Programming Universal Computers
Instruction Sets

Lecture 5

Prof. Bienvenido Velez

What do we know?

From

Instruction Set Architecture

To

Processor Implementation

What Next?

How do we get here in the first place?

Instruction Set Design

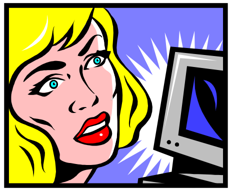
Outline

- Virtual Machines: Interpretation Revisited
- Example: From HLL to Machine Code
- Implementing HLL Abstractions
  - Control structures
  - Data Structures
  - Procedures and Functions

Virtual Machines (VM's)

Type of Virtual Machine	Examples	Instruction Elements	Data Elements	Comments
Application Programs	Spreadsheet, Word Processor	Drag & Drop, GUI ops, macros	cells, paragraphs, sections	Visual, Graphical, Interactive Application Specific Abstractions Easy for Humans Hides HLL Level
High-Level Language	C, C++, Java, FORTRAN, Pascal	if-then-else, procedures, loops	arrays, structures	Modular, Structured, Model Human Language/Thought General Purpose Abstractions Hides Lower Levels
Assembly-Level	SPIM, MASM	directives, pseudo-instructions, macros	registers, labelled memory cells	Symbolic Instructions/Data Hides some machine details like alignment, address calculations Exposes Machine ISA
Machine-Level (ISA)	MIPS, Intel 80x86	load, store, add, branch	bits, binary addresses	Numeric, Binary Difficult for Humans

Computer Science in Perspective



People

Application Programs

High-Level Language

Assembly Language

Machine Language (ISA)

INEL 4206

computers

Computer Human Interaction, User Interfaces

CS1/CS2, Programming, Data Structures

Programming Languages, Compilers

Computer Architecture

INTERPRETATION

A **CORE** theme all throughout Computer Science

Computing Integer Division
Iterative C++ Version

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

We ignore procedures and I/O for now

Easy I
A Simple Accumulator Processor
Instruction Set Architecture (ISA)

Instruction Set

Symbolic Name	Opcode	Action I=0	Symbolic Name	Action I=1
Comp	00 000	AC ← not AC	Comp	AC <- not AC
ShR	00 001	AC ← AC / 2	ShR	AC ← AC / 2
BrN*i*	00 010	AC < 0 ⇒ PC ← X	BrN	AC < 0 ⇒ PC ← MEM[X]
Jump*i*	00 011	PC ← X	Jump	PC ← MEM[X]
Store*i*	00 100	MEM[X] ← AC	Store	MEM[MEM[X]] ← AC
Load*i*	00 101	AC ← MEM[X]	Load	AC ← MEM[MEM[X]]
And*i*	00 110	AC ← AC and X	And	AC ← AC and MEM[X]
Add*i*	00 111	AC ← AC + X	Add	AC ← AC + MEM[X]

Computing Integer Division

Iterative C++ Version

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

C++
HLL

Easy-I
Assembly Language

Spring 2003

Computing Integer Division

Iterative C++ Version

Translate Data: Global Layout

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

```
0:      andi    0       # AC = 0
        addi    12
        storei  1000    # a = 12 (a   tored @ 1000)
        andi    0       # AC = 0
        addi    4
        storei  1004    # b = 4      tored @ 1004)
        andi    0       # AC =
        storei  1008    # res      0 (result @ 1008)
```

Issues
•Memory allocation
•Data Alignment
•Data Sizing

C++
HLL

Easy-I
Assembly Language

Spring 2003

Translate Code: Conditionals
If-Then

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

C++
HLL

Easy-I
Assembly Language

```
0:      andi    0       # AC = 0
        addi    12
        storei  1000    # a = 12 (a stored @ 1000)
        andi    0       # AC = 0
        addi    4
        storei  1004    # b = 4 (b stored @ 1004)
        andi    0       # AC = 0
        storei  1008    # result = 0 (result @ 1008)
main:   loadi   1004    # compute a - b in AC
        comp            # using 2's complement add
        addi    1
        add     1000
        brni    exit    # exit if AC negative

exit:
```

