Structs & Alignment

CSE 351 Spring 2024

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Dad, can i have classes?

Dad: No, we have classes at home.

Classes at home: struct

Playlist: CSE 351 24Sp Lecture Tunes!

Relevant Course Information

❖ HW 12 due tonight; Lab 2 due Friday!

- Lab 3 released at the same time; due 08 May

❖ HW13/14 due 01 May

Reading Review

- ❖ Terminology:
  - Structs: tags and fields, **.** and -> operators
  - typedef
  - Alignment, internal fragmentation, external fragmentation

Review Questions

```
struct ll_node {
    long data;
    struct ll_node* next;
} n1, n2;
```

❖ How much space (in bytes) does an instance of `struct ll_node` take?

❖ Which of the following independent statements are syntactically valid?
A. `n1.next = &n2;`
B. `n2->data = 351;`
C. `n1.next->data = 333;`
D. `(&n2)->next->next.data = 451;`

Data Structures in C

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

# Structs in C (Review)

❖ User-defined <u>structured</u> group of variables, possibly including other structs
  ▪ Kind of like Java object, but no methods nor inheritance; just fields 😤
  ▪ Way of defining compound data types

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

struct song song1;
song1.title = "Lavender Haze";
song1.lengthInSeconds = 182;
song1.yearReleased = 2022;

struct song song2;
song2.title = "State of Grace";
song2.lengthInSeconds = 295;
song2.yearReleased = 2012;
```

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

```
song1
title:  "Lavender Haze"
lengthInSeconds:      182
yearReleased:        2022
```

```
song2
title:   "State of Grace"
lengthInSeconds:      295
yearReleased:        2012
```
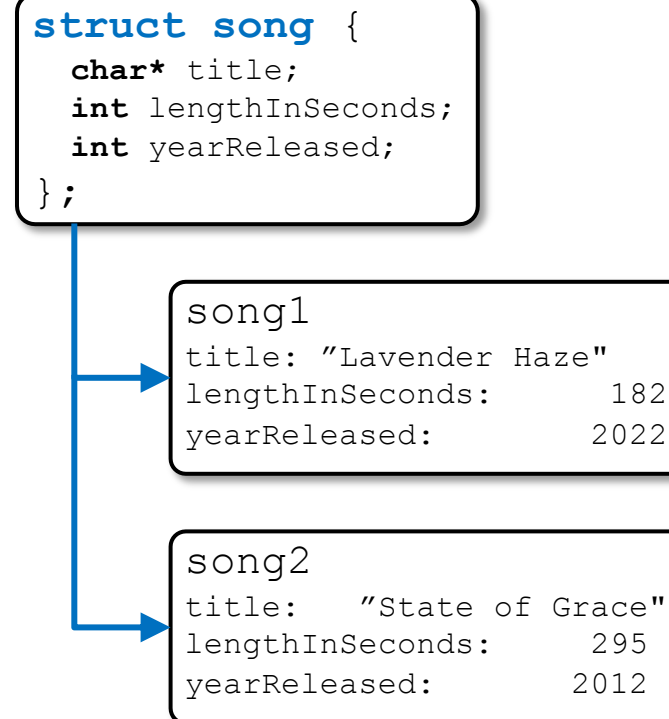
Struct Definitions (Review)

❖ Structure definition:
- Does **<u>not</u>** declare a variable; lets compiler know we're defining it and will be using instances of it
- Variable type is "`struct name`"; gotta say it all every time we declare! Or do we?...

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

Really easy to forget the semicolon!

❖ Variable declarations like any other data type:

```
struct cat matilda;        instance
struct cat *pc;            pointer
struct cat kitty_ar[3];    array
```

❖ Can also combine struct and instance definitions:

