Data: Arrays

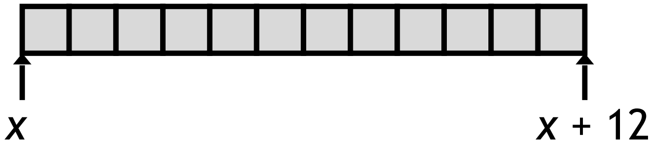
+ Array Allocation

- **Basic Principle**

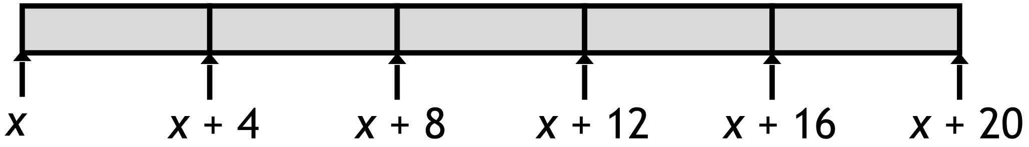
  `T A[N];`

  - Array of data type ***T*** and length ***N***
  - Contiguously allocated region of ***N*** * **sizeof**(*T*) bytes in memory

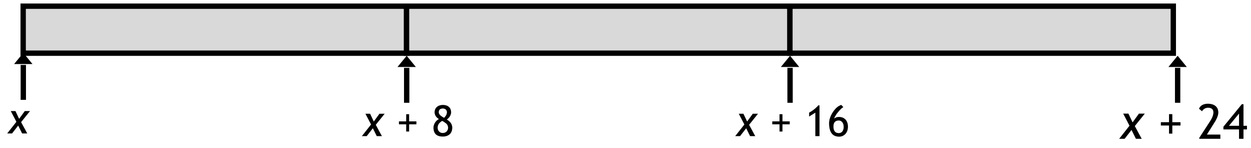
`char string[12];`



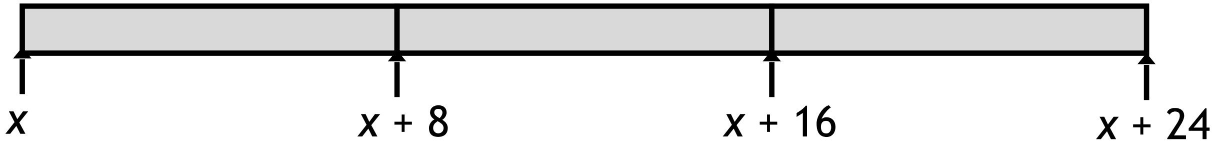
`int val[5];`



`double a[3];`



`char *p[3];`



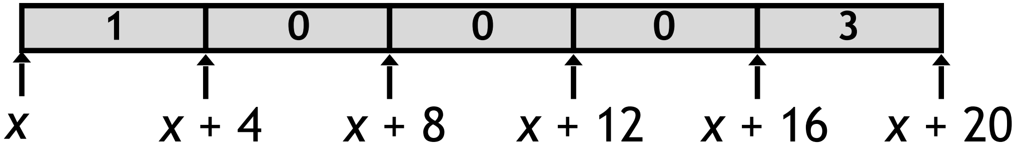
Array Access

- **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****

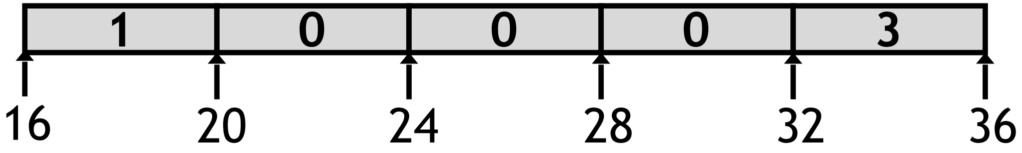
`int val[5];`



Reference	Type	Value
`val[4]`	`int`	3
`val`	`int*`	*x*
`val+1`	`int*`	*x* + 4
`&val[2]`	`int*`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	0
`val +` *i*	`int*`	*x* + 4 *i*

+ Array Accessing Example

```
int[] nyu;
```



1 0 0 0 3

16 20 24 28 32 36

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

```
# %rdi = z
# %rsi = digit
movq (%rdi,%rsi,4), %rax  # 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)`**

+ Array Loop Example

