Structs & Alignment

CSE 351 Autumn 2022

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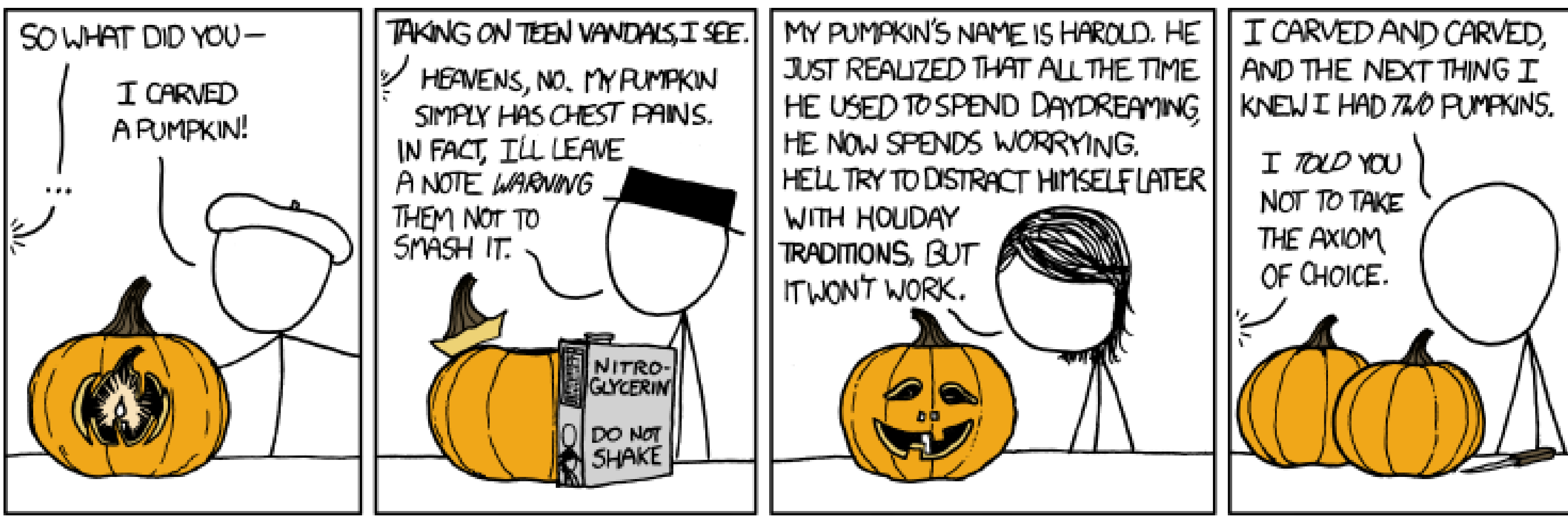


http://xkcd.com/804/

Relevant Course Information

- Lab 2 due tonight
- Lab 3 released next Monday (10/31)
  - A shorter lab, due Friday, 11/11
- hw13 due next Wednesday (11/2)

- **Take-home Midterm** (11/3 – 11/5)
  - Instructions will be posted on Ed Discussion
  - Gilligan's Island Rule: discuss high-level concepts and give hints, but not solving the problems together
  - We will be available on Ed Discussion (private posts only) and office hours to answer clarifying questions

Reading Review

- Terminology:
  - Structs: tags and fields, `.` and `->` operators
  - Typedef
  - Alignment, internal fragmentation, external fragmentation

- Questions from the Reading?

Review Questions

tag

```
struct ll_node {
8B  long data;
8B  struct ll_node* next;
} n1, n2;
```

fields

$K_{max}=8$

two instances

- How much space does (in bytes) does an instance of `struct ll_node` take? $\boxed{16\text{ B}}$
- Which of the following statements are syntactically valid?
  • . for struct instances (inst), -> for struct pointers (ptr)
  - ✓ `n1.next = &n2;` (inst ✓ ptr, ptr)
  - ✗ `n2->data = 351;` (inst ✗)
  - ✓ `n1.next->data = 333;` (inst ✓ ptr ✓ long)
  - ✗ `(&n2)->next->next.data = 451;` (ptr ✓ ptr ✓ ptr ✗)

