photo by CGP Grey

COMP201

Computer Systems & Programming

Lecture #19 – Data and Stack Frames

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Spring 2024

Recap

- Revisiting `%rip`
- Calling Functions
  - The Stack
  - Passing Control
  - Passing Data
  - Local Storage
- Register Restrictions

Recap: Calling Functions In Assembly

To call a function in assembly, we must do a few things:

- **Pass Control** – `%rip` must be adjusted to execute the callee's instructions, and then resume the caller's instructions afterwards.
- **Pass Data** – we must pass any parameters and receive any return value.
- **Manage Memory** – we must handle any space needs of the callee on the stack.

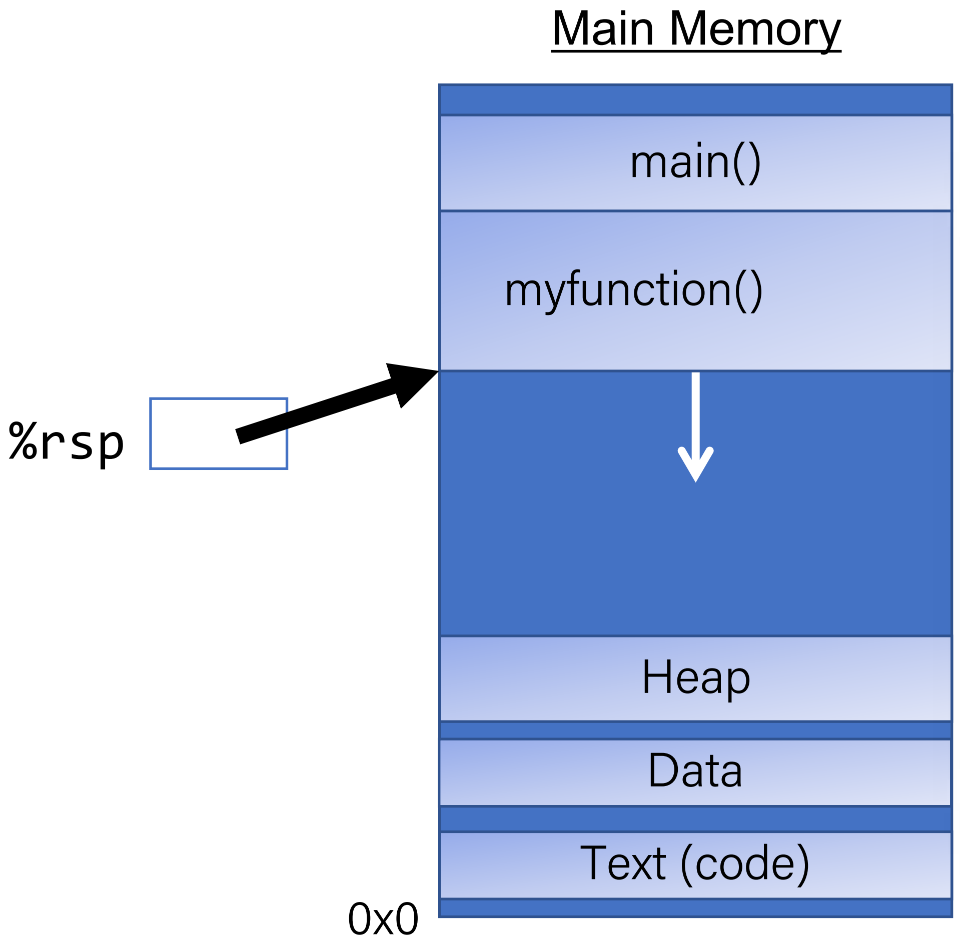
Terminology: **caller** function calls the **callee** function.

Recap: Instruction Pointer

- Machine code instructions live in main memory, just like stack and heap data.
- `%rip` is a register that stores a number (an address) of the next instruction to execute. It marks our place in the program's instructions.
- To advance to the next instruction, special hardware adds the size of the current instruction in bytes.
- **`jmp`** instructions work by adjusting `%rip` by a specified amount.

Recap: `%rsp`

- **`%rsp`** is a special register that stores the address of the current "top" of the stack (the bottom in our diagrams, since the stack grows downwards).



Key idea: `%rsp` must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

Recap: push and pop

Instruction	Effect
`pushq S`	`R[%rsp] ⟵ R[%rsp] - 8;` `M[R[%rsp]] ⟵ S`

Instruction	Effect
`popq D`	`D ⟵ M[R[%rsp]]` `R[%rsp] ⟵ R[%rsp] + 8;`

- The **push** instruction pushes the data at the specified source onto the top of the stack, adjusting **`%rsp`** accordingly.

- The **pop** instruction pops the topmost data from the stack and stores it in the specified destination, adjusting **`%rsp`** accordingly.
- **Note:** this <u>*does not*</u> remove/clear out the data! It just increments `%rsp` to indicate the next push can overwrite that location.

Recap: Call And Return

The **`call`** instruction pushes the address of the instruction immediately following the **`call`** instruction onto the stack and sets `%rip` to point to the beginning of the specified function's instructions.

```
call Label
call *Operand
```

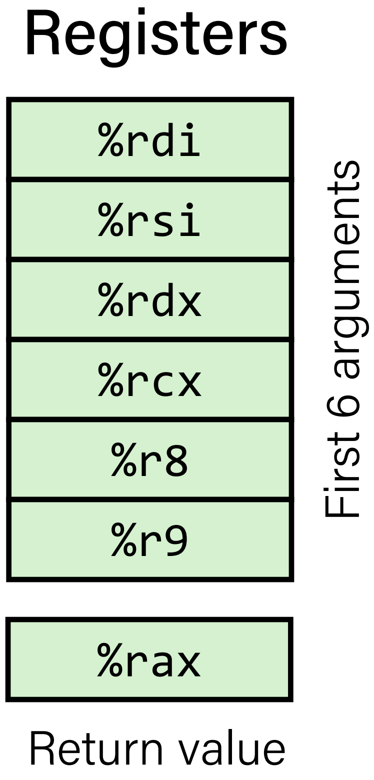
The **`ret`** instruction pops this instruction address from the stack and stores it in `%rip`.

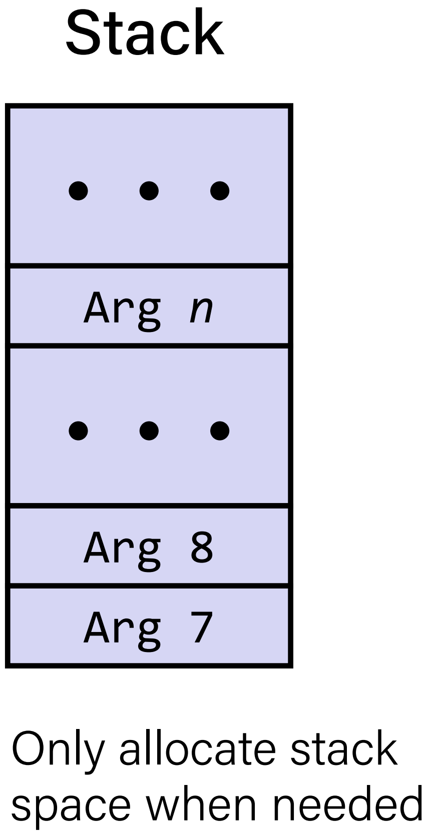
```
ret
```

The stored `%rip` value for a function is called its **return address.** It is the address of the instruction at which to resume the function's execution. (not to be confused with **return value**, which is the value returned from a function).

Recap: Parameters and Return

- There are special registers that store parameters and the return value.
- To call a function, we must put any parameters we are passing into the correct registers. (`%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`, in that order)
- Parameters beyond the first 6 are put on the stack.
- If the caller expects a return value, it looks in `%rax` after the callee completes.

