第3章 程序的机器级表示
Machine-Level Programming IV: Data

100076202： 计算机系统导论
IV: 数据
IV: Data

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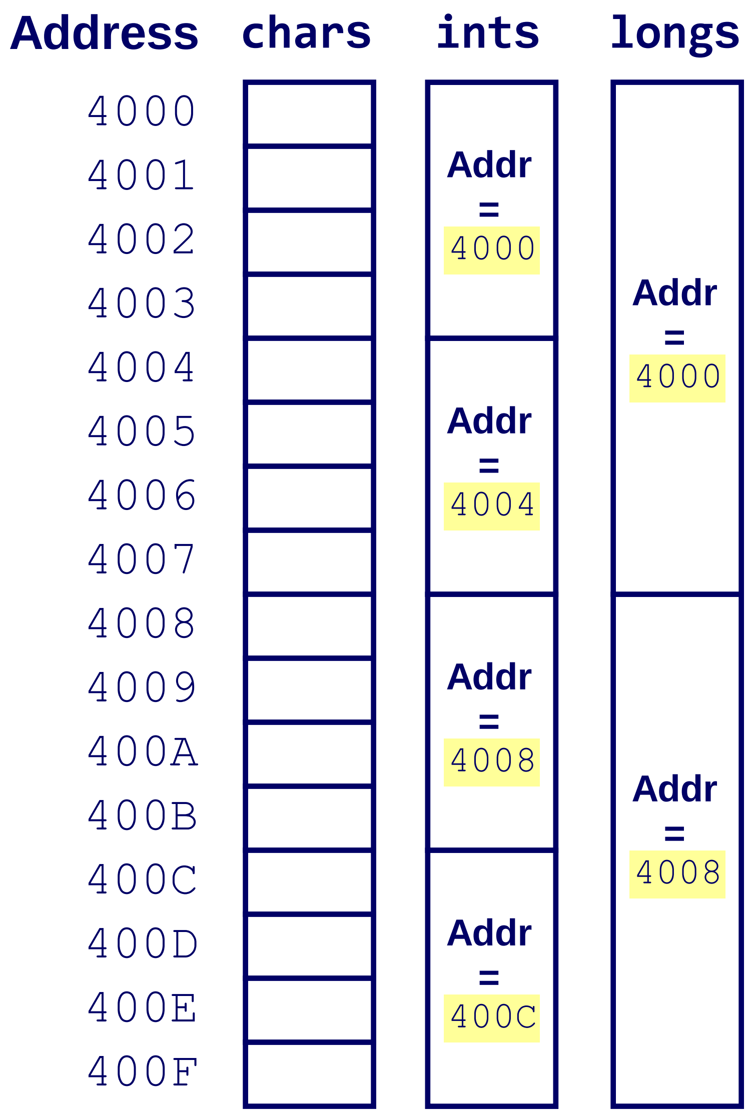
议题

- **数组 Arrays**
  - 一维 One-dimensional
  - 多维（嵌套） Multi-dimensional (nested)
  - 多级 Multi-level
- **结构 Structures**
  - 分配 Allocation
  - 访问 Access
  - 对齐 Alignment
- **浮点数 Floating Point**

提醒：内存组织
Reminder: Memory Organization

- **内存位置没有数据类型**
  Memory locations do not have data types
  - 类型隐含在机器指令如何使用内存 Types are implicit in how machine instructions *use* memory
- **地址指定字节位置**
  Addresses specify byte locations
  - 大型数据地址是其第一字节的地址 Address of a larger datum is the address of its first byte
  - 后继项目的地址根据项目大小而不同 Addresses of successive items differ by the item's size

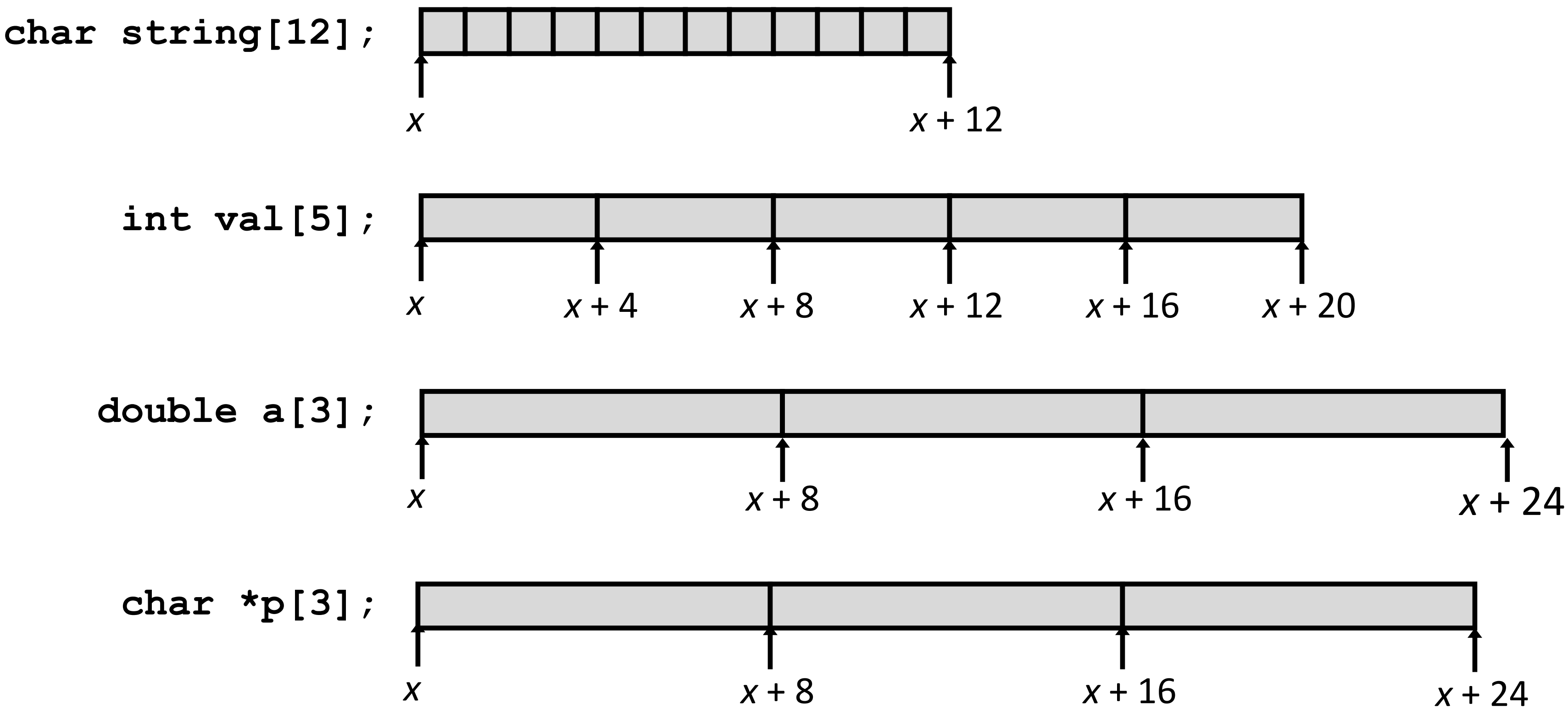


数组分配 Array Allocation

- 基本原则 Basic Principle

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

  - 数组的数据类型为T且长度为L Array of data type *T* and length *L*
  - 在内存中分配L*sizeof(T)字节的连续区域 Contiguously allocated region of *L* * **sizeof**（*T*） bytes in memory



数组访问 Array Access

- 基本原则 Basic Principle

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

  - 数组的数据类型为T且长度为L Array of data type *T* and length *L*
  - 标识符A可以用作指向数组第0个元素的指针 Identifier **A** can be used as a pointer to array element 0: Type *T**

