photo by CGP Grey

COMP201

Computer Systems & Programming

Lecture #26 – Data and Stack Frames

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2020

Image: Professor Farnsworth (Futurama)

About your midterm exam

- **Zoom** and **Blackboard**
- It will become **active at 11:50am**, and it will be released in **3 parts**
  - Each contains multi-part questions
  - 30 mins to complete in one sitting
  - Backtracking allowed
- **Open books, open notes**. You can use your own lecture notes, lecture slides and textbook, but nothing else
- **We won't take any questions during the exam**. Please write "ERROR" if you think something is wrong

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'Hallaroni's CMU 15-213 class

Lecture Plan

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

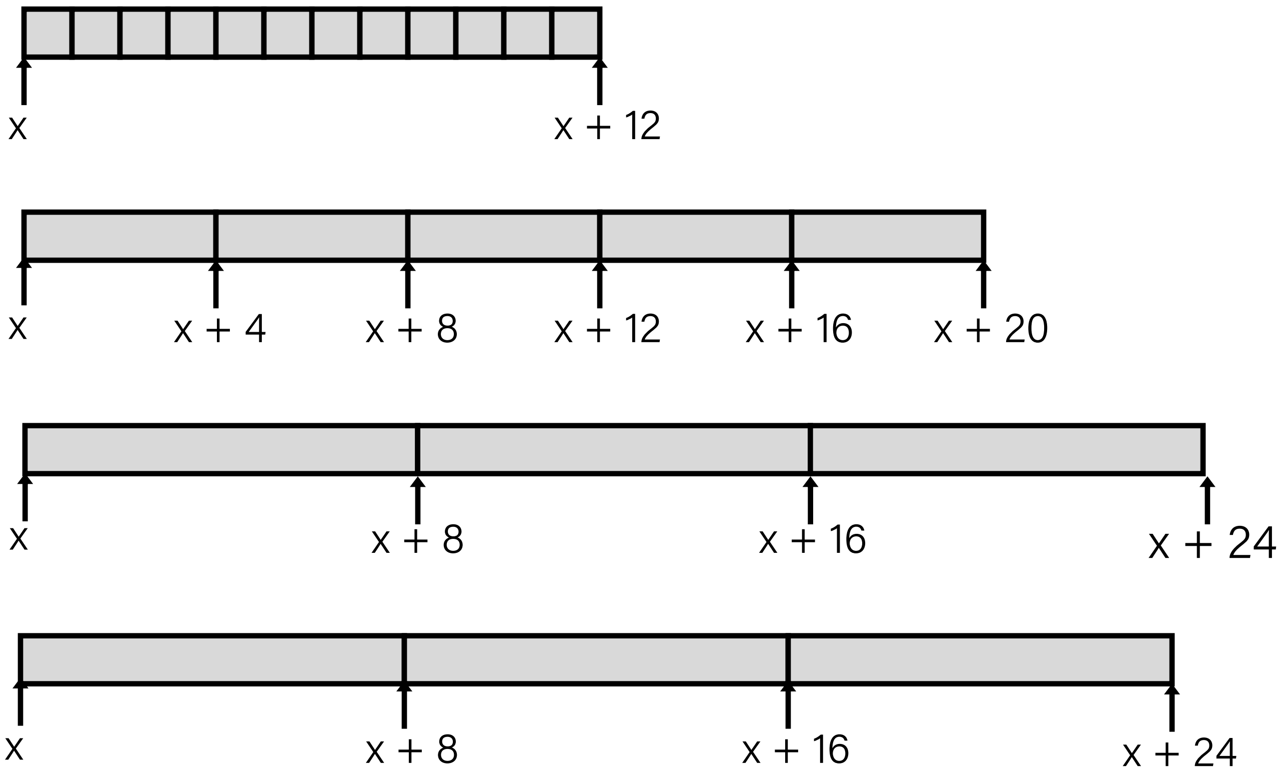
Array Allocation

Basic Principle

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

- Array of data type *T* and length *L*
- Contiguously allocated region of *L****sizeof**(*T*) bytes in memory

```
char string[12];
int val[5];
double a[3];
char *p[3];
```



