

COMP201

Computer Systems & Programming

Lecture #26 – Data and Stack Frames



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Recap

- Revisiting `%rip`
- Calling Functions
 - The Stack
 - Passing Control
 - Passing Data
 - Local Storage
- Register Restrictions
- Pulling it all together: recursion example

Plan for Today

- Arrays
- Structures
- Floating Point

Disclaimer: Slides for this lecture were borrowed from
—Randal E. Bryant and David R. O'Hallaron's CMU 15-213 class

Lecture Plan

- Arrays
 - One-dimensional
 - Multi-dimensional (nested)
 - Multi-level
- Structures
- Floating Point

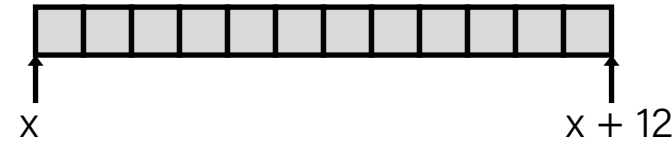
Array Allocation

Basic Principle

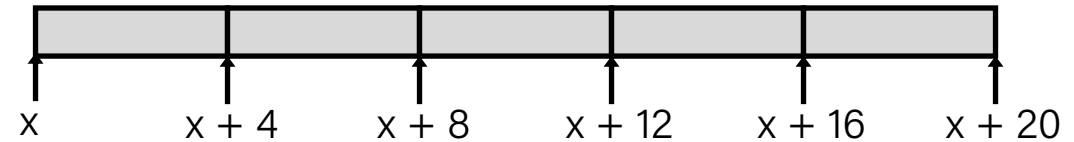
T $A[L];$

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

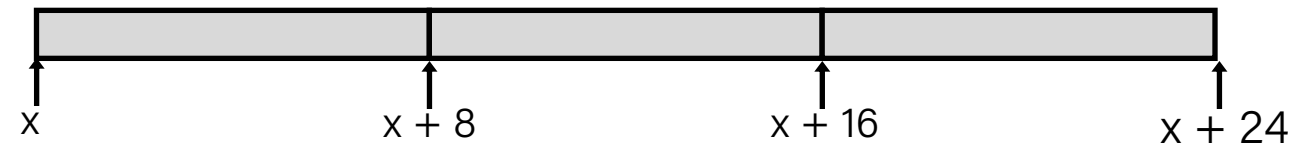
`char string[12];`



`int val[5];`



`double a[3];`



`char *p[3];`



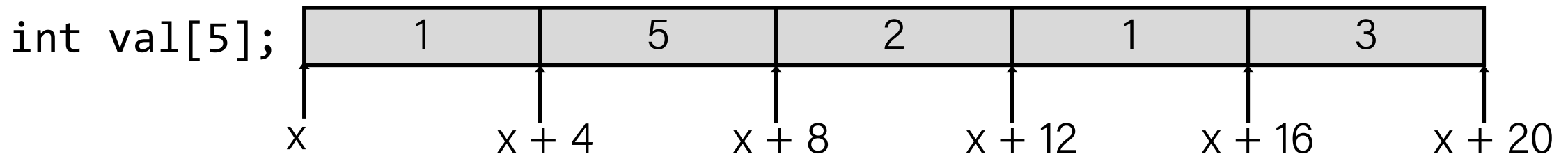
Array Access

- **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^*

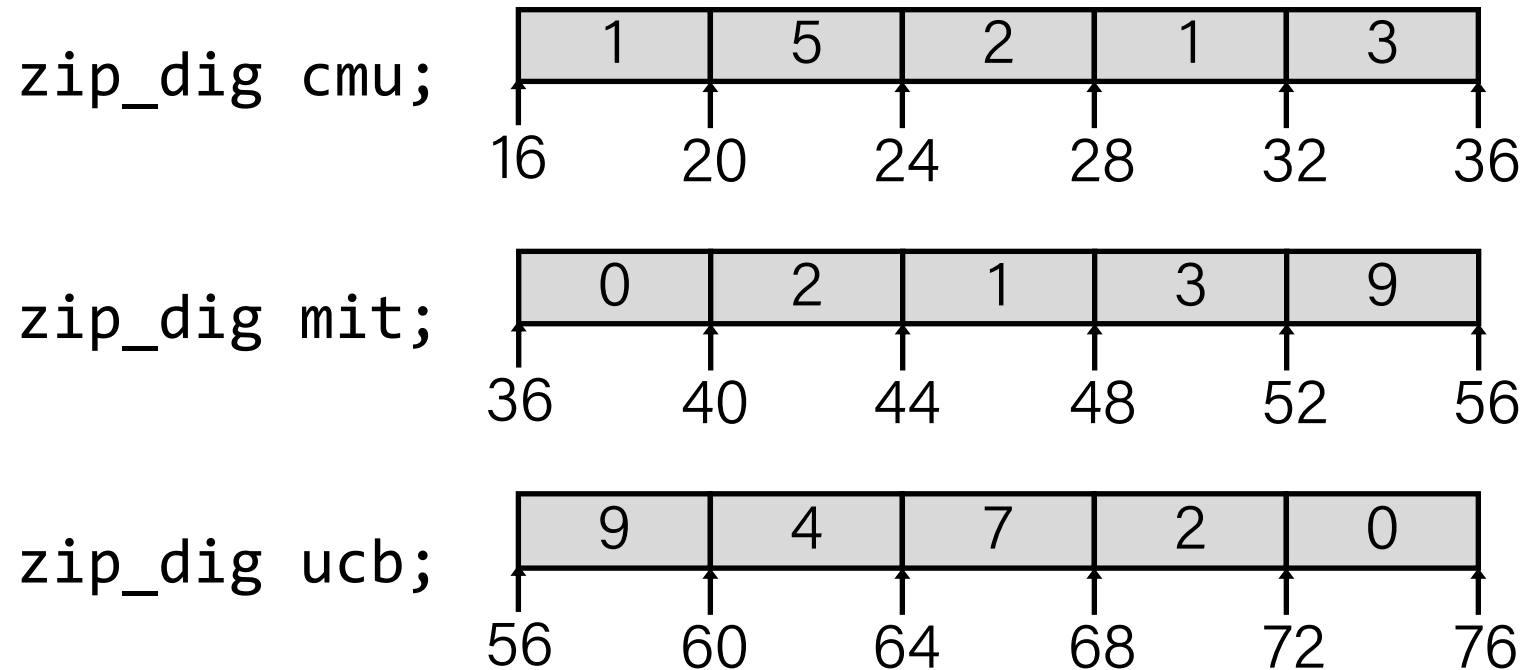
Reference	Type	Value
val[4]	int	3
val	int *	x
val+1	int *	x + 4
&val[2]	int *	x + 8
val[5]	int	??
*(val+1)	int	5
val + i	int *	x + 4 i



