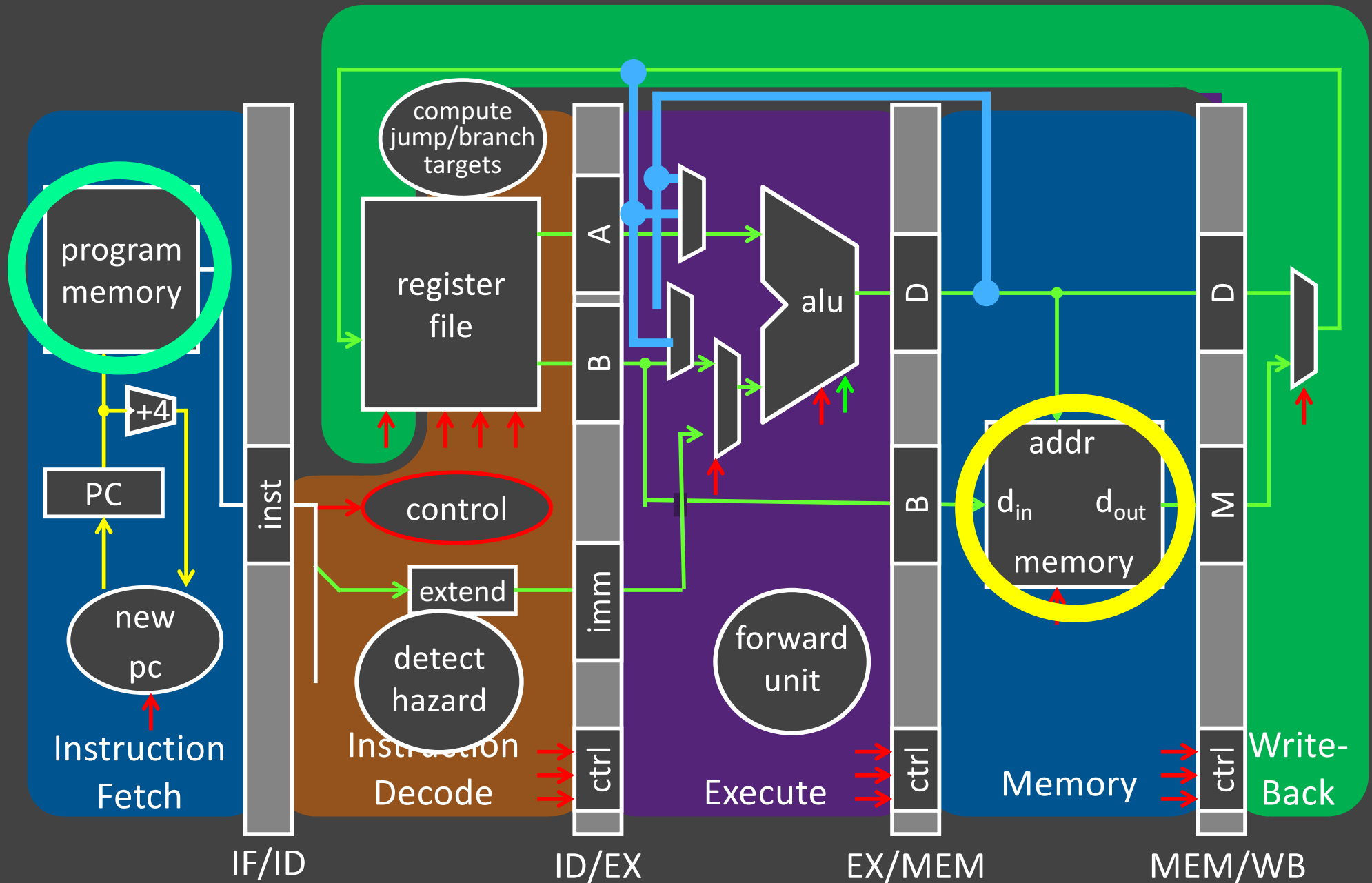# Calling Conventions

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

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

An executing program on chip

program memory

+4

PC

new pc

Instruction Fetch

inst

IF/ID

compute jump/branch targets

register file

control

extend

detect hazard

Instruction Decode

A

B

imm

ctrl

ID/EX

alu

forward unit

Execute

D

B

ctrl

EX/MEM

addr

d_{in} d_{out}

memory

Memory

D

M

ctrl

MEM/WB

Write-Back

2

An executing program in memory

0xfffffffc — top

system reserved

0x80000000
0x7ffffffc

stack

"Data Memory"

dynamic data (heap)

0x10000000 — static data

code (text) — "Program Memory"

0x00400000
0x00000000 — system reserved — bottom
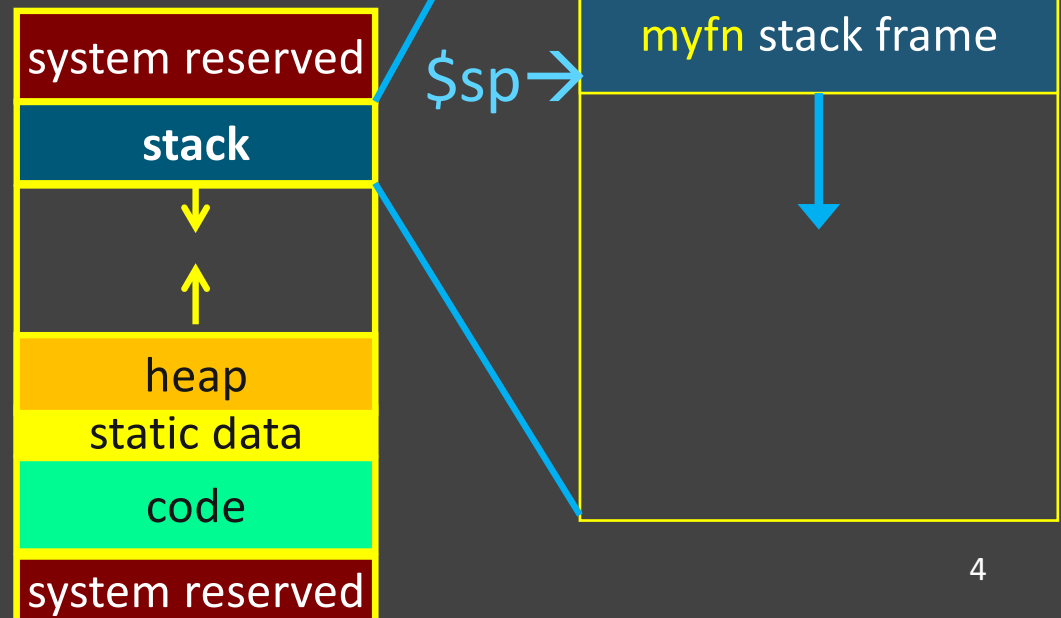
3

