CPU design options

Erik Hagersten
Uppsala University
DARK2 in a nutshell

1. Memory Systems (caches, VM, DRAM, microbenchmarks, ...)
2. Multiprocessors (TLP, coherence, interconnects, scalability, clusters, ...)
3. CPUs (pipelines, ILP, scheduling, Superscalars, VLIWs, embedded, ...)
4. Future: (physical limitations, TLP+ILP in the CPU,...)
How it all started...the fossils

- ENIAC J.P. Eckert and J. Mauchly, Univ. of Pennsylvania, WW2
  - Electro Numeric Integrator And Calculator, 18,000 vacuum tubes
- EDVAC, J. V Neumann, operational 1952
  - Electric Discrete Variable Automatic Computer (stored programs)
- EDSAC, M. Wilkes, Cambridge University, 1949
  - Electric Delay Storage Automatic Calculator
- Mark-I... H. Aiken, Harvard, WW2, Electro-mechanic
- K. Zuse, Germany, electromech. computer, special purpose, WW2
- BARK, KTH, Gösta Neovius, Electro-mechanic early 50s
- BESK, KTH, Erik Stemme (now at Chalmers) early 50s
- SMIL, LTH mid 50s
How do you tell a good idea from a bad

The Book: The performance-centric approach
- CPI = #execution-cycles / #instructions executed (~ISA goodness – lower is better)
- CPI * cycle time \(\rightarrow\) performance
- CPI = CPI_{CPU} + CPI_{Mem}

*The book rarely covers other design tradeoffs*

- The feature centric approach...
- The cost-centric approach...
- Energy-centric approach...
- Verification-centric approach...
The Book: Quantitative methodology

Make design decisions based on execution statistics. Select workloads (programs representative for usage). Instruction mix measurements: statistics of relative usage of different components in an ISA.

Experimental methodologies

- Profiling through tracing
- ISA simulators
Two guiding stars
-- the RISC approach:

Make the common case fast
- Simulate and profile anticipated execution
- Make cost-functions for features
- Optimize for overall end result (end performance)

Watch out for Amdahl's law
- \[ \text{Speedup} = \frac{\text{Execution\_time}_{\text{OLD}}}{\text{Execution\_time}_{\text{NEW}}} \]
- \[ \left[ (1 - \text{Fraction}_{\text{ENHANCED}}) + \frac{\text{Fraction}_{\text{ENHANCED}}}{\text{Speedup}_{\text{ENHANCED}}} \right] \]
Instruction Set Architecture (ISA)
-- the interface between software and hardware.

Tradeoffs between many options:
• functionality for OS and compiler
• wish for many addressing modes
• compact instruction representation
• format compatible with the memory system of choice
• desire to last for many generations
• bridging the semantic gap (old desire...)
• RISC: the biggest “customer” is the compiler
ISA trends today

- CPU families built around “Instruction Set Architectures” ISA
- Many incarnations of the same ISA
- ISAs lasting longer (~10 years)
- Consolidation in the market - fewer ISAs (not for embedded…)
- 15 years ago ISAs were driven by academia
- Today ISAs technically do not matter all that much (market-driven)
- How many of you will ever design an ISA?
- How many ISAs will be designed in Sweden?
Compiler Organization

- Fortran Front-end
- C Front-end
- C++ Front-end

Intermediate Representation

High-level Optimization

Global & Local Optimization

Code Generation

Machine-independent Translation

Procedure in-lining
Loop transformation

Register Allocation
Common sub-expressions

Instruction selection
constant folding
Compilers – a moving target!
The impact of compiler optimizations

- Compiler optimizations affect the number of instructions as well as the distribution of executed instructions (the instruction mix)
Memory allocation model also has a huge impact

- **Stack**
  - local variables in activation record
  - addressing relative to stack pointer
  - stack pointer modified on call/return

- **Global data area**
  - large constants
  - global static structures

- **Heap**
  - dynamic objects
  - often accessed through pointers
Execution in a CPU

"Machine Code"

"Data"

CPU
# Operand models

Example: $C := A + B$

<table>
<thead>
<tr>
<th>Stack</th>
<th>Accumulator</th>
<th>Register</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUSH [A]</td>
<td>LOAD [A]</td>
<td>LOAD R1,[A]</td>
</tr>
<tr>
<td>PUSH [B]</td>
<td>ADD [B]</td>
<td>ADD R1,[B]</td>
</tr>
<tr>
<td>ADD</td>
<td>STORE [C]</td>
<td>STORE [C],R1</td>
</tr>
<tr>
<td>POP [C]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Diagram showing the stack, accumulator, and register models](image-url)
Stack-based machine

Example: $C := A + B$

Mem:

A: 12
B: 14
C: 10

PUSH [A]
PUSH [B]
ADD
POP [C]
Stack-based machine

Example: $C := A + B$

Mem:

$A: 12$
$B: 14$
$C: 10$

PUSH [A]
PUSH [B]
ADD
POP [C]
Stack-based machine

Example: $C := A + B$

Mem:

```
A: 12
B: 14
C: 10
```

- PUSH [A]
- PUSH [B]
- ADD
- POP [C]
Stack-based machine

Example: \( C := A + B \)

