Structs & Alignment

CSE 351 Summer 2022

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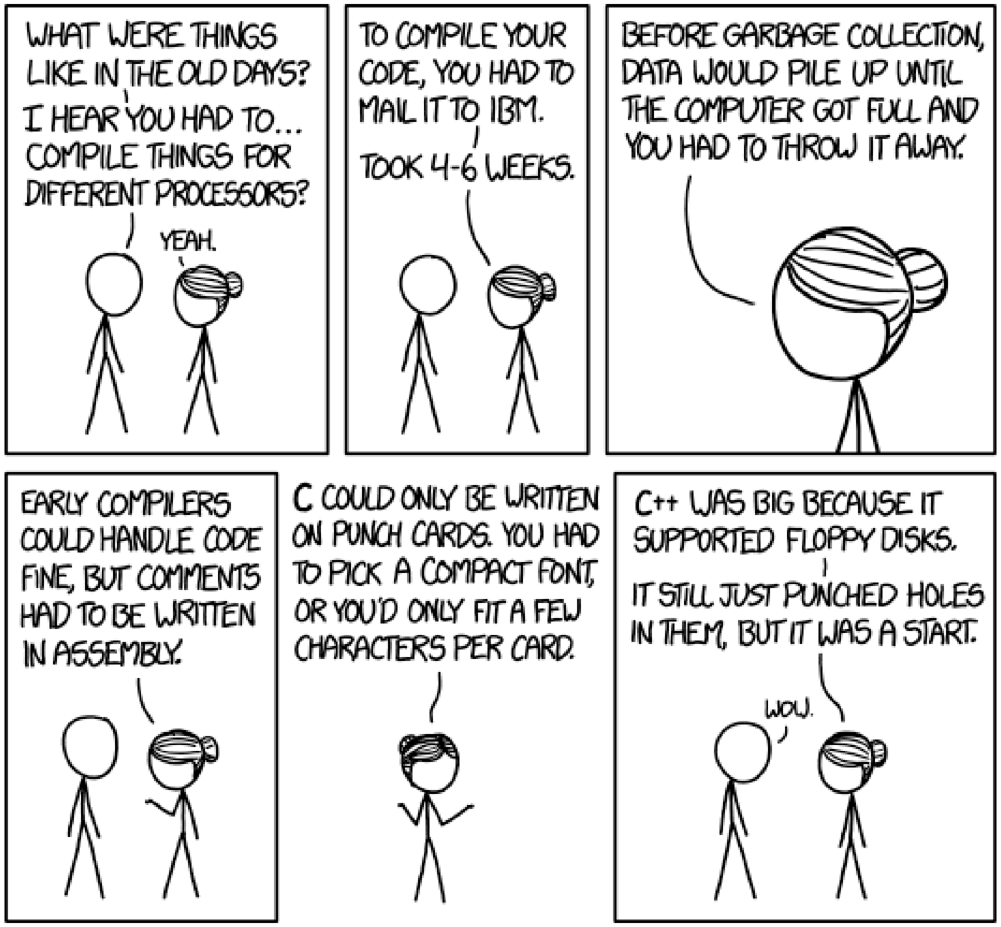

WHAT WERE THINGS LIKE IN THE OLD DAYS?
I HEAR YOU HAD TO... COMPILE THINGS FOR DIFFERENT PROCESSORS?
YEAH.
TO COMPILE YOUR CODE, YOU HAD TO MAIL IT TO IBM.
TOOK 4-6 WEEKS.
BEFORE GARBAGE COLLECTION, DATA WOULD PILE UP UNTIL THE COMPUTER GOT FULL AND YOU HAD TO THROW IT AWAY.
EARLY COMPILERS COULD HANDLE CODE FINE, BUT COMMENTS HAD TO BE WRITTEN IN ASSEMBLY.
C COULD ONLY BE WRITTEN ON PUNCH CARDS. YOU HAD TO PICK A COMPACT FONT, OR YOU'D ONLY FIT A FEW CHARACTERS PER CARD.
C++ WAS BIG BECAUSE IT SUPPORTED FLOPPY DISKS.
IT STILL JUST PUNCHED HOLES IN THEM, BUT IT WAS A START.
WOW.

