Calling Conventions

Anne Bracy

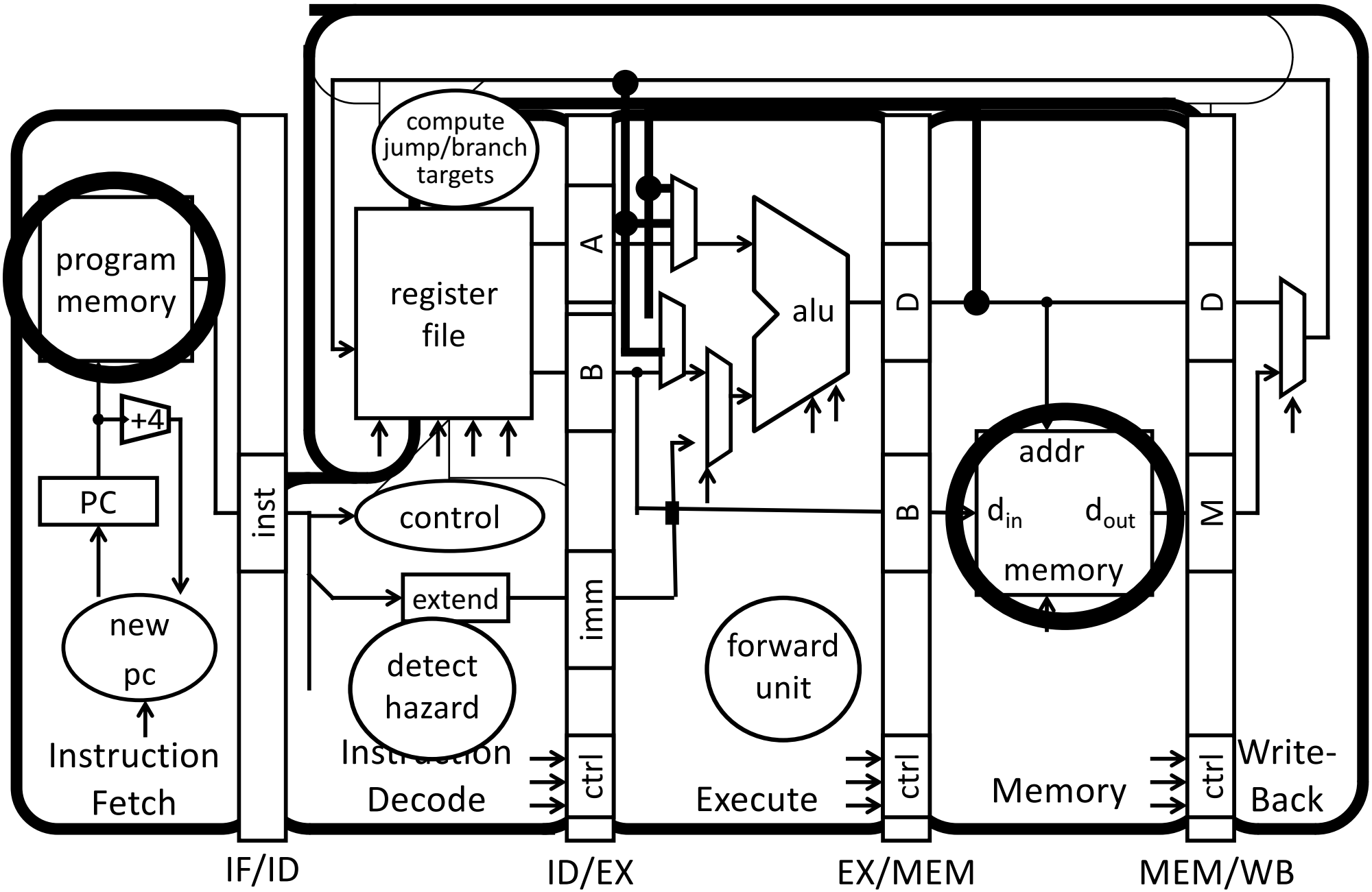
CS 3410

Computer Science

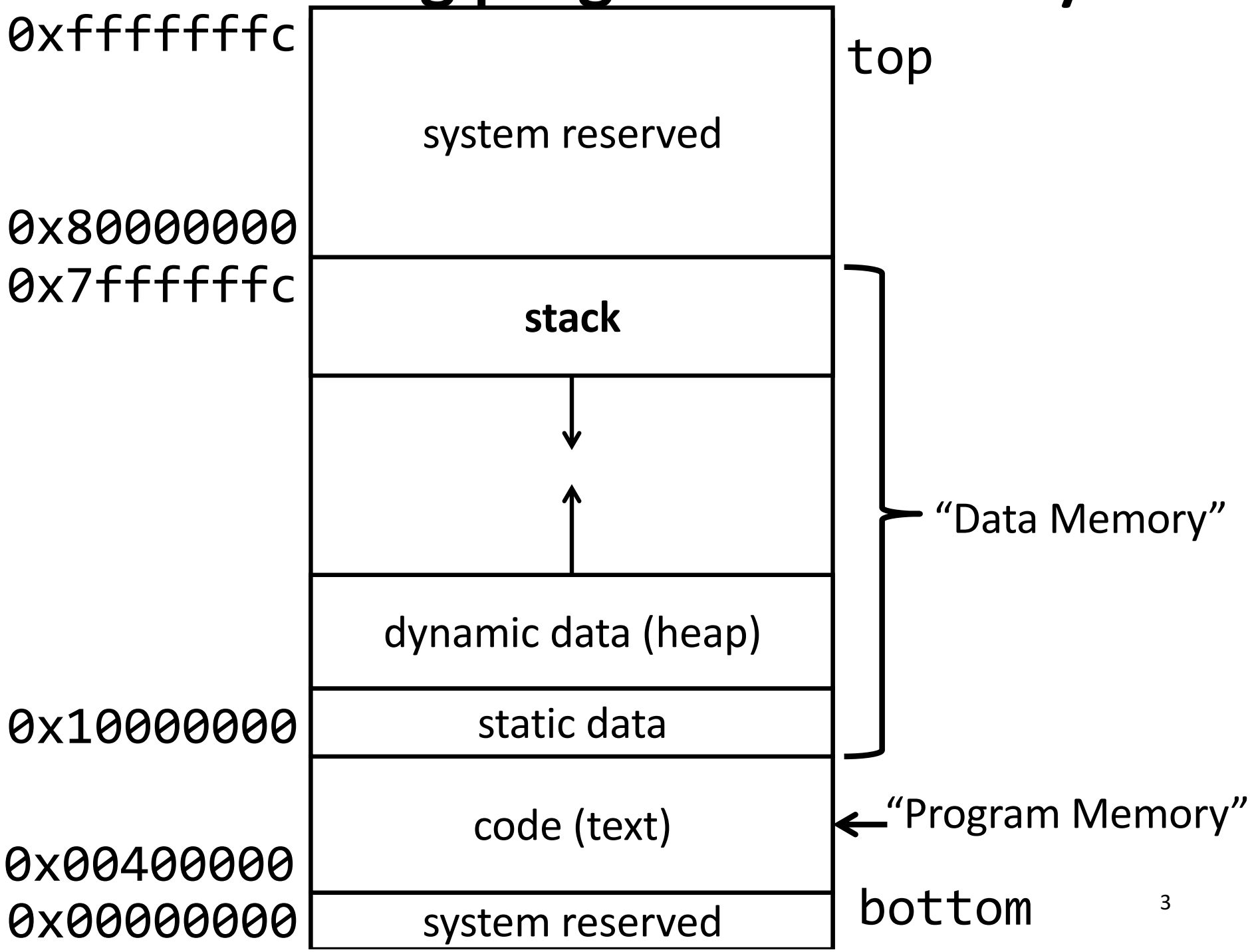
Cornell University

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

An executing program on chip



An executing program in memory



The Stack

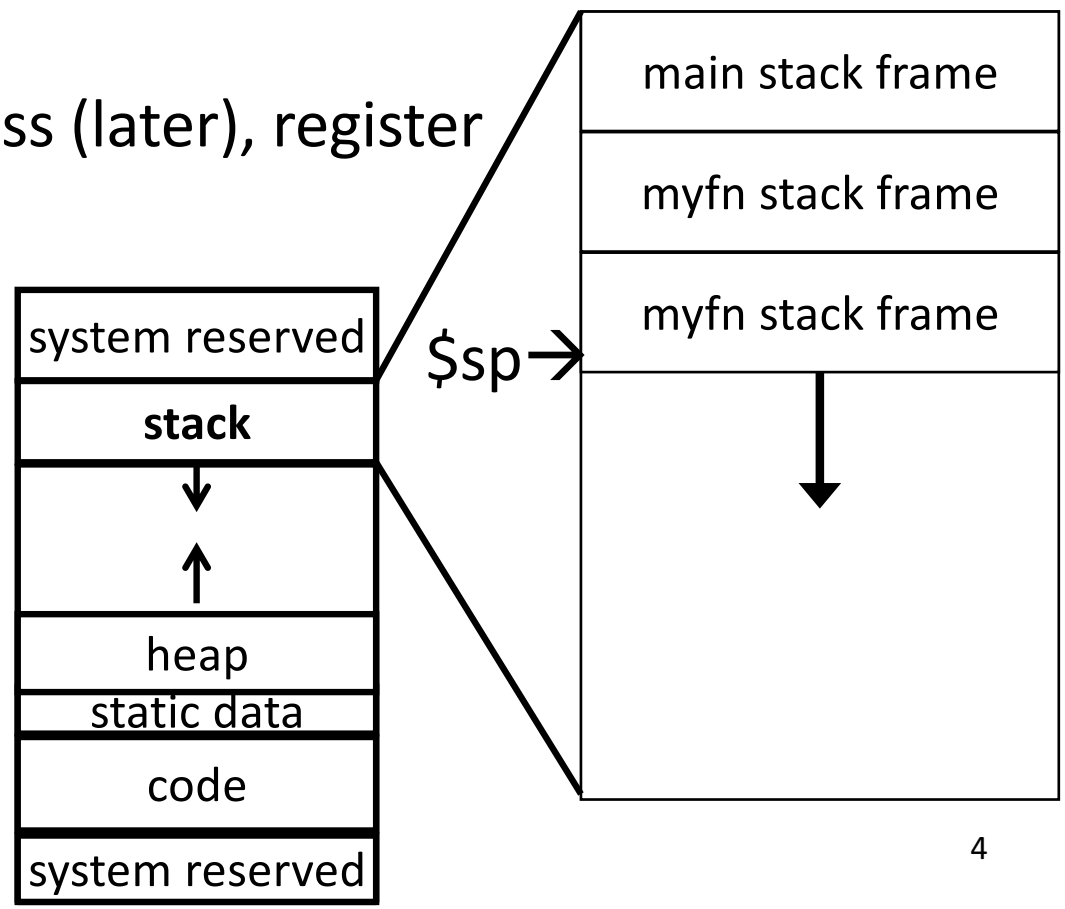
Stack contains stack frames (aka "activation records")

- 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();
}
```

