Review

- MIPS Machine Language Instruction: 32 bits representing a single instruction

R	opcode	rs	rt	rd	shamt	funct
I	opcode	rs	rt	immediate		
J	opcode	target address				

- Branches use PC-relative addressing, Jumps use absolute addressing.
- Disassembly is simple and starts by decoding opcode field. (more next lecture)

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 = 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

- 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 (shown in decimal)

```
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 (shown in decimal)
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 use `j`?
- Answer: `sum` might be called by many places, so we can't return to a fixed place. The calling proc to `sum` must be able to say "return here" somehow.

```
2000 sum: add $v0,$a0,$a1
2004 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               #goto sum
```

- After:

```
1008 jal sum  # $ra=1012,goto sum
```

- Why have a `jal`?
  - Make the common case fast: function calls very common.
  - Don't have to know where code is in 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.
- Very useful for function calls:
  - **`jal`** stores return address in register (`$ra`)
  - **`jr $ra`** jumps back to that address

Nested Procedures (1/2)

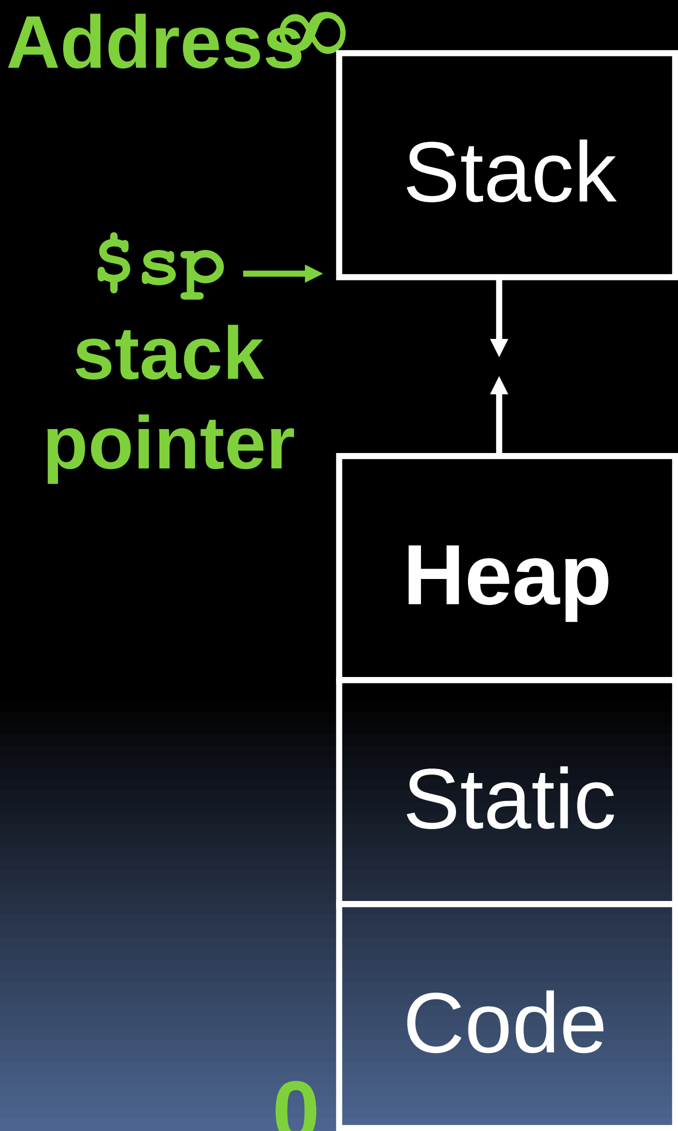
```
int sumSquare(int x, int y) {
  return mult(x,x)+ y;
}
```

- 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 via **malloc**
  - Stack: Space to be used by procedure during execution; this is where we can save register values

C Memory Allocation



Space for local vars, saved procedure information

Explicitly created space, i.e., **malloc()**

Variables declared once per program; e.g., globals (doesn't change size)

Program (doesn't change size)

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
          sw $ra, 4($sp)   # save ret addr
"push"    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
"pop"     lw $ra, 4($sp)   # get ret addr
          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

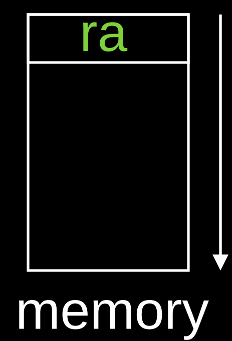
So what are they?

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
```

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

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.

Peer Instruction

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

When translating this to MIPS…

1) We COULD copy `$a0` to `$a1` (& then not store `$a0` or `$a1` on the stack) to store n across recursive calls.
2) We MUST save `$a0` on the stack since it gets changed.
3) We MUST save `$ra` on the stack since we need to know where to return to…

	123
a)	FFF
b)	FFT
c)	FTF
c)	FTT
d)	TFF
d)	TFT
e)	TTF
e)	TTT

"And in Conclusion…"

- Functions called with `jal`, return with `jr $ra`.
- The stack is your friend: Use it to save anything you need. Just leave it the way you found it!
- Instructions we know so far…

  Arithmetic: `add, addi, sub, addu, addiu, subu`

  Memory: `lw, sw, lb, sb`

  Decision: `beq, bne, slt, slti, sltu, sltiu`

  Unconditional Branches (Jumps): `j, jal, jr`
- Registers we know so far
  - All of them!