Machine-Level Programming IV: Data

Instructors:

R. Shathanaa

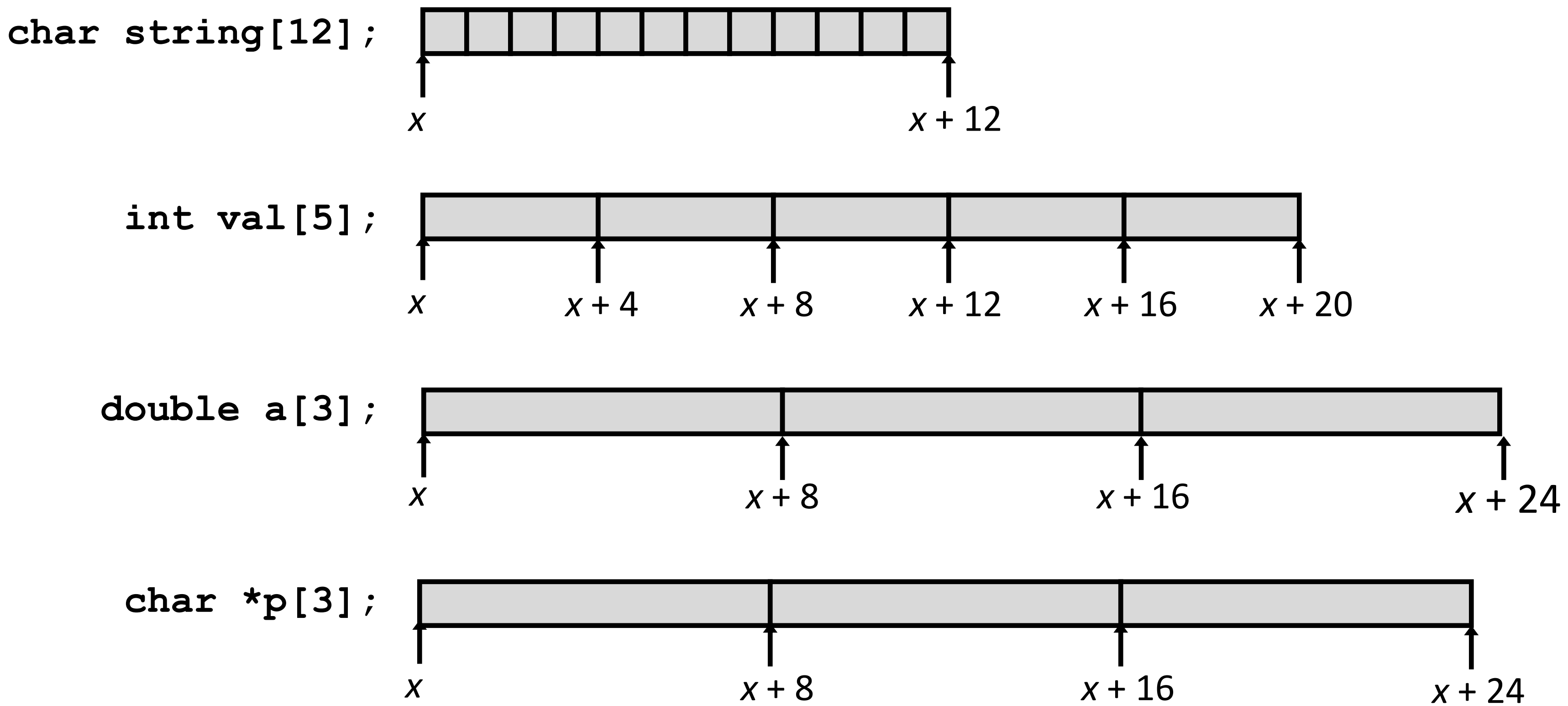
Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **Floating Point**

Array Allocation

- **Basic Principle**

  T **A[*L*];**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof** (*T*) bytes in memory



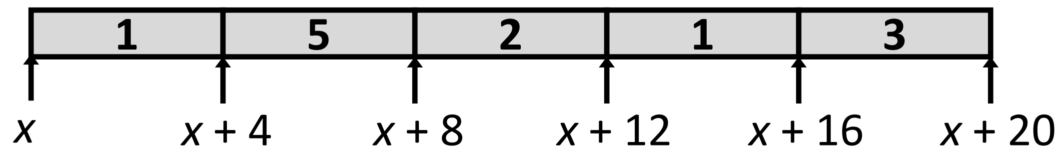
Array Access

Basic Principle

T **A[*L*];**

- Array of data type *T* and length *L*
- Identifier **A** can be used as a pointer to array element 0: Type *T**