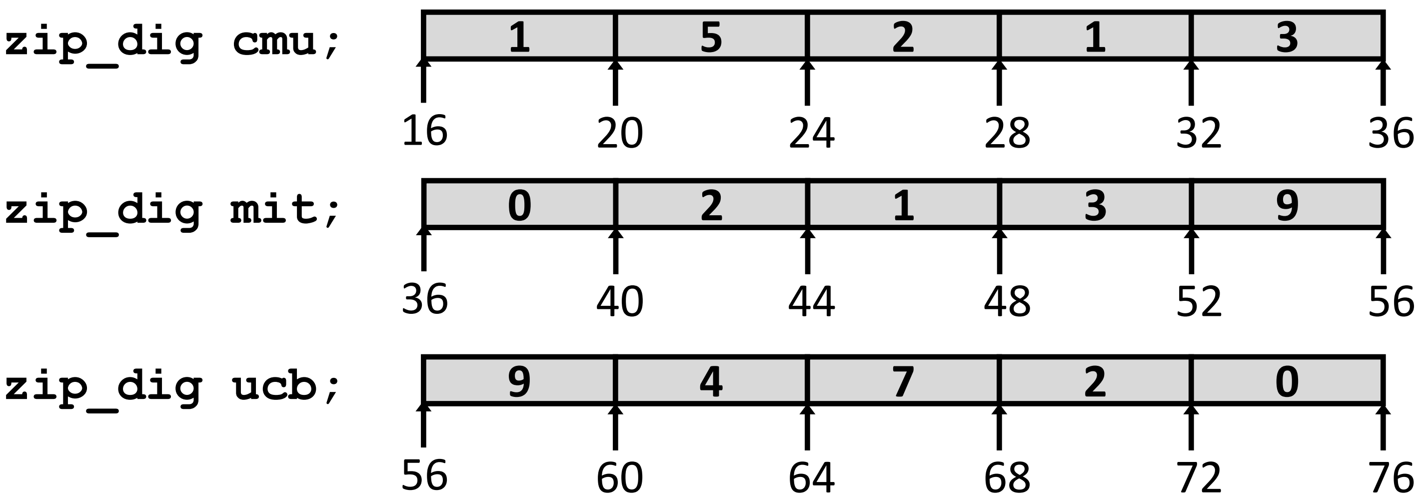
```
int val[5];
```

1	5	2	1	3	
x	$x + 4$	$x + 8$	$x + 12$	$x + 16$	$x + 20$

引用Reference	类型Type	值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 +` *i*	`int *`	$x + 4i$

数组示例 Array Example

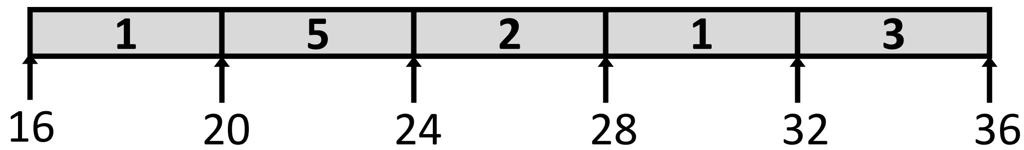
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

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



- **声明zip_dig cmu等价于int cmu[5] Declaration “`zip_dig cmu`” equivalent to “`int cmu[5]`”**
- **示例数组以连续的20字节块进行分配 Example arrays were allocated in successive 20 byte blocks**
  - 一般并不确保这样 Not guaranteed to happen in general

数组访问示例 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]
```

- 寄存器%rdi包含数组起始地址 Register `%rdi` contains starting address of array
- 寄存器%rsi包含数组索引 Register `%rsi` contains array index
- 期望的数值在 Desired digit at `%rdi + 4*%rsi`
- 使用内存引用 Use memory reference `(%rdi,%rsi,4)`

数组循环示例 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
```

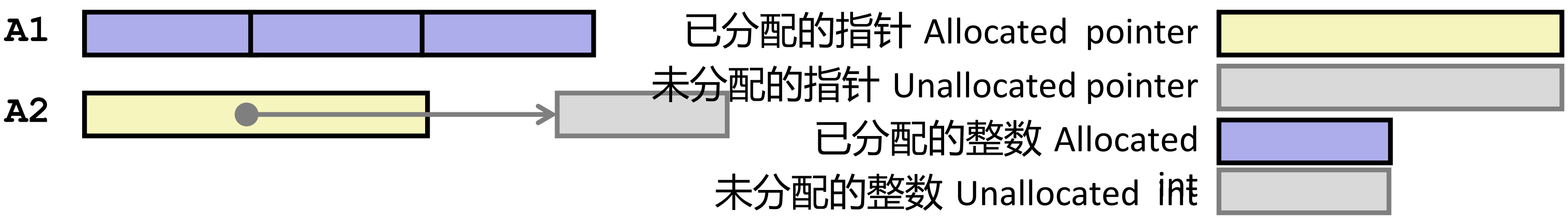
理解指针和数组 #1
Understanding Pointers & Arrays #1

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

- Cmp: Compiles (Y/N) 编译时
- Bad: Possible bad pointer reference (Y/N) 可能错误指针引用
- Size: Value returned by `sizeof` `sizeof`的返回值

理解指针和数组 #1
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

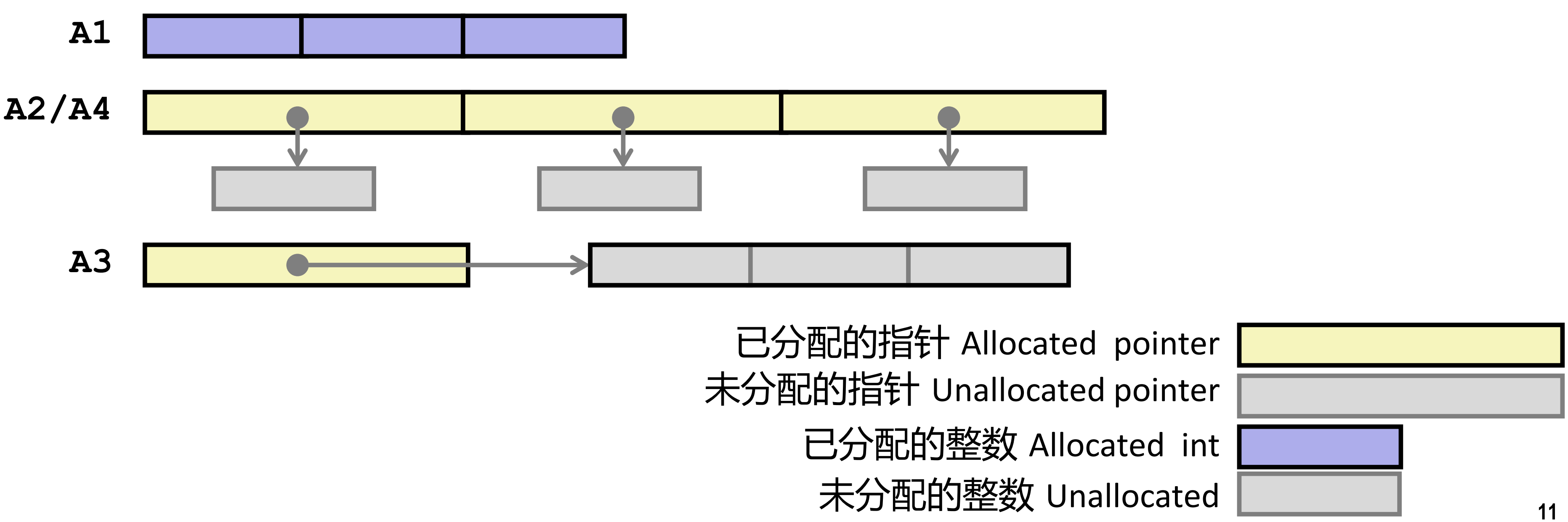


- Cmp: Compiles (Y/N) 编译时
- Bad: Possible bad pointer reference (Y/N) 可能错误指针引用
- Size: Value returned by `sizeof` `sizeof`返回值

