CSCI-UA.0201

Computer Systems Organization

Machine-Level Programming V

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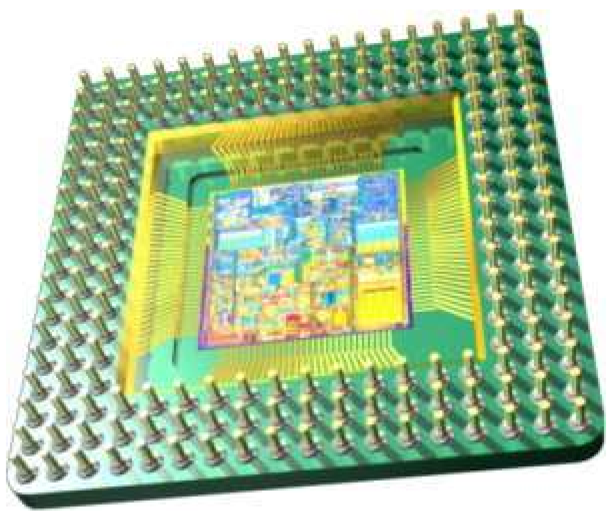
Some slides adapted (and slightly modified) from:

- Clark Barrett
- Jinyang Li
- Randy Bryant
- Dave O'Hallaron



Manipulating Data

How are data structures, like arrays, presented and manipulated in assembly?

