Machine-Level Programming IV: Data

15-213: Introduction to Computer Systems
8th Lecture, June 1, 2022

Instructor:

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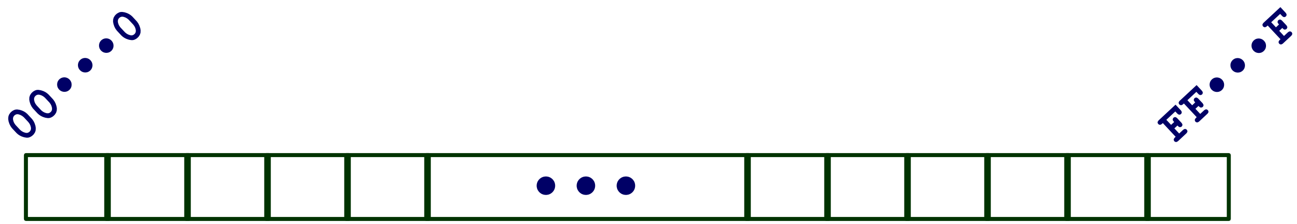
Today

- **Partial recap: Integers**
  - Word size
  - Addresses
  - Endianness
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **If we have time: Floating point and SIMD**

Byte-Oriented Memory Organization



- **Programs refer to data by address**
  - Imagine all of RAM as an enormous array of bytes
  - An address is an index into that array
    - A pointer variable stores an address
- **System provides a private *address space* to each "process"**
  - A process is an instance of a program, being executed
  - An address space is one of those enormous arrays of bytes
  - Each program can see only its own code and data within its enormous array
  - We'll come back to this later ("virtual memory" classes)

Machine Words

- **Any given computer has a "Word Size"**
  - Nominal size of integer-valued data
    - and of addresses
  - Until recently, most machines used 32 bits (4 bytes) as word size
    - Limits addresses to 4GB (2^{32} bytes)
  - Increasingly, machines have 64-bit word size
    - Potentially, could have 16 EB (exabytes) of addressable memory
    - That's 18.4×10^{18} bytes
  - Machines still support multiple data formats
    - Fractions or multiples of word size
    - Always integral number of bytes

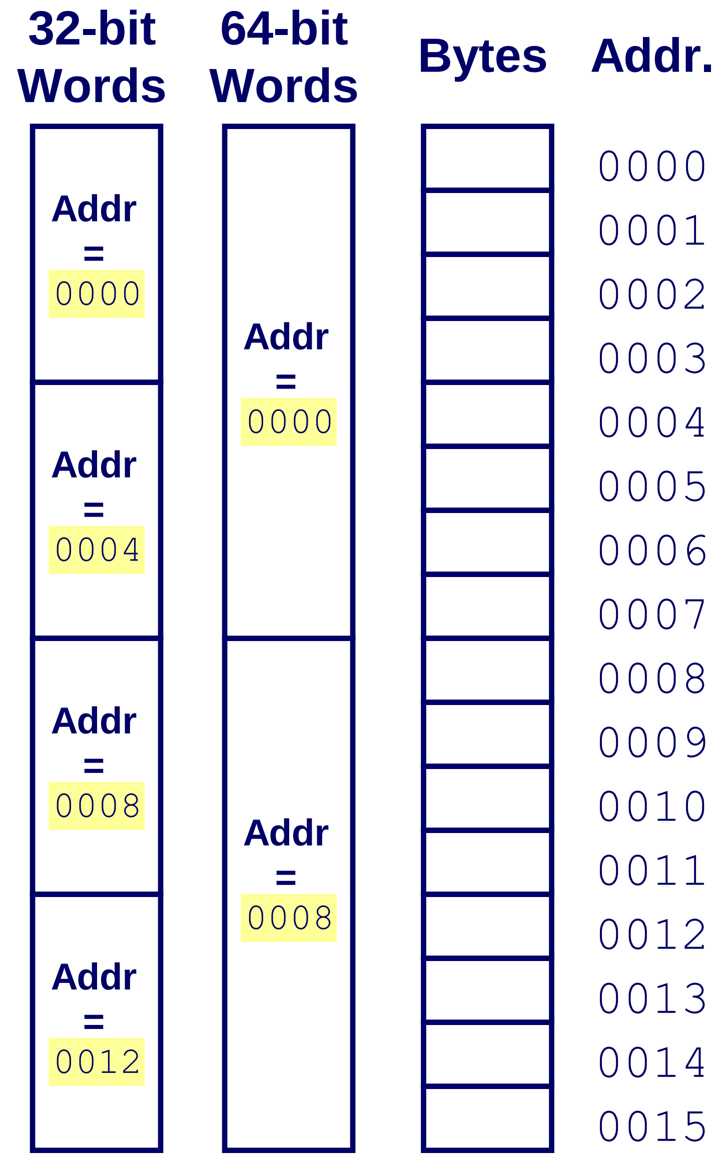
Yes, both of these numbers are correct.

This discrepancy is known as the Great Storage Industry Marketing Lie.

Ask me about it after class if you really want to know.

Addresses *Always* Specify Byte Locations

- Address of a word is address of the first byte in the word
- Addresses of successive words differ by 4 (32-bit) or 8 (64-bit)

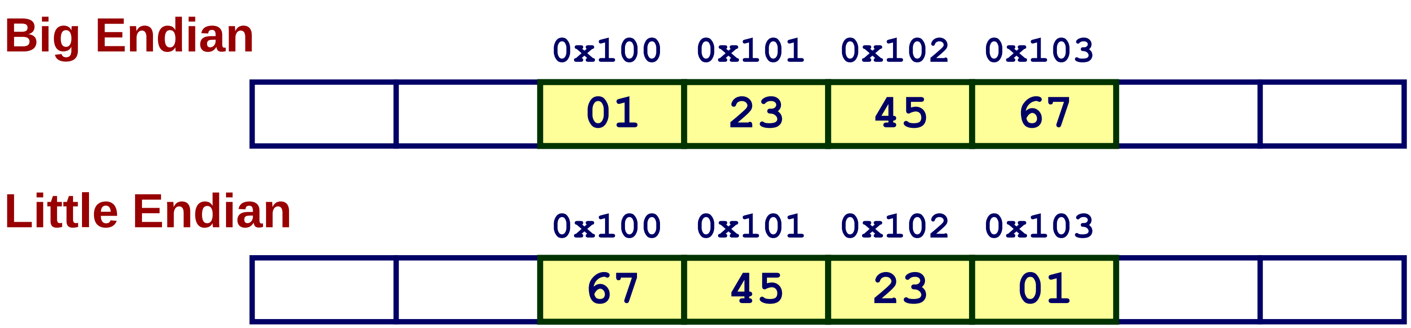


Byte Ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
- **Conventions**
  - Big Endian: Sun, PPC Mac, *network packet headers*
    - Least significant byte has highest address
  - Little Endian: *x86*, ARM processors running Android, iOS, and Windows
    - Least significant byte has lowest address

Byte Ordering Example

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



Examining Data Representations

- **Code to Print Byte Representation of Data**
  - Casting pointer to unsigned char * allows treatment as a byte array

```
void show_bytes(unsigned char *start, size_t len){
    size_t i;
    for (i = 0; i < len; i++) {
        printf("%p\t%.2x\n",
                (void *)&start[i], start[i]);
    }
}
```

Printf directives:

%p: Print pointer (must be void *)

%.2x: Print integer in hexadecimal, with at least two digits

show_bytes Execution Example

```
int a = 15213;
printf("int a = %d;\n", a);
show_bytes((unsigned char *) &a, sizeof(int));
```

Result (Linux x86-64):

```
int a = 15213;
0x7fffb7f71dbc    6d
0x7fffb7f71dbd    3b
0x7fffb7f71dbe    00
0x7fffb7f71dbf    00
```

Representing Pointers

```
int B = -15213;
int *P = &B;
```

Sun	IA32	x86-64
EF	AC	3C
FF	28	1B
FB	F5	FE
2C	FF	82
		FD
		7F
		00
		00

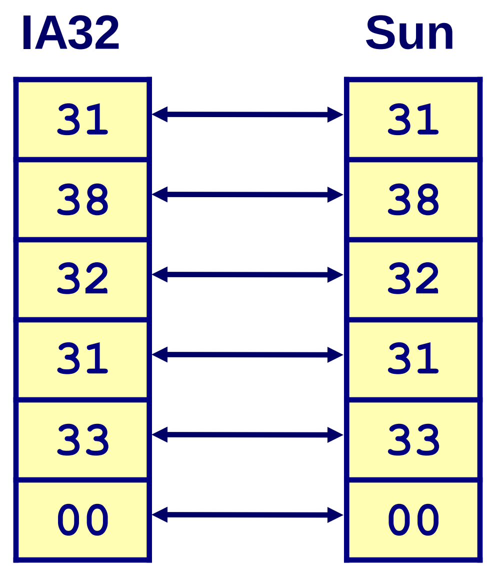
Different compilers & machines assign different locations to objects

May even get different results each time program is run (ASLR)

