Fundamentals of Computer Systems
The MIPS Instruction Set

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Instruction Set
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So, Where Are We?

Application Software  COMS 3157, 4156, et al.
Operating Systems  COMS W4118
Architecture  Second Half of 3827
Micro-Architecture  Second Half of 3827
Logic  First Half of 3827
Digital Circuits  First Half of 3827
Analog Circuits  ELEN 3331
Devices  ELEN 3106
Physics  ELEN 3106 et al.
The Rest of the Semester: The Big Picture

Software

Hardware
The Rest of the Semester: The Big Picture

Software

Instruction Set Architecture (e.g., MIPS)

Hardware
The Rest of the Semester: The Big Picture

Software

- Instruction Set Architecture (e.g., MIPS)

Hardware

- Processor (CPU)
The Rest of the Semester: The Big Picture

Software

Instruction Set Architecture (e.g., MIPS)

Hardware

Processor (CPU)
int gcd(int a, int b) {
    while (a != b) {
        if (a > b) a = a - b;
        else b = b - a;
    }
    return a;
}
int gcd(int a, int b) {
    while (a != b) {
        if (a > b) a = a - b;
        else b = b - a;
    }
    return a;
}
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    while (a != b) {
        if (a > b) a = a - b;
        else b = b - a;
    }
    return a;
}
C → Assembly → Machine Code

```c
int gcd(int a, int b) {
    while (a != b) {
        if (a > b) a = a - b;
        else b = b - a;
    }
    return a;
}
```

```assembly
beq $a0, $a1, .L2
slt $v0, $a1, $a0
bne $v0, $zero, .L1
subu $a1, $a1, $a0
b gcd
.L1:
subu $a0, $a0, $a1
b gcd
.L2:
move $v0, $a0
jr $ra
```
al·go·rithm

a procedure for solving a mathematical problem (as of finding the greatest common divisor) in a finite number of steps that frequently involves repetition of an operation; broadly: a step-by-step procedure for solving a problem or accomplishing some end especially by a computer

Merriam-Webster
The Stored-Program Computer


“Since the device is primarily a computer, it will have to perform the elementary operations of arithmetics most frequently. [...] It is therefore reasonable that it should contain *specialized organs for just these operations*.

“If the device is to be [...] as nearly as possible all purpose, then a distinction must be made between the specific instructions given for and defining a particular problem, and the general control organs which see to it that these instructions [...] are carried out. The former must be *stored in some way* [...] the latter are represented by definite operating parts of the device.

“Any device which is to carry out long and complicated sequences of operations (specifically of calculations) *must have a considerable memory*. 
Instruction Set Architecture (ISA)

ISA: The interface or contact between the hardware and the software

Rules about how to code and interpret machine instructions:

- Execution model (program counter)
- Operations (instructions)
- Data formats (sizes, addressing modes)
- Processor state (registers)
- Input and Output (memory, etc.)
Architecture: The interface the hardware presents to the software

Microarchitecture: The detailed implementation of the architecture
MIPS

Microprocessor without Interlocked Pipeline Stages

RISC vs. CISC Architectures

MIPS is a Reduced Instruction Set Computer (RISC). Others include ARM, PowerPC, SPARC, HP-PA, and Alpha.

A Complex Instruction Set Computer (CISC) is one alternative. Intel’s x86 is the most prominent example; also Motorola 68000 and DEC VAX.

RISC’s underlying principles, due to Hennessy and Patterson:

- Simplicity favors regularity
- Make the common case fast
- Smaller is faster
- Good design demands good compromises
The GCD Algorithm

Euclid, *Elements*, 300 BC.

The greatest common divisor of two numbers does not change if the smaller is subtracted from the larger.

1. Call the two numbers $a$ and $b$
2. If $a$ and $b$ are equal, stop: $a$ is the greatest common divisor
3. Subtract the smaller from the larger
4. Repeat steps 2–4
The GCD Algorithm

Let’s be a little more explicit:

1. Call the two numbers $a$ and $b$
2. If $a$ equals $b$, go to step 8
3. if $a$ is less than $b$, go to step 6
4. Subtract $b$ from $a$  \[ a > b \text{ here} \]
5. Go to step 2
6. Subtract $a$ from $b$  \[ a < b \text{ here} \]
7. Go to step 2
8. Declare $a$ the greatest common divisor
9. Go back to doing whatever you were doing before
Euclid’s Algorithm in MIPS Assembly

gcd:

```
beq $a0, $a1, .L2  # if a = b, go to exit
sgt $v0, $a1, $a0  # Is b > a?
bne $v0, $zero, .L1 # Yes, goto .L1

subu $a0, $a0, $a1  # Subtract b from a (b < a)
```

```
gcd  # and repeat
```

```
.L1:

subu $a1, $a1, $a0  # Subtract a from b (a < b)
```

```
gcd  # and repeat
```

```
.L2:

move $v0, $a0  # return a
```

```
jr $ra  # Return to caller
```

Opcodes

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Euclid’s Algorithm in MIPS Assembly

gcd:

beq $a0, $a1, .L2  # if a = b, go to exit
sgt $v0, $a1, $a0  # Is b > a?
bne $v0, $zero, .L1  # Yes, goto .L1

subu $a0, $a0, $a1  # Subtract b from a (b < a)
b    gcd  # and repeat

.L1:

subu $a1, $a1, $a0  # Subtract a from b (a < b)
b    gcd  # and repeat

.L2:

move $v0, $a0  # return a
jr $ra  # Return to caller

Operands: Registers, etc.
Euclid’s Algorithm in MIPS Assembly

gcd:
beq  $a0, $a1, .L2       # if a = b, go to exit
sgt  $v0, $a1, $a0       # Is b > a?
bne  $v0, $zero, .L1     # Yes, goto .L1

subu $a0, $a0, $a1       # Subtract b from a (b < a)
b    gcd                # and repeat

.L1:
subu $a1, $a1, $a0       # Subtract a from b (a < b)
b    gcd                # and repeat