理解指针和数组 #2

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

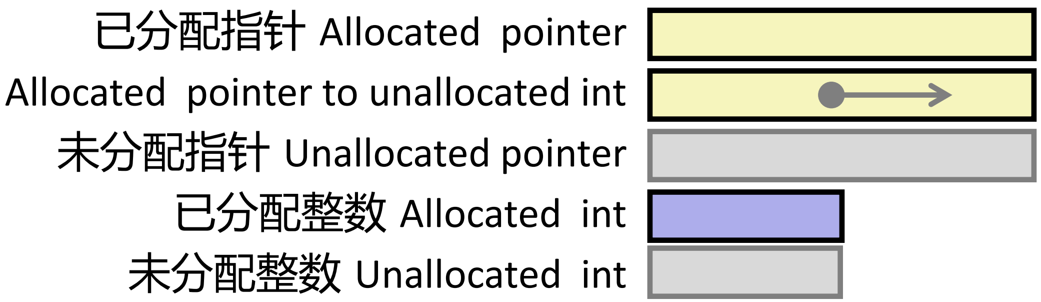


理解指针和数组 #3
Understanding Pointers & Arrays #3

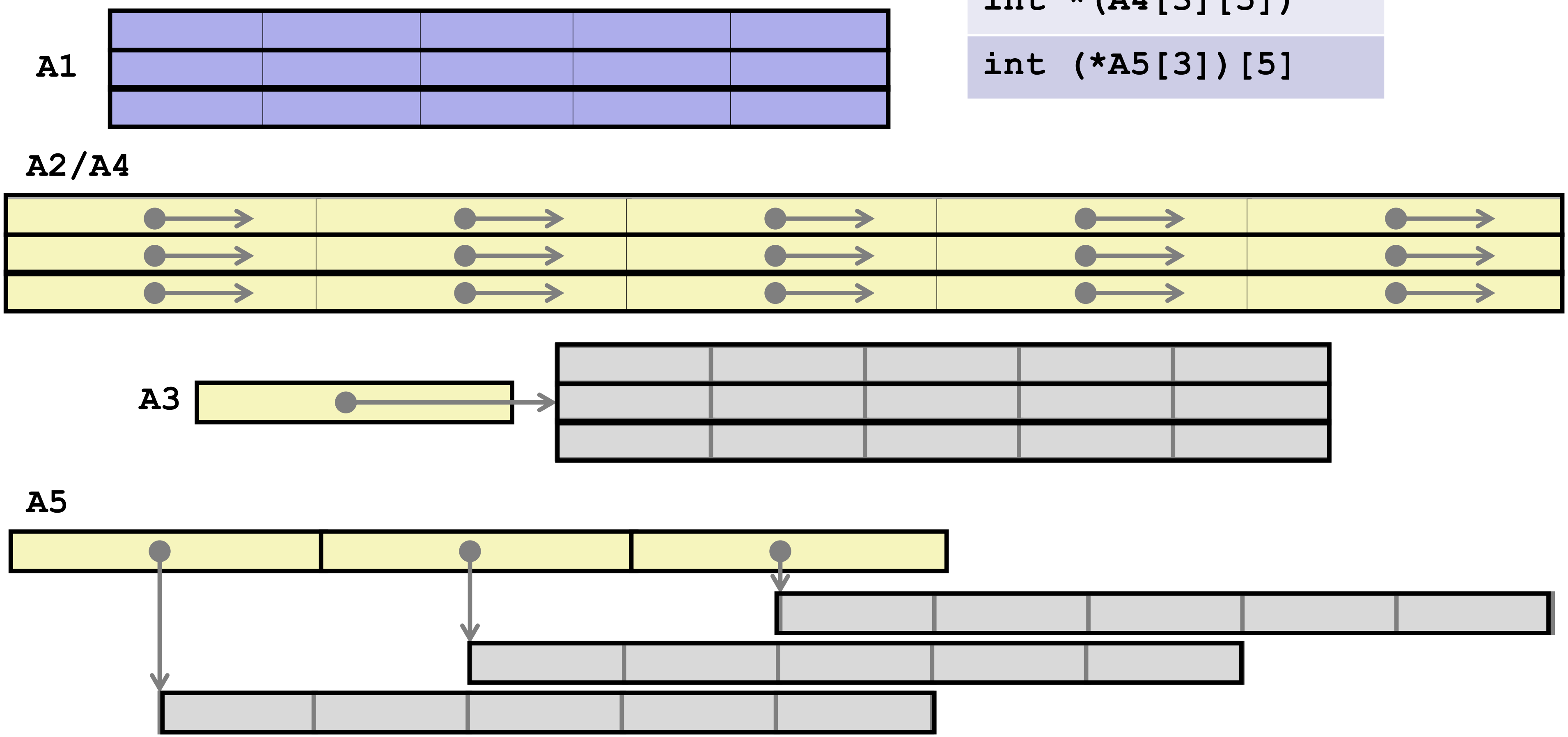
Decl	An			*An			**An		
	Cmp	Bad	Size	Cmp	Bad	Size	Cmp	Bad	Size
`int A1[3][5]`									
`int *A2[3][5]`									
`int (*A3)[3][5]`									
`int *(A4[3][5])`									
`int (*A5[3])[5]`									

- **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]`



理解指针和数组 #3
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

多维（嵌套）数组 Multidimensional (Nested) Arrays

- **声明 Declaration**

  T **A**[*R*][*C*];

  - 数据类型为T的二维数组 2D array of data type *T*
  - R行C列 *R* rows, *C* columns
  - 类型T元素需要K个字节 Type *T* element requires *K* bytes

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

- **数组大小 Array Size**
  - *R* * *C* * *K* bytes字节

- **排列 Arrangement**
  - 行优先的顺序 Row-Major Ordering

`int A[R][C];`

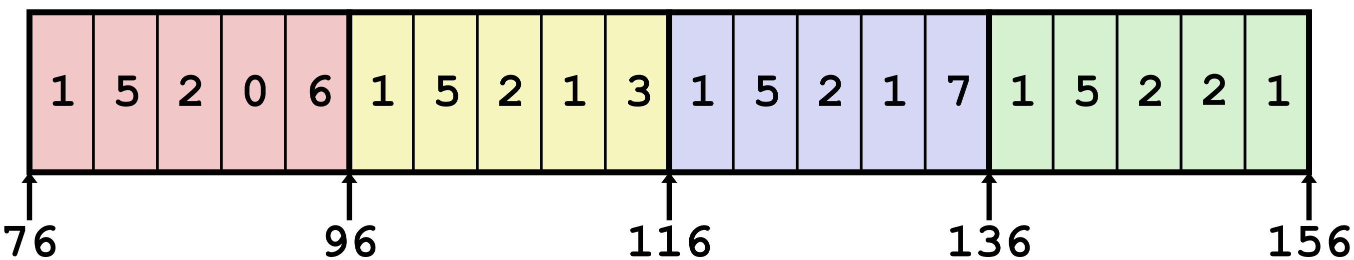
A [0] [0]	• • •	A [0] [C-1]	A [1] [0]	• • •	A [1] [C-1]	• • •	A [R-1] [0]	• • •	A [R-1] [C-1]

|← **4*R*C** Bytes →|

嵌套数组示例 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];`

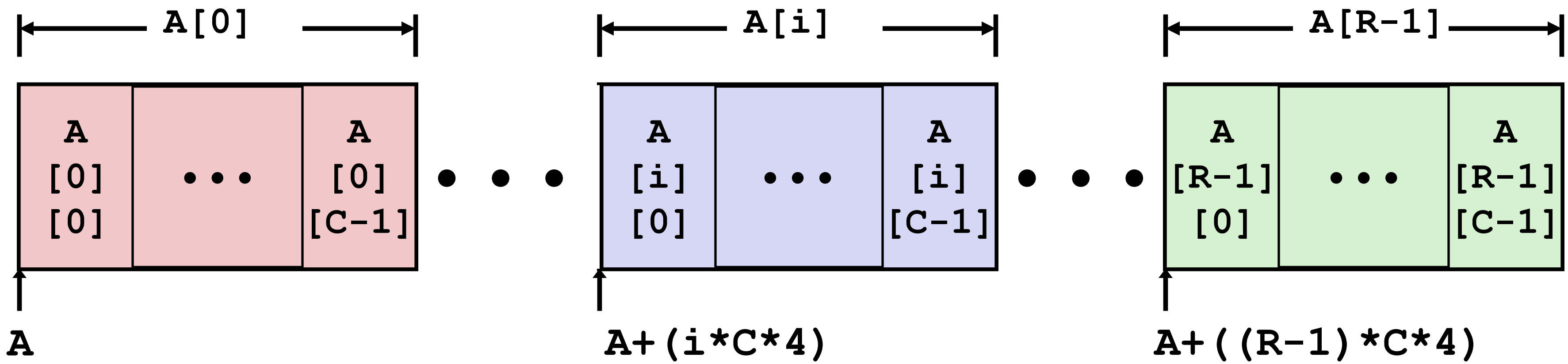


- "`zip_dig pgh[4]`" 等价于equivalent to "`int pgh[4][5]`"
  - 变量pgh：四个元素的数组，连续分配 Variable **`pgh`**: array of 4 elements, allocated contiguously
  - 每个元素是五个整数的数组，连续分配 Each element is an array of 5 **`int`**'s, allocated contiguously
- **在内存中所有元素都采用"行优先"顺序排列 "Row-Major" ordering of all elements in memory**

嵌套数组行访问 Nested Array Row Access

- **行向量 Row Vectors**
  - A[i]是C个元素的数组 **`A[i]`** is array of *C* elements
  - 每个类型为T的元素需要k字节 Each element of type *T* requires *K* bytes
  - 起始地址为 Starting address **`A +`** *i* * (*C* * *K*)