Data Structures in C

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

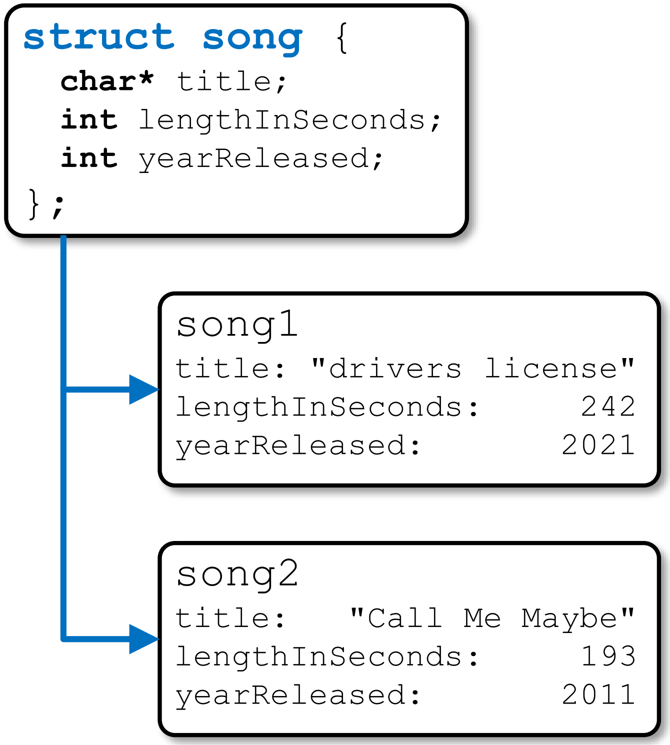
Structs in C (Review)

- 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 = "drivers license";
song1.lengthInSeconds = 242;
song1.yearReleased = 2021;

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



Struct Definitions (Review)

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

your choice

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

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 read, though

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

this is the data type (like int)

Typedef in C (Review)

- 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

(1) define struct
(2) typedef

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

combined:

unnamed!

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

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

```
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

Accessing Structure Members (Review)

```
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 (shorter): `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)

Java side-note

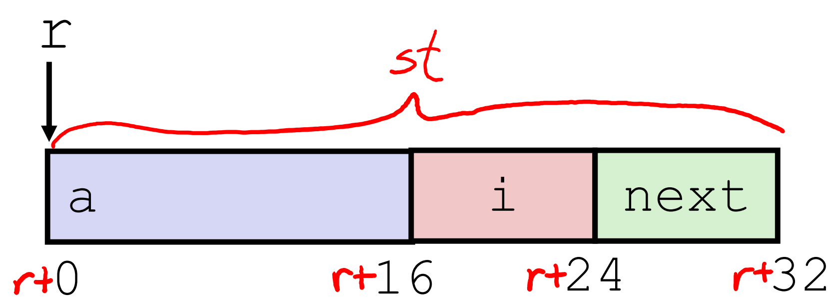
```
class Record { ... }
Record x = new Record();
```

- 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 (Review)

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

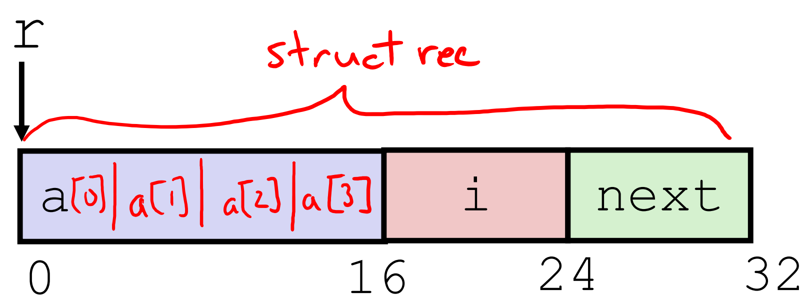
pointer
instance



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

Structure Representation (Review)

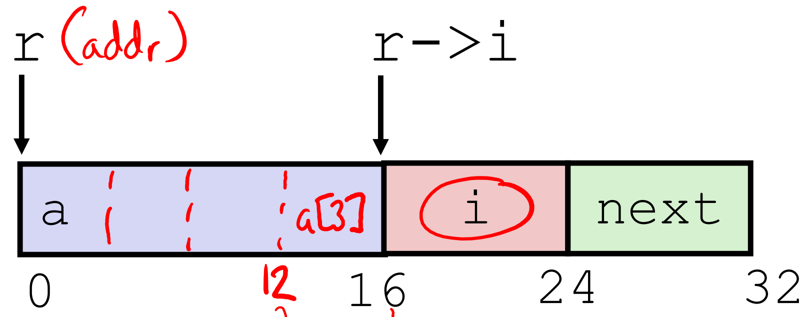
```
struct rec {
①   int a[4];
②   long i;
③   struct rec* next;
} st, *r = &st;
```



