Lecture 6: Assembly Programs

- Today's topics:
  - Procedures
  - Examples
  - Large constants
  - The compilation process
  - A full example

Procedures

- Local variables, AR, $fp, $sp
- Scratchpad and saves/restores, $fp
- Arguments and returns
- jal and $ra

Procedures

- Each procedure (function, subroutine) maintains a scratchpad of register values – when another procedure is called (the callee), the new procedure takes over the scratchpad – values may have to be saved so we can safely return to the caller
  - 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

Jump-and-Link

- A special register (storage not part of the register file) maintains the address of the instruction currently being executed – this is the *program counter* (PC)

- 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)

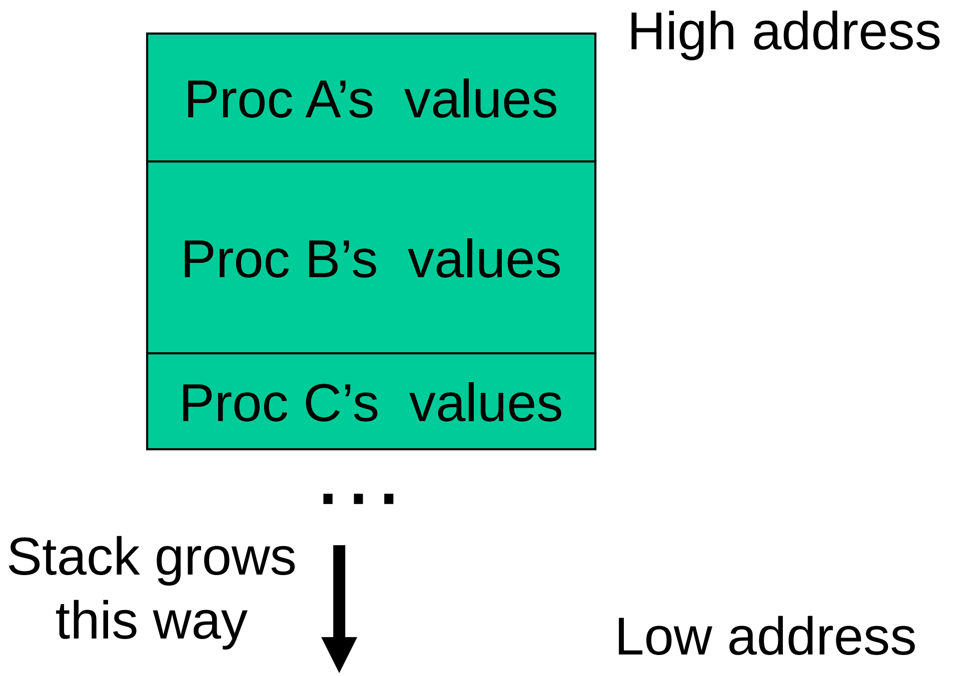
  jal NewProcedureAddress

- 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?

The Stack

The register scratchpad for a procedure seems volatile – it seems to disappear every time we switch procedures – a procedure's values are therefore backed up in memory on a stack




```
Proc  A

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

Saves and Restores

Storage Management on a Call/Return

- A new procedure must create space for all its variables on the stack
- Before/after executing the jal, the caller/callee must save relevant values in \$s0-\$s7, \$a0-\$a3, \$ra, temps into the 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/callee brings in 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 (pg. 98)

```
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
```

Notes:
In this example, the callee took care of saving the registers it needs.

The caller took care of saving its $ra and $a0-$a3.

Could have avoided using the stack altogether.

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)

- Read the Notes on the class webpage on this topic

Example 2 (pg. 101)

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

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

Notes:
The caller saves $a0 and $ra
in its stack space.
Temp register $t0 is never saved.

Dealing with Characters

- Instructions are also provided to deal with byte-sized and half-word quantities: lb (load-byte), sb, lh, sh
- These data types are most useful when dealing with characters, pixel values, etc.
- C employs ASCII formats to represent characters – each character is represented with 8 bits and a string ends in the null character (corresponding to the 8-bit number 0); A is 65, a is 97

Example 3 (pg. 108)

Convert to assembly:

```
void strcpy (char x[], char y[])
{
    int i;
    i=0;
    while  ((x[i] = y[i]) != `\0')
    i += 1;
}
```

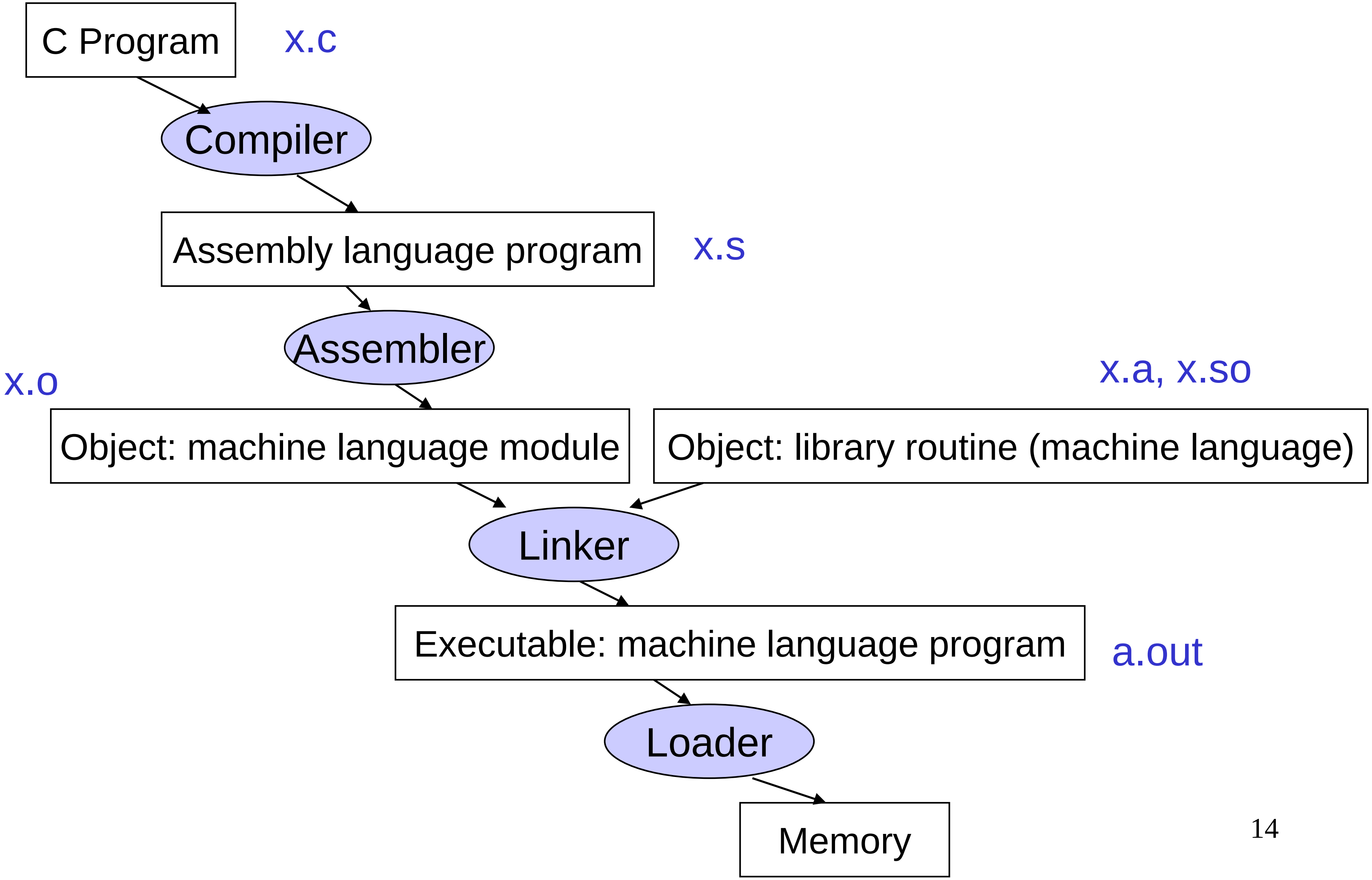
```
strcpy:
 addi    $sp, $sp, -4
 sw      $s0, 0($sp)
 add     $s0, $zero, $zero
L1: add  $t1, $s0, $a1
 lb      $t2, 0($t1)
 add     $t3, $s0, $a0
 sb      $t2, 0($t3)
 beq     $t2, $zero, L2
 addi    $s0, $s0, 1
 j       L1
L2: lw   $s0, 0($sp)
 addi    $sp, $sp, 4
 jr      $ra
```

Notes:
Temp registers not saved.

Large Constants

- Immediate instructions can only specify 16-bit constants
- The lui instruction is used to store a 16-bit constant into the upper 16 bits of a register… combine this with an OR instruction to specify a 32-bit constant
- The destination PC-address in a conditional branch is specified as a 16-bit constant, relative to the current PC
- A jump (j) instruction can specify a 26-bit constant; if more bits are required, the jump-register (jr) instruction is used

Starting a Program



Role of Assembler

- Convert pseudo-instructions into actual hardware instructions – pseudo-instrs make it easier to program in assembly – examples: “move”, “blt”, 32-bit immediate operands, etc.

- Convert assembly instrs into machine instrs – a separate object file (x.o) is created for each C file (x.c) – compute the actual values for instruction labels – maintain info on external references and debugging information

Role of Linker

- Stitches different object files into a single executable
  - patch internal and external references
  - determine addresses of data and instruction labels
  - organize code and data modules in memory
- Some libraries (DLLs) are dynamically linked – the executable points to dummy routines – these dummy routines call the dynamic linker-loader so they can update the executable to jump to the correct routine

Full Example – Sort in C (pg. 133)