Array Access

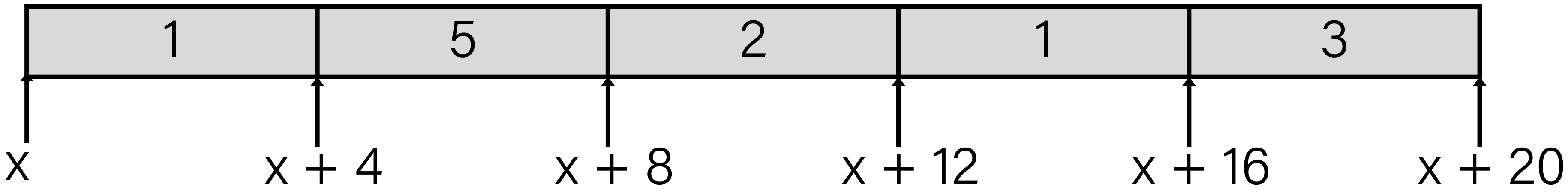
- **Basic Principle**

  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*

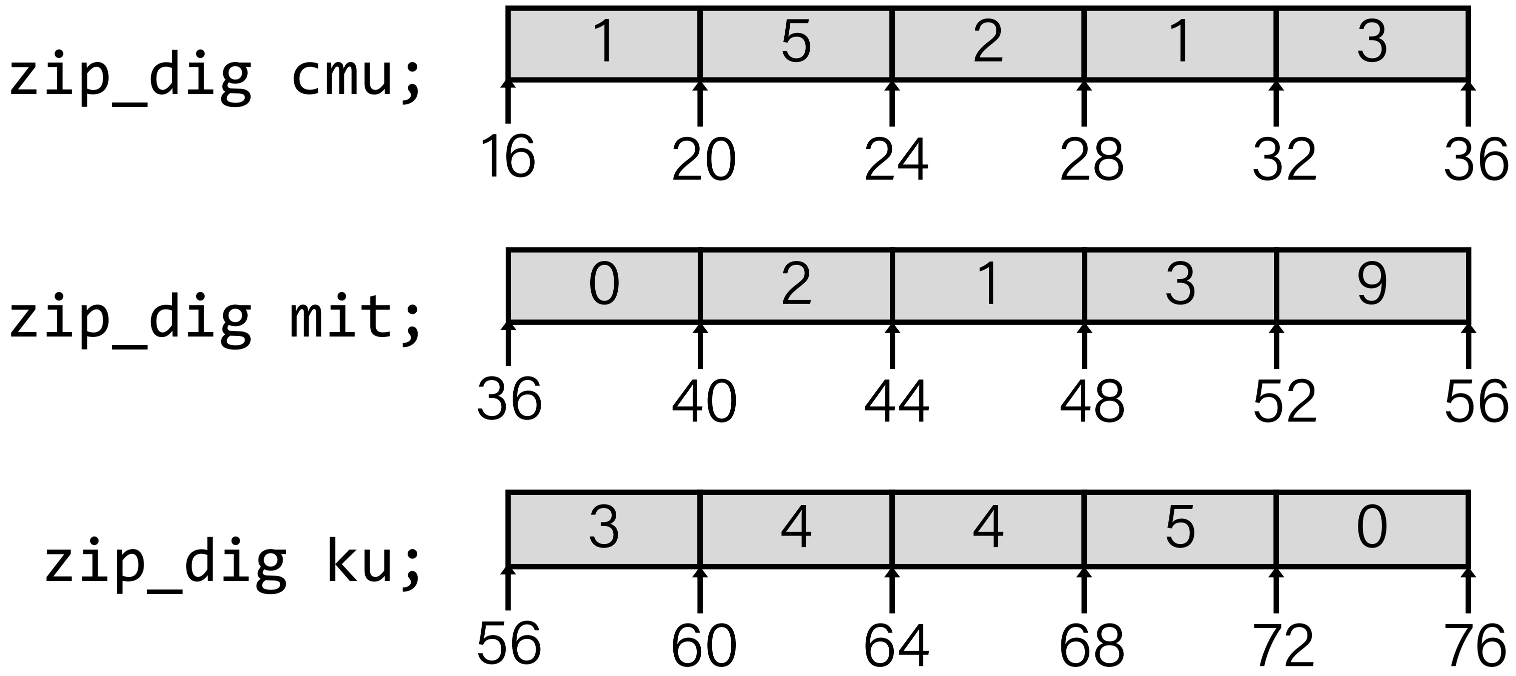
Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	x
`val+1`	`int *`	x + 4
`&val[2]`	`int *`	x + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + i`	`int *`	x + 4 i

`int val[5];`



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};
```

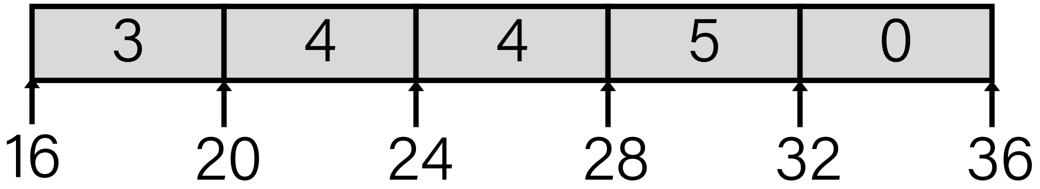


- Declaration “`zip_dig cmu`” equivalent to “`int cmu[5]`”
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Accessing Example

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

```
zip_dig ku;
```




```
# %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

```c
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

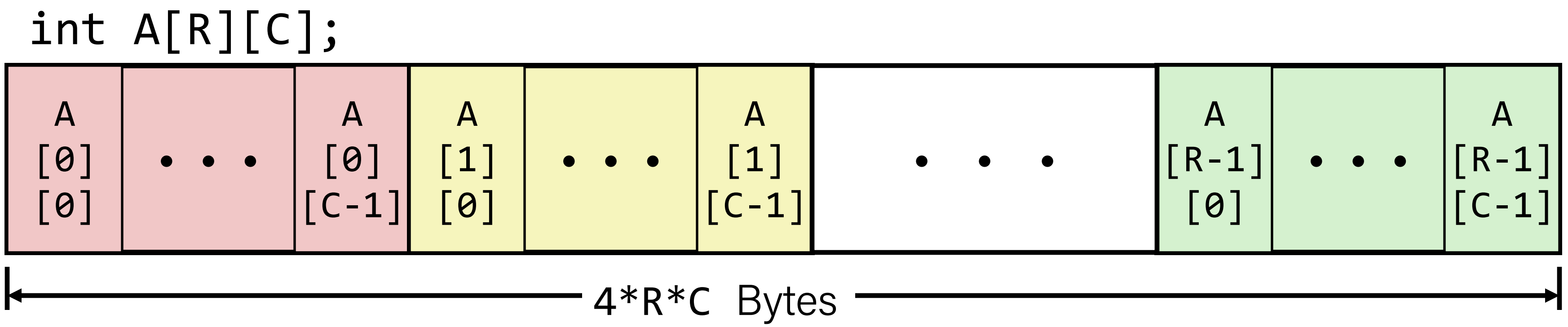
Array Size

- *R* * *C* * *K* bytes

Arrangement

- Row-Major Ordering

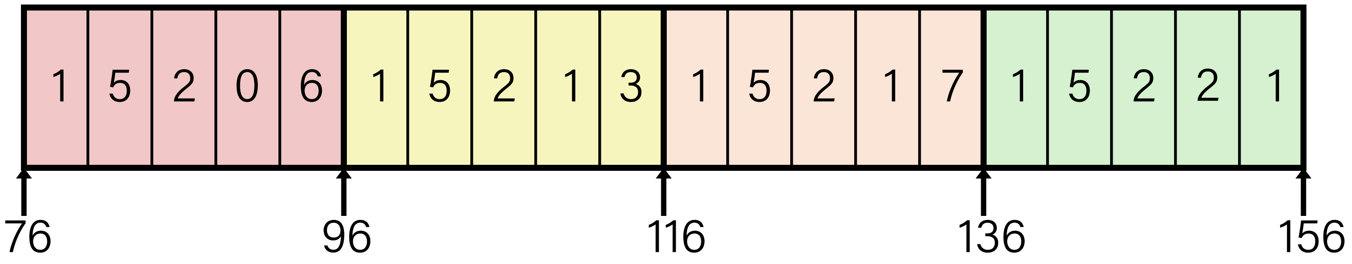
$$\begin{bmatrix} \texttt{A[0][0]} & \cdots & \texttt{A[0][C-1]} \\ \vdots & & \vdots \\ \texttt{A[R-1][0]} & \cdots & \texttt{A[R-1][C-1]} \end{bmatrix}$$



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];
```