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();
}
```

system reserved
stack
heap
static data
code
system reserved

$sp→

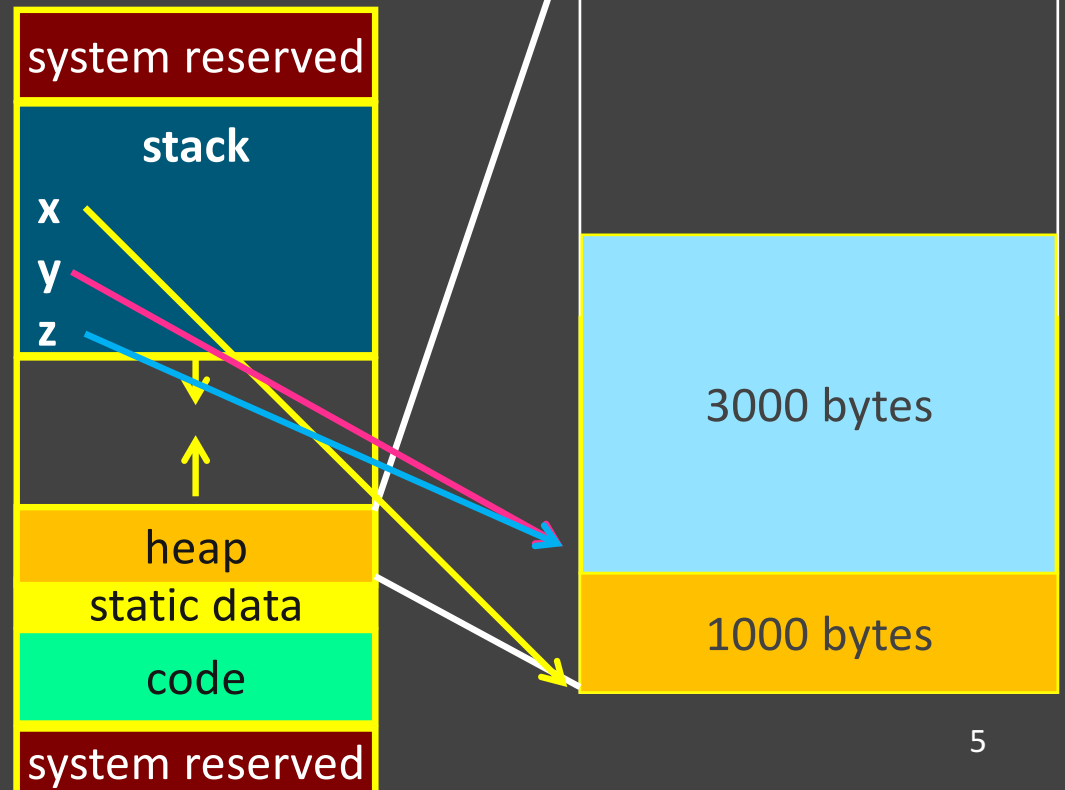| main stack frame |
|---|
| myfn stack frame |
| myfn stack frame |
| |

4

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);
}
```

system reserved

stack

x
y
z

heap
static data
code

system reserved

3000 bytes

1000 bytes

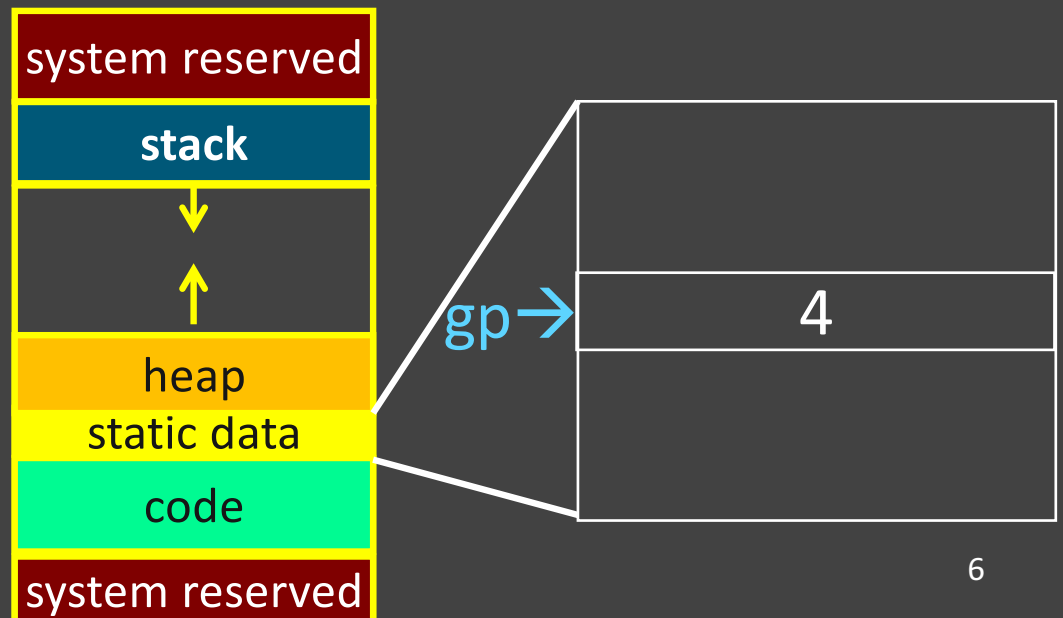# Data Segment

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(...) {
    ...
}
```

system reserved
stack
↓ ↑
heap
static data
code
system reserved

gp→

4

6

Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local			
Global			
Dynamic			

