

# Calling Conventions

**Prof. Kavita Bala and Prof. Hakim Weatherspoon**

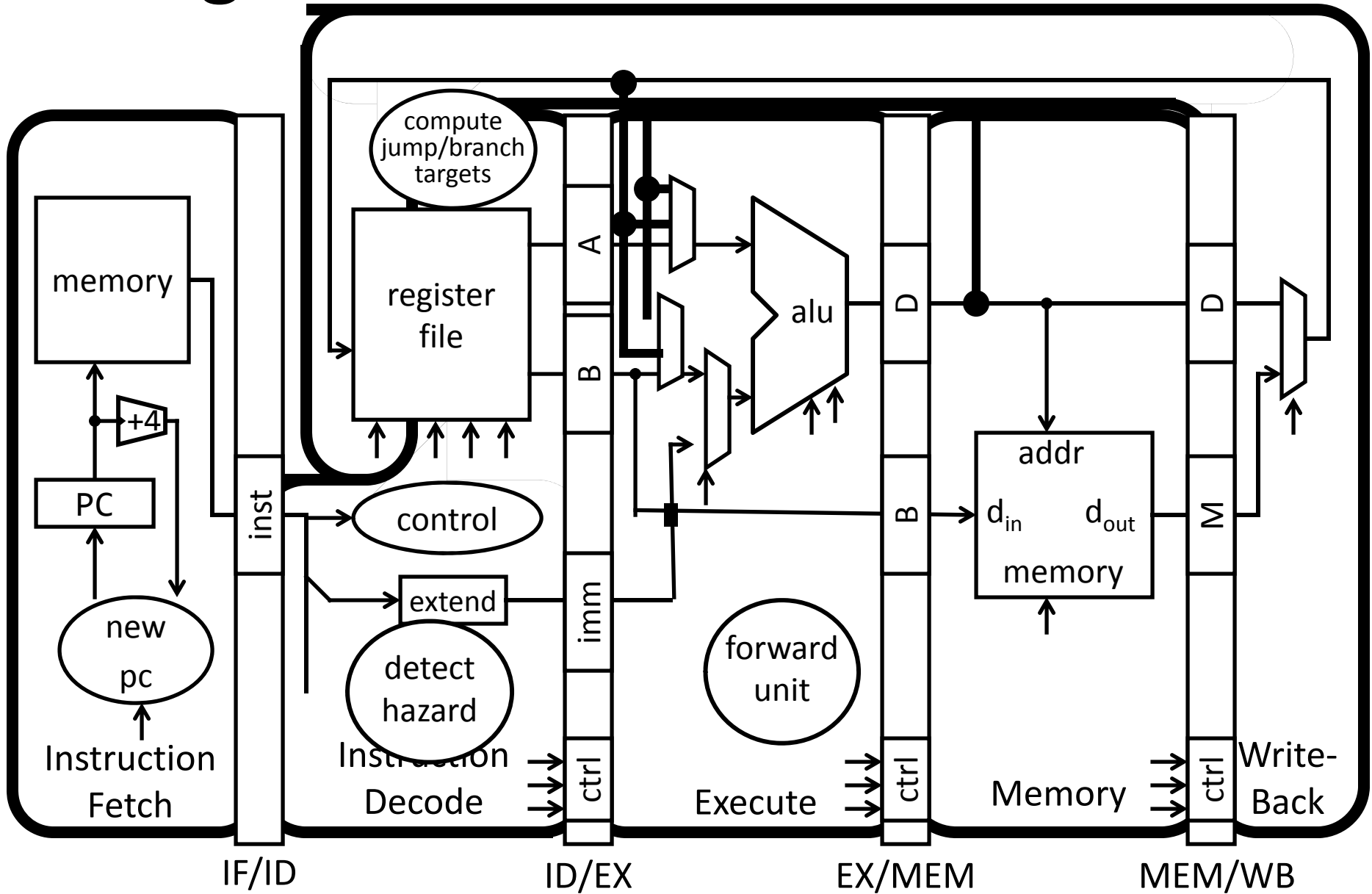
**CS 3410, Spring 2014**

Computer Science

Cornell University

See P&H 2.8 and 2.12, and A.5-6

# Big Picture: Where are we now?

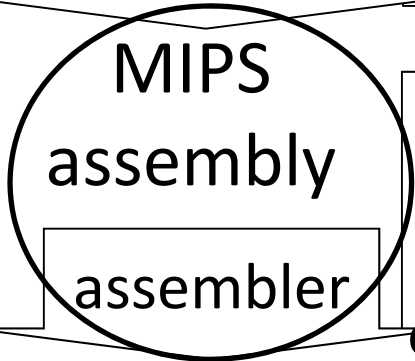


# Big Picture: Where are we going?

C

```
int x = 10;
x = 2 * x + 15;
```

compiler



```
addi r5, r0, 10
mulr r5, r5, 2
addi r5, r5, 15
```

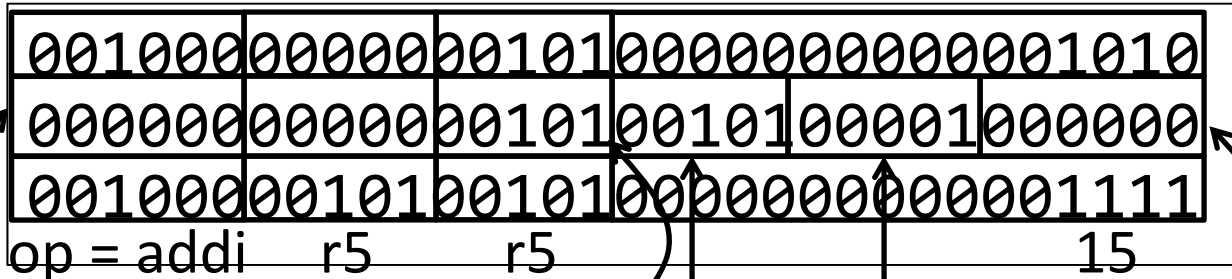
r0 = 0

r5 = r0 + 10

r5 = r5 << 1 # r5 = r5 \* 2

r5 = r5 + 15

machine code



op = r-type

r5

r5

shamt=1

func=sll

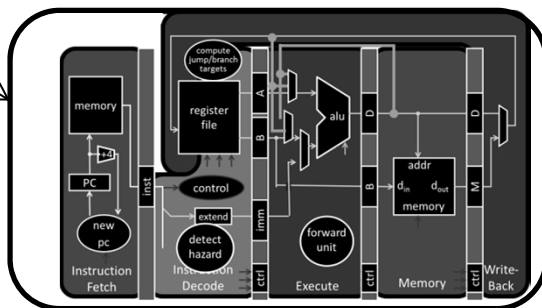
CPU

Circuits

Gates

Transistors

Silicon



# Big Picture: Where are we going?

C

compiler

```
int x = 10;  
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```

High Level  
Languages

MIPS  
assembly

assembler

