Calling Conventions

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See P&H 2.8 and 2.12

Goals for Today

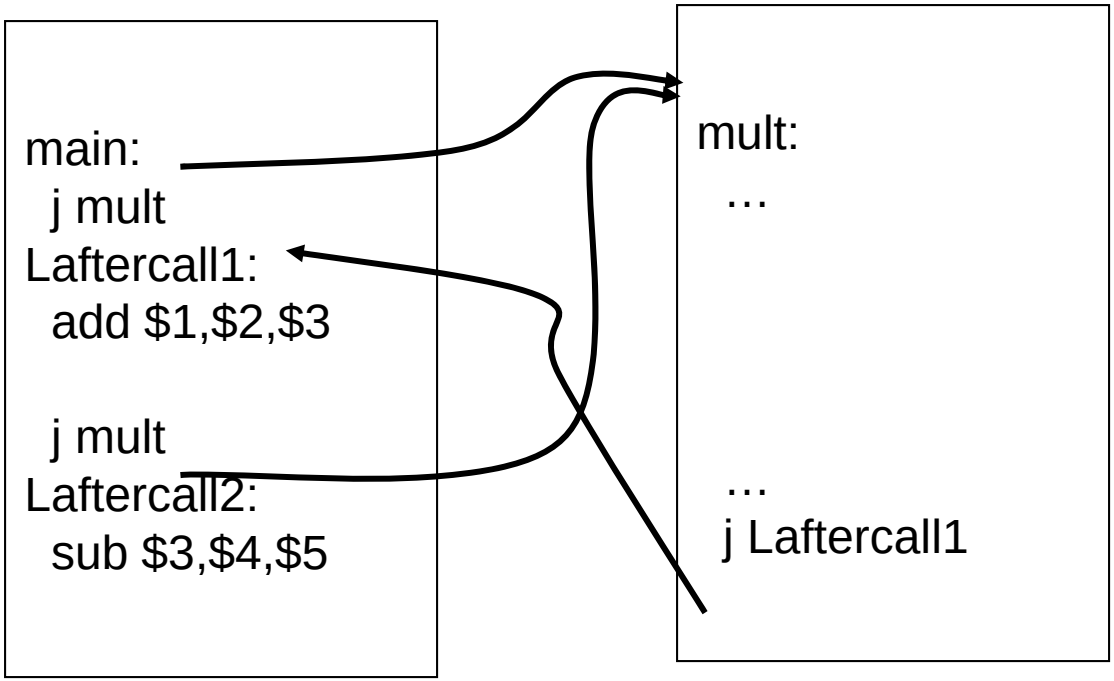
Calling Convention for Procedure Calls

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

Procedure Call Take 1: Use Jumps



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

Jumps and branches can transfer control back

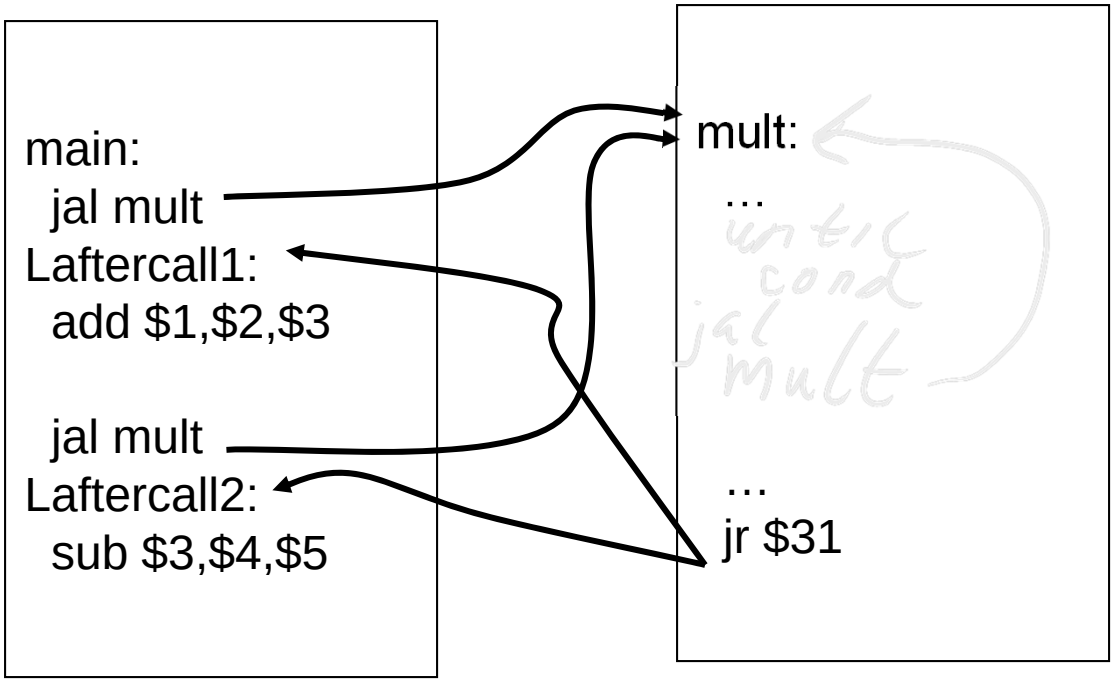
What happens when there are multiple calls from different call sites?

Jump And Link

JAL (Jump And Link) instruction moves a new value into the PC, and simultaneously saves the old value in register $31

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 Take 2: JAL/JR

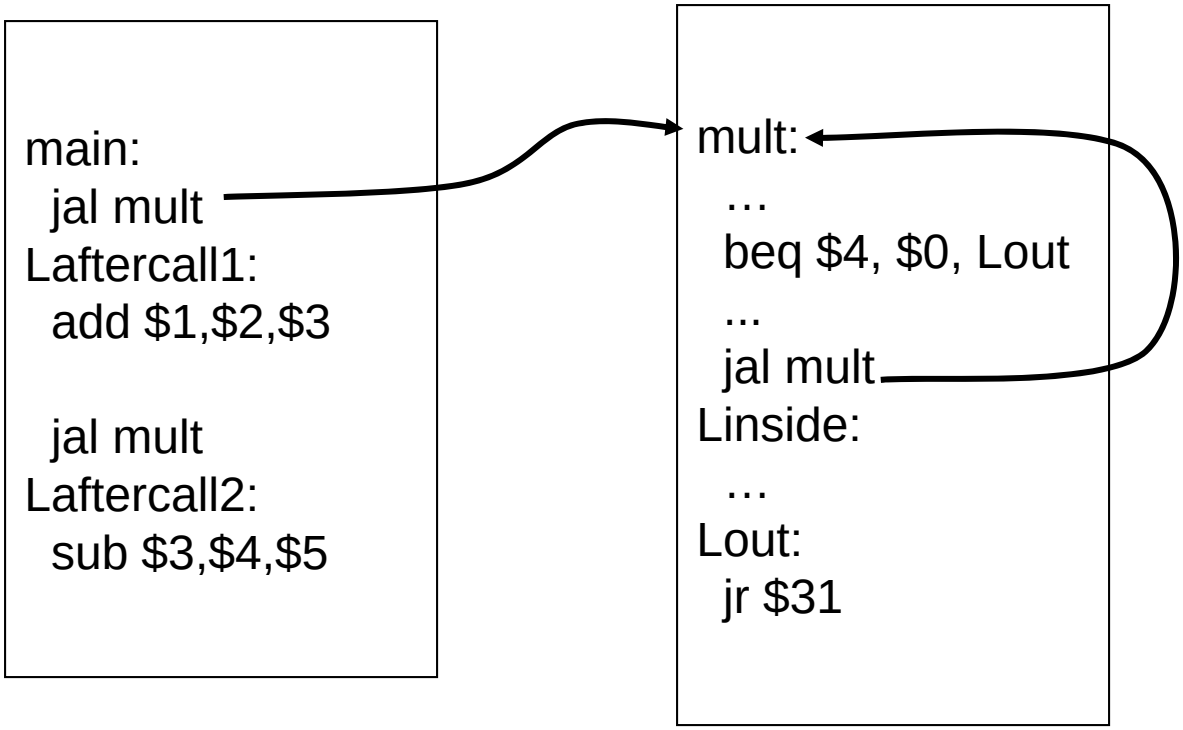


JAL saves the PC in register $31

Subroutine returns by jumping to $31

What happens for recursive invocations?

Procedure Call Take 2: JAL/JR



Recursion overwrites contents of $31

Need to save and restore the register contents

Call Stacks

Call stack

- contains activation records (aka stack frames)

Each activation record contains

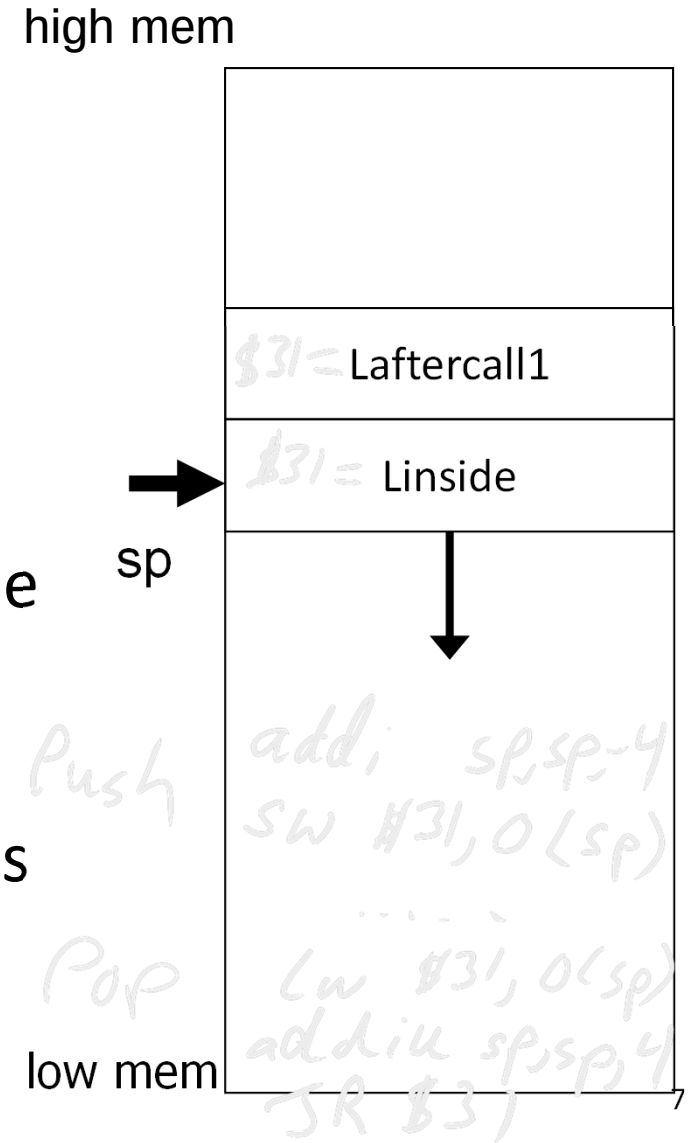
- the return address for that invocation
- the local variables for that procedure

