Roadmap

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

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
```

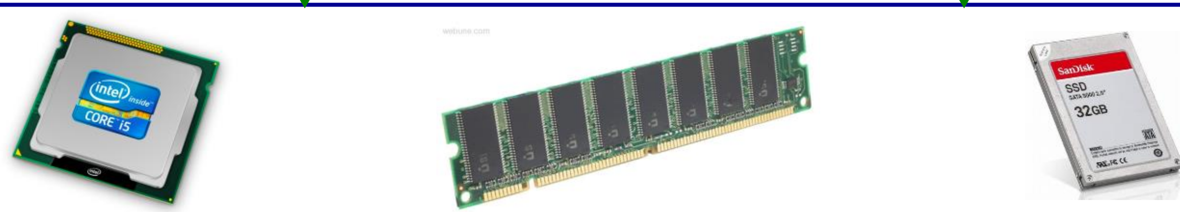
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:



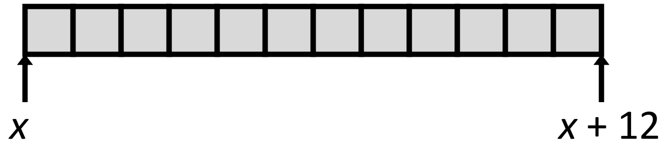
Data Structures in Assembly

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

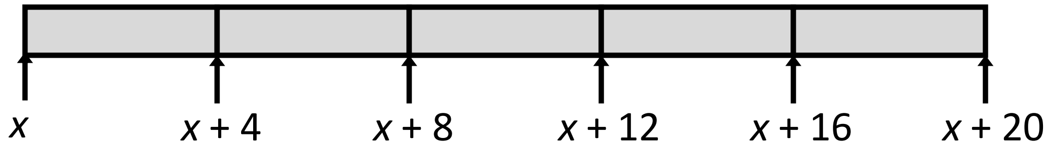
Array Allocation

- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - *Contiguously* allocated region of N * sizeof(T) bytes

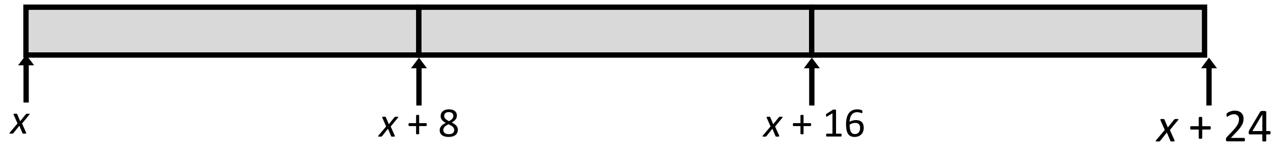
`char mesg[12];`



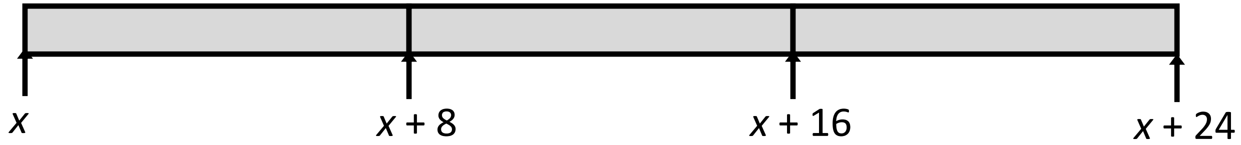
`int val[5];`



`double a[3];`



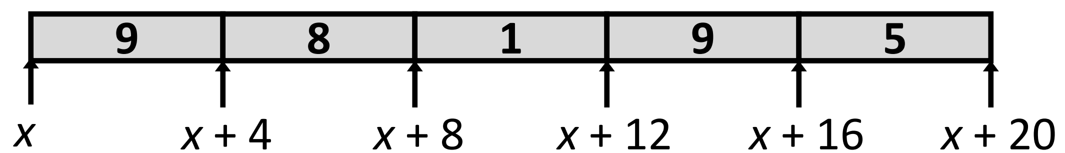
`char* p[3];`
(or `char *p[3];`)



Array Access

- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer to array element 0: Type T*

`int val[5];`

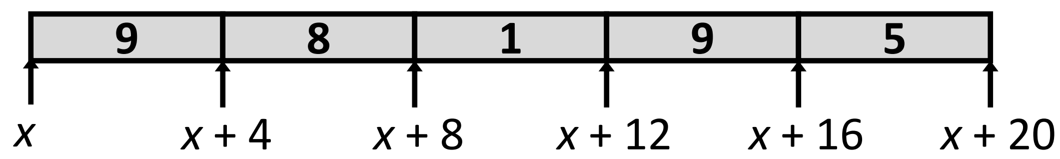


- **Reference Type Value**
  - val[4]
  - val
  - val+1
  - &val[2]
  - val[5]
  - *(val+1)
  - val + i

Array Access

- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer to array element 0: Type T*

```
int val[5];
```



Reference	Type	Value
val[4]	int	5
val	int *	*x*
val+1	int *	*x* + 4
&val[2]	int *	*x* + 8
val[5]	int	?? (whatever is in memory at address *x* + 20)
*(val+1)	int	8
val + i	int *	*x* + 4*i

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

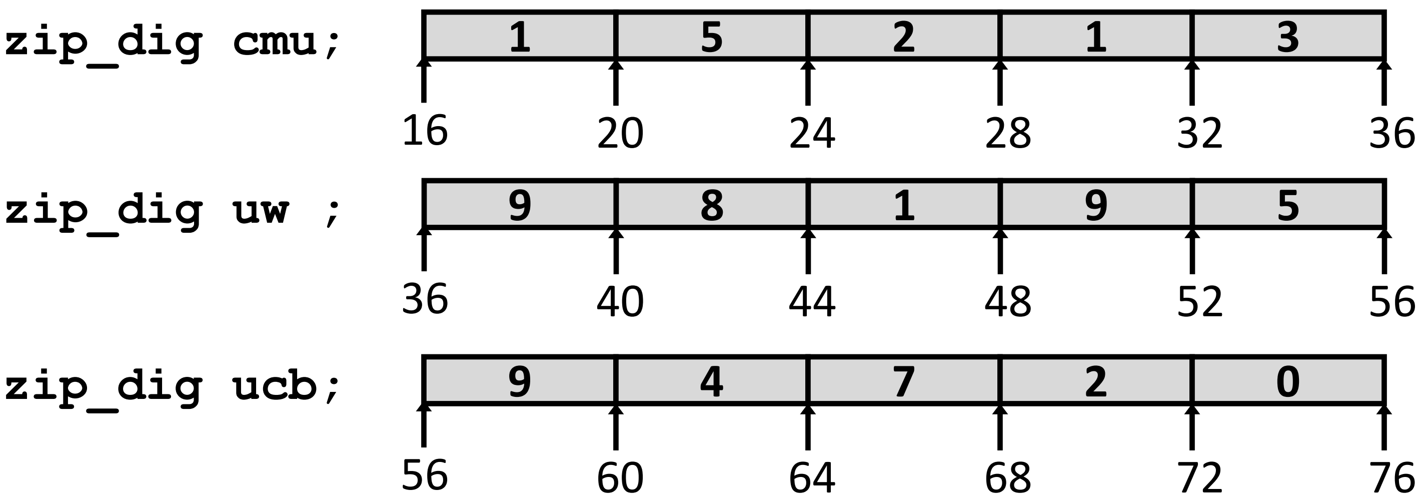
initialization

int uw[5] …

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

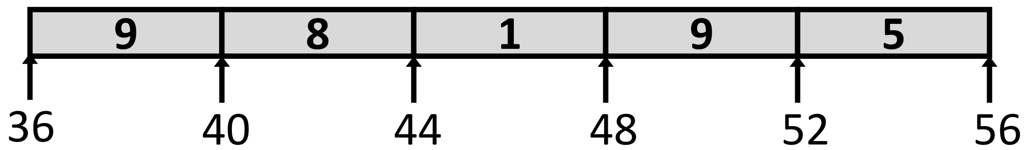


- **Declaration "`zip_dig uw`" equivalent to "`int uw[5]`"**
- **Example arrays happened to be allocated in successive 20 byte blocks**
  - Not guaranteed to happen in general