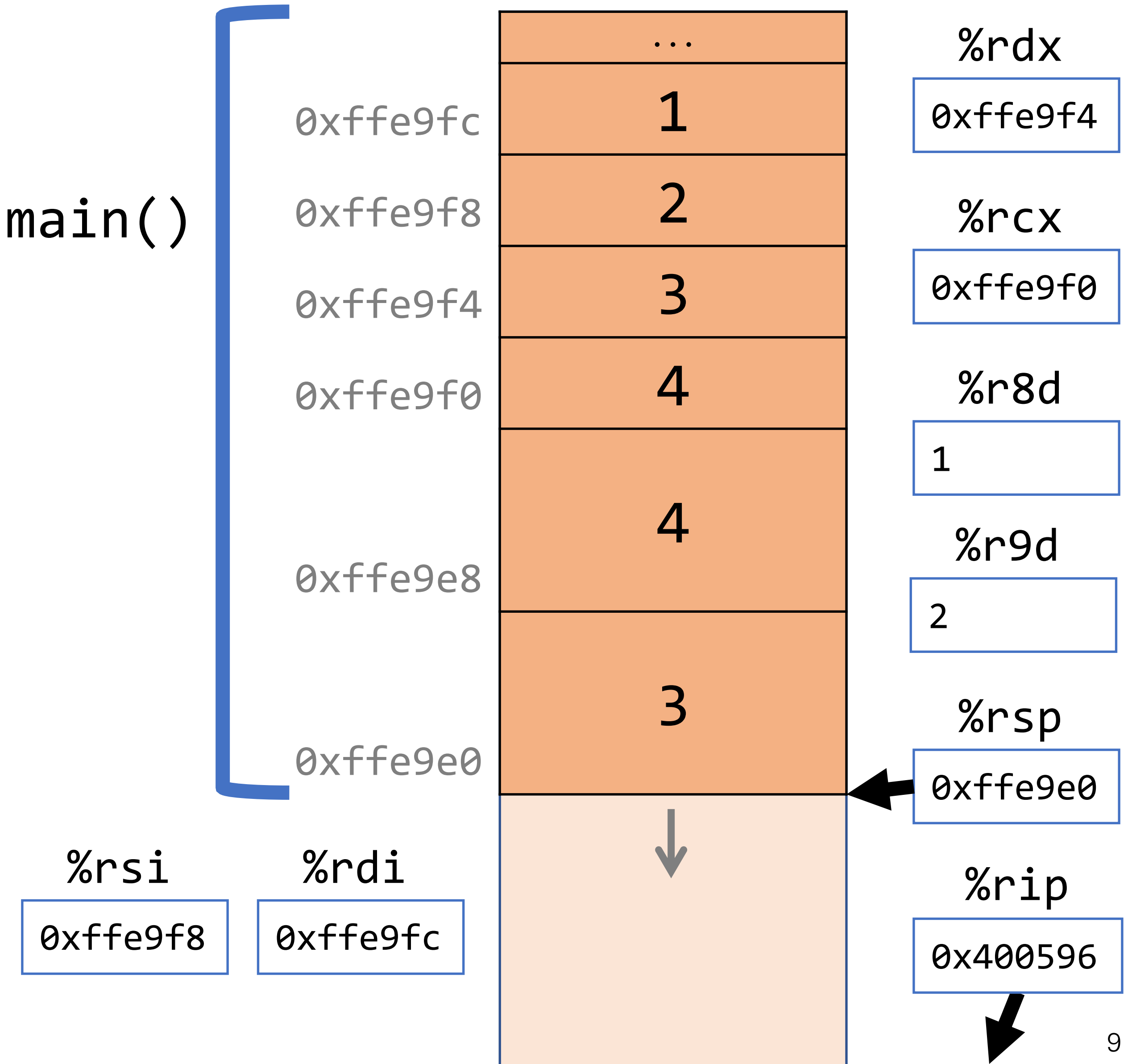




Recap: Parameters and Return

```
int main(int argc, char *argv[]) {
    int i1 = 1;
    int i2 = 2;
    int i3 = 3;
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

int func(int *p1, int *p2, int *p3, int *p4,
         int v1, int v2, int v3, int v4) {
    …
}
```

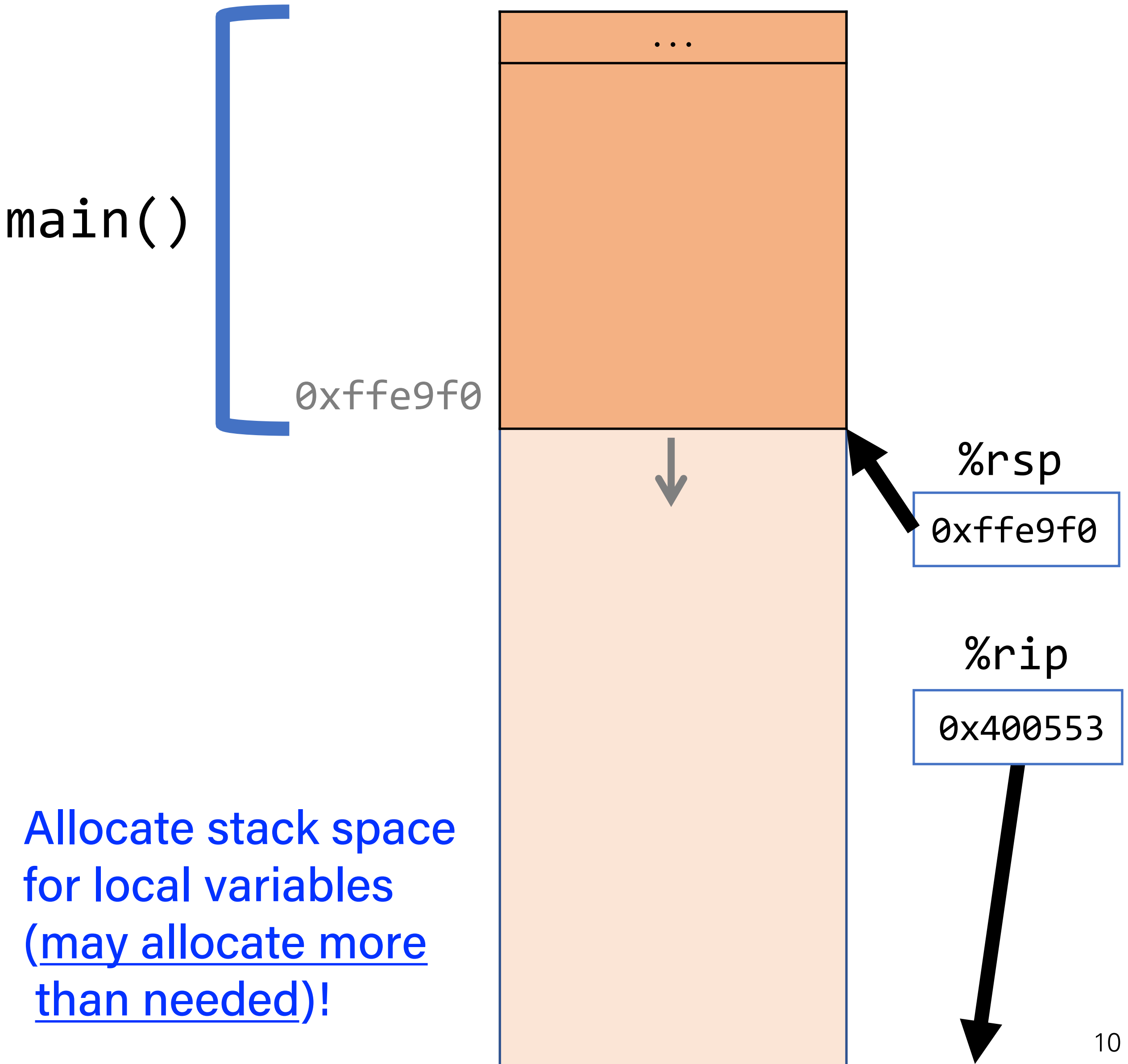
```
0x40058c <+61>:   lea    0x18(%rsp),%rsi
0x400591 <+66>:   lea    0x1c(%rsp),%rdi
0x400596 <+71>:   callq  0x400546 <func>
0x40059b <+76>:   add    $0x10,%rsp
…
```



Correction: Parameters and Return

```
int main(int argc, char *argv[]) {
    int i1 = 1;
    int i2 = 2;
    int i3 = 3;
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

int func(int *p1, int *p2, int *p3, int *p4,
         int v1, int v2, int v3, int v4) {
    …
}
```

```
0x40054f <+0>:     sub    $0x18,%rsp
0x400553 <+4>:     movl   $0x1,0xc(%rsp)
0x40055b <+12>:    movl   $0x2,0x8(%rsp)
0x400563 <+20>:    movl   $0x3,0x4(%rsp)
0x40056b <+28>:    movl   $0x4,(%rsp)
```



Allocate stack space for local variables (may allocate more than needed)!

Recap: Local Storage

- So far, we've often seen local variables stored directly in registers, rather than on the stack as we'd expect. This is for optimization reasons.
- There are **three** common reasons that local data must be in memory:
  - We've run out of registers
  - The '&' operator is used on it, so we must generate an address for it
  - They are arrays or structs (need to use address arithmetic)

Recap: Register Restrictions

Caller-Owned (Callee Saved)

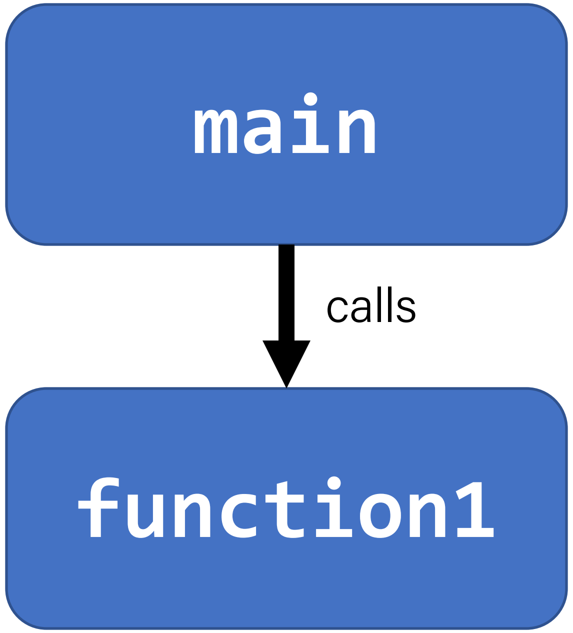
- Callee must *save* the existing value and *restore* it when done.
- Caller can store values and assume they will be preserved across function calls.

Callee-Owned (Caller Saved)

- Callee does not need to save the existing value.
- Caller's values could be overwritten by a callee! The caller may consider saving values elsewhere before calling functions.