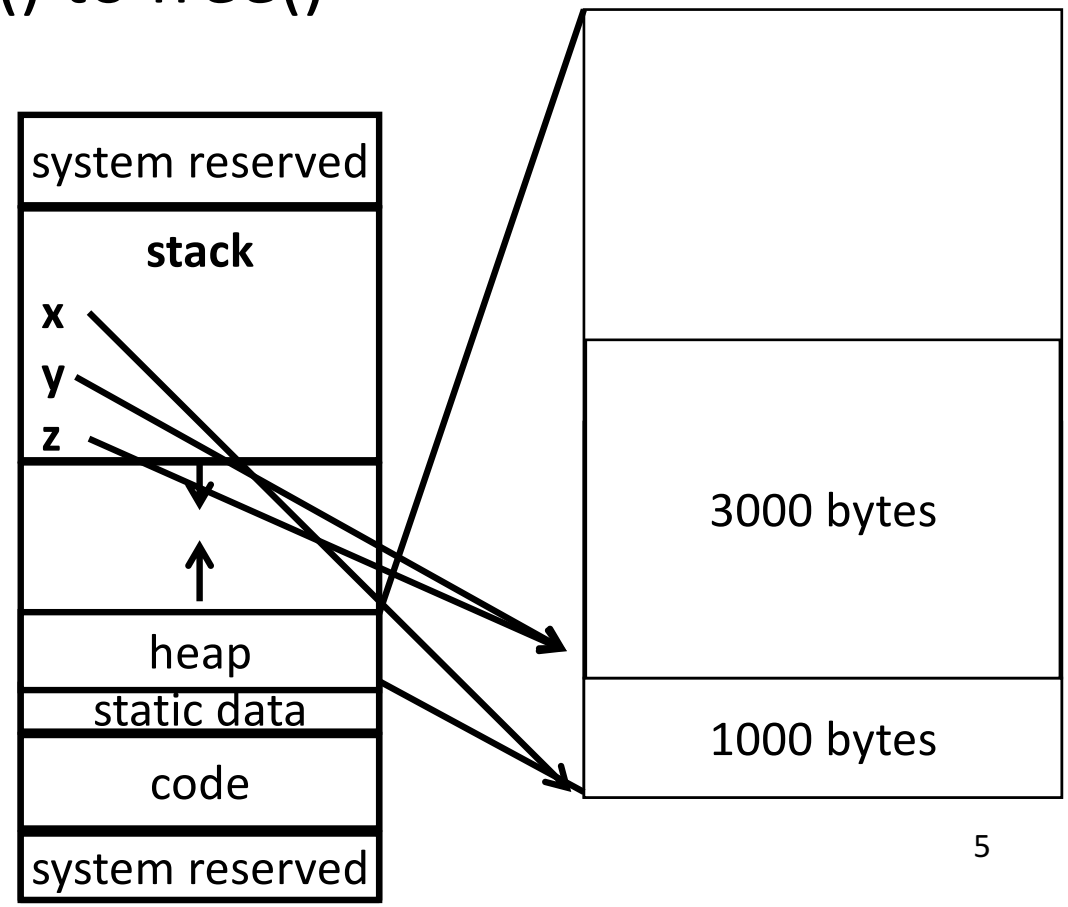


The Heap

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);
}
```

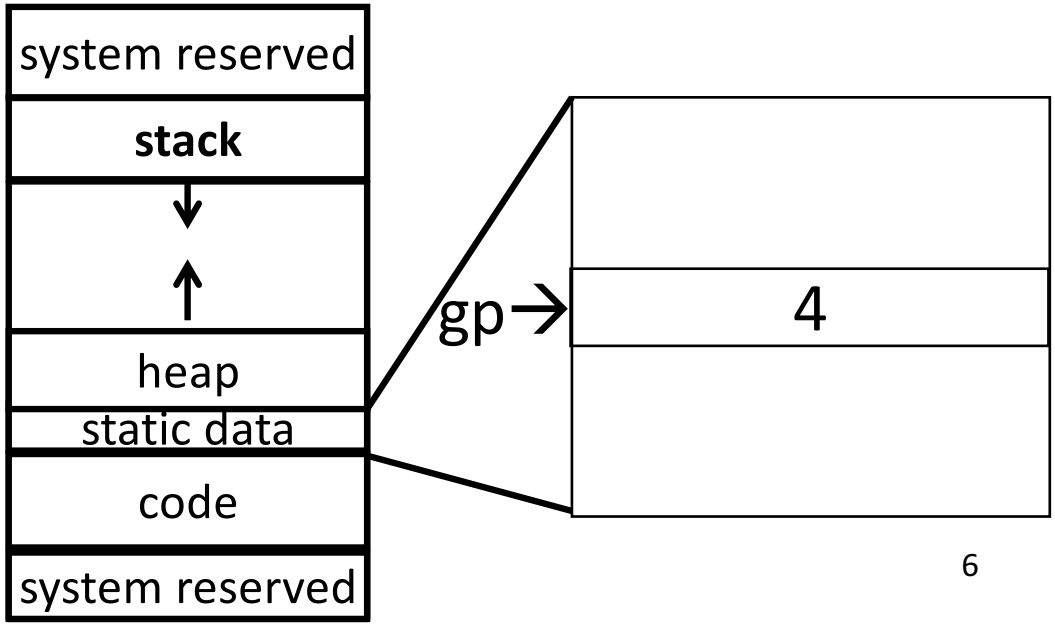


Data Segment

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);
}
```

Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local i, m, sum, A	w/in function	function invocation	stack
Global n, str	whole program	program execution	.data
Dynamic *A	Anywhere that has a pointer	b/w malloc and free	heap