https://xkcd.com/1755/

Relevant Course Information

- hw13 due Friday (7/29)
  - Can finish after today's lecture
- Lab 3 due Friday (7/29)
- Unit Portfolio 2 released today, due 8/3
  - Based on the topics from lecture 7 through 14 (today)
  - Feedback from the first unit portfolio will be released before the second one is due

Reading Review

- Terminology:
  - Structs: tags and fields, `.` and `->` operators
  - Typedef
  - Alignment, internal fragmentation, external fragmentation
- Questions from the Reading?

Review Questions

tag

$K_{max}=8$

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

fields

two instances

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

16 bytes

- Which of the following statements are syntactically valid (possibly more than one)?

. for struct instances

-> for struct pointers

✓ A. `n1.next = &n2;` (inst ✓ ptr, ptr)

✗ B. `n2->data = 351;` (inst ✗)

✓ C. `n1.next->data = 333;` (inst ✓ ptr ✓ long)

✗ D. `(&n2)->next->next.data = 451;` (ptr ✓ ptr ✓ ptr ✗)

Data Structures in C

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

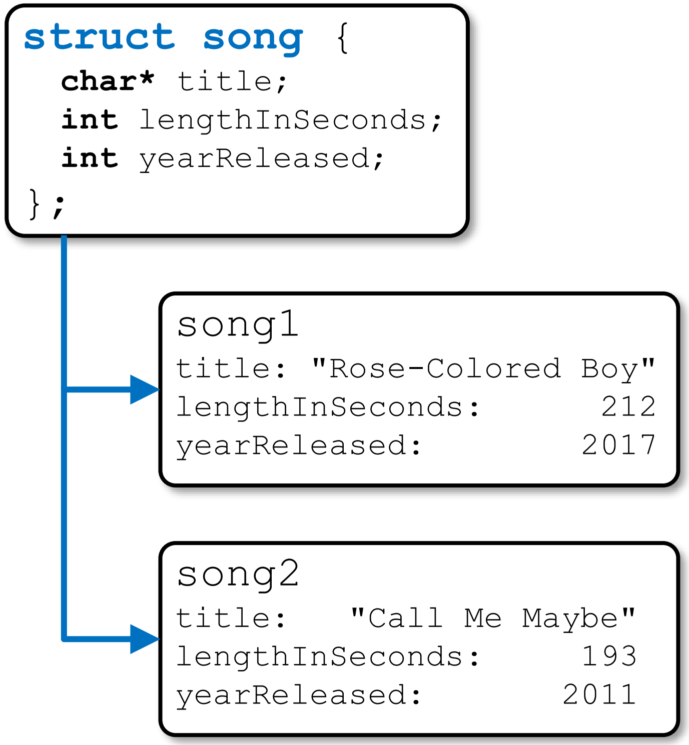
Structs in C (Review)

- 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 = "Rose-Colored Body";
song1.lengthInSeconds = 212;
song1.yearReleased = 2017;

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



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

```
song1
title: "Rose-Colored Boy"
lengthInSeconds:       212
yearReleased:         2017
```

```
song2
title:    "Call Me Maybe"
lengthInSeconds:       193
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.*, $\texttt{typedef }\underbrace{\texttt{unsigned long int}}_{\text{data type}}\ \underbrace{\texttt{uli}}_{\text{alias}}\texttt{;}$

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

no tag / unnamed!

① define struct

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

② typedef

```
typedef struct nm name;
name n1;
```

combined:

```
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

Size = **32** 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 (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:

