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.

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

Note the use of pointer arithmetic.
Example arrays were allocated in successive 20 byte block.

That's not guaranteed to happen in general.

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

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

Memory Reference Code

```
# %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).
Array Loop Example

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

```assembly
# %rdi = z
movl $0, %eax
jmp .L3

.L4:
    addl $1, (%rdi, %rax, 4)
    addq $1, %rax

.L3:
    cmpq $4, %rax
    jbe .L4
ret
```

# Instruction Set Architecture V
**Multidimensional (Nested) Arrays**

**Declaration:** \( T \quad A[R][C] \);
- 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:

\[
[A_{0,0}, \ldots, A_{0,C-1}, A_{1,0}, \ldots, A_{1,C-1}, \ldots, A_{R-1,0}, \ldots, A_{R-1,C-1}].
\]
**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:

\[
A + i \times C \times K + j \times K
\]
Nested Array Example

```c
#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 $A + (i \times C + j) \times K$.
Variable `univ` denotes an array of 3 elements.

Each element is a pointer (8 bytes).

Each pointer points to an array of ints (may vary in length).
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.

```assembly
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
int 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
int 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

```c
#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];
}

#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)];
}

/* 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];
}
```
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 $A + i \cdot (C \cdot K) + j \cdot K$
- $C = n$, $K = 4$
- 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
```
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

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 \( r + 4 \times \text{idx} \)

BTW: why does \( r \rightarrow i \) need 8 bytes? Alignment. (Next slide set)
If you have a pointer \( r \) to a structure, use \( r->x \) to access component \( x \).

If you have the structure \( s \) itself, use \( s.x \).

\( r->x \) is just syntactic sugar for \((*r).x\)
Following Linked List

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