Instruction Set Architectures
MIPS
The GCD Algorithm
MIPS Registers
Types of Instructions
  Computational
  Load and Store
  Jump and Branch
  Other
Instruction Encoding
  Register-type
  Immediate-type
  Jump-type
Assembler Pseudoinstructions

Higher-Level Constructs
  Expressions
  Conditionals
  Loops
  Arrays
  Strings & Hello World
  ASCII
Subroutines
  Towers of Hanoi Example
  Factorial Example
Memory Layout
Differences in Other ISAs
Machine, Assembly, and C Code

000100001000010100000000000000111
00000000101001000000100000101010
00010100010000000000000000000011
00000000101001000010100000100011
00000100000000011111111111111100
00000000010000101001000000100011
00000100000000011111111111111010
0000000000001000000000001000001
000000111110000000000001000001000
Machine, Assembly, and C Code

```
000100001000010100000000000000111
beq $4, $5, 28
000000001010010000000010000000101010
slt $2, $5, $4
000101000100000000000000000000011
bne $2, $0, 12
00000000101001000010100000100011
subu $5, $5, $4
00000100000000011111111111111100
bgez $0 -16
00000000100001010010000000100011
subu $4, $4, $5
00000100000000011111111111111100
bgez $0 -24
000000000000100000100000100000100001
addu $2, $0, $4
00000011111000000000000000000001000
jr $31
```
Machine, Assembly, and C Code

```
000100001000010100000000000000111
beq $4, $5, 28
0000000010100100000100000101010
slt $2, $5, $4
0001010001000000000000000000011
bne $2, $0, 12
00000000101001000001000000101010
subu $5, $5, $4
00000100000000000111111111111100
bgez $0 -16
000000001000100000000000100011
subu $4, $4, $5
000001000000000001111111111111010
bgez $0 -24
000000000000000010000100000000001
addu $2, $0, $4
0000001111100000000000000000000001000
jr $31

gcd:
  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
  j  $ra
```
Machine, Assembly, and C Code

```assembly
00010000100001010000000000000111
000000001010010000100000101010
00010100010000000000000000000011
000000001010010000100000100011
000001000000000001111111111111100
00000000100001010010000000100011
00000100000000011111111111111100
00000000000001000001000000100001
00000111111111110000000000000001000

beq $4, $5, 28
slt $2, $5, $4
bne $2, $0, 12
subu $5, $5, $4
bgez $0 -16
subu $4, $4, $5
bgez $0 -24
addu $2, $0, $4
jr $31
```

gcd:
```
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
  j  $ra
```

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

**Architecture:**
The interface the hardware presents to the software

**Microarchitecture:**
The detailed implementation of the architecture
MIPS

Microprocessor without Interlocked Pipeline Stages

MIPS developed at Stanford by Hennessey et al. MIPS Computer Systems founded 1984. SGI acquired MIPS in 1992; spun it out in 1998 as MIPS Technologies. Now, mostly an embedded core competing with ARM. In many wireless WiFi routers.
MIPS is a Reduced Instruction Set Computer. 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 $a$ $\quad a > b$ here
5. Go to step 2
6. Subtract $a$ from $b$ $\quad a < b$ 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)
    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
    j $ra  # Return to caller

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
j   $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
    j     $ra            # Return to caller

Labels
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
    j $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)
    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
    j     $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
    j $ra # Return to caller

Control-transfer instructions
# General-Purpose Registers

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

<table>
<thead>
<tr>
<th><strong>Shift Instructions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>sll</strong> Shift left logical</td>
</tr>
<tr>
<td><strong>srl</strong> Shift right logical</td>
</tr>
<tr>
<td><strong>sra</strong> Shift right arithmetic</td>
</tr>
<tr>
<td><strong>sllv</strong> Shift left logical variable</td>
</tr>
<tr>
<td><strong>srlv</strong> Shift right logical variable</td>
</tr>
<tr>
<td><strong>srav</strong> Shift right arith. variable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Multiply/Divide</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>mult</strong> Multiply</td>
</tr>
<tr>
<td><strong>multu</strong> Multiply unsigned</td>
</tr>
<tr>
<td><strong>div</strong> Divide</td>
</tr>
<tr>
<td><strong>divu</strong> Divide unsigned</td>
</tr>
<tr>
<td><strong>mfhi</strong> Move from HI</td>
</tr>
<tr>
<td><strong>mthi</strong> Move to HI</td>
</tr>
<tr>
<td><strong>mflo</strong> Move from LO</td>
</tr>
<tr>
<td><strong>mtlo</strong> Move to LO</td>
</tr>
</tbody>
</table>
Computational Instructions

