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MIPS Programming 2

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COMP1047: Systems and Architecture
Week 4

Outline

- **MIPS Decision Making and Branching**

- **MIPS Arrays**

- **MIPS Procedure**

Learning Objectives

- Understand and write MIPS programs with branching instructions
- Understand and write MIPS programs involving arrays
- Understand and write MIPS procedures
    - Understand and implement caller- and callee-saved registers
    - Understand the concept and usage of stack memory
    - Implement with procedure calling conventions.

Outline

- MIPS Decision Making and Branching
- MIPS Arrays
- MIPS Procedure






Branching and Control flow

- So far, All instructions learnt allow us to manipulate data.
- So we've built a calculator.
- In order to build a computer, we need the ability to make decisions…
- Branching and Control flow
  - Branch instruction affect the Program Counter (PC) and hence the control flow of the program
  - Conditional branch instructions perform a branch depending on a condition.
  - Unconditional branch instructions (e.g. goto) perform a branch unconditionally.

Control Flow in High Level Languages

- goto has (mostly) been eliminated from high level programming languages
  - It will lead to an unmaintainable mess
- Structured statements: if, if/else, while and for are used instead
- But in MIPS, both types of branching (goto and if-family) are provided. We will learn MIPS branching instructions that correspond to the above structs.

MIPS Branch Instructions

- beq a, b, L - Branch on equal
  - Go to instruction at label L if a==b, otherwise, continue with the next instruction
- bne a, b, L - Branch on not equal
  - Go to instruction at label L if a!=b, otherwise, continue with the next instruction
- j L – Jump to unconditional jump
  - jump to the instruction at label L

Conditional Branching (beq)

```
# MIPS assembly
 addi $s0, $0, 4          # $s0 = 0 + 4 = 4
 addi $s1, $0, 1          # $s1 = 0 + 1 = 1
 sll  $s1, $s1, 2         # $s1 = 1 << 2 = 4
 beq  $s0, $s1, target    # branch is taken
 addi $s1, $s1, 1         # not executed
 sub  $s1, $s1, $s0       # not executed

target:                   # label
 add  $s1, $s1, $s0       # $s1 = 4 + 4 = 8
```

Labels indicate instruction locations in a program. They cannot use reserve words and must be followed by a colon (:).

Conditional Branching (bne)

```
# MIPS assembly
   addi      $s0, $0, 4           # $s0 = 0 + 4 = 4
   addi      $s1, $0, 1           # $s1 = 0 + 1 = 1
   sll       $s1, $s1, 2          # $s1 = 1 << 2 = 4
   bne       $s0, $s1, target     # branch not taken
   addi      $s1, $s1, 1          # $s1 = 4 + 1 = 5
   sub       $s1, $s1, $s0        # $s1 = 5 – 4 = 1

target:
   add       $s1, $s1, $s0        # $s1 = 1 + 4 = 5
```

Unconditional Branching (j)

```
# MIPS assembly
  addi $s0, $0, 4              # $s0 = 4
      addi $s1, $0, 1          # $s1 = 1
      j     target             # jump to target
      sra   $s1, $s1, 2        # not executed
      addi  $s1, $s1, 1        # not executed
      sub   $s1, $s1, $s0      # not executed

  target:
      add   $s1, $s1, $s0      # $s1 = 1 + 4 = 5
```

What is the operand for j instruction?

Unconditional Branching (jr)

$s0里的东西会以16进制地址的形式被访问
如果$s0 = 12，那么会访问地址0x0000000C

```
# MIPS assembly
0x00002000    addi $s0, $0, 0x2010
0x00002004    jr   $s0
0x00002008    addi $s1, $0, 1
0x0000200C    sra  $s1, $s1, 2
0x00002010    lw   $s3, 44($s1)
```

jump into the location stored in the register

Translating the 'if' statement

High-level code

```
if (i == j)
  f = g + h;

f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
```

```
bne $s3 $s4 target
add $s0 $s1 $s2

target:
sub $s0 $s0 $s3
```

```
beq $s3, $s4 L0
j L1

L0: add $s0, $s1, $s2
L1: sub $s0, $s0, $s3
```

Notice that the assembly tests for the opposite case (`i != j`) than the test in the high-level code (`i == j`).