```
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);
}
```

Evil things allowed by C

Don't ever write code like this!

Dangling pointers
into freed heap mem

```
void some_function() {
  int *x = malloc(1000);
  int *y = malloc(2000);
  free(y);
  int *z = malloc(3000);
  y[20] = 7;
}
```

Dangling pointers
into old stack frames

```
void f1() {
  int *x = f2();
  int  y = *x + 2;
}
int *f2() {
  int a = 3;
  return &a;
}
```

iClicker Question

Which of the following is trouble-free code?

A
```
int *bubble()
{ int a;
  …
  return &a;
}
```

B
```
char *rubble()
{ char s[20];
  gets(s);
  return s;
}
```

C
```
int *toil()
{ s = malloc(20);
  …
  return s;
}
```

D
```
int *trouble()
{ s = malloc(20);
  …
  free(s);
  …
  return s;
}
```

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;
}
```

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

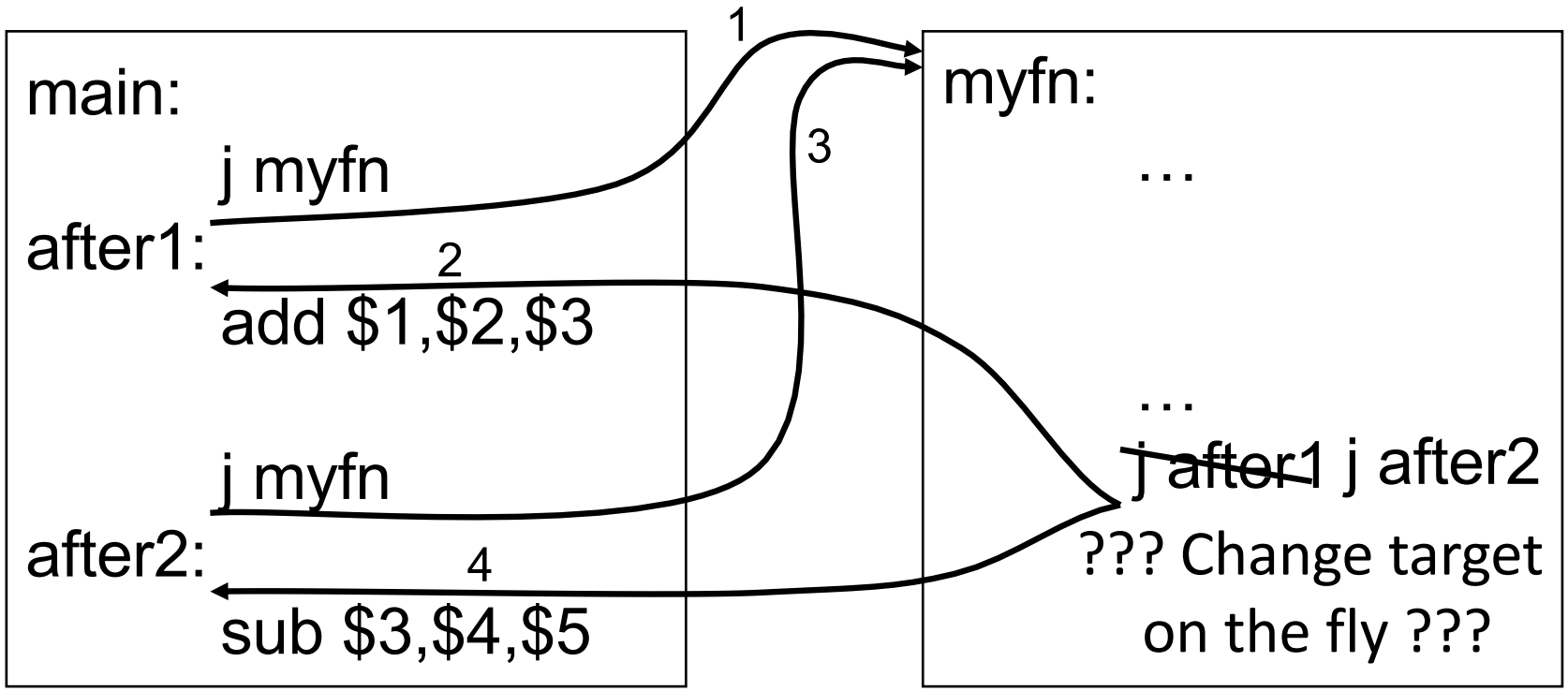
- Allow each routine to use registers
- Prevent routines from clobbering each others' data

What is a Convention?

Warning: There is no one true MIPS calling convention.

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

Jumps are not enough



Jumps to the callee

Jumps back

What about multiple sites?

