Instruction Usage

Usage of DLX Instructions By SPEC92 Integer Code

<table>
<thead>
<tr>
<th>Instruction</th>
<th>SPEC92 Instruction Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>load int</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>conditional branch</td>
<td></td>
<td>16%</td>
</tr>
<tr>
<td>add int</td>
<td></td>
<td>14%</td>
</tr>
<tr>
<td>compare int</td>
<td></td>
<td>13%</td>
</tr>
<tr>
<td>store int</td>
<td></td>
<td>9%</td>
</tr>
<tr>
<td>or</td>
<td></td>
<td>8%</td>
</tr>
<tr>
<td>and</td>
<td></td>
<td>3%</td>
</tr>
<tr>
<td>shift</td>
<td></td>
<td>2%</td>
</tr>
</tbody>
</table>

FIGURE 2.28 Graphical display of instructions executed of the five programs from SPECint92 in Figure 2.26.

Control Transfer (Flow) Instructions

beq r1,$0 SKIP ! If r1 = 0 goto SKIP
nop
add r2, r2, r5
SKIP:
add r2, r3, r4

Control transfer (control flow) instructions (CTIs) ...
... may cause next instruction to be fetched from ...
... somewhere other than PC + 4 (assuming 4-byte instructions).

Programs would be trivial without them.
Occur frequently in programs.
Often a performance bottleneck.

Names used below are common:

- **Branch**: Conditional control transfer.
- **Jump**: Unconditional control transfer.
- **Jump and Link**: Unconditional, return address (PC) saved in register.
- **Call**: Unconditional control transfer, PC, etc. saved.
- **Return**: Unconditional, PC, etc. from most recent call restored.

Usage of DLX Instructions By SPEC92 Floating-Point Code

<table>
<thead>
<tr>
<th>Instruction</th>
<th>SPEC92 Instruction Count</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>load FP</td>
<td></td>
<td>23%</td>
</tr>
<tr>
<td>conditional branch</td>
<td></td>
<td>17%</td>
</tr>
<tr>
<td>sub FP</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>add FP</td>
<td></td>
<td>13%</td>
</tr>
<tr>
<td>compare FP</td>
<td></td>
<td>8%</td>
</tr>
<tr>
<td>store FP</td>
<td></td>
<td>7%</td>
</tr>
<tr>
<td>add int</td>
<td></td>
<td>6%</td>
</tr>
<tr>
<td>mov reg FP</td>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>shift</td>
<td></td>
<td>2%</td>
</tr>
</tbody>
</table>

FIGURE 2.29 Graphical display of instructions executed of the five programs from SPECfp92 in Figure 2.27.
CTI Examples

```c
if (t2 == t3) goto TARGET1;
t4 = t5 + t6; goto TARGET2;
TARGET1: t4 = t5 * t6;
TARGET2: PROCNAME(); return;
```

MIPS Assembler Code

```assembly
sub $t1, $t2, $t3 ! $t1 = $t2 - $t3
beq $t1, $0 TARGET1 ! Branch if $t1 = 0.
nop
add $t4, $t5, $t6 ! $t4 = $t5 + $t6
j TARGET2 ! Jump unconditionally.
nop
TARGET1: ! Label. (Assembler and linker find address.)
mult $t5, $t6 ! (hi,lo) = $t5 * $t6
mflo $t4
TARGET2: ! Another label.
sw 16($t7), $ra ! Save return address (of caller to this proc.)
jal PROCNAME ! Call PROCNAME, store this return addr in $ra.
nop
lw $ra, 16($t7) ! Restore return address (overwritten by jal).
jr $ra ! Return (from this procedure).
```

Branch instruction: `beq`.
Jump instruction: `j`.
Call instruction: `jal`.
Return instruction: `jr`.

Note: call and return are sometimes special case of `jump and link` instructions.

Usage of CTI By Type

CTI by type MIPS running SPEC92 benchmarks.

![Frequency of branch classes](image)

**FIGURE 2.12** Breakdown of control flow instructions into three classes: calls or returns, jumps, and conditional branches.

Destination Address in CTIs

Any addressing mode could be used for destination.

Several are common:

- **Absolute**
  Destination address is an immediate.

  Best for procedure calls...
  ...because destination can be far away.

  Not used in MIPS or SPARC.