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 ku = {3,4,4,5,0};
```



- 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

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

zip_dig ku;

3	4	4	5	0
---	---	---	---	---

16 20 24 28 32 36

```
# %rdi = z
# %rsi = digit
movl (%rdi,%rsi,4), %eax # z[digit]
```

- Register `%rdi` contains starting address of array
- Register `%rsi` contains array index
- Desired digit at `%rdi + 4*%rsi`
- Use memory reference `(%rdi,%rsi,4)`

Array Loop Example

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

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

Multidimensional (Nested) Arrays

Declaration

T $A[R][C];$

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

Array Size

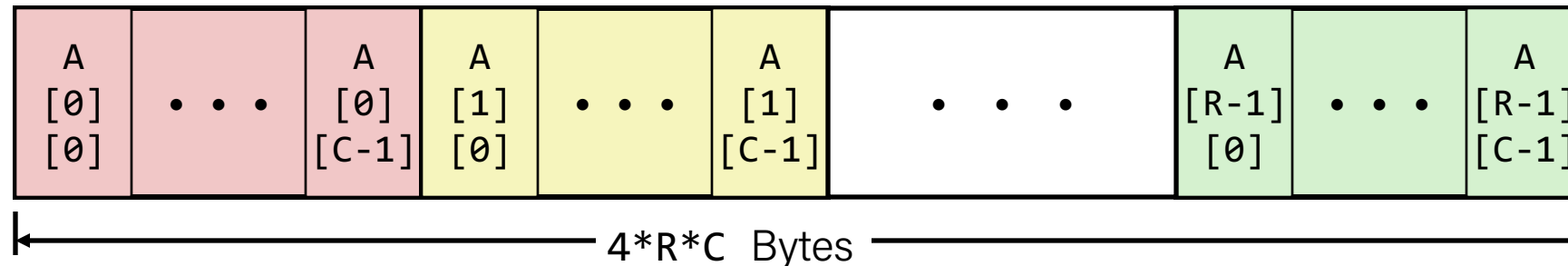
- $R * C * K$ bytes

Arrangement

- Row-Major Ordering

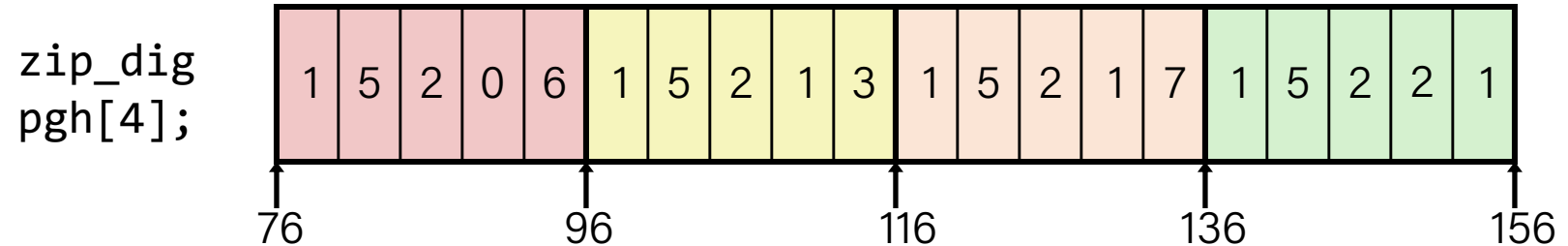
$$\begin{bmatrix} A[0][0] & \cdot & \cdot & \cdot & A[0][C-1] \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ A[R-1][0] & \cdot & \cdot & \cdot & A[R-1][C-1] \end{bmatrix}$$

$\text{int } A[R][C];$



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 }};
```



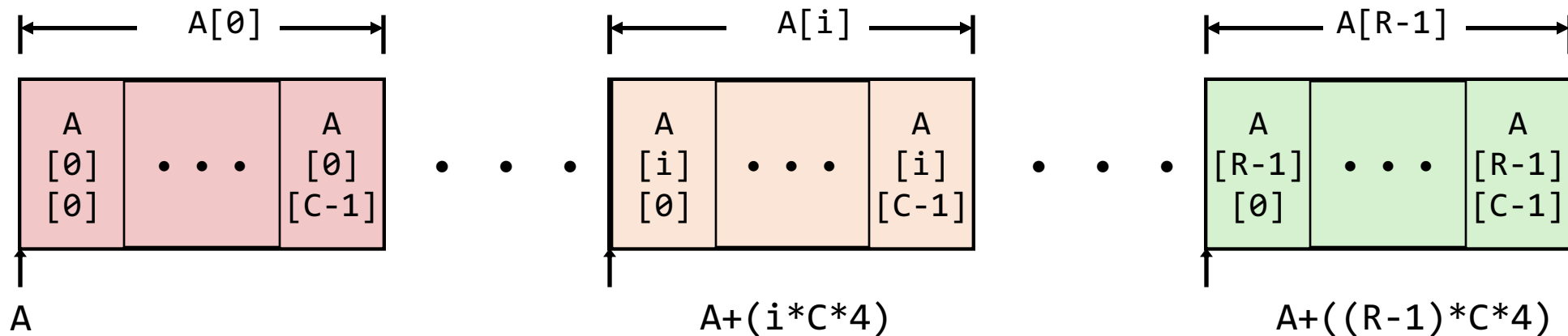
- "zip_dig pgh[4]" equivalent to "int pgh[4][5]"
 - Variable pgh: array of 4 elements, allocated contiguously
 - Each element is an array of 5 int's, allocated contiguously
- "Row-Major" ordering of all elements in memory

