Hate EMACS? Love EMACS?

Richard M. Stallman, a famous proponent of open-source software, the founder of the GNU Project, and the author of `emacs` and `gcc`, will be giving a speech. We're working on securing some type of food for the meeting, but we have secured a raffle prize valued at $100. The raffle will be open to all those who attend, so be sure to come and bring your friends!

Brought to you by CalLUG (UC Berkeley GNU/Linux User Group).
Tuesday, September 20, 6-8 PM in 100 GPB.

Our website with more information can be found at http://linux.berkeley.edu/

CS61C : Machine Structures

Lecture #6 – Intro MIPS; Load & Store

2005-09-19

There is one handout today at the front and back of the room!

Lecturer PSOE, new dad Dan Garcia

www.cs.berkeley.edu/~ddgarcia

Stolen laptop found! ⇒

Back in March, a laptop with the sensitive info of 98,000 students was stolen from Sproul. It was sold to a man in SF who sold it on Ebay, and was recovered in SC.

idalert.berkeley.edu/update914.html

Review

- Several techniques for managing heap via malloc and free: best-, first-, next-fit
  - 2 types of memory fragmentation: internal & external; all suffer from some kind of frag.
  - K&R, Slab allocator, Buddy system (adaptive)
- Automatic memory management relieves programmer from managing memory.
  - All require help from language and compiler
  - Reference Count: not for circular structures
  - Mark and Sweep: complicated and slow, works
  - Copying: Divides memory to copy good stuff
- In MIPS Assembly Language:
  - One Instruction (simple operation) per line
  - Simpler is better, smaller is faster

Assembly Variables: Registers (1/4)

- **Unlike HLL like C or Java, assembly cannot use variables**
  - **Why not? Keep Hardware Simple**
- **Assembly Operands are registers**
  - **limited number of special locations built directly into the hardware**
  - **operations can only be performed on these!**
- **Benefit: Since registers are directly in hardware, they are very fast (faster than 1 billionth of a second)**

Assembly Variables: Registers (2/4)

- **Drawback: Since registers are in hardware, there are a predetermined number of them**
  - **Solution: MIPS code must be very carefully put together to efficiently use registers**
- **32 registers in MIPS**
  - **Why 32? Smaller is faster**
- **Each MIPS register is 32 bits wide**
  - **Groups of 32 bits called a word in MIPS**

Assembly Variables: Registers (3/4)

- Registers are numbered from 0 to 31
- Each register can be referred to by number or name
- Number references:

  `$0, $1, $2, … $30, $31`

Assembly Variables: Registers (4/4)

- By convention, each register also has a name to make it easier to code
- For now:

  `$16 - $23` ➔ `$s0 - $s7`

  (correspond to C variables)

  `$8 - $15` ➔ `$t0 - $t7`

  (correspond to temporary variables)

  Later will explain other 16 register names
- In general, use names to make your code more readable

C, Java variables vs. registers

- In C (and most High Level Languages) variables declared first and given a type
  - Example:
    ```
    int fahr, celsius;
    char a, b, c, d, e;
    ```
- Each variable can ONLY represent a value of the type it was declared as (cannot mix and match `int` and `char` variables).
- In Assembly Language, the registers have no type; operation determines how register contents are treated

Comments in Assembly

- Another way to make your code more readable: comments!
- Hash (#) is used for MIPS comments
  - anything from hash mark to end of line is a comment and will be ignored
- Note: Different from C.
  - C comments have format `/* comment */` so they can span many lines

Assembly Instructions

- In assembly language, each statement (called an Instruction), executes exactly one of a short list of simple commands
- Unlike in C (and most other High Level Languages), each line of assembly code contains at most 1 instruction
- Instructions are related to operations (=, +, -, *, /) in C or Java
- Ok, enough already…gimme my MIPS!

MIPS Addition and Subtraction (1/4)

- Syntax of Instructions:

  1 2,3,4

  where:

  1) operation by name

  2) operand getting result ("destination")

  3) 1st operand for operation ("source1")

  4) 2nd operand for operation ("source2")

- Syntax is rigid:
  - 1 operator, 3 operands
  - Why? Keep Hardware simple via regularity

Addition and Subtraction of Integers (2/4)

- **Addition in Assembly**
  - Example: `add $s0,$s1,$s2` (in MIPS)

    Equivalent to: `a = b + c` (in C)

  where MIPS registers `$s0,$s1,$s2` are associated with C variables `a, b, c`

- **Subtraction in Assembly**
  - Example: `sub $s3,$s4,$s5` (in MIPS)

    Equivalent to: `d = e - f` (in C)

  where MIPS registers `$s3,$s4,$s5` are associated with C variables `d, e, f`

Addition and Subtraction of Integers (3/4)

- **How do the following C statement?**

```
a = b + c + d - e;
```

- **Break into multiple instructions**

```
add $t0, $s1, $s2 # temp = b + c
add $t0, $t0, $s3 # temp = temp + d
sub $s0, $t0, $s4 # a = temp - e
```

- **Notice: A single line of C may break up into several lines of MIPS.**
- **Notice: Everything after the hash mark on each line is ignored (comments)**

Addition and Subtraction of Integers (4/4)

- How do we do this?