Issues
- Must translate HLL boolean expression into ISA-level branching condition

Computing Integer Division
Iterative C++ Version

Translate Code: Iteration (loops)

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

C++
HLL

Easy-I
Assembly Language

```
0:      andi    0         # AC = 0
        addi    12
        storei  1000      # a = 12 (a stored @ 1000)
        andi    0         # AC = 0
        addi    4
        storei  1004      # b = 4 (b stored @ 1004)
        andi    0         # AC = 0
        storei  1008      # result = 0 (result @ 1008)
main:   loadi   1004      # compute a – b in AC
        comp              # using 2's complement add
        addi    1
        add     1000
        brni    exit      # exit if AC negative
loop:   loadi   1000
        brni    endloop




        jump    loop
endloop:
exit:
```

Computing Integer Division

Iterative C++ Version

Translate Code: Arithmetic Ops

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

```
0:        andi    0          # AC = 0
          addi    12
          storei  1000       # a = 12 (a stored @ 1000)
          andi    0          # AC = 0
          addi    4
          storei  1004       # b = 4 (b stored @ 1004)
          andi    0          # AC = 0
          storei  1008       # result = 0 (result @ 1008)
main:     loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000
          brni    exit       # exit if AC negative
loop:     loadi   1000
          brni    endloop
          loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000       # Uses indirect bit I = 1



          jumpi   loop
endloop:
exit:
```

C++
HLL

Easy-I
Assembly Language

Computing Integer Division
Iterative C++ Version

Translate Code: Assignments

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```

C++
HLL

Easy-I
Assembly Language

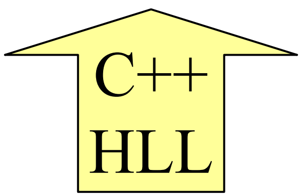
```
0:        andi    0          # AC = 0
          addi    12
          storei  1000       # a = 12 (a stored @ 1000)
          andi    0          # AC = 0
          addi    4
          storei  1004       # b = 4  (b stored @ 1004)
          andi    0          # AC = 0
          storei  1008       # result = 0 (result @ 1008)
main:     loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000
          brni    exit       # exit if AC negative
loop:     loadi   1000
          brni    endloop
          loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000       # Uses indirect bit I = 1
          storei  1000



          jump loop
endloop:
exit:
```

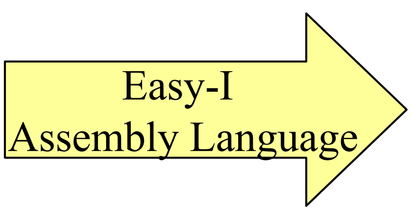
Computing Integer Division

Iterative C++ Version

Translate Code: Increments

```
int a = 12;
int b = 4;
int result = 0;
main () {
  if (a >= b) {
    while (a > 0) {
      a = a - b;
      result ++;
    }
  }
}
```






```
0:        andi   0         # AC = 0
          addi   12
          storei 1000      # a = 12 (a stored @ 1000)
          andi   0         # AC = 0
          addi   4
          storei 1004      # b = 4  (b stored @ 1004)
          andi   0         # AC = 0
          storei 1008      # result = 0 (result @ 1008)
main:     loadi  1004      # compute a - b in AC
          comp             # using 2's complement add
          addi   1
          add    1000
          brni   exit      # exit if AC negative
loop:     loadi  1000
          brni   endloop
          loadi  1004      # compute a - b in AC
          comp             # using 2's complement add
          addi   1
          add    1000      # Uses indirect bit I = 1
          storei 1000
          loadi  1008      # result = result + 1
          addi   1
          storei 1008
          jumpi  loop
endloop:
exit:
```