Nested Array Row Access

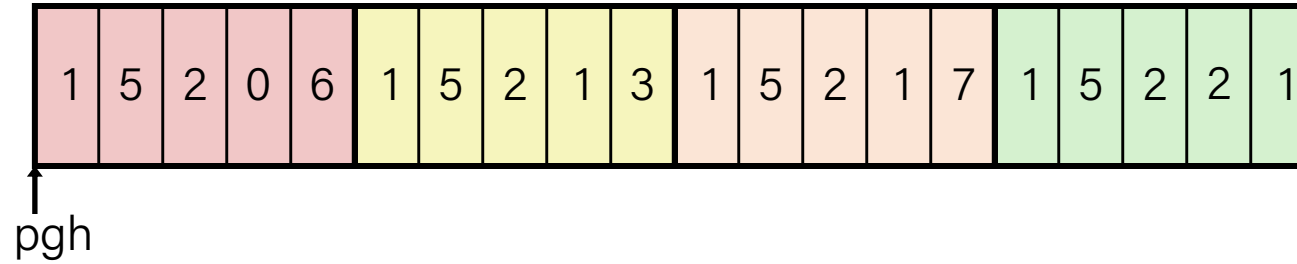
Row Vectors

- $\mathbf{A}[\mathbf{i}]$ is array of C elements
- Each element of type T requires K bytes
- Starting address $\mathbf{A} + i * (C * K)$

```
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`

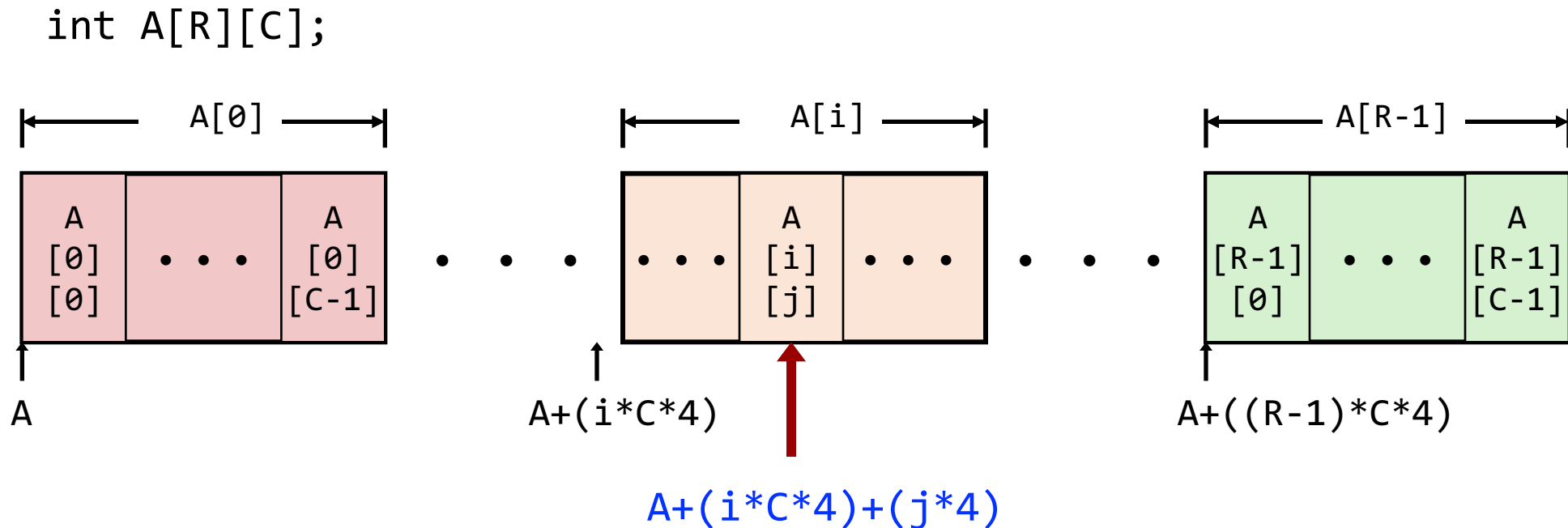
Machine Code

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

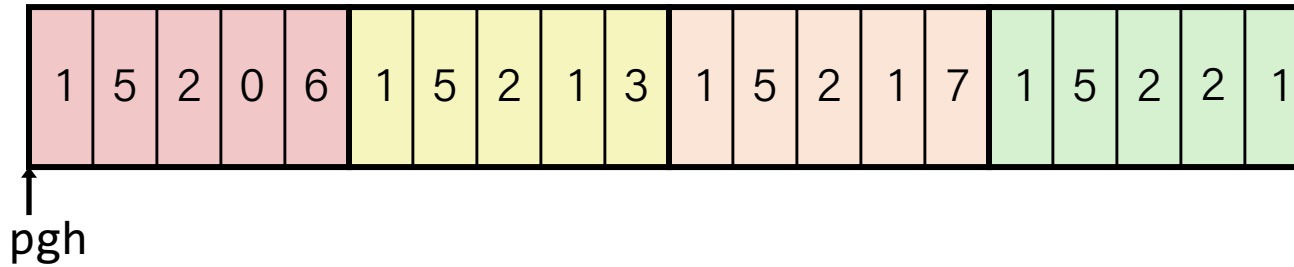
Nested Array Element Access

Array Elements

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



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: $\text{pgh} + 20 \cdot \text{index} + 4 \cdot \text{dig}$
 - $= \text{pgh} + 4 \cdot (5 \cdot \text{index} + \text{dig})$

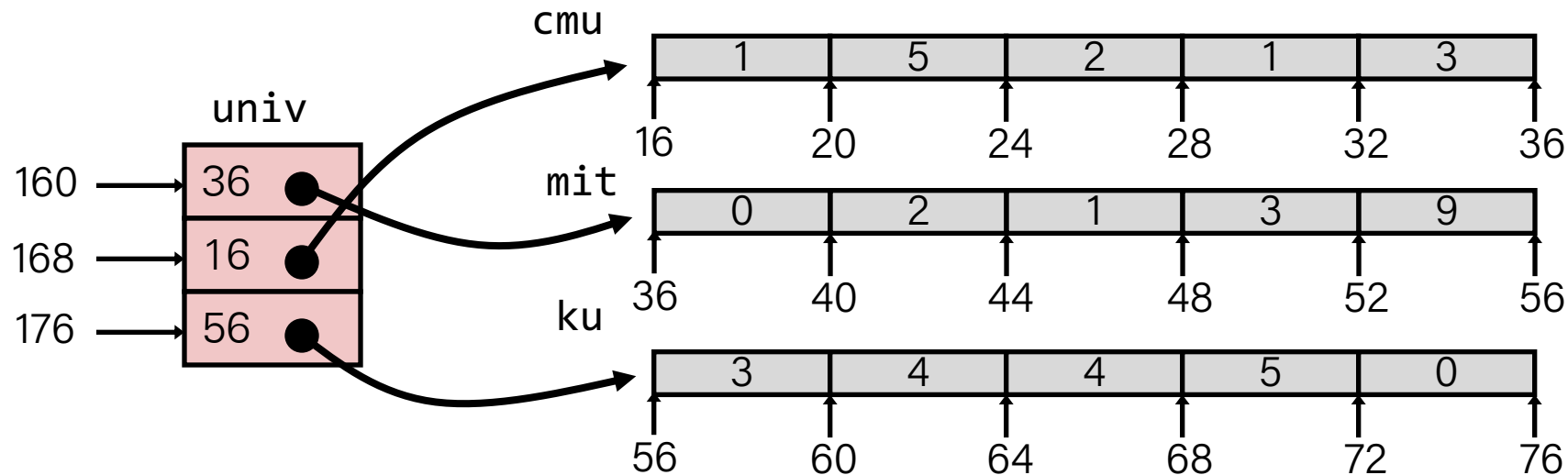
Multi-Level Array Example

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