```
struct cat {
    /* fields */
} c, *pc = &c;
```

Used in review question—this syntax can be difficult to read and do not recommend!

Typedef in C (Review)

❖ A way to create an **<u>alias</u>** for another data type:
```
typedef <data type> <alias>;
```

  ▪ After typedef, the alias can be used *interchangeably* with the original data type
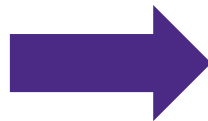
  ▪ *e.g.,* `typedef unsigned long int uli;`
     ```
     unsigned long int x = 12131989;
     uli y = 12131989;   // can now use it like this!
     ```

❖ Joint struct definition and typedef

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

```
struct cat {
  /* fields */
};
typedef struct cat kitty;
kitty olivia;
```

→

```
typedef struct {
  /* fields */
} kitty;


kitty olivia;
```

Scope of Struct Definition (Review)

❖ Why is the placement of struct definition important?
- Declaring a variable creates space for it somewhere
- Without definition, program doesn't know how much space to set aside!

```
struct data {
    int ar[4];
    long d;
};
```
← 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
- Top of singular C files, or if using a header file, place there!

Accessing Structure Members (Review)

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

❖ Given a <u>struct instance</u>, access member using the `.` operator:

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

❖ Given a <u>pointer</u> to a struct:

```
struct rec* r; // r is a pointer, remember!

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

We have **two equivalent options**:

- Use `*` and `.` operators: `(*r).i = val;`
- Use `->` operator (shorter):   `r->i = val;`

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

 ▪ Access members with offsets

Java side-note

- ❖ 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`
  - Structs are really as close you can get to "objects" in Java

- ❖ 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)

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

Structure Representation (Review)

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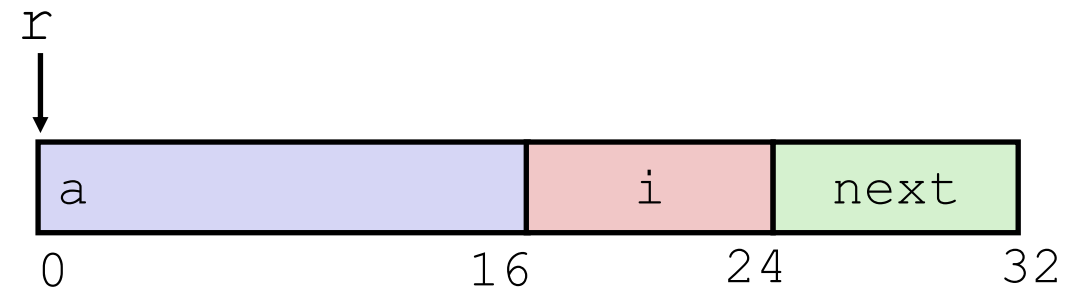
r

a	i	next

0　　　　　　　　16　　　24　　32
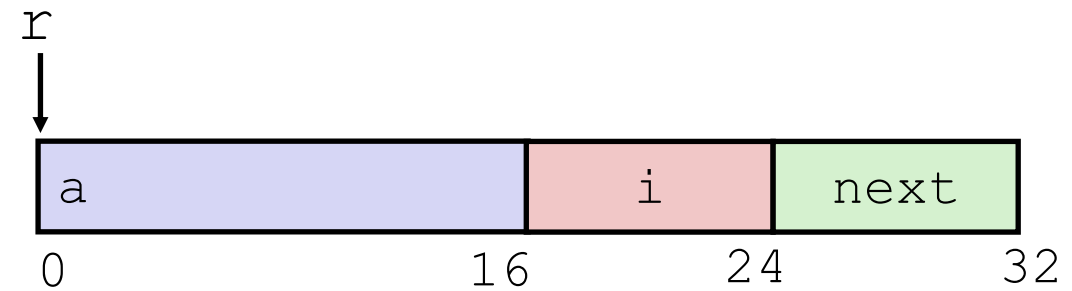
❖ Characteristics

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

Structure Representation (Review)

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

r

a	i	next

0   16   24   32

❖ Structure represented as block of memory

  ▪ Big enough to hold all the fields

❖ 🚨 **Fields ordered according to declaration order** 🚨

  ▪ **Even if another ordering would be more compact**

  ▪ Good reason: debugging is easier, since in assembly, only get addr of first byte