Computing Integer Division

Easy I
Machine Code

Data

Address	Contents
1000	a
1004	b
1008	result

Challenge
Make this program as small and fast as possible

Address	I Bit	Opcode (binary)	X (base 10)
0	0	00 110	0
2	0	00 111	12
4	0	00 100	1000
6	0	00 110	0
8	0	00 111	4
10	0	00 100	1004
12	0	00 110	0
14	0	00 100	1008
16	0	00 101	1004
18	0	00 000	unused
20	0	00 111	1
22	1	00 111	1000
24	0	00 010	46
26	0	00 101	1000
28	0	00 010	46
30	0	00 101	1004
32	0	00 000	unused
34	0	00 111	1
36	0	00 100	1000
38	0	00 101	1008
40	0	00 111	1
42	0	00 100	1008
44	0	00 011	26

Program

Computing Integer Division

Iterative C++ Version

Revised Version
Optimization at the HLL level

```
int a = 0;
int b = 4;
int result = 0;
main () {
   while (a >= b) {
      a = a - b;
      result ++;
   }
}
```

C++
HLL

Easy-I
Assembly Language

```
0:        andi    0          # AC = 0
          addi    12
          storei  1000       # a = 12 (a stored @ 1000)
          andi    0          # AC = 0
          addi    4
          storei  1004       # b = 4   (b stored @ 1004)
          andi    0          # AC = 0
          storei  1008       # result = 0 (result @ 1008)
main:
loop:     loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000
          brni    exit       # exit if AC negative
          loadi   1004       # compute a – b in AC
          comp               # using 2's complement add
          addi    1
          add     1000       # Uses indirect bit I = 1
          storei  1000
          loadi   1008       # result = result + 1
          addi    1
          storei  1008
          jumpi   loop
endloop:
exit:
```

Translating Conditional Expressions

```
int a = 0;
int b = 4;
int result = 0;
main () {
  while (a >= b) {
    a = a - b;
    result ++;
  }
}
```

Translating Logical Expressions

loop exit condition

~(a >= b) ⇔ ~((a – b) >= 0)

⇔ ((a – b) < 0)

What if Loop Exit Condition was:

~(a < b) ⇔

⇔

⇔

⇔

Computing Integer Division
Iterative C++ Version

Peephole Optimization
Optimization at Assembly level

```
int a = 0;
int b = 4;
int result = 0;
main () {
  while (a >= b) {
    a = a - b;
    result ++;
  }
}
```

C++
HLL

Easy-I
Assembly Language

```
0:        andi    0           # AC = 0
          addi    12
          storei  1000        # a = 12 (a stored @ 1000)
          andi    0           # AC = 0
          addi    4
          storei  1004        # b = 4   (b stored @ 1004)
          andi    0           # AC = 0
          storei  1008        # result = 0 (result @ 1008)
main:
loop:     loadi   1004        # compute a – b in AC
          comp                # using 2's complement add
          addi    1
          add     1000
          brni    exit        # exit if AC negative
          storei  1000
          loadi   1008        # result = result + 1
          addi    1
          storei  1008
          jumpi   loop
endloop:
exit:
```

The MIPS Architecture
ISA at a Glance

- Reduced Instruction Set Computer (RISC)
- 32 general purpose 32-bit registers
- Load-store architecture: Operands in registers
- Byte Addressable
- 32-bit address space

The MIPS Architecture

32 Register Set (32-bit registers)

Register #	Reg Name	Function
r0	r0	Zero constant
r4-r7	a0-a3	Function arguments
r1	at	Reserved for Operating Systems
r30	fp	Frame pointer
r28	gp	Global memory pointer
r26-r27	k0-k1	Reserved for OS Kernel
r31	ra	Function return address
r16-r23	s0-s7	Callee saved registers
r29	sp	Stack pointer
r8-r15	t0-t7	Temporary variables
r24-r25	t8-t9	Temporary variables
r2-r3	v0-v1	Function return values

