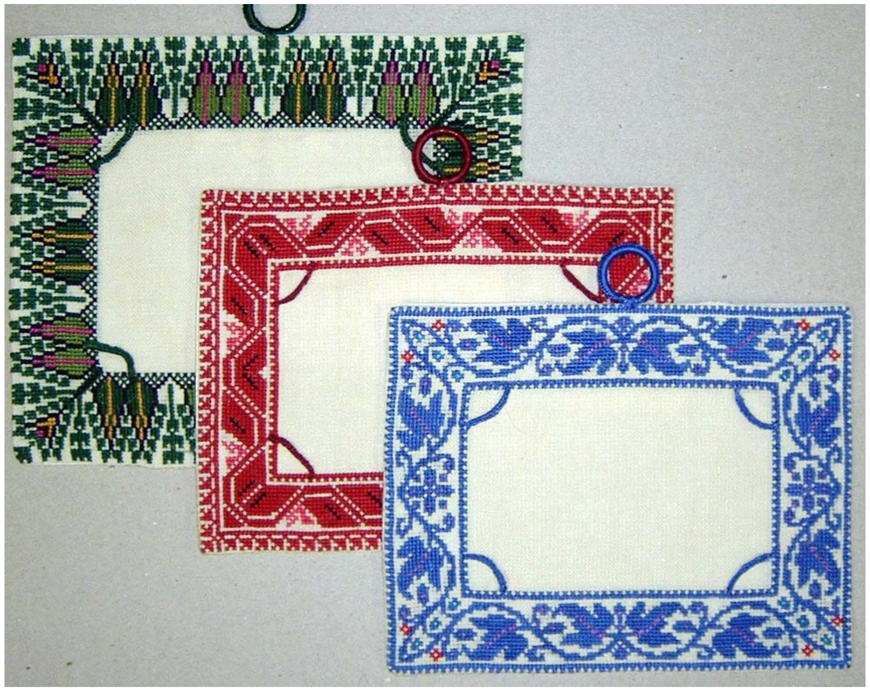
CS61C : Machine Structures

Lecture #9: MIPS Procedures



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C functions

```
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.

Instruction Support for Functions (1/6)

C

```
... sum(a,b);... /* a,b:$s0,$s1 */
}
int sum(int x, int y) {
    return x+y;
}
```

MIPS

```
address
 1000
 1004
 1008
 1012
 1016

 2000
 2004
```

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)

C

```
... sum(a,b);... /* a,b:$s0,$s1 */
}
int sum(int x, int y) {
    return x+y;
}
```

MIPS

```
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)

C

```
... sum(a,b);... /* a,b:$s0,$s1 */
}
int sum(int x, int y) {
    return x+y;
}
```

MIPS

- 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.

```
00 sum: add $v0,$a0,$a1
 4 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 `jr` (jump register):

