Calling Conventions

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CS 3410, Spring 2011
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See P&H 2.8 and 2.12

Announcements

PA2 due *next* Friday

- PA2 builds from PA1
- Work with same partner
- Due right before spring break

Use your resources

- FAQ, class notes, book, Sections, office hours, newsgroup, CSUGLab

Announcements

Prelims1: *this* Thursday, March 10th in class

- We will start at 1:25pm sharp, so come early
- Closed Book.
  - Cannot use electronic device or outside material
- Practice prelims are online in CMS
- Material covered
  - Appendix C (logic, gates, FSMs, memory, ALUs)
  - Chapter 4 (pipelined [and non-pipeline] MIPS processor with hazards)
  - Chapters 2 and Appendix B (RISC/CISC, MIPS, and calling conventions)
  - Chapter 1 (Performance)
  - HW1, HW2, PA1, PA2

Goals for Today

Last time

- Anatomy of an executing program
- Register assignment conventions,
- Function arguments, return values
- Stack frame, Call stack, Stack growth
- Variable arguments

Today

- More on stack frames
- globals vs local accessible data
- callee vs callrer saved registers

FAQ

Example program

calc.c

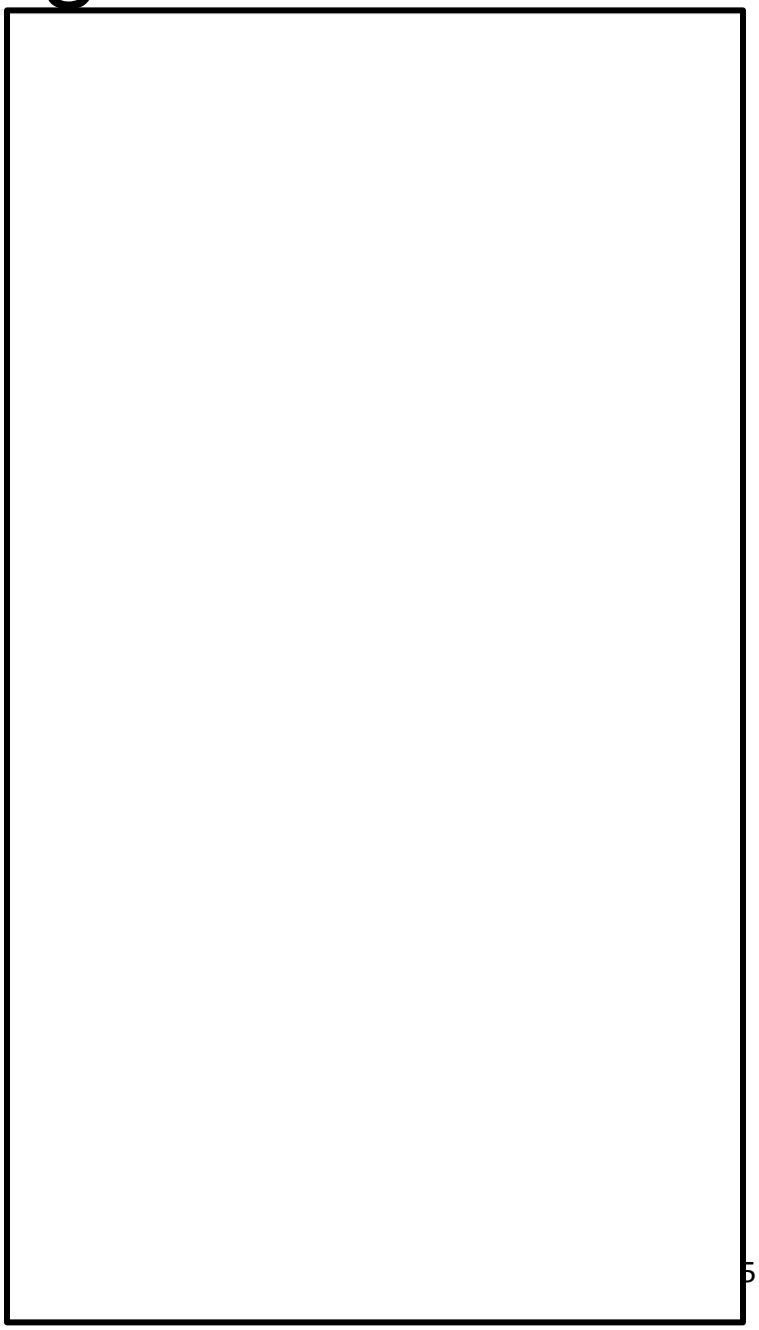
```
vector v = malloc(8);
v->x = prompt(“enter x”);
v->y = prompt(“enter y”);
int c = pi + tnorm(v);
print(“result”, c);
```