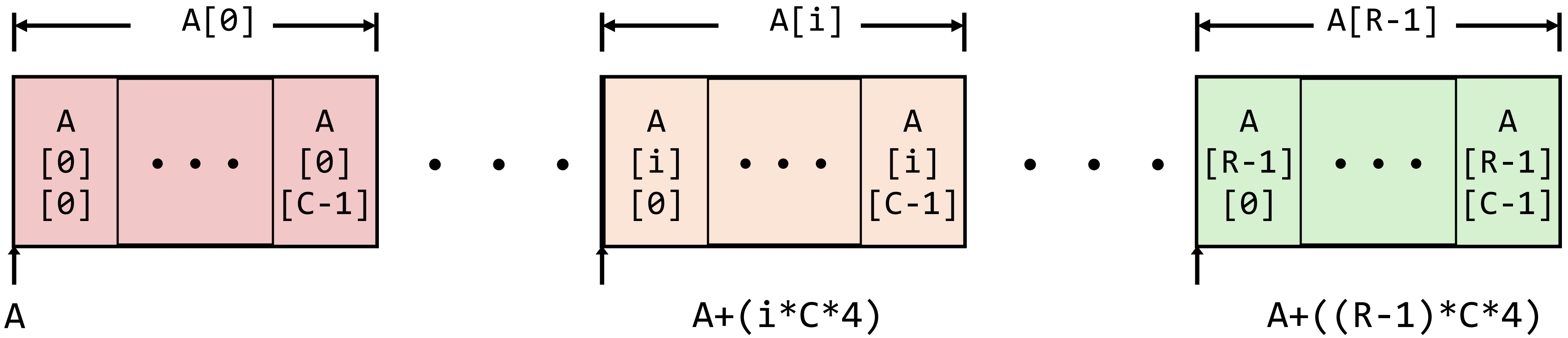
- "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable `pgh`: array of 4 elements, allocated contiguously
  - Each element is an array of 5 `int`'s, allocated contiguously
- "Row-Major" ordering of all elements in memory

Nested Array Row Access

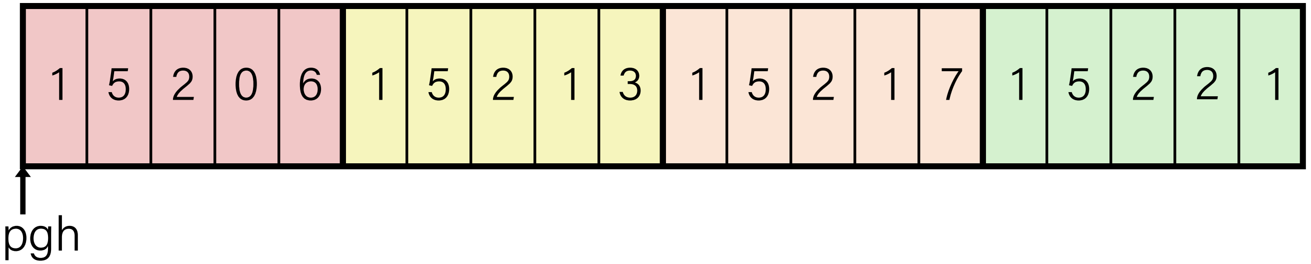
Row Vectors

- **`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




```c
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`

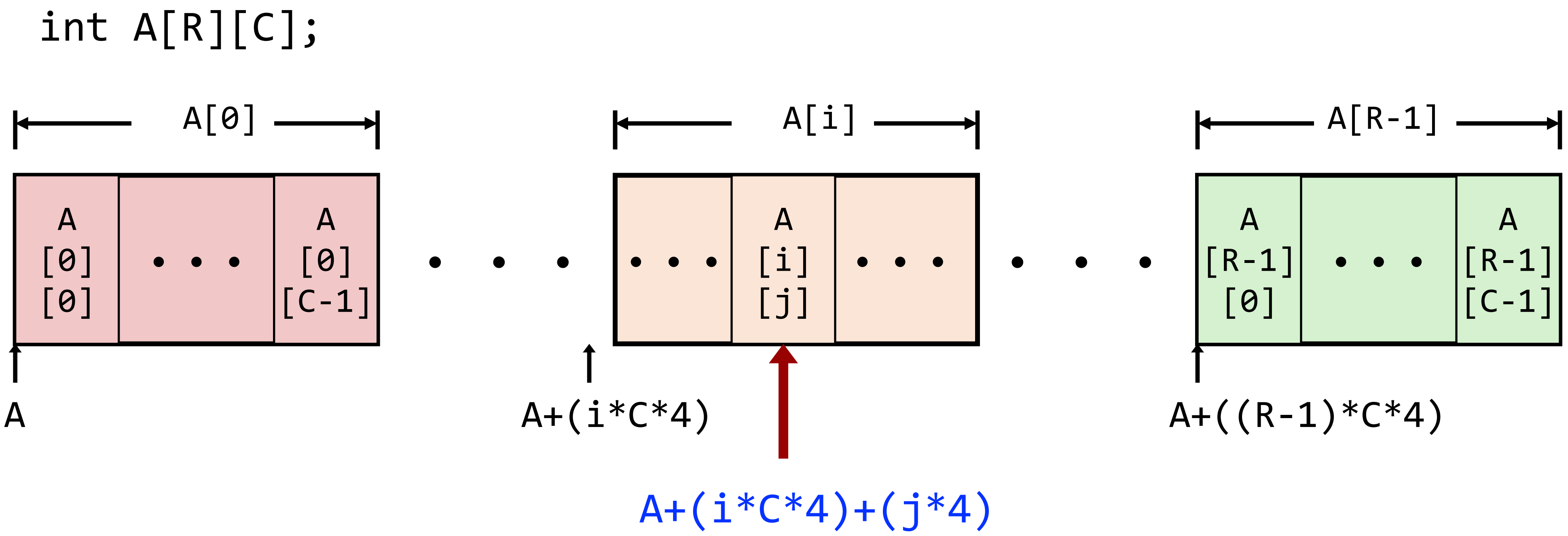
Machine Code

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

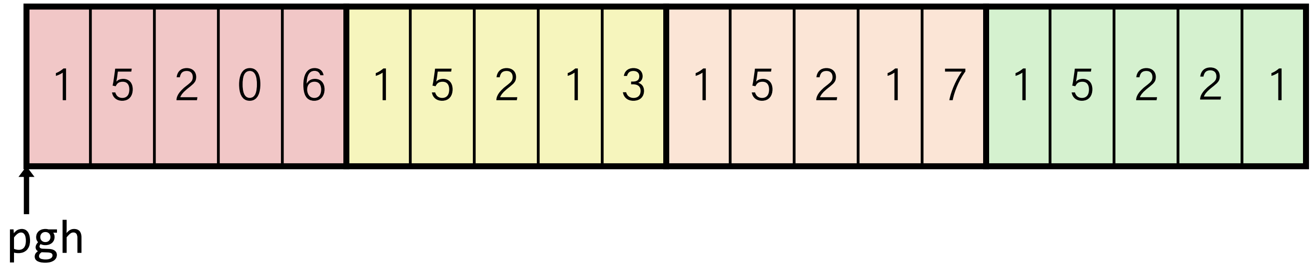
Nested Array Element Access

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)]
```

