

Fundamentals of Computer Systems

The MIPS Instruction Set

Stephen A. Edwards

Columbia University

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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

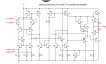
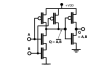
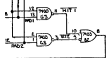
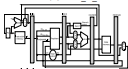
Memory Layout

Differences in Other ISAs

So, Where Are We?



```
;; voice 1 wave select
ld      a, (#CHI_W_NUM)
and    a
ld      a, (#CHI_W_SEL)
jrc    nz, #00b4
ld      a, (#CHI_E_TABLE0)
```



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

Instruction Set Architecture (e.g, MIPS)

Hardware

Processor (CPU)

C → Assembly → Machine Code

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

C → Assembly → Machine Code

Compiler



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

```
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 → Assembly → Machine Code

Compiler

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

Assembler

```
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
```

C → Assembly → Machine Code

Compiler

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

```
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
```

Assembler

```
00010000100001010000000000000111
00000000101001000001000000101010
0001010001000000000000000000011
00000000101001000010100000100011
00000100000000111111111111111100
00000000100001010010000000100011
00000100000000011111111111111010
00000000000001000001000000100001
00000011111000000000000000001000
```

```
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
```


Algorithms

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

John von Neumann, *First Draft of a Report on the EDVAC*, 1945.

“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

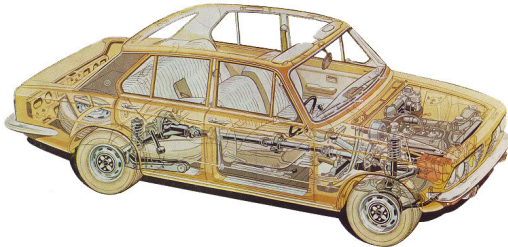
Rules about how to code and interpret machine instructions:

- ▶ 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



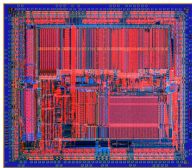
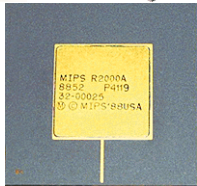
Microarchitecture:
The detailed implementation of the architecture

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.



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 $a > b$ here
5. Go to step 2
6. Subtract a from b $a < b$ 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

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

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

Arithmetic	
add	Add
addu	Add unsigned
sub	Subtract
subu	Subtract unsigned
slt	Set on less than
sltu	Set on less than unsigned
and	AND
or	OR
xor	Exclusive OR
nor	NOR

Arithmetic (immediate)	
addi	Add immediate
addiu	Add immediate unsigned
slti	Set on l. t. immediate
sltiu	Set on less than unsigned
andi	AND immediate
ori	OR immediate
xori	Exclusive OR immediate
lui	Load upper immediate

Shift Instructions	
sll	Shift left logical
srl	Shift right logical
sra	Shift right arithmetic
sllv	Shift left logical variable
srlv	Shift right logical variable
srav	Shift right arith. variable

Multiply/Divide	
mult	Multiply
multu	Multiply unsigned
div	Divide
divu	Divide unsigned
mfhi	Move from HI
mthi	Move to HI
mflo	Move from LO
mtlo	Move to LO

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 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

a	b	c	f	g	h	i	j
\$s0	\$s1	\$s2	\$s3	\$s4	\$s5	\$s6	\$s7

```
a = b - c;          subu $s0, $s1, $s2
f = (g + h) - (i + j); 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:

addiu \$t0, \$t1, 42

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

In general,

operation R_D, R_S, I

“Perform *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.,

```
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 0xCODEFACE:

```
lui $t0, 0xCODE  
ori $t0, $t0, 0xFACE
```

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

