Structs & Alignment
CSE 351 Autumn 2021

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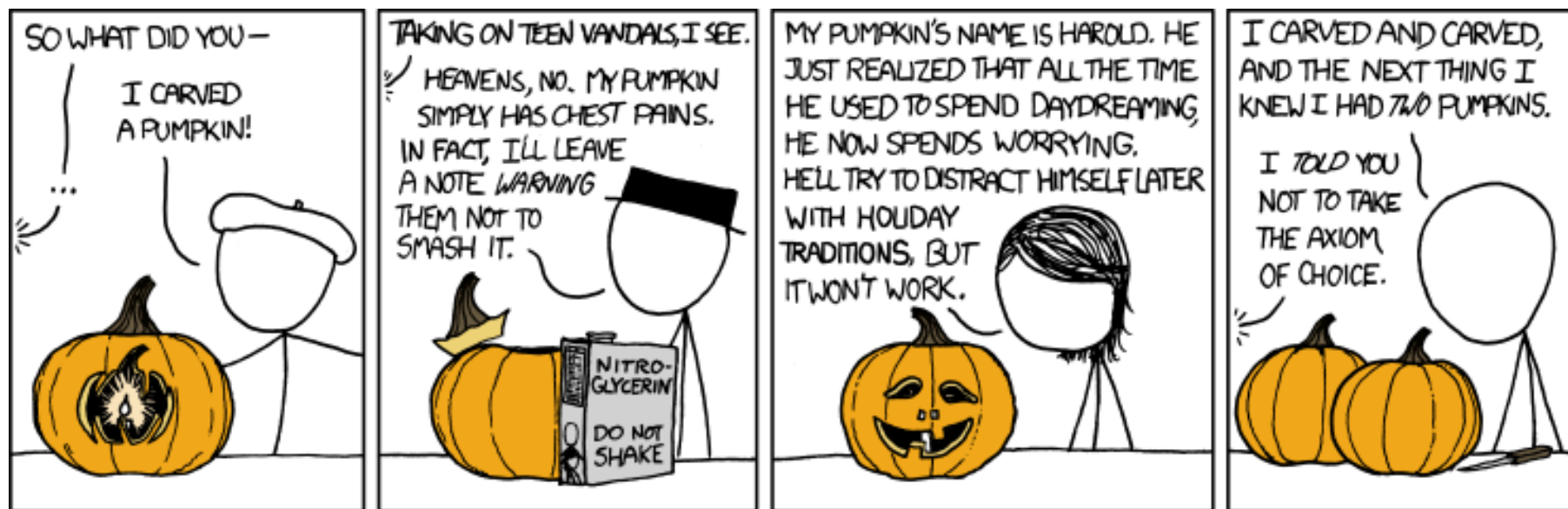
Relevant Course Information

❖ Lab 2 due tonight

❖ Lab 3 released next Monday (11/1)

  ▪ A shorter lab, due Friday, 11/12

❖ hw13 due next Wednesday (11/3)

❖ **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, please) 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;  } fields
} n1, n2;
```

$K_{max} = 8$

two instances

❖ How much space does (in bytes) does an instance of
   `struct ll_node` take?   **16 B**

❖ Which of the following statements are syntactically
   valid?
   • for struct instances, -> for struct pointers
        (inst)   (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 song {
  char* title;
  int lengthInSeconds;
  int yearReleased;
};
```

