

# Machine-Level Programming IV: Data

Introduction to Computer Systems  
7<sup>th</sup> Lecture, Sep. 30, 2024

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# Today

## ■ Arrays

- One-dimensional
- Multi-dimensional (nested)
- Multi-level

## ■ Structures

- Allocation
- Access
- Alignment

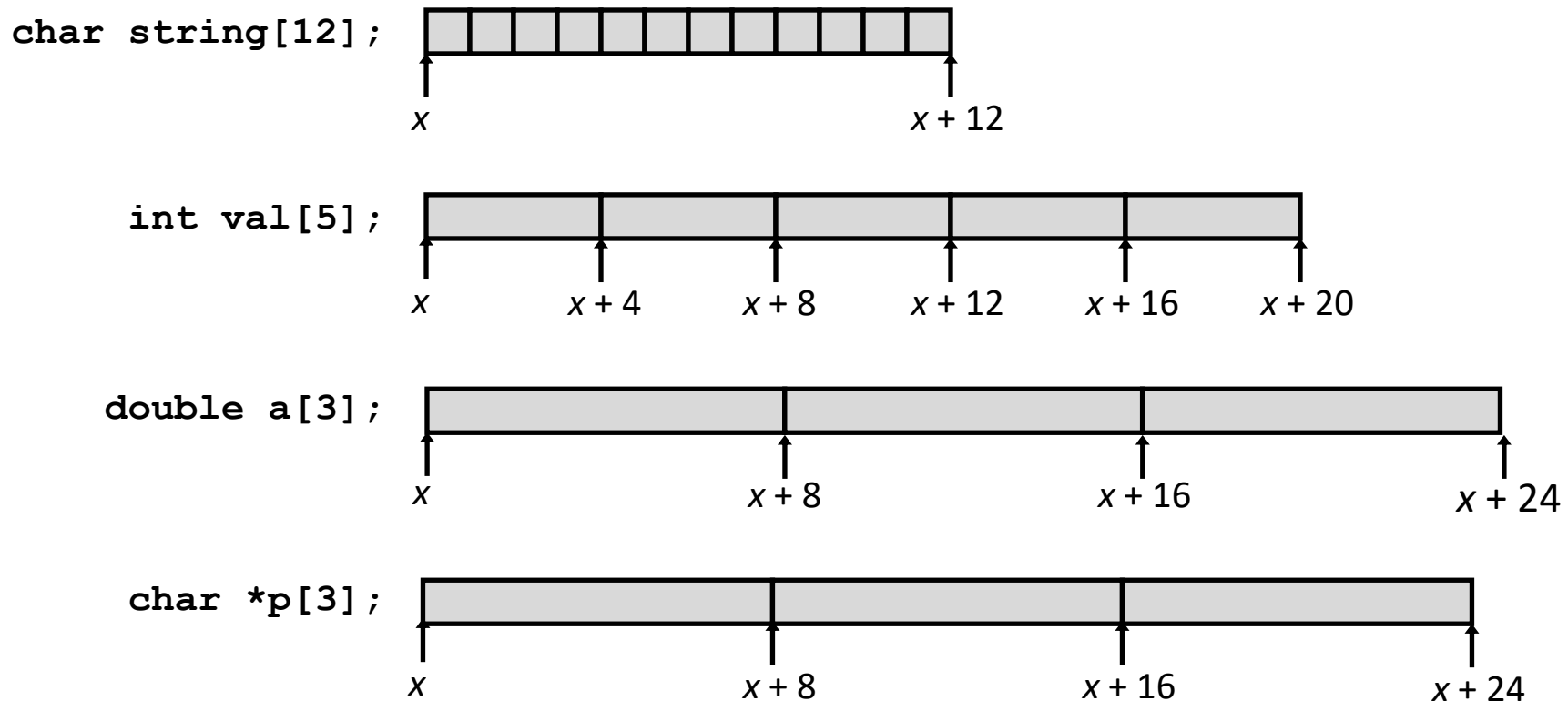
## ■ Floating Point

# Array Allocation

## ■ Basic Principle

$T$   $A[L]$  ;

- Array of data type  $T$  and length  $L$
- Contiguously allocated region of  $L * \text{sizeof}(T)$  bytes in memory

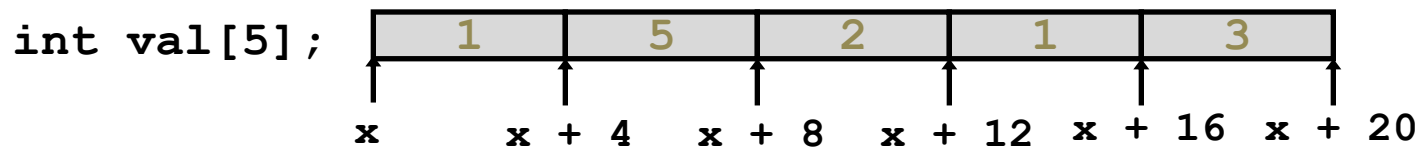


# Array Access

## ■ 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  $T^*$



## ■ Reference      Type      Value

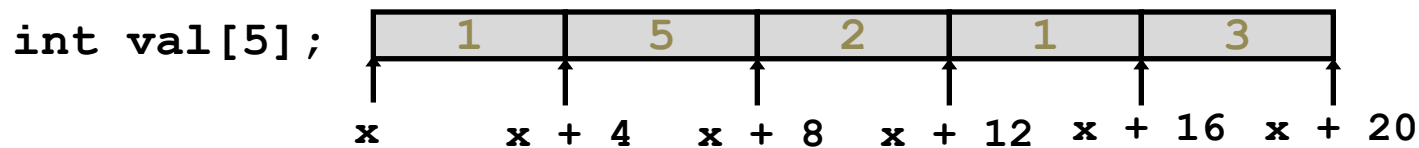
<code>val[4]</code>	<code>int</code>	
<code>val</code>	<code>int *</code>	
<code>val+1</code>	<code>int *</code>	
<code>&amp;val[2]</code>	<code>int *</code>	
<code>val[5]</code>	<code>int</code>	
<code>*(val+1)</code>	<code>int</code>	
<code>val + i</code>	<code>int *</code>	

