Chapter 2

Instructions: Language of the Computer

Instruction Set

- The repertoire of instructions of a computer
- Different computers have different instruction sets
  - But with many aspects in common
- Early computers had very simple instruction sets
  - Simplified implementation
- Many modern computers also have simple instruction sets

The MIPS Instruction Set

- Used as the example throughout the book
- Stanford MIPS commercialized by MIPS Technologies (www.mips.com)
- Large share of embedded core market
  - Applications in consumer electronics, network/storage equipment, cameras, printers, …
- Typical of many modern ISAs
  - See MIPS Reference Data tear-out card, and Appendixes B and E

Arithmetic Operations

- Add and subtract, three operands
  - Two sources and one destination

```
add a, b, c  # a gets b + c
```

- All arithmetic operations have this form
- *Design Principle 1:* Simplicity favours regularity
  - Regularity makes implementation simpler
  - Simplicity enables higher performance at lower cost

Arithmetic Example

- C code:

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

- Compiled MIPS code:

```
add t0, g, h    # temp t0 = g + h
add t1, i, j    # temp t1 = i + j
sub f, t0, t1   # f = t0 - t1
```

Register Operands

- Arithmetic instructions use register operands
- MIPS has a 32 $\times$ 32-bit register file
  - Use for frequently accessed data
  - Numbered 0 to 31
  - 32-bit data called a “word”
- Assembler names
  - \$t0, \$t1, …, \$t9 for temporary values
  - \$s0, \$s1, …, \$s7 for saved variables
- *Design Principle 2:* Smaller is faster
  - cf. main memory: millions of locations

REGISTER NAME, NUMBER, USE, CALL CONVENTION

NAME	NUMBER	USE	PRESERVED ACROSS A CALL?
$zero	0	The Constant Value 0	N.A.
$at	1	Assembler Temporary	No
$v0-$v1	2-3	Values for Function Results and Expression Evaluation	No
$a0-$a3	4-7	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	No
$gp	28	Global Pointer	Yes
$sp	29	Stack Pointer	Yes
$fp	30	Frame Pointer	Yes
$ra	31	Return Address	Yes

Register Operand Example

- C code:

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

  - f, …, j in $s0, …, $s4

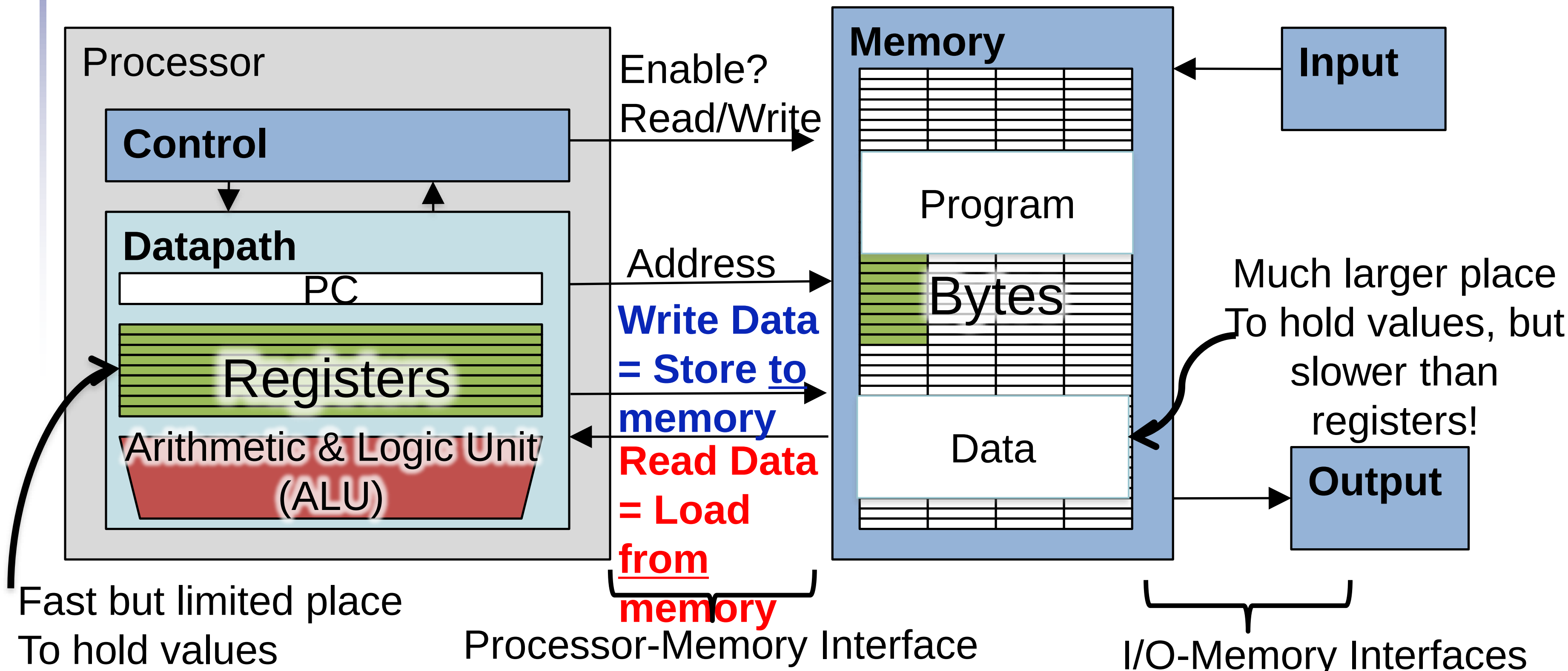
- Compiled MIPS code:

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

Memory 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
  - Address must be a multiple of 4
- MIPS is Big Endian
  - Most-significant byte at least address of a word
  - *cf.* Little Endian: least-significant byte at least address

Data Transfer: Load from and Store to memory



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!