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



嵌套数组行访问代码
Nested Array Row Access Code

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

pgh

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

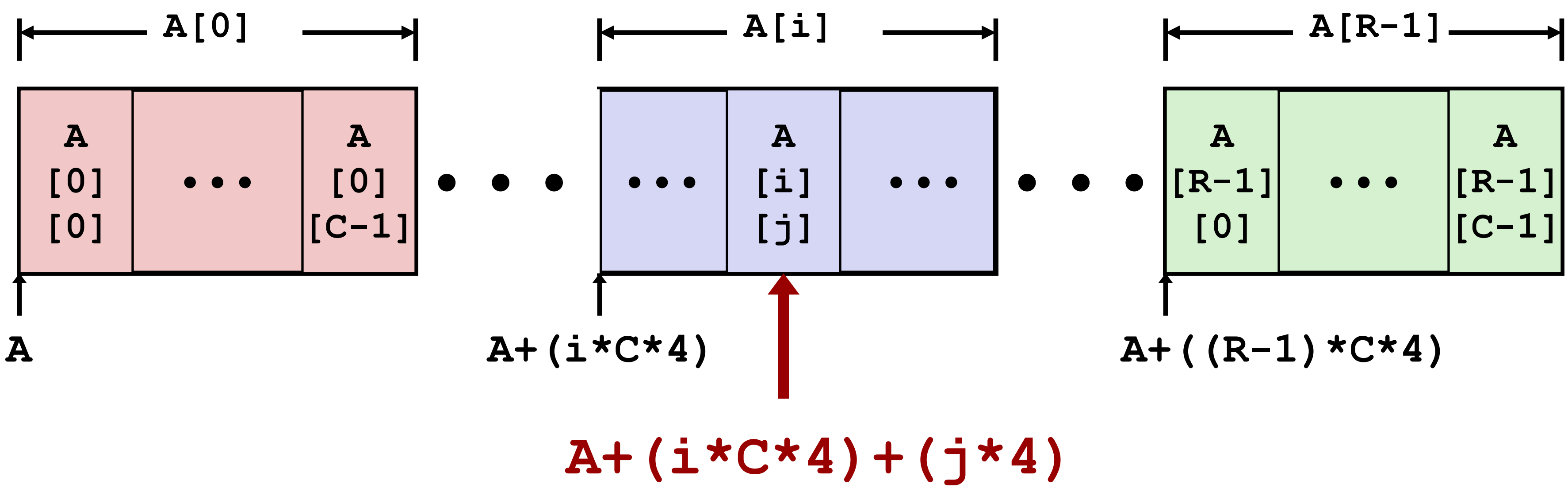
```
  # %rdi = index
  leaq (%rdi,%rdi,4),%rax # 5 * index
  leaq pgh(,%rax,4),%rax  # pgh + (20 * index)
```

- 行向量 Row Vector
  - `pgh[index]`是五个整数的数组 `pgh[index]` is array of 5 `int`'s
  - 起始地址为 Starting address `pgh+20*index`
- 机器代码 Machine Code
  - 计算和返回地址 Computes and returns address
  - 计算方法 Compute as `pgh + 4*(index+4*index)`

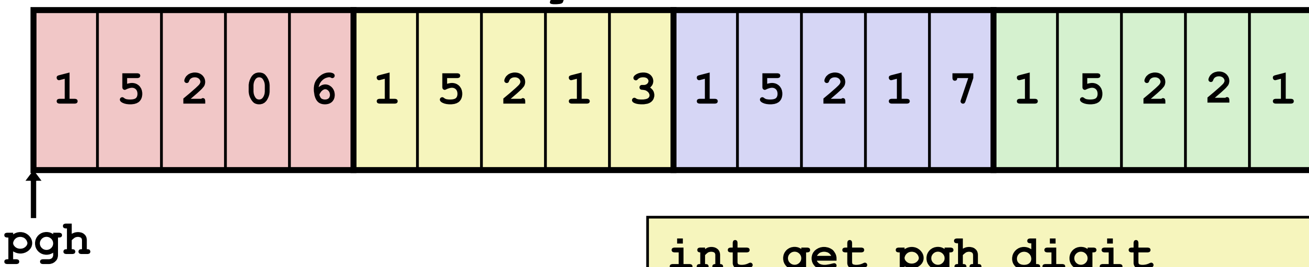
嵌套数组元素访问
Nested Array Element Access

- **数组元素 Array Elements**
  - **`A[i][j]`**是类型为T的元素，需要K字节 **`A[i][j]`** is element of type *T*, which requires *K* bytes
  - 地址为 Address **`A +`** $i * (C * K) + j * K = A + (i * C + j) * K$

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



嵌套数组元素访问代码
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)]
```

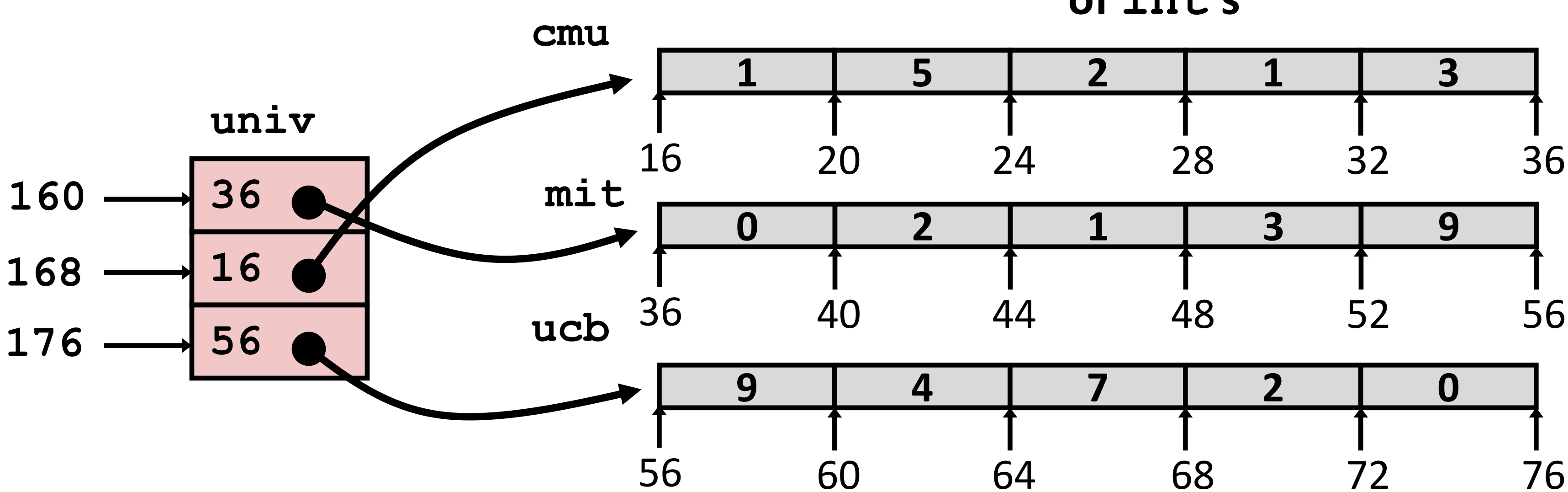
- 数组元素 Array Elements
  - 数组元素是整数 `pgh[index][dig]` is `int`
  - 地址： Address: `pgh + 20*index + 4*dig`
    - = `pgh + 4*(5*index + dig)`

多级数组示例 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 };
```

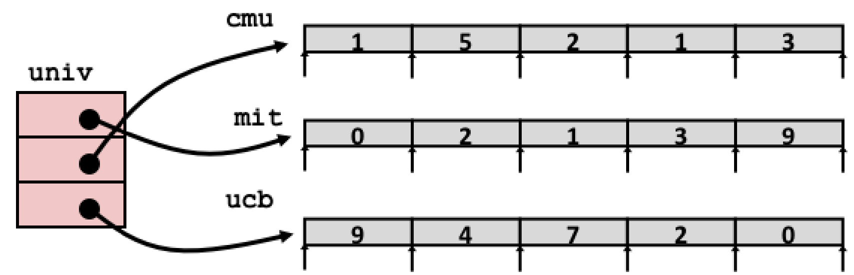
```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```

- 变量univ指向有3个元素的数组 Variable `univ` denotes array of 3 elements
- 每个元素是一个指针 Each element is a pointer
  - 8 bytes字节
- 每个指针指向整数数组 Each pointer points to array of `int`’s



在多级数组中访问元素
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
```

- **计算 Computation**
  - 元素访问 Element access **`Mem[Mem[univ+8*index]+4*digit]`**
  - 必须进行两次内存读操作 Must do two memory reads
    - 第一次得到行数组的指针 First get pointer to row array
    - 然后访问数组内元素 Then access element within array

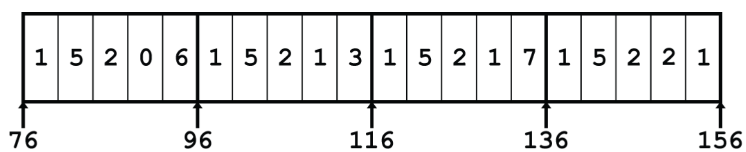
数组元素访问 Array Element Accesses

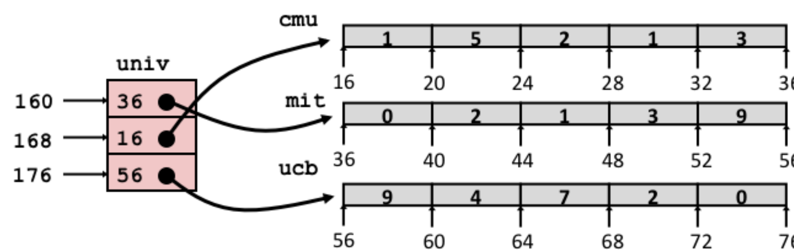
嵌套数组 Nested array

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

多级数组 Multi-level array

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





在C语言中访问看起来是类似的，但是地址计算方法非常不同

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

`Mem[pgh+20*index+4*digit]`   `Mem[Mem[univ+8*index]+4*digit]`

二维矩阵代码

N X N Matrix Code

- **固定维数 Fixed dimensions**
  - 编译时知道N的值 Know value of N at compile time
- **变化维数，显式索引 Variable dimensions, explicit indexing**
  - 传统方法实现动态数组 Traditional way to implement dynamic arrays
- **变化维数，隐式索引 Variable dimensions, implicit indexing**
  - 目前gcc支持 Now supported by gcc

```
#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];
}
```