```
typedef int zip_dig[5];
```

Array Accessing Example

```
zip_dig uw;
```




```
int get_digit(zip_dig z, int dig)
{
  return z[dig];
}
```

Assembly

```
  # %rdi = z
  # %rsi = digit
movl (%rdi,%rsi,4), %eax  # z[digit]
```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi + 4*%rsi`
- Use memory reference `(%rdi,%rsi,4)`

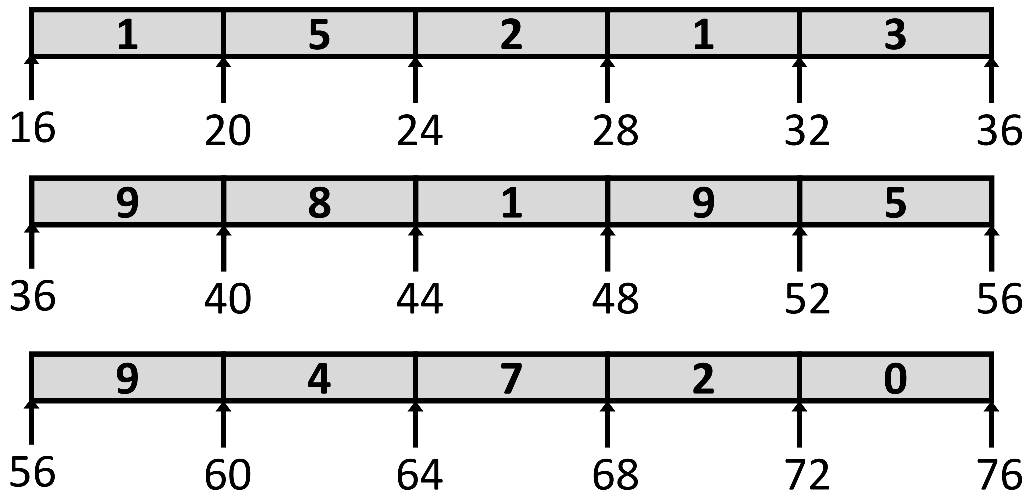
```
typedef int zip_dig[5];
```

Referencing Examples

`zip_dig cmu;`

`zip_dig  uw;`

`zip_dig ucb;`



- **Reference** **Address** **Value** **Guaranteed?**

  `uw[3]`

  `uw[6]`

  `uw[-1]`

  `cmu[15]`

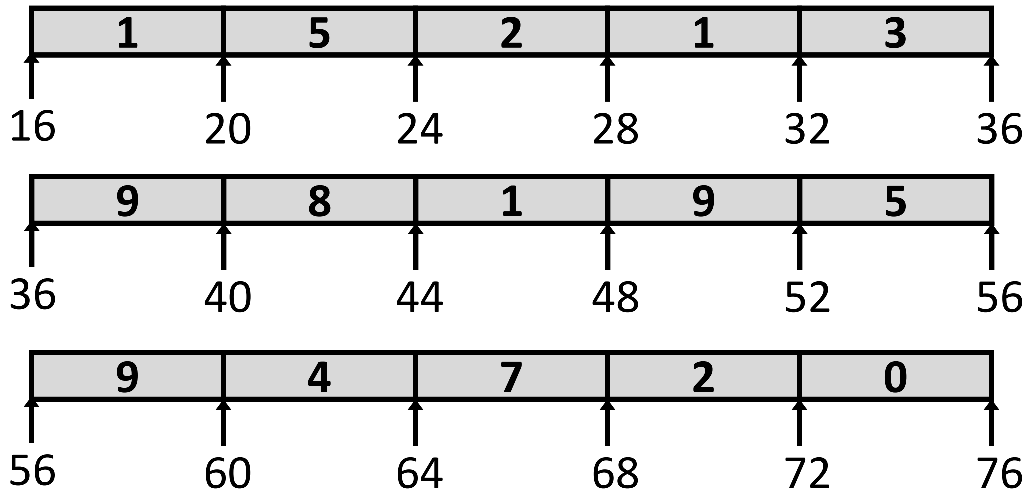
```
typedef int zip_dig[5];
```

Referencing Examples

```
zip_dig cmu;

zip_dig  uw;

zip_dig ucb;
```



Reference	Address	Value	Guaranteed?
`uw[3]`	`36 + 4* 3 = 48`	`9`	Yes
`uw[6]`	`36 + 4* 6 = 60`	`4`	No
`uw[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

- No bounds checking
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

```
typedef int zip_dig[5];
```

Array Loop Example

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

zi = 10*0 + 9 = 9

zi = 10*9 + 8 = 98

zi = 10*98 + 1 = 981

zi = 10*981 + 9 = 9819

zi = 10*9819 + 5 = 98195

9	8	1	9	5

`zip_dig uw;`

9	8	1	9	5

36 40 44 48 52 56

Array Loop Example

- **Original**

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- **Transformed**
  - Eliminate loop variable **`i`**, use pointer **`zend`** instead
  - Convert array code to pointer code
    - Pointer arithmetic on **`z`**
  - Express in do-while form (no test at entrance)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```

address of 5th digit

Increments by 4 (size of int)

Array Loop Implementation

gcc with –O1

- **Registers**

```
%rdi  z
%rax  zi
%rcx  zend
```

- **Computations**
  - `10*zi + *z` implemented as: `*z + 2*(5*zi)`
  - `z++` increments by 4 (size of int=4)

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %ecx = z
  movl $0,%eax                # rax = zi = 0
  leaq 20(%rdi),%rcx          # rcx = zend  = z+5
.L17:
  leal  (%rax,%rax,4),%edx    # zi + 4*zi = 5*zi
  movl  (%rdi),%eax           # eax = *z
  leal  (%rax,%rdx,2),%eax    # zi = *z + 2*(5*zi)
  addq $4,%rdi                # z++
  cmpq  %rcx,%rdi             # z : zend
  jne  .L17                   # if != goto loop
```

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, **`T A[N]`** is an array with elements of type **`T`**, with length **`N`**

same as:

```
int sea[4][5];
```

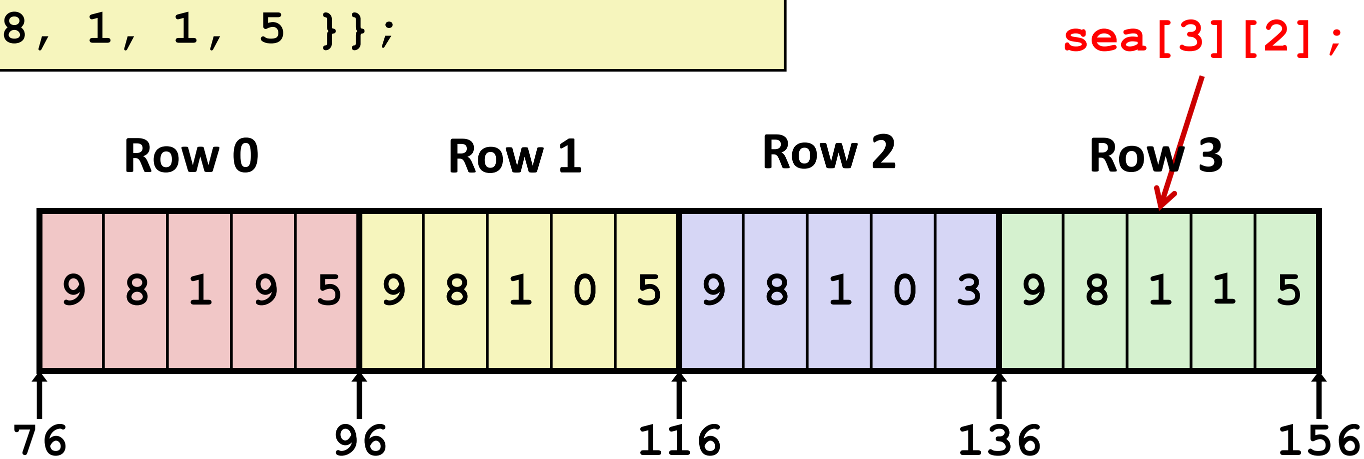
What is the layout in memory?