math.c

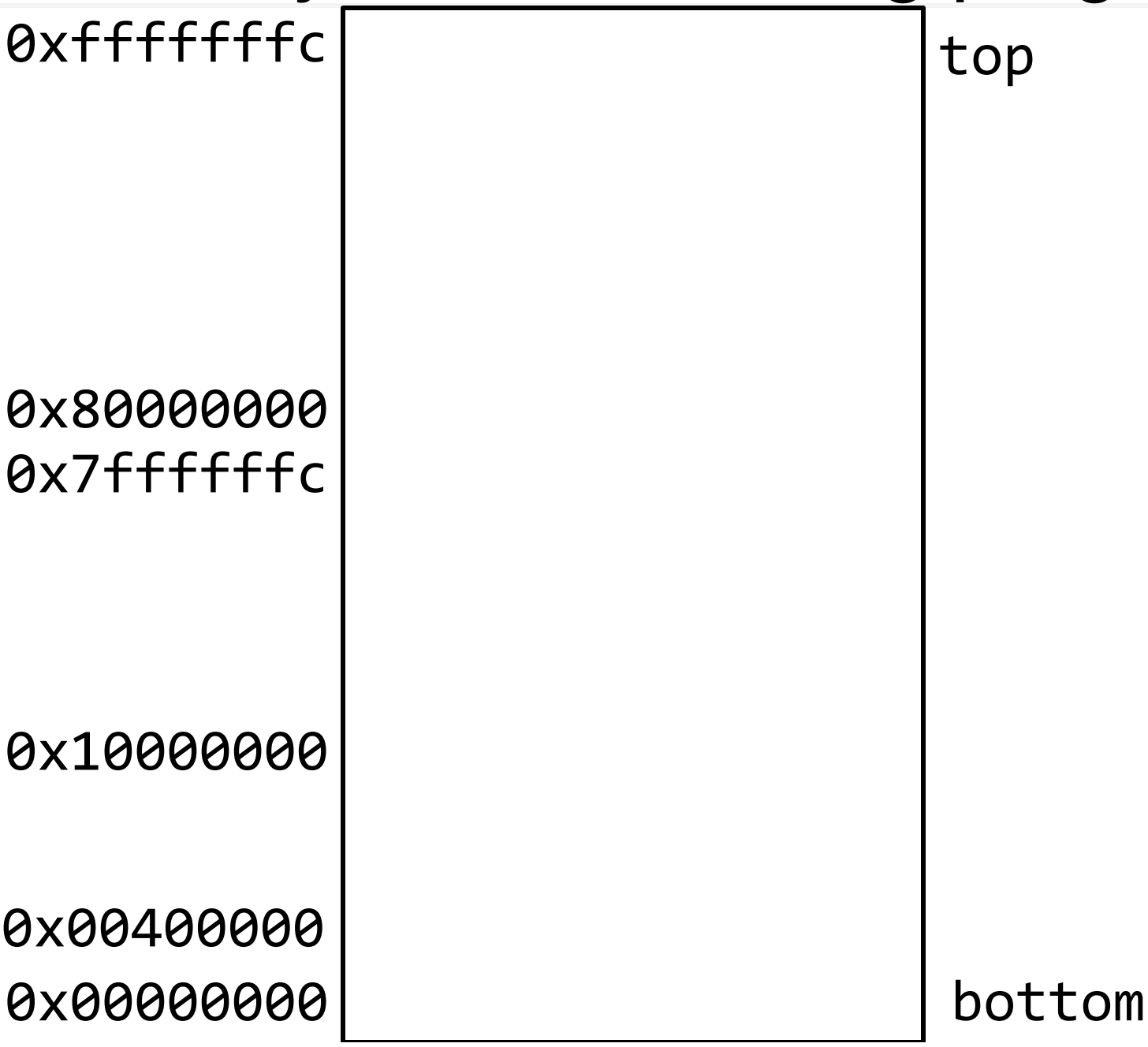
```
int tnorm(vector v) {
 return abs(v->x)+abs(v->y);
}
```

lib3410.o

```
  global variable: pi
  entry point: prompt
  entry point: print
  entry point: malloc
```