Jump-and-Link / Jump Register

First call

r31 | *after1*

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

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

1

2

```
myfn:
  …

  …
  jr $31
```

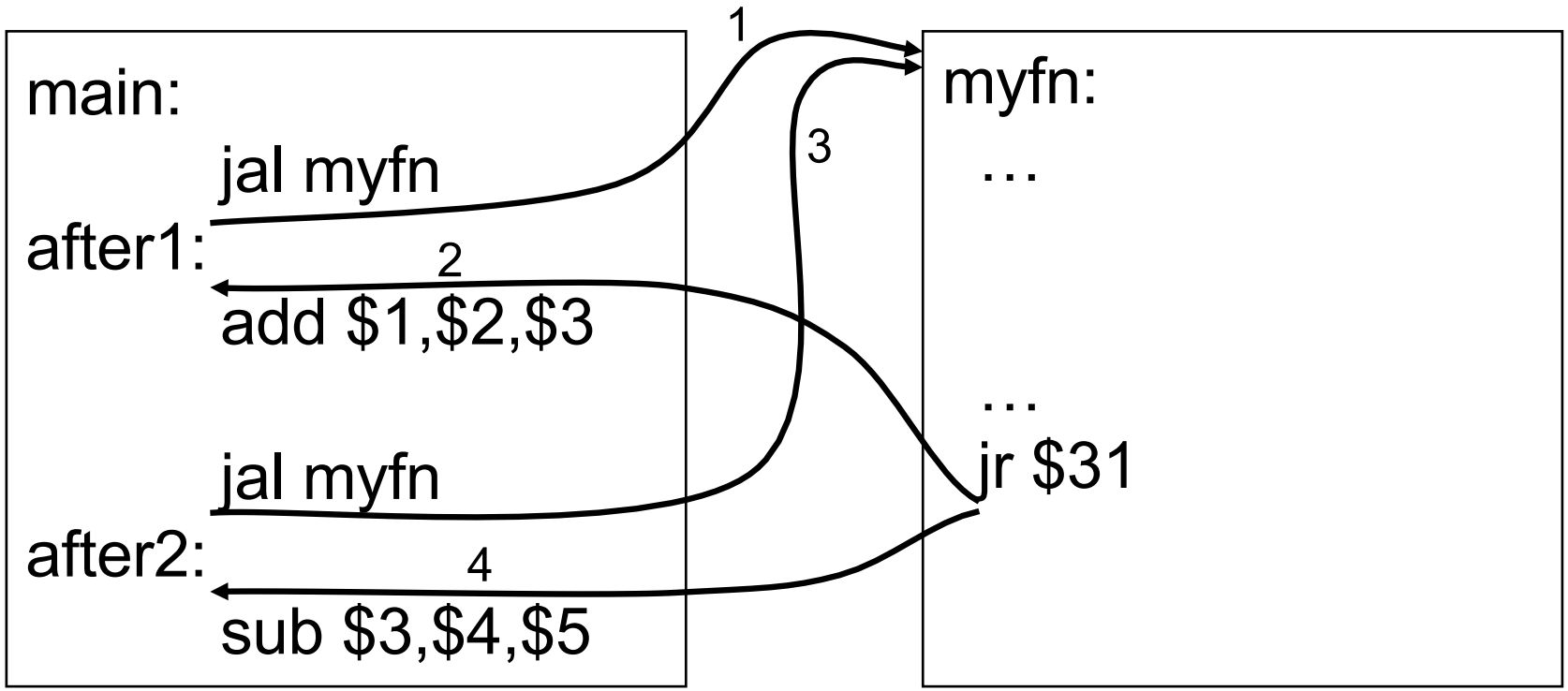
JAL saves the PC in register $31

Subroutine returns by jumping to $31

Jump-and-Link / Jump Register

Second call

r31 *after2*



JAL saves the PC in register $31

Subroutine returns by jumping to $31

What happens for recursive invocations?

JAL / JR for Recursion?

First call

r31 | *after1*

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

1

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

        jr $31
```

Problems with recursion:

- overwrites contents of $31

JAL / JR for Recursion?

Recursive Call

r31 | *after2*

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

1

2

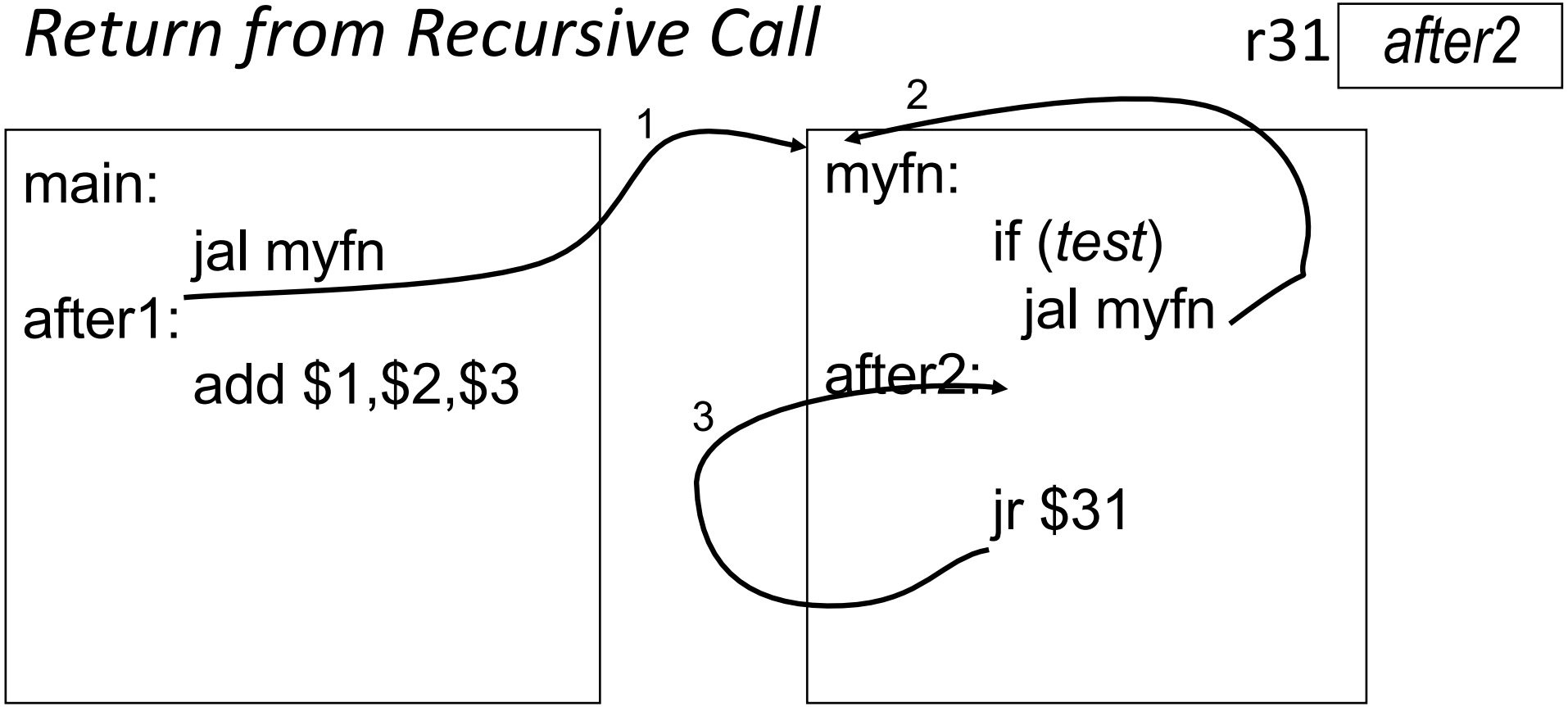
```
myfn:
        if (test)
          jal myfn
after2:

        jr $31
```

Problems with recursion:

- overwrites contents of $31

JAL / JR for Recursion?

Return from Recursive Call

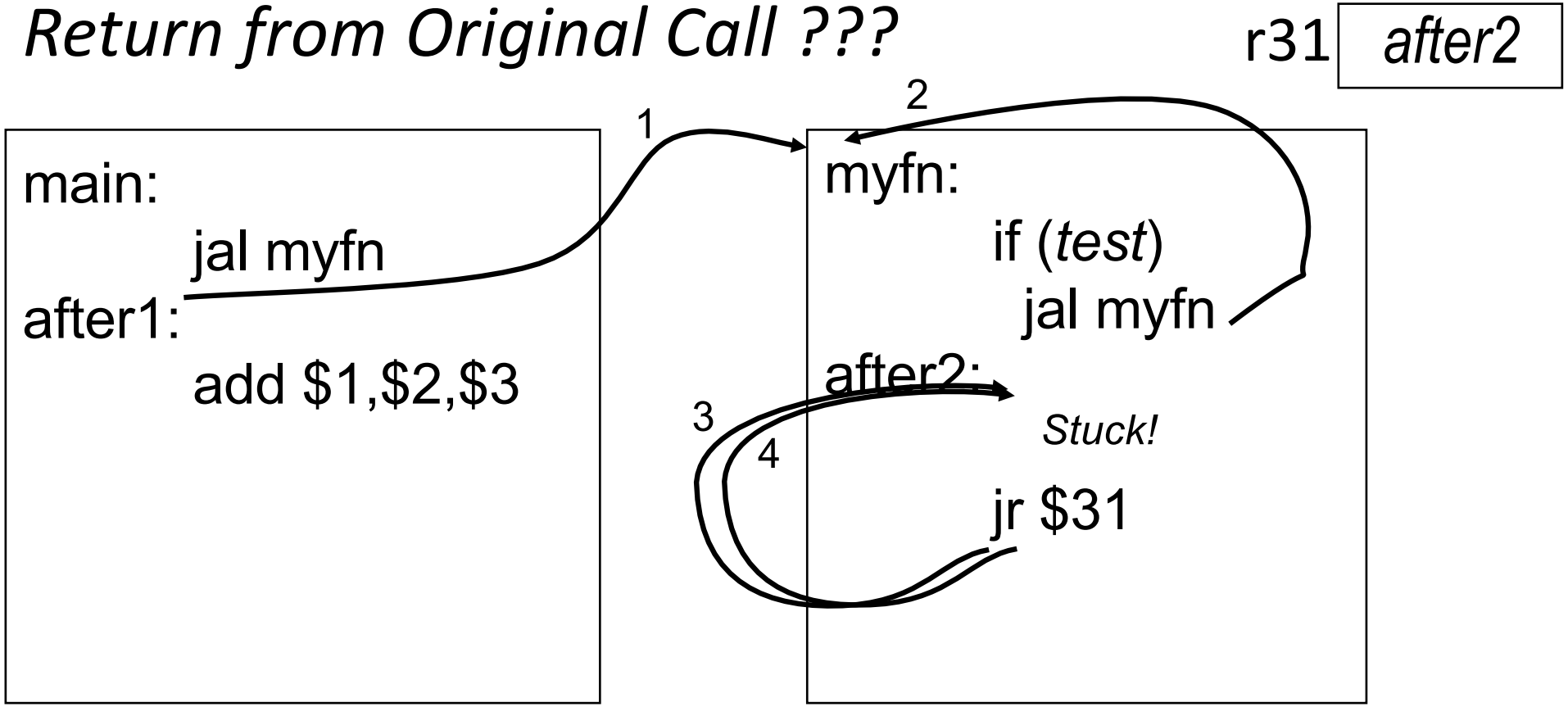


Problems with recursion:

- overwrites contents of $31

JAL / JR for Recursion?

Return from Original Call ???



Problems with recursion:

- overwrites contents of $31

JAL / JR for Recursion?

r1	5
r31	*after1*

1st time through myfn

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

1

2

