Long, long, time ago, I can still remember
How mnemonics used to make me smile...
And I knew that with just the opcode names
that I could play those assembly games
and maybe hack some programs for a while.
But Comp 411 made me shiver,
With every new lecture that was delivered,
There was bad news at the door step,
I couldn’t handle another problem set.
My whole life thus far must have flashed,
the day the MARS simulator crossed my path,
All I know is that it made my hard disk crash,
On the day the hardware died.
And I was singing...

When I find my code in tons of trouble,
Friends and colleagues come to me,
Speaking words of wisdom:
“Write in C.”
Path from Programs to Bits

- Traditional Compilation

High-level, portable (architecture independent) program description

C or C++ program

Compiler

Assembly Code

Assembler

“Object Code”

“Library Routines”

A collection of precompiled object code modules

Linker

“Executable”

Loader

“Memory”

Machine language with all memory references resolved

Program and data bits loaded into memory

Architecture dependent mnemonic program description with symbolic memory references

Machine language with symbolic memory references

“Library Routines”

Machine language with all memory references resolved

Program and data bits loaded into memory
How an Assembler Works

Three major components of assembly

1) Allocating and initializing data storage

2) Conversion of mnemonics to binary instructions

3) Resolving addresses

.data
array: .space 40
total: .word 0

.text
.globl main
main: la $t1,array
move $t2,$0
move $t3,$0
beq $0,$0,test

loop: sll $t0,$t3,2
add $t0,$t1,$t0
sw $t3,($t0)
add $t2,$t2,$t3
addi $t3,$t3,1

test: slti $t0,$t3,10
bne $t0,$0,loop
sw $t2,total
j $ra
How an Assembler Works

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```
.data
array:  .space 40
total:  .word 0

.text
.globl main
main:   la      $t1,array
       move    $t2,$0
       move    $t3,$0
       beq     $0,$0,test
loop:   sll     $t0,$t3,2
       add     $t0,$t1,$t0
       sw $t3,($t0)
       add     $t2,$t2,$t3
       addi    $t3,$t3,1
test:   slti    $t0,$t3,10
       bne     $t0,$0,loop
       sw $t2,total
j       $ra
```
How an Assembler Works

Three major components of assembly

1) Allocating and initialing data storage

2) Conversion of mnemonics to binary instructions

3) Resolving addresses

```
.data
array: .space 40
total: .word 0

.text
.globl main
main:   la     $t1, array
        move   $t2, $0
        move   $t3, $0
        beq    $0, $0, test
loop:   sll    $t0, $t3, 2
        add    $t0, $t1, $t0
        sw     $t3, ($t0)
        add    $t2, $t2, $t3
        addi   $t3, $t3, 1
test:   slti   $t0, $t3, 10
        bne    $t0, $0, loop
        sw     $t2, total
        j      $ra
```
How an Assembler Works

Three major components of assembly

1) Allocating and initializing data storage
2) Conversion of mnemonics to binary instructions
3) Resolving addresses

```
.data
array: .space 40
total: .word 0

.text
.globl main
main:  la        $t1,array
       move      $t2,$0
       move      $t3,$0
       beq       $0,$0,test
loop:  sll       $t0,$t3,2
       add       $t0,$t1,$t0
       sw        $t3,($t0)
       add       $t2,$t2,$t3
       addi      $t3,$t3,1

.globl test
loop:  slti      $t0,$t3,10
       bne       $t0,$0,loop
       sw        $t2,total
       j         $ra
```
How an Assembler Works

Three major components of assembly

1) Allocating and initializing data storage

2) Conversion of mnemonics to binary instructions

3) Resolving addresses