```
li $t1, 0xCAFE0BOE → lui $t1, 0xCAFE  
ori $t1, $t1, 0x0BOE
```

Multiplication and Division

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

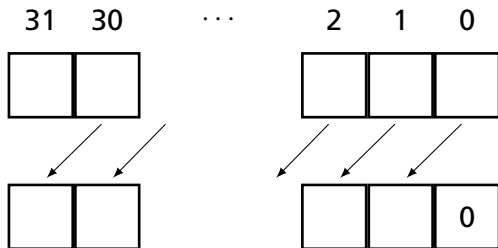
```
int multdiv(  
    int a,          // $a0  
    int b,          // $a1  
    unsigned c,    // $a2  
    unsigned d)    // $a3  
{  
    a = a * b + c;  
    c = c * d + a;  
  
    a = a / c;  
    b = b % a;  
    c = c / d;  
    d = d % c;  
  
    return a + b + c + d;  
}
```

```
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  
    divu $a0,$a2     # a / c  
    mflo $a0         # a = a/c  
    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:

```
sll $a0, $a0, 1
```



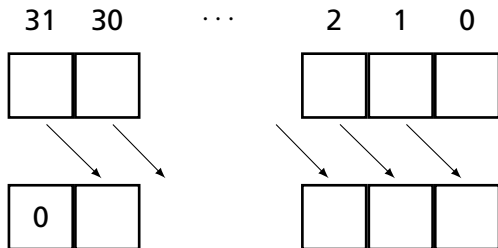
The variable form takes the number of bits to shift from a register (mod 32):

```
sllv $a1, $a0, $t0
```


Shift Right Logical

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

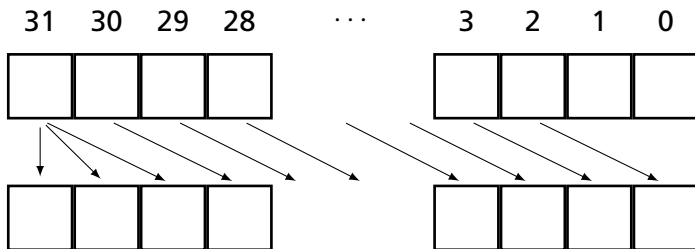
```
srl $a0, $a0, 1
```



Shift Right Arithmetic

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

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



Set on Less Than

```
slt $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.

```
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:
    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 and Store Instructions

Load/Store Instructions

lb	Load byte
lbu	Load byte unsigned
lh	Load halfword
lhu	Load halfword unsigned
lw	Load word
lwl	Load word left
lwr	Load word right
sb	Store byte
sh	Store halfword
sw	Store word
swl	Store word left
swr	Store word right

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

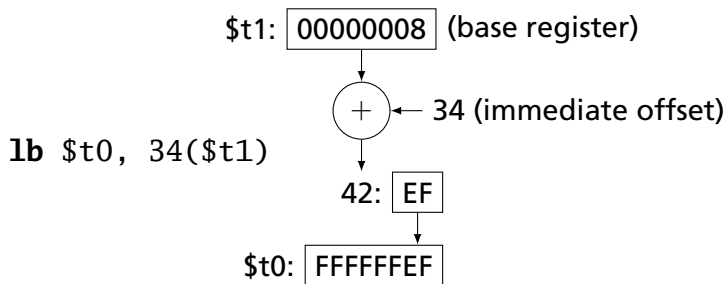
⋮

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

4 Gb total

Base Addressing in MIPS

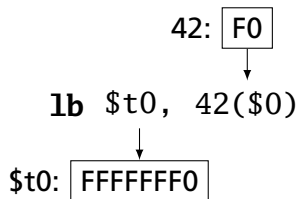
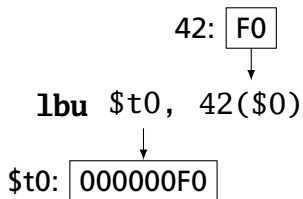
There is only one way to refer to what address to load/store in MIPS: base + offset.



$-32768 < \text{offset} < 32767$

Byte Load and Store

MIPS registers are 32 bits (4 bytes). Loading a byte into a register either clears the top three bytes or sign-extends them.



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?