16X16矩阵访问 16 X 16 Matrix Access

- **数组元素 Array Elements**
  - 地址为 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矩阵访问 n X n Matrix Access

- **数组元素 Array Elements**
  - 地址为 Address **A** + i * (C * K) + j * K
  - C = n, K = 4
  - 必须执行整数乘法 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
```

示例：数组访问 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
```

示例：数组访问 Example: Array Access

```c
#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;
}
```

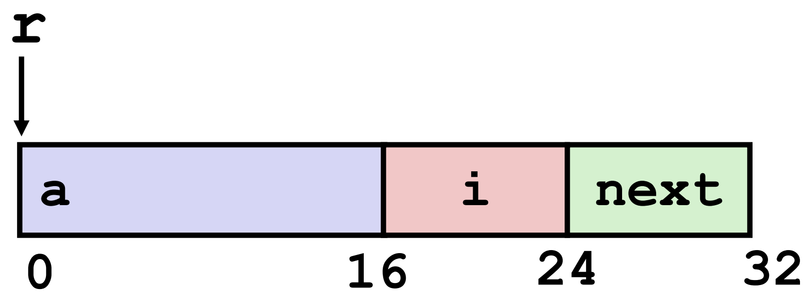
```
linux> ./array
result: 9
```

议题

- 数组 Arrays
  - 一维 One-dimensional
  - 多维（嵌套） Multi-dimensional (nested)
  - 多级 Multi-level
- **结构 Structures**
  - 分配 Allocation
  - 访问 Access
  - 对齐 Alignment
- 浮点数 Floating Point

结构表示 Structure Representation

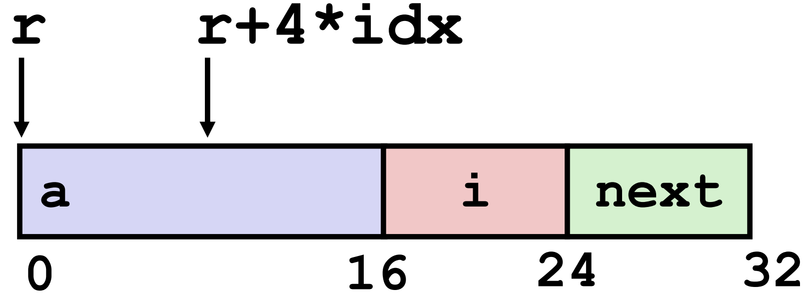
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- **结构表示为内存块 Structure represented as block of memory**
  - **大到足够装下所有字段 Big enough to hold all of the fields**
- **字段顺序按照声明顺序 Fields ordered according to declaration**
  - **即使另一种顺序可能还能够更加紧凑进行表示 Even if another ordering could yield a more compact representation**
- **编译器决定总体大小+字段位置 Compiler determines overall size + positions of fields**
  - **机器级程序并不理解源代码中的结构 Machine-level program has no understanding of the structures in the source code**

生成结构成员的指针
Generating Pointer to Structure Member

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



- **生成数组元素的指针**
  Generating Pointer to Array Element
  - 每个结构成员的偏移在编译时确定 Offset of each structure member determined at compile time
  - 计算方法 Compute as **`r + 4*idx`**

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

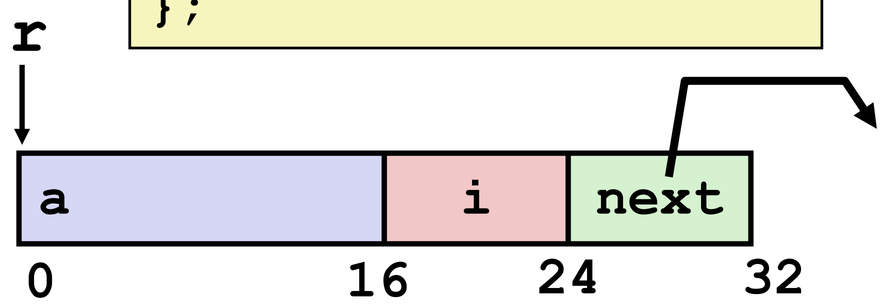
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

遍历链表#1
Following Linked List #1

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

- C代码 C Code

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



寄存器 Register	值 Value
%rdi	r
%rax	len

- 循环汇编代码 Loop assembly code

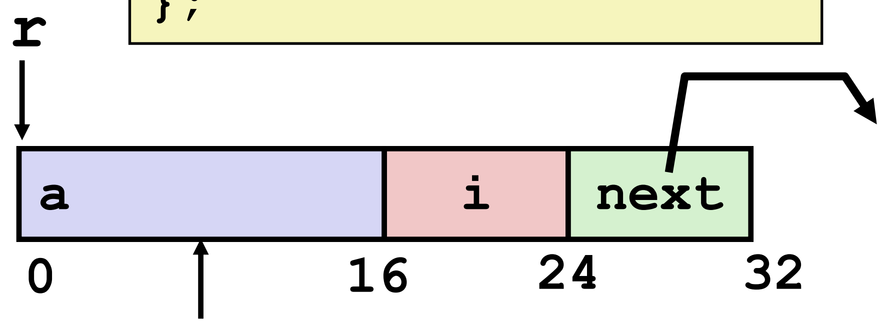
```
.L11:                          # loop:
  addq    $1, %rax             #   len ++
  movq    24(%rdi), %rdi       #   r = Mem[r+24]
  testq   %rdi, %rdi           #   Test r
  jne     .L11                 #   If != 0, goto loop
```