```assembly
.data
array:    .space 40
total:    .word 0

.text
.globl main
main:     la    $t1, array
          move  $t2,$0
          move  $t3,$0
          beq    $0,$0,test

loop:     sll    $t0,$t3,2
          add    $t0,$t1,$t0
          sw     $t3,($t0)
          add    $t2,$t2,$t3
          addi   $t3,$t3,1

test:     slti   $t0,$t3,10
          bne    $t0,$0,loop
          sw     $t2,total
          j      $ra
```

lui   $9, arrayhi
ori   $9,$9,arraylo
0x3c09?????
0x3529?????
### Resolving Addresses - 1st Pass

- **“Old-style” 2-pass assembler approach**

- In the first pass, data and instructions are encoded and assigned offsets within their segment, while the symbol table is constructed.
- Unresolved address references are set to 0

#### Symbol table after Pass 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Segment</th>
<th>Location pointer offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>data</td>
<td>0</td>
</tr>
<tr>
<td>total</td>
<td>data</td>
<td>40</td>
</tr>
<tr>
<td>main</td>
<td>text</td>
<td>0</td>
</tr>
<tr>
<td>loop</td>
<td>text</td>
<td>20</td>
</tr>
<tr>
<td>test</td>
<td>text</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment offset</th>
<th>Code</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0x3c090000</td>
<td>la $t1, array</td>
</tr>
<tr>
<td>4</td>
<td>0x35290000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0x00005021</td>
<td>move $t2, $0</td>
</tr>
<tr>
<td>12</td>
<td>0x00005821</td>
<td>move $t3, $0</td>
</tr>
<tr>
<td>16</td>
<td>0x10000000</td>
<td>beq $0, $0, test</td>
</tr>
<tr>
<td>20</td>
<td>0x000b4080</td>
<td>loop:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sll $t0, $t3, 2</td>
</tr>
<tr>
<td>24</td>
<td>0x01284020</td>
<td>add $t0, $t1, $t0</td>
</tr>
<tr>
<td>28</td>
<td>0xad0b0000</td>
<td>sw $t0, ($t0)</td>
</tr>
<tr>
<td>32</td>
<td>0x014b5020</td>
<td>add $t0, $t1, $t0</td>
</tr>
<tr>
<td>36</td>
<td>0x216b0001</td>
<td>addi $t3, $t3, 1</td>
</tr>
<tr>
<td>40</td>
<td>0x2968000a</td>
<td>test:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>slti $t0, $t3, 10</td>
</tr>
<tr>
<td>44</td>
<td>0x15000000</td>
<td>bne $t0, $0, loop</td>
</tr>
<tr>
<td>48</td>
<td>0x3c010000</td>
<td>sw $t2, total</td>
</tr>
<tr>
<td>52</td>
<td>0xac2a0000</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>0x03e00008</td>
<td>j $ra</td>
</tr>
</tbody>
</table>
Resolving Addresses – 2nd Pass

“Old-style” 2-pass assembler approach

- In the second pass, the appropriate fields of those instructions that reference memory are filled in with the correct values if possible.

**Symbol table after Pass 1**

<table>
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<tr>
<th>Symbol</th>
<th>Segment</th>
<th>Location pointer offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>data</td>
<td>0</td>
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<tr>
<td>total</td>
<td>data</td>
<td>40</td>
</tr>
<tr>
<td>main</td>
<td>text</td>
<td>0</td>
</tr>
<tr>
<td>loop</td>
<td>text</td>
<td>20</td>
</tr>
<tr>
<td>test</td>
<td>text</td>
<td>40</td>
</tr>
</tbody>
</table>
Modern Way – 1-Pass Assemblers

Modern assemblers keep more information in their symbol table which allows them to resolve addresses in a single pass.

- Known addresses (backward references) are immediately resolved.
- Unknown addresses (forward references) are “back-filled” once they are resolved.

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>SEGMENT</th>
<th>Location pointer offset</th>
<th>Resolved?</th>
