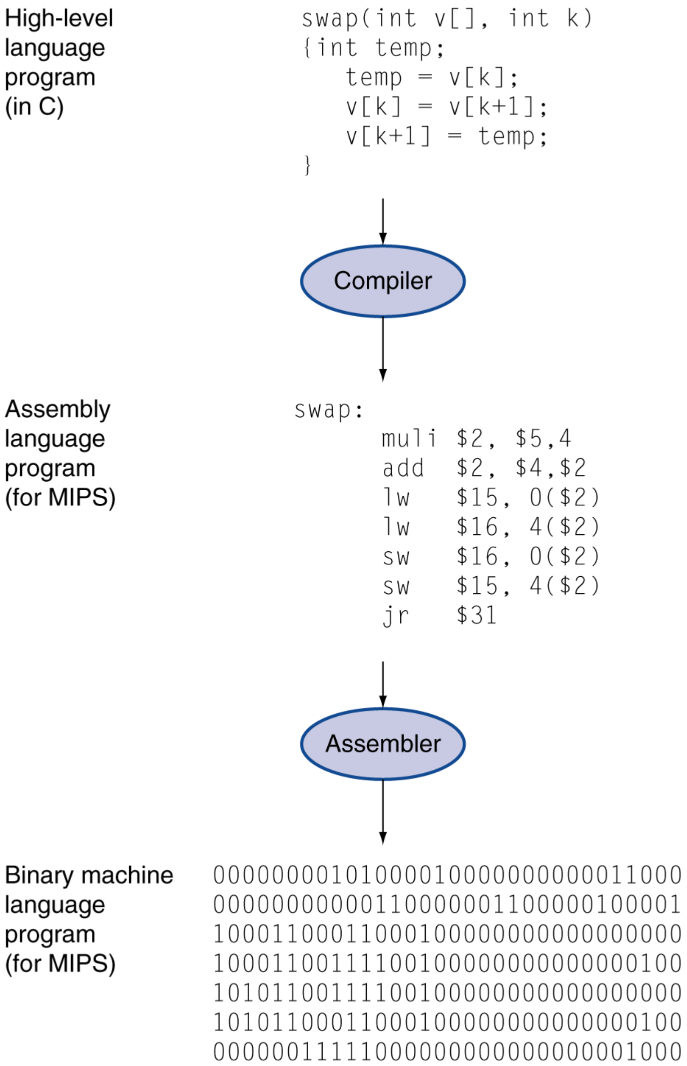
Instructions: Language of the Computer

JONGEUN LEE

SCHOOL OF ECE, UNIST



High-level language program (in C)

```
swap(int v[], int k)
{int temp;
   temp = v[k];
   v[k] = v[k+1];
   v[k+1] = temp;
}
```

Assembly language program (for MIPS)

```
swap:
      muli $2, $5,4
      add  $2, $4,$2
      lw   $15, 0($2)
      lw   $16, 4($2)
      sw   $16, 0($2)
      sw   $15, 4($2)
      jr   $31
```

Binary machine language program (for MIPS)

```
00000000101000010000000000011000
00000000000110000001100000100001
10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100
00000011111000000000000000001000
```

Key Points

Register Operands

- **Arithmetic instructions use register operands**
- **MIPS has a 32 × 32-bit register file**
  - Use for frequently accessed **integer** data
  - Numbered 0 to 31
  - 32-bit data called a “word”
- **Assembler names (vary depending on assembler)**
  - $0, $1, …, $31
  - r0, r1, …, r31 (case-insensitive)
- **Alternative naming scheme**
  - $t0, $t1, …, $t9: $8 ~ $15 (for temporary values)
  - $s0, $s1, …, $s7: $16 ~ $23 (for variables that live across function calls)

Register Operand Example

- **C code:**

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

  - f, …, j in $s0, …, $s4

- **Compiled MIPS code:**

```
add $t0, $s1, $s2
add $t1, $s3, $s4
sub $s0, $t0, $t1
```

Memory Operand Example 1

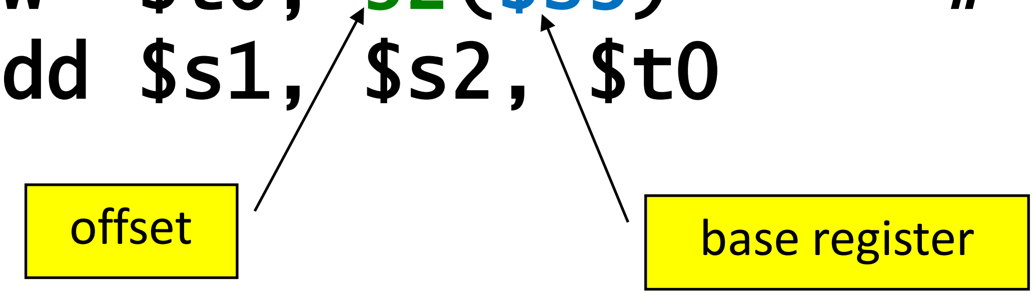
- **C code:**

```
g = h + A[8];
```

  - g in $s1, h in $s2, base address of A in $s3

- **Compiled MIPS code:**
  - Index 8 requires offset of 32
    - 4 bytes per word

```
lw  $t0, 32($s3)       # load word
add $s1, $s2, $t0
```



offset

base register

Memory Operand Example 2

- **C code:**

```
A[12] = h + A[8];
```

  - h in $s2, base address of A in $s3

- **Compiled MIPS code:**
  - Index 8 requires offset of 32

```
lw  $t0, 32($s3)    # load word
add $t0, $s2, $t0
sw  $t0, 48($s3)    # store word
```

Registers vs. Memory

- **Registers are faster to access than memory**
- **Operating on memory data requires loads and stores**
  - More instructions to be executed
- **Compiler must use registers for variables as much as possible**
  - Only spill to memory for less frequently used variables
  - Register optimization is important!

Memory Operands

- **Main memory used for composite data**
  - Arrays, structures, dynamic data
- **To apply arithmetic operations**
  - Load values from memory into registers
  - Store result from register to memory
- **Memory is byte addressed**
  - Each address identifies an 8-bit byte
- **Words are aligned in memory (word-aligned)**
  - Address must be a multiple of 4
- **MIPS is Big Endian**
  - MSB at the least address of a word
  - *c.f.* Little Endian: LSB at the least address

Immediate Operands

- Constant data specified in an instruction

```
    addi $s3, $s3, 4
```

- No subtract immediate instruction
  - Just use a negative constant

```
addi $s2, $s1, -1
```