遍历链表#2
Following Linked List #2

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

- C代码 C Code

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



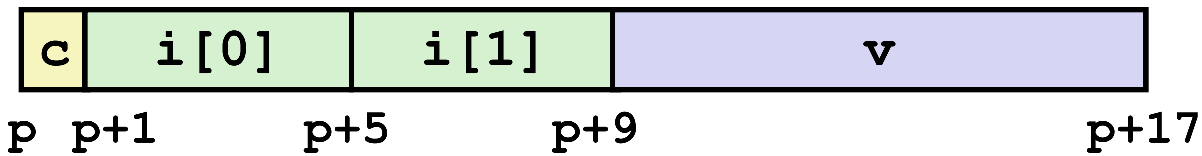
元素 Element i

寄存器 Register	值 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
```

结构和对齐 Structures & Alignment

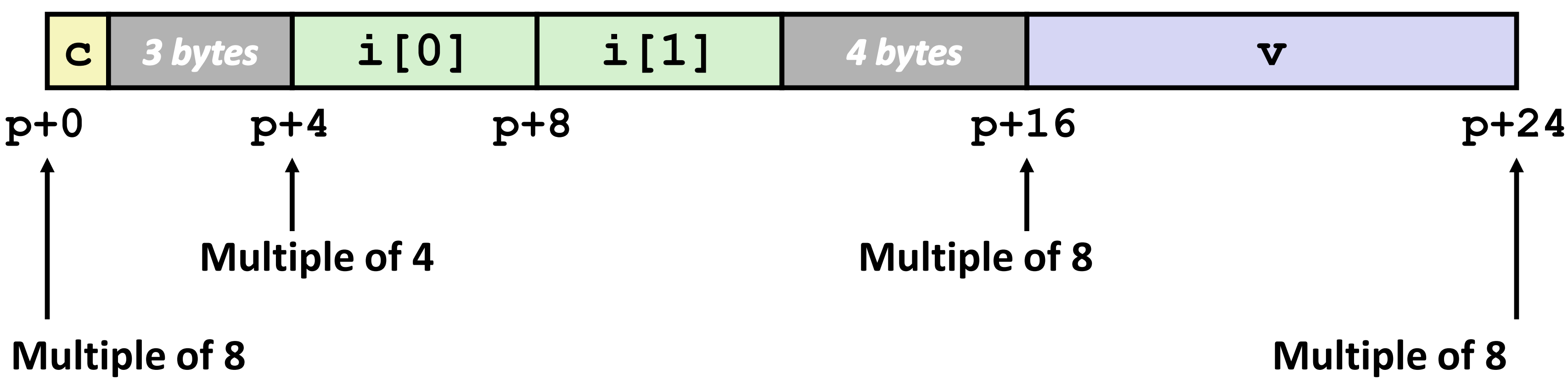
没对齐的数据 Unaligned Data




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

对齐的数据 Aligned Data

- 基本数据类型需要K字节 Primitive data type requires ***K*** bytes
- 地址必须是K的整数倍 Address must be multiple of ***K***



对齐的原则 Alignment Principles

- **对齐的数据 Aligned Data**
  - 基本数据类型需要K字节 Primitive data type requires ***K*** bytes
  - 地址必须是K的整数倍 Address must be multiple of ***K***
  - 在某些机器上严格满足该要求；在x86-64上建议满足 Required on some machines; advised on x86-64
- **对齐数据的动机 Motivation for Aligning Data**
  - 内存访问以（对齐的）4或8字节数据块（依赖于不同的系统）为单位 Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - 装载或存储数据比较低效，因为这样会跨越四字边界 Inefficient to load or store datum that spans quad word boundaries
    - 当数据跨越2页时虚拟存储器访问更棘手 Virtual memory trickier when datum spans 2 pages
- **编译器 Compiler**
  - 在结构中插入间隔以确保字段的正确对齐 Inserts gaps in structure to ensure correct alignment of fields

对齐的特殊情况（x86-64）
Specific Cases of Alignment (x86-64)

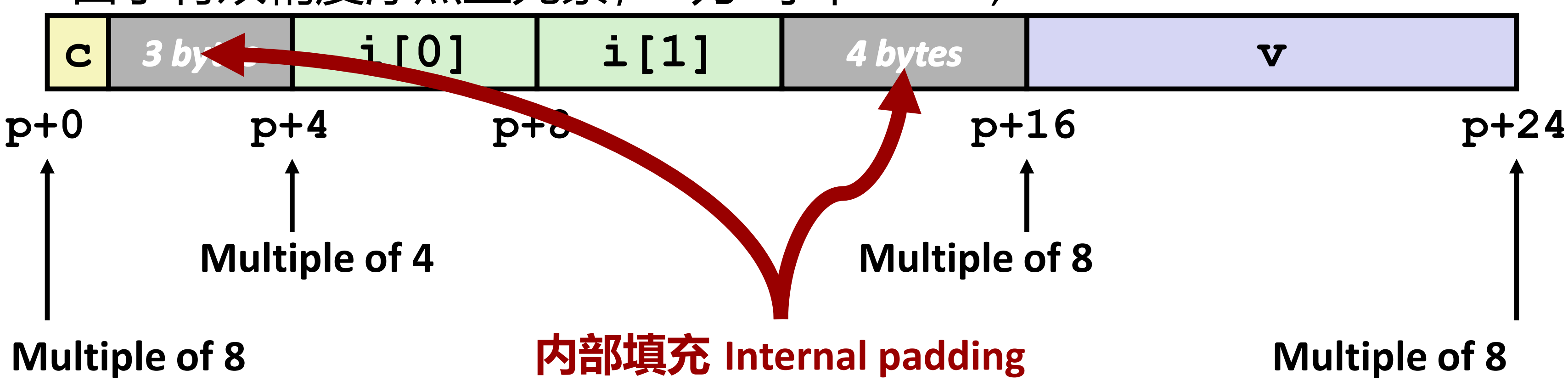
- **1 byte: `char`, …**
  - 地址没有限制 no restrictions on address
- **2 bytes: `short`, …**
  - 地址的最低一位必须为零 lowest 1 bit of address must be 0_2
- **4 bytes: `int`, `float`, …**
  - 地址的最低二位必须为00 lowest 2 bits of address must be 00_2
- **8 bytes: `double`, `long`, `char *`, …**
  - 地址的最低三位必须为000 lowest 3 bits of address must be 000_2
- **16 bytes: `long double`** (GCC on Linux)
  - 地址的最低四位必须为0000 lowest 4 bits of address must be 0000_2

结构体的对齐要求

Satisfying Alignment with Structures

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

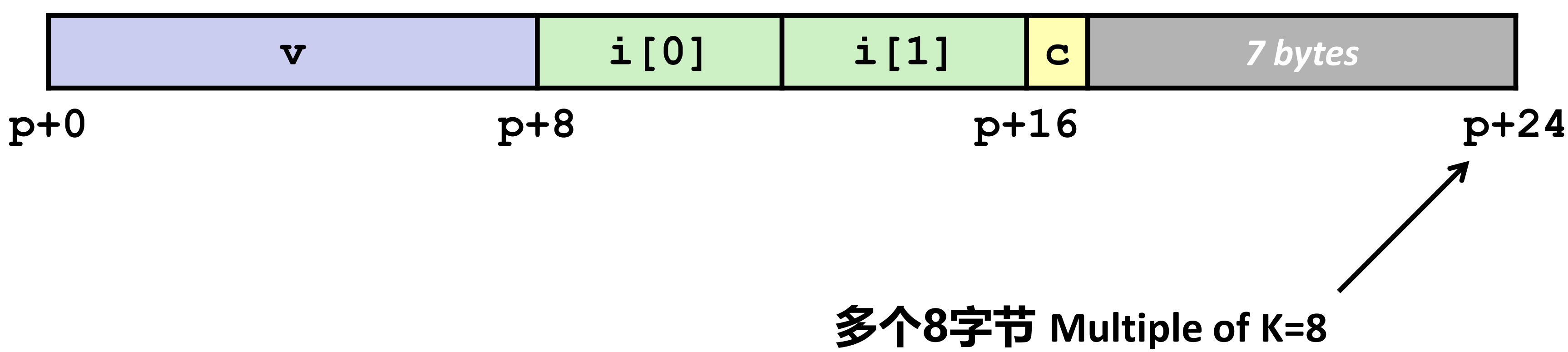
- **结构内部 Within structure:**
  - 必须满足每个元素的对齐需求 Must satisfy each element’s alignment requirement
- **整个结构的排放 Overall structure placement**
  - 每个结构有对齐需求K Each structure has alignment requirement **K**
    - K为任何元素对齐要求的最大值 K = Largest alignment of any element
  - 起始地址和结构长度必须为K的整数倍 Initial address & structure length must be multiples of **K**
- **示例 Example:**
  - 由于有双精度浮点型元素，K为8字节 K = 8, due to **`double`** element



满足整体对齐需求
Meeting Overall Alignment Requirement

- **对于最大对齐需求K For largest alignment requirement K**
- **整体结构必须是K的整数倍 Overall structure must be multiple of K**

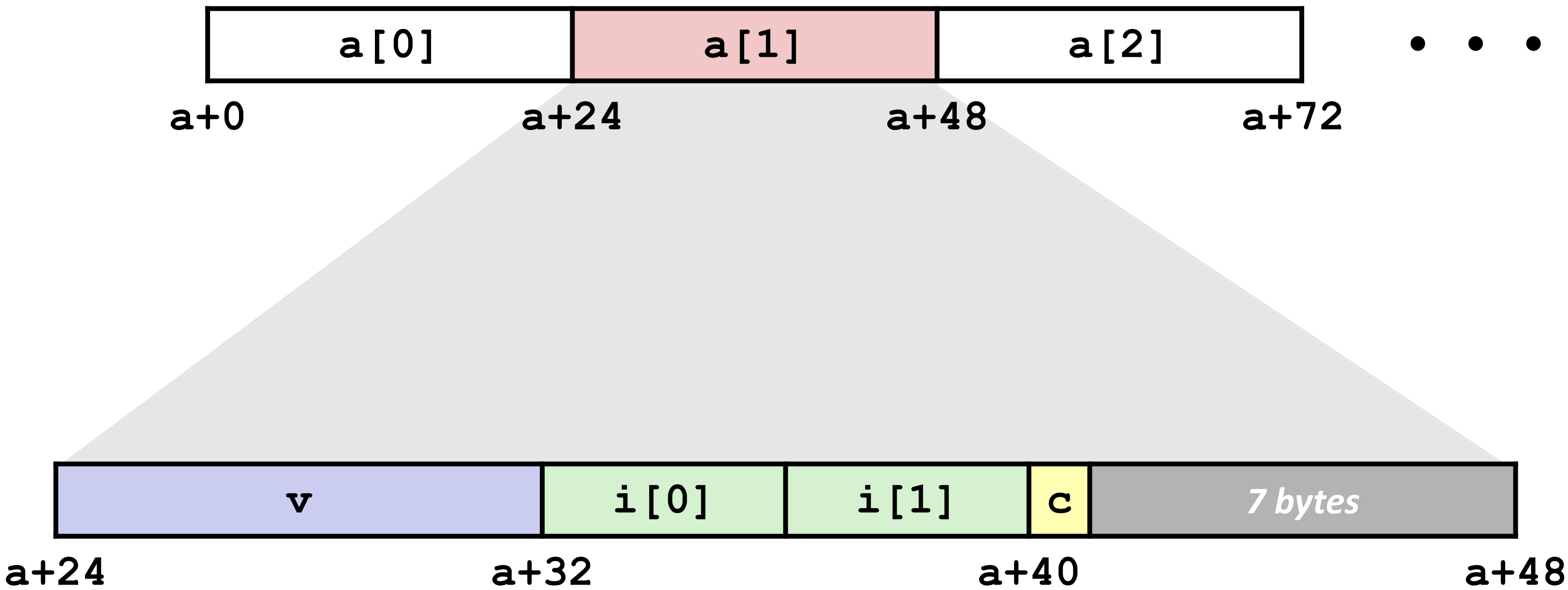
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



结构数组 Arrays of Structures

- **整体结构长度是K的整数倍**
  Overall structure length multiple of K
- **满足每个元素的对齐需求 Satisfy alignment requirement for every element**

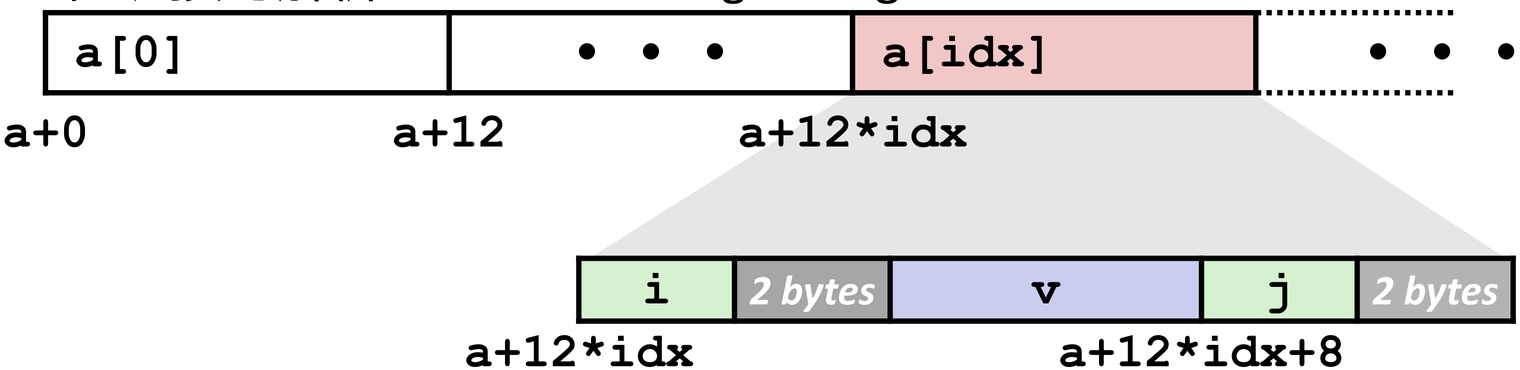
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



访问数组元素
Accessing Array Elements

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

- 计算数组的偏移 Compute array offset 12*idx
  - `sizeof(S3)`, 包括对齐所需填充空白 including alignmen
- 元素j在结构内部的偏移是8 Element `j` is at offset 8 within structure
- 汇编器给出的偏移是a+8 Assembler gives offset a+8
  - 在链接时解析 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
```