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, **`T A[N]`** is an array with elements of type **`T`**, with length **`N`**



- "Row-major" ordering of all elements
- Elements in the same row are contiguous
- Guaranteed (in C)

Two-Dimensional (Nested) Arrays

- **Declaration**
  - **T A[R][C];**
  - 2D array of data type T
  - R rows, C columns
  - Type T element requires K bytes
- **Array size?**

$$\begin{bmatrix} A[0][0] & \cdots & A[0][C-1] \\ \vdots & & \vdots \\ A[R-1][0] & \cdots & A[R-1][C-1] \end{bmatrix}$$

Two-Dimensional (Nested) Arrays

- **Declaration**
  - **T A[R][C];**
  - 2D array of data type T
  - **R** rows, **C** columns
  - Type T element requires K bytes
- **Array size:**
  - **R** * **C** * K bytes
- **Arrangement**
  - **Row-major** ordering

$$\begin{bmatrix} A[0][0] & \cdots & A[0][C-1] \\ \vdots & & \vdots \\ A[R-1][0] & \cdots & A[R-1][C-1] \end{bmatrix}$$

```
int A[R][C];
```

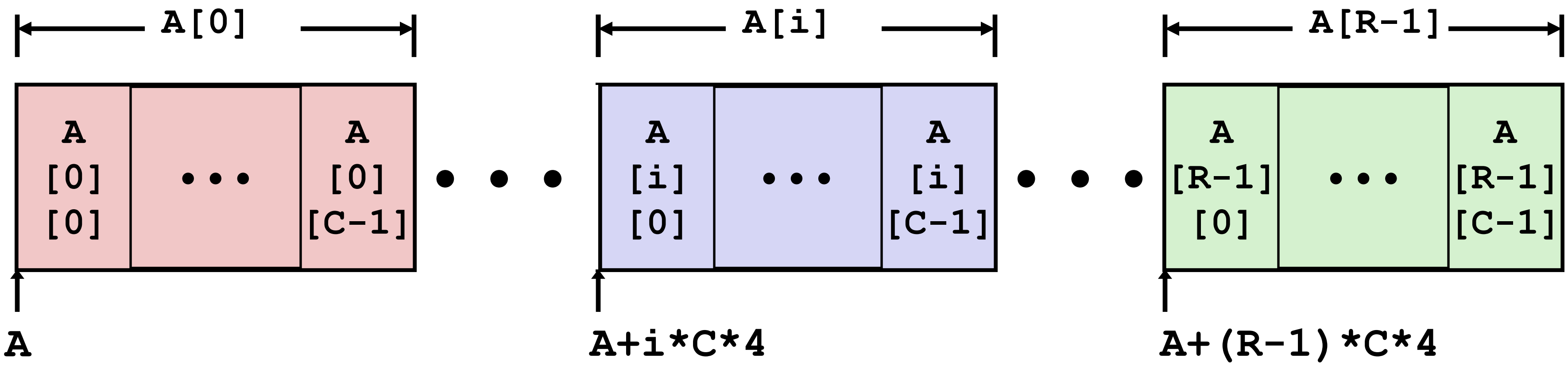
A [0] [0]	• • •	A [0] [C-1]	A [1] [0]	• • •	A [1] [C-1]	• • •	A [R-1] [0]	• • •	A [R-1] [C-1]

4*R*C Bytes

Nested Array Row Access

- **Row vectors**
  - Given: **T A[R][C]:**
    - A[i] is an array of C elements, “row i”
    - Each element of type T requires K bytes
    - A is starting address of array
    - Starting address of row i = A + i * (C * K)

```
int A[R][C];
```



Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

- What data type is `sea[index]`?
- What is its starting address?

Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

- What data type is `sea[index]`?
- What is its starting address?

```
 # %rdi = index
   leaq (%rdi,%rdi,4),%rax
   leaq sea(,%rax,4),%rax
```

Translation?

Nested Array Row Access Code

```
int* get_sea_zip(int index)
{
  return sea[index];
}
```

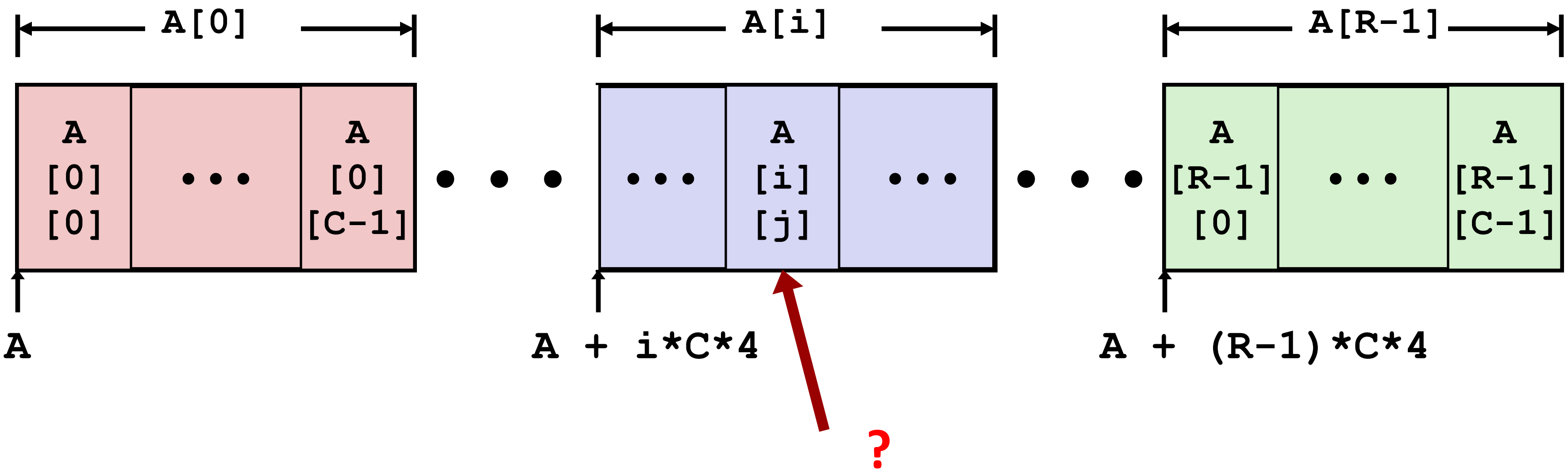
```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
# %rdi = index
  leaq (%rdi,%rdi,4),%rax # 5 * index
  leaq sea(,%rax,4),%rax  # sea + (20 * index)
```

- **Row Vector**
  - `sea[index]` is array of 5 `int`s
  - Starting address = `sea+20*index`
- **Assembly Code**
  - Computes and returns address
  - Compute as: `sea+4*(index+4*index)= sea+20*index`