`int val[5];`

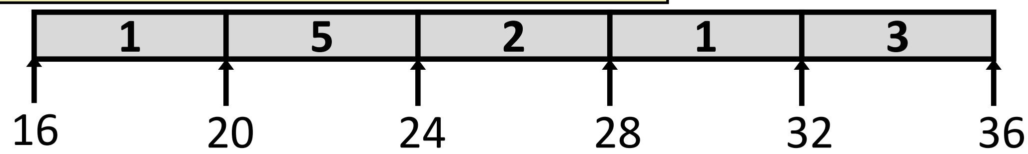


Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`*(val+1)`	`int`	5
`val +` *i*	`int *`	*x* + 4 *i*

Array Accessing Example

```
#define ZLEN 5
typedef int zip_dig[ZLEN];
```

```
zip_dig cmu;
```




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

IA32

```
  # %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)`

Array Loop Example

```
void zincr(zip_dig z) {
  size_t i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

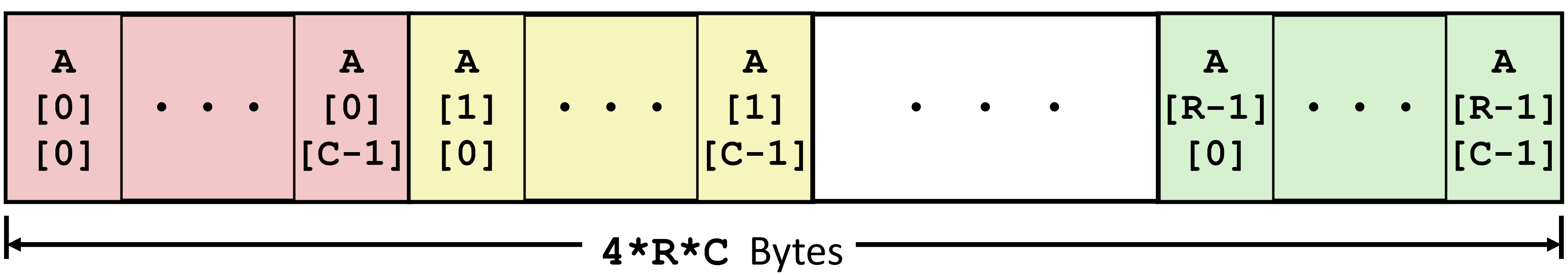
```
  # %rdi = z
  movl    $0, %eax            #   i = 0
  jmp     .L3                 #   goto middle
.L4:                          # loop:
  addl    $1, (%rdi,%rax,4)   #   z[i]++
  addq    $1, %rax            #   i++
.L3:                          # middle
  cmpq    $4, %rax            #   i:4
  jbe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

Multidimensional (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

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

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



```
int A[5][3];
```

is equivalent to the declaration

```
typedef int row3_t[3];
row3_t A[5];
```

T D[*R*][*C*];

array element D[i][j] is at memory address

$$\&\mathtt{D}[\mathtt{i}][\mathtt{j}] = x_{\mathtt{D}} + L(C \cdot i + j)$$

Figure 3.36
Elements of array in row-major order.

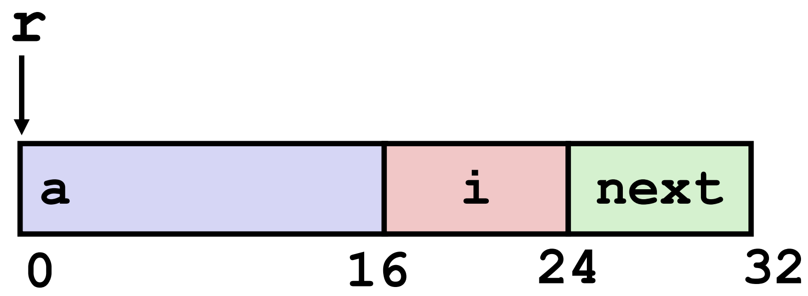
Row	Element	Address
`A[0]`	`A[0][0]`	x_A
	`A[0][1]`	$x_A + 4$
	`A[0][2]`	$x_A + 8$
`A[1]`	`A[1][0]`	$x_A + 12$
	`A[1][1]`	$x_A + 16$
	`A[1][2]`	$x_A + 20$
`A[2]`	`A[2][0]`	$x_A + 24$
	`A[2][1]`	$x_A + 28$
	`A[2][2]`	$x_A + 32$
`A[3]`	`A[3][0]`	$x_A + 36$
	`A[3][1]`	$x_A + 40$
	`A[4][2]`	$x_A + 44$
`A[4]`	`A[4][0]`	$x_A + 48$
	`A[4][1]`	$x_A + 52$
	`A[4][2]`	$x_A + 56$

where L is the size of data type T in bytes. As an example, consider the 5×3 integer array `A` defined earlier. Suppose x_A, i, and j are in registers `%rdi`, `%rsi`, and `%rdx`, respectively. Then array element `A[i][j]` can be copied to register `%eax` by the following code:

```
A in %rdi, i in %rsi, and j in %rdx
leaq    (%rsi,%rsi,2), %rax     Compute 3i
leaq    (%rdi,%rax,4), %rax     Compute x_A + 12i
movl    (%rax,%rdx,4), %eax     Read from M[x_A + 12i + 4]
```

Structure Representation

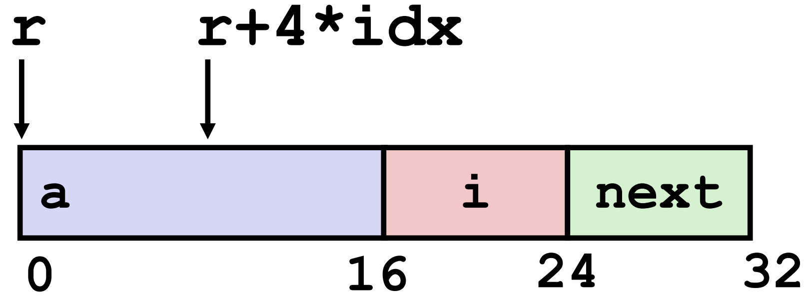
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- **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];
    size_t i;
    struct rec *next;
};
```



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

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

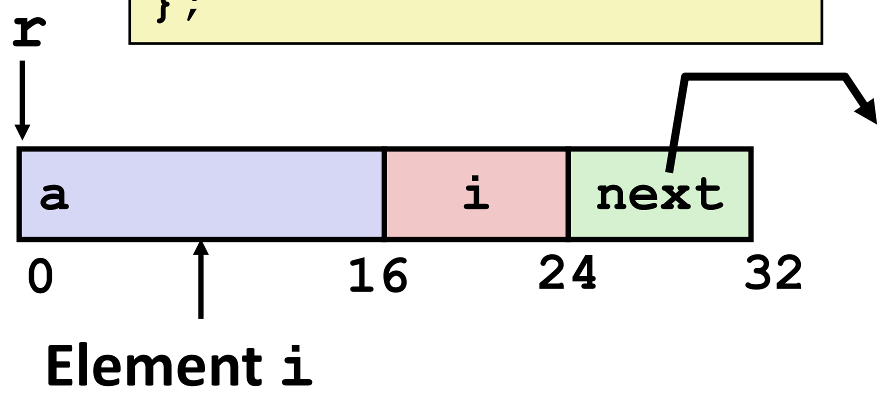
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Following Linked List

- C Code

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

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->next;
  }
}
```

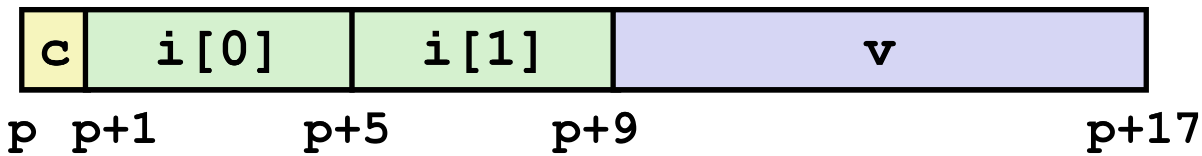


Register	Value
%rdi	r
%rsi	val