The Constant Zero

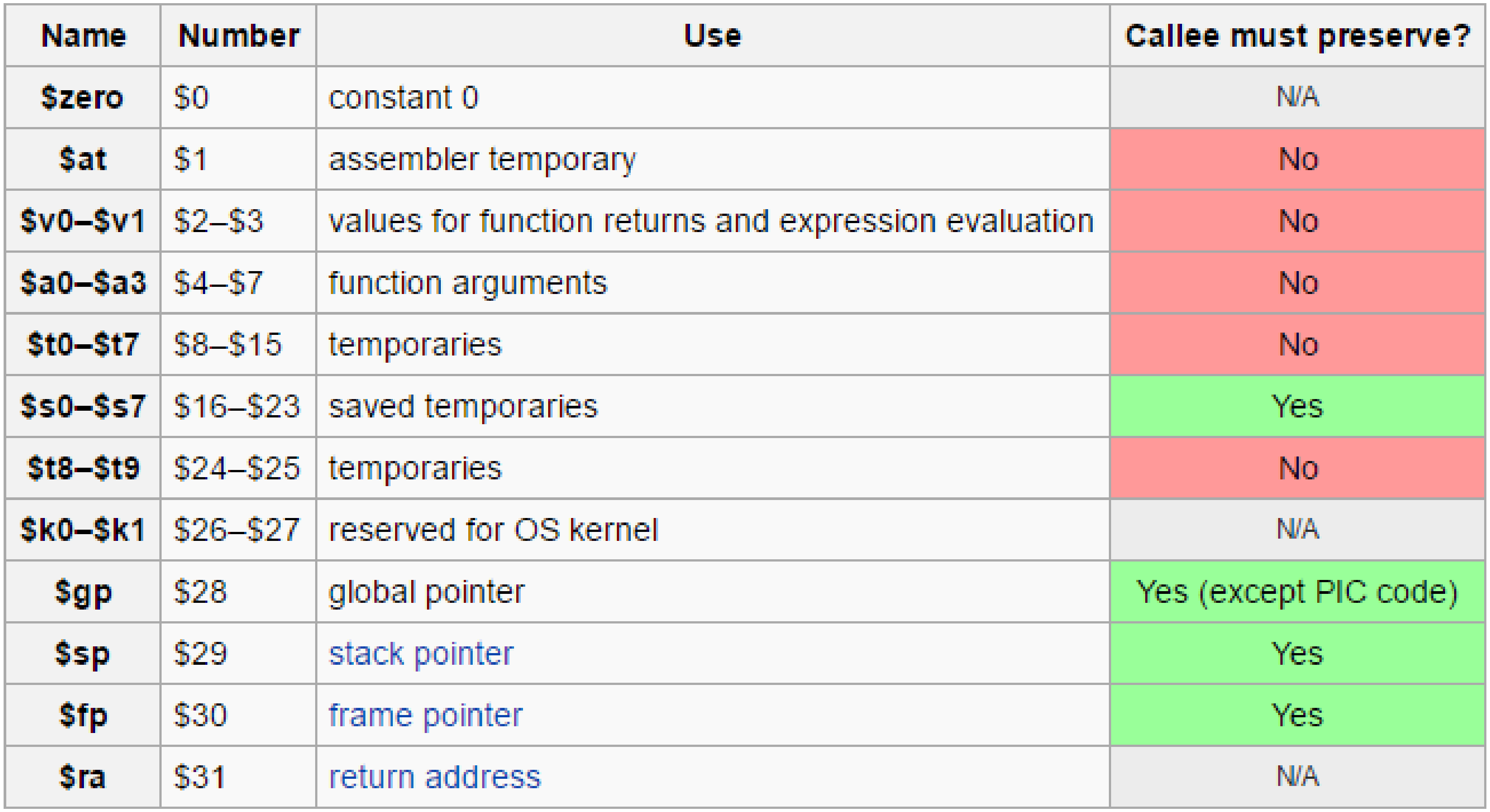
- **MIPS register 0 ($0 = r0 = $zero) is the constant 0**
  - Cannot be overwritten
- **Useful for common operations**
  - E.g., move between registers

```
add $t2, $s1, $zero
```

Design Principles

- ***Design Principle 1:*** **Simplicity favors regularity**
  - Regularity makes implementation simpler
  - Simplicity enables higher performance at lower cost
- ***Design Principle 2:* Smaller is faster**
  - c.f. main memory: millions of locations
- ***Design Principle 3:*** **Make the common case fast**
  - Small constants are common
  - Immediate operand avoids a load instruction

MIPS Register Convention



Name	Number	Use	Callee must preserve?
$zero	$0	constant 0	N/A
$at	$1	assembler temporary	No
$v0–$v1	$2–$3	values for function returns and expression evaluation	No
$a0–$a3	$4–$7	function arguments	No
$t0–$t7	$8–$15	temporaries	No
$s0–$s7	$16–$23	saved temporaries	Yes
$t8–$t9	$24–$25	temporaries	No
$k0–$k1	$26–$27	reserved for OS kernel	N/A
$gp	$28	global pointer	Yes (except PIC code)
$sp	$29	stack pointer	Yes
$fp	$30	frame pointer	Yes
$ra	$31	return address	N/A

Conditionals

Conditional Operations

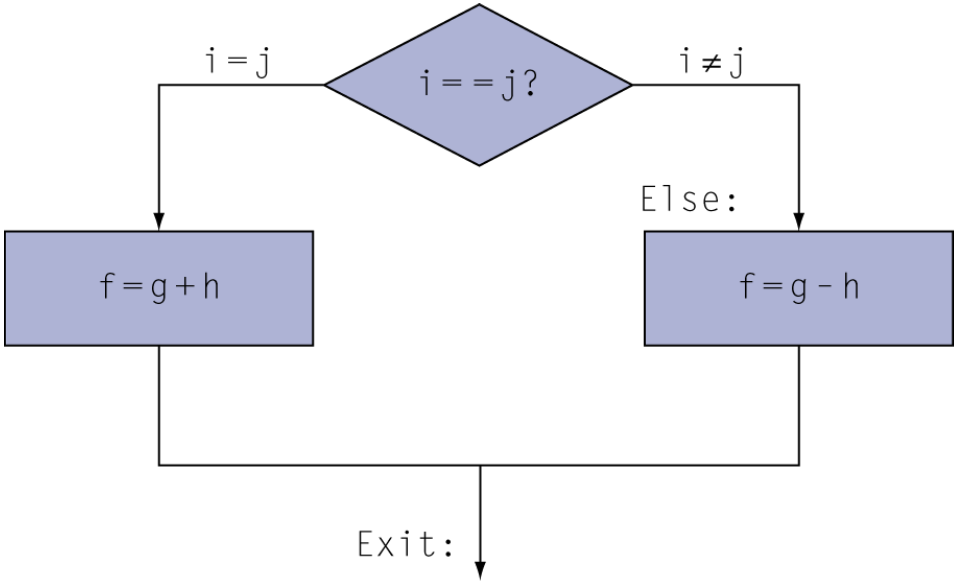
- **Branch to a labeled instruction if condition is true**
  - Otherwise, continue sequentially
- **`beq rs, rt, L1`**
  - if (rs == rt), branch to instruction labeled L1
- **`bne rs, rt, L1`**
  - if (rs != rt), branch to instruction labeled L1
- **`j L1`**
  - unconditional jump to instruction labeled L1