```
void zincr(int[] z) {
  int i;
  for (i = 0; i < 5; i++)
    z[i]++;
}
```

```
# %rdi = z, %rax = i
  movl    $0, %rax          #   i = 0
  jmp     .L3               #   goto middle
.L4:                        # loop:
  addl    $1, (%rdi,%rax,4) #   z[i]++
  addq    $1, %rax          #   i++
.L3:                        # middle
  cmpq    $4, %rax          #   i:4
  jbe     .L4               #   if <=, goto loop
  rep; ret
```

+ Multidimensional Arrays

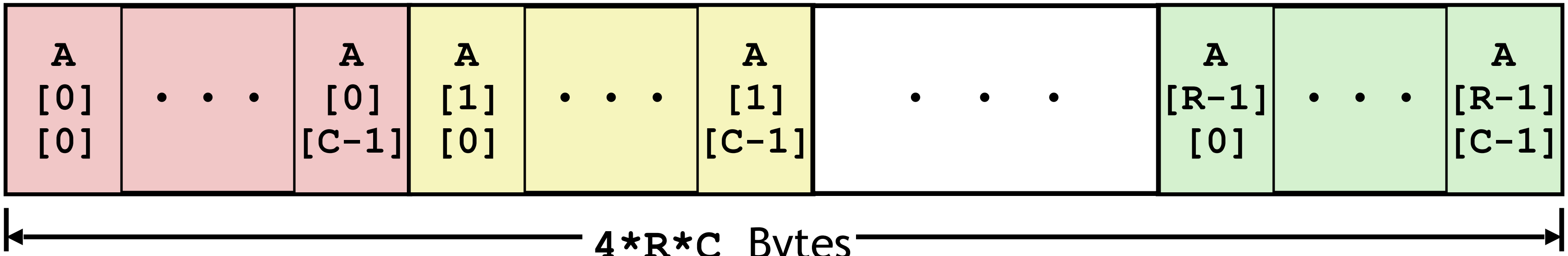
- **Declaration**

  `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

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

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

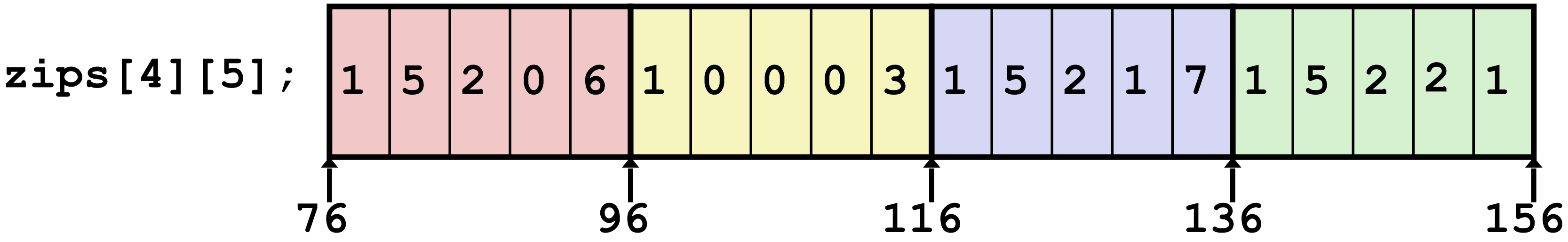


A [0] [0] • • • A [0] [C-1] A [1] [0] • • • A [1] [C-1] • • • A [R-1] [0] • • • A [R-1] [C-1]

4*R*C Bytes

+ Nested Array Example

```
int[4][5] zips =
  {{1, 5, 2, 0, 6},
   {1, 0, 0, 0, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



- Variable **zips**: array of 4 elements, allocated contiguously
- Each element is an array of 5 **int**'s, allocated contiguously
- "Row-Major" ordering of all elements in memory

Nested Array Row Access

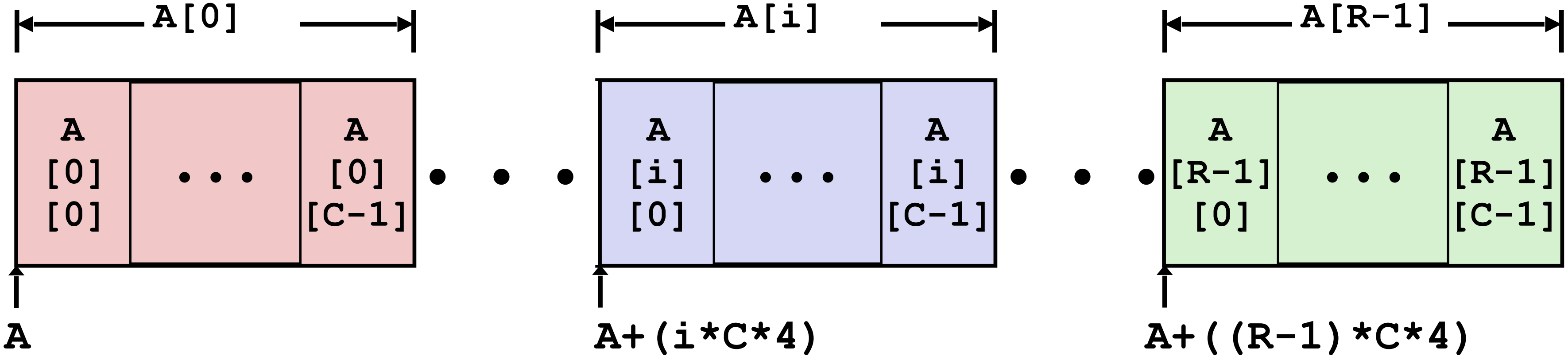
- **Declaration**

```
T  A[R][C];
```

- **Row Vectors**
  - *A[i]* is an array of *C* elements, e.g. a “row”
  - Each element of type *T* requires *K* bytes
  - Therefore the starting address of row is `A + i *(C * K)`