What if we use `beq`?

Translating the ‘if-else’ statement

High-level code

```
if (i == j)
  f = g + h;
else
  f = f - i;
```

MIPS assembly code

```
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j

      bne $s3, $s4, L1
      add $s0, $s1, $s2
      j   done
L1:   sub $s0, $s0, $s3
done:
```

Translating the ‘while loop’

High-level code

```
// determines the power
// of x such that 2^x = 128
int pow = 1;
int x   = 0;

while (pow != 128) {
  pow = pow * 2;
  x = x + 1;
}
```

MIPS assembly code

```
# $s0 = pow, $s1 = x

       addi $s0, $0, 1
       add  $s1, $0, $0
       addi $t0, $0, 128

while: beq  $s0, $t0, done
       sll  $s0, $s0, 1
       addi $s1, $s1, 1
       j    while
done:
```

Notice that the assembly tests for the opposite case (`pow == 128`) than the test in the high-level code (`pow != 128`).

What if we use `bne` here?

Translating the 'for loop'

High-level code

```
// add the numbers from 0 to 9
int i;
int sum = 0;


for (i=0; i!=10; i = i+1) {
  sum = sum + i;
}
```

MIPS assembly code

```
       addi $s0, $0, 0   # $s0 = i
       add  $s1, $0, $0  # $s1 = sum

       addi $t0, $0, 10
for:   beq  $s0, $t0, done
       add  $s1, $s1, $s0
       addi $s0, $s0, 1
       j    for
done:
```

Inequality in MIPS

- Until now, we've only tested equalities (beq and bne), but general programs need to test '<' and '>'
- Set on Less Than:
  - `slt rd, rs, rt`
    - if (rs < rt) rd = 1; else rd = 0;
  - `slti rt, rs, constant`
    - if (rs < constant) rt = 1; else rt = 0;

Compile by hand: `if (g < h) goto Less;`

Let `g: $s0, h: $s1`

```
?                    # $t0 = 1 if g<h
?                    # goto Less if $t0!=0
```

Branch Instruction Design

- MIPS has no "branch on less than", i.e., `blt`, `bge`. Why?
- Hardware for $<$, $\geq$, … are slower than $=$, $\neq$
  - Combining with branch involves more work per instruction, requiring a slower clock
  - All instructions penalized!
- Although beq and bne are less direct (need to combine with slt), this is a good design compromise between performance and code efficiency.

Signed vs. Unsigned 'slt'

- Signed comparison: `slt`, `slti`
- Unsigned comparison: `sltu`, `sltui`
- Example
  - \$s0 = 1111 1111 1111 1111 1111 1111 1111 1111
  - \$s1 = 0000 0000 0000 0000 0000 0000 0000 0001

slt \$t0, \$s0, \$s1 # signed

- $-1 < +1$, so \$t0 = 1

sltu \$t0, \$s0, \$s1 # unsigned

- $+4{,}294{,}967{,}295 > +1$, so \$t0 = 0

Using ‘slt’ in the ‘for loop’

High-level code

```
// add the powers of 2 from 1
// to 100
int sum = 0;
int i;

for (i=1; i < 101; i = i*2) {
  sum = sum + i;
}
```

MIPS assembly code

```
       addi $s0, $0, 0   # $s0 = i
       addi $s1, $0, 1   # $s1 = sum

       addi $t0, $0, 101
loop:  slt  $t1, $s0, $t0
       beq  $t1, $0, done
       add  $s1, $s1, $s0
       sll  $s0, $s0, 1
       j    loop
done:
```

$t1 = 1 if i < 101.

