Lecture 4

Instruction Set Architecture(2)

Recap

- Instruction set architecture
  - RISC vs. CISC
  - MIPS/ARM/x86
- Instructions:
  - Arithmetic instruction: add, sub, …
  - Data transfer instruction: lw, sw, lh, sh, …
  - Logical instruction: and, or, …
  - Conditional branch beq, bne, …
- Basic concepts:
  - Operands: register vs. memory vs. immediate
  - Numeric representation: signed, unsigned, sign extension
  - Instruction format: R-format vs. I-format

Today’s topic

- More control instructions
- Procedure call/return

Control Instructions: if else

- Conditional branch: Jump to instruction L1 if register1 equals register2:   beq   register1, register2, L1
  Similarly, bne and slt (set-on-less-than)

- Unconditional branch:
  j   L1
  jr $s0

Convert to assembly:

```
if  (i == j)
    f = g+h;
else
    f = g-h;
```

```
bne   $s3, $s4, Else
add   $s0, $s1, $s2
j       Exit
Else:   sub   $s0, $s1, $s2
Exit:
```

Loop

Convert to assembly:

```
while   (save[i] == k)
    i += 1;
```

i and k are in $s3 and $s5 and base of array save[] is in $s6

```
Loop:  sll    $t1, $s3, 2
       add    $t1, $t1, $s6
       lw     $t0, 0($t1)
       bne    $t0, $s5, Exit
       addi   $s3, $s3, 1
       j      Loop
Exit:
```

More Conditional Operations

- How to compile:
  - If (a < b) …, else, …
- slt rd, rs, rt
  - if (rs < rt) rd = 1; else rd = 0;
- slti rt, rs, constant
  - if (rs < constant) rt = 1; else rt = 0;
- Use in combination with beq, bne

```
slt $t0, $s1, $s2  # if ($s1 < $s2)
bne $t0, $zero, L  #   branch to L
```

Example

Convert to assembly:

Convert to assembly:

```
if  (i < j)
    f = g+h;
else
    f = g-h;
```

```
        slt    $t0, $s3, $s4
        be     $t0, $zero, Else
        add    $s0, $s1, $s2
        j      Exit
Else:   sub    $s0, $s1, $s2
Exit:
```

i and j are in $s3 and $s4,
f,g and h are in $s0, $s1 and $s2

Pseudo Instructions

- blt $s0, $s1, Label ⟺ slt $s2, $s0, $s1
  - If s0<s1, jump to Label

  bne $s2, $zero, Label
- bgt $s0, $s1, Label
  - If s0<s1, jump to Label
- ble $s0, $s1, Label
  - If s0<=s1, jump to Label
- beqz $s0, Label
  - If s0==0, jump to Label
- li $t0, 5
  - Load immediate, t0 = 5
- Move $t0, $s0
  - t0 = s0

There is no such instructions in hardware, The assembler translates them into a combination of real instructions

Branch Instruction Design

- Why not blt, bge, etc?
- Hardware for <, ≥, … slower than =, ≠
  - Combining with branch involves more work per instruction, requiring a slower clock
  - All instructions penalized!
- beq and bne are the common case
- This is a good design compromise

Signed vs. Unsigned

- Signed comparison: slt, slti
- Unsigned comparison: sltu, sltui
- Example
  - \$s0 = 1111 1111 1111 1111 1111 1111 1111 1111
  - \$s1 = 0000 0000 0000 0000 0000 0000 0000 0001
  - slt \$t0, \$s0, \$s1 # signed
    - $-1 < +1 \Rightarrow \$t0 = 1$
  - sltu \$t0, \$s0, \$s1 # unsigned
    - $+4{,}294{,}967{,}295 > +1 \Rightarrow \$t0 = 0$

The register contains bits without meaning.

Are the bits represents a signed number or unsigned one? See the instruction!

Procedures

- A procedure or function is one tool used by the programmers to structure programs
  - Benefit: easy to understand, reuse code
- We can think of a procedure like a spy
  - acquires resources → performs task → covers his tracks → returns back with desired result
- When the procedure is executed (when the caller calls the callee), there are six steps
  - parameters (arguments) are placed where the callee can see them
  - control is transferred to the callee
  - acquire storage resources for callee
  - execute the procedure
  - place result value where caller can access it
  - return control to caller