The MIPS Architecture
Main Instruction Formats

Simple and uniform 32-bit 3-operand instruction formats

–R Format: Arithmetic/Logic operations on registers

opcode 6 bits	rs 5 bits	rt 5 bits	rd 5 bits	shamt 5 bits	funct 6 bits

–I Format: Branches, loads and stores

opcode 6 bits	rs 5 bits	rt 5 bits	Address/Immediate 16 bits

–J Format: Jump Instruction

opcode 6 bits	rs 5 bits	rt 5 bits	Address/Immediate 16 bits

The MIPS Architecture

Examples of Native Instruction Set

Instruction Group	Instruction	Function
Arithmetic/ Logic	add $s1,$s2,$s3	$s1 = $s2 + $s3
	addi $s1,$s2,K	$s1 = $s2 + K
Load/Store	lw $s1,K($s2)	$s1 = MEM[$s2+K]
	sw $s1,K($s2)	MEM[$s2+K] = $s1
Jumps and Conditional Branches	beq $s1,$s2,K	if ($s1=$s2) goto PC + 4 + K
	slt $s1,$s2,$s3	if ($s2<$s3) $s1=1 else $s1=0
	j K	goto K
Procedures	jal K	$ra = PC + 4; goto K
	jr $ra	goto $ra

The SPIM Assembler

Examples of Pseudo-Instruction Set

Instruction Group	Syntax	Translates to:
Arithmetic/ Logic	neg $s1, $s2	sub $s1, $r0, $s2
	not $s1, $s2	nor $17, $18, $0
Load/Store	li $s1, K	ori $s1, $0, K
	la $s1, K	lui $at, 152 ori $s1, $at, -27008
	move $s1, $s2	
Jumps and Conditional Branches	bgt $s1, $s2, K	slt $at, $s1, $s2 bne $at, $0, K
	sge $s1, $s2, $s3	bne $s3, $s2, foo ori $s1, $0, 1 beq $0, $0, bar foo: slt $s1, $s3, $s2 bar:

Pseudo Instructions: translated to native instructions by Assembler

The SPIM Assembler

Examples of Assembler Directives

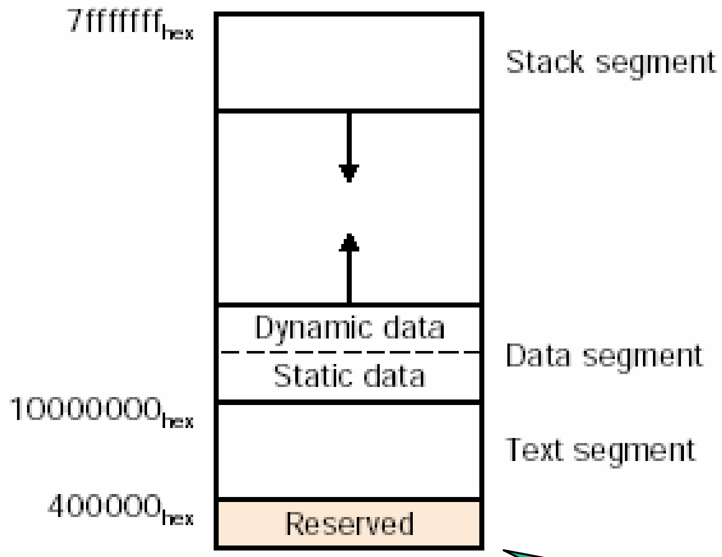
Group	Directive	Function
Memory Segmentation	.data <addr>	Data Segment starting at
	.text <addr>	Text (program) Segment
	.stack <addr>	Stack Segment
	.ktext <addr>	Kernel Text Segment
	.kdata <addr>	Kernel Data Segment
Data Allocation	x: .word <value>	Allocates 32-bit variable
	x: .byte <value>	Allocates 8-bit variable
	x: .ascii "hello"	Allocates 8-bit cell array
Other	.globl x	x is external symbol

Assembler Directives: Provide assembler additional info to generate machine code

Handy MIPS ISA References

- Appendix A: Patterson & Hennessy
- SPIM ISA Summary on class website
- Patterson & Hennessy Back Cover