```
#define UCOUNT 3
```

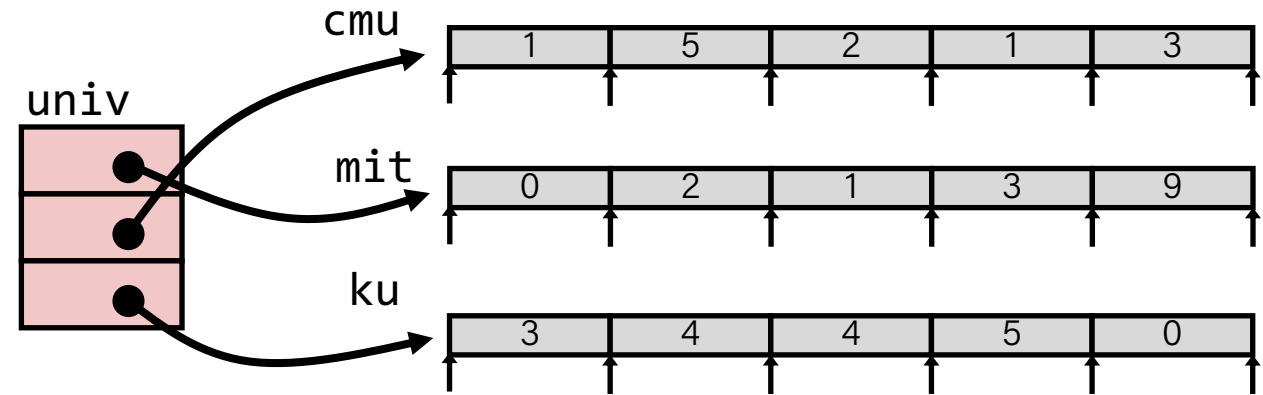
```
int *univ[UCOUNT] = {mit, cmu, ku};
```

- 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
```

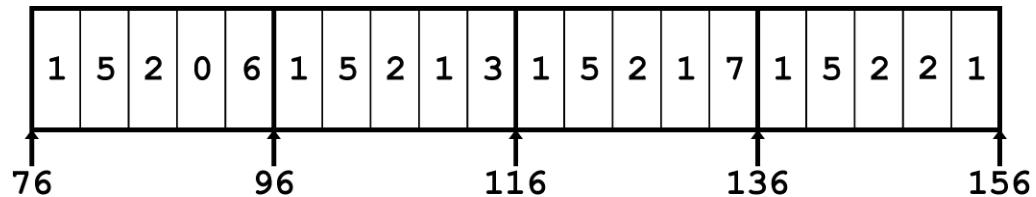
Computation

- Element access $\text{Mem}[\text{Mem}[\text{univ} + 8 * \text{index}] + 4 * \text{digit}]$
- Must do two memory reads
 - First get pointer to row array
 - Then access element within array

Array Element Accesses

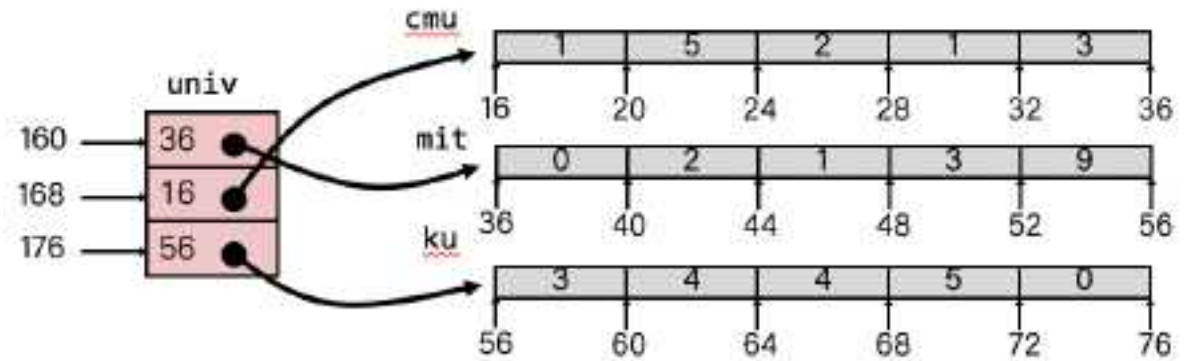
Nested array

```
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:

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

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

$N \times N$ 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 × 16 Matrix Access

```
/* 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
```

Array Elements

- Address $A + i * (C * K) + j * K$
- $C = 16, K = 4$

$n \times n$ Matrix Access

