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();
```

Assembly language:

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

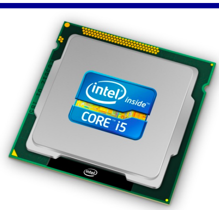
Machine code:

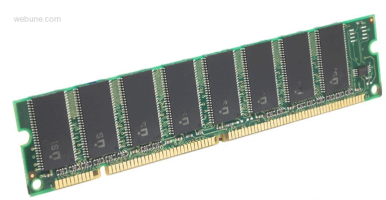
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:





- Memory & data
- Integers & floats
- Machine code & C
- x86 assembly
- Procedures & stacks
- **Arrays & structs**
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

Data Structures in Assembly

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

Review: Structs in Lab 0

```
// Use typedef to create a type: FourInts
typedef struct {
  int a, b, c, d;
} FourInts;    // Name of type is "FourInts"

int main(int argc, char* argv[]) {

 FourInts f1;  // Allocates memory to hold a FourInts
               // (16 bytes) on stack (local variable)
 f1.a = 0;     // Assign the first field in f1 to be zero

 FourInts* f2; // Declare f2 as a pointer to a FourInts

 // Allocate space for a FourInts on the heap,
 // f2 is a "pointer to"/"address of" this space.
 f2 = (FourInts*)malloc(sizeof(FourInts));
 f2->b = 17;          // Assign the second field to be 17
…
}
```

Syntax for structs without typedef

```
struct rec {            // Declares the type "struct rec"
    int a[4];           // Total size = _______ bytes
    long i;
    struct rec *next;
};
struct rec r1; // Allocates memory to hold a struct rec
               // named r1, on stack or globally,
               // depending on where this code appears

struct rec *r; // Allocates memory for a pointer
r = &r1;       // Initializes r to "point to" r1
```

Minor syntax note: Need that semicolon after a struct declaration (easy to forget)

Syntax for structs *with* typedef

```
struct rec {            // Declares the type "struct rec"
    int a[4];           // Total size = _______ bytes
    long i;
    struct rec *next;
};
struct rec r1; // Allocates memory to hold a struct rec
               // named r1, on stack or globally,
               // depending on where this code appears

struct rec *r; // Allocates memory for a pointer
r = &r1;       // Initializes r to "point to" r1
```

```
typedef struct rec {
    int a[4];
    long i;
    struct rec *next;
} Record; // typedef creates new name for 'struct rec'
          // (that doesn't need 'struct' in front of it)
Record r2; // Declare variable of type 'Record'
           // (really a 'struct rec')
```

More Structs Syntax

```
struct rec {            // Declares the type "struct rec"
    int a[4];
    long i;
    struct rec *next;
};
struct rec r1; // Declares r1 as a struct rec
```

Equivalent to:

```
struct rec {            // Declares the type "struct rec"
    int a[4];
    long i;
    struct rec *next;
} r1;                   // Declares r1 as a struct rec
```

More Structs Syntax: Pointers

```
struct rec {            // Declares the type "struct rec"
    int a[4];
    long i;
    struct rec *next;
};
struct rec *r; // Declares r as pointer to a struct rec
```

Equivalent to:

```
struct rec {            // Declares the type "struct rec"
    int a[4];
    long i;
    struct rec *next;
} *r;                   // Declares r as pointer to a struct rec
```

Accessing Structure Members

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

- **Given an instance of the struct, we can use 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:

  - Using `*` and `.` operators: `(*r).i = val;`
  - Or, use `->` operator for short: `r->i = val;`

- **The pointer is the address of the first byte of the structure**
  - Access members with offsets

Java side-note

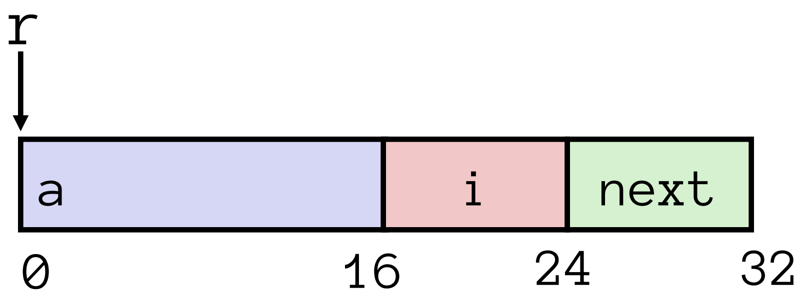
Java:

```
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`, i.e., `(*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

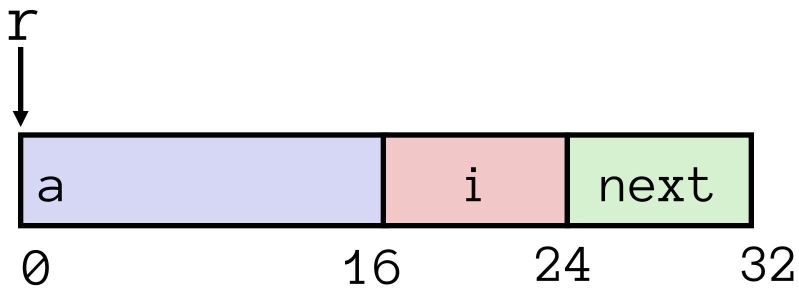
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
} *r;
```



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

Structure Representation

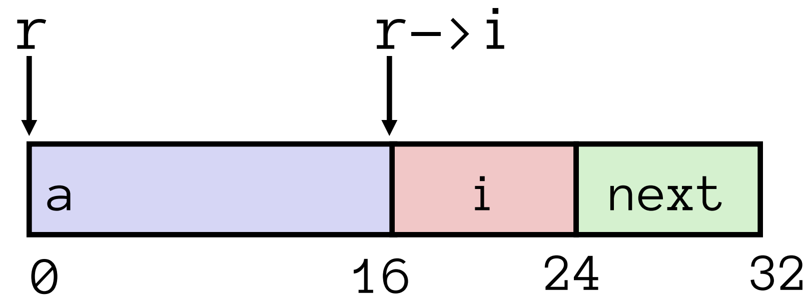
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
} *r;
```



- **Structure represented as block of memory**
  - Big enough to hold all of the fields
- **Fields ordered according to declaration order**
  - Even if another ordering could yield a more compact representation
- **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;
} *r;
```



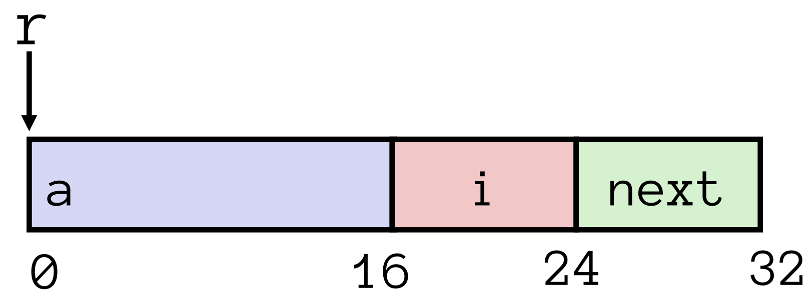
- **Compiler knows the *offset* of each member within a struct.**
  - Compute as: `*(r+offset)`

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

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

Exercise: Generating Pointer to Structure Member

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




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

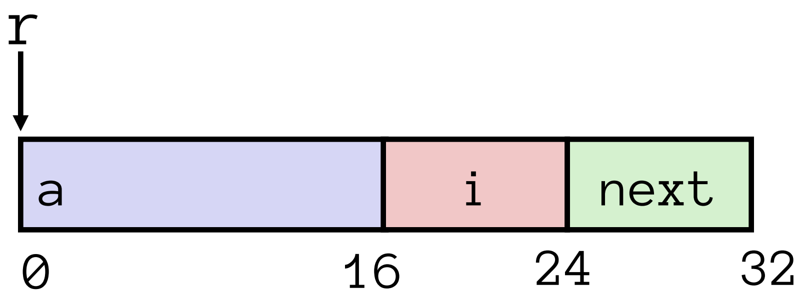
```
  # r in %rdi
  ______      ______,%rax
  ret
```

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

