Machine-Level Programming IV: Data

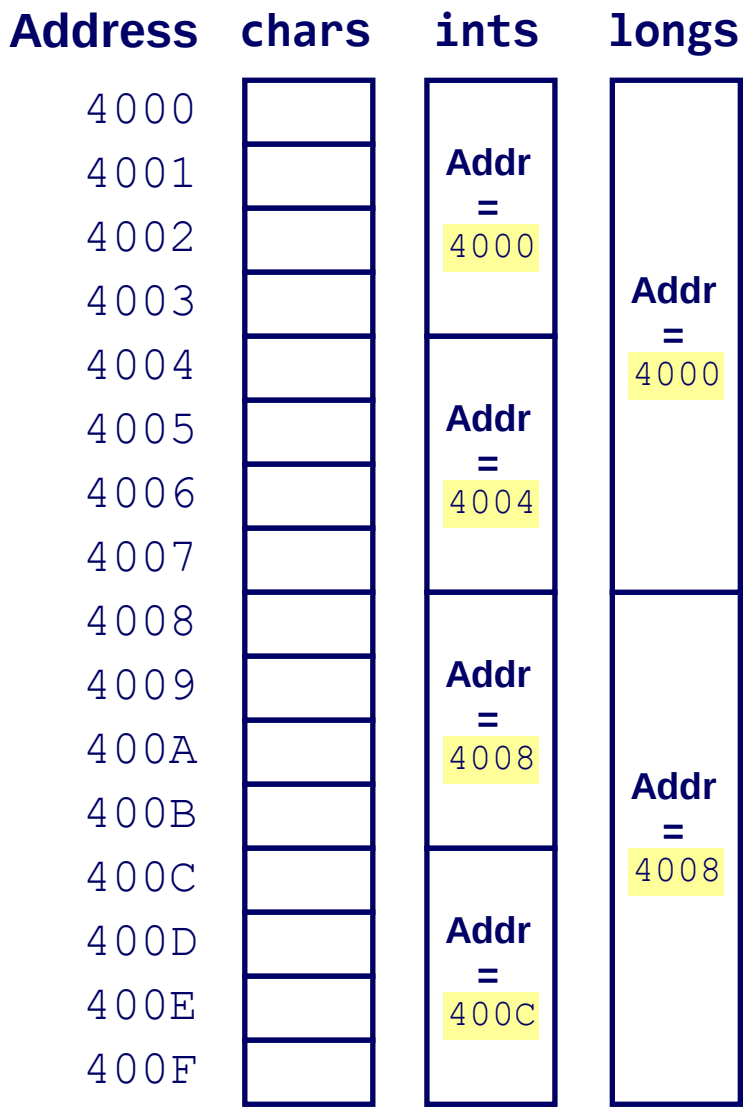
15-213/15-503: Introduction to Computer Systems
6th Lecture, May 22, 2025

Today

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

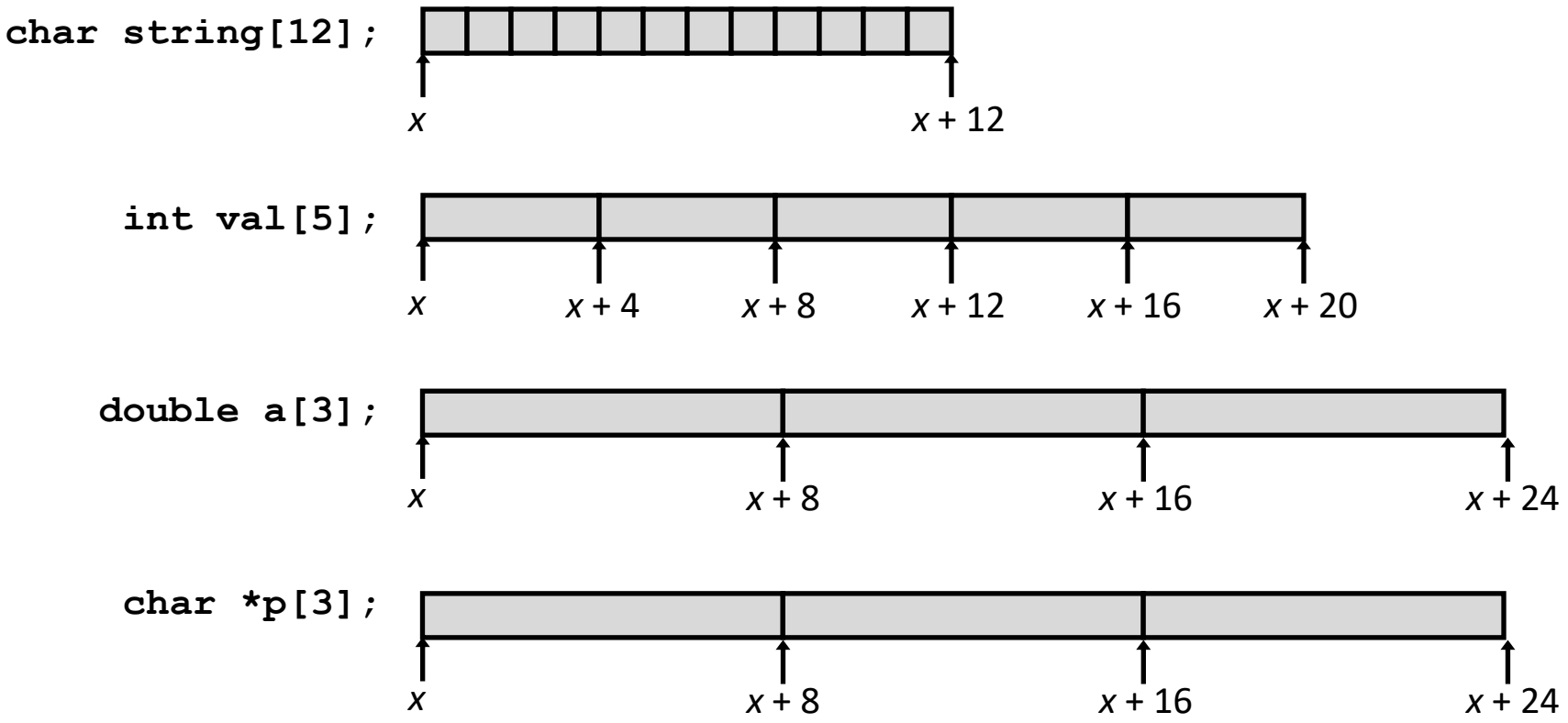
Reminder: Memory Organization

- **Memory locations do not have data types**
  - Types are implicit in how machine instructions *use* memory
- **Addresses specify byte locations**
  - Address of a larger datum is the address of its first byte
  - Addresses of successive items differ by the item's size