❖ Compiler determines overall size + positions of fields

  ▪ Machine-level program has no understanding of the structures in the source code

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Accessing a Structure Member

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

r   r->i

a	i	next

0   16   24   32
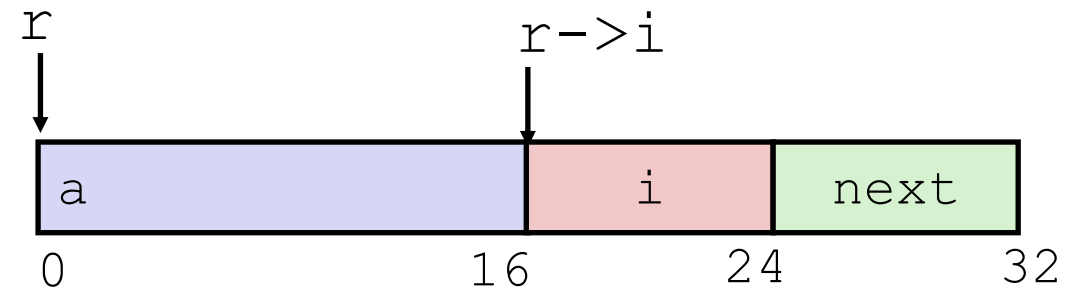
❖ Compiler knows the **offset** of each member
  ▪ No pointer arithmetic; compute as `*(r+offset_of_member)`

```
long get_i(struct rec* r) {
    return r->i;
}
```
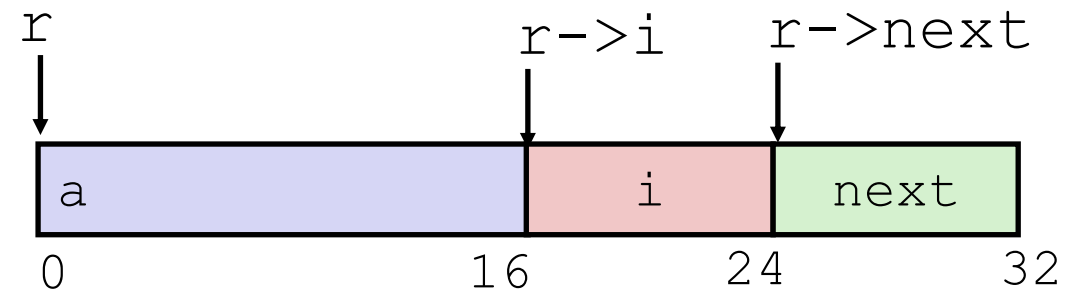
```
# pointer r in %rdi
movq   16(%rdi), %rax
ret
```

```
long get_a3(struct rec* r) {
    return r->a[3];
}
```

```
# pointer r in %rdi
movl   12(%rdi), %rax
ret
```

Pointer to Structure Member

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



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

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

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

```
# pointer r in %rdi
leaq  24(%rdi), %rax
ret
```
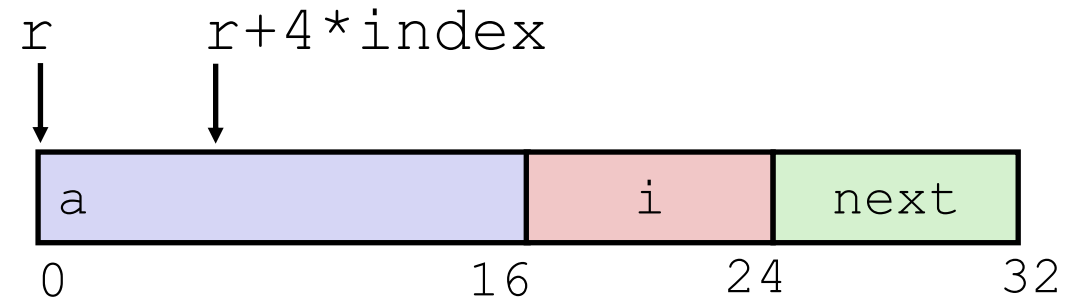
We can also get addresses of members themselves!