Mem:

\[
A:12 \\
B:14 \\
C:10
\]

PUSH [A]  
PUSH [B]  
ADD  
POP [C]
Stack-based machine

Example: C := A + B

Mem:

A:12
B:14
C:10

PUSH [A]
PUSH [B]
ADD
POP [C]
Stack-based machine

Example: \( C := A + B \)

Mem:

- **PUSH** [A]
- **PUSH** [B]
- **ADD**
- **POP** [C]

Mem:

\[
\begin{array}{c}
A: 12 \\
B: 14 \\
C: 26 \\
\end{array}
\]
Stack-based

- Implicit operands
- Compact code format (1 instr. = 1 byte)
- Simple to implement
- Not optimal for speed!!!
Accumulator-based

≈ Stack-based with a depth of one
One implicit operand from the accumulator

Mem:

A:12
B:14
C:10

PUSH [A]
ADD [B]
POP [C]
Register-based machine

Example: $C := A + B$

Data:

$A: 12$
$B: 14$
$C: 26$

"Machine Code"

→ LD R1, [A]
→ LD R7, [B]
→ ADD R2, R1, R7
→ ST R2, [C]
Register-based

- Commercial success:
  - X86,
  - RISCs (Alpha, SPARC, HP-PA...)
  - VLIW (IA64, ...)
- Explicit operands (i.e., "registers")
- Wasteful instr. format (1 instr. = 4 bytes)
- Suits optimizing compilers
- Optimal for speed!!!
Properties of operand models

<table>
<thead>
<tr>
<th></th>
<th>Compiler Construction</th>
<th>Implementation Efficiency</th>
<th>Code Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack</td>
<td>+</td>
<td>--</td>
<td>++</td>
</tr>
<tr>
<td>Accumulator</td>
<td>--</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Register</td>
<td>++</td>
<td>++</td>
<td>--</td>
</tr>
</tbody>
</table>

General-purpose register model dominates today

**Reason:** general model for compilers and efficient implementation wise
## Traditional Addressing Modes (VAX)

<table>
<thead>
<tr>
<th>Addressing mode</th>
<th>Example instruction</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate</td>
<td>Add R4,#3</td>
<td>Regs[R4] ← Regs[R4]+3</td>
</tr>
<tr>
<td>Displacement</td>
<td>Add R4,100(R1)</td>
<td>Regs[R4] ← Regs[R4]+Mem[100+Regs[R1]]</td>
</tr>
<tr>
<td>Register deferred or indirect</td>
<td>Add R4,(R1)</td>
<td>Regs[R4] ← Regs[R4]+Mem[Regs[R1]]</td>
</tr>
<tr>
<td>Direct or absolute</td>
<td>Add R1,(1001)</td>
<td>Regs[R1] ← Regs[R2]+Mem[1001]</td>
</tr>
<tr>
<td>Memory indirect or memory deferred</td>
<td>Add R1,@(R3)</td>
<td>Regs[R1] ← Regs[R1]+Mem[Mem[Regs[R3]]]</td>
</tr>
<tr>
<td>Autodecrement</td>
<td>Add R1,-(R2)</td>
<td>Regs[R2] ← Regs[R2]-d; Regs[R1] ← Regs[R1]+Mem[Regs[R2]]</td>
</tr>
<tr>
<td>Scaled (iù%)</td>
<td>Add R1,100(R2)[R3]</td>
<td>Regs[R1] ← Regs[R1]+Mem[100+Regs[R2]+Regs[R3]*d]</td>
</tr>
</tbody>
</table>
Actual use of addr. modes

What addressing modes dominate usage?

- Immediate and Displacement are the most common addressing modes in SPEC89 on a VAX
## Important Addressing Modes

<table>
<thead>
<tr>
<th>Addressing mode</th>
<th>Example instruction</th>
<th>Meaning</th>
<th>When used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Register deferred or indirect</td>
<td>Add R4,(R1)</td>
<td>Regs[R4] ← Regs[R4]+ Mem[Regs[R1]]</td>
<td>Accessing using a pointer or a computed address.</td>
</tr>
<tr>
<td>Scaled</td>
<td>Add R1,100(R2)[R3]</td>
<td>Regs[R1] ← Regs[R1]+ Mem[100+Regs[R2]+Regs[R3]*d]</td>
<td>Used to index arrays. May be applied to any indexed addressing mode in some machines.</td>
</tr>
</tbody>
</table>
Size of immediates

- Immediate operands are very important for ALU and compare operations
- 16-bit immediates seem sufficient (75%-80%)
## Operation types in the ISA

<table>
<thead>
<tr>
<th>Operator type</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetical and logical</td>
<td>Integer arithmetic and logical operations: add, and, subtract, or</td>
</tr>
<tr>
<td>Data transfer</td>
<td>Loads/stores (move instructions on machines with memory addressing)</td>
</tr>
<tr>
<td>Control</td>
<td>Branch, jump, procedure call and return</td>
</tr>
<tr>
<td>System</td>
<td>Operating system call, virtual memory management instructions</td>
</tr>
<tr>
<td>Floating point</td>
<td>Floating-point operations: add, multiply,...</td>
</tr>
<tr>
<td>Decimal</td>
<td>Decimal add, decimal multiply, decimal-to-character conversions</td>
</tr>
<tr>
<td>String</td>
<td>String move, string compare, string search</td>
</tr>
</tbody>
</table>
Control instructions

- Conditional branches
- Unconditional branches (jumps)

Conditional branches dominate by far
Intuition: program loops are common!
Branches

Three options:

- **Condition Code**: Most operations have "side effects" on set of CC-bits. A branch depends on some CC-bit

- **Condition Register**: A named register is used to hold the result from a compare instruction. A following branch instruction names the same register.