```c
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
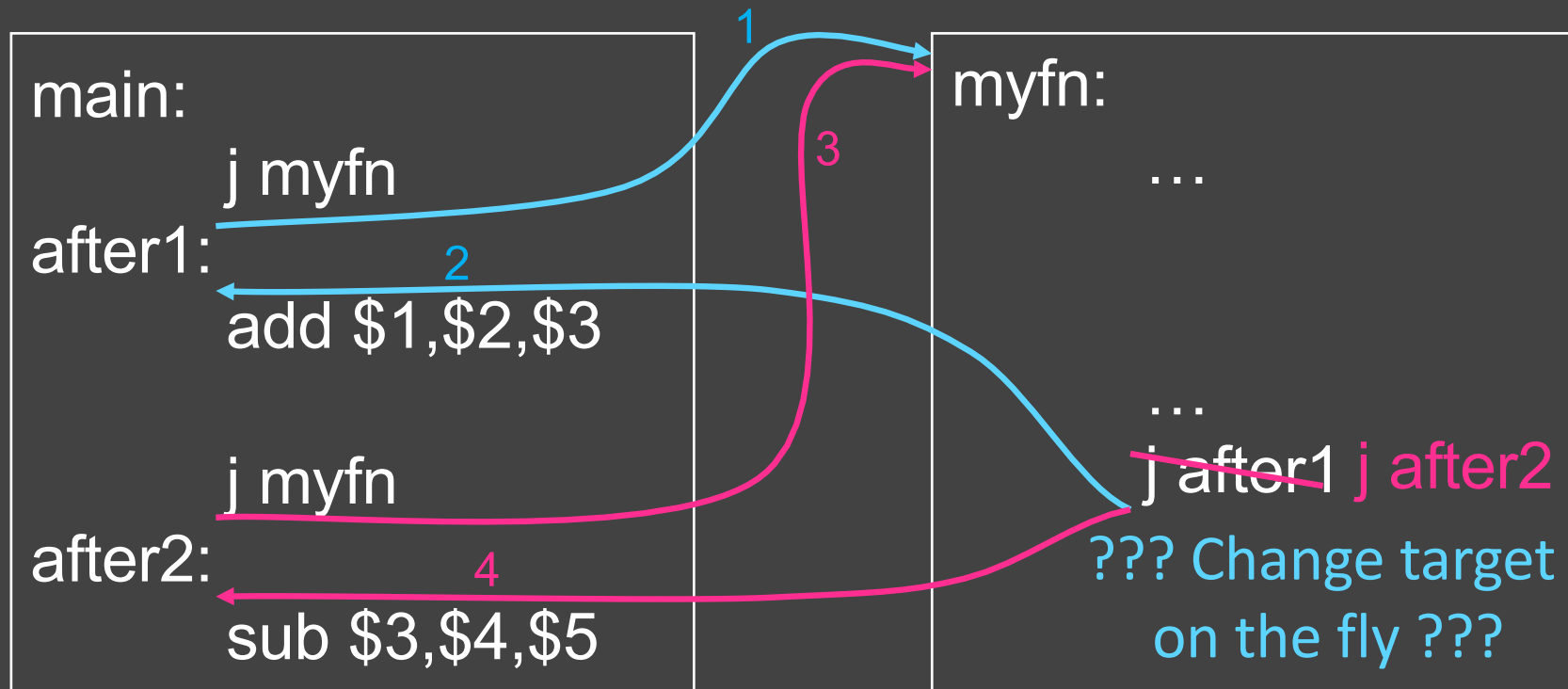- Get return value back to the caller

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

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Jumps are not enough

main:

 j myfn   *(1)*

after1:   *(2)*

 add $1,$2,$3

 j myfn

after2:   *(4)*

 sub $3,$4,$5

myfn:

 …

 …

 j after1   j after2

??? Change target on the fly ???

(3)

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
```

```
myfn:
    …


    …
    jr $31
```

1

2

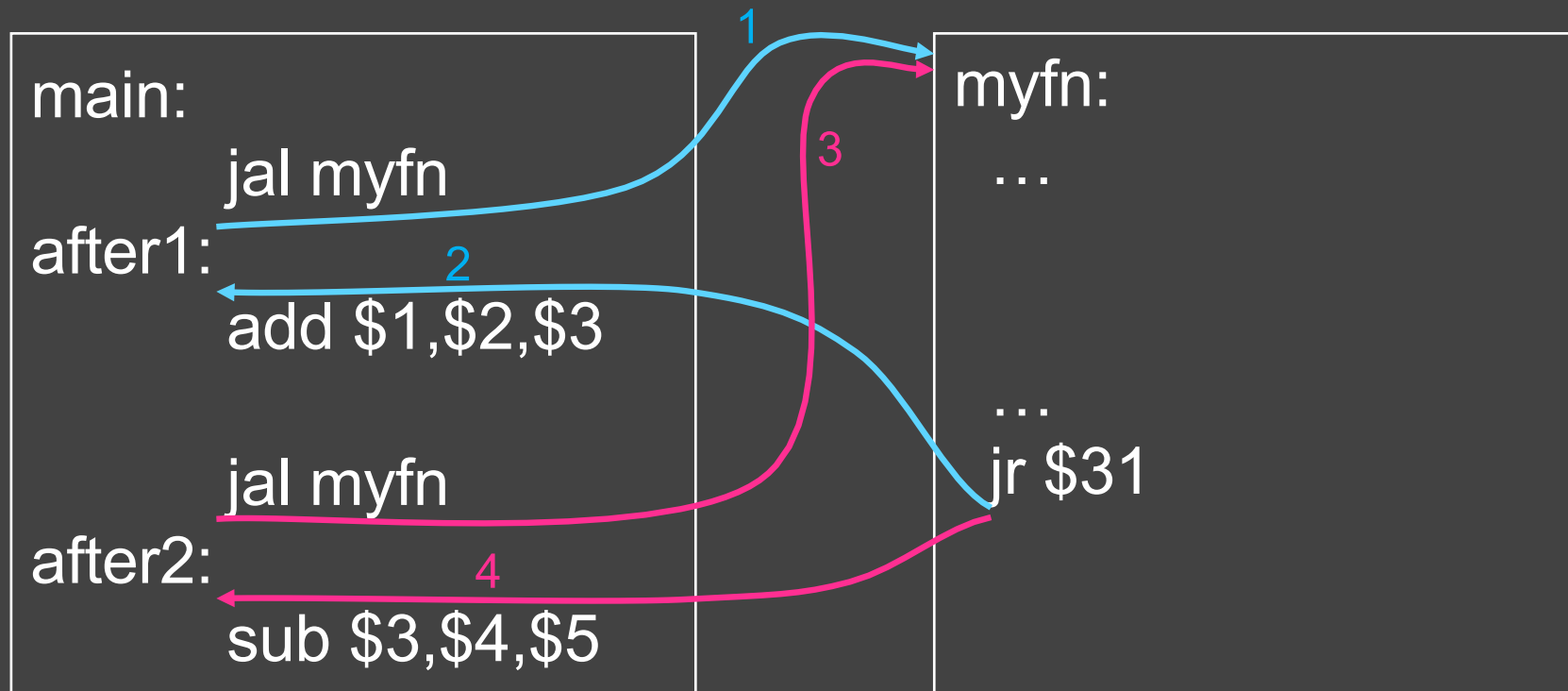JAL saves the PC in register $31

Subroutine returns by jumping to $31

Jump-and-Link / Jump Register

Second call

r31 *after2*

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


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

