Systems Architecture I

<u>Topics</u>

MIPS Instruction Set*
Branching and Procedures in MIPS**

*This lecture was derived from material in the text (sec. 3.1-3.5).

**This lecture was derived from material in the text (sec. 3.5-3.6).

Notes Courtesy of Jeremy R. Johnson

Systems Architecture I

Topic 1: MIPS Instruction Set

Introduction

- **Objective: To introduce the MIPS instruction set and to show how MIPS instructions are represented in the computer.**
- **The stored-program concept:**
  - **Instructions are represented as numbers.**
  - **Programs can be stored in memory to be read or written just like data.**

Instructions

- **Language of the machine**
- **More primitive than higher level languages (e.g. C, C++, Java)**
  - **e.g. no sophisticated control flow , primitive data structures**
- **MIPS (SGI, NEC, Nintendo) developed in the early 80's (RISC)**
  - **Regular (32 bit instructions, small number of different formats)**
  - **Relatively small number of instructions**
  - **Register (all instructions operate on registers)**
  - **Load/Store (memory accessed only with load/store instructions, with few addressing modes)**
- ***Design goals: maximize performance and minimize cost, reduce design time***

MIPS Arithmetic

- All instructions have 3 operands
- Operand order is fixed (destination first)

- Example

C code: `A = B + C`

MIPS code: `add $s0, $s1, $s2`

(associated with variables by compiler)

Temporary Variables

- Regularity of instruction format requires that expressions get mapped to a sequence of binary operations with temporary results being stored in temporary variables.

- Example

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

Assume: f,g,h,i,j in $s0 through $s4 respectively

MIPS code:
```
add $t0, $s1, $s2 # $t0 = g+h
add $t1, $s3, $s4 # $t1 = i+j
sub $s0, $t0, $t1 # f = $t0 - $t1
```

Registers vs. Memory

- operands for arithmetic instructions must be registers,
  — only 32 registers provided
- Compiler associates variables with registers
- When too many registers are used to simultaneously fit in 32 registers, the compiler must load and store temporary results to/from memory. The compiler tries to put the most frequently occurring variables in registers. Extra temporary variables must be “spilled” to memory.

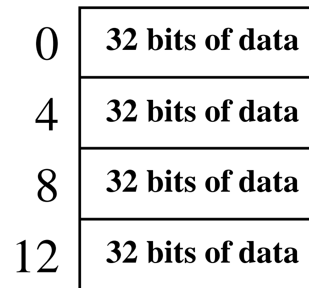
Memory Organization

- **Viewed as a large, single-dimension array, where a memory address is an index into the array**
- **In MIPS memory is "Byte addressing", which means that the index points to a byte of memory.**

0	**8 bits of data**
1	**8 bits of data**
2	**8 bits of data**
3	**8 bits of data**
4	**8 bits of data**
5	**8 bits of data**
6	**8 bits of data**
...	

Memory Organization

- Most data items are grouped into words (a MIPS word is 4 bytes)



Registers hold 32 bits of data

- 2^{32} bytes with byte addresses from 0 to 2^{32}-1
- 2^{30} words with byte addresses 0, 4, 8, ... 2^{32}-4
- Words are aligned (alignment restriction)
- bytes can be accessed from left to right (big endian) or right to left (little endian)

Load and Store

- All arithmetic instructions operate on registers
- Memory is accessed through load and store instructions

- Example:

C code: `A[12] = h + A[8];`

Assume that $s3 contains the base address of A

MIPS code:

```
lw $t0, 32($s3)
add $t0, $t0, $s2
sw $t0, 48($s3)
```

(Store word has destination last.)

Representing Instructions in the Computer

- **MIPS instructions are 32 bits**
  - opcode, operands

Example:

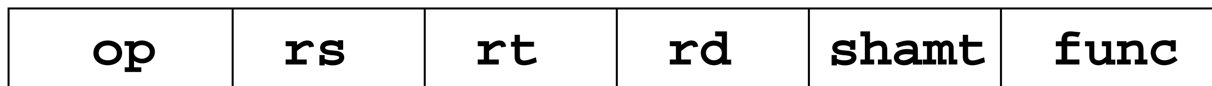
add $t0, $s0, $s1

$t0 = $8, $s0 = $16, $s1 = $17

000000	10000	10001	01000	00000	100000
op	rs	rt	rd	shamt	func

Representing Instructions in the Computer

- Instruction formats:
- R format (register format - add, sub, …)

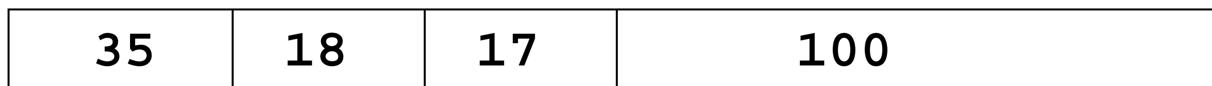


op	rs	rt	rd	shamt	func

- I format (immediate format - lw, sw, …)

op	rs	rt	address

- Example: lw $s1, 100($s2)

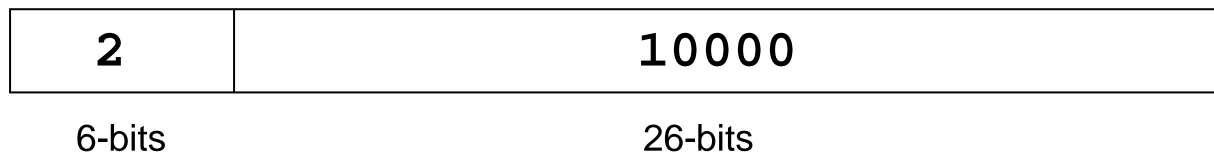


35	18	17	100

Addressing in Branches and Jumps

- J format format (jump format – j, jal)

- Example: j 10000



Design Principles

- Simplicity favors regularity
  - All instructions 32 bits
  - All instructions have 3 operands
- Smaller is faster
  - Only 32 registers
- Good design demands good compromises
  - All instructions are the same length
  - Limited number of instruction formats: R, I, J
- Make common cases fast
  - 16-bit immediate constant
  - Only two branch instructions

Systems Architecture I

Topic 2: Branching and Procedures in MIPS

Introduction

- **Objective: To illustrate how programming constructs such as conditionals, loops and procedures can be translated into MIPS instructions.**

Control Flow

- if statements, if-else statements
- Compiling an if-else statement

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

Assume f through j in $s0 through $s4

```
        bne $s3, $s4, Else
        add $s0, $s1, $s2
        j Exit
Else:  sub $s0, $s1, $s2
Exit:
```

Compiling a Less Than Test

- **Use slt instruction (only branch on equal or not equal)**

```
if (a < b)
    …

slt $t0, $s0, $s1          # $t0 gets 1 if $s0 < $s1 0 otherwise
bne $t0, $zero, Less  # goto Less if $t0 ≠ 0
```

- **MIPS does not include a blt since it is "too complicated" and would increase the complexity of its implementation.**

Loops

- **Compiling a while loop (Assume i, j, k correspond to $s3, $s4, and $s5 and that the base address of *save* is in $s6)**

```
while (save[i] == k)
   i = i + j;

Loop:   add $t1, $s3, $s3   # $t1 = 2 × i
        add $t1, $t1, $t1   # $t1 = 4 × i
        add $t1, $t1, $s6   # address of save[i]
        lw $t0, 0($t1)      # save[i]
        bne $t0, $s5, Exit  # goto Exit if save[i] ≠ k
        add $s3, $s3, $s4   # i = i + j
        j Loop
Exit:
```

Switch Statement

- Use a "jump table"

```
switch (k) {
    case 0:   f = i + j;  break;
    case 1:   f = g + h;  break;
    case 2:   f = g - h;  break;
    case 3:   f = i - j;  break;
}
```

- Variables f - k in $s0 - $s5, $t2 contains 4, $t4 contains address of jump table - JT

```
    slt $t3, $s5, $zero # k < 0?
    bne $t3,$zero, Exit
    slt $t3, $s5, $t2      # k < 4?
    beq $t3, $zero, Exit
    add $t1, $s5, $s5
    add $t1, $t1, $t1
    add $t1, $t1, $t4 # addr JT[k]
    lw $t0, 0($t1)       # JT[k]
    jr $t0
L0: add $s0, $s3, $s4
    j Exit
L1: add $s0, $s1, $s2
    j Exit
    ...
```

Procedures

- In the execution of a procedure, the program must follow these steps:
  - Place parameters in a place where the procedure can access them
  - Transfer control to the procedure
  - Acquire the storage resources needed for the procedure
  - Perform the desired task
  - Place the result in a place where the calling program can access it
  - Return control to the point of origin

Registers for Procedure Calling and the jal Instruction

- **$a0 - $a3: four argument registers in which to pass parameters**
- **$v0 - $v1: two value registers in which to return values**
- **$ra: one return address register to return to the point of origin**
- **jal ProcedureAddress: instruction to transfer control to a procedure and store the return address in $ra ($ra is set to PC + 4, address of the next instruction after procedure call)**
- **jr $ra - used to transfer control back to the calling program**

Saving Registers using a Stack

- **Additional registers used by the called procedure must be saved prior to use, or the values used by the calling procedure will be corrupted.**
- **The old values can be saved on a stack (call stack). After the called procedure completes, the old values can be popped off the stack and restored.**
- **$sp: stack pointer register contains the address of the top of the stack. By convention, address on the stack grows from higher addresses to lower address, which implies that a push subtracts from $sp and a pop adds to $sp.**

Register Conventions

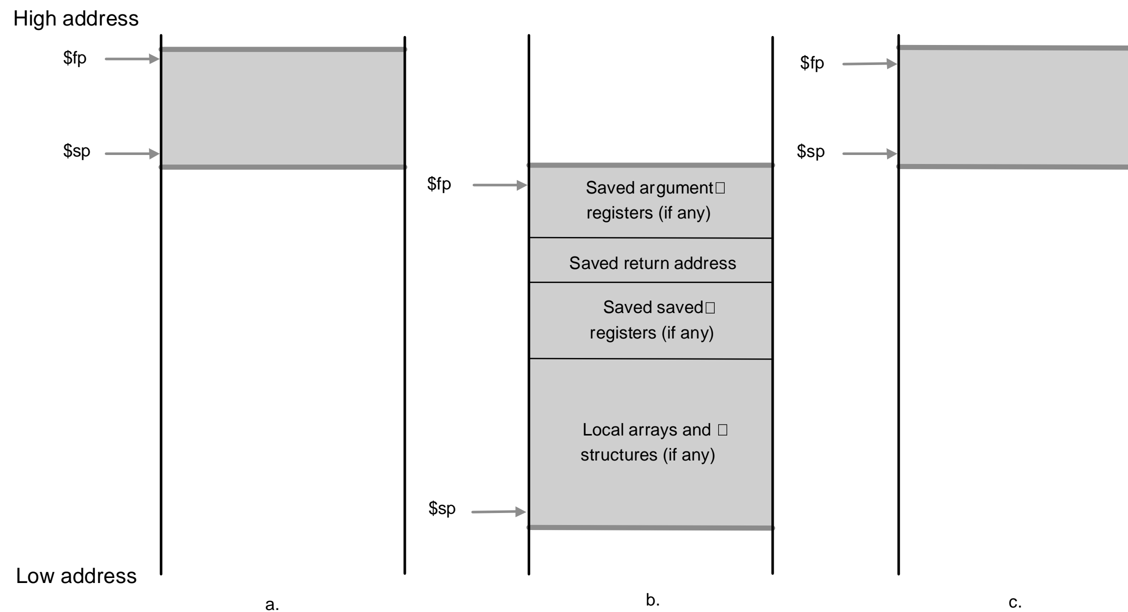
- The 8 “saved” registers \$s0 - \$s7 must be preserved on a procedure call, i.e. the called procedure must save these before using them.
- The 10 “temporary” registers \$t0 - \$t9 are not preserved by the called procedure. The calling procedure can not assume they will not change after a procedure call and, hence, must save them prior to the call if the values are needed after the call.
- Saved registers should be used for long lived variables, while temporary registers should be used for short lived variables

Nested Procedures and Automatic Variables

- **A new call frame or activation record must be created for each nested procedure call.**
- **Argument registers and the return address register must be saved in addition to saved registers since new values will be put in them for the nested procedure call.**
- **Automatic variables (i.e. variables that are local to a procedure and are discarded when the procedure completes) are also allocated on the call stack. They are popped when the call completes.**

Activation Records (Frames) and the Call Stack

- **An activation record (frame) is a segment on the stack containing a procedure's saved registers and local variables.**
- **Each time a procedure is called a frame ($fp: frame pointer register points to the current frame) is placed on the stack.**



Leaf Procedure

```
/* Example from page 134 */

int leaf_example (int g, int h, int I, int j)
{
    int f;
    f = (g+h) - (i+j);
    return f;
}
```

Leaf Procedure

```
sub   $sp,$sp,4        # push stack and save registers
sw    $s0,0($sp)

add   $t0,$a0,$a1      # g + h
add   $t1,$a2,$a3      # i + j
sub   $s0,$t0,$t1      # (g+h) - (i+j)
add   $v0,$s0,$zero    # return f = (g+h)-(i+j)

lw    $s0,0($sp)       # restore registers and pop stack
add   $sp,$sp,4
jr    $ra              # return to calling program
```

Recursive Procedure

```
/* Factorial example from pp. 136-137 */

int fact(int n)
{
    if (n < 1) return(1);
    else return(n * fact(n-1));
}
```

```
      sub    $sp,$sp,8       # push stack
      sw     $ra,4($sp)      # save return address
      sw     $a0,0($sp)      # save n

      slt    $t0,$a0,1       # test n < 1
      beq    $t0,$zero,L1    # branch if n >= 1
      add    $v0,$zero,1     # return 1
      add    $sp,$sp,8       # pop stack
      jr     $ra             # return to calling procedure
L1:
      sub    $a0,$a0,1       # set parameter to n-1
      jal    fact            # call fact(n-1)
      lw     $a0,0($sp)      # restore previous value of n
      lw     $ra,4($sp)      # restore previous return address
      mul    $v0,$a0,$v0     # return n * fact(n-1)

      add    $sp,$sp,8       # pop stack
      jr     $ra             # return to calling procedure
```