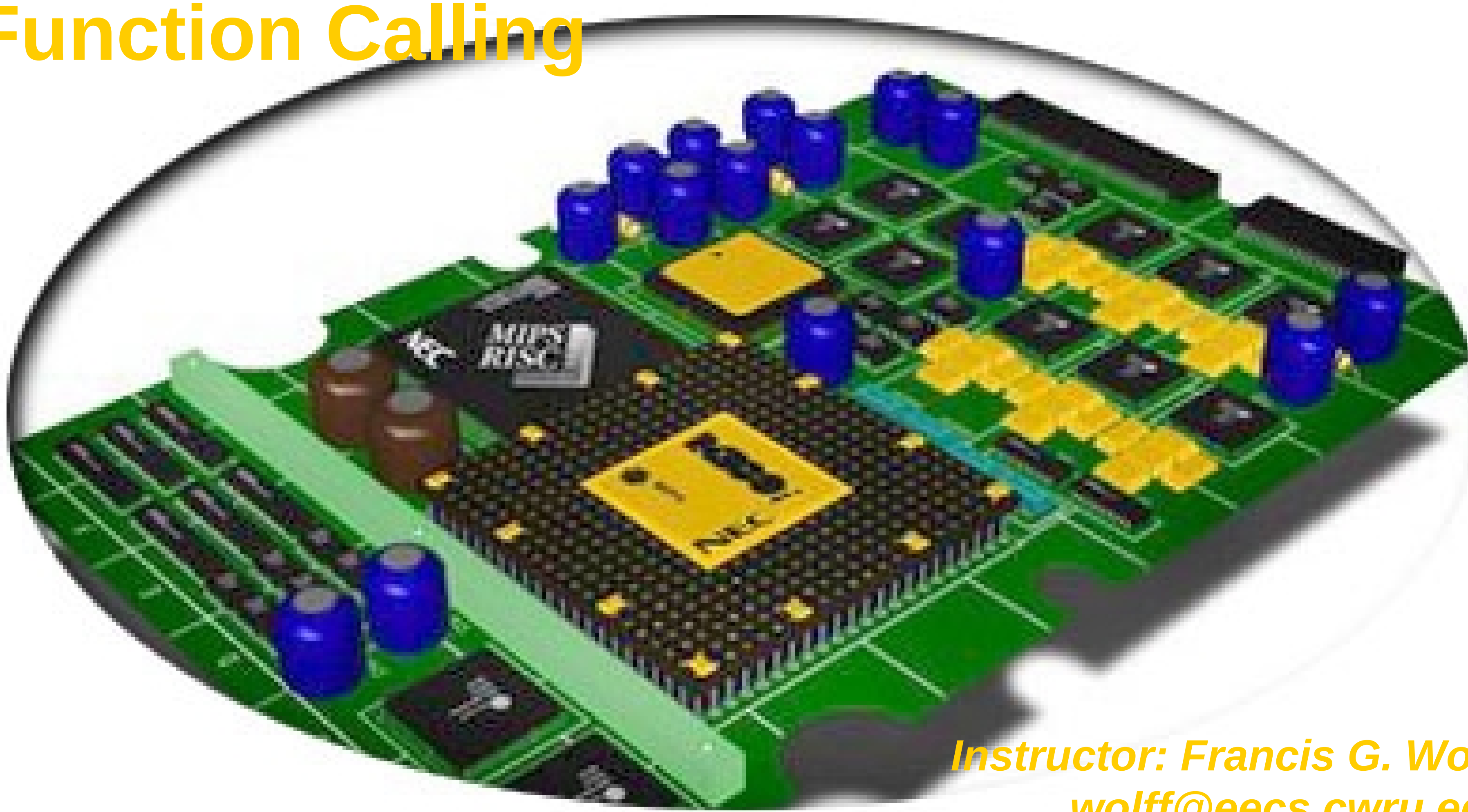
EECS 322 Computer Architecture

Language of the Machine
Function Calling



Instructor: Francis G. Wolff
wolff@eecs.cwru.edu
Case Western Reserve University
This presentation uses powerpoint animation: please viewshow