- **Compare and Branch**: The compare and the branch is performed in the same instruction.
## Branch condition evaluation

<table>
<thead>
<tr>
<th>Name</th>
<th>How?</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition Code (CC)</td>
<td>Special bits are manipulated</td>
<td>CC set for free</td>
<td>Extra state</td>
</tr>
<tr>
<td>Condition register</td>
<td>Test general purpose register</td>
<td>simple</td>
<td>Uses up registers</td>
</tr>
<tr>
<td>Compare and branch</td>
<td>Compare is part of branch</td>
<td>One instr. Instead of two</td>
<td>Extra work per instr.</td>
</tr>
</tbody>
</table>
## Instruction formats

<table>
<thead>
<tr>
<th>Operation &amp; Address specifier</th>
<th>Address field 1</th>
<th>Address field 2</th>
<th>Address field 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Variable (e.g., VAX)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation</th>
<th>Address specifier</th>
<th>Address field 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b) Fixed (e.g., DLX, MIPS, Power PC, Precision Architecture, SPARC)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation</th>
<th>Address specifier 1</th>
<th>Address specifier 2</th>
<th>Address field 1</th>
<th>Address field 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c) Hybrid (e.g., IBM 360/70, Intel 80x86)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- A variable instruction format yields compact code but instruction decoding is more complex
DLX - A generic architecture

Load/store architecture (32 bits)

- Many (32) general purpose integer registers (GPR) and single precision floating point registers (GPR0 = 0)
- Fixed instruction width and format
- Addressing modes: immediate and displacement
- Supported data types: bytes, half word (16 bits), word (32 bits), single and double precision IEEE floating points
## Generic instructions (Load/Store Architecture)

<table>
<thead>
<tr>
<th>Instruction type</th>
<th>Example</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>LW R1,30(R2)</td>
<td>Regs[R1] ← Mem[30+Regs[R2]]</td>
</tr>
<tr>
<td>Store</td>
<td>SW 30(R2),R1</td>
<td>Mem[30+Regs[R2]] ← Regs[R1]</td>
</tr>
<tr>
<td>ALU</td>
<td>ADD R1,R2,R3</td>
<td>Regs[R1] ← Regs[R2] + Regs[R3]</td>
</tr>
<tr>
<td>Control</td>
<td>BEQZ R1,KALLE</td>
<td>if (Regs[R1]==0) PC ← KALLE + 4</td>
</tr>
</tbody>
</table>


Specifying hardware

- $\leftarrow_n$: Transfer n bits
- $R7_n$: Bit n of register R7
- $R2_{0..7}$: The most significant byte of R2 (Big endian!)
- $0^8$: A byte of all zeroes (repeat the field n times)
- $M[40]$: byte 40 in memory
- $0^8 \# M[40]$: Concatenate zero-byte (MSB) with the byte @mem(40)
Generic Move Instructions

- Load and Store
  - LB, LBU, SB -- byte chunks
  - LH, LHU, SH -- half word chunks
  - LW, SW -- word chunks
  - LF, SF -- word chunks to floating point regs
  - LD, SD double precision to FP regs (2 regs per OP)
Examples Hardware Descriptions

LH R1, 40(R3) -- load halfword (signed)
R1 <--\text{32} (M[40+R3]_0)^{16} \#\# M[40+R3] \#\# M[41+R3]

\[
R1:\begin{array}{c}
\text{SSSSSSSSSSSSSSSSSSSSSSSSSSSS} \\
\end{array}
M(“40”+R3) \quad M(“41”+R3)
\]

LBU R1, 40(R3) -- load byte unsigned
R1 <--\text{32} 0^{24} \#\# M[40+R3]

\[
R1:\begin{array}{c}
\text{00000000000000000000000000000000} \\
\end{array}
M(“41”+R3)
\]
Generic ALU Instructions

- **Integer arithmetic**
  - [add, sub] x [signed, unsigned] x [register, immediate]
  - e.g., ADD, ADDI, ADDU, ADDUI, SUB, SUBI, SUBU, SUBUI

- **Logical**
  - [and, or, xor] x [register, immediate]
  - e.g., AND, ANDI, OR, ORI, XOR, XORI

- **Load upper half immediate load**
  - It takes two instructions to load a 32 bit immediate
Examples Hardware Descriptions (2)

LHI R1, #42 -- load high immediate
R1 ←^32 "42" ## 0^16

\[
\begin{array}{c}
R1:
\end{array}
\]

ADDI R1, R2, #6 -- add immediate
R1 ←^32 R3 + "6"

\[
\begin{array}{c}
R1:
\end{array}
\]
More Generic ALU Ops

- **Shifts**
  - $[\text{left, right}] \times [\text{logical, arithmetic}] \times [\text{immediate, reg}]$
  - e.g., SLL, SRAI, ...