```
addi r5, r0, 10  
mulr r5, r5, 2  
addi r5, r5, 15
```

machine  
code

```
001000000000010100000000000001010  
000000000000001010010100001000000  
001000001010010100000000000001111
```

Instruction Set  
Architecture (ISA)

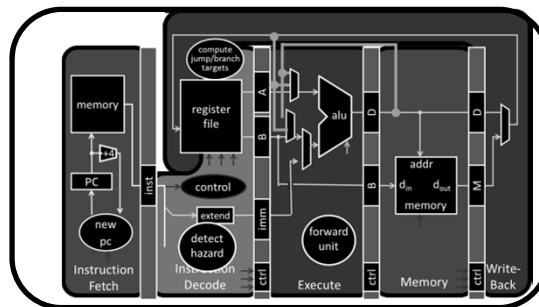
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# Goals for Today

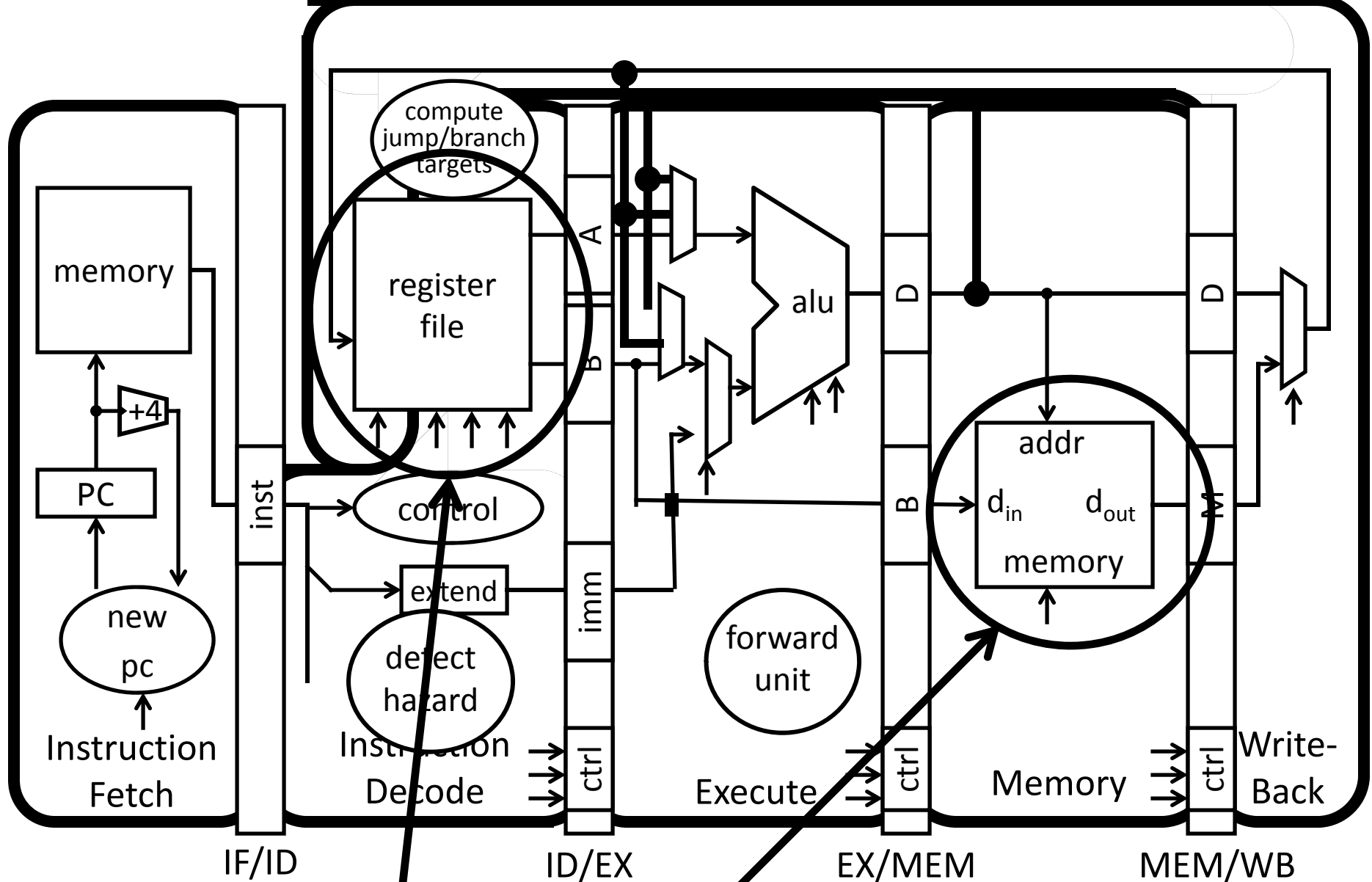
Calling Convention for Procedure Calls

Enable code to be reused by allowing code snippets to be invoked

Will need a way to

- call the routine (i.e. transfer control to procedure)
- pass arguments
  - fixed length, variable length, recursively
- return to the caller
  - Putting results in a place where caller can find them
- Manage register

# Cheat Sheet and Mental Model for Today



How do we share registers and use memory when making procedure calls?

# MIPS Register

Return address: \$31 (ra)

Stack pointer: \$29 (sp)

Frame pointer: \$30 (fp)

First four arguments: \$4-\$7 (a0-a3)

Return result: \$2-\$3 (v0-v1)

Callee-save free regs: \$16-\$23 (s0-s7)

Caller-save free regs: \$8-\$15, \$24, \$25 (t0-t9)

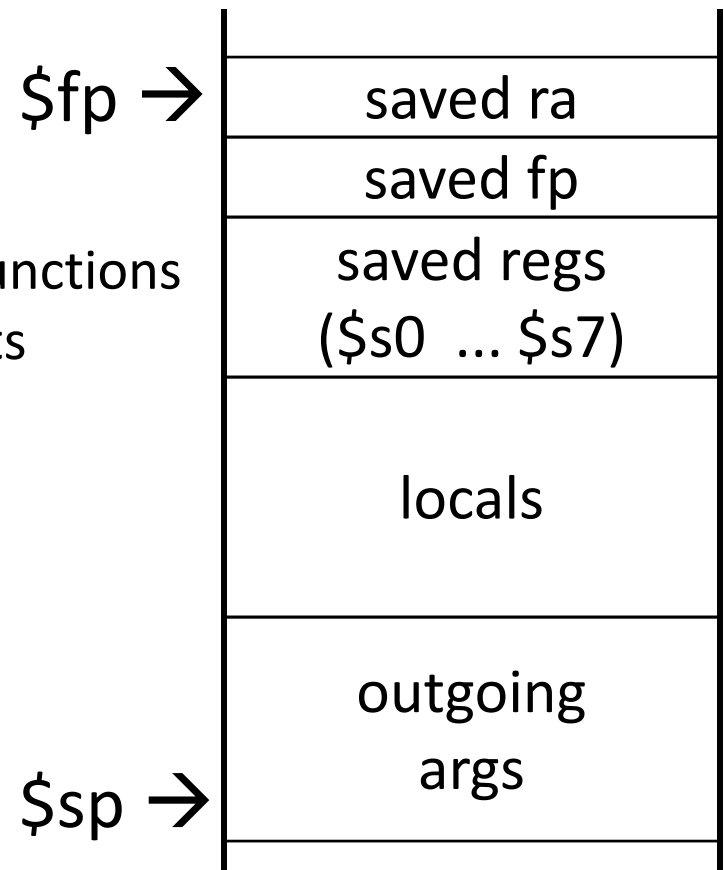
Reserved: \$26, \$27

Global pointer: \$28 (gp)

Assembler temporary: \$1 (at)

# Cheat Sheet and Mental Model for Today

- first four arg words passed in \$a0, \$a1, \$a2, \$a3
- remaining arg words passed in parent's stack frame
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)
  - contains local vars (possibly clobbered by sub-functions)
  - contains extra arguments to sub-functions
  - contains space for first 4 arguments to sub-functions
- callee save regs are preserved
- caller save regs are not
- Global data accessed via \$gp





# MIPS Register Conventions

r0	\$zero	zero	r16	\$s0	<b>saved (callee save)</b>
r1	\$at	assembler temp	r17	\$s1	
r2	\$v0	function return values	r18	\$s2	
r3	\$v1		r19	\$s3	
r4	\$a0	function arguments	r20	\$s4	
r5	\$a1		r21	\$s5	
r6	\$a2		r22	\$s6	
r7	\$a3		r23	\$s7	
r8	\$t0	<b>temps (caller save)</b>	r24	\$t8	<b>more temps (caller save)</b>
r9	\$t1		r25	\$t9	
r10	\$t2		r26	\$k0	reserved for kernel
r11	\$t3		r27	\$k1	
r12	\$t4		r28	\$gp	global data pointer
r13	\$t5		r29	\$sp	stack pointer
r14	\$t6		r30	\$fp	frame pointer
r15	\$t7	r31	\$ra	return address	

# Goals for Today

Calling Convention for Procedure Calls

Enable code to be reused by allowing code snippets to be invoked

Will need a way to

- call the routine (i.e. transfer control to procedure)
- pass arguments
  - fixed length, variable length, recursively
- return to the caller
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- Manage register

# MIPS Register “scorecard”

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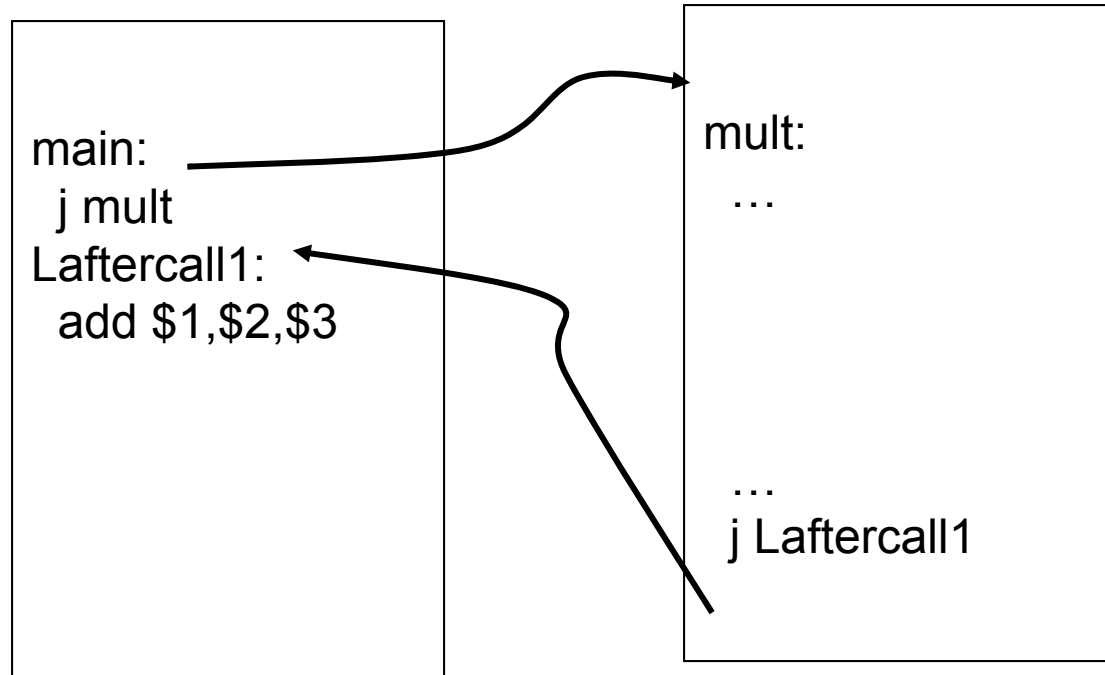
Assembler temporary: \$1 (at)

# What is the convention to call a subroutine?

```
int main (int argc, char* argv[ ]) {  
    int n = 9;  
    int result = multi(n);  
}
```

```
int multi(int n) {  
    int f = 1;  
    int i = 1;  
    int j = n - 1;  
    while(j >= 0) {  
        f *= i;  
        i++;  
        j = n - 1;  
    }  
    return f;  
}
```

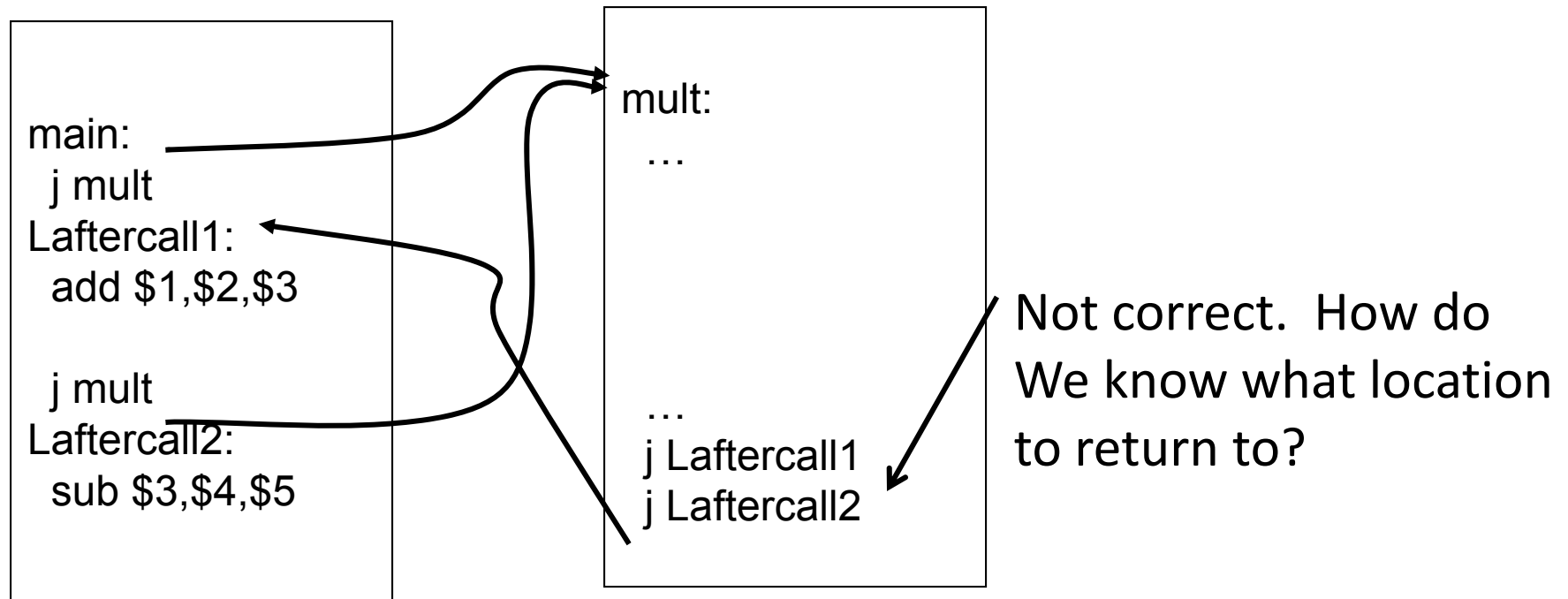
# Procedure Call – Attempt #1: Use Jumps



Jumps and branches can transfer control to the callee (called procedure)

Jumps and branches can transfer control back

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Jumps and branches can transfer control to the callee (called procedure)

Jumps and branches can transfer control back

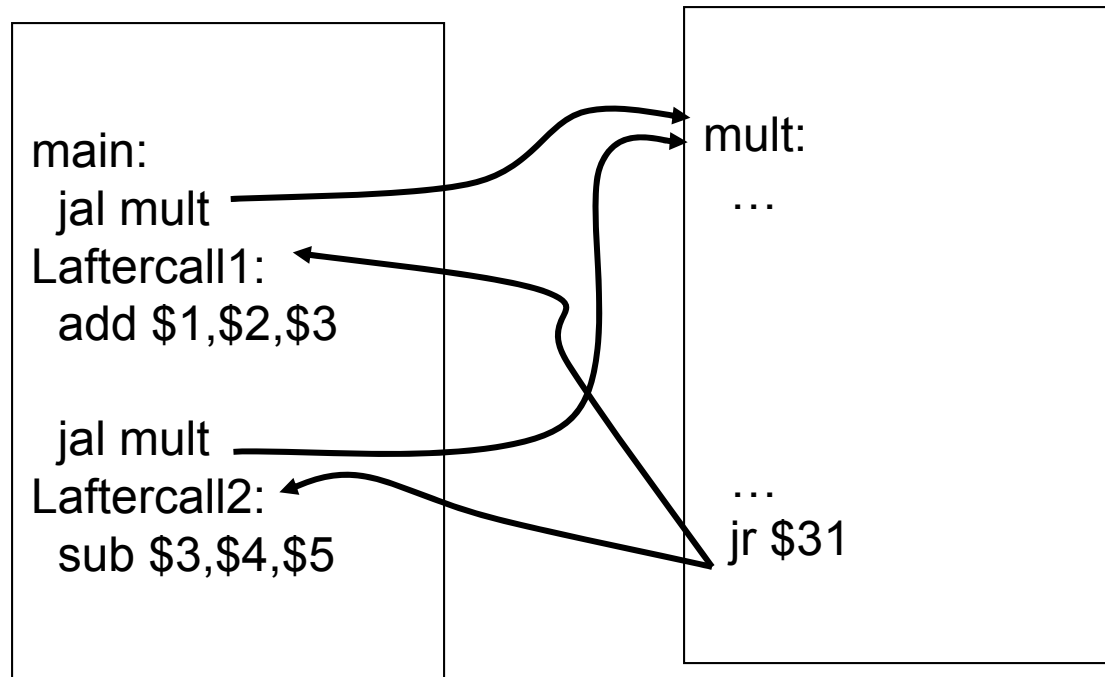
What happens when there are multiple calls from different call sites?

# Takeaway1: Need Jump And Link

JAL (Jump And Link) instruction moves a new value into the PC, and simultaneously saves the old value in register \$31 (aka \$ra or return address)

Thus, can get back from the subroutine to the instruction immediately following the jump by transferring control back to PC in register \$31

# Procedure Call – Attempt #2: JAL/JR



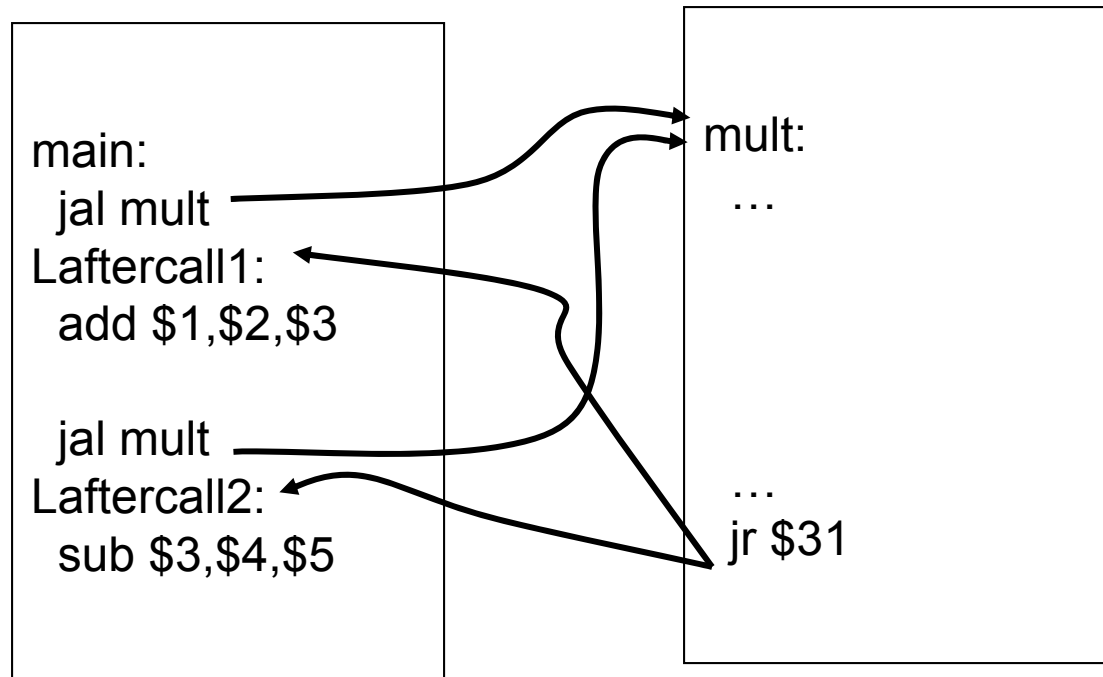
JAL saves the PC in register \$31

Subroutine returns by jumping to \$31

What happens for recursive invocations?



# Procedure Call – Attempt #2: JAL/JR



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# Procedure Call – Attempt #2: JAL/JR

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```
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    }  
    return f;  
}
```