Anatomy of an executing program



math.s

math.c

```
int abs(x) {
  return x < 0 ? -x : x;
}
int tnorm(vector v) {
 return abs(v->x)+abs(v->y);
}
```

abs:

arg in r3, return address in r31

leaves result in r3

tnorm:

arg in r4, return address in r31

leaves result in r4

calc.s

calc.c

```
vector v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result", c);
```

```
.data
str1: .asciiz "enter x"
str2: .asciiz "enter y"
str3: .asciiz "result"
.text
   .extern prompt
   .extern print
   .extern malloc
   .extern tnorm
   .global dostuff
```

```
dostuff:
   # no args, no return value, return addr in r31
   MOVE r30, r31
   LI r3, 8        # call malloc: arg in r3, ret in r3
   JAL malloc
   MOVE r6, r3 # r6 now holds v
   LA r3, str1     # call prompt: arg in r3, ret in r3
   JAL prompt
   SW r3, 0(r6)
   LA r3, str2     # call prompt: arg in r3, ret in r3
   JAL prompt
   SW r3, 4(r6)
   MOVE r4, r6 # call tnorm: arg in r4, ret in r4
   JAL tnorm
   LA r5, pi
   LW r5, 0(r5)
   ADD r5, r4, r5
   LA r3, str3     # call print: args in r3 and r4
   MOVE r4, r5
   JAL print
   JR r30
```

Calling Conventions

Calling Conventions

- where to put function arguments
- where to put return value
- who saves and restores registers, and how
- stack discipline

Why?

- Enable code re-use (e.g. functions, libraries)
- Reduce chance for mistakes

Warning: There is no one true MIPS calling convention.
lecture != book != gcc != spim != web

Example

```
void main() {
  int x = ask(“x?”);
  int y = ask(“y?”);
  test(x, y);
}

void test(int x, int y) {
  int d = sqrt(x*x + y*y);
  if (d == 1)
     print(“unit”);
  return d;
}
```

MIPS Register Conventions

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		
r14			r30		
r15			r31	$ra	return address

Example: Invoke

```
void main() {
  int x = ask(“x?”);
  int y = ask(“y?”);
  test(x, y);
}
```

```
main:

LA $a0, strX
JAL ask # result in $v0

LA $a0, strY
JAL ask # result in $v0
```

Call Stack

Call stack

- contains *activation records* (aka *stack frames*)

One for each function invocation:

- saved return address
- local variables
- … and more

Simplification:

