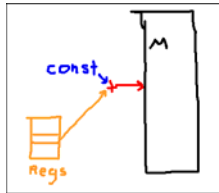


CS61C : Machine Structures

Lecture #7: MIPS Memory & Decisions



(no, I didn't draw this...)

2005-06-29

Andy Carle



Review

- In MIPS Assembly Language:
 - Registers replace C variables
 - One Instruction (simple operation) per line
 - Simpler is Better, Smaller is Faster

• New Instructions:

add, addi, sub

• New Registers:

C Variables: \$s0 - \$s7

Temporary Variables: \$t0 - \$t7

Zero: \$zero



Topic Outline

- Memory Operations
- Decisions
- More Instructions

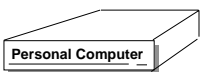


Assembly Operands: Memory

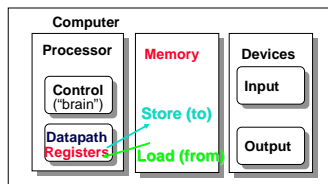
- C variables map onto registers; what about large data structures like arrays?
- 1 of 5 components of a computer: memory contains such data structures
- But MIPS arithmetic instructions only operate on registers, never directly on memory.
- **Data transfer instructions** transfer data between registers and memory:
 - Memory to register
 - Register to memory



Anatomy: 5 components of any Computer



Registers are in the datapath of the processor; if operands are in memory, we must transfer them to the processor to operate on them, and then transfer back to memory when done.



These are "data transfer" instructions...



Data Transfer: Memory to Reg (1/5)

- To specify a memory address to copy from, specify two things:
 - A register containing a pointer to memory
 - A numerical offset (in bytes)
- The desired memory address is the sum of these two values.
- Example: 8(\$t0)
 - specifies the memory address pointed to by the value in \$t0, plus 8 bytes



Data Transfer: Memory to Reg (2/5)

• Load Instruction Syntax:

`lw <reg1> <offset>(<reg2>)`

• where

- `lw`: op name to load a word from memory
- `reg1`: register that will receive value
- `offset`: numerical address offset **in bytes**
- `reg2`: register containing pointer to memory

Equivalent to:

`reg1 ← Memory [reg2 + offset]`



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Data Transfer: Memory to Reg (3/5)



Example: `lw $t0, 12($s0)`

This instruction will take the pointer in `$s0`, add 12 bytes to it, and then load the value from the memory pointed to by this calculated sum into register `$t0`

• Notes:

- `$s0` is called the **base register**
- 12 is called the **offset**
- offset is generally used in accessing elements of array or structure: base reg points to beginning of array or structure



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Data Transfer: Reg to Memory (4/5)

- Also want to store from register into memory
 - Store instruction syntax is identical to Load's

• MIPS Instruction Name:

`sw` (meaning Store Word, so 32 bits or one word are loaded at a time)



- Example: `sw $t0, 12($s0)`

This instruction will take the pointer in `$s0`, add 12 bytes to it, and then store the value from register `$t0` into that memory address

- Remember: “**Store INTO memory**”



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Data Transfer: Pointers v. Values (5/5)

- **Key Concept:** A register can hold any 32-bit value. That value can be a (signed) int, an unsigned int, a pointer (memory address), and so on
- If you write `lw $t2, 0($t0)` then `$t0` better contain a pointer
- Don't mix these up!



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Addressing: What's a Word? (1/5)

- A word is the basic unit of the computer.
 - Usually `sizeof(word) == sizeof(registers)`
 - Can be 32 bits, 64 bits, 8 bits, etc.
 - Not necessarily the smallest unit in the machine!