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



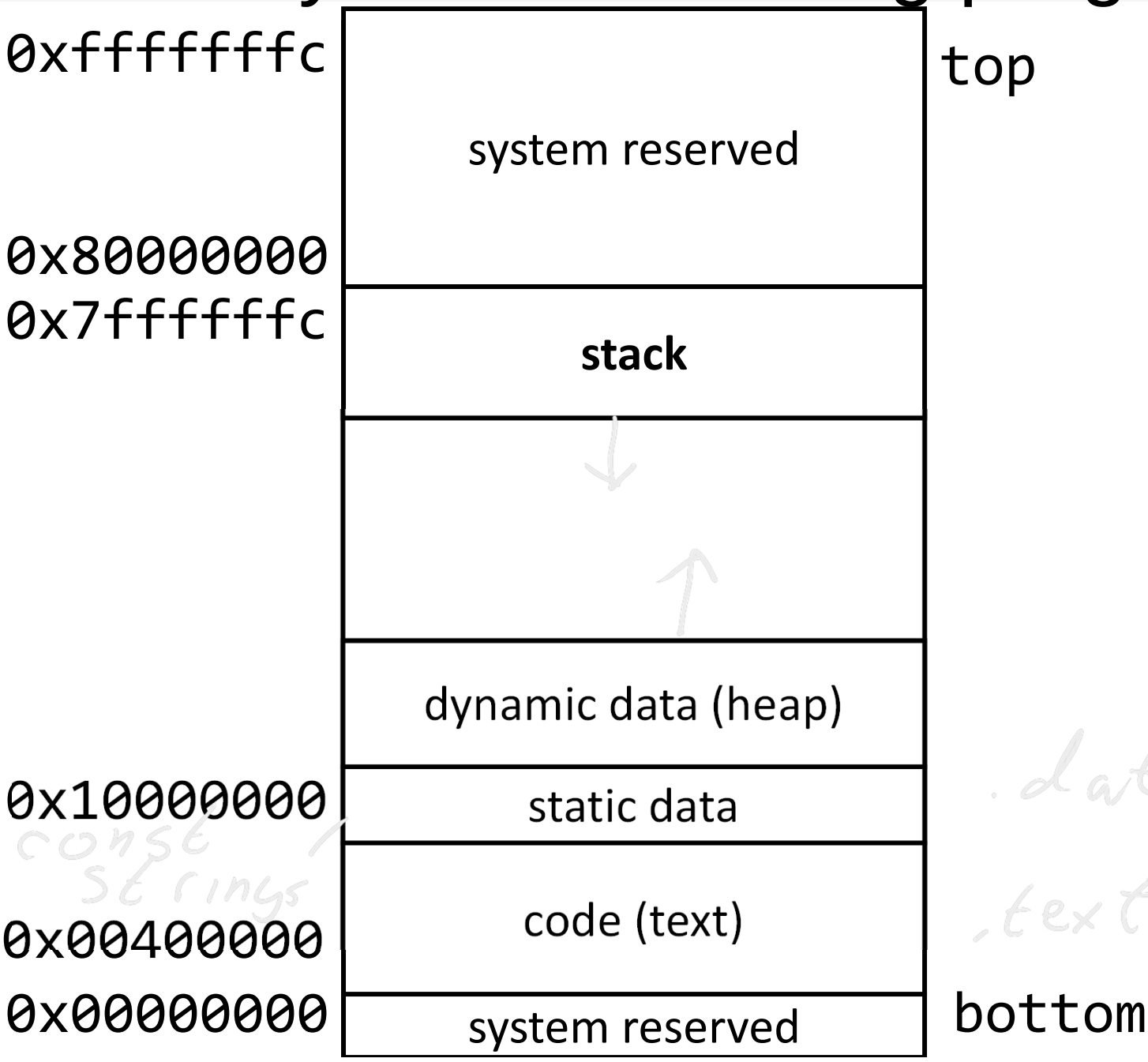
Stack Growth

Stacks start at a high address in memory

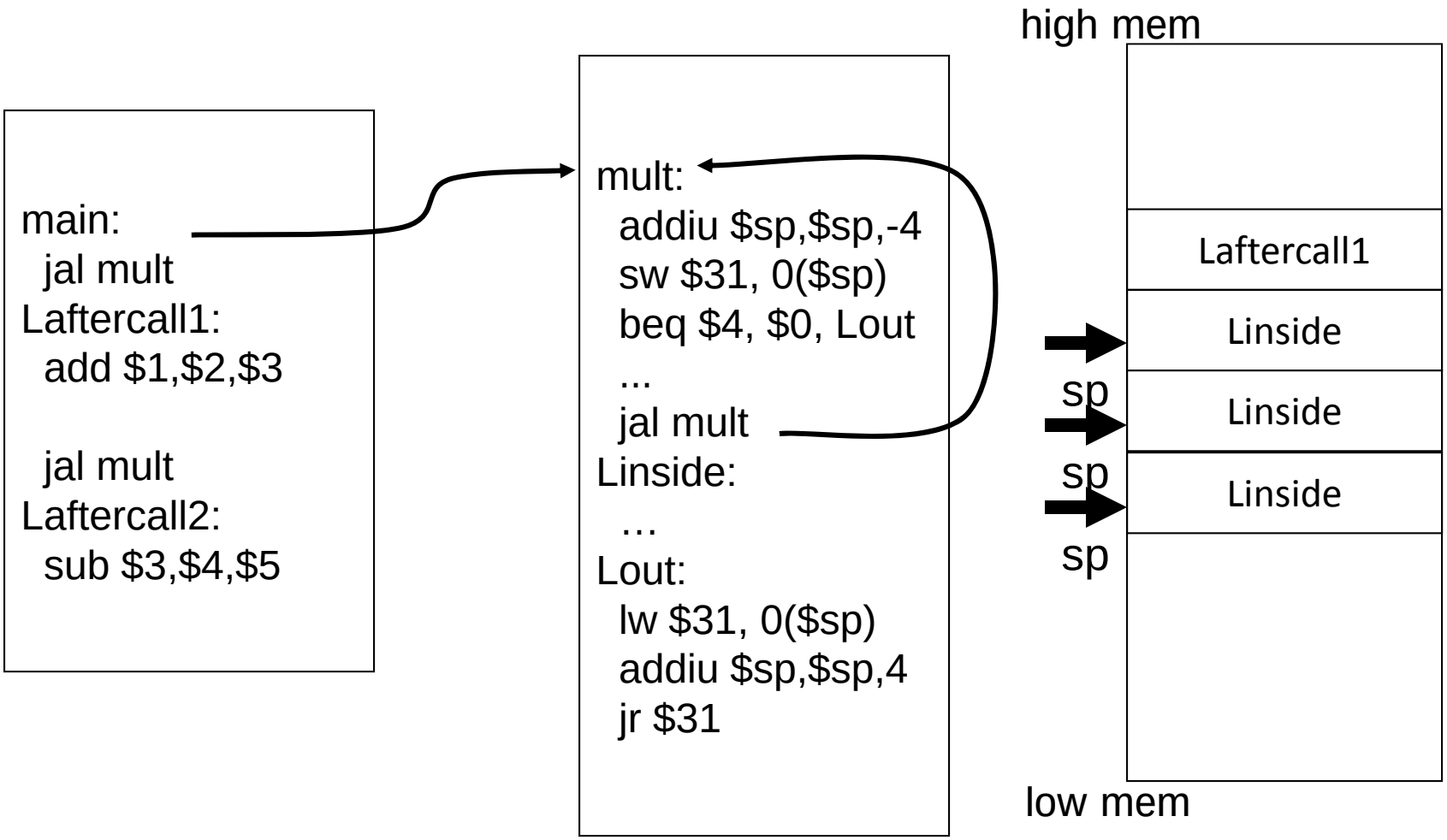
Stacks grow down as frames are pushed on