- 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
  - No pointer arithmetic; compute as `*(r+offset)`

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

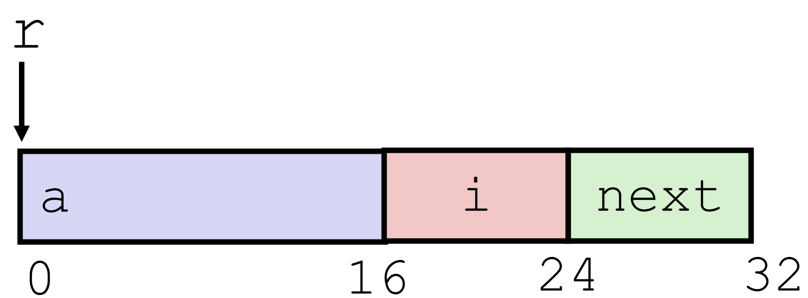
```
# r in %rdi
movq  16(%rdi), %rax
ret
```
long

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

```
# r in %rdi
movl  12(%rdi), %eax
ret
```
int

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);
}
```

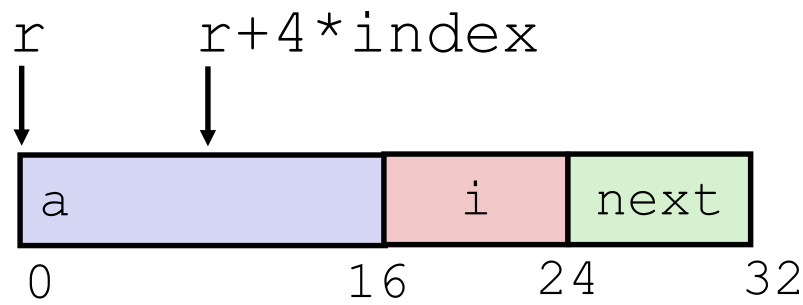
```
  # r in %rdi
  leaq   16(%rdi), %rax
  ret
```

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

```
  # 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])`

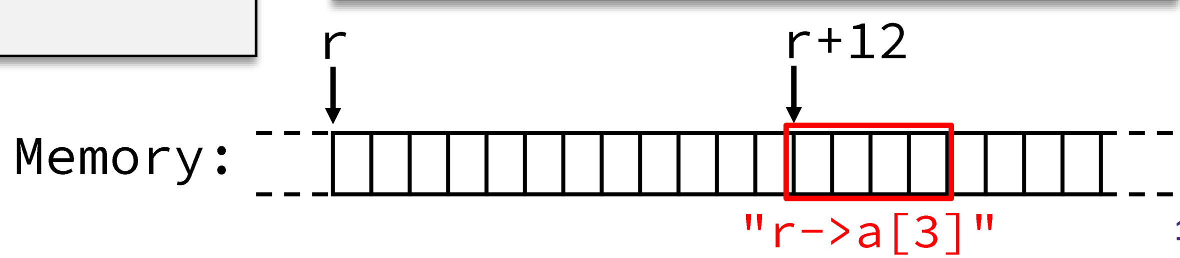
```
  # r in %rdi, index in %rsi
  leaq   (%rdi,%rsi,4), %rax
  ret
```

Struct Pointers

- Pointers store addresses, which all "look" the same
  - Lab 0 Example: 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!

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

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



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

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: $\ldots0_2$
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: $\ldots0000_2$

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.