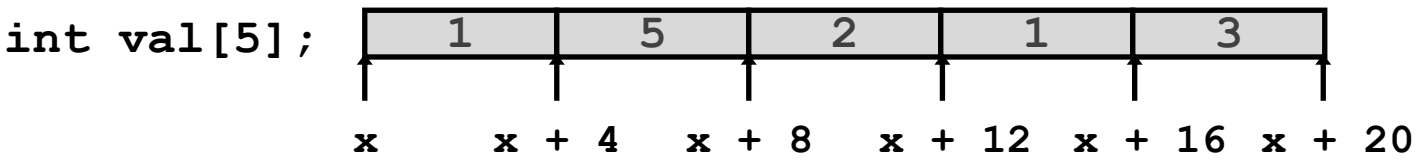
Array Allocation

- **C declaration *`Type`* `name[`*`Length`*`];`**
  - Array of data type *Type* and length *Length*
  - Contiguously allocated region of *Length* * **`sizeof`**`(`*Type*`)` bytes in memory



Array Access

- C declaration ***Type*** **name[*Length*];**
  - Array of data type *Type* and length *Length*
  - Identifier **name** acts like[1] a pointer to array element 0

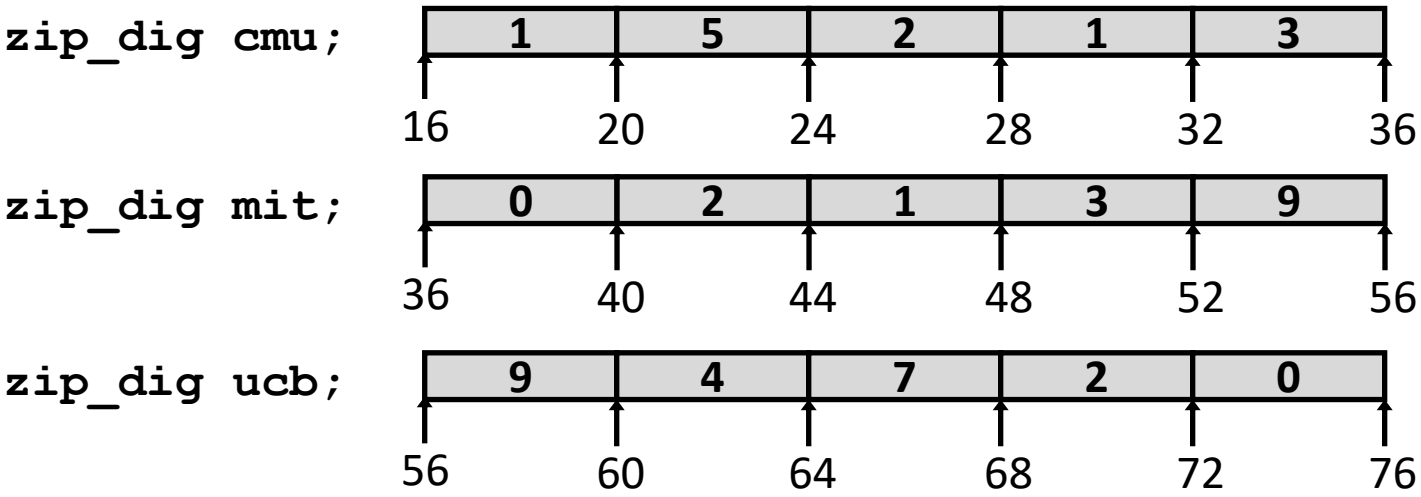


Expression	Type	Value	
`val[4]`	`int`	`3`	
`val[5]`	`int`	`??`	`// access past end`
`*(val+3)`	`int`	`1`	`// same as val[3]`
`val`	`int *`	`x`	
`val+1`	`int *`	`x + 4`	
`&val[2]`	`int *`	`x + 8`	`// same as val+2`
`val + i`	`int *`	`x + 4*i`	`// same as &val[i]`

[1] in most contexts (but not all)

Array Example

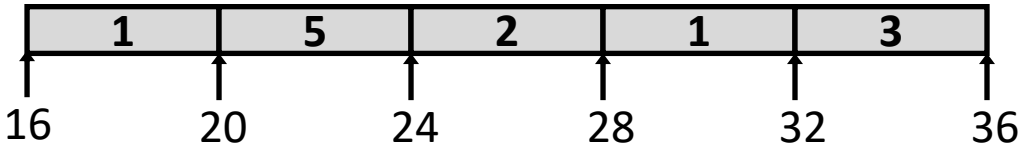
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

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



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

Array Accessing Example

```
zip_dig cmu;
```




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

x86-64

```
  # %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
  jmp     .L3
.L4:
  addl    $1, (%rdi,%rax,4)
  addq    $1, %rax
.L3:
  cmpq    $4, %rax
  jbe     .L4
  rep; ret
```