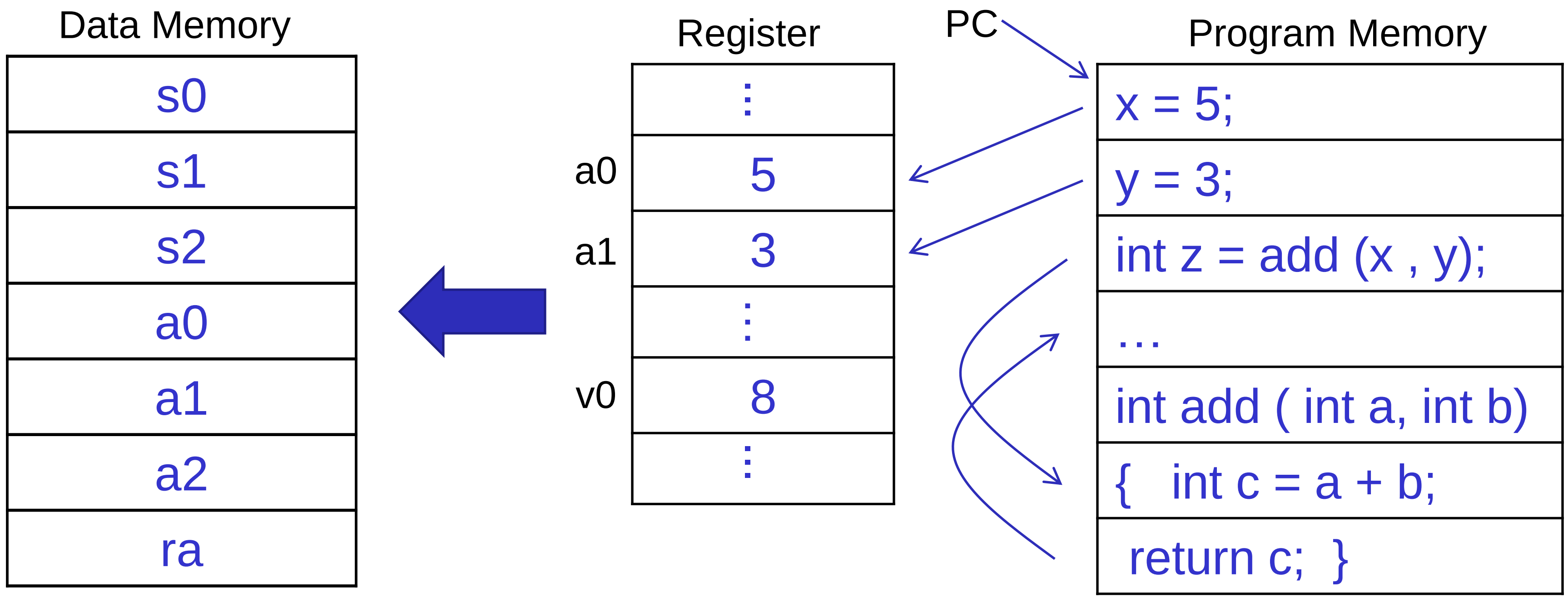
Procedure Calling

Caller:

```
int x = 5;
int y = 3;
int z = add (x , y);
x = x + 7;
…
```

callee:

```
int add ( int a, int b)
{
    int c = a + b;
    return c;
}
```



Registers Used during Procedure Calling

- The registers are used to hold data between the caller and the callee
  - $a0 - $a3: four argument registers to pass parameters
  - $v0 - $v1: two value registers to return the values
  - $ra: one return address register to return to the point of origin in the caller

Jump and Link

- *program counter* (PC)
  - A special register maintains the address of the instruction currently being executed
- The procedure call is executed by invoking the jump-and-link (jal) instruction – the current PC (actually, PC+4) is saved in the register $ra and we jump to the procedure's address (the PC is accordingly set to this address)