Representing Strings

```
char S[6] = "18213";
```

- **Strings in C**
  - Represented by array of characters
  - Each character encoded in ASCII format
    - Standard 7-bit encoding of character set
    - Character “0” has code 0x30
      - Digit *i* has code 0x30+*i*
  - String should be null-terminated
    - Final character = 0
- **Compatibility**
  - Byte ordering not an issue



A note about x86 machine code

- **x86 machine code is a sequence of *bytes***
  - Grouped into variable-length instructions, which look like strings…
  - But they contain embedded little-endian numbers…
- **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`
  - Reverse: `ab 12 00 00`

A peek at x86 instruction encoding

and its long, complex history

64-bit mode…

```
      88 0f    mov  %cl,   (%rdi)
66    89 0f    mov  %cx,   (%rdi)
      89 0f    mov  %ecx,  (%rdi)
   48 89 0f    mov  %rcx,  (%rdi)
   44 88 0f    mov  %r9b,  (%rdi)
66 44 89 0f    mov  %r9w,  (%rdi)
   44 89 0f    mov  %r9d,  (%rdi)
   4c 89 0f    mov  %r9,   (%rdi)
```

Operand size
= 16 bits

REX prefix:
adjust sizes and
register numbers

Primary opcode:
MOV reg → mem
+ some operand size info

ModRM byte:
cx/r9, di,
"addressing mode"

Same bytes interpreted in 32-bit mode…

```
   88 0f    mov  %cl,   (%edi)
66 89 0f    mov  %cx,   (%edi)
   89 0f    mov  %ecx,  (%edi)
   48       dec  %eax
   44       inc  %esp
66 44       inc  %sp
   4c       dec  %esp
```

Address size
changes to 32 bits

REX becomes
a set of primary
opcodes

and 16-bit mode …

```
   88 0f    mov  %cl,   (%bx)
66 89 0f    mov  %ecx,  (%bx)
   89 0f    mov  %cx,   (%bx)
   44       inc  %sp
66 44       inc  %esp
```

Address size
changes to 16 bits,
register numbering
is different

Now means:
Operand size
= **32** bits

Today

- **Partial recap: Integers**
  - Word size
  - Addresses
  - Endianness
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **If we have time: Floating point and SIMD**

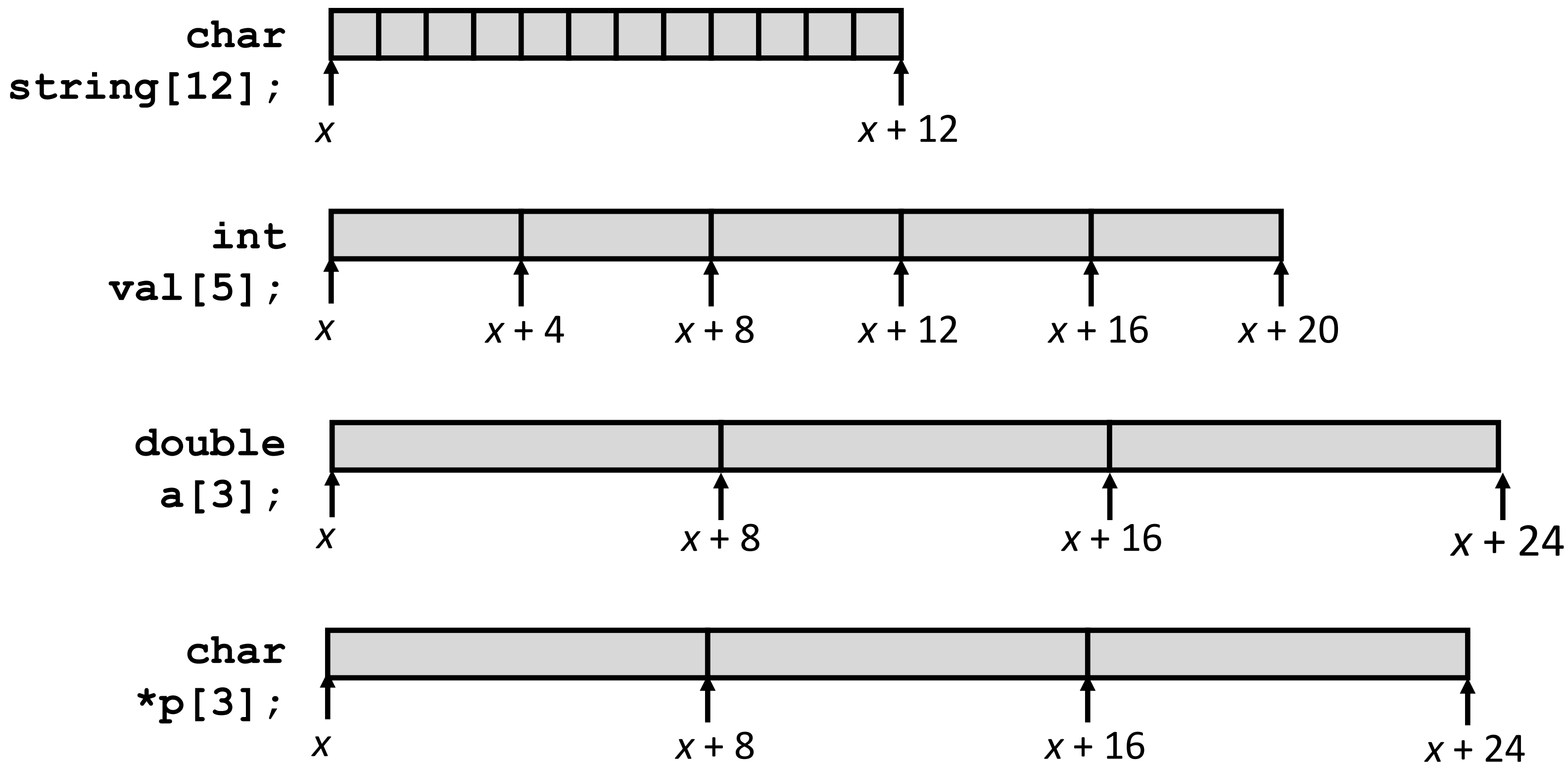
Activity break:
pick a partner (just one other student this time),
get handout
(https://www.cs.cmu.edu/afs/cs/academic/class/15213-m22/www/activities/213_lecture8.pdf),
do part 1 and 2.1

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



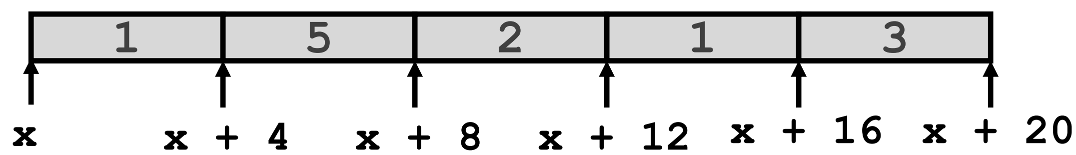
Array Access

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];`



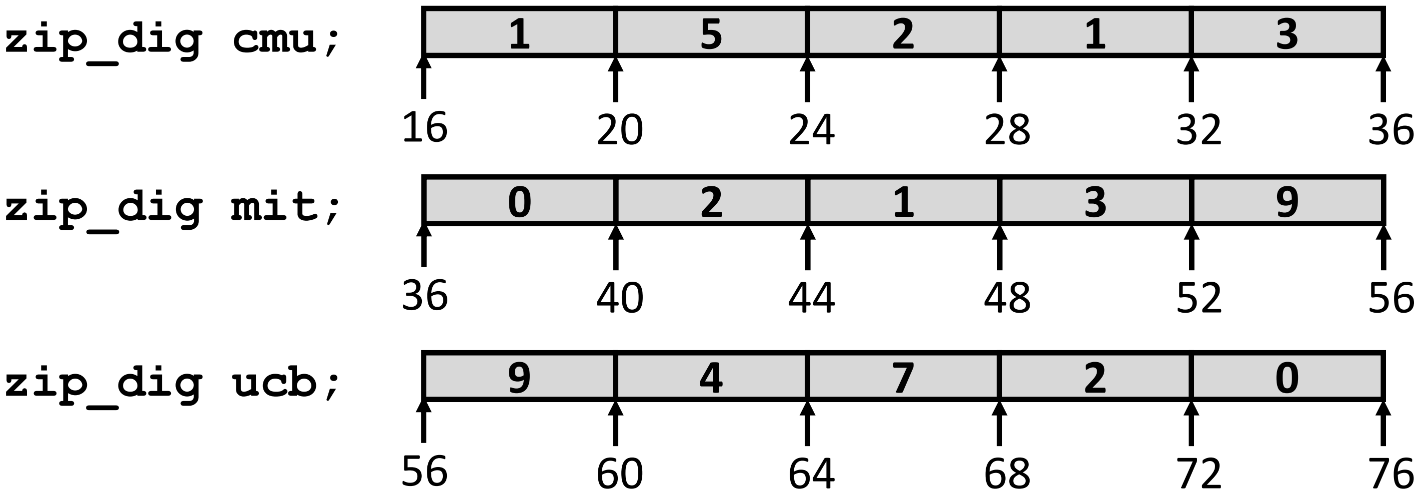
Reference Type Value

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`	`5 //val[1]`
`val + i`	`int *`	`x + 4 * i //&val[i]`

