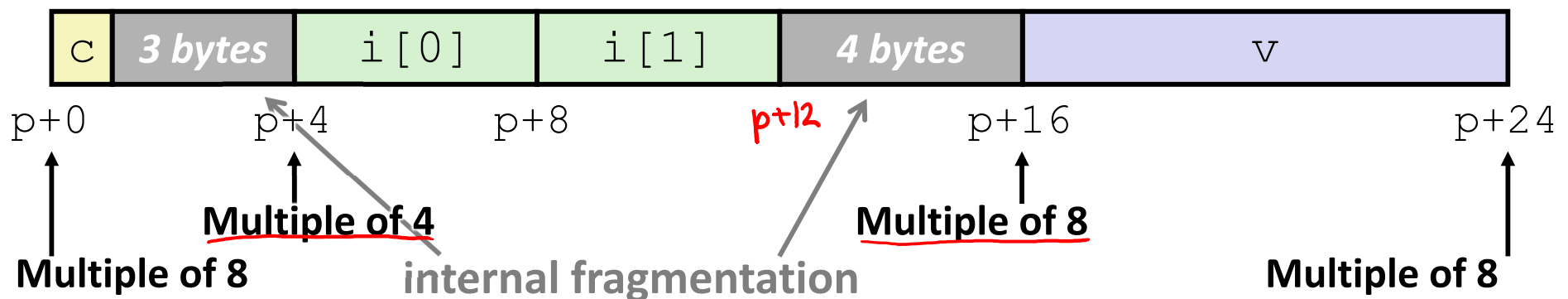
```

struct S1 {
  ① char c;
  ② int i[2];
  ③ double v;
} st, *p = &st;
    
```

$\frac{K}{1}$
 $\leftarrow 1$
 $\leftarrow 4$
 $\leftarrow 8$

❖ Aligned Data

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



24 B total

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

```

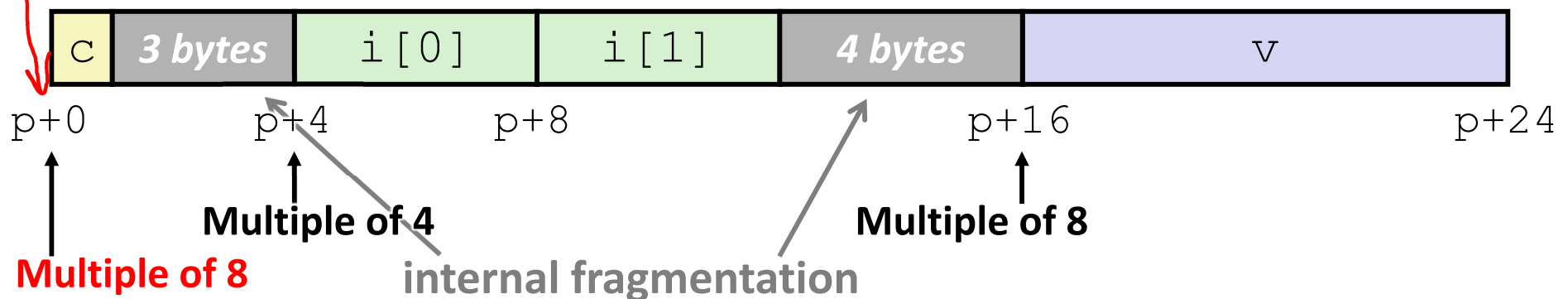
K
1
4
8
struct S1 {
    char c;
    int i[2];
    double v;
} st, *p = &st;
    
```

$K_{max} = 8$

alignment requirement of starting addr

❖ Example:

- $K_{max} = 8$, due to double element



Satisfying Alignment with Structures (2)