song1
title: "drivers license"
lengthInSeconds: 242
yearReleased: 2021

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 {           ← this is the data type (like int)
    /* fields */
} st, *p = &st;
```

Typedef in C (Review)

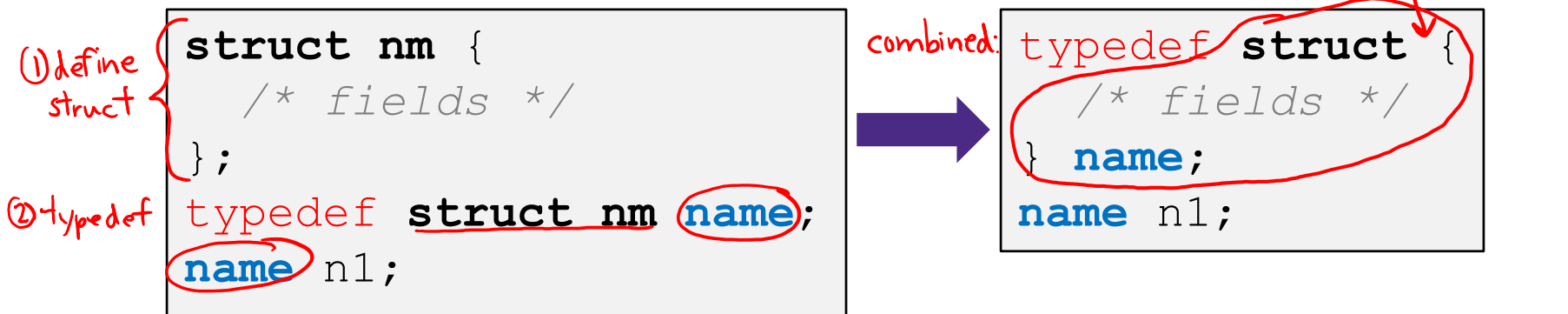❖ A way to create an *alias* for another data type:
   `typedef <data type> <alias>;`

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

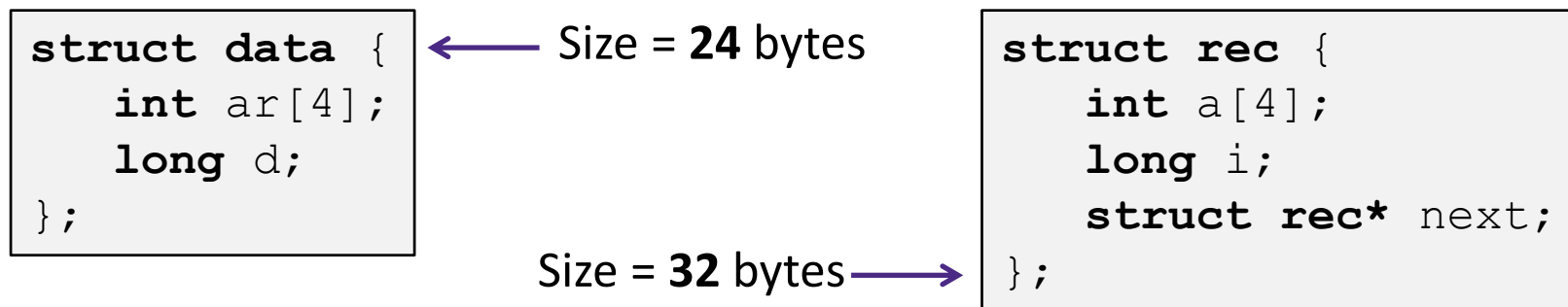   ▪ *e.g.,* `typedef unsigned long int uli;`

   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)

❖ 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;` ① dereference (get instance)
  ② access field
- 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

r

st

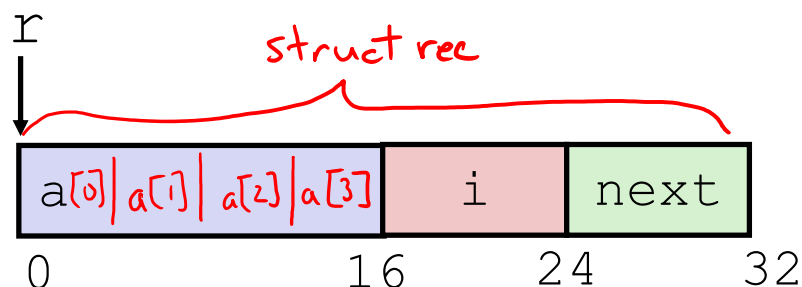| a		i	next
r+0   r+16   r+24   r+32
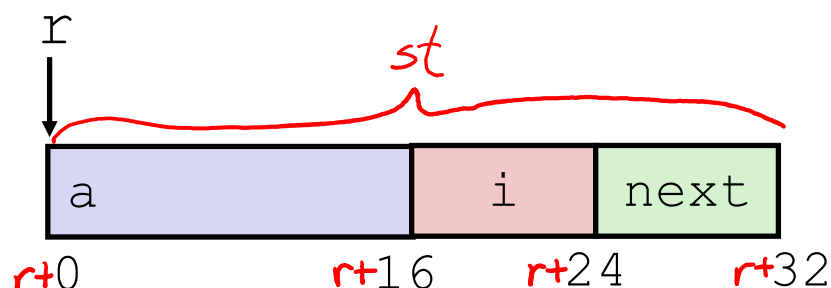
❖ Characteristics

- 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;
```