- Recall that the 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

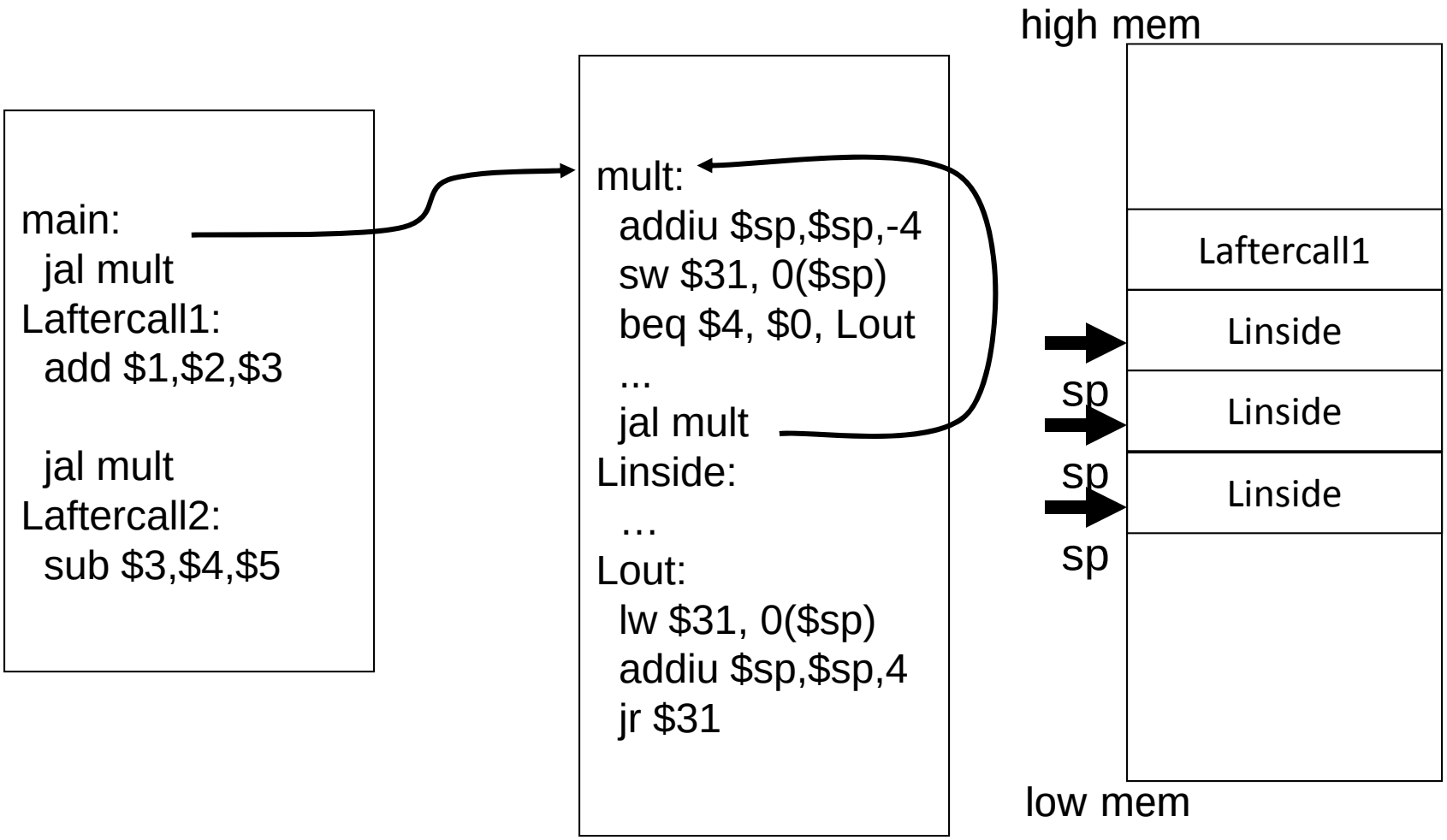


Take 3: JAL/JR with Activation Records



Stack used to save and restore contents of $31

Take 3: JAL/JR with Activation Records



Stack used to save and restore contents of $31

How about arguments?

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);`
- `int subf(int a, int b, int c, int d, int e);`
- `int isalpha(char c);`
- `int treesort(struct Tree *root);`
- `struct Node *createNode();`
- `struct Node mynode();`

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

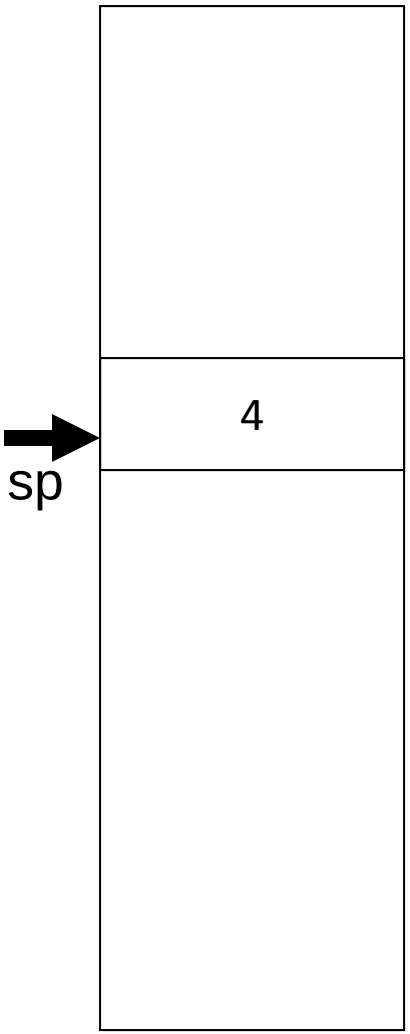
Conventions so far:

- 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
   li $8, 4
   addiu $sp,$sp,-4
   sw $8, 0($sp)
   jal subf
   // result in $v0
```



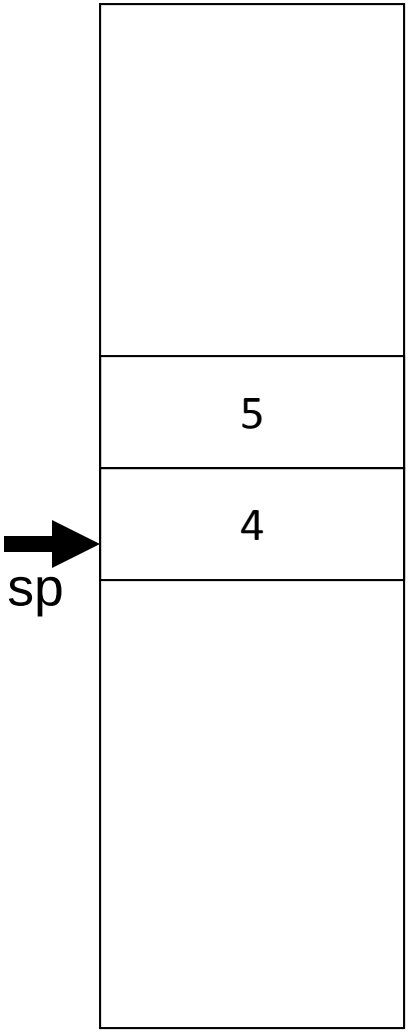
What if there are more than 4 arguments?

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 offse

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

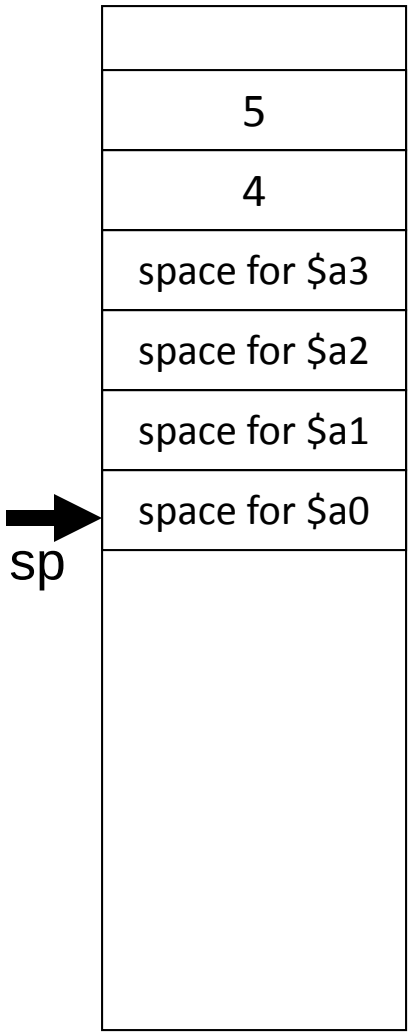
- Pass the first four arguments in registers, as usual
- Pass the rest on the stack
- Reserve space on the stack for all arguments, including the first four

Simplifies functions that use variable-length arguments

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

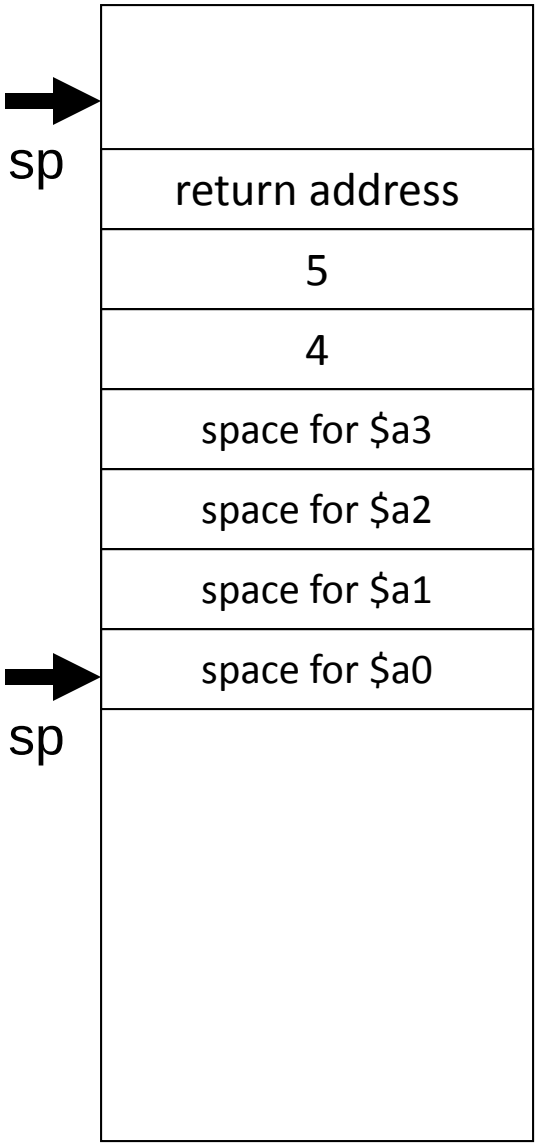
Register Layout on Stack

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



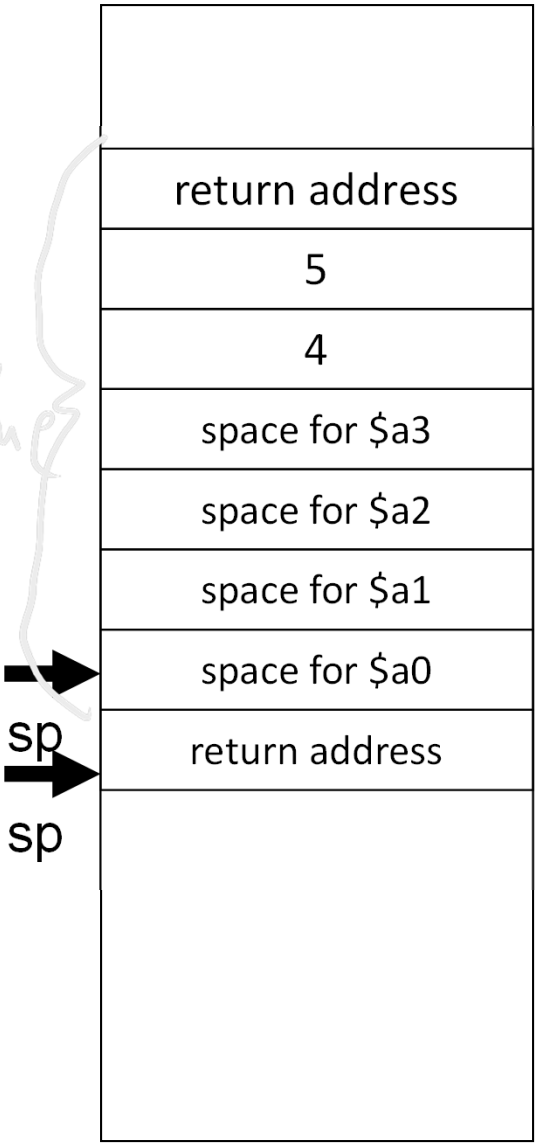
- First four arguments are in registers
- The rest are on the stack
- There is room on the stack for the first four arguments, just in case

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) {
    ...
}
```