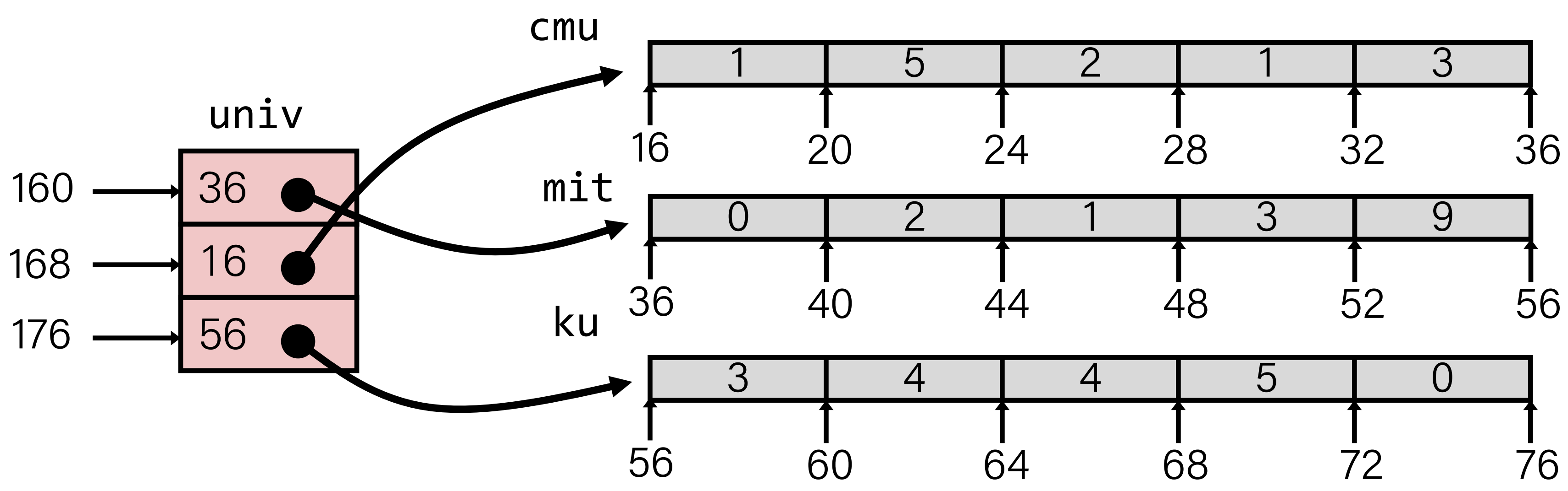
Array Elements

- `pgh[index][dig]` is `int`
- Address: `pgh + 20*index + 4*dig`
    - `= pgh + 4*(5*index + dig)`

Multi-Level Array Example

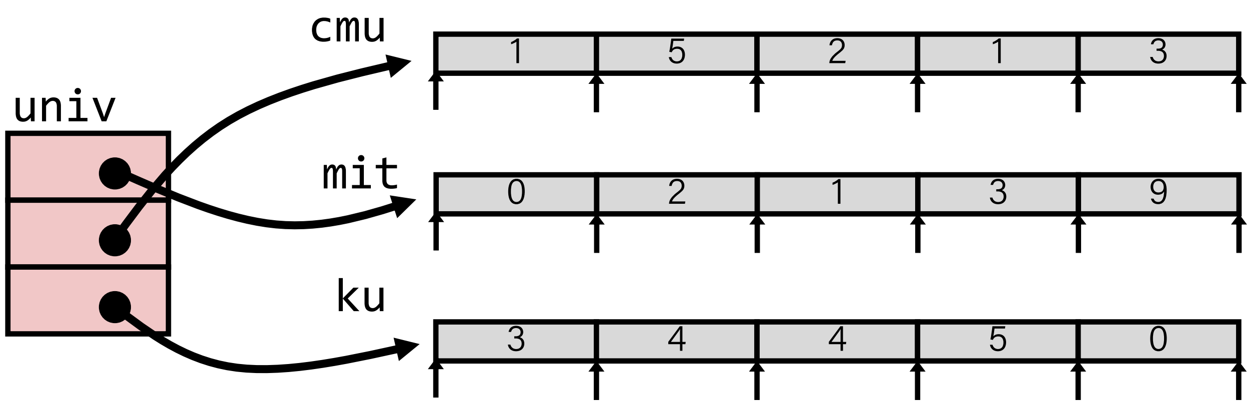
```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ku  = { 3, 4, 4, 5, 0 };

#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
```