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Addressing: Byte vs. word (2/5)

- Every word in memory has an **address**, similar to an index in an array
- Early computers numbered words like C numbers elements of an array:
 - `Memory[0], Memory[1], Memory[2], ...`
Called the “address” of a word
- Computers needed to access 8-bit **bytes** as well as words (4 bytes/word)
- Today machines address memory as bytes, (i.e., “**Byte Addressed**”) hence 32-bit (4 byte) word addresses differ by 4
 - `Memory[0], Memory[4], Memory[8], ...`



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Addressing: The Offset Field (3/5)

- What offset in `lw` to select `A[8]` in C?
- $4 \times 8 = 32$ to select `A[8]`: byte v. word
- Compile by hand using registers:
`g = h + A[8];`
 - `g: $s1, h: $s2, $s3: base address of A`
- 1st transfer from memory to register:
`lw $t0, 32($s3) # $t0 gets A[8]`
 - Add `32` to `$s3` to select `A[8]`, put into `$t0`
- Next add it to `h` and place in `g`
`add $s1, $s2, $t0 # $s1 = h + A[8]`



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Addressing: Pitfalls (4/5)

- Pitfall: Forgetting that sequential word addresses in machines with byte addressing do not differ by 1.
 - Many an assembly language programmer has toiled over errors made by assuming that the address of the next word can be found by incrementing the address in a register by 1 instead of by the word size in bytes.
 - So remember that for both `lw` and `sw`, the sum of the base address and the offset must be a multiple of 4 (to be word aligned)

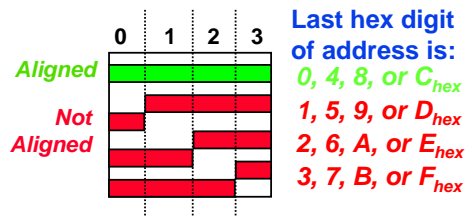


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Addressing: Memory Alignment (5/5)

- MIPS requires that all words start at byte addresses that are multiples of 4 bytes



- Called **Alignment**: objects must fall on address that is multiple of their size.



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Role of Registers vs. Memory

- What if more variables than registers?
 - Compiler tries to keep most frequently used variable in registers
 - Less common in memory: **spilling**
- Why not keep all variables in memory?
 - registers are faster than memory
- Why not have arithmetic insts to operate on memory addresses?
 - E.g. “`addmem 0($s1) 0($s2) 0($s3)`”
 - Some ISAs do things like this (x86)
 - MIPS – Keep the common case fast.



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Peer Instruction Round 1

We want to translate `*x = *y` into MIPS
(`x, y` are pointers stored in: `$s0 $s1`)



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Topic Outline

- Memory Operations
- Decisions
- More Instructions



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So Far...

- All instructions so far only manipulate data...we've built a **calculator**.
- In order to build a **computer**, we need ability to make decisions...
- C (and MIPS) provide **labels** to support "goto" jumps to places in code.
 - C: Horrible style; MIPS: Necessary!
 - Speed over ease-of-use (again!)



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Decisions: C if Statements (1/3)

- 2 kinds of if statements in C
 - `if (condition) clause`
 - `if (condition) clause1 else clause2`
- Rearrange 2nd if into following:

```
if (condition) goto L1;
    clause2;
goto L2;
L1: clause1;
L2:
```
- Not as elegant as if-else, but same meaning



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Decisions: MIPS Instructions (2/3)

- Decision instruction in MIPS:
 - `beq register1, register2, L1`
 - `beq` is "Branch if (registers are) equal"
Same meaning as (using C):
`if (register1==register2) goto L1`
- Complementary MIPS decision instruction
 - `bne register1, register2, L1`
 - `bne` is "Branch if (registers are) not equal"
Same meaning as (using C):
`if (register1!=register2) goto L1`
- Called **conditional branches**



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Decisions: MIPS Goto Instruction (3/3)

- In addition to conditional branches, MIPS has an **unconditional branch**:

```
j label
```
- Called a Jump Instruction: jump (or branch) directly to the given label without needing to satisfy any condition
- Same meaning as (using C):
`goto label`
- Technically, it's the same* as:

```
beq $0, $0, label
```

since it always satisfies the condition.