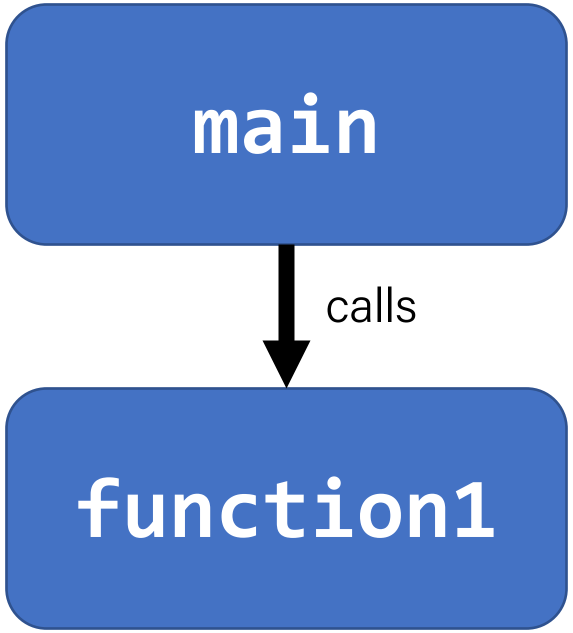
Figure 3.2 **Integer registers.** The low-order portions of all 16 registers can be accessed as byte, word (16-bit), double word (32-bit), and quad word (64-bit) quantities.

Recap: Caller-Owned Registers




```
function1:
  push %rbp
  push %rbx
  ...
  pop %rbx
  pop %rbp
  retq
```

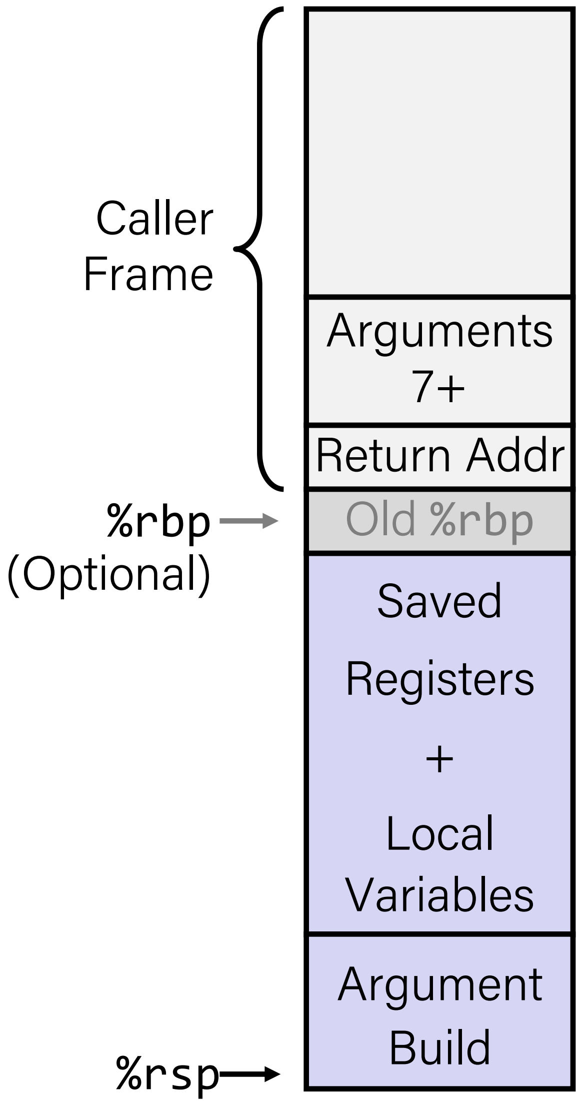
Recap: Callee-Owned Registers




```
main:
   ...
   push %r10
   push %r11
   callq function1
   pop %r11
   pop %r10
   ...
```

Recap: x86-64 Procedure Summary

- Important Points
  - Stack is the right data structure for procedure call/return
    - If P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result return in **`%rax`**
- Pointers are addresses of values
  - On stack or global



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

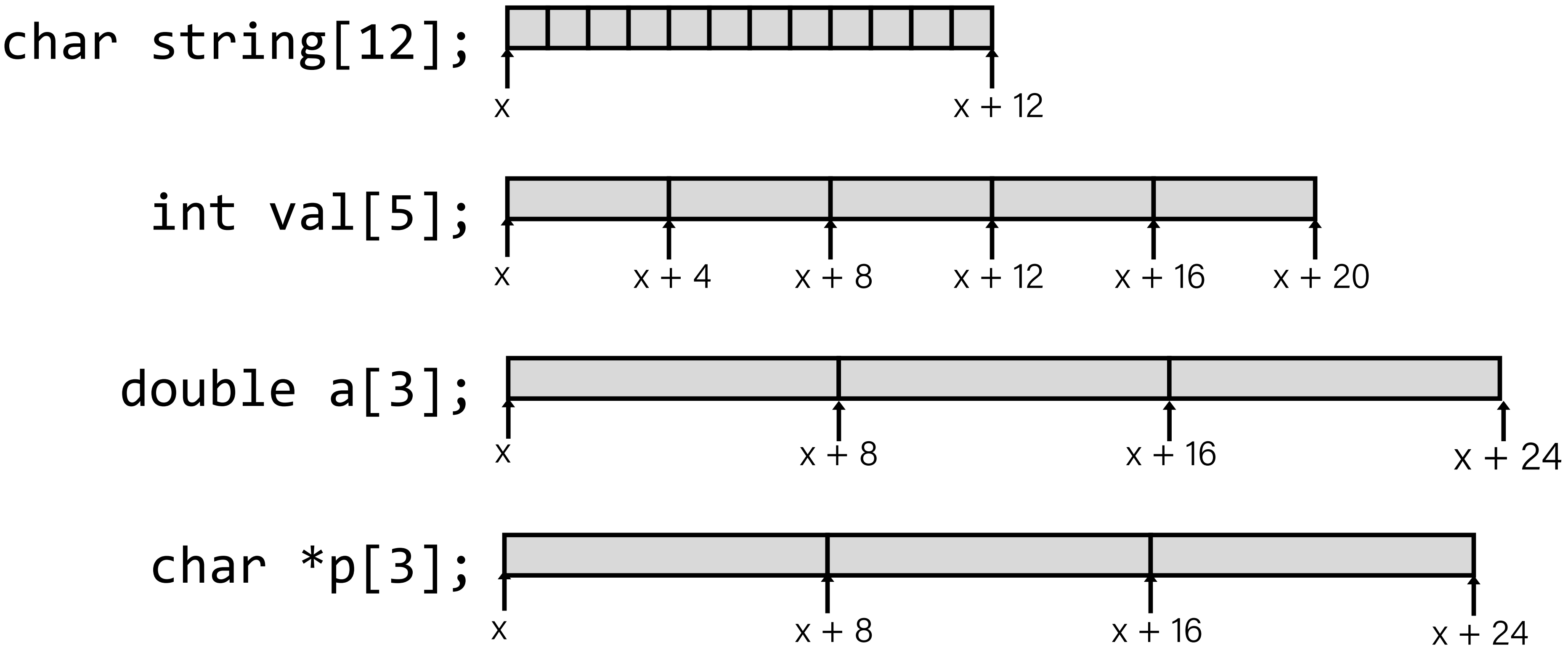
- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structures
- Floating Point