- **Set conditional**
  - $[\text{lt, gt, le, ge, eq, ne}] \times [\text{immediate, reg}]$
  - e.g., SLT, SGEI, ...
  - Puts a 1 or a 0 in the destination register
Generic Instruction Formats

**I-type**

```
0 31
 Opcode  Rs  Rd  Immediate
  6  5  5  16
```

**R-type**

```
0 31
 Opcode  Rs1  Rs2  Rd  Func
  6  5  5  5  11
```

**J-type**

```
0 31
 Opcode  Offset added to PC
  6  26
```
Generic FP Instructions

- Floating Point arithmetic
  - [add, sub, mult, div] x [double, single]
  - e.g., ADDD, ADDF, SUBD, SUBD, ...
- Compares (sets “compare bit”)
  - [lt, gt, le, ge, eq, ne] x [double, immediate]
  - e.g., LTD, GEF, ...
- Convert from/to integer, Fpregs
  - CVTF2I, CVTF2D, CVTI2D, ...
Simple Control

- **Branches if equal or if not equal**
  - BEQZ, BNEZ, cmp to register,
    \[ PC := PC + 4 + \text{immediate}_{16} \]
  - BFPT, BFPF, cmp to “FP compare bit”,
    \[ PC := PC + 4 + \text{immediate}_{16} \]

- **Jumps**
  - J: Jump --
    \[ PC := PC + \text{immediate}_{26} \]
  - JAL: Jump And Link --
    \[ R31 := PC + 4; PC := PC + \text{immediate}_{26} \]
  - JALR: Jump And Link Register --
    \[ R31 := PC + 4; PC := PC + \text{Reg} \]
  - JR: Jump Register --
    \[ PC := PC + \text{Reg} \text{ (“return from JAL or JALR”)} \]
Implementing ISAs --pipelines

Erik Hagersten
Uppsala University
EXAMPLE: pipeline implementation

Add R1, R2, R3

Registers:
• Shared by all pipeline stages
• A set of general purpose registers (GPRs)
• Some specialized registers (e.g., PC)
Load Operation:

LD R1, mem[cnst+R2]
Store Operation:

ST mem[const+R1], R2
EXAMPLE: Branch to R2 if R1 == 0

BEQZ R1, R2

OP: R1 == 0?
Initially

```
LD RegA, (100 + RegC)
IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
```
Cycle 1

<table>
<thead>
<tr>
<th>D</th>
<th>IF RegC &lt; 100 GOTO A</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>RegC := RegC + 1</td>
</tr>
<tr>
<td>B</td>
<td>RegB := RegA + 1</td>
</tr>
<tr>
<td>A</td>
<td>LD RegA, (100 + RegC)</td>
</tr>
</tbody>
</table>

PC → Mem
Cycle 2

LD RegA, (100 + RegC)
IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)
Cycle 3

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

PC \rightarrow

D
C
B
I
R
X
W
Regs

Mem
Cycle 4

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)
Cycle 5

```
LD RegA, (100 + RegC)
RegC := RegC + 1
RegB := RegA + 1
IF RegC < 100 GOTO A
LD RegA, (100 + RegC)
```
Cycle 6

PC →

<table>
<thead>
<tr>
<th>PC</th>
<th>Mem</th>
</tr>
</thead>
</table>

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

<

I R X W

Regs

Mem
Cycle 7

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

Branch ➔ Next PC
Cycle 8

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)
Example: 5-stage pipeline

[Diagram of a 5-stage pipeline with stages labeled IF, ID, EX, M, WB.]

- Instruction fetch
- Instruction decode/register fetch
- Execute/address calculation
- Memory access
- Write back
Example: 5-stage pipeline
Example: 5-stage pipeline
Example: 5-stage pipeline

Instruction fetch
Instruction decode/register fetch
Execute/address calculation
Memory access
Write back

IF
ID
EX
M
WB

Add
NPD
IR
Instruction memory
IP
Reg
ALU
MUX
Dest data
Data memory
LMO
MUX

s1
s2

st data

early reg write

pc

Zero?
Branch
taken

32
Sign
extend

16
IMM

(c)
Fundamental limitations

Hazards prevent instructions from executing in parallel:

Structural hazards: Simultaneous use of same resource
   If unified I+D$: LW will conflict with later I-fetch

Data hazards: Data dependencies between instructions
   LW R1, 100(R2) /* result avail in 2 - 100 cycles */
   ADD R5, R1, R7

Control hazards: Change in program flow
   BNEQ R1, #OFFSET
   ADD R5, R2, R3

Serialization of the execution by stalling the pipeline is one, although inefficient, way to avoid hazards
Fundamental types of data hazards

Code sequence

\[ \text{Op}_i \ A \]
\[ \text{Op}_{i+1} A \]

RAW (Read-After-Write)
Op\(_{i+1}\) reads A before Op\(_i\) modifies A. Op\(_{i+1}\) reads old A!