.L2:
move $v0, $a0            # return a
jr    $ra                # Return to caller
Euclid’s Algorithm in MIPS Assembly

gcd:
  beq $a0, $a1, .L2  # if a = b, go to exit
  sgt $v0, $a1, $a0  # Is b > a?
  bne $v0, $zero, .L1  # Yes, goto .L1

  subu $a0, $a0, $a1  # Subtract b from a (b < a)
  b  gcd  # and repeat

.L1:
  subu $a1, $a1, $a0  # Subtract a from b (a < b)
  b  gcd  # and repeat

.L2:
  move $v0, $a0  # return a
  jr  $ra  # Return to caller

Comments
Euclid’s Algorithm in MIPS Assembly

gcd:

beq $a0, $a1, .L2  # if a = b, go to exit
sgt $v0, $a1, $a0  # Is b > a?
bne $v0, $zero, .L1  # Yes, goto .L1

subu $a0, $a0, $a1  # Subtract b from a (b < a)
                # and repeat
b  gcd

.L1:

subu $a1, $a1, $a0  # Subtract a from b (a < b)
                # and repeat
b  gcd

.L2:

move $v0, $a0  # return a
jr  $ra  # Return to caller

Arithmetic Instructions
Euclid’s Algorithm in MIPS Assembly

gcd:
    beq $a0, $a1, .L2  # if a = b, go to exit
    sgt $v0, $a1, $a0  # Is b > a?
    bne $v0, $zero, .L1  # Yes, goto .L1

    subu $a0, $a0, $a1  # Subtract b from a (b < a)
    b  gcd  # and repeat

.L1:
    subu $a1, $a1, $a0  # Subtract a from b (a < b)
    b  gcd  # and repeat

.L2:
    move $v0, $a0  # return a
    jr $ra  # Return to caller

Control-transfer instructions
<table>
<thead>
<tr>
<th>Name</th>
<th>Number</th>
<th>Usage</th>
<th>Preserved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$zero</td>
<td>0</td>
<td>Constant zero</td>
<td></td>
</tr>
<tr>
<td>$at</td>
<td>1</td>
<td>Reserved (assembler)</td>
<td></td>
</tr>
<tr>
<td>$v0–$v1</td>
<td>2–3</td>
<td>Function result</td>
<td></td>
</tr>
<tr>
<td>$a0–$a3</td>
<td>4–7</td>
<td>Function arguments</td>
<td></td>
</tr>
<tr>
<td>$t0–$t7</td>
<td>8–15</td>
<td>Temporaries</td>
<td></td>
</tr>
<tr>
<td>$s0–$s7</td>
<td>16–23</td>
<td>Saved</td>
<td>yes</td>
</tr>
<tr>
<td>$t8–$t9</td>
<td>24–25</td>
<td>Temporaries</td>
<td></td>
</tr>
<tr>
<td>$k0–$k1</td>
<td>26–27</td>
<td>Reserved (OS)</td>
<td></td>
</tr>
<tr>
<td>$gp</td>
<td>28</td>
<td>Global pointer</td>
<td>yes</td>
</tr>
<tr>
<td>$sp</td>
<td>29</td>
<td>Stack pointer</td>
<td>yes</td>
</tr>
<tr>
<td>$fp</td>
<td>30</td>
<td>Frame pointer</td>
<td>yes</td>
</tr>
<tr>
<td>$ra</td>
<td>31</td>
<td>Return address</td>
<td>yes</td>
</tr>
</tbody>
</table>

Each 32 bits wide
Only 0 truly behaves differently; usage is convention
Types of Instructions

- **Computational**: Arithmetic and logical operations
- **Load and Store**: Writing and reading data to/from memory
- **Jump and branch**: Control transfer, often conditional
- **Miscellaneous**: Everything else
## Computational Instructions

<table>
<thead>
<tr>
<th>Arithmetic</th>
<th>Arithmetic (immediate)</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>add</code> Add</td>
<td><code>addi</code> Add immediate</td>
</tr>
<tr>
<td><code>addu</code> Add unsigned</td>
<td><code>addiu</code> Add immediate unsigned</td>
</tr>
<tr>
<td><code>sub</code> Subtract</td>
<td><code>slti</code> Set on l. t. immediate</td>
</tr>
<tr>
<td><code>subu</code> Subtract unsigned</td>
<td><code>sltiu</code> Set on less than unsigned</td>
</tr>
<tr>
<td><code>slt</code> Set on less than</td>
<td><code>andi</code> AND immediate</td>
</tr>
<tr>
<td><code>sltu</code> Set on less than unsigned</td>
<td><code>ori</code> OR immediate</td>
</tr>
<tr>
<td><code>and</code> AND</td>
<td><code>xor</code> Exclusive OR immediate</td>
</tr>
<tr>
<td><code>or</code> OR</td>
<td><code>nor</code> NOR</td>
</tr>
<tr>
<td><code>xor</code> Exclusive OR</td>
<td><code>lui</code> Load upper immediate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift Instructions</th>
<th>Multiply/Divide</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>sll</code> Shift left logical</td>
<td><code>mult</code> Multiply</td>
</tr>
<tr>
<td><code>srl</code> Shift right logical</td>
<td><code>multu</code> Multiply unsigned</td>
</tr>
<tr>
<td><code>sra</code> Shift right arithmetic</td>
<td><code>div</code> Divide</td>
</tr>
<tr>
<td><code>sllv</code> Shift left logical variable</td>
<td><code>divu</code> Divide unsigned</td>
</tr>
<tr>
<td><code>srlv</code> Shift right logical variable</td>
<td><code>mfhi</code> Move from HI</td>
</tr>
<tr>
<td><code>srav</code> Shift right arith. variable</td>
<td><code>mthi</code> Move to HI</td>
</tr>
<tr>
<td></td>
<td><code>mflo</code> Move from LO</td>
</tr>
<tr>
<td></td>
<td><code>mtlo</code> Move to LO</td>
</tr>
</tbody>
</table>
Computational Instructions

Arithmetic, logical, and other computations. Example:

\[ \text{add} \; t0, \; t1, \; t3 \]

“Add the contents of registers \( t1 \) and \( t3 \); store the result in \( t0 \)”

Register form:

\[ \text{operation } R_D, \; R_S, \; R_T \]

“Perform operation on the contents of registers \( R_S \) and \( R_T \); store the result in \( R_D \)”

Passes control to the next instruction in memory after running.
Arithmetic Instruction Example

