Computer Architecture

2nd Year Computer science

MIPS R3000 Assembly Language

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What is Assembly Language?

- Low-level programming language for a computer
- One-to-one correspondence with the machine instructions
- Assembly language is specific to a given processor
- Assembler: converts assembly program into machine code
- Assembly language uses:
  - Mnemonics: to represent the names of low-level machine instructions
  - Labels: to represent the names of variables or memory addresses
  - Directives: to define data and constants
  - Macros: to facilitate the inline expansion of text into other code

Assembly Language Statements

- **Three types of statements in assembly language**
  - Typically, one statement should appear on a line

1. **Executable Instructions**
   - Generate machine code for the processor to execute at runtime
   - Instructions tell the processor what to do
2. **Pseudo-Instructions and Macros**
   - Translated by the assembler into real instructions
   - Simplify the programmer task
3. **Assembler Directives**
   - Provide information to the assembler while translating a program
   - Used to define segments, allocate memory variables, etc.
   - Non-executable: directives are not part of the instruction set

3

Assembly Language Instructions

- Assembly language instructions have the format:

```
[label:]   mnemonic   [operands]   [#comment]
```

- Label: (optional)
  - Marks the address of a memory location, must have a colon
  - Typically appear in data and text segments
- Mnemonic
  - Identifies the operation (e.g. **add**, **sub**, etc.)
- Operands
  - Specify the data required by the operation
  - Operands can be registers, memory variables, or constants
  - Most instructions have three operands

```
L1:  addiu $t0, $t0, 1       #increment $t0
```

4

Comments

- Single-line comment
  - Begins with a hash symbol # and terminates at end of line
- Comments are very important!
  - Explain the program's purpose
  - When it was written, revised, and by whom
  - Explain data used in the program, input, and output
  - Explain instruction sequences and algorithms used
  - Comments are also required at the beginning of every procedure
    - Indicate input parameters and results of a procedure
    - Describe what the procedure does

Program Template

```
.data
        ------------------
        ------------------              } Data section

.text
        ------------------      # main program entry
        ------------------
        li $v0, 10 syscall        # Exit program      } Text section
```

.DATA & .TEXT Directives

- **.DATA** directive
  - Defines the data segment of a program containing data
  - The program's variables should be defined under this directive
  - Assembler will allocate and initialize the storage of variables
- **.TEXT** directive
  - Defines the code segment of a program containing instructions

Data Definition Statement

- The assembler uses directives to define data
- It allocates storage in the static data segment for a variable
- May optionally assign a name (label) to the data
- Syntax:

[*name:*] *directive* *initializer* [, *initializer*] . . .

```
var1: .WORD    10
```

- All initializers become binary data in memory

Data Directives

- **.BYTE** Directive
  - Stores the list of values as 8-bit bytes
- **.HALF** Directive
  - Stores the list as 16-bit values aligned on half-word boundary
- **.WORD** Directive
  - Stores the list as 32-bit values aligned on a word boundary
- **.FLOAT** Directive
  - Stores the listed values as single-precision floating point
- **.DOUBLE** Directive
  - Stores the listed values as double-precision floating point

String Directives

- **.ASCII** Directive
  - Allocates a sequence of bytes for an ASCII string
- **.ASCIIZ** Directive
  - Same as **.ASCII** directive, but adds a NULL char at end of string
  - Strings are null-terminated, as in the C programming language
- **.SPACE** Directive
  - Allocates space of *n* uninitialized bytes in the data segment

Examples of Data Definitions

```
.DATA
var1:   .BYTE     'A', 'E', 127, -1, '\n'
var2:   .HALF     -10, 0xffff
var3:   .WORD     0x12345678:100
var4:   .FLOAT    12.3, -0.1
var5:   .DOUBLE   1.5e-10
str1:   .ASCII    "A String\n"
str2:   .ASCIIZ   "NULL Terminated String"
array:  .SPACE    100
```

Array of 100 words Initialized with the same value (var3)

100 bytes (not initialized) (array)

Instruction Categories

- Integer Arithmetic
  - Arithmetic, logic, and shift instructions
- Data Transfer
  - Load and store instructions that access memory
  - Data movement and conversions
- Jump and Branch
  - Flow-control instructions that alter the sequential sequence