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

- Use intermediate temporary register

```
add $t0,$s1,$s2     # temp = g + h
add $t1,$s3,$s4     # temp = i + j
sub $s0,$t0,$t1     # f=(g+h)-(i+j)
```

Register Zero

- One particular immediate, the number zero (0), appears very often in code.
- So we define register zero (`$0` or `$zero`) to always have the value 0; eg

  `add $s0,$s1,$zero` (in MIPS)

  `f = g` (in C)

  where MIPS registers `$s0,$s1` are associated with C variables `f, g`

- defined in hardware, so an instruction

  `add $zero,$zero,$s0`

  will not do anything!

Immediates

- Immediates are numerical constants.
- They appear often in code, so there are special instructions for them.
- Add Immediate:

  `addi $s0,$s1,10` (in MIPS)

  `f = g + 10` (in C)

  where MIPS registers `$s0,$s1` are associated with C variables `f, g`
- Syntax similar to `add` instruction, except that last argument is a number instead of a register.

Immediates

- There is no Subtract Immediate in MIPS: Why?
- Limit types of operations that can be done to absolute minimum
  - if an operation can be decomposed into a simpler operation, don't include it
  - `addi ..., -X` = `subi ..., X` => so no `subi`
- `addi $s0,$s1,-10` (in MIPS)

  `f = g - 10` (in C)

  where MIPS registers `$s0,$s1` are associated with C variables `f, g`

Peer Instruction

A. Types are associated with declaration in C (normally), but are associated with instruction (operator) in MIPS.

B. Since there are only 8 local (`$s`) and 8 temp (`$t`) variables, we can't write MIPS for C exprs that contain > 16 vars.

C. If `p` (stored in `$s0`) were a pointer to an array of `int`s, then `p++;` would be `addi $s0 $s0 1`

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

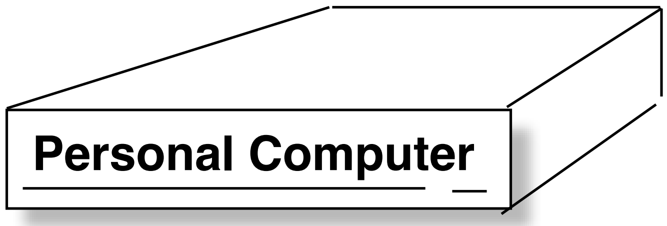
Administrivia

- Project 1 dealine extended until Monday!
  - The Autograder is up!
- `gcc -o foo foo.c`
  - We shouldn't see any `a.out` files anymore now that you've learned this!
- You should be able to finish labs within the allotted time.
  - If you can't, get checked off for what you have, finish @ home, check off next week
  - If this becomes a pattern, think about working on labs @ home
- HW2 frozen! (1 week regrades start now)

