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UCB CS61C : Machine Structures

Lecture 8 – Decisions & and Introduction to MIPS Procedures

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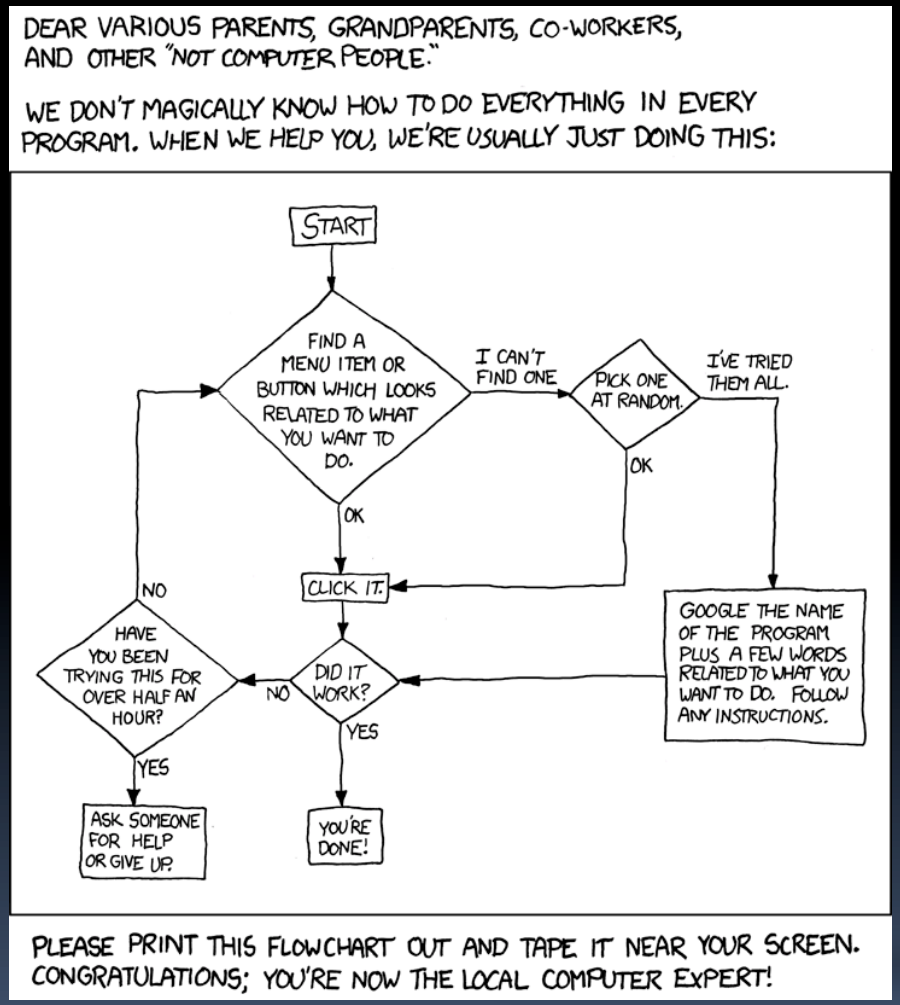
http://www.xkcd.org/627/



"And in Review…"

- Memory is byte-addressable, but `lw` and `sw` access one word at a time.
- A pointer (used by `lw` and `sw`) is just a memory address, we can add to it or subtract from it (using offset).
- 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`.
- One can store and load (signed and unsigned) bytes as well as words with `lb`, `lbu`
- Unsigned add/sub don't signal overflow
- Loops using beq and bne.
- New Instructions:

```
lw, sw, beq, bne, j, lb, sb, lbu,
  addu, addiu, subu, srl, sll … WOW
```

Inequalities in MIPS (1/4)

- Until now, we've only tested equalities (== and != in C). General programs need to test < and > as well.
- Introduce MIPS Inequality Instruction:
  - "Set on Less Than"
  - Syntax: `slt reg1,reg2,reg3`
  - Meaning: `reg1 = (reg2 < reg3);`

```
if (reg2 < reg3)
    reg1 = 1;
else reg1 = 0;
```

Same thing…

"set" means "change to 1",
"reset" means "change to 0".

Inequalities in MIPS (2/4)

- How do we use this? Compile by hand:

```
if (g < h) goto Less; #g:$s0,h:$s1
```

- Answer: compiled MIPS code…

```
slt $t0,$s0,$s1 # $t0 = 1 if g<h
                # $t0 = 0 if g>=h
bne $t0,$0,Less # goto Less
                # if $t0!=0
```

- Register **$0** always contains the value 0, so **bne** and **beq** often use it for comparison after an **slt** instruction.
- A **slt** → **bne** pair means **if(… < …)goto…**

Inequalities in MIPS (3/4)

- Now we can implement <,
  but how do we implement >, ≤ and ≥ ?
- We could add 3 more instructions, but:
  - MIPS goal: Simpler is Better
- Can we implement ≤ in one or more instructions using just `slt` and branches?
  - What about >?
  - What about ≥?