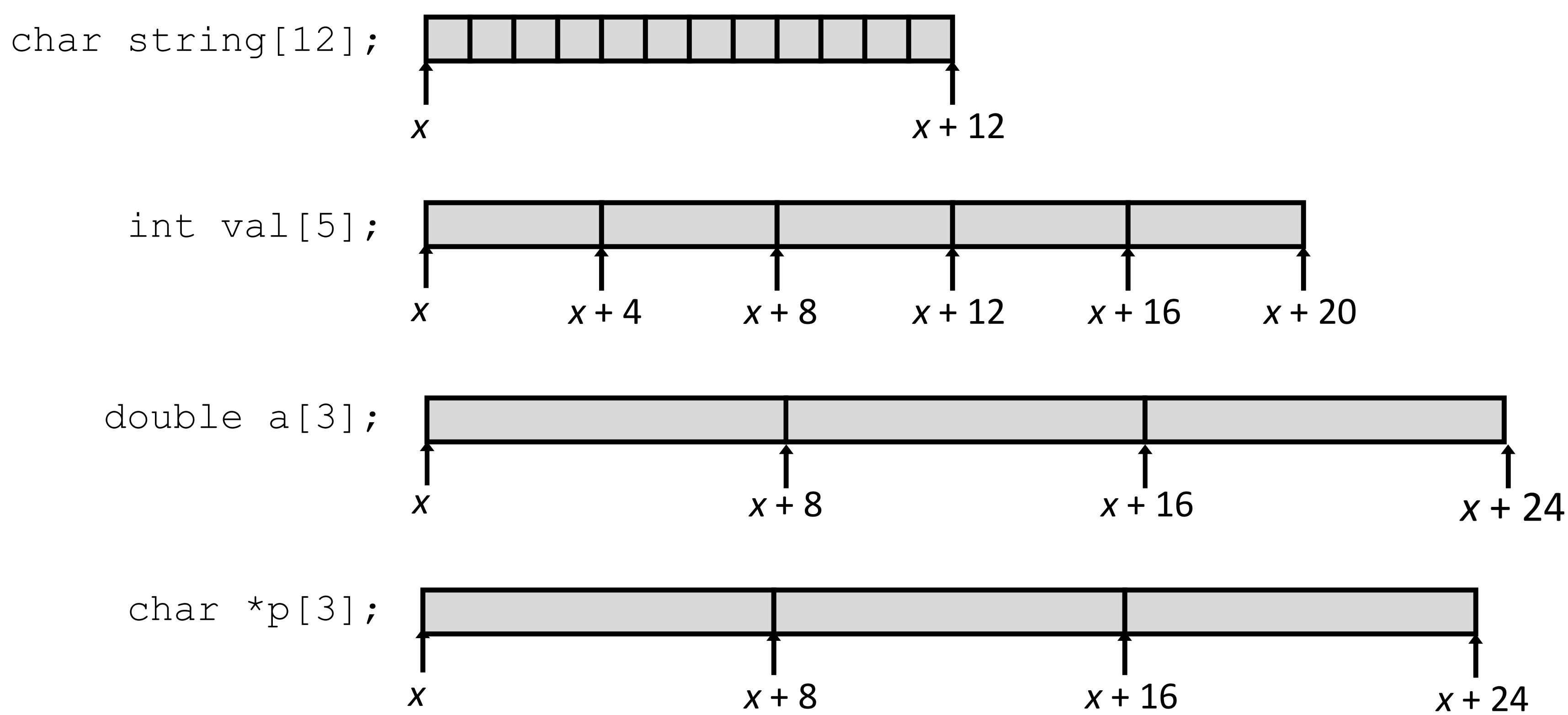
Array Allocation

- 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

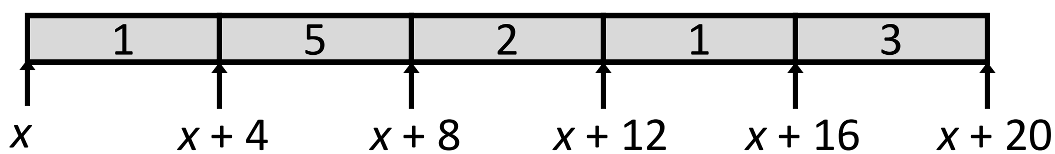
- Basic Principle

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

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

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

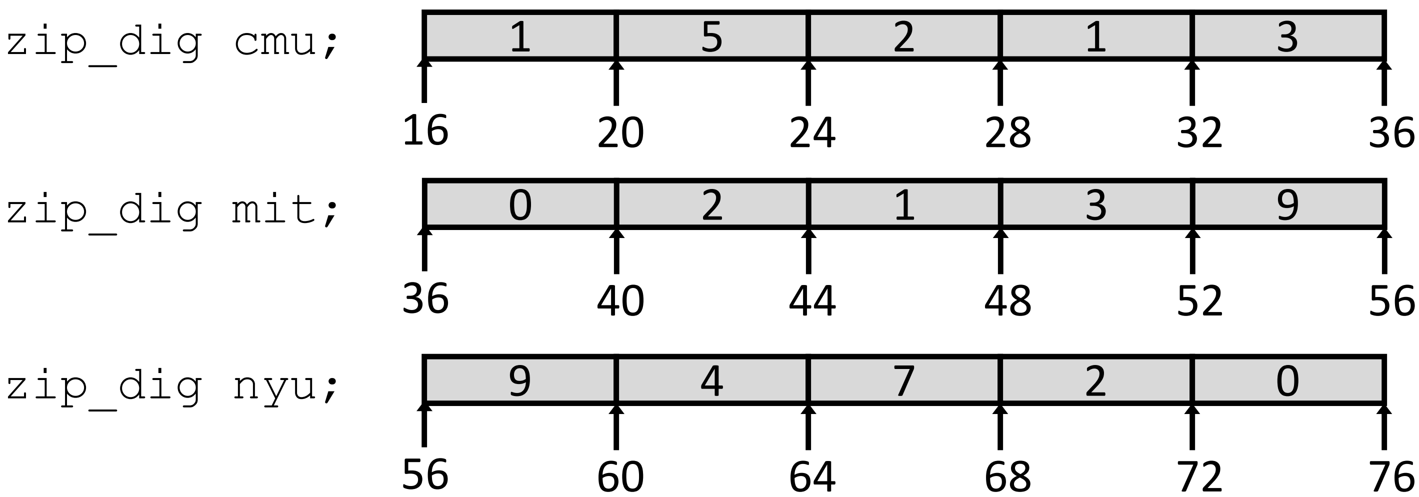
`int val[5];`



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 *`	$x + 4i$

Array Example

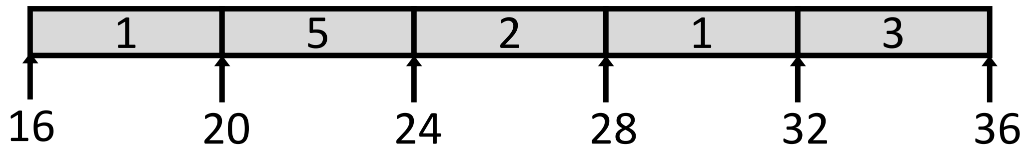
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