```
.L11:                              # loop:
  movslq  16(%rdi), %rax           #   i = M[r+16]
  movl    %esi, (%rdi,%rax,4)      #   M[r+4*i] = val
  movq    24(%rdi), %rdi           #   r = M[r+24]
  testq   %rdi, %rdi               #   Test r
  jne     .L11                     #   if !=0 goto loop
```

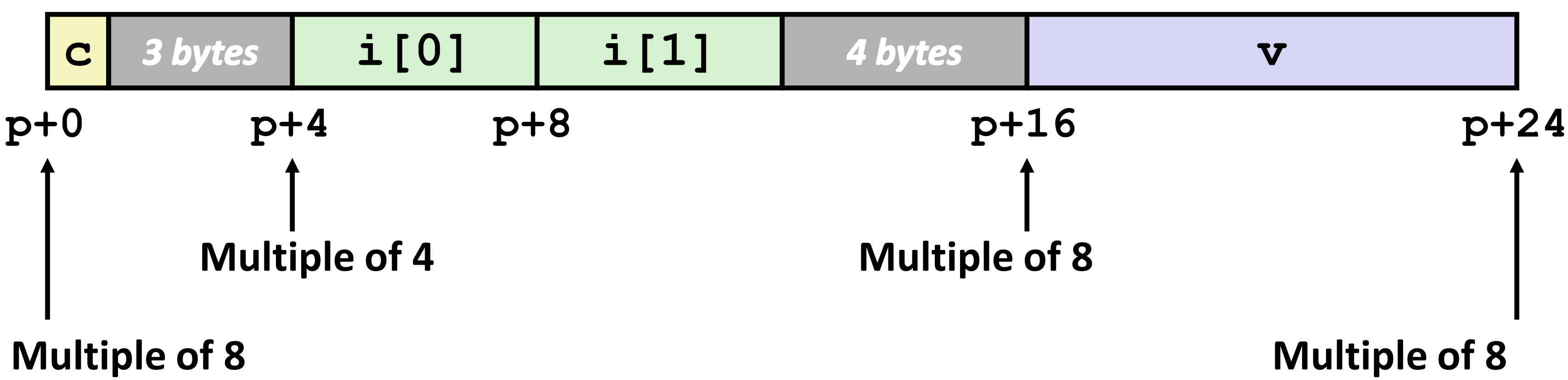
Structures & Alignment

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

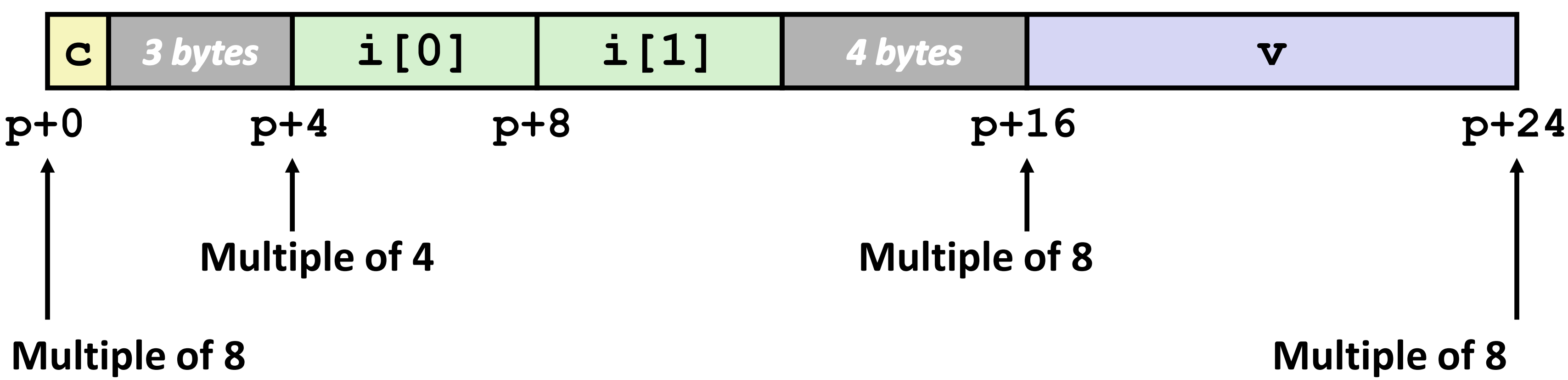
Specific Cases of Alignment (x86-64)

- **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
- **16 bytes: `long double`** (GCC on Linux)
  - lowest 4 bits of address must be 0000_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

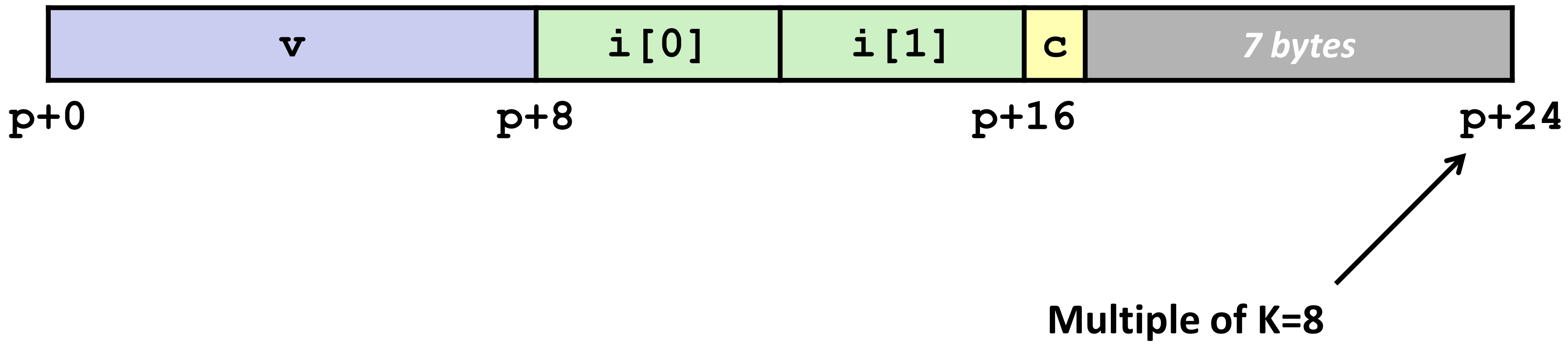
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

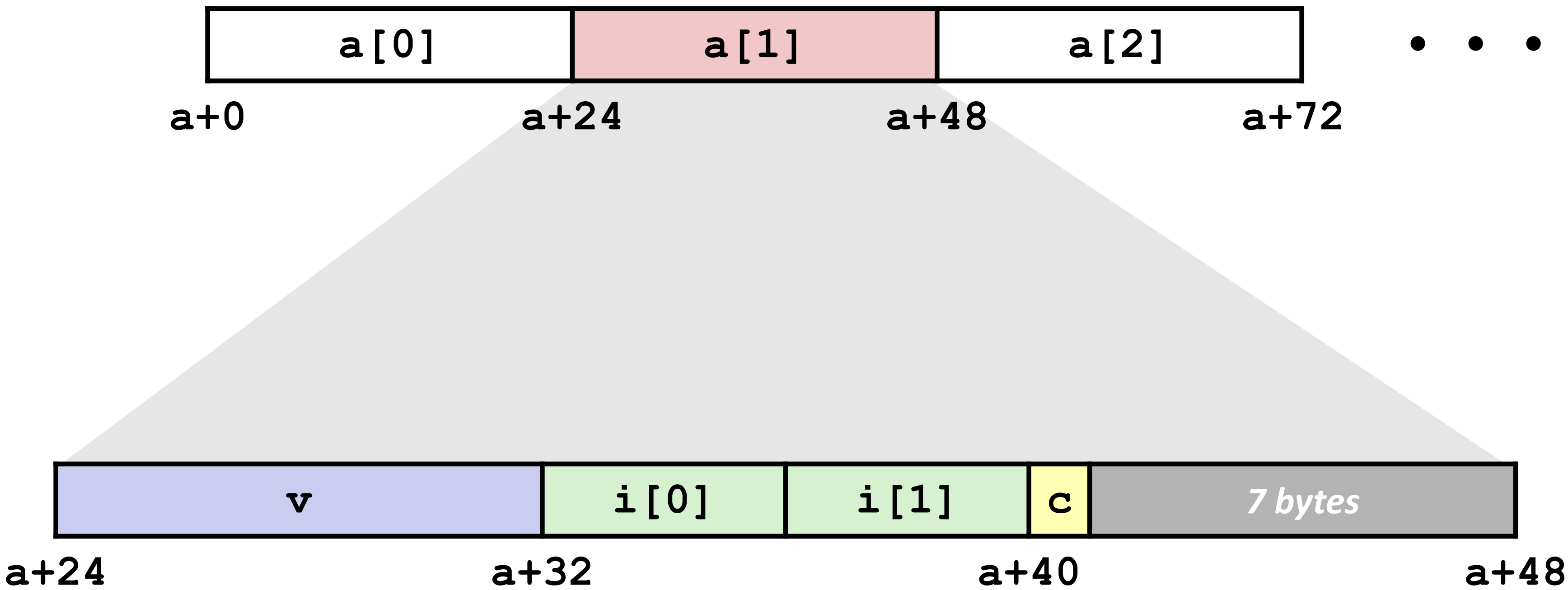
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

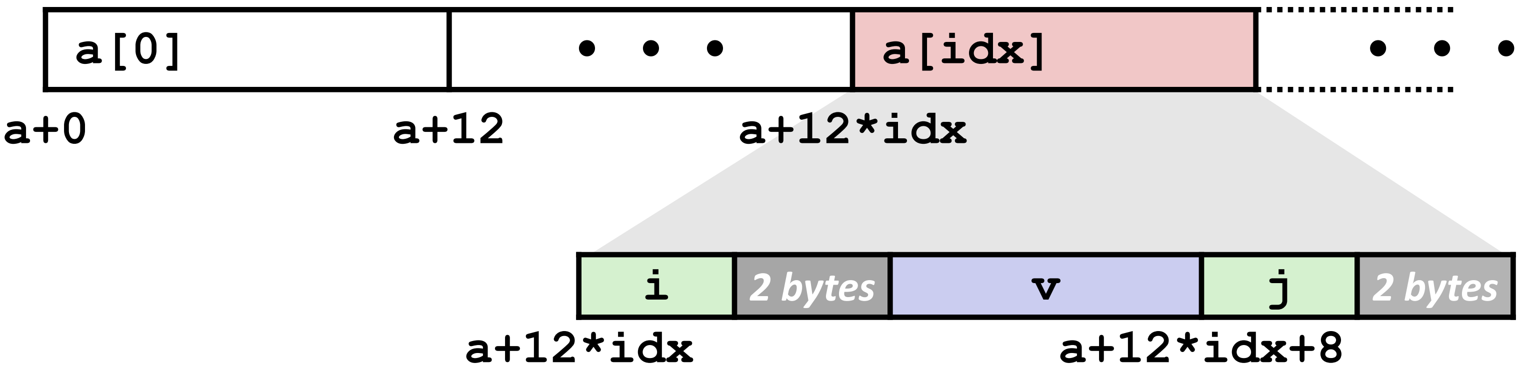
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

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

- **Compute array offset 12*idx**
  - `sizeof(S3)`, including alignment spacers
- **Element `j` is at offset 8 within structure**