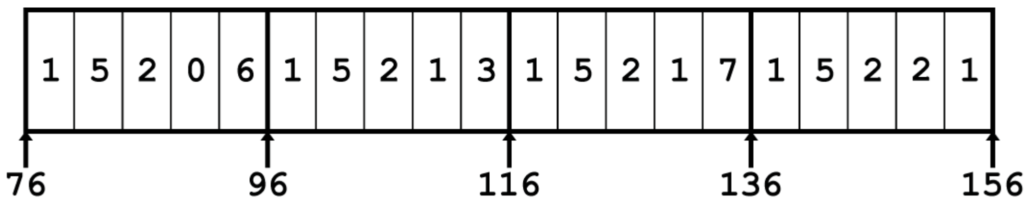
Computation

- Element access `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

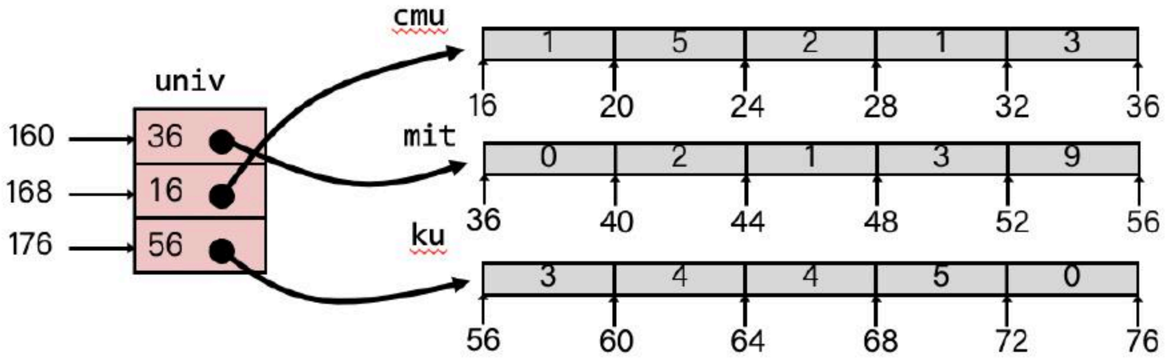
Nested array

```
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 × 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 × 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
sum_element:
  leaq  0(,%rdi,8), %rdx       Compute 8*i
  subq  %rdi, %rdx             Compute 7*i
  addq  %rsi, %rdx             Compute 7*i+j
  leaq  (%rsi,%rsi,4), %rax    Compute 5*j
  addq  %rax, %rdi             Compute i+5*j
  movq  Q(,%rdi,8), %rax       Retrieve M[Q+8*(5*j+i)]
  add   P(,%rdx,8), %rax       Add M[P+8*(7*i+j)]
  ret
```

What is the value of M and N?

M = 5 and N = 7

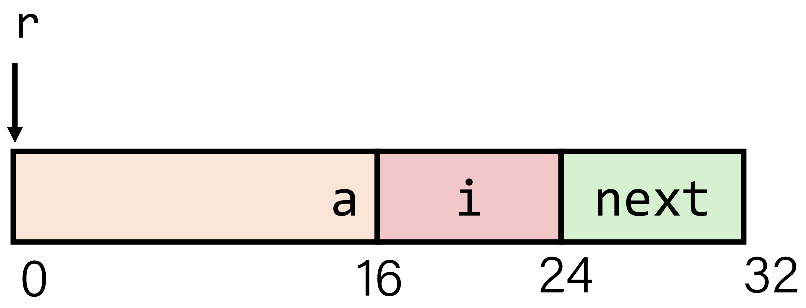
Event code: 73165

Lecture Plan

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

Structure Representation

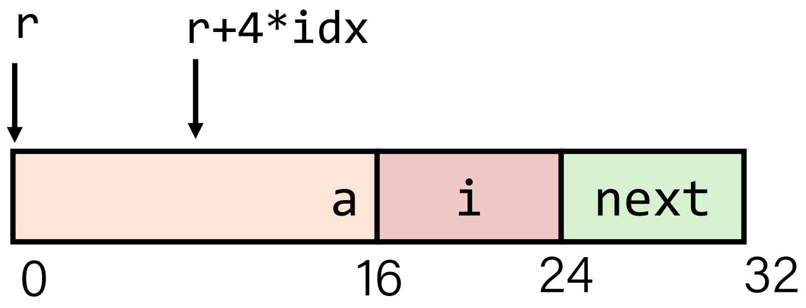
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- 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

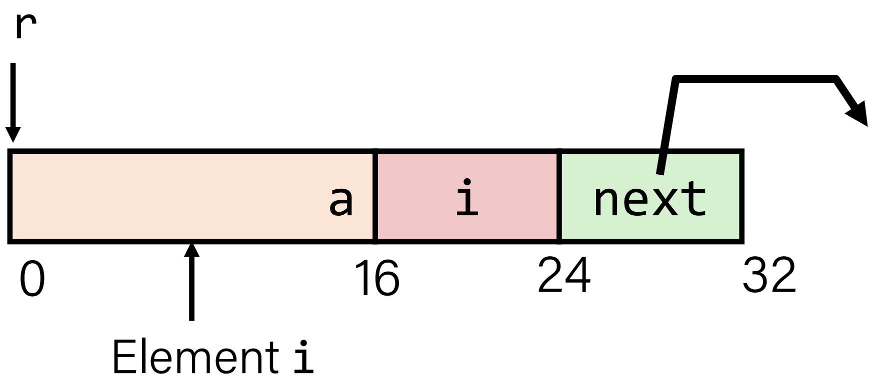
- Offset of each structure member determined at compile time
- Compute as **`r + 4*idx`**

```
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
%esi	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.

slido **Event code: 73165**

