Fundamentals of Computer Systems

The MIPS Instruction Set

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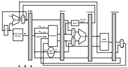
So, Where Are We?

Application Software — COMS 3157, 4156, et al.

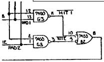
Operating Systems — COMS W4118

```
;; voice 1 wave select
ld      a,(#CH1_W_NUM)
and     a
ld      a,(#CH1_W_SEL)
jr      nz,#00b4
ld      a,(#CH1_E_TABLE0)
```

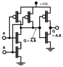
Architecture — Second Half of 3827



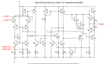
Micro-Architecture — Second Half of 3827



Logic — First Half of 3827

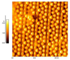


Digital Circuits — First Half of 3827



Analog Circuits — ELEN 3331

Devices — ELEN 3106



Physics — ELEN 3106 et al.

The Rest of the Semester: The Big Picture

Software

Hardware

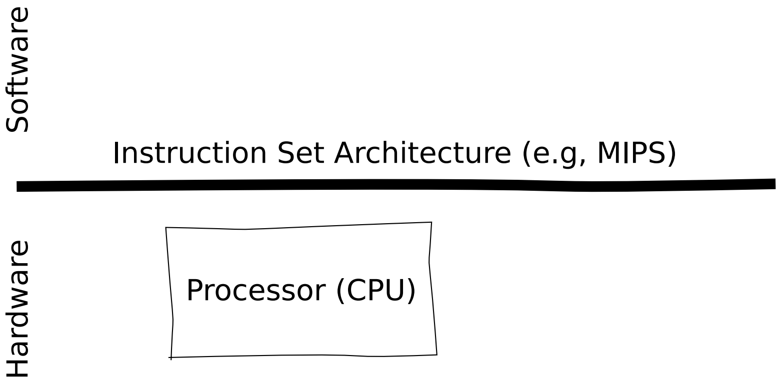
The Rest of the Semester: The Big Picture

Software

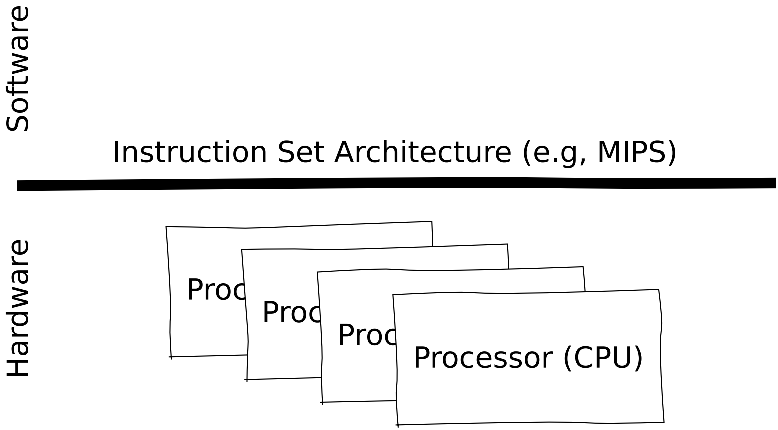
Instruction Set Architecture (e.g, MIPS)

Hardware

The Rest of the Semester: The Big Picture



The Rest of the Semester: The Big Picture



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

```c
int gcd(int a, int b)
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   while (a != b) {
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  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

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

```
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
```

```
00010000100001010000000000000111
00000000101001000001000000101010
00010100010000000000000000000011
00000000101001000010100000100011
00000100000000011111111111111100
00000000100001010010000000100011
00000100000000011111111111111010
00000000000001000001000000100001
00000011111000000000000000001000
```

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)

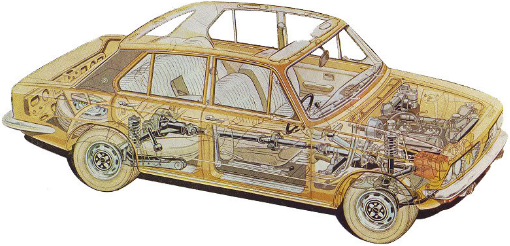
ISA: The interface or contact between the hardware and the software

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



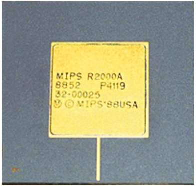
Microarchitecture:
The detailed implemention of the architecture

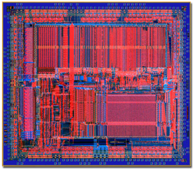
MIPS

Microprocessor without **I**nterlocked **P**ipeline **S**tages

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

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  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
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  bne  $v0, $zero, .L1 #  Yes, goto .L1

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

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  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
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  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)
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.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:

$$\textit{operation}\ R_D, R_S, R_T$$

"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;
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:

```
addiu $t0, $t1, 42
```

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

In general,

$$\textit{operation}\ R_D, R_S, I$$

"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 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.

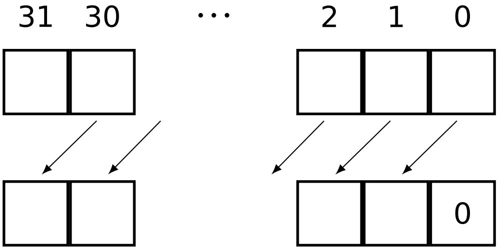
```c
int multdiv(
  int a,      // $a0
  int b,      // $a1
  unsigned c, // $a2
  unsigned d) // $a3
{
  a = a * b + c;
  c = c * d + a;

  a = a / c;
  b = b % a;
  c = c / d;
  d = d % c;

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

```
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



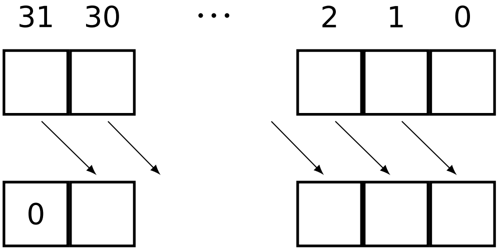
The variable form takes the number of bits to shift from a register (mod 32):

sllv $a1, $a0, $t0

Shift Right Logical

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

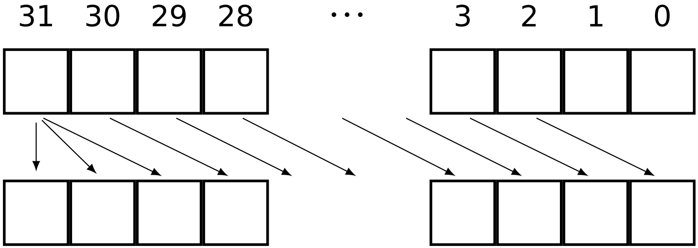
srl $a0, $a0, 1



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.

```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:
  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.

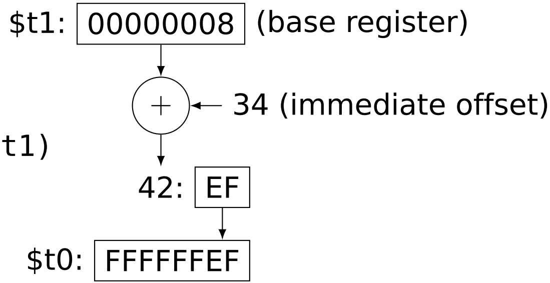
0:	7	6	5	4	3	2	1	0
1:	7	6	5	4	3	2	1	0
2:	7	6	5	4	3	2	1	0
⋮								
$2^{32}-1$:	7	6	5	4	3	2	1	0

4 Gb total

Base Addressing in MIPS

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

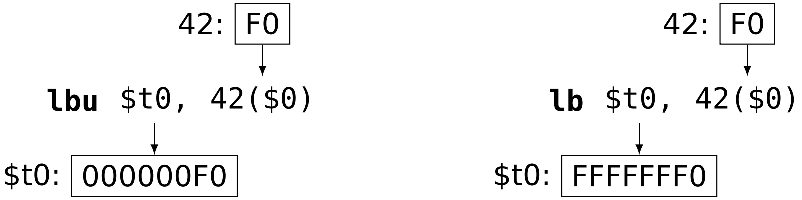
`lb $t0, 34($t1)`



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

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?

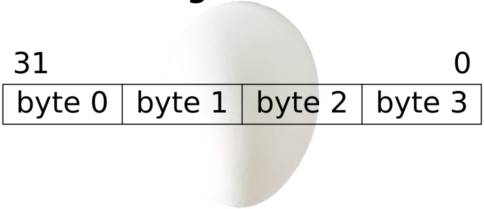
Little Endian: Intel, DEC, et al.

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

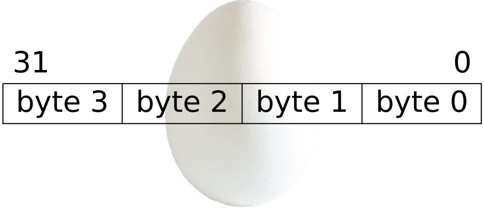
MIPS can do either

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.

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

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 greter 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,`** . . .

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

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

op:6	rs:5	rt:5	imm:16

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

op:6	addr:26

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

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

sra $t0, $s1, 5

sra encoding from the MIPS instruction set reference:

SPECIAL 000000	0 00000	rt	rd	sa	SRA 000011

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

000000	00000	10010	01000	00101	000011

Immediate-type Encoding Example

op:6	rs:5	rt:5	imm:16

addiu `$t0, $s1, -42`

addiu encoding from the MIPS instruction set reference:

ADDIU 001001	rs	rt	immediate

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

001001	10001	01000	1111 1111 1101 0110

Jump-Type Encoding Example

op:6	addr:26

`jal` `0x5014`

`jal` encoding from the MIPS instruction set reference:

JAL 000011	instr_index

Instruction index is a word address

000011	00 0000 0000 0001 0100 0000 0101

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 $0 \le j \le 65535$	**li** *d*, *j*	→ **ori** *d*, \$0, *j*
Load immediate $-32768 \le j < 0$	**li** *d*, *j*	→ **addiu** *d*, \$0, *j*
Load immediate	**li** *d*, *j*	→ **liu** *d*, hi16(*j*) **ori** *d*, *d*, 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

```c
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

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