① dereference (get instance)
② access field

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

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`

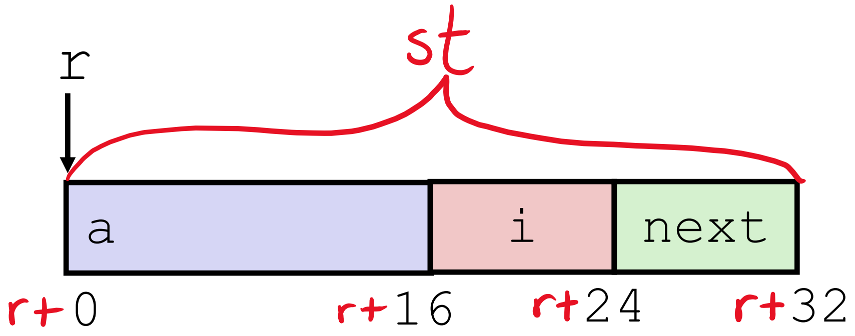
- In Java, almost everything is a pointer ("*reference*") to an object
  - Cannot declare variables or fields that are structs or arrays
  - Always a *pointer* to a struct or array
  - So every Java variable or field is ≤ 8 bytes (but can point to lots of data)

Structure Representation (Review)

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

instance

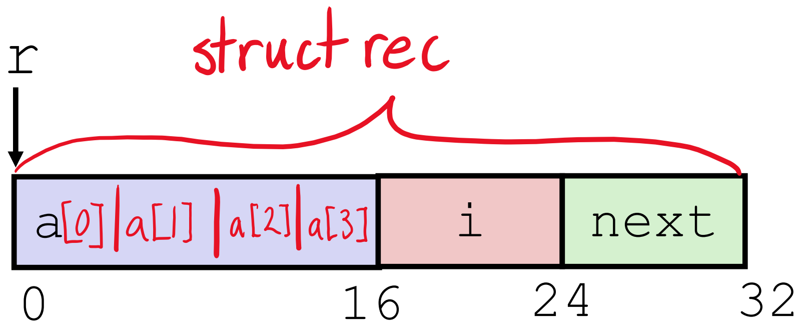
pointer



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

Structure Representation (Review)

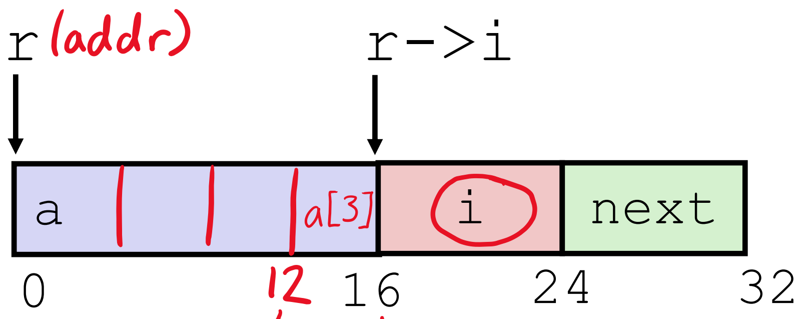
```
struct rec {
  ① int a[4];
  ② long i;
  ③ struct rec* next;
} st, *r = &st;
```



- Structure represented as block of memory
  - Big enough to hold all 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;
}
```

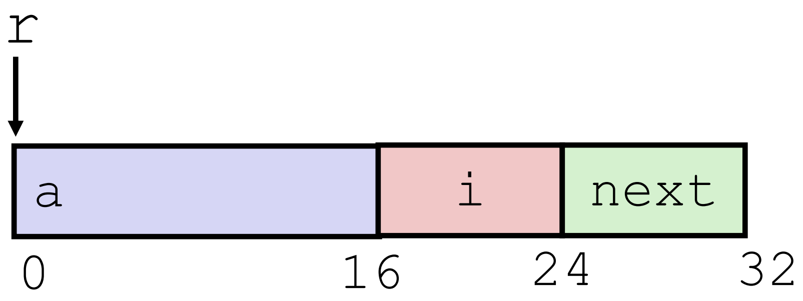
```
  # r in %rdi
  movq  16(%rdi), %rax
  ret  long
```

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