```
myfn:
        addi r1, r0, 5
        ...
        jal myfn
after2:
        addi r1, r1, 5
        jr $31
```

Problems with recursion:

- overwrites contents of $31
- Come to think of it… overwrites *all* the registers!

JAL / JR for Recursion?

r1	10
r31	*after2*

2nd time through myfn

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

1

2

```
myfn:
        addi r1, r0, 5
        ...
        jal myfn
after2:
        addi r1, r1, 5
        jr $31
```

Problems with recursion:

- overwrites contents of $31
- Come to think of it… overwrites *all* the registers!

Return Address lives in Stack Frame

Stack Manipulated by push/pop operations

Context: after 2nd JAL to myfn (from myfn)

PUSH: ADDIU $sp, $sp, -20 // move sp down

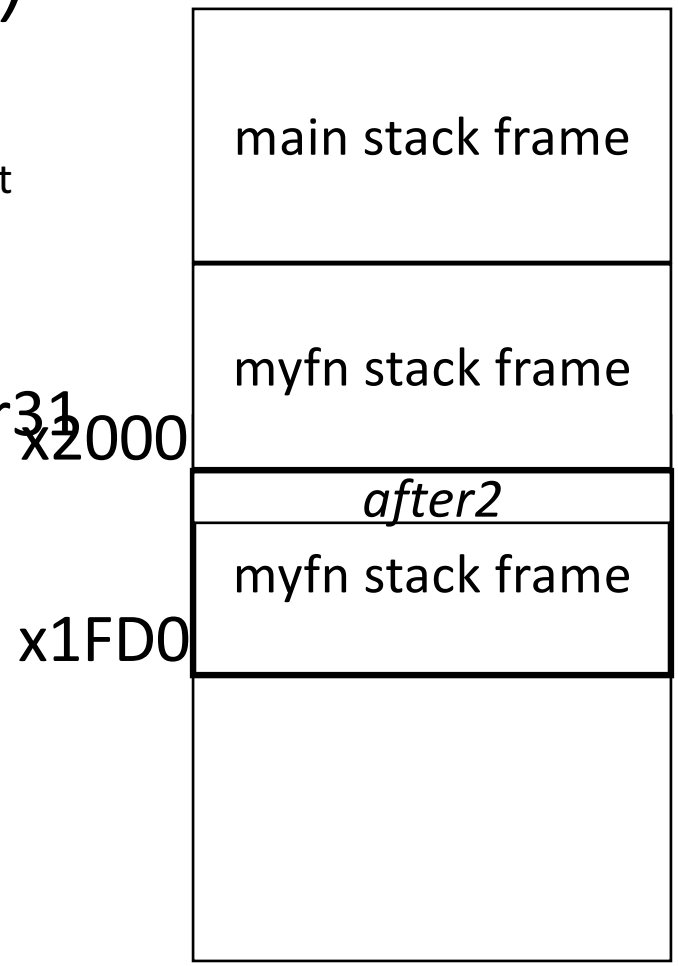
SW $31, 16($sp) // store retn PC 1st

Context: 2nd myfn is done (r31 == ???)

POP: LW $31, 16($sp) // restore retn PC →r31

ADDIU $sp, $sp, 20 // move sp up

JR $31 // return



r29 x1FD0

r31 *XXXX*

For now: Assume each frame = x20 bytes (just to make this example concrete)

iClicker Question

Why do we need a JAL instruction for procedure calls?

A. The only way to change the PC of your program is with a JAL instruction.
B. The system won't let you jump to a procedure with just a JMP instruction.
C. If you JMP to a function, it doesn't know where to return to upon completion.
D. Actually, JAL only works for the first function call. With multiple active functions, JAL is not the right instruction to use.

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

Simple Argument Passing (1-4 args)

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

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

First four arguments:

passed in registers $4-$7

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

Returned result:

passed back in a register

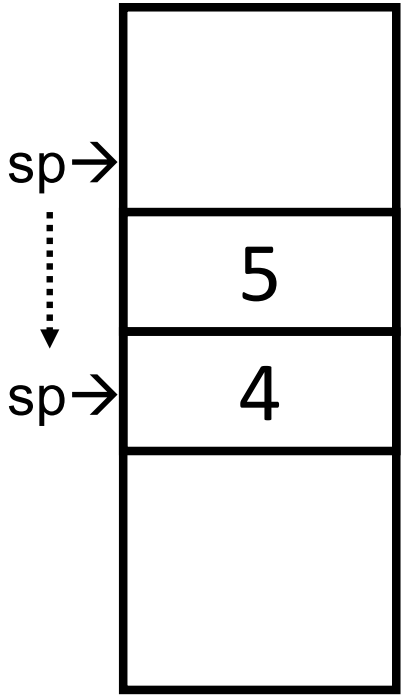
- Specifically, $2, aka $v0

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

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:

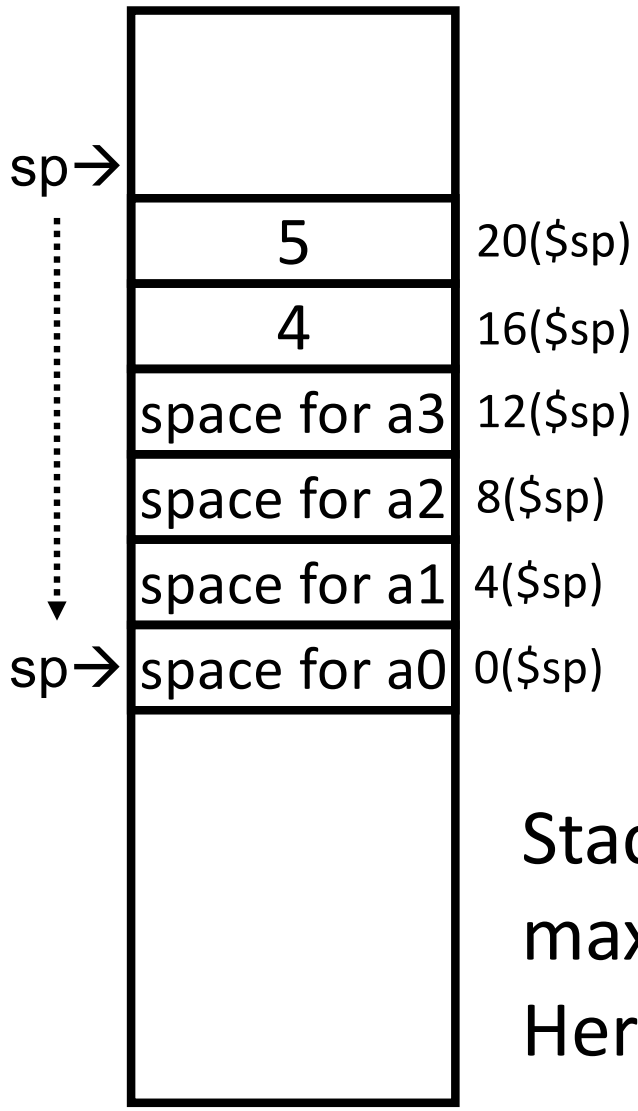
"spill" onto the stack

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 decrimented 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!)

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

iClicker Question

Which is a true statement about the arguments to the function