- frame size & layout decided at compile time for each function

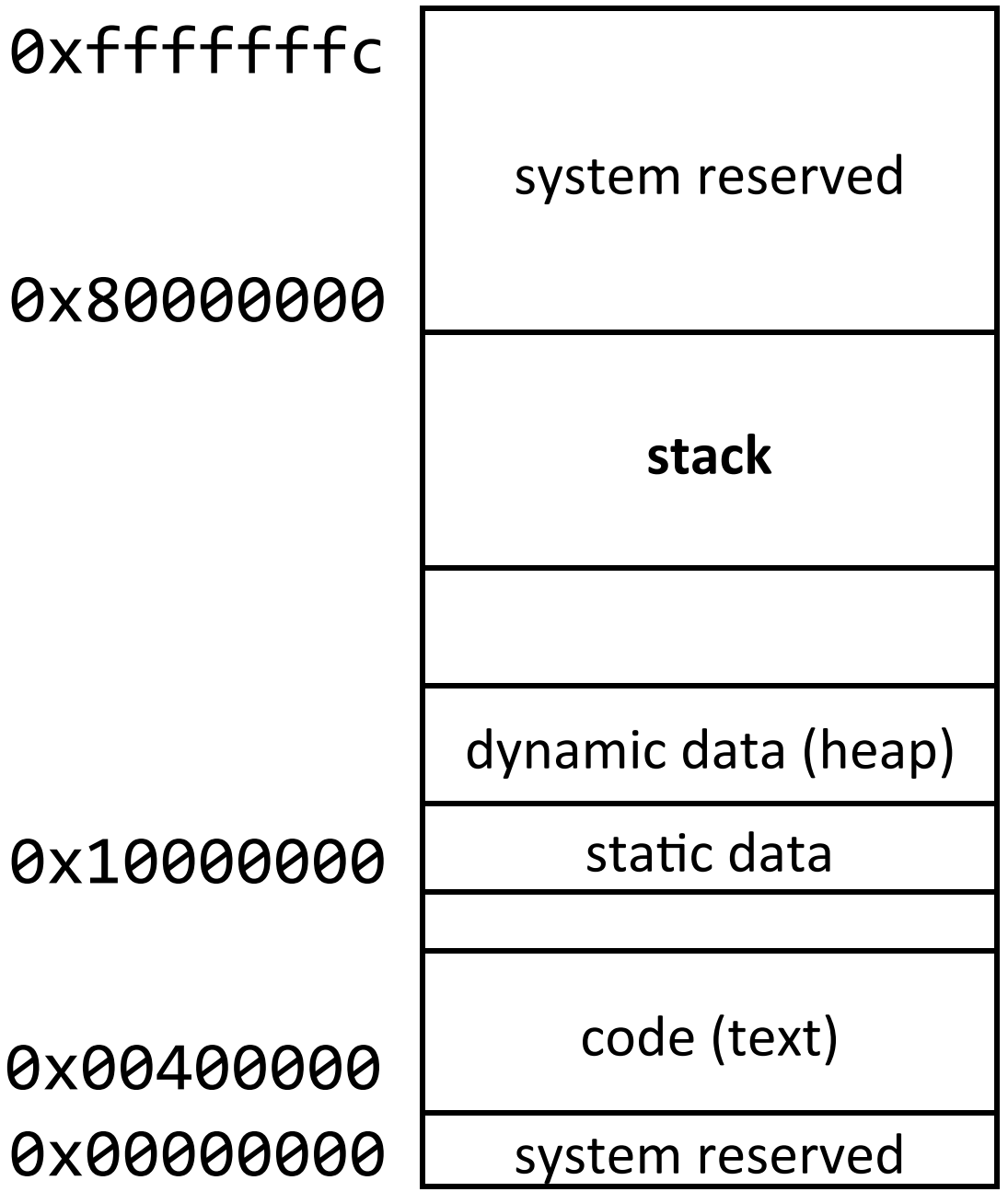
Stack Growth

Convention:

- r29 is $sp (bottom elt of call stack)

Stack grows **down**

Heap grows **up**



Example: Stack frame push / pop

```
void main() {
  int x = ask(“x?”);
  int y = ask(“y?”);
  test(x, y);
}
```

```
main:
  # allocate frame
  ADDUI $sp, $sp, -12 # $ra, x, y
  # save return address in frame
  SW  $ra, 8($sp)
```

```
  # restore return address
  LW $ra, 8($sp)
  # deallocate frame
  ADDUI $sp, $sp, 12
```

Recap

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)
  - contains local vars (possibly clobbered by sub-functions)

Q: What about real argument lists?

Arguments & Return Values

```
int min(int a, int b);
int paint(char c, short d, struct point p);
int treesort(struct Tree *root, int[] A);
struct Tree *createTree();
int max(int a, int b, int c, int d, int e);
```

Conventions:

- align everything to multiples of 4 bytes
- first 4 words in $a0...$a3, “spill” rest to stack

Argument Spilling

invoke sum(0, 1, 2, 3, 4, 5);

```
main:
...
LI $a0, 0
LI $a1, 1
LI $a2, 2
LI $a3, 3
ADDI $sp, $sp, -8
LI r8, 4
SW r8,   0($sp)
LI r8, 5
SW r8,   4($sp)
JAL sum
ADDI $sp, $sp, 8
```

```
sum:
...
ADD $v0, $a0, $a1
ADD $v0, $v0, $a2
ADD $v0, $v0, $a3
LW $v1, 0($sp)
ADD $v0, $v0, $v1
LW $v1, 4($sp)
ADD $v0, $v0, $v1
...
JR $ra
```