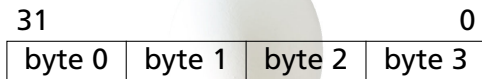
Little Endian: Intel, DEC, et al.

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

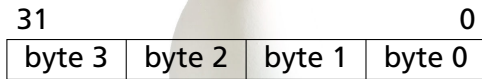
MIPS can do either

SPIM adopts its host's convention

Big Endian



Little Endian



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.

```
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
```

Byte load/store has no such constraint.

Jump and Branch Instructions

Jump and Branch Instructions

j	Jump
jal	Jump and link
jr	Jump to register
jalr	Jump and link register
beq	Branch on equal
bne	Branch on not equal
blez	Branch on less than or equal to zero
bgtz	Branch on greater than zero
bltz	Branch on less than zero
bgez	Branch on greater than or equal to zero
bltzal	Branch on less than zero and link
bgezal	Branch on greter than or equal to zero and link



Jumps

The simplest form,

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

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:

```
    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**.

Other Instructions

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()`.

```
# 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

tge tlt ...	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 lwl ...	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
lwc1 swc1 ...	Load/store to (32) floating-point registers
bct1t ...	Conditional branches

Instruction Encoding

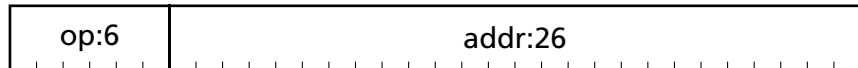
Register-type: **add**, **sub**, **xor**, ...



Immediate-type: **addi**, **ori**, **beq**, ...



Jump-type: **j**, **jal** ...



Register-type Encoding Example

op:6	rs:5	rt:5	rd:5	shamt:5	funct:6
------	------	------	------	---------	---------

add \$t0, \$s1, \$s2

add encoding from the MIPS instruction set reference:

SPECIAL 000000	rs	rt	rd	0 00000	ADD 100000
-------------------	----	----	----	------------	---------------

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

000000	10001	10010	01000	00000	100000
--------	-------	-------	-------	-------	--------

Register-type Shift Instructions

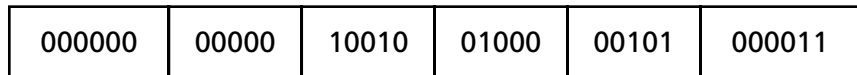


sra \$t0, \$s1, 5

sra encoding from the MIPS instruction set reference:



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



Immediate-type Encoding Example

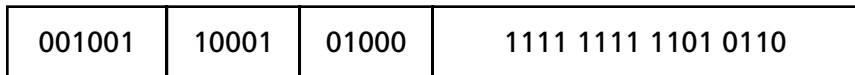


addiu \$t0, \$s1, -42

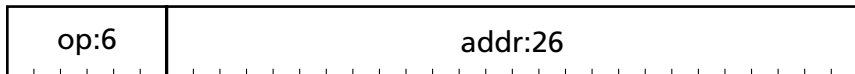
addiu encoding from the MIPS instruction set reference:



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

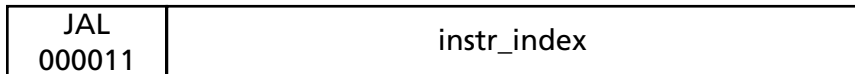


Jump-Type Encoding Example

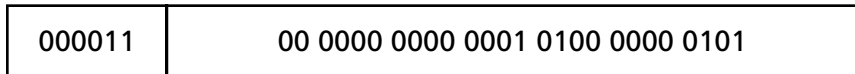


jal 0x5014

jal encoding from the MIPS instruction set reference:



Instruction index is a word address



Assembler Pseudoinstructions

Branch always	b label	→ beq \$0, \$0, label
Branch if equal zero	beqz s, label	→ beq s, \$0, label
Branch greater or equal	bge s, t, label	→ slt \$1, s, t beq \$1, \$0, label
Branch greater or equal unsigned	bgeu s, t, label	→ sltu \$1, s, t beq \$1, \$0, label
Branch greater than	bgt s, t, label	→ slt \$1, t, s bne \$1, \$0, label
Branch greater than unsigned	bgtu s, t, label	→ sltu \$1, t, s bne \$1, \$0, label
Branch less than	blt s, t, label	→ slt \$1, s, t bne \$1, \$0, label
Branch less than unsigned	bltu s, t, label	→ sltu \$1, s, t bne \$1, \$0, label