Array Example

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

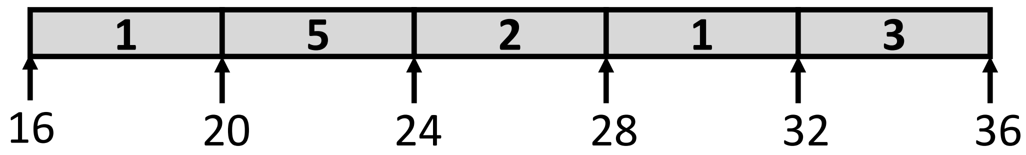
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- **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)`

Understanding Pointers & Arrays #1

Decl	*An*			***An**		
	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`						
`int *A2`						

- **Cmp: Compiles (Y/N)**
- **Bad: Possible bad pointer reference (Y/N)**
- **Size: Value returned by `sizeof`**

Understanding Pointers & Arrays #1

Decl	`An`			`*An`		
	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`	Y	N	12	Y	N	4
`int *A2`	Y	N	8	Y	Y	4

- **Cmp: Compiles (Y/N)**
- **Bad: Possible bad pointer reference (Y/N)**
- **Size: Value returned by `sizeof`**

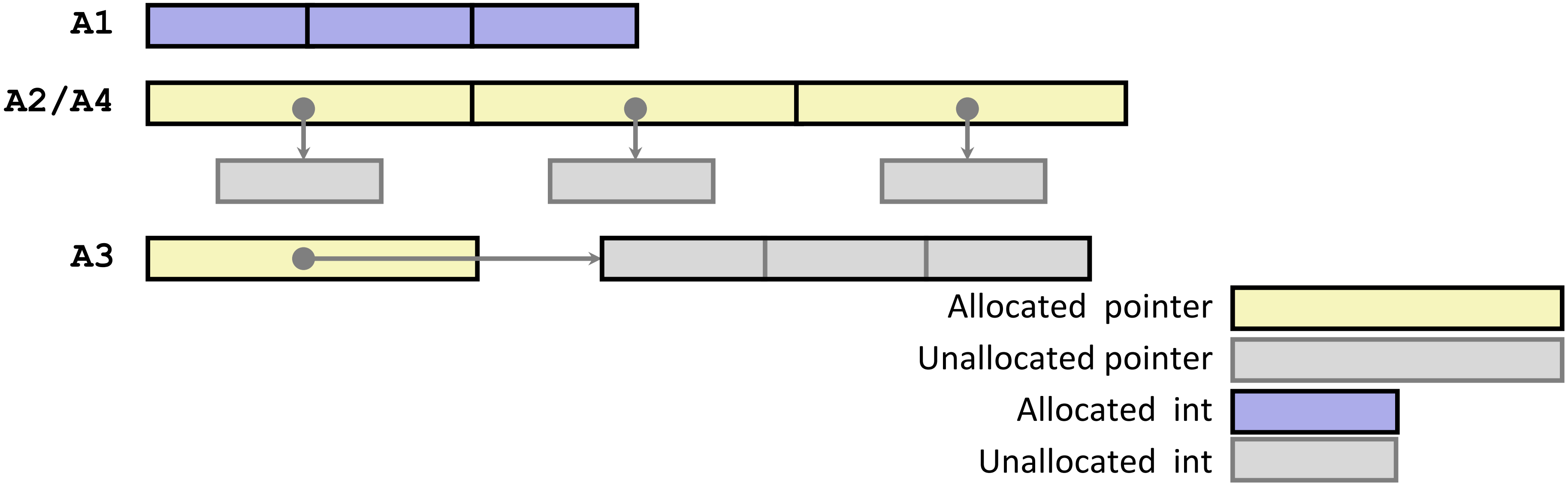
Understanding Pointers & Arrays #2

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`									
`int *A2[3]`									
`int (*A3)[3]`									
`int (*A4[3])`									

- **Cmp: Compiles (Y/N)**
- **Bad: Possible bad pointer reference (Y/N)**
- **Size: Value returned by `sizeof`**

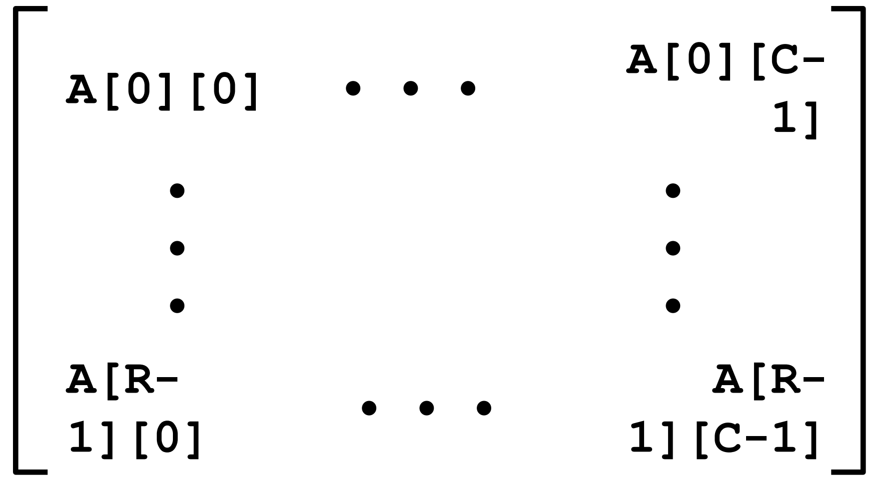
Understanding Pointers & Arrays #2

Decl	*An*			***An**			****An**		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3]`	Y	N	12	Y	N	4	N	-	-
`int *A2[3]`	Y	N	24	Y	N	8	Y	Y	4
`int (*A3)[3]`	Y	N	8	Y	Y	12	Y	Y	4
`int (*A4[3])`	Y	N	24	Y	N	8	Y	Y	4

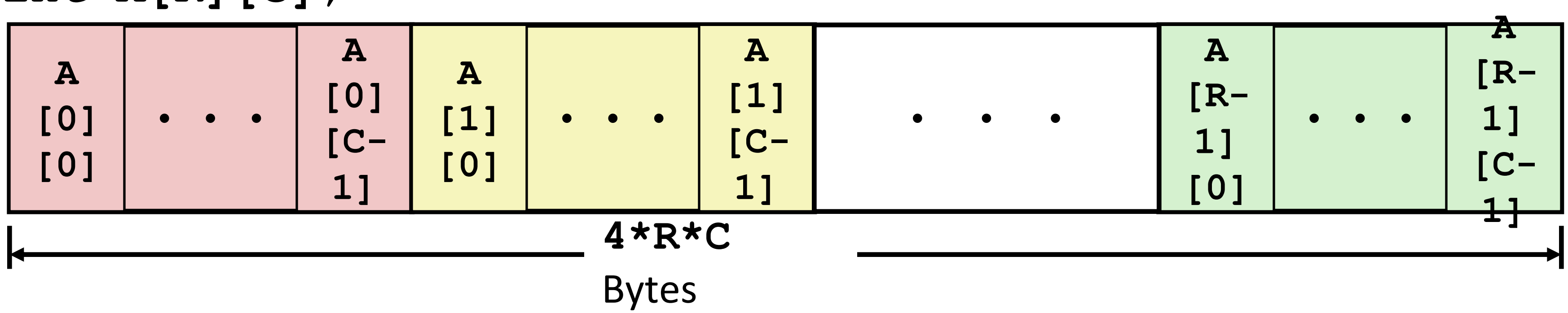


Multidimensional (Nested) Arrays

- **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



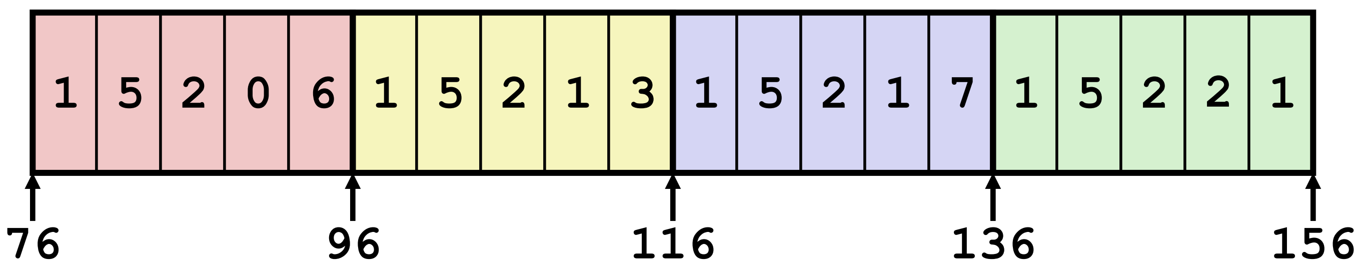
`int A[R][C];`



Nested Array Example

```
#define PCOUNT 4
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];
```