- **Example**

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



A[0]

A[i]

A[R-1]

A [0] [0]

• • •

A [0] [C-1]

• • •

A [i] [0]

• • •

A [i] [C-1]

• • •

A [R-1] [0]

• • •

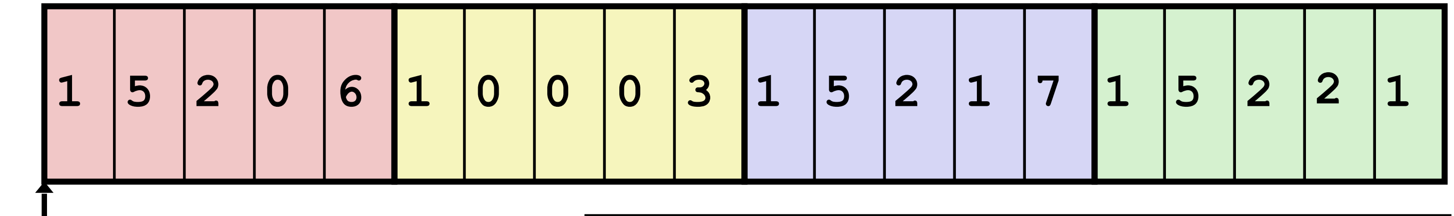
A [R-1] [C-1]

A

A+(i*C*4)

A+((R-1)*C*4)

+ Nested Array Row Access Code



1	5	2	0	6	1	0	0	0	3	1	5	2	1	7	1	5	2	2	1

```
int* get_a_zip(int index){
  return zips[index];
}
```

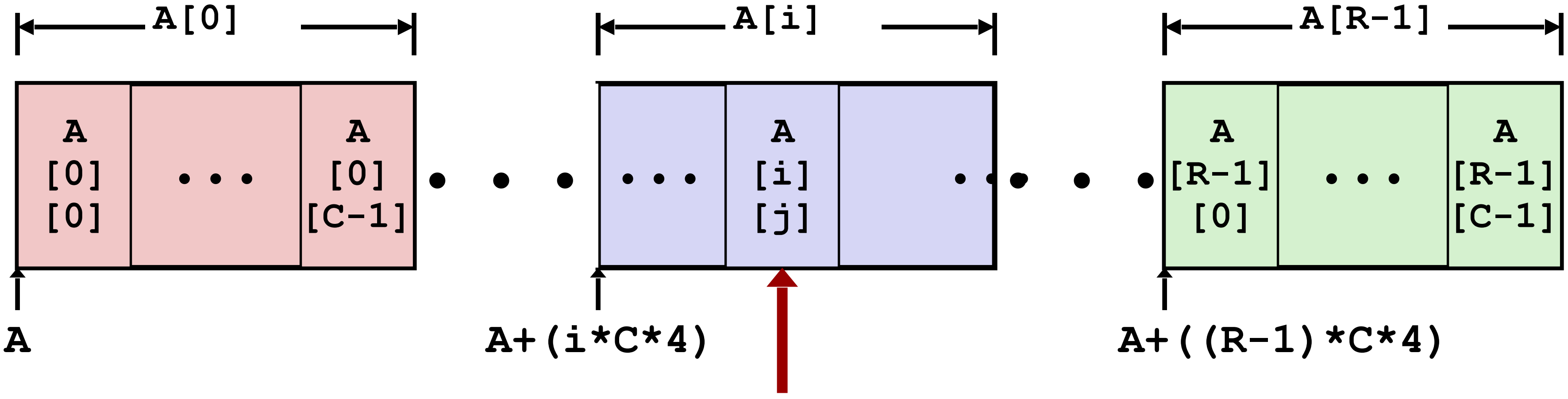
```
# %rdi = index
leaq (%rdi,%rdi,4), %rax        # 5 * index
leaq zips(,%rax,4), %rax        # zips + (20 * index)
```

- **Row Vector**
  - `zips[index]` is array of 5 **int**'s
  - Starting address `zips + 20 * index`
- **Machine Code**
  - Computes and returns address
  - Compute as `zips + 4 * (index + 4 * index)`