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



Array Access

- **Basic Principle**

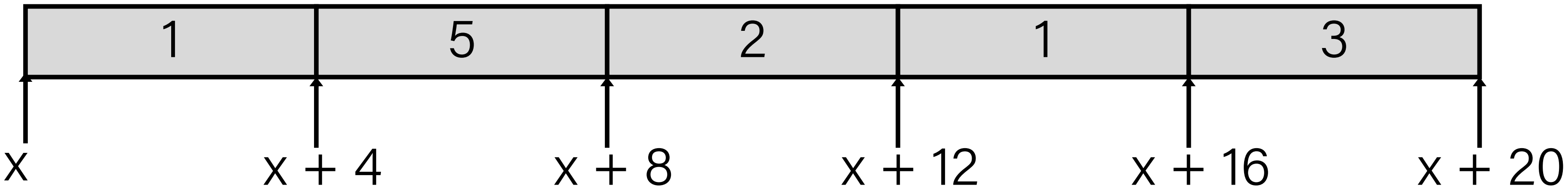
  T **A[***L***];**

  – Array of data type *T* and length *L*

  – Identifier **A** can be used as a pointer to array element 0: Type *T**

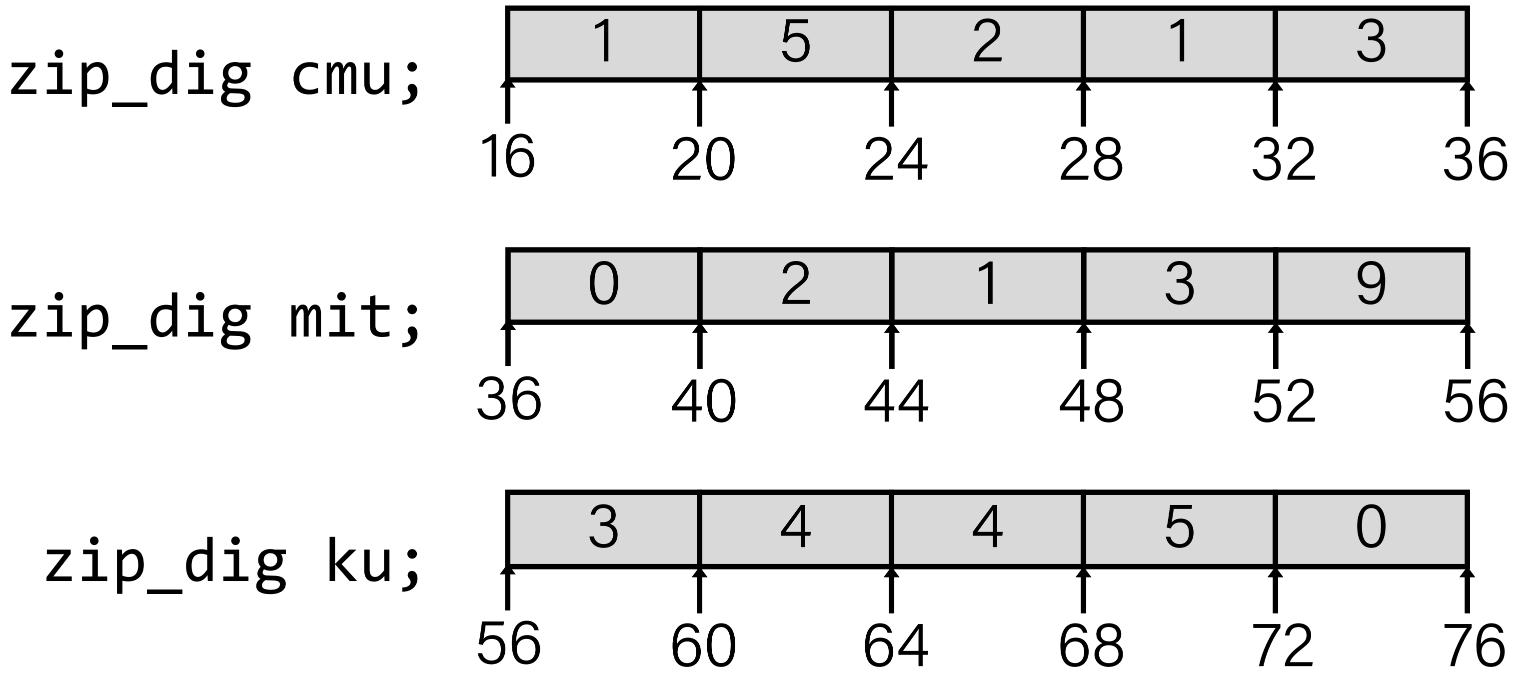
Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	x
`val+1`	`int *`	x + 4
`&val[2]`	`int *`	x + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + i`	`int *`	x + 4 i

`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};
```

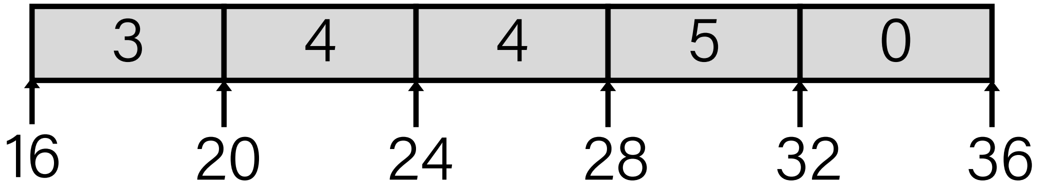


- Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

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

```
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*`];`

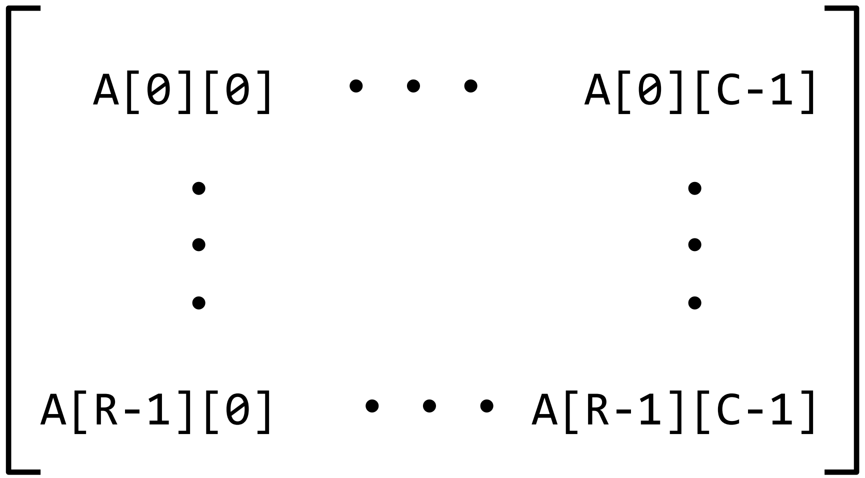
- 2D array of data type *T*
- *R* rows, *C* columns
- Type *T* element requires *K* bytes