- ❖ 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;
```

r (addr)   r->i

a   a[3]   i   next

0   12 16   24   32
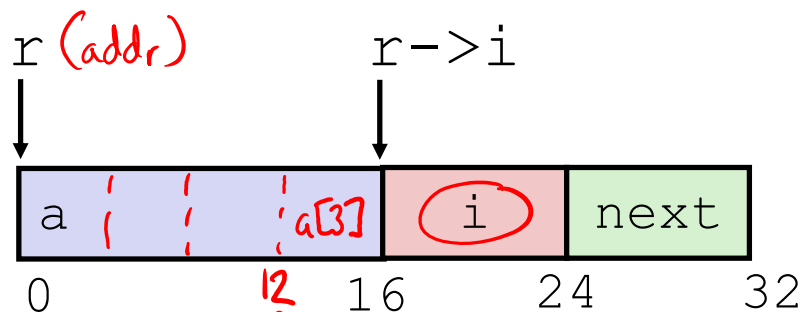
❖ Compiler knows the *offset* of each member

- 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;
```
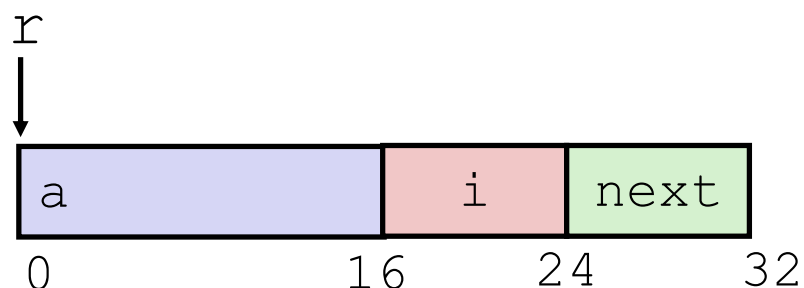


```
long* addr_of_i(struct rec* r)
{
    return &(r->i);
}
```

```
# r in %rdi

leaq  16(%rdi), %rax
ret
```

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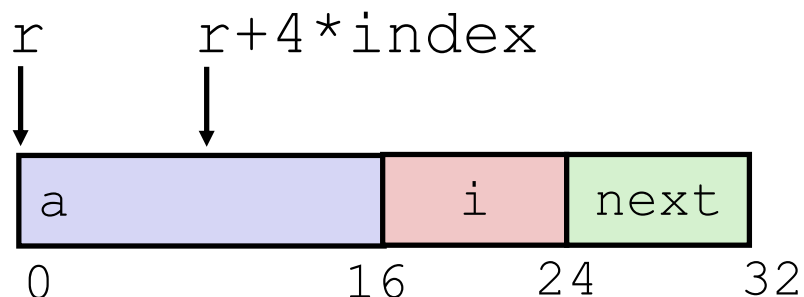
```
# r in %rdi

leaq  24(%rdi), %rax
ret
```

Generating Pointer to Array Element

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

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
```

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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 `ints` 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]"
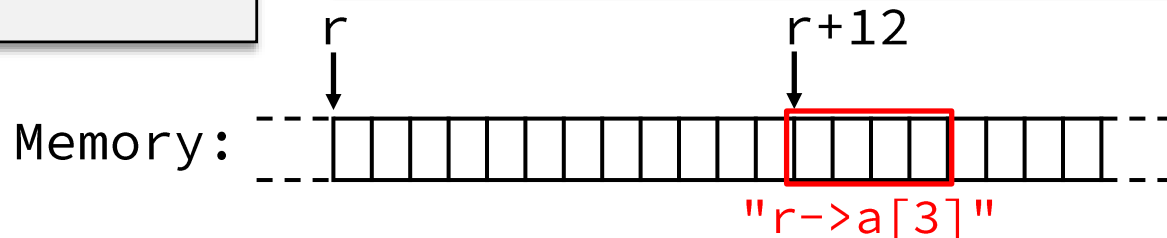
Alignment Principles

❖ 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)

  - 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
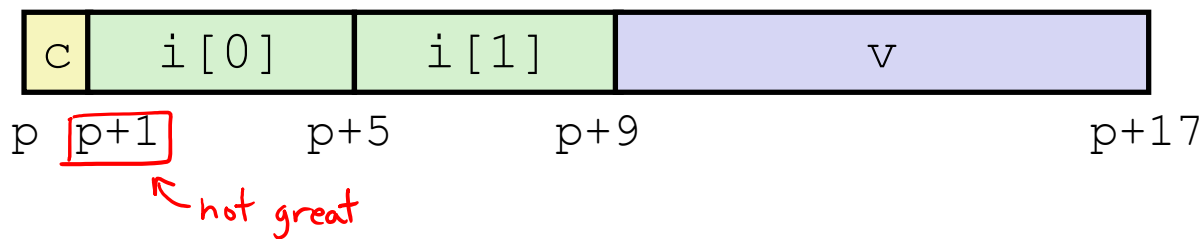
❖ Aligned addresses for data types:

K	Type	Addresses
1	char	No restrictions
2	short	Lowest bit must be zero: ...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

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

Structures & Alignment (Review)

❖ <u>Unaligned</u> Data

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

c	i[0]	i[1]	v

p p+1 *← not great*   p+5   p+9   p+17

24 B total

❖ 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+12*   p+16   p+24

Multiple of 8

Multiple of 4 — *internal fragmentation* — **Multiple of 8**

Multiple of 8
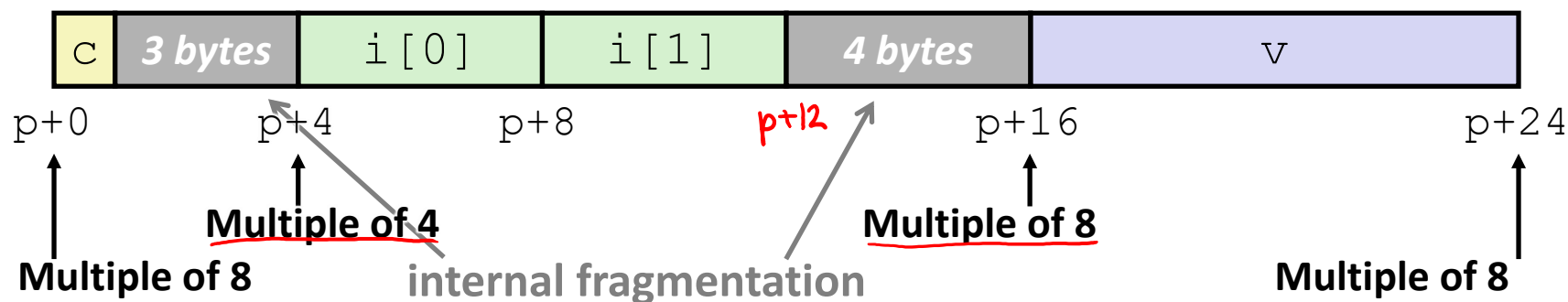
Satisfying Alignment with Structures (1)

❖ <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}
  - $\boxed{K_{max}}$ = Largest alignment of any element
