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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

Data Transfer: Memory to Reg (1/4)
- To transfer a word of data, we need to specify two things:
  - Register: specify this by # [s0 - $s31] or symbolic name [$s0, ... $t0, ...]
  - Memory address: more difficult
    - Think of memory as a single one-dimensional array, so we can address it simply by supplying a pointer to a memory address.
    - Other times, we want to be able to offset from this pointer.
  - Remember: “Load FROM memory”

Data Transfer: Memory to Reg (2/4)
- 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 (3/4)

- **Load Instruction Syntax:**
  1. `lw 2,3($s0)`
  - where
    1) operation name
    2) register that will receive value
    3) numerical offset in bytes
    4) register containing pointer to memory

- **MIPS Instruction Name:**
  - `lw` (meaning Load Word, so 32 bits or one word are loaded at a time)

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 (note offset must be a constant known at assembly time)

Data Transfer: Memory to Reg (4/4)

Data flow

Example:
```
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```
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Data Transfer: Reg to Memory

- 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 is stored 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”

Pointers v. Values

- Key Concept: A register can hold any 32-bit value. That value can be a (signed) int, an unsigned int, a pointer (memory addr), and so on
  - E.g., if you write: add $t2,$t1,$t0
  - then `$t0` and `$t1` better contain values that can be added
  - E.g., if you write: `lw $t2,0($t0)`
  - then `$t0` better contain a pointer
  - Don’t mix these up!

Addressing: Byte vs. Word

- 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]`

Compilation with Memory

- Compile by hand using registers:
  - `g = h + A[5];`
  - `g; $s1, h; $s2, $s3: base address of A`
- 1st transfer from memory to register:
  - `lw$t0,20($s3) # $t0 gets A[5]`
  - `Add 20 to $s3 to select A[5], put into $t0`
- Next add it to `h` and place in `g`
  - `add $s1, $s2, $t0 # $s1 = h + A[5]`
Notes about Memory

- 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.
  - Also, 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).

More Notes about Memory: Alignment

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

<table>
<thead>
<tr>
<th>Last hex digit of address is:</th>
<th>0, 4, 8, or C&lt;sub&gt;hex&lt;/sub&gt;</th>
<th>1, 5, 9, or D&lt;sub&gt;hex&lt;/sub&gt;</th>
<th>2, 6, A, or E&lt;sub&gt;hex&lt;/sub&gt;</th>
<th>3, 7, B, or F&lt;sub&gt;hex&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Aligned</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Role of Registers vs. Memory

- What if more variables than registers?
  - Compiler tries to keep most frequently used variable in registers
  - Less common variables in memory: spilling

- Why not keep all variables in memory?
  - Smaller is faster: registers are faster than memory
  - Registers more versatile:
    - MIPS arithmetic instructions can read 2, operate on them, and write 1 per instruction
    - MIPS data transfer only read or write 1 operand per instruction, and no operation

Administivia

- Project 1 due on Saturday
- Other things to announce?

So Far...

- All instructions so far only manipulate data…we’ve built a calculator of sorts.
- 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!

- Heads up: pull out some papers and pens, you’ll do an in-class exercise!

C Decisions: if Statements

- 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
**MIPS Decision Instructions**

- **Decision instruction in MIPS:**
  
  \[
  \text{beq register1, register2, L1}
  \]

  Same meaning as (using C):
  
  \[
  \text{if (register1==register2) goto L1}
  \]

- **Complementary MIPS decision instruction**
  
  \[
  \text{bne register1, register2, L1}
  \]

  Same meaning as using C: goto label

- **Called conditional branches**

**MIPS Goto Instruction**

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

  \[
  \text{j label}
  \]

- 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 effect as:

  \[
  \text{beq } 0, 0, \text{label}
  \]

  since it always satisfies the condition.

---

**Compiling C if into MIPS (1/2)**

- **Compile by hand**

  \[
  \text{if (i == j) } f=g+h; \\
  \text{else } f=g-h;
  \]

- **Use this mapping:**

  \[
  \begin{align*}
  f &: s0 \\
  g &: s1 \\
  h &: s2 \\
  i &: s3 \\
  j &: s4
  \end{align*}
  \]

**Compiling C if into MIPS (2/2)**

- **Compile by hand**

  \[
  \text{if (i == j) } f=g+h; \\
  \text{else } f=g-h;
  \]

- **Final compiled MIPS code:**

  \[
  \begin{align*}
  \text{beq } s3, s4, \text{True} & \quad \# \text{branch } i=j \\
  \text{sub } s0, s1, s2 & \quad \# f=g-h (false) \\
  j & \quad \# \text{goto } \text{Fin} \\
  \text{Exit} & \\
  \text{True: add } s0, s1, s2 & \quad \# f=g-h (true) \\
  \text{Fin:}
  \end{align*}
  \]

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

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**Peer Instruction**

We want to translate \( *x = *y \) into MIPS

(\( x, y \) pstr stored in: \( s0, s1 \))

\[
\begin{align*}
1: & \text{add } s0, s1, \text{zero} \\
2: & \text{add } s1, s0, \text{zero} \\
3: & \text{lw } $s0, 0($s1) \\
4: & \text{lw } $s1, 0($s0) \\
5: & \text{lw } $t0, 0($s1) \\
6: & \text{sw } $s0, 0($t0) \\
7: & \text{lw } $s0, 0($t0) \\
8: & \text{sw } $s1, 0($t0)
\end{align*}
\]

- a) 1 or 2
- b) 3 or 4
- c) 5-6
- d) 6-7
- e) 7-8

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**“And in Conclusion...”**

- Memory is byte-addressable, but \( \text{lw} \) and \( \text{sw} \) access one word at a time.

- A pointer (used by \( \text{lw} \) and \( \text{sw} \)) is just a memory address, 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:

  \[
  \\text{lw, sw, beq, bne, j}
  \]