Arithmetic, logical, and other computations. Example:

```
add $t0, $t1, $t3
```

"Add the contents of registers $t1 and $t3; store the result in $t0"

Register form:

```
operation RD, RS, RT
```

"Perform operation on the contents of registers RS and RT; store the result in RD"

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 (\texttt{add/sub}) throw an exception on a two’s-complement overflow; “Unsigned” variants (\texttt{addu/subu}) do not. Resulting bit patterns identical.

Use \texttt{unsigned} to, \texttt{t1} actually unnecessary here.
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:

\[ \text{addiu } \$t0, \$t1, 42 \]

"Add the contents of register \$t1 and 42; store the result in register \$t0"

In general,

\[ \text{operation } R_D, R_S, I \]

"Perform \textit{operation} on the contents of register \( R_S \) and the signed 16-bit immediate \( I \); store the result in \( R_D \)"

Thus, \( I \) 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.,

\[
\text{li } \$t0, 42 \\
\text{ori } \$t0, \$0, 42
\]

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 \text{0xC0DEFACE}:

\[
\text{lui } \$t0, 0x\text{CODE} \\
\text{ori } \$t0, \$t0, 0xFACE
\]

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

\[
\text{li } \$t1, 0x\text{CAFE0BOE} \rightarrow \text{lui } \$t1, 0x\text{CAFE} \\
\text{ori } \$t1, \$t1, 0x\text{0BOE}
\]
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;
}
```

```
multdiv:
    mult $a0,$a1  # a * b
    mflo $t0
    addu $a0,$t0,$a2  # a = a*b + c
    mult $a2,$a3    # c * d
    mflo $t1
    addu $a2,$t1,$a0  # c = c*d + a
    div $0,$a1,$a0  # b % a
    mfhi $a1        # b = b%a
    divu $a2,$a3    # c / d
    mflo $a2        # c = c/d
    addu $t2,$a0,$a1  # a + b
    addu $t2,$t2,$a2  # (a+b) + c
    divu $a3,$a2    # d % c
    mfhi $a3        # d = d%c
    addu $v0,$t2,$a3  # ((a+b)+c) + d
    j $ra
```
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:

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

![Diagram showing bit shifting]

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

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

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

$srl \; \$a0, \$a0, \; 1$

```
  31  30  ...  2  1  0
  \empty  \empty  \empty  \empty  \empty  \empty
  0       \empty  \empty  \empty
```
Shift Right Arithmetic

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

\[ \text{sra} \ \$a0, \ \$a0, \ 2 \]

```
  31  30  29  28  ...
  ______________
    1  1  1  ...