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Generating Pointer to Array Element

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

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])

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

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Struct Pointers

- ❖ Pointers store addresses, which all "look" the same
  - ▪ <u>Lab 0 Example</u>: struct instance `Scores` could be treated as array of `int`s of size 4 via pointer casting
  - ▪ A struct pointer doesn't *have* to point to a declared instance of that struct type
- ❖ Different struct fields may or may not be meaningful, depending on what the pointer points to
  - ▪ 🚨 **This will be important for Lab 5!** 🚨

```
long get_a3(struct rec* r) {
  return r->a[3];
}
```

```
movl   12(%rdi), %rax
ret
```

r   r+12

Memory:

"r->a[3]"
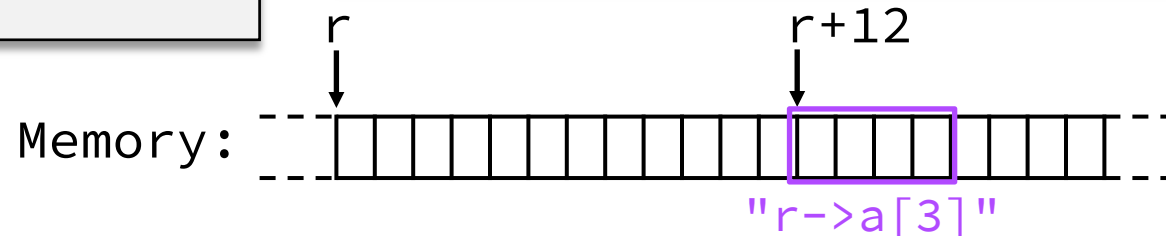
Alignment Principles

❖ 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)

  - Important for caching and paging, virtual memory

  - 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

Memory Alignment in x86-64

Remember withinBlock from Lab1a? Yeah, you were essentially checking that the 6 LSBs were the same 😅
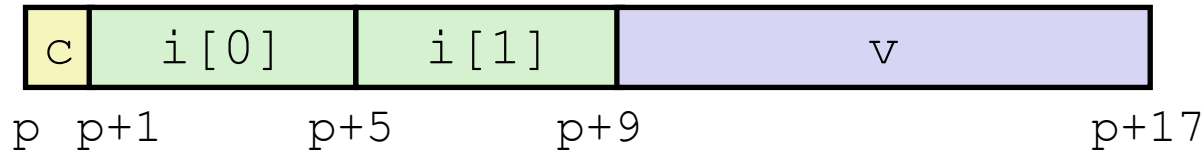
- ❖ ***Aligned*** means that any primitive object of K bytes must have an address that is a multiple of K

- ❖ Aligned addresses for data types:

K	Type	Addresses
1	`char`	No restrictions
2	`short`	Lowest bit must be zero: $\ldots0_2$
4	`int, float`	Lowest 2 bits zero: $\ldots00_2$
8	`long, double, *`	Lowest 3 bits zero: $\ldots000_2$
16	`long double`	Lowest 4 bits zero: $\ldots0000_2$

0   2   4   6   8
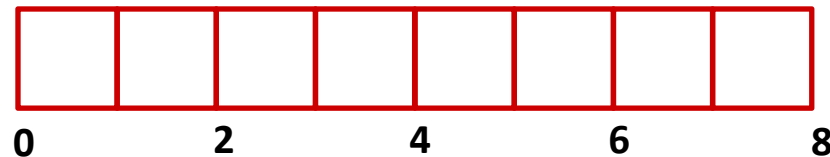
Structures & Alignment (Review)

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

❖ **Unaligned Data**: just pack all together!

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

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

❖ **Aligned Data**: unused space, but benefits later on.

