Functions in MIPS

Today’s lecture: Implementing Functions!

- The program’s flow of control must be changed.
  - The Jump and Link (jal) instruction (NEW!)
  - Using Jump Register (jr)
- Arguments and return values are passed back & forth.
  - Register Conventions
- Allocating (and deallocating) space for local variables
  - The stack
  - The stack pointer ($sp)

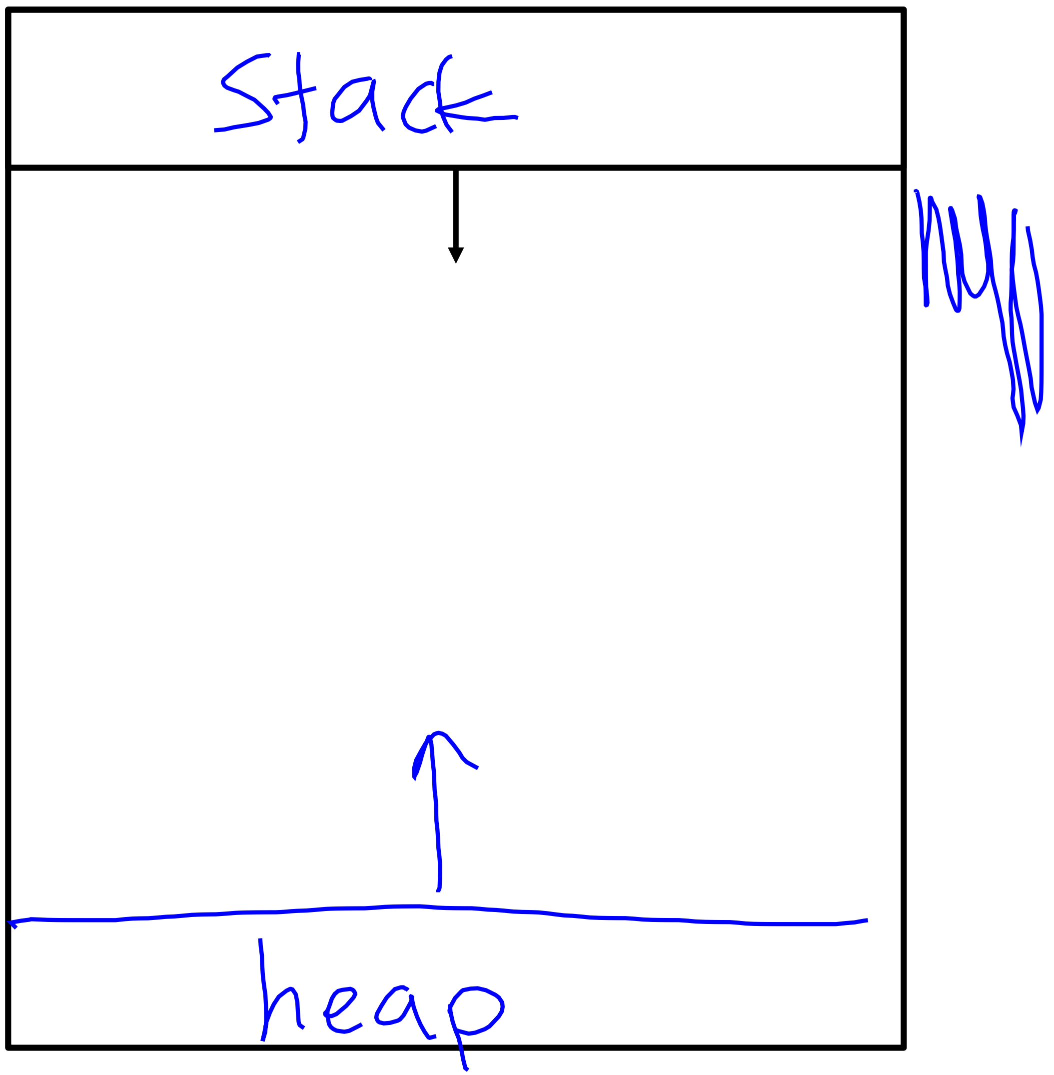
Invoking a function changes control flow by calling and returning from the function

- 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, in effect, 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;
}
```

Calling a function allocates stack frame, returning dellocates stack frame




```
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;
}
```

Use `jal` to call functions, `jr` to return

- `jal` saves the return address (the address of the *next* instruction) in the dedicated register $ra, before jumping to the function.

31

PC ← Fact

```
jal Fact
```

→ R[31] ← PC + 4

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

```
jr $ra
```

Go to Handout!

Let’s call our functions and return from them

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;
}
```

By convention, MIPS uses $a0-$a3 for arguments and $v0-$v1 for return values

- 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.