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



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

Array Accessing Example

```
zip_dig nyu;
```




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

IA32

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

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

Array Loop Example

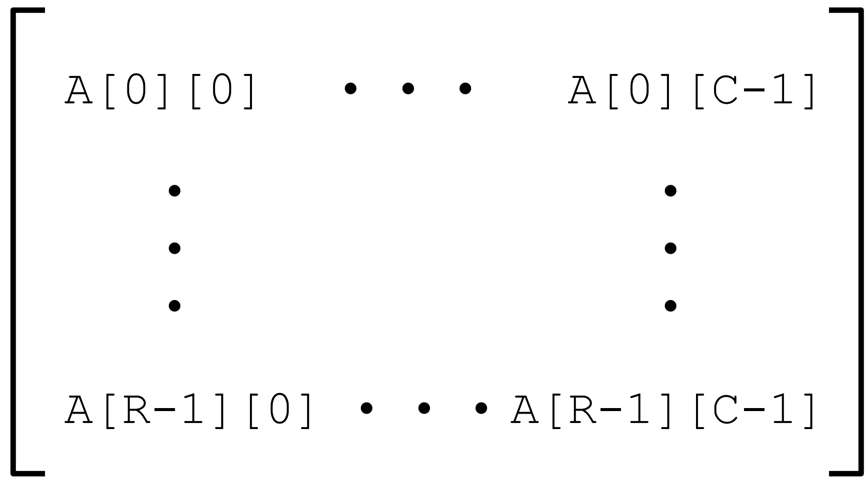
```
void zincr(int * z) {
  int i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # %rdi = z
  # ZLEN is 5
  movl    $0, %eax              #   i = 0
  jmp     .L3                   #   goto middle
.L4:                            # loop:
  addl    $1, (%rdi,%rax,4)     #   z[i]++
  addl    $1, %eax              #   i++
.L3:                            # middle
  cmpl    $4, %eax              #   i:4
  jbe     .L4                   #   if <=, goto loop
  rep; ret
```