```
myfn:
    …



    …
    jr $31
```
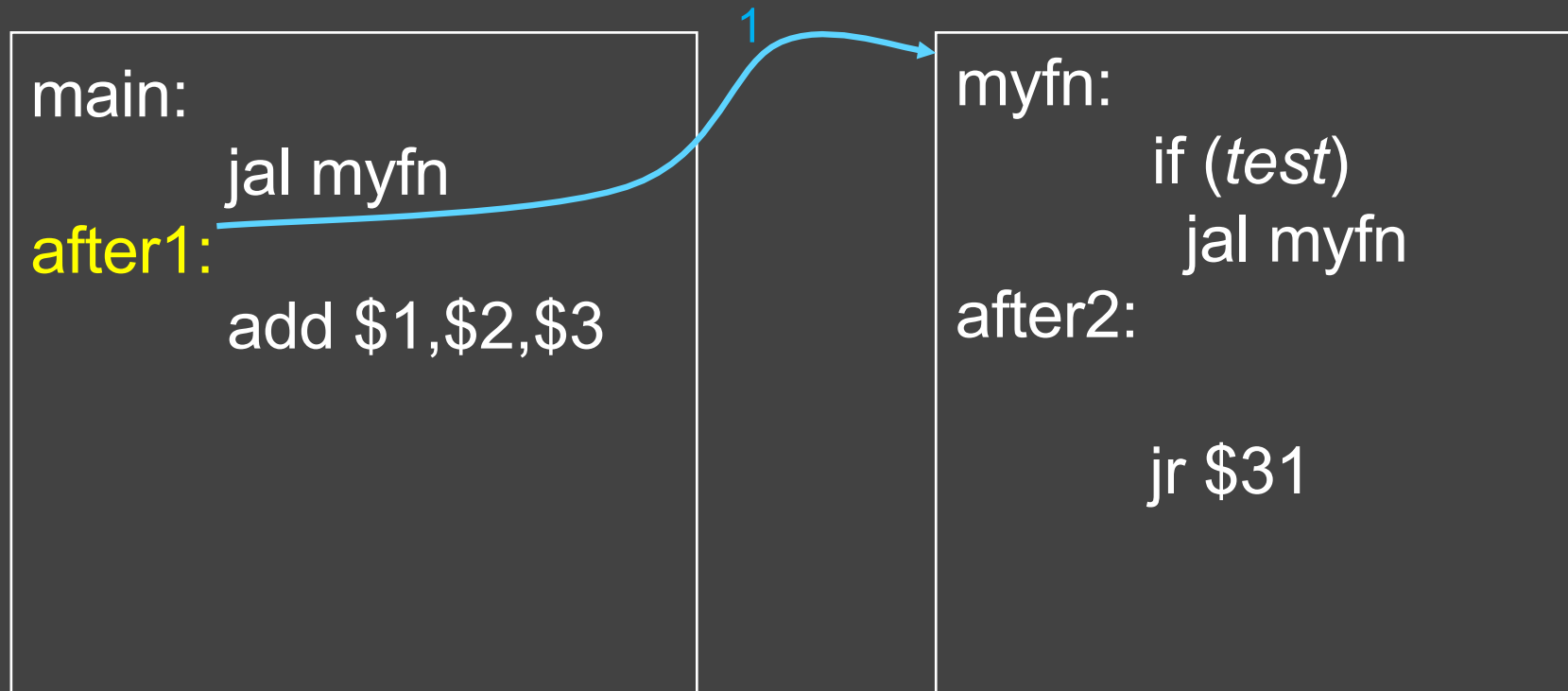
1 2 3 4

JAL saves the PC in register $31

Subroutine returns by jumping to $31

What happens for recursive invocations?

JAL / JR for Recursion?
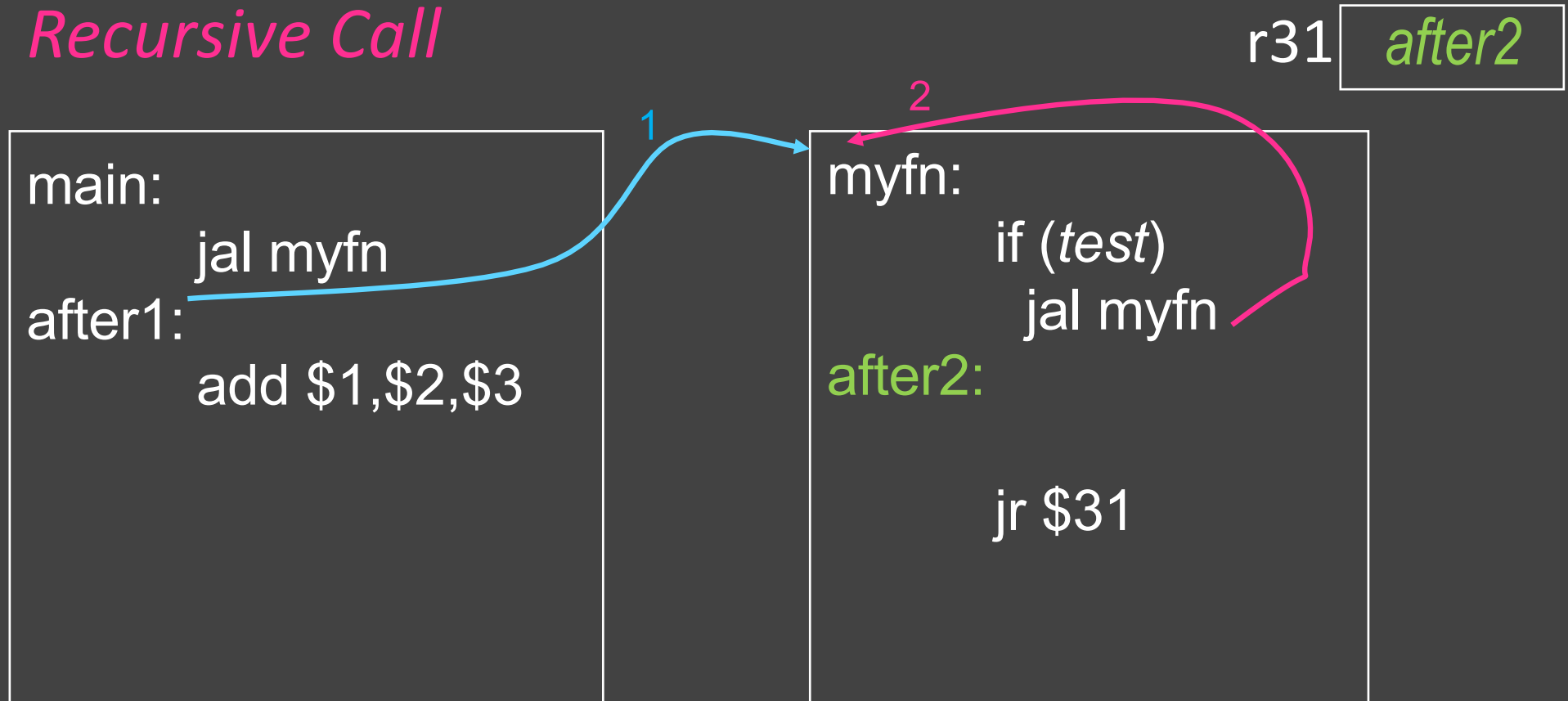
First call

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*

1

2

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

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

    jr $31

Problems with recursion:

• overwrites contents of $31

JAL / JR for Recursion?