WAR (Write-After-Read) Op\(_{i+1}\) modifies A before Op\(_i\) reads A. Op\(_i\) reads new A

WAW (Write-After-Write) Op \(i+1\) modifies A before Op\(_i\). The value in A is the one written by Op\(_i\), i.e., an old A.
Hazard avoidance techniques

Static techniques (compiler): code scheduling to avoid hazards

Dynamic techniques: hardware mechanisms to eliminate or reduce impact of hazards (e.g., out-of-order stuff)

Hybrid techniques: rely on compiler as well as hardware techniques to resolve hazards (e.g. VLIW support – later)
Cycle 3

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

RegA := Mem[100 + RegC]
RegC := RegC + 1
RegB := RegA + 1
PC := PC + 1

LD RegA, (100 + RegC)
Fix alt1: code scheduling

IF RegC < 100 GOTO A
RegB := RegA + 1
RegC := RegC + 1
LD RegA, (100 + RegC)
Fix alt2: Bypass hardware

- Forwarding (or bypassing): provides a direct path from M and WB to EX
- Only helps for ALU ops. What about load operations?
DLX with bypass

Data$

DTLB

... L2$

... Mem

Instr$

ITLB

... L2$

... Mem

IF  ID  EX  M  WB

Instr$  ITLB  ... L2$  ... Mem

Mem

ALU output

st data

dest data

s1  s2

(d)

pc

dest data

data

PC$  Mem

……

L2$

……

Mem

ALU

Mul
Branch delays

```
LD RegA, (100 + RegC)
IF RegC < 100 GOTO A
RegB := RegA + 1
RegC := RegC + 1
```

8 cycles per iteration of 4 instructions 😞

Need longer basic blocks with independent instr.
Avoiding control hazards

Duplicate resources in ALU to compute branch condition and branch target address earlier

Branch delay cannot be completely eliminated

Branch prediction and code scheduling can reduce the branch penalty
Taking a Branch

PC := PC + Imm
Fix1: Minimizing Branch Delay Effects

Move Earlier

(d)

s1
s2

Instruction fetch
Instruction decode
Register file
Memory access
Write back

Add

NPG

Instruction memory

IR

R

(d)

PC

st data

dest data

IF

ID

EX

M

WB

Zero? Branch taken Cond

ALU

Mux

Mux

Mux

Mux

Mux

Mux

Data memory

LMD

Mux
Fix2: Static tricks

Delayed branch (schedule useful instr. in delay slot)
- Define branch to take place after a following instruction
- CONS: this is visible to SW, i.e., forces compatibility between generations

Predict Branch not taken (a fairly rare case)
- Execute successor instructions in sequence
- “Squash” instructions in pipeline if the branch is actually taken
- Works well if state is updated late in the pipeline
- 30%-38% of conditional branches are not taken on average

Predict Branch taken (a fairly common case)
- 62%-70% of conditional branches are taken on average
- Does not make sense for the generic arch. but may do for other pipeline organizations
Static scheduling to avoid stalls

- Scheduling an instruction from before is always safe.
- Scheduling from target or from the not-taken path is not always safe; must be guaranteed that speculative instr. do no harm.
Static Scheduling of Instructions

Erik Hagersten
Uppsala University
Sweden
## Architectural assumptions

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP ALU</td>
<td>FP ALU</td>
<td>3</td>
</tr>
<tr>
<td>FP ALU</td>
<td>SD</td>
<td>2</td>
</tr>
<tr>
<td>LD</td>
<td>FP ALU</td>
<td>1</td>
</tr>
</tbody>
</table>

Latency = number of cycles between the two adjacent instructions

Delayed branch: one cycle delay slot
Scheduling example

for (i=1; i<=1000; i=i+1)
    x[i] = x[i] + 10;

Iterations are independent => parallel execution

loop:          LD    F0, 0(R1) ; F0 = array element
               ADDD  F4, F0, F2 ; Add scalar constant
               SD    0(R1), F4 ; Save result
               SUBI  R1, R1, #8 ; decrement array ptr.
               BNEZ  R1, loop ; reiterate if R1 != 0

Can we eliminate all penalties in each iteration?
How about moving SD down?
Scheduling in each loop iteration

Original loop

| loop: | LD       | F0, 0(R1) |
|       | stall    |           |
|       | ADDD     | F4, F0, F2|
|       | stall    |           |
|       | stall    |           |
|       | SD       | 0(R1), F4 |
|       | SUBI     | R1, R1, #8|
|       | BNEZ     | R1, loop  |
|       | stall    |           |

5 instructions + 4 bubbles = 9 cycles / iteration
(~one cycle per iteration on a vector architecture)

Can we do better by scheduling across iterations?
Scheduling in each loop iteration

Original loop:

```
loop:
  LD F0, 0(R1)
stall
  ADDD F4, F0, F2
  SUBI R1, R1, #8
  SD 0(R1), F4
  BNEZ R1, loop
```

5 instruction + 4 bubbles = 9c / iteration

Statically scheduled loop:

```
loop:
  LD F0, 0(R1)
  ADDD F4, F0, F2
  SUBI R1, R1, #8
  BNEZ R1, loop
  SD 8(R1), F4
```

