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CS61C : Machine Structures

Lecture 12 – Introduction to MIPS Procedures II, Logical and Shift Ops

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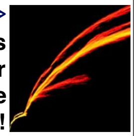

Devolab allows researchers to study self-replicating computer programs (Agent Smith?), and they've seen them adapt & being creative!

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Review

- 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!
  - There are CONVENTIONS when calling procedures!

Register Conventions (1/4)

- Calle<u>R</u>: the calling function
- Calle<u>E</u>: 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 (2/4) - saved

- `$0`: No Change. Always 0.
- `$s0-$s7`: Restore if you change. Very important, that's why they're called saved registers. If the <u>callee</u> changes these in any way, it must restore the original values before returning.
- `$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

- `$ra`: Can Change. The `jal` call itself will change this register. <u>Caller</u> needs to save on stack if nested call.
- `$v0-$v1`: Can Change. These will contain the new returned values.
- `$a0-$a3`: Can change. These are volatile argument registers. <u>Caller</u> needs to save if they'll need them after the call.
- `$t0-$t9`: Can change. That's why they're called temporary: any procedure may change them at any time. <u>Caller</u> 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: Calle<u>r</u>/calle<u>e</u> need to save only temporary/saved registers they are using, not all registers.

Parents leaving for weekend analogy (1/5)

- Parents (`main`) leaving for weekend
- They (`caller`) give keys to the house to kid (`callee`) with the rules (`calling conventions`):
  - You can trash the temporary room(s), like the den and basement (`registers`) if you want, we don't care about it
  - BUT you'd better leave the rooms (`registers`) that we want to save for the guests untouched. "these rooms better look the same when we return!"
- Who hasn't heard this in their life?

Parents leaving for weekend analogy (2/5)

- Kid now "owns" rooms (`registers`)
- Kid wants to use the saved rooms for a wild, wild party (`computation`)
- What does kid (`callee`) do?
  - Kid takes what was in these rooms and puts them in the garage (`memory`)
  - Kid throws the party, trashes everything (except garage, who goes there?)
  - Kid restores the rooms the parents wanted saved after the party by replacing the items from the garage (`memory`) back into those saved rooms

Parents leaving for weekend analogy (3/5)

- Same scenario, except before parents return and kid replaces saved rooms…
- Kid (`callee`) has left valuable stuff (`data`) all over.
  - Kid's friend (`another callee`) wants the house for a party when the kid is away
  - Kid knows that friend might trash the place destroying valuable stuff!
  - Kid remembers rule parents taught and now becomes the "heavy" (`caller`), instructing friend (`callee`) on good rules (`conventions`) of house.

Parents leaving for weekend analogy (4/5)

- If kid had data in temporary rooms (which were going to be trashed), there are three options:
  - Move items directly to garage (`memory`)
  - Move items to saved rooms whose contents have already been moved to the garage (`memory`)
  - Optimize lifestyle (`code`) so that the amount you've got to shlep stuff back and forth from garage (`memory`) is minimized
- Otherwise: "Dude, where's my data?!"

Parents leaving for weekend analogy (5/5)

- Friend now "owns" rooms (`registers`)
- Friend wants to use the saved rooms for a wild, wild party (`computation`)
- What does friend (`callee`) do?
  - Friend takes what was in these rooms and puts them in the garage (`memory`)
  - Friend throws the party, trashes everything (except garage)
  - Friend restores the rooms the kid wanted saved after the party by replacing the items from the garage (`memory`) back into those saved rooms

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 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.,

A	B	A AND B	A OR B
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

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 `and`ing a bit with 0 produces a 0 at the output while `and`ing 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 `and`ing 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:

```
andi  $t0,$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;` (in C)

  would compile to:

  `sll    $s0,$s0,3` (in MIPS)

- Likewise, shift right to divide by powers of 2
  - remember to use `sra`

Peer Instruction

```
r: ...     # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem
   ...     ### PUSH REGISTER(S) TO STACK?
   jal e   # Call e
   ...     # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem
   jr $ra  # Return to caller of r

e: ...     # R/W $s0,$v0,$t0,$a0,$sp,$ra,mem
   jr $ra  # Return to r
```

What does `r` have to push on the stack before "`jal e`"?

```
1:  1 of ($s0,$sp,$v0,$t0,$a0,$ra)
2:  2 of ($s0,$sp,$v0,$t0,$a0,$ra)
3:  3 of ($s0,$sp,$v0,$t0,$a0,$ra)
4:  4 of ($s0,$sp,$v0,$t0,$a0,$ra)
5:  5 of ($s0,$sp,$v0,$t0,$a0,$ra)
6:  6 of ($s0,$sp,$v0,$t0,$a0,$ra)
7:  0 of ($s0,$sp,$v0,$t0,$a0,$ra)
```


"And in Conclusion…"

- 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`

Example: Fibonacci Numbers 1/8

- The Fibonacci numbers are defined as follows: F(n) = F(n – 1) + F(n – 2), F(0) and F(1) are defined to be 1
- In scheme, this could be written:

```
(define (Fib n)
 (cond      ((= n 0) 1)
            ((= n 1) 1)
            (else (+ (Fib (- n 1))
                     (Fib (- n 2)))))
```


Example: Fibonacci Numbers 2/8

- Rewriting this in C we have:

```
int fib(int n) {
  if(n == 0) { return 1; }
  if(n == 1) { return 1; }
  return (fib(n - 1) + fib(n - 2));
}
```


Example: Fibonacci Numbers 3/8

- Now, let's translate this to MIPS!
- You will need space for three words on the stack
- The function will use one $s register, $s0
- Write the Prologue:

```
fib:
addi $sp, $sp, -12     # Space for three words
sw $ra, 8($sp)         # Save the return address
sw $s0, 4($sp)         # Save $s0
```


Example: Fibonacci Numbers 4/8

- Now write the Epilogue:

```
fin:
lw $s0, 4($sp)         # Restore $s0
lw $ra, 8($sp)         # Restore return address
addi $sp, $sp, 12      # Pop the stack frame
jr $ra                 # Return to caller
```


Example: Fibonacci Numbers 5/8

- Finally, write the body. The C code is below. Start by translating the lines indicated in the comments

```
int fib(int n) {
 if(n == 0) { return 1; } /*Translate
 Me!*/ if(n == 1) { return 1; }
 /*Translate Me!*/ return (fib(n - 1) +
 fib(n - 2));
}
addi $v0, $zero, 1     # $v0 = 1
beq $a0, $zero, fin    # if (n == 0). . .
addi $t0, $zero, 1     # $t0 = 1
beq $a0, $t0, fin      # if (n == 1). . .
Continued on next slide. . .
```


Example: Fibonacci Numbers 6/8

- Almost there, but be careful, this part is tricky!

```
int fib(int n) {
 . . .
 return (fib(n - 1) + fib(n - 2));
}
addi $a0, $a0, -1      # $a0 = n - 1
sw $a0, 0($sp)         # Need $a0 after jal
jal fib                # fib(n - 1)
lw $a0, 0($sp)         # Restore $a0
addi $a0, $a0, -1      # $a0 = n – 2
Continued on next slide. . .
```

Example: Fibonacci Numbers 7/8

° Remember that $v0 is caller saved!

```
int fib(int n) {
 . . .
 return (fib(n - 1) + fib(n - 2));
}
```

```
add $s0, $v0, $zero    # Place fib(n – 1)
                       # somewhere it won't get
                       # clobbered
jal fib                # fib(n – 2)
add $v0, $v0, $s0      # $v0 = fib(n-1) + fib(n-2)
To the epilogue and beyond. . .
```


Example: Fibonacci Numbers 8/8

° Here's the complete code for reference:

```
fib:
addi $sp, $sp, -12
sw $ra, 8($sp)
sw $s0, 4($sp)
addi $v0, $zero, 1
beq $a0, $zero, fin
addi $t0, $zero, 1
beq $a0, $t0, fin
addi $a0, $a0, -1
sw $a0, 0($sp)
jal fib
lw $a0, 0($sp)
addi $a0, $a0, -1
add $s0, $v0, $zero
jal fib
add $v0, $v0, $s0
fin:
lw $s0, 4($sp)
lw $ra, 8($sp)
addi $sp, $sp, 12
jr $ra
```


BONUS: Uses for Shift Instructions (1/4)

- Suppose we want to isolate byte 0 (rightmost 8 bits) of a word in $t0. Simply use:

```
andi  $t0,$t0,0xFF
```

- Suppose we want to isolate byte 1 (bit 15 to bit 8) of a word in $t0. We can use:

```
andi  $t0,$t0,0xFF00
```

but then we still need to shift to the right by 8 bits...

BONUS: Uses for Shift Instructions (2/4)

- Could use instead:

```
sll  $t0,$t0,16
srl  $t0,$t0,24
```

0001 0010 0011 0100 0101 0110 0111 1000

0101 0110 0111 1000 0000 0000 0000 0000

0000 0000 0000 0000 0000 0000 0101 0110

BONUS: Uses for Shift Instructions (3/4)

- In decimal:
  - Multiplying by 10 is same as shifting left by 1:
    - $714_{10} \times 10_{10} = 7140_{10}$
    - $56_{10} \times 10_{10} = 560_{10}$
  - Multiplying by 100 is same as shifting left by 2:
    - $714_{10} \times 100_{10} = 71400_{10}$
    - $56_{10} \times 100_{10} = 5600_{10}$
  - Multiplying by 10^n is same as shifting left by n

BONUS: Uses for Shift Instructions (4/4)

- In binary:
  - Multiplying by 2 is same as shifting left by 1:
    - $11_2 \times 10_2 = 110_2$
    - $1010_2 \times 10_2 = 10100_2$
  - Multiplying by 4 is same as shifting left by 2:
    - $11_2 \times 100_2 = 1100_2$
    - $1010_2 \times 100_2 = 101000_2$
  - Multiplying by 2^n is same as shifting left by n