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
    ```

- *Design Principle 3:* Make the common case fast
  - Small constants are common
  - Immediate operand avoids a load instruction

The Constant Zero

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

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

Unsigned Binary Integers

- Given an n-bit number

$$x = x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

- Range: 0 to $+2^n - 1$
- Example
  - $0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 0000\ 1011_2$
    $= 0 + \ldots + 1\times 2^3 + 0\times 2^2 + 1\times 2^1 + 1\times 2^0$
    $= 0 + \ldots + 8 + 0 + 2 + 1 = 11_{10}$
- Using 32 bits
  - 0 to +4,294,967,295

2s-Complement Signed Integers

- Given an n-bit number

$$x = -x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

- Range: -2^{n-1} to $+2^{n-1} - 1$
- Example
  - $1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1111\ 1100_2$
    $= -1 \times 2^{31} + 1 \times 2^{30} + \ldots + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$
    $= -2{,}147{,}483{,}648 + 2{,}147{,}483{,}644 = -4_{10}$
- Using 32 bits
  - –2,147,483,648 to +2,147,483,647

2s-Complement Signed Integers

- Bit 31 is sign bit
  - 1 for negative numbers
  - 0 for non-negative numbers
- $-(-2^{n-1})$ can't be represented
- Non-negative numbers have the same unsigned and 2s-complement representation
- Some specific numbers
  - 0: 0000 0000 … 0000
  - –1: 1111 1111 … 1111
  - Most-negative: 1000 0000 … 0000
  - Most-positive: 0111 1111 … 1111

Signed Negation

- Complement and add 1
  - Complement means 1 → 0, 0 → 1

$$x + \overline{x} = 1111...111_2 = -1$$

$$\overline{x} + 1 = -x$$

- Example: negate +2
  - $+2 = 0000\ 0000\ \ldots\ 0010_2$
  - $-2 = 1111\ 1111\ \ldots\ 1101_2 + 1$
    $= 1111\ 1111\ \ldots\ 1110_2$

Sign Extension

- Representing a number using more bits
  - Preserve the numeric value
- In MIPS instruction set
  - `addi`: extend immediate value
  - `lb`, `lh`: extend loaded byte/halfword
  - `beq`, `bne`: extend the displacement
- Replicate the sign bit to the left
  - cf. unsigned values: extend with 0s
- Examples: 8-bit to 16-bit
  - +2: 0000 0010 => 0000 0000 0000 0010
  - –2: 1111 1110 => 1111 1111 1111 1110

Representing Instructions

- Instructions are encoded in binary
  - Called machine code
- MIPS instructions
  - Encoded as 32-bit instruction words
  - Small number of formats encoding **operation code (opcode)**, register numbers, …
  - Regularity!
- Register numbers
  - \$t0 – \$t7 are reg's 8 – 15
  - \$t8 – \$t9 are reg's 24 – 25
  - \$s0 – \$s7 are reg's 16 – 23

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 (00000 for now)
  - 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:
  - Instr code: ae0b 0004

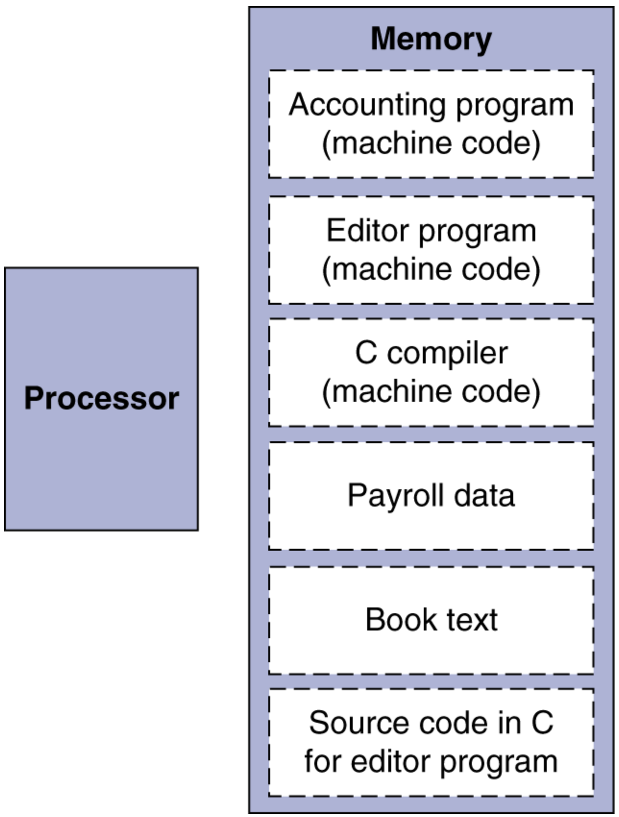
MIPS I-format Instructions

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

Stored Program Computers

The BIG Picture



- 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

Logical 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

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 multiplies by 2^i
- Shift right logical
  - Shift right and fill with 0 bits
  - `srl` by *i* bits divides by 2^i (unsigned only)