```
/* 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
```

Array Elements

- Address $A + i * (C * K) + j * K$
- $C = 16, K = 4$
- Must perform integer multiplication

Practice 1: Reverse Engineering

```
#define M ??  
#define N ??  
  
long P[M][N];  
long Q[N][M];  
long sum_elem(long i, long j)  
{  
    return P[i][j] + Q[j][i];  
}
```

```
# long sum_elem(long i, long j)  
# in %rdi, j in %rsi  
1 sum_element:  
2     leaq    0(,%rdi,8), %rdx  
3     subq    %rdi, %rdx  
4     addq    %rsi, %rdx  
5     leaq    (%rsi,%rsi,4), %rax  
6     addq    %rax, %rdi  
7     movq    Q(,%rdi,8), %rax  
8     add     P(,%rdx,8), %rax  
9     ret
```

Compute $8*i$

Compute $7*i$

Compute $7*i+j$

Compute $5*j$

Compute $i+5*j$

Retrieve $M[Q+8*(5*j+i)]$

Add $M[P+8*(7*i+j)]$

What is the value of M and N?

M = 5 and N = 7

slido

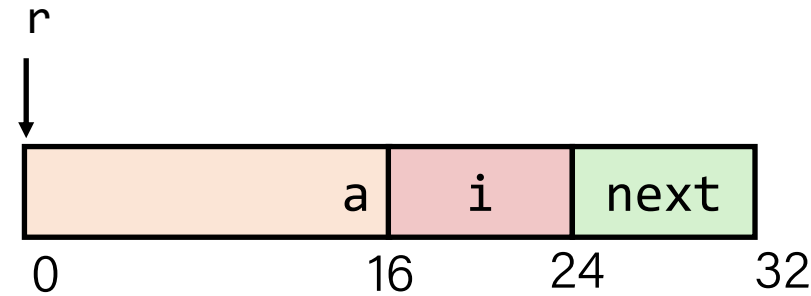
**Event code:
73165**

Lecture Plan

- Arrays
- Structures
 - Allocation
 - Access
 - Alignment
- Floating Point

Structure Representation

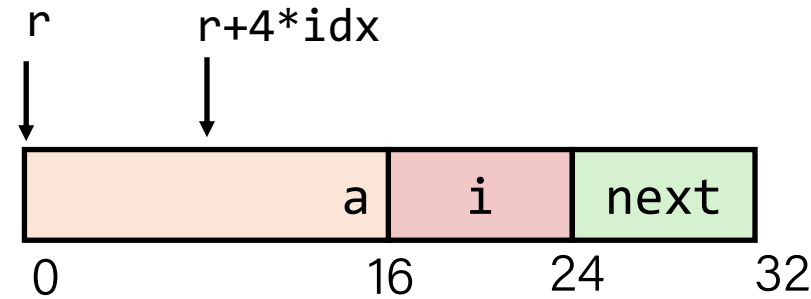
```
struct rec {  
    int a[4];  
    size_t i;  
    struct rec *next;  
};
```



- 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`**

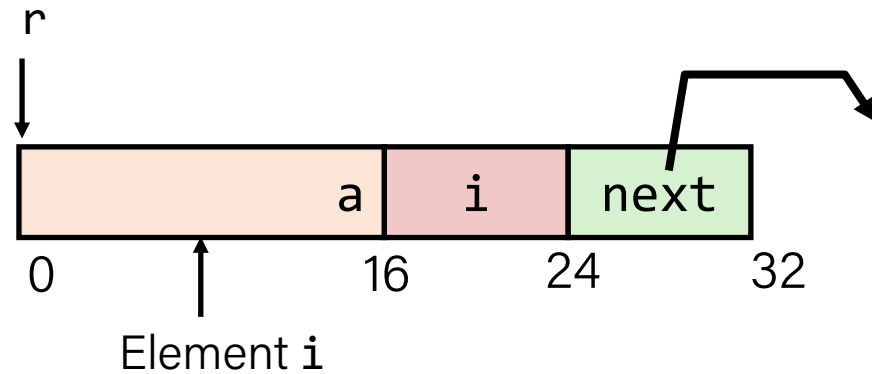
```
int *get_ap  
(struct rec *r, size_t idx)  
{  
    return &r->a[idx];  
}
```

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

Following Linked List

```
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
```

Practice 2: Reverse Engineering

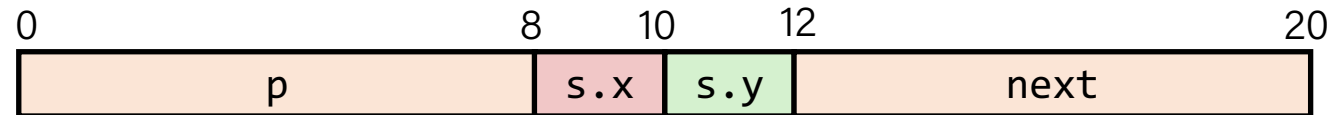
Fill in the blanks by inspecting the assembly code generated by gcc.



Event code:
73165

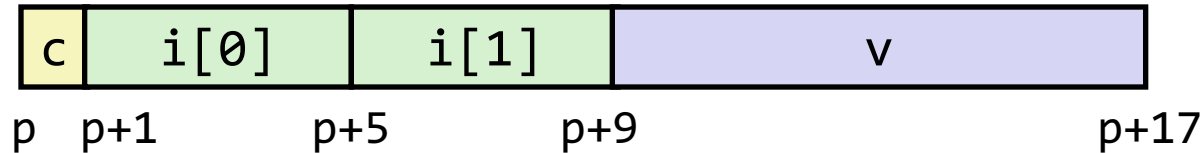
```
struct test {  
    short *p;  
    struct {  
        short x;  
        short y;  
    } s;  
    struct test *next;  
};  
  
void st_init(struct test *st) {  
    st->s.y = st->s.x;  
    st->p   = &(st->s.y);  
    st->next = st;  
}
```