- **PC-Relative or Displacement**
  Destination is displacement added to program counter.

  ISA design choice: displacement size.

  Good for conditional branches...
  ...because destination usually close by...
  ...and so small immediates suffice.

  Used in branch instructions by most ISAs, including MIPS and SPARC.
**Register Indirect**
Destination in register.
Used for subroutine return addresses.
Used for function address passed as parameters, as with `qsort`.
Also used by ISAs in which immediates smaller than addresses.
Used in MIPS (`jr` and `jalr`) and SPARC (`jmpl`).

**Indexed**
Destination is sum of two registers.
Useful for C `switch` and similar statements.
Used in SPARC `jmpl` (jump and link), not used in MIPS.

**Region**
Destination is high few bits of PC concatenated with immediate.
Used in MIPS `j` and `jal` instructions.

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**Destination Address Examples**

### Absolute and PC-Relative Examples (Generic ISA)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>jump_abs</code> TARGET1</td>
<td>Instruction contains entire address, TARGET1.</td>
</tr>
<tr>
<td><code>add r1, r2, r3</code></td>
<td>When <code>jump_rel</code> executes, PC = TARGET1.</td>
</tr>
<tr>
<td><code>jump_rel</code> TARGET2</td>
<td>Instruction contains TARGET2-TARGET1.</td>
</tr>
<tr>
<td><code>sub r4, r5, r6</code></td>
<td></td>
</tr>
<tr>
<td><code>and r7, r8, r9</code></td>
<td></td>
</tr>
</tbody>
</table>

To compute target address of `jump_rel` processor adds operand to PC.
Names `jump_abs` and `jump_rel` are made up.

---

### Jump and link SPARC instruction.

First two operands specify address: a register plus immediate.
Last operand is register to save PC in.
Register `g0` is a dummy register.

```
jmpl %l0+0,%o7 ! Call address in %l0, PC saved in %o7
nop
```

**SUBROUTINE:**
```
add %l1, %l2, %l3 ! 13 = 12 + 11 (Note that 13 is desto.)
jmpl %o7+0, %g0 ! Return using address in %7. Save PC in dummy reg.
nop
```

---

### Branch Displacement Size

Branch distances on DLX running SPEC92 programs.

![Branch Distance Distribution](image.png)

**FIGURE 2.13** Branch distances in terms of number of instructions between the target and the branch instruction.

In DLX branch displacement limited to 16 bits.
Branch Conditions

How branch condition might be specified:

- Test value of general-purpose register (GPR).
- Test value of special-purpose condition code register (CCR).
- Test value of special-purpose loop-counter register.
- Comparison specified in branch instruction.

Note: test value means test if value is zero ... which is much faster than test if value greater than constant.

A typical ISA would use one or two of these methods.

Branch Condition Example (MIPS)

MIPS uses two methods: GPR and CCR.

Integer compare instructions (e.g., `slt`) write result comparison into any GPR ... where it is read by a branch.

Floating-point compare instructions (e.g., `c.gt.d`) write result into special FP status (condition-code) register.

```plaintext
# MIPS Mnemonics:

`slt` r1, r2, r3 ! Compare r2 and r3, set r1=1 if r2 < r3.
`beq` r1, $0 TARGET1 ! Branch if r1 = 0. (r2 >= r3).
`c.eq.d` f0, f2 ! Compare f0 and f2, set FP CCR true if f0 = f2.
`bc1t` TARGET1 ! Branch if FP CCR is true.

# Branch Condition Example, Itanium (IA-64)

Itanium has special counted loop branches and a loop count register (LC).

If LC register non-zero counted loop branch is taken and register decremented.

```plaintext
# Itanium Mnemonics:

`mov lc = 10` ! Set loop count to 10.
`loop` ! There are 128 64-bit GPRs.
`br.cloop LOOP;;` ! if( lc > 0 ) { lc--; goto LOOP; }
```

Branch Condition Example, SPARC

Sparc uses an integer condition codes register (actually part of a larger status register).

ALU instructions can optionally set condition codes.

Register has several 1-bit fields which describe outcome: negative, zero, overflow, and carry.

Branch instruction can test for many combinations (e.g., not negative and not zero, not negative, negative).