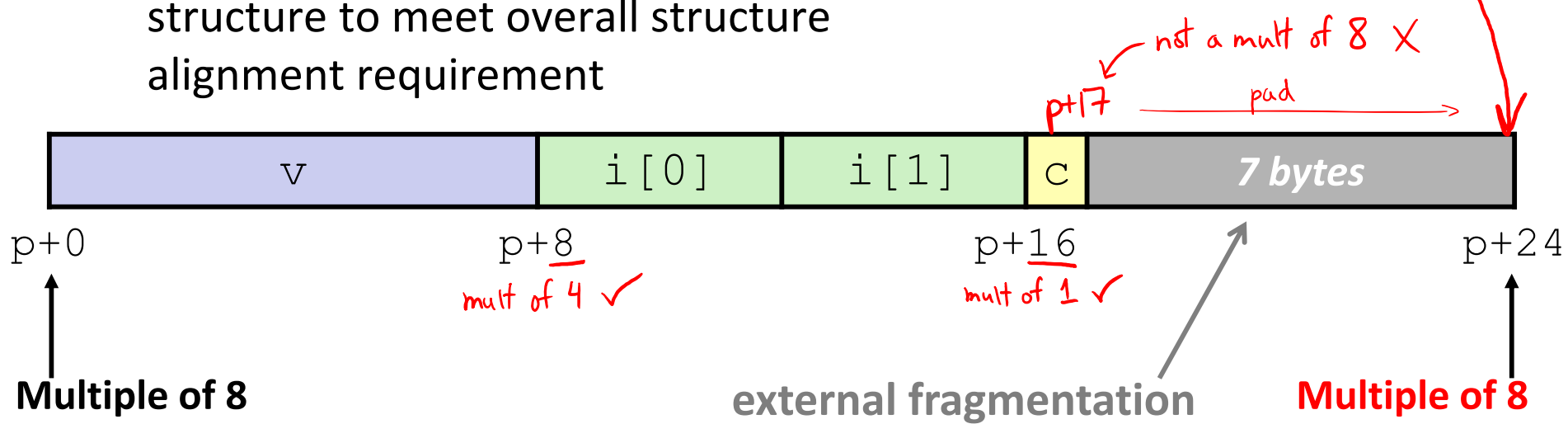
- ❖ Can find offset of individual fields using `offsetof()`
 - Need to `#include <stddef.h>`
 - Example: `offsetof(struct S2, c)` returns 16

```

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

- ❖ For largest alignment requirement K_{max} , overall structure size must be multiple of $K_{max} = 8$

- Compiler will add padding at end of structure to meet overall structure alignment requirement

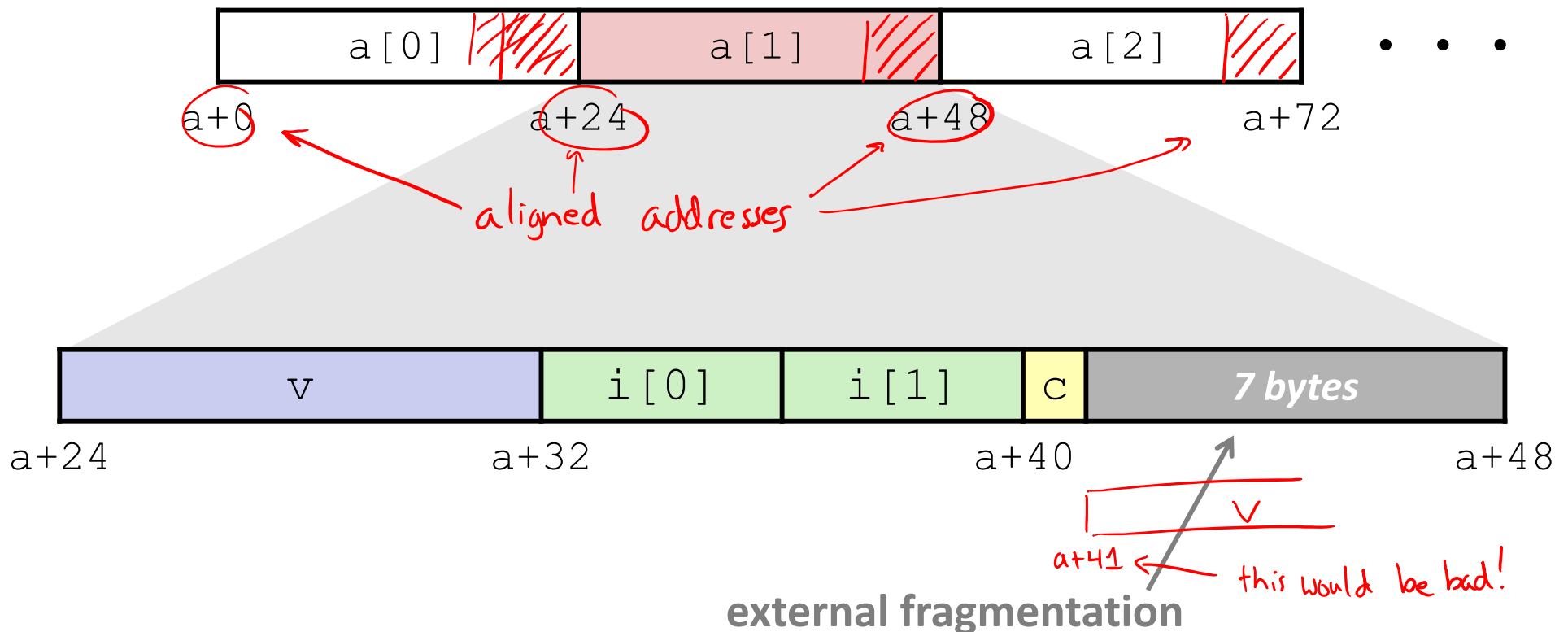


Arrays of Structures

- ❖ 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];
    
```