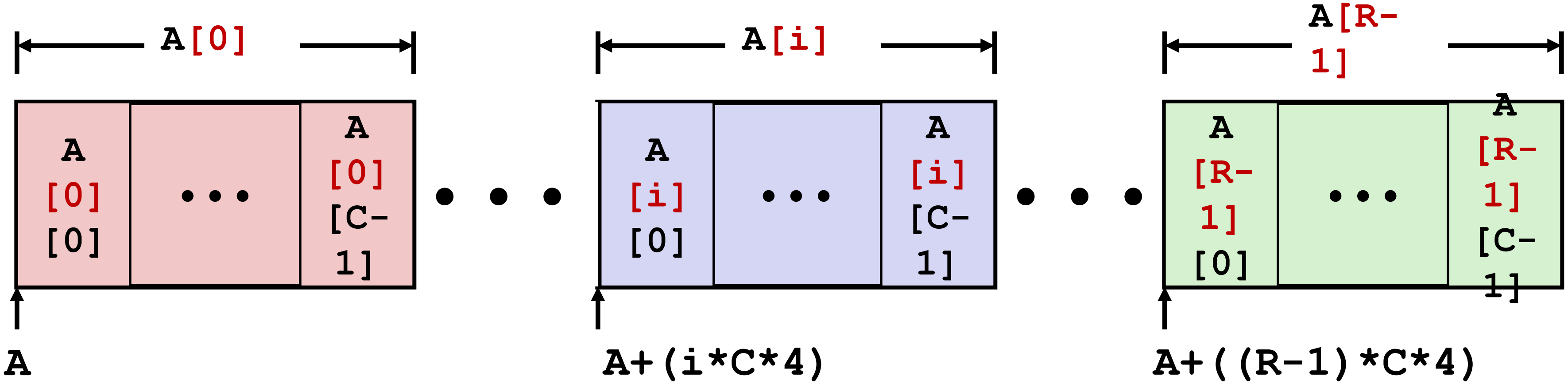


- "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable **`pgh`**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **`int`**'s, allocated contiguously
- "Row-Major" ordering of all elements in memory

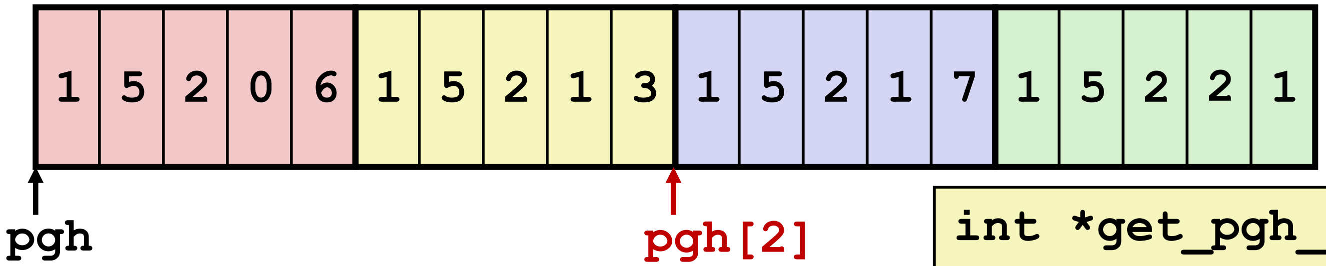
Nested Array Row Access

- **Row Vectors**
  - **`A[i]`** is array of *C* elements
  - Each element of type *T* requires *K* bytes
  - Starting address **`A + i * (C * K)`**

```
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**

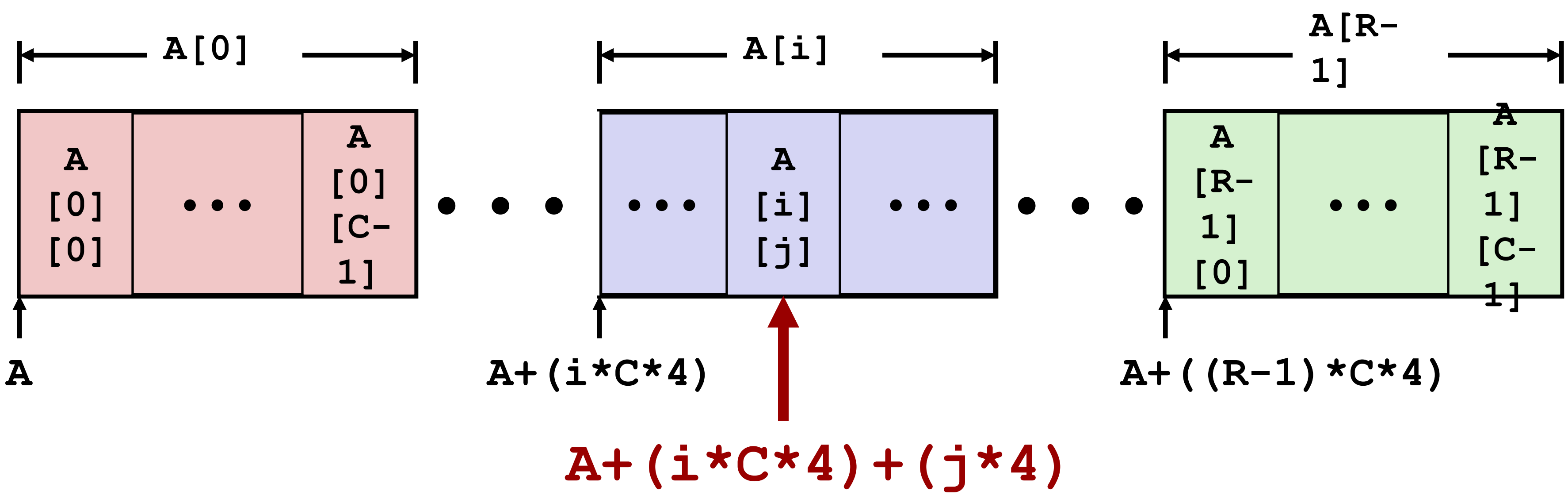
Machine Code
- Computes and returns address
- Compute as **pgh + 4*(index+4*index)**

Nested Array Element Access

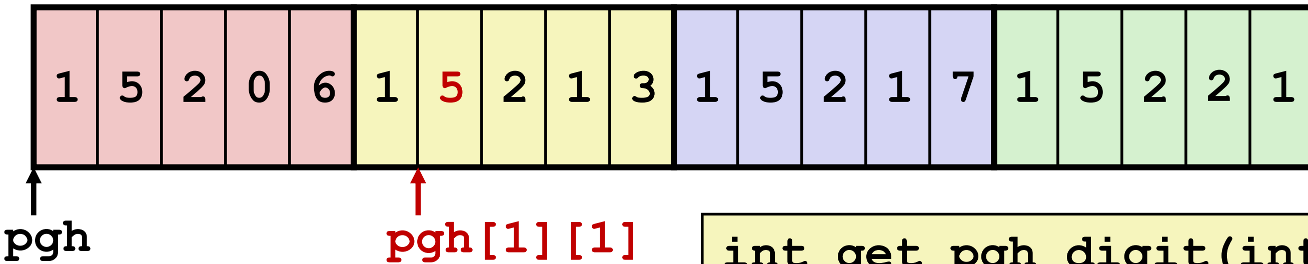
Array Elements

- `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`

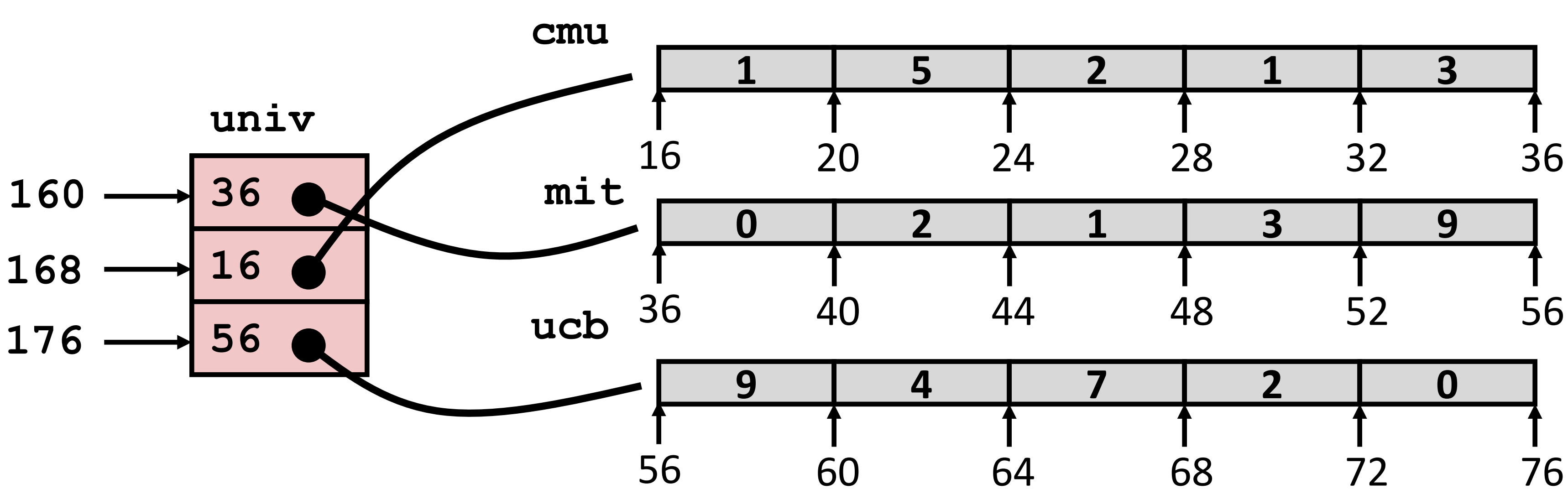
    = `pgh + 4*(5*index + dig)`

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 };
```