- **Assembler gives offset `a+8`**
  - Resolved during linking




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

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

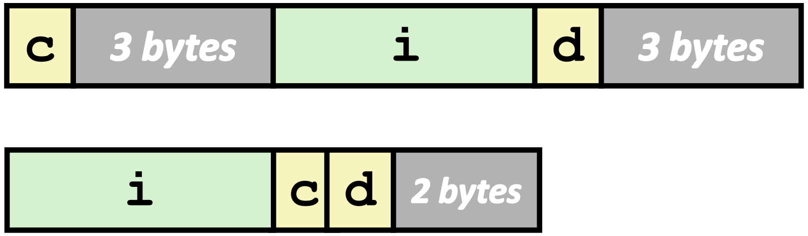
Saving Space

- **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=4)**



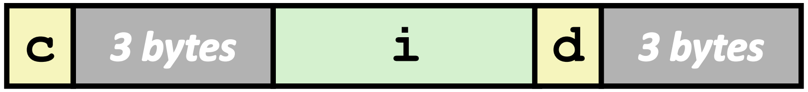
Saving Space

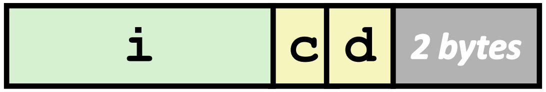
- Put large data types first

```
struct s1 {
  char c;
  int i;
  double d;
} *p;
```

```
struct s2 {
  double d;
  int i;
  char c;
} *p;
```

- Effect (K=4)





- **Quiz**