Inequalities in MIPS (4/4)

- Lets compile this by hand:

```
if (g >= h) goto Less; #g:$s0,h:$s1
```

- Answer: compiled MIPS code…

```
slt $t0,$s0,$s1 # $t0 = 1 if g<h
                # $t0 = 0 if g>=h
beq $t0,$0,Less # goto less if g>=h
```

Two independent variations possible:

Use `slt $t0,$s1,$s0` instead of `slt $t0,$s0,$s1`

Use `bne` instead of `beq`

Immediates in Inequalities

- There is also an immediate version of `slt` to test against constants: `slti`
  - Helpful in `for` loops

C

```
Loop: ...
      if (g >= 1) goto Loop;
```

MIPS

```
Loop:   . . .

slti $t0,$s0,1      # $t0 = 1 if g < i
                    # $t0 = 0 if g>=1)
beq  $t0,$0,Loop    # goto Loop if g>=1
```

An `slt` → `beq` pair means `if(… ≥ …)goto…`

What about unsigned numbers?

- Also unsigned inequality instructions:

  `sltu`, `sltiu`

…which sets result to `1` or `0` depending on unsigned comparisons

- What is value of `$t0`, `$t1`?

(`$s0 = FFFF FFFA`$_{hex}$, `$s1 = 0000 FFFA`$_{hex}$)

```
slt $t0, $s0, $s1
sltu $t1, $s0, $s1
```

MIPS Signed vs. Unsigned – diff meanings!

- MIPS terms Signed/Unsigned "overloaded":
  - Do/Don't sign extend
    - `(lb, lbu)`
  - Do/Don't overflow
    - `(add, addi, sub, mult, div)`
    - `(addu, addiu, subu, multu, divu)`
  - Do signed/unsigned compare
    - `(slt, slti/sltu, sltiu)`

Peer Instruction

```
Loop:addi $s0,$s0,-1    # i = i - 1
     slti $t0,$s1,2     # $t0 = (j < 2)
     beq  $t0,$0 ,Loop  # goto Loop if $t0 == 0
     slt  $t0,$s1,$s0   # $t0 = (j < i)
     bne  $t0,$0 ,Loop  # goto Loop if $t0 != 0
```

($s0=i, $s1=j)

What C code properly fills in the blank in loop below?

```
do {i--;} while(____);
```

a)	j	<	2	&&	j	<	i
b)	j	≥	2	&&	j	<	i
c)	j	<	2	&&	j	≥	i
d)	j	≥	2	&&	j	≥	i
e)	j	>	2	&&	j	<	i
a)	j	<	2	||	j	<	i
b)	j	≥	2	||	j	<	i
c)	j	<	2	||	j	≥	i
d)	j	≥	2	||	j	≥	i
e)	j	>	2	||	j	<	i

Administrivia

- Project 1 due Friday!
  - (ok, Saturday, but tell your brain it's Friday!)
- Projector bulb is dying
  - I tried to adjust the color scheme accordingly. I called ETS. Should be fixed soon.
- HW 3 and 4 now online
- Midterm:
  - TWO WEEKS FROM TOMORROW!
  - Friday, July 16th. 9:30am-12:30pm. Room: **100 Lewis**
- Other administrivia?

C functions

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

What information must compiler/programmer keep track of?

```
/* 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 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;
 }
```

- 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.

