Machine-Level Programming IV: Data

CSci 2021: Machine Architecture and Organization
March 2nd-4th, 2020

Your instructor: Stephen McCamant

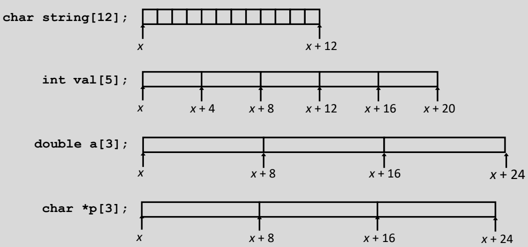
Based on slides originally by:
Randy Bryant, Dave O'Hallaron

Today

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment

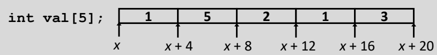
Array Allocation

- **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**

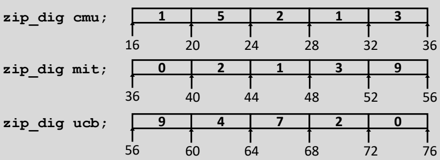


Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + i`	`int *`	*x* + 4 *i*

Array Example

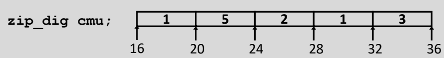
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

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



- **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];
}
```

x86:

```
  # %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)`**

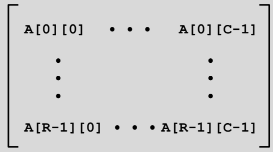
Array Loop Example

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

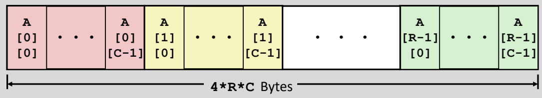
```
  # %rdi = z
  movl    $0, %eax            #   i = 0
  jmp     .L3                 #   goto middle
.L4:                          # loop:
  addl    $1, (%rdi,%rax,4)   #   z[i]++
  addq    $1, %rax            #   i++
.L3:                          # middle
  cmpq    $4, %rax            #   i:4
  jbe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

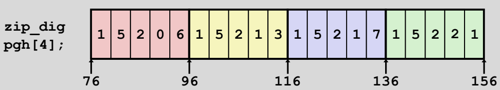


`int A[R][C];`



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 }};
```

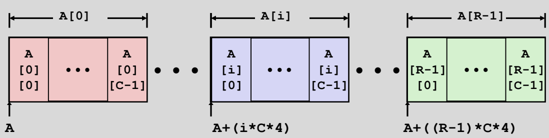


- **"`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"**
  - Variable `pgh`: array of 4 elements, allocated contiguously
  - Each element is an array of 5 `int`'s, allocated contiguously
- **"Row-Major" ordering of all elements in memory**

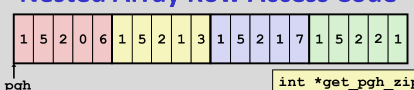
Nested Array Row Access

- **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];
}
```

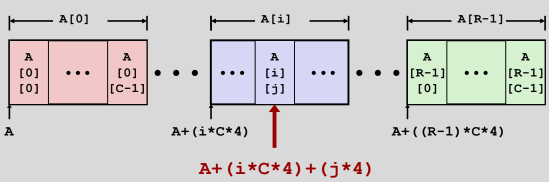
```
  # %rdi = index
  leaq (%rdi,%rdi,4),%rax  # 5 * index
  leaq pgh(,%rax,4),%rax   # pgh + (20 * index)
```

- **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)`

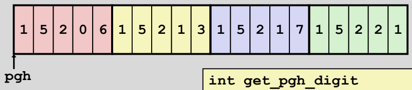
Nested Array Element Access

- **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)]
```