```
  # r in %rdi
  movl  12(%rdi), %rax
  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);
}
```

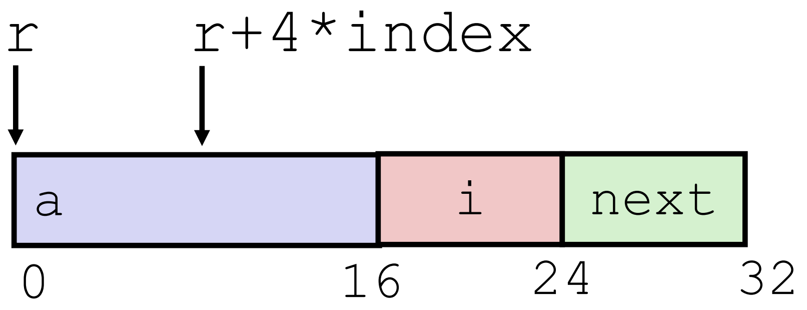
```
  # r in %rdi
  leaq  16(%rdi), %rax
  ret
```

```
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];
}
```

$\underline{\texttt{\&r->a[index]}} \rightarrow$ `&(r->a[index])`

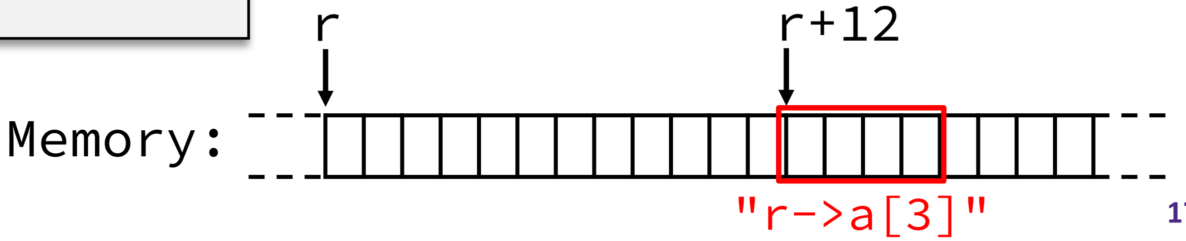
```
  # r in %rdi, index in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

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!

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

lowest $\log_2(k)$ bits should be 0

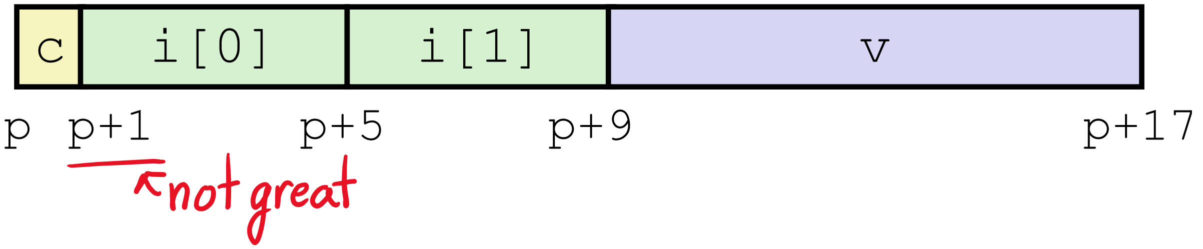
"multiple of" means no remainder when you divide by.
Since K is a power of 2, dividing by K is equivalent to $\gg \log_2(K)$.
No remainder means no weight is "lost" during the shift $\rightarrow$ all zeros in lowest $\log_2(K)$ bits.

Structures & Alignment (Review)

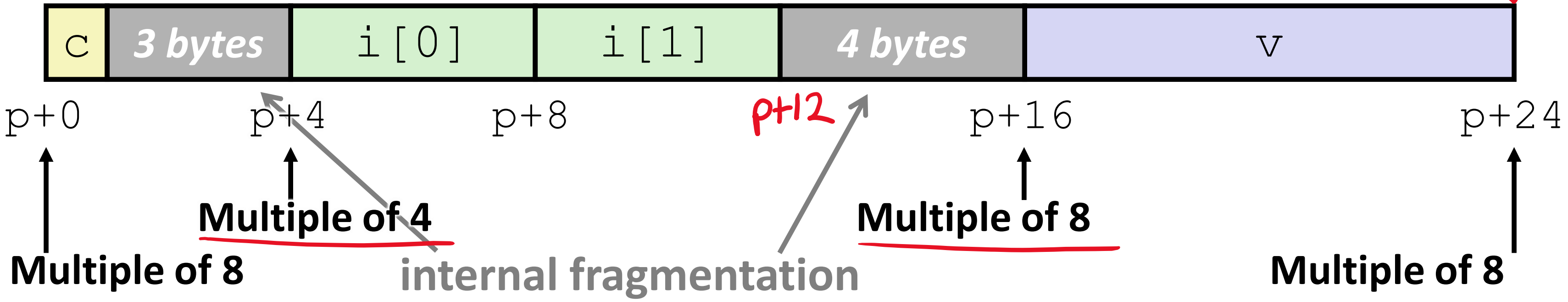
```
struct S1 {      K
  ① char c;      1
  ② int i[2];    4
  ③ double v;    8
} st, *p = &st;
```