```
  move $a0, $0  # a = 0
  move $a1, $0  # b = 0
  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?
```

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*.

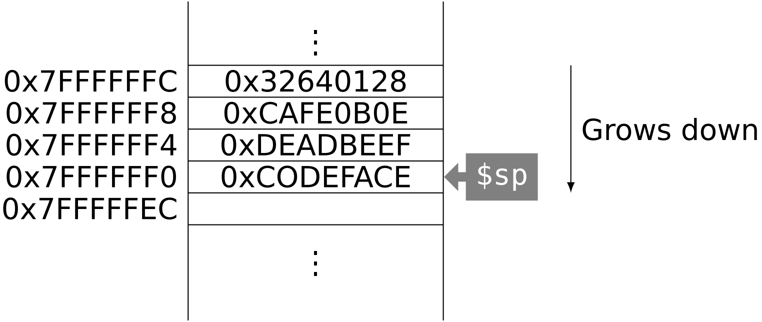
Exist for three reasons:

- 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

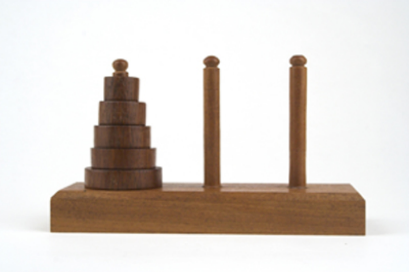
Calling Conventions

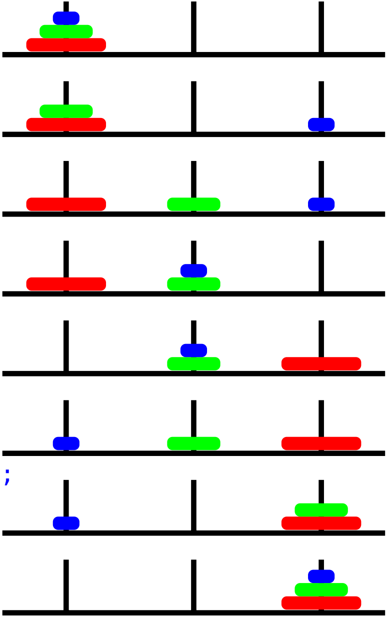
```
    # Call mysub: args in $a0,...,$a3
    jal mysub
    # Control returns here
    # Return value in $v0 & $v1
    # $s0,...,$s7, $gp, $sp, $fp, $ra unchanged
    # $a0,...,$a3, $t0,...,$t9 possibly clobbered

  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


0x7FFFFFFC
0x32640128
0x7FFFFFF8
0xCAFE0B0E
0x7FFFFFF4
0xDEADBEEF
0x7FFFFFF0
0xC0DEFACE
0x7FFFFFEC
$sp
Grows down

Towers of Hanoi





```c
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);
  }
}
```

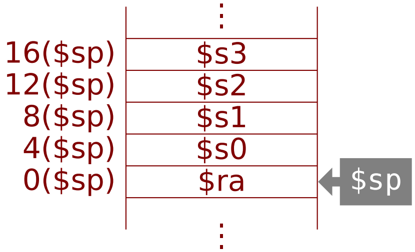
```
hmove:
  addiu $sp, $sp, -24
  beq   $a3, $0, L1
  sw    $ra, 0($sp)
  sw    $s0, 4($sp)
  sw    $s1, 8($sp)
  sw    $s2, 12($sp)
  sw    $s3, 16($sp)
```

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

Allocate 24 stack bytes: multiple of 8 for alignment

Check whether n == 0

Save $ra, $s0, . . . , $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)
```

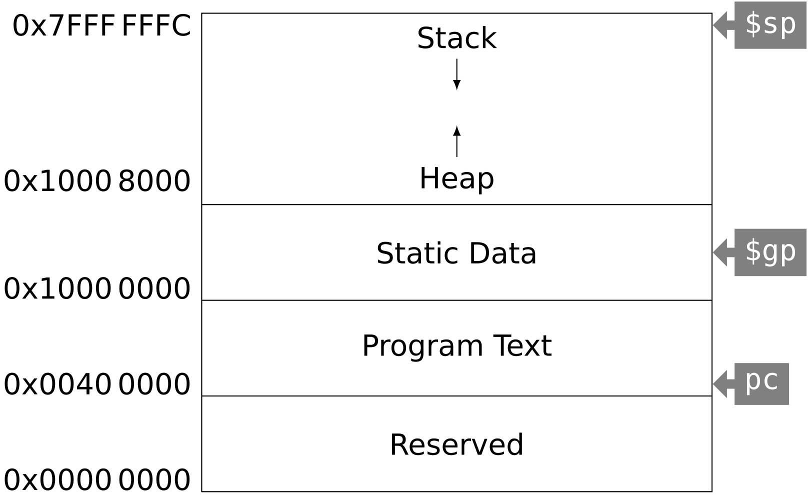
Restore variables

```
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)