Assembly IV: Complex Data Types

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Basic Data Types

- **Integer**
  - Stored & operated on in general registers
  - Signed vs. unsigned depends on instructions used

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

- **Floating point**
  - Stored & operated on in floating point registers

<table>
<thead>
<tr>
<th></th>
<th>Intel</th>
<th>GAS</th>
<th>Bytes</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>Single</td>
<td>s</td>
<td>4</td>
<td>float</td>
</tr>
<tr>
<td>Double</td>
<td>Double</td>
<td>l</td>
<td>8</td>
<td>double</td>
</tr>
<tr>
<td>Extended</td>
<td>Extended</td>
<td>t</td>
<td>10/12</td>
<td>long double</td>
</tr>
</tbody>
</table>
Complex Data Types

- Complex data types in C
  - Pointers
  - Arrays
  - Structures
  - Unions
  - ...

- Can be combined
  - Pointer to pointer, pointer to array, ...
  - Array of array, array of structure, array of pointer, ...
  - Structure in structure, pointer in structure, array in structure, ...
Array Allocation

- **Basic principle:** \( T \ A[L]; \)
  - Array 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[4];
char *p[3];
```
Array Access

- Basic principle: \( T \ A[L] \);
  - Array of data type \( T \) and length \( L \)
  - Identifier \( A \) can be used as a pointer to element 0

```
int val[5];
```

```
<table>
<thead>
<tr>
<th>Reference</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>val[4]</td>
<td>int</td>
<td>3</td>
</tr>
<tr>
<td>val</td>
<td>int *</td>
<td>x</td>
</tr>
<tr>
<td>val + 1</td>
<td>int *</td>
<td>x + 4</td>
</tr>
<tr>
<td>&amp;val[2]</td>
<td>int *</td>
<td>x + 8</td>
</tr>
<tr>
<td>val[5]</td>
<td>int</td>
<td>??</td>
</tr>
<tr>
<td>*(val+1)</td>
<td>int</td>
<td>5</td>
</tr>
<tr>
<td>val + i</td>
<td>int *</td>
<td>x + 4 * i</td>
</tr>
</tbody>
</table>
```
## Array Example

```c
typedef int zip_dig[5];

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

<table>
<thead>
<tr>
<th>zip_dig cmu;</th>
<th>1</th>
<th>5</th>
<th>2</th>
<th>1</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>20</td>
<td>24</td>
<td>28</td>
<td>32</td>
<td>36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>zip_dig mit;</th>
<th>0</th>
<th>2</th>
<th>1</th>
<th>3</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>40</td>
<td>44</td>
<td>48</td>
<td>52</td>
<td>56</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>zip_dig ucb;</th>
<th>9</th>
<th>4</th>
<th>7</th>
<th>2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>60</td>
<td>64</td>
<td>68</td>
<td>72</td>
<td>76</td>
</tr>
</tbody>
</table>

### Notes

- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general
Array Accessing Example (1)

- Computation
  - Register `%edx` contains starting address of array
  - Register `%eax` contains array index
  - Desired digit at 4 * `%eax` + `%edx`
  - Use memory reference: (%edx, %eax, 4)

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

```
# %edx = z
# %eax = dig
movl (%edx,%eax,4),%eax # z[dig]
```
### Array Accessing Example (2)

- **Code does not do any bounds checking!**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Address</th>
<th>Value</th>
<th>Guaranteed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>mit[3]</td>
<td>36 + 4 * 3 = 48</td>
<td>3</td>
<td>Yes</td>
</tr>
<tr>
<td>mit[5]</td>
<td>36 + 4 * 5 = 56</td>
<td>9</td>
<td>No</td>
</tr>
<tr>
<td>mit[-1]</td>
<td>36 * 4 * (-1) = 32</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>cmu[15]</td>
<td>16 + 4 * 15 = 76</td>
<td>??</td>
<td>No</td>
</tr>
</tbody>
</table>

- Out of range behavior implementation-dependent

- No guaranteed relative allocation of different arrays
Array Loop Example (1)

- Original source

- Transformed version
  - As generated by GCC
  - Eliminate loop variable \( i \)
  - Convert array code to pointer code
  - Express in do-while form
    - No need to test at entrance

```c
int zd2int(zip_dig z){
    int i;
    int zi = 0;
    for (i = 0; i < 5; i++)
        zi = 10 * zi + z[i];
    return zi;
}
```

```c
int zd2int(zip_dig z) {
    int zi = 0;
    int *zend = z + 4;
    do {
        zi = 10 * zi + *z;
        z++;
    } while(z <= zend);
    return zi;
}
```
### Array Loop Example (2)