Compiling If Statements

- **C code:**

```
if (i==j) f = g+h;
else f = g-h;
```

  - f, g, … in $s0, $s1, …



- **Compiled MIPS code:**

```
      bne $s3, $s4, Else
      add $s0, $s1, $s2
      j   Exit
Else: sub $s0, $s1, $s2
Exit: …
```

Assembler calculates addresses

Compiling Loop Statements

- **C code:**

```
while (save[i] == k) i += 1;
```

  - i in $s3, k in $s5, address of save in $s6

- **Compiled MIPS code:**

```
Loop: sll  $t1, $s3, 2
      add  $t1, $t1, $s6
      lw   $t0, 0($t1)
      bne  $t0, $s5, Exit
      addi $s3, $s3, 1
      j    Loop
Exit: …
```

More Conditional Operations

- **Set result to 1 if a condition is true**
  - Otherwise, set to 0
- **`slt rd, rs, rt`**
  - if (rs < rt) rd = 1; else rd = 0;
- **`slti rt, rs, constant`**
  - if (rs < constant) rt = 1; else rt = 0;
- **Use in combination with beq, bne**

```
slt $t0, $s1, $s2    # if ($s1 < $s2)
bne $t0, $zero, L    #   branch to L
```

Branch Instruction Design

- **Why not: `blt`, bge, …?**
- **Hardware for <, ≥, … slower than =, ≠**
  - Combining with branch involves more work per instruction, requiring a slower clock
  - All instructions are penalized!

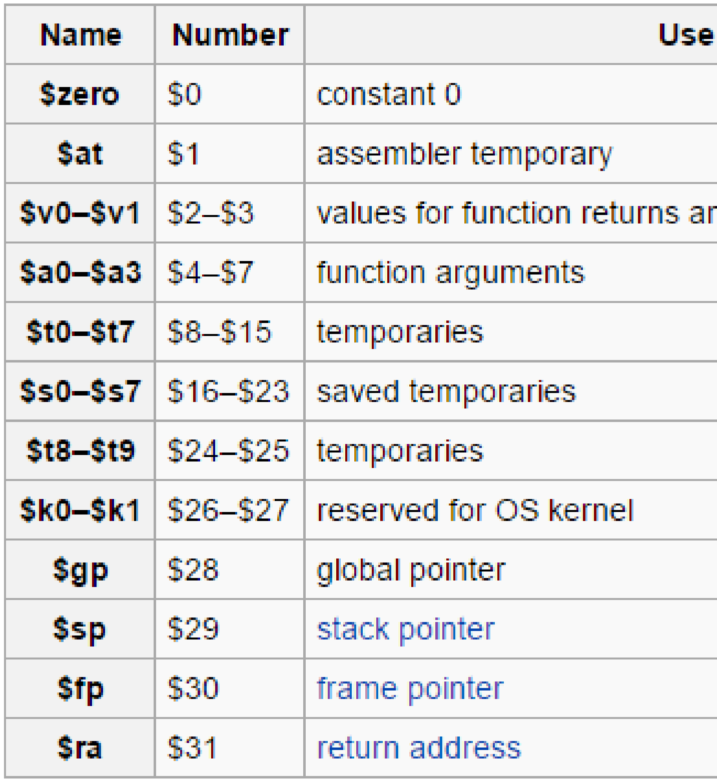
- **beq and bne are the common case**
- **This is a good design compromise**

Instruction Encoding

Representing Instructions

§2.5 Representing Instructions in th

- **Instructions are encoded in binary**
  - Called machine code
- **MIPS instructions**
  - Encoded as 32-bit instruction words
  - Small number of formats
  - Regularity!
- **Register numbers**
  - $t0 – $t7 are $8 – $15
  - $s0 – $s7 are $16 – $23
  - $t8 – $t9 are $24 – $25



Name	Number	Use
$zero	$0	constant 0
$at	$1	assembler temporary
$v0–$v1	$2–$3	values for function returns ar
$a0–$a3	$4–$7	function arguments
$t0–$t7	$8–$15	temporaries
$s0–$s7	$16–$23	saved temporaries
$t8–$t9	$24–$25	temporaries
$k0–$k1	$26–$27	reserved for OS kernel
$gp	$28	global pointer
$sp	$29	stack pointer
$fp	$30	frame pointer
$ra	$31	return address

MIPS I-format Instructions

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

- **Immediate arithmetic and load/store instructions**
  - **rt**: destination (or source) register number
  - Constant: –2^{15} to +2^{15} – 1
  - Address: offset added to base address in **rs**

- ***Design Principle 4:*** **Good design demands good compromises**
  - Different formats complicate decoding, but allow 32-bit instructions uniformly
  - Keep formats as similar as possible

MIPS R-format Instructions

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

- **Instruction fields**
  - op: operation code (opcode)
  - rs: first source register number
  - rt: second source register number
  - rd: destination register number
  - shamt: shift amount
  - funct: function code (extends opcode)

R-format Example

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

```
add $t0, $s1, $s2
```

special	$s1	$s2	$t0	0	add
0	17	18	8	0	32
000000	10001	10010	01000	00000	100000

$00000010001100100100000000100000_2 = 02324020_{16}$

Hexadecimal

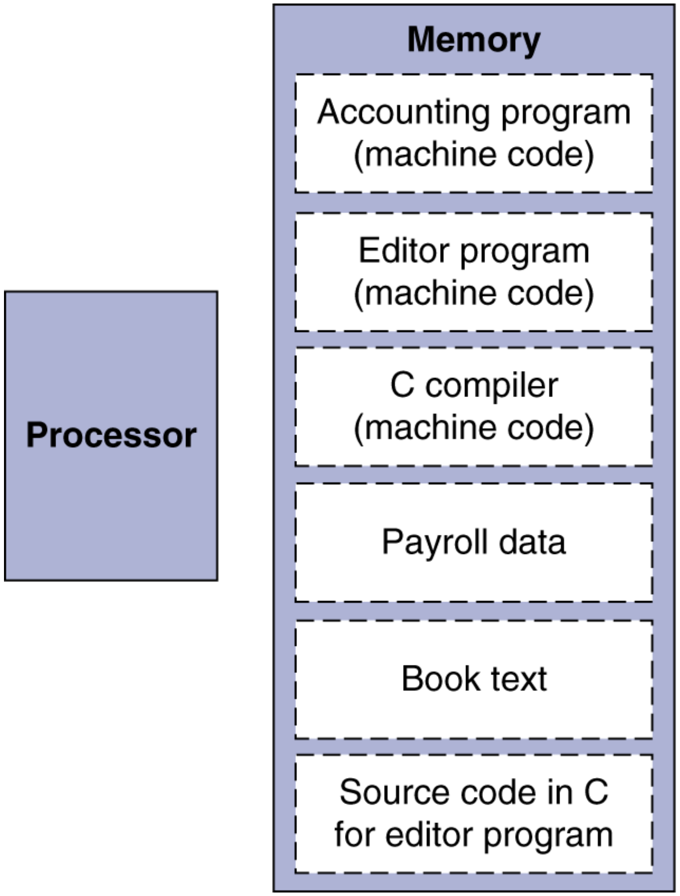
- **Base 16**
  - Compact representation of bit strings
  - 4 bits per hex digit