Array Size

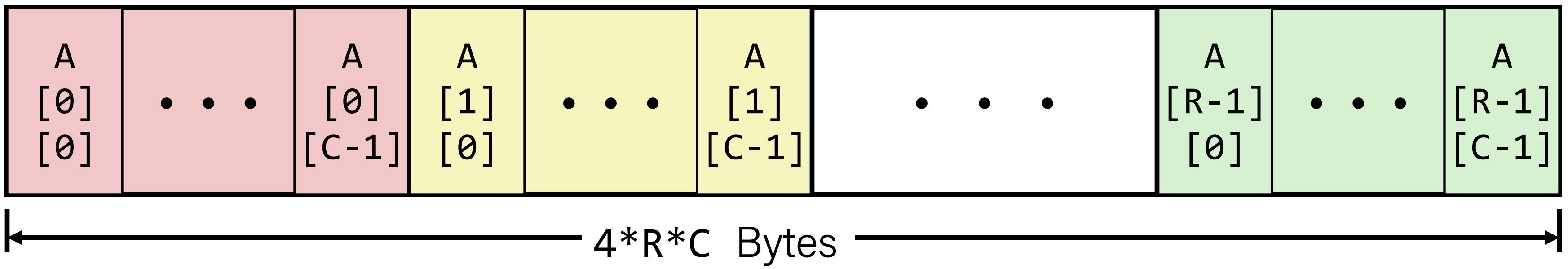
- *R* * *C* * *K* bytes

Arrangement

- Row-Major Ordering

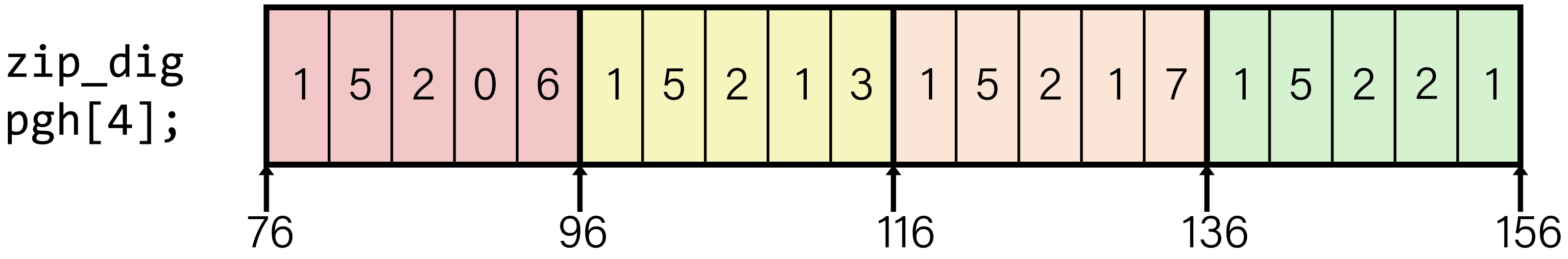



```
int A[R][C];
```



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 }};
```



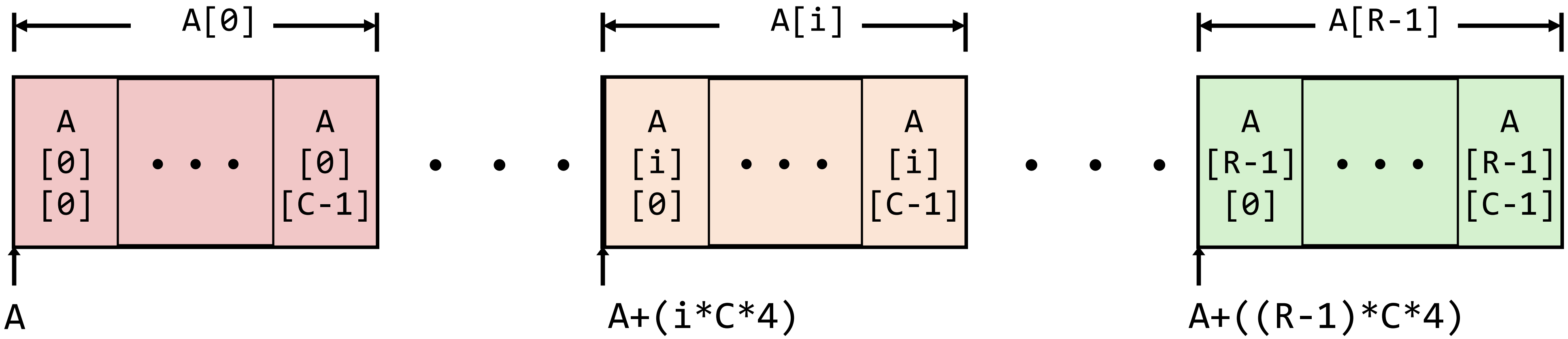
- "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable `pgh`: array of 4 elements, allocated contiguously
  - Each element is an array of 5 `int`'s, allocated contiguously
- "Row-Major" ordering of all elements in memory

Nested Array Row Access

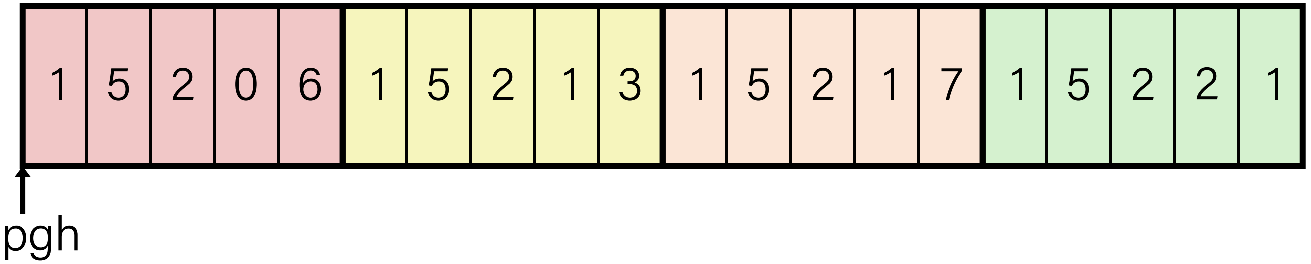
Row Vectors

- **`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`

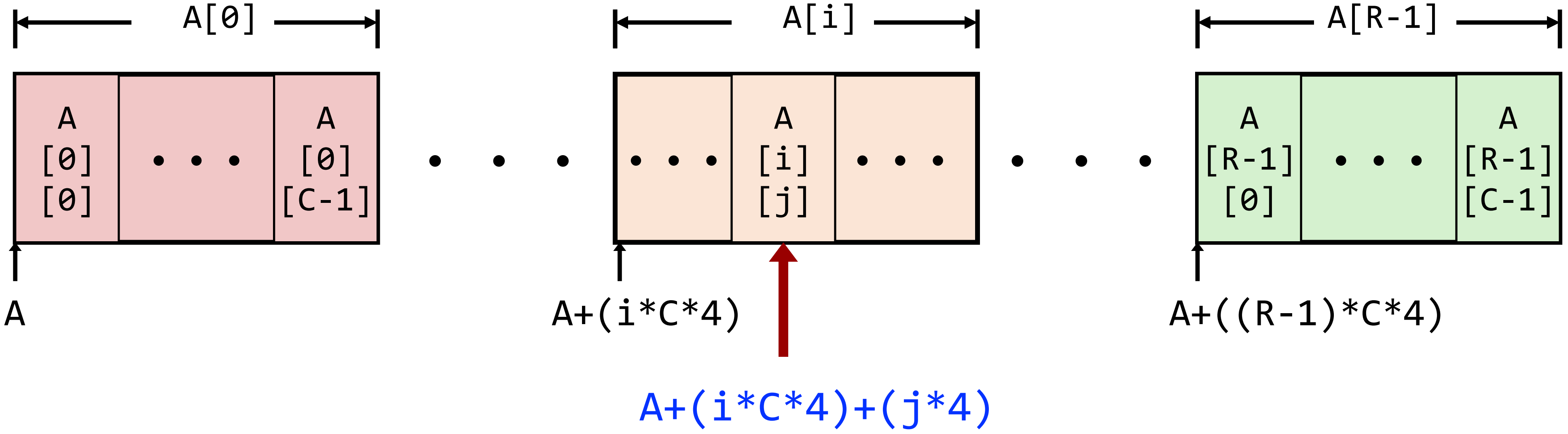
Machine Code
- Computes and returns address
- Compute as `pgh+4*(index+4*index)`

Nested Array Element Access

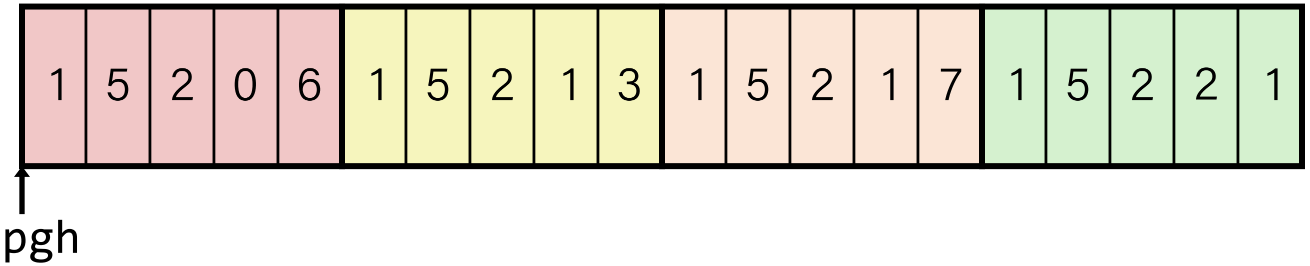
Array Elements

- `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)]
```

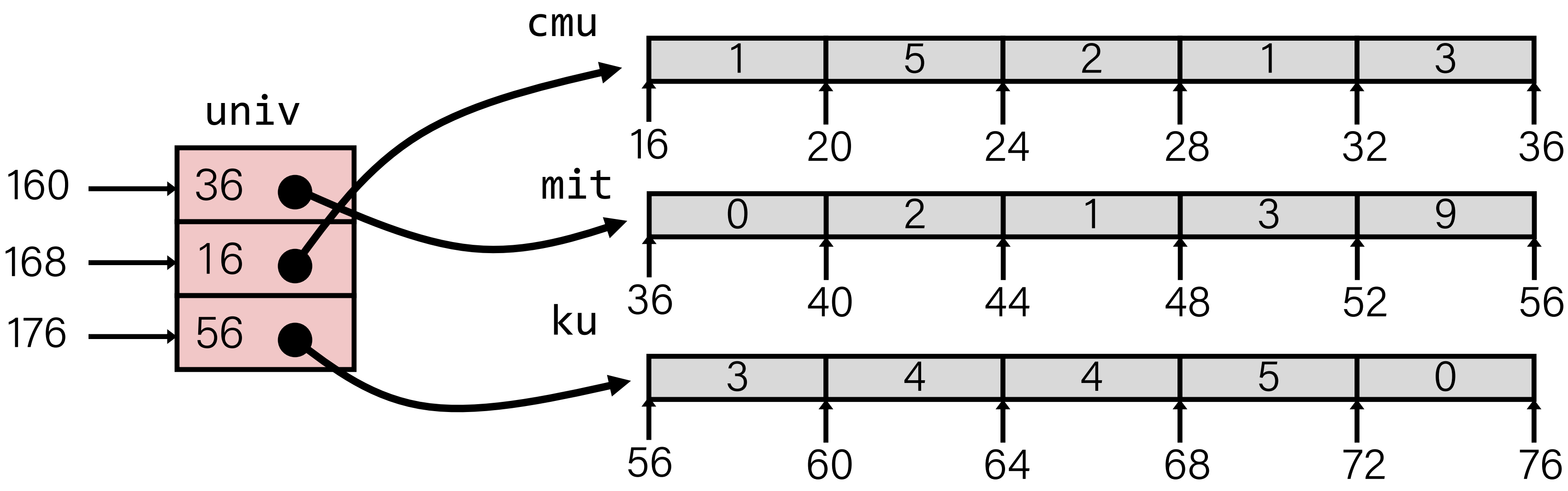
Array Elements

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

Multi-Level Array Example

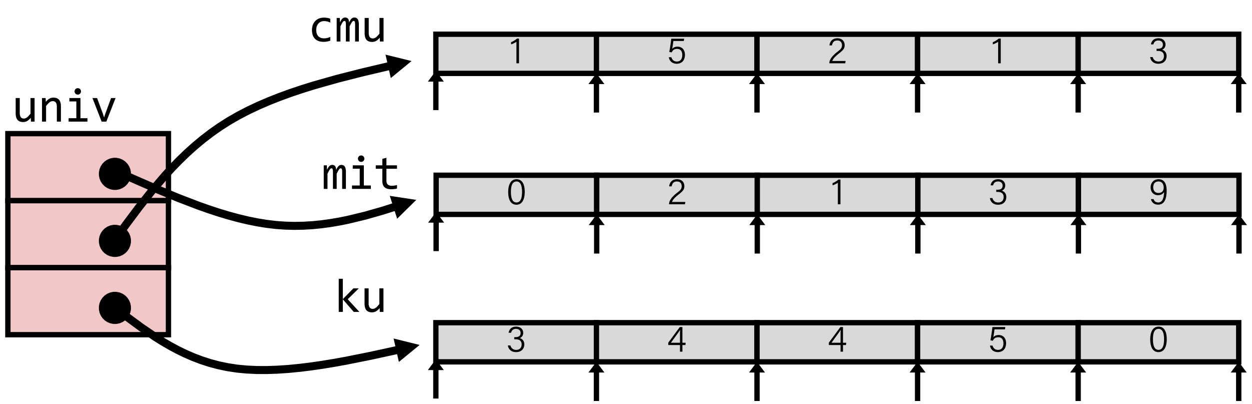
```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ku  = { 3, 4, 4, 5, 0 };

#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
```

