Calling Conventions

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CS 3410

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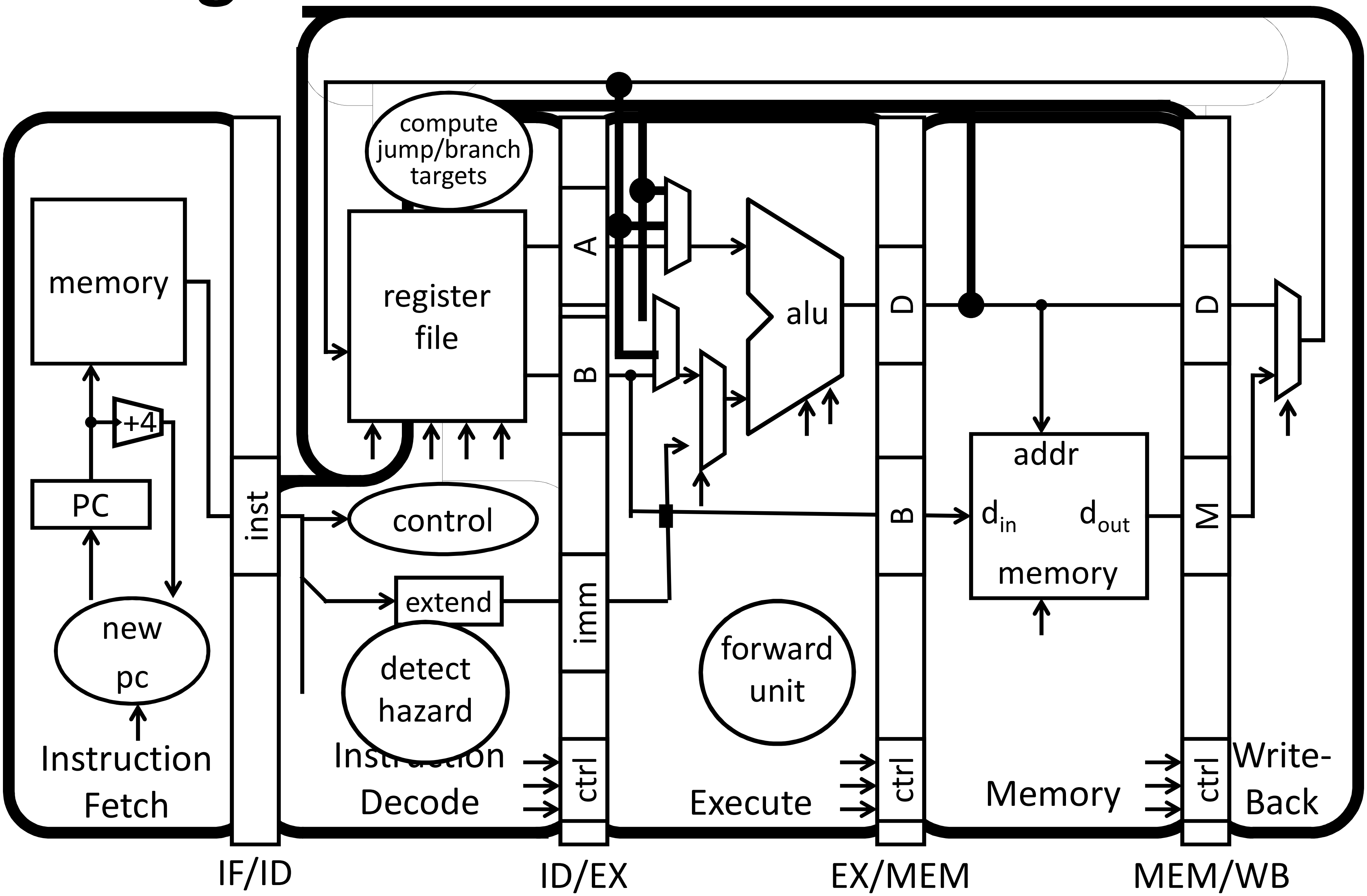
The slides are the product of many rounds of teaching CS 3410 by Professors Weatherspoon, Bala, Bracy, McKee, and Sirer.

Big Picture: Where are we now?



Big Picture: Where are we going?

C

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

compiler

MIPS assembly

```
addiu r5, r0, 10
muli  r5, r5, 2
addiu r5, r5, 15
```

r0 = 0

r5 = r0 + 10

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

r5 = r15 + 15

assembler

machine code

op = addiu r0 r5 10

001000	00000	00101	0000000000001010		
000000	00000	00101	00101	00001	000000
001000	00101	00101	0000000000001111		

op = addiu r5 r5 15

op = r-type r5 r5 shamt=1 func=sll

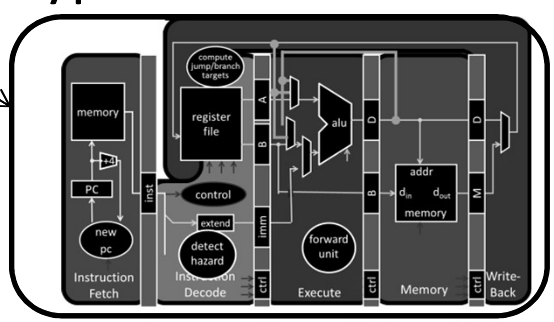
CPU

Circuits

Gates

Transistors

Silicon



Goals for this week

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

Calling Convention for Procedure Calls

Transfer Control

- Caller → Routine
- Routine → Caller

Pass Arguments to and from the routine

- fixed length, variable length, recursively
- Get return value back to the caller

Manage Registers

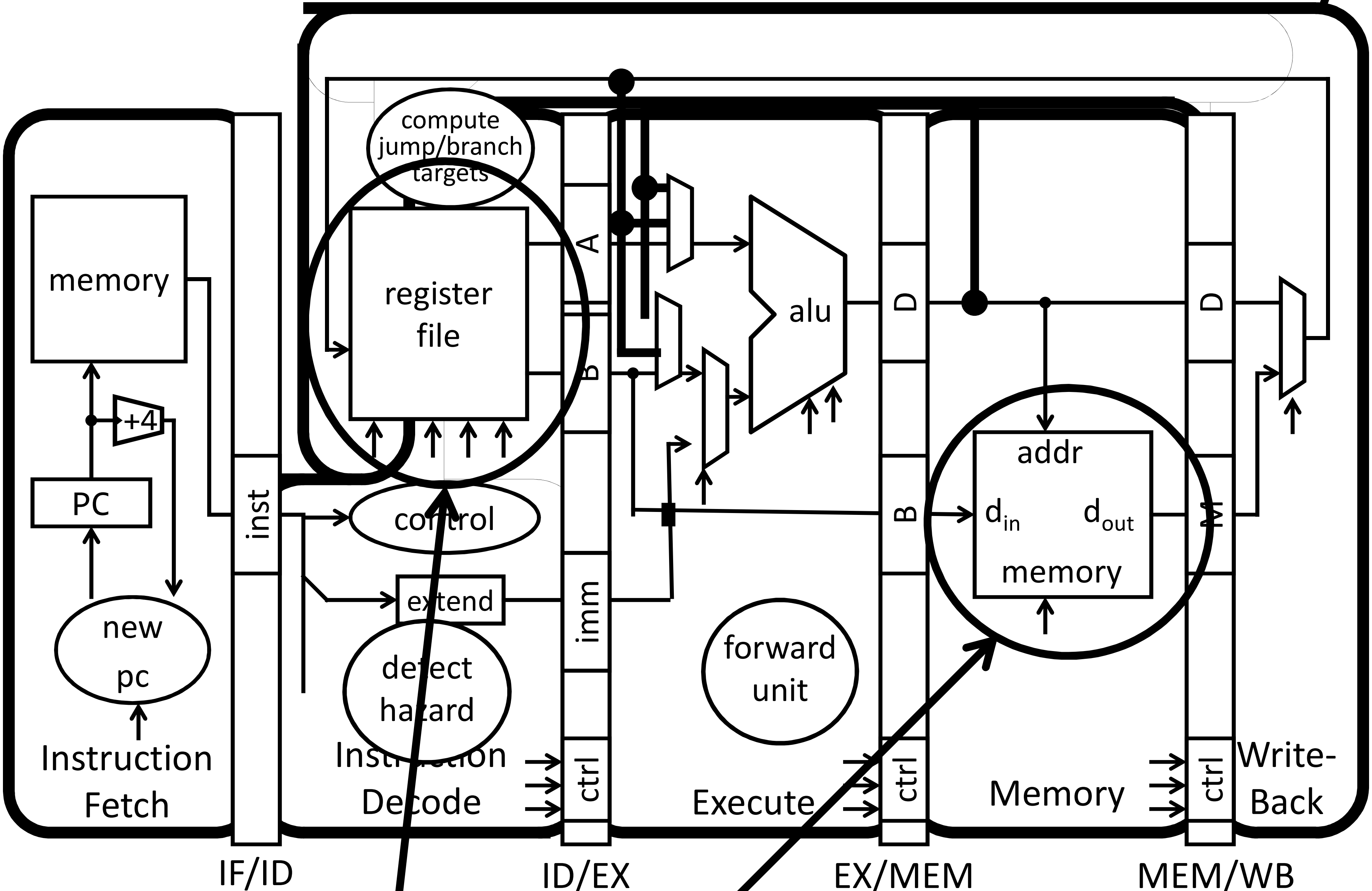
- Allow each routine to use registers
- Prevent routines from clobbering each others' data

What is a Convention?

Warning: There is no one true MIPS calling convention.

lecture != book != gcc != spim != web

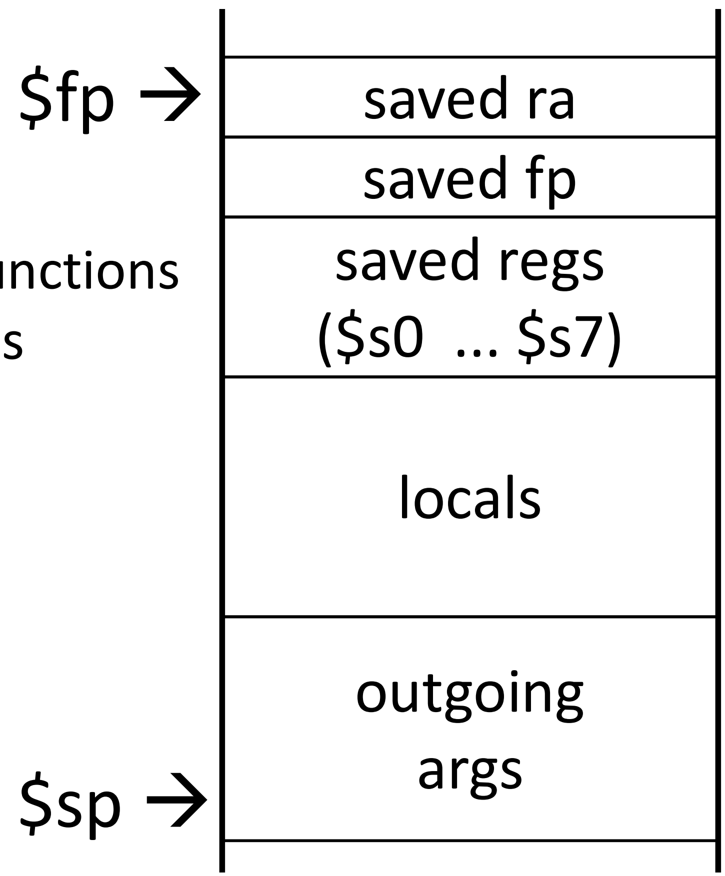
Cheat Sheet and Mental Model for Today



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

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

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

Calling Convention for Procedure Calls

Transfer Control

- Caller → Routine
- Routine → Caller

Pass Arguments to and from the routine

- fixed length, variable length, recursively
- Get return value back to the caller

Manage Registers

- Allow each routine to use registers
- Prevent routines from clobbering each others' data

What is a Convention?

Warning: There is no one true MIPS calling convention.