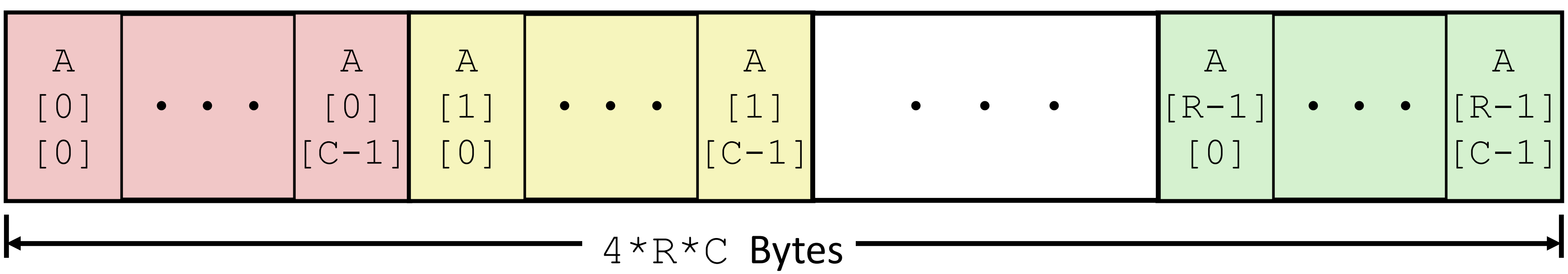
Multidimensional (Nested) Arrays

- 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

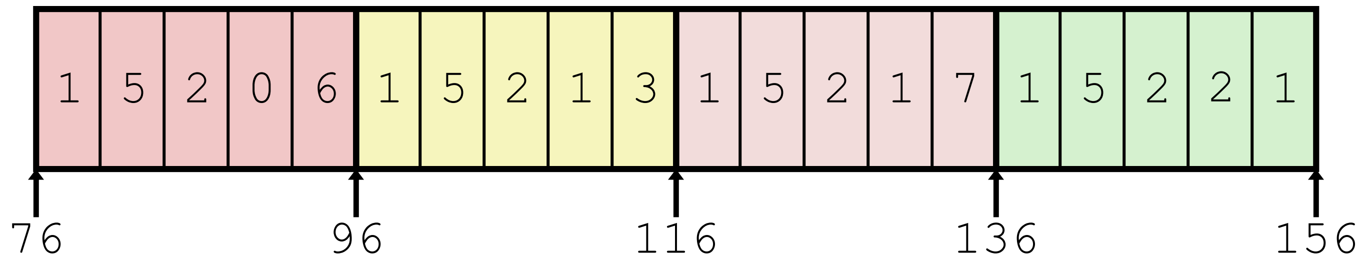



```
int A[R][C];
```



Nested Array Example

```
int pgh[4][5] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



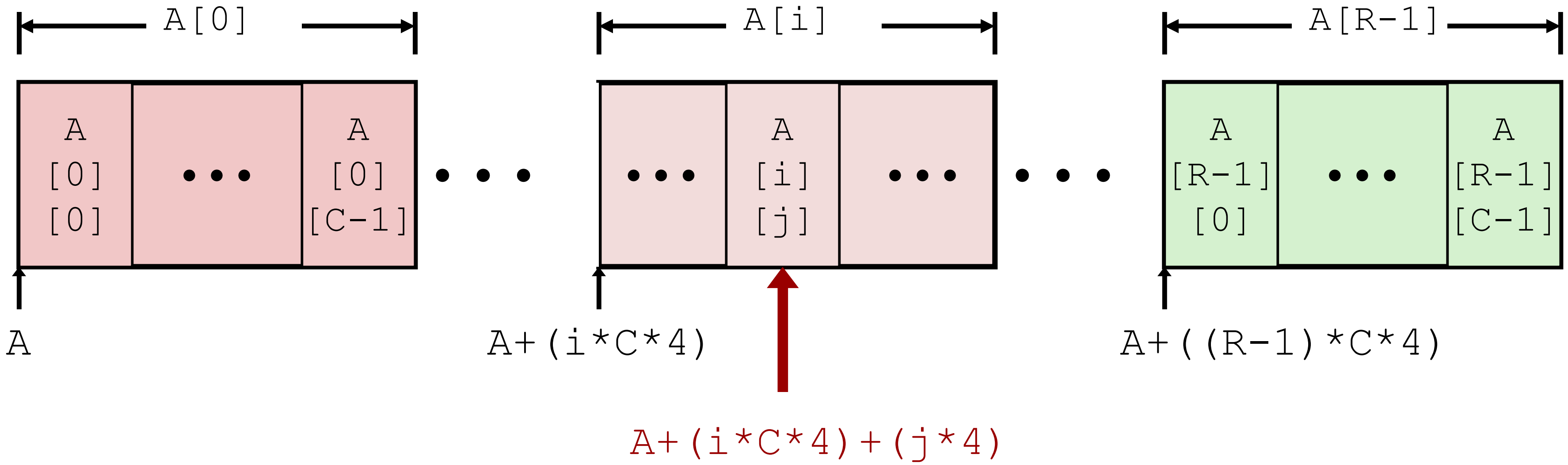
- – Variable **`pgh`**: array of 4 elements, allocated contiguously
- – Each element is an array of 5 **`int`**’s, allocated contiguously

- “Row-Major” ordering of all elements in memory

Nested Array 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];
```