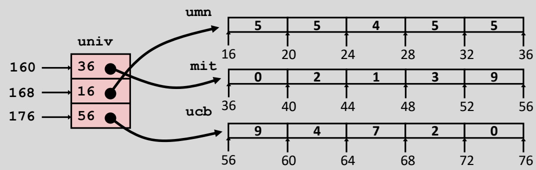
- **Array Elements**
  - `pgh[index][dig]` is `int`
  - Address: `pgh + 20*index + 4*dig`
    - `= pgh + 4*(5*index + dig)`

Multi-Level Array Example

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

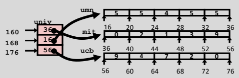
```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, umn, ucb};
```

- 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

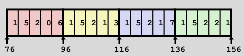
Array Element Accesses

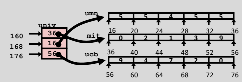
Nested array

```
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 X 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 X 16 Matrix Access

- **Array Elements**
  - 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 Matrix Access

- **Array Elements**
  - Address **A** + *i* * (*C* * *K*) + *j* * *K*
  - C = n, K = 4
  - 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];
}
```

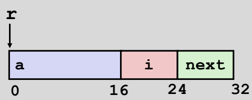
```
  # n in %rdi, a in %rsi, i in %rdx, j in %rcx
  imulq   %rdx, %rdi            # n*i
  leaq    (%rsi,%rdi,4), %rax   # a + 4*n*i
  movl    (%rax,%rcx,4), %eax   # a + 4*n*i + 4*j
  ret
```


Today

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - Allocation
  - Access
  - Alignment

Structure Representation

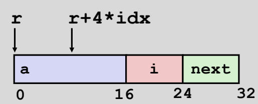
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- **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];
}
```

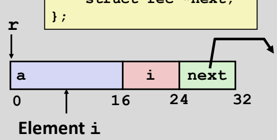
```
  # r in %rdi, idx in %rsi
  leaq  (%rdi,%rsi,4), %rax
  ret
```


Following Linked List

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

- **C Code**

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->next;
  }
}
```

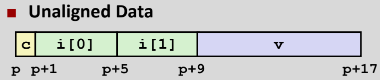


Register	Value
%rdi	r
%rsi	val

```
.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
```

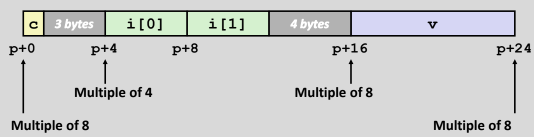

Structures & Alignment

- **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

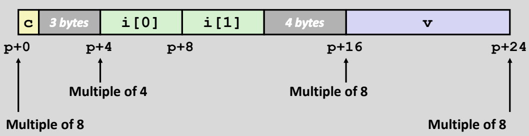
Specific Cases of Alignment (x86-64)

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

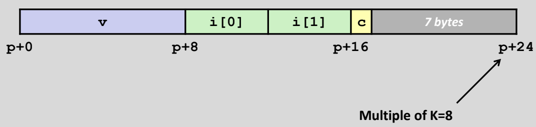
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



Meeting Overall Alignment Requirement

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

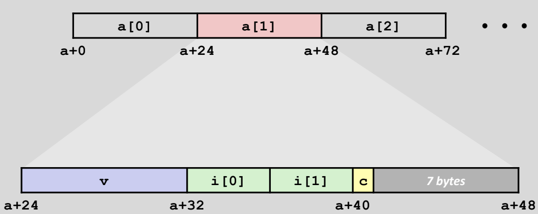
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

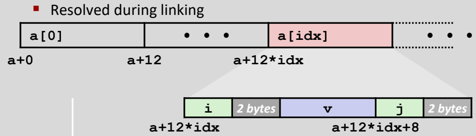
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



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
```

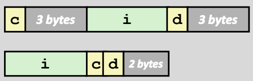
Saving Space

- **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)**



Summary

- **Arrays**
  - Elements packed into contiguous region of memory
  - Use index arithmetic to locate individual elements
- **Structures**
  - Elements packed into single region of memory
  - Access using offsets determined by compiler
  - Possible require internal and external padding to ensure alignment
- **Combinations**
  - Can nest structure and array code arbitrarily