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CS61C : Machine Structures

Lecture #8 – MIPS Procedures

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Review

- A Decision allows us to decide what to execute at run-time rather than compile-time.
- C Decisions are made using conditional statements within `if`, `while`, `do while`, `for`.
- MIPS Decision making instructions are the conditional branches: `beq` and `bne`.
- In order to help the conditional branches make decisions concerning inequalities, we introduce a single instruction: "Set on Less Than" called `slt`, `slti`, `sltu`, `sltiu`
- Unsigned add/sub don't cause overflow
- New MIPS Instructions:

```
beq, bne, j, sll, srl
slt, slti, sltu, sltiu
addu, addiu, subu
```


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

- 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
```

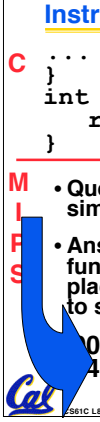
Instruction Support for Functions (3/6)

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
04 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 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)

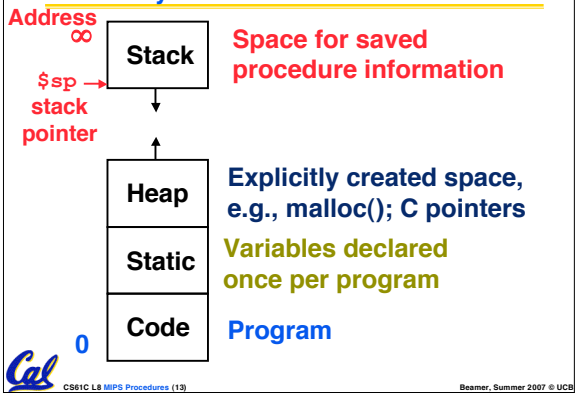
```
int sumSquare(int x, int y) {
    return mult(x,x)+ y;
}
```

- 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



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

        add $a1,$a0,$zero # prep args
        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

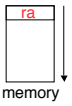
- Called with a `jal` instruction, returns with a `jr $ra`
- Accepts up to 4 arguments in `$a0`, `$a1`, `$a2` and `$a3`
- Return value is always in `$v0` (and if necessary in `$v1`)
- Must follow register conventions (even in functions that only you will call)! So what are they?
  - We'll see these in a few slides…

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 (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.

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

Peer Instruction

```
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…

	ABC
1:	FFF
2:	FFT
3:	FTF
4:	FTT
5:	TFF
6:	TFT
7:	TTF
8:	TTT

Bonus Example: 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;
 }
```

Bonus Example: 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); ... }
```

Bonus Example: 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

Bonus Example: Compile This (4/5)

```
mult:
    add   $t0,$0,$0      # prod=0
Loop:
    slt   $t1,$0,$a1     # mlr > 0?
    beq   $t1,$0,Fin     # no=>Fin
    add   $t0,$t0,$a0    # prod+=mc
    addi  $a1,$a1,-1     # mlr-=1
    j     Loop           # goto Loop
Fin:
    add   $v0,$t0,$0     # $v0=prod
    jr    $ra            # return
```

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

Bonus Example: 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)

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.

"And in Conclusion…"

- 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, lb, sb, lbu`
  - 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!