<th>Reference list</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>data</td>
<td>0</td>
<td>y</td>
<td>null</td>
</tr>
<tr>
<td>total</td>
<td>data</td>
<td>40</td>
<td>y</td>
<td>null</td>
</tr>
<tr>
<td>main</td>
<td>text</td>
<td>0</td>
<td>y</td>
<td>null</td>
</tr>
<tr>
<td>loop</td>
<td>text</td>
<td>16</td>
<td>y</td>
<td>null</td>
</tr>
<tr>
<td>test</td>
<td>text</td>
<td>?</td>
<td>n</td>
<td>16</td>
</tr>
</tbody>
</table>
The Role of a Linker

Some aspects of address resolution cannot be handled by the assembler alone.

1) References to data or routines in other object modules
2) The layout of all segments in memory
3) Support for REUSABLE code modules
4) Support for RELOCATABLE code modules

This final step of resolution is the job of a LINKER
Static and Dynamic Libraries

- LIBRARIES are commonly used routines stored as a concatenation of “Object files”. A global symbol table is maintained for the entire library with entry points for each routine.

- When routines in LIBRARIES are referenced by assembly modules, the routine’s entry points are resolved by the LINKER, and the appropriate code is added to the executable. This sort of linking is called STATIC linking.

- Many programs use common libraries. It is wasteful of both memory and disk space to include the same code in multiple executables. The modern alternative to STATIC linking is to allow the LOADER and THE PROGRAM ITSELF to resolve the addresses of libraries routines. This form of lining is called DYNAMIC linking (e.g., .dll).
Dynamically Linked Libraries

- C call to library function:
  ```c
  printf("sqr[%d] = %d\n", x, y);
  ```

- Assembly code
  ```
  addi  $a0,$0,1
  la    $a1,ctrlstring
  lw    $a2,x
  lw    $a3,y
  call  fprintf
  ```

- Maps to:
  ```
  addi  $a0,$0,1
  lui   $a1,ctrlstringHi
  ori   $a1,ctrlstringLo
  lui   $at,xhi
  lw    $a2,xlo($at)
  lw    $a3,ylo($at)
  lui   $at,fprintfHi
  ori   $at,fprintfLo
  jalr  $at
  ```

How does dynamic linking work?
Dynamically Linked Libraries

- **C call to library function:**
  ```
  printf("sqr[%d] = %d\n", x, y);
  ```

- **Assembly code**
  ```
  addi   $a0,$0,1
  la     $a1,ctrlstring
  lw     $a2,x
  lw     $a3,y
  call   fprintf
  ```

- **Maps to:**
  ```
  addi   $a0,$0,1
  lui    $a1,ctrlstringHi
  ori    $a1,ctrlstringLo
  lui    $at,xhi
  lw     $a2,xlo($at)
  lw     $a3,ylo($at)
  lui    $at,fprintfHi
  ori    $at,fprintfLo
  jalr   $at
  ```

**How does dynamic linking work?**

**Why are we loading the function’s address into a register first, and then calling it?**
Modern Languages

- Intermediate "object code language"

High-level, portable (architecture independent) program description

PORTABLE mnemonic program description with symbolic memory references

An application that EMULATES a virtual machine. Can be written for any Instruction Set Architecture. In the end, machine language instructions must be executed for each JVM bytecode

Java program

Compiler

JVM bytecodes

"Library Routines"

Interpreter
Modern Languages

- Intermediate “object code language”

High-level, portable (architecture independent) program description

PORTABLE mnemonic program description with symbolic memory references

While interpreting on the first pass it keeps a copy of the machine language instructions used. Future references access machine language code, avoiding further interpretation

Java program

Compiler

JVM bytecodes

JIT Compiler

“Library Routines”

“Memory”

Today’s JITs are nearly as fast as a native compiled code (ex. .NET).
Compiler Optimizations

Example “C” Code:

```c
int a[10];
int total;

int main( ) {
    int i;

    total = 0;
    for (i = 0; i < 10; i++) {
        a[i] = i;
        total = total + i;
    }
}
```
Unoptimized Assembly Output

With debug flags set:

.globl main
.text
main:
    addu $sp,$sp,-8  # allocates space for ra and i
    sw $0,total    # total = 0
    sw $0,0($sp)   # i = 0
    lw $8,0($sp)   # copy i to $t0
    b  L.3         # goto test
L.2:
    sll $24,$8,2   # make i a word offset
    sw $8,array($24)  # array[i] = i
    lw $24,total   # total = total + i
    addu $24,$24,$8
    sw $24,total
    addi $8,$8,1   # i = i + 1
L.3:
    sw $8,0($sp)   # update i in memory
    la $24,10      # loads const 10
    blt $8,$24,L.2 #} loops while i < 10
    addu $sp,$sp,8
    j $31
Register Allocation

- Assign local variables to registers

```
.globl main
.text
main:
    addu $sp,$sp,-4      #allocates space for ra
    sw $0,total         #total = 0
    move $8,$0           #i = 0
    b  L.3               #goto test
L.2:                        #for(...) {
    sll $24,$8,2         #  make i a word offset
    sw $8,array($24)     #  array[i] = i
    lw $24,total         #  total = total + i
    addu $24,$24,$8      #
    sw $24,total         #
    addi $8,$8,1         #  i = i + 1
L.3:                        #}
    la $24,10            #loads const 10
    blt $8,$24,L.2       #} loops while i < 10
    addu $sp,$sp,4       #
j $31                   #
```
Loop-Invariant Code Motion

- Assign globals to temp registers and move assignments outside of loop

```assembly
.globl main
.text
main:
    addu $sp,$sp,-4          #allocates space for ra
    sw $0,total             #total = 0
    move $9,$0               #temp for total
    move $8,$0               #i = 0
    b  L.3                   #goto test
L.2:
    sll $24,$8,2             # make i a word offset
    sw $8,array($24)        # array[i] = i
    addu $9,$9,$8
    sw $9,total
    addi $8,$8,1             # i = i + 1
L.3:
    la $24,10               # loads const 10
    blt $8,$24,L.2          #} loops while i < 10
    addu $sp,$sp,4
    j $31
```
Remove Unnecessary Tests

- Since “i” is initially set to “0”, we already know it is less than “10”, so why test it the first time through?

```assembly
.globl main
.text
main:
    addu $sp,$sp,-4        #allocates space for ra
    sw $0,total           #total = 0
    move $9,$0             #temp for total
    move $8,$0             #i = 0
L.2:                        #for(...) {
    sll $24,$8,2           #  make i a word offset
    sw $8,array($24)       #  array[i] = i
    addu $9,$9,$8
    addi $8,$8,1
    slti $24,$8,10
    bne $24,$0,L.2         #} loops while i < 10
    sw  $9,total
    addu $sp,$sp,4
    j $31
```
Remove Unnecessary Stores

- All we care about it the value of total after the loop, and simplify loop

```assembly
.globl main
.text
main:
    addu $sp,$sp,-4        #allocates space for ra and i
    sw $0,total            #total = 0
    move $9,$0             #temp for total
    move $8,$0             #i = 0
.L.2:
    sll $24,$8,2           #for(...) {
    sw $8,array($24)       #  array[i] = i
    addu $9,$9,$8
    addi $8,$8,1           #  i = i + 1
    slti $24,$8,10         #  loads const 10
    bne $24,$0,L.2         #} loops while i < 10
    sw $9,total
    addu $sp,$sp,4
    j $31
```
Unrolling Loop

- Two copies of the inner loop reduce the branching overhead

```
.globl main
.text
main:
    addu $sp,$sp,-4        #allocates space for ra and i
    sw $0,total           #total = 0
    move $9,$0             #temp for total
    move $8,$0             #i = 0
L.2:
    sll $24,$8,2           #for(...) {
    sw $8,array($24)       #  array[i] = i
    addu $9,$9,$8          #
    addi $8,$8,1           #  i = i + 1
    sll $24,$8,2           #
    sw $8,array($24)       #  array[i] = i
    addu $9,$9,$8          #
    addi $8,$8,1           #  i = i + 1
    slti $24,$8,10         #  loads const 10
    bne $24,$0,L.2         #} loops while i < 10
    sw  $9,total
    addu $sp,$sp,4
    j $31
```