Today

- One complete example
  - To put together the snippets of assembly code we have seen
- Functions in MIPS

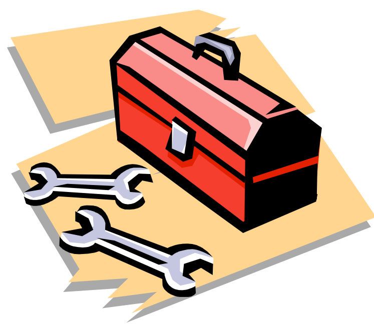
Putting it all together

- Count the numbers of bits set to 1 in register $a0 (input).

```
int count = 0;
for (int i = 0 ; i < 32 ; i ++) {
    int bit = input & 1;
    if (bit != 0) {
        count ++;
    }
    input = input >> 1;
}
```

Functions in MIPS

- We'll talk about the 3 steps in handling function calls:
  1. The program's flow of control must be changed.
  2. Arguments and return values are passed back and forth.
  3. Local variables can be allocated and destroyed.
- And how they are handled in MIPS:
  - New instructions for calling functions.
  - Conventions for sharing registers between functions.
  - Use of a stack.



Control flow in C

- Invoking a function changes the control flow of a program twice.
  1. Calling the function
  2. Returning from the function
- In this example the main function calls fact twice, and fact returns twice—but to *different* locations in main.
- Each time fact is called, the CPU has to remember the appropriate return address.
- Notice that main itself is also a function! It is called by the operating system when you run the program.

```
int main()
{
    ...
    t1 = fact(8);
    t2 = fact(3);
    t3 = t1 + t2;
    ...
}


int fact(int n)
{
    int i, f = 1;
    for (i = n; i > 1; i--)
        f = f * i;
    return f;
}
```

Control flow in MIPS

- MIPS uses the jump-and-link instruction jal to call functions.
  - The jal saves the return address (the address of the *next* instruction) in the dedicated register $ra, before jumping to the function.
  - jal is the only MIPS instruction that can access the value of the program counter, so it can store the return address PC+4 in $ra.

```
jal Fact
```

- To transfer control back to the caller, the function just has to jump to the address that was stored in $ra.

```
jr $ra
```

- Let's now add the jal and jr instructions that are necessary for our factorial example.

Data flow in C

- Functions accept arguments and produce return values.
- The blue parts of the program show the actual and formal arguments of the fact function.
- The purple parts of the code deal with returning and using a result.

```
int main()
{
    ...
    t1 = fact(8);
    t2 = fact(3);
    t3 = t1 + t2;
    ...
}

int fact(int n)
{
    int i, f = 1;
    for (i = n; i > 1; i--)
        f = f * i;
    return f;
}
```

Data flow in MIPS

- MIPS uses the following conventions for function arguments and results.
  - Up to four function arguments can be “passed” by placing them in argument registers $a0-$a3 before calling the function with jal.
  - A function can “return” up to two values by placing them in registers $v0-$v1, before returning via jr.
- These conventions are not enforced by the hardware or assembler, but programmers agree to them so functions written by different people can interface with each other.
- Later we’ll talk about handling additional arguments or return values.

A note about types

- Assembly language is untyped—there is no distinction between integers, characters, pointers or other kinds of values.
- It is up to ***you*** to “type check” your programs. In particular, make sure your function arguments and return values are used consistently.
- For example, what happens if somebody passes the *address* of an integer (instead of the integer itself) to the fact function?

The big problem so far

- There is a big problem here!
  - The main code uses $t1 to store the result of fact(8).
  - But $t1 is also used within the fact function!
- The subsequent call to fact(3) will overwrite the value of fact(8) that wa stored in $t1.

Nested functions

- A similar situation happens when you call a function that then calls another function.
- Let's say A calls B, which calls C.
  - The arguments for the call to C would be placed in $a0-$a3, thus *overwriting* the original arguments for B.
  - Similarly, jal C overwrites the return address that was saved in $ra by the earlier jal B.

```
A:   ...
     # Put B's args in $a0-$a3
     jal   B         # $ra = A2
A2:  ...
```

```
B:   ...
     # Put C's args in $a0-$a3,
     # erasing B's args!
     jal   C         # $ra = B2
B2:  ...
     jr    $ra       # Where does
                     # this go???
```

```
C:   ...
     jr    $ra
```

Spilling registers

- The CPU has a limited number of registers for use by all functions, and it’s possible that several functions will need the same registers.
- We can keep important registers from being overwritten by a function call, by saving them before the function executes, and restoring them after the function completes.
- But there are two important questions.
  - Who is responsible for saving registers—the caller or the callee?
  - Where exactly are the register contents saved?

Who saves the registers?

- Who is responsible for saving important registers across function calls?
  - The caller knows which registers are important to it and should be saved.
  - The callee knows exactly which registers it will use and potentially overwrite.
- However, in the typical “black box” programming approach, the caller and callee do not know anything about each other’s implementation.
  - Different functions may be written by different people or companies.
  - A function should be able to interface with any client, and different implementations of the same function should be substitutable.
- So how can two functions cooperate and share registers when they don’t know anything about each other?