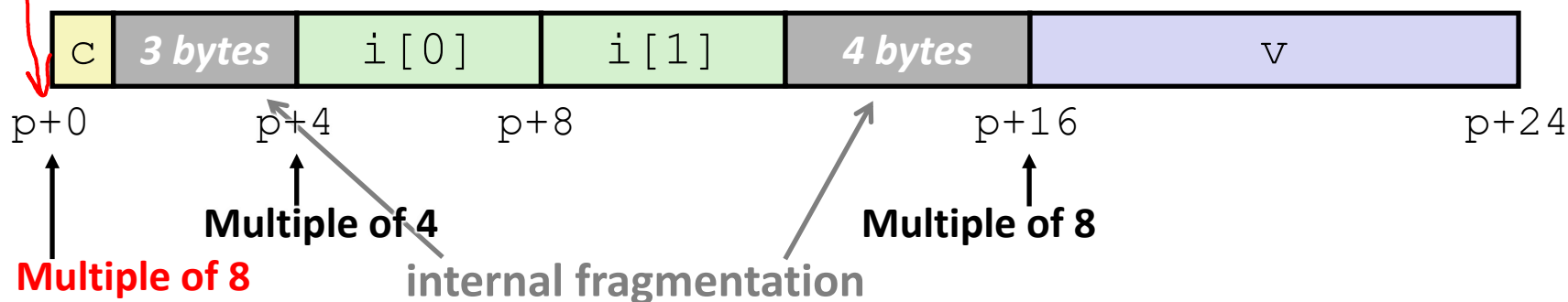 - Counts array elements individually as elements

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

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

internal fragmentation

Satisfying Alignment with Structures (2)

❖ Can find offset of individual fields
   using `offsetof()`

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

   ▪ Need to `#include <stddef.h>`

   ▪ <u>Example</u>: `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
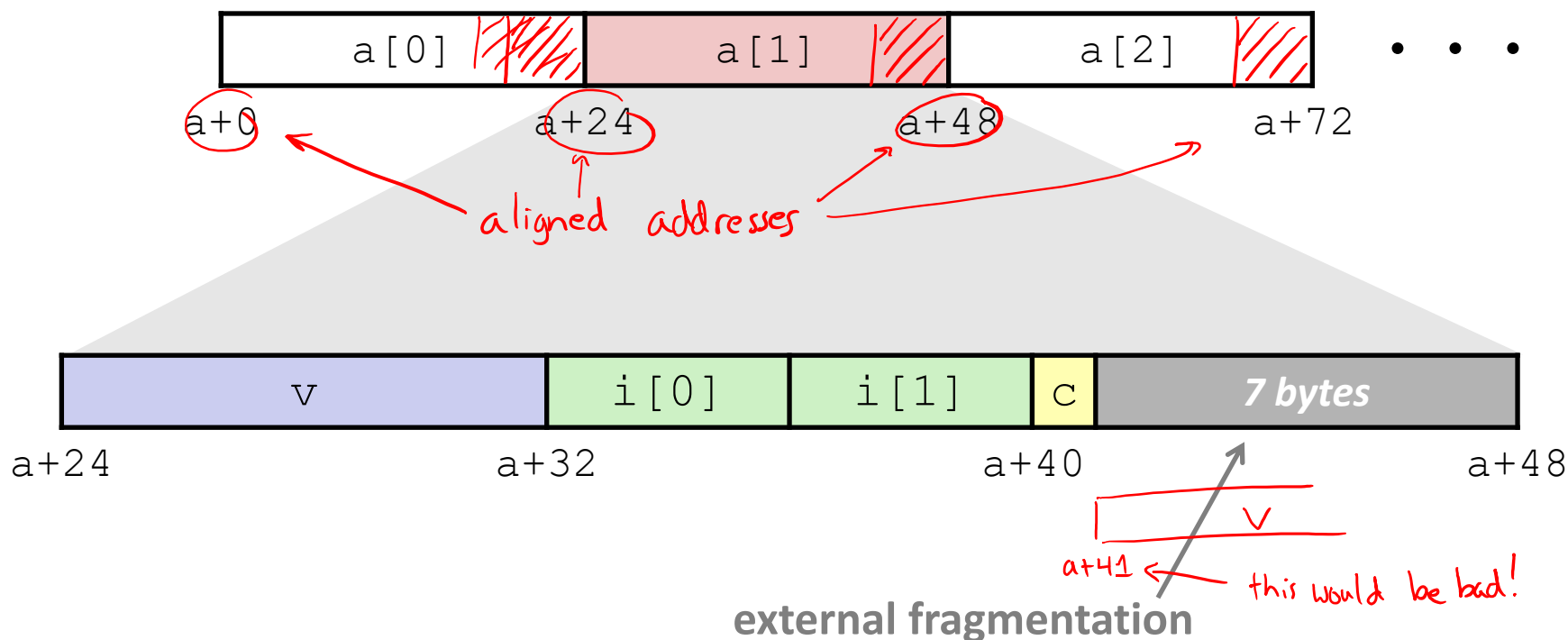   structure to meet overall structure
     alignment requirement

not a mult of 8 ✗

p+17   *pad*

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

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

mult of 4 ✓   *mult of 1* ✓

Multiple of 8   **external fragmentation**   **Multiple of 8**
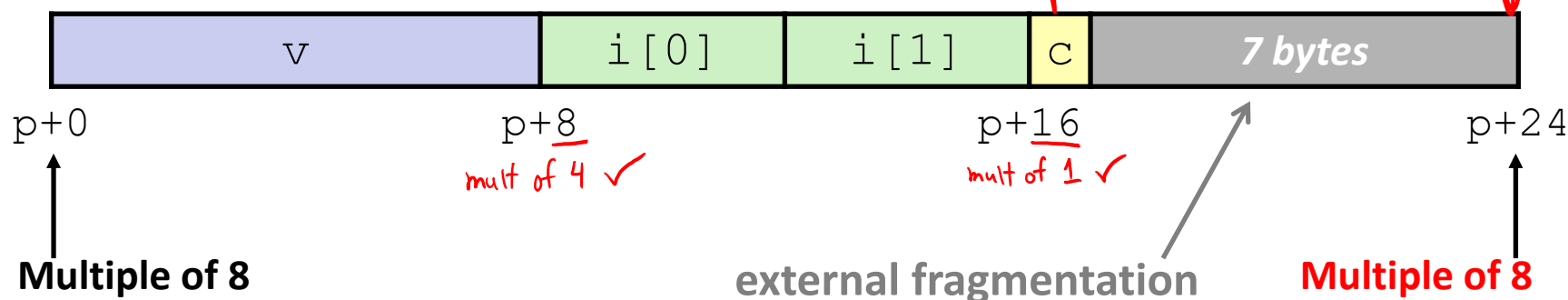
Arrays of Structures

❖ 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

aligned addresses

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

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

a+41

this would be bad!

external fragmentation

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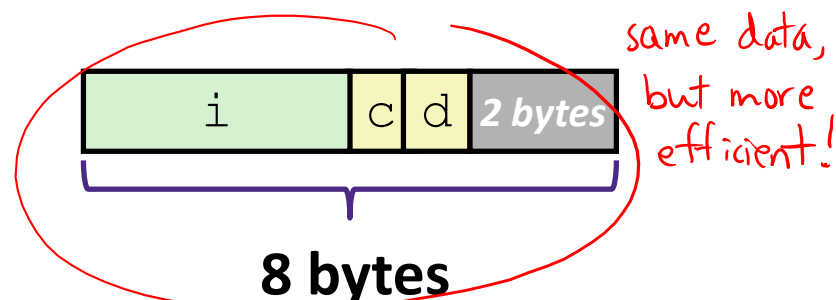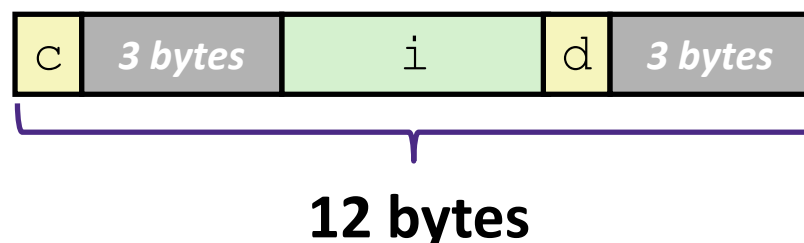 - `sizeof` should be used to get true size of structs

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;
```