0	0000	4	0100	8	1000	c	1100
1	0001	5	0101	9	1001	d	1101
2	0010	6	0110	a	1010	e	1110
3	0011	7	0111	b	1011	f	1111

- Example: 0x eca8 6420
  - 1110 1100 1010 1000 0110 0100 0010 0000

Stored-Program Computers

The BIG Picture


Memory
Accounting program (machine code)
Editor program (machine code)
C compiler (machine code)
Payroll data
Book text
Source code in C for editor program
Processor

- **Instructions represented in binary, just like data**
- **Instructions and data stored in memory**
- **Programs can operate on programs**
  - e.g., compilers, linkers, …
- **Binary compatibility allows compiled programs to work on different computers**
  - Standardized ISAs

Procedure – Leaf

Procedure Calling

- **Steps required**
    1. Place parameters in registers
    2. Transfer control to procedure
    3. Acquire storage for procedure
    4. Perform procedure’s operations
    5. Place result in register for caller
    6. Return to place of call

Procedure Call Instructions

- **Procedure call: jump-and-link**

  `jal ProcedureLabel`

  – Address of following instruction put in $ra

  – Jumps to target address

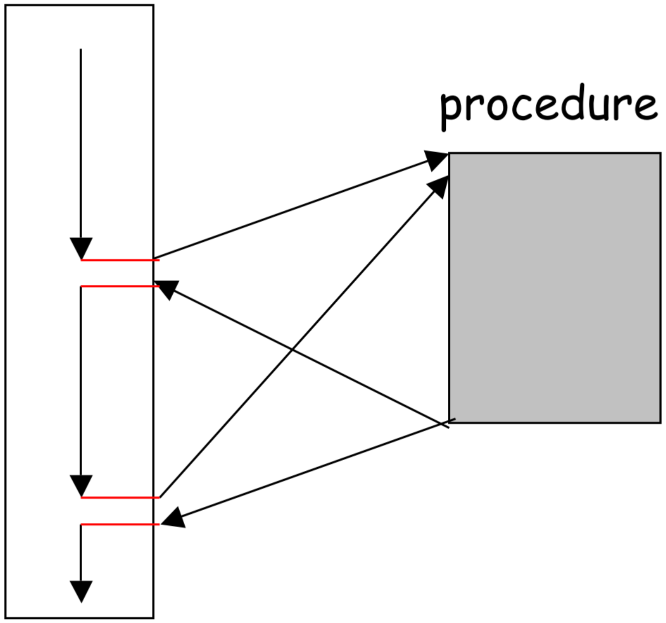
- **Procedure return: jump-on-register**

  `jr $ra`

  – Copies $ra to program counter

  – Can also be used for computed jumps

    - e.g., for switch/case statements



Leaf Procedure Example

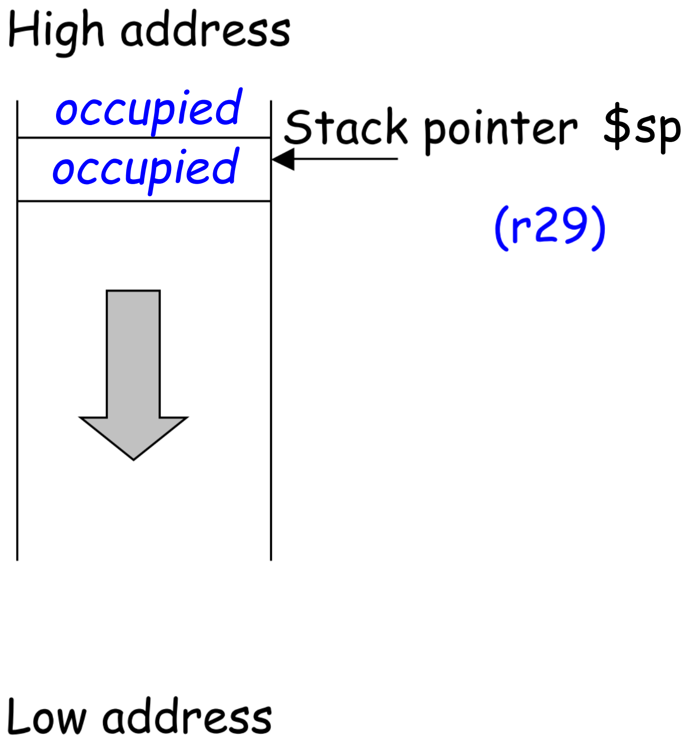
- **C code:**

```
int leaf_example (int g, h, i, j)
 {
   int f;
  f = (g + h) - (i + j);
  return f;
}
```

  - Arguments g, …, j in $a0, …, $a3
  - f in $s0 (hence, need to save $s0 on stack)
  - Result in $v0

Stack

- A part of the main memory
- In MIPS it grows from high address to low address
- Purely software convention
  - $sp points to the lowest occupied location



High address

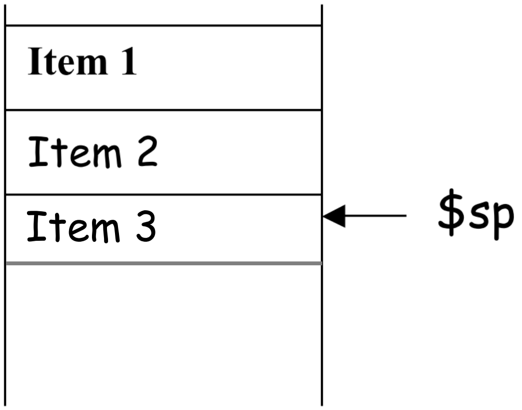
occupied

occupied

Stack pointer $sp

(r29)

Low address



Item 1

Item 2

Item 3

$sp

Leaf Procedure Example

- **MIPS code:**

```
leaf_example:
  addi $sp, $sp, -4
  sw   $s0, 0($sp)            Save $s0 on stack
  add  $t0, $a0, $a1
  add  $t1, $a2, $a3          Procedure body
  sub  $s0, $t0, $t1
  add  $v0, $s0, $zero        Result
  lw   $s0, 0($sp)
  addi $sp, $sp, 4            Restore $s0
  jr   $ra                    Return
```

Procedure – Non-Leaf

Non-Leaf Procedures

- **Procedures that call other procedures**
- **For nested call, caller needs to save on the stack:**
  - Its return address
  - Any arguments and temporaries needed after the call
- **Restore from the stack after the call**