Argument Spilling

printf(fmt, …)

```
main:
…
LI $a0, str0
LI $a1, 1
LI $a2, 2
LI $a3, 3
# 2 slots on stack
LI r8, 4
SW r8,   0($sp)
LI r8, 5
SW r8,   4($sp)
JAL sum
```

```
printf:
…
if (argno == 0)
      use $a0
else if (argno == 1)
      use $a1
else if (argno == 2)
      use $a2
else if (argno == 3)
      use $a3
else
      use $sp+4*argno
…
```

VarArgs

Variable Length Arguments

Initially confusing but ultimately simpler approach:

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

Simplifies varargs functions

- Store a0-a3 in the slots allocated in parent's frame
- Refer to all arguments through the stack

Recap

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 local vars (possibly clobbered by sub-functions)
  - contains extra arguments to sub-functions
  - contains **space** for first 4 arguments to sub-functions

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
	0x0040010a
	0x00000000
	0x00000000
	0x00000000
	0x00000000
	0x004010c4
	0x00000000
	0x00000000
	0x00000015
0x7FFFFFB0	0x10000004
	0x00401090

Frame Pointer

Frame pointer marks boundaries

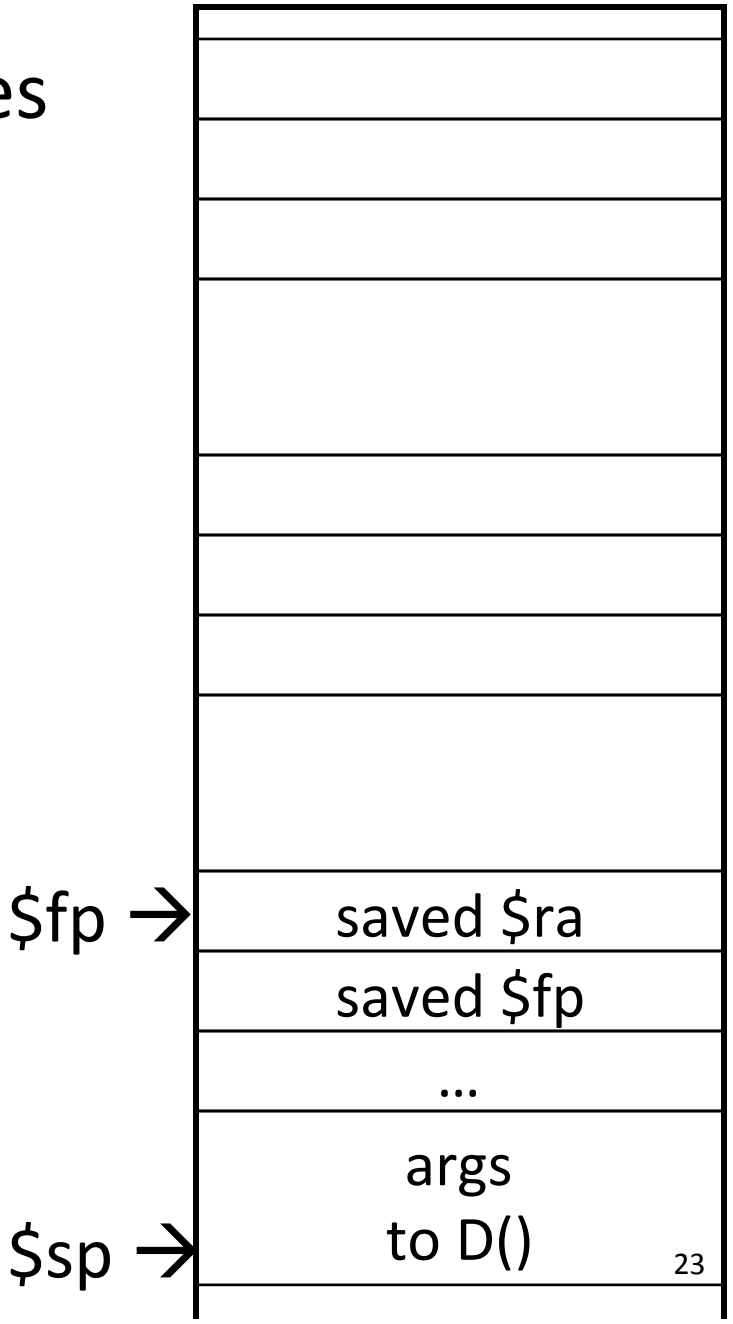
- Optional (for debugging, mostly)