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

12 bytes

| i | c | d | 2 bytes |

same data, but more efficient!

8 bytes

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?

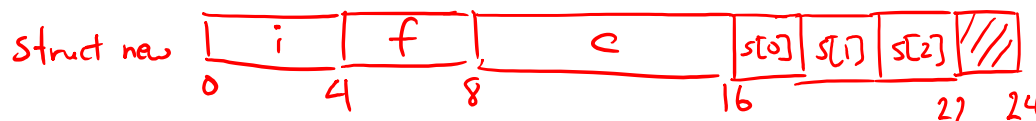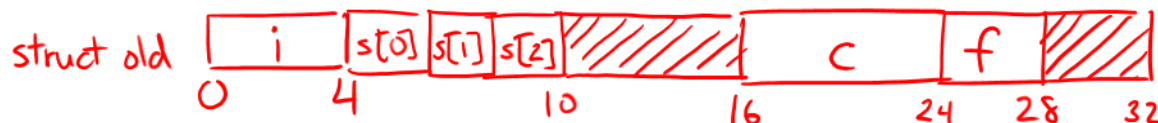`sizeof(struct old)` = 32 B   `sizeof(struct new)` = _____

A. **22 bytes**

B. **24 bytes**

C. **28 bytes**

D. **32 bytes**

E. **We're lost…**

struct old: i (0) | s[0] s[1] s[2] (4) /// (10) | c (16) | f (24) /// (28) 32

struct new: i (0) | f (4) | c (8) | s[0] s[1] s[2] (16) /// 22 24

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