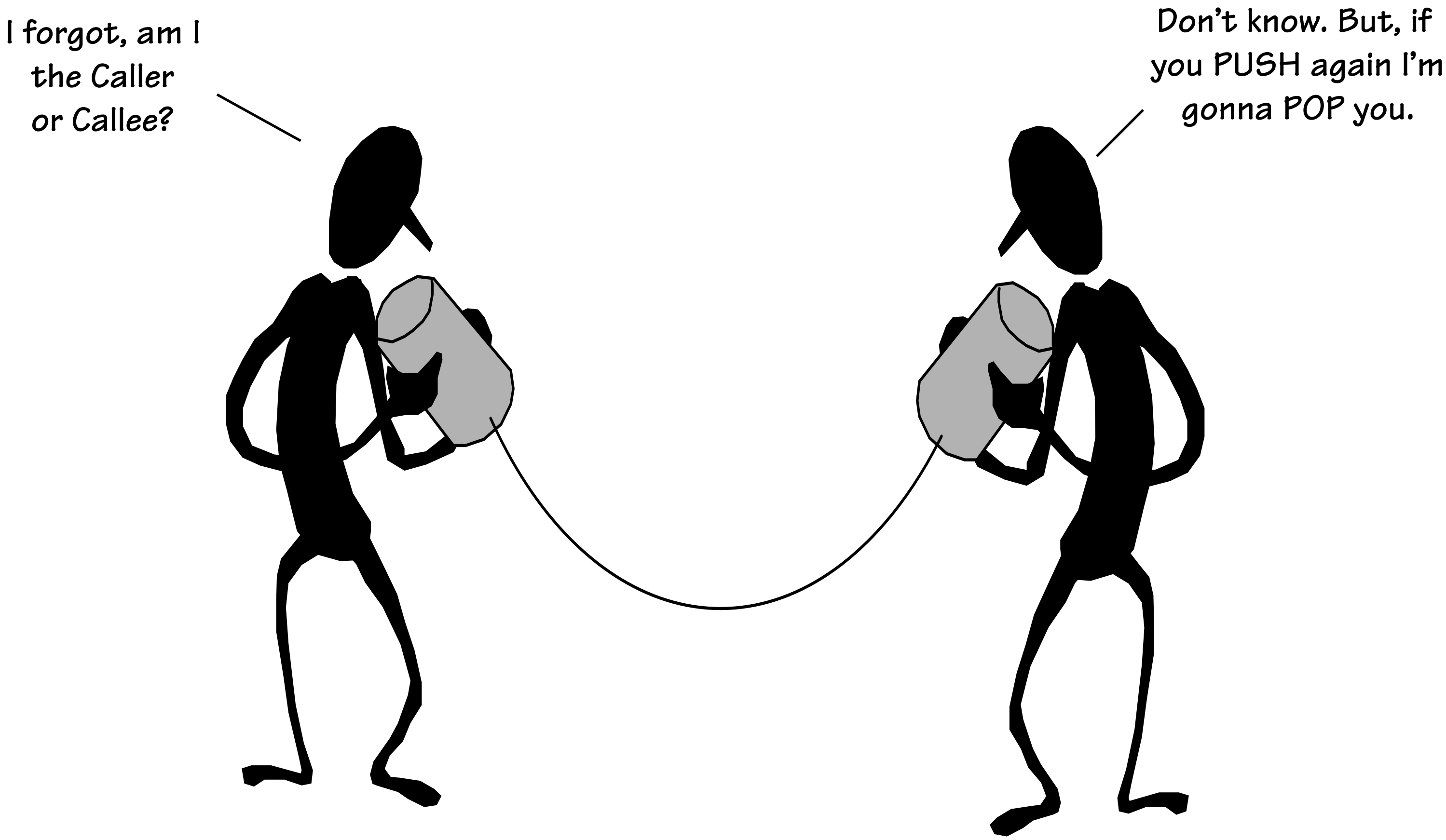
Stacks and Procedures

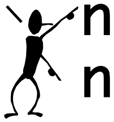


Support for High-Level Language constructs are an integral part of modern computer organization. In particular, support for subroutines, procedures, and functions.

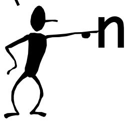
An Aside: Pseudoinstructions

MIPS has relatively few instructions, however, it is possible to "fake" new instructions by taking advantage of special ISA properties (i.e. %0 is always zero, clever use of immediate values)

Examples:



Why both?



Do Nothing

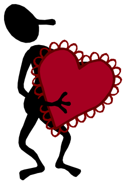
```
move  $d,$s         becomes     addi   $d,$s,0
neg   $d,$s         becomes     sub    $d,$0,$s
negu  $d,$s         becomes     subu   $d,$0,$s
not   $d,$s         becomes     nor    $d,$s,$0
subiu $d,$s,imm16 becomes     addiu  $d,$s,-imm16
b     label         becomes     beq    $0,$0,label
sge   $d,$s,$t      becomes     slt    $d,$t,$s
nop                 becomes     sll    $0,$0,0
```

Uber Pseudoinstruction

There is one pseudo instruction where MIPS goes crazy. It essentially generates different instructions depending on the context:

la $d, offset($base)
la $d, offset
la $d, ($base)

The MIPS compiler loves this pseudoinstruction



It mimics the format of lw/sw instructions, but rather than reading /writing the contents of memory, it loads it destination register with the effective address that would have been accessed. As a result it can generate any one of the following five sequences:

```
lui $d,offset
ori $d,$d,offset
```

```
lui  $1,offset
ori  $1,$1,offset
addu $d,$base,$1
```

```
ori $d,$0,offset
```

```
ori $d,$0,offset
addu $d,$base,$1
```

```
addiu $d,$base,offset
```

The Beauty of Procedures

- Reusable code fragments (modular design)

```
clear_screen();
  …                    # code to draw a bunch of lines
clear_screen();
  …
```

- Parameterized functions (variable behaviors)

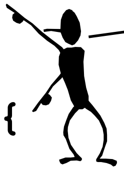
```
line(x1, y1, x2, y2, color);
line(x2,y2,x3,y3, color);
  …
```

```
for (i=0; i < N-1; i++)
   line(x[i],y[i],x[i+1],y[i+1],color);
line(x[i],y[i],x[0],y[0],color);
```

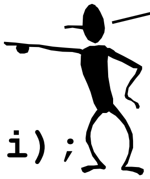
More Procedure Power

- Global vs. Local scope (Name Independence)

```
int x = 9;

int fee(int x) {
   return x+x-1;
}

int foo(int i) {
   int x = 0;
   while (i > 0) {
        x = x + fee(i);
        i = i - 1;
   }
  return x;
}

main() {
     fee(foo(x));
}
```



These are different “x”s



This is yet another “x”

How do we keep track of all the variables

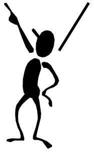
That “fee()” seems odd to me? And, foo()’s a little square.

Using Procedures

- A "calling" program (Caller) must:
  - Provide procedure parameters. In other words, put the arguments in a place where the procedure can access them
  - Transfer control to the procedure. Jump to it
- A "called" procedure (Callee) must:
  - Acquire the resources needed to perform the function
  - Perform the function
  - Place results in a place where the Caller can find them
  - Return control back to the Caller
- Solution (a least a partial one):
  - WE NEED CONVENTIONS, agreed upon standards for how arguments are passed in and how function results are retrieved
  - Solution #1: Allocate registers for these specific functions

MIPS Register Usage

- Conventions designate registers for procedure arguments ($4-$7) and return values ($2-$3).
- The ISA designates a “linkage register” for calling procedures ($31)
- Transfer control to Callee using the `jal` instruction
- Return to Caller with the `j $31` or `j $ra` instruction



The “linkage register” is where the return address of back to the callee is stored. This allows procedures to be called from any place, and for the caller to come back to the place where it was invoked.

Name	Register number	Usage
`$zero`	0	the constant value 0
`$at`	1	assembler temporary
`$v0-$v1`	2-3	procedure return values
`$a0-$a3`	4-7	procedure arguments
`$t0-$t7`	8-15	temporaries
`$s0-$s7`	16-23	saved by callee
`$t8-$t9`	24-25	more temporaries
`$k0-$k1`	26-27	reserved for operating system
`$gp`	28	global pointer
`$sp`	29	stack pointer
`$fp`	30	frame pointer
`$ra`	31	return address

And It "Sort Of" Works

- Example:

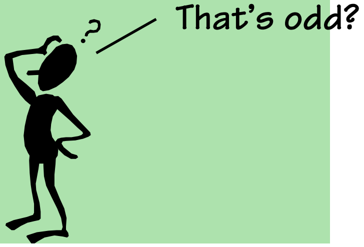
```
.globl x
.data
x:   .word 9
```

Callee

```
.globl fee
.text
fee:
     addu  $v0,$a0,$a0
     addiu $v0,$v0,-1
     jr    $ra
```

Caller

```
.globl main
.text
main:
      lw      $a0,x
      jal     fee
      jr      $ra
```



Works for special cases where the Callee needs few resources and calls no other functions.

This type of function (one that calls no others) is called a LEAF function.

But there are lots of issues:

- How can fee call functions?
- More than 4 arguments?
- Local variables?
- Where will main return to?

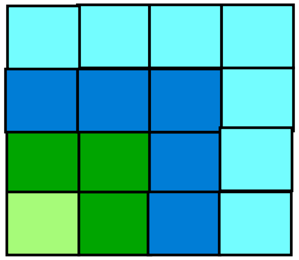
Let's consider the worst case of a Callee as a Caller…

Writing Procedures

```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}
```

How do we go about writing callable procedures? We'd like to support not only LEAF procedures, but also procedures that call other procedures, ad infinitum (e.g. a recursive function).

```
main()
{
  sqr(10);
}
```



sqr(10) = sqr(9)+10+10-1 = 100
sqr(9) = sqr(8)+9+9-1 = 81
sqr(8) = sqr(7)+8+8-1 = 64
sqr(7) = sqr(6)+7+7-1 = 49
sqr(6) = sqr(5)+6+6-1 = 36
sqr(5) = sqr(4)+5+5-1 = 25
sqr(4) = sqr(3)+4+4-1 = 16
sqr(3) = sqr(2)+3+3-1 = 9
sqr(2) = sqr(1)+2+2-1 = 4
sqr(1) = 1
sqr(0) = 0

Procedure Linkage: First Try

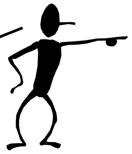
Callee/Caller

```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}
```

Caller

```
main()
{
  sqr(10);
}
```

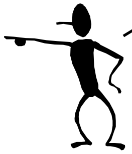
```
sqr:    addiu  $t0,$0,1
        slt    $t0,$t0,$a0    # 1 < x ?
        beq    $t0,$0,endif
        move   $t0,$a0        # save x
        addiu  $a0,$a0,-1
        jal    sqr            # sqr(x-1)
        addu   $v0,$v0,$t0
        addu   $v0,$v0,$t0
        addiu  $v0,$v0,-1
        b      rtn
endif:  move   $v0,$a0
rtn:    jr     $ra
```



$t0 is clobbered on successive calls.

Will saving "x" in some register or at some fixed location in memory help?

(Nope)



We also clobber our return address, so there's no way back!

MIPS Convention:

- pass 1st arg x in $a0
- save return addr in $ra
- return result in $v0
- use only temp registers to avoid saving stuff

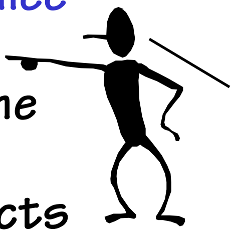
A Procedure's Storage Needs

Basic Overhead for Procedures/Functions:

- Caller sets up ARGUMENTs for callee

  `f(x,y,z)` or worse... `sin(a+b)`

- Caller invokes Callee while saving the Return Address to get back
- Callee saves stuff that Caller expects to remain unchanged
- Callee executes
- Callee passes results back to Caller.



In C it's the caller's job to evaluate its arguments as expressions, and pass the resulting values to the callee… Therefore, the CALLEE has to save arguments if it wants access to them after calling some other procedure, because they might not be around in any variable, to look up later.

Local variables of Callee:

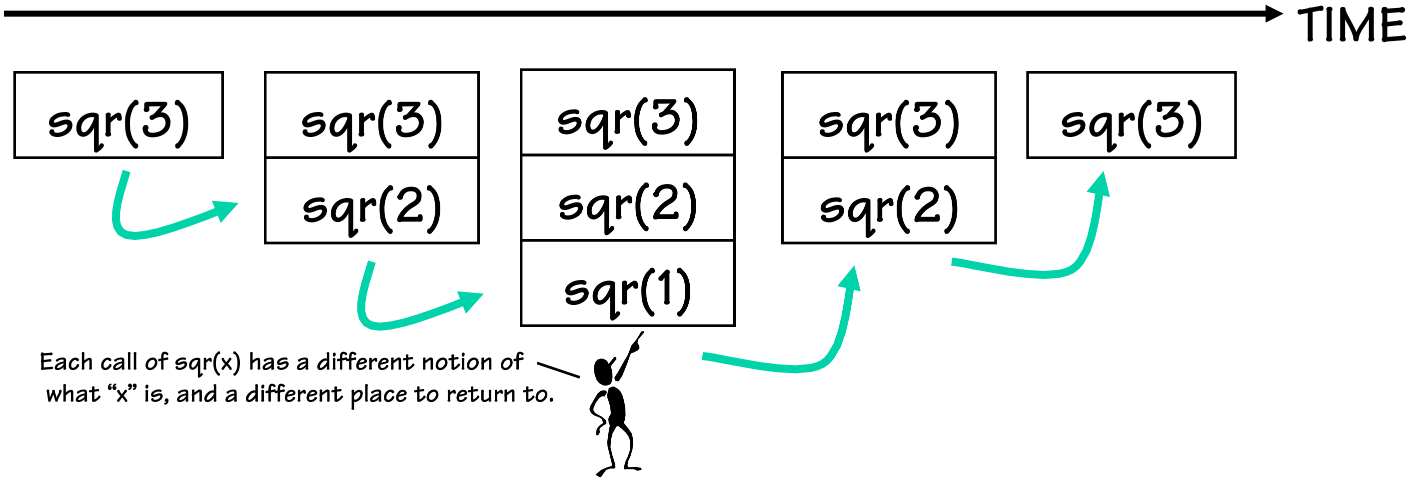
```
...
{
  int x, y;
  ... x ... y ...;
}
```

Each of these is specific to a "particular" invocation or *activation* of the Callee. Collectively, the arguments passed in, the return address, and the callee's local variables are its *activation record*, or *call frame*.

Lives of Activation Records

```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}
```

Where do we store activation records?



TIME

sqr(3)

sqr(3)
sqr(2)

sqr(3)
sqr(2)
sqr(1)

sqr(3)
sqr(2)

sqr(3)

Each call of sqr(x) has a different notion of what “x” is, and a different place to return to.

A procedure call creates a new activation record. Caller’s record is preserved because we’ll need it when call finally returns.

Return to previous activation record when procedure finishes, permanently discarding activation record created by call we are returning from.

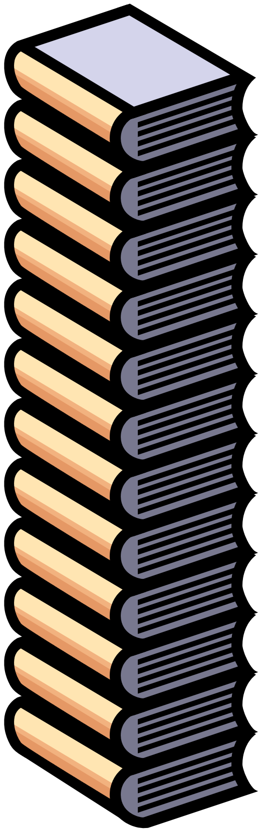
We Need Dynamic Storage!

What we need is a SCRATCH memory for holding temporary variables. We'd like for this memory to grow and shrink as needed. And, we'd like it to have an easy management policy.

One possibility is a

STACK

A last-in-first-out (LIFO) data structure.



Some interesting properties of stacks:

SMALL OVERHEAD. Everything is referenced relative to the top, the so-called "top-of-stack"

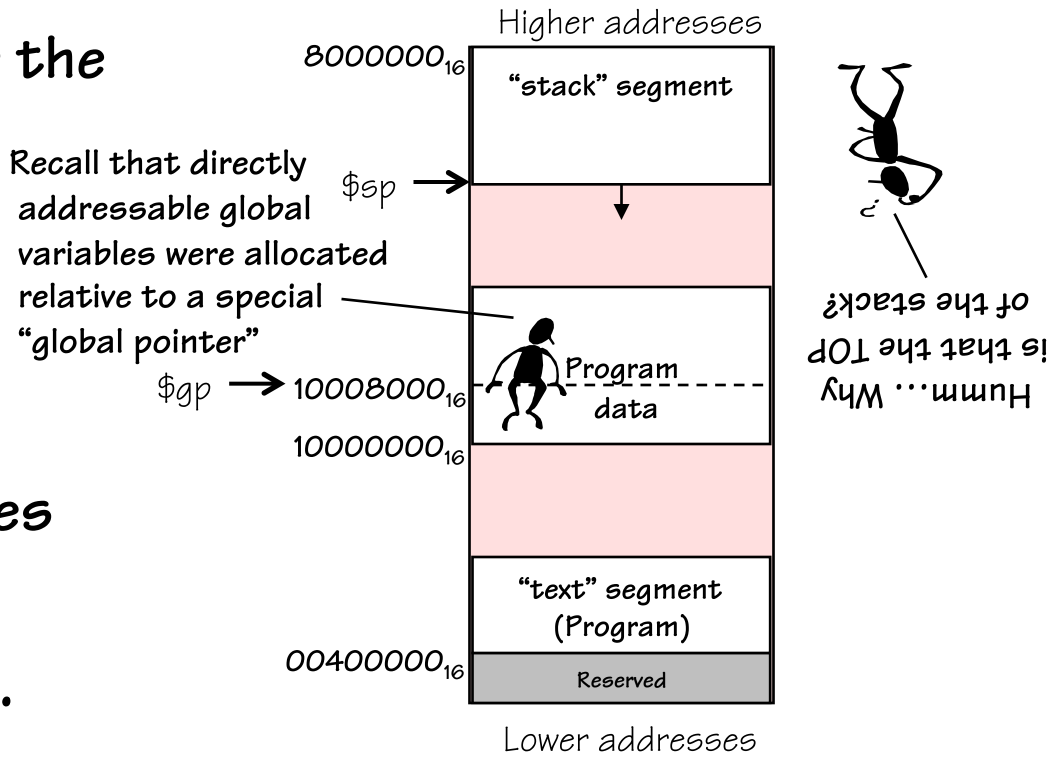
Add things by PUSHING new values on top.

Remove things by POPPING off values.

MIPS Stack Convention

CONVENTIONS:

- Waste a register for the Stack Pointer ($sp = $29).
- Stack grows DOWN (towards lower addresses) on pushes and allocates
- $sp points to the TOP *used* location.
- Stack is placed far away from the program and its data



Recall that directly addressable global variables were allocated relative to a special "global pointer"

Other possible implementations include:
1) stacks that grow "UP"
2) SP points to first UNUSED location

Stack Management Primitives

ALLOCATE k: reserve k WORDS of stack

Reg[SP] = Reg[SP] - 4*k

```
addiu $sp,$sp,-4*k
```

DEALLOCATE k: release k WORDS of stack

Reg[SP] = Reg[SP] + 4*k

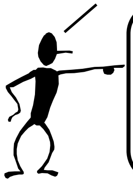
```
addiu $sp,$sp,4*k
```

PUSH $x: push Reg[x] onto stack

Reg[SP] = Reg[SP] - 4

Mem[Reg[SP]] = Reg[x]

An ALLOCATE 1 followed by a store



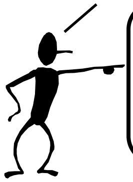
```
addiu $sp,$sp,-4
sw    $x, ($sp)
```

POP $x: pop the value on the top of the stack into Reg[x]

Reg[x] = Mem[Reg[SP]]

Reg[SP] = Reg[SP] + 4;

A load followed by a DEALLOCATE 1

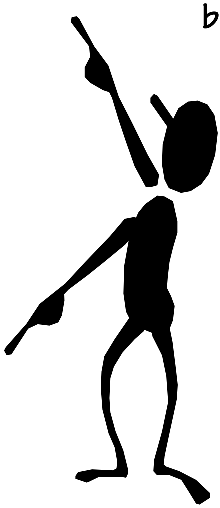


```
lw     $x, ($sp)
addiu  $sp,$sp,4
```

Fun with Stacks

Stacks can be used to squirrel away variables for later. For instance, the following code fragment can be inserted anywhere within a program.

```
            #
            # Argh!!! I'm out of registers Scotty!!
            #
            addiu    $sp,$sp,-8        # allocate 2
            sw       $s0,4($sp)        # Free up s0
            sw       $s1,0($sp)        # Free up s1
            lw       $s0,dilithum_xtals
            lw       $s1,seconds_til_explosion
suspense:   addiu    $s1,$s1,-1
            bne      $s1,$0,suspense
            sw       $s0,warp_engines
            lw       $s1,0($sp)        # Restore s1
            lw       $s0,4($sp)        # Restore s0
            addiu    $sp,$sp,8         # deallocate 2
```


You should ALWAYS allocate prior to saving, and deallocate after restoring in order to be SAFE!

AND Stacks can also be used to solve other problems...

More MIPS Procedure Conventions

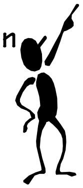
What needs to be saved?

CHOICE 1… anything that a Callee touches
(except the return value registers)

CHOICE 2… Give the Callee access to everything
(make the Caller will save those
registers it expects to be unchanged)

CHOICE 3… Something in between.
(Give the Callee some registers to
play with. But, make him save others
if they are not enough, and also
provide a few registers that the caller
can assume will not be changed by the
callee.)

Of course, the
MIPS convention
is this case.



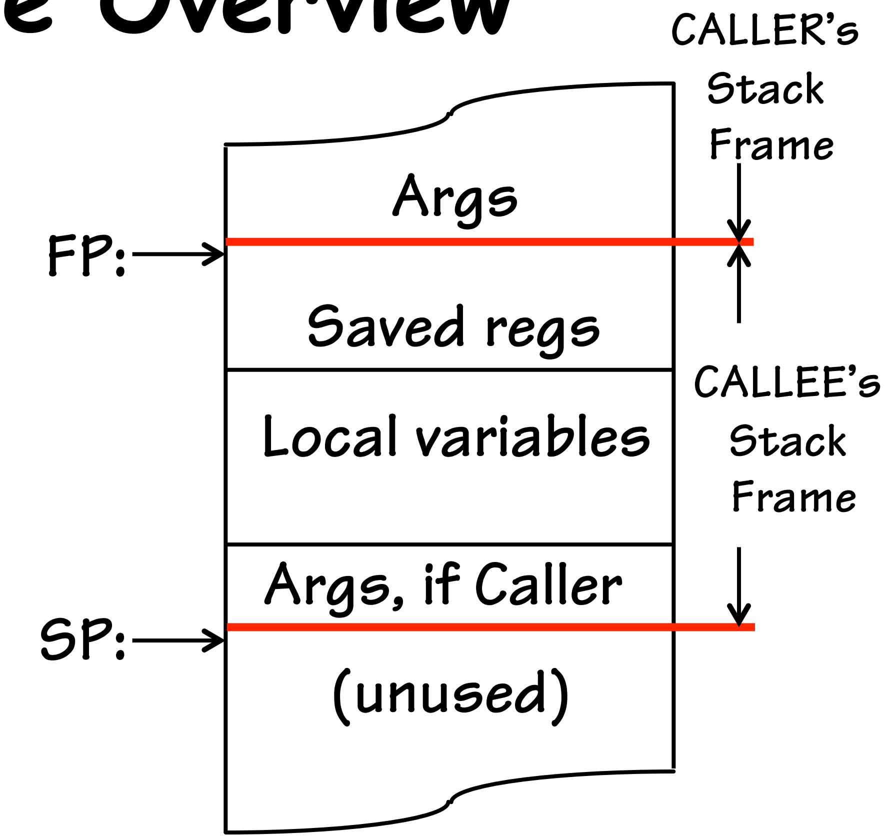
Stack Frame Overview

The STACK FRAME contains storage for the CALLER's volatile state that it wants preserved after the invocation of CALLEEs.

In addition, the CALLEE will use the stack for the following:

1) Accessing the arguments that the CALLER passes to it (specifically, the 5th and greater)
2) Saving non-temporary registers that it wishes to modify
3) Accessing its own local variables

The boundary between stack frames falls at the first word of state saved by the CALLEE, and just after the 5th argument (if used) passed in from the CALLER. The FRAME POINTER keeps track of this boundary between stack frames.



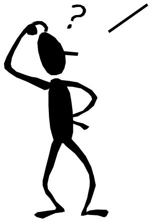
It's possible to use only the SP to access a stack frame, but offsets may change due to ALLOCATEs and DEALLOCATEs. For convenience a $fp is used to provide CONSTANT offsets to local variables and arguments

Procedure Stack Usage

ADDITIONAL space must be allocated in the stack frame for:

1. Any LOCAL variables declared within the procedure
2. Any SAVED registers the procedure uses ($s0-$s7, $ra, $fp)
3. Any TEMPORARY registers that the procedure wants preserved IF it calls other procedures ($t0-$t9)
4. Other TEMP space IF the procedure runs out of registers (RARE)
5. Enough "outgoing" arguments to satisfy the worse case ARGUMENT SPILL of ANY procedure it calls. (SPILL is the number of arguments greater than 4).

Reminder; stack frames are extended by multiples of 2 word (8 bytes). By convention, the above order is the order in which storage is allocated



Each procedure has keep track of how many SAVED and TEMPORARY registers are on the stack in order to calculate the offsets to LOCAL VARIABLES.

PRO: The MIPS stack frame convention minimizes the number of stack ALLOCATEs

CON: The MIPS stack frame convention tends to allocate larger stack frames than needed, thus wasting memory

More MIPS Register Usage

- The registers \$s0-\$s7, \$sp, \$ra, \$gp, \$fp, and the stack above the memory above the stack pointer must be preserved by the CALLEE
- The CALLEE is free to use \$t0-\$t9, \$a0-\$a3, and \$v0-\$v1, and the memory below the stack pointer.
- No "user" program can use \$k0-\$k1, or \$at

Name	Register number	Usage
`$zero`	0	the constant value 0
`$at`	1	assembler temporary
`$v0-$v1`	2-3	procedure return values
`$a0-$a3`	4-7	procedure arguments
`$t0-$t7`	8-15	temporaries
`$s0-$s7`	16-23	saved by callee
`$t8-$t9`	24-25	more temporaries
`$k0-$k1`	26-27	reserved for operating system
`$gp`	28	global pointer
`$sp`	29	stack pointer
`$fp`	30	frame pointer
`$ra`	31	return address

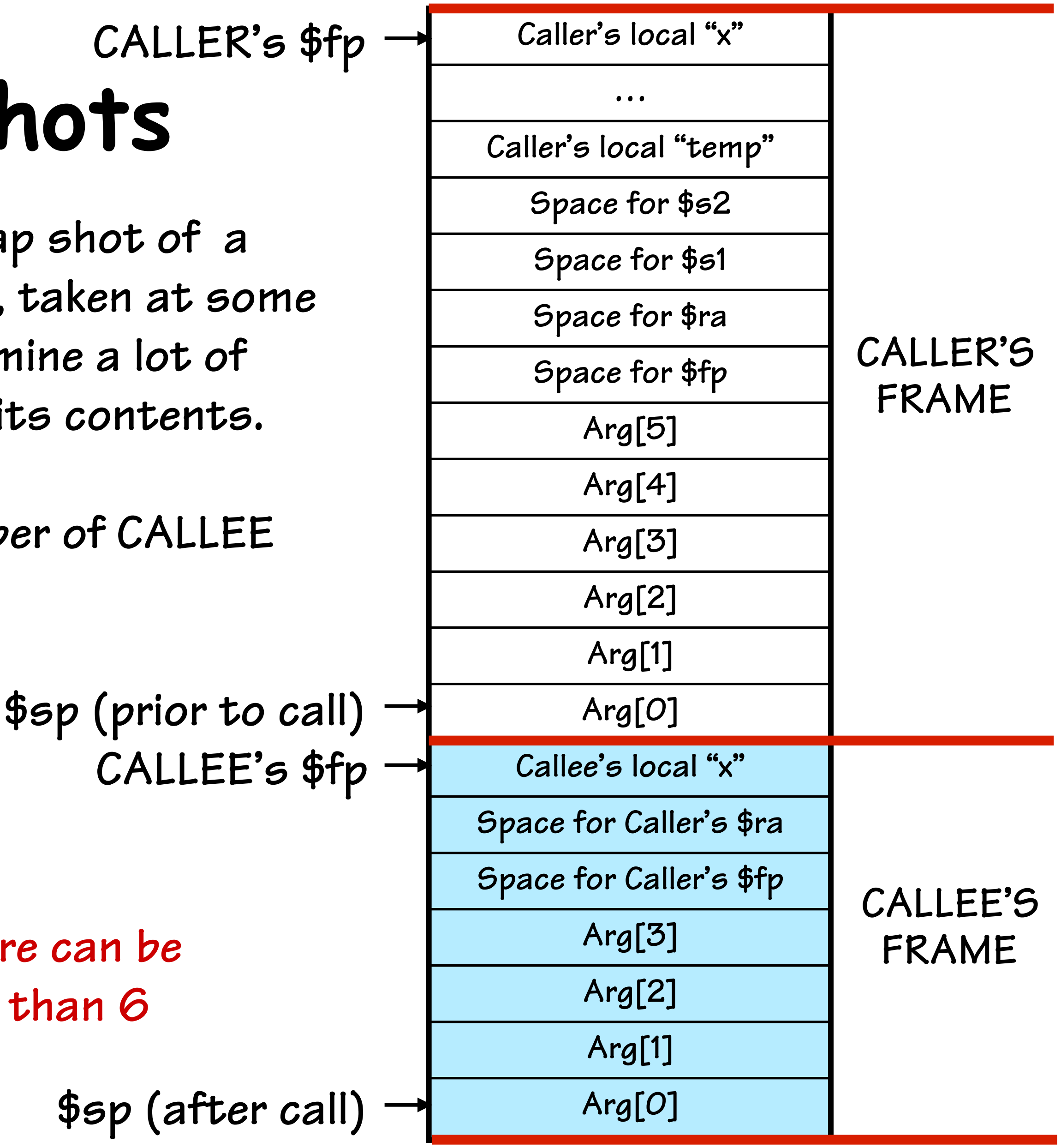
Stack Snap Shots

Shown on the right is a snap shot of a program's stack contents, taken at some instance in time. One can mine a lot of information by inspecting its contents.

Can we determine the number of CALLEE arguments? NOPE

Can we determine the maximum number of arguments needed by any procedure called by the CALLER? Yes, there can be no more than 6

Where in the CALLEE's stack frame might one find the CALLER's $fp? It MIGHT be at Mem[$fp+4]+4



Simple Cases

A leaf needing minimal resources:

```
int isOdd(int x) {
    return (x & 1);
}
```

A function that calls others and has local variables:

```
int parity(a,b,c,d) {
    int sum = a + b + c + d;
    return isOdd(sum);
}
```

Generated assembly code:

No stack funny business at all?

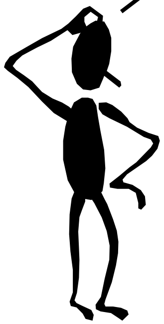
```
isOdd:  andi    $2,$4,1
L_1:    jr      $31

parity: addiu   $sp,$sp,-32
        sw      $31,20($sp)
        sw      $4,32($sp)
        sw      $5,36($sp)
        sw      $6,40($sp)
        sw      $7,44($sp)
        lw      $24,0+32($sp)
        lw      $15,4+32($sp)
        addu    $24,$24,$15
        lw      $15,8+32($sp)
        addu    $24,$24,$15
        lw      $15,12+32($sp)
        addu    $24,$24,$15
        sw      $24,-4+32($sp)
        lw      $4,-4+32($sp)
        jal     isOdd
L_2:    lw      $31,20($sp)
        addiu   $sp,$sp,32
        jr      $31
```

Address	Contents
$sp+44	$a3 = d
$sp+40	$a2 = c
$sp+36	$a1 = b
$sp+32	$a0 = a
$sp+28	"sum"
$sp+24	**unused**
$sp+20	$ra
$sp+16	$fp
$sp+12	$a3
$sp+8	$a2
$sp+4	$a1
$sp →	$a0

Back to our Recursive Example

Now let's make our example work, using the MIPS procedure linking and stack conventions.

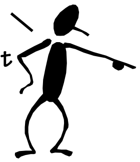
```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}


main()
{
  sqr(10);
}
```



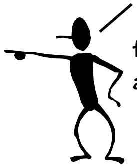
Q: Why isn't the $fp being used?

A: Stack frame is remaining constant, so the compiler is making all accesses relative to $sp.

```
sqr:    addiu   $sp,$sp,-32
        sw      $ra,20($sp)
        sw      $s0,24($sp)
        move    $s0,$a0
        addiu   $t8,$0,1
        slt     $1,$t8,$s0
        beq     $1,$0,endif
        addiu   $a0,$s0,-1
        jal     sqr
        addu    $v0,$v0,$s0
        addu    $v0,$v0,$s0
        addiu   $v0,$v0,-1
        b       rtn
endif:  move    $v0,$s0
rtn:    lw      $s0,24($sp)
        lw      $ra,20($sp)
        addiu   $sp,$sp,32
        jr      $ra
```

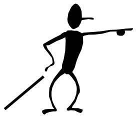


Save registers that must survive the call.

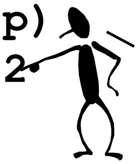


ALLOCATE stack frame. With room for the return address, a local saved register, and the argument spill for calls.

Pass arguments



Restore saved registers.

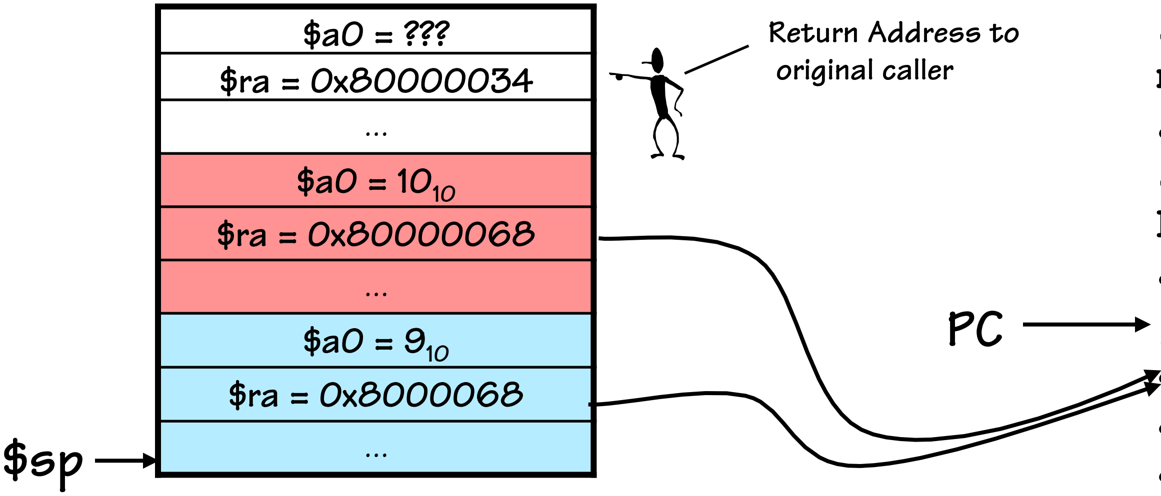


DEALLOCATE stack frame.

Address	Contents
$sp+44	$a3
$sp+40	$a2
$sp+36	$a1
$sp+32	$a0 = x
$sp+28	**unused**
$sp+24	$s0
$sp+20	$ra
$sp+16	$fp
$sp+12	$a3
$sp+8	$a2
$sp+4	$a1
$sp →	$a0

Testing Reality's Boundaries

Now let's take a look at the active stack frames at some point during the procedure's execution.



```
sqr:    addiu  $sp,$sp,-32
        sw     $ra,20($sp)
        sw     $s0,24($sp)
        move   $s0,$a0
        addiu  $t8,$0,1
        slt    $1,$t8,$s0
        beq    $1,$0,endif
        addiu  $a0,$s0,-1
        jal    sqr
        addu   $v0,$v0,$s0
        addu   $v0,$v0,$s0
        addiu  $v0,$v0,-1
        b      rtn
endif:  move   $v0,$s0
rtn:    lw     $s0,24($sp)
        lw     $ra,20($sp)
        addiu  $sp,$sp,32
        jr     $ra
```

Procedure Linkage is Nontrivial

The details can be overwhelming.

What's the solution for managing this complexity?

Abstraction!

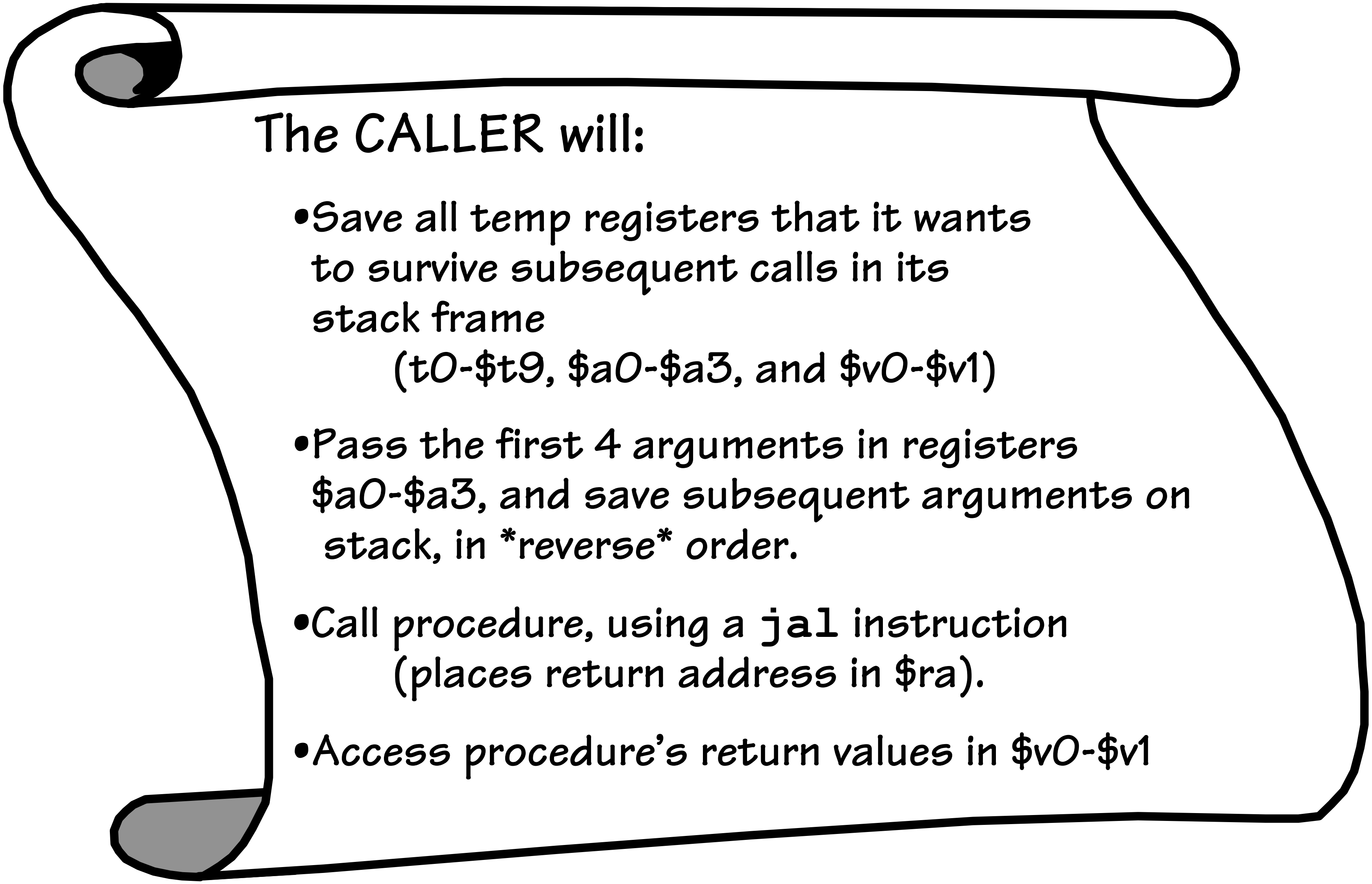
- High-level languages can provide compact notation that hides the details.

We have another problem, there are great many CHOICEs that we can make in realizing a procedure (which variables are saved, who saves them, etc.), yet we will want to design SOFTWARE SYSTEM COMPONENTS that interoperate. How did we enable composition in that case?

Contracts!

- But, first we must agree on the details? Not just the HOWs, but WHENs.

Procedure Linkage: Caller Contract

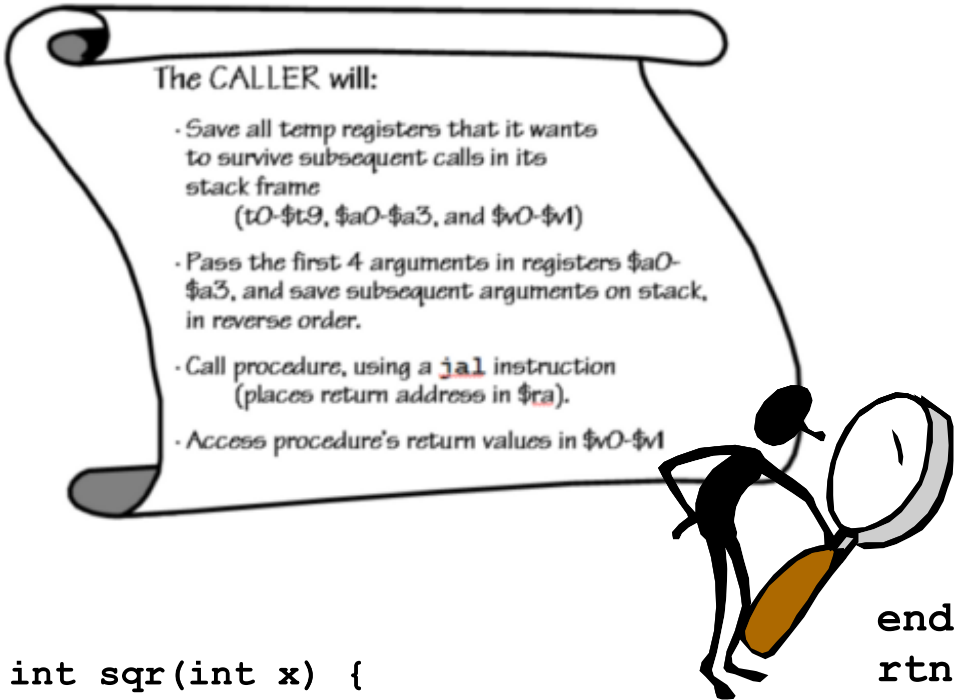


The CALLER will:

- Save all temp registers that it wants to survive subsequent calls in its stack frame
  (t0-$t9, $a0-$a3, and $v0-$v1)
- Pass the first 4 arguments in registers $a0-$a3, and save subsequent arguments on stack, in *reverse* order.
- Call procedure, using a `jal` instruction
  (places return address in $ra).
- Access procedure's return values in $v0-$v1

Code Lawyer

Our running example is a CALLER. Let’s make sure it obeys its contractual obligations



The CALLER will:

- Save all temp registers that it wants to survive subsequent calls in its stack frame
  (t0-$t9, $a0-$a3, and $v0-$v1)
- Pass the first 4 arguments in registers $a0-$a3, and save subsequent arguments on stack, in reverse order.
- Call procedure, using a `jal` instruction
  (places return address in $ra).
- Access procedure’s return values in $v0-$v1

```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}
```

```
sqr:    addiu   $sp,$sp,-32
        sw      $ra,20($sp)
        sw      $s0,24($sp)
        move    $s0,$a0
        addiu   $t8,$0,1
        slt     $1,$t8,$s0
        beq     $1,$0,endif
        addiu   $a0,$s0,-1
        jal     sqr
        addu    $v0,$v0,$s0
        addu    $v0,$v0,$s0
        addiu   $v0,$v0,-1
        b       rtn
endif:  move    $v0,$s0
rtn:    lw      $s0,24($sp)
        lw      $ra,20($sp)
        addiu   $sp,$sp,32
        jr      $ra
```

Procedure Linkage: Callee Contract

If needed the CALLEE will:

1) Allocate a stack frame including space for saved registers, local variables, and spilled arguments

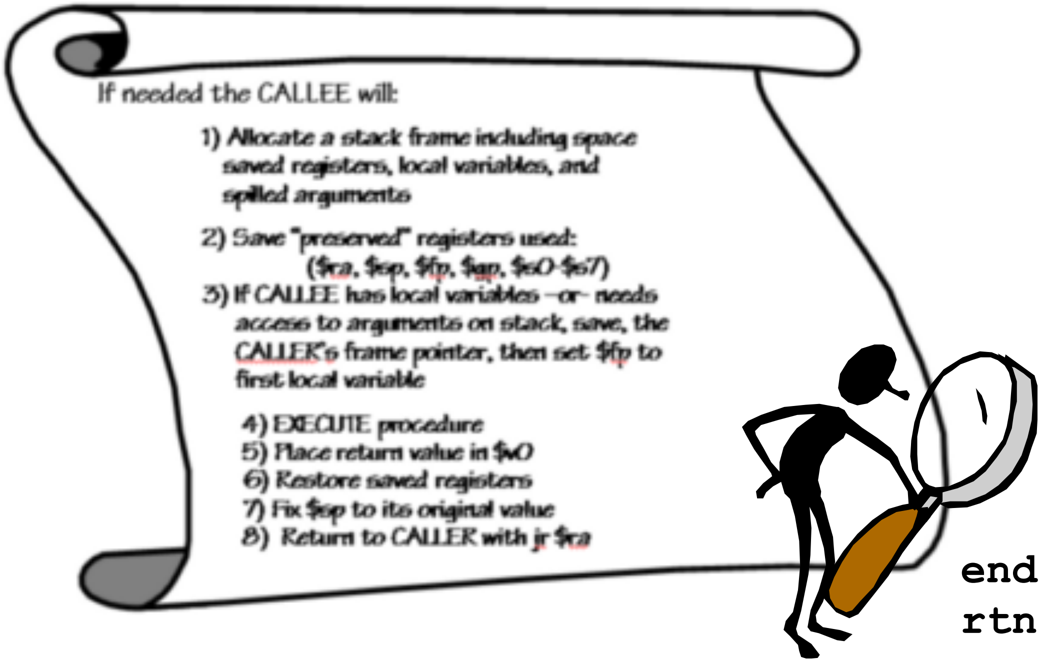
2) Save any "preserved" registers used:
($ra, $sp, $fp, $gp, $s0-$s7)

3) If CALLEE has local variables -or- needs access to arguments on the stack, save the CALLER's frame pointer and set $fp to 1st entry of the CALLEE's stack

4) EXECUTE procedure
5) Place return value in $v0
6) Restore saved registers
7) Fix $sp to its original value
8) Return to CALLER with jr $ra

More Legalese

Our running example is also a CALLEE. Are these contractual obligations satisfied?



If needed the CALLEE will:

1) Allocate a stack frame including space saved registers, local variables, and spilled arguments
2) Save "preserved" registers used: ($ra, $sp, $fp, $gp, $s0-$s7)
3) If CALLEE has local variables –or– needs access to arguments on stack, save, the CALLER's frame pointer, then set $fp to first local variable
4) EXECUTE procedure
5) Place return value in $v0
6) Restore saved registers
7) Fix $sp to its original value
8) Return to CALLER with jr $ra

```
sqr:    addiu   $sp,$sp,-32
        sw      $ra,20($sp)
        sw      $s0,24($sp)
        move    $s0,$a0
        addiu   $t8,$0,1
        slt     $1,$t8,$s0
        beq     $1,$0,endif
        addiu   $a0,$s0,-1
        jal     sqr
        addu    $v0,$v0,$s0
        addu    $v0,$v0,$s0
        addiu   $v0,$v0,-1
        b       rtn
endif:  move    $v0,$s0
rtn:    lw      $s0,24($sp)
        lw      $ra,20($sp)
        addiu   $sp,$sp,32
        jr      $ra
```

```
int sqr(int x) {
  if (x > 1)
    x = sqr(x-1)+x+x-1;
  return x;
}
```