```
    jr register
```

- Instead of providing a label to jump to, the `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:
  - `jal` stores return address in register (`$ra`)
  - `jr $ra` jumps back to that address

Nested Procedures (1/2)

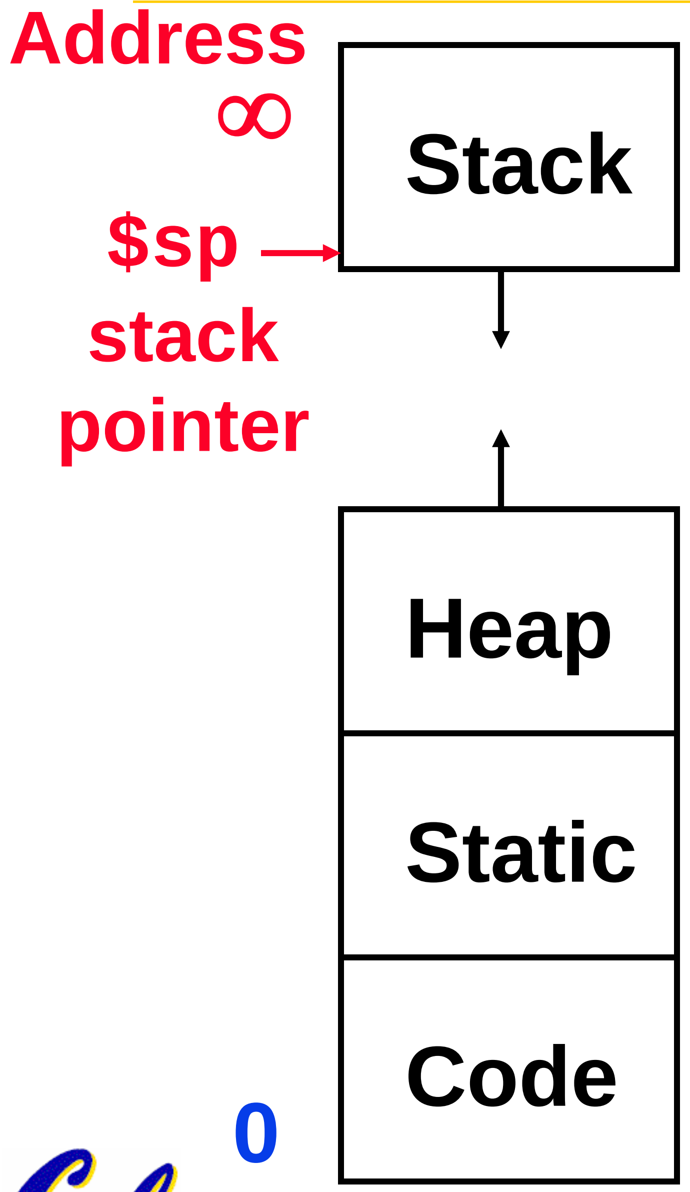
```
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
 }
```

- 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



Space for saved procedure information

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

Variables declared once per 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?

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

Using the Stack (2/2)

- Hand-compile `int sumSquare(int x, int y) {`
  `return mult(x,x)+ y; }`

```
sumSquare:
        addi $sp,$sp,-8 # space on stack
"push"  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
"pop"   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

The constant 0	$0	$zero
Reserved for Assembler	$1	$at
Return Values	$2-$3	$v0-$v1
Arguments	$4-$7	$a0-$a3
Temporary	$8-$15	$t0-$t7
Saved	$16-$23	$s0-$s7
More Temporary	$24-$25	$t8-$t9
Used by Kernel	$26-27	$k0-$k1
Global Pointer	$28	$gp
Stack Pointer	$29	$sp
Frame Pointer	$30	$fp
Return Address	$31	$ra

(From COD 3rd Ed. green insert)
Use names for registers -- code is clearer!

Other Registers

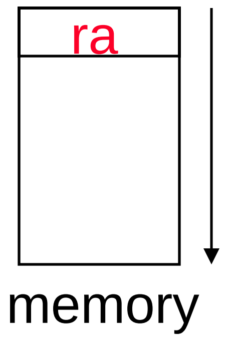
- `$at`: may be used by the assembler at any time; unsafe to use
- `$k0-$k1`: may be used by the OS at any time; unsafe to use
- `$gp`, `$fp`: don’t worry about them
- Note: Feel free to read up on `$gp` and `$fp` in Appendix A, but you can write perfectly good MIPS code without them.

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
```

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 ➔ inefficient
  - Caller will be saving lots of regs that callee doesn’t use!
- all guaranteed ➔ 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: Calle<u>r</u>/calle<u>e</u> need to save only temporary/saved registers they are using, not all registers.

Peer Instruction 1

```
int fact(int n){
 if(n == 0) return 1; else return(n*fact(n-1));}
```

When translating this to MIPS…

A. We COULD copy `$a0` to `$a1` (& 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…

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 the 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.,

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 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:

```
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

$$\searrow \qquad \searrow$$

0000 0000 0001 0010 0011 0100 0101 0110

  - Example: shift left by 8 bits

0001 0010 0011 0100 0101 0110 0111 1000

$$\swarrow \qquad \swarrow$$

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 <u>fills emptied bits with 0s</u>

  2. `srl` (shift right logical): shifts right and <u>fills emptied bits with 0s</u>

  3. `sra` (shift right arithmetic): shifts right and <u>fills emptied bits by sign extending</u>

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: Compile This (1/5)

```
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;
 }
```