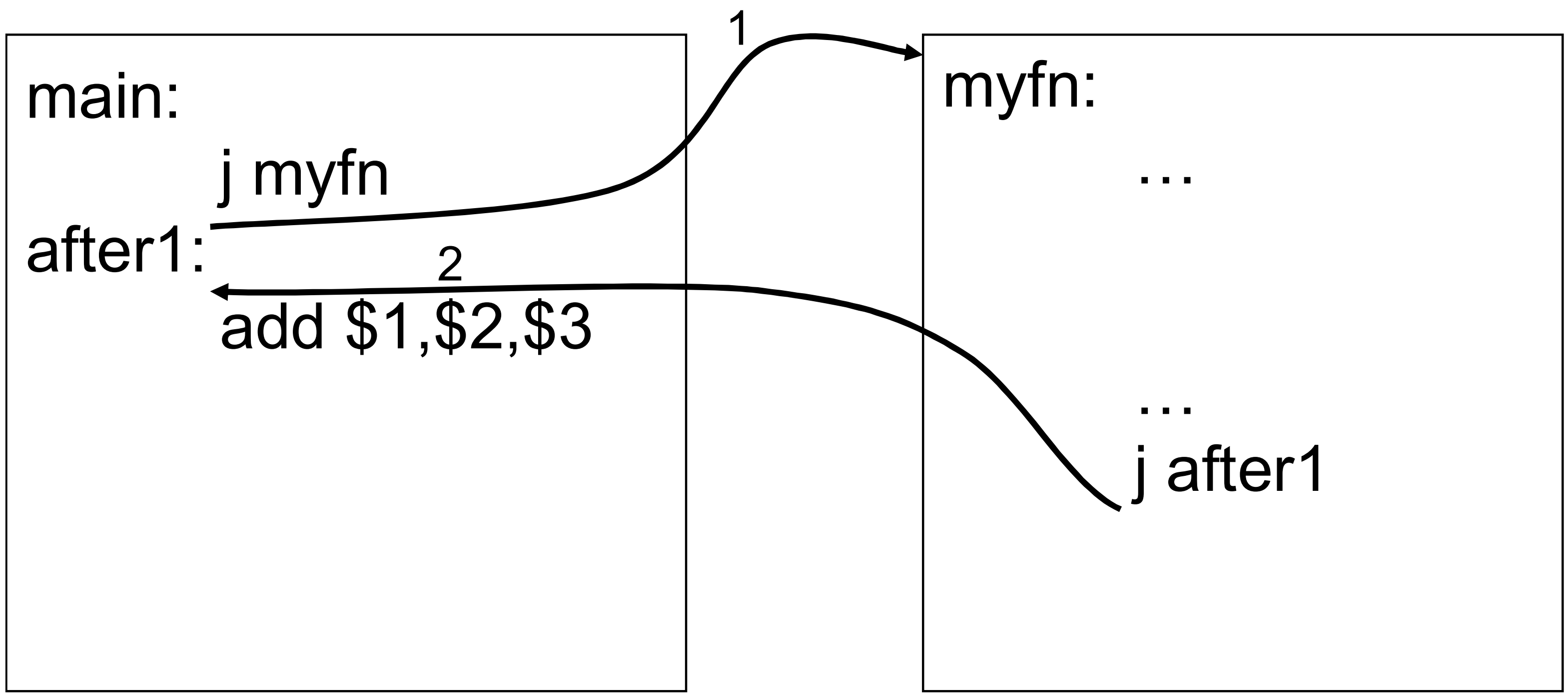
lecture != book != gcc != spim != web

How does a function call work?

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

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

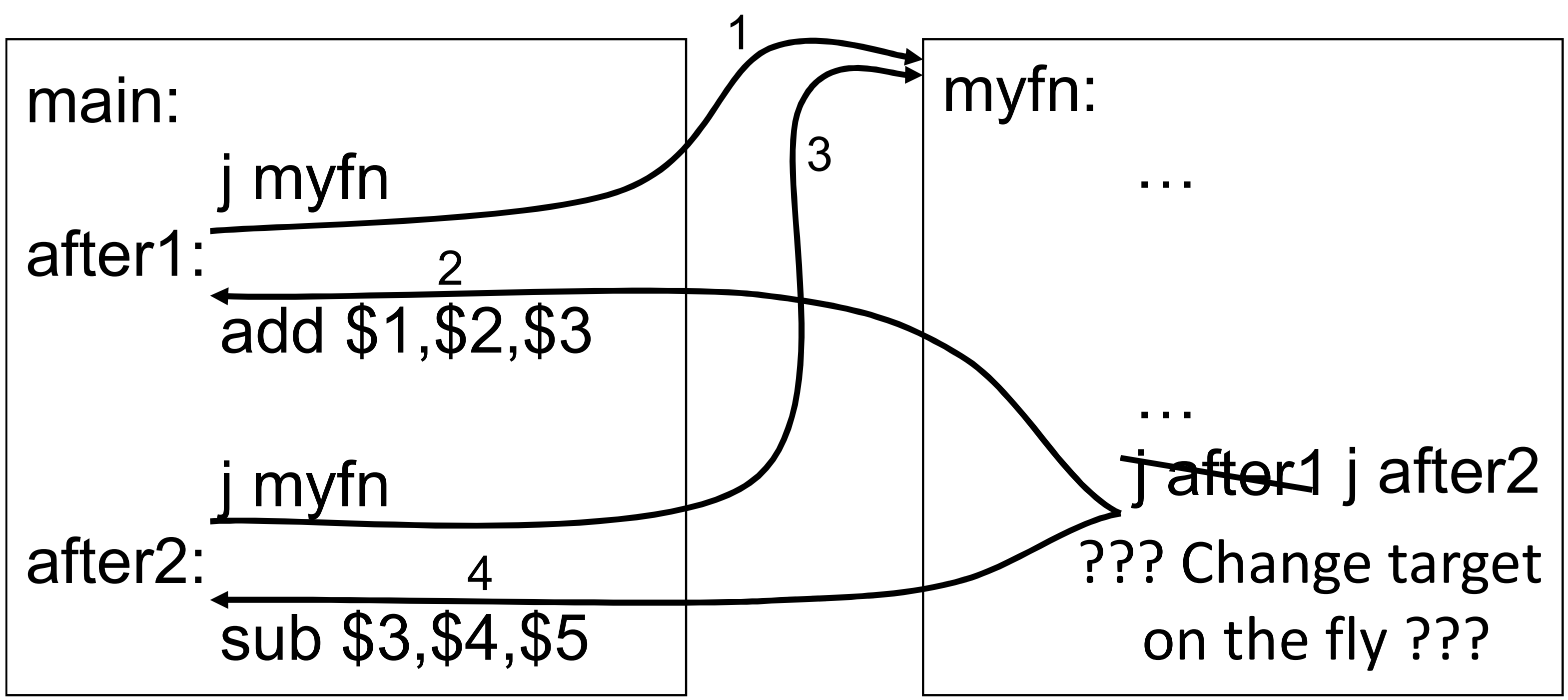
Jumps are not enough



Jumps to the callee

Jumps back

Jumps are not enough



Jumps to the callee

Jumps back

What about multiple 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

Jump-and-Link / Jump Register

First call

r31

```
main:
        jal myfn
after1:
        add $1,$2,$3

        jal myfn
after2:
        sub $3,$4,$5
```

```
myfn:
  …



  …
  jr $31
```

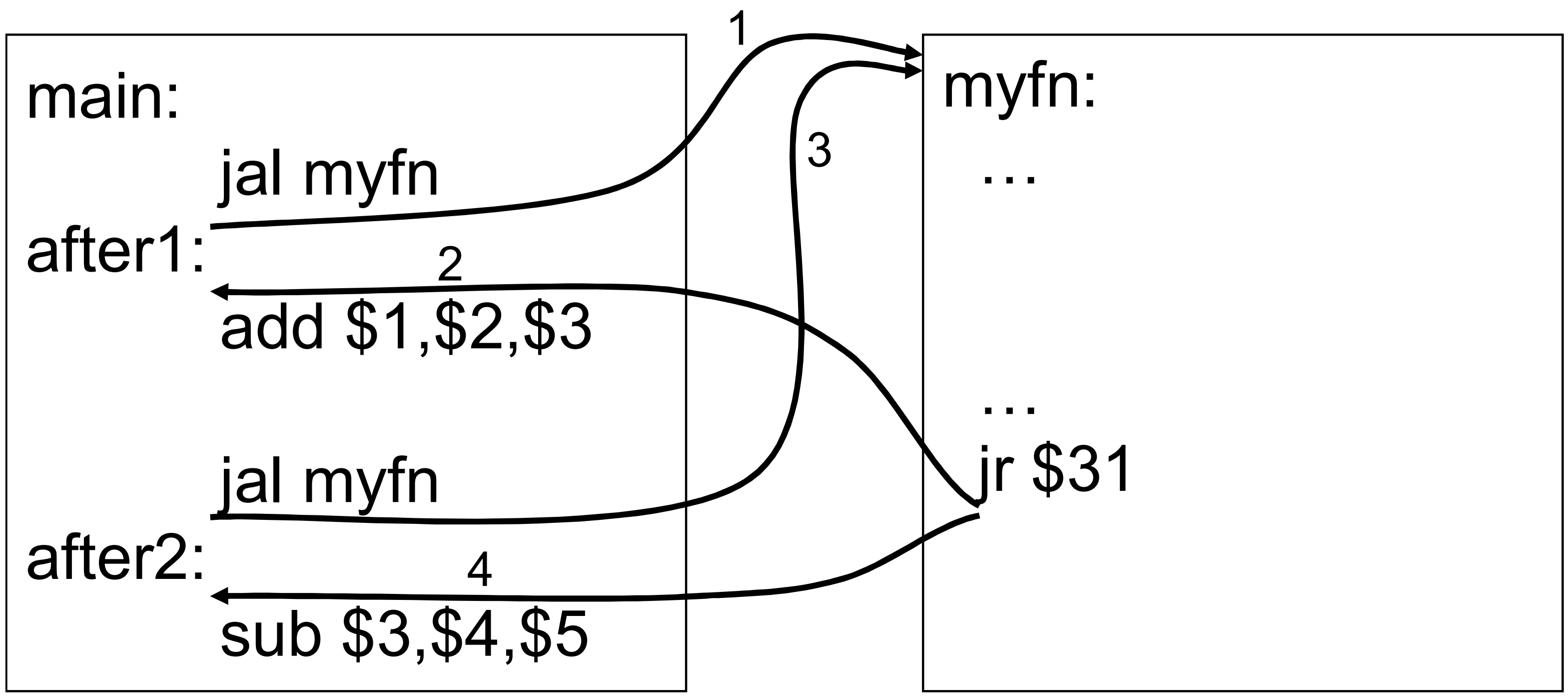
JAL saves the PC in register $31

Subroutine returns by jumping to $31

Jump-and-Link / Jump Register

Second call

r31



JAL saves the PC in register $31

Subroutine returns by jumping to $31

What happens for recursive invocations?

JAL / JR for Recursion?

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


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

JAL / JR for Recursion?

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


int myfn(int n) {

      if(n > 0) {
            return n * myfn(n - 1);
      } else {
            return 1;
      }
}
```

JAL / JR for Recursion?

First call

r31

1

```
main:
        jal myfn
after1:
        add $1,$2,$3
```

```
myfn:
        if (test)
          jal myfn
after2:

        jr $31
```

Problems with recursion:

JAL / JR for Recursion?

Recursive Call

r31

1

2

```
main:
        jal myfn
after1:
        add $1,$2,$3
```

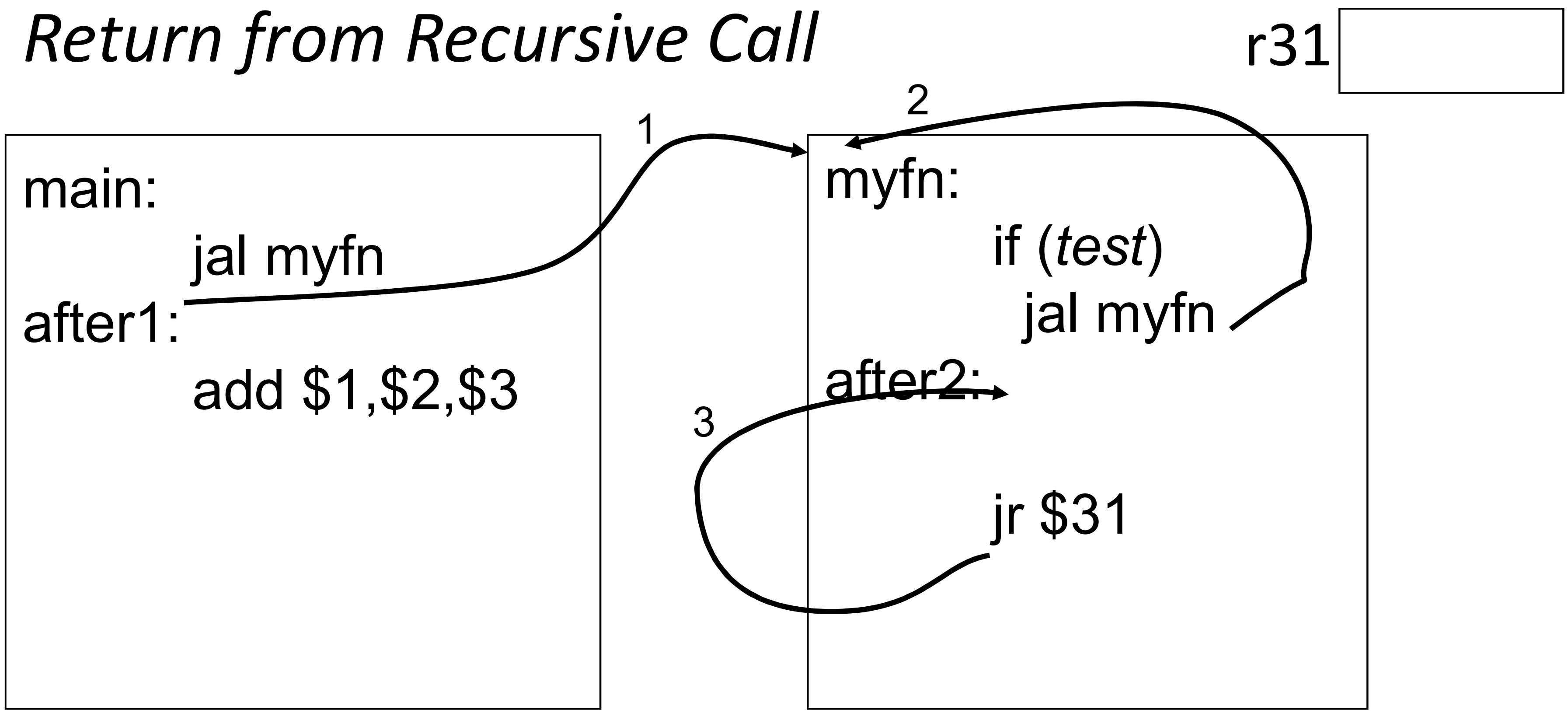
```
myfn:
        if (test)
          jal myfn
after2:

        jr $31
```

Problems with recursion:

JAL / JR for Recursion?

Return from Recursive Call



Problems with recursion:

Need a "Call Stack"

Call stack

- contains activation records (aka stack frames)

Each activation record contains

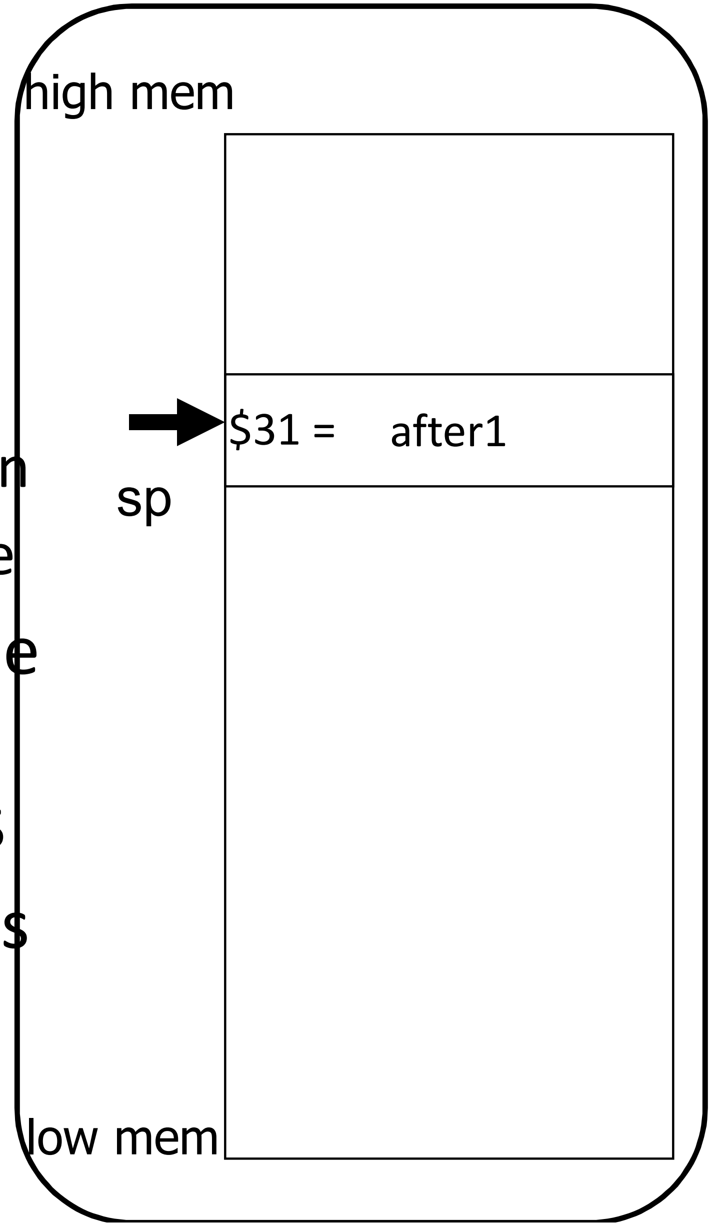
- the return address for that invocation
- the local variables for that procedure

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

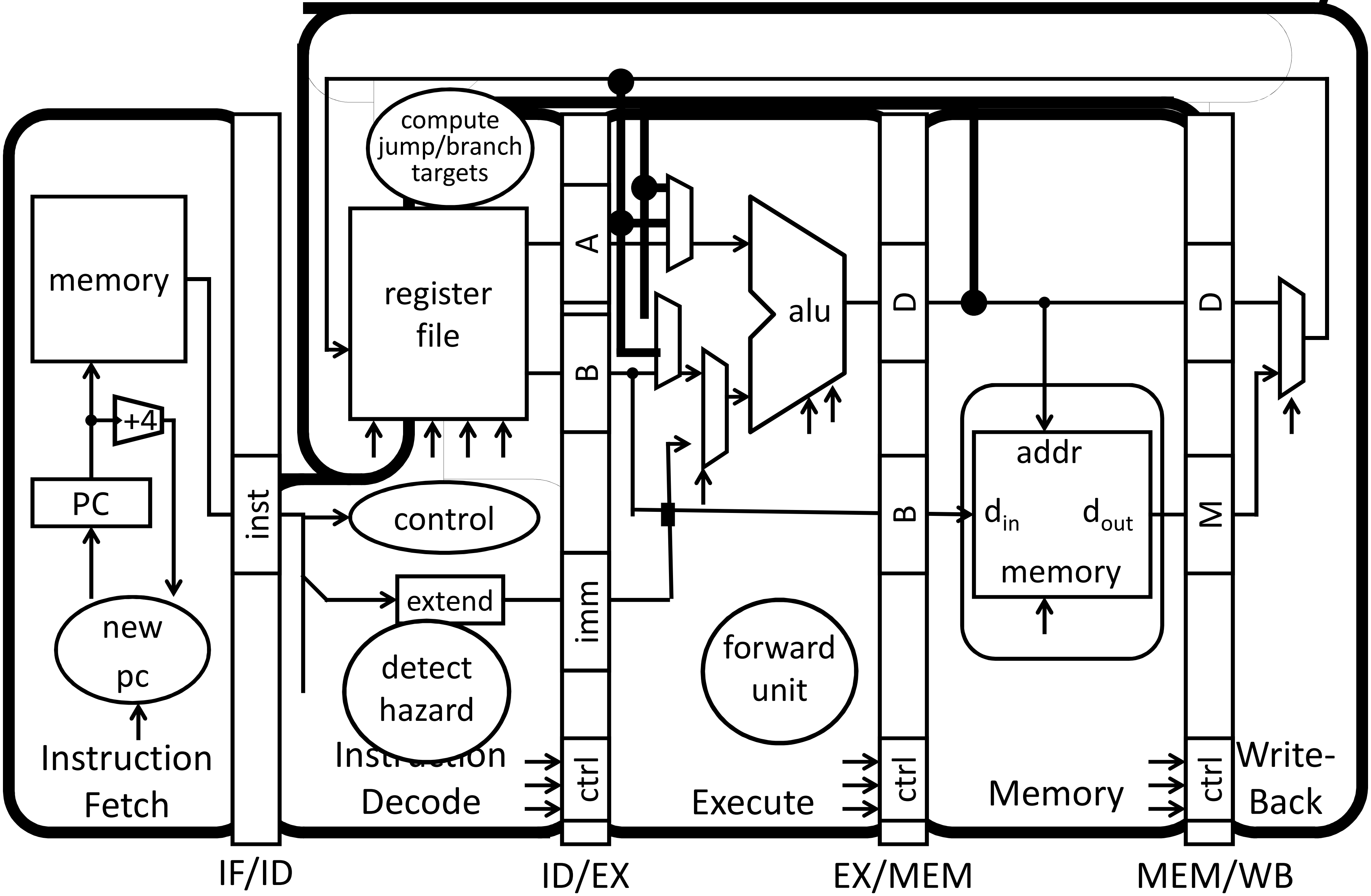
- dedicated register ($29) on the MIPS

Manipulated by push/pop operations

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



Cheat Sheet and Mental Model for Today



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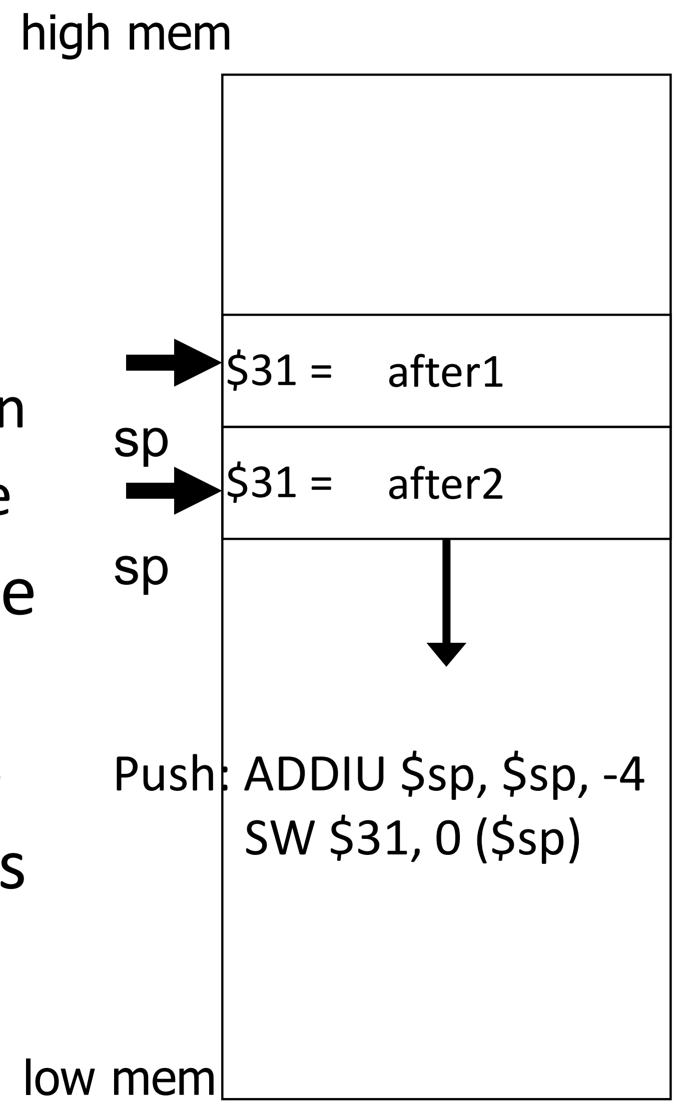

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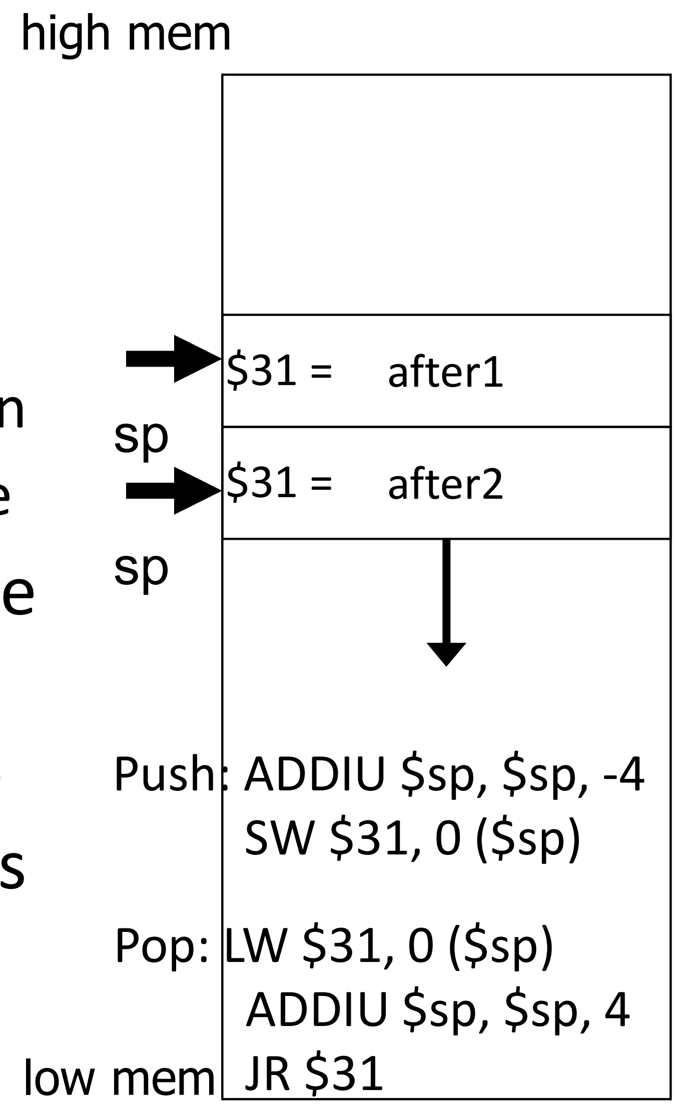


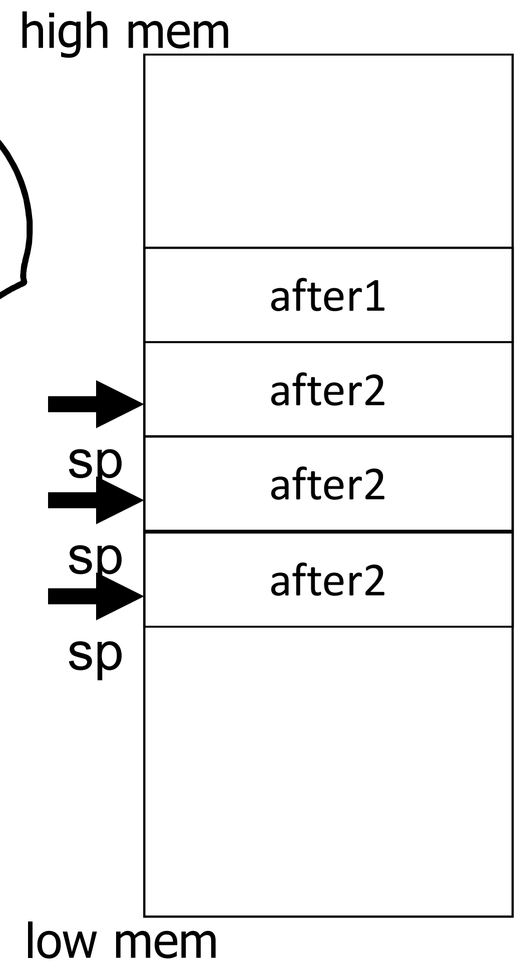
Need a “Call Stack”

1