Review: Control Flow

- A Decision allows us to decide which pieces of code to execute at run-time rather than at compile-time.
- C Decisions are made using conditional statements within an if, while, do while or for.
- MIPS Decision making instructions are the conditional branches: beq and bne.
- In order to help the conditional branches make decisions concerning inequalities, we introduce a single instruction: “Set on Less Than”called slt, slti, sltu, sltui

Review: Control flow: if, ?:, while, for

- if (*condition*) *s1; else s2;*

```
if  (! condition) goto L1;
        s1;
        goto L2;
L1:  s2; /* else */
L2:
```

- variable = *condition ? s1 : s2;*

```
if  (! condition) goto L1;
        variable=s1;
        goto L2;
L1:  variable=s2; /* else */
L2:
```

- while (*condition*) *s1;*

```
L2: if  (! condition) goto L1;
        s1;
        goto L2;

L1: /* exit loop */
```

- for (init; *condition; inc*) *s1;*

```
init;
L2: if  (! condition) goto L1;
        s1;
        inc;
        goto L2;
L1: /* exit loop */
```

Control flow: do-while

- while (*condition*) *s1;*
- for(;condition;) s1;

```
L2: if  (! condition) goto L1;
        s1;
        goto L2;

L1: /* exit loop */
```

- Tests the termination condition at the top.
- 0 or more times

- do s1; while (*condition*)*;*
- for(s1;condition;) s1;

```
L2:
        s1;
        if  (condition) goto L2;

 /* exit loop by fall though */
```

- Tests the termination condition at the bottom after making each pass through the loop body.
- 1 or more times

Control flow: break (from K&R)

- A **break** causes the **innermost** enclosing loop or switch to be exited immediately.

```
/*clear lower triangle array*/
for(i=0; i<10;  i++ ) {
        for(j=0; j<10;  j++ ) {

                if (i>=j) break;
                a[i][j]=0;


        }


}
```

```
i=0;
L2: if  (i >= 10) goto L1;
        j=0;
        L4: if (j >= 10) goto L3;
                if (i>=j) goto L3;
                 a[i][j]=0;
                j++;
                goto L4;
        L3: /* exit loop */
        i++;
        goto L2;
 L1: /* exit loop */
```

MIPS Goto Instruction

- In addition to conditional branches, MIPS has an unconditional branch: j label
- Called a Jump Instruction: jump (or branch) directly to the given label without needing to satisfy any condition.
- Same meaning as (using C): goto label
- Technically, it's the same as: beq $0,$0,label
- since it always satisfies the condition.

Structured programming (Programming Languages, K. Louden)

- Ever since a famous letter by E. W. Dijkstra in 1968, GOTOs have been considered suspect, since
- they can so easily lead to unreadable "spaghetti" code.
- The GOTO statement is very close to actual machine code.
- As Dijkstra pointed out, its "unbridled" use can compromise even the most careful language design and lead to undecipherable programs.
- Dijkstra proposed that its use be severely controlled or even abolished.
- This unleashed one of the most persistent controversies in programming, which still rages today...

Structured programming (Programming Languages, K. Louden)

- efficiency: One group argues that the GOTO is indispensable for efficiency & even for good structure.
  - Such as state machines (LEX, YACC, parsers)
  - Break out of deeply nested loop in one step
    - C/C++ can only do inner most loop
    - C/C++ can use exit flags in each loop level (ugly)
  - GOTOs should only jump forward (never backward)
  - Error handling (gotos are still more efficient)
    - C/C++/Unix can use the signal( ) function
    - C++ can use the throw/catch statements
- limited: Another argues that it can be useful under carefully limited circumstances. (parsers, state machines).
- abolish: A third argues that it is an anachronism that should truly be abolished henceforth from all computer languages.