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		
r1	$at	assembler temp	r17		
r2	$v0	function return values	r18		
r3	$v1		r19		
r4	$a0	function arguments	r20		
r5	$a1		r21		
r6	$a2		r22		
r7	$a3		r23		
r8			r24		
r9			r25		
r10			r26	$k0	reserved for OS kernel
r11			r27	$k1	
r12			r28		
r13			r29	$sp	
r14			r30		
r15			r31	$ra	return address

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 p1, struct Point p2);`
- Treat like a collection of consecutive 32-bit arguments, use registers for first 4 words, stack for rest
- Inefficient and to be avoided, better to use
  `int distance(struct Point *p1, struct Point *p2);`
  in all cases

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; }

addr a

Global and Locals

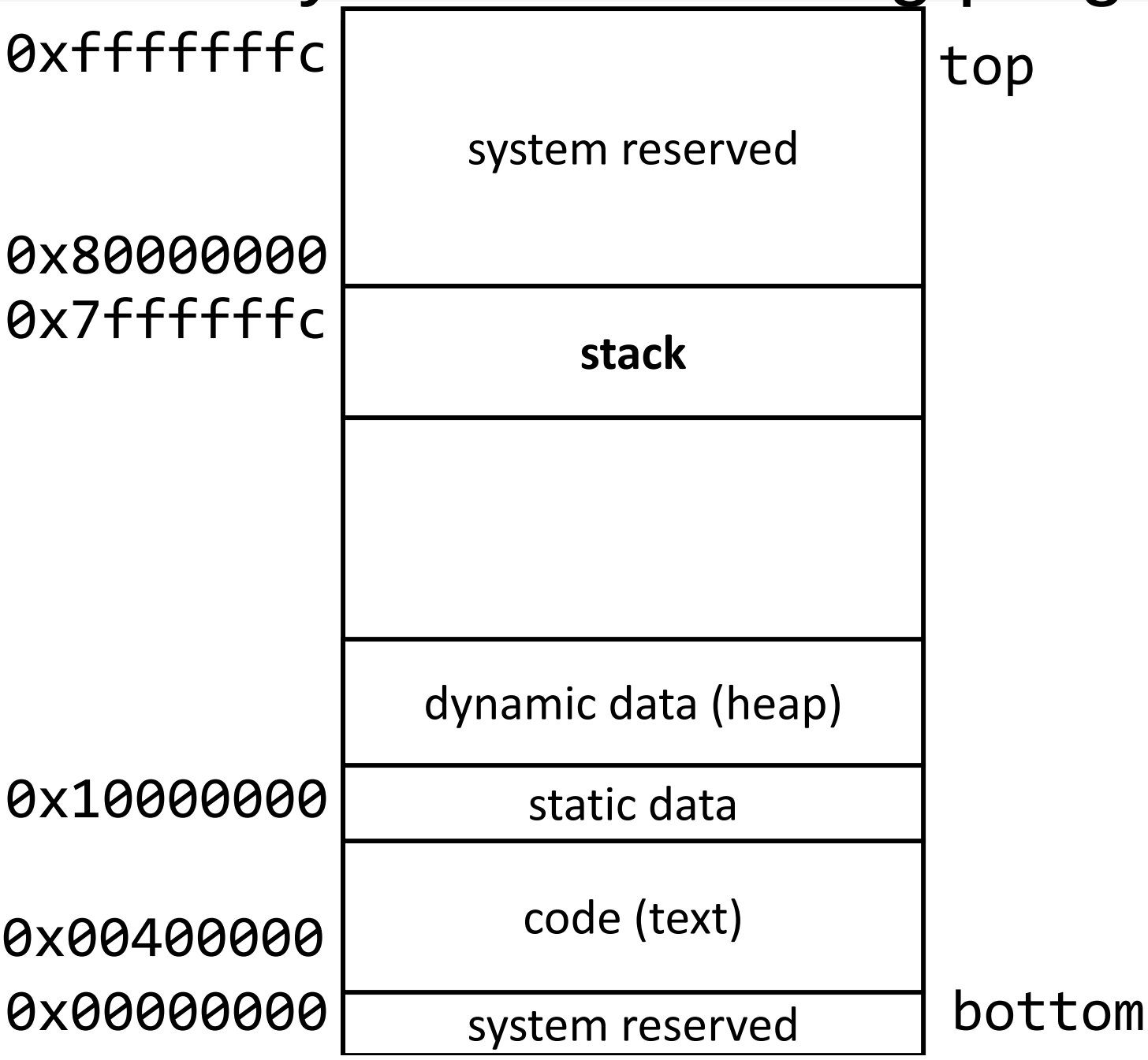
How does a function load global data?