Convention:

- r30 is $fp
  (top elt of current frame)
- Callee: always push old $fp
  on stack

E.g.:

A() called B()
B() called C()
C() about to call D()



MIPS Register Conventions

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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	**stack pointer**
r14			r30	$fp	**frame pointer**
r15			r31	$ra	return address

Global Pointer

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)

MIPS Register Conventions

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	$gp	**global pointer**
r13			r29	$sp	stack pointer
r14			r30	$fp	frame pointer
r15			r31	$ra	return address

Callee and Caller Saved Registers

Q: Remainder of registers?

A: Any function can use for any purpose

- places to put extra local variables, local arrays, …
- places to put callee-save

Callee-save: Always…

- save before modifying
- restore before returning

Caller-save: If necessary…

- save before calling anything
- restore after it returns

```
int main() {
   int x = prompt("x?");
   int y = prompt("y?");
   int v = tnorm(x, y)
   printf("result is %d", v);
}
```

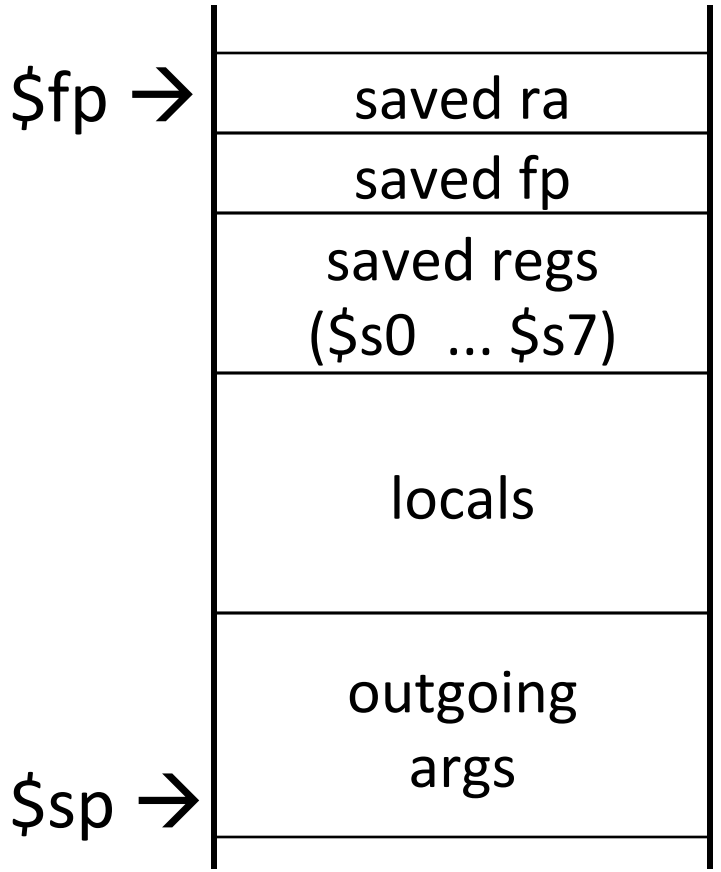
MIPS Register Conventions

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

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
- globals accessed via $gp
- callee save regs are preserved
- caller save regs are not