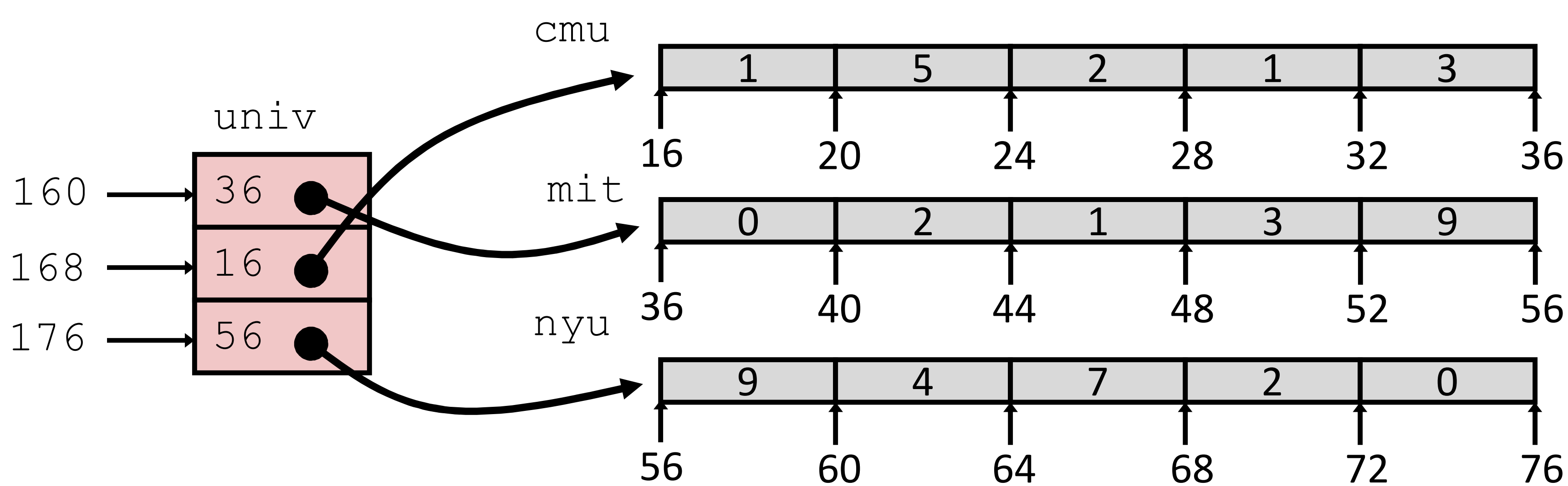


Multi-Level Array Example

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int mit[5] = { 0, 2, 1, 3, 9 };
int nyu[5] = { 9, 4, 7, 2, 0 };
```

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

- 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

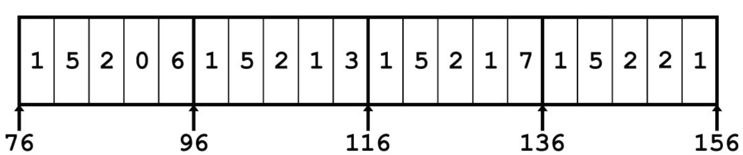
Array Element Accesses

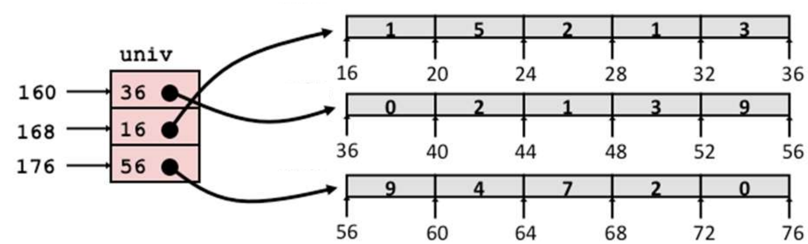
Nested array

```
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];
}
```





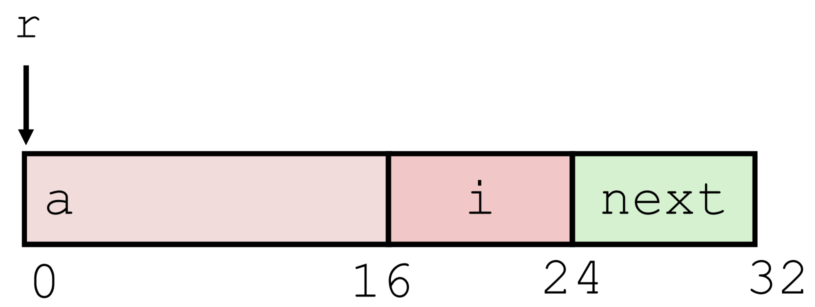
Accesses looks similar in C, but address computations very different:

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

How about structures?

Structure Representation

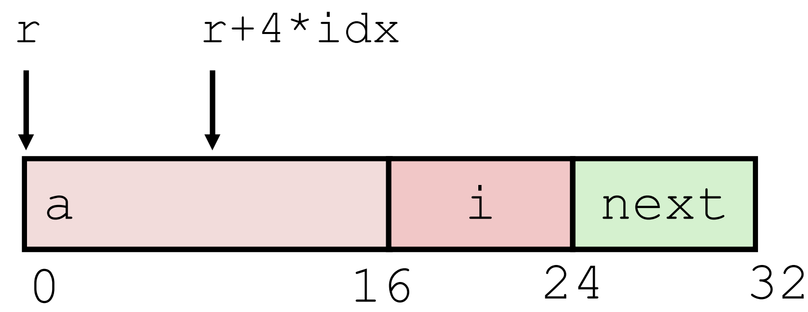
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- Structure represented as block of memory
  – **Big enough to hold all of the fields**
- Fields ordered according to declaration
  – **Even if another ordering could yield a more compact representation**
- Compiler determines overall size + positions of fields
  – **Machine-level program has no understanding of the structures in the source code**

Generating Pointer to Structure Member

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



- Generating Pointer to Array Element
  - Offset of each structure member determined at compile time
  - Compute as **`r + 4*idx`**

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

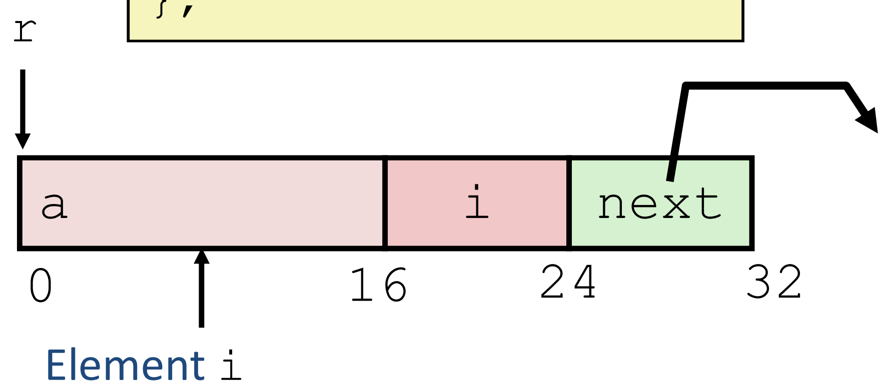
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```

Following Linked List

- C Code