# 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  $T^*$



## ■ Reference      Type      Value

`val[4]`      `int`      3

`val`      `int *`

`val+1`      `int *`

`&val[2]`      `int *`

`val[5]`      `int`

`*(val+1)`      `int`

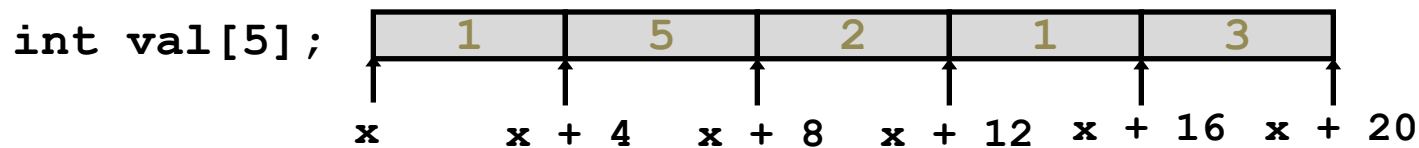
`val + i`      `int *`

# 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  $T^*$

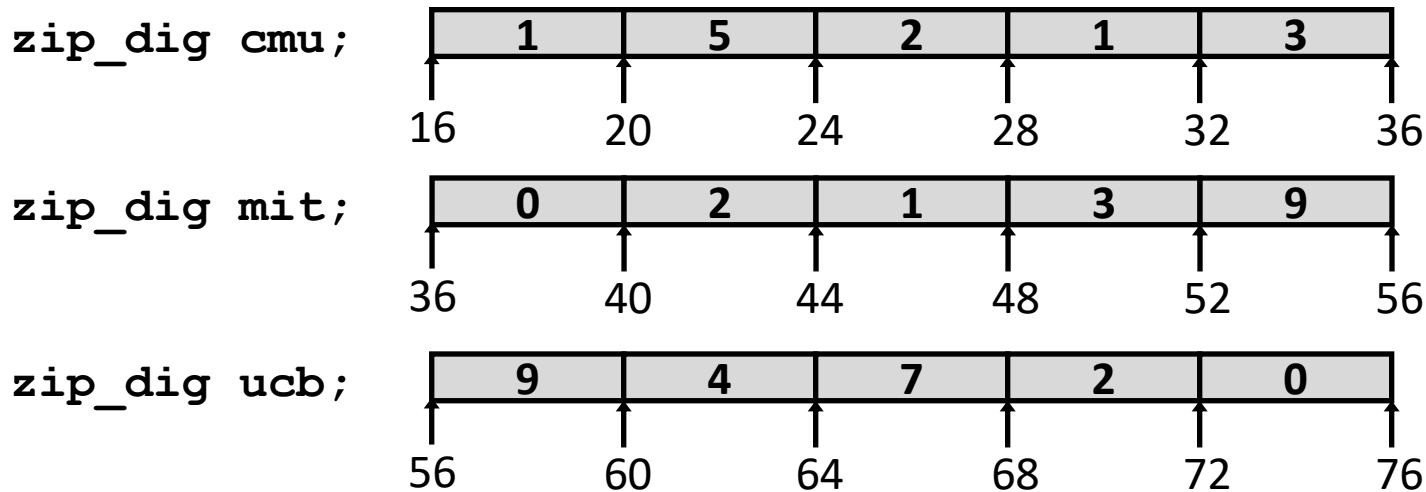


■ Reference	Type	Value
<code>val[4]</code>	<code>int</code>	3
<code>val</code>	<code>int *</code>	<code>x</code>
<code>val+1</code>	<code>int *</code>	<code>x + 4</code>
<code>&amp;val[2]</code>	<code>int *</code>	<code>x + 8</code>
<code>val[5]</code>	<code>int</code>	??
<code>*(val+1)</code>	<code>int</code>	5 <code>//val[1]</code>
<code>val + i</code>	<code>int *</code>	<code>x + 4 * i</code> <code>//&amp;val[i]</code>

# Array Example

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

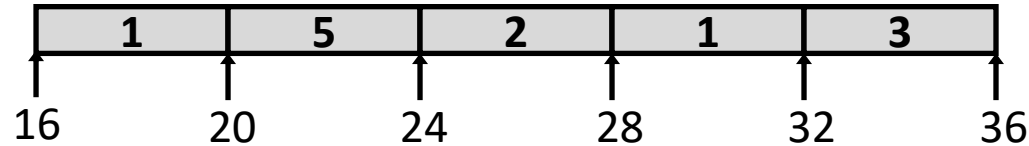
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- 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];
}
```

## 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  $\text{\%rdi} + 4 * \text{\%rsi}$
- Use memory reference  $(\text{\%rdi}, \text{\%rsi}, 4)$



# 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

$T \ A[R][C];$

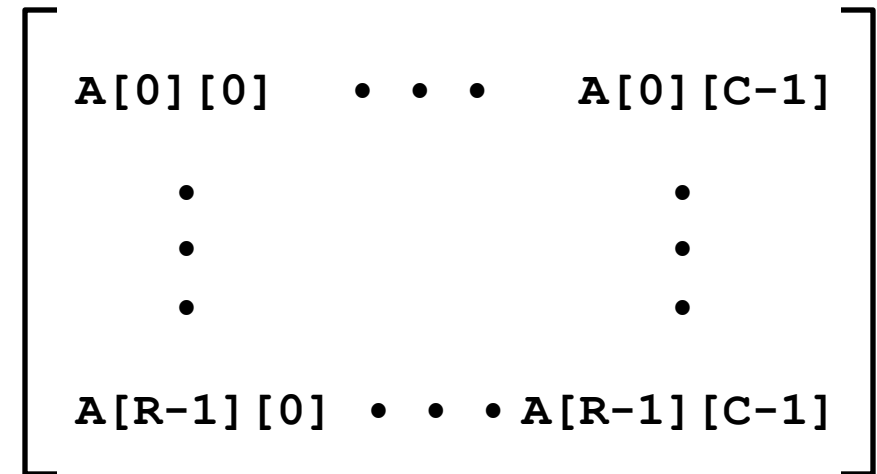
- 2D array of data type  $T$
- $R$  rows,  $C$  columns
- Type  $T$  element requires  $K$  bytes

## ■ Array Size

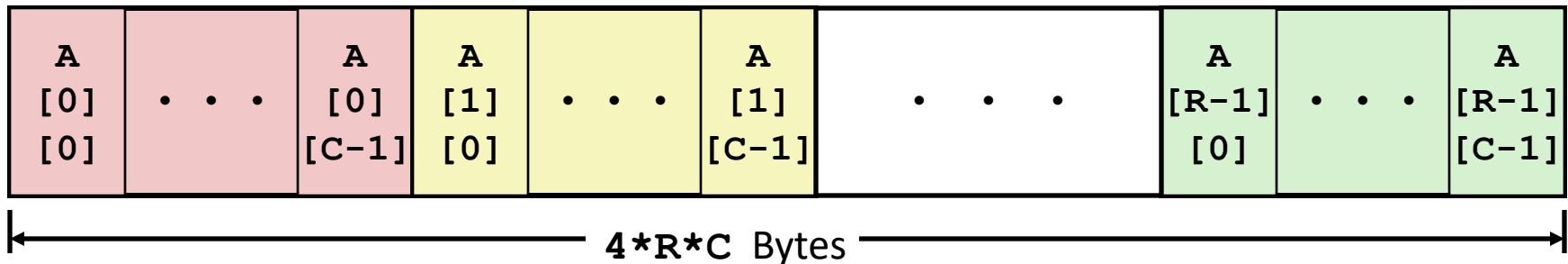
- $R * C * K$  bytes

## ■ Arrangement

- Row-Major Ordering

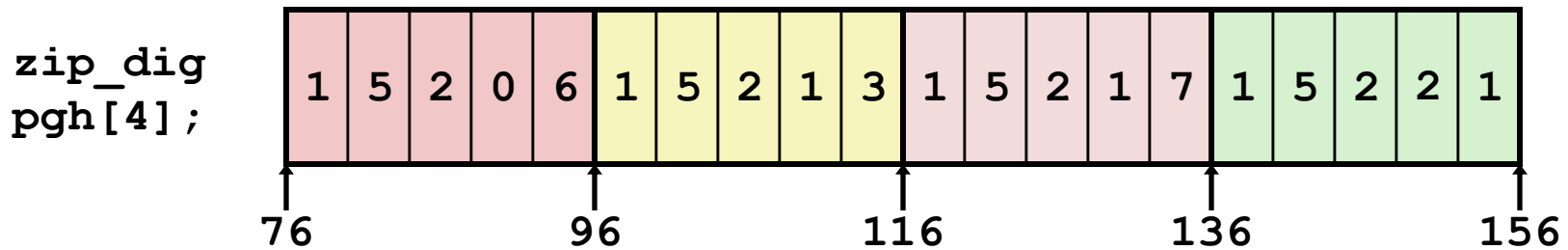


`int A[R][C];`



# 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 }};
```



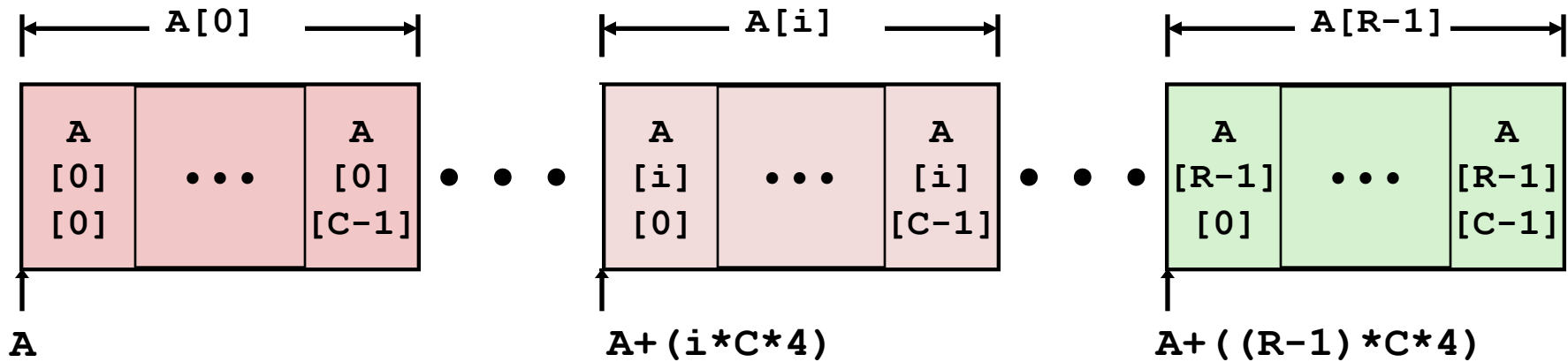
- “zip\_dig pgh[4]” equivalent to “int pgh[4][5]”
  - Variable **pgh**: array of 4 elements, allocated contiguously
  - Each element is an array of 5 **int**’s, allocated contiguously
- “Row-Major” ordering of all elements in memory

# Nested Array Row Access

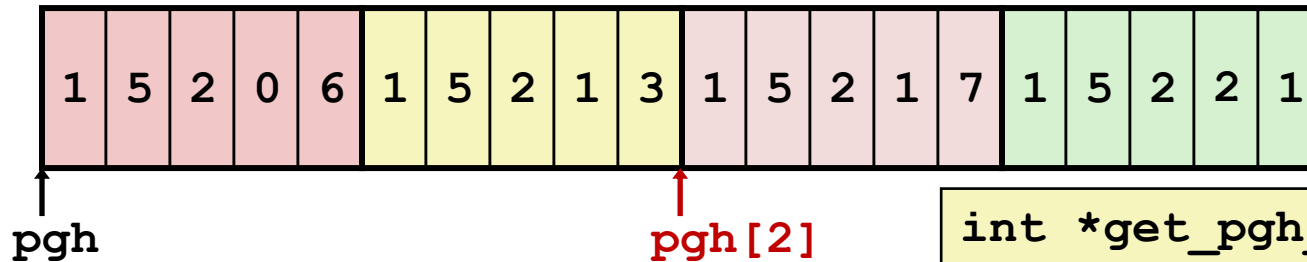
## ■ Row Vectors

- $A[i]$  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

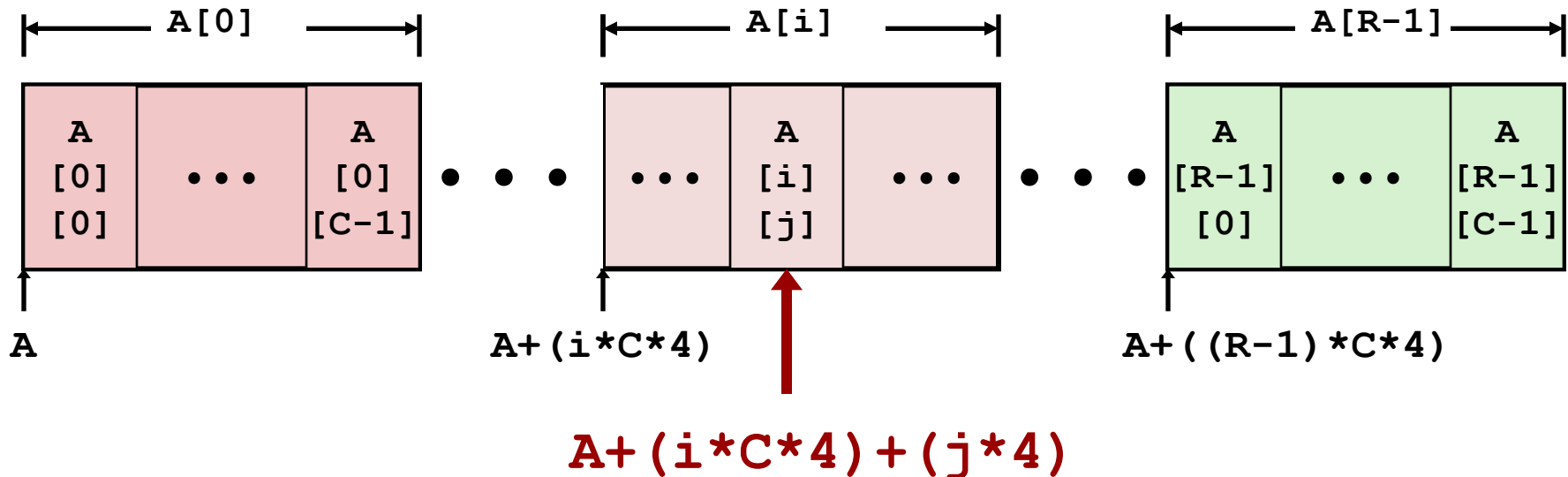
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