```
main:
    jal myfn
after1:
    add $1,$2,$3
```

2

```
myfn:
        addiu $sp,$sp,-4
        sw $31, 0($sp)
        if (test)
            jal myfn
after2:
        lw $31, 0($sp)
        addiu $sp,$sp,4
        jr $31
```



Stack used to save and restore contents of $31

Need a “Call Stack”

1

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main:
    jal myfn
after1:
    add $1,$2,$3
```

2

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myfn:
        addiu $sp,$sp,-4
        sw $31, 0($sp)
        if (test)
            jal myfn
after2:
        lw $31, 0($sp)
        addiu $sp,$sp,4
        jr $31
```
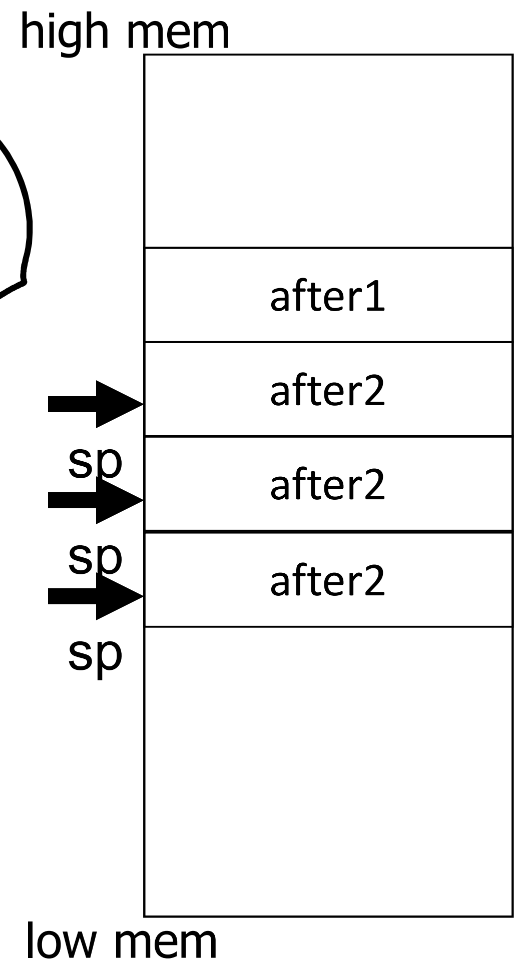



Stack used to save and restore contents of $31

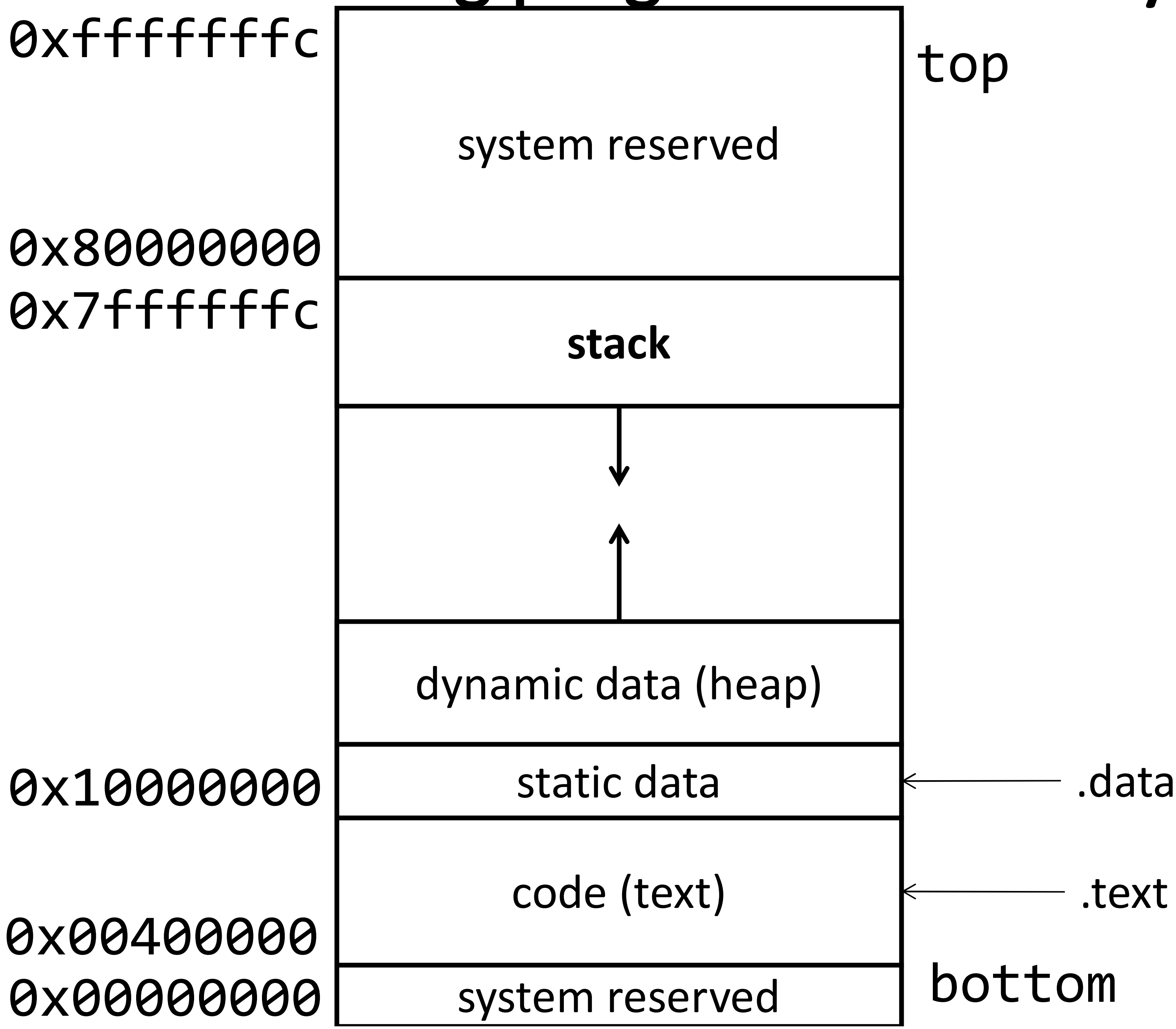
Stack Growth

(Call) Stacks start at a high address in memory

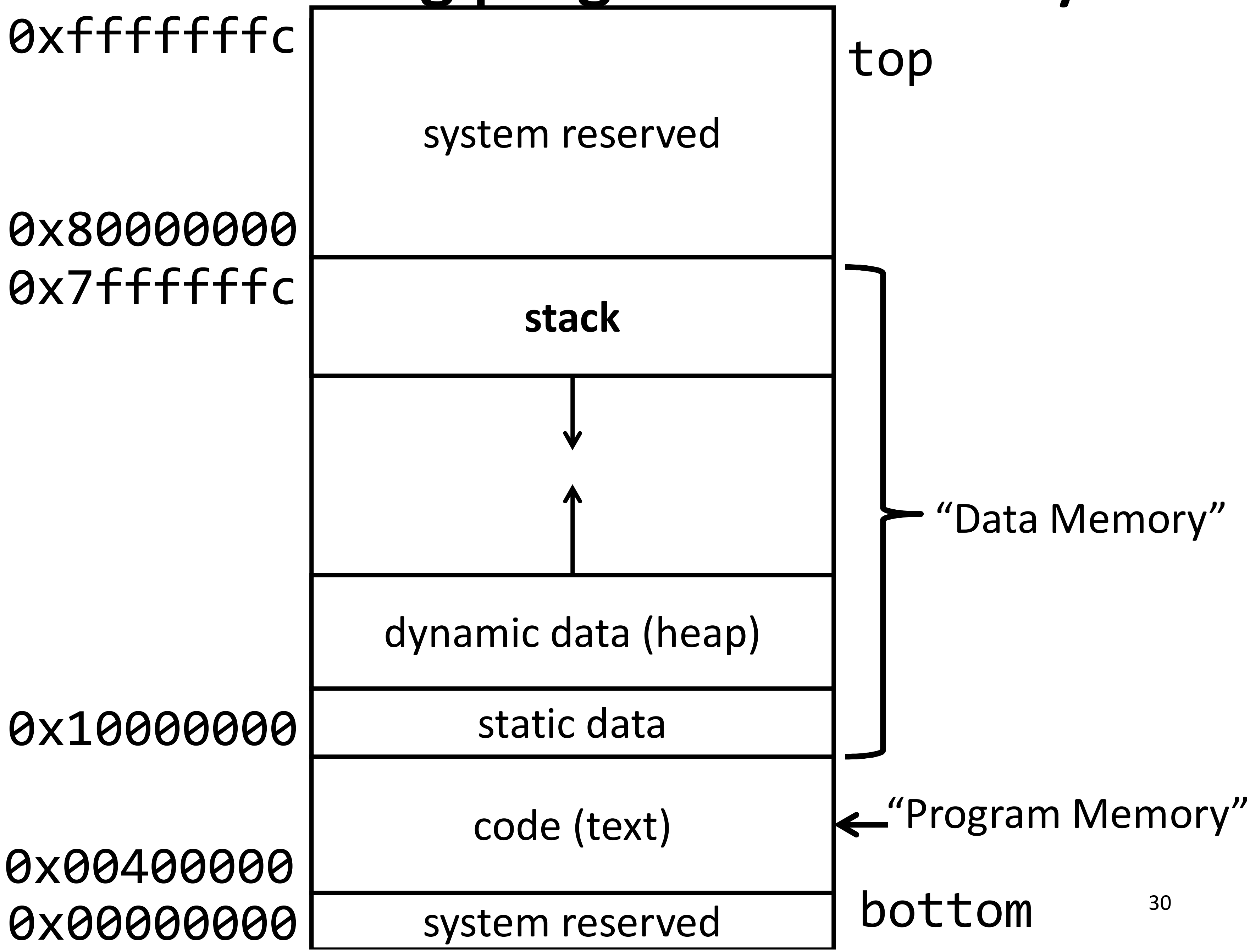
Stacks grow down as frames are pushed on

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

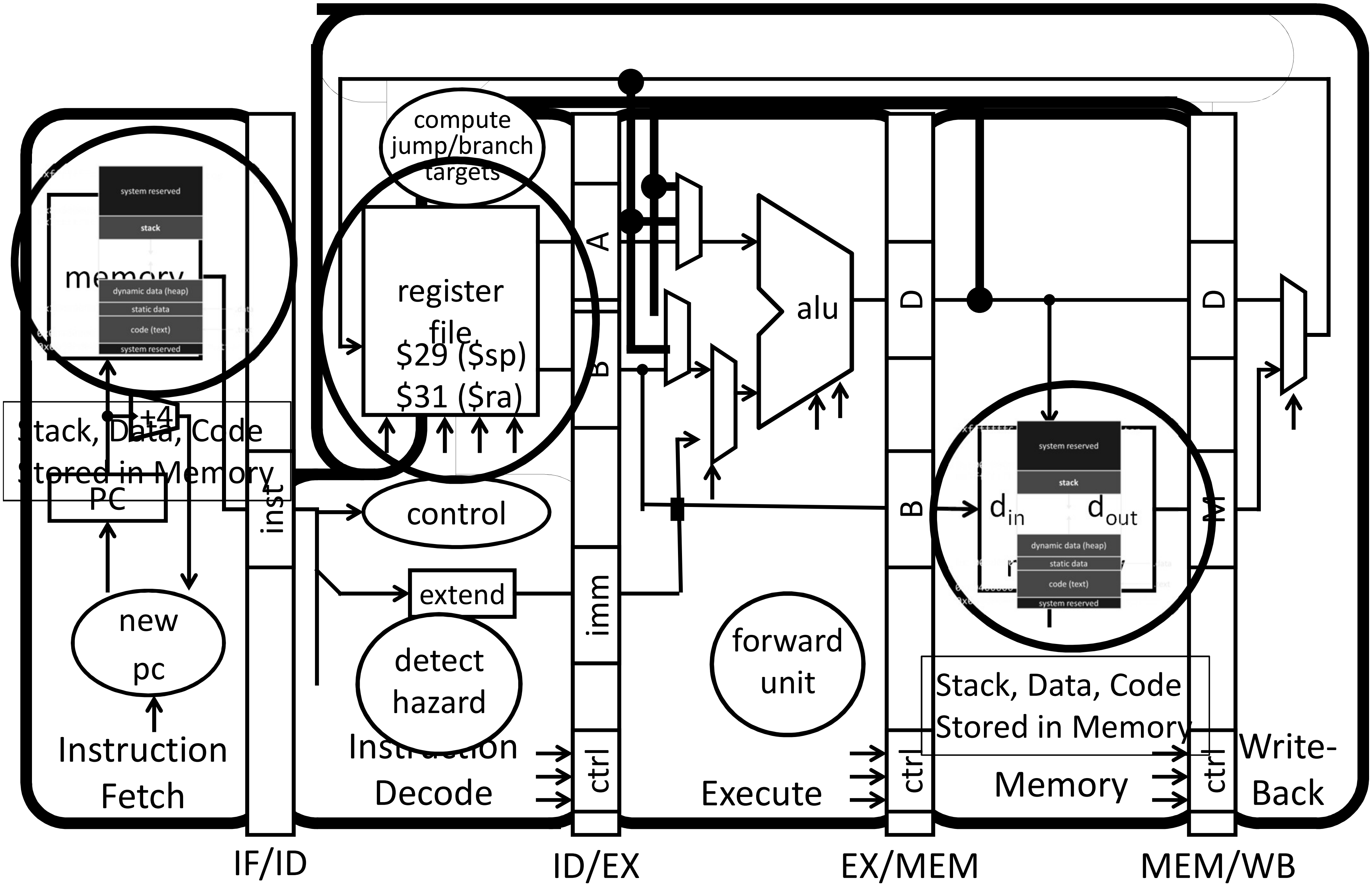
An executing program in memory



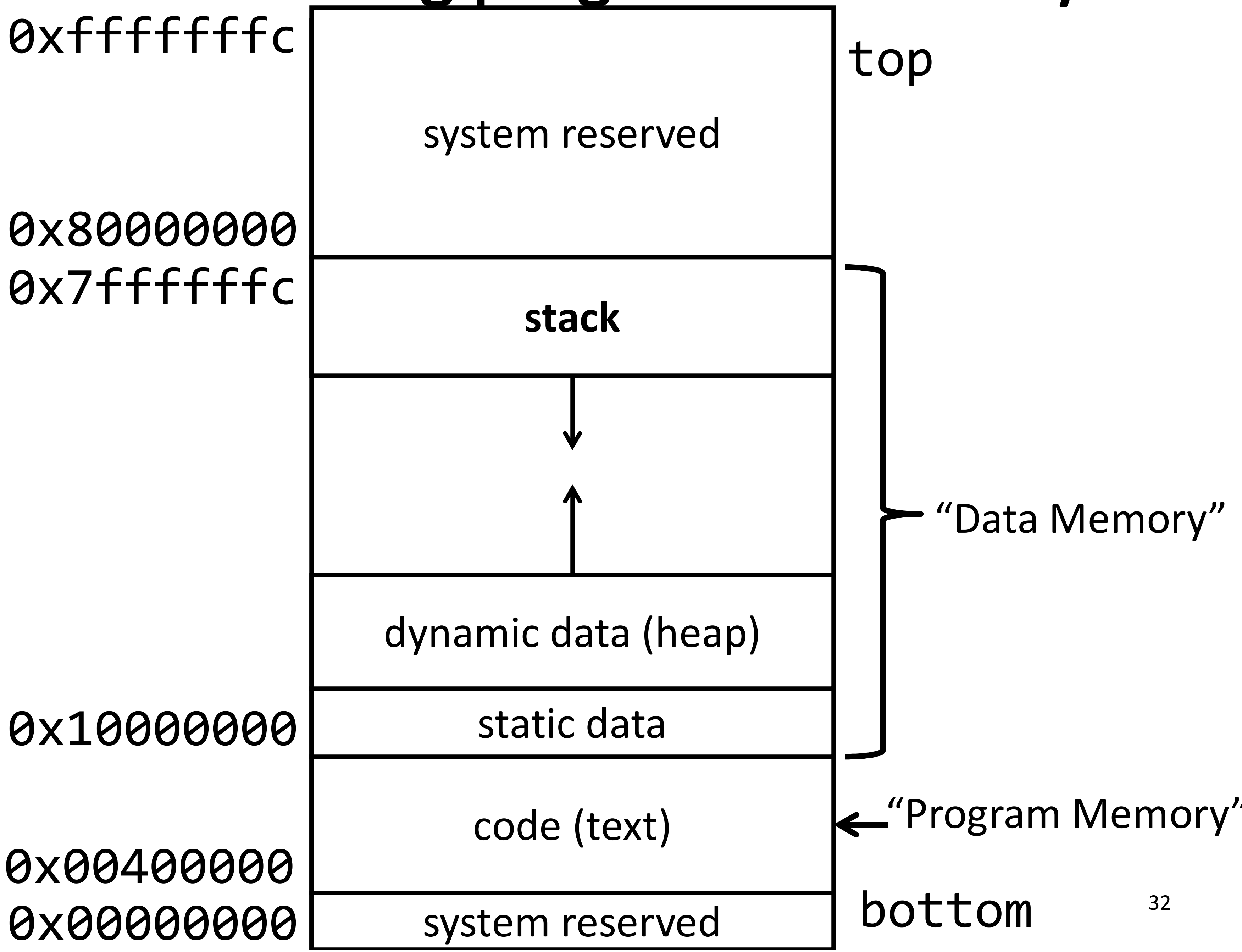
An executing program in memory



Anatomy of an executing program



An executing program in memory



The Stack

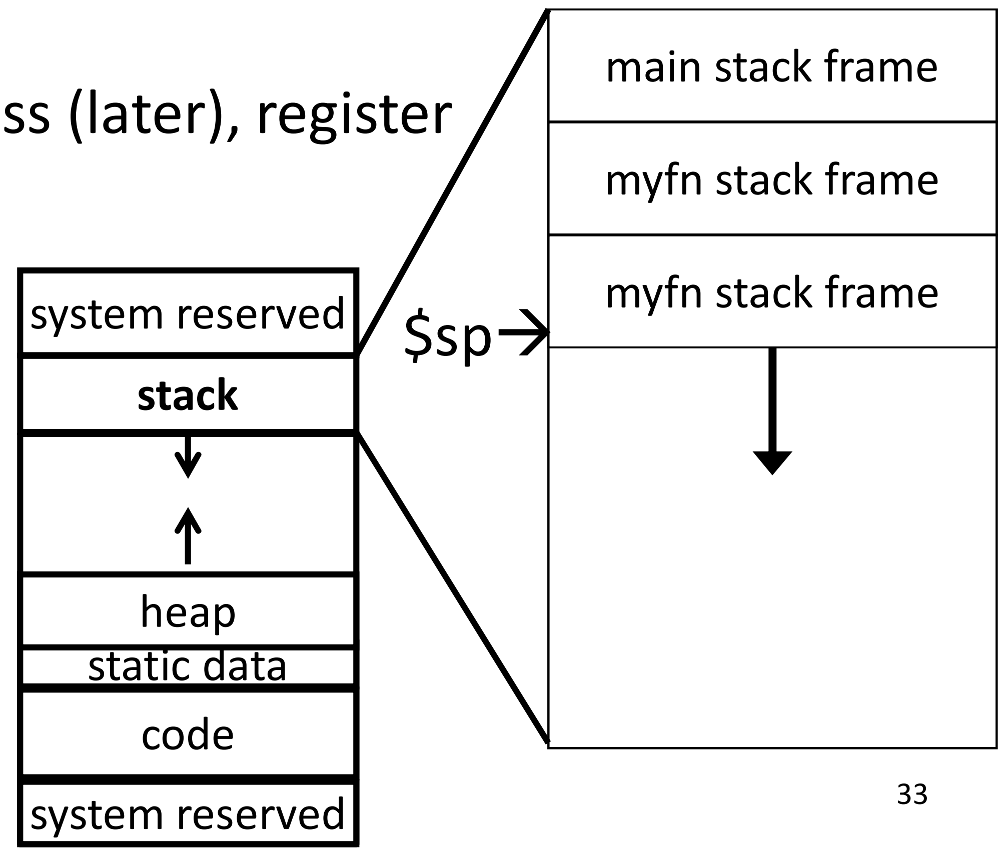
Stack contains stack frames (aka "activation records")

- 1 stack frame per dynamic function
- Exists only for the duration of function
- Grows down, "top" of stack is $sp, r29
- Example: lw $r1, 0($sp) puts word at top of stack into $r1

Each stack frame contains:

- Local variables, return address (later), register backups (later)