Exercise: Maximum of two numbers

```
        .text
main:   li $t0, 0
        li $v0, 5
        syscall
        move $s0, $v0        # read and store input x in $s0
        li $v0, 5
        syscall              # read and store input y in $v0
        ?                    # if $v0 < $s0, $t0 = 1
        ?                    # if $t0 != 0 (i.e., $t0 = 1, $v0 < $s0), goto out
        ?                    # otherwise (i.e., $v0 >= $s0), store large in $s0
out:    move $a0, $s0        # print maximum number stored in $a0
        li $v0, 1
        syscall              # print integer
        li $v0, 10
        syscall              # exit
```

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Arrays

- A data structure that is useful for accessing large amounts of similar data
- Array element: accessed by index
- Array size: number of elements in the array

```
int z[10];              //  an array of 10 ints, z points to start
z[0] = 2; z[1] = 3;     //  assigns 2 to the first, 3 to the next
```

Accessing Array Data in MIPS

- Since arrays can store lots of data, and we have only a small (~32) number of registers, it is infeasible to use the registers for long-term storage of the array data
  - Hence, arrays are stored in the data segment of a MIPS program
- E.g. the declaration of an array with 8 elements is:

```
arr: .word 3, 10, 4, 1, 15, 9, 2, 6
```

- To access the data in the array requires that we know the address of the data and then use the load word (`lw`) or store word (`sw`) instructions

Accessing Array Data in MIPS

```
arr: .word 3, 10, 4, 15, 5, 9, 2, 6
```

- To find where the array is: `la $t0, arr`
  - `$t0` contains the address of the first element '3' in the array
  - The index address of the second element '10' is $t0 + 4
  - The address of the fifth element '5' is $t0 + 16
- The following code will place the value of arr[6] into the `$t4`:

```
la  $t3, arr         # put address of arr into $t3
li  $t2, 6           # put the index into $t2
sll $t2, $t2, 2      # 4x the index to find the byte location
add $t1, $t2, $t3    # obtain the address
lw $t4, 0($t1)       # get the value from the array cell
```

Another way to load the array head

- Given the base address = 0x12348000 (address of the first array element, `array[0]`)
- Use lui + ori to load 32-bit base address into a register
- lui (load upper immediate)
  - `lui   $s0, 0x1234        # $s0 = 0x12340000`
- ori (or immediate)
  - `ori   $s0, $s0, 0x8000 # $s0 = 0x12348000`

0x12340010	array[4]
0x1234800C	array[3]
0x12348008	array[2]
0x12348004	array[1]
0x12348000	array[0]

Notice the usage difference between `li` and `lui`, when loading an immediate.

- If the constant would fit 16 bits, use `li`
- If the constant needs (16, 32] bits, use `lui` + `ori`

Another way to load the array head

```
// High-level code
   int array[5];
   array[0] = array[0] * 2;
   array[1] = array[1] * 2;

# MIPS assembly code
# array base address = $s0
   lui  $s0, 0x1234       # put 0x1234 in upper half of $S0
   ori  $s0, $s0, 0x8000 # put 0x8000 in lower half of $s0

   lw   $t1, 0($s0)          # $t1 = array[0]
   sll  $t1, $t1, 1          # $t1 = $t1 * 2
   sw   $t1, 0($s0)          # array[0] = $t1

   lw   $t1, 4($s0)          # $t1 = array[1]
   sll  $t1, $t1, 1          # $t1 = $t1 * 2
   sw   $t1, 4($s0)          # array[1] = $t1
```

MIPS String

- Assembly strings are arrays of ASCII characters
  - A string is finished with a NUL (0) character.
  - 1 ASCII character is 1 byte.
- Declare a string in assembly code
  - with the `.asciiz` directive

```
li $v0, 0           # length = 0 ;
j strlen_cond       # assume $a0 points to the string head

strlen_loop:
    addi $v0, $v0, 1                  # length++

strlen_cond:
    lbu $t0, ($a0)                    # load char at address $a0
    addi $a0, $a0, 1                  # point $a0 to next char
    bne $t0, $zero, strlen_loop       # while not NUL
end:                                  # now $v0 contains the string length
```