```c
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         ;
}
```

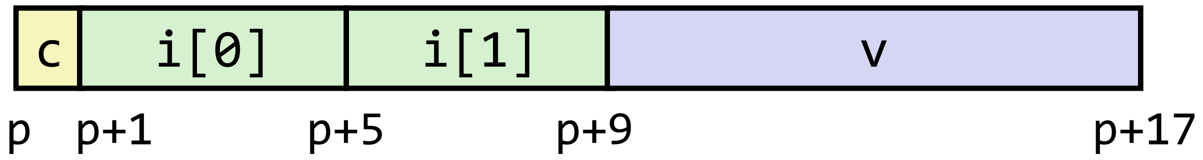
```
# void st_init(struct test *st)
# st in %rdi
st_init:
    movl 8(%rdi), %eax       Get st->s.x
    movl %eax, 10(%rdi)      Save in st->s.y
    leaq 10(%rdi), %rax      Compute &(st->s.y)
    movq %rax, (%rdi)        Store in st->p
    movq %rdi, 12(%rdi)      Store st in st->next
    ret
```

0	8	10	12	20
p	s.x	s.y	next	

Structures & Alignment

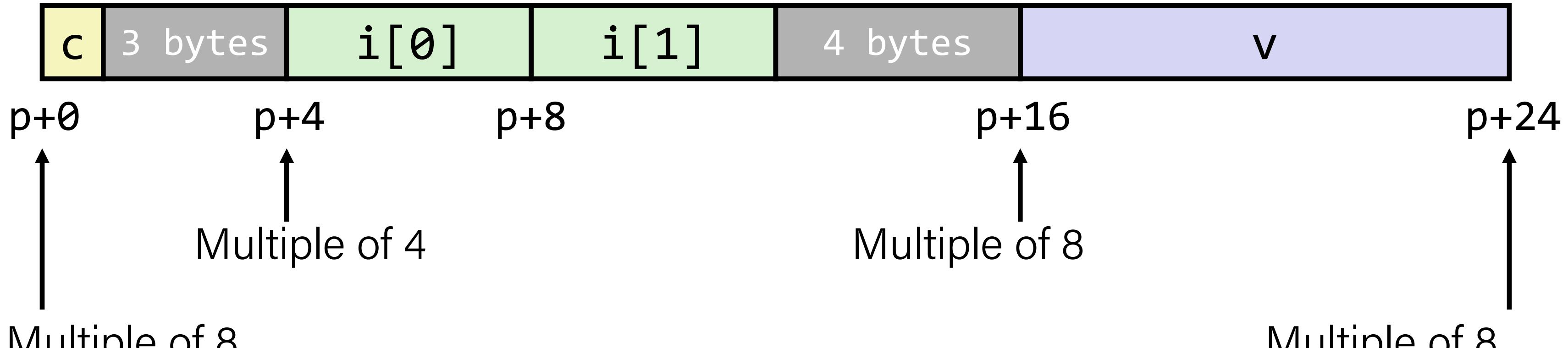
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Unaligned Data