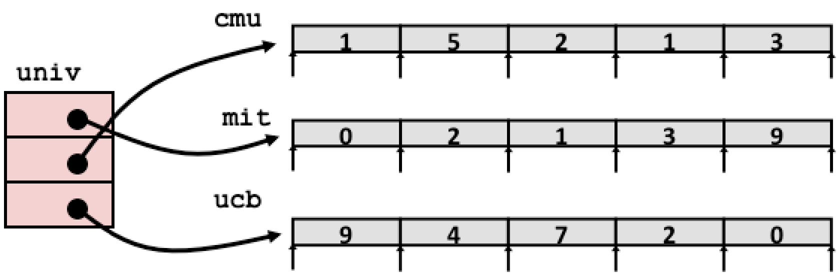
```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```

- **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

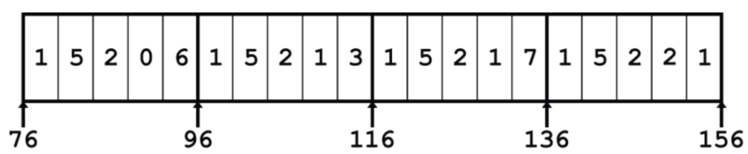
Array Element Accesses

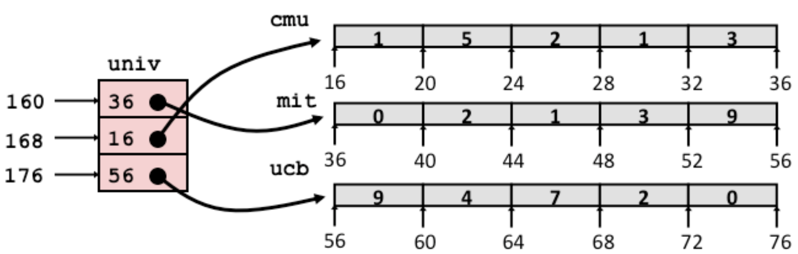
Nested array

```
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

```
#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];
}
```

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

```
#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)];
}
```

- **Variable dimensions, implicit indexing**
  - "New" feature in C99

```
/* 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];
}
```

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
```

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;
}
```

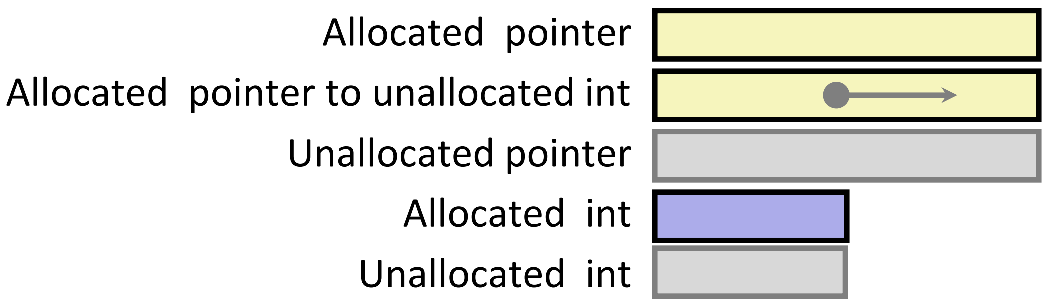
```
linux> ./array
result: 9
```

Understanding Pointers & Arrays #3

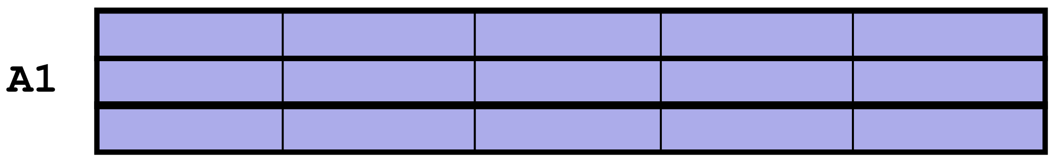
Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`									
`int *A2[3][5]`									
`int (*A3)[3][5]`									
`int *(A4[3][5])`									
`int (*A5[3])[5]`									

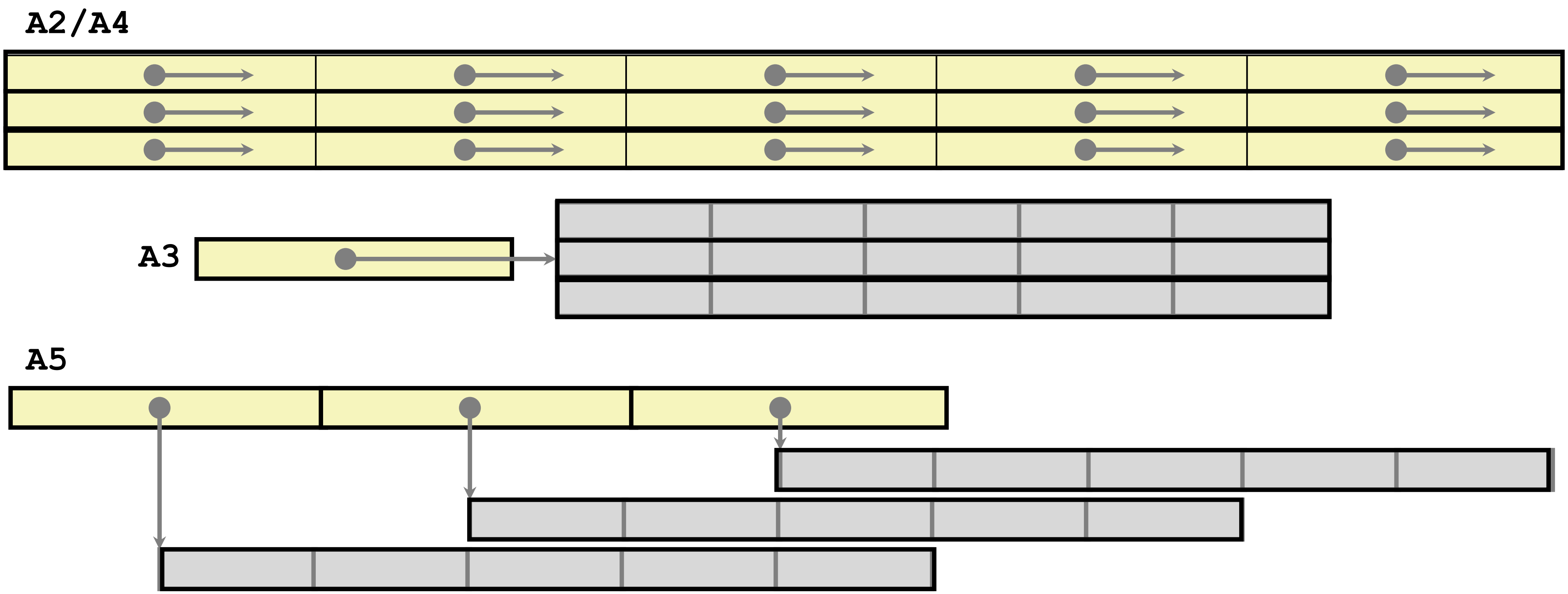
- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

Decl	***An		
	Cmp	Bad	Size
`int A1[3][5]`			
`int *A2[3][5]`			
`int (*A3)[3][5]`			
`int *(A4[3][5])`			
`int (*A5[3])[5]`			



Declaration
`int A1[3][5]`
`int *A2[3][5]`
`int (*A3)[3][5]`
`int *(A4[3][5])`
`int (*A5[3])[5]`





Understanding Pointers & Arrays #3

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`	Y	N	60	Y	N	20	Y	N	4
`int *A2[3][5]`	Y	N	120	Y	N	40	Y	N	8
`int (*A3)[3][5]`	Y	N	8	Y	Y	60	Y	Y	20
`int *(A4[3][5])`	Y	N	120	Y	N	40	Y	N	8
`int (*A5[3])[5]`	Y	N	24	Y	N	8	Y	Y	20

- Cmp: Compiles (Y/N)
- Bad: Possible bad pointer reference (Y/N)
- Size: Value returned by `sizeof`

Decl	***An		
	Cmp	Bad	Size
`int A1[3][5]`	N	-	-
`int *A2[3][5]`	Y	Y	4
`int (*A3)[3][5]`	Y	Y	4
`int *(A4[3][5])`	Y	Y	4
`int (*A5[3])[5]`	Y	Y	4