```
struct rec {
    int a[3];
    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
```

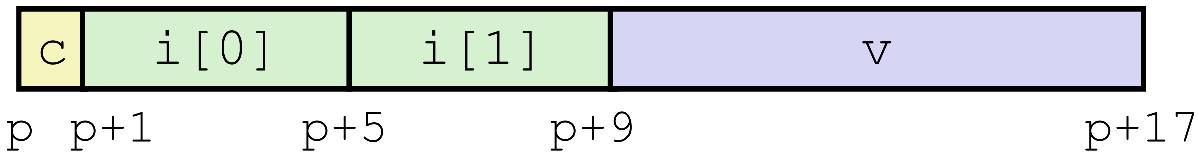
Alignment

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
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields

Structures & Alignment

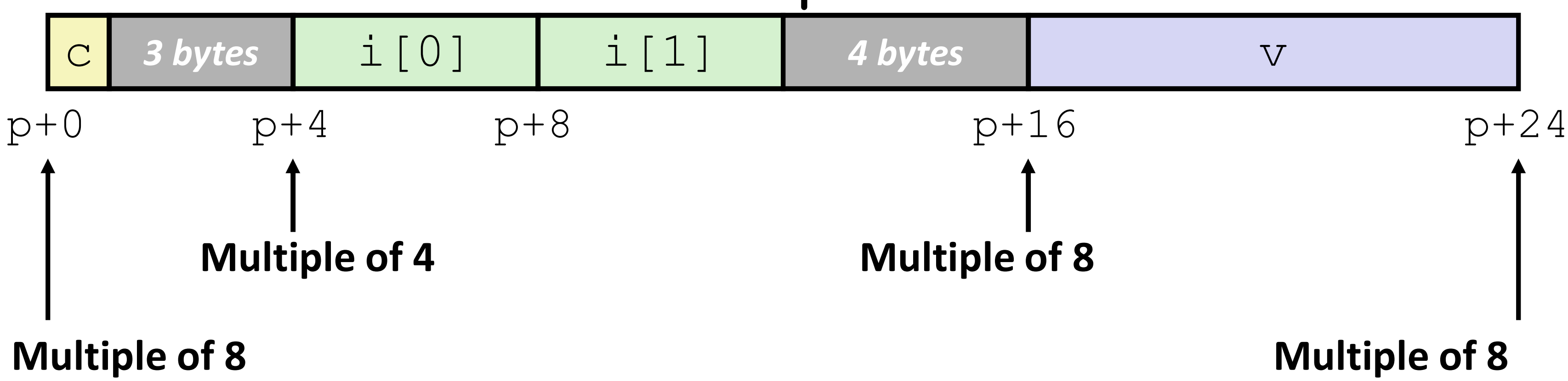
- Unaligned Data



p is multiple of 8

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

- Aligned Data
  - Primitive data type requires *K* bytes
  - Address must be multiple of *K*



Specific Cases of Alignment (x86-64)

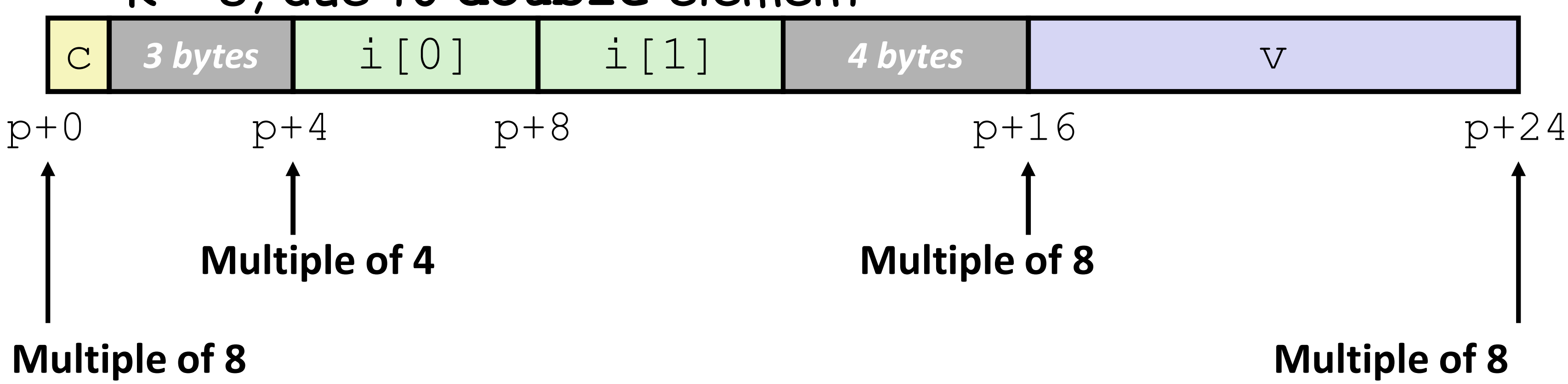
- 1 byte: **`char`**, …
  - no restrictions on address
- 2 bytes: **`short`**, …
  - address must be multiple of 2
- 4 bytes: **`int`**, **`float`**, …