# Procedure Call – Attempt #2: JAL/JR

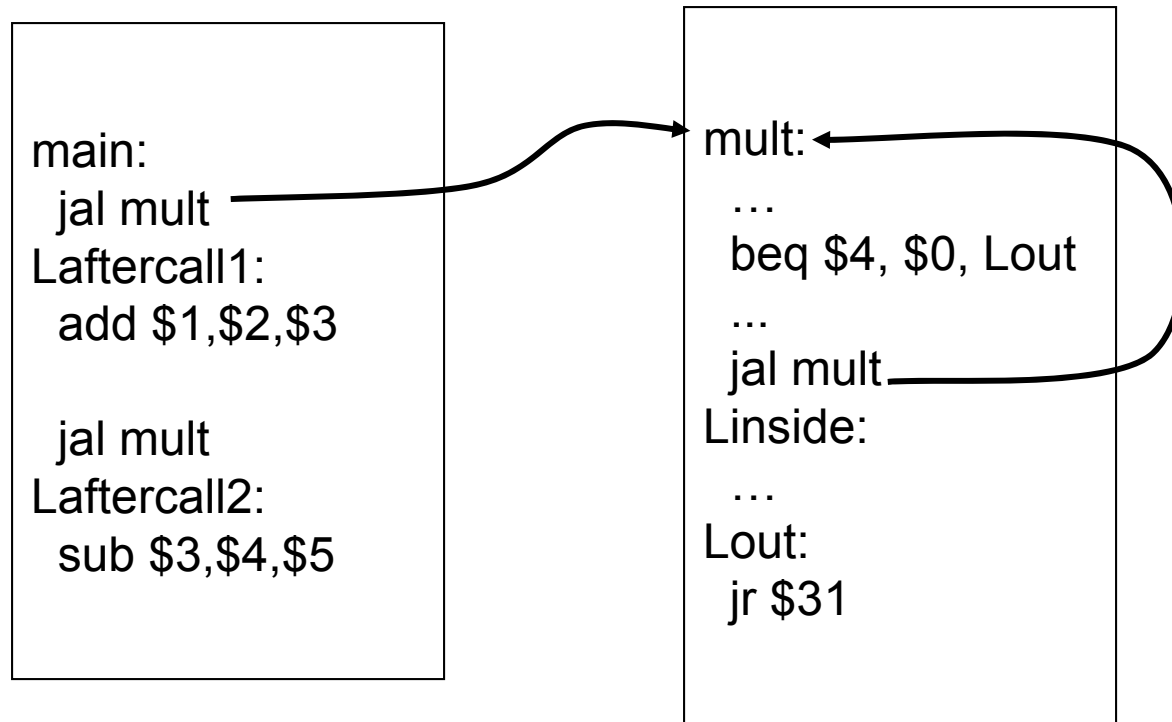
```
int main (int argc, char* argv[ ]) {  
    int n = 9;  
    int result = multi(n);  
}
```

What happens for recursive invocations?

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

The diagram illustrates a recursive call. An arrow starts from the `multi(n - 1)` expression in the `return` statement and points back to the opening curly brace of the `multi` function. The `multi(n - 1)` expression is circled, indicating the recursive invocation.

# Procedure Call – Attempt #2: JAL/JR



What happens for recursive invocations?

Recursion overwrites contents of \$31

Need to save and restore the register contents

# Need a “Call Stack”

## Call stack

- contains activation records (aka stack frames)

## Each activation record contains

- the return address for that invocation
- the local variables for that procedure

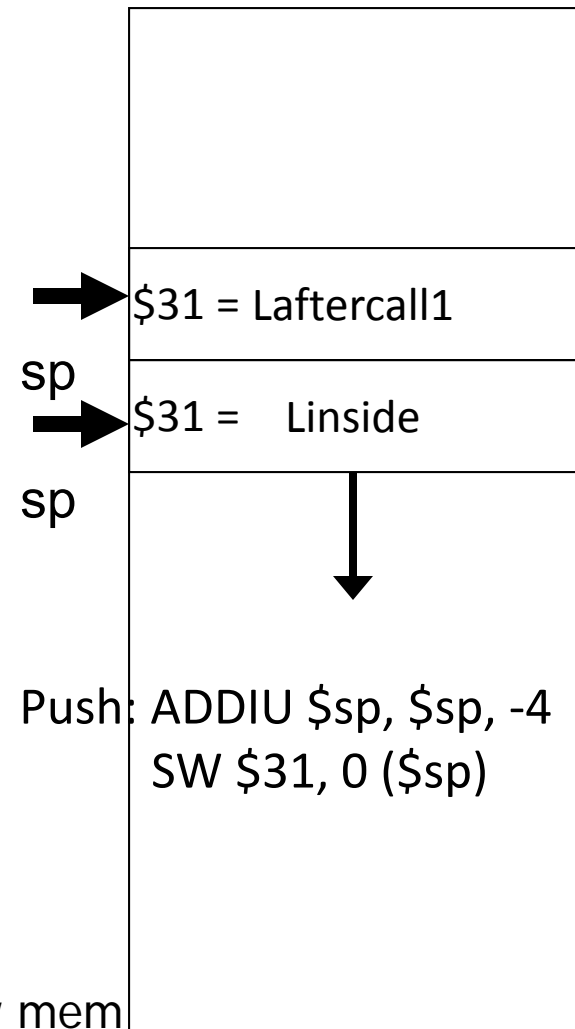
A stack pointer (*sp*) keeps track of the top of the stack

- dedicated register ( $\$29$ ) on the MIPS

Manipulated by push/pop operations

- push: move *sp* down, store
- pop: load, move *sp* up

high mem



low mem

# Need a “Call Stack”

## Call stack

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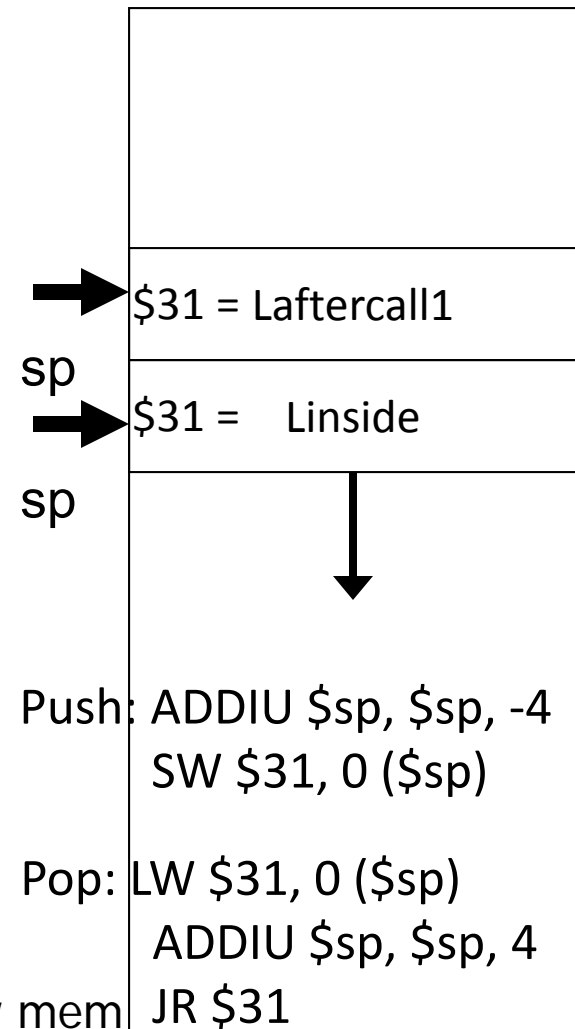
A stack pointer (sp) keeps track of the top of the stack

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## Manipulated by push/pop operations

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high mem



# Stack Growth

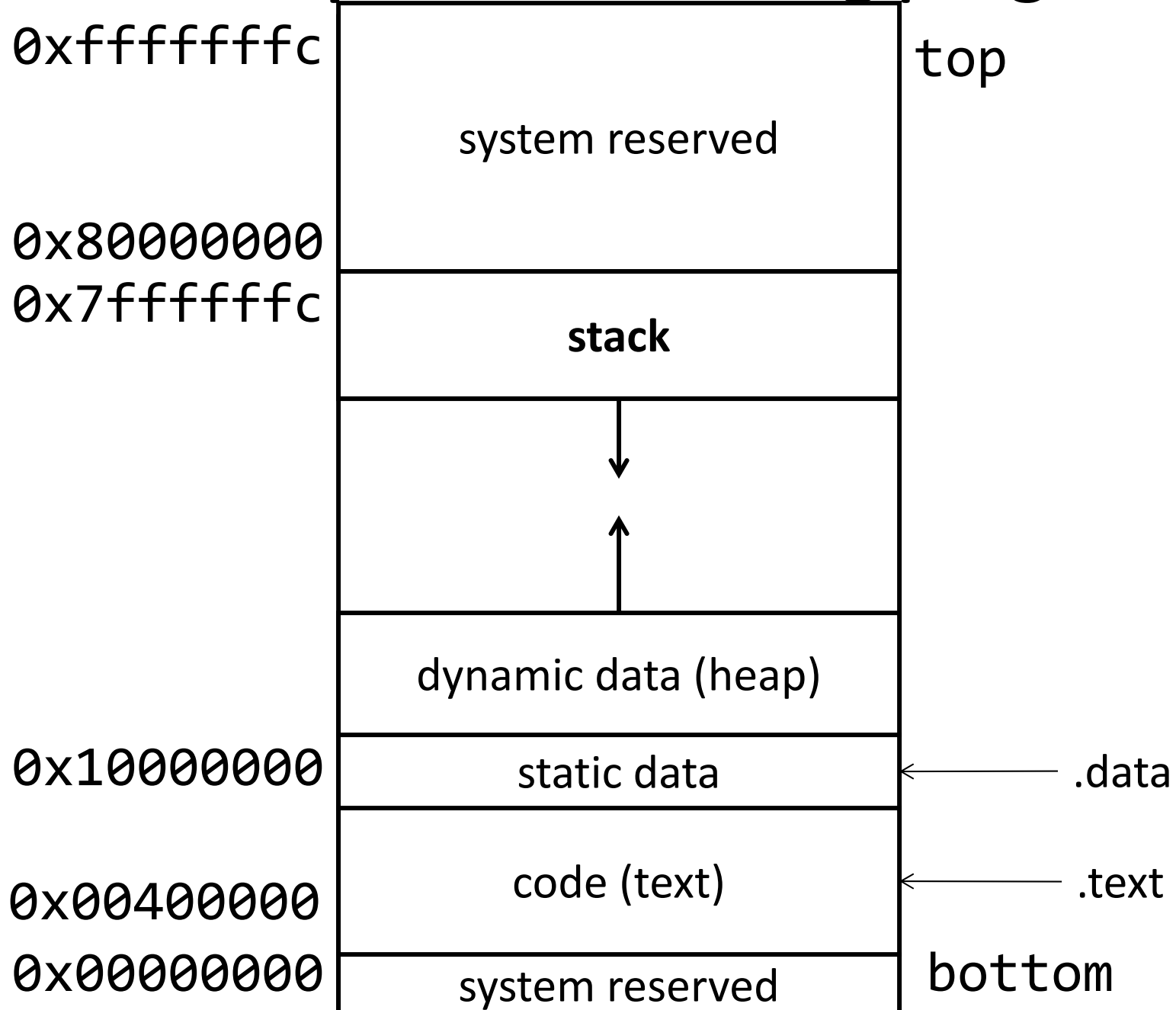
(Call) Stacks start at a high address in memory