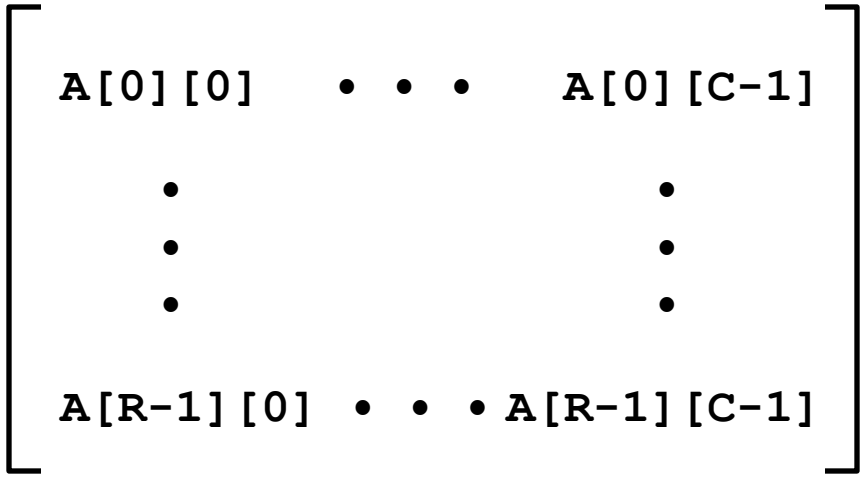
Array Loop Example

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

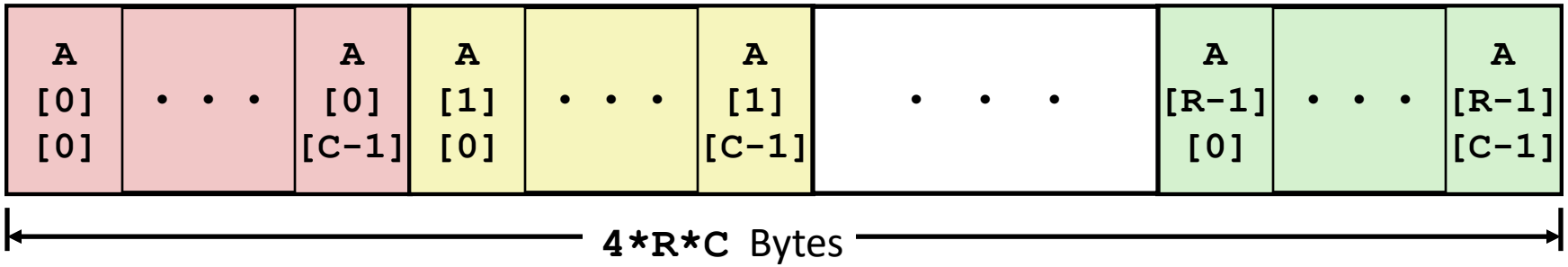
```
  # %rdi = z
  movl    $0, %eax            #   i = 0
  jmp     .L3                 #   goto middle
.L4:                          # loop:
  addl    $1, (%rdi,%rax,4)   #   z[i]++
  addq    $1, %rax            #   i++
.L3:                          # middle
  cmpq    $4, %rax            #   i:4
  jbe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

Multidimensional (Nested) Arrays

- **Declaration**
  - *T* **A**[*R*][*C*];
  - 2D array of data type *T*
  - *R* rows, *C* columns
- **Array Size**
  - *R* * *C* * **sizeof**(*T*) bytes
- **Arrangement**
  - Row-Major Ordering

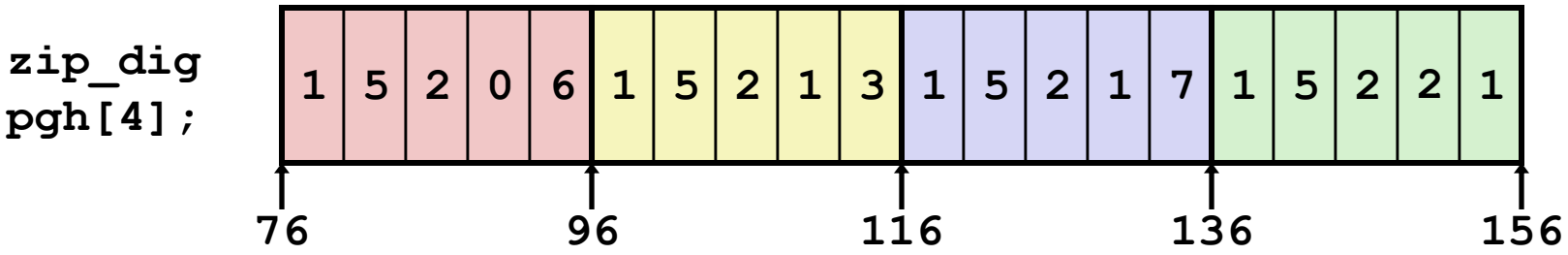


int A[R][C];



Nested Array Example

```
#define PCOUNT 4
typedef int zip_dig[5];

zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6 },
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

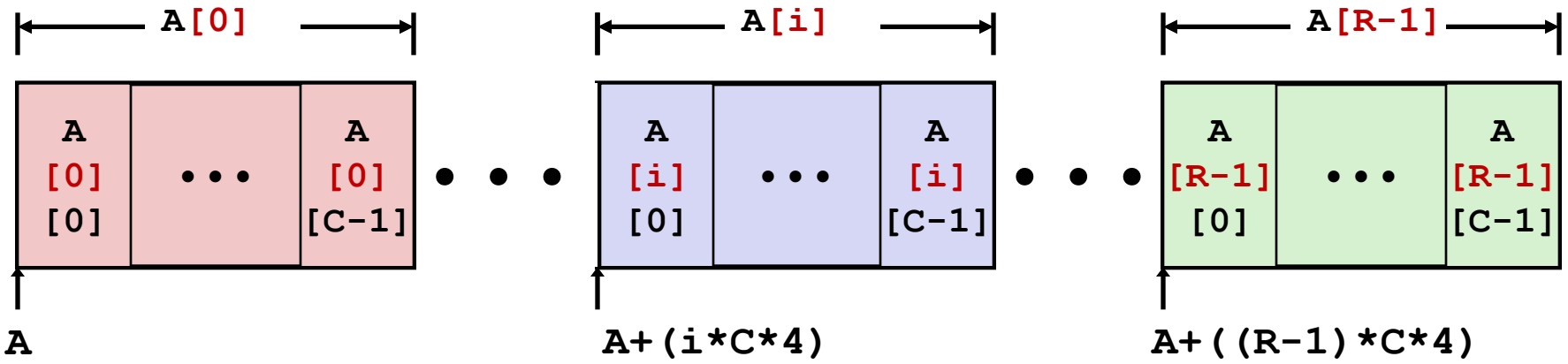


- **"`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"**
  - Variable **`pgh`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**'s, allocated contiguously
- **"Row-Major" ordering of all elements in memory**

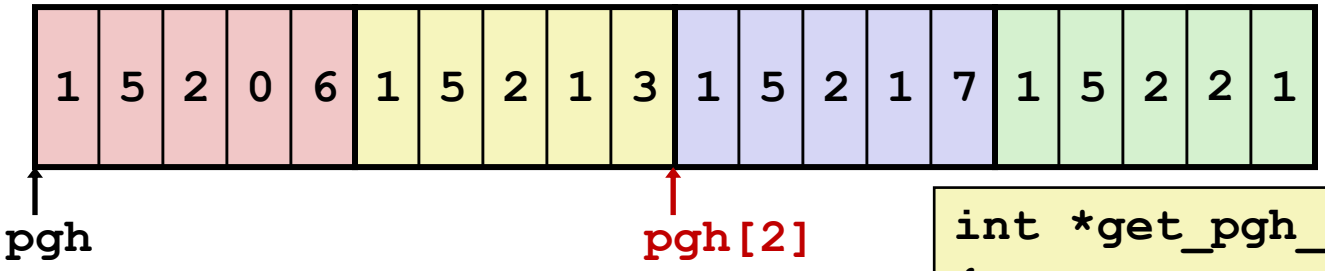
Nested Array Row Access

- **Row Vectors**
  - `A[i]` is array of *C* elements of type *T*
  - Starting address `A + i * (C * sizeof(`*T*`))`