Assembler Pseudoinstructions

Load immediate $0 \leq j \leq 65535$	li d, j	→ ori $d, \$0, j$
Load immediate $-32768 \leq j < 0$	li d, j	→ addiu $d, \$0, j$
Load immediate	li d, j	→ liu $d, \text{hi16}(j)$ ori $d, d, \text{lo16}(j)$
Move	move d, s	→ or $d, s, \$0$
Multiply	mul d, s, t	→ mult s, t mflo d
Negate unsigned	negu d, s	→ subu $d, \$0, s$
Set if equal	seq d, s, t	→ xor d, s, t sltiu $d, d, 1$
Set if greater or equal	sge d, s, t	→ slt d, s, t xori $d, d, 1$
Set if greater or equal unsigned	sgeu d, s, t	→ sltu d, s, t xori $d, d, 1$
Set if greater than	sgt d, s, t	→ slt d, t, s

Expressions

Initial expression:

$$x + y + z * (w + 3)$$

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

$$(((w + 3) * z) + y) + x$$

```
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:

$$(x + y) + ((w + 3) * z)$$

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

Conditionals

```

                                addu  $t0, $a0, $a1 # x + y
                                slti  $t0, $t0, 3  # (x+y)<3
if ((x + y) < 3)               beq   $t0, $0, ELSE
    x = x + 5;                  addiu $a0, $a0, 5  # x += 5
else                             b     DONE
    y = y + 4;                  ELSE:
                                addiu $a1, $a1, 4  # y += 4
                                DONE:
```

Do-While Loops

Post-test loop: body always executes once

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

```
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;           move $a0, $0 # a = 0
b = 0;           move $a1, $0 # b = 0
while (b != 10) { li $t0, 10
    a = a + b;    b TEST # test first
    b = b + 1;    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

```
int a[5];
```

```
void main() {  
    a[4] = a[3] = a[2] =  
        a[1] = a[0] = 3;  
    a[1] = a[2] * 4;  
    a[3] = a[4] * 2;  
}
```

	⋮
0x10010010:	a[4]
0x1001000C:	a[3]
0x10010008:	a[2]
0x10010004:	a[1]
0x10010000:	a[0]
	⋮

```
.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, 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
```

Summing the contents of an array

```
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

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

```
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 0000000a r l d ! . . . .
```

ASCII

	0	1	2	3	4	5	6	7
0:	NUL '\0'	DLE		0	@	P	'	p
1:	SOH	DC1	!	1	A	Q	a	q
2:	STX	DC2	"	2	B	R	b	r
3:	ETX	DC3	#	3	C	S	c	s
4:	EOT	DC4	\$	4	D	T	d	t
5:	ENQ	NAK	%	5	E	U	e	u
6:	ACK	SYN	&	6	F	V	f	v
7:	BEL '\a'	ETB	'	7	G	W	g	w
8:	BS '\b'	CAN	(	8	H	X	h	x
9:	HT '\t'	EM	)	9	I	Y	i	y
A:	LF '\n'	SUB	*	:	J	Z	j	z
B:	VT '\v'	ESC	+	;	K	[	k	{
C:	FF '\f'	FS	,	<	L	\	l	|
D:	CR '\r'	GS	-	=	M	]	m	}
E:	SO	RS	.	>	N	^	n	~
F:	SI	US	/	?	O	_	o	DEL

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
```