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 has NOR 3-operand 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

Conditional Operations

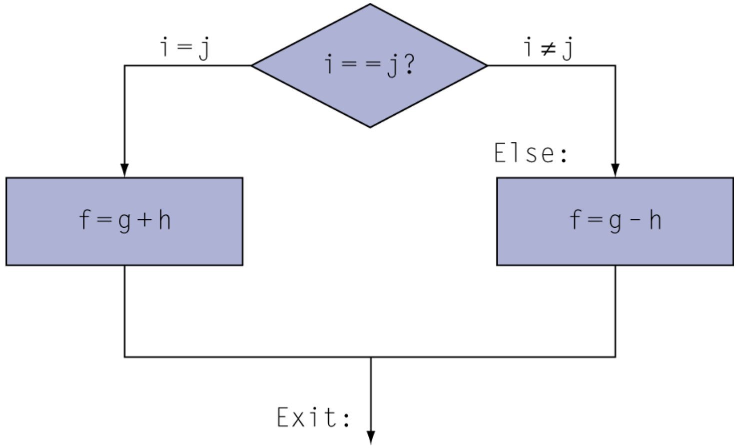
- Branch to a labeled instruction if a condition is true
  - Otherwise, continue sequentially
- `beq rs, rt, L1`
  - if (rs == rt) branch to instruction labeled L1;
- `bne rs, rt, L1`
  - if (rs != rt) branch to instruction labeled L1;
- `j L1`
  - unconditional jump to instruction labeled L1

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:

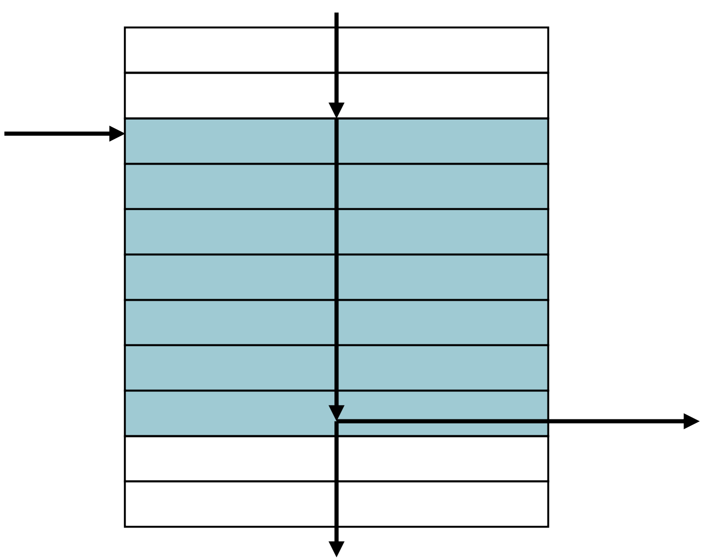
```
while (save[i] == k) i += 1;
```

  - 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: …
```

Basic Blocks

- A basic block is a sequence of instructions with
  - No embedded branches (except at end)
  - No branch targets (except at beginning)



- A compiler identifies basic blocks for optimization
- An advanced processor can accelerate execution of basic blocks

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`, etc?
- Hardware for <, ≥, … slower than =, ≠
  - Combining with branch involves more work per instruction, requiring a slower clock
  - All instructions penalized!
- `beq` and `bne` are the common case
- This is a good design compromise

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`
    - $-1 < +1 \Rightarrow$ \$t0 = 1
  - `sltu $t0, $s0, $s1  # unsigned`
    - $+4{,}294{,}967{,}295 > +1 \Rightarrow$ \$t0 = 0
  - Bounds check shortcut

Case/Switch Statement

- A chain of if-then-else statements
- Jump address table/Jump table
  - jr instruction

Check Yourself

- Why does C provide two sets of operators for AND (& and &&) and two sets of operators for OR (| and ||), while MIPS doesn't?

```
#include <stdio.h>
int main()
{       int i = 1, j = -1;
        int test = (i>0) && (j<0);
        printf("test = %d\n", test);
        return 0;
}
```

http://reliant.colab.duke.edu/c2mips/

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

Register Usage

- $a0 – $a3: arguments (reg's 4-7)
- $v0, $v1: result values (reg's 2 and 3)
- $t0 – $t9: temporaries (reg's 8-15, 24, 25)
  - Can be overwritten by callee
- $s0 – $s7: saved (reg's 16-23)
  - Must be saved/restored by callee
- $gp: global pointer for static data (reg 28)
- $sp: stack pointer (reg 29)
- $fp: frame pointer (reg 30)
- $ra: return address (reg 31)

Procedure Call Instructions

- Procedure call: jump and link

  `jal ProcedureLabel`
  - Address of following instruction put in $ra
  - Jumps to target address
- Procedure return: jump register

  `jr $ra`
  - Copies $ra to program counter
  - Can also be used for computed jumps
    - e.g., for case/switch 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

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
```