Non-Leaf Procedure Example

- **C code:**

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

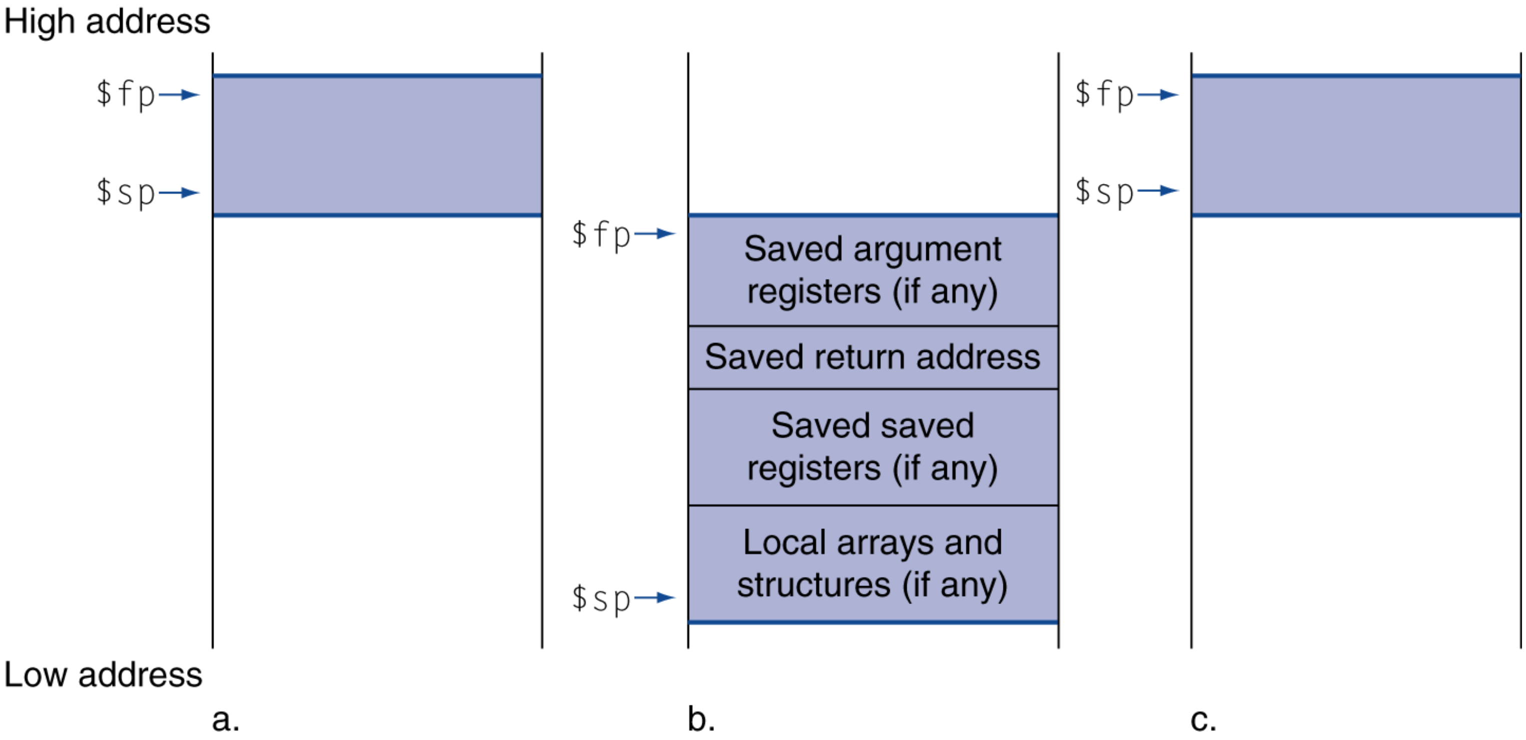
  - Argument n in $a0
  - Result in $v0

Non-Leaf Procedure Example

- **MIPS code:**

```
fact:
    addi $sp, $sp, -8     # adjust stack for 2 items
    sw   $ra, 4($sp)      # save return address
    sw   $a0, 0($sp)      # save argument
    slti $t0, $a0, 1      # test for n < 1
    beq  $t0, $zero, L1
    addi $v0, $zero, 1    # if so, result is 1
    addi $sp, $sp, 8      #   pop 2 items from stack
    jr   $ra              #   and return
L1: addi $a0, $a0, -1     # else decrement n
    jal  fact             # recursive call
    lw   $a0, 0($sp)      # restore original n
    lw   $ra, 4($sp)      #   and return address
    addi $sp, $sp, 8      # pop 2 items from stack
    mul  $v0, $a0, $v0    # multiply to get result
    jr   $ra              # and return
```

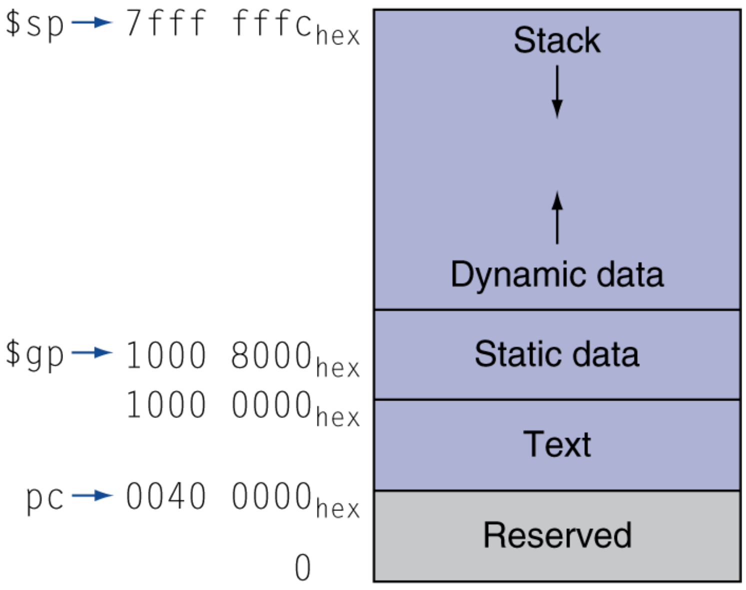
Local Data on the Stack


High address
$fp
$sp
$fp
Saved argument registers (if any)
Saved return address
Saved saved registers (if any)
Local arrays and structures (if any)
$sp
$fp
$sp
Low address
a.
b.
c.

- **Local data allocated by callee**
  - e.g., C automatic variables
- **Procedure frame (activation record)**
  - Used by some compilers to manage stack storage

Memory Layout

- **Text: program code**
- **Static data: global variables**
  - e.g., static variables in C, constant arrays and strings
  - $gp initialized to address allowing ±offsets into this segment
- **Dynamic data: heap**
  - E.g., malloc in C, new in Java
- **Stack: automatic storage**



Branch Addressing

Branch Addressing

- **Branch instructions specify**
  - Opcode, two registers, target address
- **Most branch targets are near branch**
  - Forward or backward

op	rs	rt	constant or address
6 bits	5 bits	5 bits	16 bits

- PC-relative addressing
  - Target address = PC + offset × 4
  - PC already incremented by 4 by this time

Jump Addressing

- **Jump (`j` and `jal`) targets could be anywhere in text segment**
  - Encode full address in instruction

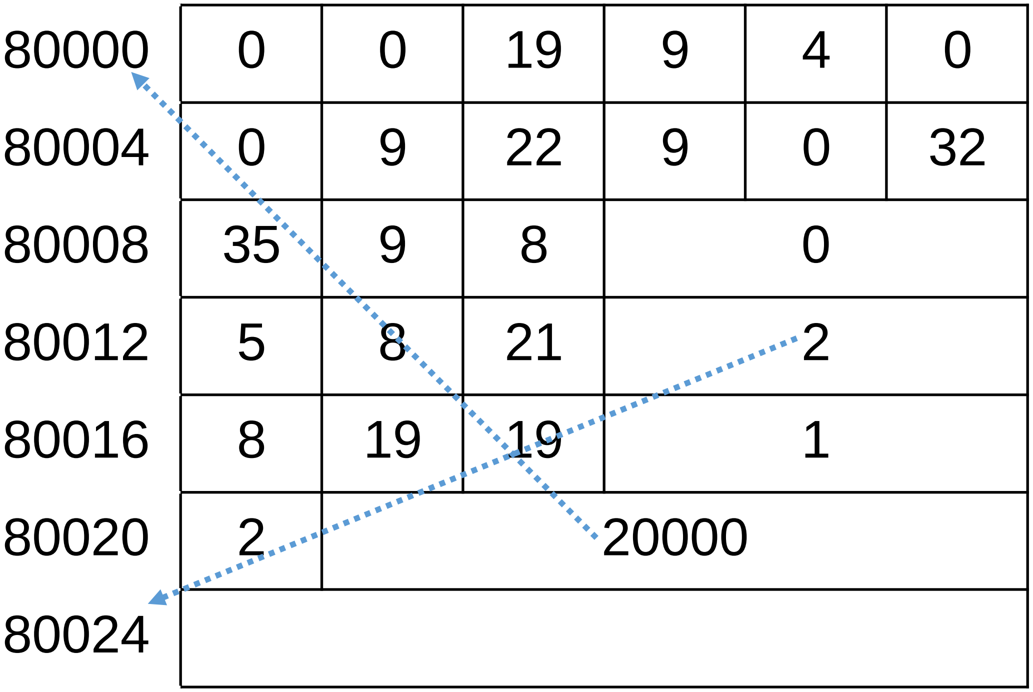
op	address
6 bits	26 bits

- (Pseudo)Direct jump addressing
  - Target address = $PC_{31…28}$: (address × 4)

Target Addressing Example

- **Loop code from earlier example**
  - Assume Loop at location 80000

```
Loop: sll  $t1, $s3, 2
      add  $t1, $t1, $s6
      lw   $t0, 0($t1)
      bne  $t0, $s5, Exit
      addi $s3, $s3, 1
      j    Loop
Exit: …
```



80000	0	0	19	9	4	0
80004	0	9	22	9	0	32
80008	35	9	8	0		
80012	5	8	21	2		
80016	8	19	19	1		
80020	2	20000				
80024						

Branching Far Away

- If branch target is too far to encode with 16-bit offset, assembler rewrites the code
- Example

```
          beq $s0,$s1, L1
                 ↓
          bne $s0,$s1, L2
          j L1
    L2:   …
```

Signed vs Unsigned

Signed vs. Unsigned

- **Signed comparison: `slt`, `slti`**
- **Unsigned comparison: `sltu`, `sltui`**

- **Example**
  - $s0 = `1111 1111 1111 1111 1111 1111 1111 1111`
  - $s1 = `0000 0000 0000 0000 0000 0000 0000 0001`
  - `slt  $t0, $s0, $s1  # signed`
    - –1 < +1 ⇒ $t0 = 1
  - `sltu $t0, $s0, $s1  # unsigned`
    - +4,294,967,295 > +1 ⇒ $t0 = 0

Byte/Halfword Operations

- **MIPS byte/halfword load/store**
  - String processing is a common case

```
lb rt, offset(rs)     lh rt, offset(rs)
```

  - Sign extend to 32 bits in rt

```
lbu rt, offset(rs)    lhu rt, offset(rs)
```

  - Zero extend to 32 bits in rt

```
sb rt, offset(rs)     sh rt, offset(rs)
```

  - Store just rightmost byte/halfword

Zero vs. Sign Extension

- **Representing a number using more bits**
  - Preserve the numeric value
  - Sign extension: Replicate the sign bit to the left
  - Zero extension (for unsigned values): extend with 0s
- **Sign extension example: 8-bit to 16-bit**
  - `+2: 0000 0010 => 0000 0000 0000 0010`
  - `–2: 1111 1110 => 1111 1111 1111 1110`
- **Sign extension in MIPS instruction set**
  - **addi**: extend immediate value
  - **lb, lh**: extend loaded byte/halfword
  - **beq, bne**: extend the displacement

Bit-manipulating Instructions

§2.6 Logical Operations

Bit-manipulating Operations

- **Instructions for bitwise manipulation**

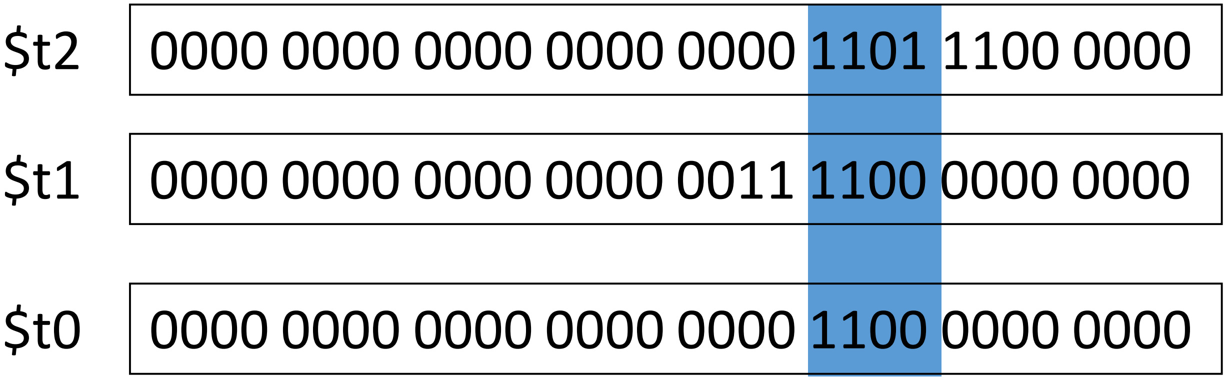
Operation	C	Java	MIPS
Shift left	<<	<<	**`sll`**
Shift right	>>	>>>	**`srl`**
Bitwise AND	&	&	**`and, andi`**
Bitwise OR	|	|	**`or, ori`**
Bitwise NOT	~	~	**`nor`**