Assembly language is untyped, you need to “type check your code

Untyped —there is no distinction between integers, characters, pointers or other kinds of values.

int x = 42

... = fact(&x);

There is a big problem here!

- The main code stores the result of fact (8) in $t1, but $t1 is also used within the fact function!
- The subsequent call to fact(3) will overwrite the value of fact(8) that was stored in $t1.

Calling a function within another function (Nested functions) can overwrite values we need

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.

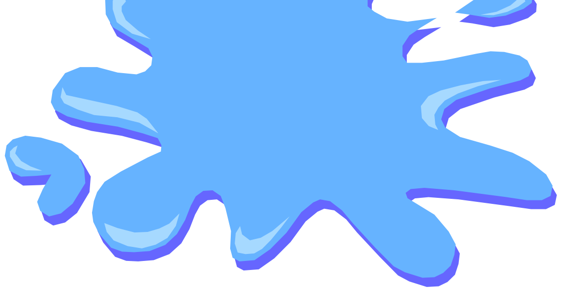
```
A:    ...
      # Put B's args in $a0-$a3
      jal B       # $ra = A2
A2:   ...
```

```
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
```

a) A
b) A2
c) B
d) B2
e) C

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.

  $s0-$s7

  Thus the caller may assume these registers are not changed by the callee.
- $ra is ~~special~~; it is "used" by jal. It is saved by a callee who is also a caller.