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 1;
  else return n * fact(n - 1);
}
```

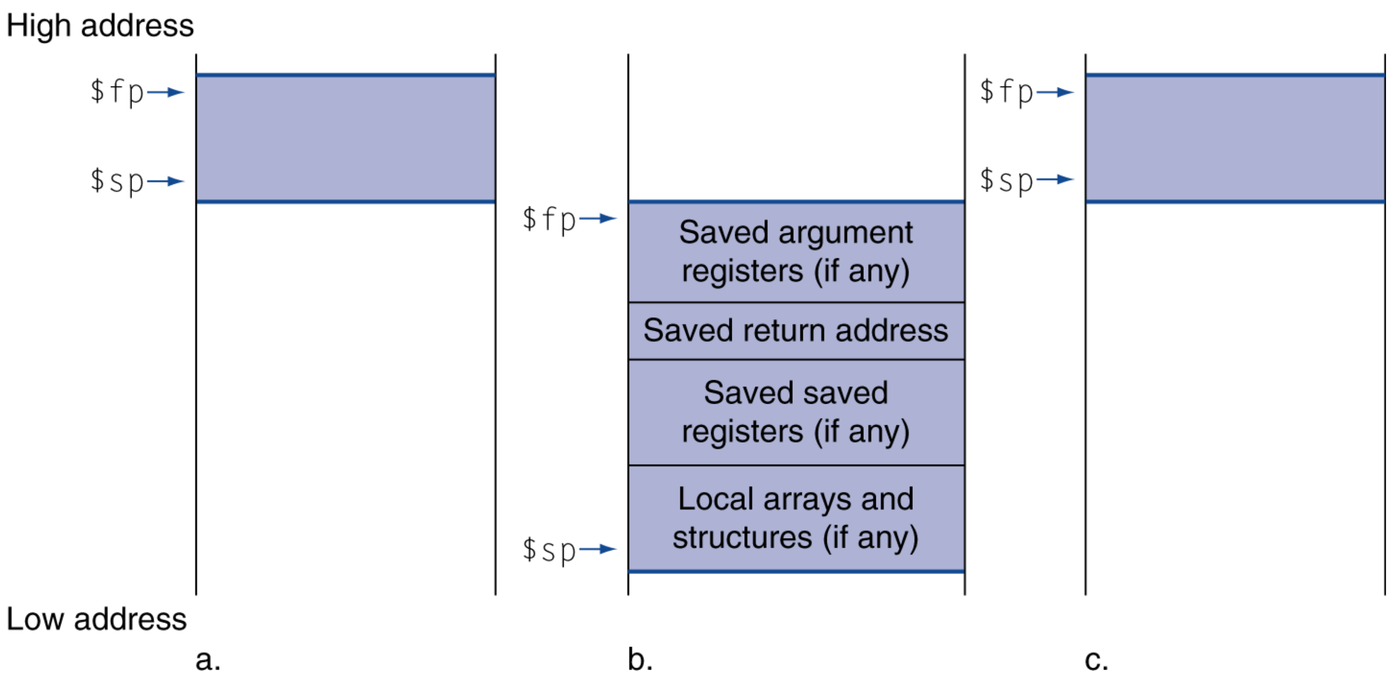
  - Argument n in $a0
  - Result in $v0

Non-Leaf Procedure Example

- MIPS code:

```
fact:
    addi $sp, $sp, -8
    sw   $ra, 4($sp)
    sw   $a0, 0($sp)
    slti $t0, $a0, 1
    beq  $t0, $zero, L1
    addi $v0, $zero, 1
    addi $sp, $sp, 8
    jr   $ra
L1: addi $a0, $a0, -1
    jal  fact
    lw   $a0, 0($sp)
    lw   $ra, 4($sp)
    addi $sp, $sp, 8
    mul  $v0, $a0, $v0
    jr   $ra
```

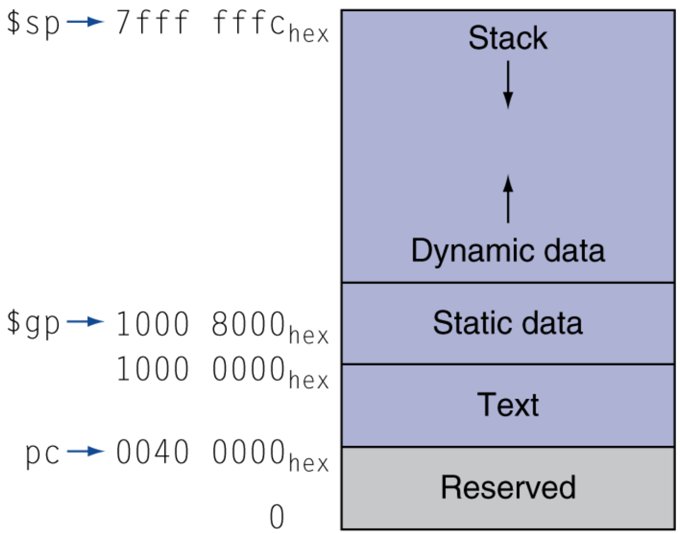
Local Data on the Stack



- 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 $\pm$offsets into this segment
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: automatic storage



Character Data

- Byte-encoded character sets
  - ASCII: 128 characters
    - 95 graphic, 33 control
  - Latin-1: 256 characters
    - ASCII, +96 more graphic characters
- Unicode: 32-bit character set
  - Used in Java, C++ wide characters, …
  - Most of the world's alphabets, plus symbols
  - UTF-8, UTF-16: variable-length encodings

Byte/Halfword Operations

- Could use bitwise 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

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
     sw   $s0, 0($sp)
     add  $s0, $zero, $zero
L1:  add  $t1, $s0, $a1
     lbu  $t2, 0($t1)
     add  $t3, $s0, $a0
     sb   $t2, 0($t3)
     beq  $t2, $zero, L2
     addi $s0, $s0, 1
     j    L1
L2:  lw   $s0, 0($sp)
     addi $sp, $sp, 4
     jr   $ra
```