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

internal fragmentation

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

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

Multiple of 4   Multiple of 8

Multiple of 8   Multiple of 8
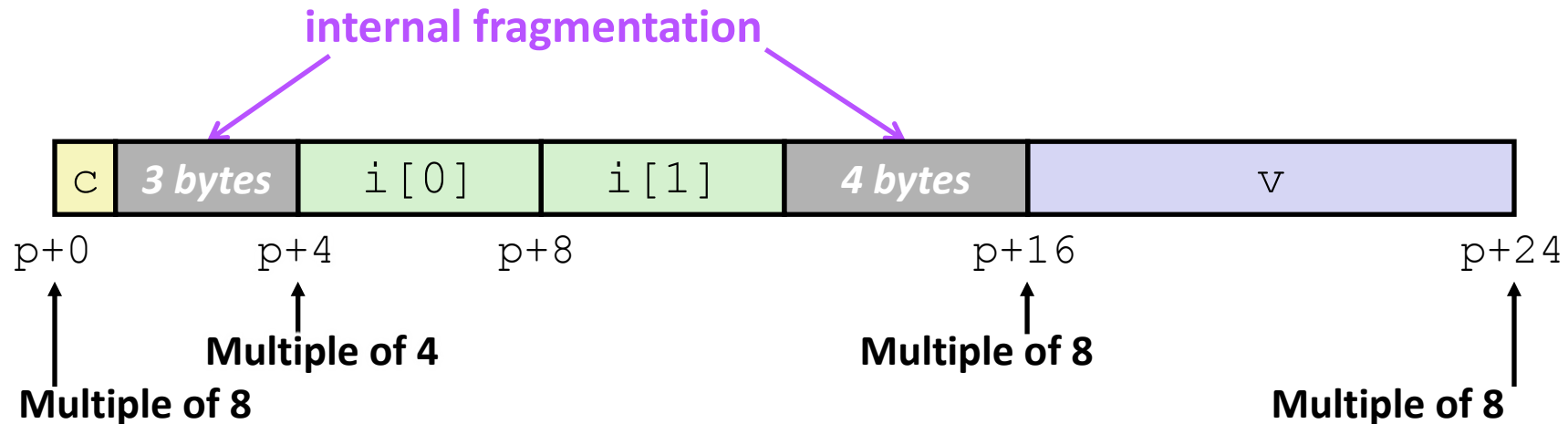
Satisfying Alignment with Structures

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

❖ <u>Within</u> structure:

- Must satisfy each element's alignment requirement

❖ <u>Overall</u> structure placement

- Each <u>structure</u> 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

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

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

Multiple of 4   **Multiple of 8**
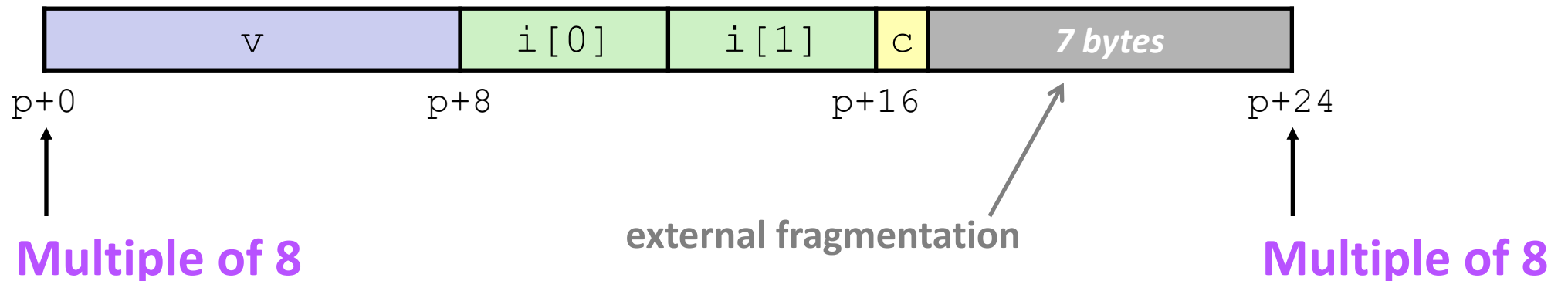
Multiple of 8