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s0</td>
<td>$s1</td>
<td>$s2</td>
<td>$s3</td>
<td>$s4</td>
<td>$s5</td>
<td>$s6</td>
<td>$s7</td>
</tr>
</tbody>
</table>

a = b - c;

f = (g + h) - (i + j);

subu $s0, $s1, $s2
addu $t0, $s4, $s5
addu $t1, $s6, $s7
subu $s3, $t0, $t1

“Signed” addition/subtraction (add/sub) throw an exception on a two’s-complement overflow; “Unsigned” variants (addu/subu) do not. Resulting bit patterns otherwise identical.
Bitwise Logical Operator Example

```
li    $t0, 0xFF00FF00  # "Load immediate"
li    $t1, 0xF0F0F0F0  # "Load immediate"

nor   $t2, $t0, $t1   # Puts 0x000F000F in $t2

li    $v0, 1          # print_int
move  $a0, $t2        # print contents of $t2
syscall
```
Immediate Computational Instructions

Example:

\texttt{addiu \ $t0, \ $t1, \ 42}

“Add the contents of register $t1 and 42; store the result in register $t0”

In general,

\texttt{operation \ \textit{R}_D, \ \textit{R}_S, \ \textit{I}}

“Perform \textit{operation} on the contents of register $R_S$ and the signed 16-bit immediate \textit{I}; store the result in \textit{R}_D”

Thus, \textit{I} can range from $-32768$ to $32767$. 
32-Bit Constants and lui

It is easy to load a register with a constant from −32768 to 32767, e.g.,

    ori $t0, $0, 42

Larger numbers use “load upper immediate,” which fills a register with a 16-bit immediate value followed by 16 zeros; an OR handily fills in the rest. E.g., Load $t0 with 0xC0DEFACE:

    lui $t0, 0xC0DE
    ori $t0, $t0, 0xFACE

The assembler automatically expands the li pseudo-instruction into such an instruction sequence

    li $t1, 0xCAFE0B0E → lui $t1, 0xCAFE
    ori $t1, $t1, 0x0B0E
Multiplication and Division

Multiplication gives 64-bit result in two 32-bit registers: HI and LO. Division: LO has quotient; HI has remainder.

```c
int multdiv(
    int a, // $a0
    int b, // $a1
    unsigned c, // $a2
    unsigned d) // $a3
{
    a = a * b + c;
    c = c * d + a;
    a = a / c;
    b = b % a;
    c = c / d;
    d = d % c;

    return a + b + c + d;
}
```
Shift Left

Shifting left amounts to multiplying by a power of two. Zeros are added to the least significant bits. The constant form explicitly specifies the number of bits to shift:

\[
\text{sll} \ \$a0, \ $a0, \ 1
\]

The variable form takes the number of bits to shift from a register (mod 32):

\[
\text{sl}lv \ \$a1, \ $a0, \ $t0
\]
Shift Right Logical

The logical form of right shift adds 0’s to the MSB.

\( \text{srl \ $a0, \ $a0, \ 1} \)

\[ \begin{array}{cccccc}
    & & & 31 & 30 & \cdots \\
\end{array} \] \quad \begin{array}{cccc}
    & & & 2 & 1 & 0
\end{array}
Shift Right Arithmetic

The “arithmetic” form of right shift sign-extends the word by copying the MSB.

```
sra $a0, $a0, 2
```

31 30 29 28  ...  3 2 1 0
Set on Less Than

\[
\text{slt } \texttt{$t0, $t1, $t2}
\]

Set $t0$ to 1 if the contents of $t1 < t2$; 0 otherwise. $t1$ and $t2$ are treated as 32-bit signed two’s complement numbers.

```c
int compare(int a, /* $a0*/ int b, /* $a1*/ unsigned c, /* $a2*/ unsigned d) /* $a3*/
{
    int r = 0; /* $v0*/
    if (a < b) r += 42;
    if (c < d) r += 99;
    return r;
}
```

```
compare:
mov $v0, $zero
slt $t0, $a0, $a1
beq $t0, $zero, .L1
addi $v0, $v0, 42
.L1:
sltu $t0, $a2, $a3
beq $t0, $zero, .L2
addi $v0, $v0, 99
.L2:
j $ra
```
Load and Store Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lb</td>
<td>Load byte</td>
</tr>
<tr>
<td>lbu</td>
<td>Load byte unsigned</td>
</tr>
<tr>
<td>lh</td>
<td>Load halfword</td>
</tr>
<tr>
<td>lhu</td>
<td>Load halfword unsigned</td>
</tr>
<tr>
<td>lw</td>
<td>Load word</td>
</tr>
<tr>
<td>lwl</td>
<td>Load word left</td>
</tr>
<tr>
<td>lwr</td>
<td>Load word right</td>
</tr>
<tr>
<td>sb</td>
<td>Store byte</td>
</tr>
<tr>
<td>sh</td>
<td>Store halfword</td>
</tr>
<tr>
<td>sw</td>
<td>Store word</td>
</tr>
<tr>
<td>swl</td>
<td>Store word left</td>
</tr>
<tr>
<td>swr</td>
<td>Store word right</td>
</tr>
</tbody>
</table>

The MIPS is a load/store architecture: data must be moved into registers for computation.

Other architectures e.g., (x86) allow arithmetic directly on data in memory.
Memory on the MIPS

Memory is byte-addressed. Each byte consists of eight bits:

```
 7 6 5 4 3 2 1 0
```

Bytes have non-negative integer addresses. Byte addresses on the 32-bit MIPS processor are 32 bits; 64-bit processors usually have 64-bit addresses.

```
 0:  7 6 5 4 3 2 1 0
 1:  7 6 5 4 3 2 1 0
 2:  7 6 5 4 3 2 1 0
  ...
2^{32} - 1: 7 6 5 4 3 2 1 0
```

4 Gb total
There is only one way to refer to what address to load/store in MIPS: base + offset.

\[
\text{lb } \$t0, 34(\$t1)
\]

$\$t1: \begin{array}{c} 00000008 \end{array}$ (base register)

\[
= \begin{array}{c} 42: \text{EF} \end{array}
\]

$\$t0: \begin{array}{c} \text{FFFFFFFEF} \end{array}$

\[-32768 < \text{offset} < 32767\]
MIPS registers are 32 bits (4 bytes). Loading a byte into a register either clears the top three bytes or sign-extends them.

\[
\text{lbu } \text{t0}, 42(\text{t0}) \quad \text{42: F0} \\
\text{t0: 000000F0}
\]

\[
\text{lb } \text{t0}, 42(\text{t0}) \quad \text{42: F0} \\
\text{t0: FFFFFFFF0}
\]
The Endian Question

MIPS can also load and store 4-byte words and 2-byte halfwords.