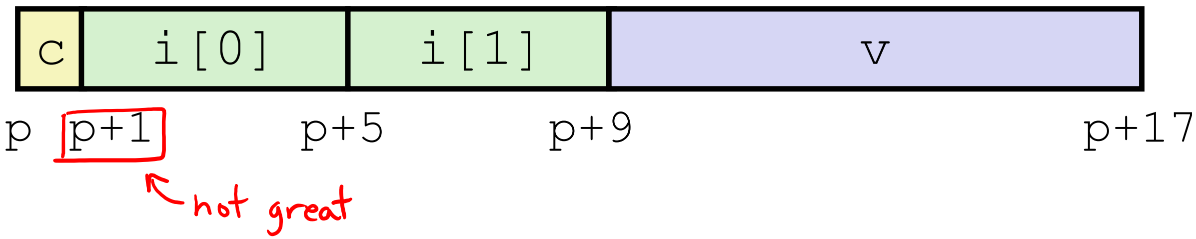
Structures & Alignment (Review)

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

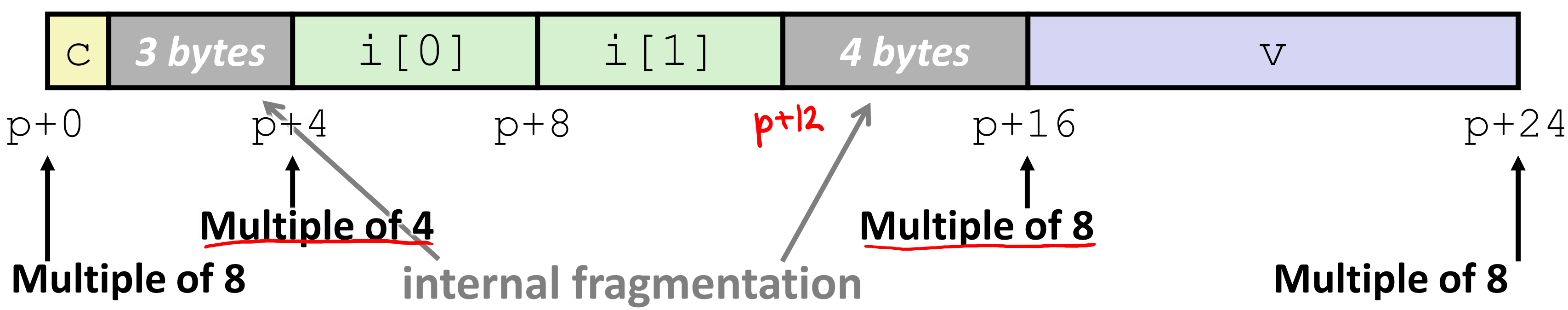
K: ① char → 1; ② int → 4; ③ double → 8

24 B total

- 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;
} st, *p = &st;
```

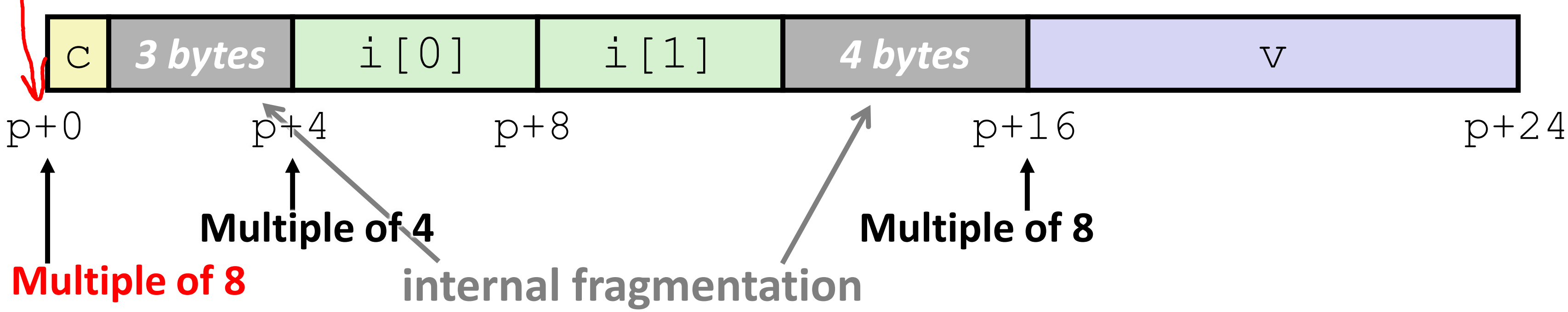
K
1
4
8

- **Within structure:**
  - Must satisfy each element's alignment requirement
- **Overall structure placement**
  - Each structure has alignment requirement K_{max}
    - $\boxed{K_{\text{max}}}$ = Largest alignment of any element
    - Counts array elements individually as elements

$K_{max} = 8$

alignment requirement of starting addr

- **Example:**
  - K_{max} = 8, due to `double` element

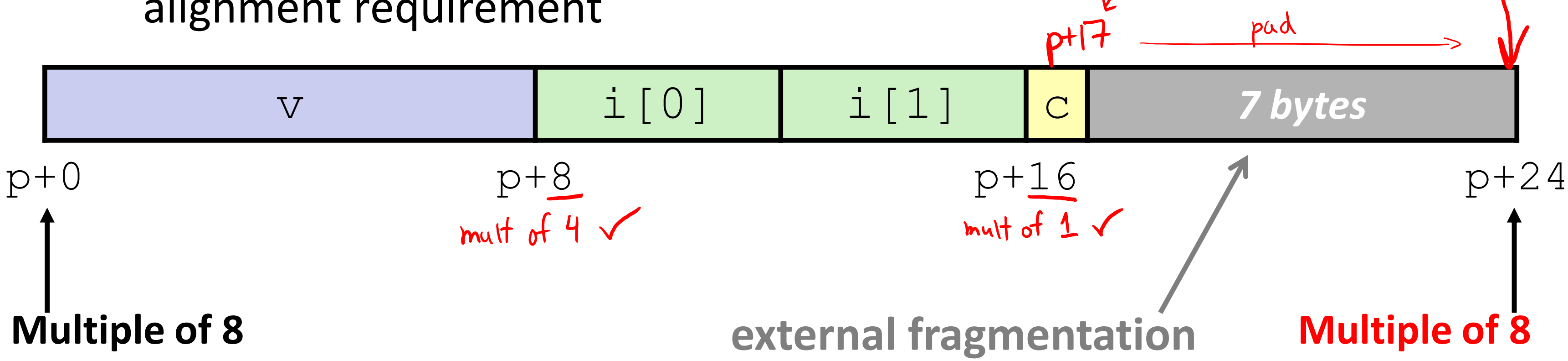


Satisfying Alignment with Structures (2)