Outline

- **MIPS Decision Making and Branching**
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Procedures

- Procedures are portion of code, within a larger program, which runs frequently
- Procedures help to
  - Reduce code duplication
  - Improve code re-usability
  - Decompose complex programs into manageable parts
- Other names
  - Methods – java and other OO languages
  - Functions – C, C++, Haskell
  - Routines, subroutines – (seems not popular now)

Procedure Calls

Definitions

- Caller: calling procedure (in this example, `main`)
- Callee: called procedure (in this example, `sum`)

High-level code

```
void main()
{
  int y;
  y = sum(42, 7);
  ...
}

int sum(int a, int b)
{
  return (a + b);
}
```

Procedure Calling Conventions

Procedure calling conventions:

- Caller:
  - passes **arguments** to callee.
- Callee:
  - **must not overwrite** registers or memory needed by the caller
  - **returns to the point of call**
  - **returns the result** to caller

MIPS conventions:

- Call procedure: jump and link (`jal`)
- Return from procedure: jump register (`jr`)
- Argument values: `$a0 - $a3`
- Return value: `$v0, ($v1 for 64-bit double)`

High-level code

```
void main()
{
  int y;
  y = sum(42, 7);
  ...
}

int sum(int a, int b)
{
  return (a + b);
}
```

Procedure Calls

High-level code

```
int main() {
  simple();
  a = b + c;
}

void simple() {
  return;
}
```

MIPS assembly code

```
0x00400200 main: jal   simple
0x00400204       add   $s0, $s1, $s2
...

0x00401020 simple: jr $ra
```

`jal`: jumps to `simple` and saves PC+4 to the return address register ($ra).
In this case, $ra = 0x00400204 after jal executes.

`jr $ra`: jumps to address in $ra, in this case 0x00400204.

Input Arguments and Return Values

High-level code

```
int main()
{
  int y;
  ...
  y = diffofsums(2, 3, 4, 5);  // 4 arguments
  ...
}

int diffofsums(int f, int g, int h, int i)
{
  int result;
  result = (f + g) - (h + i);
  return result;
}
```

MIPS assembly code

```
main:
  ...
  addi $a0, $0, 2     # argument 0 = 2
  addi $a1, $0, 3     # argument 1 = 3
  addi $a2, $0, 4     # argument 2 = 4
  addi $a3, $0, 5     # argument 3 = 5
  jal  diffofsums     # call procedure
  add  $s0, $v0, $0   # y = returned value
  ...

# $s0 = result
diffofsums:
  add $s2, $a0, $a1   # $s2 = f + g
  add $s1, $a2, $a3   # $s1 = h + i
  sub $s0, $s2, $s1   # result = (f + g) - (h + i)
  add $v0, $s0, $0    # put return value in $v0
  jr  $ra             # return to caller
```

Input Arguments and Return Values

MIPS assembly code

```
diffofsums:
  add $s2, $a0, $a1   # $s2 = f + g
  add $s1, $a2, $a3   # $s1 = h + i
  sub $s0, $s2, $s1   # result = (f + g) - (h + i)
  add $v0, $s0, $0    # put return value in $v0
  jr  $ra             # return to caller
```

`diffofsums` overwrites 3 registers: `$s2`, `$s1`, and `$s0`

`diffofsums` can use stack to temporarily store registers

The Stack

- Memory used to temporarily save variables
- Like a stack of dishes, last-in-first-out (LIFO) queue
- *Expands*: uses more memory when more space is needed
- *Contracts*: uses less memory when the space is no longer needed

The Stack

- Grows down (from higher to lower memory addresses)
- Stack pointer: `$sp`, points to top of the stack

Address	Data	
7FFFFFFC	12345678	← $sp
7FFFFFF8		
7FFFFFF4		
7FFFFFF0		
⋮	⋮	

Address	Data	
7FFFFFFC	12345678	
7FFFFFF8	AABBCCDD	
7FFFFFF4	11223344	← $sp
7FFFFFF0		
⋮	⋮	