24 bytes 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;
```

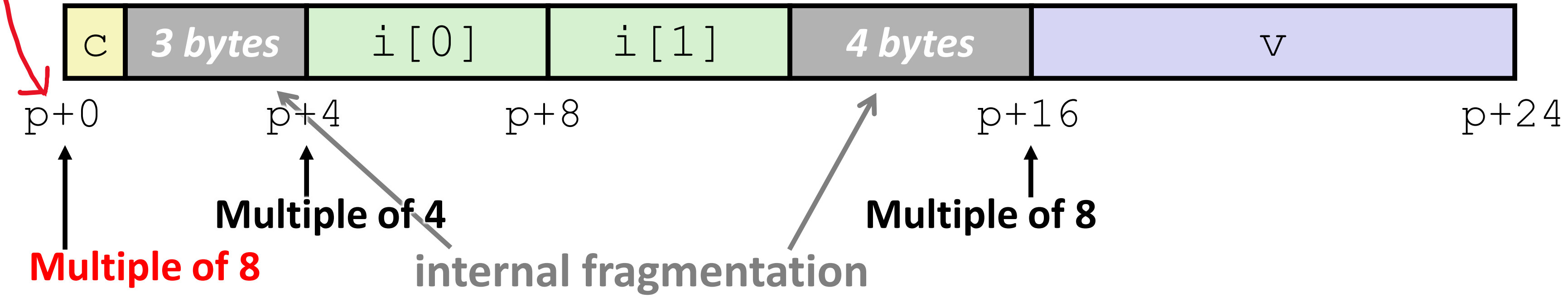
K
1
4
8

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

alignment requirement of starting addr

$K_{max} = 8$

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

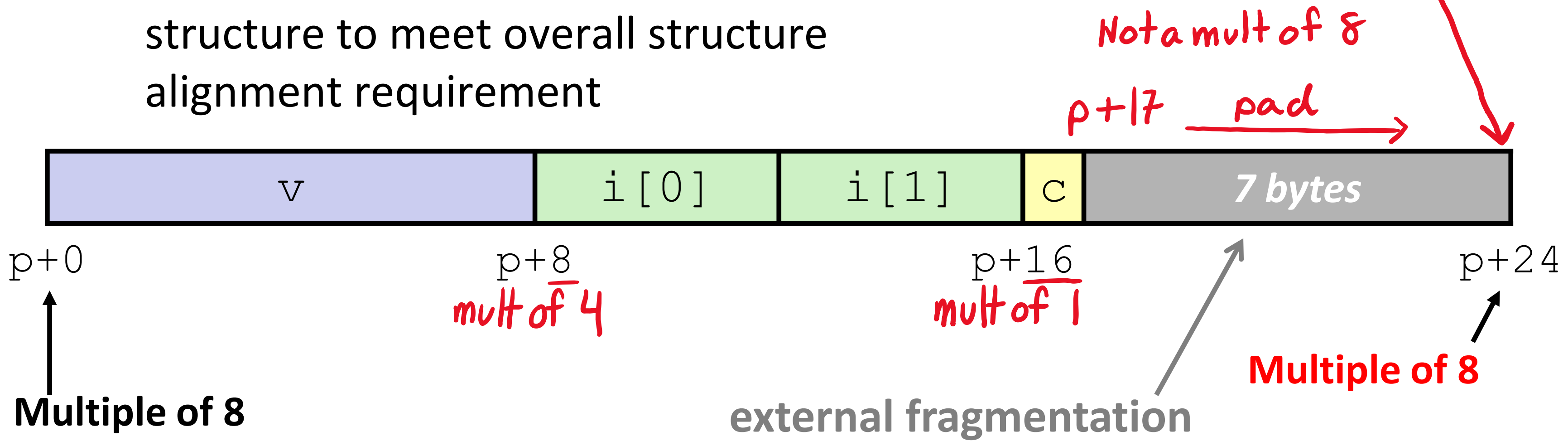


Satisfying Alignment with Structures (2)

- 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;
```