The MIPS Architecture Memory Model



32-bit byte addressable address space

Computing Integer Division

Iterative C++ Version

MIPS/SPIM Version

```
int a = 12;
int b = 4;
int result = 0;
main () {
    while (a >= b)
       a = a - b;
       result ++;
    }
  }
}
```

C++

MIPS Assembly Language

```
            .data                              # Use HLL program as a comment
x:          .word       12                     # int x = 12;
y:          .word       4                      # int y = 4;
res:        .word       0                      # int res = 0;
            .globl      main
            .text
main:       la          $s0, x                 # Allocate registers for globals
            lw          $s1, 0($s0)            #   x in $s1
            lw          $s2, 4($s0)            #   y in $s2
            lw          $s3, 8($s0)            #   res in $s3
while:      bgt         $s2, $s1, endwhile     # while (x >= y) {
            sub         $s1, $s1, $s2                     #   x = x - y;
            addi        $s3, $s3, 1            #   res ++;
            j           while                  # }
endwhile:
            la          $s0, x                 # Update variables in memory
            sw          $s1, 0($s0)
            sw          $s2, 4($s0)
            sw          $s3, 8($s0)
```

Computing Integer Division

Iterative C++ Version

MIPS/SPIM Version

Input/Output in SPIM

```
int a = 12;
int b = 4;
int result = 0;
main () {
    while (a >= b) {
      a = a - b;
      result ++;
    }
  }
}
```

C++

MIPS Assembly Language

```
            .data                                   # Use HLL program as a comment
x:          .word       12                          # int x = 12;
y:          .word       4                           # int y = 4;
res:        .word       0                           # int res = 0;
pf1:        .asciiz     "Result = "
            .globl      main
            .text
main:       la          $s0, x                      # Allocate registers for globals
            lw          $s1, 0($s0)                 #   x in $s1
            lw          $s2, 4($s0)                 #   y in $s2
            lw          $s3, 8($s0)                 #   res in $s3
while:      bgt         $s2, $s1, endwhile          # while (x >= y) {
            sub         $s1, $s1, $s2               #   x = x - y;
            addi        $s3, $s3, 1                 #   res ++;
            j           while                       # }
endwhile:
            la          $a0, pf1                    # printf("Result = %d \n");
            li          $v0, 4                      # //system call to print_str
            syscall
            move        $a0, $s3
            li          $v0, 1                      # //system call to print_int
            syscall
            la          $s0, x                      # Update variables in memory
            sw          $s1, 0($s0)
            sw          $s2, 4($s0)
            sw          $s3, 8($s0)
```

SPIM Assembler Abstractions

- Symbolic Labels
  - Instruction addresses and memory locations
- Assembler Directives
  - Memory allocation
  - Memory segments
- Pseudo-Instructions
  - Extend native instruction set without complicating arquitecture
- Macros

Implementing Procedures

- Why procedures?
  - Abstraction
  - Modularity
  - Code re-use
- Initial Goal
  - Write segments of assembly code that can be re-used, or "called" from different points in the main program.
  - KISS: Keep It Simple Stupid:
    - no parameters, no recursion, no locals, no return values

Procedure Linkage Approach I

- Problem
  - procedure must determine where to return after servicing the call
- Solution: Architecture Support
  - Add a jump instruction that saves the return address in some place known to callee
    - MIPS: jal instruction saves return address in register $ra
  - Add an instruction that can jump to return address
    - MIPS: jr instruction jumps to the address contained in its argument register

Computing Integer Division (Procedure Version)

Iterative C++ Version

```
int a = 0;
int b = 0;
int res = 0;
main () {
  a = 12;
  b = 5;
  res = 0;
  div();
  printf("Res
}
void div(voic
  while (a >=
    a = a - b
    res ++;
  }
}
```