The caller could save the registers…

- One possibility is for the *caller* to save any important registers that it needs before making a function call, and to restore them after.
- But the caller does not know what registers are actually written by the function, so it may save more registers than necessary.
- In the example on the right, frodo wants to preserve $a0, $a1, $s0 and $s1 from gollum, but gollum may not even use those registers.

```
frodo:  li      $a0, 3
        li      $a1, 1
        li      $s0, 4
        li      $s1, 1

        # Save registers
        # $a0, $a1, $s0, $s1

        jal     gollum

        # Restore registers
        # $a0, $a1, $s0, $s1

        add     $v0, $a0, $a1
        add     $v1, $s0, $s1
        jr      $ra
```

…or the callee could save the registers…

- Another possibility is if the *callee* saves and restores any registers it might overwrite.
- For instance, a gollum function that uses registers $a0, $a2, $s0 and $s2 could save the original values first, and restore them before returning.
- But the callee does not know what registers are important to the caller, so again it may save more registers than necessary.

```
gollum:
        # Save registers
        # $a0 $a2 $s0 $s2

        li      $a0, 2
        li      $a2, 7
        li      $s0, 1
        li      $s2, 8
        ...

        # Restore registers
        # $a0 $a2 $s0 $s2

        jr      $ra
```

…or they could work together

- MIPS uses conventions again to split the register spilling chores.
- The *caller* is responsible for saving and restoring any of the following caller-saved registers that it cares about.

  $t0-$t9 $a0-$a3 $v0-$v1

  In other words, the callee may freely modify these registers, under the assumption that the caller already saved them if necessary.
- The *callee* is responsible for saving and restoring any of the following callee-saved registers that it uses. (Remember that $ra is "used" by jal.)

  $s0-$s7 $ra

  Thus the caller may assume these registers are not changed by the callee.
  - $ra is tricky; it is saved by a callee who is also a caller.
- Be especially careful when writing nested functions, which act as both a caller and a callee!

Register spilling example

- This convention ensures that the caller and callee together save all of the important registers—frodo only needs to save registers $a0 and $a1, while gollum only has to save registers $s0 and $s2.

```
frodo:  li      $a0, 3
        li      $a1, 1
        li      $s0, 4
        li      $s1, 1

        # Save registers
        # $a0 and $a1

        jal     gollum

        # Restore registers
        # $a0 and $a1

        add     $v0, $a0, $a1
        add     $v1, $s0, $s1
        jr      $ra
```

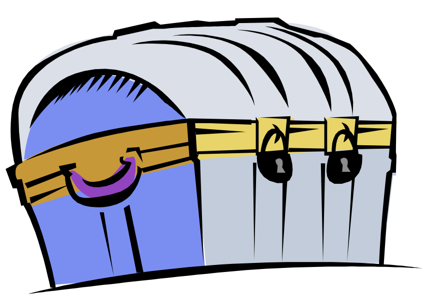
```
gollum:
        # Save registers
        # $s0 and $s2

        li      $a0, 2
        li      $a2, 7
        li      $s0, 1
        li      $s2, 8
        ...

        # Restore registers
        # $s0 and $s2

        jr      $ra
```

How to fix factorial

- In the factorial example, main (the caller) should save two registers.
  - $t1 must be saved before the second call to fact.
  - $ra will be implicitly overwritten by the jal instructions.
- But fact (the callee) does not need to save anything. It only writes to registers $t0, $t1 and $v0, which should have been saved by the caller.

Where are the registers saved?

- Now we know who is responsible for saving which registers, but we still need to discuss where those registers are saved.
- It would be nice if each function call had its own private memory area.
  - This would prevent other function calls from overwriting our saved registers—otherwise using memory is no better than using registers.
  - We could use this private memory for other purposes too, like storing local variables.

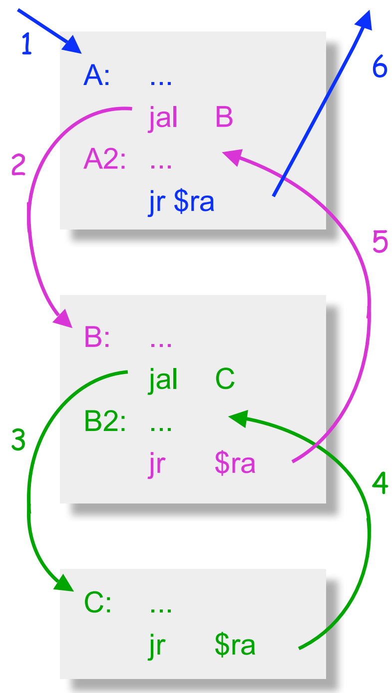


Function calls and stacks

- Notice function calls and returns occur in a stack-like order: the most recently called function is the first one to return.

  1. Someone calls A
  2. A calls B
  3. B calls C
  4. C returns to B
  5. B returns to A
  6. A returns

- Here, for example, C must return to B *before* B can return to A.