Return from Recursive Call

r31 *after2*

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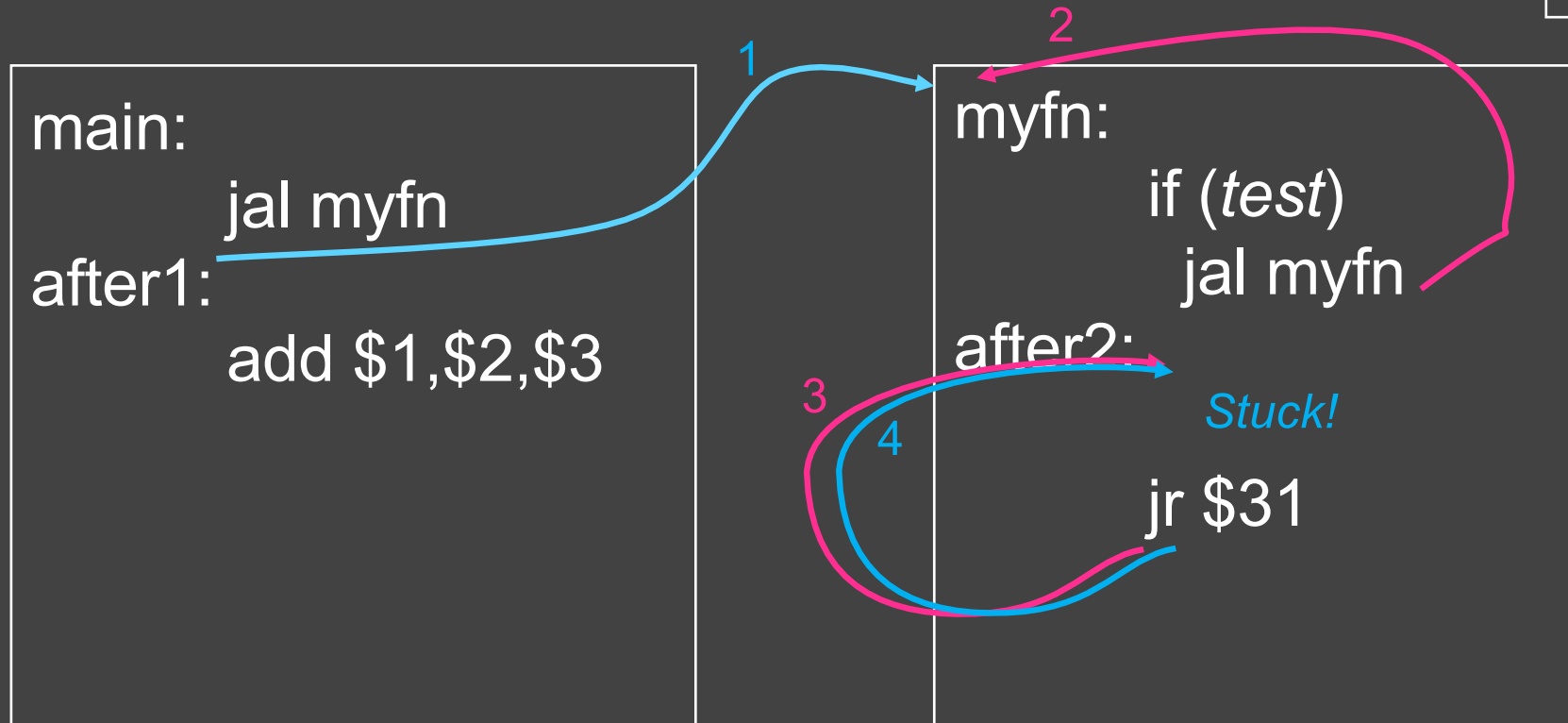   add $1,$2,$3

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

   jr $31

1

2

3
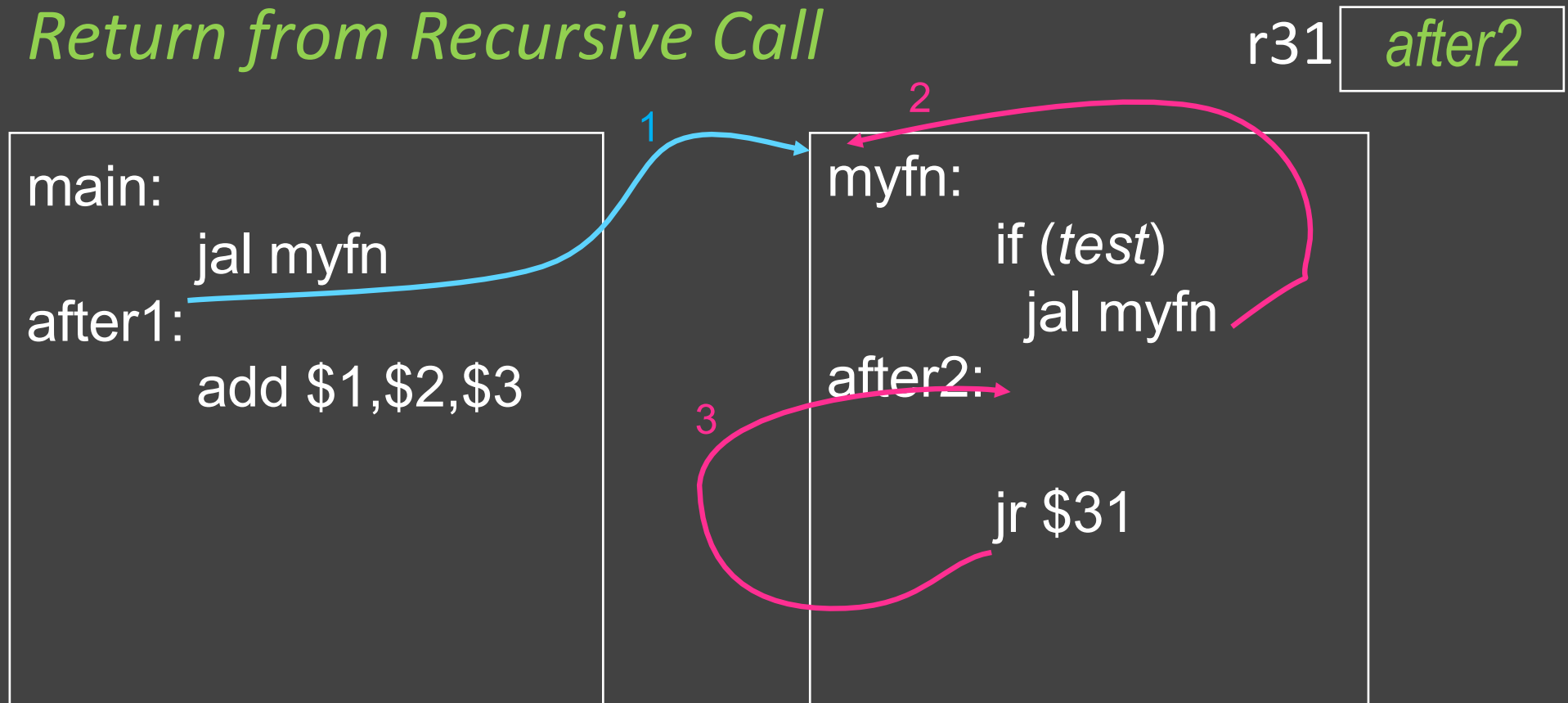
Problems with recursion:

- overwrites contents of $31

JAL / JR for Recursion?

Return from Original Call ???

r31 | *after2*

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

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

        jr $31
```