LOAD /STORE Instructions

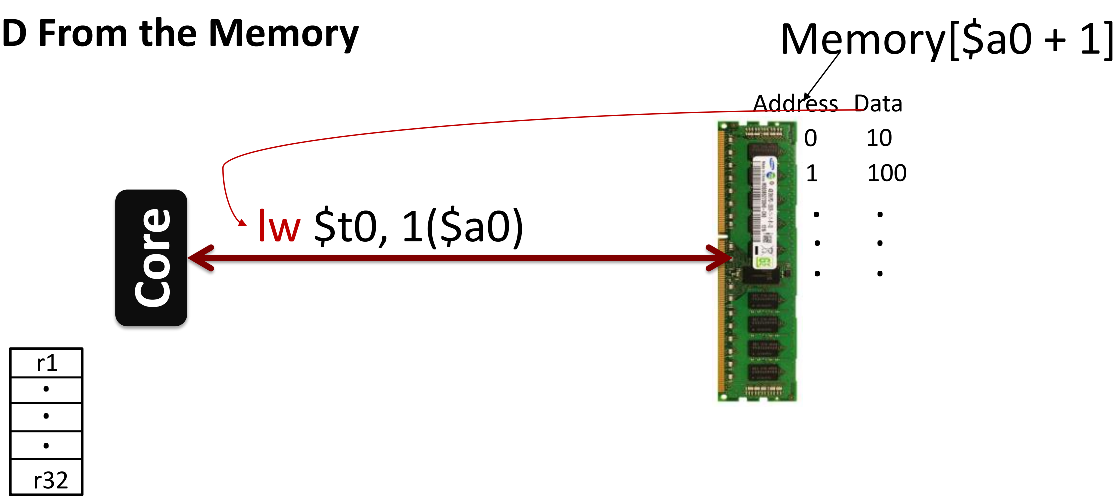
load word	lw
load byte	lb
load byte unsigned	lbu
load half	lh
load half unsigned	lhu

load immediate	li
load address	la

13

LOAD /STORE Instructions

LOAD From the Memory



14

LOAD /STORE Instructions

LOAD From the Memory

- **Memory reads are called loads**
- **Mnemonic: load word (lw)**

Example: read a word of data at memory address 1 into $s3

- **Memory address calculation:**

add the base address ($0) to the offset (1)

  - address = ($0 + 1) = 1
  - `$s3` holds the value **`0xF2F1AC07`** after the instruction completes

- **Any register may be used to store the base address**

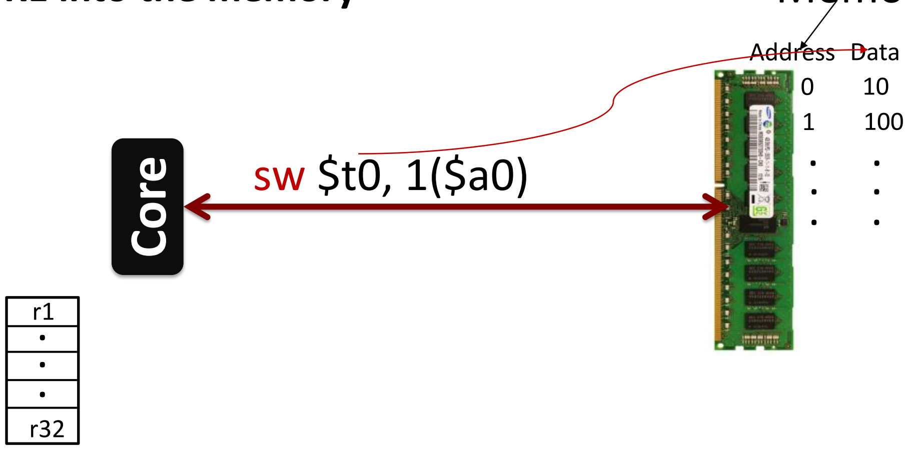
```
lw $s3, 1($0)  # read memory word 1 into $s3
```

15

LOAD /STORE Instructions

STORE into the memory

Memory[$a0 + 1]



16

LOAD /STORE Instructions

STORE into the memory

- Memory writes are called stores
- Mnemonic: store word (sw)
- Example: Write (store) the value held in `$t4` into memory address 7
- Memory address calculation:
  - add the base address ($0) to the offset (7)
  - address = ($0 + 7) = 7
  - Offset can be written in decimal (default) or hexadecimal
- Any register may be used to store the base address

```
sw $t4, 0x7($0)  # write the value
                          # to memory word 7
```

17

LOAD /STORE Instructions

STORE into the memory

- Li - Load immediate -

  Li Rdest, Imm

Exemple:

Li $t0, 23

- La - Load address-
- **La Rdest, adress**
- Copy of Register

  Move Rdest, Rsrc

```
li    $t0, 42          # $t1 =42
move  $t1, $t0
```

18

Arithmetic instructions

Instruction	Meaning
`add  $t1, $t2, $t3`	`$t1 = $t2 + $t3`
`addu $t1, $t2, $t3`	`$t1 = $t2 + $t3`
`sub  $t1, $t2, $t3`	`$t1 = $t2 - $t3`
`subu $t1, $t2, $t3`	`$t1 = $t2 - $t3`

- add, sub: arithmetic overflow causes an exception
  - In case of overflow, result is not written to destination register
- addu, subu: arithmetic overflow is ignored
- addu, subu: compute the same result as add, sub
- Many programming languages ignore overflow
  - The **+** operator is translated into **addu**
  - The **–** operator is translated into **subu**

Arithmetic instructions

add $0, $1, $2

add: operation, $0: Destination, $1 & $2: Source(s)

Most of the arithmetic/logical: two sources and one destination

Arithmetic instructions

Constants and Immediate

x=x+10

No need of a register

addi $s0, $s0, 10

i: immediate, for constants

constant: **16 bits**.

21

Arithmetic instructions

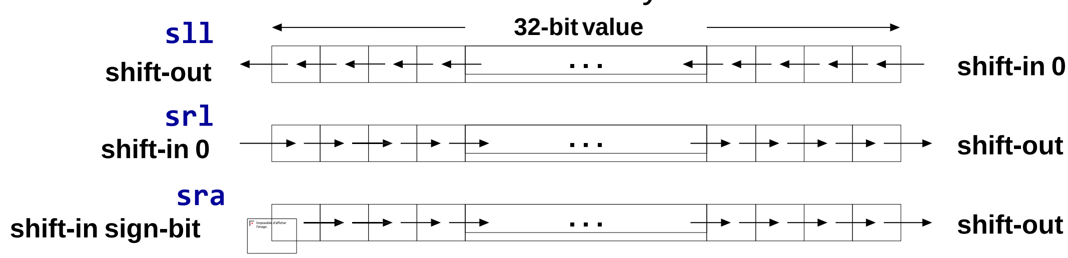
- Consider the translation of: **`f = (g+h)-(i+j)`**
- Programmer / Compiler allocates registers to variables
- Given that: **`$t0=f, $t1=g, $t2=h, $t3=i, and $t4=j`**
- Called temporary registers: **`$t0=$8, $t1=$9, …`**
- Translation of: **`f = (g+h)-(i+j)`**

```
addu  $t5,  $t1,  $t2   # $t5 = g + h
addu  $t6,  $t3,  $t4   # $t6 = i + j
subu $t0, $t5, $t6      # f = (g+h)-(i+j)
```

22

Shift Instructions

- Shifting is to move the 32 bits of a number left or right
- `sll` means **shift left logical** (insert zero from the right)
- `srl` means **shift right logical** (insert zero from the left)
- `sra` means **shift right arithmetic** (insert sign-bit)
- The **5-bit shift amount** field is used by these instructions



Logic Bitwise Instructions

Instruction	Meaning
`and $t1, $t2, $t3`	`$t1 = $t2 & $t3`
`or  $t1, $t2, $t3`	`$t1 = $t2 | $t3`
`xor $t1, $t2, $t3`	`$t1 = $t2 ^ $t3`
`nor $t1, $t2, $t3`	`$t1 = ~($t2|$t3)`

- Examples:

Given: `$t1 = 0xabcd1234` and `$t2 = 0xffff0000`

```
and    $t0, $t1, $t2         # $t0  =  0xabcd0000
or     $t0, $t1, $t2         # $t0  =  0xffff1234
xor    $t0, $t1, $t2         # $t0  =  0x54321234
nor    $t0, $t1, $t2         # $t0  =  0x0000edcb
```

Branching

- **Allows a program to execute instructions out of sequence**
- ***Conditional branches***
  - branch if equal: **beq**
  - branch if not equal: **bne**
- ***Unconditional branches***
  - jump: **`j,b`**
  - jump register: **`jr`**
  - jump and link: **`jal`**

Conditional Branching

beq $s0, $s1, label	if $s0==$s1 goto label
bne $s0, $s1, label	if $s0!=$s1 goto label
bge $s0, $s1, label	if $s0>=$s1 goto label
bgt $s0, $s1, label	if $s0> $s1 goto label
ble $s0, $s1, label	if $s0<=$s1 goto label
blt $s0, $s1, label	if $s0<$s1 goto label
bgez $s0, label	if $s0>=0 goto label
bgtz $s0, label	if $s0> 0 goto label
blez $s0, label	if $s0<=0 goto label
bltz $s0, label	if $s0< 0 goto label
bnez $s0, label	if $s0!=0 goto label
beqz $s0, label	if $s0==0 goto label