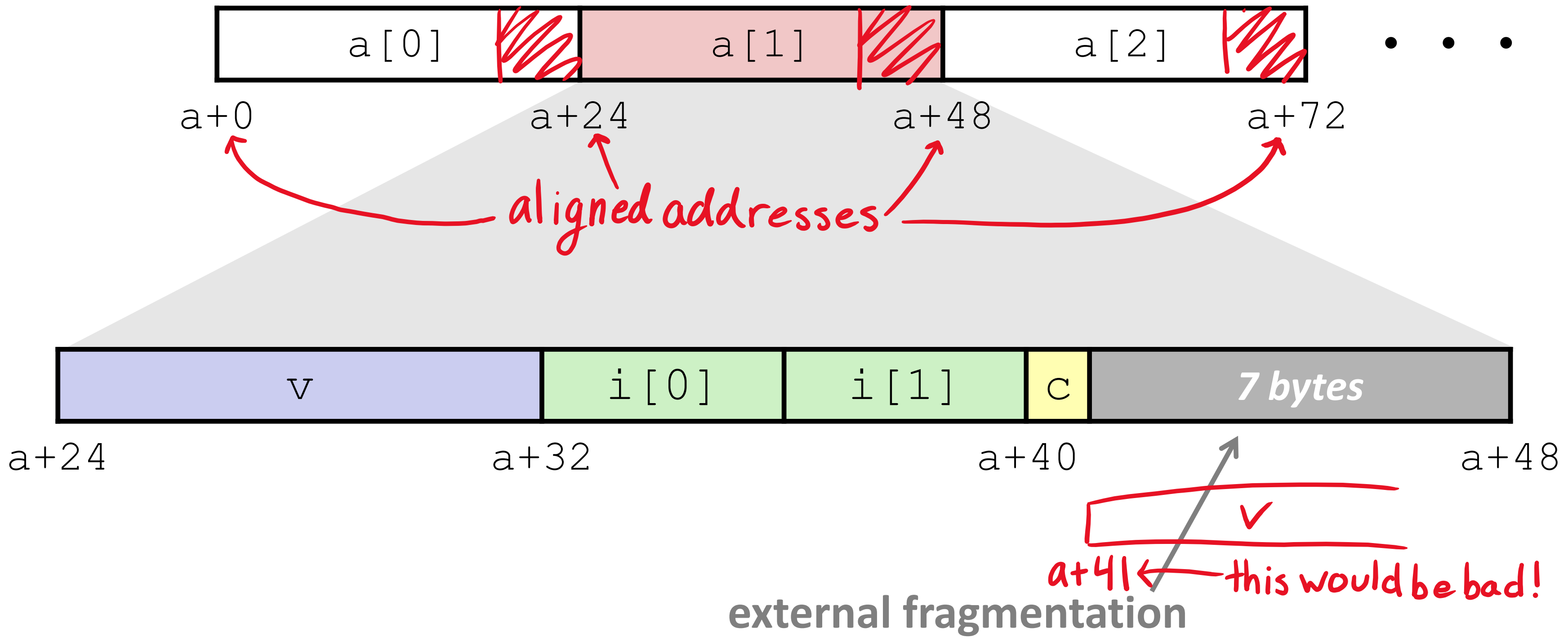
- For largest alignment requirement $K_{\max}$, overall structure size must be multiple of $K_{\max}$ = 8
  - Compiler will add padding at end of structure to meet overall structure alignment requirement



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 (Review)