```
  # r in %rdi
  ______      ______,%rax
  ret
```

Exercise: Generating Pointer to Structure Member

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




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

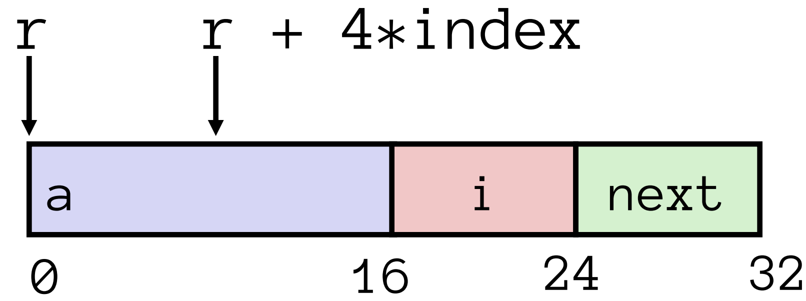
```
  # r in %rdi
  leaq  16(%rdi), %rax
  ret
```

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

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

Generating Pointer to Structure Member

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



- **Generating Pointer to Array Element**
  - Offset of each structure member determined at compile time
  - Compute as: **`r + 4*index`**

```
int* find_address_of_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

- **For good memory system performance, Intel recommends data be aligned**
  - However the x86-64 hardware will work correctly regardless of alignment of data.
- ***Aligned* means:**
  - Any primitive object of K bytes must have an address that is a multiple of K.
- **This means we could expect these types to have starting addresses that are the following multiples:**

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, pointers`	Lowest 3 bits zero: $\ldots000_2$
16	`long double`	Lowest 4 bits zero: $\ldots0000_2$

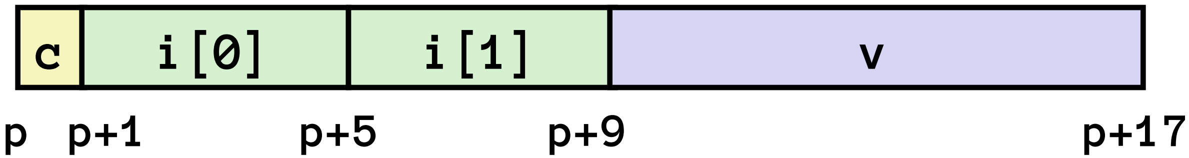
Alignment Principles

- **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 4 or 8 bytes (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)