```plaintext
# SPARC Mnemonics:

```

```
Tradeoffs between Methods to Specify Branch Condition

Factors

For compact code and programmer convenience:
⇒ Comparison in branch instruction.

For fast implementation:
⇒ Test GPR. (But may “waste” registers.)
⇒ Test CCR. (Maybe limited to one condition at a time.)
⇒ Test loop counter.

Procedure Call and Return

Procedures (A.k.a., subroutines, functions.)

Fundamental part of every nontrivial program.

Requires careful support in ISA.

Mandatory ISA Support

Call instruction saves PC in register.

Return restores saved PC.

Additional Support, Provided by ISA or Software (ABI).

Save and restore registers.

Prepare stack frame of called procedure.

Application Binary Interface (ABI)

Rules for writing machine-language programs.

More restrictive than ISA …
… but not enforced by hardware.

Code adhering to ABI rules called compliant.

Given an ABI, …
… any compliant procedure …
… can call any other compliant procedure …
… (if call parameter and return value types match).

⇒ ABI determines how “Additional Support” provided.

Implementation of Call and Return Steps

Mostly Hardware

Powerful call and return instructions do most of the work.

Call instruction …
… saves program counter and other registers.

Return instruction …
… adjusts stack and restores registers.
Implementation of Call and Return Steps

Mostly Software

Simple call and return only handle program counter.

Remainder done by general-purpose instructions ... using ABI guidelines.

Before call, using general-purpose instructions, ...
... procedure may save some registers.

Call instruction ...
... places return address in an ABI-specified register.

Called procedure, using general-purpose instructions, ...
... adjusts stack and may save registers.

Procedure return is similar.

CTI Variations

CTI Behaviors Chosen to Speed Implementation

Delayed Transfer:
Control transfer occurs 1 instruction after CTI.

E.g., consider execution of instruction 1 of DLX code:

```
1   j TARGET  ! Jump to TARGET.
2   add r1,r2,r3  ! Executed after jump.
3   sub r4,r5,r6
```

TARGET:

Without delayed CT, instruction 2 not executed.

With delayed CT instruction 2 is executed, but not 3.

Speeds simple implementations, but complicates modern designs.

Delayed control transfers used on many RISC ISAs, including MIPS, SPARC.

Not included on Alpha.

CTI Variations

Branch Instructions with Prediction Hints

Programmer indicates (hints) whether ...
... branch is expected to be taken most of the time or ...
... not taken most of the time.

Hint only affects execution speed, not what the program does.

If programmer correct, execution may be faster ...
... if programmer wrong execution is correct but slower.

A low-cost implementation might ignore the hint.

Example: Hypothetical prediction hints added to MIPS.

```
bltz, pn r1, LINE1  ! Programmer expects r1 to be nonnegative most of the time.
nop
bgtz, pt r2, LINE2  ! Programmer expects r2 positive most of the time.
nop
add   r3, r4, r5
LINE1:
addi  r3, r3, 1
LINE2:
add   r3, r6, r7
```
Predicated Execution

*Predicated Instructions:* Arithmetic or register move instructions along with a condition.

Results written only if condition true.

If condition false instruction may still be executed . . . though results not written.

When predicated execution used fewer branches needed . . . though total number of instructions may be greater.

Because branches can slow implementations . . . execution can be faster with predication even though more instructions executed.

Example: Add predication to MIPS (hypothetical). (Pay Attention)

Predicate indicated in parenthesis before mnemonic.

((rp)) means write results if (rp) nonzero . . .

. . . (!rp)) means write results if (rp) is zero.

! High level code: if( r1 == 0 ) r2 = r2 + r5 else r2 = r2 + r4;
! Without predicated execution.
   beq r1,$0 LINE1
   nop
   add r2, r2, r4
   j LINE2
   nop
LINE1: add r2, r2, r5
LINE2: ...

! With predicated execution.
   (r1) add r2, r2, r4 ! Execute if r1 nonzero.
   (!r1) add r2, r2, r5 ! Execute if r1 zero.

Is it a coincidence that the destination and first source operands were the same in the adds?

ISA Classification

Consider the way cars are classified:

Criteria: performance, comfort, off-road capabilities.

Classifications: sports cars, luxury cars, SUVs.

A classification may be based on one or more criteria . . .