  jal   NewProcedureAddress

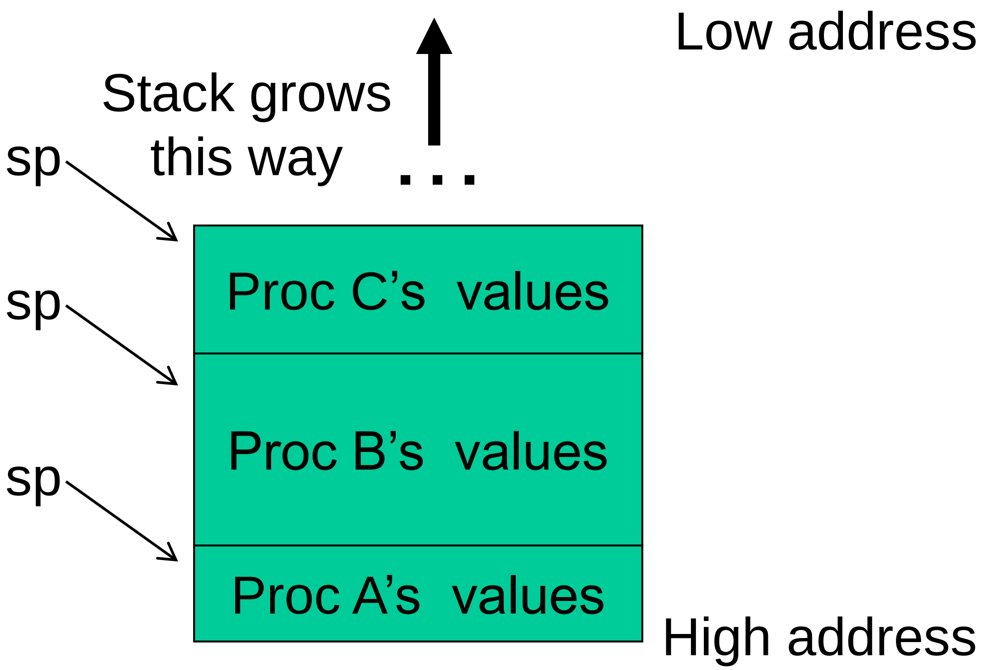
- Since jal may over-write a relevant value in $ra, it must be saved somewhere (in memory?) before invoking the jal instruction
- How do we return control back to the caller after completing the callee procedure?

Registers

- The 32 MIPS registers are partitioned as follows:
  - Register 0 : $zero always stores the constant 0
  - Regs 2-3 : $v0, $v1 return values of a procedure
  - Regs 4-7 : $a0-$a3 input arguments to a procedure
  - Regs 8-15 : $t0-$t7 temporaries
  - Regs 16-23: $s0-$s7 variables
  - Regs 24-25: $t8-$t9 more temporaries
  - Reg 28 : $gp global pointer
  - Reg 29 : $sp stack pointer
  - Reg 30 : $fp frame pointer
  - Reg 31 : $ra return address

The Stack

The registers for a procedure are volatile, it disappears every time we switch procedures. Therefore, a procedure's values in the registers are backed up in memory on a stack




```
Proc  A

            call  Proc B
                     …
                     call Proc C
                        …
                     return
            return
return
```

Storage Management on a Call/Return

- A new procedure must create space for all its variables on the stack
- Before executing the jal, the caller must save relevant values in $s0-$s7, $a0-$a3, $ra, temps into its own stack space
- Arguments are copied into $a0-$a3; the jal is executed
- After the callee creates stack space, it updates the value of $sp
- Once the callee finishes, it copies the return value into $v0, frees up stack space, and $sp is incremented
- On return, the caller may bring in its stack values, ra, temps into registers
- The responsibility for copies between stack and registers may fall upon either the caller or the callee

Example 1- leaf procedure

```
int  leaf_example (int g, int h, int i, int j)
{
    int f ;
    f = (g + h) – (i + j);
    return f;
}
```

```
leaf_example:
   addi    $sp,  $sp,  -12
   sw      $t1, 8($sp)
   sw      $t0, 4($sp)
   sw      $s0, 0($sp)
   add     $t0, $a0, $a1
   add     $t1, $a2, $a3
   sub     $s0, $t0, $t1
   add     $v0, $s0, $zero
   lw      $s0, 0($sp)
   lw      $t0, 4($sp)
   lw      $t1, 8($sp)
   addi    $sp, $sp, 12
   jr      $ra
```