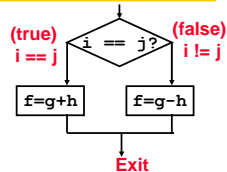
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Example: Compiling C if into MIPS (1/2)

- Compile by hand

```
if (i == j) f=g+h;
else f=g-h;
```



- Use this mapping:

```
f: $s0
g: $s1
h: $s2
i: $s3
j: $s4
```



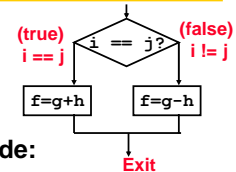
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Example: Compiling C if into MIPS (2/2)

- Compile by hand

```
if (i == j) f=g+h;
else f=g-h;
```



- Final compiled MIPS code:

```
beq $s3, $s4, True # branch i==j
sub $s0, $s1, $s2 # f=g-h(false)
j Fin # goto Fin
True: add $s0, $s1, $s2 # f=g+h(true)
Fin:
```

- Note: Compiler automatically creates labels to handle decisions (branches).
Generally not found in HLL code.



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Topic Outline

- Memory Operations
- Decisions
- More Instructions
 - Memory
 - Unsigned
 - Logical
 - Inequalities



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More Memory Ops: Byte Ops 1/2

- In addition to word data transfers (`lw`, `sw`), MIPS has byte data transfers:
 - load byte: `lb`
 - store byte: `sb`
 - same format as `lw`, `sw`
- What's the alignment for byte transfers?



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More Memory Ops: Byte Ops 2/2

- What do we do with other 24 bits in the 32 bit register?

- `lb`: sign extends to fill upper 24 bits



- Normally don't want to sign extend chars
- MIPS instruction that doesn't sign extend when loading bytes:

load byte unsigned: `lbu`



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Overflow in Arithmetic (1/2)

- Reminder: Overflow occurs when there is a mistake in arithmetic due to the limited precision in computers.

- Example (4-bit unsigned numbers):

+15	1111
+3	0011
+18	10010

- But we don't have room for 5-bit solution, so the solution would be 0010, which is +2, and wrong.



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Overflow in Arithmetic (2/2)

- Some languages detect overflow (Ada), some don't (C)
- MIPS solution is 2 kinds of arithmetic instructions to recognize 2 choices:
 - add (`add`), add immediate (`addi`) and subtract (`sub`) **cause overflow to be detected**
 - add unsigned (`addu`), add immediate unsigned (`addiu`) and subtract unsigned (`subu`) do **not** cause overflow detection
- Compiler selects appropriate arithmetic
 - MIPS C compilers produce `addu`, `addiu`, `subu`



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Two Logic Instructions (1/1)

- More Arithmetic Instructions

- Shift Left: `sll $s1, $s2, 2` #`s1=s2<<2`

- Store in `$s1` the value from `$s2` shifted 2 bits to the left, **inserting 0's** on right; `<<` in C

Before: `0000 0002hex`
`0000 0000 0000 0000 0000 0000 0010two`

After: `0000 0008hex`
`0000 0000 0000 0000 0000 0000 1000two`

- What arithmetic effect does shift left have?

- Shift Right: `srl` is opposite shift; `>>`



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Inequalities in MIPS (1/3)

- Until now, we've only tested equalities (== and != in C). General programs need to test < and > as well.

- Create a MIPS Inequality Instruction:

- "Set on Less Than"

- Syntax: `slt reg1, reg2, reg3`

- Meaning: `reg1 = (reg2 < reg3);`

```
if (reg2 < reg3)
    reg1 = 1;
else reg1 = 0;
```

- "set" means "set to 1",
"reset" means "set to 0".



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Inequalities in MIPS (2/3)

- How do we use this?

```
if (g < h) goto Less; #g:$s0, h:$s1
```

```
slt $t0, $s0, $s1 # $t0 = 1 if g<h
bne $t0, $0, Less # goto Less
                  # if $t0!=0
                  # (if (g<h)) Less:
```

- Branch if `$t0 != 0` → (g < h)

- Register \$0 always contains the value 0, so `bne` and `beq` often use it for comparison after an `slt` instruction.



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Inequalities in MIPS (3/3)

- Now, we can implement <, but how do we implement >, ≤ and ≥?