Quick Test

1) Types are associated with declaration in C (normally), but are associated with instructions (operators) in MIPS32.
2) Since there are only 32 registers, we can't write MIPS32 for C expressions that contain > 32 vars.
3) If `p` (stored in `$9`) were a pointer to an array of `int`s, then `p++;` would be
   `addi $9 $9 1`
4) add $10, $11,4($12)is valid in MIPS32
5) can byte address 8GB of memory with an MIPS32 word
6) imm must be multiple of 4 for lw $10,imm($10) to be valid

Quick Test

- What's in **`$12`**?

addi $11,$0,0x83F5

sw $11,0($5)

lb $12,1($5)

Quick Test

(1)We want to translate *x=*y into MIPS

(x,y ptrs stored in $s0,$s1)

(2) int x = 5;

*p =*p + x + 10;

assume $s0 holds p; $s1 is x

```
lw t0 , 0($s1)
sw t0, 0($s0)
```

```
addi $s1, $0, 5
lw $t0, 0($s0)
add $t0, $t0, $s1
addi $t0, $t0, 10
sw $t0, 0($s0)
```

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

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

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 $\times$ 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 = $PC_{31\ldots28}$: (address $\times$ 4)

Target Addressing Example

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

`Loop: sll $t1, $s3, 2`	80000	0	0	19	9	2	0
`add $t1, $t1, $s6`	80004	0	9	22	9	0	32
`lw $t0, 0($t1)`	80008	35	9	8	0		
`bne $t0, $s5, Exit`	80012	5	8	21	?		
`addi $s3, $s3, 1`	80016	8	19	19	1		
`j Loop`	80020	2	?				
`Exit: …`	80024						

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: …
```

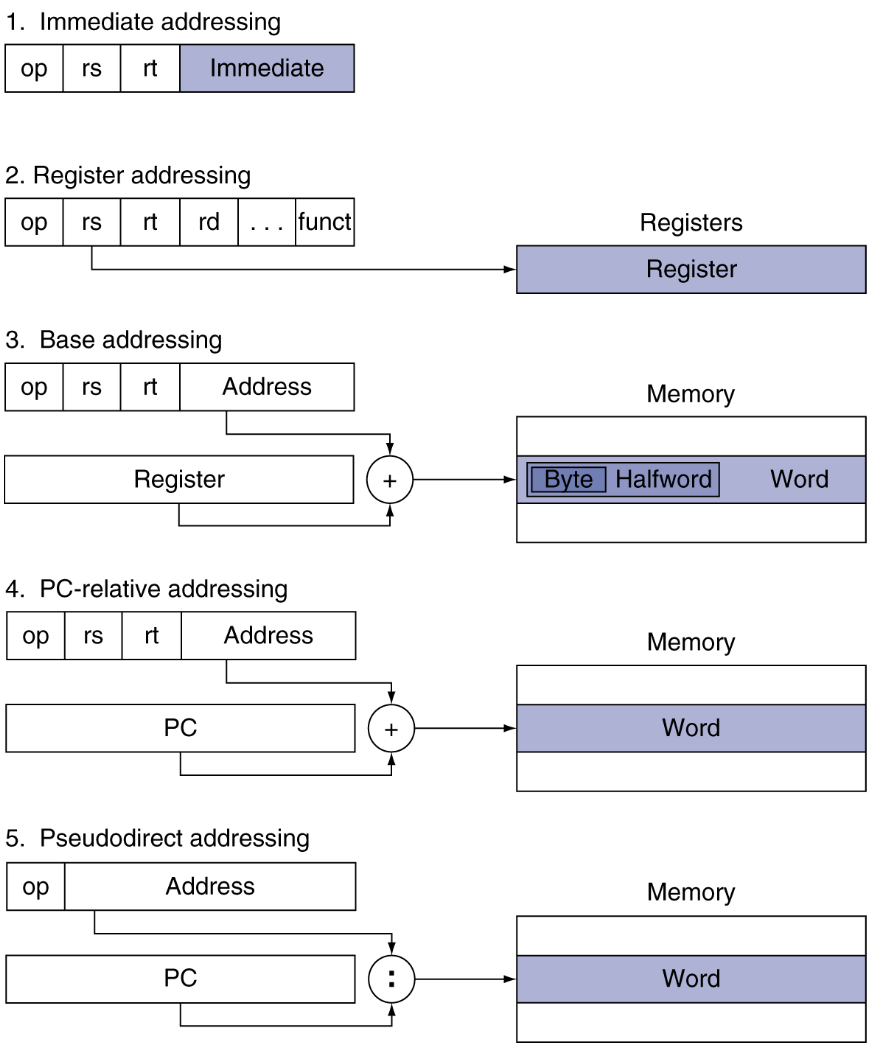
80000	0	0	19	9	2	0
80004	0	9	22	9	0	32
80008	35	9	8	0		
80012	5	8	21	2		
80016	8	19	19	1		
80020	2	20000				
80024						

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: …
```