#### Registers

- `%ecx` : `z`
- `%eax` : `zi`
- `%ebx` : `zend`

```c
int zd2int(zip_dig z) {
    int zi = 0;
    int *zend = z + 4;
    do {
        zi = 10 * zi + *z;
        z++;
    } while(z <= zend);
    return zi;
}
```

- **%ecx** = `z`
- **%eax** = `zi`
- **%ebx** = `zend`

**z++ increments by 4**

- `10 * zi + *z` = `*z + 2*(zi+4*zi)`

### Assembly Code

```assembly
# %ecx = z
xorl %eax,%eax
leal 16(%ecx),%ebx
# %eax = %edx + 16
.L59:
leal (%eax,%eax,4),%edx
# 5*zi
movl (%ecx),%eax
# *z
addl $4,%ecx
# z++
leal (%eax,%edx,2),%eax
# zi = *z + 2*(5*zi)
cmpl %ebx,%ecx
# z : zend
jle .L59
# if <= goto loop
```
Nested Array (1)

- **Declaration:** \( T \ A[R][C] \)
  - 2D array of data type \( T \)
  - \( R \) rows, \( C \) columns
  - Array size = \( R \times C \times \text{sizeof}(T) \)

- **Arrangement**
  - Row-major ordering

\[
\begin{bmatrix}
A[0][0] & \cdots & A[0][C-1] \\
\vdots & \ddots & \vdots \\
A[R-1][0] & \cdots & A[R-1][C-1]
\end{bmatrix}
\]

\[
\begin{array}{cccc}
A[0][0] & \cdots & A[0][C-1] \\
\vdots & \ddots & \vdots \\
A[R-1][0] & \cdots & A[R-1][C-1]
\end{array}
\]

\[
\begin{array}{cccc}
A[0][0] & \cdots & A[0][C-1] \\
\vdots & \ddots & \vdots \\
A[R-1][0] & \cdots & A[R-1][C-1]
\end{array}
\]

- 4*R*C Bytes
Nested Array (2)

- **C code**
  - Variable `pgh` denotes array of 4 elements
    - Allocated contiguously
  - Each element is an array of 5 `int`'s
    - Allocated contiguously

- **Row-major ordering of all elements guaranteed**

```c
int pgh[4][5] = {
    {1, 5, 2, 0, 6},
    {1, 5, 2, 1, 3 },
    {1, 5, 2, 1, 7 },
    {1, 5, 2, 2, 1 }};
```
Nested Array Access (1)

- **Row vectors**
  - $A[i]$ is array of $C$ elements
  - Each element of type $T$ requires $K$ bytes
  - Starting address $A + i \times (C \times K)$

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

![Diagram of nested array access](image-url)
Nested Array Access (2)

- **Row vector**
  - `pgh[index]` is array of 5 int’s
  - Starting address `pgh + 20 * index`

```
int *get_pgh_zip(int index)
{
    return pgh[index];
}
```

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

```c
# %eax = index
leal (%eax,%eax,4),%eax  # 5 * index
leal pgh(,%eax,4),%eax   # pgh + (20 * index)
```
Nested Array Access (3)

- **Array elements**
  - $A[i][j]$ is element of type $T$
  - Address $A+i*(C*K)+j*K = A+(i*C+j)*K$

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

```
A

<table>
<thead>
<tr>
<th>A[0]</th>
<th>A[0][0]</th>
<th>A[0][1]</th>
<th>...</th>
<th>A[0][C-1]</th>
</tr>
</thead>
</table>

```

```
A+i*C*4

```

```
A+(i*C+j)*4

```

```
A+(R-1)*C*4

```
Nested Array Access (4)

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

- **Code**
  - Computes address `pgh+4*dig+4*(index+4*index)`
  - `movl` performs memory reference

```c
int get_pgh_digit (int index, int dig)
{
    return pgh[index][dig];
}
```

```
# %ecx = dig  
# %eax = index  
leal 0(%ecx,4),%edx     # 4*dig  
leal (%eax,%eax,4),%eax  # 5*index  
movl pgh(%edx,%eax,4),%eax  # *(pgh + 4*dig + 20*index)
```
Nested Array Access (5)