The * endian question: when you read a word, in what order do the bytes appear?

Little Endian: Intel, DEC, et al.

Big Endian: Motorola, IBM, Sun, et al.

MIPS can do either

SPIM adopts its host’s convention
Testing Endianness

```
.data  # Directive: ‘‘this is data’’
myword:
  .word 0  # Define a word of data (=0)
.text  # Directive: ‘‘this is program’’
main:
  la $t1, myword  # pseudoinstruction: load address
  li  $t0, 0x11
  sb  $t0, 0($t1)  # Store 0x11 at byte 0
  li  $t0, 0x22
  sb  $t0, 1($t1)  # Store 0x22 at byte 1
  li  $t0, 0x33
  sb  $t0, 2($t1)  # Store 0x33 at byte 2
  li  $t0, 0x44
  sb  $t0, 3($t1)  # Store 0x44 at byte 3
  lw  $t2, 0($t1)  # 0x11223344 or 0x44332211?
  j   $ra
```
Alignment

Word and half-word loads and stores must be *aligned*: words must start at a multiple of 4 bytes; halfwords on a multiple of 2.

Byte load/store has no such constraint.

\[
\begin{align*}
\text{lw} & \quad \text{t0}, \quad 4(0) \quad \# \quad \text{OK} \\
\text{lw} & \quad \text{t0}, \quad 5(0) \quad \# \quad \text{BAD: } 5 \mod 4 = 1 \\
\text{lw} & \quad \text{t0}, \quad 8(0) \quad \# \quad \text{OK} \\
\text{lw} & \quad \text{t0}, \quad 12(0) \quad \# \quad \text{OK} \\
\text{lh} & \quad \text{t0}, \quad 2(0) \quad \# \quad \text{OK} \\
\text{lh} & \quad \text{t0}, \quad 3(0) \quad \# \quad \text{BAD: } 3 \mod 2 = 1 \\
\text{lh} & \quad \text{t0}, \quad 4(0) \quad \# \quad \text{OK}
\end{align*}
\]
<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>j</td>
<td>Jump</td>
</tr>
<tr>
<td>jal</td>
<td>Jump and link</td>
</tr>
<tr>
<td>jr</td>
<td>Jump to register</td>
</tr>
<tr>
<td>jalr</td>
<td>Jump and link register</td>
</tr>
<tr>
<td>beq</td>
<td>Branch on equal</td>
</tr>
<tr>
<td>bne</td>
<td>Branch on not equal</td>
</tr>
<tr>
<td>blez</td>
<td>Branch on less than or equal to zero</td>
</tr>
<tr>
<td>bgtz</td>
<td>Branch on greater than zero</td>
</tr>
<tr>
<td>bltz</td>
<td>Branch on less than zero</td>
</tr>
<tr>
<td>bgez</td>
<td>Branch on greater than or equal to zero</td>
</tr>
<tr>
<td>bltzal</td>
<td>Branch on less than zero and link</td>
</tr>
<tr>
<td>bgezal</td>
<td>Branch on greater than or equal to zero and link</td>
</tr>
</tbody>
</table>
Jumps

The simplest form,

```
  j  mylabel
  # ...
mylabel:
  # ...
```

sends control to the instruction at \textit{mylabel}. Instruction holds a 26-bit constant multiplied by four; top four bits come from current PC. Uncommon.

Jump to register sends control to a 32-bit absolute address in a register:

```
  jr  $t3
```

Instructions must be four-byte aligned; the contents of the register must be a multiple of 4.
Jump and Link

Jump and link stores a return address in $ra for implementing subroutines:

```
jal mysub
  # Control resumes here after the jr
  # ...  
```

```
mysub:
  # ...
  jr $ra  # Jump back to caller
```

`jalr` is similar; target address supplied in a register.
Branches

Used for conditionals or loops. E.g., “send control to *myloop* if the contents of $t0$ is not equal to the contents of $t1$.”

```
myloop:
    # ...
    bne $t0, $t1, myloop
    # ...
```

*beq* is similar “branch if equal”

A “jump” supplies an absolute address; a “branch” supplies an offset to the program counter.

On the MIPS, a 16-bit signed offset is multiplied by four and added to the address of the next instruction.
Branches

Another family of branches tests a single register:

```
    bgez $t0, myelse  # Branch if $t0 positive
    # ...
```

myelse:
```
    # ...
```

Others in this family:

```
    blez        Branch on less than or equal to zero
    bgtz        Branch on greater than zero
    bltz        Branch on less than zero
    bltzal      Branch on less than zero and link
    bgez        Branch on greater than or equal to zero
    bgezal      Branch on greater than or equal to zero and link
```

“and link” variants also (always) put the address of the next instruction into $ra, just like `jal`.
syscall causes a system call exception, which the OS catches, interprets, and usually returns from.