Nested Array Element Access

```
int A[R][C];
```

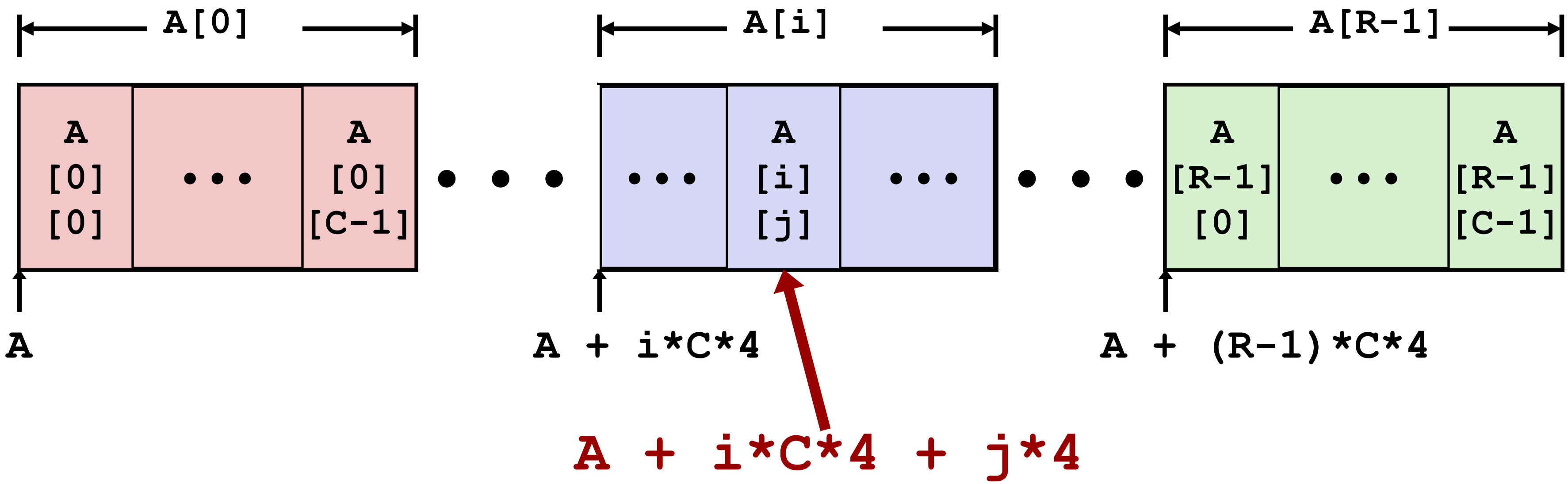


Nested Array Element Access

- **Array Elements**
  - A[i][j] is element of type T, which requires K bytes
  - Address of A[i][j] is

$$A + i * (C * K) + j * K \quad = \quad A + (i * C + j) * K$$

```
int A[R][C];
```



Nested Array Element Access Code

```
int get_sea_digit
  (int index, int dig)
{
  return sea[index][dig];
}
```

```
int sea[4][5] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

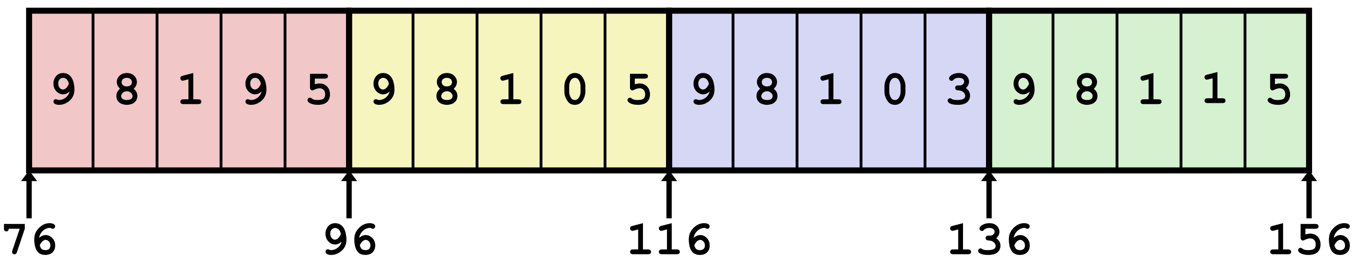
```
leaq   (%rdi,%rdi,4), %rax    # 5*index
addl   %rax, %rsi             # 5*index+dig
movl   sea(,%rsi,4), %eax     # *(sea + 4*(5*index+dig))
```

- **Array Elements**
  - sea[index][dig] is an **`int`**
  - Address = sea + 20*index + 4*dig
- **Assembly Code**
  - Computes address as: sea + 4*dig + 4*(index+4*index)
  - **`movl`** performs memory reference

```
typedef int zip_dig[5];
```

Strange Referencing Examples

```
zip_dig sea[4];
```



- **Reference Address Value Guaranteed?**

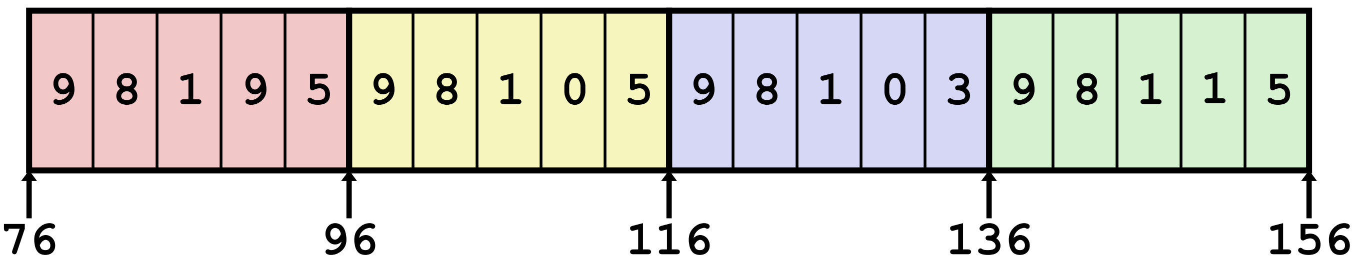
Reference	Address	Value	Guaranteed?
`sea[3][3]`			
`sea[2][5]`			
`sea[2][-1]`			
`sea[4][-1]`			
`sea[0][19]`			
`sea[0][-1]`			

  - Code does not do any bounds checking
  - Ordering of elements within array guaranteed

```
typedef int zip_dig[5];
```

Strange Referencing Examples

```
zip_dig sea[4];
```



- **Reference** / **Address** / **Value** / **Guaranteed?**

Reference	Address	Value	Guaranteed?
`sea[3][3]`	`76+20*3+4*3 = 148`	`1`	Yes
`sea[2][5]`	`76+20*2+4*5 = 136`	`9`	Yes
`sea[2][-1]`	`76+20*2+4*-1 = 112`	`5`	Yes
`sea[4][-1]`	`76+20*4+4*-1 = 152`	`5`	Yes
`sea[0][19]`	`76+20*0+4*19 = 152`	`5`	Yes
`sea[0][-1]`	`76+20*0+4*-1 = 72`	`??`	No

  - Code does not do any bounds checking
  - Ordering of elements within array guaranteed

Multi-Level Array Example

Multi-Level Array Declaration(s):

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {uw, cmu, ucb};
```

2D Array Declaration:

```
zip_dig univ2D[3] = {
  { 9, 8, 1, 9, 5 },
  { 1, 5, 2, 1, 3 },
  { 9, 4, 7, 2, 0 }
};
```

Is a multi-level array the same thing as a 2D array?

NO

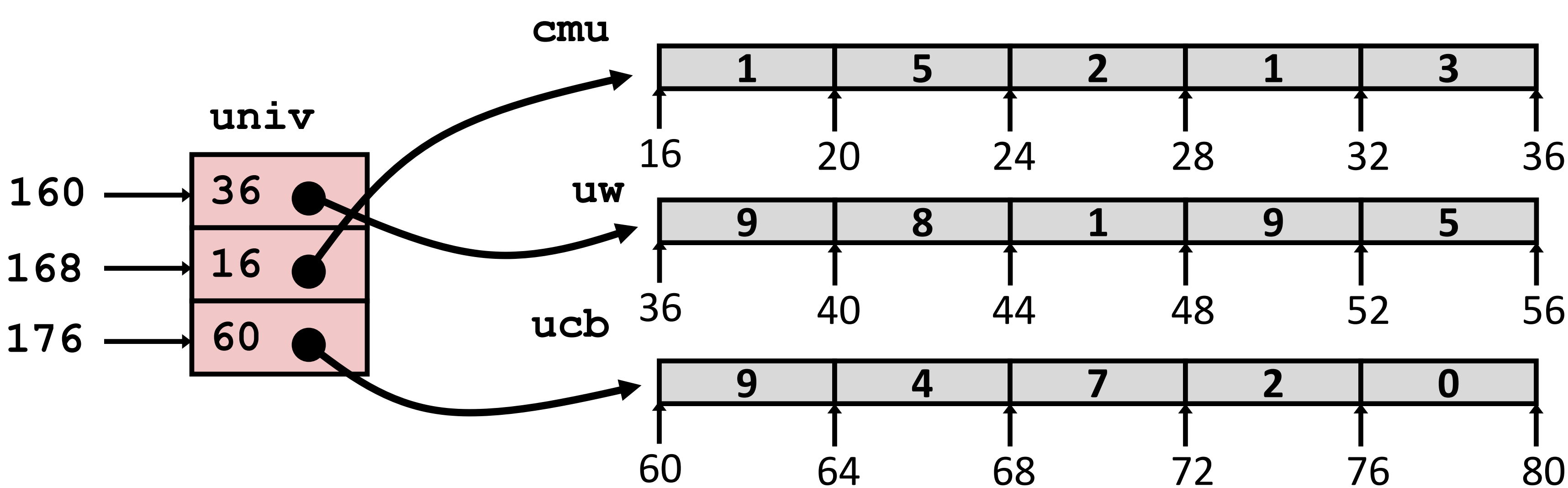
One array declaration = one contiguous block of memory