  3  2  1  0
  ______________
```

31 30 29 28 ... 0
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;
}
```

```assembly
compare:
    move $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/Store Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
<th>Size (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lb</td>
<td>Load byte</td>
<td>8</td>
</tr>
<tr>
<td>lbu</td>
<td>Load byte unsigned</td>
<td>8</td>
</tr>
<tr>
<td>lh</td>
<td>Load halfword</td>
<td>16</td>
</tr>
<tr>
<td>lhu</td>
<td>Load halfword unsigned</td>
<td>16</td>
</tr>
<tr>
<td>lw</td>
<td>Load word</td>
<td>32</td>
</tr>
<tr>
<td>lwl</td>
<td>Load word left</td>
<td>32</td>
</tr>
<tr>
<td>lwr</td>
<td>Load word right</td>
<td>32</td>
</tr>
<tr>
<td>sb</td>
<td>Store byte</td>
<td>8</td>
</tr>
<tr>
<td>sh</td>
<td>Store halfword</td>
<td>16</td>
</tr>
<tr>
<td>sw</td>
<td>Store word</td>
<td>32</td>
</tr>
<tr>
<td>swl</td>
<td>Store word left</td>
<td>32</td>
</tr>
<tr>
<td>swr</td>
<td>Store word right</td>
<td>32</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
Base Addressing in MIPS

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

$lb \enspace $t0, 34($t1)$

$\text{in a register }$\text{t1: 00000008 (base register)}$

$\text{offset = reg + immediate offset}$

$\text{42: EF}$

$\text{16-bit signed}$

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

\[
\begin{align*}
&42: \text{F0} \\
&\text{lbu } \$t0, 42(\$0) \\
&\$t0: \text{000000F0} \\
&\text{always zero}
\end{align*}
\]

\[
\begin{align*}
&42: \text{F0} \\
&\text{lb } \$t0, 42(\$0) \\
&\$t0: \text{FFFFFFF0} \\
&\text{msb of the byte}
\end{align*}
\]
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

Word values:
1: 0 1
2: 22
3: 33
4: 44
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.

```
lw   $t0, 4($0)    # OK
lw   $t0, 5($0)    # BAD: 5 mod 4 = 1
lw   $t0, 8($0)    # OK
lw   $t0, 12($0)   # OK

lh   $t0, 2($0)    # OK
lh   $t0, 3($0)    # BAD: 3 mod 2 = 1
lh   $t0, 4($0)    # OK
```
### Jump and Branch Instructions

<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,

```assembly
j  mylabel
# ...
```

`mylabel:`

```assembly
# ...
```

sends control to the instruction at `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:

```assembly
jr  $t3
```

Instructions must be four-byte aligned; the contents of the register must be a multiple of 4.
Jump and link stores a return address in $ra for implementing subroutines:

```assembly
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:

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

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

Others in this family:

```assembly
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, sbrk() (memory request), and exit().

```assembly
# 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
```
## Other Instructions

### Exception Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>tge tlt</td>
<td>Conditional traps</td>
</tr>
<tr>
<td>break</td>
<td>Breakpoint trap, for debugging</td>
</tr>
<tr>
<td>eret</td>
<td>Return from exception</td>
</tr>
</tbody>
</table>

### Multiprocessor Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ll sc</td>
<td>Load linked/store conditional for atomic operations</td>
</tr>
<tr>
<td>sync</td>
<td>Read/Write fence: wait for all memory loads/stores</td>
</tr>
</tbody>
</table>

### Coprocessor 0 Instructions (System Mgmt)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lwr lw1</td>
<td>Cache control</td>
</tr>
<tr>
<td>tlbr tblwi</td>
<td>TLB control (virtual memory)</td>
</tr>
<tr>
<td>...</td>
<td>Many others (data movement, branches)</td>
</tr>
</tbody>
</table>

### Floating-point Coprocessor Instructions

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>add.d sub.d</td>
<td>Arithmetic and other functions</td>
</tr>
<tr>
<td>lwc1 swc1</td>
<td>Load/store to (32) floating-point registers</td>
</tr>
<tr>
<td>bct1t</td>
<td>Conditional branches</td>
</tr>
</tbody>
</table>
### Instruction Encoding

#### Register-type: `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>

32 bits

#### Immediate-type: `addi`, `subi`, `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: `j`, `jal` ...

<table>
<thead>
<tr>
<th>op:6</th>
<th>addr:26</th>
</tr>
</thead>
</table>
Register-type Encoding Example

```
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,

| 000000 | 10001 | 10010 | 01000 | 00000 | 100000 |
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>000000</th>
<th>rt</th>
<th>rd</th>
<th>sa</th>
<th>SRA 000011</th>
</tr>
</thead>
<tbody>
<tr>
<td>000000</td>
<td>000000</td>
<td>rt</td>
<td>rd</td>
<td>sa</td>
<td>SRA 000011</td>
<td></td>
</tr>
</tbody>
</table>

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

| 000000 | 000000 | 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:

<table>
<thead>
<tr>
<th>ADDIU</th>
<th>rs</th>
<th>rt</th>
<th>immediate</th>
</tr>
</thead>
<tbody>
<tr>
<td>001001</td>
<td>10001</td>
<td>01000</td>
<td>1111 1111 1101 0110</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>JAL 000011</th>
<th>instr_index</th>
</tr>
</thead>
</table>

Instruction index is a word address

| 000011 | 00 0000 0000 0001 0100 0000 0101 |
## Assembler Pseudoinstructions

<table>
<thead>
<tr>
<th>Branch Condition</th>
<th>Pseudoinstruction</th>
<th>Translation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch always</td>
<td><code>b label</code></td>
<td><code>beq $0, $0, label</code></td>
</tr>
<tr>
<td>Branch if equal zero</td>
<td><code>beqz s, label</code></td>
<td><code>beq s, $0, label</code></td>
</tr>
<tr>
<td>Branch greater or equal</td>
<td><code>bge s, t, label</code></td>
<td><code>slt $1, s, t</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>beq $1, $0, label</code></td>
</tr>
<tr>
<td>Branch greater or equal unsigned</td>
<td><code>bgeu s, t, label</code></td>
<td><code>slt $1, s, t</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>beq $1, $0, label</code></td>
</tr>
<tr>
<td>Branch greater than</td>
<td><code>bgt s, t, label</code></td>
<td><code>slt $1, t, s</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>bne $1, $0, label</code></td>
</tr>
<tr>
<td>Branch greater than unsigned</td>
<td><code>bgtu s, t, label</code></td>
<td><code>slt $1, t, s</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>bne $1, $0, label</code></td>
</tr>
<tr>
<td>Branch less than</td>
<td><code>blt s, t, label</code></td>
<td><code>slt $1, s, t</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>bne $1, $0, label</code></td>
</tr>
<tr>
<td>Branch less than unsigned</td>
<td><code>bltu s, t, label</code></td>
<td><code>slt $1, s, t</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>bne $1, $0, label</code></td>
</tr>
</tbody>
</table>
## Assembler Pseudoinstructions

<table>
<thead>
<tr>
<th>Operation</th>
<th>Pseudoinstruction</th>
<th>Equivalent Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load immediate 0 ≤ j ≤ 65535</td>
<td>\texttt{li d, j}</td>
<td>\texttt{ori d, $0, j}</td>
</tr>
<tr>
<td>Load immediate −32768 ≤ j &lt; 0</td>
<td>\texttt{li d, j}</td>
<td>\texttt{addiu d, $0, j}</td>
</tr>
<tr>
<td>Load immediate j</td>
<td>\texttt{li d, j}</td>
<td>\texttt{liu d, hi16(j)}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\texttt{ori d, d, lo16(j)}</td>
</tr>
<tr>
<td>Move</td>
<td>\texttt{move d, s}</td>
<td>\texttt{or d, s, $0}</td>
</tr>
<tr>
<td>Multiply</td>
<td>\texttt{mul d, s, t}</td>
<td>\texttt{mult s, t}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\texttt{mflo d}</td>
</tr>
<tr>
<td>Negate unsigned</td>
<td>\texttt{negu d, s}</td>
<td>\texttt{subu d, $0, s}</td>
</tr>
<tr>
<td>Set if equal</td>
<td>\texttt{seq d, s, t}</td>
<td>\texttt{xor d, s, t}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\texttt{slt d, d, 1}</td>
</tr>
<tr>
<td>Set if greater or equal</td>
<td>\texttt{sge d, s, t}</td>
<td>\texttt{slt d, s, t}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\texttt{xori d, d, 1}</td>
</tr>
<tr>
<td>Set if greater or equal unsigned</td>
<td>\texttt{sgeu d, s, t}</td>
<td>\texttt{sltu d, s, t}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>\texttt{xori d, d, 1}</td>
</tr>
<tr>
<td>Set if greater than</td>
<td>\texttt{sgt d, s, t}</td>
<td>\texttt{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.