Stacks grow down as frames are pushed on

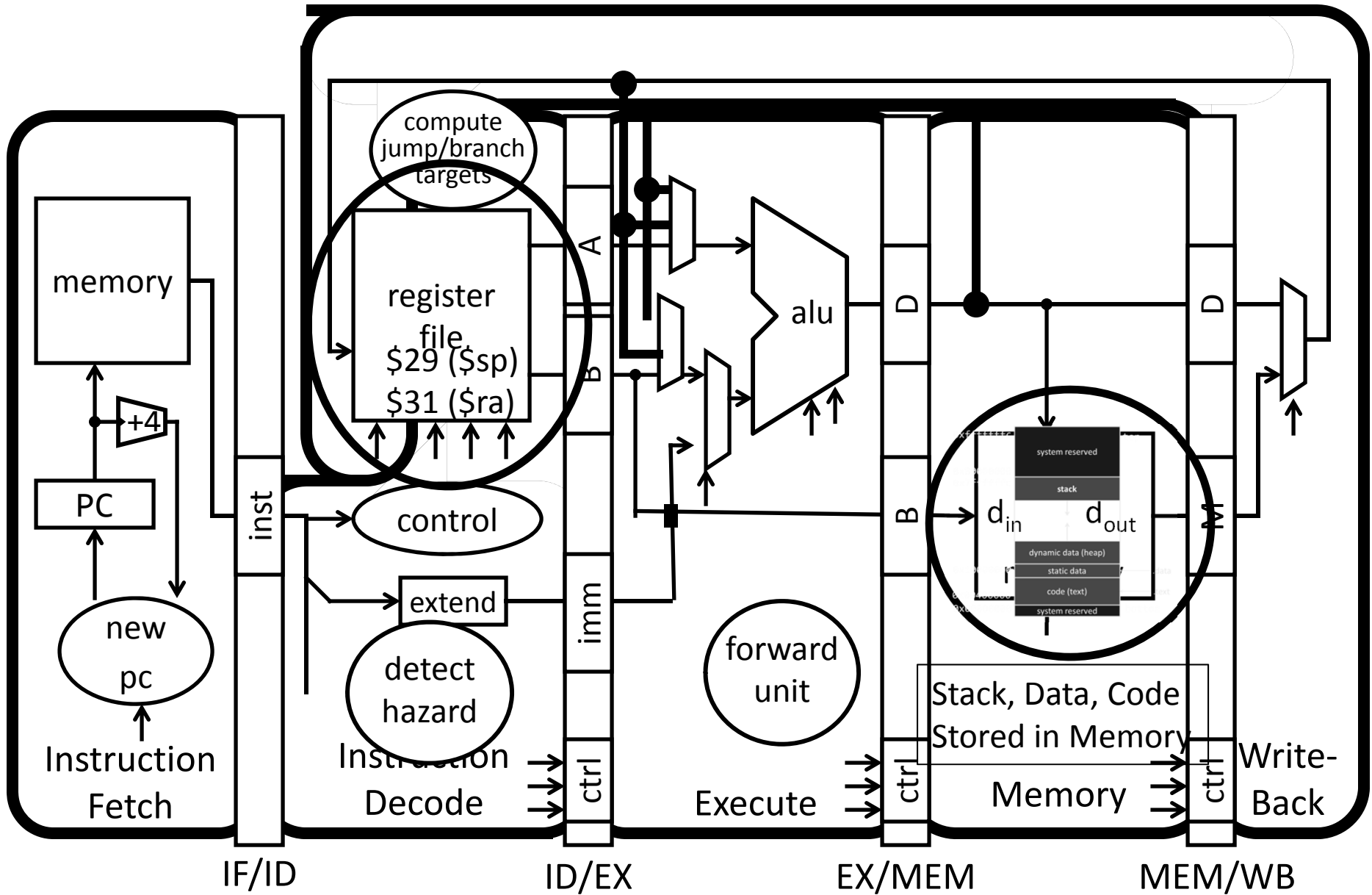
- Note: data region starts at a low address and grows up
- The growth potential of stacks and data region are not artificially limited



# Anatomy of an executing program



# Anatomy of an executing program

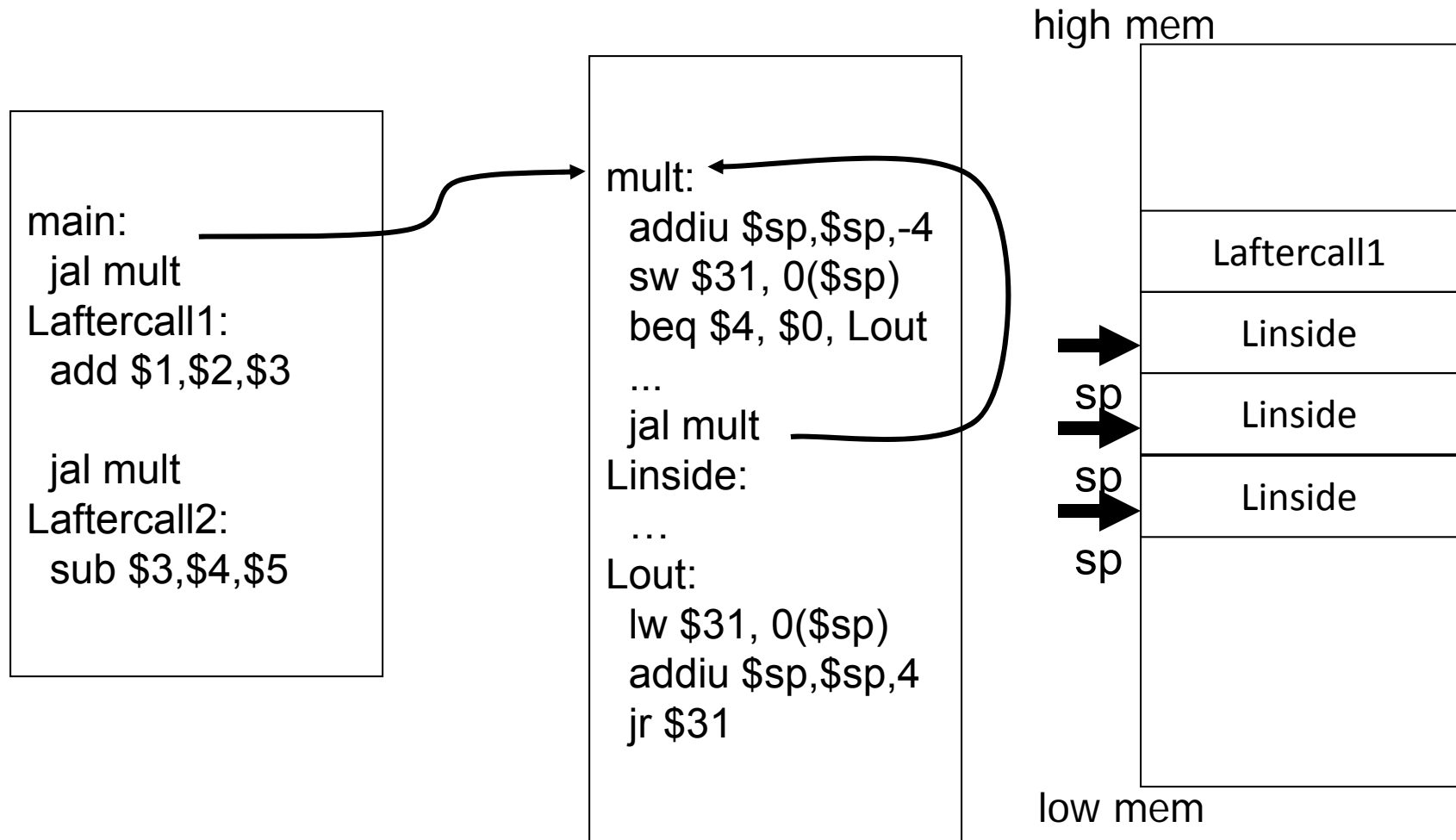


## Takeaway2: Need a Call Stack

JAL (Jump And Link) instruction moves a new value into the PC, and simultaneously saves the old value in register \$31 (aka \$ra or return address). Thus, can get back from the subroutine to the instruction immediately following the jump by transferring control back to PC in register \$31.

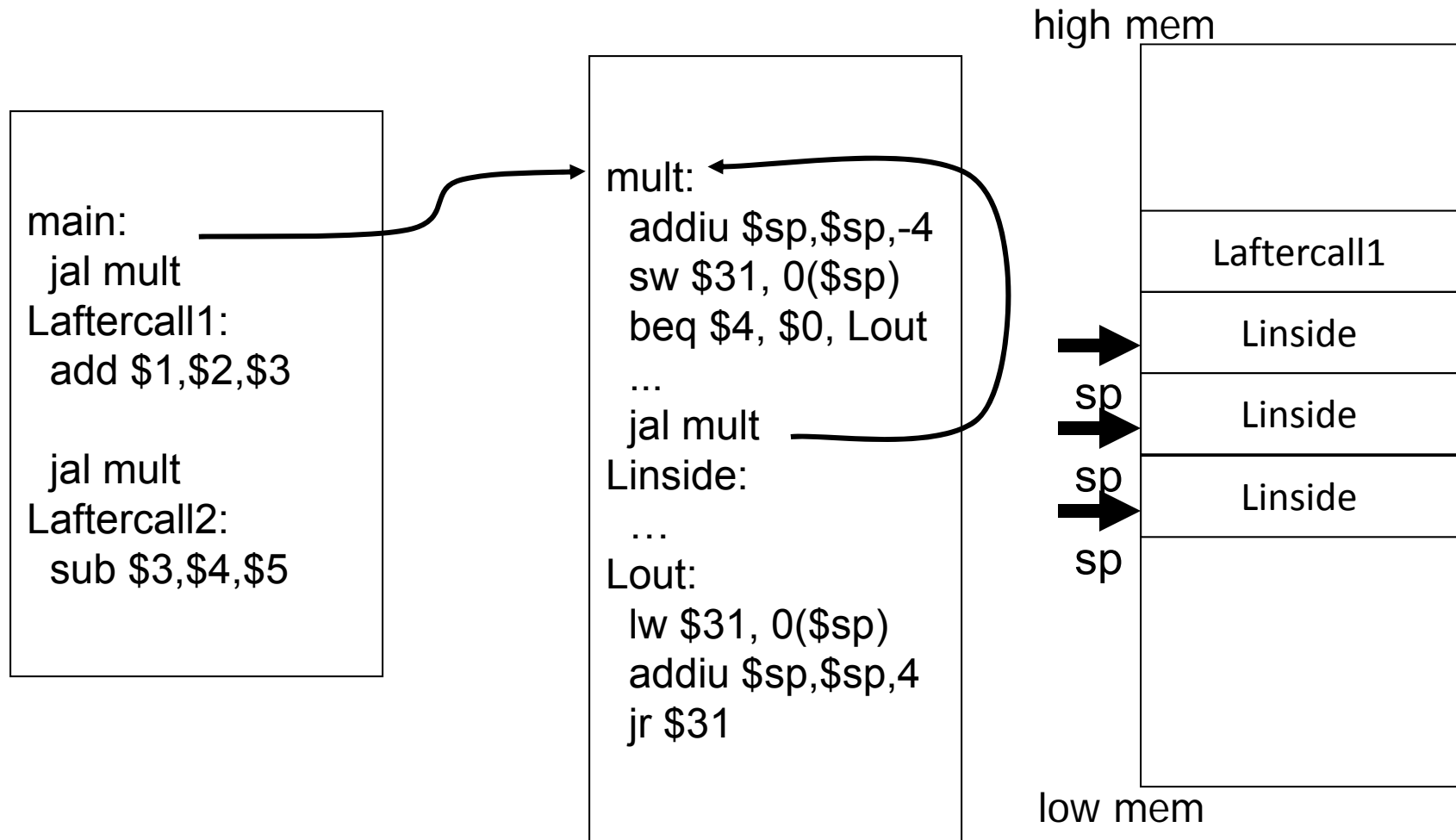
Need a Call Stack to return to correct calling procedure. To maintain a stack, need to store an ***activation record*** (aka a “stack frame”) in memory. Stacks keep track of the correct return address by storing the contents of \$31 in memory (the stack).