Multi-Level Array Example

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {uw, cmu, ucb};
```

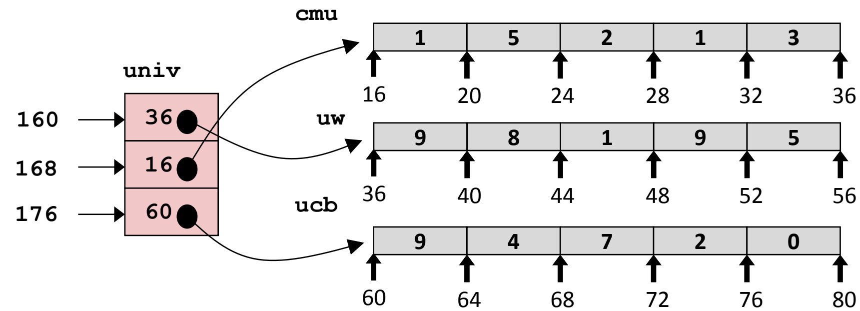
- **Variable `univ` denotes array of 3 elements**
- **Each element is a pointer**
  - 8 bytes each
- **Each pointer points to array of `int`s**



Note: this is how Java represents multi-dimensional arrays.

Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```



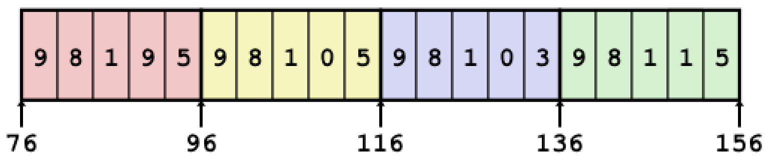

```
salq    $2, %rsi            # rsi = 4*digit
addq    univ(,%rdi,8), %rsi # p = univ[index] + 4*digit
movl    (%rsi), %eax        # return *p
ret
```

- Computation
  - Element access **Mem[Mem[univ+8*index]+4*dig]**
  - Must do **two memory reads**
    - First get pointer to row array
    - Then access element within array

Array Element Accesses

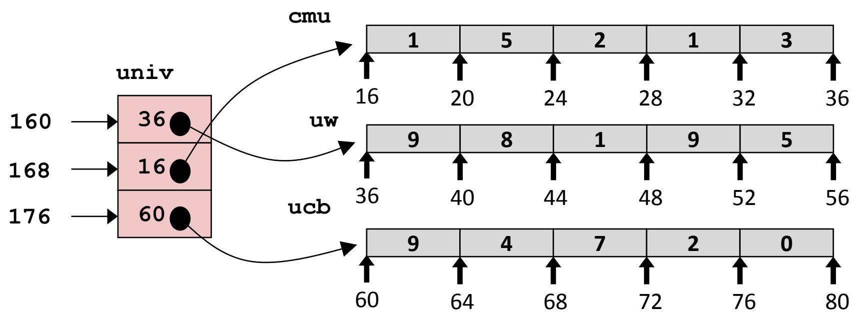
Nested array

```
int get_sea_digit
   (int index, int dig)
{
  return sea[index][dig];
}
```



Multi-level array

```
int get_univ_digit
   (int index, int dig)
{
  return univ[index][dig];
}
```

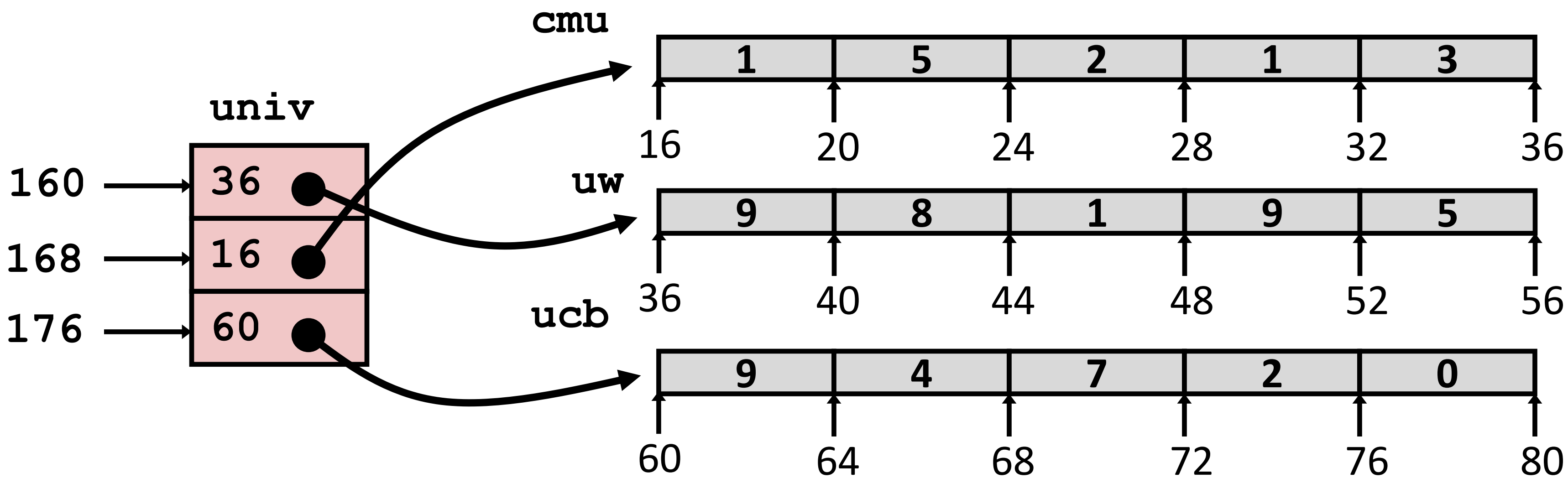


Access looks similar, but it isn't:

`Mem[sea+20*index+4*dig]`

`Mem[Mem[univ+8*index]+4*dig]`

Strange Referencing Examples



- **Reference** **Address** **Value** **Guaranteed?**

  `univ[2][3]`

  `univ[1][5]`

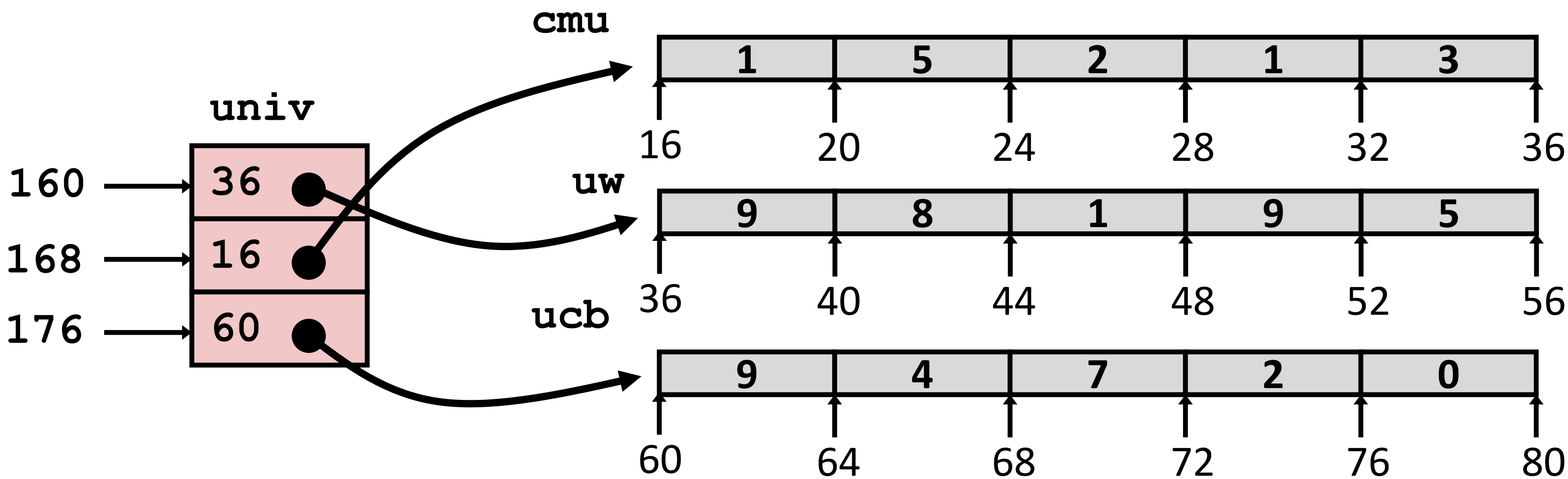
  `univ[2][-2]`

  `univ[3][-1]`

  `univ[1][12]`

  - C Code does not do any bounds checking
  - Location of each lower-level array in memory is not guaranteed

Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`60+4*3 = 72`	2	Yes
`univ[1][5]`	`16+4*5 = 36`	9	No
`univ[2][-2]`	`60+4*-2 = 52`	5	No
`univ[3][-1]`	`#@%!^??`	??	No
`univ[1][12]`	`16+4*12 = 64`	4	No

- C Code does not do any bounds checking
- Location of each lower-level array in memory is not guaranteed

Summary: Arrays in C

- **Contiguous allocations of memory**
- **No bounds checking**
- **Can usually be treated like a pointer to first element**
- **int a[4][5] => array of arrays**
  - all levels in one contiguous block of memory
- **int* b[4] => array of pointers to arrays**
  - first level in one contiguous block of memory
  - Each element in the first level points to another “sub” array
  - parts anywhere in memory

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
…
}
```