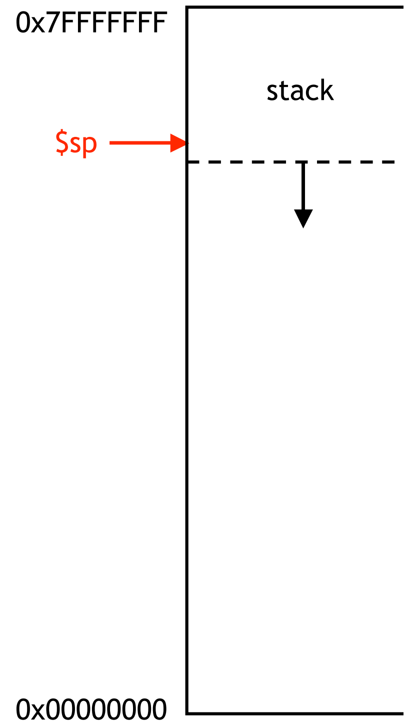


Stacks and function calls

- It's natural to use a stack for function call storage. A block of stack space, called a stack frame, can be allocated for each function call.
  - When a function is called, it creates a new frame onto the stack, which will be used for local storage.
  - Before the function returns, it must pop its stack frame, to restore the stack to its original state.
- The stack frame can be used for several purposes.
  - Caller- and callee-save registers can be put in the stack.
  - The stack frame can also hold local variables, or extra arguments and return values.

The MIPS stack

- In MIPS machines, part of main memory is reserved for a stack.
  - The stack grows downward in terms of memory addresses.
  - The address of the top element of the stack is stored (by convention) in the “stack pointer” register, $sp.
- MIPS does not provide “push” and “pop” instructions. Instead, they must be done explicitly by the programmer.



Pushing elements

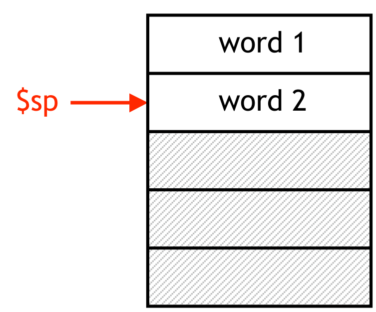
- To push elements onto the stack:
  - Move the stack pointer $sp down to make room for the new data.
  - Store the elements into the stack.
- For example, to push registers $t1 and $t2 onto the stack:

```
sub   $sp, $sp, 8
sw    $t1, 4($sp)
sw    $t2, 0($sp)
```

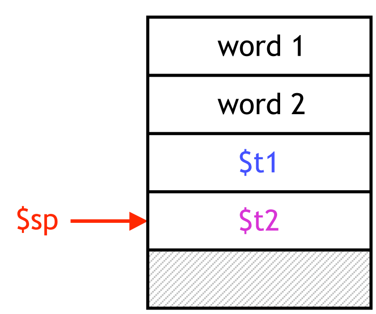
- An equivalent sequence is:

```
sw    $t1, -4($sp)
sw    $t2, -8($sp)
sub   $sp, $sp, 8
```

- Before and after diagrams of the stack are shown on the right.



Before



After

Accessing and popping elements

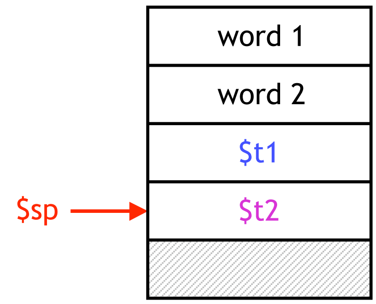
- You can access any element in the stack (not just the top one) if you know where it is relative to $sp.
- For example, to retrieve the value of $t1:

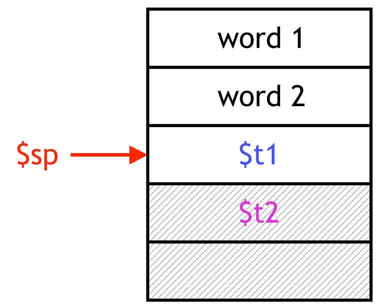
```
lw      $s0, 4($sp)
```

- You can pop, or "erase," elements simply by adjusting the stack pointer upwards.
- To pop the value of $t2, yielding the stack shown at the bottom:

```
addi    $sp, $sp, 4
```

- Note that the popped data is still present in memory, but data past the stack pointer is considered invalid.





Summary

- Today we focused on implementing function calls in MIPS.
  - We call functions using jal, passing arguments in registers $a0-$a3.
  - Functions place results in $v0-$v1 and return using jr $ra.
- Managing resources is an important part of function calls.
  - To keep important data from being overwritten, registers are saved according to conventions for caller-save and callee-save registers.
  - Each function call uses stack memory for saving registers, storing loca variables and passing extra arguments and return values.
- Assembly programmers must follow many conventions. Nothing prevents rogue program from overwriting registers or stack memory used by some other function.