```
int main(…) {
     …
     myfn(x);
}
int myfn(int n) {
     …
     myfn();
}
```

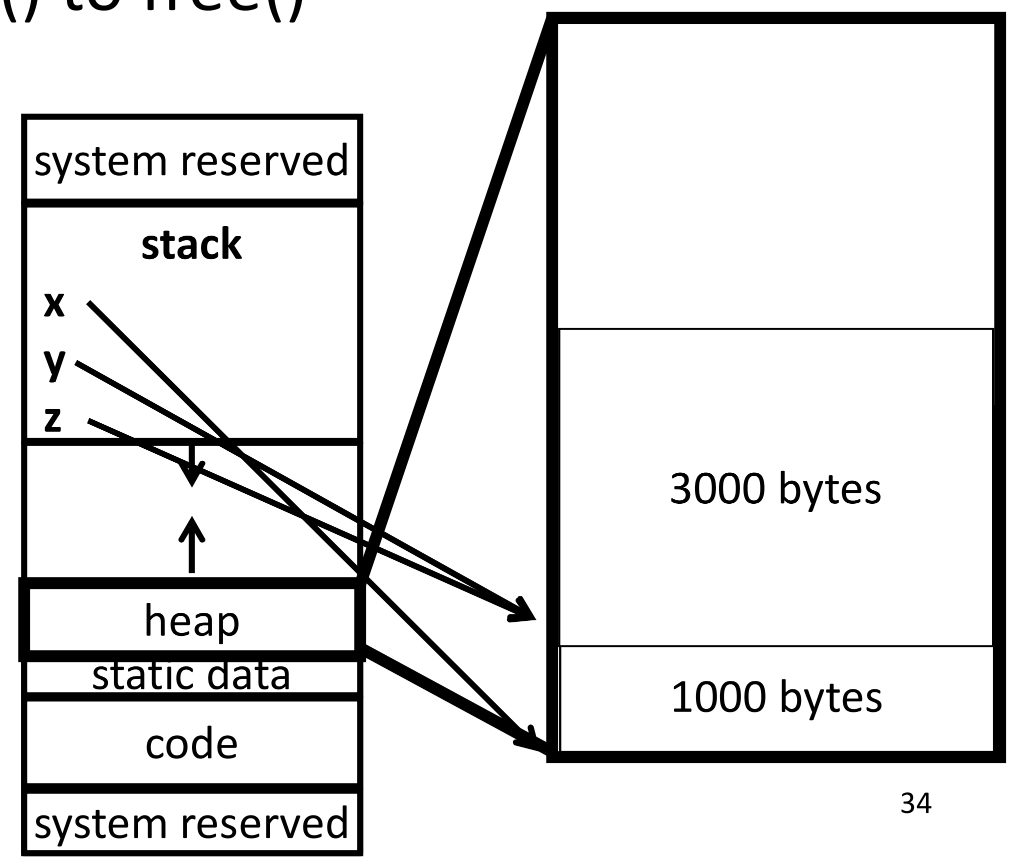


The Heap

Heap holds dynamically allocated memory

- Program must maintain pointers to anything allocated
  - Example: if $r3 holds x
  - lw $r1, 0($r3) gets first word x points to
- Data exists from malloc() to free()