```
# void st_init(struct test *st)  
# st in %rdi  
1 st_init:  
2     movl 8(%rdi), %eax    Get st->s.x  
3     movl %eax, 10(%rdi)   Save in st->s.y  
4     leaq 10(%rdi), %rax   Compute &(st->s.y)  
5     movq %rax, (%rdi)     Store in st->p  
6     movq %rdi, 12(%rdi)   Store st in st->next  
7     ret
```



Structures & Alignment

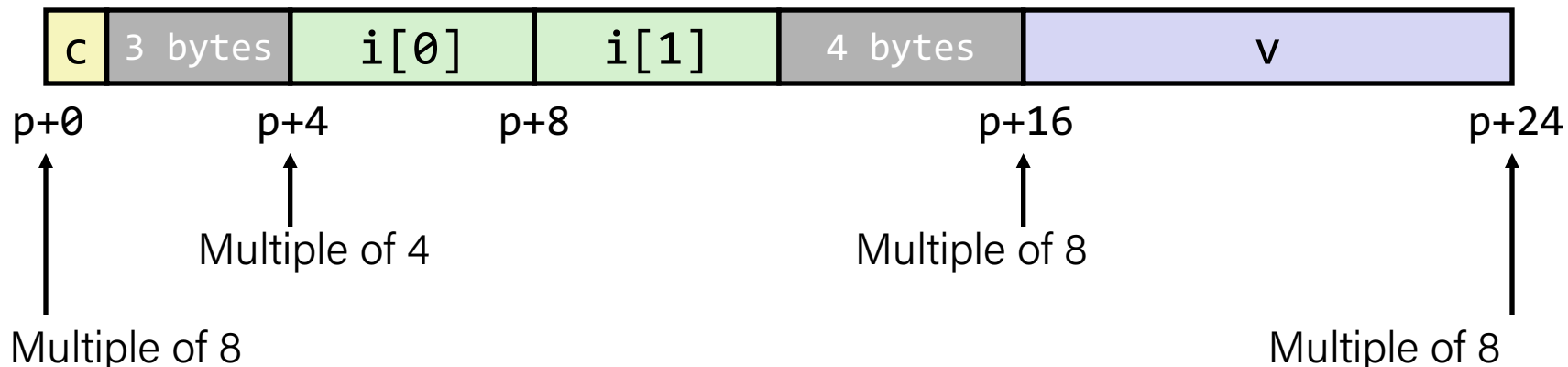
Unaligned Data



```
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

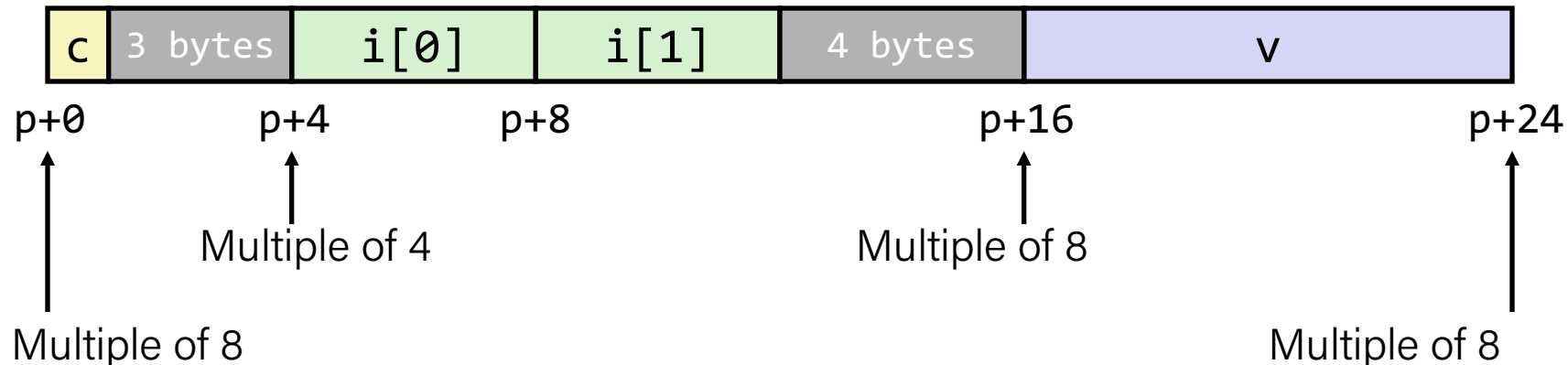
Overall structure placement

- 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:

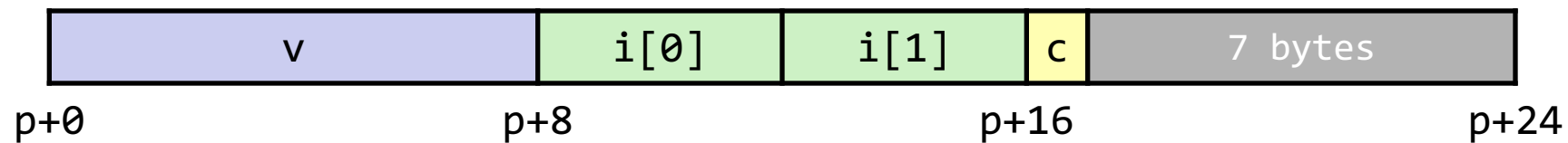
- K = 8, due to **double** element



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;
```



Multiple of $K=8$

Practice 3: Alignment



Event code:
73165

Determine the offset of each field, the total size of the structure, and its alignment requirement for x86-64.