MIPS

```
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)

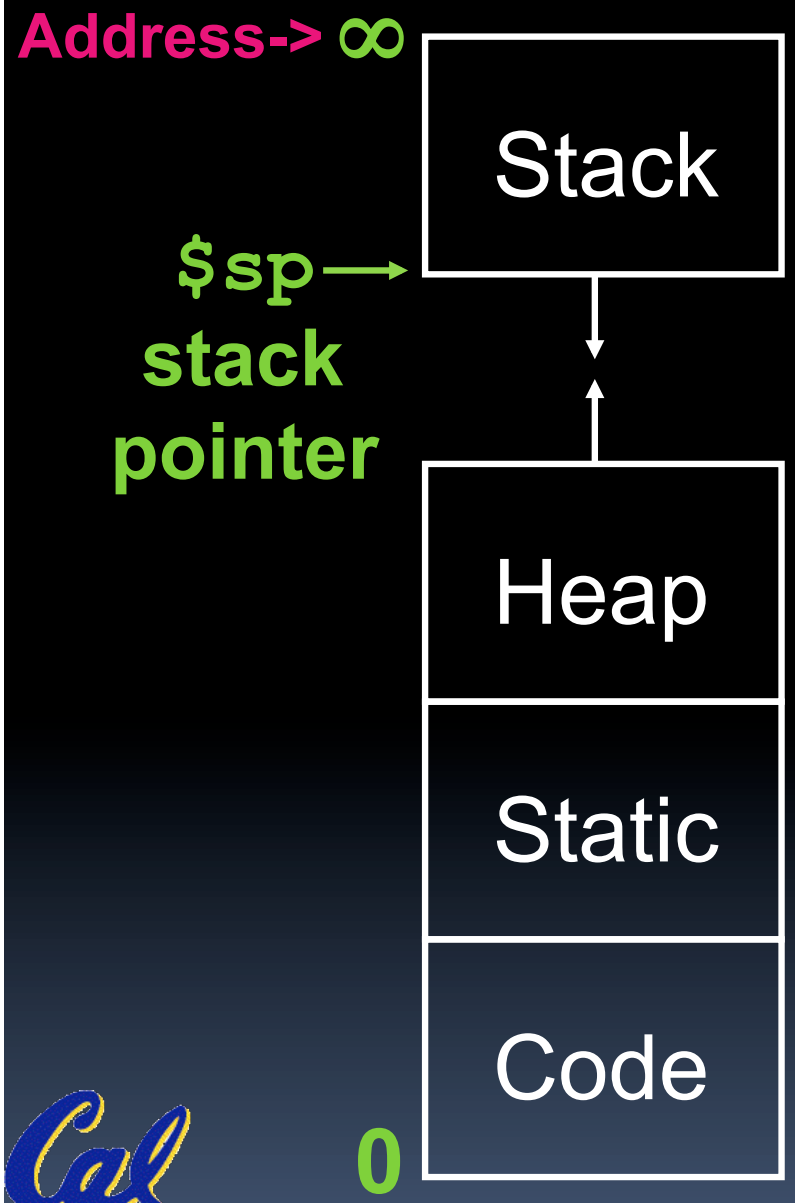
```
int sumSquare(int x, int y) {
   return mult(x,x)+ y;
}
```

- 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 review



Space for saved procedure information

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

Variables declared once per program; e.g., globals

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
        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

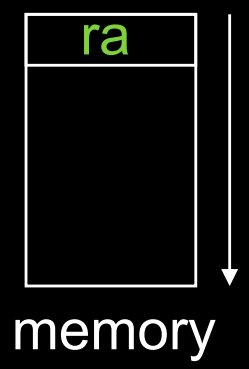
So what are they? NEXT TIME

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

Already discussed New Not yet

(From MIPS green sheet)
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.

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…"

- 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`
- 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!

"And in Conclusion to the conclusion…"

We are 1/4th of the way done!

Bonus Slides

Example: The C Switch Statement (1/3)

- Choose among four alternatives depending on whether `k` has the value 0, 1, 2 or 3. Compile this C code:

```
switch (k) {
 case 0: f=i+j; break; /* k=0 */
 case 1: f=g+h; break; /* k=1 */
 case 2: f=g-h; break; /* k=2 */
 case 3: f=i-j; break; /* k=3 */
}
```

Example: The C Switch Statement (2/3)

- This is complicated, so simplify.
- Rewrite it as a chain of if-else statements, which we already know how to compile:

```
if(k==0) f=i+j;
   else if(k==1) f=g+h;
      else if(k==2) f=g-h;
         else if(k==3) f=i-j;
```

- Use this mapping:

```
f:$s0, g:$s1, h:$s2,
i:$s3, j:$s4, k:$s5
```

Example: The C Switch Statement (3/3)

- Final compiled MIPS code:

```
     bne $s5,$0,L1      # branch k!=0
     add  $s0,$s3,$s4  #k==0 so f=i+j
     j    Exit          # end of case so Exit
L1:  addi $t0,$s5,-1   # $t0=k-1
     bne  $t0,$0,L2    # branch k!=1
     add  $s0,$s1,$s2  #k==1 so f=g+h
     j    Exit          # end of case so Exit
L2:  addi $t0,$s5,-2   # $t0=k-2
     bne  $t0,$0,L3    # branch k!=2
     sub  $s0,$s1,$s2  #k==2 so f=g-h
     j    Exit          # end of case so Exit
L3:  addi $t0,$s5,-3   # $t0=k-3
     bne  $t0,$0,Exit  # branch k!=3
     sub  $s0,$s3,$s4  # k==3 so f=i-j
Exit:
```