CS429: Computer Organization and Architecture
Instruction Set Architecture V

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## Basic Data Types

### Integral
- Stored and operated on in general registers.
- Signed vs. unsigned depends on instructions used.

<table>
<thead>
<tr>
<th>Intel</th>
<th>GAS</th>
<th>Bytes</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>byte</td>
<td>b</td>
<td>1</td>
<td>[unsigned] char</td>
</tr>
<tr>
<td>word</td>
<td>w</td>
<td>2</td>
<td>[unsigned] short</td>
</tr>
<tr>
<td>double word</td>
<td>l</td>
<td>4</td>
<td>[unsigned] int</td>
</tr>
<tr>
<td>quad word</td>
<td>q</td>
<td>8</td>
<td>[unsigned] long int</td>
</tr>
</tbody>
</table>

### Floating Point
- Stored and operated on in floating point registers.

<table>
<thead>
<tr>
<th>Intel</th>
<th>GAS</th>
<th>Bytes</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>s</td>
<td>4</td>
<td>float</td>
</tr>
<tr>
<td>Double</td>
<td>l</td>
<td>8</td>
<td>double</td>
</tr>
<tr>
<td>Extended</td>
<td>t</td>
<td>10/12</td>
<td>long double</td>
</tr>
</tbody>
</table>
**Basic Principle:** $T \ A[L]$

- Array (named $A$) of data type $T$ and length $L$.
- Contiguously allocated region of $L \times \text{sizeof}(T)$ bytes.

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

Note the use of pointer arithmetic.
```c
#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 };
```

Example arrays were allocated in successive 20 byte block.

That’s not guaranteed to happen in general.

Declaration `zip_dig cmu` is equivalent to `int cmu[5]`. 
Array Accessing Example

```c
int get_digit ( zip_digit z, int dig )
{
    return z[dig];
}
```

Memory Reference Code

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

Computation

- Register `%rdi` contains the starting address of the array.
- Register `%rsi` contains the array index.
- The desired digit is at `%rdi + (4 * %rsi)`.
- User memory reference (%rdi,%rsi,4).
void zincr(zip dig z) {
    size_t i;
    for (i = 0; i < ZLEN; i++)
        z[i]++;
}

# %rdi = z
movl $0, %eax
jmp .L3
.L4:
    addl $1, (%rdi, %rax, 4)  # z[i]++
    addq $1, %rax  # i++
.L3:
    cmpq $4, %rax  # i:4
    jbe .L4  # if <=, goto loop
ret  # return
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:**  \( R \times C \times K \) bytes

**Arrangement:** Row-Major ordering (guaranteed)

Row major order means the elements are stored in the following order:

\[ [A_{0,0}, \ldots, A_{0,C-1}, A_{1,0}, \ldots, A_{1,C-1}, \ldots, A_{R-1,0}, \ldots, A_{R-1,C-1}] \]
Multidimensional Array Access

**Declaration:** \( T \ A[R][C] \);
- 2D array of data type \( T \)
- \( R \) rows, \( C \) columns
- Type \( T \) element requires \( K \) bytes

To access element \( A[i][j] \), perform the following computation:

\[
A + i \times C \times K + j \times K
\]
#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}};

- Declaration “`zip_dig pgh[4]`” is equivalent to “`int pgh[4][5].`”
- Variable `pgh` denotes an array of 4 elements allocated contiguously.
- Each element is an array of 5 ints, which are allocated contiguously.
- This is “row-major” ordering of all elements, guaranteed.
Row Vectors:

Given a nested array declaration $T \ A[R][C]$, you can think of this as an array of arrays.

- $A[i]$ is an array of $C$ elements.
- Each element of $A[i]$ has type $T$, and requires $K$ bytes.
- The starting address of $A[i]$ is $A + i \times C \times K$.
Array Elements

- $A[i][j]$ is an element of type $T$, which requires $K$ bytes.
- The address is $A + (i \times C + j) \times K$. 

![Diagram of nested array access]
Variable `univ` denotes an array of 3 elements.
- Each element is a pointer (8 bytes).
- Each pointer points to an array of ints.
Element Access in a Multi-Level Array

```c
int get_univ_digit (size_t index, size_t dig)
{
    return univ[index][dig];
}
```

Computation

- Element access
  Mem[Mem[univ+8*index] + 4*dig]
- Must do two memory reads:
  - First get pointer to row array.
  - Then access element within the row.

```
salq  $2, %rsi  # 4*dig
addq  univ(,%rdi,8),%rsi  # p = univ[dig] + 4*dig
movl  (%rsi), %eax  # return *p
ret
```
Array Element Accesses

**Nested Array**

```c
t
*get_pgh_digit*
(
  size_t index,
  size_t dig
)
{
    return pgh[index][dig];
}
```

Element at
Mem[pgh+20*index+4*dig]

**Multi-Level Array**

```c
t
*get_univ_digit*
(
  size_t index,
  size_t dig
)
{
    return univ[index][dig];
}
```

Element at
Mem[Mem[univ+8*index]+4*dig]

Similar C references, but different address computations.
Fixed dimensions:
Know value of N at compile time.

Variable dimensions, explicit indexing:
Traditional way to implement dynamic arrays

Variable dimensions, implicit indexing:
Now supported by gcc
Array Elements

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

```c
/* Get element a[i][j] */
int fix_ele ( fix_matrix a, size_t i, size_t j ) {
    return a[i][j];
}
```

```c
# 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]
```
Array Elements

- Address $A + i \times (C \times K) + j \times K$
- $C = n$, $K = 4$
- Must perform integer multiplication

```c
/* 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];
}
```

```assembly
# 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
```
Structure represented as block of memory
- Big enough to hold all the fields

Fields ordered according to declaration
- Even if another ordering could yield a more compact representation

Compiler determines overall size and position of fields
- Machine-level program has no understanding of the structures in the source code.
Generating Pointer to Structure Member

```c
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`

BTW: why does `r->i` need 8 bytes? Alignment. (Next slide set)
void set_val
    (struct rec *r, int val)
{
    while (r) {
        int i = r->i;
        r->a[i] = val;
        r = r->next;
    }
}

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

.L11:
    testq %rdi, %rdi
    je .L12
    movq 16(%rdi), %rax
    movl %esi, (%rdi, %rax, 4)
    movq 24(%rdi), %rdi
    jmp .L11

.L12:
    # Test r
    # if != 0, goto done
    # i = M[r+16]
    # M[r+4*i] = val
    # r = M[r+24]
    # goto loop
    # done: