Lecture #8: MIPS Procedures

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Topic Outline

• Functions

• More Logical Operations
C functions

```c
main() {
    int i, j, k, m;
    ...
    i = mult(j, k); ...
    m = mult(i, i); ...
}

/* really dumb mult function */
int mult (int mcand, int mlier) {
    int product;

    product = 0;
    while (mlier > 0) {
        product = product + mcand;
        mlier = mlier -1;
    }
    return product;
}
```

What information must compiler/programmer keep track of?

What instructions can accomplish this?
Function Call Bookkeeping

• What are the properties of a function?
  • Function call transfers control somewhere else and then returns.
  • Arguments
  • Return Value
  • Black-box operation/scoping
  • Re-entrance
Function Call Bookkeeping

- Registers play a major role in keeping track of information for function calls.

- **Register conventions:**
  - Return address: $ra
  - Arguments: $a0, $a1, $a2, $a3
  - Return value: $v0, $v1
  - Local variables: $s0, $s1, …, $s7

- The stack is also used; more later.
In MIPS, all instructions are 4 bytes, and stored in memory just like data. So here we show the addresses of where the programs are stored.
instruction Support for Functions (2/6)

... sum(a,b);... /* a,b:$s0,$s1 */
}

int sum(int x, int y) {
    return x+y;
}

C

M

address

1000 add $a0,$s0,$zero    # x = a
1004 add $a1,$s1,$zero    # y = b
1008 addi $ra,$zero,1016  # ra=1016
1012 j sum             # jump to sum
1016 ...

2000 sum: add $v0,$a0,$a1
2004 jr $ra      # new instruction
Instruction Support for Functions (3/6)

... sum(a,b);... /* a,b:$s0,$s1 */
}

int sum(int x, int y) {
    return x+y;
}

# new instruction

• Question: Why use `jr` here? Why not simply use `j`?

• Answer: `sum` might be called by many functions, so we can’t return to a fixed place. The calling proc to `sum` must be able to say “return here” somehow.

```mips
2000  sum: add $v0,$a0,$a1
    jr $ra  # new instruction
```
Instruction Support for Functions (4/6)

• Single instruction to jump and save return address: jump and link (jal)

• Before:

1008 addi $ra,$zero,1016 #$ra=1016
1012 j sum #go to sum

• After:

1008 jal sum # $ra=1012, go to sum

• Why have a jal? Make the common case fast: function calls are very common. Also, you don’t have to know where the code is loaded into memory with jal.
Instruction Support for Functions (5/6)

- Syntax for `jal` (jump and link) is same as for `j` (jump):
  
  `jal label`

- `jal` should really be called `laj` for “link and jump”:
  - Step 1 (link): Save address of next instruction into $ra (Why next instruction? Why not current one?)
  - Step 2 (jump): Jump to the given label
Instruction Support for Functions (6/6)

• Syntax for \texttt{jr} (jump register):
  \texttt{jr register}

• Instead of providing a label to jump to, the \texttt{jr} instruction provides a register which contains an address to jump to.

• Only useful if we know exact address to jump to.

• Very useful for function calls:
  • \texttt{jal} stores return address in register ($ra)
  • \texttt{jr} $ra jumps back to that address
Nested Procedures (1/2)

```c
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
}
```

• Something called `sumSquare`, now `sumSquare` is calling `mult`.

• So there's a value in $ra$ that `sumSquare` wants to jump back to, but this will be overwritten by the call to `mult`.

• Need to save `sumSquare` return address before call to `mult`.
Nested Procedures (2/2)

• In general, may need to save some other info in addition to $ra.$

• When a C program is run, there are 3 important memory areas allocated:
  • **Static**: Variables declared once per program, cease to exist only after execution completes. E.g., C globals
  • **Heap**: Variables declared dynamically
  • **Stack**: Space to be used by procedure during execution; this is where we can save register values
C memory Allocation review

Address

∞

$sp →

stack

pointer

Stack

Space for saved procedure information

Heap

Explicitly created space, e.g., malloc(); C pointers

Static

Variables declared once per program

Code

Program

Program
Using the Stack (1/2)

- So we have a register $sp$ which always points to the last used space in the stack.

- To use stack, we decrement this pointer by the amount of space we need and then fill it with info.

- So, how do we compile this?

```c
int sumSquare(int x, int y) {
    return mult(x, x) + y;
}
```
Using the Stack (2/2)

*Hand-compile*  

```c
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
}
```

sumSquare:

```
addi $sp,$sp,-8    # space on stack
sw $ra, 4($sp)    # save ret addr
sw $a1, 0($sp)    # save y

add $a1,$a0,$zero # mult(x,x)
jal mult          # call mult

lw $a1, 0($sp)    # restore y
add $v0,$v0,$a1   # mult()+y
lw $ra, 4($sp)    # get ret addr

addi $sp,$sp,8    # restore stack
jr $ra
```

```
mult: ...
```

“push”

- `addi $sp,$sp,-8`  
  - Space on stack
- `sw $ra, 4($sp)`  
  - Save return address
- `sw $a1, 0($sp)`  
  - Save y

```
add $a1,$a0,$zero # mult(x,x)
jal mult          # call mult
```

“pop”

- `lw $a1, 0($sp)`  
  - Restore y
- `add $v0,$v0,$a1`  
  - mult()+y
- `lw $ra, 4($sp)`  
  - Get return address

```
addi $sp,$sp,8    # restore stack
jr $ra
```

```
mult: ...
```
Steps for Making a Procedure Call

1) Save necessary values onto stack.
2) Assign argument(s), if any.
3) jal call
4) Restore values from stack.
Rules for Procedures

- Called with a jal instruction, returns with a jr $ra
- Accepts up to 4 arguments in $a0, $a1, $a2 and $a3
- Return value is always in $v0 (and if necessary in $v1)
- Must follow register conventions (even in functions that only you will call)!

So what are they?
### MIPS Registers

<table>
<thead>
<tr>
<th>Category</th>
<th>Register Ranges</th>
<th>Alternate Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>The constant 0</td>
<td>$0$</td>
<td>$\text{zero}$</td>
</tr>
<tr>
<td>Reserved for Assembler</td>
<td>$1$</td>
<td>$\text{at}$</td>
</tr>
<tr>
<td>Return Values</td>
<td>$2$-$3$</td>
<td>$\text{v0}$-$\text{v1}$</td>
</tr>
<tr>
<td>Arguments</td>
<td>$4$-$7$</td>
<td>$\text{a0}$-$\text{a3}$</td>
</tr>
<tr>
<td>Temporary</td>
<td>$8$-$15$</td>
<td>$\text{t0}$-$\text{t7}$</td>
</tr>
<tr>
<td>Saved</td>
<td>$16$-$23$</td>
<td>$\text{s0}$-$\text{s7}$</td>
</tr>
<tr>
<td>More Temporary</td>
<td>$24$-$25$</td>
<td>$\text{t8}$-$\text{t9}$</td>
</tr>
<tr>
<td>Used by Kernel</td>
<td>$26$-$27$</td>
<td>$\text{k0}$-$\text{k1}$</td>
</tr>
<tr>
<td>Global Pointer</td>
<td>$28$</td>
<td>$\text{gp}$</td>
</tr>
<tr>
<td>Stack Pointer</td>
<td>$29$</td>
<td>$\text{sp}$</td>
</tr>
<tr>
<td>Frame Pointer</td>
<td>$30$</td>
<td>$\text{fp}$</td>
</tr>
<tr>
<td>Return Address</td>
<td>$31$</td>
<td>$\text{ra}$</td>
</tr>
</tbody>
</table>

(From COD 3\textsuperscript{rd} Ed. green insert)

Use **names** for registers -- code is clearer!
Other Registers

• $at: may be used by the assembler at any time; unsafe to use

• $k0–$k1: may be used by the OS at any time; unsafe to use

• $gp, $fp: don’t worry about them

• Note: Feel free to read up on $gp and $fp in Appendix A, but you can write perfectly good MIPS code without them.
Basic Structure of a Function

**Prologue**

entry_label:
addi $sp,$sp, -framesize
sw $ra, framesize-4($sp)  # save $ra
save other regs if need be

**Body**  ⋯  (call other functions…)

**Epilogue**

restore other regs if need be
lw $ra, framesize-4($sp)  # restore $ra
addi $sp,$sp, framesize
jr $ra

ra
memory
Register Conventions (1/4)

- **CalleR**: the calling function
- **CalleE**: the function being called

- When callee returns from executing, the caller needs to know which registers may have changed and which are guaranteed to be unchanged.

- **Register Conventions**: A set of generally accepted rules as to which registers will be unchanged after a procedure call (jal) and which may be changed.
Register Conventions (1/4)

- none guaranteed $\Rightarrow$ inefficient
  - Caller will be saving lots of regs that callee doesn’t use!

- all guaranteed $\Rightarrow$ inefficient
  - Callee will be saving lots of regs that caller doesn’t use!

- Register convention: A balance between the two.
Register Conventions (2/4) - saved

• **$0**: No Change. Always 0.

• **$s0-$s7**: Restore if you change. Very important, that’s why they’re called saved registers. If the callee changes these in any way, it must restore the original values before returning.

• **$sp**: Restore if you change. The stack pointer must point to the same place before and after the jal call, or else the caller won’t be able to restore values from the stack.

• HINT -- All saved registers start with S!
Register Conventions (3/4) - volatile

- **$ra**: Can Change. The `jal` call itself will change this register. Caller needs to save on stack if nested call.

- **$v0-$v1**: Can Change. These will contain the new returned values.

- **$a0-$a3**: Can change. These are volatile argument registers. Caller needs to save if they’ll need them after the call.

- **$t0-$t9**: Can change. That’s why they’re called temporary: any procedure may change them at any time. Caller needs to save if they’ll need them afterwards.
Register Conventions (4/4)

• What do these conventions mean?
  • If function R calls function E, then function R must save any temporary registers that it may be using onto the stack before making a `jal` call.
  • Function E must save any S (saved) registers it intends to use before garbling up their values.
  • Remember: Caller/callee need to save only temporary/saved registers they are using, not all registers.
Peer Instruction 1

When translating this to MIPS…

A. We COULD copy $a0 to $a1 (and then not store $a0 or $a1 on the stack) to store n across recursive calls.

B. We MUST save $a0 on the stack since it gets changed.

C. We MUST save $ra on the stack since we need to know where to return to…
Administtrivia

• HW2 Due Tonight
• HW3 Due Tuesday
• PROJ1 Due next Friday
  • Start now!
• MT1: next Friday (7/8), 11-2
  • location TBD
Topic Outline

• Functions

• More Logical Operations
Bitwise Operations

- Up until now, we’ve done arithmetic (add, sub, addi), memory access (lw and sw), and branches and jumps.

- All of these instructions view contents of register as a single quantity (such as a signed or unsigned integer).

- **New Perspective**: View contents of register as 32 raw bits rather than as a single 32-bit number.

- Since registers are composed of 32 bits, we may want to access individual bits (or groups of bits) rather than the whole.

- Introduce two new classes of instructions:
  - Logical & Shift Ops
Logical Operators (1/3)

- Two basic logical operators:
  - **AND**: outputs 1 only if both inputs are 1
  - **OR**: outputs 1 if at least one input is 1

- **Truth Table**: standard table listing all possible combinations of inputs and resultant output for each. E.g.,

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>A AND B</th>
<th>A OR B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Logical Operators (2/3)

• Logical Instruction Syntax:
  1  2,3,4
  • where
    1) operation name
    2) register that will receive value
    3) first operand (register)
    4) second operand (register) or immediate (numerical constant)

• In general, can define them to accept >2 inputs, but in the case of MIPS assembly, these accept exactly 2 inputs and produce 1 output

• Again, rigid syntax, simpler hardware
Logical Operators (3/3)

• Instruction Names:
  • `and, or`: Both of these expect the third argument to be a register
  • `andi, ori`: Both of these expect the third argument to be an immediate

• MIPS Logical Operators are all bitwise, meaning that bit 0 of the output is produced by the respective bit 0’s of the inputs, bit 1 by the bit 1’s, etc.
  • C: Bitwise AND is `&` (e.g., `z = x & y;`)
  • C: Bitwise OR is `|` (e.g., `z = x | y;`)
Uses for Logical Operators (1/3)

- Note that anding a bit with 0 produces a 0 at the output while anding a bit with 1 produces the original bit.

- This can be used to create a mask.
  - Example:
    - 1011 0110 1010 0100 0011 1101 1001 1010
    - mask: 0000 0000 0000 0000 0000 1111 1111 1111
    - The result of anding these:
      - 0000 0000 0000 0000 0000 1101 1001 1010
      - mask last 12 bits
Uses for Logical Operators (2/3)

• The second bitstring in the example is called a **mask**. It is used to isolate the rightmost 12 bits of the first bitstring by masking out the rest of the string (e.g. setting it to all 0s).

• Thus, the **and** operator can be used to set certain portions of a bitstring to 0s, while leaving the rest alone.
  
  • In particular, if the first bitstring in the above example were in $t0$, then the following instruction would mask it:

    \[
    \text{andi} \quad t0, t0, 0xFFF
    \]
Uses for Logical Operators (3/3)

• Similarly, note that or'ing a bit with 1 produces a 1 at the output while or'ing a bit with 0 produces the original bit.

• This can be used to force certain bits of a string to 1s.
  • For example, if $t0$ contains 0x12345678, then after this instruction:
    ```
    ori $t0, $t0, 0xFFFF
    ```
  • ...$t0$ contains 0x1234FFFF (e.g. the high-order 16 bits are untouched, while the low-order 16 bits are forced to 1s).
Shift Instructions (1/4)

- Move (shift) all the bits in a word to the left or right by a number of bits.
  - Example: shift right by 8 bits
    0001 0010 0011 0100 0101 0110 0111 1000
    0000 0000 0001 0010 0011 0100 0101 0110
  - Example: shift left by 8 bits
    0001 0010 0011 0100 0101 0110 0111 1000
    0011 0100 0101 0110 0111 1000 0000 0000
Shift Instructions (2/4)

• Shift Instruction Syntax:
  1 2,3,4
  • where
    1) operation name
    2) register that will receive value
    3) first operand (register)
    4) shift amount (constant <= 32)

• MIPS shift instructions:
  1. sll (shift left logical): shifts left and fills emptied bits with 0s
  2. srl (shift right logical): shifts right and fills emptied bits with 0s
  3. sra (shift right arithmetic): shifts right and fills emptied bits by sign extending
Shift Instructions (3/4)

• Example: shift right arith by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

0000 0000 0001 0010 0011 0100 0101 0110

• Example: shift right arith by 8 bits

1001 0010 0011 0100 0101 0110 0111 1000

1111 1111 1001 0010 0011 0100 0101 0110
Shift Instructions (4/4)

• Since shifting may be faster than multiplication, a good compiler usually notices when C code multiplies by a power of 2 and compiles it to a shift instruction:

\[
a *= 8; \quad \text{(in C)}
\]

would compile to:

\[
sll \quad $s0,$s0,3 \quad \text{(in MIPS)}
\]

• Likewise, shift right to divide by powers of 2

  • remember to use \textit{sra}
main() {
    int i,j,k,m; /* i-m: $s0-$s3 */
    ...
    i = mult(j,k); ...
    m = mult(i,i); ...
}

int mult (int mcand, int mlier){
    int product;

    product = 0;
    while (mlier > 0) {
        product += mcand;
        mlier -= 1;
    }
    return product;
}
Peer Instruction: Compile This (2/5)

__start:

add $a0,$s1,$0  # arg0 = j
add $a1,$s2,$0  # arg1 = k
jal mult        # call mult
add $s0,$v0,$0  # i = mult()
...

add $a0,$s0,$0  # arg0 = i
add $a1,$s0,$0  # arg1 = i
jal mult       # call mult
add $s3,$v0,$0  # m = mult()
...

done

main() {
  int i,j,k,m; /* i-m:$s0-$s3 */
  ...
  i = mult(j,k); ...
  m = mult(i,i); ... }

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Peer Instruction: Compile This (3/5)

• Notes:

  • `main` function ends with `done`, not `jr $ra`, so there’s no need to save $ra onto stack

  • all variables used in `main` function are saved registers, so there’s no need to save these onto stack
Peer Instruction: Compile This (4/5)

```c
int mult (int mcand, int mlr){
    int product = 0;
    while (mlr > 0) {
        product += mcand;
        mlr -= 1;
    }
    return product;
}
```
Peer Instruction: Compile This (5/5)

• Notes:
  
  • no jal calls are made from mult and we don’t use any saved registers, so we don’t need to save anything onto stack
  
  • temp registers are used for intermediate calculations (could have used s registers, but would have to save the caller’s on the stack.)
  
  • $a1 is modified directly (instead of copying into a temp register) since we are free to change it
  
  • result is put into $v0 before returning (could also have modified $v0 directly)
“And in Conclusion…” (1/2)

• Functions called with jal, return with jr $ra.

• The stack is your friend: Use it to save anything you need. Just be sure to leave it the way you found it.

• Instructions we know so far
  
  Arithmetic: add, addi, sub, addu, addiu, subu
  Memory:   lw, sw
  Decision:  beq, bne, slt, slti, sltu, sltiu
  Unconditional Branches (Jumps): j, jal, jr

• Registers we know so far
  • All of them!
“And in Conclusion…” (2/2)

- **Register Conventions**: Each register has a purpose and limits to its usage. Learn these and follow them, even if you’re writing all the code yourself.

- **Logical and Shift Instructions**
  - Operate on bits individually, unlike arithmetic, which operate on entire word.
  - Use to isolate fields, either by masking or by shifting back and forth.
  - Use **shift left logical**, `sll`, for multiplication by powers of 2
  - Use **shift right arithmetic**, `sra`, for division by powers of 2.

- **New Instructions**: `and, andi, or, ori, sll, srl, sra`