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

\[ \text{addiu } \$t0, \$a0, 3 \quad \# w: \$a0 \]
\[ \text{mul } \$t0, \$t0, \$a3 \quad \# x: \$a1 \]
\[ \text{addu } \$t0, \$t0, \$a2 \quad \# y: \$a2 \]
\[ \text{addu } \$t0, \$t0, \$a1 \quad \# z: \$a3 \]

\[ \text{result} \]

Consider an alternative:

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

\[ \text{addu } \$t0, \$a1, \$a2 \]
\[ \text{addiu } \$t1, \$a0, 3 \quad \# \text{Need a second temporary} \]
\[ \text{mul } \$t1, \$t1, \$a3 \]
\[ \text{addu } \$t0, \$t0, \$t1 \]
if ((x + y) < 3)
    x = x + 5;
else
    y = y + 4;

addu $t0, $a0, $a1  # x + y
slti $t0, $t0, 3   # (x+y)<3
beq $t0, $0, ELSE
addiu $a0, $a0, 5  # x += 5
b    DONE

ELSE:
    addiu $a1, $a1, 4  # y += 4
DONE:
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?
    10
```
While Loops

Pre-test loop: body may never execute

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

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

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

bne $a1, $t0, BODY  # b != 10?

BODY:

```
```
For Loops

“Syntactic sugar” for a while loop

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

is equivalent to

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

```plaintext
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() {
}
```

```assembly
.comm a, 20  # Allocate 20
.text  # Program next
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, 1  # * 2
    lw $t1, 16($t0)  # a[4]
    sll $t1, $t1, 2  # * 4
    sw $t1, 4($t0)  # a[1]
    lw $t1, 12($t0)  # a[3]
    jr $ra
```

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10010010:</td>
<td>a[4]</td>
</tr>
<tr>
<td>0x1001000C:</td>
<td>a[3]</td>
</tr>
<tr>
<td>0x10010008:</td>
<td>a[2]</td>
</tr>
<tr>
<td>0x10010004:</td>
<td>a[1]</td>
</tr>
<tr>
<td>0x10010000:</td>
<td>a[0]</td>
</tr>
</tbody>
</table>
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
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!
"
.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] 1140ffff  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 0000000a r l d ! . . . . .
### ASCII

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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</table>
Subroutines

a.k.a. procedures, functions, methods, et al.
Code that can run 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>
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<tr>
<td>0x7FFFFFFFC</td>
<td>0x32640128</td>
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<tr>
<td>0x7FFFFFF8</td>
<td>0xCafe0B0E</td>
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<tr>
<td>0x7FFFFFF4</td>
<td>0xDEADBEEF</td>
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<tr>
<td>0x7FFFFFF0</td>
<td>0xCODEFACE</td>
</tr>
<tr>
<td>0x7FFFFFFEC</td>
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</tr>
</tbody>
</table>

Grows down

$sp$
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);
    }
}
Allocate 24 stack bytes:
- multiple of 8 for alignment
- Check whether n == 0
- Save $ra, $s0, ..., $s3 on the stack
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               \text{Save src in $s0}
    move $s1, $a1               \text{Save tmp in $s1}
    move $s2, $a2               \text{Save dst in $s2}
    addiu $s3, $a3, -1          \text{Save n – 1 in $s3}
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
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

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)
  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
li $v0, 1 # print_int
move $a0, $s2
syscall
li $v0, 4 # print_str
la $a0, arrow
syscall

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
arrow: .asciiz "->"
newline: .asciiz "\n"
Factorial Example

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

```
fact:
    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
    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

2 GB

0x7FFF FFFC

Stack

Heap

0x1000 8000

Static Data

0x1000 0000

Program Text

0x0040 0000

Reserved

0x0000 0000

$gp

$sp

pc
Differences in Other ISAs

More or fewer general-purpose registers (Itanium: 128; 6502: 3)

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

Registers that are more specialized (x86)

More addressing modes (x86: 6; VAX: 20)

Arithmetic instructions that also access memory (x86; VAX)

Arithmetic instructions on other data types (bytes and halfwords)

Variable-length instructions (x86; ARM)

Predicated instructions (ARM, VLIW)

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