5 instruction + 1 bubble = 6c / iteration

Can we do even better by scheduling across iterations?
Unoptimized loop unrolling 4x

loop:

LD
stall
ADD
stall
SD
LD
stall
ADD
stall
SD
LD
stall
ADD
stall
SD
LD
stall
ADD
stall
SD
SUBI
BNEZ
SD

\[
\text{24c/ 4 iterations} = 6 \text{ c / iteration}
\]
Optimized scheduled unrolled loop

loop:  
LD  F0, 0(R1)  
LD  F6, -8(R1)  
LD  F10, -16(R1)  
LD  F14, -24(R1)  
ADDD  F4, F0, F2  
ADDD  F8, F6, F2  
ADDD  F12, F10, F2  
ADDD  F16, F14, F2  
SD  0(R1), F4  
SD  -8(R1), F8  
SD  -16(R1), F12  
SUBI  R1, R1, #32  
BNEZ  R1, loop  
SD  8(R1), F16

Important steps:  
Push loads up  
Push stores down  
Note: the displacement of the last store must be changed

Benefits of loop unrolling:  
Provides a larger seq. instr. window (larger basic block)  
Simplifies for static and dynamic methods to extract ILP

All penalties are eliminated. CPI=1  
14 cycles / 4 iterations ==> 3.5 cycles / iteration  
From 9c to 3.5c per iteration ==> speedup 2.6
Software pipelining 1(3)
Symbolic loop unrolling

- The instructions in a loop are taken from different iterations in the original loop.
Example:

loop:

LD F0,0(R1)
ADDD F4,F0,F2
SD 0(R1),F4
SUBI R1,R1,#8
BNEZ R1,loop

Looking at three rolled-out iterations of the loop body:

LD F0,0(R1) ; Iteration i
ADDD F4,F0,F2
SD 0(R1),F4

LD F0,0(R1) ; Iteration i+1
ADDD F4,F0,F2
SD 0(R1),F4

LD F0,0(R1) ; Iteration i+2
ADDD F4,F0,F2
SD 0(R1),F4

Execute in the same loop!!
Software pipelining 3(3)

Instructions from three consecutive iterations form the loop body:

\[
\begin{align*}
\text{< prologue code >} \\
\text{loop: SD 0(R1),F4} &; \text{from iteration i} \\
\text{ADDD F4,F0,F2} &; \text{from iteration i+1} \\
\text{LD F0,-16(R1)} &; \text{from iteration i+2} \\
\text{SUBI R1,R1,#8} & \\
\text{BNEZ R1,loop} & \\
\text{< prologue code >}
\end{align*}
\]

- No data dependencies within a loop iteration
- The dependence distance is 1 iterations
- WAR hazard elimination is needed (register renaming)
- 5c / iteration, but only uses 2 FP regs (instead of 8)
Software pipelining

- "Symbolic Loop Unrolling"
- Very tricky for complicated loops
- Less code expansion than outlining
- Register-poor if "rotating" is used
- Needed to hide large latencies (see IA-64)
Dependencies: Revisited

Two instructions must be independent in order to execute in parallel

• Three classes of dependencies that limit parallelism:
  • Data dependencies
    \[ X := \ldots \]
    \[ \ldots := \ldots X \ldots \]
  • Name dependencies
    \[ \ldots := \ldots X \]
    \[ X := \ldots \]
  • Control dependencies
    If \( X > 0 \) then
    \[ Y := \ldots \]
Getting desperate for ILP

Erik Hagersten
Uppsala University
Sweden
Multiple instruction issue per clock

Goal: Extracting ILP so that CPI < 1, i.e., IPC > 1

**Superscalar:**
- Combine static and dynamic scheduling to issue multiple instructions per clock
- HW finds independent instructions in “sequential” code
- Predominant: (PowerPC, SPARC, Alpha, HP-PA)

**Very Long Instruction Words (VLIW):**
- Static scheduling used to form packages of independent instructions that can be issued together
- Relies on compiler to find independent instructions (IA-64)
Superscalars

Thread 1

Issue logic

Regs

2 cycles

10 cycles

30 cycles

150 cycles

SEK

€

£

Mem

2kB

64kB

2MB

1GB

90
Example: A Superscalar DLX

- Issue 2 instructions simultaneously: 1 FP & 1 integer
  - Fetch 64-bits/clock cycle; Integer instr. on left, FP on right
  - Can only issue 2nd instruction if 1st instruction issues
  - Need more ports to the register file

<table>
<thead>
<tr>
<th>Type</th>
<th>Pipe stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int.</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>Int.</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>Int.</td>
<td>IF ID EX MEM WB</td>
</tr>
<tr>
<td>FP</td>
<td>IF ID EX MEM WB</td>
</tr>
</tbody>
</table>

- EX stage should be fully pipelined
- 1 load delay slot corresponds to three instructions!
Statically Scheduled  Superscalar DLX

