CS378: Machine Organization and Assembly Language

Lecture 2 - Fall 2008

Review:
The MIPS (a) is a load/store architecture, (b) is a register-register machine, (c) has an ISA, (d) all of the above.
What does ISA stand for?
In a machine instruction the registers are called (a) operands, (b) noops, (c) opcodes.
How many bits are needed to name a MIPS register?
What is the C equivalent to: `sub $10, $11, $12`?

Memory review
- Memory sizes are specified much like register files; here is a $2^n \times n$ RAM.

<table>
<thead>
<tr>
<th>CS</th>
<th>WR</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Read selected address</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Write selected address</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>None</td>
</tr>
</tbody>
</table>

- A chip select input CS enables or “disables” the RAM.
- ADRES specifies the memory location to access.
- WR selects between reading from or writing to the memory.
  - To read from memory, WR should be set to 0. OUT will be the n-bit value stored at ADRES.
  - To write to memory, we set WR = 1. DATA is the n-bit value to store in memory.

MIPS memory
- MIPS memory is byte-addressable, which means that each memory address references an 8-bit quantity.
- The MIPS architecture can support up to 32 address lines.
  - This results in a $2^{32} \times 8$ RAM, which would be 4 GB of memory.
  - Not all actual MIPS machines will have this much!

Loading and storing bytes
- The MIPS instruction set includes dedicated load and store instructions for accessing memory.
- The main difference is that MIPS uses indexed addressing.
  - The address operand specifies a signed constant and a register.
  - These values are added to generate the effective address.
- The MIPS “load byte” instruction `lb` transfers one byte of data from main memory to a register.
  \[ lb \ g{lo}, 20(b{lo}) \]  # $t{lo} = Memory[$a{lo} + 20] 
- The “store byte” instruction `sb` transfers the lowest byte of data from a register into main memory.
  \[ sb \ g{lo}, 20(b{lo}) \]  # Memory[$a{lo} + 20] = $t{lo} 

Loading and storing words
- You can also load or store 32-bit quantities—a complete word instead of just a byte—with the `lw` and `sw` instructions.
  \[ lw \ g{lo}, 20(b{lo}) \]  # $t{lo} = Memory[$a{lo} + 20] 
  \[ sw \ g{lo}, 20(b{lo}) \]  # Memory[$a{lo} + 20] = $t{lo} 
- Most programming languages support several 32-bit data types.
  - Integers
    - Single-precision floating-point numbers
  - Memory addresses, or pointers
- Unless otherwise stated, we’ll assume words are the basic unit of data.
Computing with memory

- So, to compute with memory-based data, you must:
  1. Load the data from memory to the register file.
  2. Do the computation, leaving the result in a register.
  3. Store that value back to memory if needed.
- For example, let’s say that you wanted to do the same addition, but the values were in memory. How can we do the following using MIPS assembly language? (A’s address is in $s0, result’s address is in $s1)

  ```
  char A[4] = {1, 2, 3, 4};
  int result;
  ```

Memory alignment

- Keep in mind that memory is byte-addressable, so a 32-bit word actually occupies four contiguous locations (bytes) of main memory.

<table>
<thead>
<tr>
<th>Address</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-bit data</td>
<td>Word 1</td>
<td>Word 2</td>
<td>Word 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The MIPS architecture requires words to be aligned in memory; 32-bit words must start at an address that is divisible by 4.
  - 0, 4, 8, and 12 are valid word addresses.
  - 1, 2, 3, 5, 6, 7, 9, 10 and 11 are not valid word addresses.
- Unaligned memory accesses result in a **bus error**, which you may have unfortunately seen before.
- This restriction has relatively little effect on high-level languages and compilers, but it makes things easier and faster for the processor.

Control flow in high-level languages

- The instructions in a program usually execute one after another, but it’s often necessary to alter the normal control flow.
- Conditional statements execute only if some test expression is true.

```java
// Find the absolute value of a0
v0 = a0;
if (v0 < 0) {
  v0 = -v0;  // This might not be executed
}
```

```java
// Sum the elements of a five-element array a0
v0 = 0;
t0 = 0;
while (t0 < 5) {
  v0 = v0 + a0[t0];  // These statements will
t0++;  // be executed five times
}
```

Control-flow graphs

```java
// Find the absolute value of a0
v0 = a0;
if (v0 < 0) {
  v0 = -v0;
}
```

```java
// Sum the elements of
v0 = 0;
t0 = 0;
while (t0 < 5) {
  v0 = v0 + a0[t0];
t0++;
}
```
MIPS control instructions