```
struct mystruct {
    int *a;
    float b;
    char c;
    short d;
    long e;
    double f;
    int g;
    char *h;
};
```

Field	*a	b	c	d	e	f	g	*h	Total	Alignment
Size	8	4	1	2	8	8	4	8	56	8
Offset	0	8	12	16	24	32	40	48		

Rearranged structure with minimum wasted space:

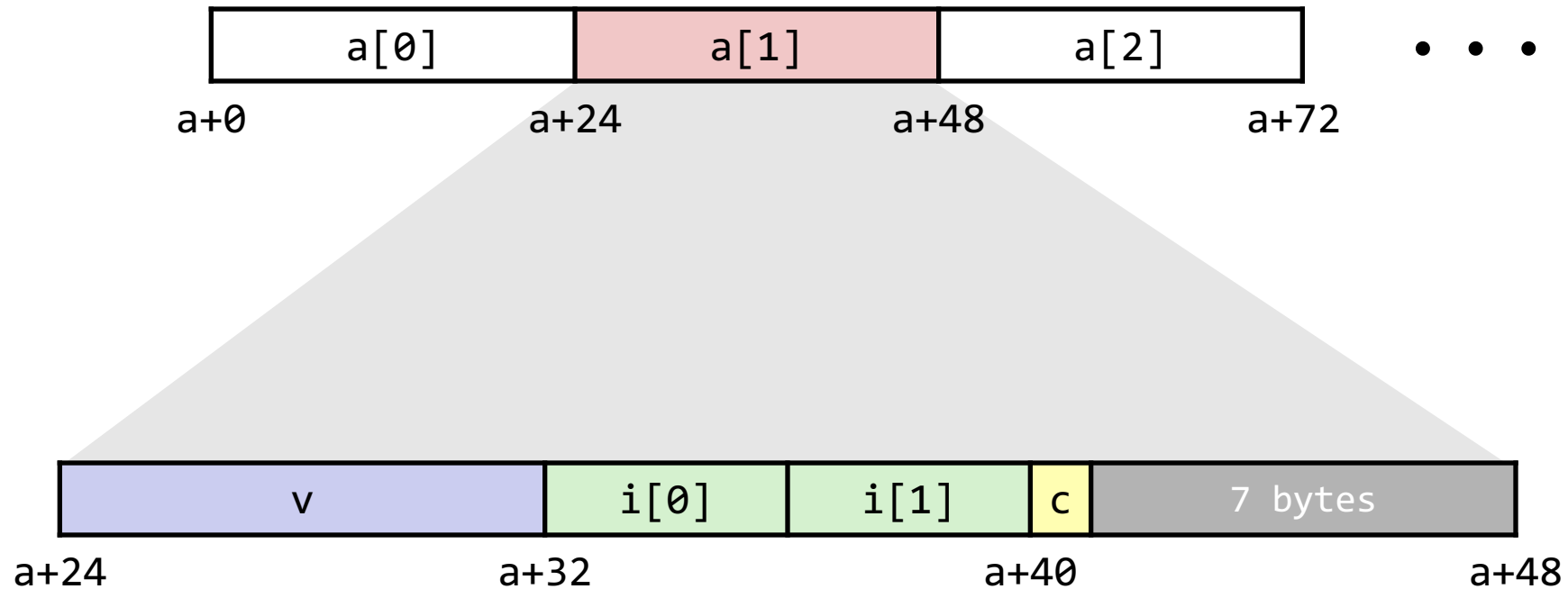
Field	*a	h	f	e	b	g	d	c	Total	Alignment
Size	8	8	8	8	4	4	2	1	48	8
Offset	0	8	16	24	32	36	40	42		

5 bytes padded to satisfy alignment requirement

Arrays of Structures

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

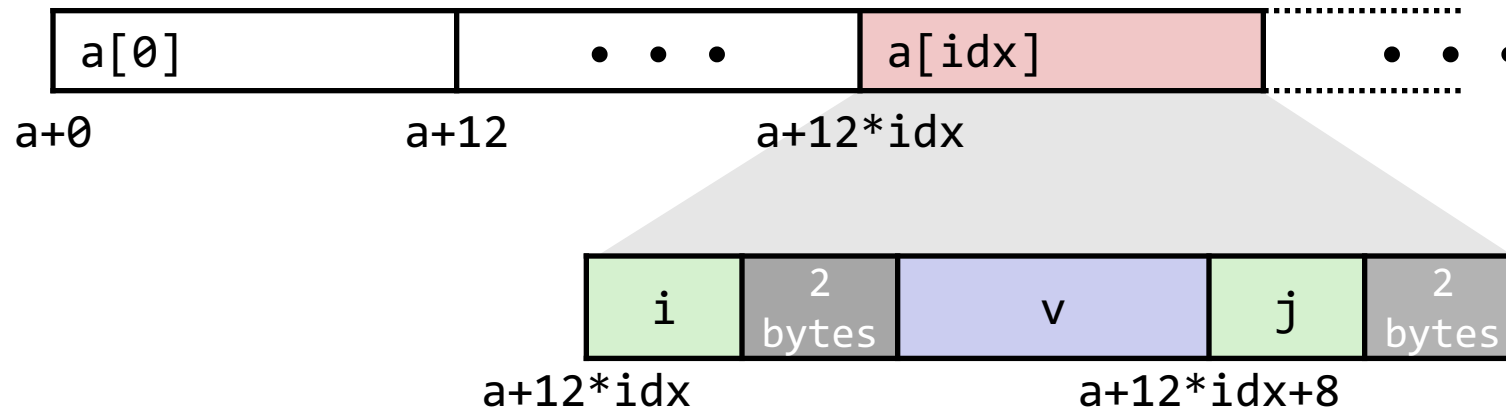
```
struct S2 {  
    double v;  
    int i[2];  
    char c;  
} a[10];
```



Accessing Array Elements

- Compute array offset $12 \cdot \text{idx}$
 - `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];
```



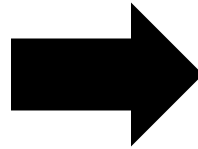
```
short get_j(int idx) {  
    return a[idx].j;  
}
```

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

Saving Space

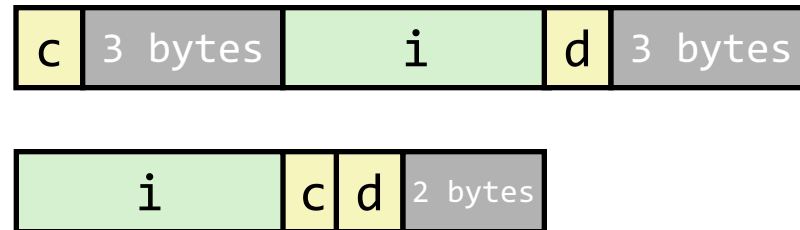
- Put large data types first

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



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

- Effect (K=4)



Lecture Plan

- Arrays
 - One-dimensional
 - Multi-dimensional (nested)
 - Multi-level
- Structures
- Floating Point

Background

- History
 - x87 FP
 - Legacy, very ugly
 - Streaming SIMD Extensions (SSE) FP
 - SIMD: single instruction, multiple data
 - Special case use of vector instructions
 - AVX FP
 - Newest version
 - Similar to SSE
 - Documented in book