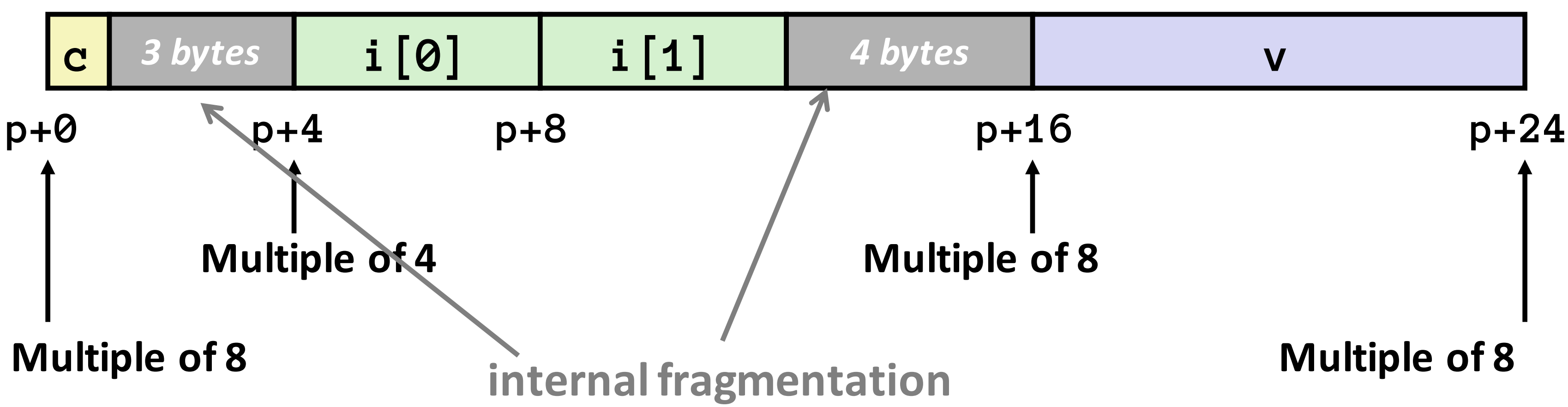
Structures & Alignment

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

- **Unaligned Data**



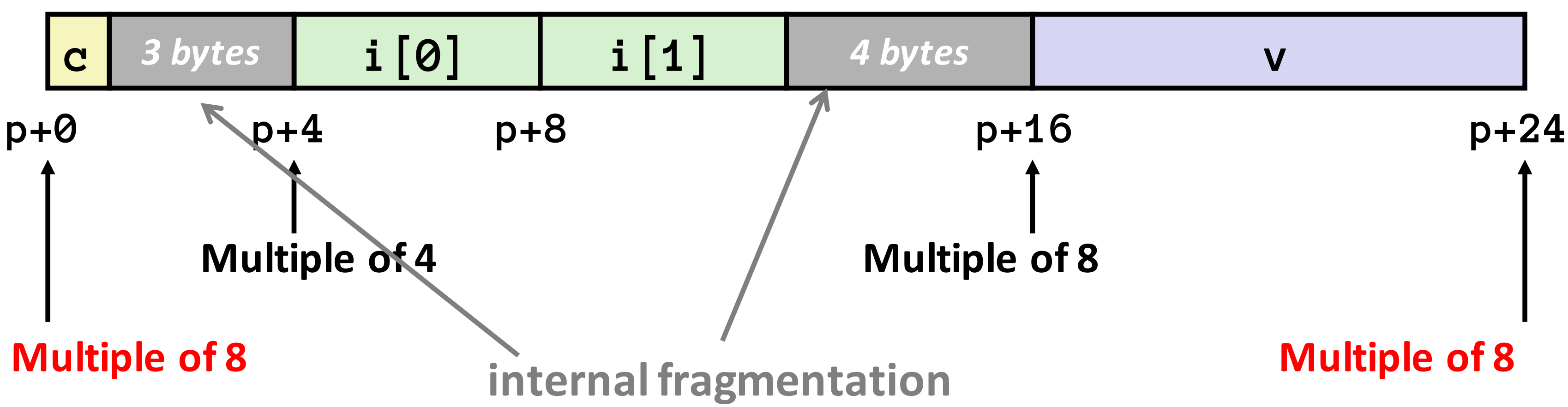
- **Aligned Data**
  - Primitive data type requires ***K*** bytes
  - Address must be multiple of ***K***



Satisfying Alignment with Structures

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

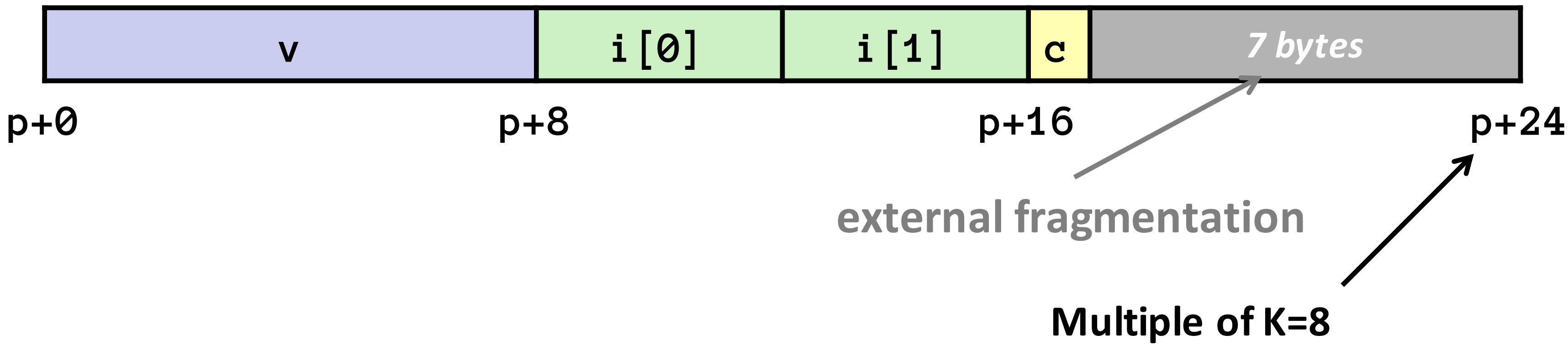
- **Within structure:**
  - Must satisfy each element's alignment requirement
- **Overall structure placement**
  - Each structure has alignment requirement **K**
    - **K** = Largest alignment of any element
  - **Initial address of structure & structure length must be multiples of K**
- **Example:**
  - K = 8, due to `double` element



