Stacks and Procedures

I forgot, am I the Caller or Callee?

Don't know. But, if you PUSH again I'm gonna POP you.

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:

- **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,$t 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:

1) \texttt{la } \$d, \texttt{offset($base)}
2) \texttt{la } \$d, \texttt{offset}
3) \texttt{la } \$d, \texttt{($base)}

It mimics the format of \texttt{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:

2) \texttt{lui } \$d,\texttt{offset} \quad 1) \texttt{lui } \$1,\texttt{offset} \\
   \texttt{ori } \$d,\$d,\texttt{offset} \quad \quad \quad \texttt{ori } \$1,\$1,\texttt{offset} \\
   \texttt{addu } \$d,\$base,\$1

ori \$d,\$0,\texttt{offset} \quad ori \$1,\$0,\texttt{offset} \quad \texttt{addiu } \$d,\$base,\texttt{offset} \\
\texttt{addu } \$d,\$base,\$1
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;  // These are different “x”s

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”

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

How do we keep track of all the variables?
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

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<td>24-25</td>
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</tr>
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</tr>
<tr>
<td>$gp</td>
<td>28</td>
<td>global pointer</td>
</tr>
<tr>
<td>$sp</td>
<td>29</td>
<td>stack pointer</td>
</tr>
<tr>
<td>$fp</td>
<td>30</td>
<td>frame pointer</td>
</tr>
<tr>
<td>$ra</td>
<td>31</td>
<td>return address</td>
</tr>
</tbody>
</table>

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.
And It “Sort Of” Works

- Example:
  ```
  .globl x
  .data
  x: .word 9
  .globl fee
  .text
  fee:
  addu $v0,$a0,$a0
  addiu $v0,$v0,-1
  jr $ra
  `.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

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).

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

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

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

Oh, recursion gives me a headache.
Procedure Linkage: First Try

Callee/Caller

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

```plaintext
Procedure Linkage: First Try

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
```

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

Caller

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

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!
A Procedure's Storage Needs

Basic Overhead for Procedures/Functions:

- **Caller** sets up ARGUMENTs for **callee**
  
  \[ f(x, y, z) \text{ or worse... } \sin(a+b) \]

- **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**.

Local variables of **Callee**:

```c
...
{
    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**.

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.
Lives of Activation Records

int \texttt{sqr}(\texttt{int} \ x) \{ \\
\quad \text{if} \ (x > 1) \\
\quad \quad x = \texttt{sqr}(x-1)+x+x-1; \\
\quad \text{return} \ x; \\
\}

Where do we store activation records?

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.

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

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

\[
\text{Reg}[SP] = \text{Reg}[SP] - 4\times k
\]

\[
\text{addiu } \$sp,\$sp,-4\times k
\]

**DEALLOCATE** \( k \): release \( k \) WORDS of stack

\[
\text{Reg}[SP] = \text{Reg}[SP] + 4\times k
\]

\[
\text{addiu } \$sp,\$sp,4\times k
\]

**PUSH** \( x \): push \( \text{Reg}[x] \) onto stack

\[
\text{Reg}[SP] = \text{Reg}[SP] - 4
\]

\[
\text{Mem}[\text{Reg}[SP]] = \text{Reg}[x]
\]

\[
\text{addiu } \$sp,\$sp,-4
\]

\[
\text{sw } \$x, (\$sp)
\]

**POP** \( x \): pop the value on the top of the stack into \( \text{Reg}[x] \)

\[
\text{Reg}[x] = \text{Mem}[\text{Reg}[SP]]
\]

\[
\text{Reg}[SP] = \text{Reg}[SP] + 4;
\]

\[
\text{lw } \$x, (\$sp)
\]

\[
\text{addiu } \$sp,\$sp,4
\]
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
```

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 5\textsuperscript{th} 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 5\textsuperscript{th} 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

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<td>$ra</td>
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Stack Snap Shots

Shown on the right is a snapshot 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**

### Stack Contents

<table>
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<tr>
<th>Caller’s FRAME</th>
<th>CALLEE’s FRAME</th>
</tr>
</thead>
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<tr>
<td>Caller’s local “x”</td>
<td>Callee’s local “x”</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>Caller’s local “temp”</td>
<td></td>
</tr>
<tr>
<td>Space for $s2</td>
<td>Space for Caller’s $ra</td>
</tr>
<tr>
<td>Space for $s1</td>
<td>Space for Caller’s $fp</td>
</tr>
<tr>
<td>Space for $ra</td>
<td>Arg[5]</td>
</tr>
<tr>
<td>Space for $fp</td>
<td>Arg[4]</td>
</tr>
<tr>
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<td>Arg[0]</td>
</tr>
<tr>
<td>Arg[1]</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
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</table>

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Simple Cases

A leaf needing minimal resources:

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

A function that calls others and has local variables:

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

Generated assembly code:

```assembly
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
```

No stack funny business at all?

<table>
<thead>
<tr>
<th>Address</th>
<th>Contents</th>
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<tr>
<td>$sp+44</td>
<td>$a3 = d</td>
</tr>
<tr>
<td>$sp+40</td>
<td>$a2 = c</td>
</tr>
<tr>
<td>$sp+36</td>
<td>$a1 = b</td>
</tr>
<tr>
<td>$sp+32</td>
<td>$a0 = a</td>
</tr>
<tr>
<td>$sp+28</td>
<td>“sum”</td>
</tr>
<tr>
<td>$sp+24</td>
<td><strong>unused</strong></td>
</tr>
<tr>
<td>$sp+20</td>
<td>$ra</td>
</tr>
<tr>
<td>$sp+16</td>
<td>$fp</td>
</tr>
<tr>
<td>$sp+12</td>
<td>$a3</td>
</tr>
<tr>
<td>$sp+8</td>
<td>$a2</td>
</tr>
<tr>
<td>$sp+4</td>
<td>$a1</td>
</tr>
<tr>
<td>$sp</td>
<td>$a0</td>
</tr>
</tbody>
</table>
Back to our Recursive Example

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

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

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

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

Pass arguments

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

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

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

Restore saved registers.

DEALLOCATE stack frame.

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
```

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

```
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 1\textsuperscript{st} 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?

```
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
```