<table>
<thead>
<tr>
<th>Integer instruction</th>
<th>FP instruction</th>
<th>Clock cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LD</td>
<td>F0,0(R1)</td>
<td>1</td>
</tr>
<tr>
<td>LD</td>
<td>F6,-8(R1)</td>
<td>2</td>
</tr>
<tr>
<td>LD</td>
<td>F10,-16(R1)</td>
<td>3</td>
</tr>
<tr>
<td>LD</td>
<td>F14,-24(R1)</td>
<td>4</td>
</tr>
<tr>
<td>LD</td>
<td>F18,-32(R1)</td>
<td>5</td>
</tr>
<tr>
<td>SD</td>
<td>0(R1),F4</td>
<td>6</td>
</tr>
<tr>
<td>SD</td>
<td>-8(R1),F8</td>
<td>7</td>
</tr>
<tr>
<td>SD</td>
<td>-16(R1),F12</td>
<td>8</td>
</tr>
<tr>
<td>SD</td>
<td>-24(R1),F16</td>
<td>9</td>
</tr>
<tr>
<td>SUBI</td>
<td>R1,R1,#40</td>
<td>10</td>
</tr>
<tr>
<td>BNEZ</td>
<td>R1,LOOP</td>
<td>11</td>
</tr>
<tr>
<td>SD</td>
<td>-32(R1),F20</td>
<td>12</td>
</tr>
</tbody>
</table>

Can be scheduled dynamically with Tomasulo’s alg.

Issue: Difficult to find a sufficient number of instr. to issue
Limits to superscalar execution

- Difficulties in scheduling within the constraints on number of functional units and the ILP in the code chunk
- Instruction decode complexity increases with the number of issued instructions
- Data and control dependencies are in general more costly in a superscalar processor than in a single-issue processor

Techniques to enlarge the instruction window to extract more ILP are important

Simple superscalars relying on compiler instead of HW complexity $\rightarrow$ VLIW
VLIW: Very Long Instruction Word
Very Long Instruction Word (VLIW)

Compiler is **responsible** for instruction scheduling

<table>
<thead>
<tr>
<th>Mem ref 1</th>
<th>Mem ref 2</th>
<th>FP op 1</th>
<th>FP op 2</th>
<th>Int op/ branch</th>
<th>Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD F0,0(R1)</td>
<td>LD F6,-8(R1)</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>1</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>LD F14,-24(R1)</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>2</td>
</tr>
<tr>
<td>LD F18,-32(R1)</td>
<td>LD F22,-40(R1)</td>
<td>ADDD F4,F0,F2</td>
<td>ADDD F8,F6,F2</td>
<td>NOP</td>
<td>3</td>
</tr>
<tr>
<td>LD F26,-48(R1)</td>
<td>NOP</td>
<td>ADDD F12,F10,F2</td>
<td>ADDD F16,F14,F2</td>
<td>NOP</td>
<td>4</td>
</tr>
<tr>
<td>NOP</td>
<td>NOP</td>
<td>ADDD F20,F18,F2</td>
<td>ADDD F24,F22,F2</td>
<td>NOP</td>
<td>5</td>
</tr>
<tr>
<td>SD 0(R1), F4</td>
<td>SD -8(R1), F8</td>
<td>ADDD F28,F26,F2</td>
<td>NOP</td>
<td>NOP</td>
<td>6</td>
</tr>
<tr>
<td>SD -16(R1), F12</td>
<td>SD -24(R1), F8</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>7</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td>SD -40(R1),F24</td>
<td>NOP</td>
<td>NOP</td>
<td>SUBI R1,R1,#48</td>
<td>8</td>
</tr>
<tr>
<td>SD 0(R1),F28</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>BNEZ R1,LOOP</td>
<td>9</td>
</tr>
</tbody>
</table>

VLIW will be revisited later on....
Dynamic branch prediction

Branches limit performance because:

- **Branch penalties are high**
- **Prevent a lot of ILP from being exploited**

Solution: *Dynamic branch prediction* to predict the outcome of conditional branches.

**Benefits:**

- **Reduce time to determine branch condition**
- **Reduce time to calculate the branch target address**
Predict next PC

PC → bubble
bubble
bubble
bubble

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

Branch → Next PC

I R X W
Regs

Mem
Cycle 4

Guess the next PC here!!

IF RegC < 100 GOTO A
RegC := RegC + 1
RegB := RegA + 1
LD RegA, (100 + RegC)

LD RegA, (100 + RegC)
Branch history table
A simple branch prediction scheme

- The branch-prediction buffer is indexed by bits from branch-instruction PC values
- If prediction is wrong, then invert prediction

Problem: can cause two mispredictions in a row
A two-bit prediction scheme

- Requires prediction to miss twice in order to change prediction => better performance
Dynamic Scheduling Of Branches

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST

LD
ADD
SUB
ST
N-level history

- Not only the PC of the BR instruction matters, also how you’ve got there is important

- Approach:
  - Record the outcome of the last N branches in a vector of N bits
  - Include the bits in the indexing of the branch table

- Pros/Cons: Same BR instruction may have multiple entries in the branch table

\[(N,M)\text{ prediction} = N \text{ levels of } M\text{-bit prediction}\]
Tournament prediction

- Issues:
  - No one predictor suits all applications

- Approach:
  - Implement several predictors and dynamically select the most appropriate one

- Performance example SPEC98:
  - 2-bit prediction: 7% miss prediction
  - (2,2) 2-level, 2-bit: 4% miss prediction
  - Tournaments: 3% miss prediction
Branch target buffer