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

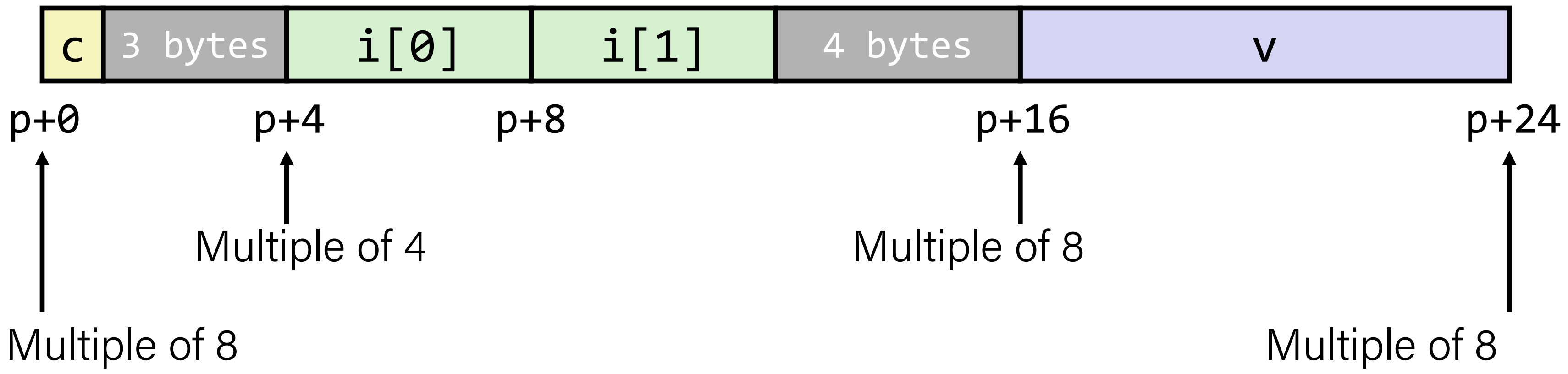
Overall structure placement

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

Example:

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

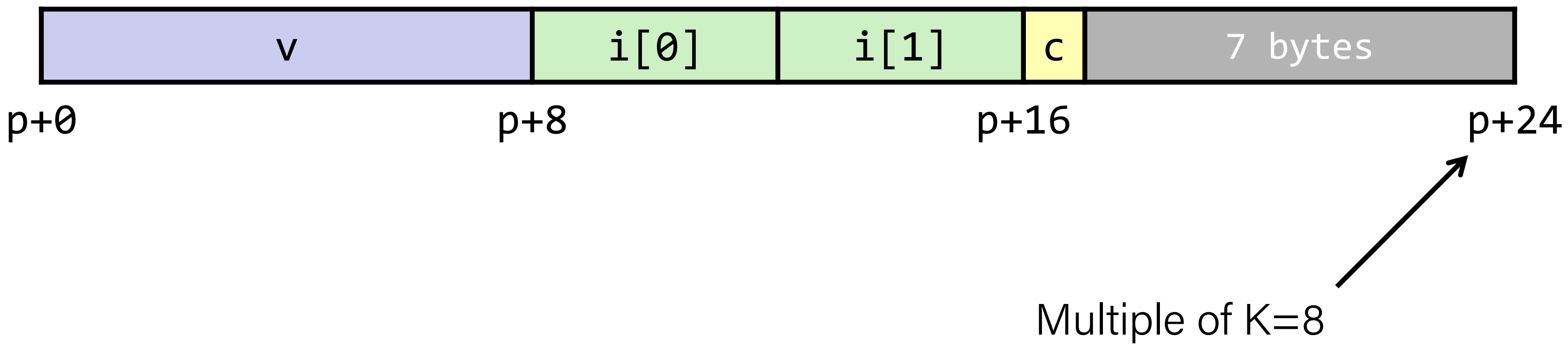
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

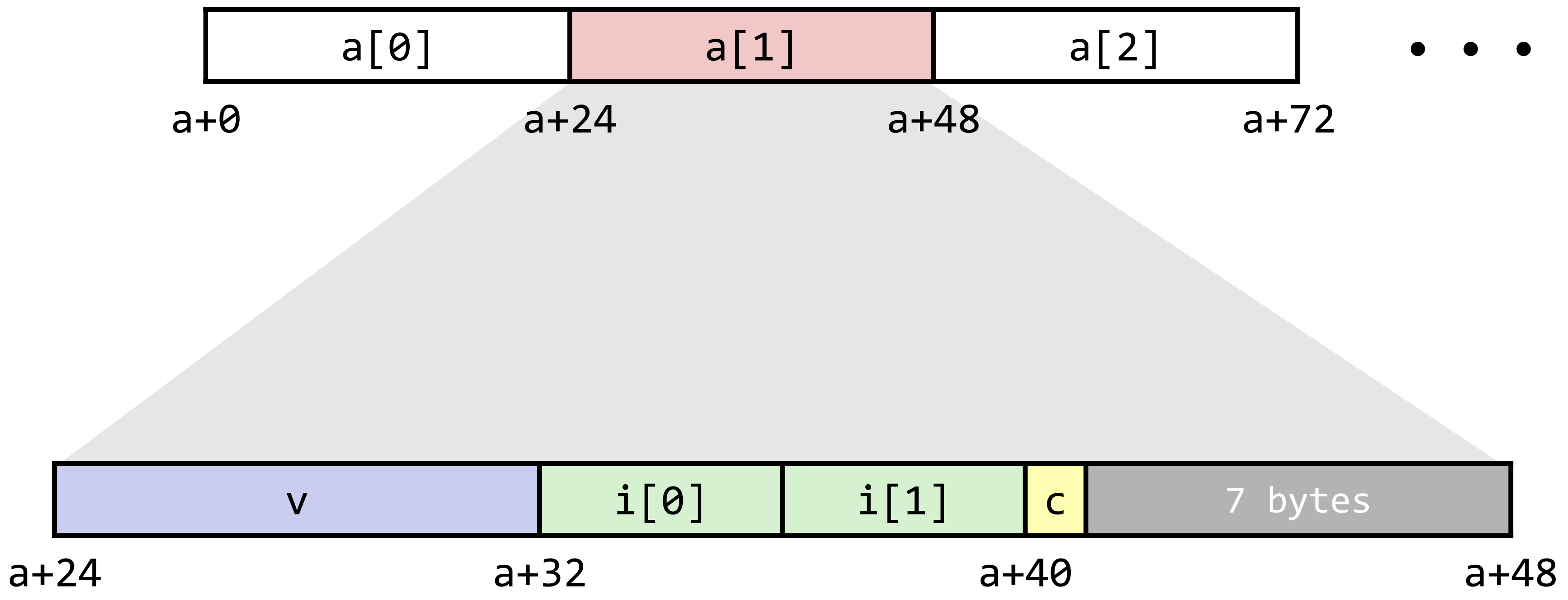
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

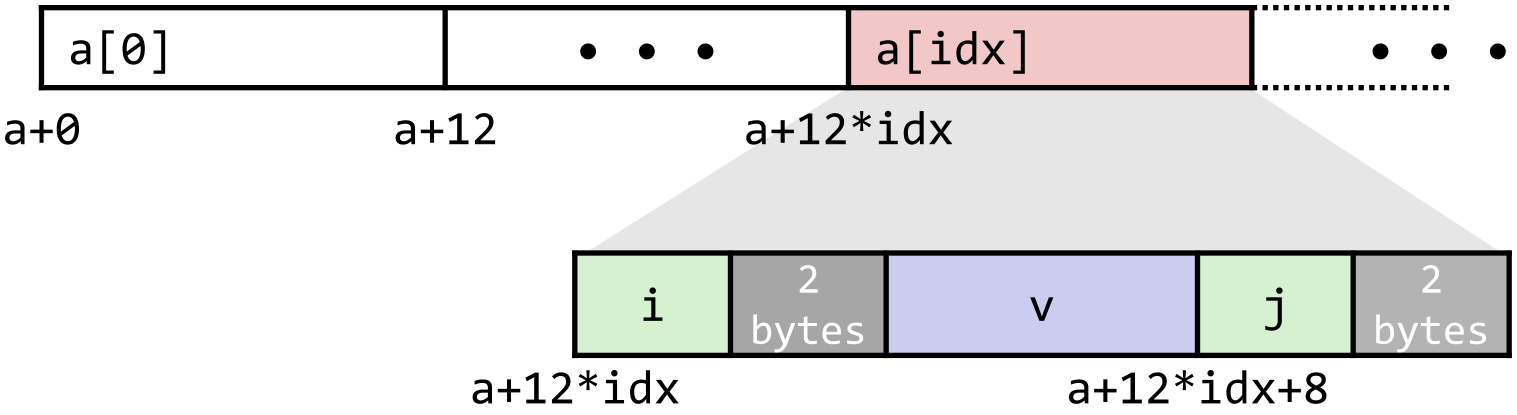
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



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
```