C++

```
            .data
x:          .word   0
y:          .word   0
res:        .word   0
pf1:        .asciiz "Result = "
pf2:        .asciiz "Remainder = "
            .globl      main
            .text
main:                                      # int main() {
                                           ssumes registers sx unused
            la          $s0, x
            li          $s1, 12
            sw          $s1, 0($s0)
            la          $s0, y
            li          $s2, 5
            sw          $s2, 0($s0)
            la          $s0, res                   #   res = 0;
            li          $s3, 0
            sw          $s3, 0($s0)
            jal         d                          #   div();
            lw          $s3, 0($s0)
            la          $a0, pf1                   #   printf("Result = %d \n");
            li          $v0, 4                     #   //system call to print_str
            syscall
            move        $a0, $s3
            li          $v0, 1                     #   //system call to print_int
            syscall
            la          $a0, pf2                   #   printf("Remainder = %d \n");
            li          $v0, 4                     #   //system call to print_str
            syscall
            move        $a0, $s1
            li          $v0, 1                     #   //system call to print_int
            syscall
            jr          $ra                        #   return // TO Operating System
```

Function Call

MIPS Assembly Language

Computing Integer Division (Procedure Version)

Iterative C++ Version

```
int a = 0;
int b = 0;
int res = 0;
main () {
  a = 12;
  b = 5;
  res = 0;
  div();
  printf("Res = %c
}
void div(void) {
  while (a >= b) {
    a = a - b;
    res ++;
  }
}
```

```
# div function
# PROBLEM: Must save args and registers before using them
d:                                          # void d(void) {
                                            #   // Allocate registers for globals
          la        $s0, x                  #   // x in $s1
          lw        $s1, 0($s0)
          la        $s0, y                  #   // y in $s2
          lw        $s2, 0($s0)
          la        $s0, res                #   // res in $s3
          lw        $s3, 0($s0)
while:    bgt       $s2, $s1, ewhile        #   while (x <= y) {
          sub       $s1, $s1, $s2           #     x = x - y
          addi      $s3, $s3, 1             #     res ++
          j         while                   #   }
ewhile:                                     #   // Update variables in memory
          la        $s0, x
          sw        $s1, 0($s0)
          la        $s0, y
          sw        $s2, 0($s0)
          la        $s0, res
          sw        $s3, 0($s0)
enddiv:   jr        $ra                     #   return;
                                            # }
```