Control flow: continue (from K&R)

- The continue statement is related to the break. C/C++ is one of the few languages to have this feature.
- It causes the next iteration of the enclosing for, while, or do loop to begin.
- In the while and do, this means that the condition part is executed immediately.
- In the for, control passes to the increment step.

```
/* abs(array) */
for(i=0; i < n;  i++ ) {
        if (a[i] > 0) continue;
        a[i] = -a[i];
}
```

```
i=0;
L2: if (i >= n) goto L1;
        if (a[i] > 0) goto L2c;
        a[i] = -a[i];
L2c:    i++;
        goto L2;
L1:
```

Logical Operators: && and | |

(From K&R)

- More interesting are the logical operators && and | |.
- Bitwise and (&), bitwise or (|), bitwise not (~)
  - Bitwise operators imply no order and parallel in nature
- Logical and (&&), logical or(| |), logical not (!)
  - Logical operators imply order and sequential in nature
- Expressions connected by && and | | are evaluated left to right, and
- evaluation stops as soon as the truth or falsehood of the result is know.
- Most C programs rely on the above properties: (1) left to right evaluation (2) stop as soon as possible.

Logical Operators: example

(From K&R)

- For example, here is a loop from the input function getline

```
for(i=0; i<limit-1 && (c=getchar())!='\n' && c!=EOF ;  i++ ) {
        a[i] = c;
}
```

```
i=0;
L2:     if  (i >= limit-1) goto L1;
        c=getchar();
        if (c == '\n') goto L1;
        if (c ==EOF) goto L1;
        a[i] = c;
        i++;
        goto L2;
L1:
```

- Before reading a new character it is necessary to check that there is room to store it in the array a.
- So the test i<limit-1 must be made first
- Moreover, if the test fails, we must not go on and read another character

Review: slti example

- C code fragment

```
if (i < 20) { f=g+h; }
else        { f=g-h; }
```

The $0 register becomes useful again for the beq

- re-written C code

```
temp = (i < 20)? 1 : 0;
if (temp == 0) goto L1;
        f=g+h;
        goto L2;
L1:
        f=g-h;
L2:
```

- MIPS code

```
        slti  $t1,$s3,20
        beq   $t1,$0,L1
        add   $s0,$s1,$s2
        j     L2
L1:
        sub   $s0,$s1,$s2
L2:
```

signed char Array example

unsigned char Array:

```
register int g, h, i;
unsigned char  A[66];
g = h + A[i];
```

Load byte unsigned: load a byte and fills the upper 24 register bits with zeros.

```
add  $t1,$t1,$s4
lbu  $t0,0($t1)
add  $s1,$s2,$t0
```

signed char Array:

```
register int g, h, i;
signed char  A[66];
g = h + A[i];
```

8 bit sign = 128 = 0x00000080

if ($t0 >= 128) { $t0 |= 0xffffff00; }

```
     add   $t1,$t1,$s4
     lbu   $t0,0($t1)
     slti  $t1,$t0,128
     bne   $t1,$0,L2
     ori   $t0,0xff00
     lui   $t0,0xfffff
L2:  add   $s1,$s2,$t0
```

- **Data types make a big impact on performance!**

C functions

```
main() {
  int i, j, k, m;
  i = mult(j,k); ... ;
  m = mult(i,i); ...
}
int mult (int x, int y) {
  int f;
  for (f= 0; y > 0; y- - ) {
    f += x;
  }
  return f;
}
```

- Functions, procedures one of main ways to give a **program structure**, and encourage **reuse** of code.
- But they **do not** add any more computational power.

What information must compiler/programmer keep track of?