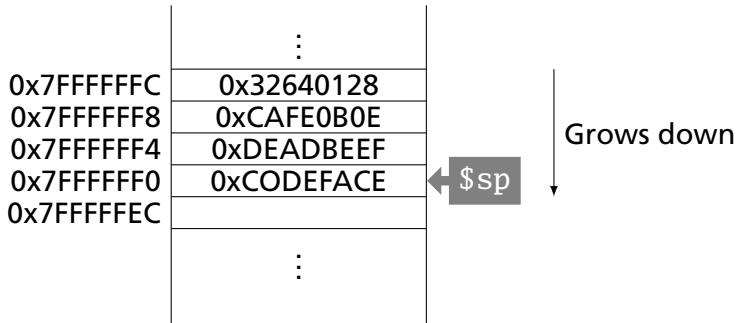
```
# ... body of the subroutine ...
```

```
# $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
```



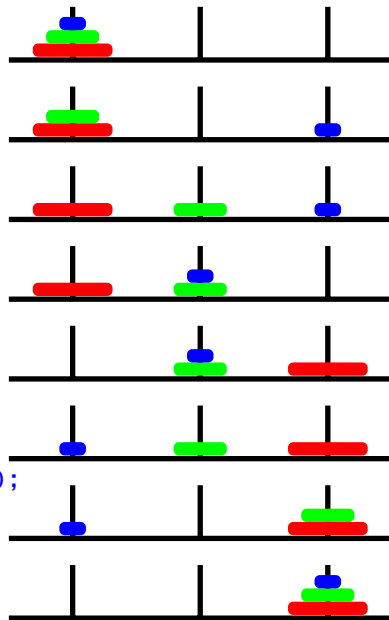
The Stack



Towers of Hanoi



```
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:

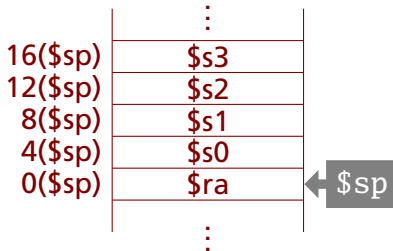
```
addiu $sp, $sp, -24
beq   $a3, $0, L1
sw    $ra, 0($sp)
sw    $s0, 4($sp)
sw    $s1, 8($sp)
sw    $s2, 12($sp)
sw    $s3, 16($sp)
```

\$a0	\$a1	\$a2	\$a3
src	tmp	dst	n

Allocate 24 stack bytes:
multiple of 8 for alignment

Check whether $n == 0$

Save $\$ra, \$s0, \dots, \$s3$ 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  
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, $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
```

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, $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

```

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  $a1, $s2
    move  $a2, $s1
    move  $a3, $s3
    jal   hmove

    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)

```

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, $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
    .data
arrow:  .asciiz "->"
newline: .asciiz "\n"

```

Factorial Example

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

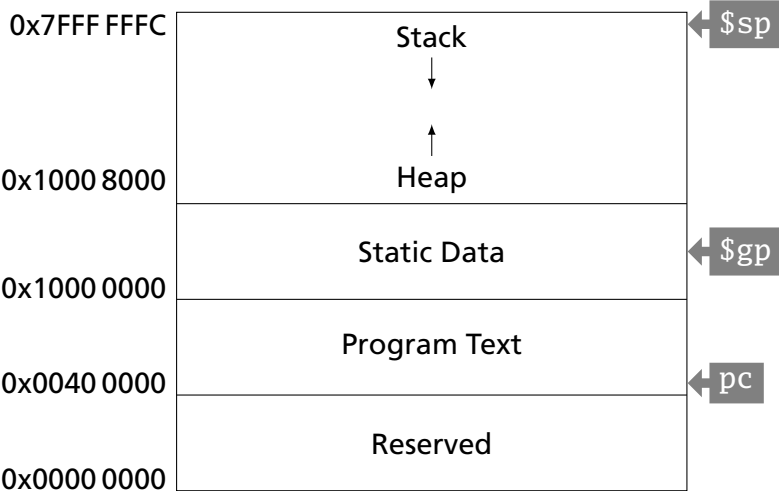
fact:

```
    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



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)