```
void some_function() {
  int *x = malloc(1000);
  int *y = malloc(2000);
  free(y);
  int *z = malloc(3000);
}
```

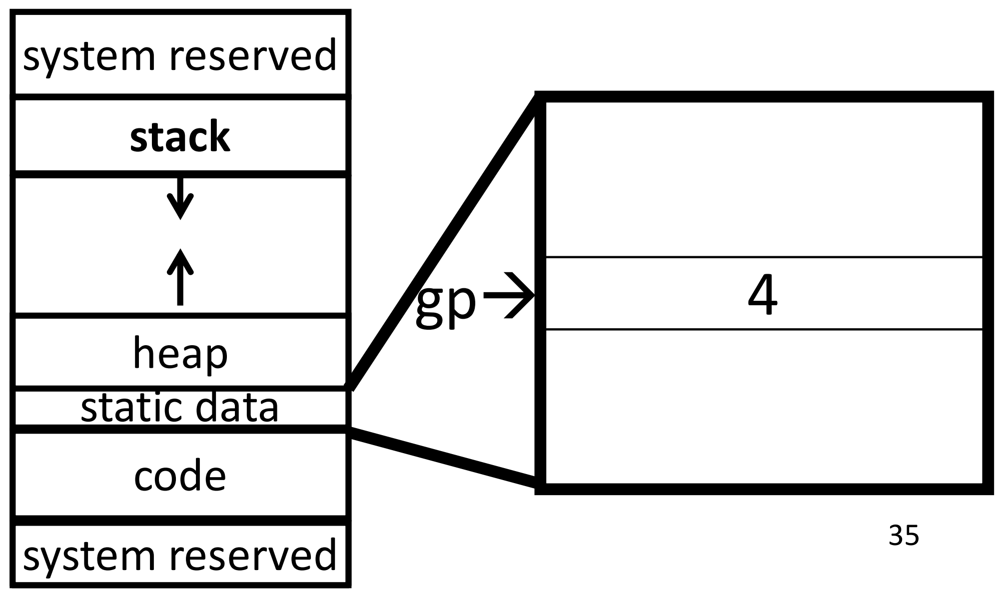


Data Segment

Data segment contains global variables

- Exist for all time, accessible to all routines
- Accessed w/global pointer
  - $gp, r28, points to middle of segment
  - Example: lw $r1, 0($gp) gets middle-most word (here, max_players)

```
int max_players = 4;

int main(...) {
    ...
}
```



Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local			
Global			
Dynamic			

```
int n = 100;
int main (int argc, char* argv[ ]) {
     int i, m = n, sum = 0;
     int* A = malloc(4*m + 4);
     for (i = 1; i <= m; i++) {
        sum += i; A[i] = sum; }
     printf ("Sum 1 to %d is %d\n", n, sum);
}
```

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).

Calling Convention for Procedure Calls

~~Transfer Control~~

- ~~Caller → Routine~~
- ~~Routine → Caller~~

Pass Arguments to and from the routine

- fixed length, variable length, recursively
- Get return value back to the caller

Manage Registers

- Allow each routine to use registers
- Prevent routines from clobbering each others' data

Next Goal

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

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 (1-4 args)

```
main() {
  int x = myfn(6, 7);
  x = x + 2;
}
```

```
main:
  li $a0, 6
  li $a1, 7
  jal myfn
  addiu $r1, $v0, 2
```

First four arguments:

passed in registers $4-$7

- aka $a0, $a1, $a2, $a3

Returned result:

passed back in a register

- Specifically, $2, aka $v0

Note: This is *not* the entire story for 1-4 arguments. Please see *the Full Story* slides.

Conventions so far:

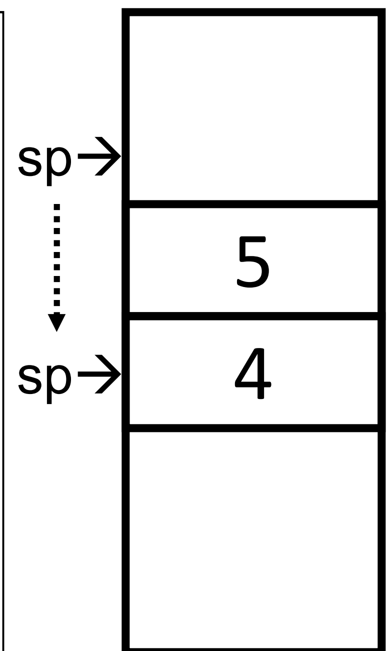
- args passed in $a0, $a1, $a2, $a3
- return value (if any) in $v0, $v1
- stack frame at $sp
  - contains $ra (clobbered on JAL to sub-functions)

Q: What about argument lists?

Many Arguments (5+ args)

```
main() {
  myfn(0,1,2,3,4,5);
  …
}
```

```
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 myfn
```



First four arguments:

passed in \$4-\$7

- aka \$a0-\$a3

Subsequent arguments:

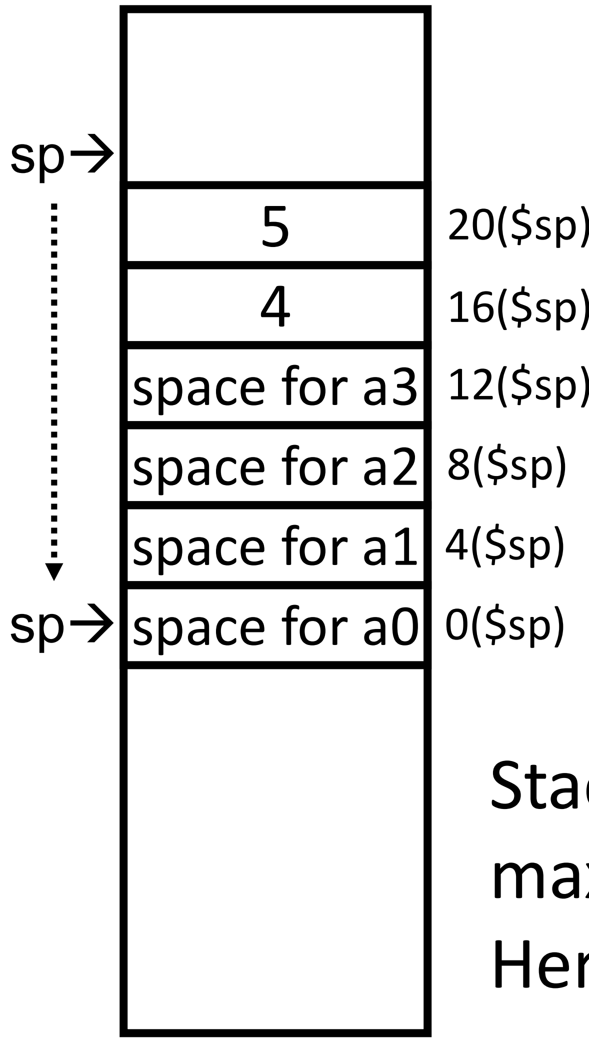
"spill" onto the stack

Note: This is *not* the entire story for 5+ arguments. Please see *the Full Story* slides.

Argument Passing: *the Full Story*

```
main() {
   myfn(0,1,2,3,4,5);
   …
}
```

```
main:
   li $a0, 0
   li $a1, 1
   li $a2, 2
   li $a3, 3
   addiu $sp,$sp,-24
   li $8, 4
   sw $8, 16($sp)
   li $8, 5
   sw $8, 20($sp)
   jal myfn
```



Arguments 1-4:

passed in \$4-\$7

room on stack

Arguments 5+:

placed on stack

Stack decremented by max(16, #args x 4)

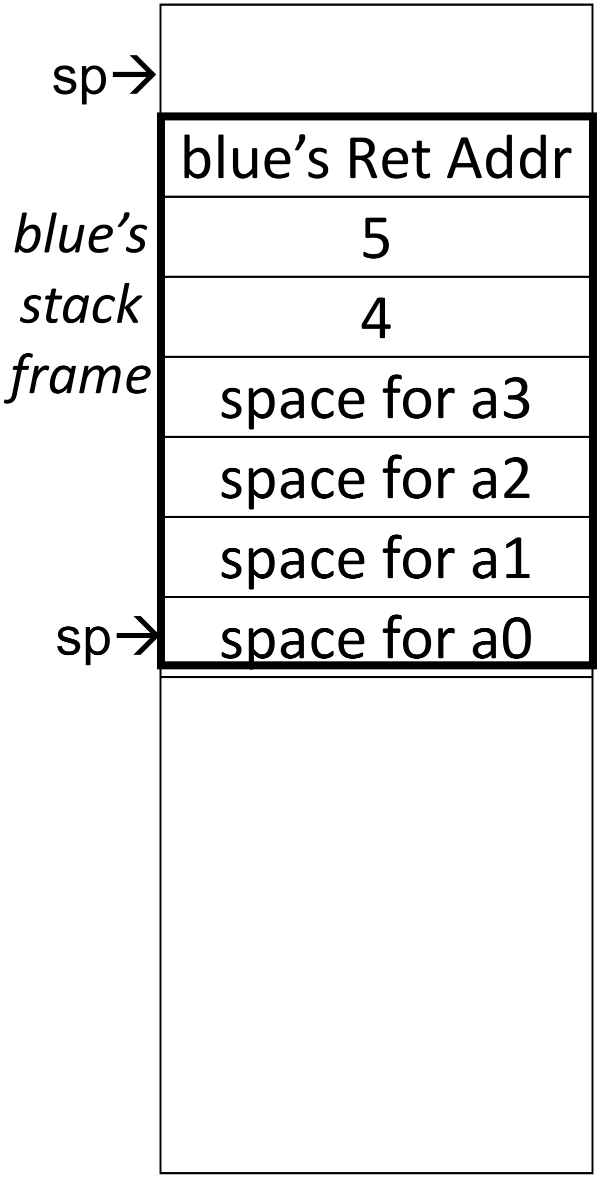
Here: max (16, 24) = 24

Pros of Argument Passing Convention

- Consistent way of passing arguments to and from subroutines
- Creates single location for all arguments
  - Caller makes room for $a0-$a3 on stack
  - Callee must copy values from $a0-$a3 to stack

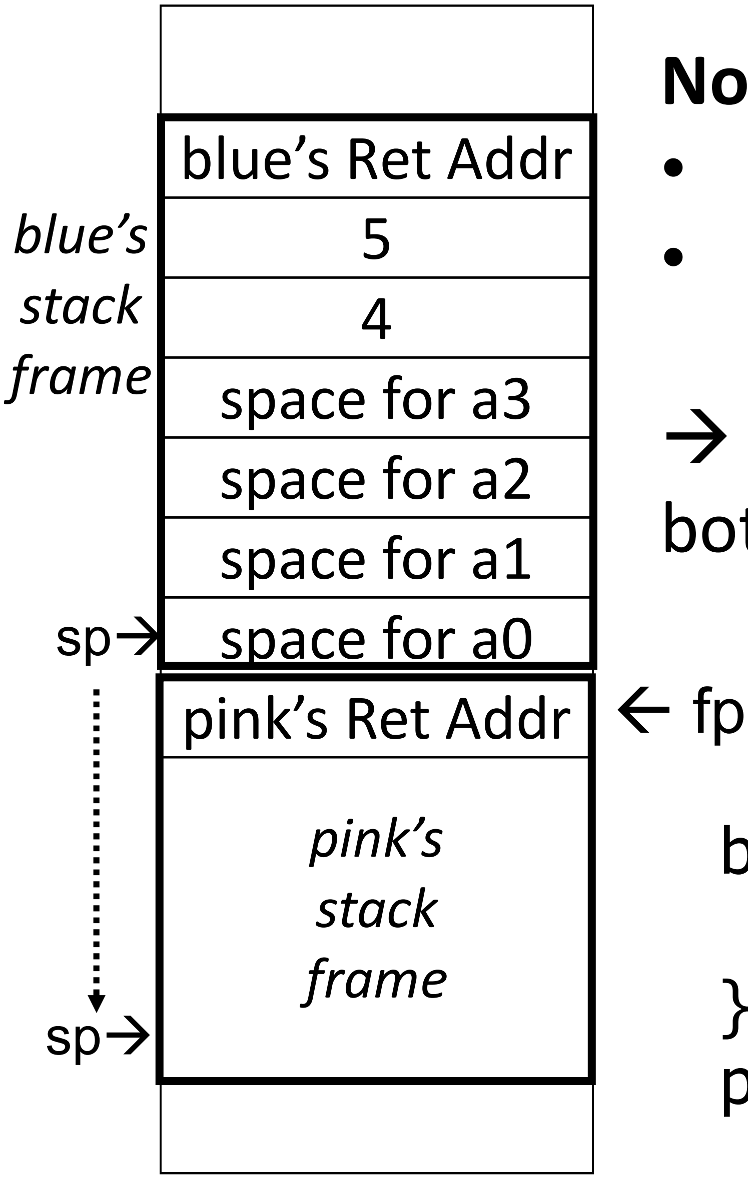
    → callee may treat all args as an array in memory
  - Particularly helpful for functions w/ variable length inputs: printf("Scores: %d %d %d\n", 1, 2, 3);
- Aside: not a bad place to store inputs if callee needs to call a function (your input cannot stay in $a0 if you need to call another function!)

Frame Layout & the Frame Pointer




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

Frame Layout & the Frame Pointer



Notice

- Pink's arguments are on **blue's** stack
- **sp** changes as functions call other functions, complicates accesses

→ Convenient to keep pointer to bottom of stack == **frame pointer**

$30, aka $fp

can be used to restore $sp on exit

```
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 in parent's stack frame
- return value (if any) in $v0, $v1
- stack frame ($fp to $sp) contains:
  - $ra (clobbered on JAL to sub-functions)
  - space for 4 arguments to Callees
  - arguments 5+ to Callees

MIPS Register Conventions so far:

r0	$zero	zero	r16		
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
r11			r27	$k1	for OS kernel
r12			r28		
r13			r29		
r14			r30		
r15			r31	$ra	return address

Pseudo-Instructions

e.g. BLZ

SLT $at

BNE $at, 0, L

C & MIPS: the fine print

C allows passing whole structs

- `int dist(struct Point p1, struct Point p2);`
- Treated as collection of consecutive 32-bit arguments
  - Registers for first 4 words, stack for rest
- Better: `int dist(struct Point *p1, struct Point *p2);`

Where are the arguments to:

```
void sub(int a, int b, int c, int d, int e);
void isalpha(char c);
void treesort(struct Tree *root);
```

Where are the return values from:

```
struct Node *createNode();
struct Node mynode();
```

Many combinations of char, short, int, void *, struct, *etc.*

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

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; }`

Global and Locals

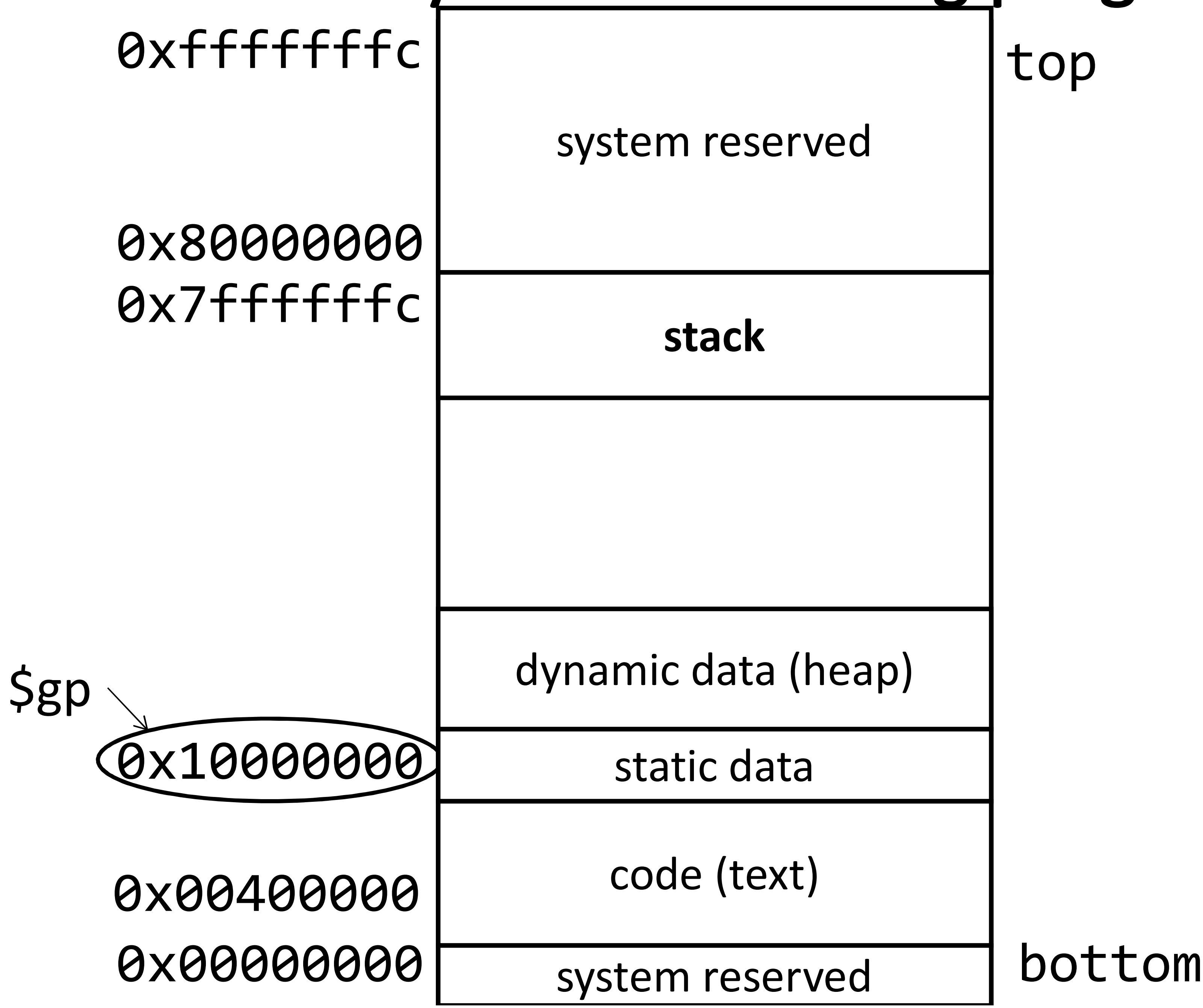
How does a function load global data?

- 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



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 top 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

Conventions so far

- first four arg words passed in \$a0-\$a3
- remaining args passed in parent's stack frame
- return value (if any) in \$v0, \$v1
- stack frame (\$fp to \$sp) contains:
  - \$ra (clobbered on JALs)
  - space for 4 arguments to Callees
  - arguments 5+ to Callees
- global data accessed via \$gp

Calling Convention for Procedure Calls

~~Transfer Control~~

- ~~Caller → Routine~~
- ~~Routine → Caller~~

~~Pass Arguments to and from the routine~~

- ~~fixed length, variable length, recursively~~
- ~~Get return value back to the caller~~

Manage Registers

- Allow each routine to use registers
- Prevent routines from clobbering each others’ data

Next Goal

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

Register Management

Functions:

- Are compiled in isolation
- Make use of general purpose registers
- Call other functions in the middle of their execution
  - These functions also use general purpose registers!
  - No way to coordinate between caller & callee

→ Need a convention for register management

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

Caller-saved

Registers that the caller cares about: $t0… $t9

About to call a function?

- Need value in a t-register *after* function returns?
  - → save it to the stack before fn call
  - → restore it from the stack after fn returns
- Don't need value? → do nothing

Suppose:

$t0 holds x

$t1 holds y

$t2 holds z

Where do we save and restore?

```
void myfn(int a) {
  int x = 10;
  int y = max(x, a);
  int z = some_fn(y);
  return (z + y);
}
```

Functions

- Can freely use these registers
- Must assume that their contents are destroyed by other functions

Callee-saved

Registers a function intends to use: \$s0… \$s9

About to use an s-register? You **MUST**:

- Save the current value on the stack ***before*** using
- Restore the old value from the stack before fn returns

Suppose:

\$s0 holds x

\$s1 holds y

\$s2 holds z

Where do we save and restore?

Functions

- Must save these registers before using them
- May assume that their contents are preserved even across fn calls

```
void myfn(int a) {
  int x = 10;
  int y = max(x, a);
  int z = some_fn(y);
  return (z + y);
}
```

Caller-Saved Registers in Practice

```
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, use with no overhead

Since subroutines will do the same, must protect values needed later:

Save before fn call

Restore after fn call

Notice: Good registers to use if you don't call too many functions or if the values don't matter later on anyway.

Caller-Saved Registers in Practice

```
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, use with no overhead

Since subroutines will do the same, must protect values needed later:

- Save before fn call
- Restore after fn call

Notice: Good registers to use if you don't call too many functions or if the values don't matter later on anyway.

Callee-Saved Registers in Practice

```
main:
 addiu $sp,$sp,-32
 sw $31,28($sp)
 sw $30, 24($sp)
 sw $17, 20($sp)
 sw $16, 16($sp)
 addiu  $fp, $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

Save on entry

Restore on exit

Notice: Good registers to use if you make a lot of function calls and need values that are preserved across all of them.

Also, good if caller is actually using the registers, otherwise the save and restores are wasted. But hard to know this.

Callee-Saved Registers in Practice

```
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
```

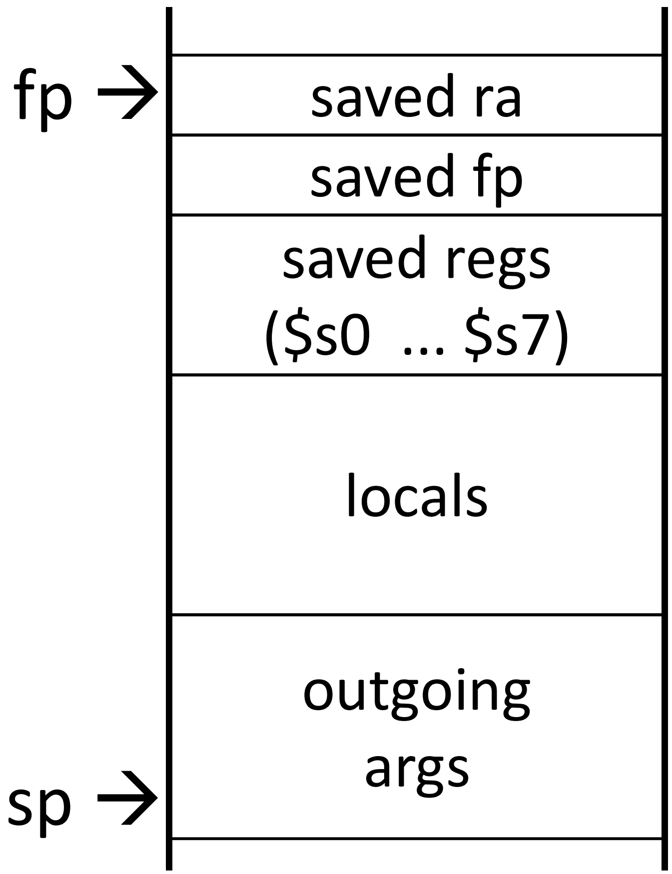
Assume caller is using the registers

- Save on entry
- Restore on exit

Notice: Good registers to use if you make a lot of function calls and need values that are preserved across all of them.

Also, good if caller is actually using the registers, otherwise the save and restores are wasted. But hard to know this.

Frame Layout on Stack



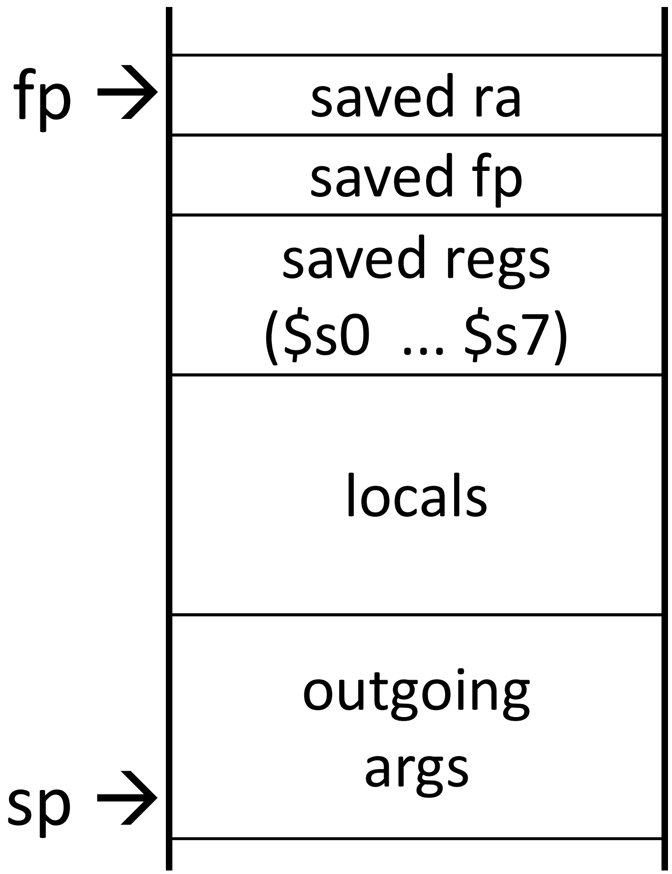
Assume a function uses two callee-save registers.

How do we allocate a stack frame?
How large is the stack frame?

What should be stored in the stack frame?

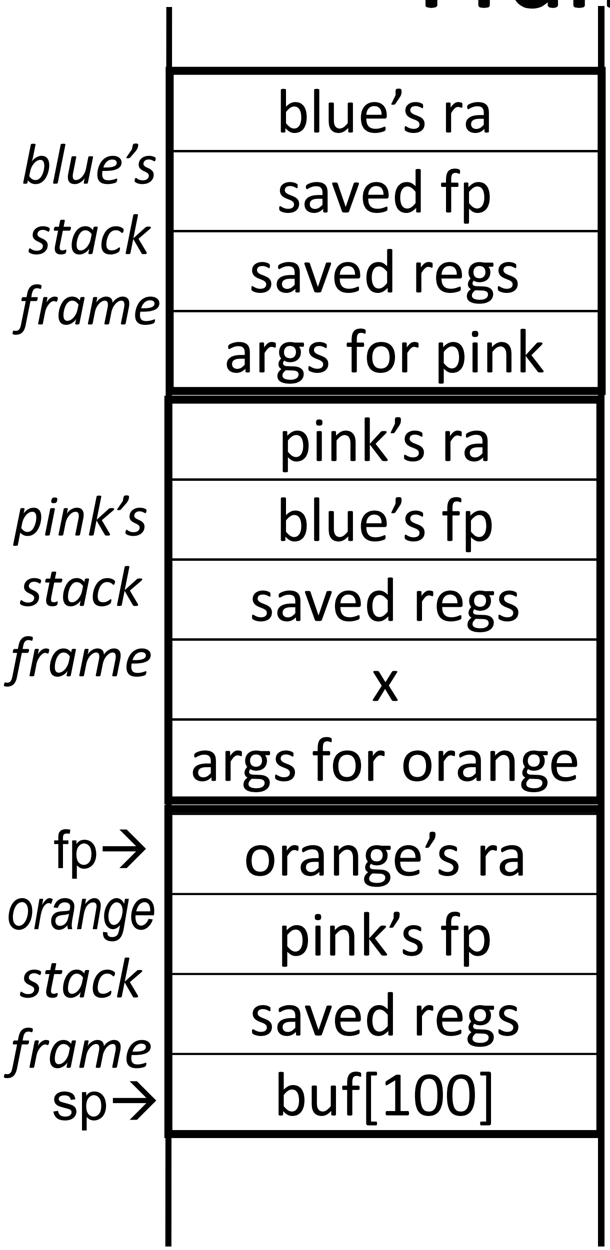
Where should everything be stored?

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);
}

pink(int a, int b, int c, int d, int e, int f) {
    int x;
    orange(10,11,12,13,14);
}

orange(int a, int b, int c, int, d, int e) {
        char buf[100];
        gets(buf);      // no bounds check!
}
```