How Procedures Use the Stack

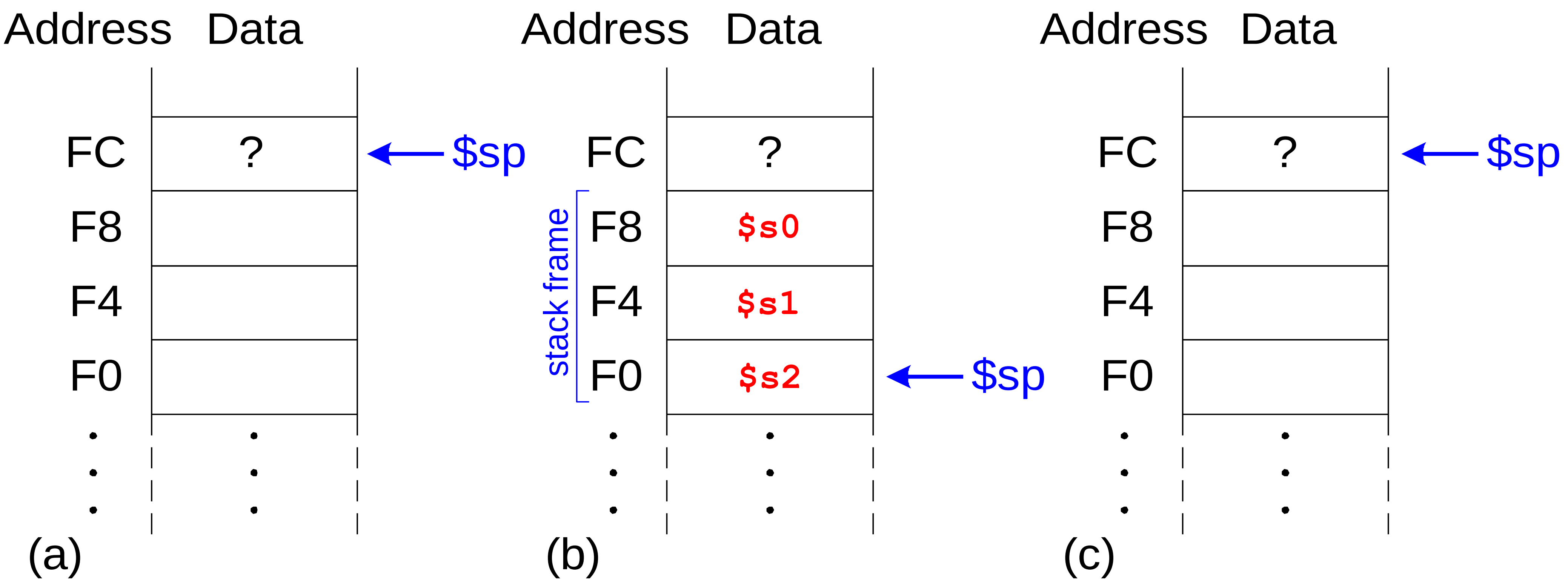
- The callee must make no unintended side effects on the caller.
- But `diffofsums` overwrites 3 registers: **$s2, $s1, $s0**

```
# MIPS assembly
# $s0 = result
diffofsums:
  add $s2, $a0, $a1   # $s2 = f + g
  add $s1, $a2, $a3   # $s1 = h + i
  sub $s0, $s2, $s1   # result = (f + g) - (h + i)
  add $v0, $s0, $0    # put return value in $v0
  jr  $ra             # return to caller
```

Use Stack to Protect Caller Values

```
diffofsums:
    addi $sp, $sp, -12   # make space on stack
                         # to store 3 registers
    sw   $s0, 8($sp)     # save $s0 on stack
    sw   $s1, 4($sp)     # save $s1 on stack
    sw   $s2, 0($sp)     # save $s2 on stack
    add  $s2, $a0, $a1   # $s2 = f + g
    add  $s1, $a2, $a3   # $s1 = h + i
    sub  $s0, $s2, $s1   # result = (f + g) - (h + i)
    add  $v0, $s0, $0    # put return value in $v0
    lw   $s2, 0($sp)     # restore $s2 from stack
    lw   $s1, 4($sp)     # restore $s1 from stack
    lw   $s0, 8($sp)     # restore $s0 from stack
    addi $sp, $sp, 12    # deallocate stack space
    jr   $ra             # return to caller
```

The Stack During `diffofsums` Call



Who should push/pop which Registers?