# Nested Array Element Access

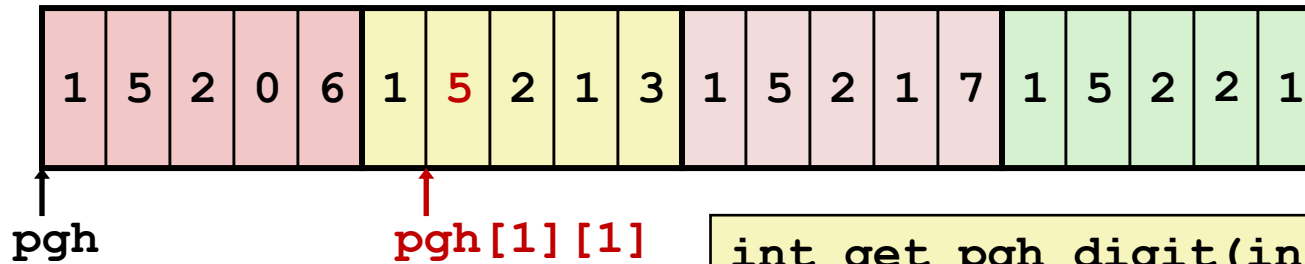
## ■ Array Elements

- $A[i][j]$  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

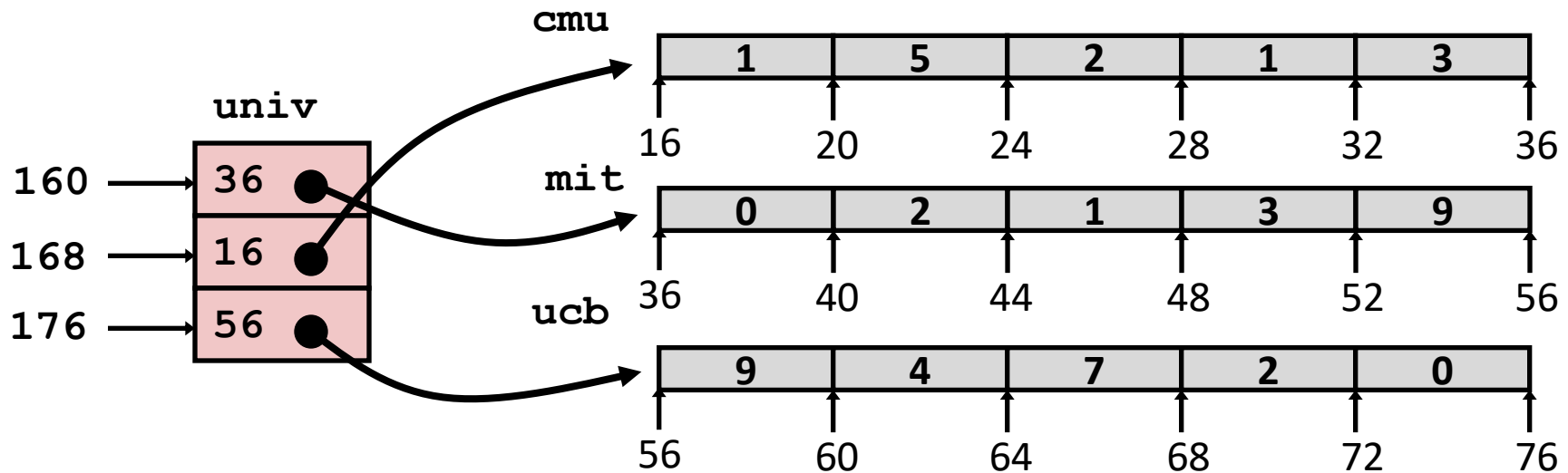
- `pgh[index][dig]` is `int`
- Address:  $\text{pgh} + 20 \cdot \text{index} + 4 \cdot \text{dig}$   
 $= \text{pgh} + 4 \cdot (5 \cdot \text{index} + \text{dig})$

# 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};
```

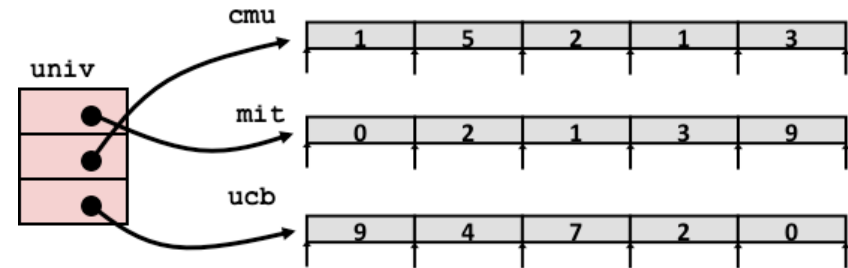
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes
- Each pointer points to array of `int`'s





# 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
```

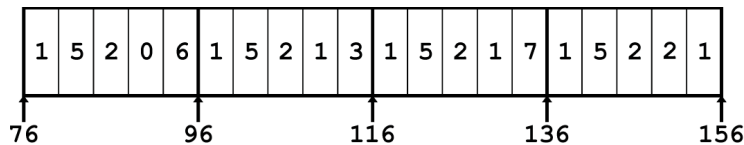
## ■ Computation

- 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

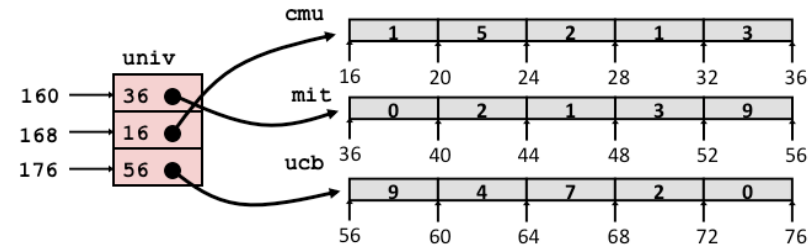
## Nested array

```
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:

$\text{Mem}[\text{pgh} + 20 * \text{index} + 4 * \text{digit}]$        $\text{Mem}[\text{Mem}[\text{univ} + 8 * \text{index}] + 4 * \text{digit}]$

# 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

- Now supported by gcc

```
/* 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

- 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 # M[a + 64*i + 4*j]
ret
```

# n X n Matrix Access

## ■ Array Elements

- Address  $\mathbf{A} + i * (\mathbf{C} * \mathbf{K}) + j * \mathbf{K}$
- $\mathbf{C} = \mathbf{n}, \mathbf{K} = 4$
- 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  # 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

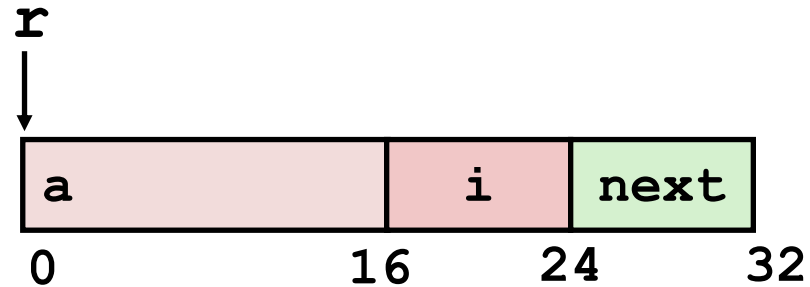
- Allocation
- Access
- Alignment

## ■ Floating Point



# Structure Representation

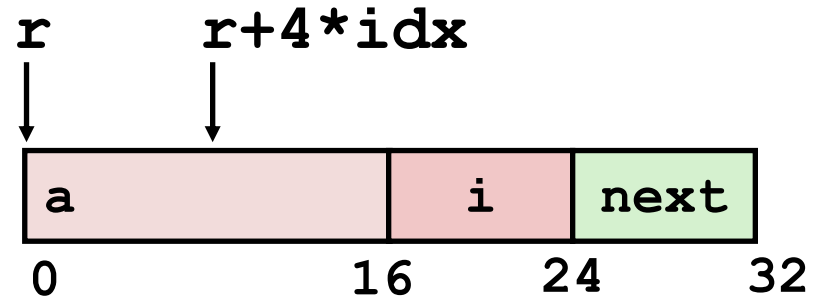
```
struct rec {  
    int a[4];  
    size_t i;  
    struct rec *next;  
};
```



- **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];
}
```