```
void sort (int v[ ], int n)
{
    int i, j;
    for (i=0; i<n; i+=1) {
        for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) {
            swap (v,j);
        }
    }
}
```

```
void swap (int v[ ], int k)
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

- Allocate registers to program variables
- Produce code for the program body
- Preserve registers across procedure invocations

The swap Procedure

- Register allocation: $a0 and $a1 for the two arguments, $t0 for the temp variable – no need for saves and restores as we're not using $s0-$s7 and this is a leaf procedure (won't need to re-use $a0 and $a1)

```
swap:   sll   $t1, $a1, 2
        add   $t1, $a0, $t1
        lw    $t0, 0($t1)
        lw    $t2, 4($t1)
        sw    $t2, 0($t1)
        sw    $t0, 4($t1)
        jr    $ra
```

```
void swap (int v[], int k)
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

The sort Procedure

- Register allocation: arguments v and n use $a0 and $a1, i and j use $s0 and $s1; must save $a0 and $a1 before calling the leaf procedure

- The outer for loop looks like this: (note the use of pseudo-instrs)

```
            move   $s0, $zero          # initialize the loop
loopbody1:  bge    $s0, $a1, exit1     # will eventually use slt and beq
            … body of inner loop …
            addi   $s0, $s0, 1
            j      loopbody1
exit1:
```

```
for (i=0; i<n; i+=1) {
  for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) {
        swap (v,j);
  }
}
```

The sort Procedure

- The inner for loop looks like this:

```
            addi    $s1, $s0, -1          # initialize the loop
loopbody2:  blt     $s1, $zero, exit2     # will eventually use slt and beq
            sll     $t1,  $s1, 2
            add     $t2, $a0, $t1
            lw      $t3, 0($t2)
            lw      $t4, 4($t2)
            bgt     $t3, $t4, exit2
            … body of inner loop …
            addi    $s1, $s1, -1
            j       loopbody2
exit2:
```

```
for (i=0; i<n; i+=1) {
  for (j=i-1; j>=0 && v[j] > v[j+1]; j-=1) {
      swap (v,j);
  }
}
```

Saves and Restores

- Since we repeatedly call "swap" with $a0 and $a1, we begin "sort" by copying its arguments into $s2 and $s3 – must update the rest of the code in "sort" to use $s2 and $s3 instead of $a0 and $a1

- Must save $ra at the start of "sort" because it will get over-written when we call "swap"

- Must also save $s0-$s3 so we don't overwrite something that belongs to the procedure that called "sort"

Saves and Restores

```
sort:   addi    $sp, $sp, -20
        sw      $ra, 16($sp)
        sw      $s3, 12($sp)
        sw      $s2, 8($sp)
        sw      $s1, 4($sp)
        sw      $s0, 0($sp)
        move    $s2, $a0
        move    $s3, $a1
          …
        move    $a0, $s2        # the inner loop body starts here
        move    $a1, $s1
        jal     swap
          …
exit1:  lw      $s0, 0($sp)
          …
        addi    $sp, $sp, 20
        jr      $ra
```

9 lines of C code → 35 lines of assembly

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