1
2
3
4

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

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
```

```
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!
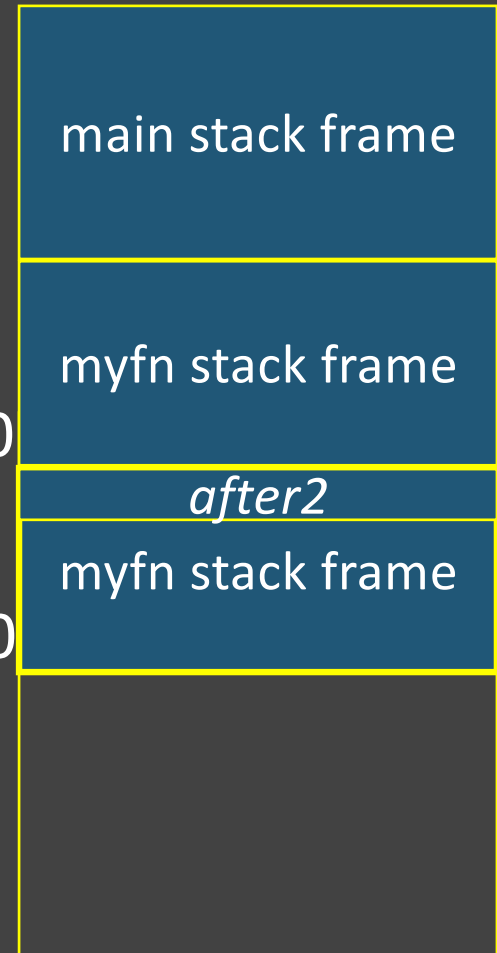
Return Address lives in Stack Frame

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

main stack frame
myfn stack frame
after2
myfn stack frame

x2000

x1FD0

r29 x1FD0

r31 *XXXX*

For now: Assume each frame = x20 bytes
(just to make this example concrete) 22

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.
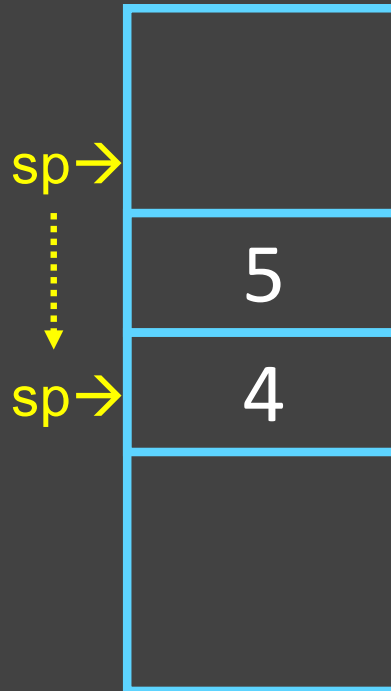
25

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
```

sp→

sp→

| 5 |
| 4 |

First four arguments:

passed in $4-$7

- aka $a0-$a3

Subsequent arguments:
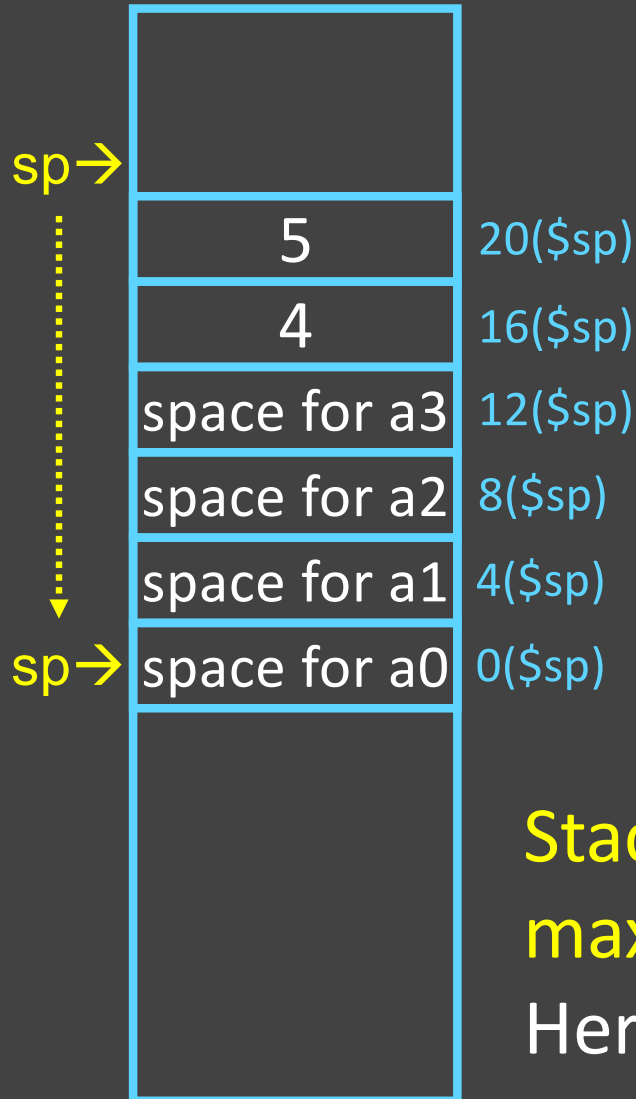
"spill" onto the stack

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

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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
```

sp→

5	20($sp)
4	16($sp)
space for a3	12($sp)
space for a2	8($sp)
space for a1	4($sp)
space for a0	0($sp)