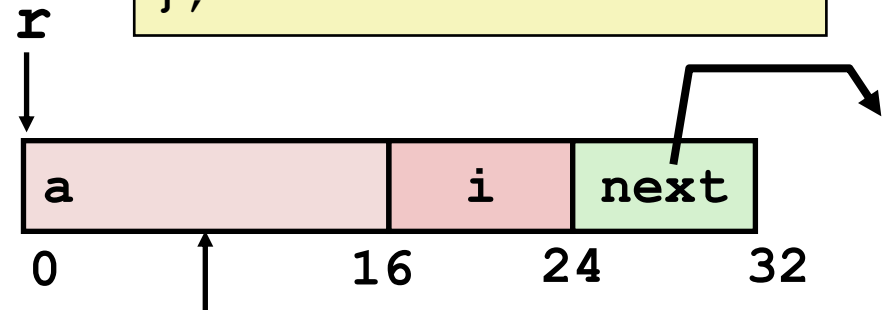
```
# r in %rdi, idx in %rsi
leaq (%rdi,%rsi,4), %rax
ret
```

# Following Linked List

## ■ C Code

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

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



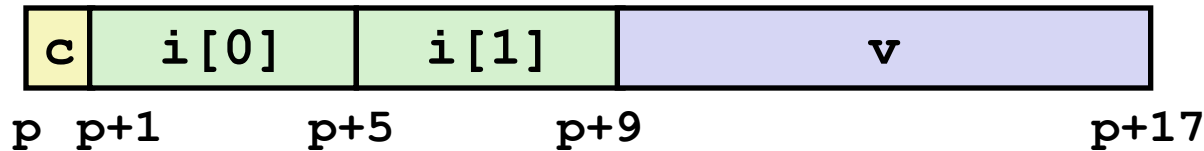
Element i

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

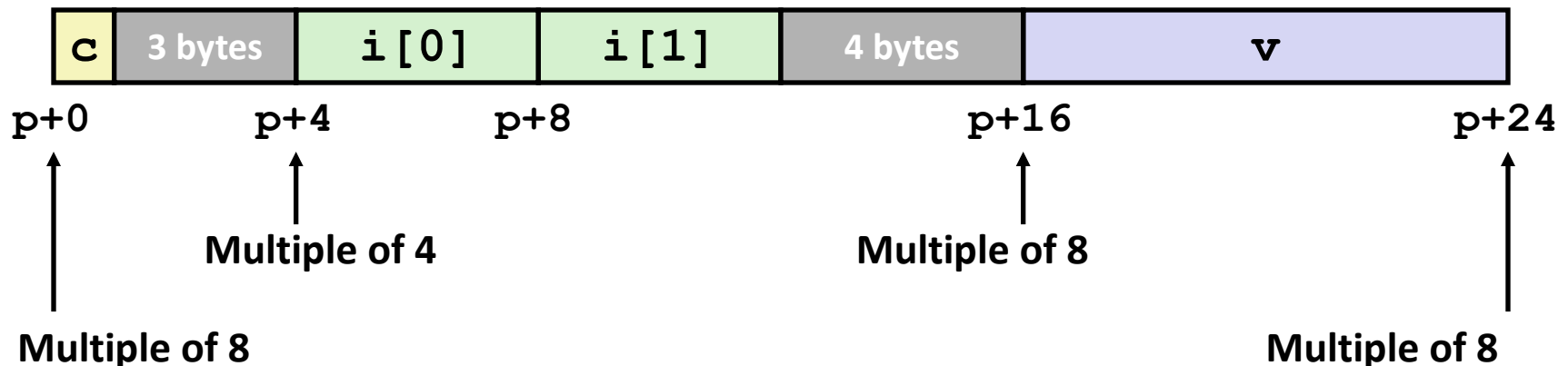
## ■ Unaligned Data



```
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

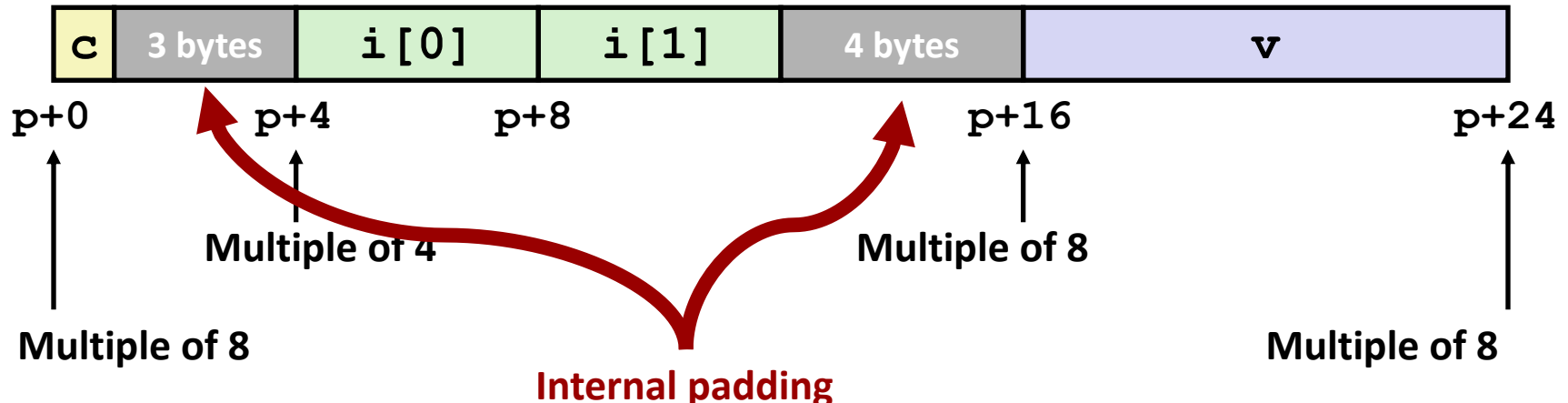
- Each structure has alignment requirement  $K$ 
  - $K$  = Largest alignment of any element
- Initial address & structure length must be multiples of  $K$

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

## ■ Example:

- $K = 8$ , due to **double** element

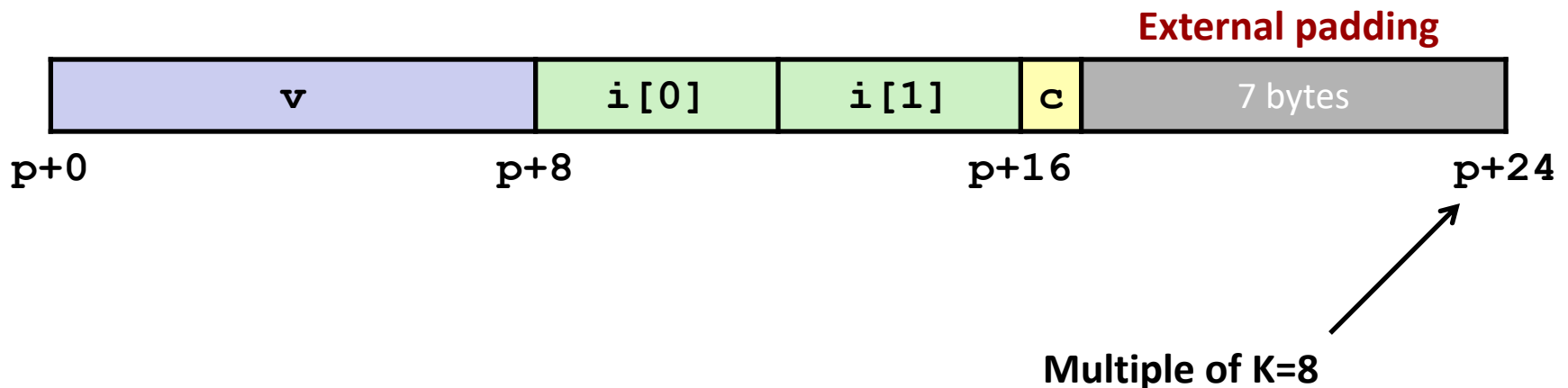
NOTE:  $K < \text{sizeof}(\text{struct S1})$



# 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;
```