21
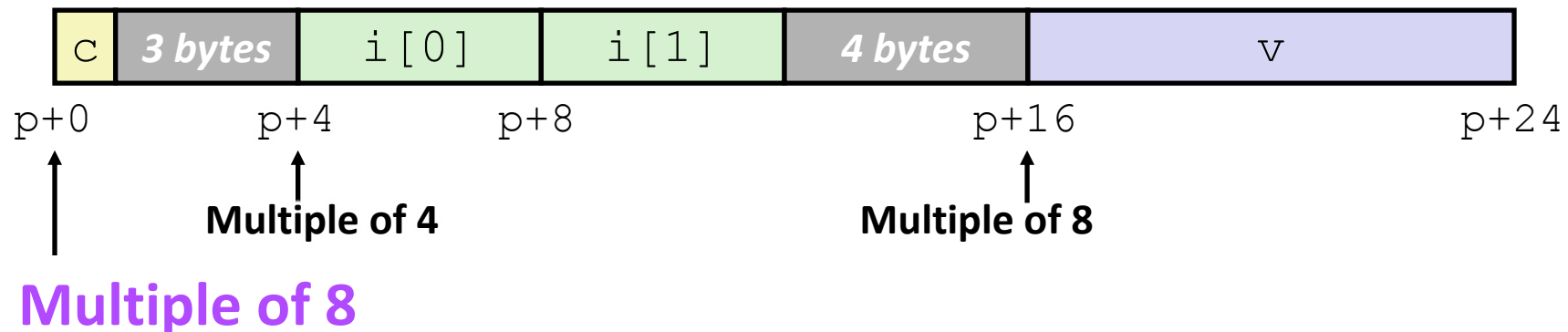
Okay, let's try to do that...

❖ Can find offset of individual fields
  using `offsetof()`
  - Need to `#include <stddef.h>`
  - <u>Example</u>: `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}
  - Compiler will add padding <u>at end </u>of structure to meet overall structure
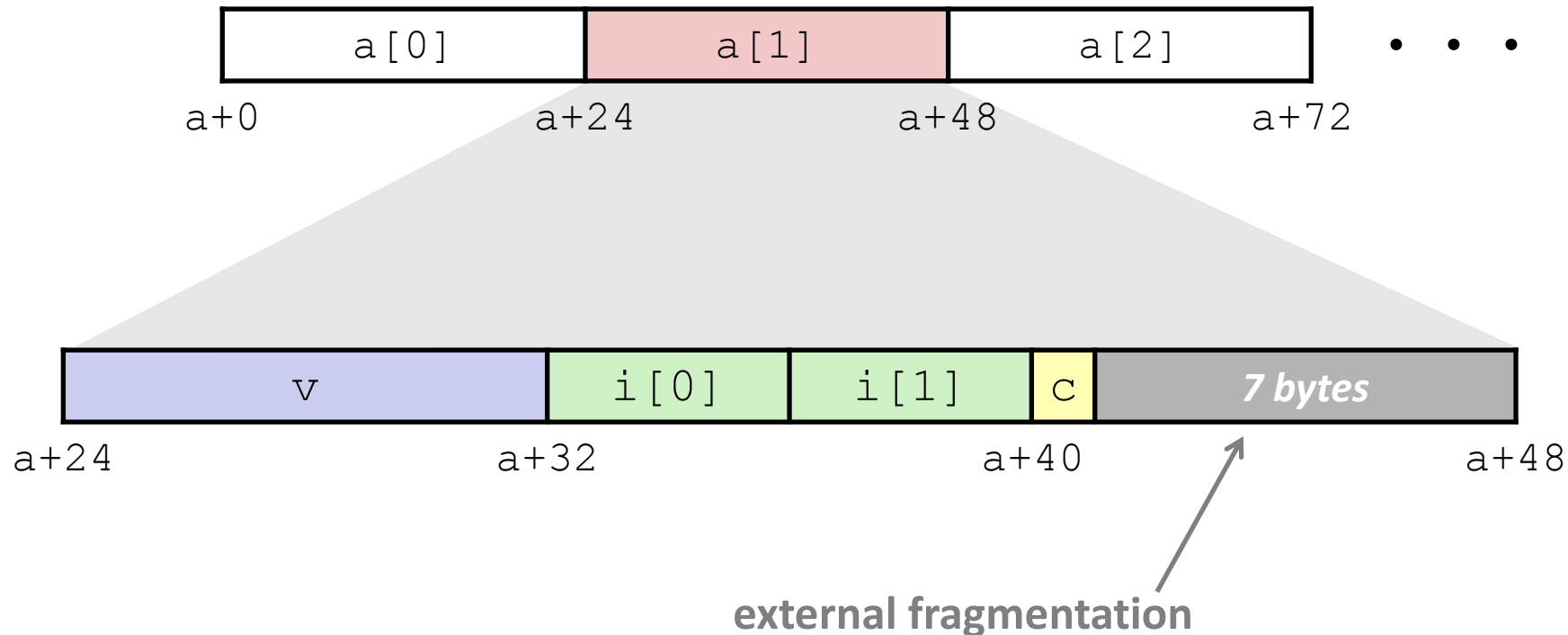   alignment requirement