- Useful for extracting and inserting groups of bits in a word

AND Operations

- **Useful to mask bits in a word**
  - Select some bits, clear others to 0

```
and $t0, $t1, $t2
```



$t2 0000 0000 0000 0000 0000 1101 1100 0000

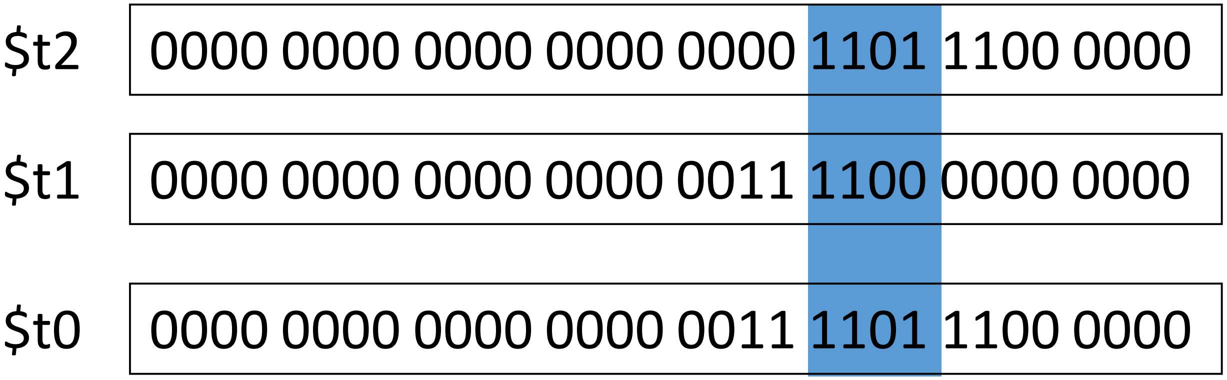
$t1 0000 0000 0000 0000 0011 1100 0000 0000

$t0 0000 0000 0000 0000 0000 1100 0000 0000

OR Operations

- **Useful to include bits in a word**
  - Set some bits to 1, leave others unchanged

```
or $t0, $t1, $t2
```



$t2	0000 0000 0000 0000 0000 1101 1100 0000
$t1	0000 0000 0000 0000 0011 1100 0000 0000
$t0	0000 0000 0000 0000 0011 1101 1100 0000

NOT Operations

- **Useful to invert bits in a word**
  - Change 0 to 1, and 1 to 0
- **MIPS provides NOR instruction**
  - a NOR b == NOT (a OR b)

```
nor $t0, $t1, $zero
```

Register 0: always read as zero

$t1	0000 0000 0000 0000 0011 1100 0000 0000
$t0	1111 1111 1111 1111 1100 0011 1111 1111

Shift Operations

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

- **shamt: how many positions to shift**
- **Shift left logical**
  - Shift left and fill with 0 bits
  - **`sll`** by *i* bits is equivalent to multiply-by-2^i
- **Shift right logical**
  - Shift right and fill with 0 bits
  - **`srl`** by *i* bits is equivalent to divide-by-2^i (unsigned only)
- **Shift right arithmetic (sra)**
  - Shift right and fill with the sign bit
  - **`sra`** by *i* bits is equivalent to divide-by-2^i (both signed and unsigned)

Misc Topics

Assembler Pseudoinstructions

- **Most assembler instructions represent machine instructions one-to-one**
- **Pseudoinstructions: figments of the assembler’s imagination**

```
move $t0, $t1          →    add $t0, $zero, $t1
blt $t0, $t1, L         →   slt $at, $t0, $t1
                            bne $at, $zero, L
```

  - $at (=$1): assembler temporary

32-bit Constants

- **Most constants are small**
  - 16-bit immediate is sufficient
- **For the occasional 32-bit constant**

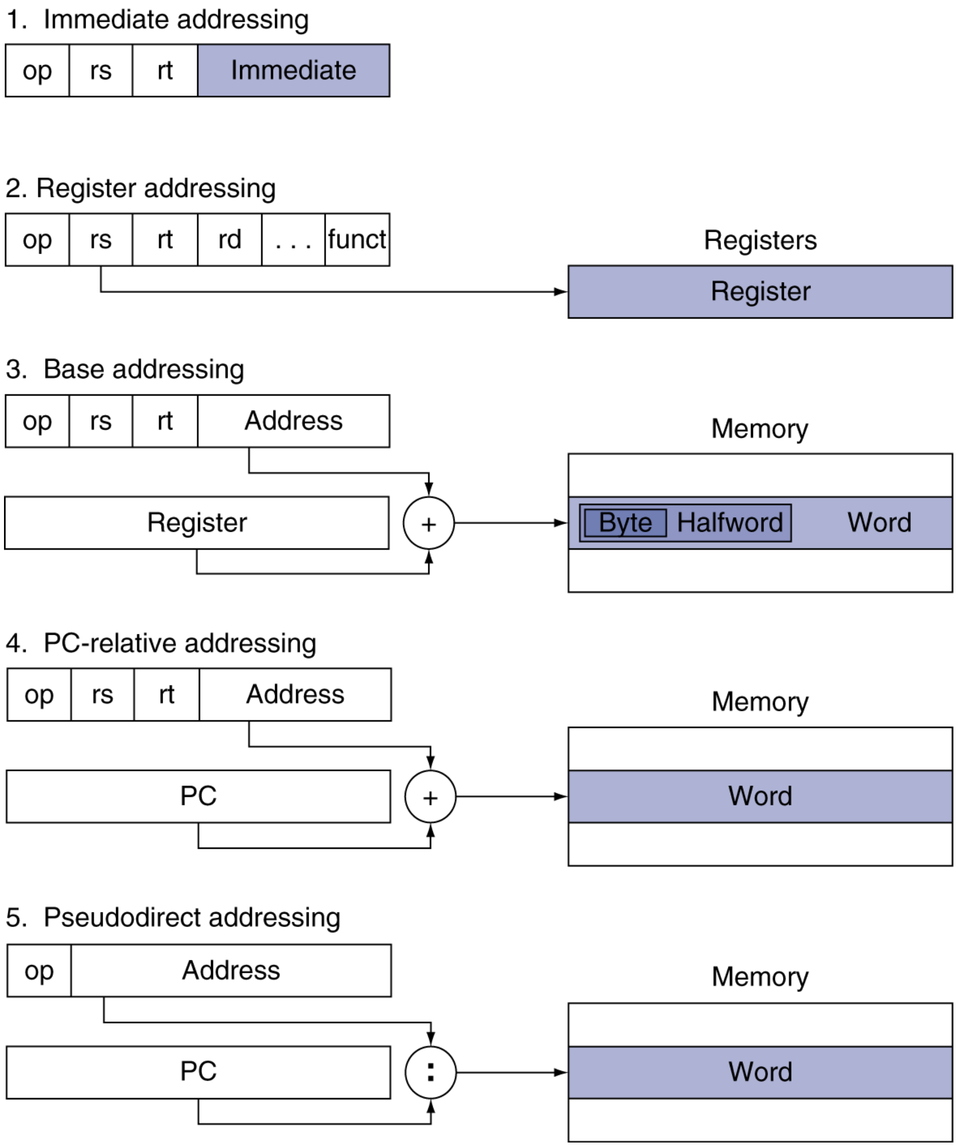
`lui rt, constant`

  - Copies 16-bit constant to left 16 bits of rt
  - Clears right 16 bits of rt to 0