- MIPS's control-flow instructions
  - `|` // for unconditional jumps
  - `bne` and `beq` // for conditional branches
  - `slt` and `sll` // set if less than (w/o and w an immediate)

- Now we'll talk about
  - MIPS's pseudo branches
  - `if`/`else`
  - `case`/`switch`

Implementing pseudo-branches

- Most pseudo-branches are implemented using `slt`. For example, a branch-if-less-than-instruction `slt $at, $s0, label` is translated into the following:
  ```
slt $at, $s0, $s1 // Set = 1 if $s0 < $s1
bne $at, $0, label // Branch if $at != 0
```

- This supports immediate branches, which are also pseudo-instructions.
  For example, `sll $at, 5, Label` is translated into two instructions:
  ```
sll $at, $a0, 5 // Set = 1 if $a0 < 5
bne $at, $0, label // Branch if $at != 0
```

- All of the pseudo-branches need a register to save the result of `slt`, even though it's not needed afterwards.
  - MIPS assemblers use register `$t1`, or `$at`, for temporary storage.
  - You should be careful in using `$at` in your own programs, as it may be overwritten by assembler-generated code.

Translating an if-then statement

- We can use branch instructions to translate if-then statements into MIPS assembly code.
  ```
v0 = a0;
if (v0 = 0) {
  move $v0, $a0
bge $v0, $0, Label
v1 = v0 + v0;
}
```

- Sometimes it's easier to invert the original condition.
  - In this case, we changed "continue if $v0 < 0" to "skip if $v0 > 0".
  - This saves a few instructions in the resulting assembly code.

What does this code do?

```python
label: sub $a0, $a0, 1
bne $a0, $zero, label
```

Loops

```python
Loop: j Loop  # goto Loop

for (i = 0; i < 4; i++) {
    // stuff
}
add $t0, $s0, $zero # i is initialized to 0, $t0 = 0
Loop: j Loop $t0, $t0, $zero  # stuff
add $s1, $t0, 1  # i++
add $t1, $t0, 4  # $t1 = 4i < 4
bne $t0, $t1, Loop  # goto Loop if i < 4
```

Let’s write a program to count how many bits are set in a 32-bit word.

```assembly
main:
    li  $a0, 0x1234  ## input = 0x1234
    li  $t0, 0      ## int count = 0;
    li  $t1, 0      ## for (int i = 0

main_loop:
    bge  $t1, 32, main_exit  ## exit loop if i >= 32
    andi $t2, $a0, 1        ## bit = input & 1
    beq  $t2, $0, main_skip  ## skip if bit == 0
    addi $t0, $t0, 1        ## count ++

main_skip:
    srl  $a0, $a0, 1        ## input = input >> 1
    add  $t1, $t1, 1        ## i ++
    j  main_loop

main_exit:
    jr   $ra
```

Control-flow Example

- Let’s write a program to count how many bits are set in a 32-bit word.

```assembly
int count = 0;
for (int i = 0; i < 32; i++) {
    if (input & 1) {
        count ++;
    } else if (input == 1) {
        count += 1;
    } else {
        input = input >> 1;
    }
}
```

Case/Switch Statement

- Many high-level languages support multi-way branches, e.g.

```assembly
switch (two_bits) {
    case 0: break;
    case 1: /* fall through */
    case 2: count ++; break;
    case 3: count += 2; break;
}
```

- We could just translate the code to if, then, and else:

```assembly
if ((two_bits == 1) || (two_bits == 2)) { count ++;
} else if (two_bits == 3) { count += 2;
}
```

- This isn’t very efficient if there are many, many cases.

Translating an if-then-else statement

- If there is an else clause, it is the target of the conditional branch
- And the then clause needs a jump over the else clause

```assembly
// increase the magnitude of v0 by one
if (v0 < 0) bge $v0, $0, E
v0 --; sub $v0, $v0, 1 j L
else
    v0 ++;
    add $v0, $v0, 1
    j   L
E:
    add $v0, $v0, 1
    v1 = v0; L: move $v1, $v0
```

Drawing the control-flow graph can help you out.

Case/Switch Statement

- Alternatively, we can:
  1. Create an array of jump targets
  2. Load the entry indexed by the variable two_bits
  3. Jump to that address using the jump register, or jr, instruction

- This is much easier to show than to tell.