+ Nested Array Element Access

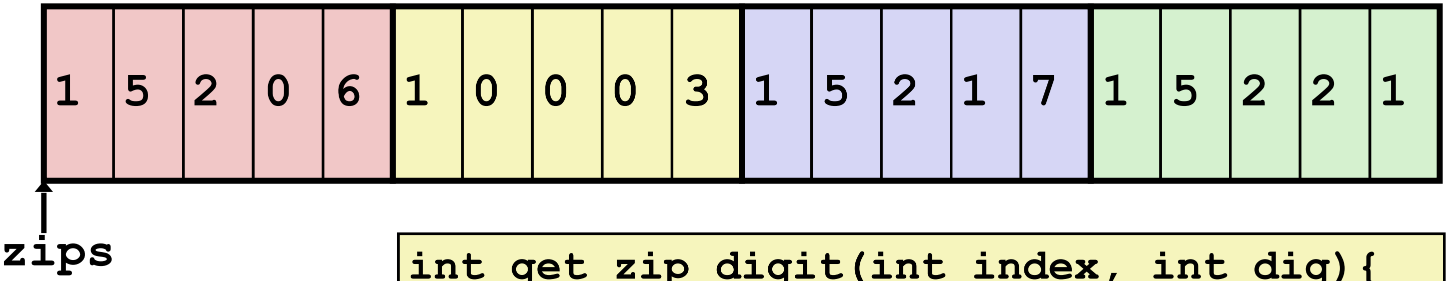
- Array Elements
  - `A[i][j]` is element of type *T*, which requires *K* bytes
  - Address: `A +` *i* `*(`*C* `*` *K*`) +` *j* `*` *K*

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



A+(i*C*4)+(j*4)

Nested Array Element Access Code



1 5 2 0 6 1 0 0 0 3 1 5 2 1 7 1 5 2 2 1

zips

```
int get_zip_digit(int index, int dig){
  return zips[index][dig];
}
```

```
leaq    (%rdi,%rdi,4), %rax    # 5 * index (%rdi is index)
addl    %rax, %rsi             # 5 * index + dig
movl    zips(,%rsi,4), %rax    # M[zips + 4*(5 * index + dig)]
```

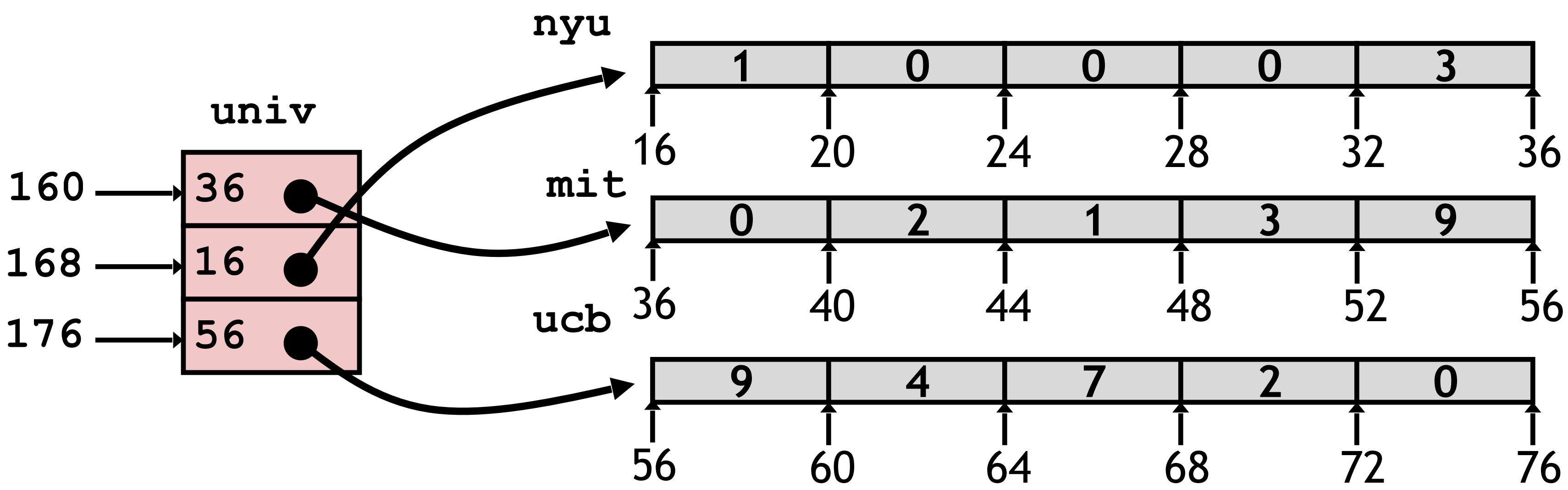
- Array Elements
  - `zips[index][dig]`is an int
  - Address: `zips + 20*index + 4*dig`
    - Expressed in assembly as `zips + 4*(5 * index + dig)`