Example

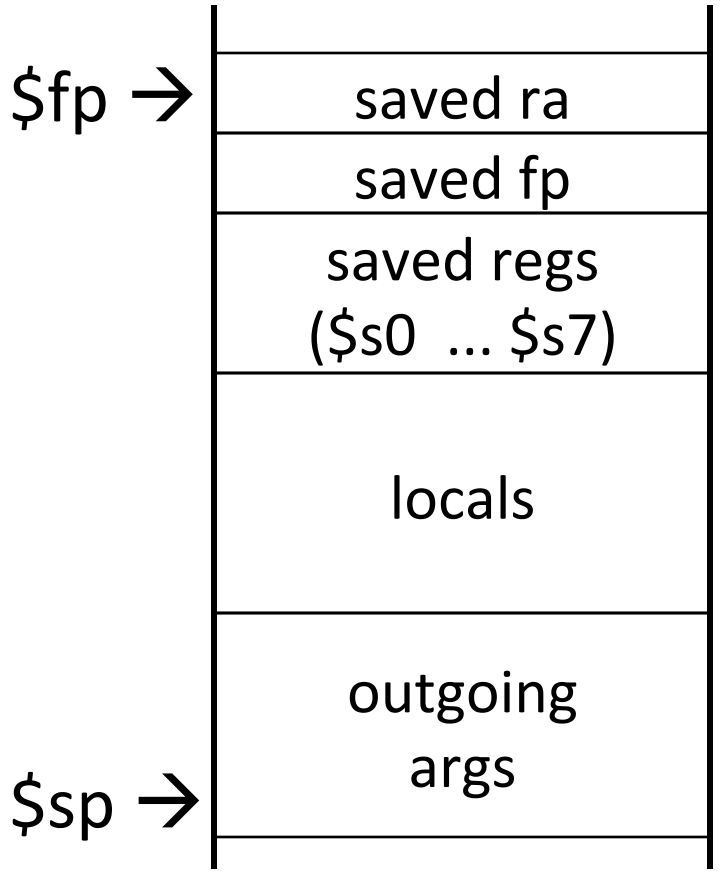
```
int test(int a, int b) {
   int tmp = (a&b)+(a|b);
   int s = sum(tmp,1,2,3,4,5);
   int u = sum(s,tmp,b,a,b,a);
   return u + a + b;
}
```

Prolog, Epilog

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

Recap

Minimum stack size for a standard function?



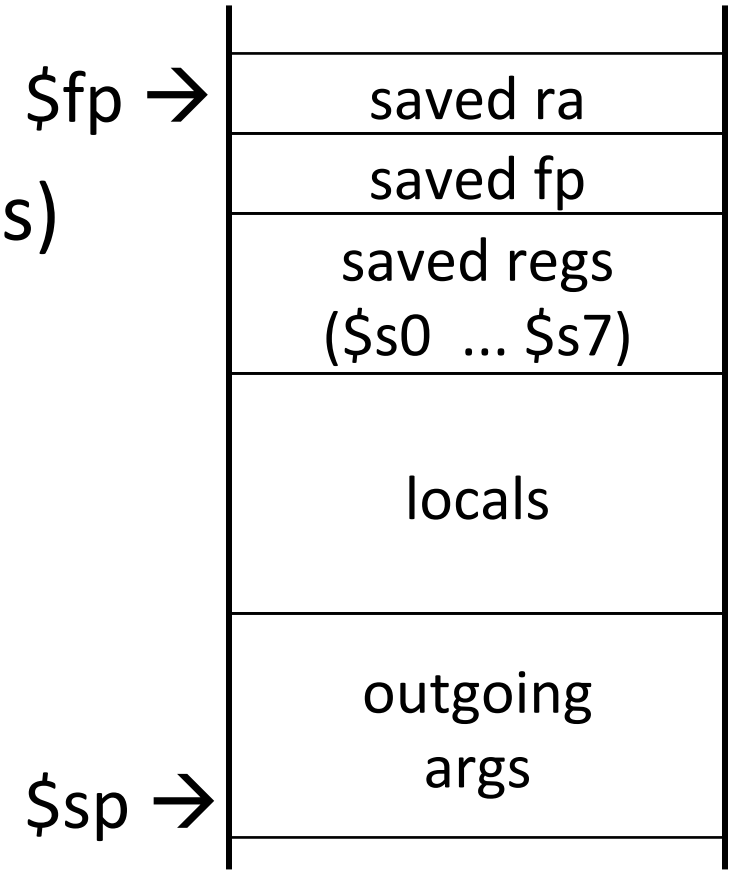
Leaf Functions

Leaf function does not invoke any other functions

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

Optimizations?