Strange referencing examples

- Code does not do any bounds checking
- Ordering of elements within array guaranteed

```c
int pgh[4][5];

int Address = Value Guaranteed?

pgh[3][3] 76 + 20*3 + 4*3 = 148 2 Yes
pgh[2][5] 76 + 20*2 + 4*5 = 136 1 Yes
pgh[2][-1] 76 + 20*2 + 4*(-1) = 112 3 Yes
pgh[4][-1] 76 + 20*4 + 4*(-1) = 152 1 Yes
pgh[0][19] 76 + 20*0 + 4*19 = 152 1 Yes
pgh[0][-1] 76 + 20*0 + 4*(-1) = 72 ?? No
```
Summary

- **Arrays in C**
  - Contiguous allocation of memory
  - Pointer to first element
  - No bounds checking

- **Compiler optimizations**
  - Compiler often turns array code into pointer code
  - Uses addressing modes to scale array indices
  - Lots of tricks to improve array indexing in loops
Structures

- Concept
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Members may be of different type

```c
struct rec {
    int i;
    int a[3];
    int *p;
};
```

```c
void set_i (struct rec *r, int val) {
    r->i = val;
}
```

**Memory Layout**

```
0 4 16 20
```

**Assembly**

```
# %eax = val
# %edx = r
movl %eax,(%edx)  # Mem[r] = val
```
Structure Referencing (1)

- Generating pointer to structure member
  - Offset of each member determined at compile time

```c
struct rec {
    int i;
    int a[3];
    int *p;
};

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

```
# %ecx = idx
# %edx = r
leal 0(%ecx,4),%eax   # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```
Structure Referencing (2)

- Generating pointer to member (cont’d)

```c
struct rec {
    int i;
    int a[3];
    int *p;
};

void set_p (struct rec *r) {
    r->p = &r->a[r->i];
}
```

---

```asm
# %edx = r
movl (%edx),%ecx    # r->i
leal 0(,%ecx,4),%eax  # 4*(r->i)
leal 4(%eax,%edx),%eax  # r+4+4*(r->i)
movl %eax,16(%edx)    # update r->p
```
Alignment (1)

- **Aligned data**
  - Primitive data type requires $K$ bytes
  - Address must be multiple of $K$
  - Required on some machines; advised on IA-32
    - treated differently by Linux and Windows

- **Motivation for aligning data**
  - Memory accessed by (aligned) double or quad-words
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory very tricky when datum spans 2 pages

- **Compiler**
  - Inserts gaps (or “pads”) in structure to ensure correct alignment of fields
Alignment (2)

- Size of primitive data type:
  - 1 byte (e.g., char): No restrictions on address
  - 2 bytes (e.g., short)
    - lowest 1 bit of address must be 0₂
  - 4 bytes (e.g., int, float, char *, etc)
    - lowest 2 bits of address must be 00₂
  - 8 bytes (e.g., double)
    - Windows (and most other OS’s & instruction sets): lowest 3 bits of address must be 000₂
    - Linux: lowest 2 bits of address must be 00₂ (i.e., treated the same as a 4-byte primitive data type)
  - 12 bytes (long double)
    - Windows, Linux: lowest 2 bits of address must be 00₂ (i.e., treated the same as a 4-byte primitive data type)
Alignment (3)

- **Offsets within structure**
  - Must satisfy element’s alignment requirement

- **Overall structure placement**
  - Each structure has alignment requirement $K$
    - Largest alignment of any element
  - Initial address & structure length must be multiples of $K$

- **Example (under Windows):**
  - $K = 8$, due to `double` element

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

```
c
  p+0
  Multiple of 8

i[0]
  p+4
  Multiple of 4

i[1]
  p+8

v
  p+16
  Multiple of 8

p+24
  Multiple of 8
```
Alignment (4)

- Linux vs. Windows
  - Windows (including Cygwin): $K = 8$

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

- Linux: $K = 4$
### Overall alignment requirement

- **Windows:** $p+24$
- **Linux:** $p+20$

$p$ must be multiple of 4 (all cases)

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

$p$ must be multiple of:
- 8 for Windows
- 4 for Linux

```
struct S3 {
    float x[2];
    int i[2];
    char c;
} *p;
```
Alignment (6)

- Ordering elements within structure

```
struct S4 {
    char c1;
    double v;
    char c2;
    int i;
} *p;
```

```
struct S5 {
    double v;
    char c1;
    char c2;
    int i;
} *p;
```

10 bytes wasted space in Windows

2 bytes wasted space
Union Allocation

- Principles
  - Overlay union elements
  - Allocate according to largest element
  - Can only use one field at a time

```c
union U1 {
    char c;
    int i[2];
    double v;
} *up;

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

(Windows alignment)
Summary

- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment

- **Unions**
  - Overlay declarations
  - Way to circumvent type system