+ Multi-Level Array Example

```
int* nyu = { 1, 0, 0, 0, 3 };
int* mit = { 0, 2, 1, 3, 9 };
int* ucb = { 9, 4, 7, 2, 0 };
```

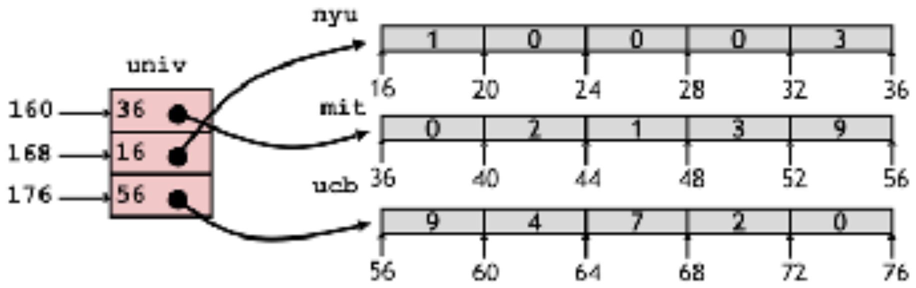
```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, nyu, ucb};
```

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



+ Element Access in Multi-Level Array

```
int get_uni_digit
  (size_t index, size_t digit){
  return univ[index][digit];
}
```



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

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

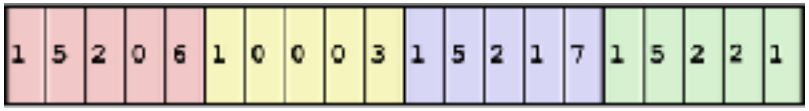
+ Array Element Accesses

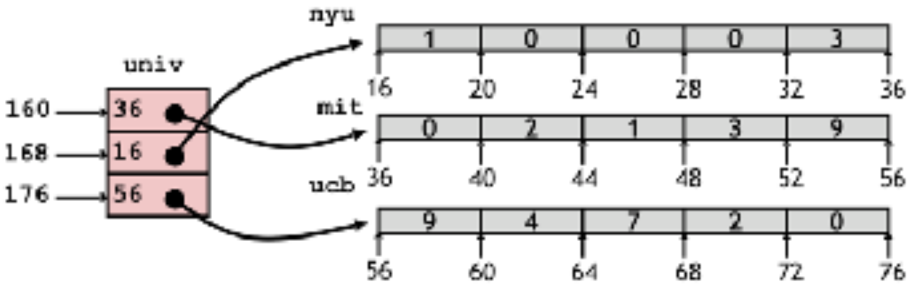
Nested array

```
int get_zip_digit
  (size_t index, size_t digit)
{
  return zips[index][digit];
}
```

Multi-level array

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





Accesses looks similar in C, but address computations very different:

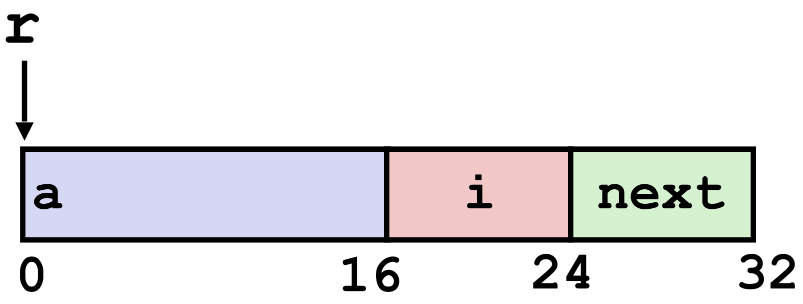
`Mem[zips+20*index+4*digit]`

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

Data: Structs

+ Structure Representation

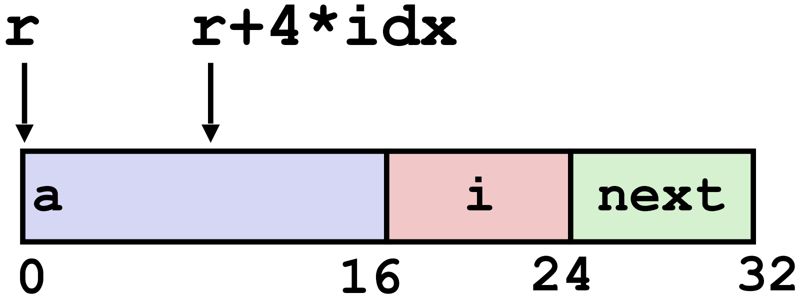
```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};
```