  $ra

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, $a1, $ra

       jal  gollum

       # Restore registers
       # $a0, $a1, $ra

       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
```

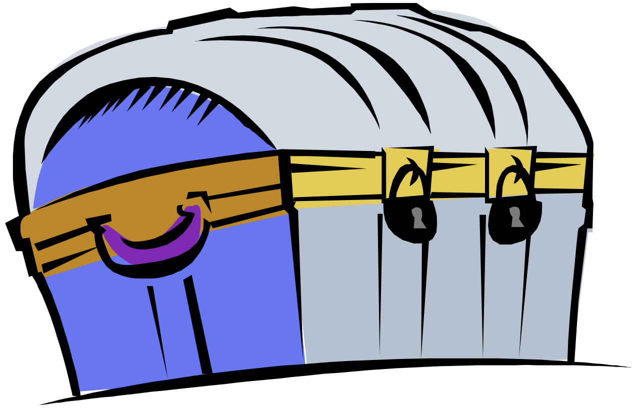
In the factorial example, main (the caller) should save two registers

- —$t1 must be saved before the second call to fact.
- —$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.

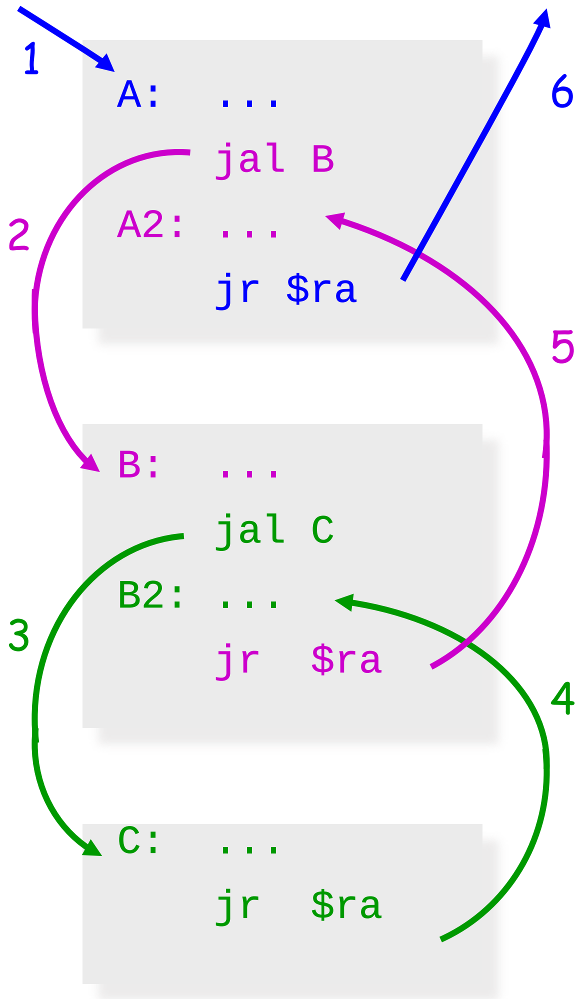


Use the stack for caller and callee saves

- 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.

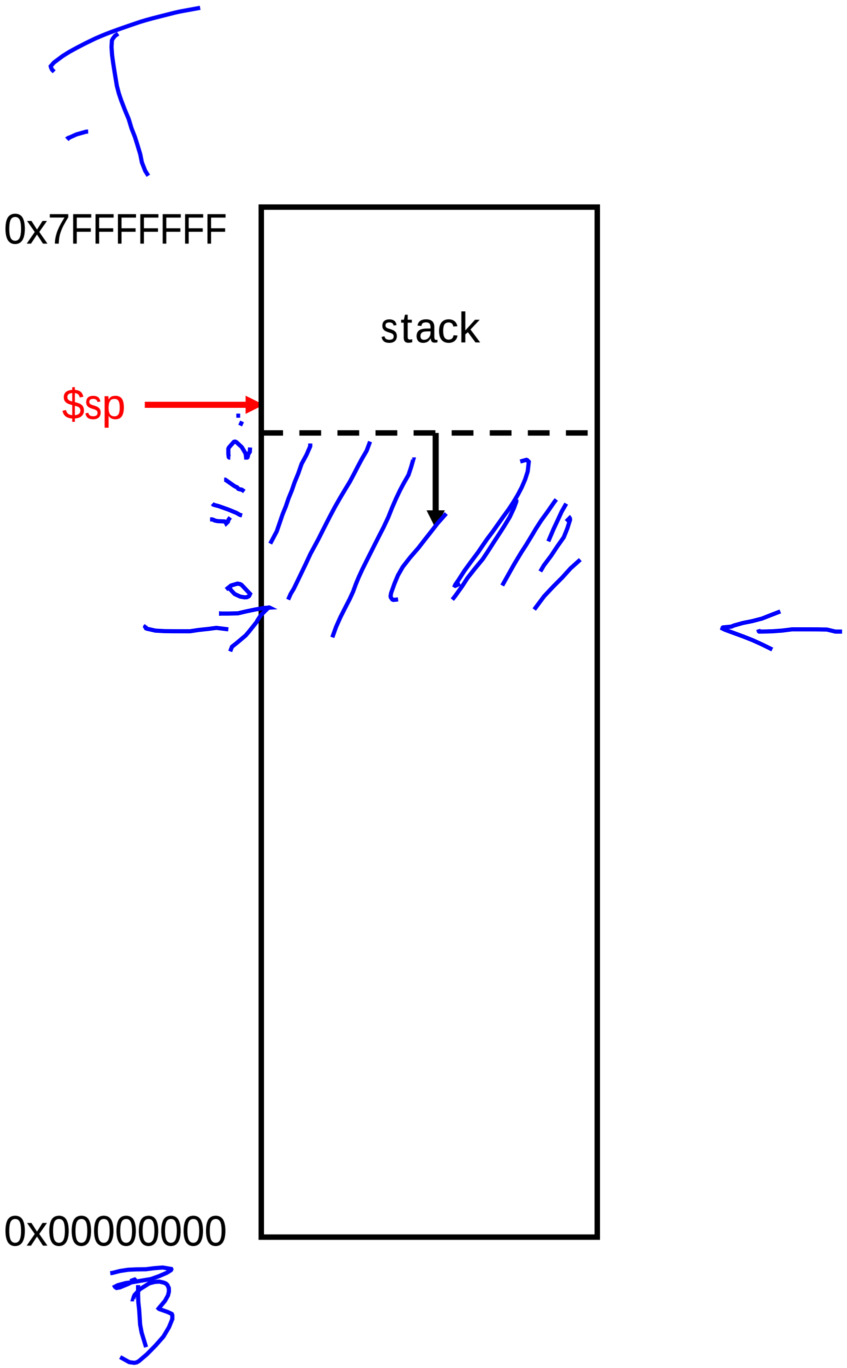


Stacks and function calls

- 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

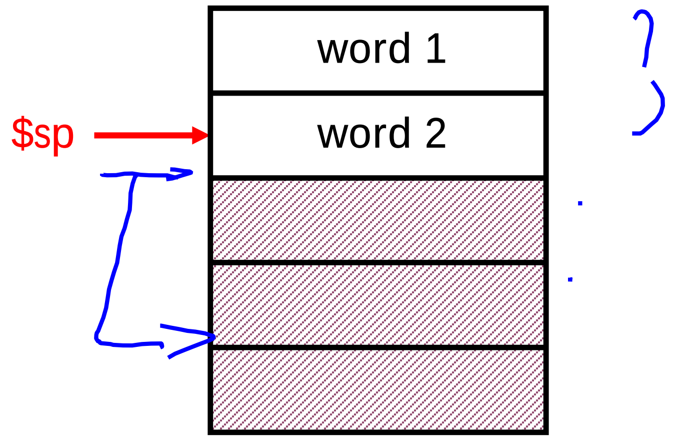
- To push elements onto the stack:
  - Move the stack pointer $sp down to make room for the new data.
  - Store the elements into the stack.
- For example, to push registers $t1 and $t2 onto the stack:

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

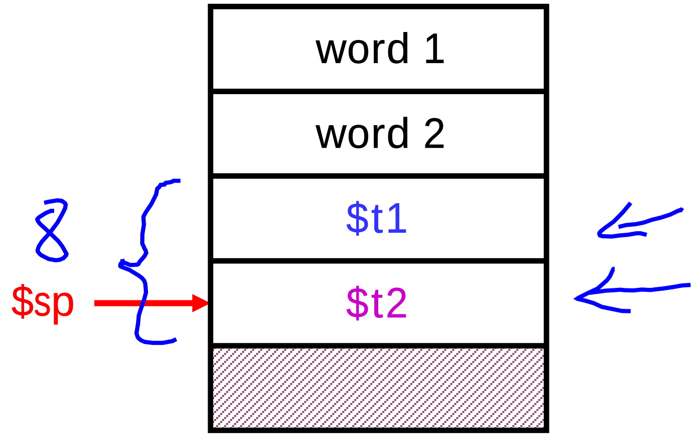
- An equivalent sequence is:

```
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

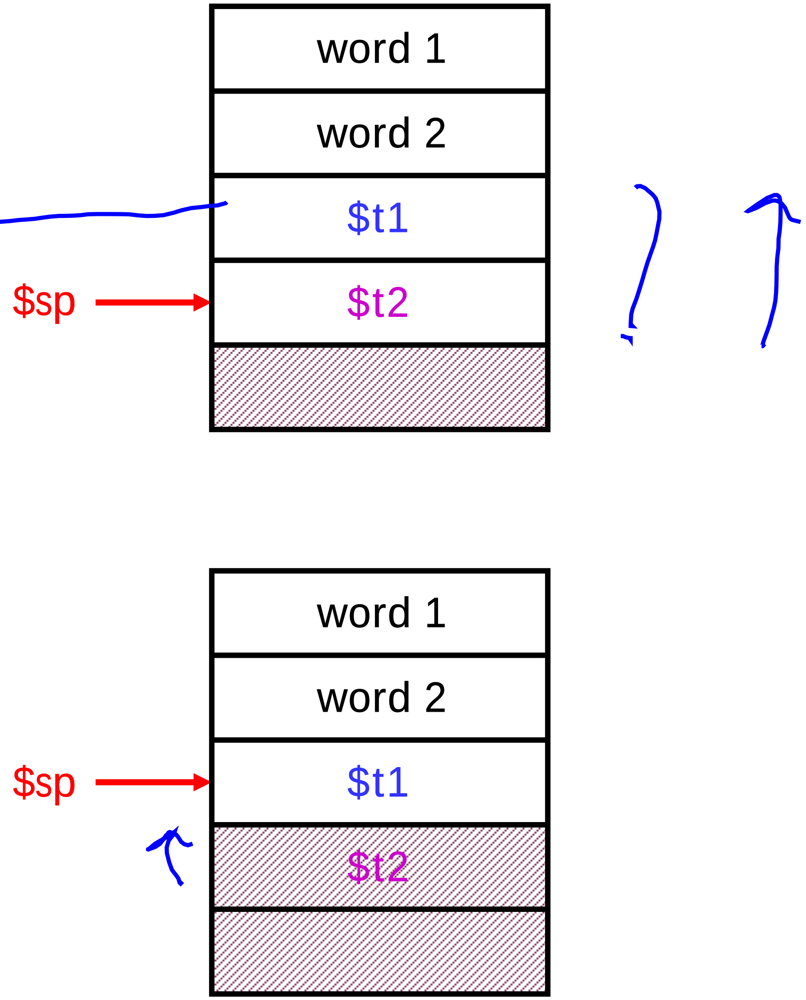
- You can access any element in the stack (not just the top one) if you know where it is relative to $sp.
- For example, to retrieve the value of $t1:

```
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 local variables and passing extra arguments and return values.
- Assembly programmers must follow many conventions. Nothing prevents a rogue program from overwriting registers or stack memory used by some other function.
- On Monday, we'll look at writing recursive functions.