`lhi $s0, 61`	0000 0000 0111 1101	0000 0000 0000 0000
`ori $s0, $s0, 2304`	0000 0000 0111 1101	0000 1001 0000 0000

§2.10 MIPS Addressing for 32-Bit Immediates and Addresses

Addressing Mode Summary



- **Measure MIPS instruction executions in benchmark programs**
  - Consider making the common case fast
  - Consider compromises

Instruction class	MIPS examples	SPEC2006 Int	SPEC2006 FP
Arithmetic	`add, sub, addi`	16%	48%
Data transfer	`lw, sw, lb, lbu, lh, lhu, sb, lui`	35%	36%
Logical	`and, or, nor, andi, ori, sll, srl`	12%	4%
Cond. Branch	`beq, bne, slt, slti, sltiu`	34%	8%
Jump	`j, jr, jal`	2%	0%

§2.16 Real Stuff: ARM Instructions

ARM & MIPS Similarities

- ARM: the most popular embedded core
- Similar basic set of instructions to MIPS

	ARM	MIPS
Date announced	1985	1985
Instruction size	32 bits	32 bits
Address space	32-bit flat	32-bit flat
Data alignment	Aligned	Aligned
Data addressing modes	9	3
Registers	15 × 32-bit	31 × 32-bit
Input/output	Memory mapped	Memory mapped

Examples

String Copy Example

- **C code (naïve):**
  - Null-terminated string

```
void strcpy (char x[], char y[])
{
  int i;
  i = 0;
  while ((x[i]=y[i])!='\0')
    i += 1;
}
```

  - Addresses of x, y in $a0, $a1
  - i in $s0

String Copy Example

- **MIPS code:**

```
strcpy:
    addi $sp, $sp, -4      # adjust stack for 1 item
    sw   $s0, 0($sp)       # save $s0
    add  $s0, $zero, $zero # i = 0
L1: add  $t1, $s0, $a1     # addr of y[i] in $t1
    lbu  $t2, 0($t1)       # $t2 = y[i]
    add  $t3, $s0, $a0     # addr of x[i] in $t3
    sb   $t2, 0($t3)       # x[i] = y[i]
    beq  $t2, $zero, L2    # exit loop if y[i] == 0
    addi $s0, $s0, 1       # i = i + 1
    j    L1                # next iteration of loop
L2: lw   $s0, 0($sp)       # restore saved $s0
    addi $sp, $sp, 4       # pop 1 item from stack
    jr   $ra               # and return
```

§2.13 A C Sort Example to Put It All Together

C Sort Example

- **Illustrates use of assembly instructions for a C bubble sort function**
- **Swap procedure (leaf)**

```
void swap(int v[], int k)
{
  int temp;
  temp = v[k];
  v[k] = v[k+1];
  v[k+1] = temp;
}
```

  - v in $a0, k in $a1, temp in $t0

The Procedure Swap

```
swap: sll $t1, $a1, 2   # $t1 = k * 4
      add $t1, $a0, $t1 # $t1 = v+(k*4)
                        #   (address of v[k])
      lw $t0, 0($t1)    # $t0 (temp) = v[k]
      lw $t2, 4($t1)    # $t2 = v[k+1]
      sw $t2, 0($t1)    # v[k] = $t2 (v[k+1])
      sw $t0, 4($t1)    # v[k+1] = $t0 (temp)
      jr $ra            # return to calling routine
```

The Sort Procedure in C

- **Non-leaf (calls swap)**

```
void sort (int v[], int n)
{
  int i, j;
  for (i = 0; i < n; i += 1) {
    for (j = i – 1;
         j >= 0 && v[j] > v[j + 1];
         j -= 1) {
      swap(v,j);
    }
  }
}
```

  – v in $a0, k in $a1, i in $s0, j in $s1

The Procedure Body

```
         move $s2, $a0           # save $a0 into $s2
         move $s3, $a1           # save $a1 into $s3
```

Move params

```
         move $s0, $zero         # i = 0
for1tst: slt  $t0, $s0, $s3      # $t0 = 0 if $s0 ≥ $s3 (i ≥ n)
```

Outer loop

```
         beq  $t0, $zero, exit1  # go to exit1 if $s0 ≥ $s3 (i ≥ n)
         addi $s1, $s0, –1       # j = i – 1
for2tst: slti $t0, $s1, 0        # $t0 = 1 if $s1 < 0 (j < 0)
         bne  $t0, $zero, exit2  # go to exit2 if $s1 < 0 (j < 0)
         sll  $t1, $s1, 2        # $t1 = j * 4
         add  $t2, $s2, $t1      # $t2 = v + (j * 4)
         lw   $t3, 0($t2)        # $t3 = v[j]
         lw   $t4, 4($t2)        # $t4 = v[j + 1]
         slt  $t0, $t4, $t3      # $t0 = 0 if $t4 ≥ $t3
         beq  $t0, $zero, exit2  # go to exit2 if $t4 ≥ $t3
```

Inner loop

```
         move $a0, $s2           # 1st param of swap is v (old $a0)
         move $a1, $s1           # 2nd param of swap is j
         jal  swap               # call swap procedure
```

Pass params & call

```
         addi $s1, $s1, –1       # j –= 1
         j    for2tst            # jump to test of inner loop
```

Inner loop

```
exit2:   addi $s0, $s0, 1        # i += 1
         j    for1tst            # jump to test of outer loop
```

Outer loop

The Full Procedure

```
sort:    addi $sp,$sp, -20      # make room on stack for 5 registers
         sw $ra, 16($sp)        # save $ra on stack
         sw $s3,12($sp)         # save $s3 on stack
         sw $s2, 8($sp)         # save $s2 on stack
         sw $s1, 4($sp)         # save $s1 on stack
         sw $s0, 0($sp)         # save $s0 on stack
         …                      # procedure body
         …
         exit1: lw $s0, 0($sp)  # restore $s0 from stack
         lw $s1, 4($sp)         # restore $s1 from stack
         lw $s2, 8($sp)         # restore $s2 from stack
         lw $s3,12($sp)         # restore $s3 from stack
         lw $ra,16($sp)         # restore $ra from stack
         addi $sp,$sp, 20       # restore stack pointer
         jr $ra                 # return to calling routine
```