- **Structure represented as block of memory**
  - Big enough to hold all of the fields
- **Fields ordered according to declaration**
  - 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];
    int i;
    struct rec* next;
};
```



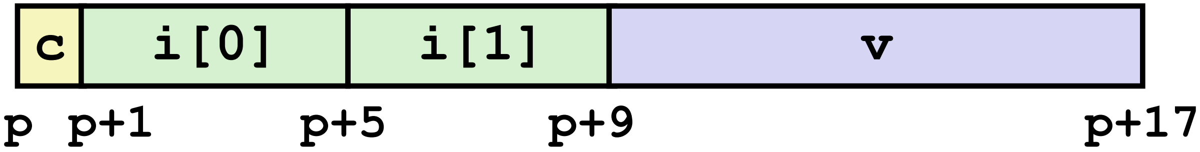
```
int* get_array_ptr(struct rec* r, int idx){
  return &r->a[idx];
}
```

```
leaq  (%rdi,%rsi,4), %rax   # r in %rdi, idx in %rsi
ret                         # move ptr into %rax, return
```

- **Generating pointer to array element**
  - Offset of each structure member determined at compile time
  - Compute as **`r + 4 * idx`**

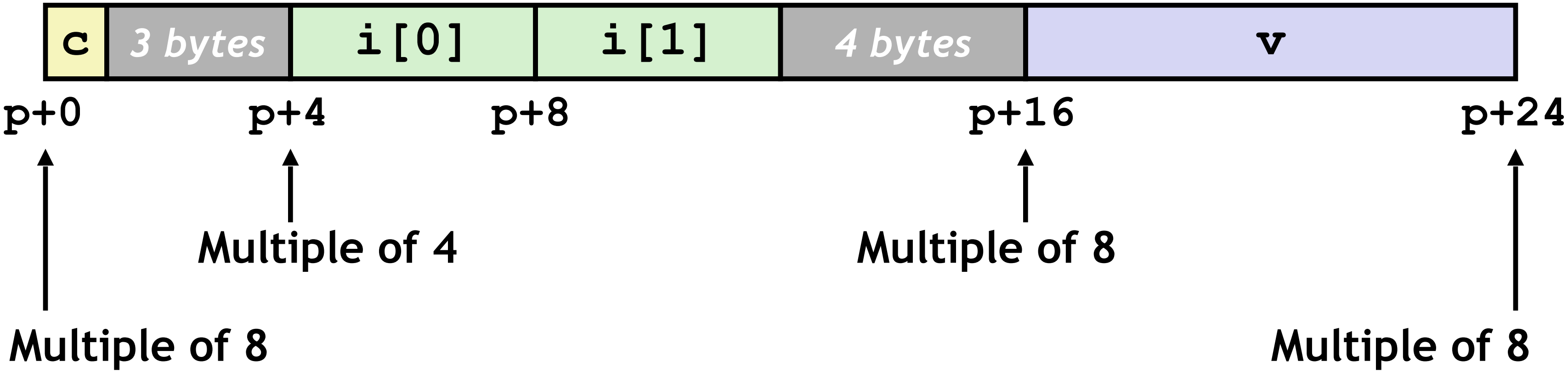
+ Structures & Alignment

- **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 word boundaries
    - Virtual memory trickier when you allow unaligned data.

- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields

+ 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`, `char *`, …**
  - lowest 3 bits of address must be 000_2

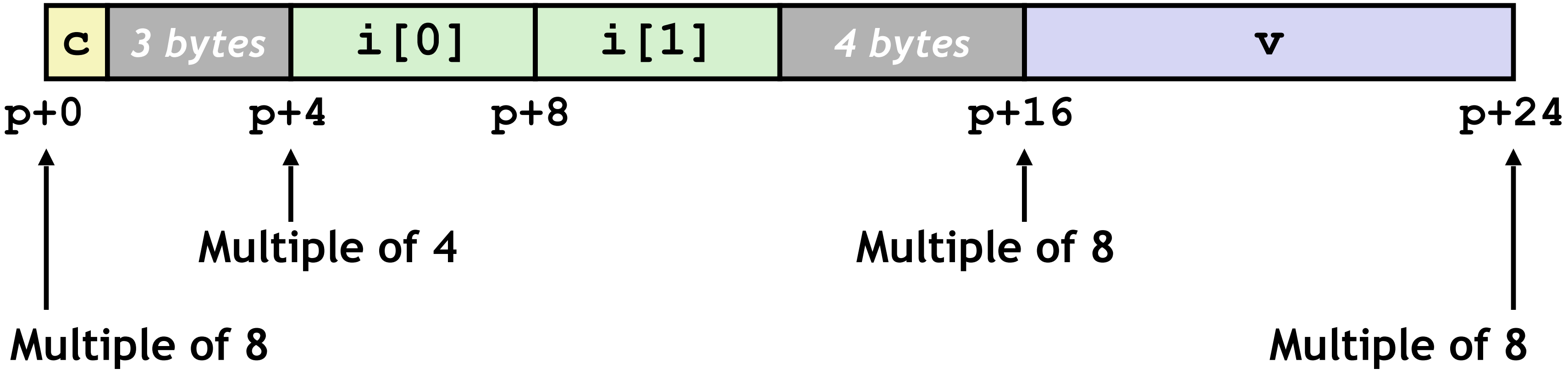
+ Satisfying Alignment with Structures

- **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 & structure length must be multiples of **K**

- **Example:**
  - K = 8, due to **double** element

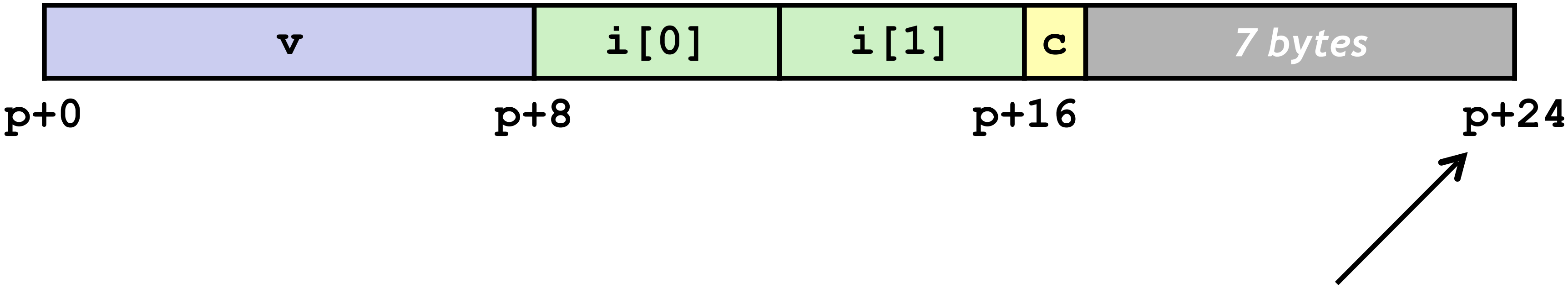
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



+ Meeting Overall Alignment Requirement

- For largest alignment requirement K
- Overall structure must be multiple of K

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



v

i[0]

i[1]

c

7 bytes

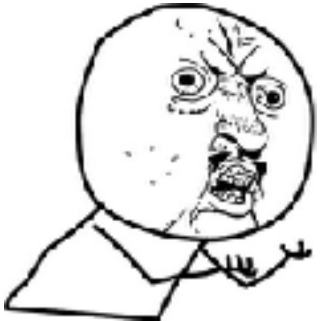
p+0

p+8

p+16

p+24

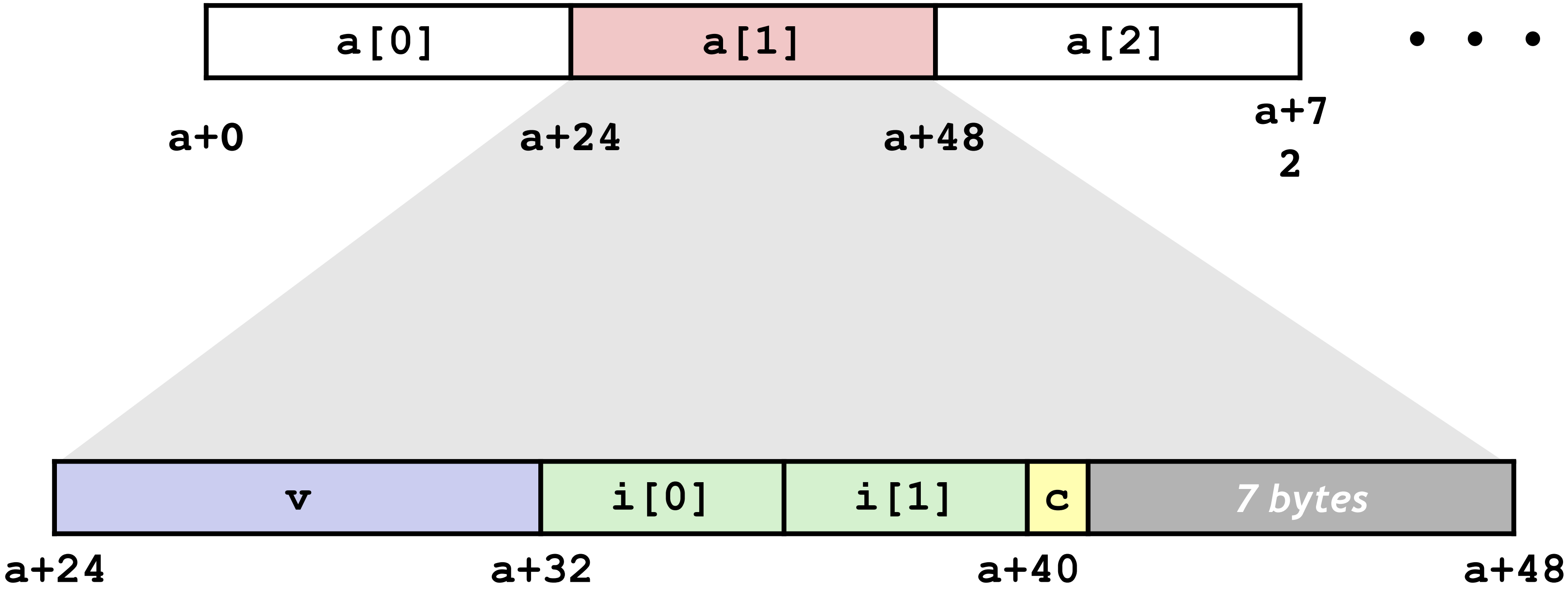