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

- 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} = 8
  - Compiler will add padding at end of structure to meet overall structure alignment requirement

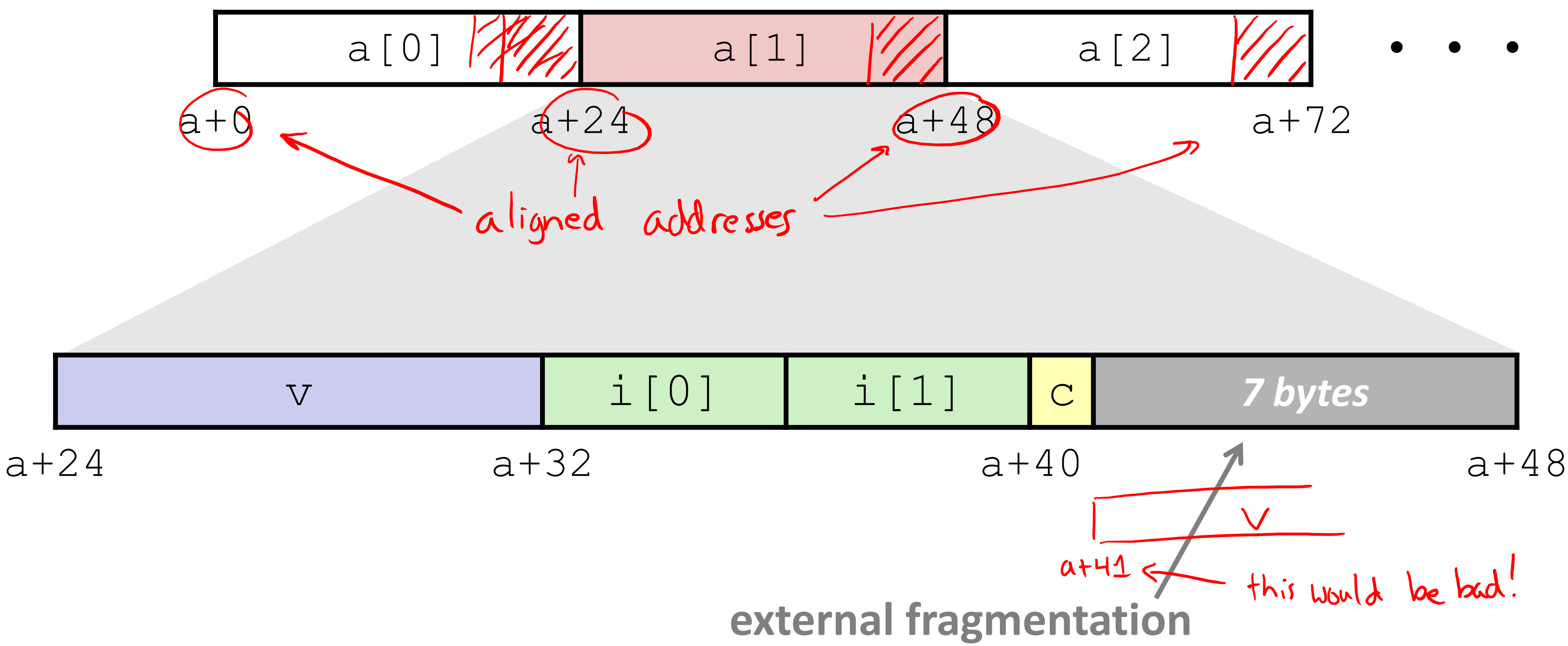
not a mult of 8 X



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 (Review)

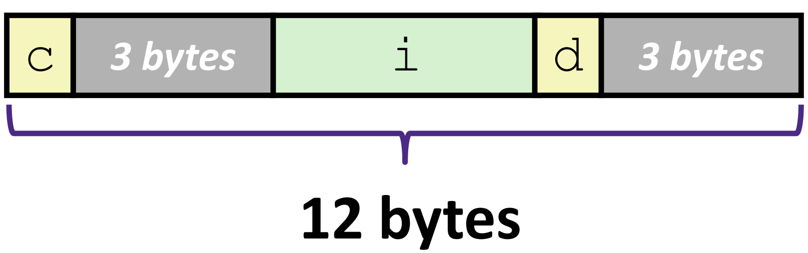
- Compiler will do the following:
  - Maintains declared *ordering* of fields in struct
  - Each ***field*** must be aligned *within* the struct *(may insert padding)*
    - `offsetof` can be used to get actual field offset
  - Overall struct must be ***aligned*** according to largest field
  - Total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

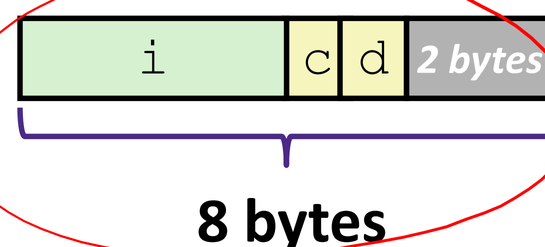
How the Programmer Can Save Space

- 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;
} st;
```