- We could add 3 more instructions, but:

- MIPS goal: **Simpler is Better**

- Can we implement ≤ in one or more instructions using just `slt` and the branches?

- What about >?

- What about ≥?



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Immediates in Inequalities (1/1)

- There is also an immediate version of `slt` to test against constants: `slti`

- Helpful in `for` loops

```
C    if (g >= 1) goto Loop
```

```
M    Loop: . . .
```

```
I    slti $t0, $s0, 1    # $t0 = 1 if
P    # $s0 < 1 (g < 1)
S    beq  $t0, $0, Loop # goto Loop
                  # if $t0 == 0
                  # (if (g >= 1))
```



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What about unsigned numbers?

- Also **unsigned** inequality instructions:

```
sltu, sltiu
```

...which set result to 1 or 0 depending on unsigned comparisons

- What is value of `$t0`, `$t1`?

(`$s0 = FFFF FFFAhex`, `$s1 = 0000 FFFAhex`)

```
slt $t0, $s0, $s1
```

```
sltu $t1, $s0, $s1
```



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MIPS Signed vs. Unsigned – diff meanings!

- MIPS Signed v. Unsigned is an "overloaded" term

- Do/Don't sign extend (lb, lbu)

- Don't overflow (but still 2s-comp) (addu, addiu, subu, multu, divu)

- Do signed/unsigned compare (slt, slti/sltu, sltiu)



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Loops in C/Assembly (1/3)

- Simple loop in C; A[] is an array of ints

```
do {
    g = g + A[i];
    i = i + j;
} while (i != h);
```

- Rewrite this as:

```
Loop: g = g + A[i];
      i = i + j;
      if (i != h) goto Loop;
```

- Use this mapping:

g, h, i, j, base of A
\$s1, \$s2, \$s3, \$s4, \$s5



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Loops in C/Assembly (2/3)

- Final compiled MIPS code:

```
Loop: sll $t1,$s3,2 # $t1= 4*I
      add $t1,$t1,$s5 # $t1=addr A
      lw $t1,0($t1) # $t1=A[i]
      add $s1,$s1,$t1 # g=g+A[i]
      add $s3,$s3,$s4 # i=i+j
      bne $s3,$s2,Loop # goto Loop
                        # if i!=h
```

- Original code:

```
Loop: g = g + A[i];
      i = i + j;
      if (i != h) goto Loop;
```



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Loops in C/Assembly (3/3)

- There are three types of loops in C:

- while
- do... while
- for

- Each can be rewritten as either of the other two, so the method used in the previous example can be applied to while and for loops as well.

- **Key Concept:** Though there are multiple ways of writing a loop in MIPS, the key to decision making is **conditional branch**



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Peer Instruction

```
Loop: addi $s0,$s0,-1
      slti $t0,$s1,2
      beq $t0,$0,Loop
      slt $t0,$s1,$s0
      bne $t0,$0,Loop
```

(\$s0=i, \$s1=j)

What C code properly fills in the blank in loop below?

```
do {i--;} while(____);
```



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Summary (1/2)

- Memory is **byte**-addressable, but **lw** and **sw** access one **word** at a time.
- A pointer (used by **lw** and **sw**) is just a memory address, so we can add to it or subtract from it (using offset).
- A Decision allows us to decide what to execute at run-time rather than compile-time.
- C Decisions are made using **conditional statements** within **if**, **while**, **do while**, **for**.
- MIPS Decision making instructions are the **conditional branches**: **beq** and **bne**.
- New Instructions:
lw, sw, beq, bne, j



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Summary (2/2)

- In order to help the **conditional branches** make decisions concerning inequalities, we introduce a single instruction: "Set on Less Than" called **slt**, **slti**, **sltu**, **sltiu**
- One can load and store (signed and unsigned) **bytes** as well as words
- Unsigned add/sub **don't detect overflow**
- New MIPS Instructions:
sll, srl
slt, slti, sltu, sltiu
addu, addiu, subu



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