Satisfying Alignment Requirements: Another Example

- For largest alignment requirement K
- Overall structure size must be multiple of K
- Compiler will add padding at end of structure to meet overall structure alignment requirement

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



Alignment of Structs

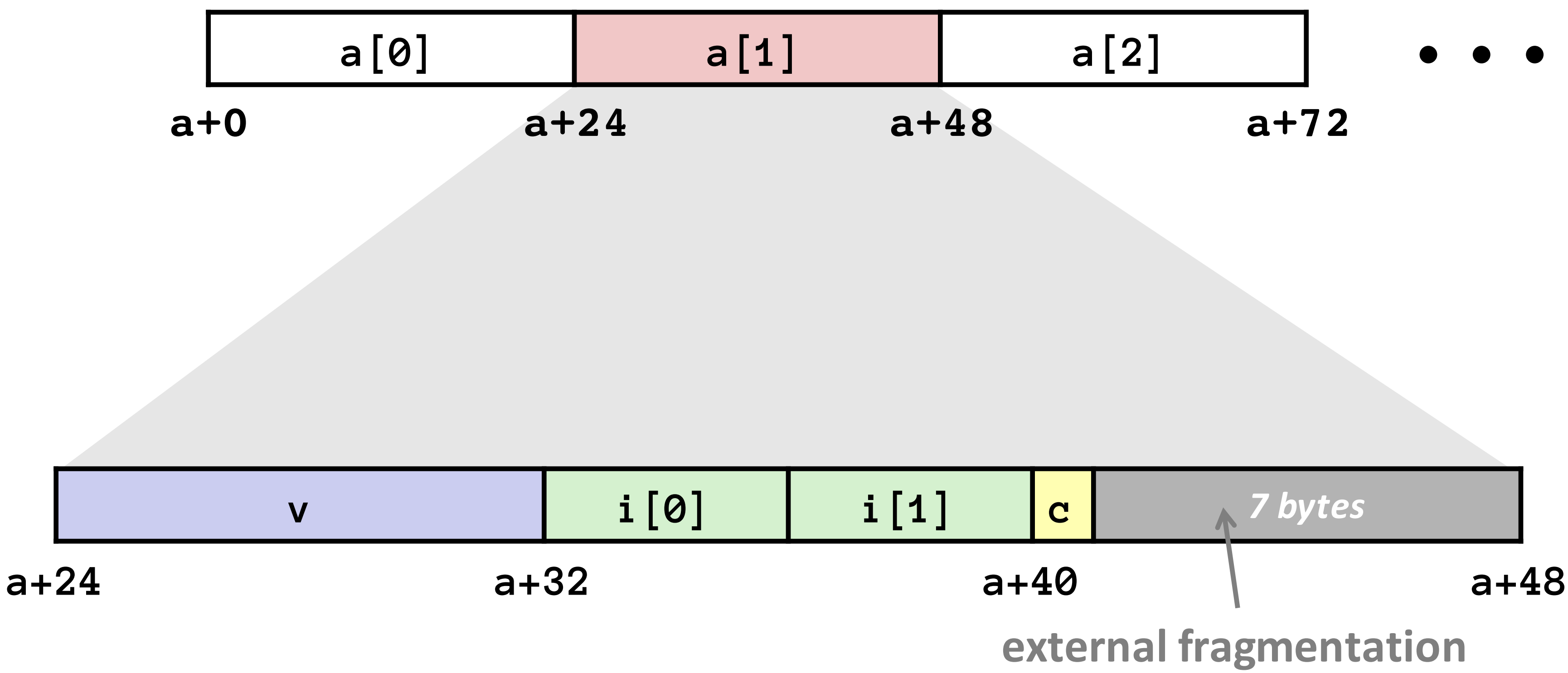
- **Compiler:**
  - Maintains declared *ordering* of fields in struct
  - Each ***field*** must be aligned *within* the struct *(may insert padding)*
    - `offsetof` can be used to find the actual offset of a field
  - Overall struct must be ***aligned*** according to largest field
  - Total struct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