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)

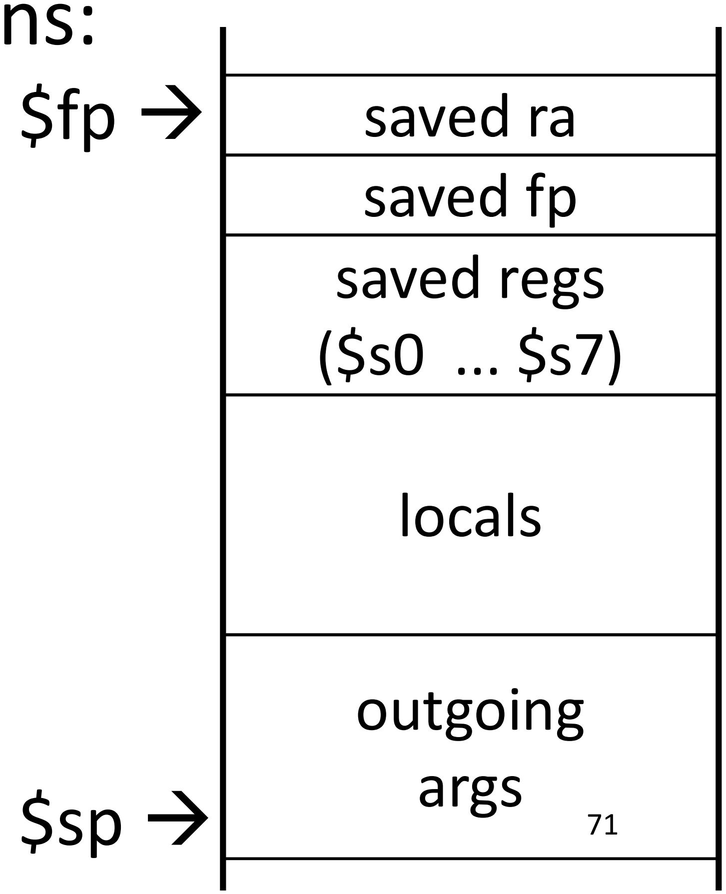
Assembler temporary: \$1 (at)

MIPS Register Conventions

r0	$zero	zero
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

Convention recap so far

- first four arg words passed in $a0-$a3
- remaining args passed in parent's stack frame
- return value (if any) in $v0, $v1
- stack frame ($fp to $sp) contains:
  - $ra (clobbered on JALs)
  - local variables
  - space for 4 arguments to Callees
  - arguments 5+ to Callees
- callee save regs: preserved
- caller save regs: not preserved
- global data accessed via $gp



Activity #1: Calling Convention Examp

```
int test(int a, int b) {
    int tmp = (a&b)+(a|b);
    int s = sum(tmp,1,2,3,4,5);
    int u = sum(s,tmp,b,a,b,a);
    return u + a + b;
}
```

<u>Correct Order:</u>

1. Body First
2. Determine stack frame size
3. Complete Prologue/Epilogue

Activity #2: Calling Convention Example: Prologue, Epilogue

test:

allocate frame

save $ra

save old $fp

callee save ...

callee save ...

set new frame ptr

…

…

restore …

restore …

restore old $fp

restore $ra

dealloc frame

Next Goal

Can we optimize the assembly code at all?

Activity #3: Calling Convention Example

```
int test(int a, int b) {
    int tmp = (a&b)+(a|b);
    int s = sum(tmp,1,2,3,4,5);
    int u = sum(s,tmp,b,a,b,a);
    return u + a + b;
}
```

How can we optimize the assembly code?

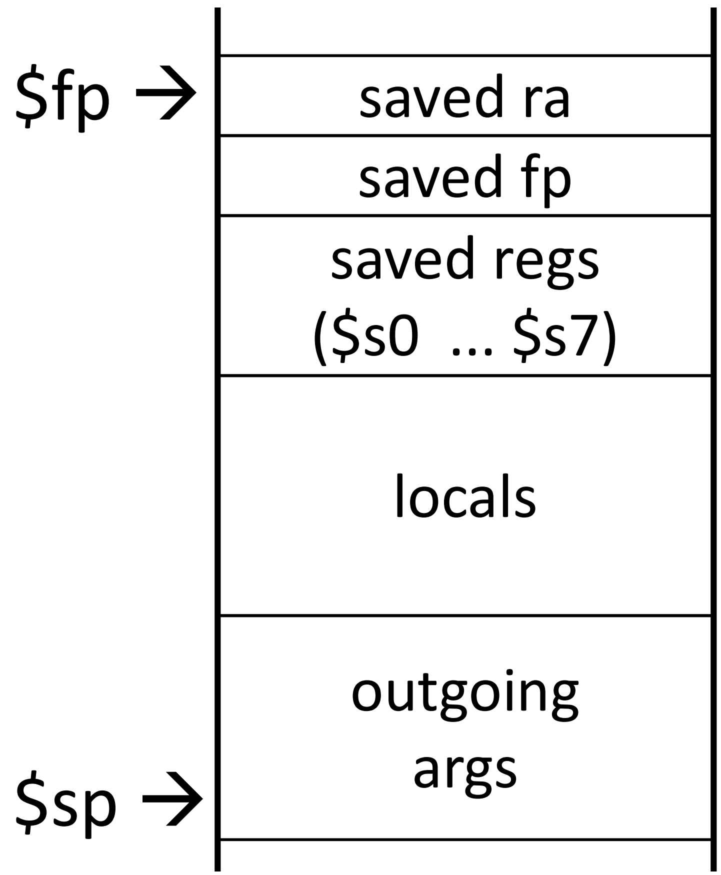
Activity #3: Calling Convention Example: Prologue, Epilogue

test:

allocate frame
save $ra
save old $fp
callee save ...
callee save ...
set new frame ptr
...
...
restore …
restore …
restore old $fp
restore $ra
dealloc frame

Minimum stack size for a standard function?

Minimum stack size for a standard function?



Leaf Functions

Leaf function does not invoke any other functions

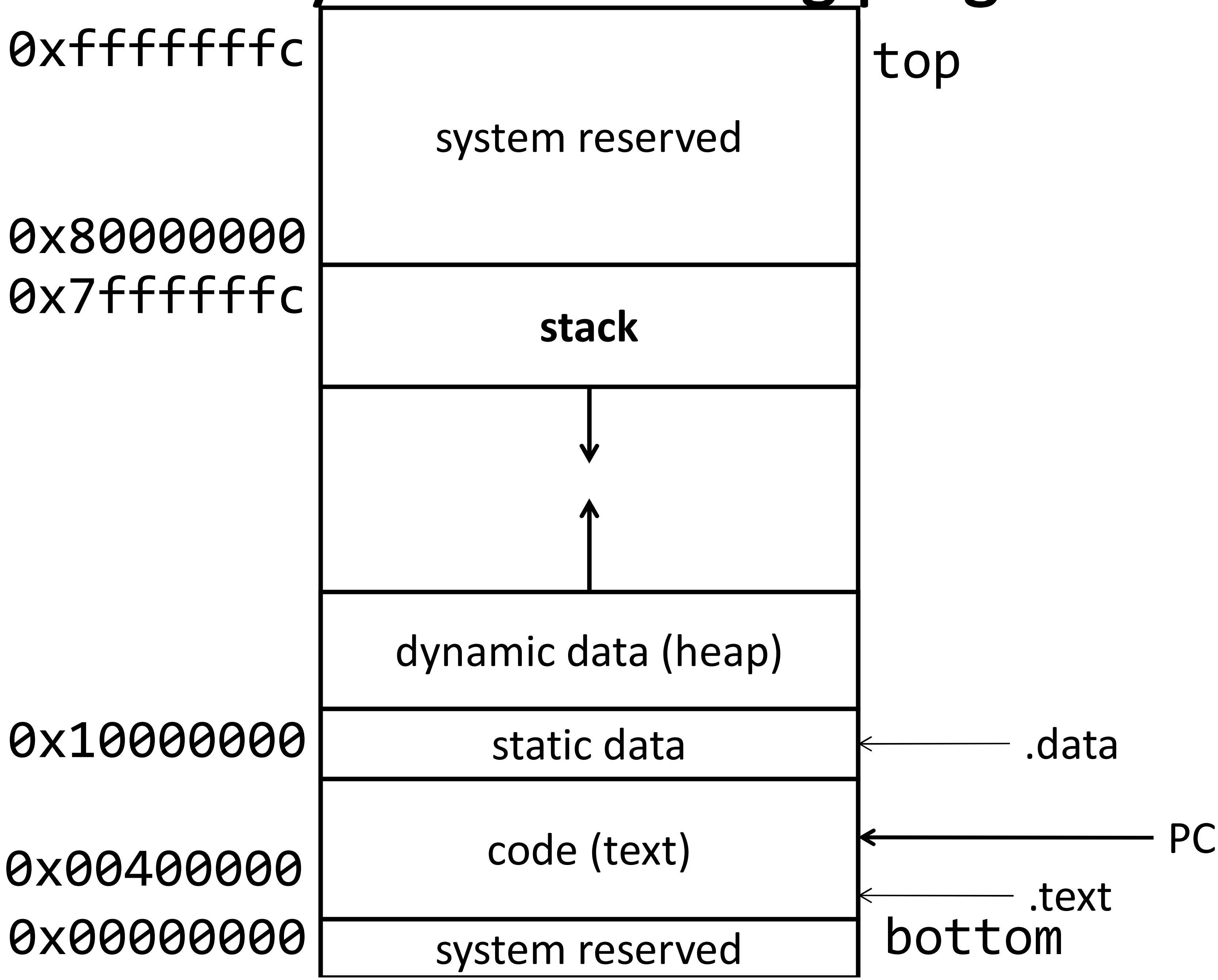
```
int f(int x, int y) { return (x+y); }
```

Optimizations?

Next Goal

Given a running program (a process), how do we know what is going on (what function is executing, what arguments were passed to where, where is the stack and current stack frame, where is the code and data, etc)?

Anatomy of an executing program



Activity #4: Debugging

init():	0x400000
printf(s, ...):	0x4002B4
vnorm(a,b):	0x40107C
main(a,b):	0x4010A0
pi:	0x10000000
str1:	0x10000004

CPU:
$pc=0x004003C0
$sp=0x7FFFFFAC
$ra=0x00401090

What func is running?

Who called it?

Has it called anything?

Will it?

Args?

Stack depth?

Call trace?

	0x00000000
	0x0040010c
	0x7FFFFFF4
	0x00000000
	0x00000000
	0x00000000
	0x00000000
	0x004010c4
	0x7FFFFFDC
	0x00000000
	0x00000000
	0x00000015
0x7FFFFFB0	0x10000004
	0x00401090

Convention Summary

- How to write and Debug a MIPS program using calling convention
- 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, $v1
- stack frame ($fp to $sp) contains:
  - $ra (clobbered on JAL to sub-functions)
  - $fp
  - local vars (possibly clobbered by sub-functions)
  - contains extra arguments to sub-functions (i.e. argument "spilling)
  - contains space for first 4 arguments to sub-functions
- callee save regs are preserved
- caller save regs are not
- Global data accessed via $gp