Calling functions: Bookkeeping

• **Function address**	**Labels**
• **Return address**	**\$ra**
• **Arguments**	**\$a0, \$a1, \$a2, \$a3**
• **Return value**	**\$v0, \$v1**
• **Local variables**	**\$s0, \$s1, …, \$s7**

- **Most problems above are solved simply by using register conventions.**

Calling functions: example

```
        … c=sum(a,b); …  /* a,b,c:$s0,$s1,$s2 */
}
int sum(int x, int y) {
        return x+y;
}
```

<u>address</u>

```
1000    add   $a0,$s0,$0       # x = a
1004    add   $a1,$s1,$0       # y = b
1008    addi  $ra,$0,1016      # $ra=1016
1012    j     sum              # jump to sum
1016    add   $s2,$0,$v0       # c=$v0
...
2000    sum: add $v0,$a0,$a1   # x+y
2004    jr   $ra               # pc = $ra = 1016
```

Why jr $ra vs. j 1016 to return?

Calling functions: jal, jump and link

- Single instruction to jump and save return address: jump and link (jal)

- slow way:

```
1008    addi  $ra,$zero,1016   #$ra=1016
1012    j     sum              #go to sum
```

- *faster way* and save one instruction:

```
1012    jal   sum              # pc = $ra = 1016
```

- *but adds more complexity to the hardware*

- Why have a jal? Make the common case fast: functions are very common.

Calling functions: setting the return address

- Syntax for jal (jump and link) is same as for j (jump):

  jal label # reg[$ra]=pc+4; pc=label

- jal should really be called laj for "link and jump":

- Step 1 (link):
  Save address of *next* instruction into $ra (Why?)

- Step 2 (jump):
  Jump to the given label

Calling functions: return

- Syntax for jr (jump register):

    jr $register # reg[$pc] = $register

- Instead of providing a label to jump to, the jr instruction provides a register that contains an address to jump to.
- Usually used in conjunction with jal, to jump back to the address that jal stored in $ra before function call.

Calling nested functions: example

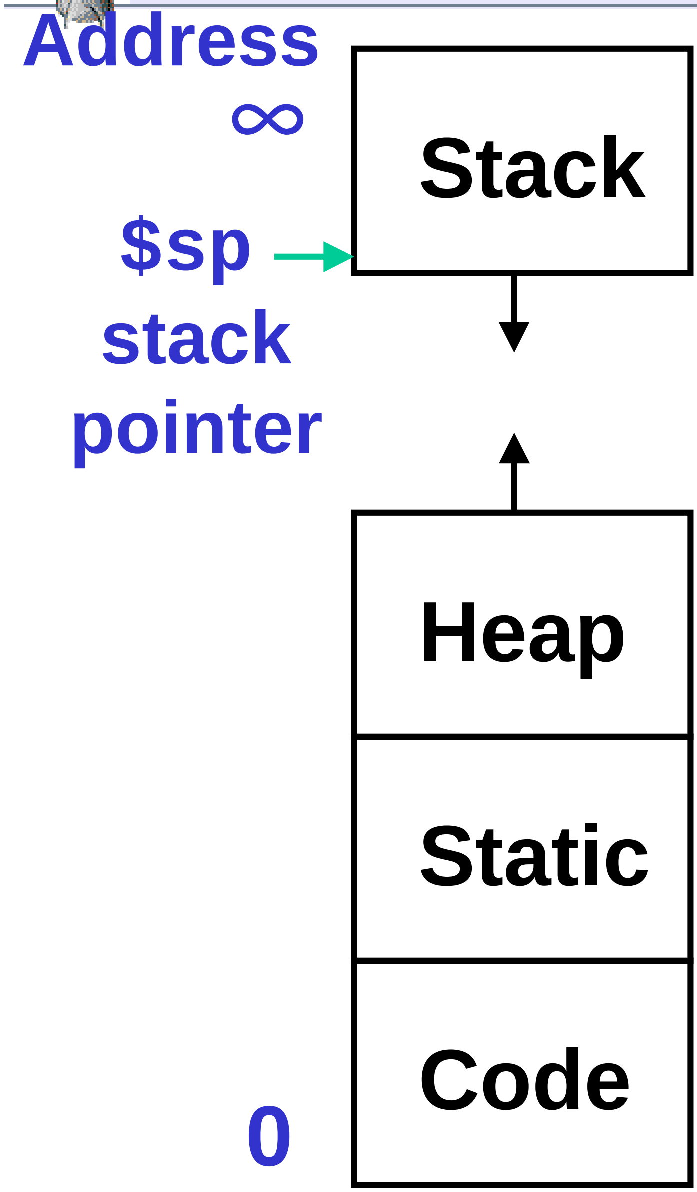
```
int sumSquare(int x, int y) {
        return mult(x, x)+ y;
  }
```