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



Nested Array Row Access Code




```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

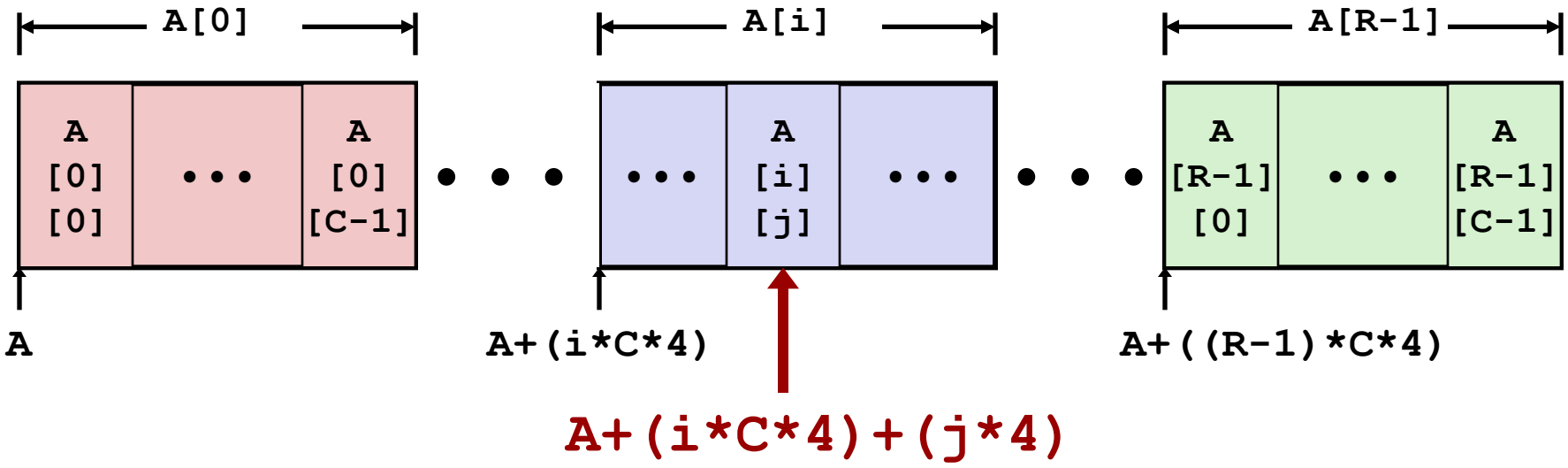
```
# %rdi = index
 leaq (%rdi,%rdi,4),%rax # 5 * index
 leaq pgh(,%rax,4),%rax  # pgh + (20 * index)
```

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

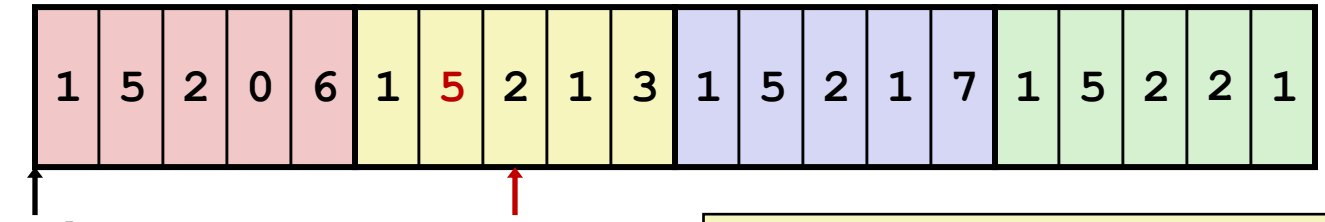
Nested Array Element Access

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

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



Nested Array Element Access Code




```
int get_pgh_digit(int index, int dig)
{
  return pgh[index][dig];
}
```

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

- **Array Elements**
  - `pgh[index][dig]` is `int`
  - Address: `pgh + 20*index + 4*dig`

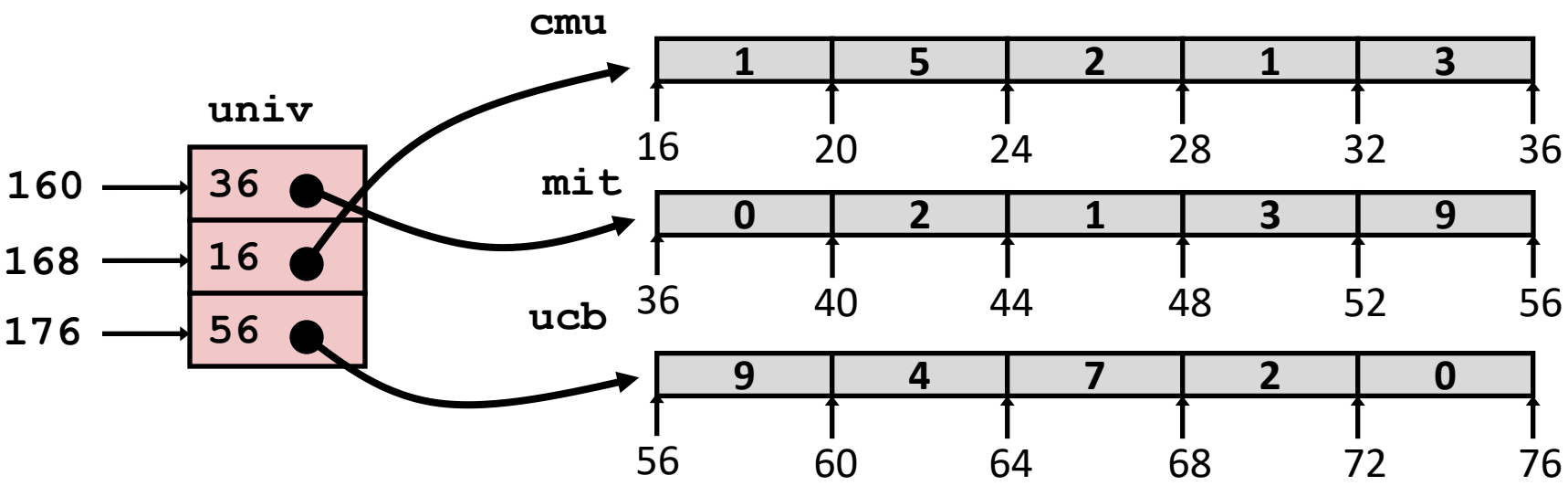
    `= pgh + 4*(5*index + dig)`

Multi-Level Array Example

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

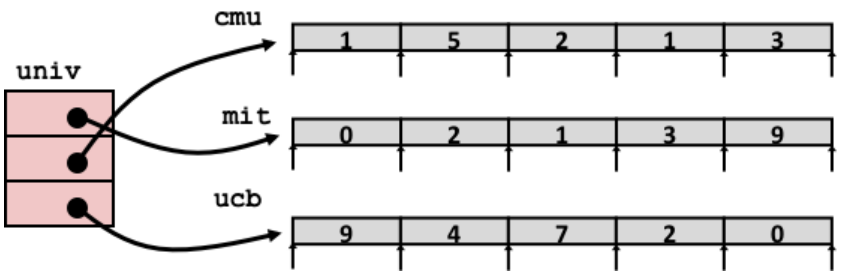
```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```