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

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

Multiple of 8   external fragmentation   **Multiple of 8**

A Benefit: 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;
} st, *p = &st;
```
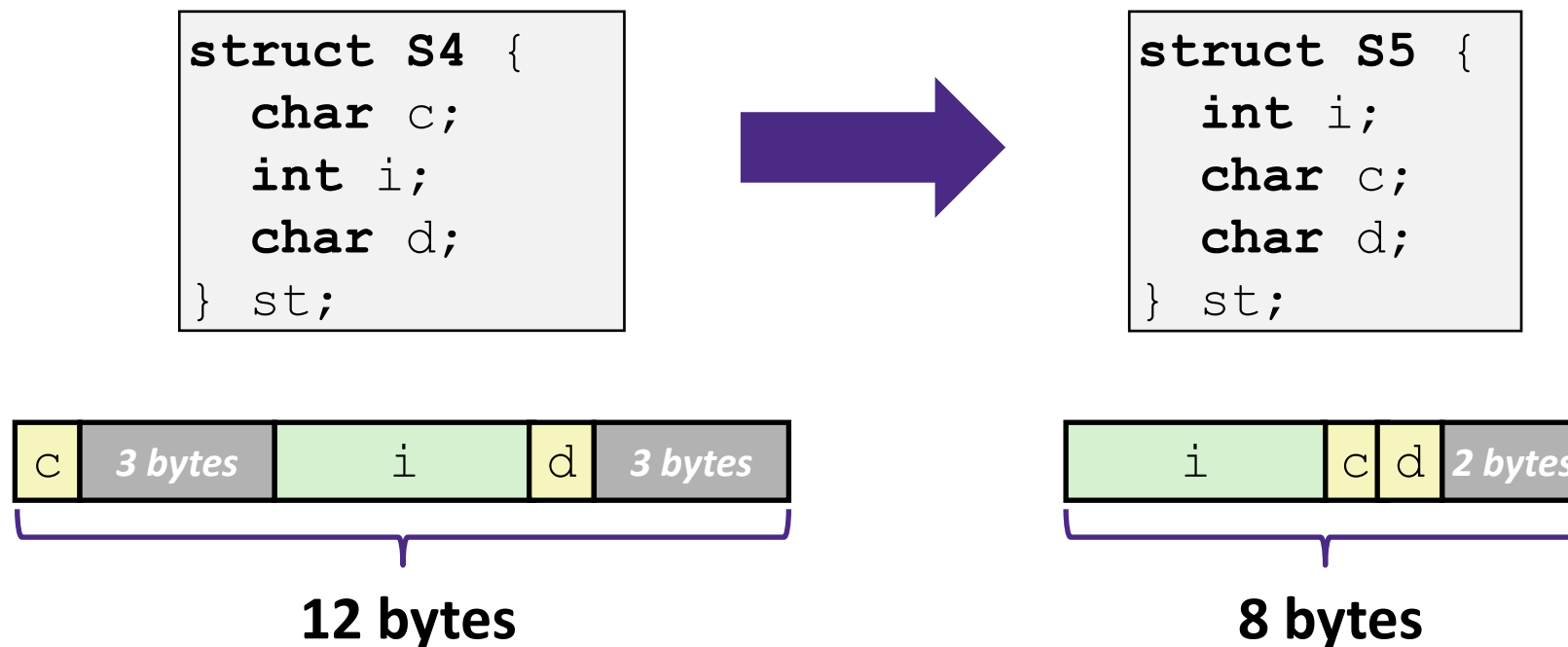

external fragmentation

Alignment of Structs (Review)

❖ Compiler will do the following:

- Still maintains declared <u>ordering</u> of fields in struct

- Each ***field*** must be aligned <u>within</u> the struct
  (may insert padding)

  - `offsetof` can be used to get actual field offset