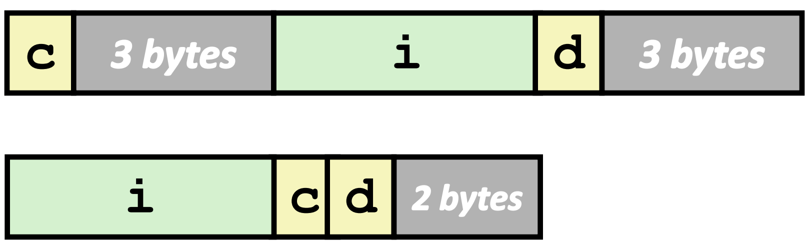
节省空间 Saving Space

- 首先存放大的数据 Put large data types first

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

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

- 效果 Effect (K=4)



示例 结构 问题

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.

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

示例 结构 问题（续）

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

议题

- **数组 Arrays**
  - 一维 One-dimensional
  - 多维（嵌套） Multi-dimensional (nested)
  - 多级 Multi-level
- **结构 Structures**
  - 分配 Allocation
  - 访问 Access
  - 对齐 Alignment
- **浮点数 Floating Point**

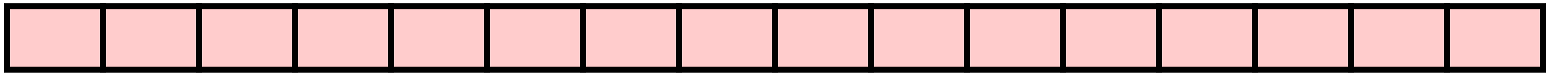
背景 Background

- **历史 History**
  - x87 FP
    - 遗留表示，非常丑陋 Legacy, very ugly
  - 流式SIMD扩展 SSE FP
    - Shark机器支持 Supported by Shark machines
    - 向量指令的特殊情况 Special case use of vector instructions
  - 高级向量扩展 AVX FP
    - 最新的版本 Newest version
    - 类似于SSE Similar to SSE
    - 参考教材内容 Documented in book

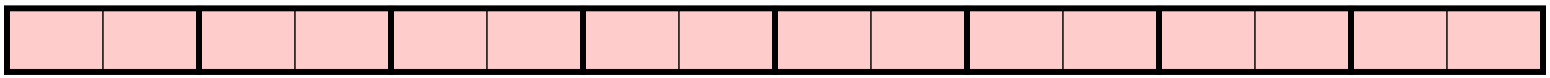
SSE4编程 Programming with SSE4

扩展多媒体寄存器 XMM Registers

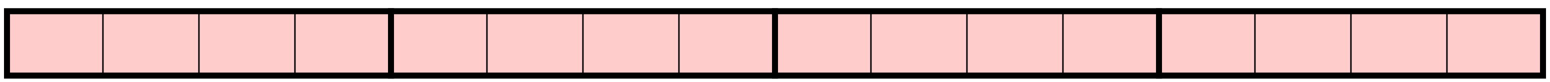
- 16个，每个16字节 16 total, each 16 bytes
- 16个单字节整数 16 single-byte integers