- Variable `univ` denotes 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_univ_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), %eax          # 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

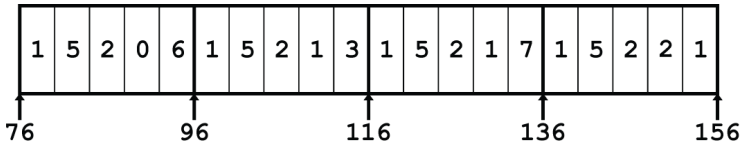
Array Element Accesses

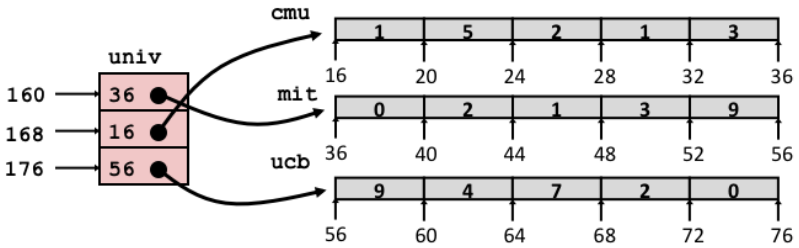
Nested array

```
int get_pgh_digit
   (size_t index, size_t digit)
{
  return pgh[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[pgh+20*index+4*digit]` **`Mem[Mem[univ+8*index]+4*digit]`**

N X *N* Matrix Code

- **Fixed dimensions**
  - Know value of *N* at compile time

- **Variable dimensions, explicit indexing**
  - Traditional way to implement dynamic arrays

- **Variable dimensions, implicit indexing**
  - Not in K&R; added to language in 1999

```
#define N 16
typedef int fix_matrix[N][N];
/* Get element A[i][j] */
int fix_ele(fix_matrix A,
            size_t i, size_t j)
{
  return A[i][j];
}
```

```
#define IDX(n, i, j) ((i)*(n)+(j))
/* Get element A[i][j] */
int vec_ele(size_t n, int *A,
            size_t i, size_t j)
{
  return A[IDX(n,i,j)];
}
```

```
/* Get element A[i][j] */
int var_ele(size_t n, int A[n][n],
            size_t i, size_t j) {
  return A[i][j];
}
```

16 X 16 Matrix Access

- **Array Elements**
  - `int A[16][16];`
  - Address `A + i * (C * K) + j * K`
  - C = 16, K = 4

```
/* Get element A[i][j] */
int fix_ele(fix_matrix A, size_t i, size_t j) {
  return A[i][j];
}
```

```
  # A in %rdi, i in %rsi, j in %rdx
  salq    $6, %rsi                # 64*i
  addq    %rsi, %rdi              # A + 64*i
  movl    (%rdi,%rdx,4), %eax     # Mem[A + 64*i + 4*j]
  ret
```

n X *n* Matrix Access

- **Array Elements**
  - `size_t n;`
  - `int A[n][n];`
  - Address `A + i * (C * K) + j * K`
  - C = n, K = 4
  - Must perform integer multiplication

```
/* Get element A[i][j] */
int var_ele(size_t n, int A[n][n], size_t i, size_t j)
{
  return A[i][j];
}
```

```
  # n in %rdi, A in %rsi, i in %rdx, j in %rcx
  imulq   %rdx, %rdi              # n*i
  leaq    (%rsi,%rdi,4), %rax     # A + 4*n*i
  movl    (%rax,%rcx,4), %eax     # Mem[A + 4*n*i + 4*j]
  ret
```

Example: Array Access

```
#include <stdio.h>
#define ZLEN 5
#define PCOUNT 4
typedef int zip_dig[ZLEN];

int main(int argc, char** argv) {
zip_dig pgh[PCOUNT] =
    {{1, 5, 2, 0, 6},
     {1, 5, 2, 1, 3 },
     {1, 5, 2, 1, 7 },
     {1, 5, 2, 2, 1 }};
    int *linear_zip = (int *) pgh;
    int *zip2 = (int *) pgh[2];
    int result =
        pgh[0][0] +
        linear_zip[7] +
        *(linear_zip + 8) +
        zip2[1];
    printf("result: %d\n", result);
    return 0;
}
```

```
linux> ./array
```

Example: Array Access

```
#include <stdio.h>
#define ZLEN 5
#define PCOUNT 4
typedef int zip_dig[ZLEN];

int main(int argc, char** argv) {
zip_dig pgh[PCOUNT] =
    {{1, 5, 2, 0, 6},
     {1, 5, 2, 1, 3 },
     {1, 5, 2, 1, 7 },
     {1, 5, 2, 2, 1 }};
    int *linear_zip = (int *) pgh;
    int *zip2 = (int *) pgh[2];
    int result =
        pgh[0][0] +
        linear_zip[7] +
        *(linear_zip + 8) +
        zip2[1];
    printf("result: %d\n", result);
    return 0;
}
```

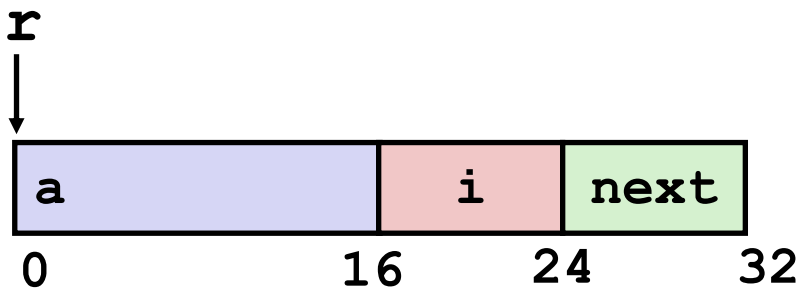
```
linux> ./array
result: 9
```

Today

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

Structure Representation

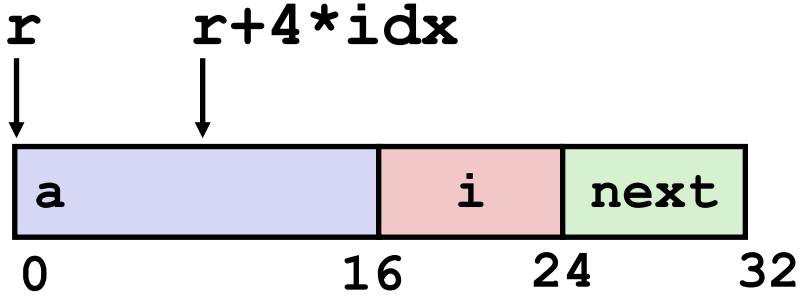
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- Structure represented as block of memory
  - Big enough to hold all the fields
- Fields ordered according to declaration
  - Even if another ordering could be more compact
- Compiler determines overall size + positions of fields
  - In assembly, we see only offsets, not field names

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];
}
```