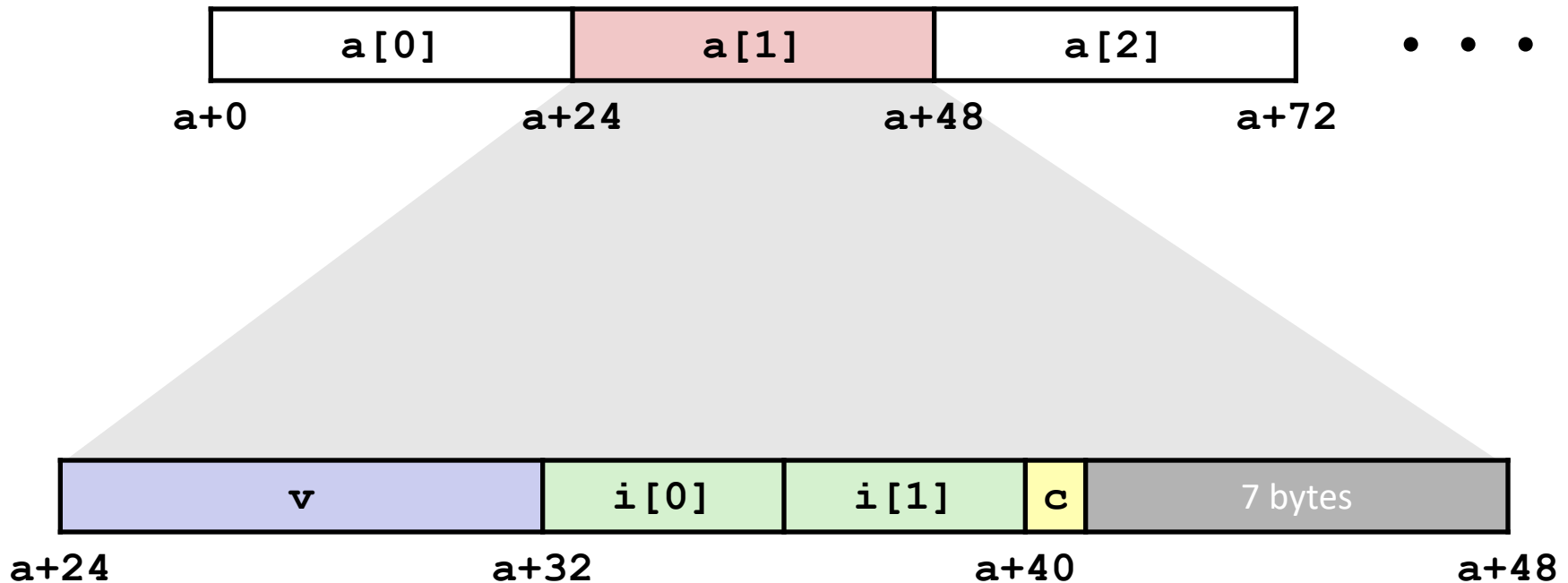




# Arrays of Structures

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

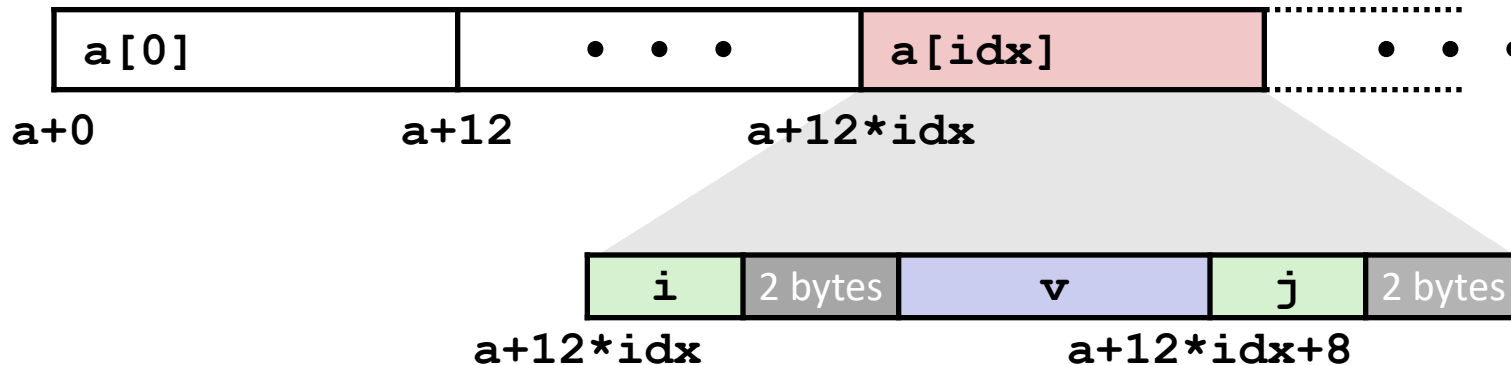
```
struct S2 {  
    double v;  
    int i[2];  
    char c;  
} a[10];
```



# Accessing Array Elements

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

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



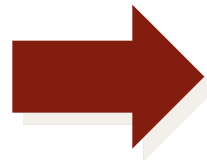
```
short get_j(int idx)
{
    return a[idx].j;
}
```

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

# Saving Space

- Put large data types first

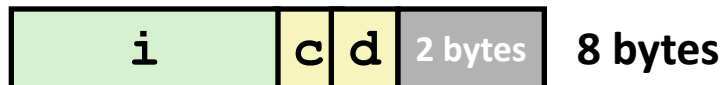
```
struct S4 {
    char c;
    int i;
    char d;
} *p;
```



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



- Effect (largest alignment requirement  $K=4$ )



# Today

## ■ Arrays

- One-dimensional
- Multi-dimensional (nested)
- Multi-level

## ■ Structures

- Allocation
- Access
- Alignment

## ■ Floating Point

# Background

## ■ History

- x87 FP
  - Legacy, very ugly
- SSE FP
  - Supported by server 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