. . . for example sports cars are high performance and comfortable (excluding ride).

Processors are also classified based on multiple criteria.

Processor Classification: Three Criteria

Address space size: 32-bit, 64-bit, etc.

Register use by instructions: Load/store, memory/memory, stack, etc.

Instruction format: Fixed length, variable length, bundled (VLIW).

Criterion: Address Space Size

Describes address space size.

*n*-bit processor indicates . . .

. . . *n*-bit address space and fast *n*-bit integer instructions for pointer arithmetic.

Terminology widely adopted but not universal.

Temptation to inflate *n*, e.g., 128-bit processor (may refer to bus width).
Criterion: Register Use

Describes how instructions can use registers and addressing modes.

Load/Store, General Purpose Register
Memory only accessed by special load and store instructions.
Few special purpose registers.
Arithmetic and logic instructions use register or immediates.
Examples include most ISAs developed in 1980s and 1990s.

Memory/Memory, General Purpose Register
Memory can be read and written by arithmetic and logic instructions.
Arithmetic and logic instructions can also use register and immediate operands.
Few special purpose registers.
Characteristic of older ISAs.

Accumulator
Arithmetic instructions implicitly use accumulator.
May include other special-purpose registers.

Stack
Instructions refer to stack.
Used in several old and new machines.

Criterion: Instruction Format

Describes allowed instruction sizes and something called bundling.

Fixed Size
All instructions same size. (E.g., 32 bits).
All instructions do about same amount of work.
Eases implementation.
Characteristic of newer ISAs.

Variable Size
Instruction size depends on instruction and operands.
Potential for compact code.
Implementation difficult.
Characteristic of older and special-purpose ISAs.

Bundled (VLIW, EPIC)
Instructions grouped into bundles, to be executed as a group.
Bundles also contain information to speed execution.
Used in new Itanium ISA and older experimental machines.
ISA Classifications

Common Classifications and Status

**RISC (Reduced Instruction Set Computing)**
- Current General Purpose.

**CISC (Complex Instruction Set Computing)**
- Former and Legacy (still used) General Purpose.

**VLIW (Very Long Instruction Word)**
- Future General Purpose?

Stack
- Embedded (built in).

Accumulator
- Past General Purpose.

CISC (Complex Instruction Set Computing)

Criteria
- Register Use: Memory/Memory, General Purpose Register
- Instruction Format: Variable Instruction Size

Characteristics
- Programmer friendly, lots of instruction choices.
- Programmer un-friendly, may contain many almost-useful special purpose instructions.
- Average code size.
- Implementation cost inflated by ISA complexity.

From mid 1980s to late 1990s ISA complexity slowed implementations but... 
... fin-de-siècle \(^1\) CISC processors nearly as fast as RISC processors.

Examples: VAX, 68000, arguably IA-32 (popularly known as 80x86).

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RISC (Reduced Instruction Set Computing)

Criteria
- Register Use: Load/Store, General Purpose Register
- Instruction Format: Fixed Instruction Sizes

Characteristics
- Work performed by each instruction balanced to ease implementation.
- Few special purpose, rarely used instructions.
- Code size large. (Because of fixed instruction size.)

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RISC Characteristics, continued.

Instructions designed to speed implementation...
- Though sometimes design biased towards contemporary technology...
- Ignoring future technology that might be used in later implementations.

Some implementations rely on compiler to arrange (schedule) instruction for fast execution (discussed later).

Most major ISAs since 1985 are RISC types.

Examples: SPARC V9, Alpha, MIPS, HP PA (Precision Architecture), Power4, PowerPC.
**VLW (Very Long Instruction Word)**

Special case: EPIC (Explicitly Parallel Instruction Computing)

Criteria

Instruction Format: Bundled.

Characteristics

Extra information in bundles allows higher speed implementations.

Examples: TI 320C6 (meant for signal processing), . . .

. . . the new Intel Itanium ISA (implemented by the Itanium processor).

Discussed further later in the course.

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**Stack**

Criteria

Register Use: Stack

Instruction Format: Variable Width

Characteristics

Small code size. Important for *embedded* [in cell phone, VCR, automobile engine, etc.] processors.

Limited speed because stack limits execution overlap opportunities.

Examples: Burroughs Corp. machines (1961-1977), INMOS Transputer (1983-).