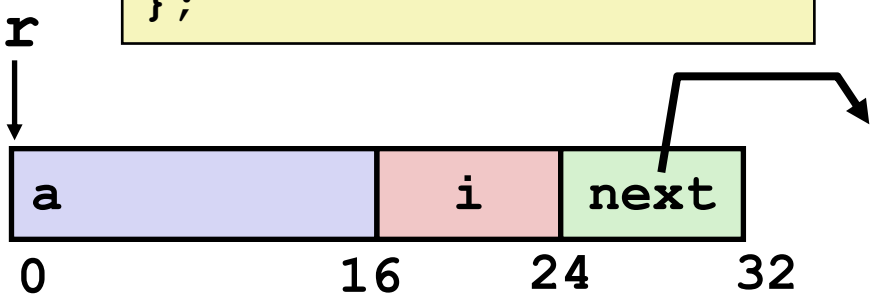
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Following Linked List #1

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

- C Code

```
long length(struct rec*r) {
    long len = 0L;
    while (r) {
        len ++;
        r = r->next;
    }
    return len;
}
```



Register	Value
%rdi	r
%rax	len

- Loop assembly code

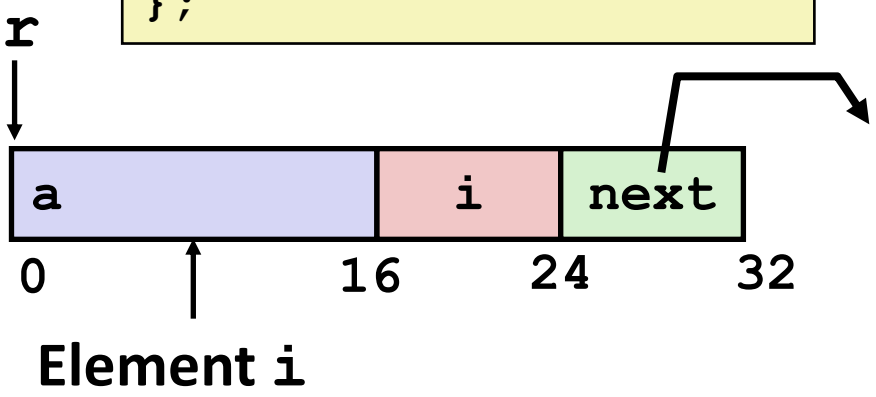
```
.L11:                           # loop:
  addq    $1, %rax              #   len ++
  movq    24(%rdi), %rdi        #   r = Mem[r+24]
  testq   %rdi, %rdi            #   Test r
  jne     .L11                  #   If != 0, goto loop
```