# Attempt #3: JAL/JR with Activation Records



Stack used to save and restore contents of \$31

# Attempt #3: JAL/JR with Activation Records



Stack used to save and restore contents of \$31

How about arguments?

# Next Goal

Need consistent way of passing arguments and getting the result of a subroutine invocation

# MIPS Register “scorecard”

Return address: \$31 (ra)

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Reserved: \$26, \$27

Global pointer: \$28 (gp)

Assembler temporary: \$1 (at)

# Attempt #4: Arguments & Return Values

Need consistent way of passing arguments and getting the result of a subroutine invocation

Given a procedure signature, need to know where arguments should be placed

- `int min(int a, int b);`  $\$a0, \$a1$
- `int subf(int a, int b, int c, int d, int e);`  $\text{stack}$
- `int isalpha(char c);`
- `int treesort(struct Tree *root);`
- `struct Node *createNode();`  $\$a0$
- `struct Node mynode();`  $\$v0, \$v1$

Too many combinations of char, short, int, void \*, struct, etc.

- MIPS treats char, short, int and void \* identically



# Simple Argument Passing

```
main:  
  li $a0, 6  
  li $a1, 7  
  jal min  
  // result in $v0
```

First four arguments are passed in registers

- Specifically, \$4, \$5, \$6 and \$7, aka \$a0, \$a1, \$a2, \$a3

The returned result is passed back in a register

- Specifically, \$2, aka \$v0

# Conventions so far:

- args passed in \$a0, \$a1, \$a2, \$a3
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)

Q: What about argument lists?

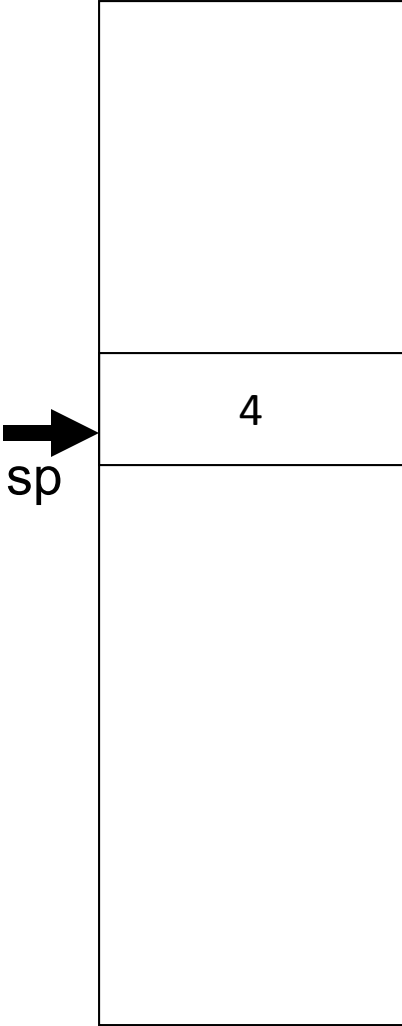
# Many Arguments

```
main:  
    li $a0, 0  
    li $a1, 1  
    li $a2, 2  
    li $a3, 3  
    jal subf  
    // result in $v0
```

What if there are  
more than 4  
arguments?

# Many Arguments

```
main:  
  li $a0, 0  
  li $a1, 1  
  li $a2, 2  
  li $a3, 3  
  li $8, 4  
  addiu $sp,$sp,-4  
  sw $8, 0($sp)  
  jal subf  
  // result in $v0
```



What if there are more than 4 arguments?

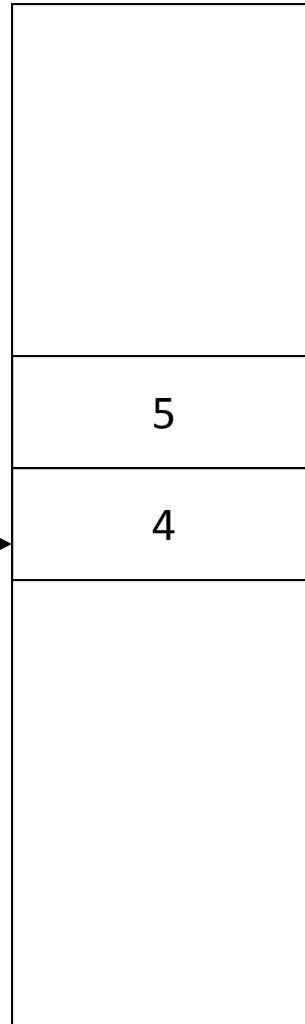
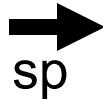
Use the stack for the additional arguments

- “spill”

# Many Arguments

main:

```
li $a0, 0
li $a1, 1
li $a2, 2
li $a3, 3
addiu $sp,$sp,-8
li $8, 4
sw $8, 0($sp)
li $8, 5
sw $8, 4($sp)
jal subf
// result in $v0
```



What if there are more than 4 arguments?

Use the stack for the additional arguments

- “spill”

# Variable Length Arguments

```
printf("Coordinates are: %d %d %d\n", 1, 2, 3);
```

Could just use the regular calling convention, placing first four arguments in registers, spilling the rest onto the stack

- Callee requires special-case code
- if(argno == 1) use a0, ... else if (argno == 4) use a3, else use stack offset

Best to use an (initially confusing but ultimately simpler) approach:

- Pass the first four arguments in registers, as usual
- Pass the rest on the stack
- Reserve space on the stack for all arguments, including the first four

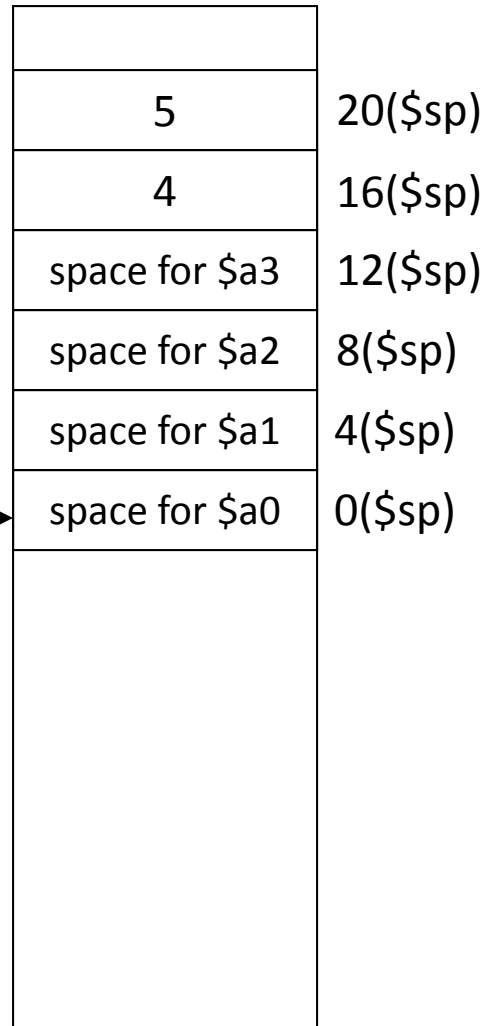
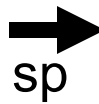
Simplifies functions that use variable-length arguments

- Store a0-a3 on the slots allocated on the stack, refer to all arguments through the stack

# Register Layout on Stack

main:

```
li $a0, 0
li $a1, 1
li $a2, 2
li $a3, 3
addiu $sp,s$sp,-24
li $8, 4
sw $8, 16($sp)
li $8, 5
sw $8, 20($sp)
jal subf
// result in$ v0
```

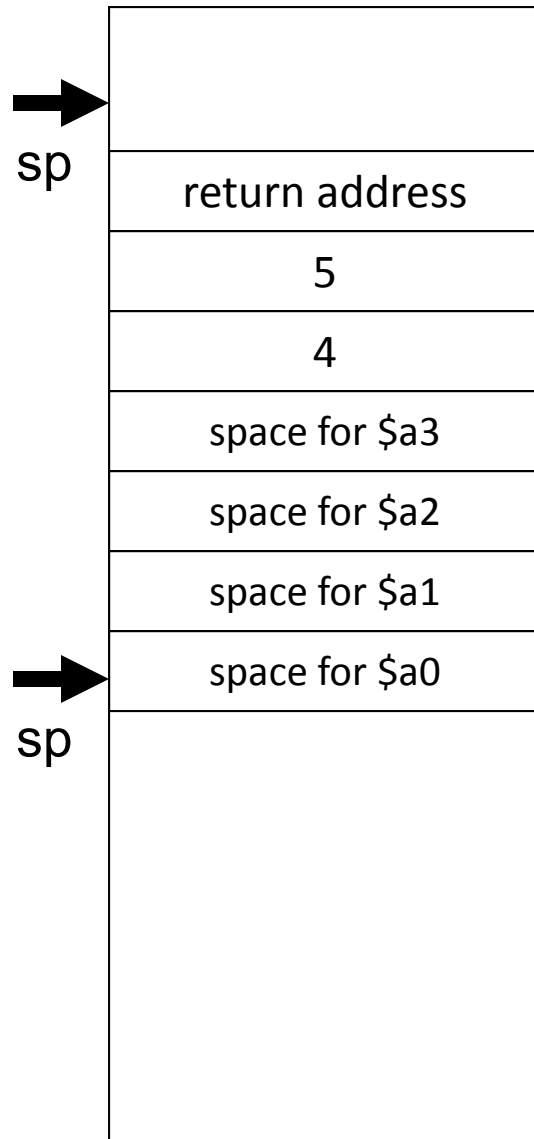


First four arguments are in registers

The rest are on the stack

There is room on the stack for the first four arguments, just in case

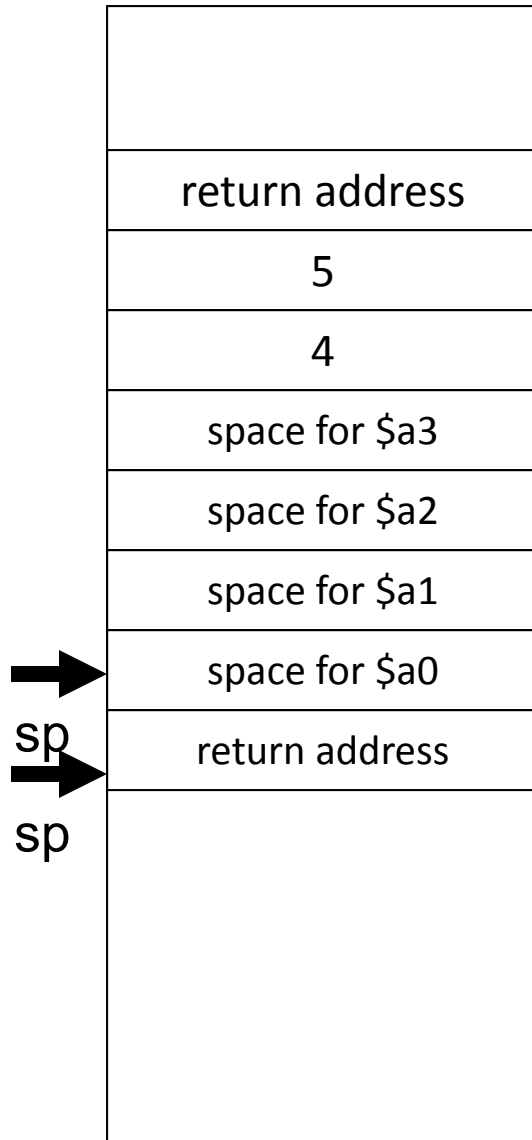
# Frame Layout on Stack



```
blue() {  
    pink(0,1,2,3,4,5);  
}
```