Save t0,t1,s0
Protect environment

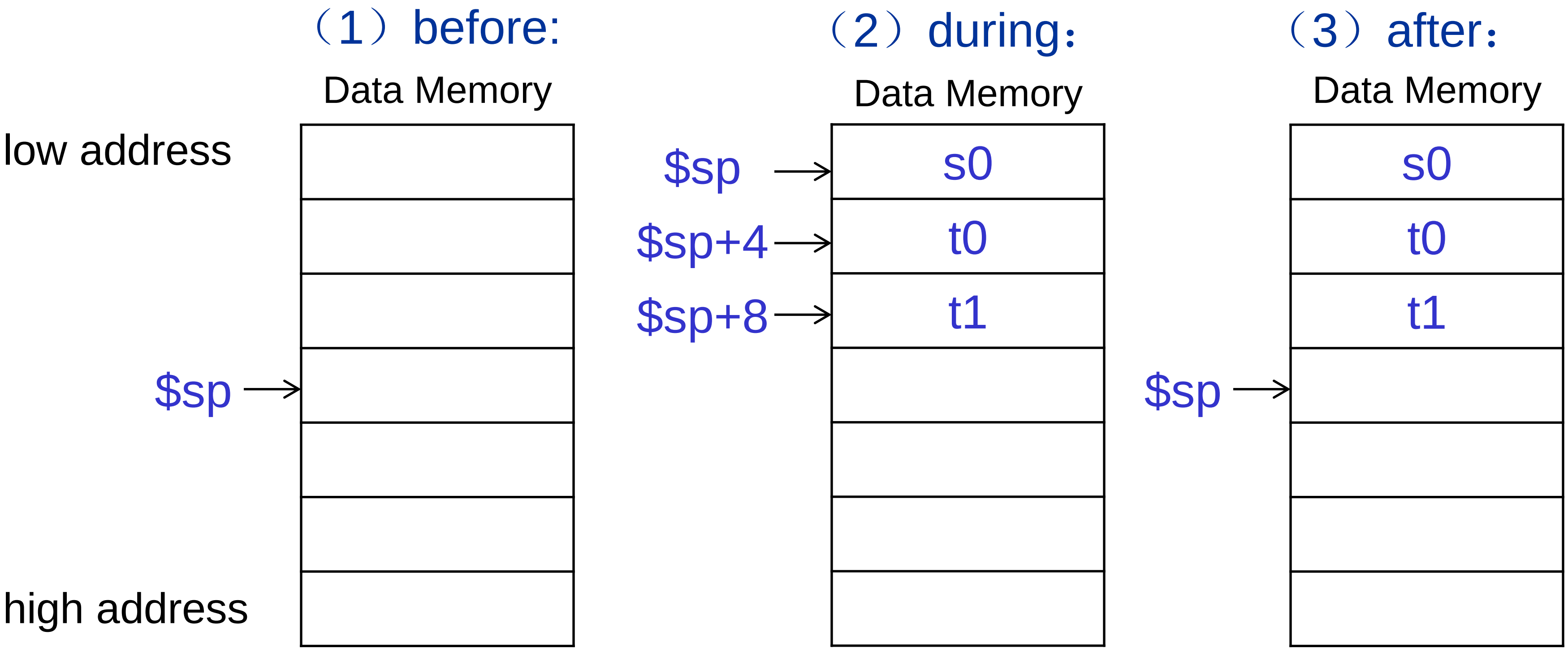
Procedure body

Restore t0 t1 s0

Return result

The caller has saved:
g→$a0,
h→$a1,
i→$a2,
j→$a3,
return address → $ra

Data in the stack in example 1



To avoid too many memory operations:

$t0 - $t9: temporary registers are not preserved by the callee

$s0 - $s7: saved registers must be preserved by the callee if used

Example 2 – non-leaf procedure

- Procedures that call other procedures
- For nested call, caller needs to save on the stack:
  - Its return address
  - Any arguments and temporaries needed after the call
- Restore from the stack after the call

Example 2 – non-leaf procedure

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

```
fact:
    addi     $sp, $sp, -8
    sw       $ra, 4($sp)
    sw       $a0, 0($sp)
    slti     $t0, $a0, 1
    beq      $t0, $zero, L1
      addi   $v0, $zero, 1
      addi   $sp, $sp, 8
      jr     $ra
L1:
    addi     $a0, $a0, -1
    jal      fact
    lw       $a0, 0($sp)
    lw       $ra, 4($sp)
    addi     $sp, $sp, 8
    mul      $v0, $a0, $v0
    jr       $ra
```

Compare n<1

Return 1

Fact(n-1)

Return n*fact(n-1)

Notes:

The caller saves $a0 and $ra in its stack space.

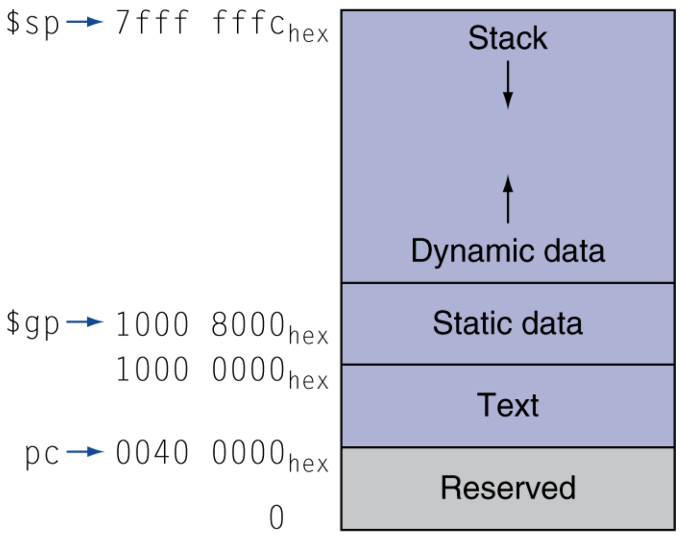
Temps are never saved.