Following Linked List #2

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

- C Code

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    size_t i = r->i;
    // No bounds check
    r->a[r->i] = val;
    r = r->next;
  }
}
```

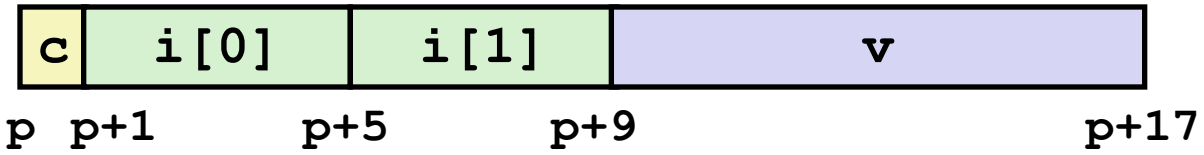


Register	Value
%rdi	r
%rsi	val

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

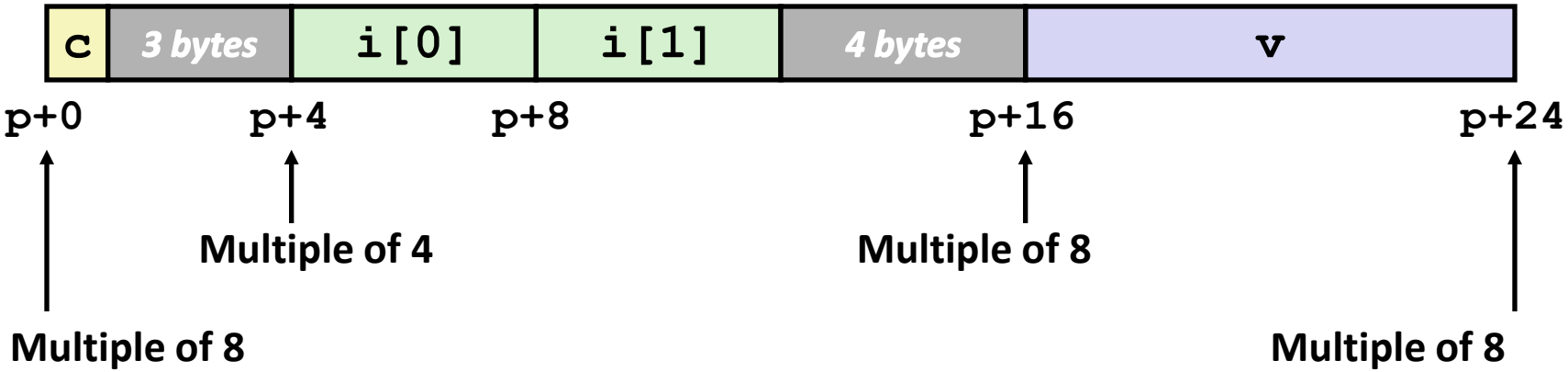
Structures & Alignment

- **Unaligned Data**




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

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



Alignment Principles

- **Aligned Data**
  - Primitive data type requires ***B*** bytes
  - Address must be multiple of ***B***
  - 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 cache lines (64 bytes). Intel states should avoid crossing 16 byte boundaries.

      [Cache lines will be discussed in Lecture 10.]
    - Virtual memory trickier when datum spans 2 pages (4 KB pages)

      [Virtual memory pages will be discussed in Lecture 17.]
- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields

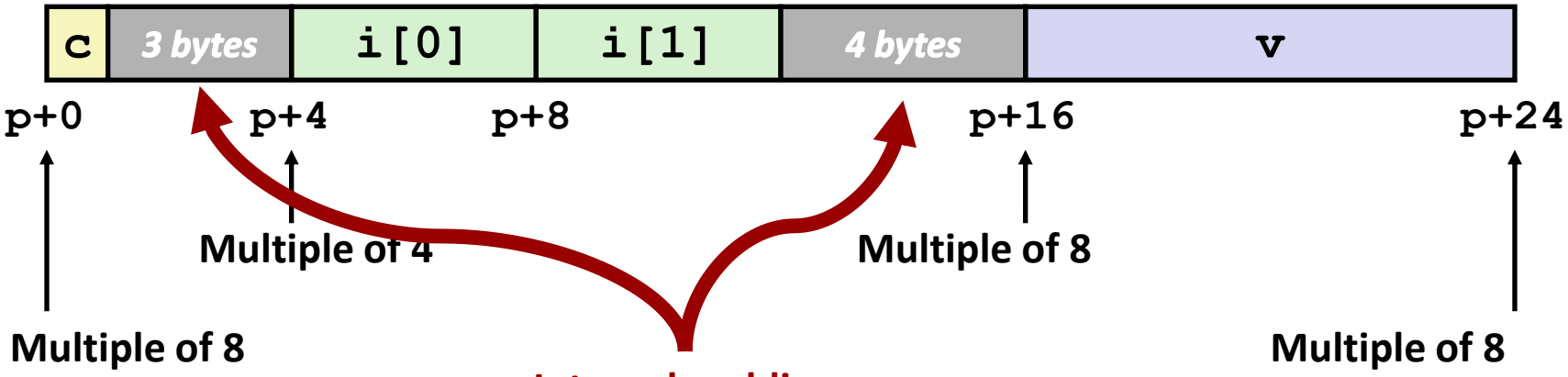
Specific Cases of Alignment (x86-64)

- **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
    NOTE: K < sizeof(struct S1)

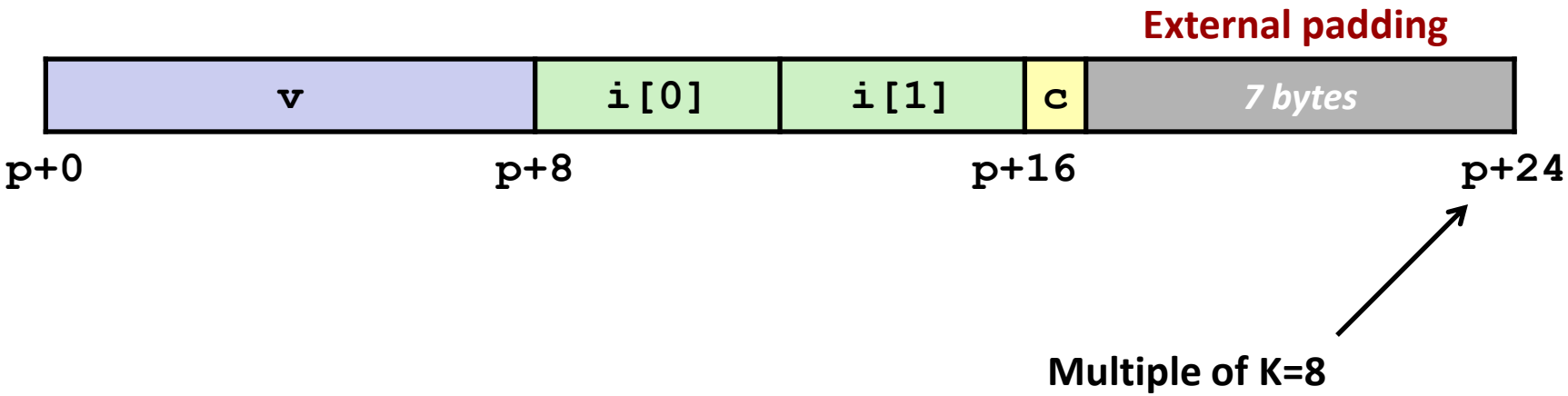
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

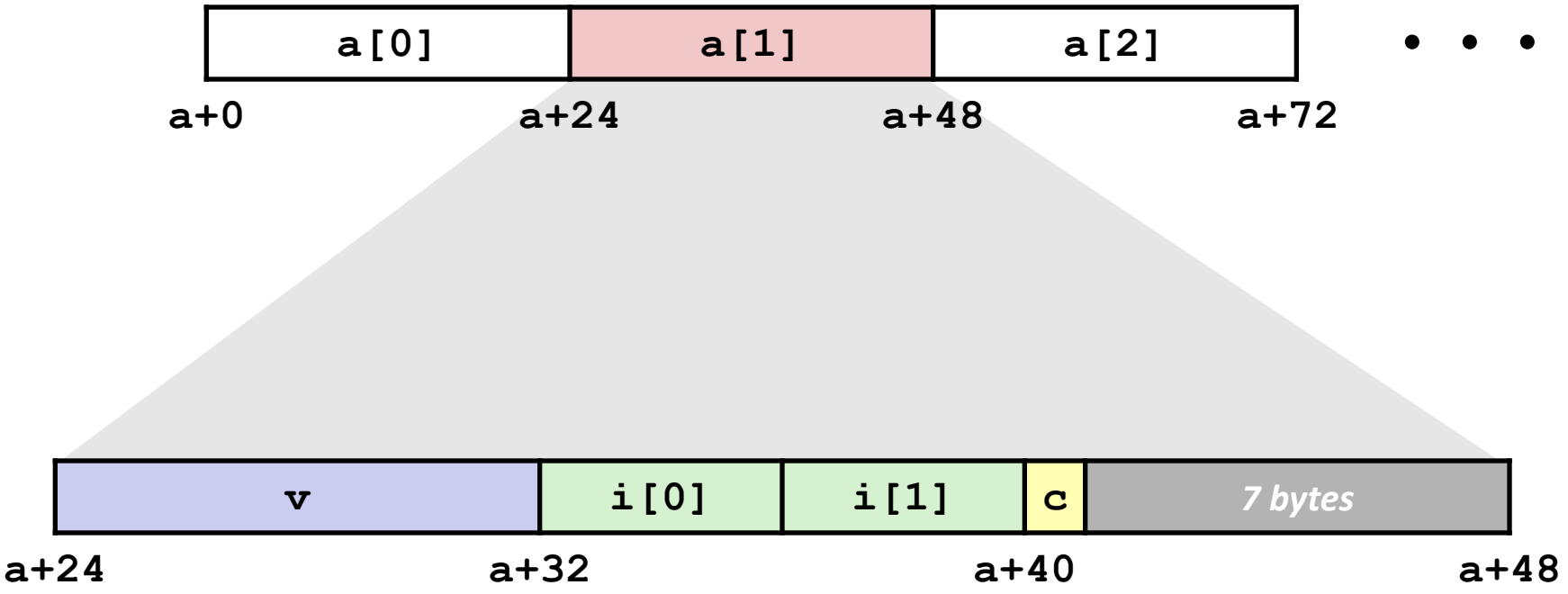
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

- No padding in between array elements
- Overall structure length multiple of K
- Satisfy alignment requirement for every element

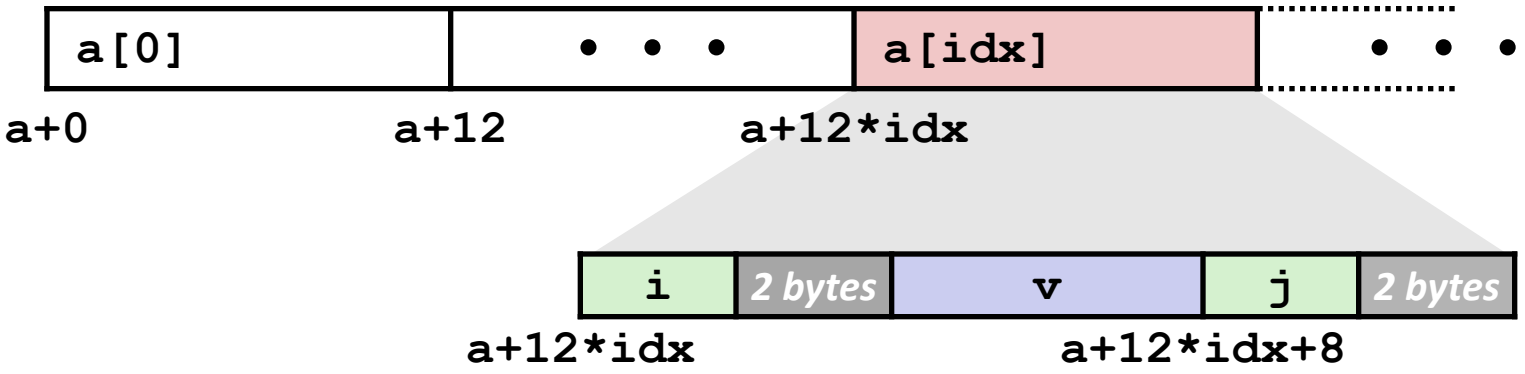
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