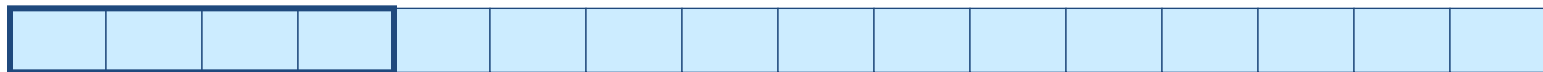
■ 4 single-precision floats



■ 2 double-precision floats



■ 1 single-precision float



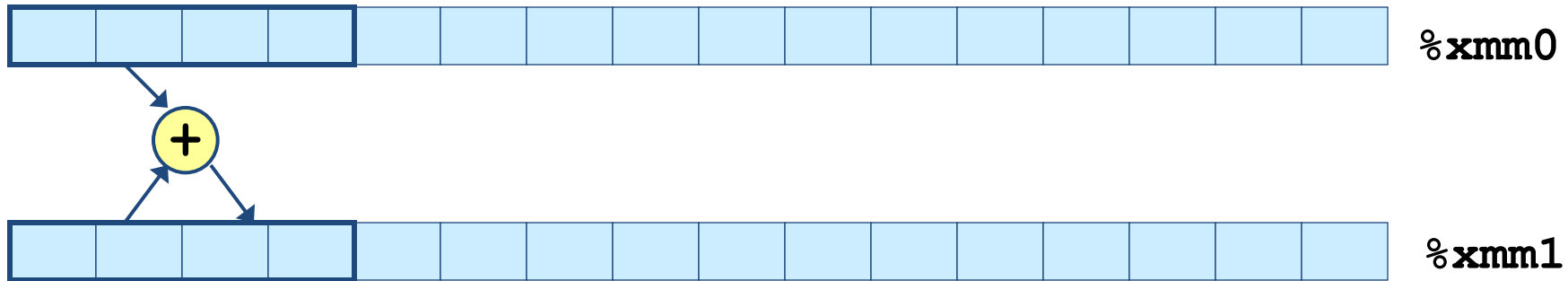
■ 1 double-precision float



# Scalar & SIMD Operations

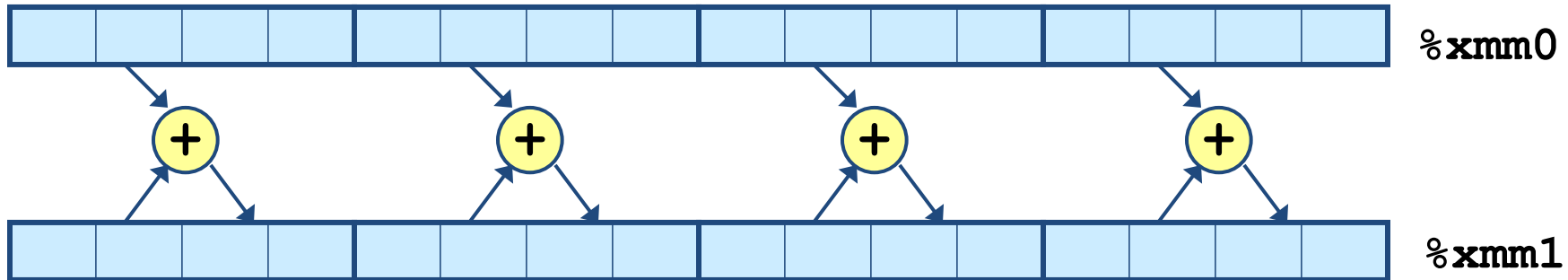
## ■ Scalar Operations: Single Precision

**addss** %xmm0, %xmm1



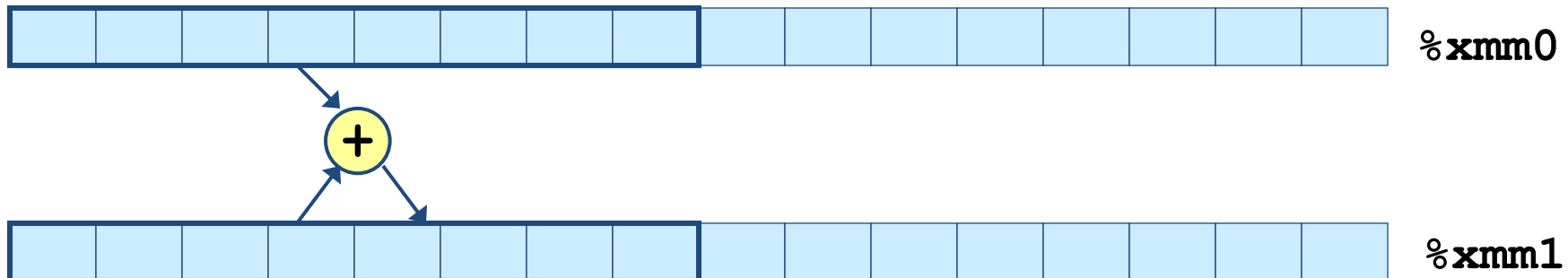
## ■ SIMD Operations: Single Precision

**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 ZF, **PF** and CF
- Zeros OF and SF

Parity Flag

UNORDERED: ZF,PF,CF←111
GREATER_THAN: ZF,PF,CF←000
LESS_THAN: ZF,PF,CF←001
EQUAL: ZF,PF,CF←100

## ■ 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

# Additional Slides

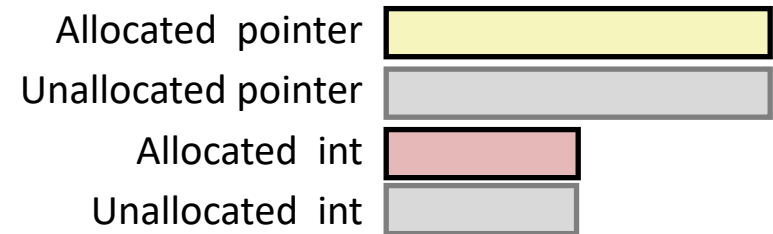
# Understanding Pointers & Arrays #1

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
<code>int A1[3]</code>	Y	N	12	Y	N	4
<code>int *A2</code>	Y	N	8	Y	Y	4



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

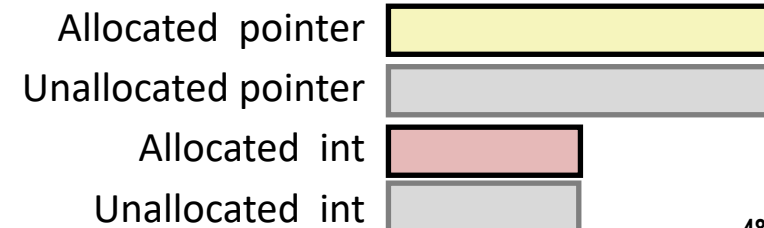
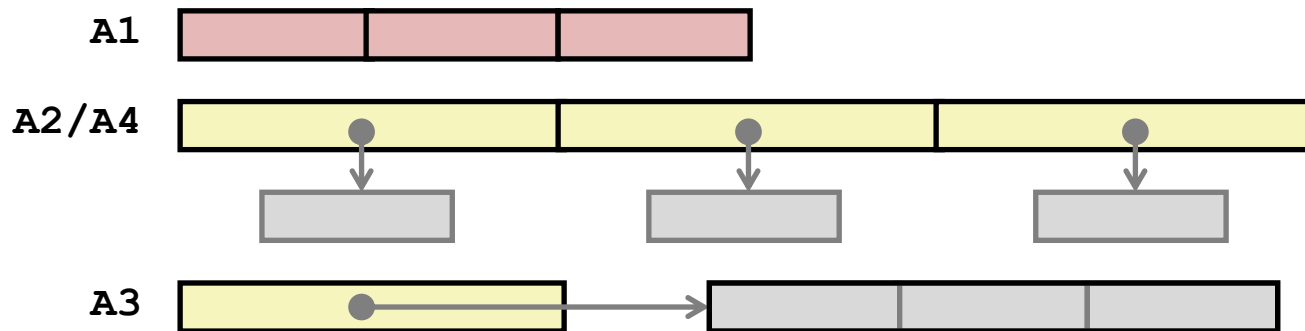
# Understanding Pointers & Arrays #2