C++

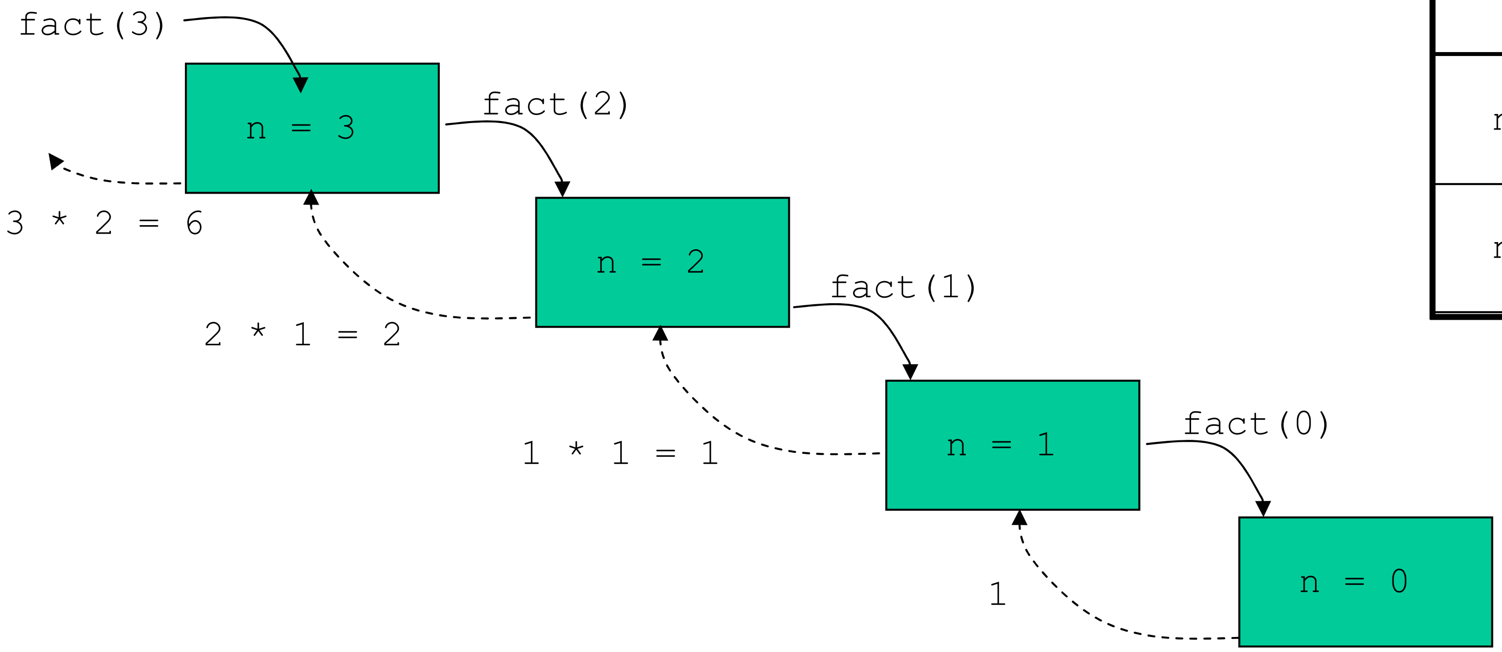
MIPS
Assembly Language

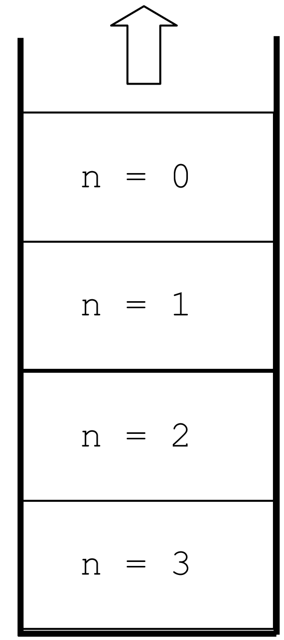
Pending Problems With Linkage Approach I

- Registers shared by all procedures
  - procedures must save/restore registers (use stack)
- Procedures should be able to call other procedures
  - save multiple return addresses (use stack)
- Lack of parameters forces access to globals
  - pass parameters in registers
- Recursion requires multiple copies of local data
  - store multiple procedure activation records (use stack)
- Need a convention for returning function values
  - return values in registers

Recursion Basics

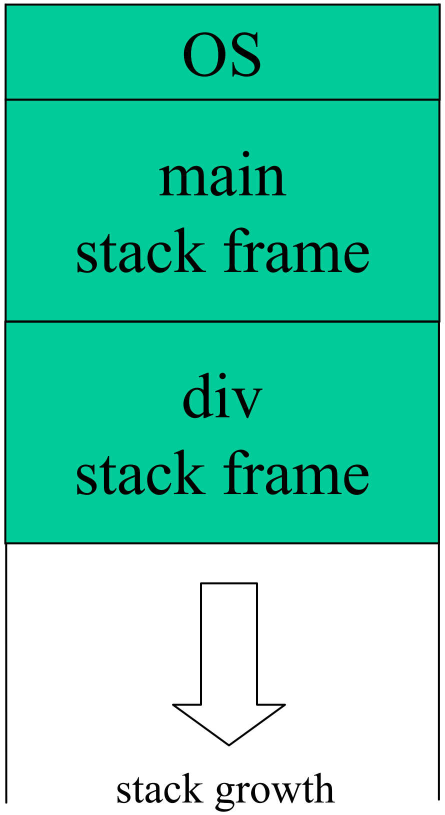
```
int fact(int n) {
    if (n == 0) {
        return 1;
    else
        return (fact(n-1) * n);
}
```