- global variables are just above 0x10000000

Convention: *global pointer*

- r28 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



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 top of the stack frame

- Simplifies the task of referring to items on the stack

A frame pointer, $30, aka $fp

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

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
```

Assume caller is using the registers

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
```

Assume caller is using the registers

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]
```

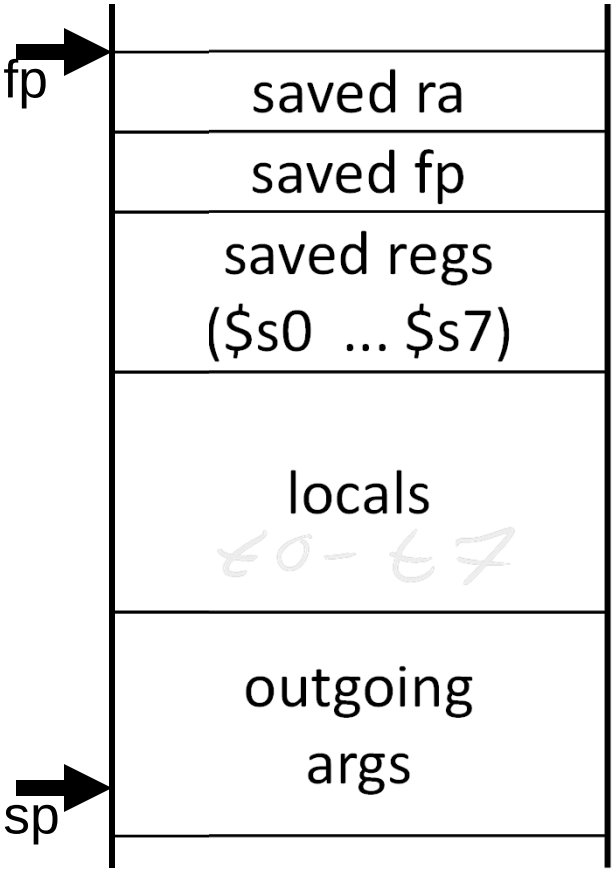
- Assume the registers are free for the taking, clobber them
- But since other subroutines will do the same, must protect values that will be used later
- By saving and restoring them before and after subroutine invocations
- Pays off if a routine makes few calls to other routines with values that need 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]
```

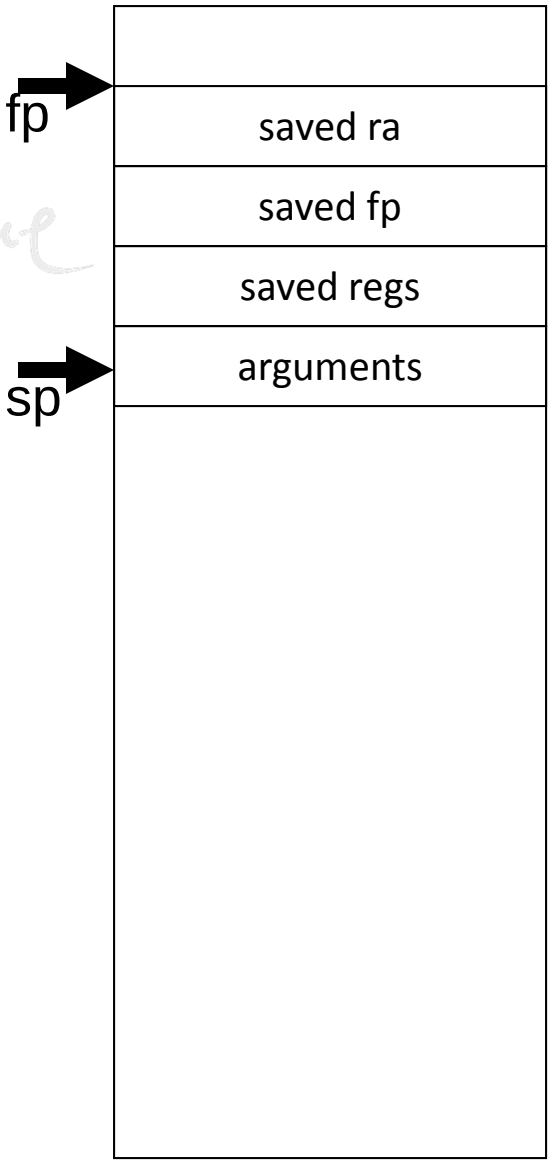
- Assume the registers are free for the taking, clobber them
- But since other subroutines will do the same, must protect values that will be used later
- By saving and restoring them before and after subroutine invocations
- Pays off if a routine makes few calls to other routines with values that need to be preserved

Frame Layout on Stack




```
# allocate frame
# save $ra
# save old $fp
# save ...
# save ...
# set new frame pointer
    ...
    ...
# restore …
# restore …
# restore old $fp
# restore $ra
# dealloc frame
```