- MIPS registers are divided into two types: caller-saved and callee-saved.

Callee-Saved *(since caller may have used them)*	*Caller-Saved* *(since callee may use them)*
`$s0 - $s7`	`$t0 - $t9`
`$ra`	`$a0 - $a3`
`$sp`	`$v0 - $v1`

Use Stack to Protect Caller/Callee Values

Caller

```
main:
   ...
   addi $a0, $0, 2     # argument 0
   addi $a1, $0, 3     # argument 1
   addi $a2, $0, 4     # argument 2
   addi $a3, $0, 5     # argument 3

   addi $sp, $sp, -8
   sw   $t0, 4($sp)
   sw   $t1, 0($sp)
   jal  diffofsums     # call procedure
   lw   $t1, 0($sp)
   lw   $t0, 4($sp)
   addi $sp, $sp, 8
   add  $s0, $v0, $0
   ...
   add $t0, $t1, $s1
   ...
```

Callee

```
diffofsums:

   addi $sp, $sp, -12
   sw   $s0, 8($sp)
   sw   $s1, 4($sp)
   sw   $s2, 0($sp)
   add  $s2, $a0, $a1
   add  $s1, $a2, $a3
   sub  $s0, $s2, $s1
   add  $t0, $0,  $a1
   add  $t1, $0,  $a2
   add  $v0, $s0, $0
   lw   $s2, 0($sp)
   lw   $s1, 4($sp)
   lw   $s0, 8($sp)
   addi $sp, $sp, 12
   jr   $ra
```

pp. 43: Use Stack to Protect Caller/Callee Values

Caller

```
main:
  ...
  addi $a0, $0, 2     # argument 0
  addi $a1, $0, 3     # argument 1
  addi $a2, $0, 4     # argument 2
  addi $a3, $0, 5     # argument 3

  addi $sp, $sp, -8
  sw   $t0, 4($sp)
  sw   $t1, 0($sp)
  jal  diffofsums     # call procedure
  lw   $t1, 0($sp)
  lw   $t0, 4($sp)
  addi $sp, $sp, 8
  add  $s0, $v0, $0
  ...
  add $t0, $t1, $s1
  ...
```

Callee

```
diffofsums:
  addi $sp, $sp, -16
  sw   $ra, 12(sp)
  sw   $s0, 8($sp)
  sw   $s1, 4($sp)
  sw   $s2, 0($sp)
  add  $s2, $a0, $a1
  add  $s1, $a2, $a3
  sub  $s0, $s2, $s1
  add  $t0, $0,  $a1
  add  $t1, $0,  $a2
  add  $v0, $s0, $0
  lw   $s2, 0($sp)
  lw   $s1, 4($sp)
  lw   $s0, 8($sp)
  lw   $ra, 12(sp)
  addi $sp, $sp, 16
  jr   $ra
```

MIPS Calling Convention

- Caller
  - Push any of `$a0-$a3`, `$v0-$v1` and `$t0-$t9` if necessary
  - Place arguments in `$a0` to `$a3` if needed
  - Make the call using `jal callee`
  - Pop saved registers and/or extra arguments off stack
- Callee
  - Push any of `$ra`, `$s0-$s7` that may be overwritten
  - Perform desired task
  - Place result in `$v0` and `$v1`
  - Pop above registers off the stack
  - Return to caller with `jr $ra`

Summary

- MIPS branching instructions and programming
- MIPS arrays
- MIPS procedures
  - caller- and callee-saved registers
  - stack memory
  - procedure calling conventions

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