Addressing Mode Summary



关于PC寻址的几个问题

1、如果代码移动了，分支字段的值会改变吗？

2、如果目标地址与分支地址相差>2^{15}，怎么办？

3、我们为什么需要多种寻址方式？一个可以吗？

4、如果确实需要一个32位转移地址，怎么办？

5、把A和B两个C语言程序分别编译，然后合成一个执行程序，Jump和Branch指令都不需要变化吗？

Synchronization

- Two processors sharing an area of memory
  - P1 writes, then P2 reads
  - Data race if P1 and P2 don't synchronize
    - Result depends of order of accesses
- Hardware support required
  - Atomic read/write memory operation
  - No other access to the location allowed between the read and write
- Could be a single instruction
  - E.g., atomic swap of register ↔ memory
  - Or an atomic pair of instructions

Synchronization in MIPS

- Load linked: `ll rt, offset(rs)`
- Store conditional: `sc rt, offset(rs)`
  - Succeeds if location not changed since the `ll`
    - Returns 1 in rt
  - Fails if location is changed
    - Returns 0 in rt
- Example: atomic swap (to test/set lock variable)

```
try: add $t0,$zero,$s4 ;copy exchange value
     ll  $t1,0($s1)    ;load linked
     sc  $t0,0($s1)    ;store conditional
     beq $t0,$zero,try ;branch store fails
     add $s4,$zero,$t1 ;put load value in $s4
```

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, n in $a1, i in $s0, j in $s1

The Procedure Body

Move params

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

Outer loop

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

Inner 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
```

Pass params & call