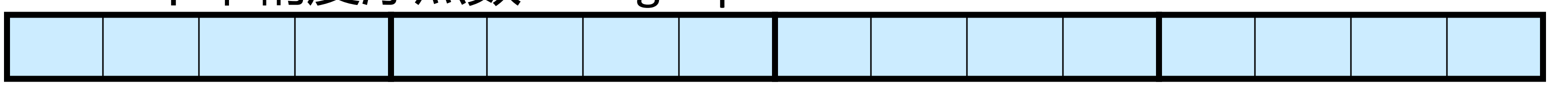
- 8个16位整数 8 16-bit integers



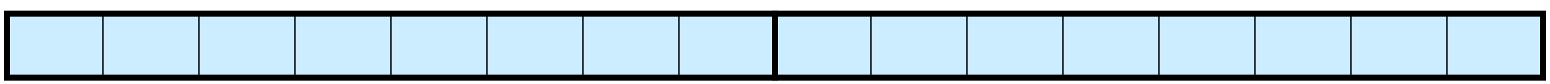
- 4个32位整数 4 32-bit integers



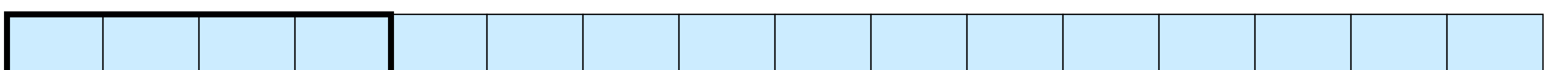
- 4个单精度浮点数 4 single-precision floats



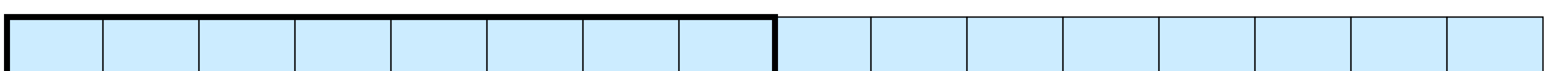
- 2个双精度浮点数 2 double-precision floats



- 1个单精度浮点数 1 single-precision float



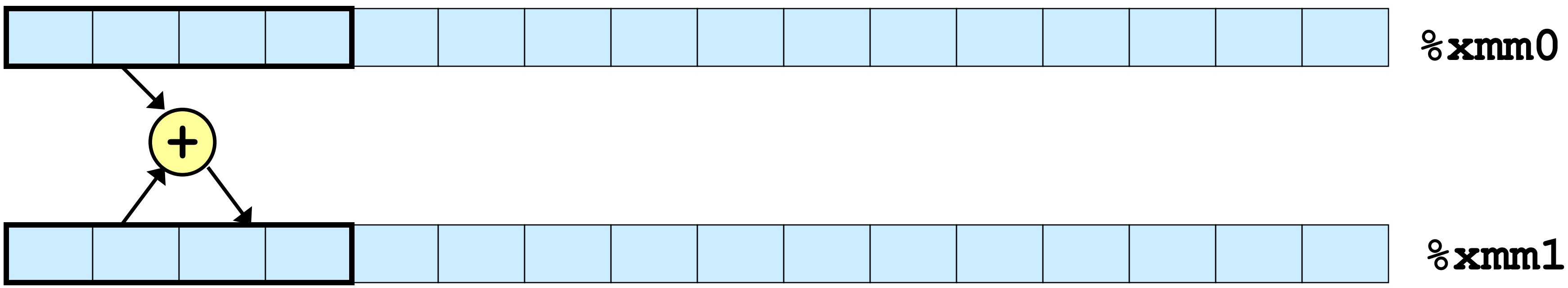
- 1个双精度浮点数 1 double-precision float



标量和SIMD操作 Scalar & SIMD Operations

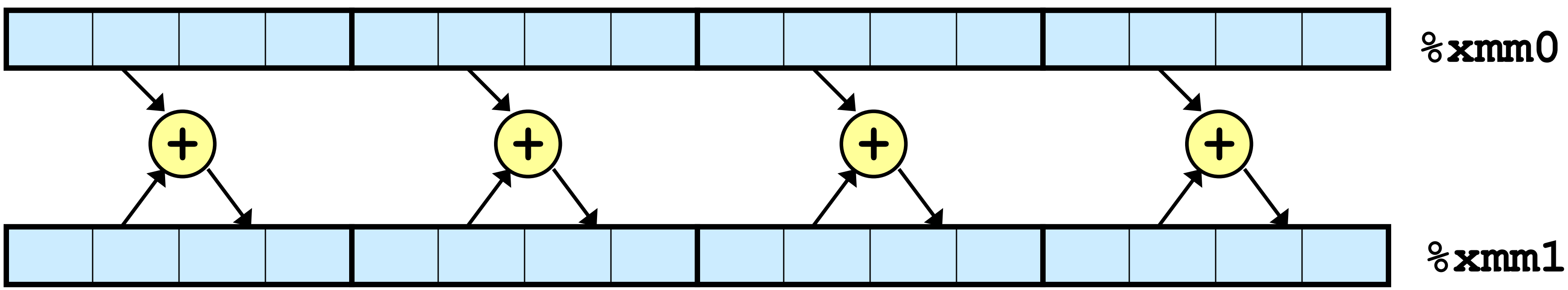
- 标量操作：单精度 Scalar Operations: Single Precision

```
addss %xmm0,%xmm1
```



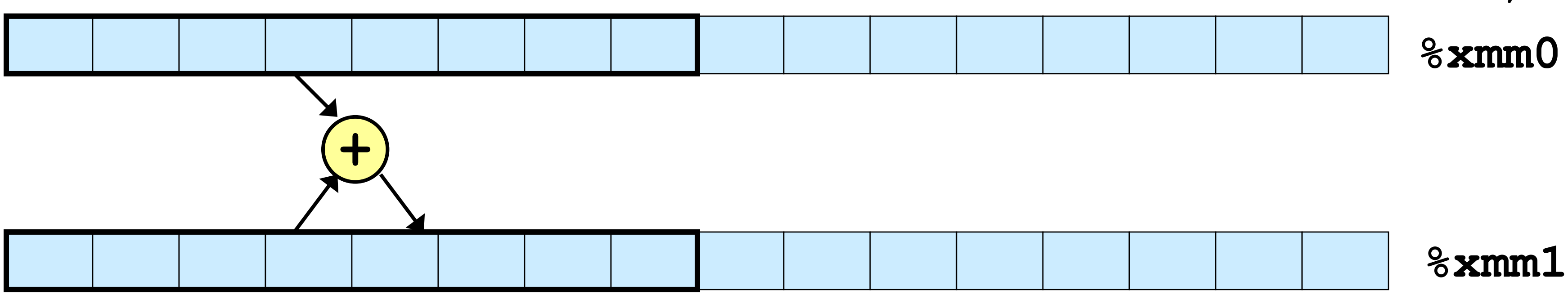
- SIMD操作：单精度 SIMD Operations: Single Precision

```
addps %xmm0,%xmm1
```



- 标量操作：双精度 Scalar Operations: Double Precision

```
addsd %xmm0,%xmm1
```



浮点数基础 FP Basics

- 参数传递用 Arguments passed in `%xmm0`, `%xmm1`, ...
- 结果返回用 Result returned in `%xmm0`
- 所有XMM寄存器都由调用者保存 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
```

浮点数传送操作 FP Movement Operations

- **在内存和寄存器之间，以及寄存器和寄存器之间传送值**
  Transfer values between memory and registers, as well as pairs of registers

指令 Instruction	源 Source	目的 Dest	描述 Description
vmovss	M_{32}	XMM	Move single precision单精度
vmovss	XMM	M_{32}	Move single precision单精度
vmovsd	M_{64}	XMM	Move double precision双精度
vmovsd	XMM	M_{64}	Move double precision双精度
vmovaps	XMM	XMM	Move aligned, packed single precision 对齐的单精度
vmovapd	XMM	XMM	Move aligned, packed double precision 对齐的双精度

浮点数算术运算 FP Arithmetic Operations

- **一个（s1）或两个（s1，s2）源操作数和一个目的操作数D One (S_1) or two (S_1, S_2) source operands and a destination operand D**
  - S1可以是XMM寄存器或内存单元 S_1 can be XMM register or a memory location
  - S2和D必须是XMM寄存器 S_2 and D must be XMM registers

单精度 Single	双精度 Double	效果 Effect	描述 Description
vaddss	vaddsd	$D \leftarrow S_2 + S_1$	FP add 加
vsubss	vsubsd	$D \leftarrow S_2 - S_1$	FP subtract 减
vmulss	vmulsd	$D \leftarrow S_2 \times S_1$	FP multiply 乘
vdivss	vdivsd	$D \leftarrow S_2 / S_1$	FP divide 除
vmaxss	vmaxsd	$D \leftarrow \max(S_2, S_1)$	FP maximum 最大
vminss	vminsd	$D \leftarrow \min(S_2, S_1)$	FP minimum 最小
sqrtss	sqrtsd	$D \leftarrow S_1$+ ^ (1/2)	FP square root 开平方

浮点代码中使用比特级运算
Using Bitwise Operations in FP Code

单精度 Single	双精度 Double	效果 Effect	描述 Description
vxorps	xorpd	$D \leftarrow S_2 \mathbin{\hat{}} S_1$	Bitwise EXCLUSIVE-OR 比特位级异或
vandps	andpd	$D \leftarrow S_2 \,\&\, S_1$	Bitwise AND 比特位级与

```
double simple (...){
    ...
    return 0.0;
}
```

```
simple:
   ...
   vxorpd %xmm0, %xmm0, %xmm0
   ret
```

浮点数内存引用 FP Memory Referencing

- 整数（和指针）参数传递用常规的寄存器 Integer (and pointer) arguments passed in regular registers
- 浮点值传递用XMM寄存器 FP values passed in XMM registers
- 不同的mov指令在XMM寄存器之间和内存与XMM寄存器之间传送 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
  vmovapd  %xmm0, %xmm1   # Copy v
  vmovsd   (%rdi), %xmm0  # x = *p
  vaddsd   %xmm0, %xmm1   # t = x + v
  vmovsd   %xmm1, (%rdi)  # *p = t
  ret
```

浮点代码的其它方面
Other Aspects of FP Code

- ***很多指令Lots*** **of instructions**
  - 不同的操作，不同的格式 Different operations, different formats, ...
- **浮点数比较 Floating-point comparisons**
  - 指令**ucomiss**和**ucomisd** Instructions **`ucomiss`** and **`ucomisd`**
  - 设置条件码 Set condition codes ZF, PF, and CF
  - OF和SF置零 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

- **使用常量值 Using constant values**
  - 设置XMM0寄存器为0用指令 Set XMM0 register to 0 with instruction **`xorpd %xmm0, %xmm0`**
  - 其它从内存装入 Others loaded from memory

小结 Summary

- **数组 Arrays**
  - 元素包装进连续的内存区域 Elements packed into contiguous region of memory
  - 使用索引计算来定位单独的元素 Use index arithmetic to locate individual elements
- **结构 Structures**
  - 元素包装进单个内存区域 Elements packed into single region of memory
  - 使用由编译器确定的偏移进行访问 Access using offsets determined by compiler
  - 可能需要内部和外部填充确保对齐 Possible require internal and external padding to ensure alignment
- **组合 Combinations**
  - 可以任意嵌套结构和数组代码 Can nest structure and array code arbitrarily
- **浮点数 Floating Point**
  - 数据装入XMM寄存器进行操作 Data held and operated on in XMM registers