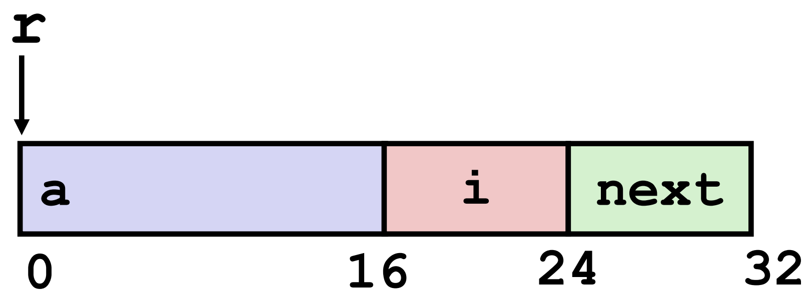
Today

- **Partial recap: Integers**
  - Word size
  - Addresses
  - Endianness
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **If we have time: Floating point and SIMD**

Activity break:
do part 2.2 now

Structure Representation

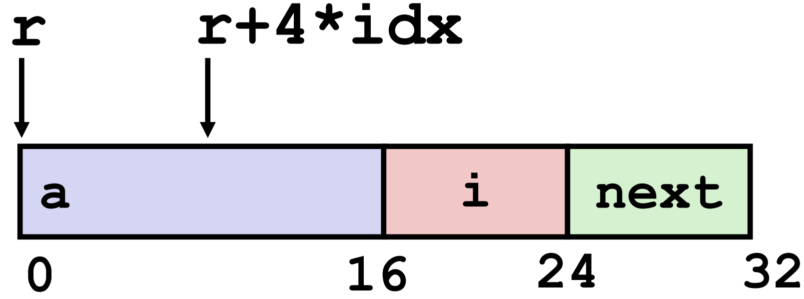
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- **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];
}
```

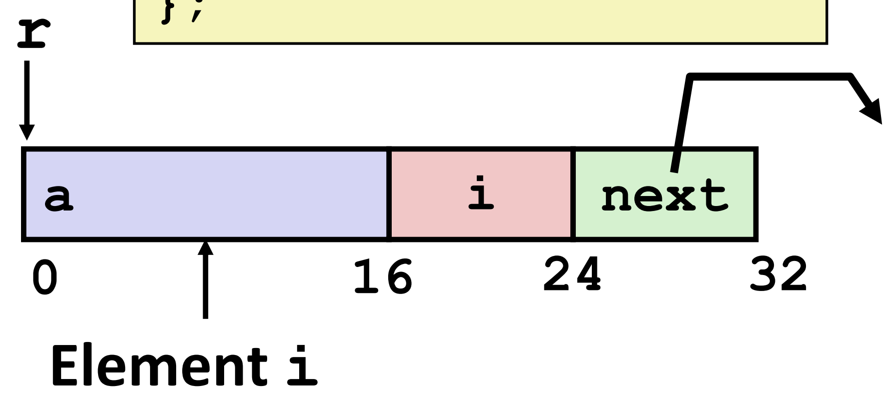
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Following Linked List

- C Code

```
struct rec {
    int a[4];
    int 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;
  }
}
```

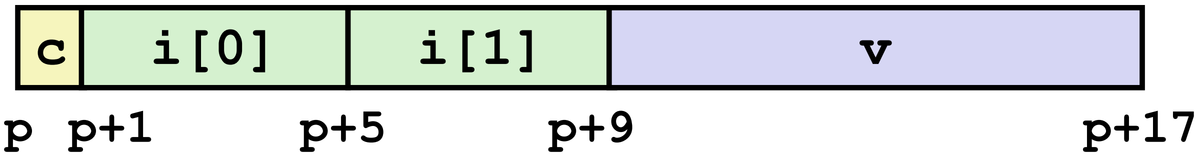


Register	Value
%rdi	r
%rsi	val

```
.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

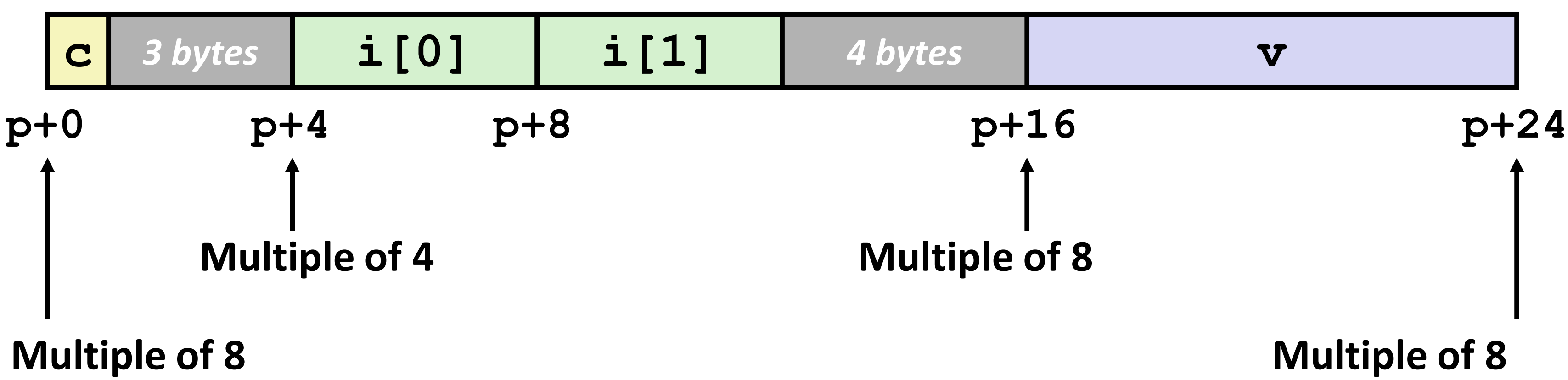
Unaligned Data




```
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

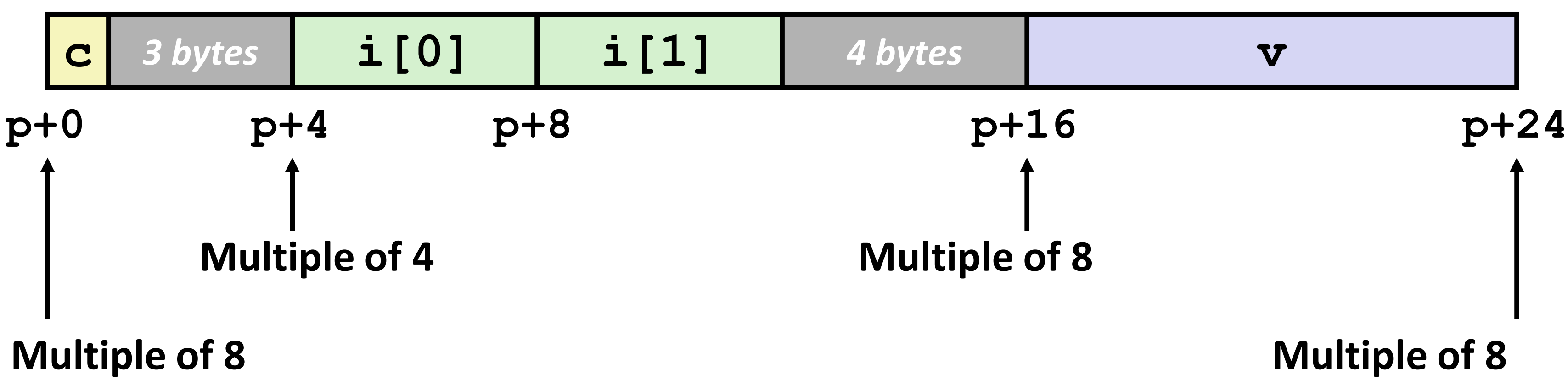
Specific Cases of Alignment (x86-64)

- **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

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

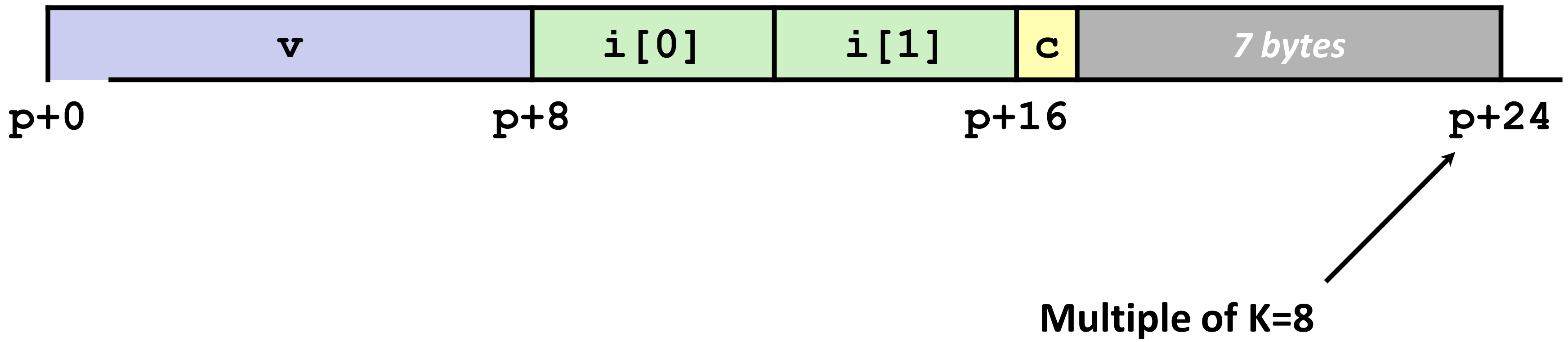
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

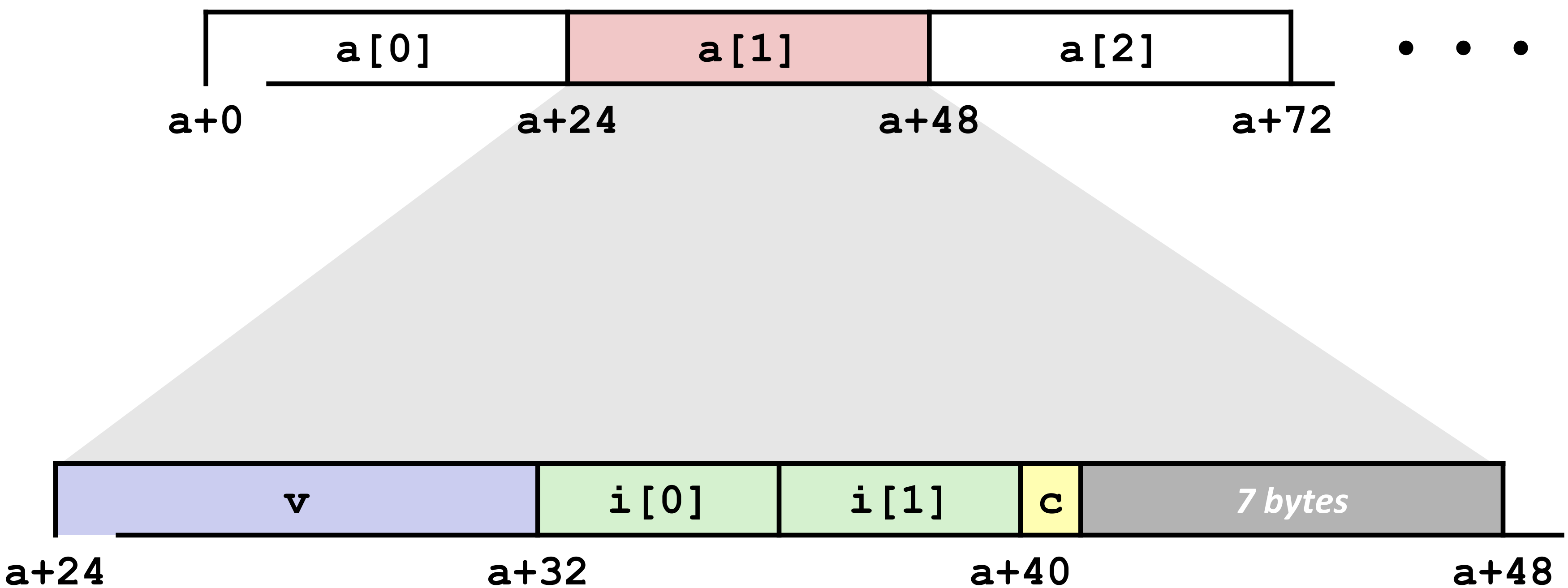
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

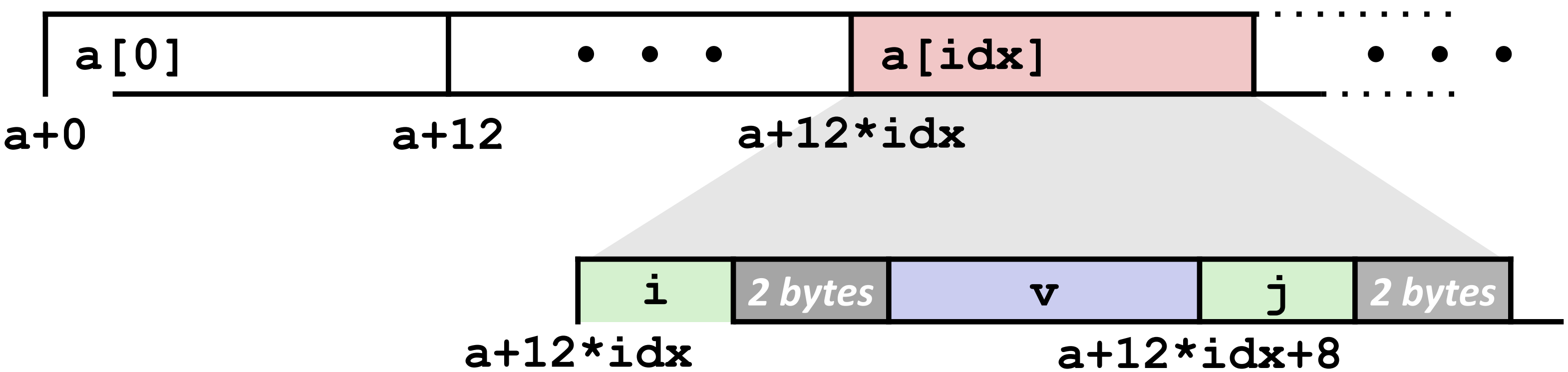
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