```
         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
```

Inner loop

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

Outer loop

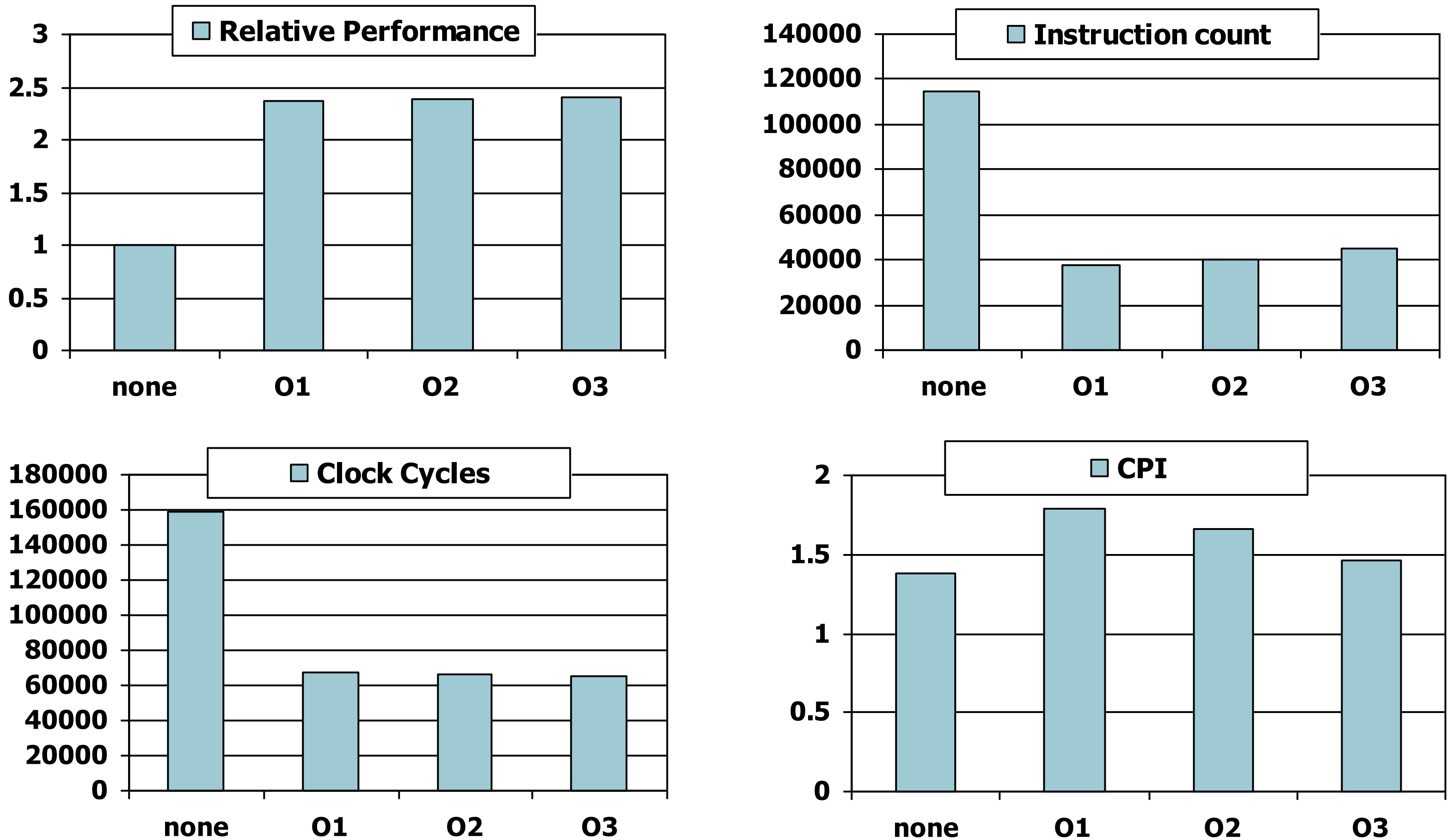
```
exit2:   addi $s0, $s0, 1        # i += 1
         j    for1tst            # jump to test of outer loop
```

The Full Procedure

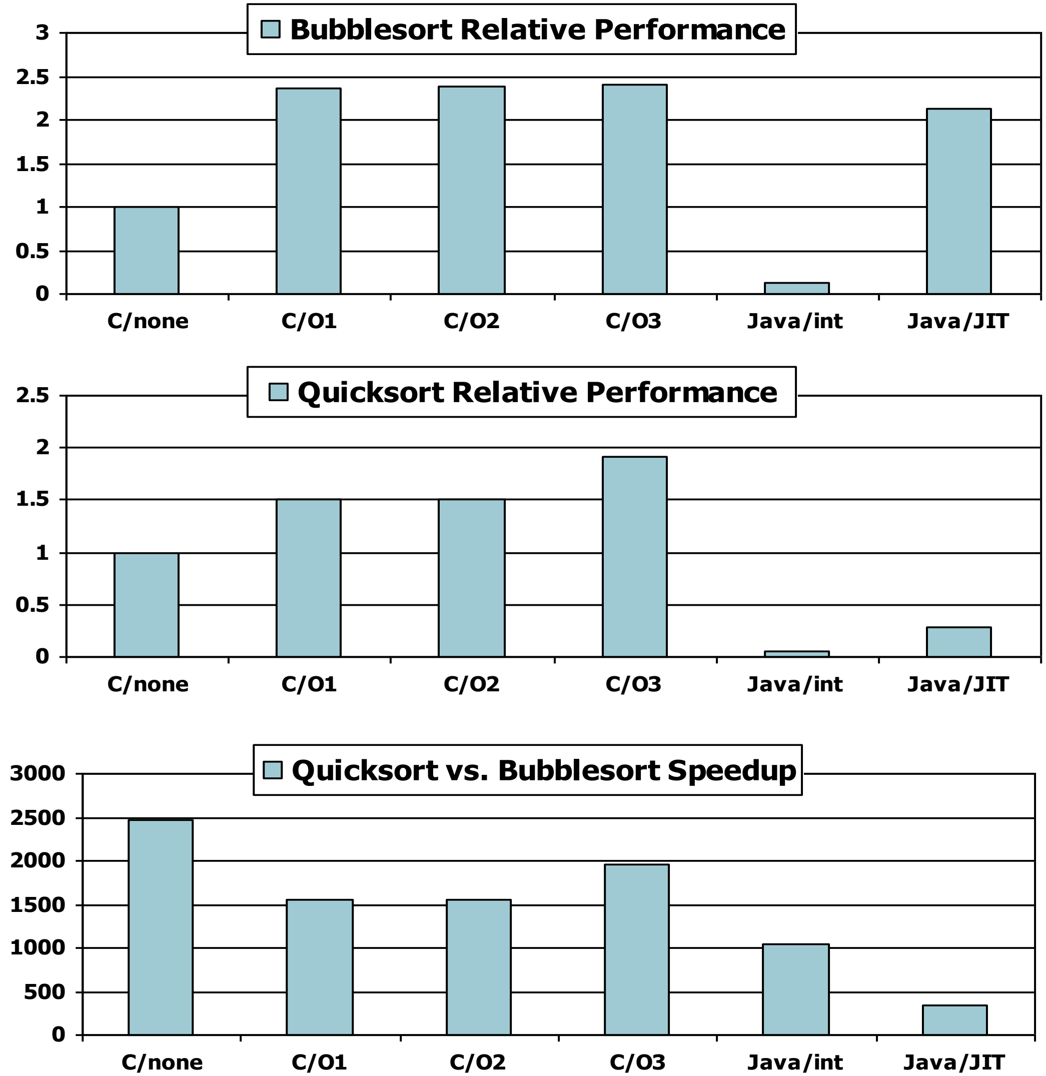
```
sort:    addi $sp,$sp, -20      # make room on stack for 5 registers
         sw $ra, 16($sp)        # save $ra on stack
         sw $s3,12($sp)         # save $s3 on stack
         sw $s2, 8($sp)         # save $s2 on stack
         sw $s1, 4($sp)         # save $s1 on stack
         sw $s0, 0($sp)         # 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
```

Effect of Compiler Optimization

Compiled with gcc for Pentium 4 under Linux



Effect of Language and Algorithm



Lessons Learnt

- Instruction count and CPI are not good performance indicators in isolation
- Compiler optimizations are sensitive to the algorithm
- Java/JIT compiled code is significantly faster than JVM interpreted
  - Comparable to optimized C in some cases
- Nothing can fix a dumb algorithm!

2.14 Arrays vs. Pointers

- Array indexing involves
  - Multiplying index by element size
  - Adding to array base address
- Pointers correspond directly to memory addresses
  - Can avoid indexing complexity

Example: Clearing an Array