```
void sub(int a, int b, int c, int d, int e);
```

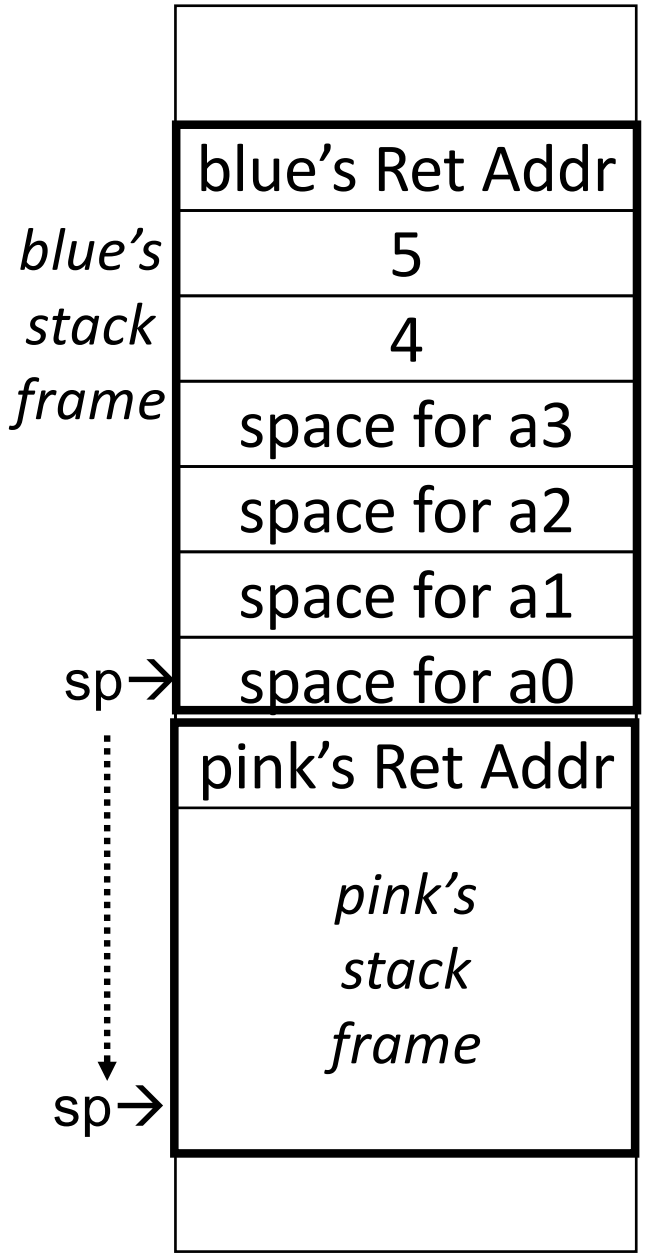
A. Arguments a-e are all passed in registers.

B. Arguments a-e are all stored on the stack.

C. Only e is stored on the stack, but space is allocated for all 5 arguments.

D. Only a-d are stored on the stack, but space is allocated for all 5 arguments.

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

← 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) {
    ...
}
```

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

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

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:

$t0 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 $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 $ra,28($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

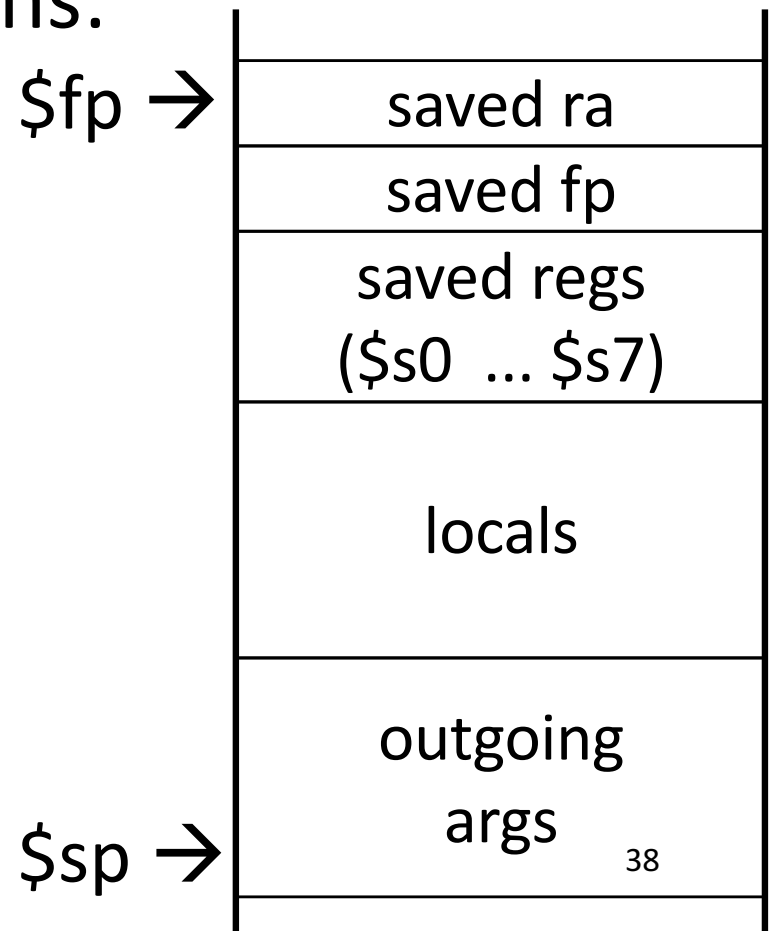
Restore on exit

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.