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





same data, but more efficient!

Practice Question

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

```
struct old {      K
  int i;          4
  short s[3];     2
  char* c;        8
  float f;        4
};
```

$K_{max} = 8$

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

could also switch these (internal vs. external frag)

- What is the new size of the struct?

sizeof(struct old) = 32 B   sizeof(struct new) = ______

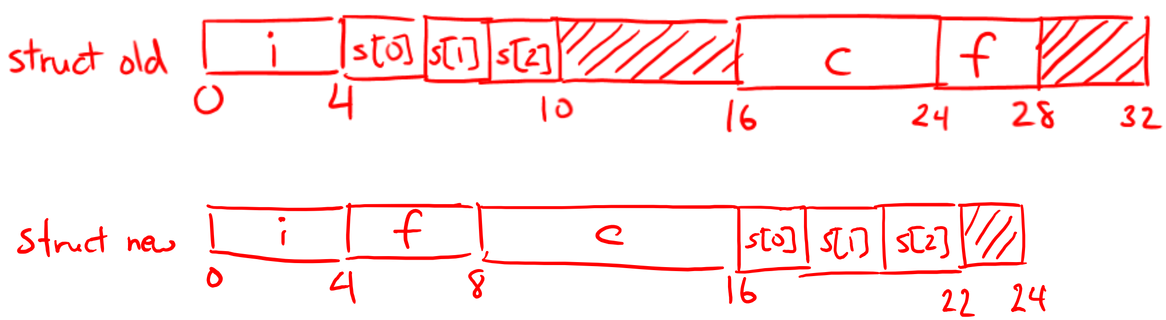
A. 22 bytes

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