Aside: 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
```

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 Pointer Syntax

```
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, (just like Java):

```
struct rec r1;

r1.i = val;
```

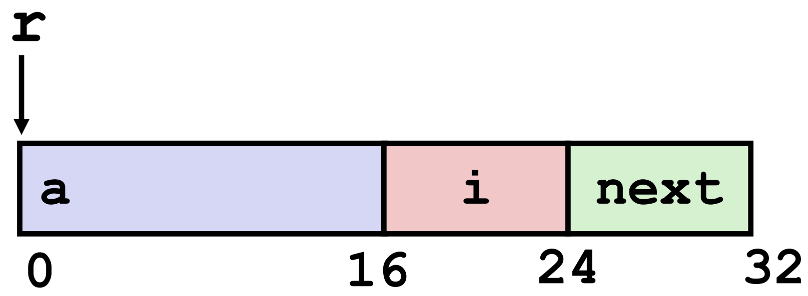
- Given a *pointer* to a struct:

```
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

Structure Representation

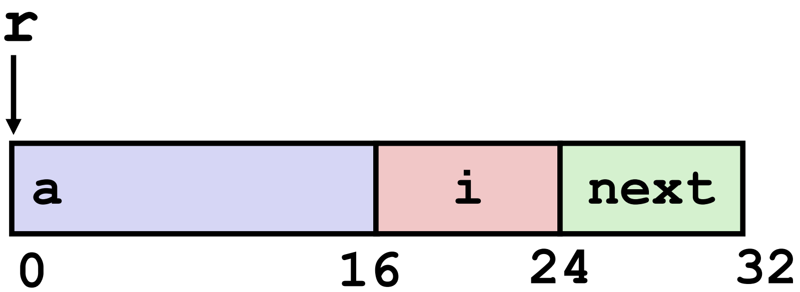
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
} *r;
```



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

Structure Representation

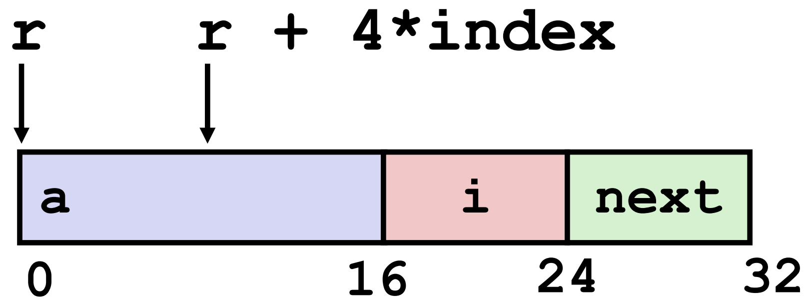
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
} *r;
```



- 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

Generating Pointer to Structure Member

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



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

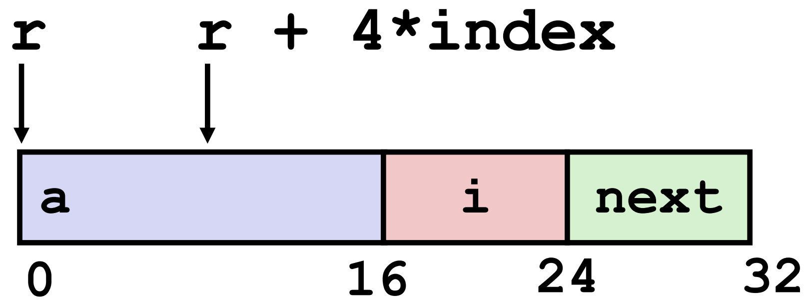
```
int *find_address_of_elem
  (struct rec *r, long index)
{
  return &r->a[index];
}
```

`&(r->a[index])`

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

Exercise: Generating Pointer to Structure Member

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




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

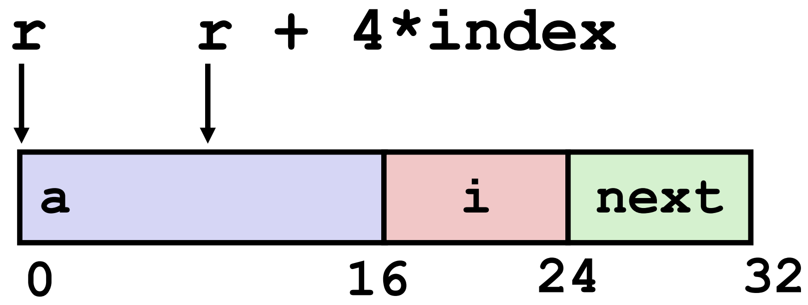
```
# r in %rdi
leaq  __________,%rax
ret
```

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

```
# r in %rdi
leaq  __________,%rax
ret
```

Exercise: Generating Pointer to Structure Member

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