- Something called sumSquare,
  now sumSquare is calling mult(x, x).
- So there's a value in $ra that sumSquare wants to jump back to,
  - but this will be overwritten by the call to mult.
- Need to save sumSquare return address before call to mult(x, x).

Calling nested functions: memory areas

- In general, may need to save some other info in addition to $ra.
- When a C program is run, there are 3 important memory areas allocated:
  - –Static: Variables declared once per program, cease to exist only after execution completes
  - –Heap: Variables declared dynamically
  - –Stack: Space to be used by procedure during execution; this is where we can save register values
    - *Not* identical to the "stack" data structure!

C memory Allocation



Space for saved procedure information

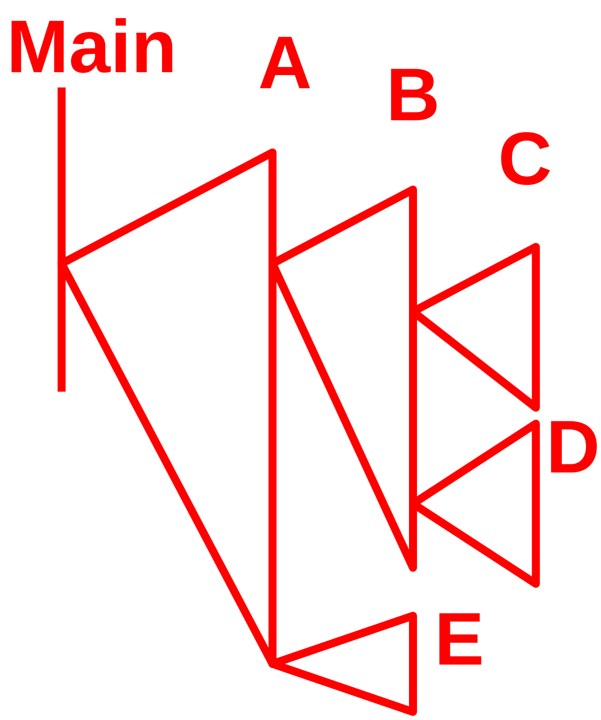
Explicitly created space, e.g., malloc(); C pointers

Variables declared once per program (.data segment)

Program (.text segment)

Stack Discipline

- C,C++, Java follow **"Stack Discipline";**
  - e.g., D cannot return to A bypassing B
  - Frames can be adjacent in memory
  - Frames can be allocated, discarded as a LIFO (stack)



- So we have a register **$sp** which always points to the last used space in the stack.
- To use stack, we **decrement** this pointer by the amount of space we need **and then** fill it with info.

Compiling nested C func into MIPS

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

sumSquare:

Prologue	subi	$sp, $sp,12	*# push stack stack*
	sw	$ra, 8($sp)	*# push return addr*
	sw	$a1, 4($sp)	*# push y*
	sw	$a0, 0($sp)	*# push x*
Body	addi	$a1, $a0,$0	*# mult(x,x)*
	jal	mult	*# call mult*
Epilogue	lw	$a0,0($sp)	*# pop x*
	lw	$a1,4($sp)	*# pop y*
	lw	$ra, 8($sp)	*# pop return addr*
	add	$v0,$v0,$a1	*# mult()+y*
	addi	$sp,$sp,12	*# pop stack space*
	jr	$ra	