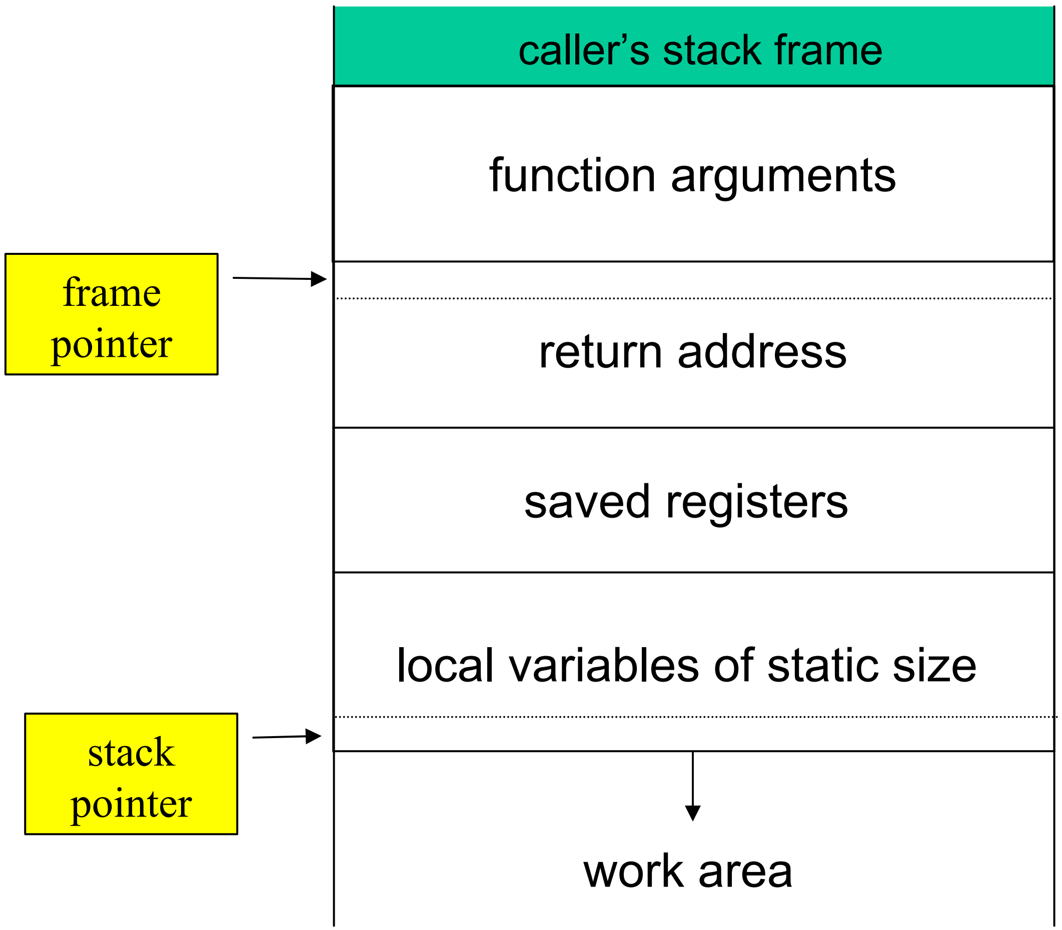


Solution: Use Stacks of Procedure Frames

- Stack frame contains:
  - Saved arguments
  - Saved registers
  - Return address
  - Local variables



Anatomy of a Stack Frame



Contract: Every function must leave the stack the way it found it

Example: Function Linkage using Stack Frames

```
int x = 0;
int y = 0;
int res = 0;
main () {
  x = 12;
  y = 5;
  res = div(x,y);
  printf("Res = %d",res);
}
int div(int a,int b) {
  int res = 0;
  if (a >= b) {
    res = div(a-b,b) + 1;
  }
  else {
    res = 0;
  }
  return res;
}
```

- Add return values
- Add parameters
- Add recursion
- Add local variables

Example: Function Linkage using Stack Frames

MIPS: Procedure Linkage Summary

- First 4 arguments passed in $a0-$a3
- Other arguments passed on the stack
- Return address passed in $ra
- Return value(s) returned in $v0-$v1
- Sx registers saved by callee
- Tx registers saved by caller