SPIM provides simple services: printing and reading integers, strings, and floating-point numbers, \texttt{sbrk()} (memory request), and \texttt{exit()}.

\begin{verbatim}
   # prints "the answer = 5"
.data
str:
    .asciiz "the answer = "
.text
li $v0, 4    # system call code for print_str
la $a0, str  # address of string to print
syscall      # print the string

li $v0, 1    # system call code for print_int
li $a0, 5    # integer to print
syscall      # print it
\end{verbatim}
### Other Instructions

#### Exception Instructions
- **tge tl  ...**: Conditional traps
- **break**: Breakpoint trap, for debugging
- **eret**: Return from exception

#### Multiprocessor Instructions
- **ll sc**: Load linked/store conditional for atomic operations
- **sync**: Read/Write fence: wait for all memory loads/stores

#### Coprocessor 0 Instructions (System Mgmt)
- **lwr lw  ...**: Cache control
- **tlbr tblwi  ...**: TLB control (virtual memory)
- **...**: Many others (data movement, branches)

#### Floating-point Coprocessor Instructions
- **add.d sub.d  ...**: Arithmetic and other functions
- **lwcl swcl  ...**: Load/store to (32) floating-point registers
- **bctlt  ...**: Conditional branches
### Instruction Encoding

#### Register-type: \texttt{add, sub, xor, ...}

<table>
<thead>
<tr>
<th>op:6</th>
<th>rs:5</th>
<th>rt:5</th>
<th>rd:5</th>
<th>shamt:5</th>
<th>funct:6</th>
</tr>
</thead>
</table>

#### Immediate-type: \texttt{addi, ori, beq, ...}

<table>
<thead>
<tr>
<th>op:6</th>
<th>rs:5</th>
<th>rt:5</th>
<th>imm:16</th>
</tr>
</thead>
</table>

#### Jump-type: \texttt{j, jal ...}

| op:6 | addr:26 |
Register-type Encoding Example

\[
\begin{array}{cccccc}
\text{op:6} & \text{rs:5} & \text{rt:5} & \text{rd:5} & \text{shamt:5} & \text{funct:6} \\
\end{array}
\]

**add** $t0, s1, s2$

**add** encoding from the MIPS instruction set reference:

<table>
<thead>
<tr>
<th>SPECIAL</th>
<th>rs</th>
<th>rt</th>
<th>rd</th>
<th>0</th>
<th>ADD</th>
</tr>
</thead>
<tbody>
<tr>
<td>000000</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>100000</td>
</tr>
</tbody>
</table>

Since $t0$ is register 8; $s1$ is 17; and $s2$ is 18,

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>000000</td>
<td>10001</td>
<td>10010</td>
<td>01000</td>
<td>00000</td>
<td>100000</td>
<td></td>
</tr>
</tbody>
</table>
Register-type Shift Instructions

<table>
<thead>
<tr>
<th>op:6</th>
<th>rs:5</th>
<th>rt:5</th>
<th>rd:5</th>
<th>shamt:5</th>
<th>funct:6</th>
</tr>
</thead>
</table>

**sra** $t0$, $s1$, 5

**sra** encoding from the MIPS instruction set reference:

<table>
<thead>
<tr>
<th>SPECIAL</th>
<th>0</th>
<th>rt</th>
<th>rd</th>
<th>sa</th>
<th>SRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>000000</td>
<td>00000</td>
<td></td>
<td></td>
<td>000011</td>
<td>000011</td>
</tr>
</tbody>
</table>

Since $t0$ is register 8 and $s1$ is 17,

| 000000 | 00000 | 10010 | 01000 | 00101 | 000011 |
Immediate-type Encoding Example

<table>
<thead>
<tr>
<th>op:6</th>
<th>rs:5</th>
<th>rt:5</th>
<th>imm:16</th>
</tr>
</thead>
</table>

```addiu $t0, $s1, -42```

**addiu** encoding from the MIPS instruction set reference:

ADDIU 001001  
<table>
<thead>
<tr>
<th>rs</th>
<th>rt</th>
<th>immediate</th>
</tr>
</thead>
</table>

Since $t0$ is register 8 and $s1$ is 17,

| 001001 | 10001 | 01000 | 1111 1111 1101 0110 |
Jump-Type Encoding Example

<table>
<thead>
<tr>
<th>op:6</th>
<th>addr:26</th>
</tr>
</thead>
</table>

jal 0x5014

jal encoding from the MIPS instruction set reference:

| JAL 000011 | instr_index |

Instruction index is a word address

<p>| 000011 | 00 0000 0000 0000 0000 0100 0000 0101 |</p>
<table>
<thead>
<tr>
<th>Branch always</th>
<th>( b \ label ) → ( \text{beq }$0, $0, label$ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch if equal zero</td>
<td>( \text{beqz }s, \ label ) → ( \text{beq }s, $0, label$ )</td>
</tr>
<tr>
<td>Branch greater or equal</td>
<td>( \text{bge }s, t, \ label ) → ( \text{slt }$1, s, t$ ) ( \text{beq }$1, $0, label$ )</td>
</tr>
<tr>
<td>Branch greater or equal unsigned</td>
<td>( \text{bgeu }s, t, \ label ) → ( \text{sltu }$1, s, t$ ) ( \text{beq }$1, $0, label$ )</td>
</tr>
<tr>
<td>Branch greater than</td>
<td>( \text{bgt }s, t, \ label ) → ( \text{slt }$1, t, s$ ) ( \text{bne }$1, $0, label$ )</td>
</tr>
<tr>
<td>Branch greater than unsigned</td>
<td>( \text{bgtu }s, t, \ label ) → ( \text{sltu }$1, t, s$ ) ( \text{bne }$1, $0, label$ )</td>
</tr>
<tr>
<td>Branch less than</td>
<td>( \text{blt }s, t, \ label ) → ( \text{slt }$1, s, t$ ) ( \text{bne }$1, $0, label$ )</td>
</tr>
<tr>
<td>Branch less than unsigned</td>
<td>( \text{bltu }s, t, \ label ) → ( \text{sltu }$1, s, t$ ) ( \text{bne }$1, $0, label$ )</td>
</tr>
</tbody>
</table>
### Assembler Pseudoinstructions

<table>
<thead>
<tr>
<th>Description</th>
<th>Instruction 1</th>
<th>Instruction 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load immediate</td>
<td>\textbf{li} , d, , j</td>
<td>\rightarrow \textbf{ori} , d, , $0, , j$</td>
</tr>
<tr>
<td>[0 \leq j \leq 65535]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load immediate</td>
<td>\textbf{li} , d, , j</td>
<td>\rightarrow \textbf{addiu} , d, , $0, , j$</td>
</tr>
<tr>
<td>([-32768 \leq j &lt; 0)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load immediate</td>
<td>\textbf{li} , d, , j</td>
<td>\rightarrow \textbf{liu} , d, , \text{hi16}(j) \textbf{ori} , d, , d, , \text{lo16}(j)$</td>
</tr>
<tr>
<td>Move</td>
<td>\textbf{move} , d, , s</td>
<td>\rightarrow \textbf{or} , d, , s, , $0$</td>
</tr>
<tr>
<td>Multiply</td>
<td>\textbf{mul} , d, , s, , t</td>
<td>\rightarrow \textbf{mult} , s, , t \textbf{mflo} , d</td>
</tr>
<tr>
<td>Negate unsigned</td>
<td>\textbf{negu} , d, , s</td>
<td>\rightarrow \textbf{subu} , d, , $0, , s$</td>
</tr>
<tr>
<td>Set if equal</td>
<td>\textbf{seq} , d, , s, , t</td>
<td>\rightarrow \textbf{xor} , d, , s, , t \textbf{sltiu} , d, , d, , 1</td>
</tr>
<tr>
<td>Set if greater or equal</td>
<td>\textbf{sge} , d, , s, , t</td>
<td>\rightarrow \textbf{slt} , d, , s, , t \textbf{xori} , d, , d, , 1</td>
</tr>
<tr>
<td>Set if greater or equal unsigned</td>
<td>\textbf{sgeu} , d, , s, , t</td>
<td>\rightarrow \textbf{sltu} , d, , s, , t \textbf{xori} , d, , d, , 1</td>
</tr>
<tr>
<td>Set if greater than</td>
<td>\textbf{sgt} , d, , s, , t</td>
<td>\rightarrow \textbf{slt} , d, , t, , s</td>
</tr>
</tbody>
</table>
Expressions

Initial expression:

\[ x + y + z \times (w + 3) \]

Reordered to minimize intermediate results; fully parenthesized to make order of operation clear.

\[((w + 3) \times z) + y\] + x