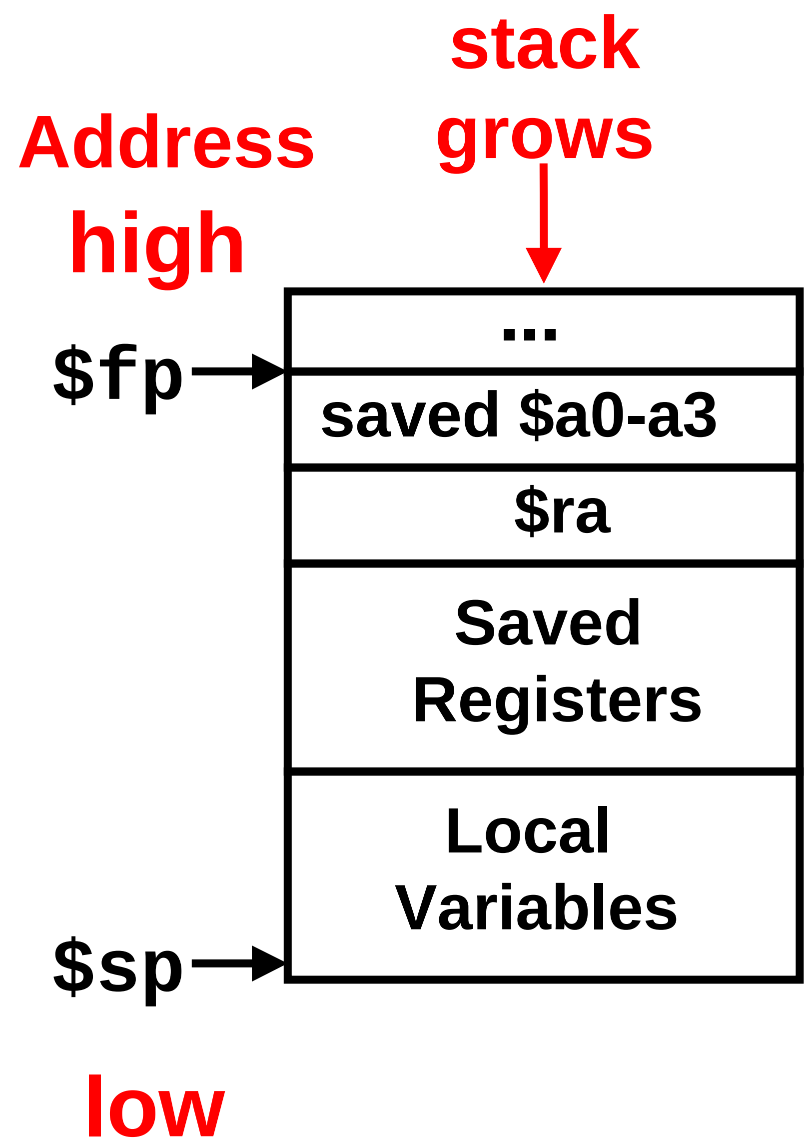
Frame Pointer

- The $fp points to the first word of the frame of a function.
- A $sp might change during a function and so references to a local variable in memory might have different offsets depending where they are in the function, making it harder to understand.

```
int f(int x, int y) {
        int i, a=4, f;
        for(i=0;i<10;i++) {
                int a[20];
                if (!i) { a[0]=x; }  else { a[i]=a[i-1]+y; }
                f=a[i];
}       }
```

Memory Allocation

- C Procedure Call Frame
- Pass arguments ($a0-$a3)
- Save caller-saved regs
- call function: jal
- space on stack ($sp-n)
  $sp@last word of frame
- Save callee-saved regs
- set $fp ($sp+n-4)
  $fp@first word of frame



MIPS Register Summary

• Registers	Total Regs
–$Zero, $0	1
–(Return) Value registers ($v0,$v1)	3
–Argument registers ($a0-$a3)	7
–Return Address ($ra)	8
–Saved registers ($s0-$s7)	16
–Temporary registers ($t0-$t9)	26
–Global Pointer ($gp)	27
–Stack Pointer ($sp)	28
–Frame Pointer ($fp), or $t10	29

- 2 for OS ($k0, $k1), 1 for assembler ($at)