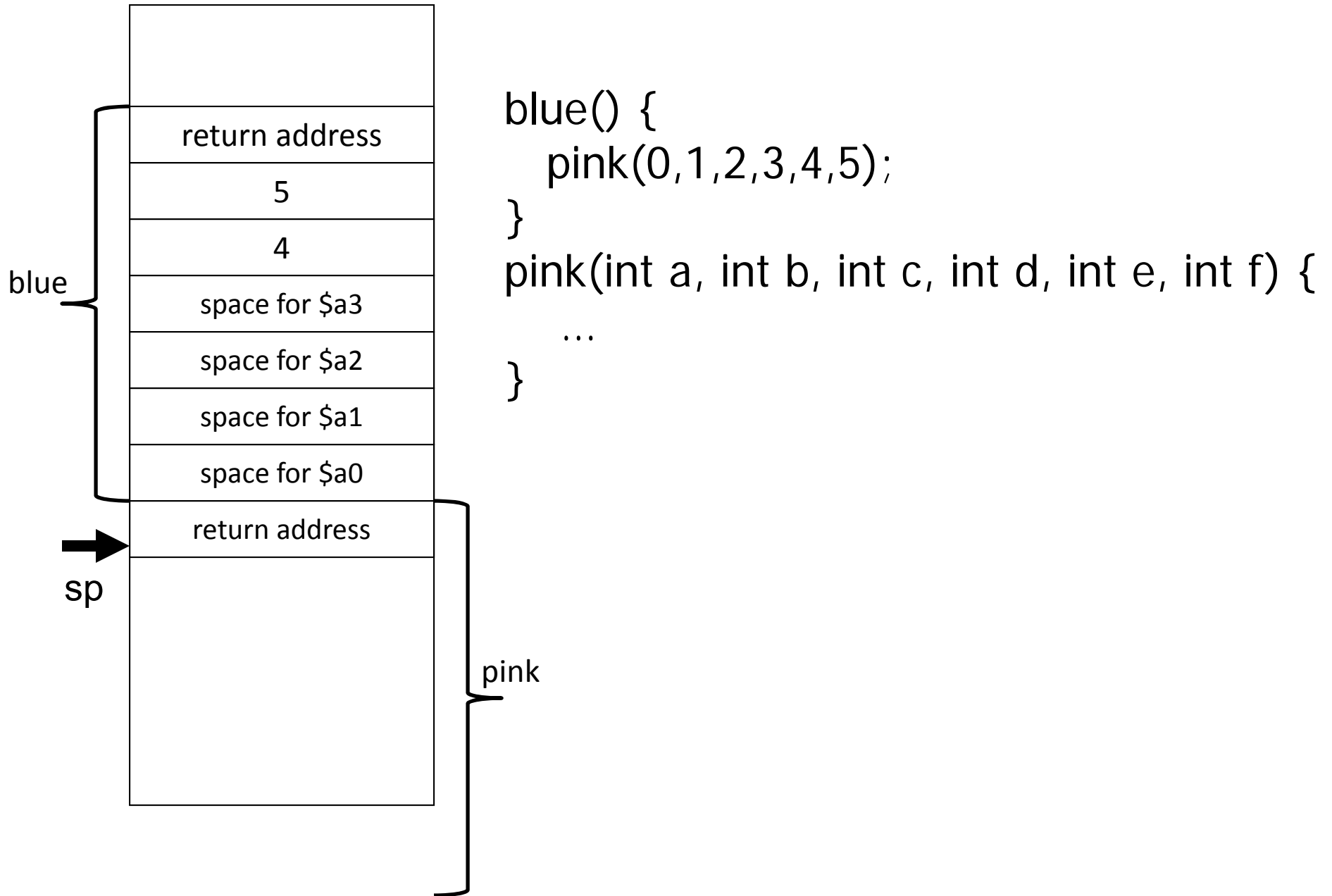


# Frame Layout on Stack



```
blue() {  
    pink(0,1,2,3,4,5);  
}  
pink(int a, int b, int c, int d, int e, int f) {  
    ...  
}
```

# Frame Layout on Stack



# Conventions so far:

- first four arg words passed in \$a0, \$a1, \$a2, \$a3
- remaining arg words passed on the stack
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)
  - contains extra arguments to sub-functions
  - contains **space** for first 4 arguments to sub-functions

# MIPS Register Conventions so far:

r0	\$zero	zero	r16		Pseudo-Instructions e.g. BLZ  SLT \$at BNE \$at, 0, L
r1	\$at	assembler temp	r17		
r2	\$v0	function	r18		
r3	\$v1	return values	r19		
r4	\$a0		r20		
r5	\$a1	function	r21		
r6	\$a2	arguments	r22		
r7	\$a3		r23		
r8			r24		
r9			r25		
r10			r26	\$k0	reserved for OS kernel
r11			r27	\$k1	
r12			r28		
r13			r29		
r14			r30		
r15			r31	\$ra	return address

# Pseudo-Instructions

## Pseudo-Instructions

NOP # do nothing

- SLL r0, r0, 0

MOVE reg, reg # copy between regs

- ADD R2, R0, R1 # copies contents of R1 to R2

LI reg, imm # load immediate (up to 32 bits)

LA reg, label # load address (32 bits)

B label # unconditional branch

BLT reg, reg, label # branch less than

- SLT r1, rA, rB # r1 = 1 if R[rA] < R[rB]; o.w. r1 = 0
- BNE r1, r0, label # go to address label if r1!=r0; i.t. rA < rB

# Java vs C: Pointers and Structures

Pointers are 32-bits, treat just like ints

Pointers to structs are pointers

C allows passing whole structs

- `int distance(struct Point $a0, $a1p1, struct Point $a2, $a3p2)`
- Treat like a collection of consecutive 32-bit arguments, use registers for first 4 words, stack for rest

- Of course, Inefficient and to be avoided, better to use  
`int distance(struct Point *p1, struct Point *p2)`  
in all cases `$a0` `$a1`

# MIPS Register “scorecard”

Return address: \$31 (ra)

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Caller-save free regs: \$8-\$15, \$24, \$25 (t0-t9)

Reserved: \$26, \$27

Global pointer: \$28 (gp)

Assembler temporary: \$1 (at)

# Globals and Locals

Global variables are allocated in the “data” region of the program

- Exist for all time, accessible to all routines

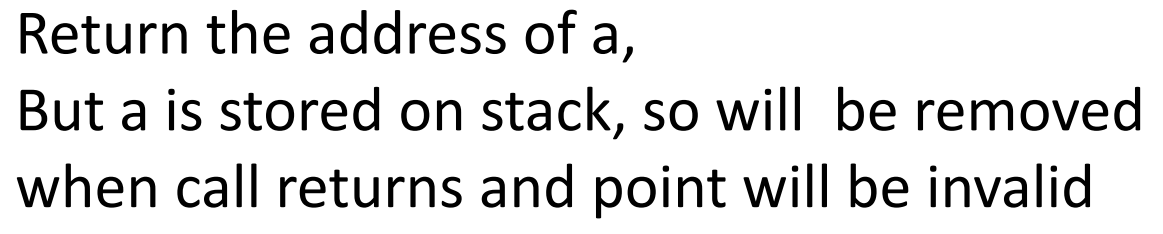
Local variables are allocated within the stack frame

- Exist solely for the duration of the stack frame

Dangling pointers are pointers into a destroyed stack frame

- C lets you create these, Java does not

- `int *foo() { int a; return &a; }`



Return the address of a,  
But a is stored on stack, so will be removed  
when call returns and point will be invalid



# Global and Locals

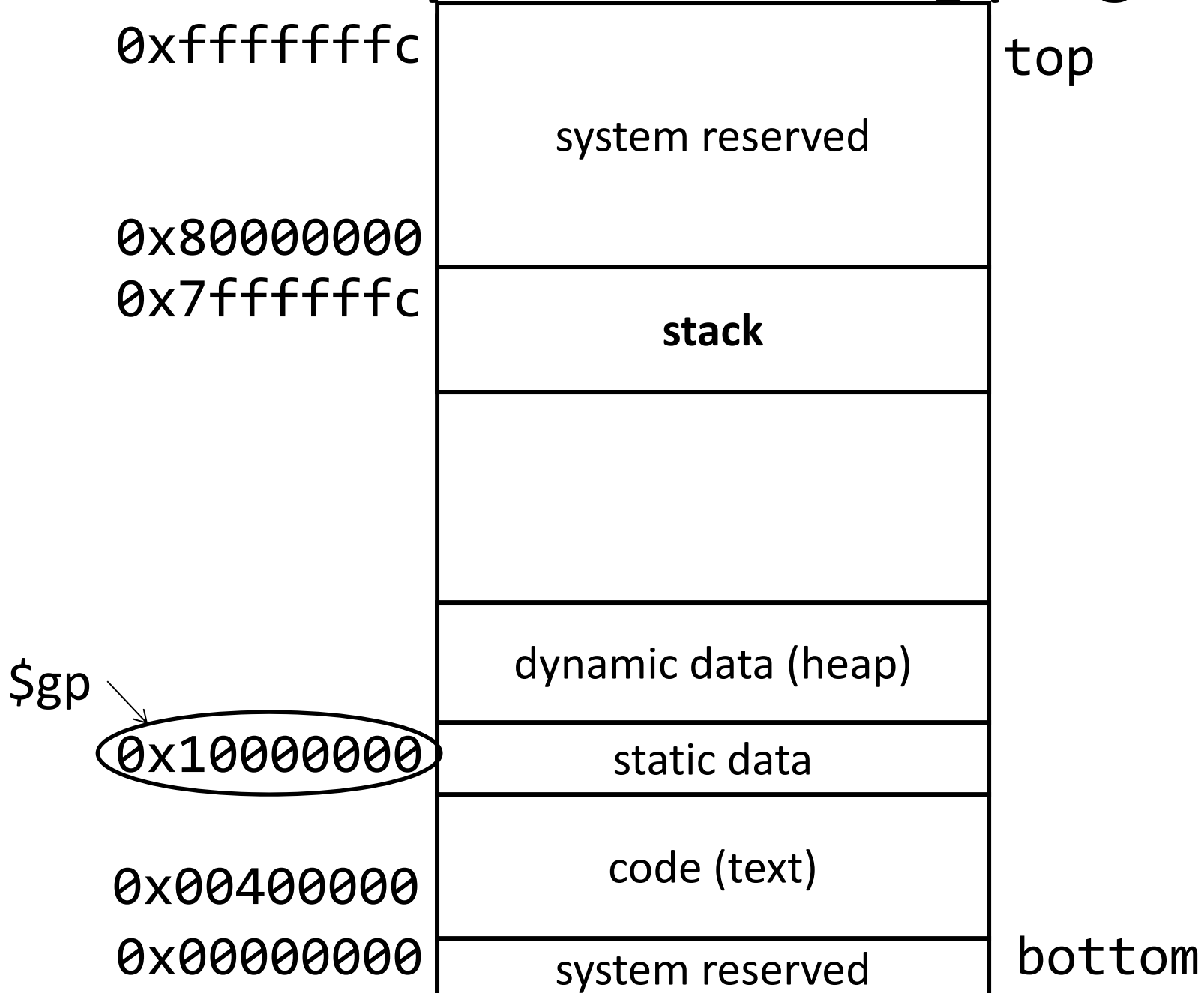
How does a function load global data?