```
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
```

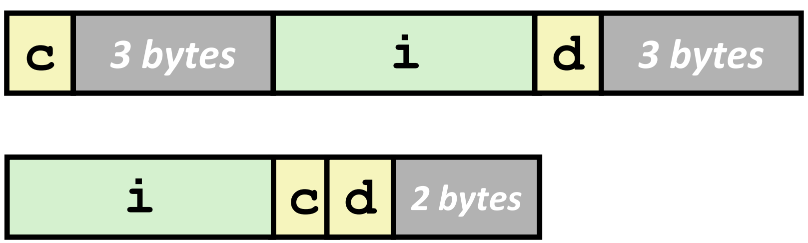
Saving Space

- **Put large data types first**

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

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

- **Effect (K=4)**



Example Struct Exam Question

Problem 5. (8 points):

Struct alignment. Consider the following C struct declaration:

```
typedef struct {
  char a;
  long b;
  float c;
  char d[3];
  int *e;
  short *f;
} foo;
```

1. Show how `foo` would be allocated in memory on an x86-64 Linux system. Label the bytes with the names of the various fields and **clearly mark the end of the struct**. Use an X to denote space that is allocated in the struct as padding.

```
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

http://www.cs.cmu.edu/~213/oldexams/exam1-f12.pdf

Example Struct Exam Question

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  long b;
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```

1. Show how `foo` would be allocated in memory on an x86-64 Linux system. Label the bytes with the names of the various fields and **clearly mark the end of the struct**. Use an X to denote space that is allocated in the struct as padding.

a	X	X	X	X	X	X	X	b	b	b	b	b	b	b	b
c	c	c	c	d	d	d	X	e	e	e	e	e	e	e	e
f	f	f	f	f	f	f	f								

http://www.cs.cmu.edu/~213/oldexams/exam1-f12.pdf

Example Struct Exam Question (Cont'd)

Problem 5. (8 points):

Struct alignment. Consider the following C struct declaration:

```
typedef struct {
  char a;
  long b;
  float c;
  char d[3];
  int *e;
  short *f;
} foo;
```

2. Rearrange the elements of `foo` to conserve the most space in memory. Label the bytes with the names of the various fields and **clearly mark the end of the struct**. Use an X to denote space that is allocated in the struct as padding.

```
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+--+
```

http://www.cs.cmu.edu/~213/oldexams/exam1-f12.pdf

Example Struct Exam Question (Cont'd)

Problem 5. (8 points):

Struct alignment. Consider the following C struct declaration:

```
typedef struct {
  char a;
  long b;
  float c;
  char d[3];
  int *e;
  short *f;
} foo;
```