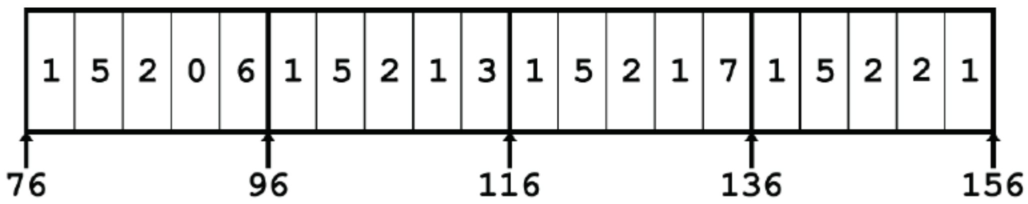
Computation

- 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

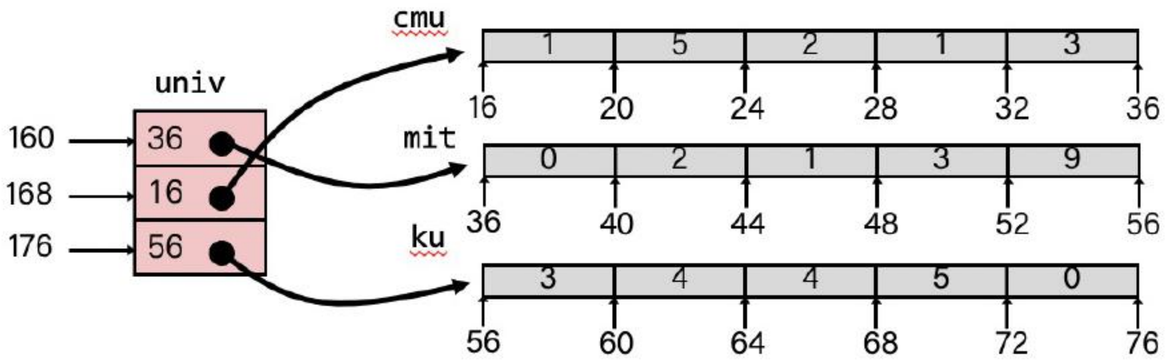
Nested array

```
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)
# i 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?

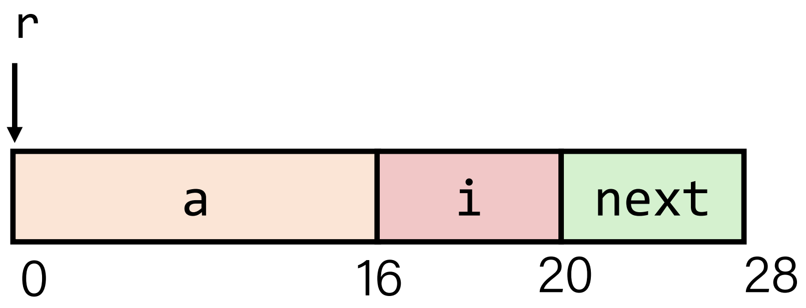
M = 5 and N = 7

Lecture Plan

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

Structure Representation

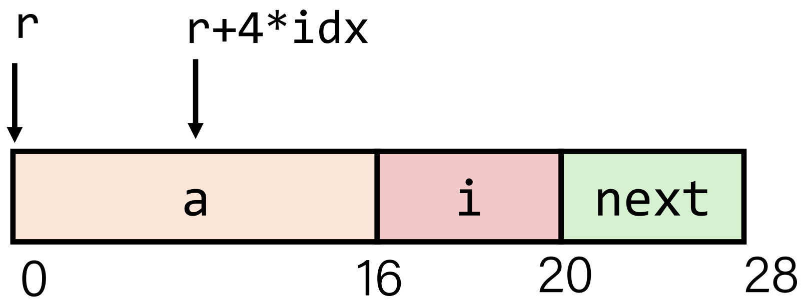
```
struct rec {
    int a[4];
    int i;
    struct rec *next;
};
```



- 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];
    int i;
    struct rec *next;
};
```



Generating Pointer to Array Element

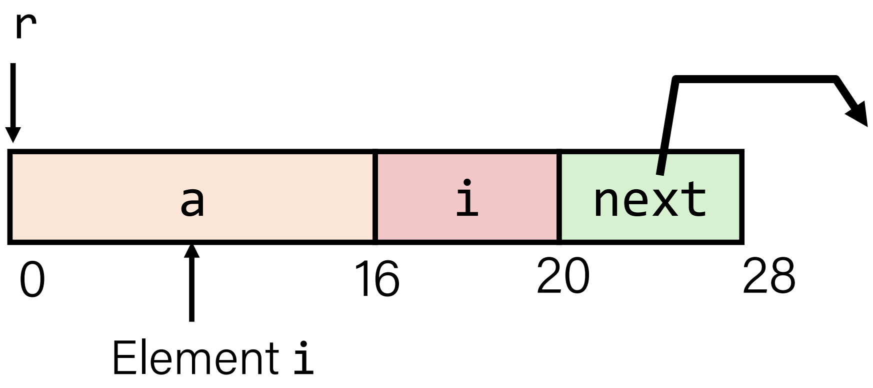
- Offset of each structure member determined at compile time
- Compute as **`r + 4*idx`**

```
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    20(%rdi), %rdi       #   r = M[r+20]
  testq   %rdi, %rdi           #   Test r
  jne     .L11                 #   if !=0 goto loop
```

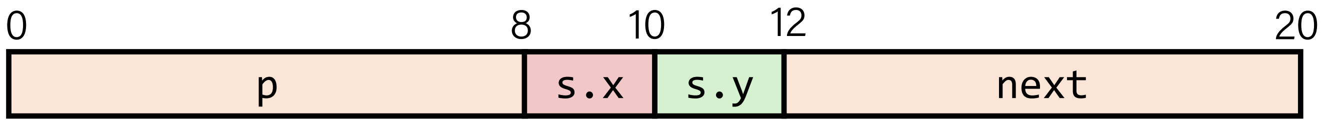
Practice 2: Reverse Engineering

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

slido

```
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         ;
}
```

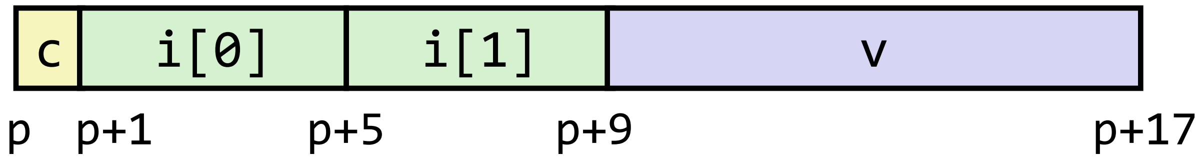
```
# void st_init(struct test *st)
# st in %rdi
st_init:
    movl 8(%rdi), %eax      Get st->s.x
    movl %eax, 10(%rdi)     Save in st->s.y
    leaq 10(%rdi), %rax     Compute &(st->s.y)
    movq %rax, (%rdi)       Store in st->p
    movq %rdi, 12(%rdi)     Store st in st->next
    ret
```



Structures & Alignment

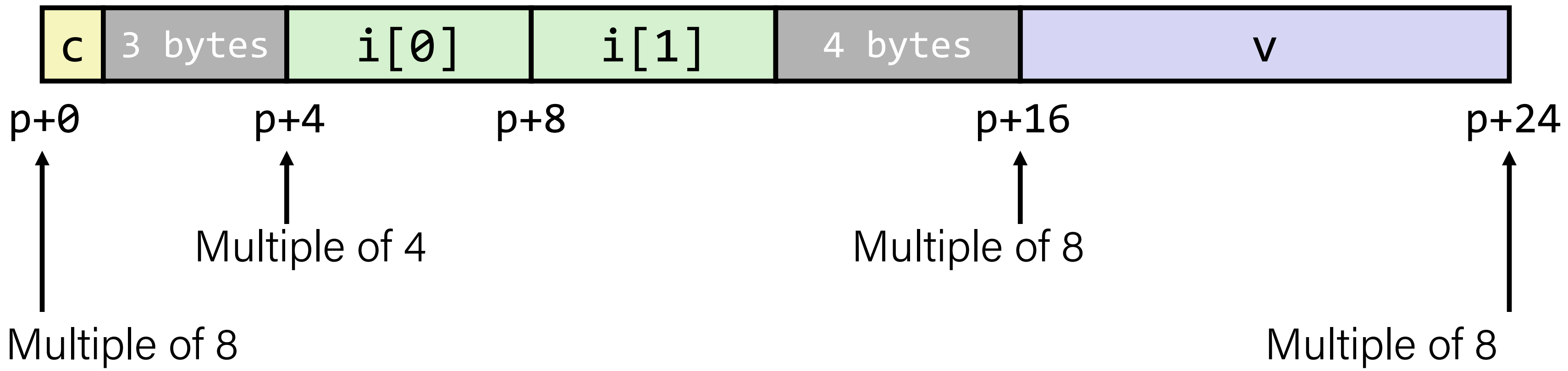
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