Decl	<i>A<sub>n</sub></i>			<i>*A<sub>n</sub></i>			<i>**A<sub>n</sub></i>		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
<code>int A1[3]</code>									
<code>int *A2[3]</code>									
<code>int (*A3)[3]</code>									
<code>int (*A4[3])</code>									

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

# Understanding Pointers & Arrays #2

Decl	<i>A<sub>n</sub></i>			<i>*A<sub>n</sub></i>			<i>**A<sub>n</sub></i>		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
<code>int A1[3]</code>	Y	N	12	Y	N	4	N	–	–
<code>int *A2[3]</code>	Y	N	24	Y	N	8	Y	Y	4
<code>int (*A3)[3]</code>	Y	N	8	Y	Y	12	Y	Y	4
<code>int (*A4[3])</code>	Y	N	24	Y	N	8	Y	Y	4



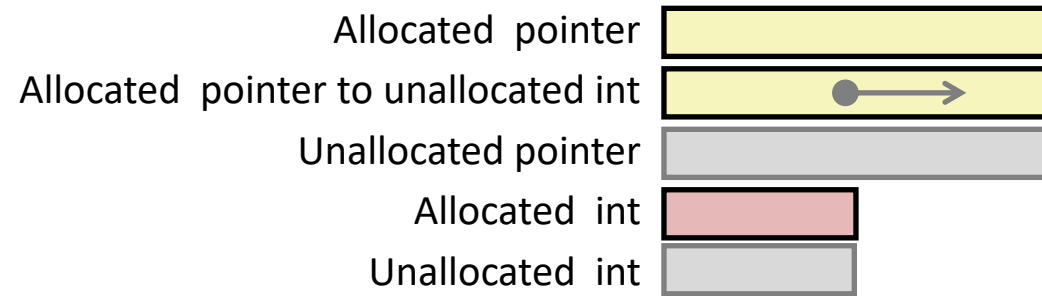


# Understanding Pointers & Arrays #3

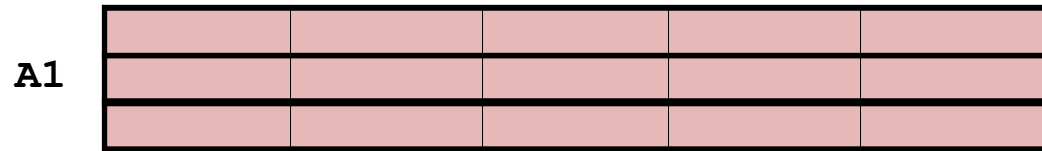
Decl	<i>A<sub>n</sub></i>			<i>*A<sub>n</sub></i>			<i>**A<sub>n</sub></i>		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
<code>int A1[3][5]</code>									
<code>int *A2[3][5]</code>									
<code>int (*A3)[3][5]</code>									
<code>int *(A4[3][5])</code>									
<code>int (*A5[3])[5]</code>									

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

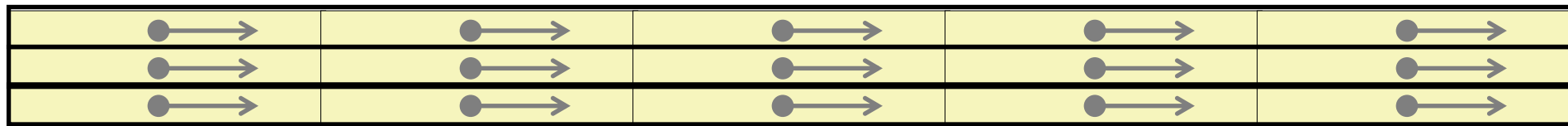
Decl	<i>***A<sub>n</sub></i>		
	Cmp	Bad	Size
<code>int A1[3][5]</code>			
<code>int *A2[3][5]</code>			
<code>int (*A3)[3][5]</code>			
<code>int *(A4[3][5])</code>			
<code>int (*A5[3])[5]</code>			



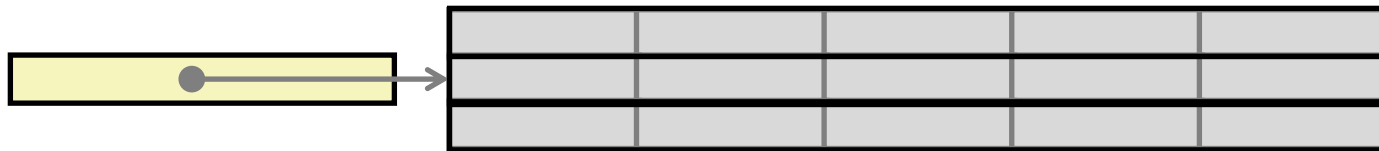
Declaration
<code>int A1[3][5]</code>
<code>int *A2[3][5]</code>
<code>int (*A3)[3][5]</code>
<code>int *(A4[3][5])</code>
<code>int (*A5[3])[5]</code>



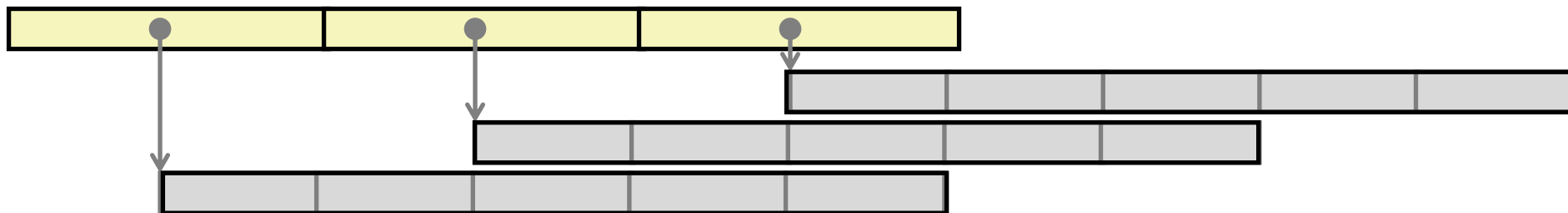
A2/A4



A3



A5



# Understanding Pointers & Arrays #3

Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
<code>int A1[3][5]</code>	Y	N	60	Y	N	20	Y	N	4
<code>int *A2[3][5]</code>	Y	N	120	Y	N	40	Y	N	8
<code>int (*A3)[3][5]</code>	Y	N	8	Y	Y	60	Y	Y	20
<code>int *(A4[3][5])</code>	Y	N	120	Y	N	40	Y	N	8
<code>int (*A5[3])[5]</code>	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
<code>int A1[3][5]</code>	N	–	–
<code>int *A2[3][5]</code>	Y	Y	4
<code>int (*A3)[3][5]</code>	Y	Y	4
<code>int *(A4[3][5])</code>	Y	Y	4
<code>int (*A5[3])[5]</code>	Y	Y	4