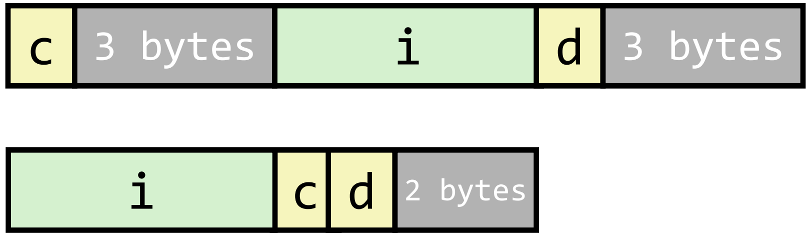
Saving Space

- 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)



Practice 3: Alignment

slido Event code: 73165

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

```c
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	48	8
Offset	0	8	12	14	16	24	32	36		

6 bytes padded to satisfy alignment requirement

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

Lecture Plan

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

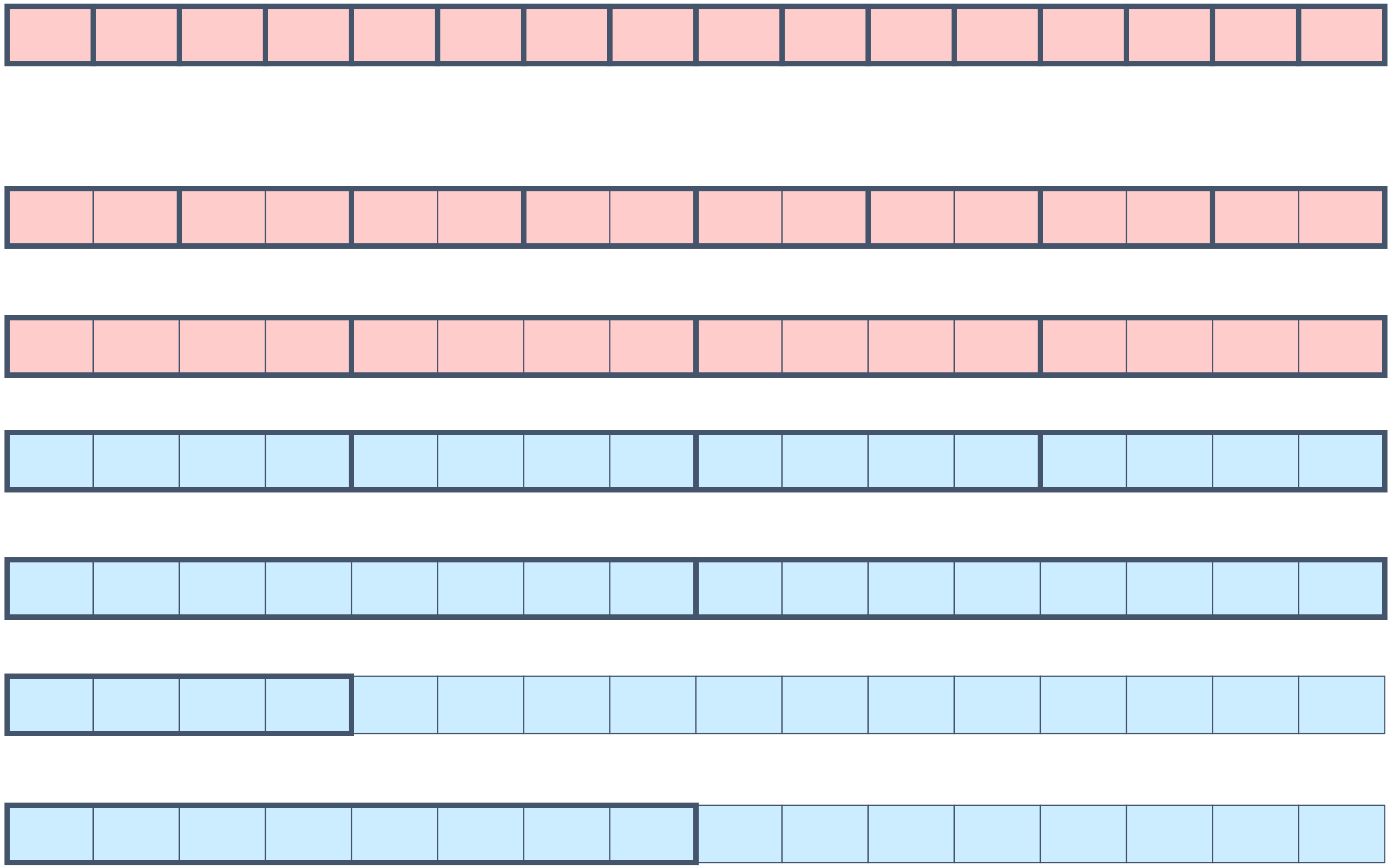
Background

- 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

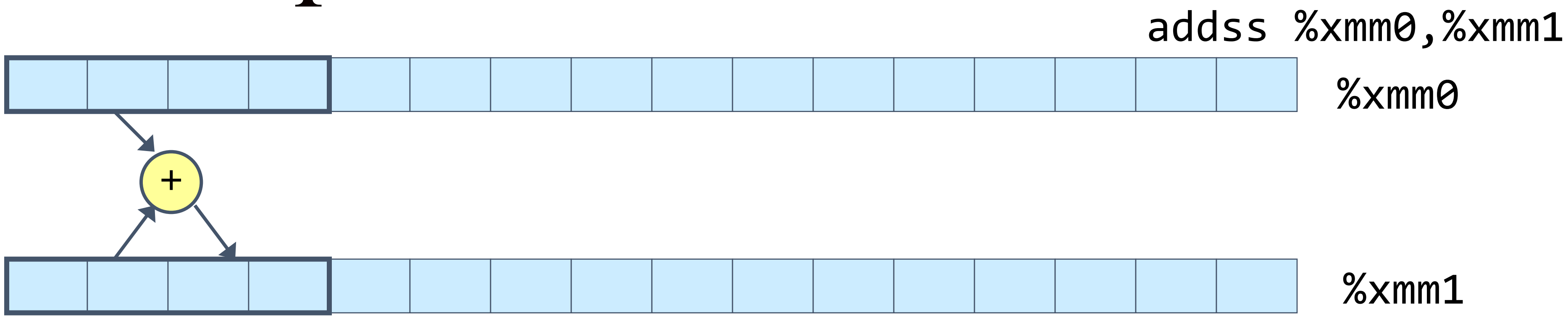
XMM Registers

- 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

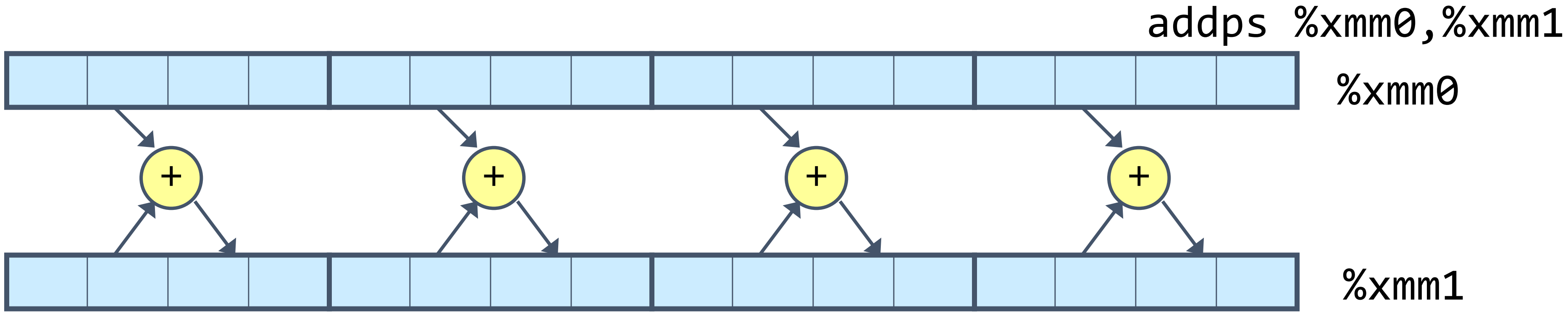


Scalar & SIMD Operations

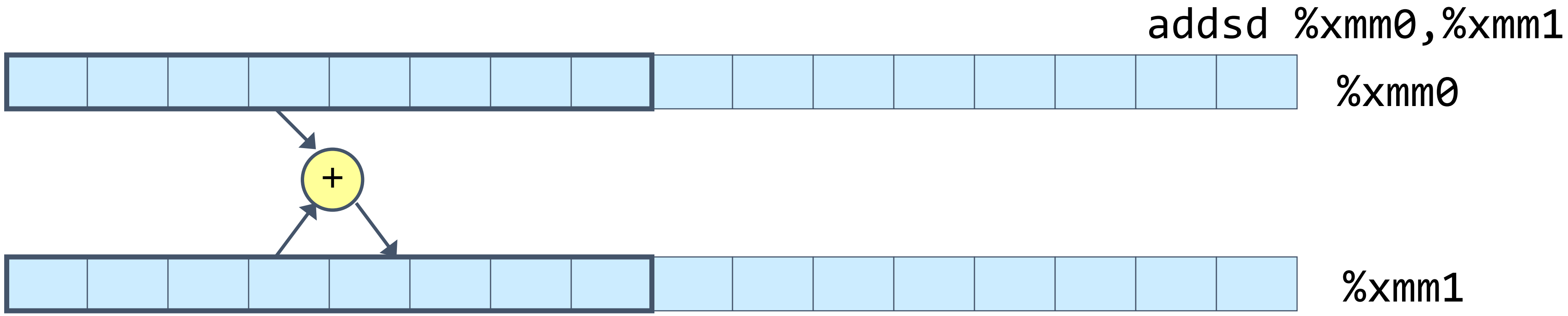
- Scalar Operations: Single Precision



- 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;
}
```

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

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

```
# 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

```c
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