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

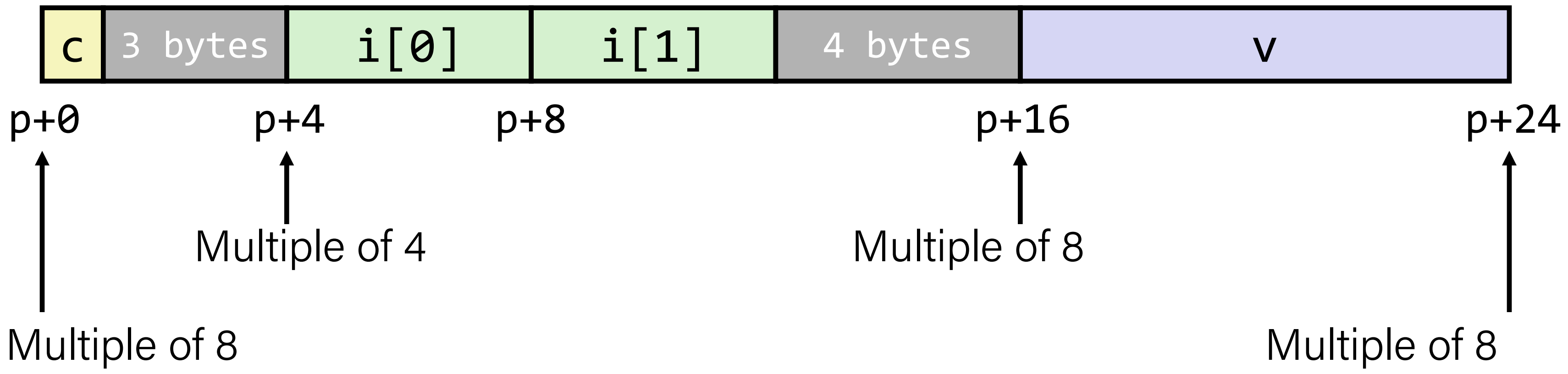
Overall structure placement

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

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

Example:

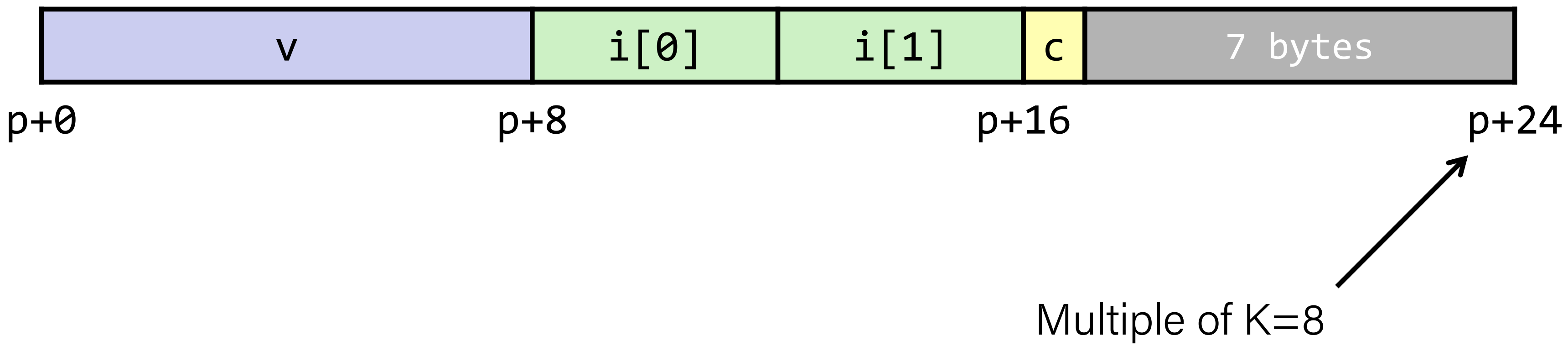
- K = 8, due to **`double`** element



Meeting Overall Alignment Requirement

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

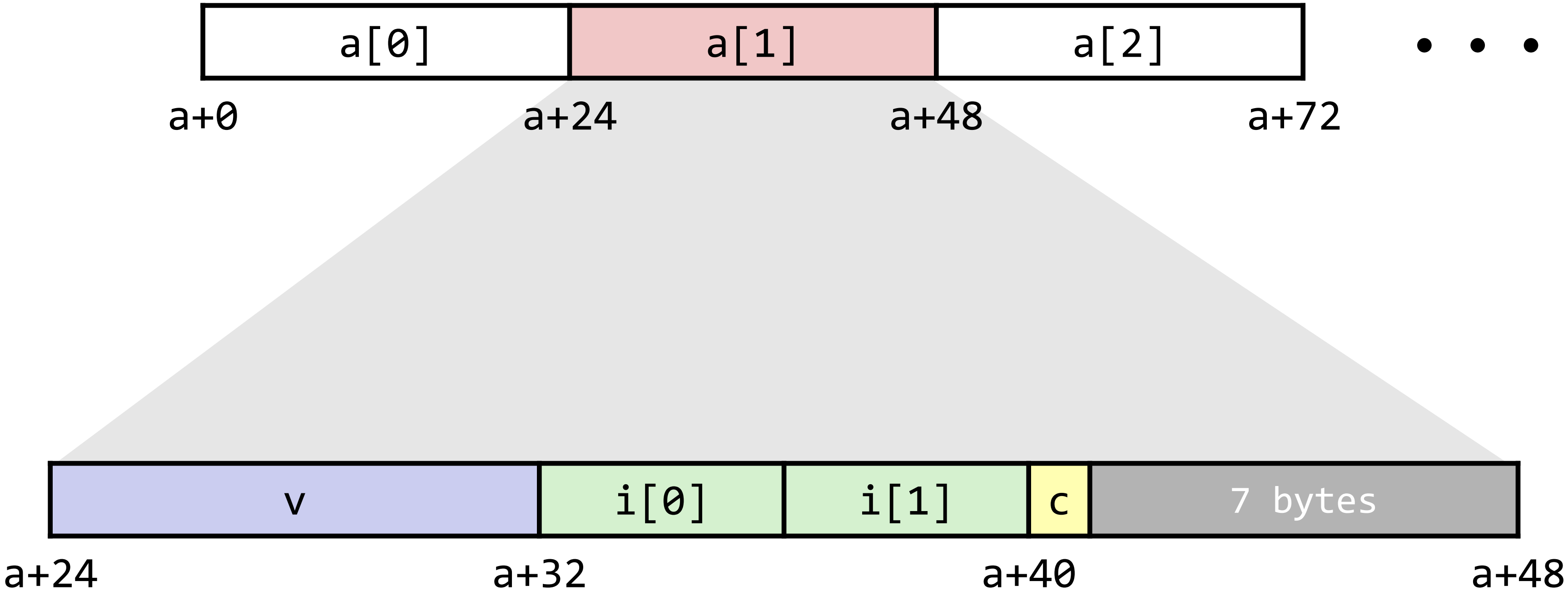
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

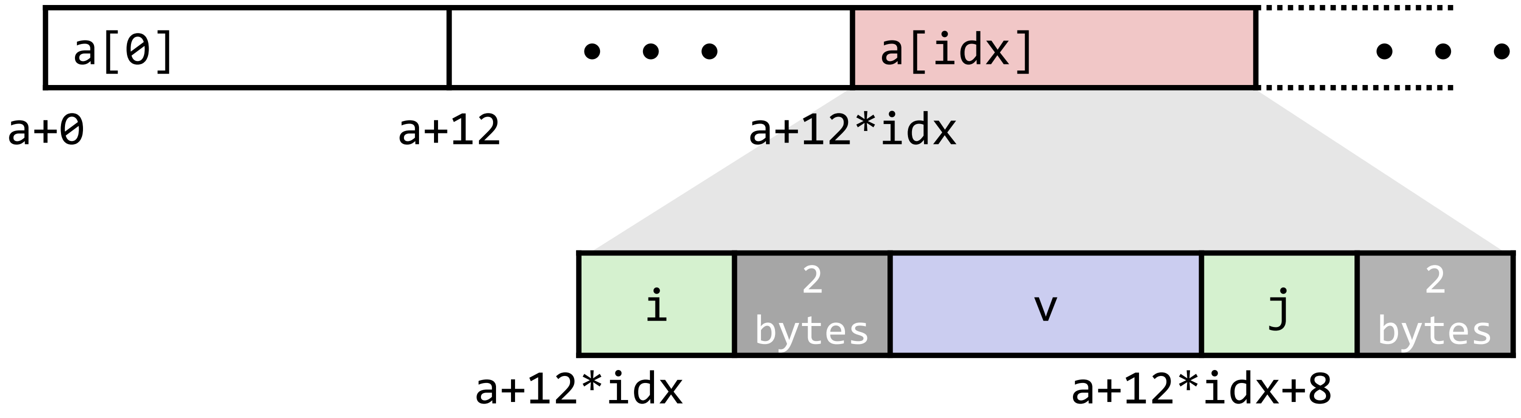
- Overall structure length multiple of K
- Satisfy alignment requirement for every element



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
```

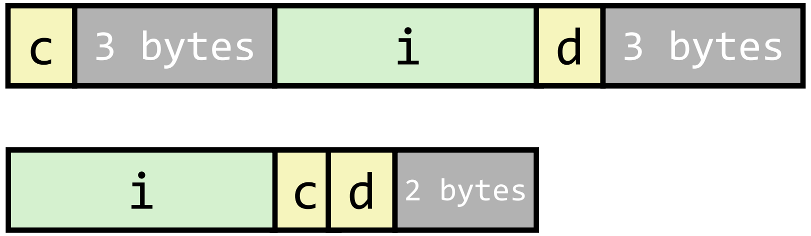
Saving Space

- 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

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;
    float e;
    double f;
    int g;
    char *h;
};
```

Field	*a	b	c	d	e	f	g	*h	Total	Alignment
Size	8	4	1	2	4	8	4	8	48	8
Offset	0	8	12	14	16	24	32	40		