```
addiu $t0, $a0, 3  # w: $a0
mul $t0, $t0, $a3  # x: $a1
addu $t0, $t0, $a2  # y: $a2
addu $t0, $t0, $a1  # z: $a3
```

Consider an alternative:

\[(x + y) + ((w + 3) \times z)\]

```
addu $t0, $a1, $a2
addiu $t1, $a0, 3  # Need a second temporary
mul $t1, $t1, $a3
addu $t0, $t0, $t1
```
Conditionals

\[
\text{if } ((x + y) < 3) \quad x = x + 5; \\
\text{else} \quad y = y + 4;
\]

\[
\begin{align*}
\text{addu} & \quad t0, a0, al \quad # x + y \\
\text{slti} & \quad t0, t0, 3 \quad # (x+y)<3 \\
\text{beq} & \quad t0, 0, ELSE \\
\text{addiu} & \quad a0, a0, 5 \quad # x += 5 \\
\text{b} & \quad DONE \\
\text{ELSE:} & \quad \text{addiu} \quad a1, a1, 4 \quad # y += 4 \\
\text{DONE:} & \quad \text{DONE}
\end{align*}
\]
Do-While Loops

Post-test loop: body always executes once

```plaintext
a = 0;
b = 0;
do {
    a = a + b;
b = b + 1;
} while (b != 10);
```

```assembly
move $a0, $0 # a = 0
move $a1, $0 # b = 0
li $t0, 10 # load constant

TOP:
addu $a0, $a0, $a1 # a = a + b
addiu $a1, $a1, 1 # b = b + 1
bne $a1, $t0, TOP # b != 10?
```
While Loops

Pre-test loop: body may never execute

```
a = 0;
b = 0;
while (b != 10) {
a = a + b;
b = b + 1;
}
```

```
mov $a0, $0  # a = 0
mov $a1, $0  # b = 0
lit $t0, 10
bte TEST    # test first

BODY:
addu $a0, $a0, $a1  # a = a + b
addiu $a1, $a1, 1  # b = b + 1

TEST:
bne $a1, $t0, BODY  # b != 10?
```
For Loops

“Syntactic sugar” for a while loop

```
for (a = b = 0; b != 10; b++)
    a += b;
```

is equivalent to

```
a = b = 0;
while (b != 10) {
    a = a + b;
    b = b + 1;
}
```

```
move $a1, $0 # b = 0
move $a0, $a1 # a = b
li $t0, 10
b TEST # test first

BODY:
    addu $a0, $a0, $a1 # a = a + b
    addiu $a1, $a1, 1 # b = b + 1

TEST:
    bne $a1, $t0, BODY # b != 10?
```
Arrays

```c
int a[5];

void main() {
}
```

```
.text
main:
    la $t0, a       # Address of a
    li $t1, 3
    sw $t1, 0($t0) # a[0]
    sw $t1, 4($t0) # a[1]
    sw $t1, 8($t0) # a[2]
    sw $t1, 12($t0) # a[3]
    sw $t1, 16($t0) # a[4]
    lw $t1, 8($t0) # a[2]
    sll $t1, $t1, 2  # * 4
    sw $t1, 4($t0) # a[1]
    lw $t1, 16($t0) # a[4]
    sll $t1, $t1, 1  # * 2
    sw $t1, 12($t0) # a[3]
    jr $ra
```

```
.comm a, 20 # Allocate 20
```
Summing the contents of an array

```c
int i, s, a[10];
for (s = i = 0 ; i < 10 ; i++)
  s = s + a[i];

move $a1, $0  # i = 0
move $a0, $a1  # s = 0
li $t0, 10
la $t1, a  # base address of array
b TEST

BODY:
  sll $t3, $a1, 2  # i * 4
  addu $t3, $t1, $t3  # &a[i]
  lw $t3, 0($t3)  # fetch a[i]
  addu $a0, $a0, $t3  # s += a[i]
  addiu $a1, $a1, 1

TEST:
  sltu $t2, $a1, $t0  # i < 10?
  bne $t2, $0, BODY
```

Summing the contents of an array

```c
int s, *i, a[10];
for (s=0, i = a+9 ; i >= a ; i--)
    s += *i;
```

```assembly
move $a0, $0          # s = 0
la      $t0, a        # &a[0]
addiu    $t1, $t0, 36  # i = a + 9
b TEST

BODY:
    lw      $t2, 0($t1)   # *i
    addu    $a0, $a0, $t2  # s += *i
    addiu    $t1, $t1, -4  # i--