```
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




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

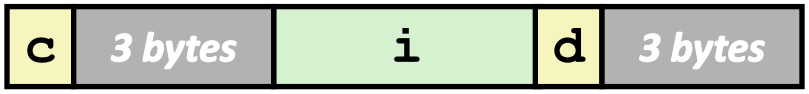
```
# %rdi = idx
leaq (%rdi,%rdi,2),%rax # 3*idx
movzwl a+8(,%rax,4),%eax
```

Saving Space

- Put large data types first

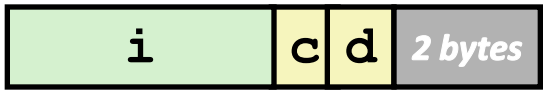
```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

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



12 bytes

- Effect (largest alignment requirement K=4)



8 bytes

Quiz

https://canvas.cmu.edu/courses/47415/quizzes/143261

Saving Space

- Put small data types first

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

```
struct S6 {
  char c;
  char d;
  int i;
} *p;
```

12 bytes

- Effect (largest alignment requirement K=4)

8 bytes

Saving Space

- **Space is reduced so long as fields are ordered by size**

- **Why doesn't the compiler do this?**
  - The compiler has to follow the field order
  - There can be other reasons for specific orders:
    - Programmer understanding
    - Commonly accessed fields near each other

Putting it Together

- How large is struct S7?

```
struct S6 {
  short s;
  char t[3];
};
```

```
struct S7 {
  struct S6 st;
  char c;
};
```

Today

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

Summary

- **Arrays**
  - Elements packed into contiguous region of memory
  - Use index arithmetic to locate individual elements
- **Structures**
  - Elements packed into single region of memory
  - Access using offsets determined by compiler
  - Possible require internal and external padding to ensure alignment
- **Combinations**
  - Can nest structure and array code arbitrarily
- **Floating Point**
  - Data held and operated on in XMM registers

Today

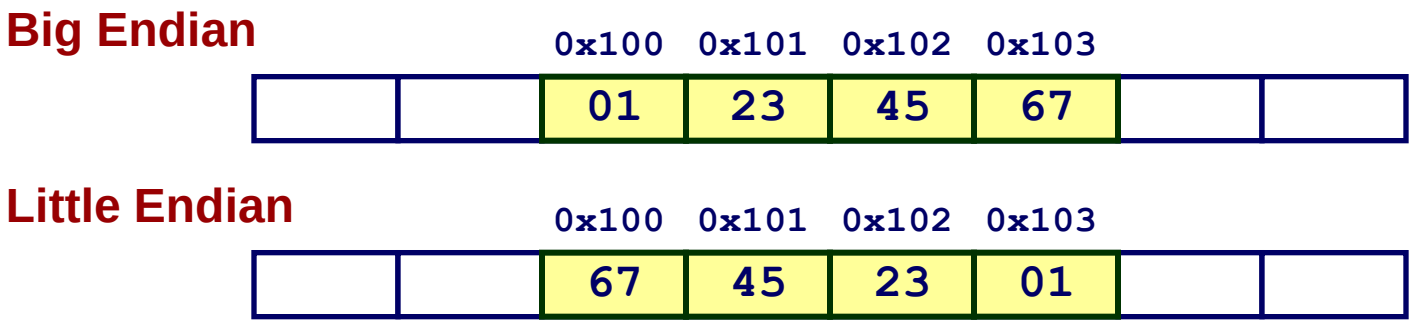
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **Byte Ordering**

Byte Ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
- **Conventions**
  - Big Endian: Sun (Oracle SPARC), PPC Mac, *Internet*
    - Least significant byte has highest address
  - Little Endian: *x86*, ARM processors running Android, iOS, and Linux
    - Least significant byte has lowest address
- **Becomes a concern when data is communicated**
  - Over a network, via files, etc.
- **Important notes**
  - Bits are not reversed, as the low order bit is the reference point.
  - Doesn't affect chars, or strings (arrays of chars), as chars are only one byte

Byte Ordering Example

- **Example**
  - Variable x has 4-byte value of 0x01234567
  - Address given by &x is 0x100



Reading Byte-Reversed Listings

- **Disassembly**
  - Text representation of binary machine code
  - Generated by program that reads the machine code
- **Example Fragment**

Address	Instruction Code	Assembly Rendition
8048365	5b	pop %ebx
8048366	81 c3 ab 12 00 00	add $0x12ab,%ebx
804836c	83 bb 28 00 00 00 00	cmpl $0x0,0x28(%ebx)

- **Deciphering Numbers**
  - Value: 0x12ab
  - Pad to 32 bits: 0x000012ab
  - Split into bytes: 00 00 12 ab
  - Order by lsb: ab 12 00 00