Frame Layout on Stack

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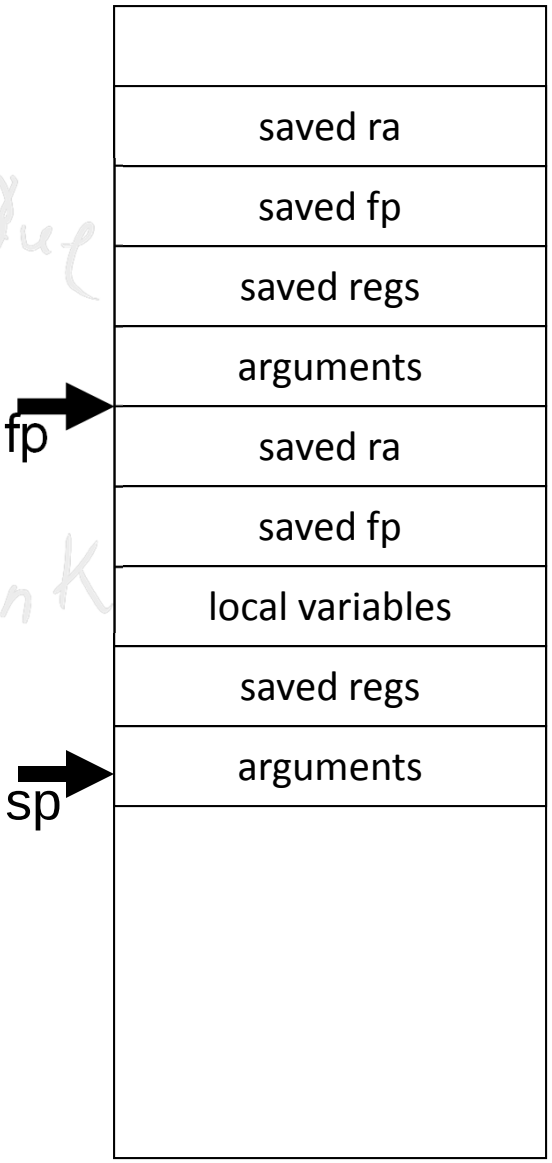
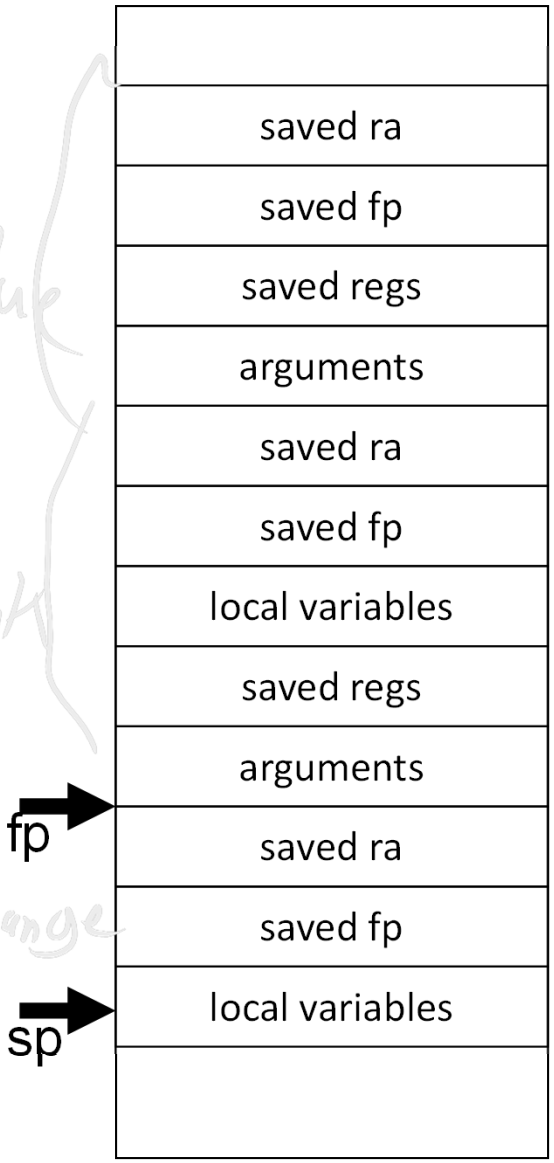
blue() {
   pink(0,1,2,3,4,5);
}
```

Frame Layout on Stack



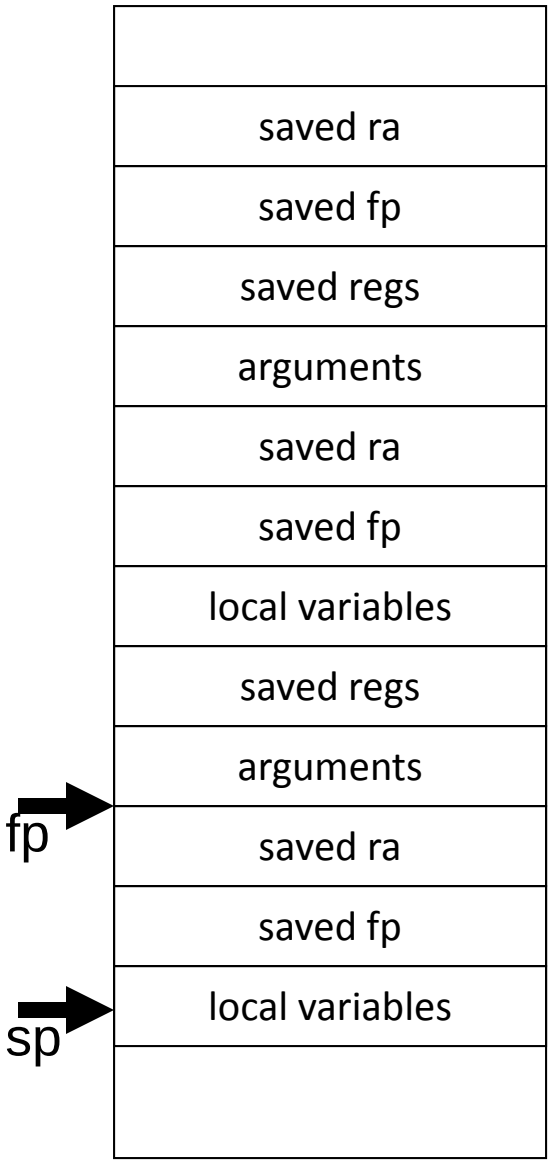

```
blue() {
   pink(0,1,2,3,4,5);
}
pink(int a, int b, int c, int d, int e, int f) {
    orange(10,11,12,13,14);
}
```

Frame Layout on Stack




```
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!
}
```

Buffer Overflow

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}
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!
}
```

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