TEST:
    sltu    $t2, $t1, $t0  # i < a
    beq      $t2, $0, BODY
```

Strings: Hello World in SPIM

# For SPIM: "Enable Mapped I/O" must be set
# under Simulator/Settings/MIPS

.data
hello:
    .asciiz "Hello World!\n"

.text
main:
    la $t1, 0xffff0000  # I/O base address
    la $t0, hello
wait:
    lw $t2, 8($t1)     # Read Transmitter control
    andi $t2, $t2, 0x1 # Test ready bit
    beq $t2, $0, wait
    lbu $t2, 0($t0)    # Read the byte
    beq $t2, $0, done  # Check for terminating 0
    sw $t2, 12($t1)    # Write transmit data
    addiu $t0, $t0, 1  # Advance to next character
    b wait
done:
    jr $ra
Hello World in SPIM: Memory contents

[00400024] 3c09ffff  lui  $9, -1
[00400028] 3c081001  lui  $8, 4097 [hello]
[0040002c] 8d2a0008  lw  $10, 8($9)
[00400030] 314a0001  andi  $10, $10, 1
[00400034] 1140fffe  beq  $10, $0, -8 [wait]
[00400038] 910a0000  lbu  $10, 0($8)
[0040003c] 11400004  beq  $10, $0, 16 [done]
[00400040] ad2a000c  sw  $10, 12($9)
[00400044] 25080001  addiu  $8, $8, 1
[00400048] 0401fff9  bgez  $0 -28 [wait]
[0040004c] 03e00008  jr  $31

[10010000] 6c6c6548 6f57206f  H e l l o  W o
[10010008] 21646c72 00000000a r l d ! . . . . .
<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:</td>
<td>NUL '\0'</td>
<td>DLE</td>
<td>0</td>
<td>@</td>
<td>P</td>
<td>'</td>
<td>p</td>
</tr>
<tr>
<td>1:</td>
<td>SOH</td>
<td>DC1</td>
<td>!</td>
<td>1</td>
<td>A</td>
<td>Q</td>
<td>a</td>
</tr>
<tr>
<td>2:</td>
<td>STX</td>
<td>DC2</td>
<td>&quot;</td>
<td>2</td>
<td>B</td>
<td>R</td>
<td>b</td>
</tr>
<tr>
<td>3:</td>
<td>ETX</td>
<td>DC3</td>
<td>#</td>
<td>3</td>
<td>C</td>
<td>S</td>
<td>c</td>
</tr>
<tr>
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<td>EOT</td>
<td>DC4</td>
<td>$</td>
<td>4</td>
<td>D</td>
<td>T</td>
<td>d</td>
</tr>
<tr>
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<td>ENQ</td>
<td>NAK</td>
<td>%</td>
<td>5</td>
<td>E</td>
<td>U</td>
<td>e</td>
</tr>
<tr>
<td>6:</td>
<td>ACK</td>
<td>SYN</td>
<td>&amp;</td>
<td>6</td>
<td>F</td>
<td>V</td>
<td>f</td>
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<tr>
<td>7:</td>
<td>BEL</td>
<td>\a</td>
<td>ETB</td>
<td>'</td>
<td>7</td>
<td>G</td>
<td>W</td>
</tr>
<tr>
<td>8:</td>
<td>BS</td>
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<td>CAN</td>
<td>(</td>
<td>8</td>
<td>H</td>
<td>X</td>
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<td>EM</td>
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<td>I</td>
<td>Y</td>
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<td>SUB</td>
<td>*</td>
<td>:</td>
<td>J</td>
<td>Z</td>
</tr>
<tr>
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<td>VT</td>
<td>\v</td>
<td>ESC</td>
<td>+</td>
<td>;</td>
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<td>[</td>
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<tr>
<td>C:</td>
<td>FF</td>
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<td>GS</td>
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<td>=</td>
<td>M</td>
<td>]</td>
</tr>
<tr>
<td>E:</td>
<td>SO</td>
<td>RS</td>
<td>.</td>
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<td>N</td>
<td>^</td>
<td>n</td>
</tr>
<tr>
<td>F:</td>
<td>SI</td>
<td>US</td>
<td>/</td>
<td>?</td>
<td>0</td>
<td>_</td>
<td>o</td>
</tr>
</tbody>
</table>
Subroutines

a.k.a. procedures, functions, methods, et al.

Code that can run by itself, then *resume whatever invoked it*.

Exist for three reasons:

- **Code reuse**
  Recurring computations aside from loops
  Function libraries

- **Isolation/Abstraction**
  Think Vegas:
  What happens in a function stays in the function.

- **Enabling Recursion**
  Fundamental to divide-and-conquer algorithms
Calling Conventions

# Call mysub: args in $a0,...,$a3
jal mysub
# Control returns here
# Return value in $v0 & $v1
# $s0,...,$s7, $gp, $sp, $fp, $ra unchanged
# $a0,...,$a3, $t0,...,$t9 possibly clobbered

mysub: # Entry point: $ra holds return address
# First four args in $a0, $a1, .., $a3

# ... body of the subroutine ...

# $v0, and possibly $v1, hold the result
# $s0,...,$s7 restored to value on entry
# $gp, $sp, $fp, and $ra also restored
jr $ra # Return to the caller
## The Stack

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x7FFFFFFFC</td>
<td>0x32640128</td>
</tr>
<tr>
<td>0x7FFFFFF8</td>
<td>0xCAFE0B0E</td>
</tr>
<tr>
<td>0x7FFFFFF4</td>
<td>0xDEADBEEF</td>
</tr>
<tr>
<td>0x7FFFFFF0</td>
<td>0xCODEFACE</td>
</tr>
<tr>
<td>0x7FFFFFFEC</td>
<td></td>
</tr>
</tbody>
</table>

$sp$ grows down

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void move(int src, int tmp, int dst, int n)
{
    if (n) {
        move(src, dst, tmp, n-1);
        printf("%d->%d\n", src, dst);
        move(tmp, src, dst, n-1);
    }
}
hmove:
  addiu $sp, $sp, -24
  beq $a3, $0, L1
  sw $ra, 0($sp)
  sw $s0, 4($sp)
  sw $s1, 8($sp)
  sw $s2, 12($sp)
  sw $s3, 16($sp)

Allocate 24 stack bytes:
multiple of 8 for alignment

Check whether n == 0

Save $ra, $s0, . . . , $s3 on the stack

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{src} & \text{tmp} & \text{dst} & n \\
\hline
\text{a0} & \text{a1} & \text{a2} & \text{a3} \\
\hline
\end{array}
\]
hmove:
  addiu $sp, $sp, -24
  beq $a3, $0, L1
  sw $ra, 0($sp)
  sw $s0, 4($sp)
  sw $s1, 8($sp)
  sw $s2, 12($sp)
  sw $s3, 16($sp)
  move $s0, $a0
  move $s1, $a1
  move $s2, $a2
  addiu $s3, $a3, -1

Save src in $s0
Save tmp in $s1
Save dst in $s2
Save n – 1 in $s3
hmove:

addiu $sp, $sp, -24
beq $a3, $0, L1
sw $ra, 0($sp)
sw $s0, 4($sp)
sw $s1, 8($sp)
sw $s2, 12($sp)
sw $s3, 16($sp)

move $s0, $a0
move $s1, $a1
move $s2, $a2
addiu $s3, $a3, -1
move $a1, $s2
move $a2, $s1
move $a3, $s3
jal hmove

Call
hmove(src, dst, tmp, n-1)
hmove:

```
addiu $sp, $sp, -24
beq $a3, $0, L1
sw $ra, 0($sp)
sw $s0, 4($sp)
sw $s1, 8($sp)
sw $s2, 12($sp)
sw $s3, 16($sp)
move $s0, $a0
move $s1, $a1
move $s2, $a2
addiu $s3, $a3, -1
move $a1, $s2
move $a2, $s1
move $a3, $s3
jal hmove
```

```
li $v0, 1 # print_int
move $a0, $s2
syscall
```

```
li $v0, 4 # print_str
la $a0, newline
syscall
```

Print src -> dst
Call

hmove(tmp, src, dst, n–1)
hmove:
  addiu $sp, $sp, -24
  beq $a3, $0, L1
  sw $ra, 0($sp)
  sw $s0, 4($sp)
  sw $s1, 8($sp)
  sw $s2, 12($sp)
  sw $s3, 16($sp)
  move $s0, $a0
  move $s1, $a1
  move $s2, $a2
  addiu $s3, $a3, -1
  move $s0, $a0
  move $s1, $a1
  move $s2, $a2
  addiu $s3, $a3, -1
  move $a1, $s2
  move $a2, $s1
  move $a3, $s3
  jal hmove
  li $v0, 1 # print_int
  move $a0, $s2
  syscall
  li $v0, 4 # print_str
  la $a0, newline
  syscall
  move $a0, $s1
  move $a1, $s0
  move $a2, $s2
  move $a3, $s3
  jal hmove
  lw $ra, 0($sp)
  lw $s0, 4($sp)
  lw $s1, 8($sp)
  lw $s2, 12($sp)
  lw $s3, 16($sp)

Restore variables
hmove:
  addiu $sp, $sp, -24
  beq $a3, $0, L1
  sw $ra, 0($sp)
  sw $s0, 4($sp)
  sw $s1, 8($sp)
  sw $s2, 12($sp)
  sw $s3, 16($sp)
  move $s0, $a0
  move $s1, $a1
  move $s2, $a2
  addiu $s3, $a3, -1
  move $a1, $s2
  move $a2, $s1
  move $a3, $s3
  jal hmove
  li $v0, 1 # print_int
  move $a0, $s2
  syscall
  li $v0,4 # print_str
  la $a0, newline
  syscall
  move $a0, $s1
  move $a1, $s0
  move $a2, $s2
  move $a3, $s3
  jal hmove
  lw $ra, 0($sp)
  lw $s0, 4($sp)
  lw $s1, 8($sp)
  lw $s2, 12($sp)
  lw $s3, 16($sp)
L1:
  addiu $sp, $sp, 24 # free
  jr $ra # return
.data
  li $v0, 1 # print_int
  move $a0, $s0
  syscall
  li $v0,4 # print_str
  la $a0, arrow
  syscall
  li $v0,1 # print_int
  move $a0, $s2
  syscall
  li $v0,4 # print_str
  la $a0, newline
  syscall
  move $a0, $s1
  move $a1, $s0
  move $a2, $s2
  move $a3, $s3
  jal hmove
  lw $ra, 0($sp)
  lw $s0, 4($sp)
  lw $s1, 8($sp)
  lw $s2, 12($sp)
  lw $s3, 16($sp)
L1:
  addiu $sp, $sp, 24 # free
  jr $ra # return
Factorial Example

```c
int fact(int n) {
    if (n < 1) return 1;
    else return (n * fact(n - 1));
}
```

fact:

```assembly
addiu $sp, $sp, -8  # allocate 2 words on stack
sw $ra, 4($sp)      # save return address
sw $a0, 0($sp)      # and n
slti $t0, $a0, 1    # n < 1?
beq $t0, $0, ELSE   # n < 1?
li $v0, 1           # Yes, return 1
addiu $sp, $sp, 8   # Pop 2 words from stack
jr $ra               # return
ELSE:
addiu $a0, $a0, -1  # No: compute n-1
jal fact             # recurse (result in $v0)
lw $a0, 0($sp)       # Restore n and
lw $ra, 4($sp)       # return address
mul $v0, $a0, $v0    # Compute n * fact(n-1)
addiu $sp, $sp, 8    # Pop 2 words from stack
jr $ra               # return
Memory Layout

0x7FFF FFFC
Stack

0x1000 8000
Heap

0x1000 0000
Static Data

0x1000 0000
Program Text

0x0040 0000
Reserved

0x0000 0000
Differences in Other ISAs

More or fewer general-purpose registers (E.g., Itanium: 128; 6502: 3)

Arithmetic instructions affect condition codes (e.g., zero, carry); conditional branches test these flags

Registers that are more specialized (E.g., x86)

More addressing modes (E.g., x86: 6; VAX: 20)

Arithmetic instructions that also access memory (E.g., x86; VAX)

Arithmetic instructions on other data types (E.g., bytes and halfwords)

Variable-length instructions (E.g., x86; ARM)

Predicated instructions (E.g., ARM, VLIW)

Single instructions that do much more (E.g., x86 string move, procedure entry/exit)