Conditional Branching (beq)

```
# MIPS assembly
 addi   $s0,  $0, 4
 addi   $s1,  $0, 1
 sll    $s1,  $s1,   2
 beq    $s0,  $s1,   target
 addi   $s1,  $s1,   1
 sub    $s1,  $s1,   $s0

target:
 add  $s1, $s1, $s0
```

Blackboard

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

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

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

The Branch Not Taken (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
```

29

Unconditional Branching / Jumping (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
```

30

Unconditional Branching (jr)

```
# MIPS assembly
0x00002000      addi   $s0,   $0,  0x2010       # load 0x2010 to $s0
0x00002004      jr     $s0                      # jump to $s0
0x00002008      addi   $s1,   $0,  1            # not executed
0x0000200C      sra    $s1,  $s1, 2             # not executed
0x00002010      lw     $s3,  44($s1)            # program continues
```

31

High-Level Code Constructs

- `if` statements
- `if/else` statements
- `while` loops
- `for` loops

32

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
```


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, L1
    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)**

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
```


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:
```

While Loops

High-level code

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

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

MIPS assembly code

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

37

While Loops

High-level code

```
// determines the power
// of x such that 2x = 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)**

38

For Loops

The general form of a for loop is:

```
for (initialization; condition; loop operation)
  loop body
```

- `initialization`: **executes before the loop begins**
- `condition`: **is tested at the beginning of each iteration**
- `loop operation`: **executes at the end of each iteration**
- `loop body`: **executes each time the condition is met**

For Loops

High-level code

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

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

MIPS assembly code

```
# $s0 = i, $s1 = sum
```

For Loops

High-level code

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

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

MIPS assembly code

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

- **Notice that the assembly tests for the opposite case (i == 10) than the test in the high-level code (i != 10)**

41

Less Than Comparisons

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

```
# $s0 = i, $s1 = sum
```

42

Less Than Comparisons

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

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

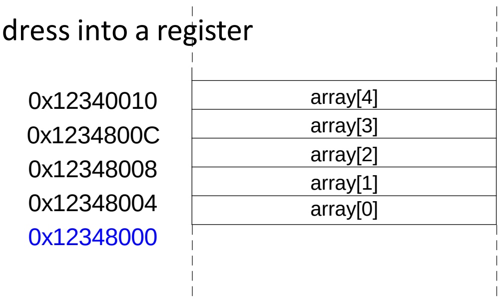
- **$t1 = 1 if i < 101**

Arrays

- **Useful for accessing large amounts of similar data**
- **Array element: accessed by index**
- **Array size: number of elements in the array**

Arrays

- **5-element array**
- **Base address = `0x12348000`**
  (address of the first array element, array[0])
- **First step in accessing an array:**
  - Load base address into a register



Arrays

High-level code

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

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
```

Arrays

High-level code

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

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
 lui    $s0,  0x1234          #  upper  $s0
 ori    $s0,  $s0, 0x8000     #  lower  $s0
```

47

Arrays

High-level code

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

MIPS Assembly code

```
# MIPS assembly code
# array base address = $s0

# Initialize $s0 to 0x12348000
lui   $s0, 0x1234            # upper $s0
ori   $s0, $s0, 0x8000 # lower $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
```

48

Arrays Using For Loops

High-level code

```
// high-level code int
arr[1000];  int i;

for (i = 0; i < 1000; i = i + 1)
    arr[i] = arr[i] * 8;
```

MIPS Assembly code

```
# $s0 = array base, $s1 = i
lui  $s0, 0x23B8         # upper $s0
ori   $s0, $s0, 0xF000 # lower $s0
```

49

Arrays Using For Loops

High-level code

```
// high-level code int
arr[1000];  int i;

for (i = 0; i < 1000; i = i + 1)
    arr[i] = arr[i] * 8;
```


MIPS Assembly code

```
# $s0 = array base, $s1 = i
lui  $s0, 0x23B8         # upper $s0
ori   $s0, $s0, 0xF000 # lower $s0

addi $s1, $0, 0    # i = 0
addi $t2, $0, 1000 # $t2 = 1000

loop:
slt  $t0, $s1, $t2 # i < 1000?
beq     $t0,  $0, done    # if not done
sll     $t0,  $s1, 2      # $t0=i * 4
add     $t0,  $t0, $s0    # addr of arr[i]
lw      $t1,  0($t0)      # $t1=arr[i]
sll     $t1,  $t1, 3      # $t1=arr[i]*8
sw      $t1,  0($t0)      # arr[i] = $t1
addi    $s1,  $s1, 1      # i = i + 1
j       loop              # repeat
done:
```