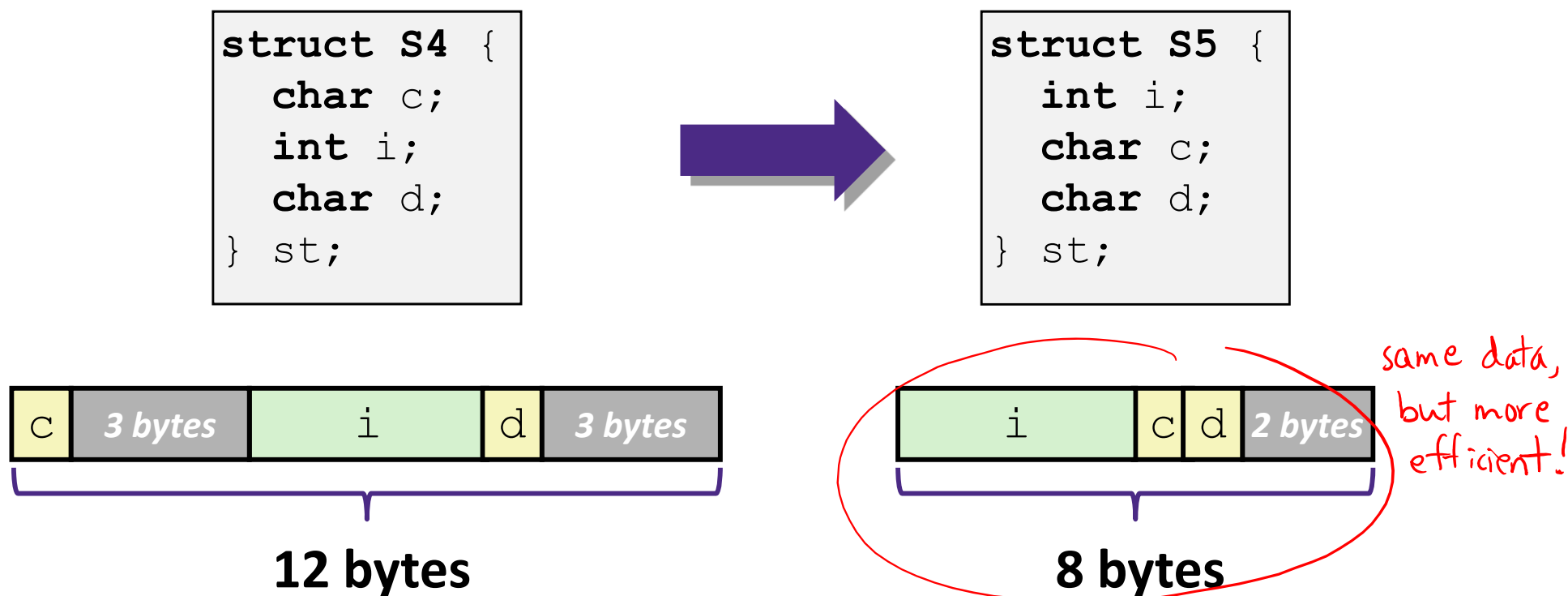


Alignment of Structs

- ❖ 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



Polling Question

Vote on `sizeof(struct old)`:
<http://PollEv.com/justinh>

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

$K = 4$

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

$K_{max} = 8$



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

could also switch these (internal vs. external frag)

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

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

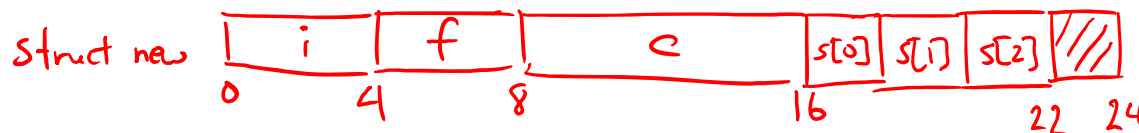
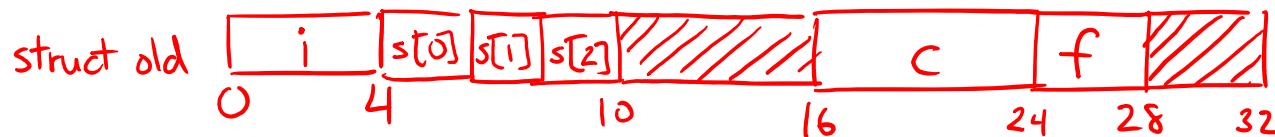
A. 16 bytes

B. 22 bytes

C. 28 bytes

D. 32 bytes

E. We're lost...



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