Arrays of Structures

- Overall structure length multiple of K
- Satisfy alignment requirement for every element in array

Create an array of ten S2 structs called "a"

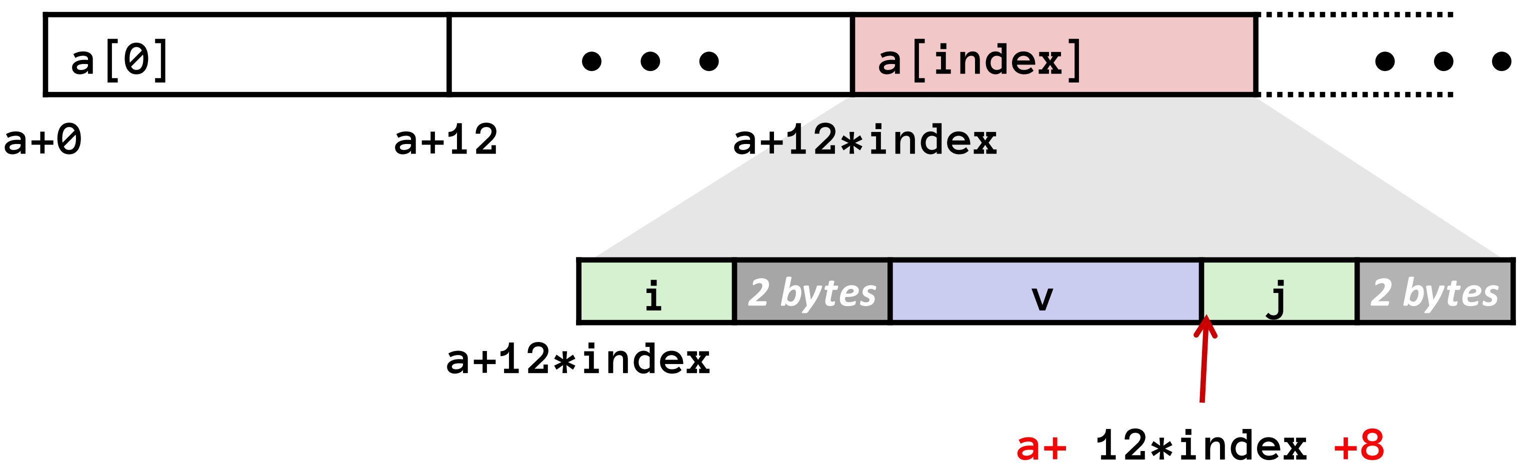
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

- **Compute start of array element as: 12*index**
  - `sizeof(S3) = 12`, including alignment padding
- **Element `j` is at offset 8 within structure**
- **Assembler gives offset a+8**

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```




```
short get_j(int index)
{
  return a[index].j;
}
```

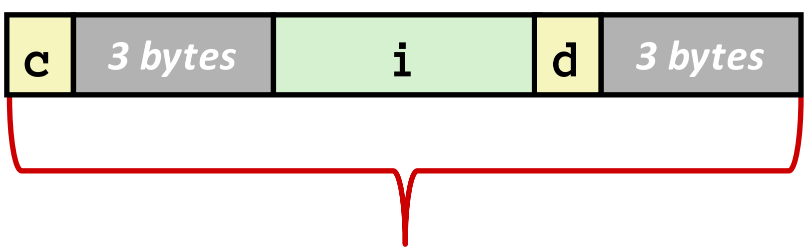
```
# %rdi = index
leaq (%rdi,%rdi,2),%rax # 3*index
movzwl a+8(,%rax,4),%eax
```