- global variables are just above 0x10000000

Convention: *global pointer*

- \$28 is \$gp (pointer into *middle* of global data section)  
\$gp = 0x10008000
- Access most global data using LW at \$gp +/- offset  
LW \$v0, 0x8000(\$gp)  
LW \$v1, 0x7FFF(\$gp)

# Anatomy of an executing program



# MIPS Register “scorecard”

Return address: \$31 (ra)

Stack pointer: \$29 (sp)

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# Frame Pointer

It is often cumbersome to keep track of location of data on the stack

- The offsets change as new values are pushed onto and popped off of the stack

Keep a pointer to the bottom of the stack frame

- Simplifies the task of referring to items on the stack
- Note “bottom of the stack frame” is the highest addr of the stack frame

A frame pointer, `$30`, aka `$fp`

- Value of `$sp` upon procedure entry
- Can be used to restore `$sp` on exit

# Conventions so far

- first four arg words passed in \$a0, \$a1, \$a2, \$a3
- remaining arg words passed in parent's stack frame
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)
  - contains extra arguments to sub-functions
  - contains space for first 4 arguments to sub-functions

# Next Goal

What convention should we use to share use of registers across procedure calls?

# MIPS Register “scorecard”

Return address: \$31 (ra)

Stack pointer: \$29 (sp)

Frame pointer: \$30 (fp)

First four arguments: \$4-\$7 (a0-a3)

Return result: \$2-\$3 (v0-v1)

Callee-save free regs: \$16-\$23 (s0-s7)

Caller-save free regs: \$8-\$15, \$24, \$25 (t0-t9)

Reserved: \$26, \$27

Global pointer: \$28 (gp)

Assembler temporary: \$1 (at)

# Register Usage

Suppose a routine would like to store a value in a register

Two options: callee-save and caller-save

Callee-save:

- Assume that one of the callers is already using that register to hold a value of interest
- Save the previous contents of the register on procedure entry, restore just before procedure return
- E.g. \$31

Caller-save:

- Assume that a caller can clobber any one of the registers
- Save the previous contents of the register before proc call
- Restore after the call

MIPS calling convention supports both



# Callee-Save

main:

addiu \$sp,\$sp,-32

sw \$31,28(\$sp)

sw \$30, 24(\$sp)

sw \$17, 20(\$sp)

sw \$16, 16(\$sp)

addiu \$30, \$sp, 28

...

[use \$16 and \$17]

lw \$31,28(\$sp)

lw \$30,24(\$sp)

lw \$17, 20(\$sp)

lw \$16, 16(\$sp)

addiu \$sp,\$sp,32

jr \$31

Assume caller is using the registers

Callee must save on entry, restore on exit

Pays off if caller is actually using the registers, else the save and restore are wasted

# Callee-Save

main:

addiu \$sp, \$sp, -32

sw \$ra, 28(\$sp)

sw \$fp, 24(\$sp)

sw \$s1, 20(\$sp)

sw \$s0, 16(\$sp)

addiu \$fp, \$sp, 28

...

[use \$s0 and \$s1]

lw \$ra, 28(\$sp)

lw \$fp, 24(\$sp)

lw \$s1, 20(\$sp)

lw \$s0, 16(\$sp)

addiu \$sp, \$sp, 32

jr \$ra

Assume caller is using the registers

Callee must save on entry, restore on exit

Pays off if caller is actually using the registers, else the save and restore are wasted

# Caller-Save

```
main:
```

```
...
```

```
[use $8 & $9]
```

```
...
```

```
addiu $sp,$sp,-8
```

```
sw $9, 4($sp)
```

```
sw $8, 0($sp)
```

```
jal mult
```

```
lw $9, 4($sp)
```

```
lw $8, 0($sp)
```

```
addiu $sp,$sp,8
```

```
...
```

```
[use $8 & $9]
```

Assume the registers are free for the taking, clobber them

But since other subroutines will do the same, must protect values that will be used later

By saving and restoring them before and after subroutine invocations

Pays off if a routine makes few calls to other routines with values that need to be preserved

# Caller-Save

```
main:
```

```
...
```

```
[use $t0 & $t1]
```

```
...
```

```
addiu $sp,$sp,-8
```

```
sw $t1, 4($sp)
```

```
sw $t0, 0($sp)
```

```
jal mult
```

```
lw $t1, 4($sp)
```

```
lw $t0, 0($sp)
```

```
addiu $sp,$sp,8
```

```
...
```

```
[use $t0 & $t1]
```

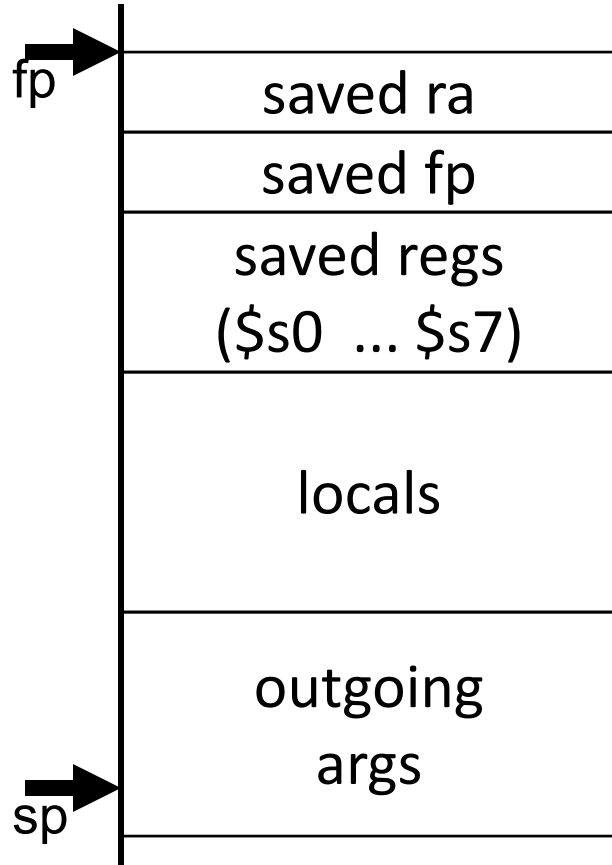
Assume the registers are free for the taking, clobber them

But since other subroutines will do the same, must protect values that will be used later

By saving and restoring them before and after subroutine invocations

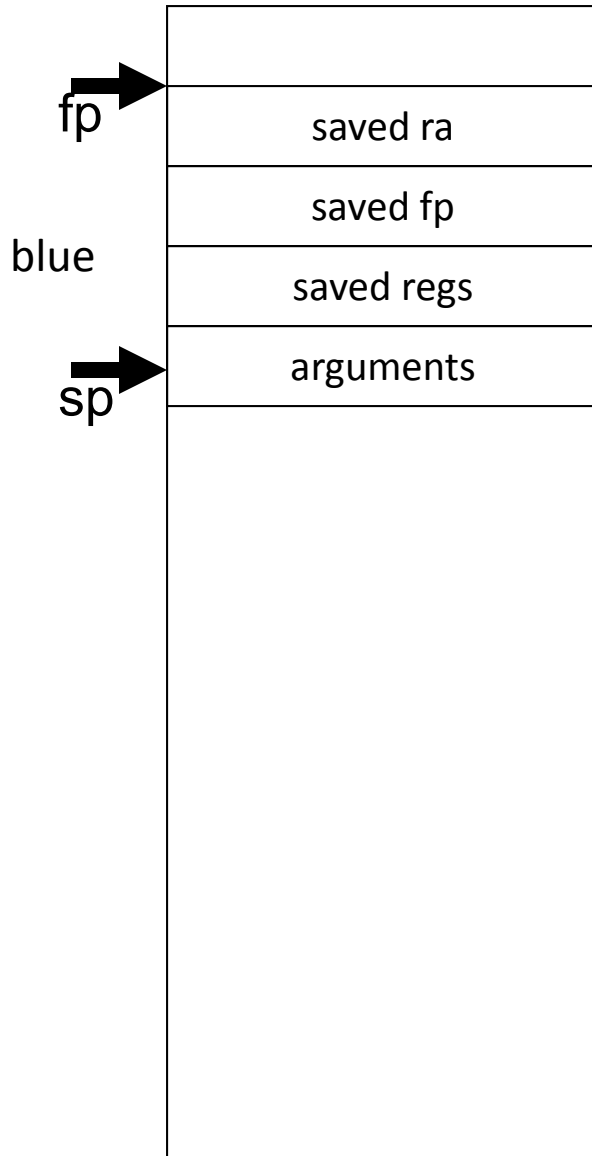
Pays off if a routine makes few calls to other routines with values that need to be preserved

# Frame Layout on Stack



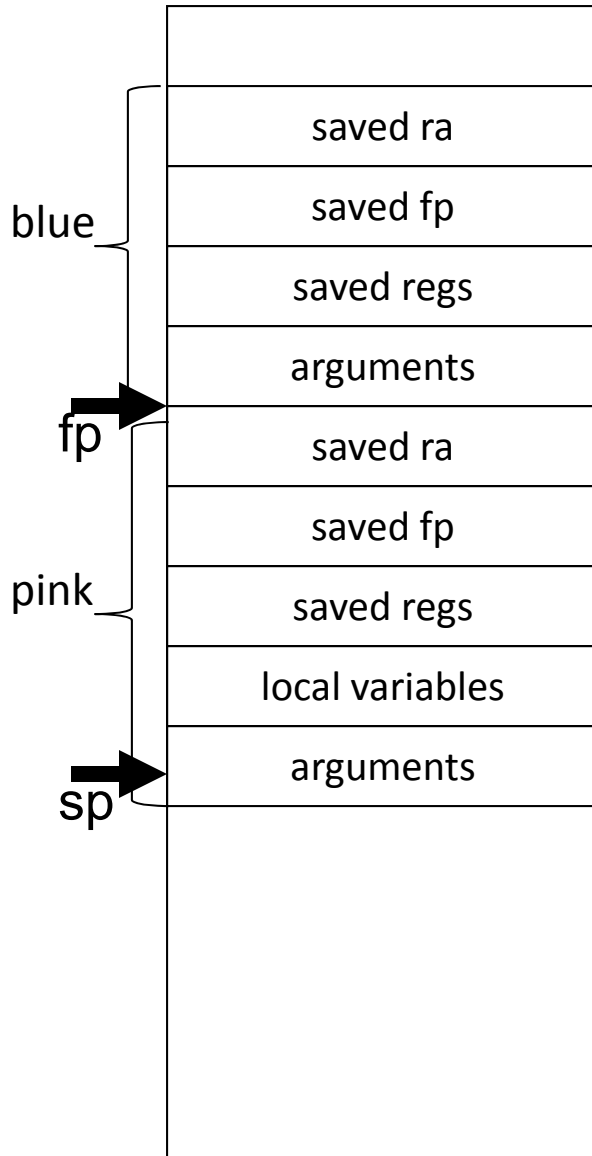
```
ADDIU $sp, $sp, -32 # allocate frame
SW $ra, 28($sp)    # save $ra
SW $fp, 24($sp)    # save old $fp
SW $s1, 20($sp)    # save ...
SW $s0, 16($sp)    # save ...
ADDIU $fp, $sp, 28 # set new frame ptr
...
...
BODY
...
...
LW $s0, 16($sp)    # restore ...
LW $s1, 20($sp)    # restore ...
LW $fp, 24($sp)    # restore old $fp
LW $ra, 28($sp)    # restore $ra
ADDIU $sp,$sp, 32  # dealloc frame
JR $ra
```