Programming with SSE3

XMM Registers

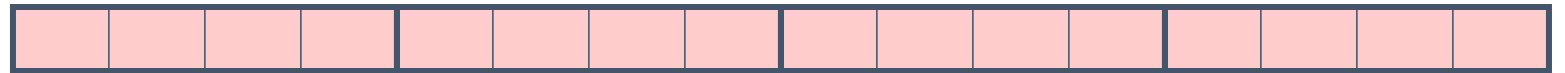
- 16 total, each 16 bytes
- 16 single-byte integers



- 8 16-bit integers



- 4 32-bit integers



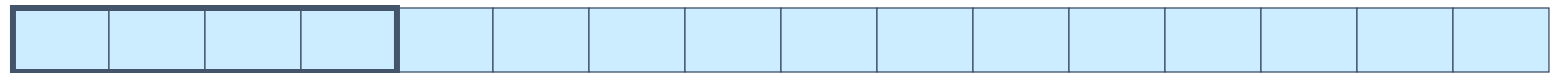
- 4 single-precision floats



- 2 double-precision floats



- 1 single-precision float

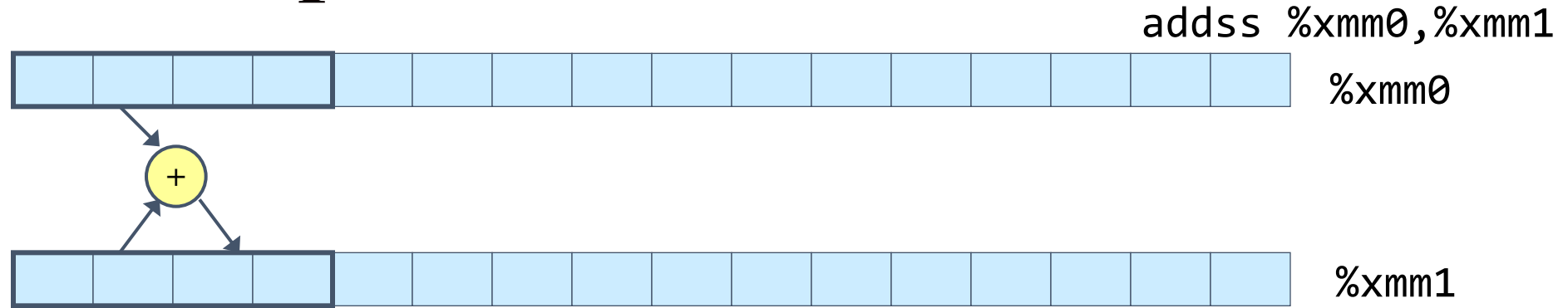


- 1 double-precision float

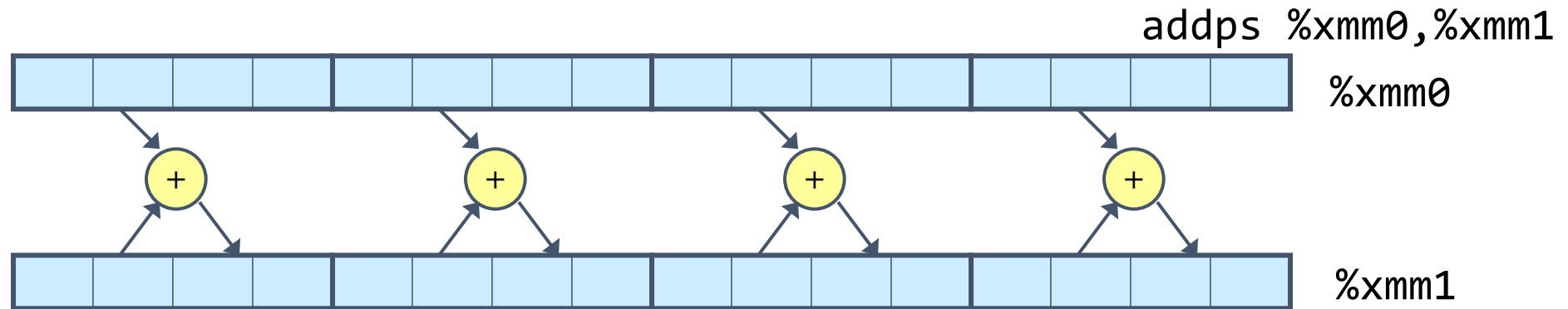


Scalar & SIMD Operations

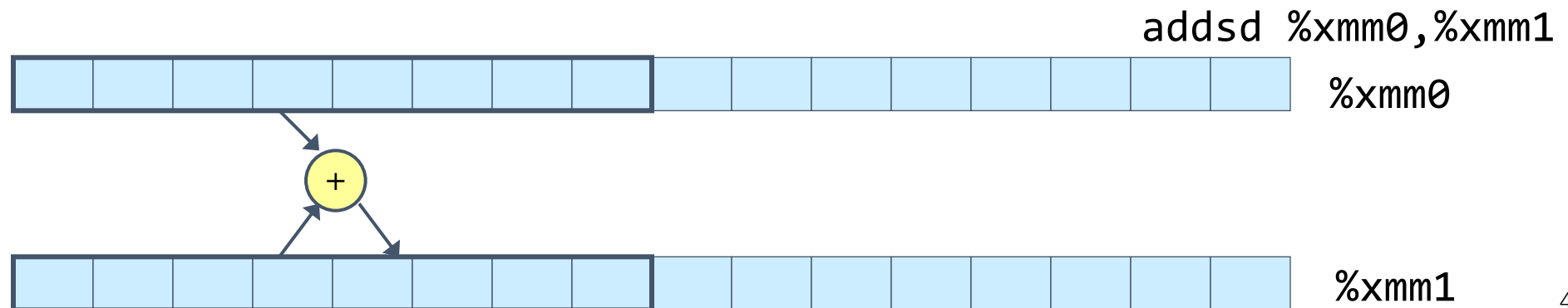
- Scalar Operations:
Single Precision



- SIMD Operations:
Single Precision



- Scalar Operations:
Double Precision



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

Recap

- Arrays
- Structures
- Floating Point

That's it for assembly!

Next time: security vulnerabilities, memory hierarchy