Saving Conventions

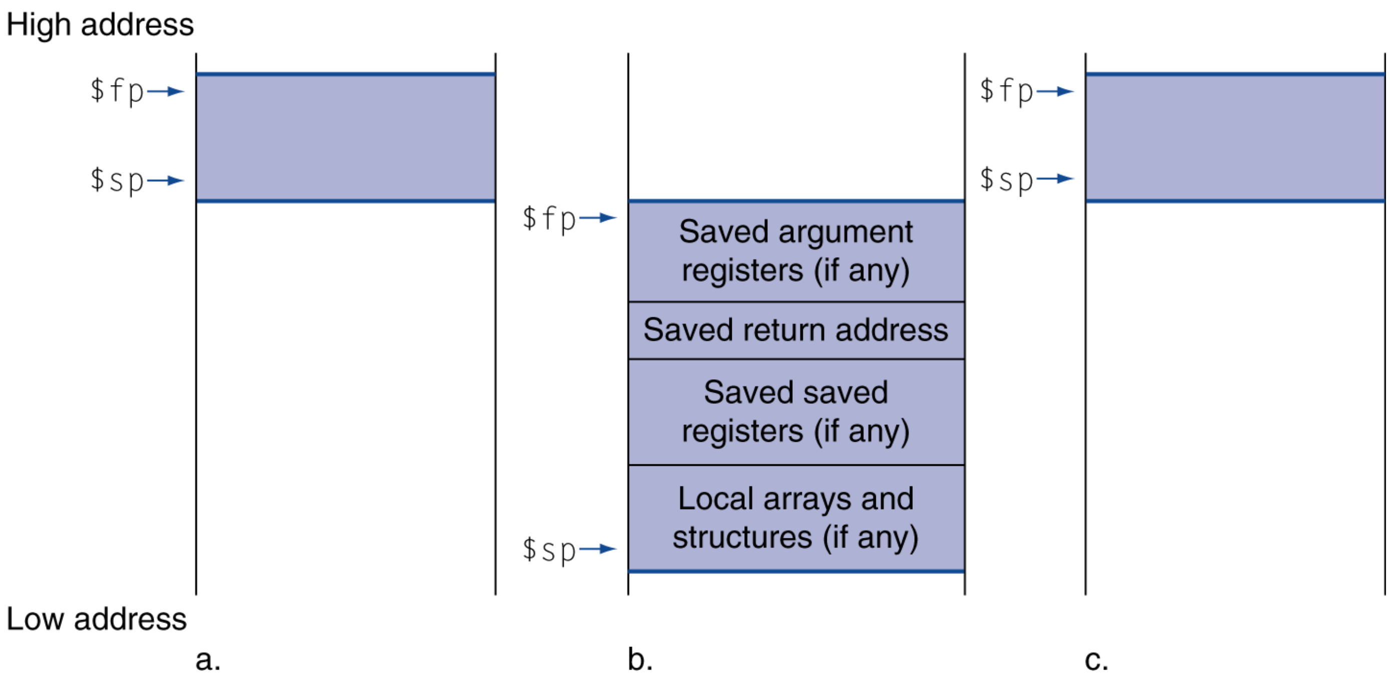
- Caller saved: Temp registers \$t0-\$t9 (the callee won't bother saving these, so save them if you care), \$ra (it's about to get over-written), \$a0-\$a3 (so you can put in new arguments)
- Callee saved: \$s0-\$s7 (these typically contain "valuable" data)

Memory Layout

- Text: program code
- Static data: global variables
  - e.g., static variables in C, constant arrays and strings
  - $gp initialized to address allowing $\pm$offsets into this segment
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: automatic storage



Local Data on the Stack



- Local data allocated by callee
  - e.g., C automatic variables
- Procedure frame (activation record)
  - Used by some compilers to manage stack storage

Homework #3

- Chapter 2： 2.19, 2.26, 2.31
- Due on Mar. 19