# Frame Layout on Stack



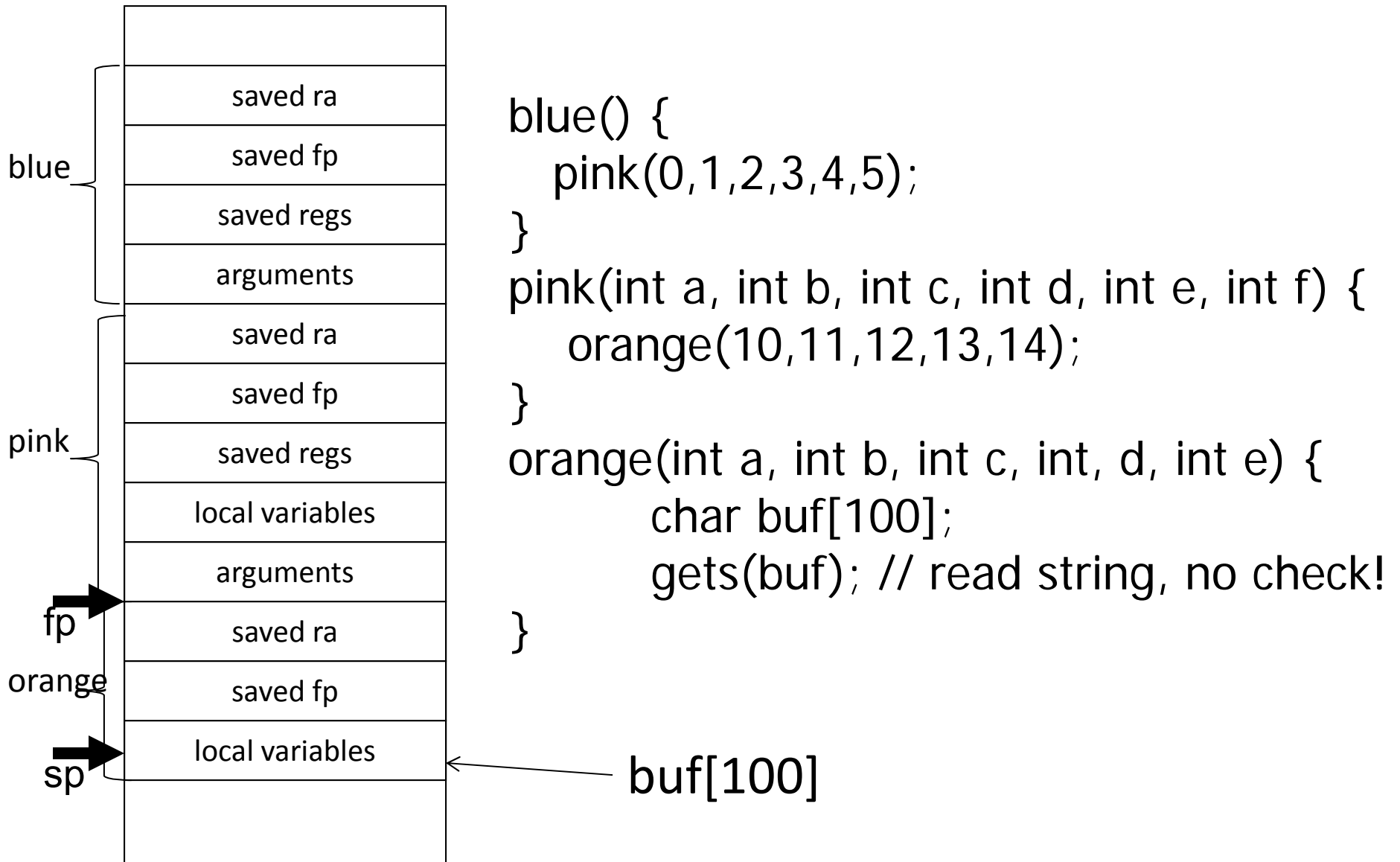
```
blue() {  
    pink(0,1,2,3,4,5);  
}
```

# Frame Layout on Stack



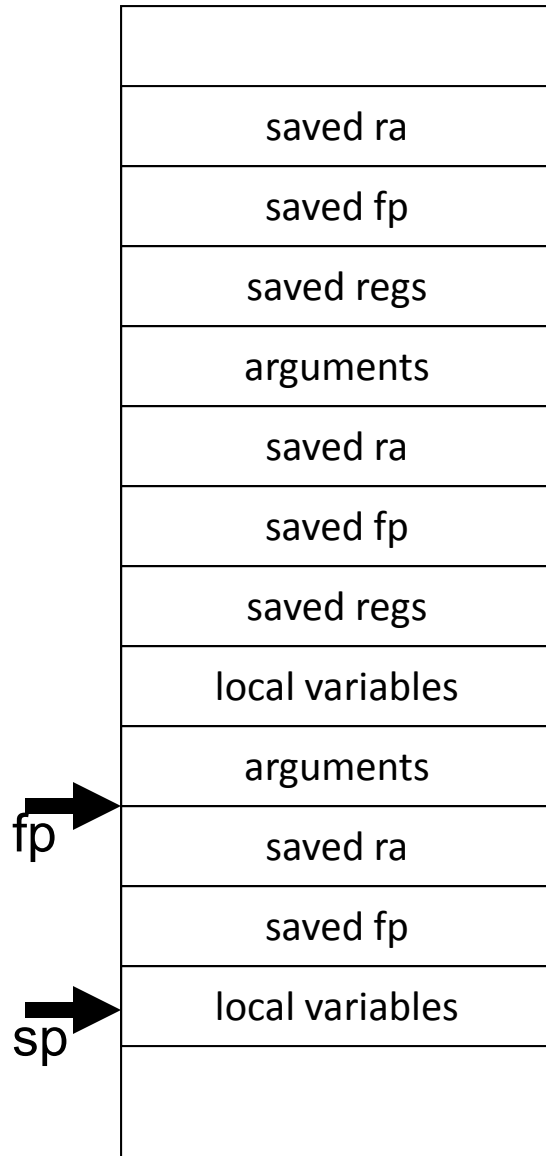
```
blue() {  
    pink(0,1,2,3,4,5);  
}  
pink(int a, int b, int c, int d, int e, int f) {  
    orange(10,11,12,13,14);  
}
```

# Frame Layout on Stack





# Buffer Overflow



```
blue() {  
    pink(0,1,2,3,4,5);  
}  
pink(int a, int b, int c, int d, int e, int f) {  
    orange(10,11,12,13,14);  
}  
orange(int a, int b, int c, int, d, int e) {  
    char buf[100];  
    gets(buf); // read string, no check!  
}
```

buf[100]

What happens if more than 100 bytes is written to buf?

# MIPS Register Recap

Return address: \$31 (ra)

Stack pointer: \$29 (sp)

Frame pointer: \$30 (fp)

First four arguments: \$4-\$7 (a0-a3)

Return result: \$2-\$3 (v0-v1)

Callee-save free regs: \$16-\$23 (s0-s7)

Caller-save free regs: \$8-\$15, \$24, \$25 (t0-t9)

Reserved: \$26, \$27

Global pointer: \$28 (gp)

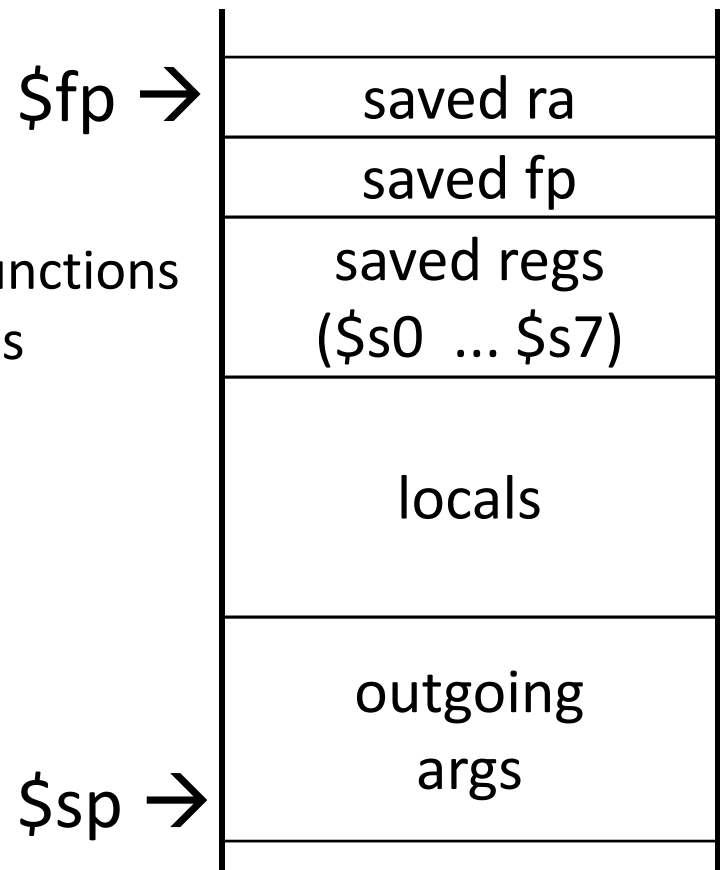
Assembler temporary: \$1 (at)

# MIPS Register Conventions

r0	\$zero	zero	r16	\$s0	<b>saved (callee save)</b>
r1	\$at	assembler temp	r17	\$s1	
r2	\$v0	function return values	r18	\$s2	
r3	\$v1		r19	\$s3	
r4	\$a0	function arguments	r20	\$s4	
r5	\$a1		r21	\$s5	
r6	\$a2		r22	\$s6	
r7	\$a3		r23	\$s7	
r8	\$t0	<b>temps (caller save)</b>	r24	\$t8	<b>more temps (caller save)</b>
r9	\$t1		r25	\$t9	
r10	\$t2		r26	\$k0	reserved for kernel
r11	\$t3		r27	\$k1	
r12	\$t4		r28	\$gp	global data pointer
r13	\$t5		r29	\$sp	stack pointer
r14	\$t6		r30	\$fp	frame pointer
r15	\$t7	r31	\$ra	return address	

# Recap: Conventions so far

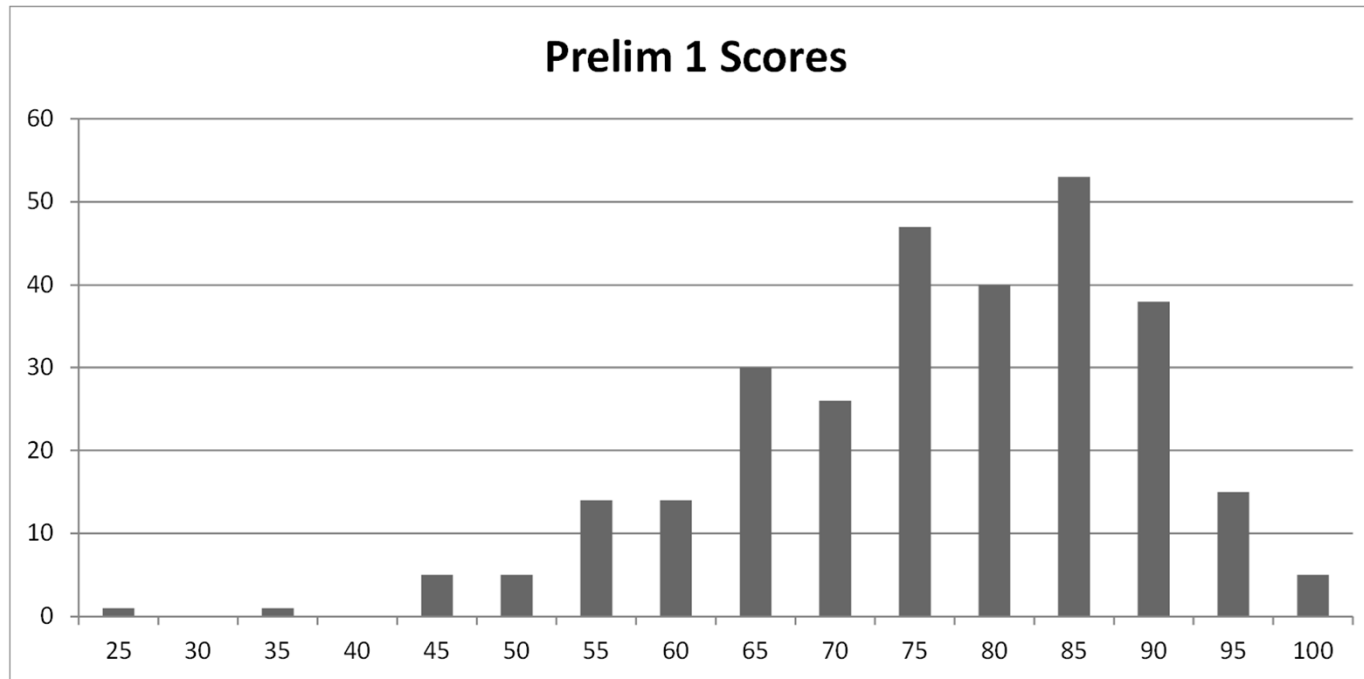
- first four arg words passed in \$a0, \$a1, \$a2, \$a3
- remaining arg words passed in parent's stack frame
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)
  - contains local vars (possibly clobbered by sub-functions)
  - contains extra arguments to sub-functions
  - contains space for first 4 arguments to sub-functions
- callee save regs are preserved
- caller save regs are not
- Global data accessed via \$gp



# Administrivia

## Prelim1 results

- Mean 74.8 (median 76), standard deviation 12.5



- Prelims available in *216 Gates*
- Regrade requires written request
  - ***Whole test is regraded***
  - ***Submit to a PhD TA: Paul Upchurch, Zhiming Shen, Andrew Hirsch, or Pu Zheng***