50

Procedures

- **Definitions**
  - ***Caller:*** calling procedure (in this case, main)
  - ***Callee:*** called procedure (in this case, sum)

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

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


Procedure Calling Conventions

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

MIPS Procedure Calling Conventions

- **Call procedure:**
  - jump and link (`jal`)
- **Return from procedure:**
  - jump register (`jr`)
- **Argument values:**
  - `$a0 - $a3`
- **Return value:**
  - `$v0`

53

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
```

- ***void*** **means that simple doesn't return a value**

54

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 in the return address register (`$ra`)**
  - In this case, `$ra` = `0x00400204` after `jal` executes
- **`jr $ra`: jumps to address in `$ra`**
  - in this case jump to address `0x00400204`

55

Input Arguments and Return Values

- **MIPS conventions:**
  - Argument values: `$a0 - $a3`
  - Return value: `$v0`

56

Input Arguments and Return Values

```c
// High-level code
int main()
{
  int y;
  ...
  // 4 arguments
  y = diffofsums(2, 3, 4, 5);
  ...
}
int diffofsums(int f, int g,
  int h, int i)
{
  int result;
  result = (f + g) - (h + i);
  return result; // return value
}
```

```
# MIPS assembly code #
$s0 = y

  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 $t0, $a0, $a1       # $t0 = f + g #
  add $t1, $a2, $a3       $t1 = h + i
  sub $s0, $t0, $t1       # result = (f + g) - (h + i) #
  add $v0, $s0, $0 jr     put return value in $v0
      $ra                 # return to caller
```

57

Input Arguments and Return Values

```
# $s0 = result
diffofsums:
  add  $t0,  $a0,  $a1    # $t0 = f + g
  add  $t1,  $a2,  $a3    # $t1 = h + i
  sub  $s0,  $t0,  $t1    # result = (f + g) - (h + i)
  add  $v0,  $s0,  $0     # put return value in $v0
  jr   $ra                # return to caller
```

- `diffofsums` **overwrote 3 registers: `$t0`, `$t1`, and `$s0`**
- `diffofsums` **can use the *stack* to temporarily store registers (comes next)**

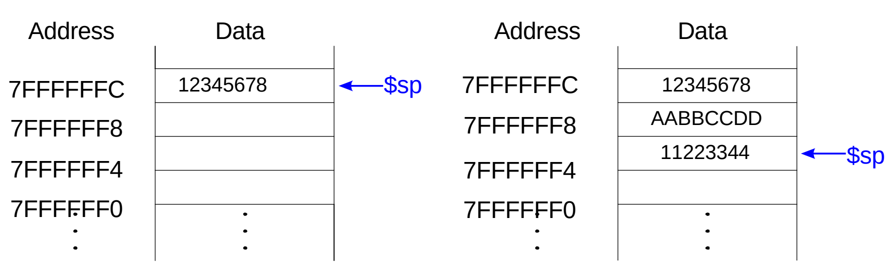
58

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



How Procedures use the Stack

- **Called procedures must have no other unintended side effects**
- **But `diffofsums` overwrites 3 registers: `$t0`, `$t1`, `$s0`**

```
# MIPS assembly # $s0 = result
diffofsums:

  add   $t0,   $a0,  $a1    # $t0 = f + g
  add   $t1,   $a2,  $a3    # $t1 = h + i
  sub   $s0,   $t0,  $t1    # result = (f + g) - (h + i)
  add   $v0,   $s0,  $0     # put return value in $v0
  jr    $ra                 # return to caller
```

61

Storing Register Values on the Stack

```
# $s0 = result
diffofsums:
   addi   $sp,   $sp, -12      # make space on stack
                               # to store 3 registers
   sw     $s0,   8($sp)        # save $s0 on stack
   sw     $t0,   4($sp)        # save $t0 on stack
   sw     $t1,   0($sp)        # save $t1 on stack
   add    $t0,   $a0, $a1      # $t0 = f + g
   add    $t1,   $a2, $a3      # $t1 = h + i
   sub    $s0,   $t0, $t1      # result = (f + g) - (h + i)
   add    $v0,   $s0, $0       # put return value in $v0
   lw     $t1,   0($sp)        # restore $t1 from stack
   lw     $t0,   4($sp)        # restore $t0 from stack
   lw     $s0,   8($sp)        # restore $s0 from stack
   addi   $sp,   $sp, 12       # deallocate stack space
   jr     $ra                  # return to caller
```

62