How the Programmer Can Save Space

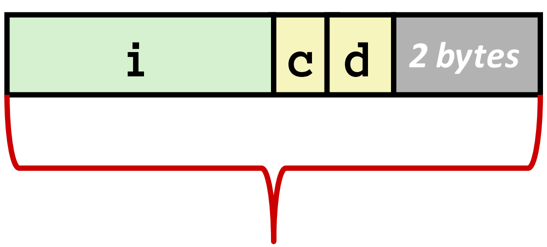
- **Compiler must respect order elements are declared in**
  - Sometimes the programmer can save space by declaring large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```



12 bytes



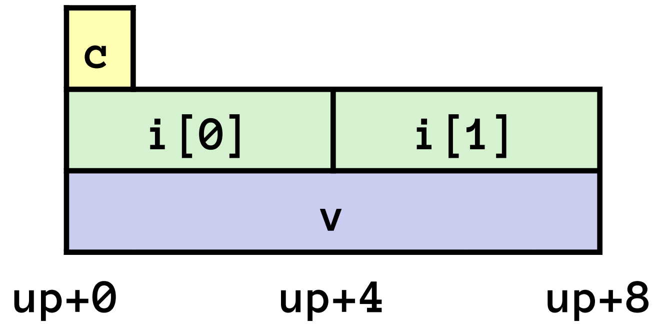
8 bytes

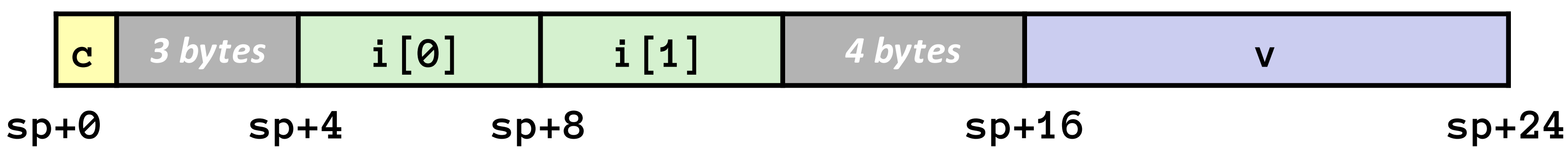
Unions

- Only allocates enough space for the largest element in union
- Can only use one member at a time

```
union U {
  char c;
  int i[2];
  double v;
} *up;
```

```
struct S {
  char c;
  int i[2];
  double v;
} *sp;
```





What Are Unions Good For?

- **Unions allow the same region of memory to be referenced as different types**
  - Different "views" of the same memory location
  - Can be used to circumvent C's type system (bad idea and technically not guaranteed to work)
- **Better idea: use a struct inside a union to access some memory location either as a whole or by its parts**
- **But watch out for endianness at a small scale…**
- **Layout details are implementation/machine-specific…**

```
union int_or_bytes {
    int i;
    struct bytes {
      char b0, b1, b2, b3;
    }
}
```

Unions For Embedded Programming

```
typedef union
{
   unsigned char byte;
   struct {
      unsigned char reserved:4;
      unsigned char b3:1;
      unsigned char b2:1;
      unsigned char b1:1;
      unsigned char b0:1;
   } bits;
} hw_register;

hw_register reg;
reg.byte = 0x3F;          // 00111111₂
reg.bits.b2 = 0;          // 00111011₂
reg.bits.b3 = 0;          // 00110011₂
unsigned short a = reg.byte;
printf("0x%X\n", a);    // output: 0x33
```

(Note: the placement of these fields and other parts of this example are implementation-dependent)

Summary

- **Arrays in C**
  - Contiguous allocations of memory
  - No bounds checking
  - Can usually be treated like a pointer to first element
  - Aligned to satisfy every element's alignment requirement
- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- **Unions**
  - Provide different views of the same memory location