2. Rearrange the elements of `foo` to conserve the most space in memory. Label the bytes with the names of the various fields and **clearly mark the end of the struct**. Use an X to denote space that is allocated in the struct as padding.

```
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| a | d | d | d | c | c | c | c | b | b | b | b | b | b | b | b |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| e | e | e | e | e | e | e | e | f | f | f | f | f | f | f | f |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

http://www.cs.cmu.edu/~213/oldexams/exam1-f12.pdf

Today

- **Partial recap: Integers**
  - Word size
  - Addresses
  - Endianness
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment
- **If we have time: Floating point and SIMD**

Activity break:
do part 2.3, 2.4, 2.5 now

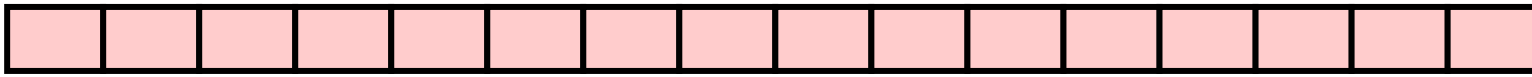
Background

- **History**
  - x87 FP
    - Legacy, very ugly
  - SSE FP
    - Supported by Shark machines
    - Special case use of vector instructions
  - AVX FP
    - Newest version
    - Similar to SSE
    - Documented in book

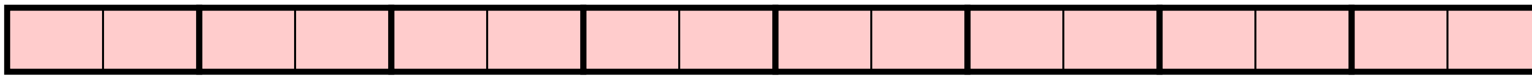
Programming with SSE3

XMM Registers

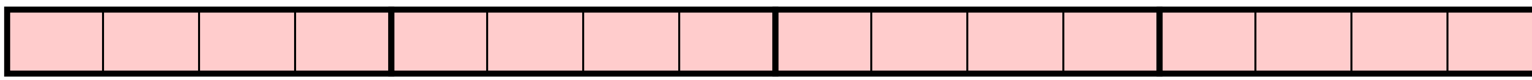
- 16 total, each 16 bytes
- 16 single-byte integers



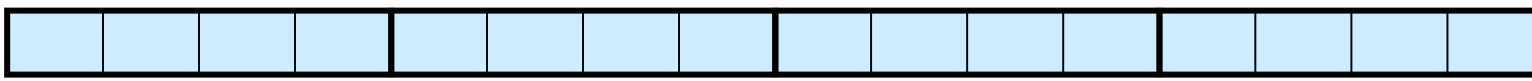
- 8 16-bit integers



- 4 32-bit integers

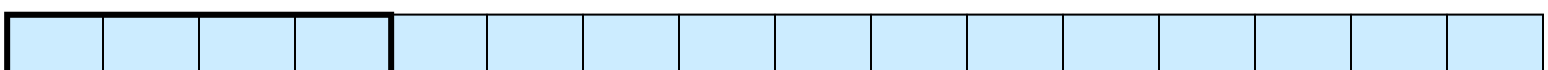


- 4 single-precision floats

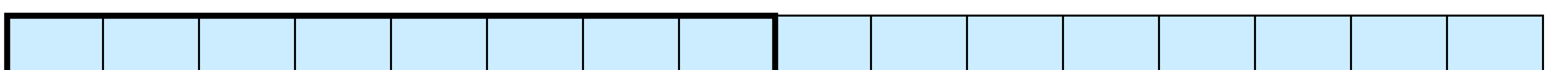


- 2 double-precision floats

- 1 single-precision float



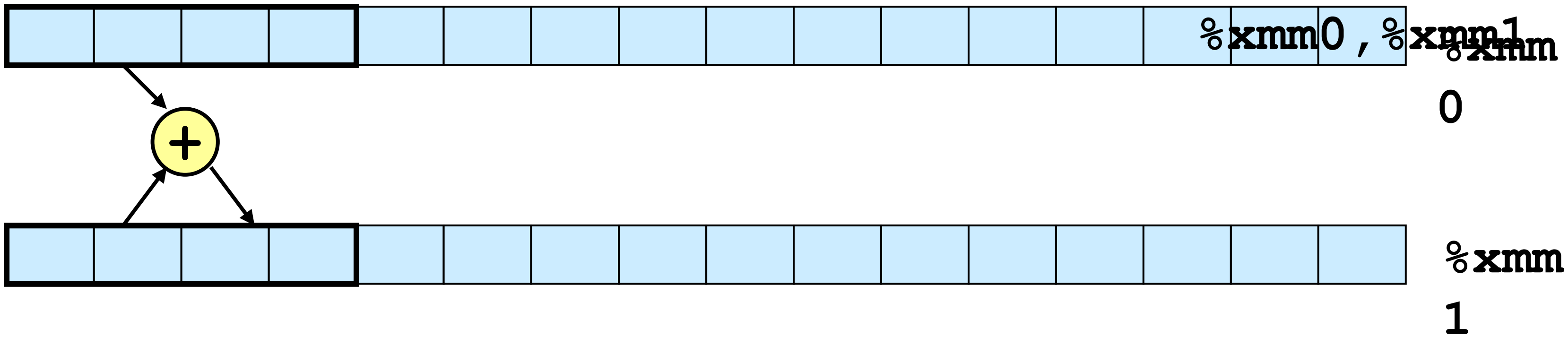
- 1 double-precision float



Scalar & SIMD Operations

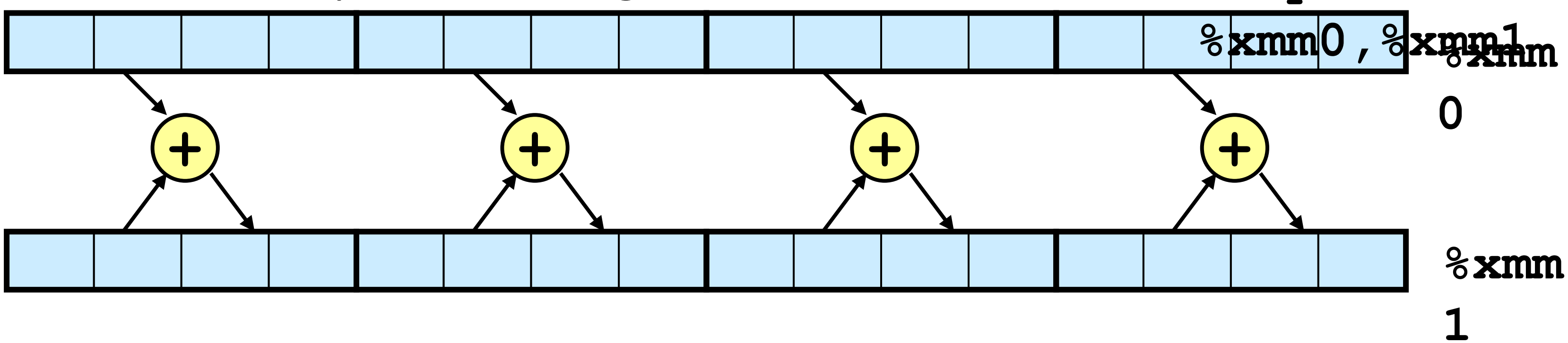
- Scalar Operations: Single Precision

addss %xmm0,%xmm1



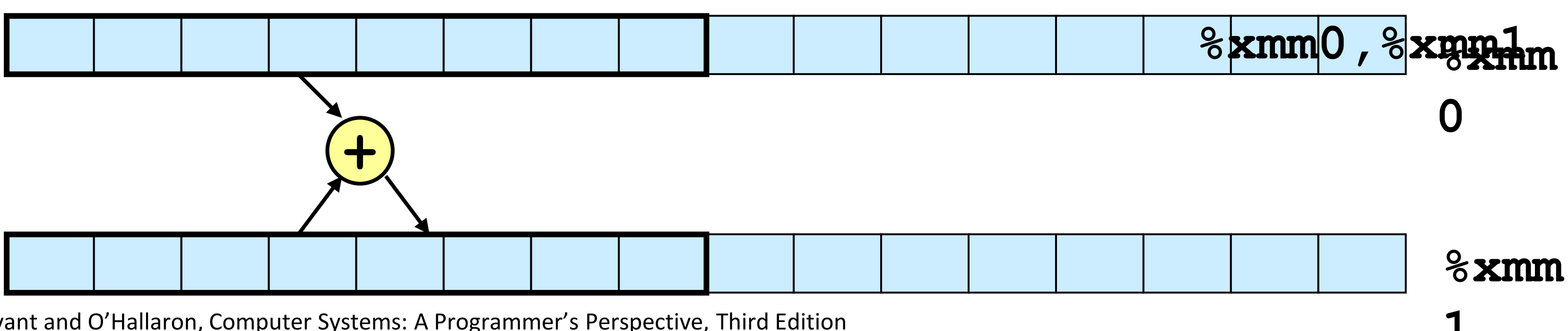
- SIMD Operations: Single Precision

addps %xmm0,%xmm1



- Scalar Operations: Double Precision

addsd %xmm0,%xmm1



FP Basics

- Arguments passed in `%xmm0`, `%xmm1`, ...
- Result returned in `%xmm0`
- All XMM registers caller-saved

```
float fadd(float x, float y)
{
    return x + y;
}
```

```
double dadd(double x, double y)
{
    return x + y;
}
```

```
  # x in %xmm0, y in %xmm1
  addss   %xmm1, %xmm0
  ret
```

```
  # x in %xmm0, y in %xmm1
  addsd   %xmm1, %xmm0
  ret
```

FP Memory Referencing

- Integer (and pointer) arguments passed in regular registers
- FP values passed in XMM registers
- Different mov instructions to move between XMM registers, and between memory and XMM registers

```
double dincr(double *p, double v)
{
    double x = *p;
    *p = x + v;
    return x;
}
```

```
  # p in %rdi, v in %xmm0
  movapd  %xmm0, %xmm1    # Copy v
  movsd   (%rdi), %xmm0   # x = *p
  addsd   %xmm0, %xmm1    # t = x + v
  movsd   %xmm1, (%rdi)   # *p = t
  ret
```

Other Aspects of FP Code

- ***Lots* of instructions**
  - Different operations, different formats, ...
- **Floating-point comparisons**
  - Instructions **`ucomiss`** and **`ucomisd`**
  - Set condition codes CF, ZF, and PF
- **Using constant values**
  - Set XMM0 register to 0 with instruction **`xorpd %xmm0, %xmm0`**
  - Others loaded from memory

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