No extra padding needed to satisfy alignment requirement

Rearranged structure with minimum wasted space:

Field	*a	f	h	b	e	g	d	c	Total	Alignment
Size	8	8	8	4	4	4	2	1	40	8
Offset	0	8	16	24	28	32	36	38		

1 bytes padded to satisfy alignment requirement

Lecture Plan

- Arrays
- Structures
- Floating Point

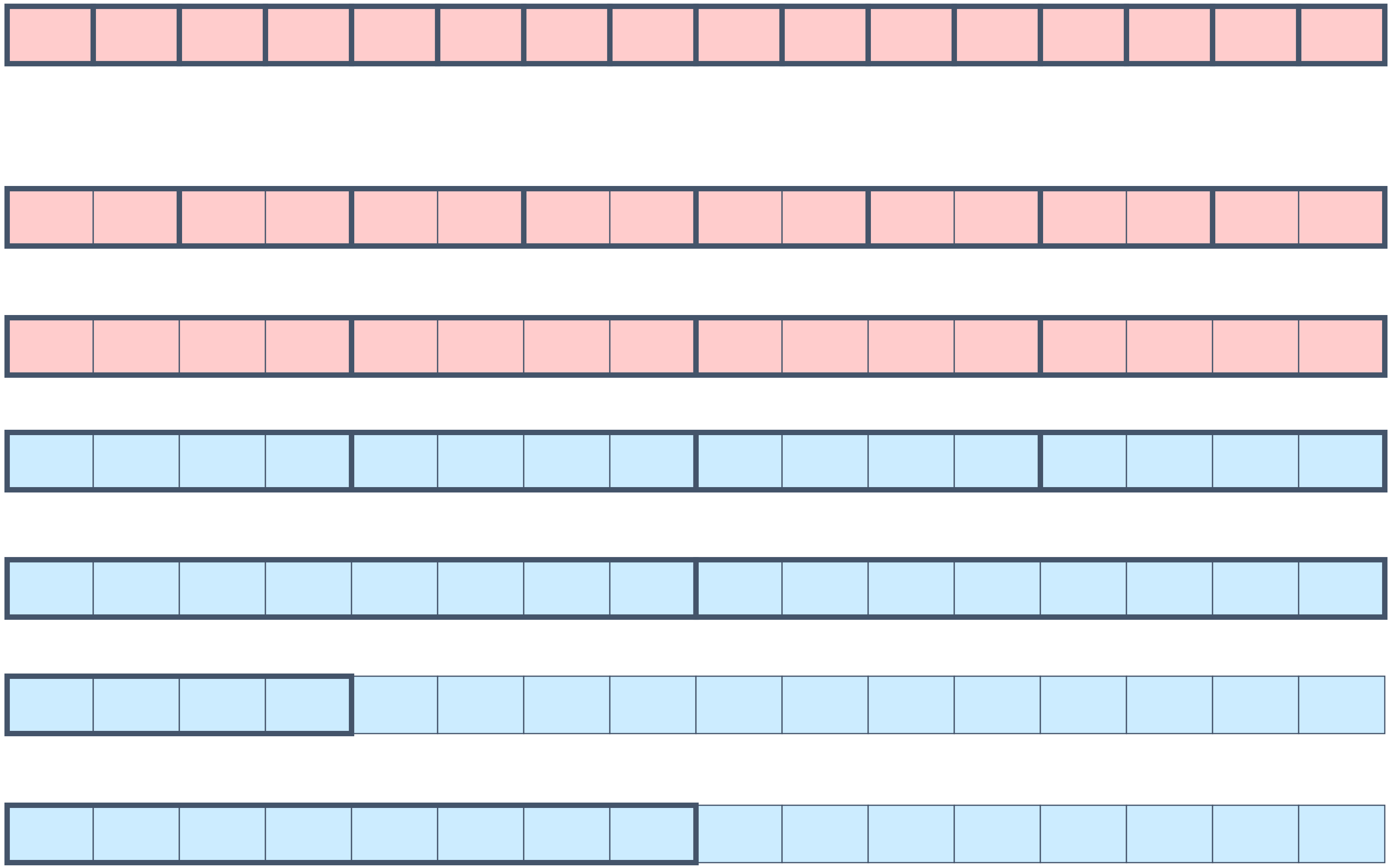
Background

- 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

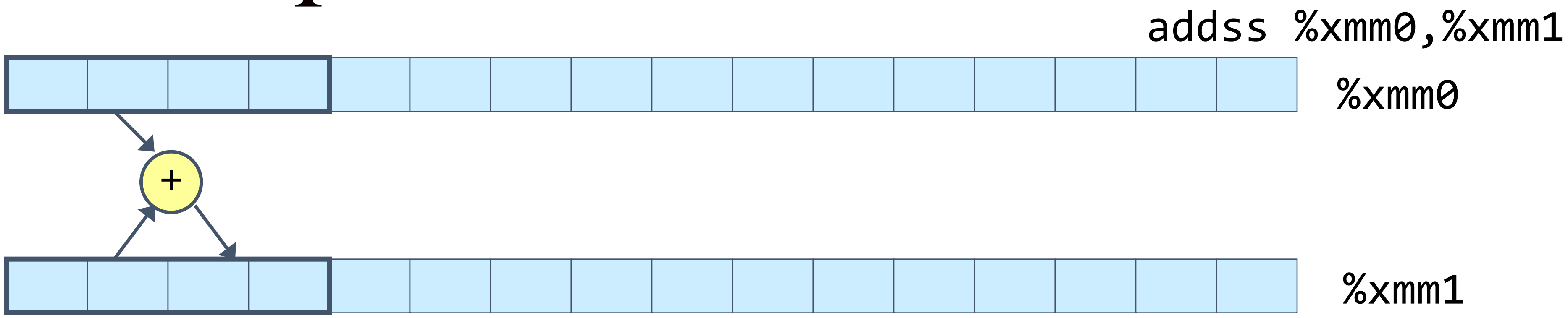
XMM Registers

- 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

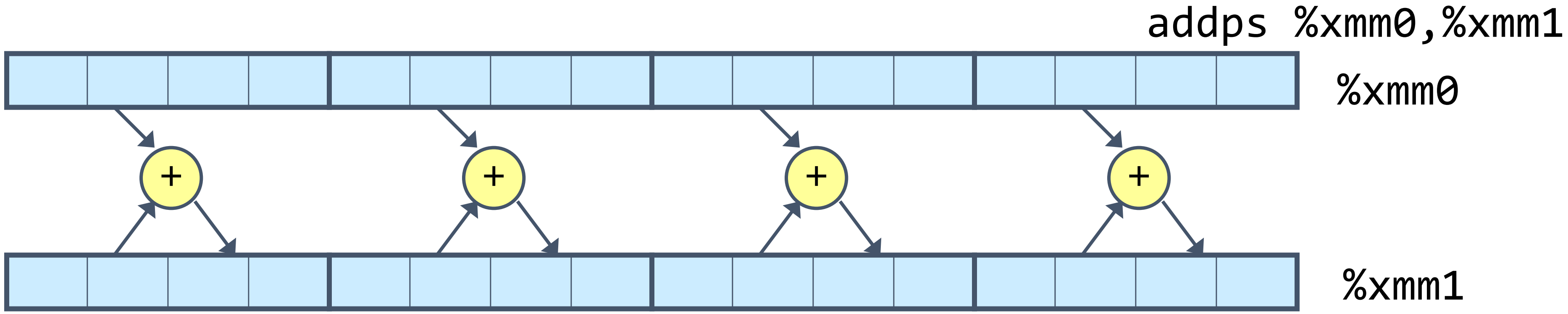


Scalar & SIMD Operations

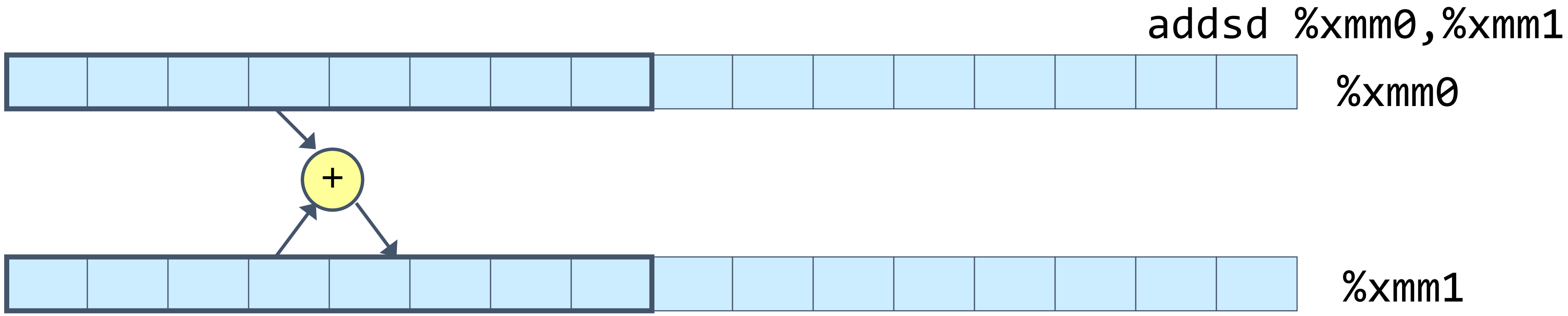
- Scalar Operations: Single Precision



- 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

```
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*