- Overall struct must be <u>aligned</u> according to largest field

- Total struct ***size*** must be multiple of its alignment
  (may insert padding)

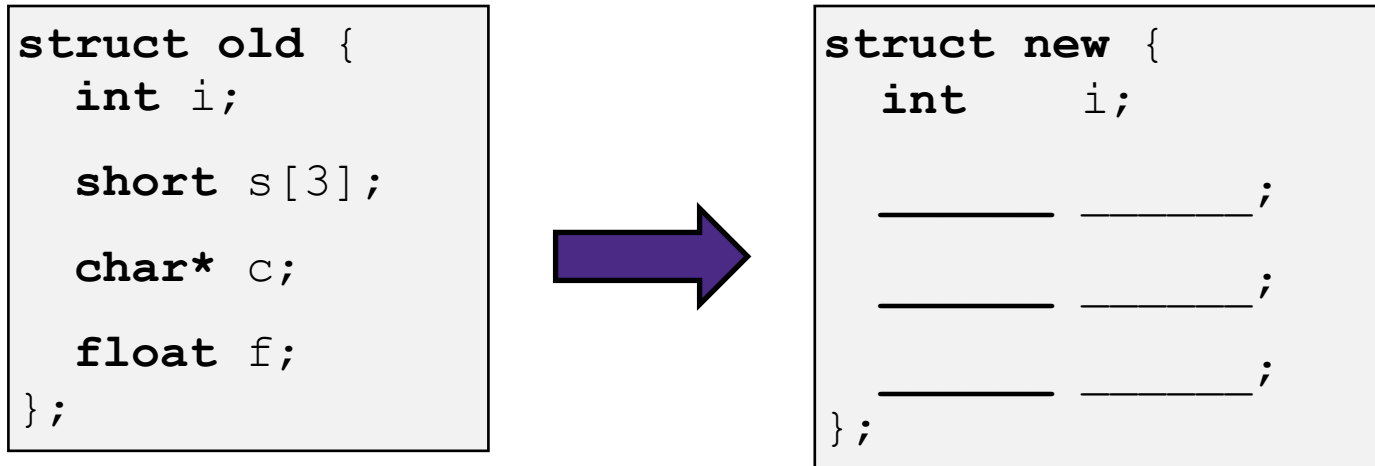 - `sizeof` should be used to get true size of structs

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;
} st;
```

→

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

| c | 3 bytes | i | d | 3 bytes |

12 bytes

| i | c | d | 2 bytes |

8 bytes

Practice 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)` = 32 B   `sizeof(struct new)` = _____

A. **22 bytes**

B. **24 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