```
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
```

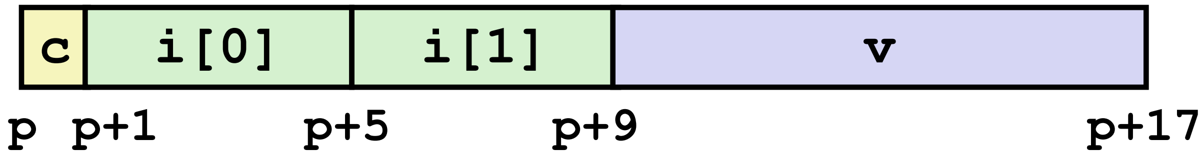
Review: Memory Alignment in x86-64

- **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
1	char
2	short
4	int, float
8	long, double, pointers

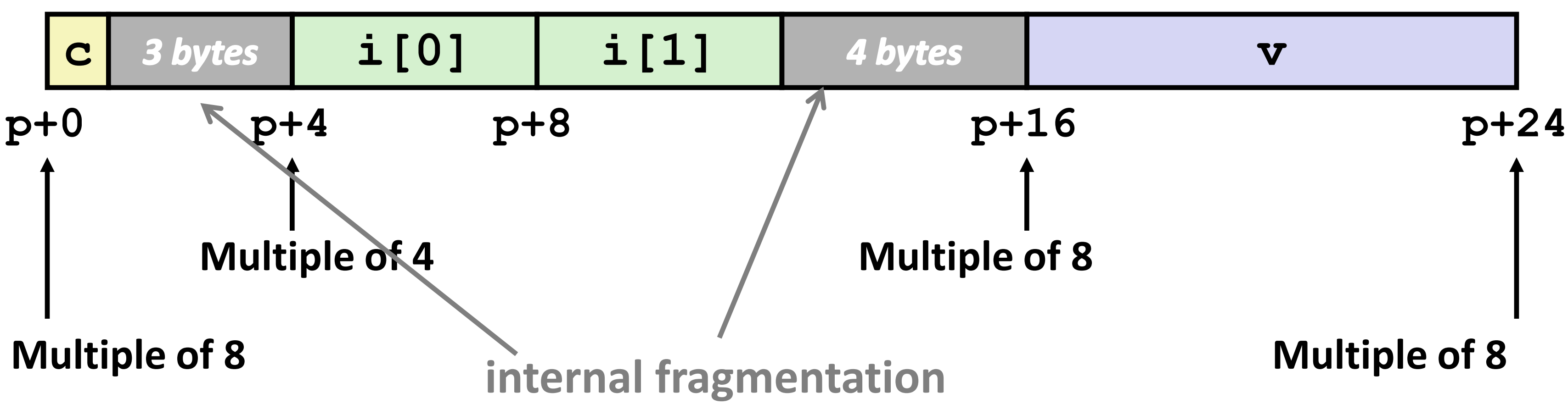
Structures & Alignment

- **Unaligned Data**




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

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



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 datum that spans quad word boundaries
    - Virtual memory trickier when datum spans 2 pages (more on this later)
- **Compiler**
  - Maintains declared *ordering* of fields in struct
  - Inserts padding in structure to ensure correct *alignment* of fields
  - **`sizeof()`** should be used to get true size of structs
  - **`offsetof(struct, field`**) can be used to find the actual offset of a field

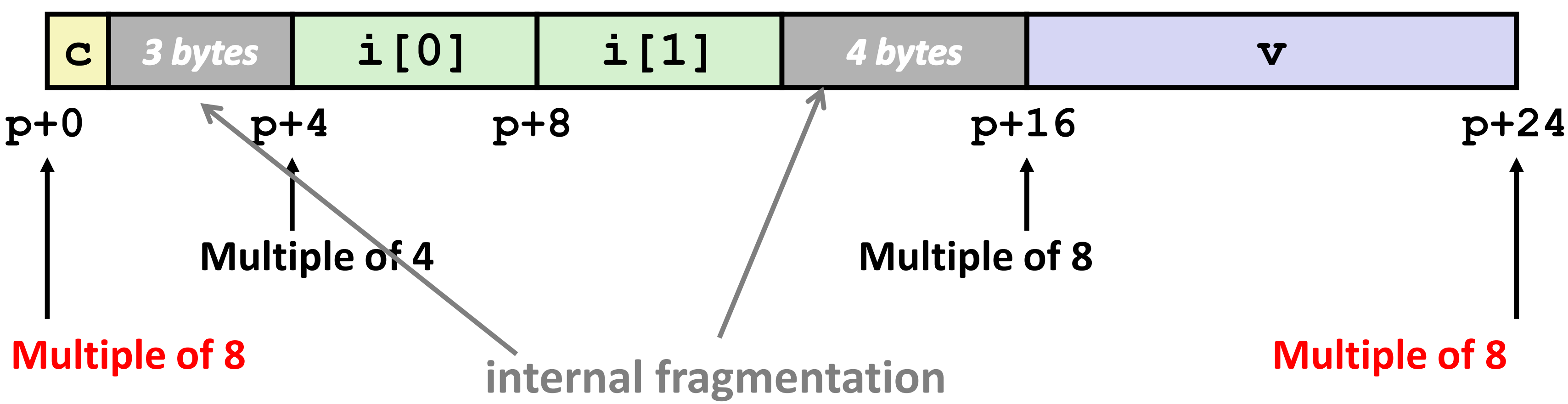
Specific Cases of Alignment (x86-64)

- **1 byte: `char`, …**
  - no restrictions on address
- **2 bytes: `short`, …**
  - lowest 1 bit of address must be 0_2
- **4 bytes: `int`, `float`, …**
  - lowest 2 bits of address must be 00_2
- **8 bytes: `double`, `long`, pointers, …**
  - lowest 3 bits of address must be 000_2
- **16 bytes: `long double`** (GCC on Linux)
  - lowest 4 bits of address must be 0000_2

Satisfying Alignment with Structures

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

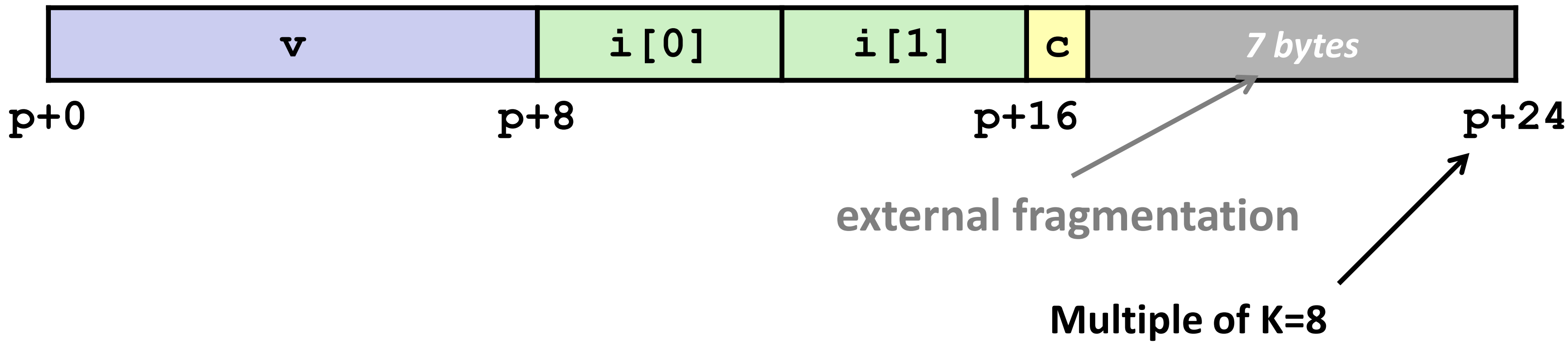
- **<u>Within</u> structure:**
  - Must satisfy each element's alignment requirement
- **<u>Overall</u> structure placement**
  - Each <u>structure</u> has alignment requirement **K**
    - **K** = Largest alignment of any element
  - **Initial address of structure & structure length must be multiples 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;
```