sp→

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

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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
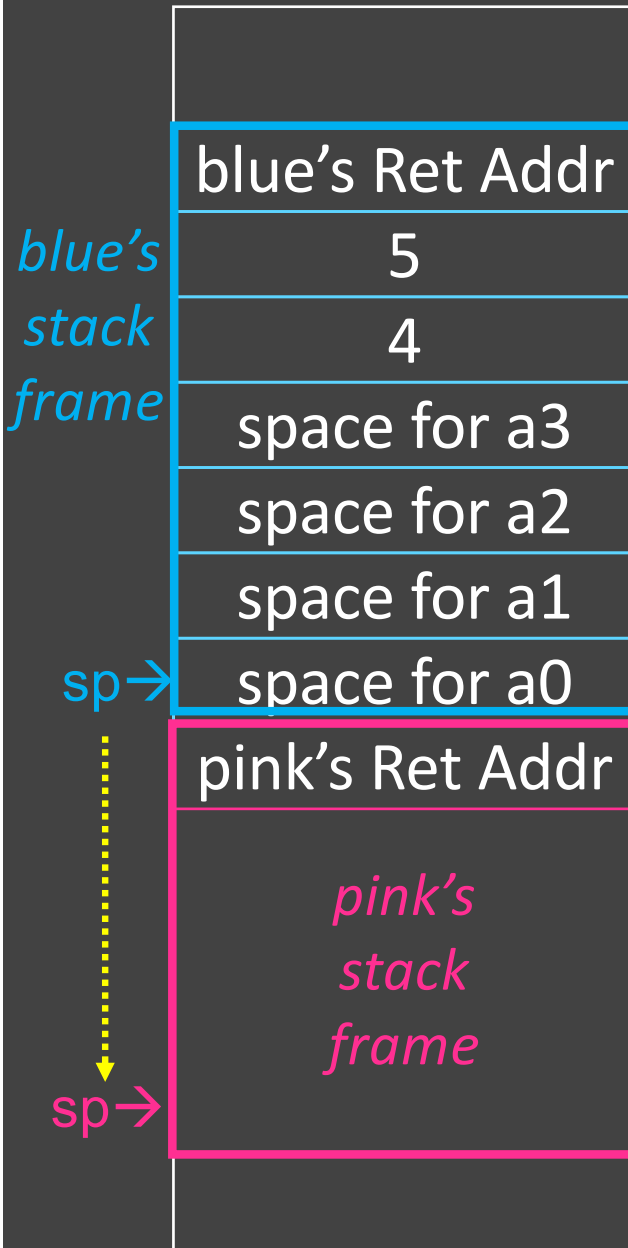
iClicker Question

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

blue's Ret Addr
5
4
space for a3
space for a2
space for a1
space for a0

blue's stack frame

sp→

pink's Ret Addr
pink's stack frame

← fp

sp→

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) {
    ...
}
```

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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

Functions

- Can freely use these registers
- Must assume that their contents

are destroyed by other functions

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);
}
```

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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.

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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

$fp →

saved ra
saved fp
saved regs ($s0 ... $s7)
locals
outgoing args

$sp →

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MIPS Register Conventions

r0	$zero	zero	r16	$s0	
r1	$at	assembler temp	r17	$s1	
r2	$v0	function return values	r18	$s2	**saved (callee save)**
r3	$v1		r19	$s3	
r4	$a0	function arguments	r20	$s4	
r5	$a1		r21	$s5	
r6	$a2		r22	$s6	
r7	$a3		r23	$s7	
r8	$t0	**temps (caller save)**	r24	$t8	**more temps (caller save)**
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

Frame Layout on Stack

fp →
saved ra
saved fp
saved regs ($s0 ... $s7)
locals
outgoing args
sp →
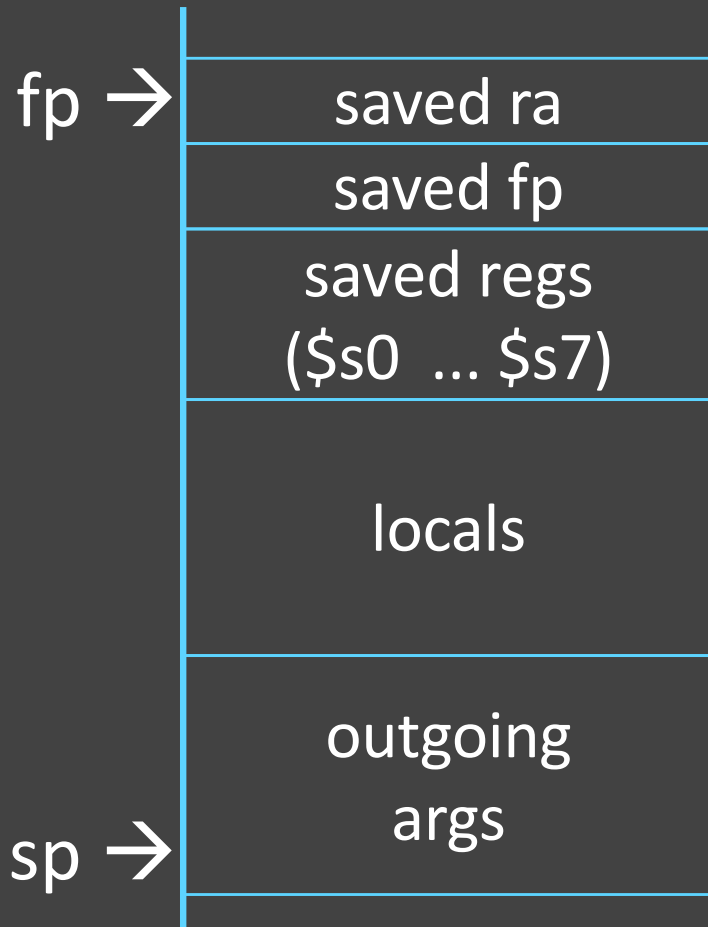
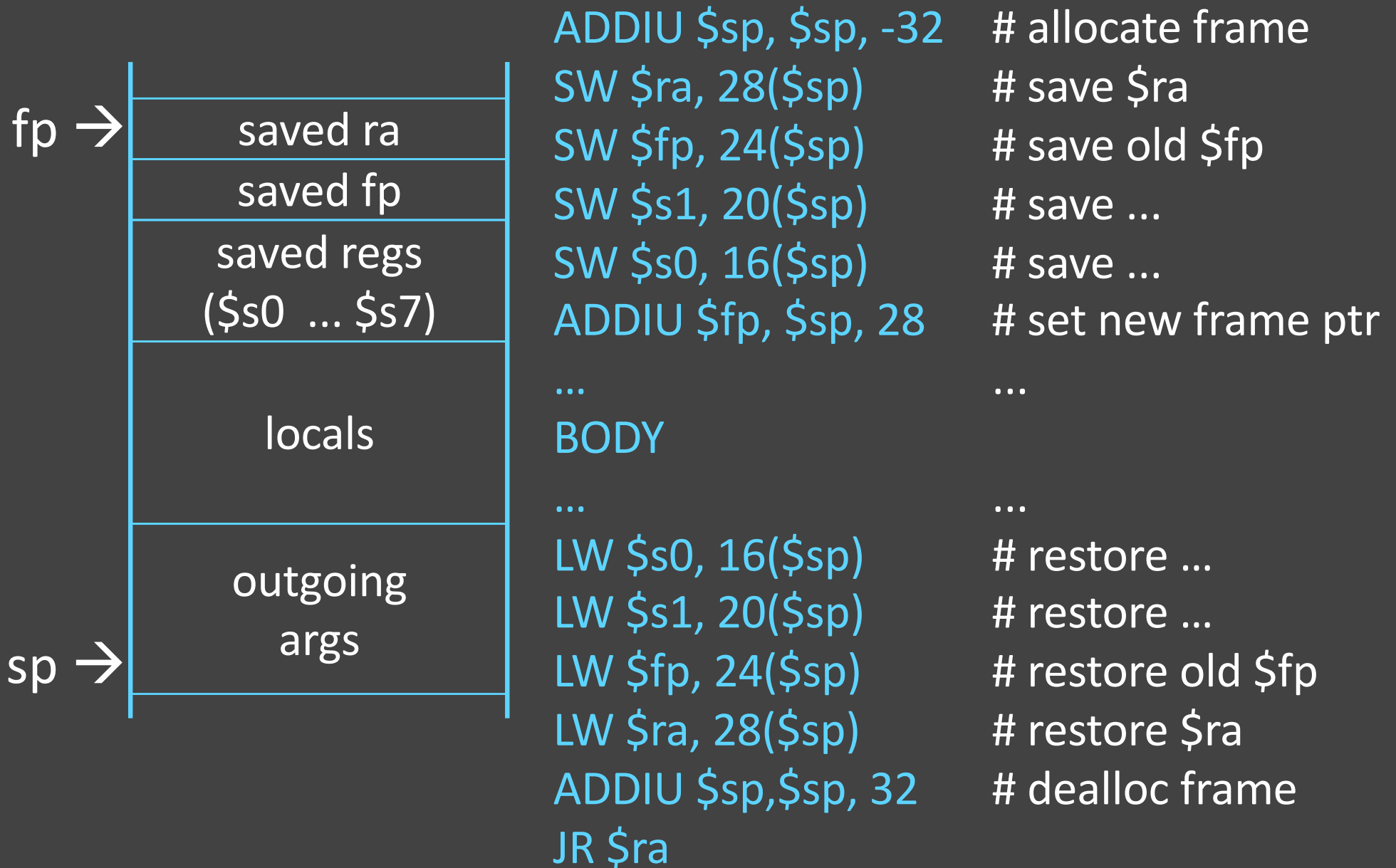Assume a function uses two callee-save registers.