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



Globals and Locals

Global variables in data segment

- Exist for all time, accessible to all routines

Dynamic variables in heap segment

- Exist between malloc() and free()

Local variables in stack frame

- Exist solely for the duration of the stack frame

Dangling pointers into freed heap mem are bad

Dangling pointers into old stack frames are bad

- C lets you create these, Java does not
- int *foo() { int a; return &a; }

FAQ

FAQ

- caller/callee saved registers
- CPI
- writing assembling
- reading assembly

Caller-saved vs. Callee-saved

Caller-save: If necessary… ($t0 .. $t9)

- save before calling anything; restore after it returns

Callee-save: Always… ($s0 .. $s7)

- save before modifying; restore before returning

Caller-save registers are responsibility of the caller

- Caller-save register values saved only if used after call/return
- The callee function can use caller-saved registers

Callee-save register are the responsibility of the callee

- Values must be saved by callee before they can be used
- Caller can assume that these registers will be restored

Caller-saved vs. Callee-saved

Caller-save: If necessary… ($t0 .. $t9)

- save before calling anything; restore after it returns

Callee-save: Always… ($s0 .. $s7)

- save before modifying; restore before returning

eax, ecx, and edx are caller-save…

- … a function can freely modify these registers
- … but must assume that their contents have been destroyed if it in turns calls a function.

ebx, esi, edi, ebp, esp are callee-save

- A function may call another function and know that the callee-save registers have not been modified
- However, if it modifies these registers itself, it must restore them to their original values before returning.

Caller-saved vs. Callee-saved

Caller-save: If necessary… ($t0 .. $t9)

- save before calling anything; restore after it returns

Callee-save: Always… ($s0 .. $s7)

- save before modifying; restore before returning

A caller-save register must be saved and restored around any call to a subprogram.

In contrast, for a callee-save register, a caller need do no extra work at a call site (the callee saves and restores the register if it is used).

Caller-saved vs. Callee-saved

Caller-save: If necessary… ($t0 .. $t9)

- save before calling anything; restore after it returns

Callee-save: Always… ($s0 .. $s7)

- save before modifying; restore before returning

CALLER SAVED: MIPS calls these temporary registers, $t0-t9

- the calling program saves the registers that it does not want a called procedure to overwrite
- register values are NOT preserved across procedure calls

CALLEE SAVED: MIPS calls these saved registers, $s0-s8

- register values are preserved across procedure calls
- the called procedure saves register values in its AR, uses the registers for local variables, restores register values before it returns.

Caller-saved vs. Callee-saved

Caller-save: If necessary… ($t0 .. $t9)

- save before calling anything; restore after it returns

Callee-save: Always… ($s0 .. $s7)

- save before modifying; restore before returning

Registers $t0-$t9 are caller-saved registers

- … that are used to hold temporary quantities
- … that need not be preserved across calls

Registers $s0-s8 are callee-saved registers

- … that hold long-lived values
- … that should be preserved across calls

caller-saved register

- A register saved by the routine being called

callee-saved register

- A register saved by the routine making a procedure call

What is it?

CPI

Cycles Per Instruction

~~A measure of latency (delay)?~~

~~"ADD takes 5 cycles to finish"~~

or

A measure of throughput?

"N ADDs are completed in N cycles"

CPI = weighted average *throughput* over all instructions *in a given workload*

CPI = 1.0 means that on average…

… an instruction is completed every 1 cycle

CPI = 2.0 means that on average…

… an instruction is completed every 2 cycles

CPI = 5.0 means that on average…

… an instruction is completed every 5 cycles

Example CPI = 1.0

CPI = 1.0 means that on average…

… an instruction is completed every 1 cycle

Example CPI = 2.0

CPI = 2.0 means that on average…

… an instruction is completed every 2 cycles

Example CPI = 0.5

CPI = 0.5 means that on average…

… an instruction is completed every 0.5 cycles

CPI Calculation

Suppose 10 stage pipeline and…

- 1 instruction zapped on every taken jump or branch
- 3 stalls for every memory operation

Q: What is CPI?

… for pure arithmetic workload?

… for pure memory workload?

… for pure jump workload?

… for 50/50 arithmetic/jump workload?

… for 50%/25%/25% arith/mem/branch?

… if one fifth of the branches are taken?