Convention Summary

- 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

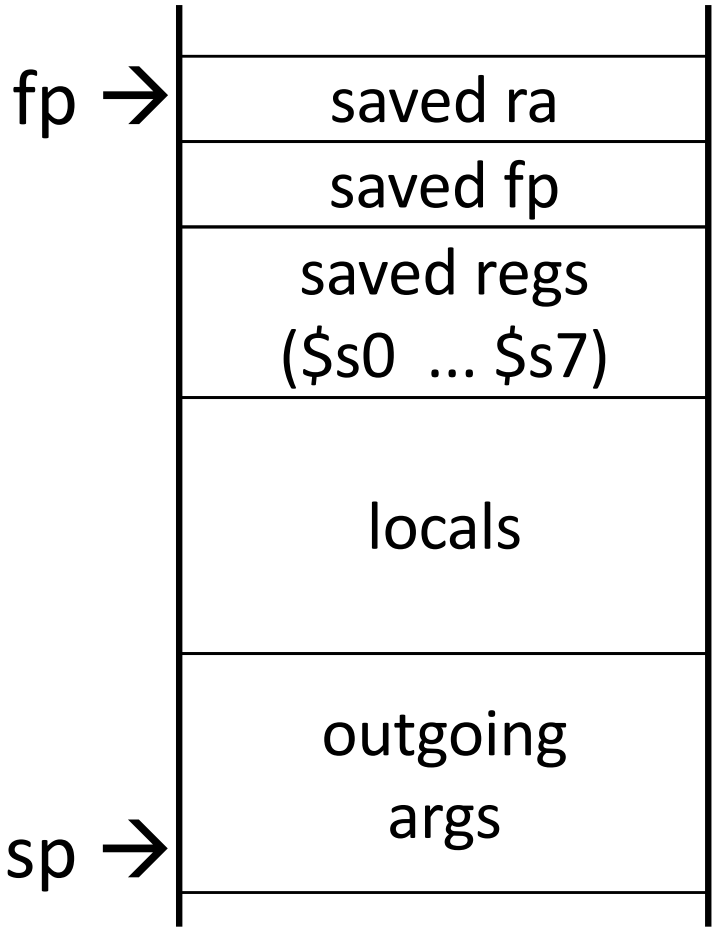


MIPS Register Conventions

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

Frame Layout on Stack



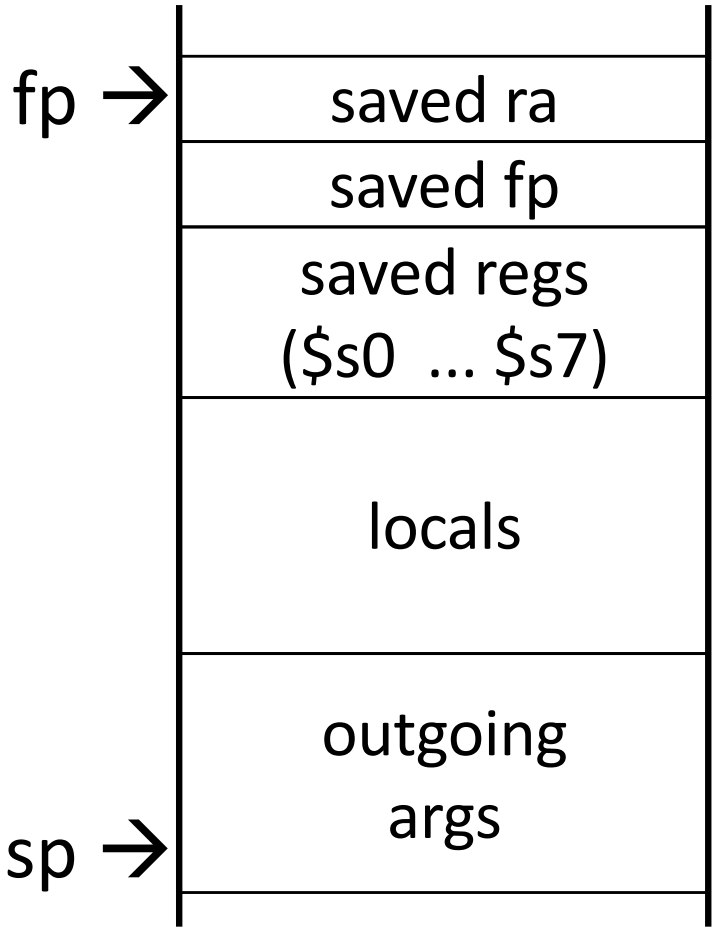
Assume a function uses two callee-save registers.

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

What should be stored in the stack frame?

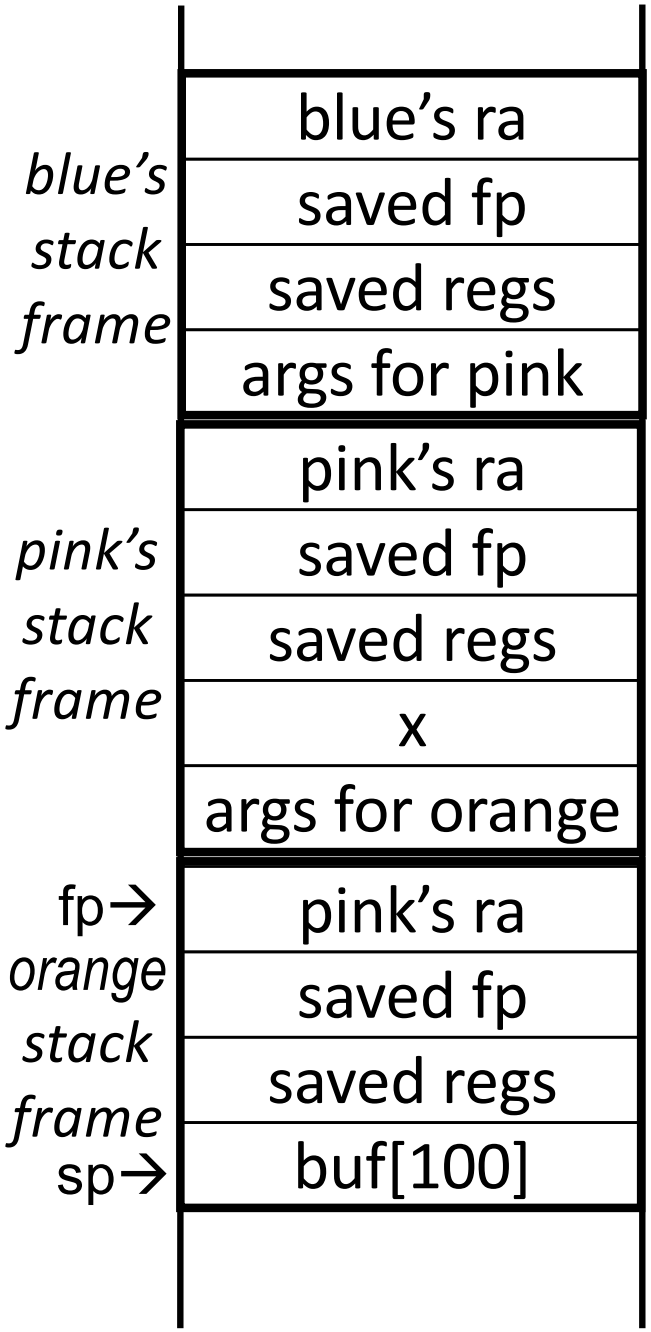
Where should everything be stored?

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
```

Buffer Overflow




```
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?

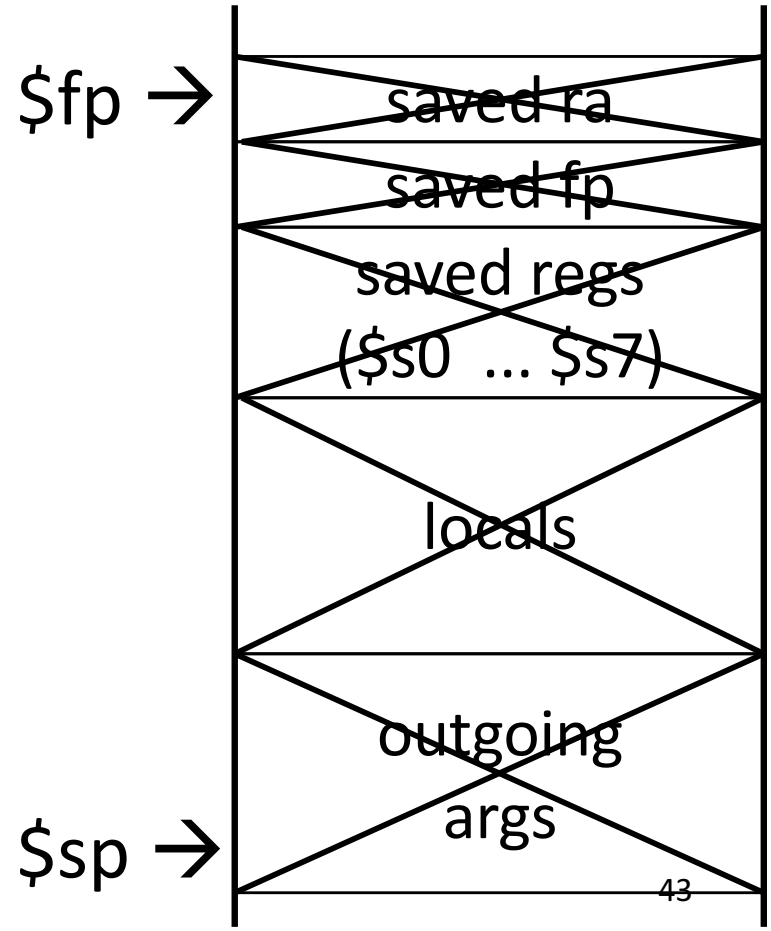
Optimizing Leaf Functions

Leaf function does not invoke any other functions

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

Optimizations?