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

```
fp →  ┌─────────────────┐
      │    saved ra     │
      ├─────────────────┤
      │    saved fp     │
      ├─────────────────┤
      │  saved regs     │
      │  ($s0 ... $s7)  │
      ├─────────────────┤
      │                 │
      │     locals      │
      │                 │
      ├─────────────────┤
      │                 │
      │    outgoing     │
      │     args        │
sp →  └─────────────────┘
```

```
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's ra
saved fp
saved regs
args for pink

blue's stack frame

pink's ra
saved fp
saved regs
x
args for orange

pink's stack frame

pink's ra
saved fp
saved regs
buf[100]

fp→
orange stack frame
sp→

```
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?

42

Optimizing Leaf Functions

Leaf function does not invoke any other functions

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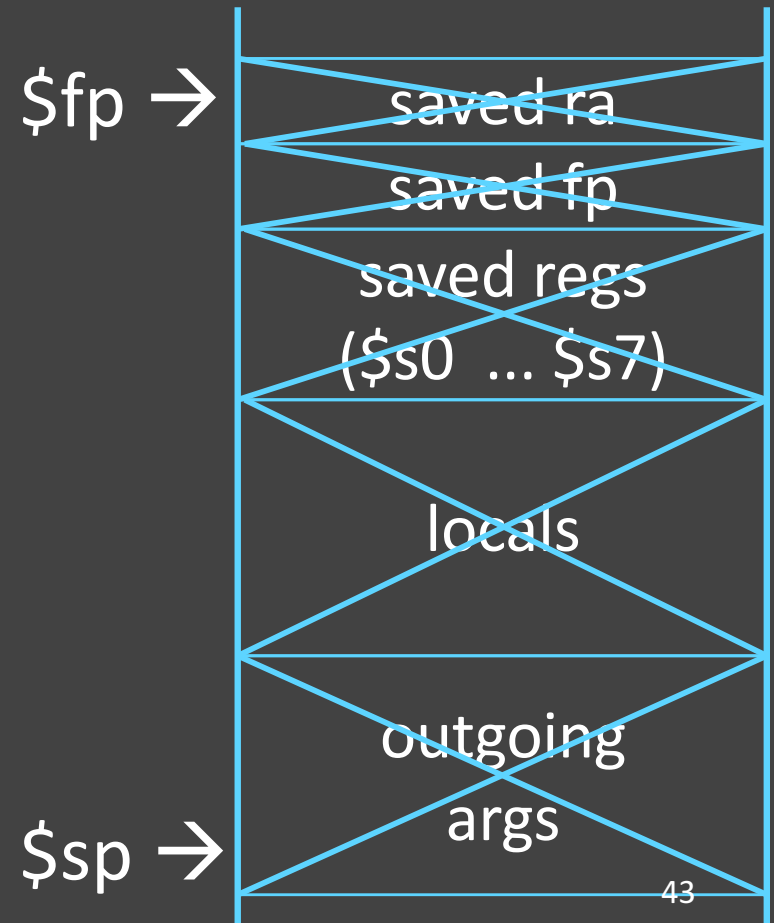
Optimizations?

No saved regs (or locals)

No outgoing args

Don't push $ra

No frame at all? *Possibly…*

$fp → | saved ra |
| saved fp |
| saved regs ($s0 … $s7) |
| locals |
| outgoing args |
$sp →

43

```
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;
}
```

Correct Order:
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)

45

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

Minimum stack size for
a standard function?

Clicker Question

saved ra
saved fp
saved regs ($s0 and $s1)
locals ($t0)
outgoing args space for a0 - a3 and 5th and 6th arg

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

saved ra
saved fp
saved regs ($s0 and $s1)
locals ($t0)
outgoing args space for a0 - a3 and 5th and 6th arg

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

48

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

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

```
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
```