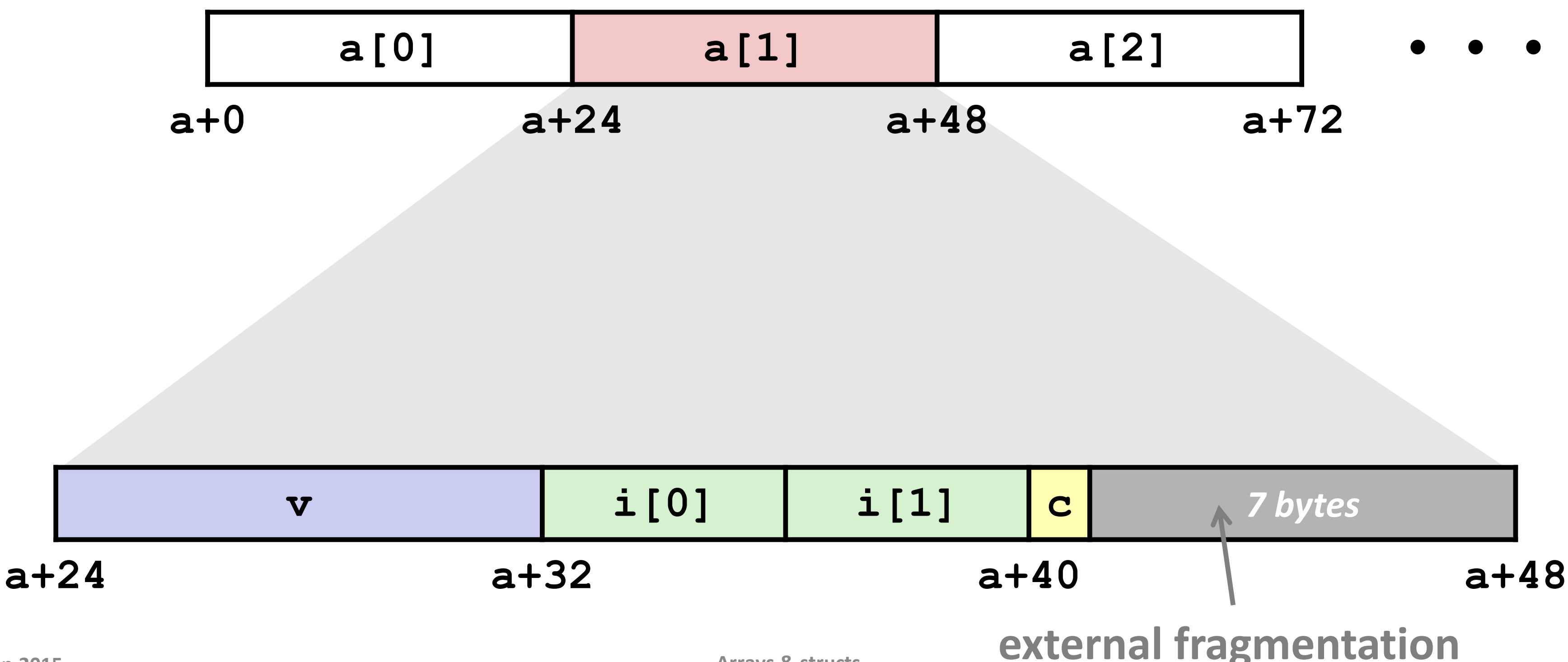


Arrays of Structures

Create an array of ten S2 structs called “a”

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

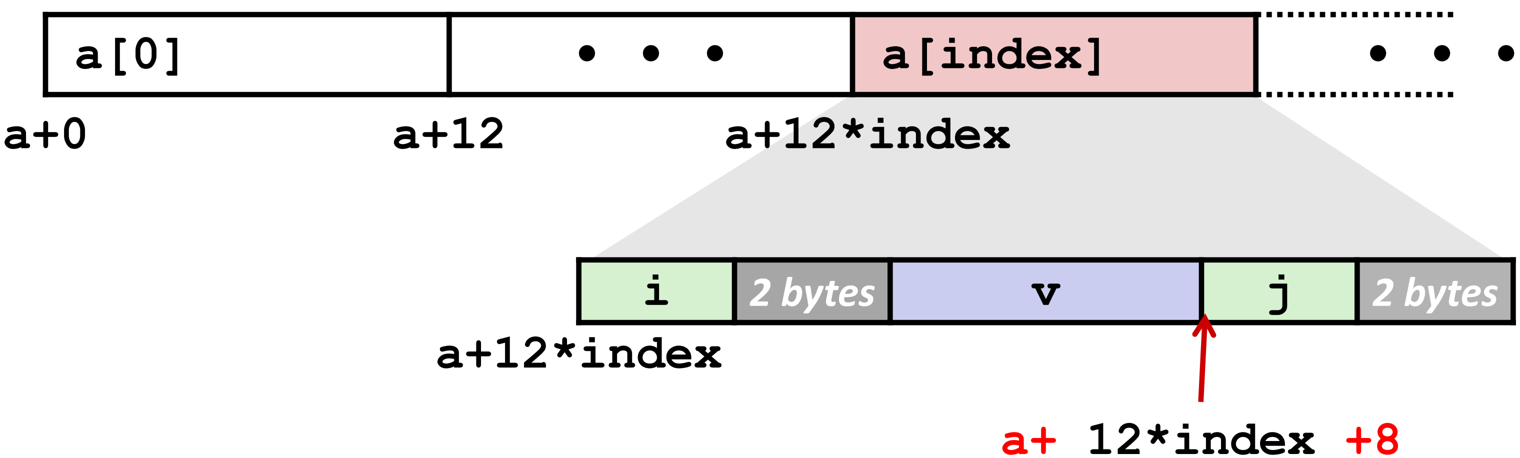
- Overall structure length multiple of K
- Satisfy alignment requirement for every element in array



Accessing Array Elements

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

- 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`




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

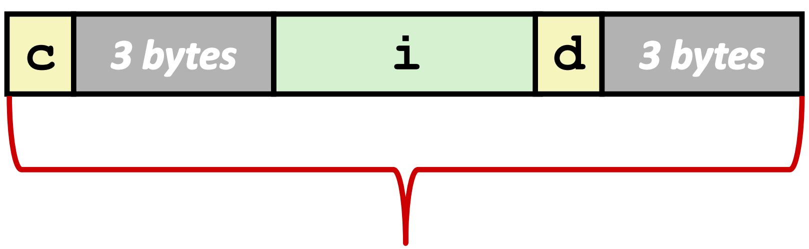
```
# %rdi = index
leaq (%rdi,%rdi,2),%rax # 3*index
movzwl a+8(,%rax,4),%eax
```

How the Programmer Can Save Space

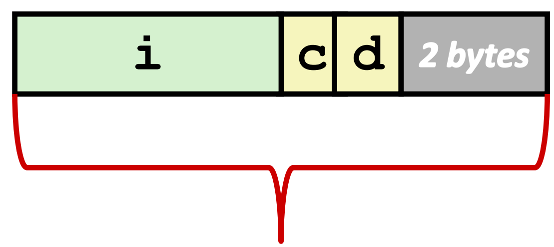
- Sometimes the programmer can save space by declaring large data types first
- Compiler must respect order elements are declared in

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

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



12 bytes



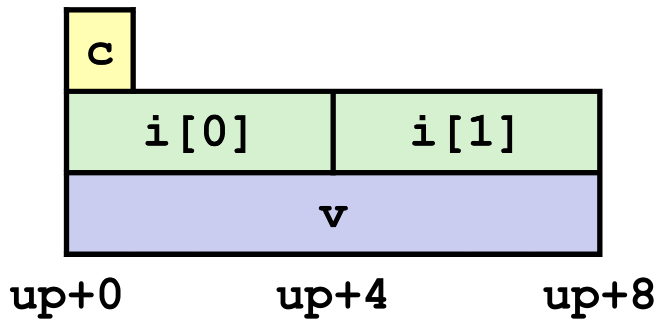
8 bytes

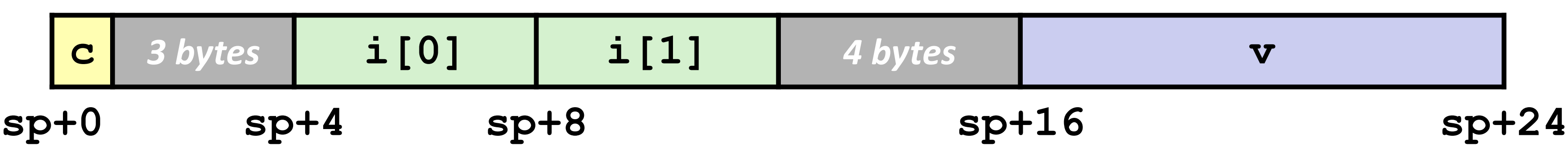
Unions

- 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)
- **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;
    }
}
```

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