```c
clear1(int array[], int size) {
  int i;
  for (i = 0; i < size; i += 1)
    array[i] = 0;
}
```

```c
clear2(int *array, int size) {
  int *p;
  for (p = &array[0]; p < &array[size];
       p = p + 1)
    *p = 0;
}
```

```
       move $t0,$zero   # i = 0
loop1: sll $t1,$t0,2    # $t1 = i * 4
       add $t2,$a0,$t1  # $t2 =
                        #   &array[i]
       sw $zero, 0($t2) # array[i] = 0
       addi $t0,$t0,1   # i = i + 1
       slt $t3,$t0,$a1  # $t3 =
                        #   (i < size)
       bne $t3,$zero,loop1 # if (…)
                           # goto loop1
```

```
       move $t0,$a0     # p = & array[0]
       sll $t1,$a1,2    # $t1 = size * 4
       add $t2,$a0,$t1  # $t2 =
                        #   &array[size]
loop2: sw $zero,0($t0)  # Memory[p] = 0
       addi $t0,$t0,4   # p = p + 4
       slt $t3,$t0,$t2  # $t3 =
                        #(p<&array[size])
       bne $t3,$zero,loop2 # if (…)
                           # goto loop2
```

Comparison of Array vs. Ptr

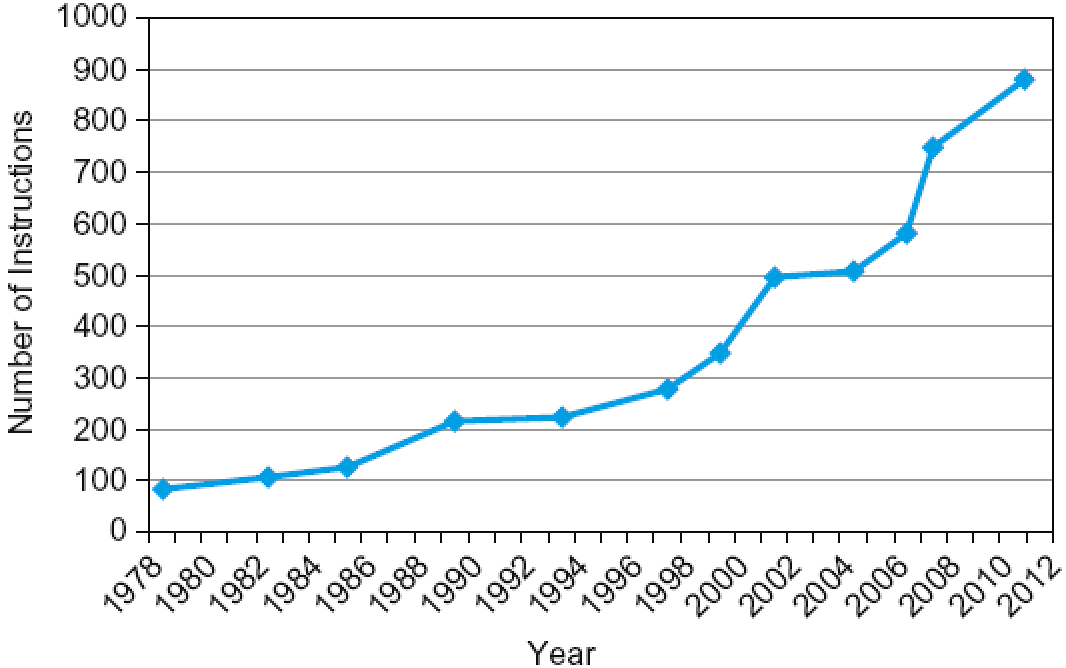
- Multiply “strength reduced” to shift
- Array version requires shift to be inside loop
  - Part of index calculation for incremented i
  - cf. incrementing pointer
- Compiler can achieve same effect as manual use of pointers
  - Induction variable elimination
  - Better to make program clearer and safer

Fallacies

- Powerful instruction ⇒ higher performance
  - Fewer instructions required
  - But complex instructions are hard to implement
    - May slow down all instructions, including simple ones
  - Compilers are good at making fast code from simple instructions
- Use assembly code for high performance
  - But modern compilers are better at dealing with modern processors
  - More lines of code ⇒ more errors and less productivity

Fallacies

- Backward compatibility ⇒ instruction set doesn't change
  - But they do accrete more instructions



x86 instruction set

Pitfalls

- Sequential words are not at sequential addresses
  - Increment by 4, not by 1!
- Keeping a pointer to an automatic variable after procedure returns
  - e.g., passing pointer back via an argument
  - Pointer becomes invalid when stack popped

Concluding Remarks

- Design principles
  1. Simplicity favors regularity
  2. Smaller is faster
  3. Make the common case fast
  4. Good design demands good compromises
- Layers of software/hardware
  - Compiler, assembler, hardware
- MIPS: typical of RISC ISAs
  - c.f. x86

Concluding Remarks

- 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%

Homework

- 2.4, 2.5
- 2.25
- 2.39, 2.40, 2.41, 2.42
- 2.43, 2.44
- X86与MIPS32过程调用的异同比较