Multiple of K=8



+ Arrays of Structures

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

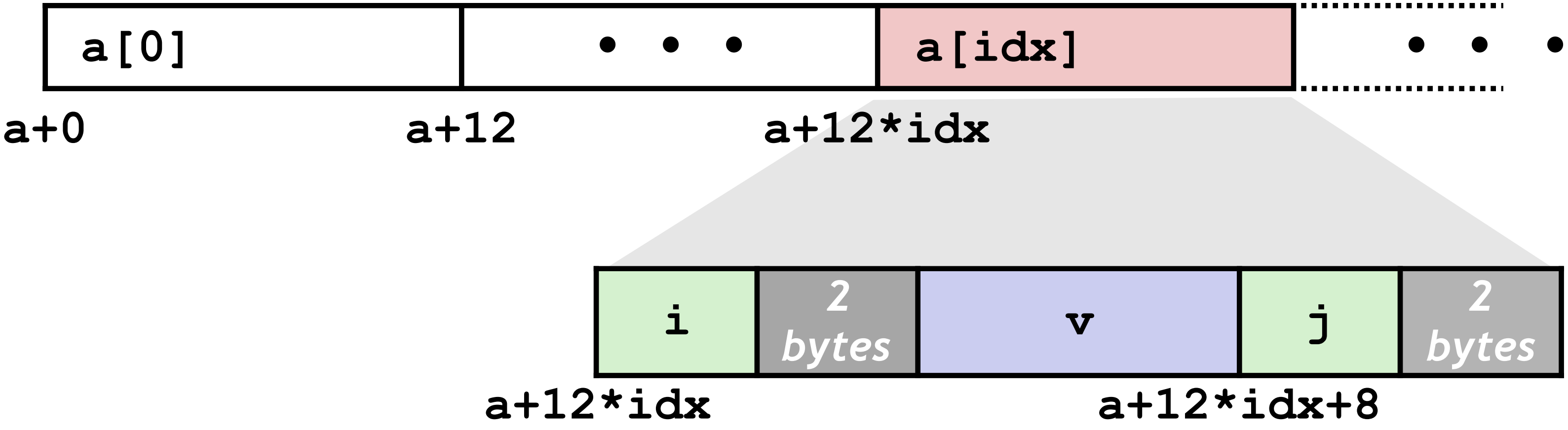
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



+ Accessing Members in Array of Struct

- Compute array offset `12 * idx`
  - `sizeof(i) + sizeof(v) + sizeof(j) + 4 bytes == sizeof(S3) == 12 bytes` (4 bytes is the padding)
- Element j is at an offset of 8 bytes within structure
  - `sizeof(i) + 2 bytes + sizeof(float) == 8 bytes`

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



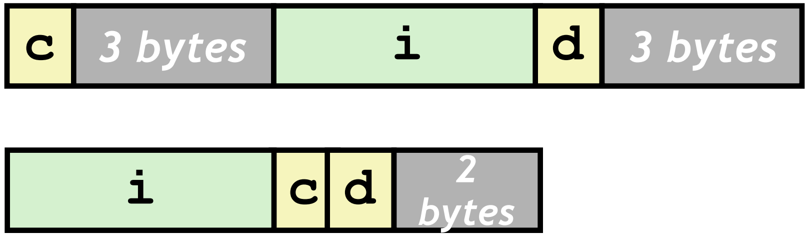
Saving Space (Struct packing)

- Put large data types first

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

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

- Effect (K=12 -> K=4)


c
3 bytes
i
d
3 bytes
i
c
d
2 bytes