  - address must be multiple of 4
- 8 bytes: **`double`**, **`long`**, **`char *`**, …
  - address must be multiple of 8
- 16 bytes: **`long double`** (GCC on Linux)
  - address must be multiple of 16

How about structures?

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

- 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**

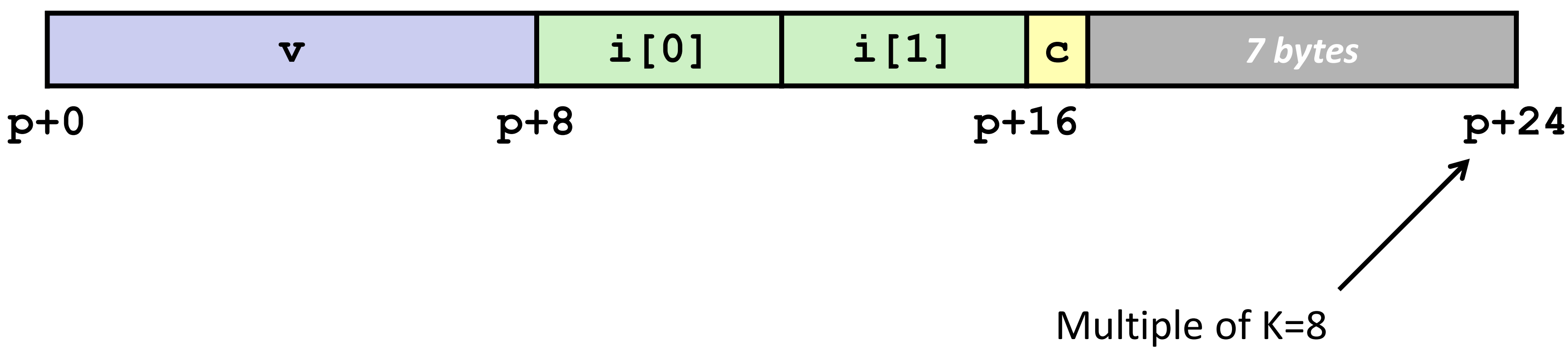
- Example:
  - K = 8, due to **double** element



Meeting Overall Alignment Requirement

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

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



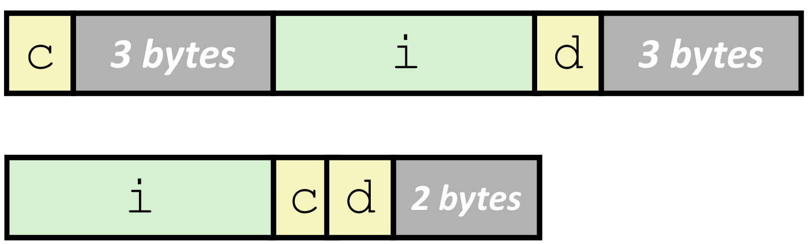
Saving Space

- 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)

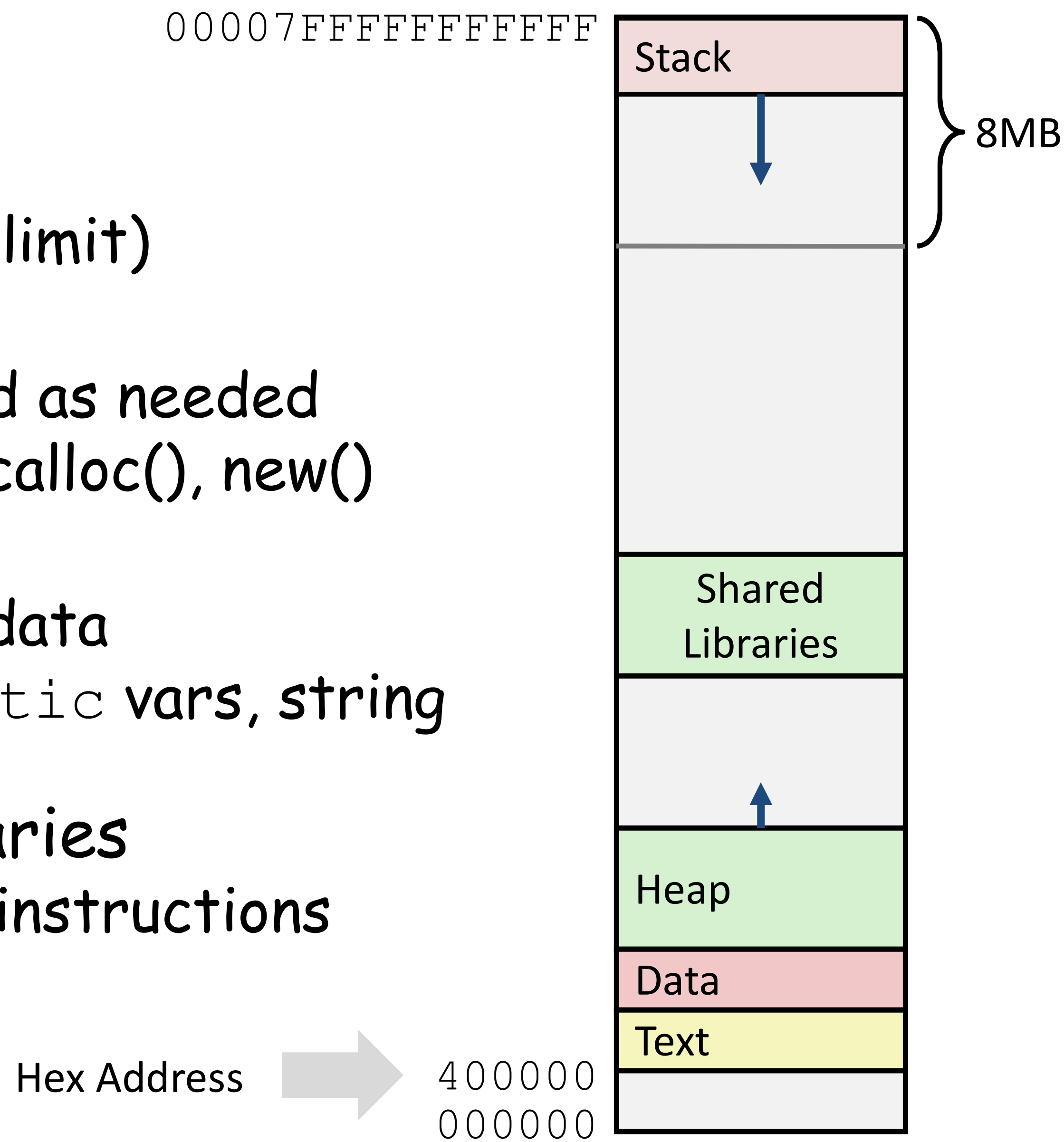


Final Look at Memory Layout

x86-64 Linux Memory Layout

not drawn to scale

- Stack
  - Runtime stack (8MB limit)
- Heap
  - Dynamically allocated as needed
  - When call malloc(), calloc(), new()
- Data
  - Statically allocated data
  - E.g., global vars, `static` vars, string constants
- Text / Shared Libraries
  - Executable machine instructions
  - Read-only



Conclusions

- We have not covered everything in x86-64, just gave you a glimpse and a feel for it.
- Compiler does more than blind translating your HLL code:
  - It manages the stack.
  - It translates the sophisticated data structure access to assembly
  - It optimizes your code
- No matter how sophisticated your HLL language code, it will be translated to assembly with 16 registers and basic data types!