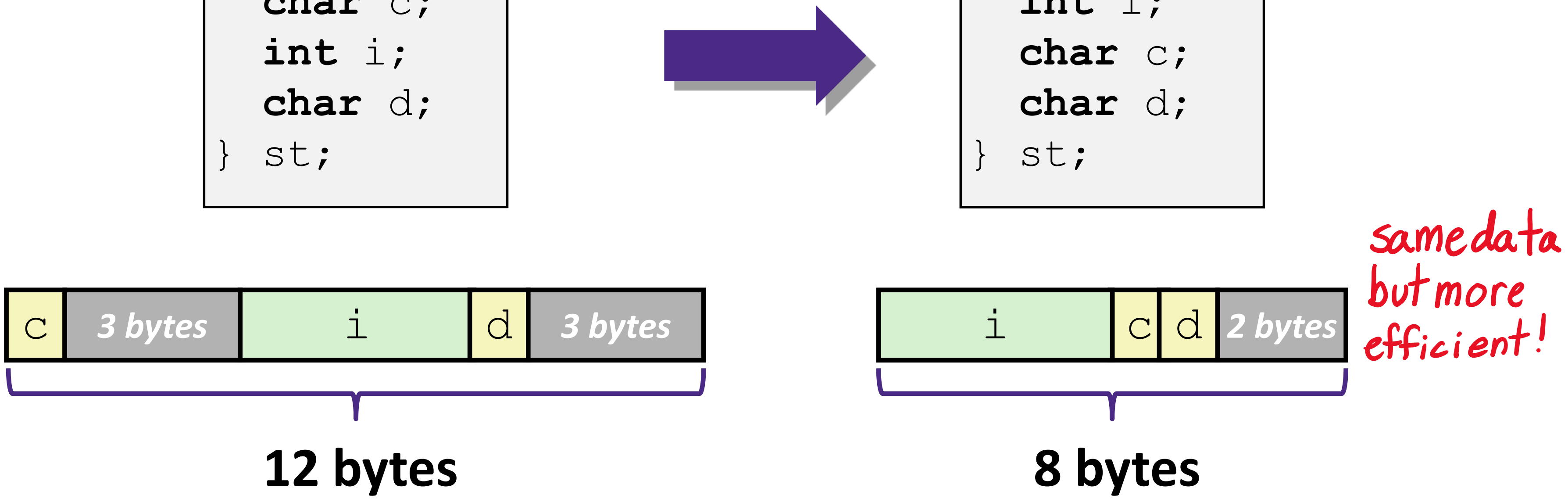
- Compiler will do the following:
  - Maintains declared *ordering* of fields in struct
  - Each ***field*** must be aligned *within* the struct *(may insert padding)*
    - `offsetof` can be used to get actual field offset
  - Overall struct must be ***aligned*** according to largest field
  - Total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



Practice Question

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

K
4
2
8
4
$K_{max}=8$

```
struct old {
  int i;

  short s[3];

  char* c;

  float f;
};
```

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

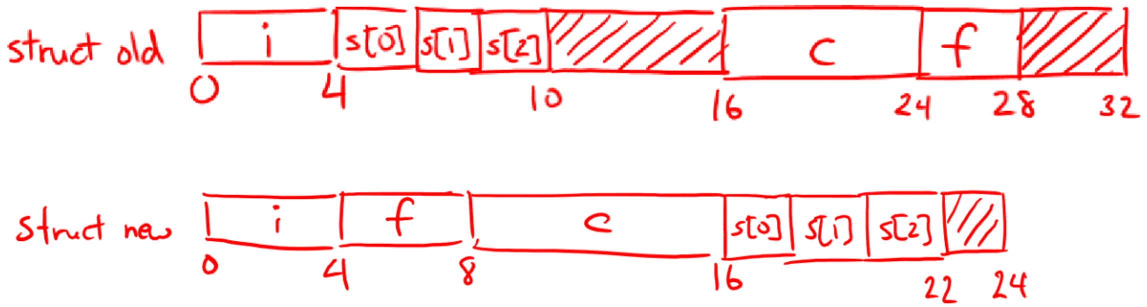
A. 22 bytes

[✓ 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