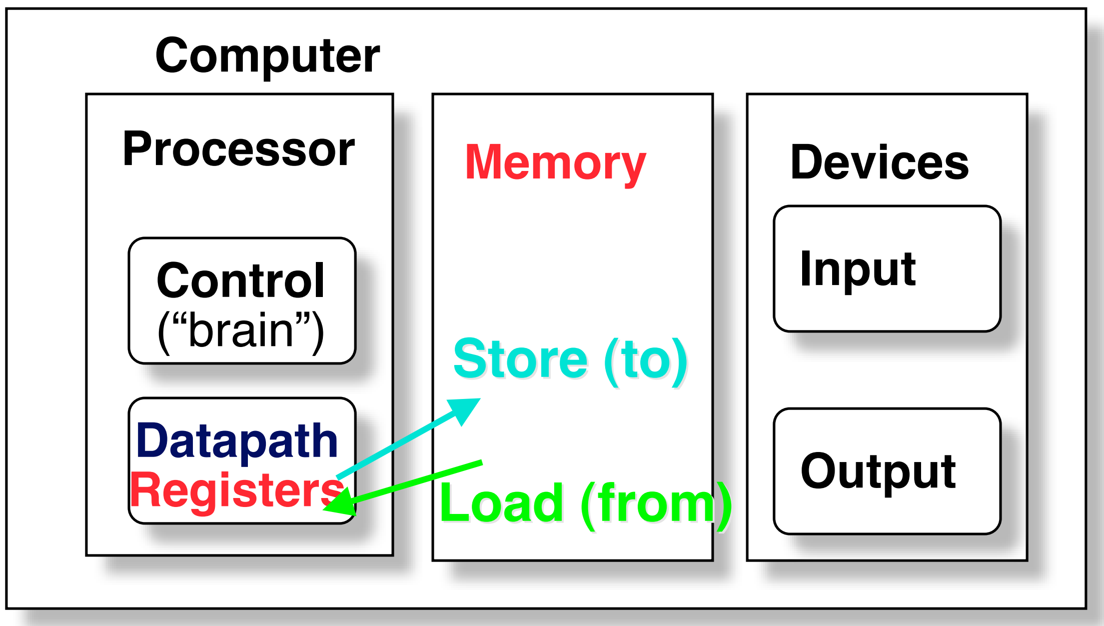
Assembly Operands: Memory

- 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 (1/4)

- To transfer a word of data, we need to specify two things:
  - Register: specify this by # ($0 - $31) or symbolic name ($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   2,3(4)

  - 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)

Data Transfer: Memory to Reg (4/4)

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

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 are loaded at a time)

Data flow

- 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 address), and so on**
- **If you write `add $t2,$t1,$t0` then `$t0` and `$t1` better contain values**
- **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

- What offset in `lw` to select `A[5]` in C?
- 4x5=20 to select `A[5]`: byte v. word
- 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`

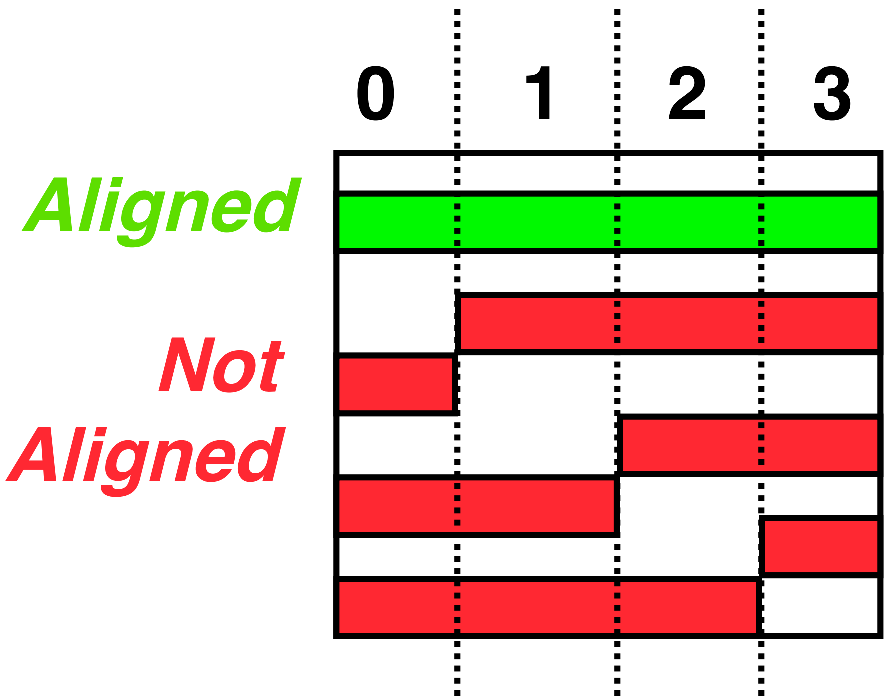
```
add $s1,$s2,$t0   # $s1 = h+A[5]
```

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.**
  - **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)**

More Notes about Memory: Alignment

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



Last hex digit of address is:

0, 4, 8, or C_{hex}

1, 5, 9, or D_{hex}

2, 6, A, or E_{hex}

3, 7, B, or F_{hex}

- Called Alignment: objects must 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 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**

Loading, Storing bytes 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`

Loading, Storing bytes 2/2

- What do with other 24 bits in the 32 bit register?
    - `lb`: sign extends to fill upper 24 bits

`xxxx xxxx xxxx xxxx xxxx xxxx xzzz zzzz`

...is copied to "sign-extend"

byte loaded

This bit

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

load byte unsigned: `lbu`

"And in conclusion…"

- In MIPS Assembly Language:
  - Registers replace C variables
  - One Instruction (simple operation) per line
  - Simpler is better, smaller is faster
- Memory is byte-addressable, but `lw` and `sw` access one word at a time.
  - One can store & load (signed and unsigned) bytes too
- A pointer (used by `lw` & `sw`) is just a mem address, so we can add to it or subtract from it (via offset).
- New Instructions:

  `add, addi, sub, lw, sw, lb, sb, lbu`
- New Registers:

  C Variables: `$s0` - `$s7`

  Temporary Variables: `$t0` - `$t9`

  Zero: `$zero`