- No saved regs (or locals)
- No outgoing args
- Don't push $ra
- No frame at all? *Possibly…*



Activity #1: Body

```
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 #1: Body

```
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;
}
```

We'll assume the yellow in order to force your hand on the rest.

$s0 for $a0 / a

$s1 for $a1 / b

$t0 for tmp

Can we get rid of the NOP?

We want to do the lw…

```
test:
  Prologue
  MOVE $s0, $a0
  MOVE $s1, $a1
  AND $t0, $a0, $a1
  OR $t1, $a0, $a1
  ADD $t0, $t0, $t1
  MOVE $a0, $t0
  LI $a1, 1
  LI $a2, 2
  LI $a3, 3
  LI $t1, 4
  SW $t1 16($sp)
  LI $t1, 5
  SW $t1, 20($sp)
  SW $t0, 24($sp)
  JAL sum
  NOP
  LW $t0, 24($sp)
```

Activity #1: Body

```
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;
}
```

```
MOVE $a0, $v0     # s
MOVE $a1, $t0     # tmp
MOVE $a2, $s1     # b
MOVE $a3, $s0     # a
SW $s1, 16($sp)   # b
SW $s0, 20($sp)   # a
JAL sum
NOP

ADD $v0, $v0, $s0     # u + a
ADD $v0, $v0, $s1     #  + b
```

Epilogue

Activity #2: Frame Size

```
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 many bytes do we need to allocate for the stack frame?

a) 24
b) 36
c) 44
d) 48
e) 52

Clicker Question

Minimum stack size for a standard function?

Activity #2: Frame Size

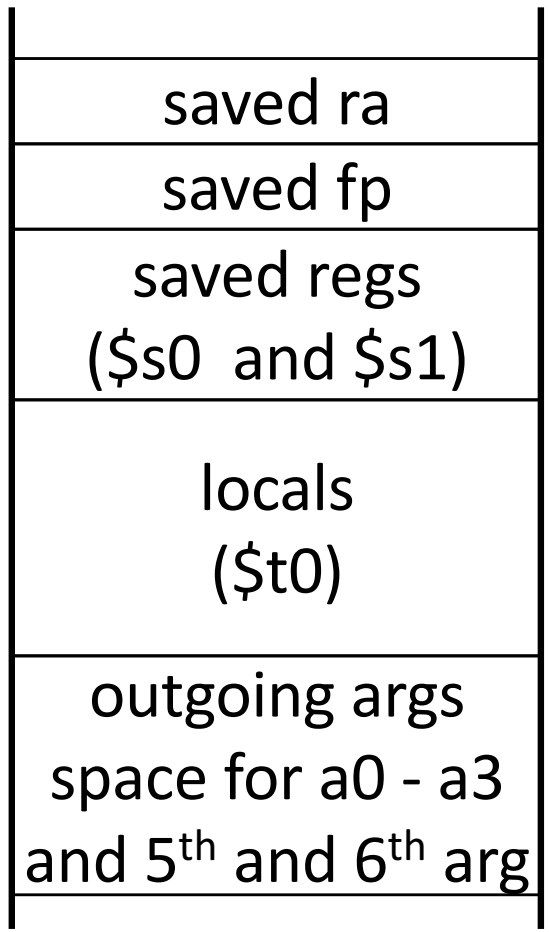
```
int test(int a, int b) {
    int tmp = (a&b)+(a|b);
    int s = sum(tmp,1,2,3,4,5);
    int u = sum(s,tmp,b,a,b,a);
    return u + a + b;
}
```

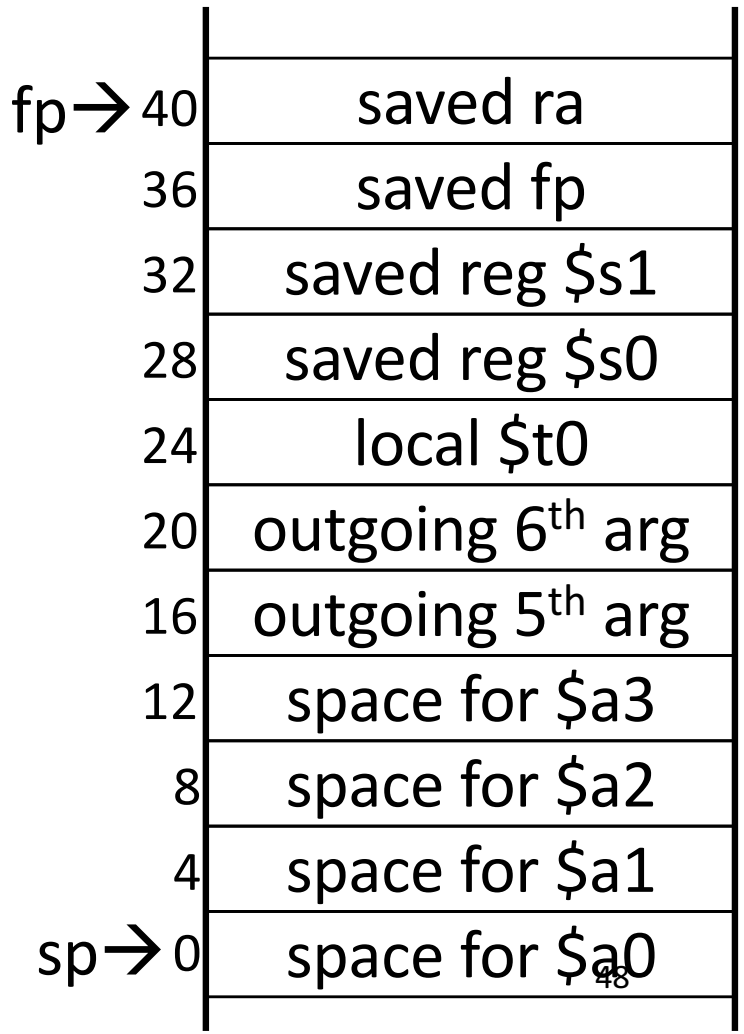
How many bytes do we need to allocate for the stack frame?

44

Minimum stack size for a standard function?

$ra + $fp + 4 args =
6 x 4 bytes = 24 bytes





Activity #3: Prologue & Epilogue

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

Activity #3: Prologue & Epilogue

fp→	40	saved ra
	36	saved fp
	32	saved reg $s1
	28	saved reg $s0
	24	local $t0
	20	outgoing 6th arg
	16	outgoing 5th arg
	12	space for $a3
	8	space for $a2
	4	space for $a1
sp→	0	space for $a0

```
ADDIU $sp, $sp, -44      # allocate frame
SW $ra, 40($sp)          # save $ra
SW $fp, 36($sp)          # save old $fp
SW $s1, 32($sp)          # callee save ...
SW $s0, 28($sp)          # callee save ...
ADDIU $fp, $sp, 40       # set new frame ptr
```

Body
(previous slide, Activity #1)

…
…

```
LW $s0, 28($sp)          # restore …
LW $s1, 32($sp)          # restore …
LW $fp, 36($sp)          # restore old $fp
LW $ra, 40($sp)          # restore $ra
ADDIU $sp, $sp, 44       # dealloc frame
JR $ra
NOP
```