- Predicts branch target address in the IF stage
- Can be combined with 2-bit branch prediction
Putting it together

- BTB stores info about taken instructions
- Combined with a separate branch history table
- Instruction fetch stage highly integrated for branch optimizations
Folding branches

- BTB often contains the next few instructions at the destination address
- Unconditional branches (and some cond as well) branches execute in zero cycles
  - Execute the dest instruction instead of the branch (if there is a hit in the BTB at the IF stage)
  - ”Branch folding”
Procedure calls & BTB

BTB can predict “normal” branches

Procedure A

A(x,y)

BR

call1

return 1

BR

A(x,y)

BR

call2

return 2

BTB can do a good job

BTB does not stand a chance

A(x,y)
Return address stack

- Popular subroutines are called from many places in the code.
- Branch prediction may be confused!!
- May hurt other predictions
- New approach:
  - Push the return address on a [small] stack at the time of the call
  - Pop addresses on return
Overlapping Execution

Erik Hagersten
Uppsala University
Sweden
Multicycle operations in the pipeline (floating point)

(Not a SuperScalar...)

- Integer unit: Handles integer instructions, branches, and loads/stores.
- Other units: May take several cycles each. Some units are pipelined (mult, add) others are not (div).
Parallelism between integer and FP instructions

### How to avoid structural and RAW hazards:

**Stall in ID stage when**
- The functional unit can be occupied
- Many instructions can reach the WB stage at the same time

**RAW hazards:**
- Normal bypassing from MEM and WB stages
- Stall in ID stage if any of the source operands is a destination operand of an instruction in any of the FP functional units
WAR and WAW hazards for multicycle operations

WAR hazards are a non-issue because operands are read in program order (in-order)

WAW hazards are avoided by:

- stalling the SUBF until DIVF reaches the MEM stage, or
- disabling the write to register F0 for the DIVF instruction

WAW Example:

```
DIVF F0,F2,F4 FP divide 24 cycles
...
SUBF F0,F8,F10 FP sub 3 cycles
```

SUB finishes before DIV; out-of-order completion
Dynamic Instruction Scheduling

Key idea: allow subsequent independent instructions to proceed

DIVD F0,F2,F4 ; takes long time
ADDD F10,F0,F8 ; stalls waiting for F0
SUBD F12,F8,F13 ; Let this instr. bypass the ADDD
- Enables out-of-order execution (& out-of-order completion)

Two historical schemes used in “recent” machines:
- Tomasulo in IBM 360/91 in 1967 (also in Power-2)
- Scoreboard dates back to CDC 6600 in 1963
Simple Scoreboard Pipeline
(covered briefly in this course)

- **Issue**: Decode and check for structural hazards
- **Read operands**: wait until no RAW hazard, then read operands (RAW)
- All data hazards are handled by the scoreboard mechanism
**Extended Scoreboard**

**Issue**: Instruction is issued when:
- No structural hazard for a functional unit
- No WAW with an instruction in execution

**Read**: Instruction reads operands when they become available (RAW)

**EX**: Normal execution

**Write**: Instruction writes when all previous instructions have read or written this operand (WAW, WAR)

*The scoreboard is updated when an instruction proceeds to a new stage*
Limitations with scoreboards

The scoreboard technique is limited by:

- Number of scoreboard entries (window size)
- Number and types of functional units
- Number of ports to the register bank
- Hazards caused by name dependencies

Tomasulo’s algorithm addresses the last two limitations
A more complicated example

```
DIV F0, F2, F4
ADDD F6, F0, F8
WAW F8, F10, F14
SUBD F6, F10, F8
MULD tmp1, F10, F14
MULD tmp2, F10, tmp1
```

;delayed a long time

WAR and WAW avoided through “register renaming”

Register Renaming:

```
DIV F0, F2, F4
ADDD F6, F0, F8
SUBD tmp1, F10, F14 ;can be executed right away
MULD tmp2, F10, tmp1 ;delayed a few cycles
```
Tomasulo’s Algorithm

- IBM 360/91 mid 60’s
- High performance without compiler support
- Extended for modern architectures
- Many implementations (PowerPC, Pentium…)

"Tomasulo’s Algorithms"

IBM 360/91 mid 60’s
Simple Tomasulo’s Algorithm

Res. Station

Common Data Bus (CDB)

Register renaming!

ReOrder Buffer (ROB)

Write Stage

Op: div
D: F0
S1: F2
S2: F4
#3

#3 DIV
F0, F2, F4

#4 ADDD
F6, F0, F8

#5 SUBD
F8, F10, F14

#6 MULD
F6, F10, F8

IF X W
Tomasulo’s: What is going on?

1. Read Register:
   - Rename DestReg to the Res. Station location
2. Wait for all dependencies at Res. Station
3. After Execution
   a) Put result in Reorder Buffer (ROB)
   b) Broadcast result on CDB to all waiting instructions
   c) Rename DestReg to the ROB location
4. When all preceeding instr. have arrived at ROB:
   - Write value to DestReg
Simple Tomasulo’s Algorithm

Res. Station

Common Data Bus (CDB)

Reg. Write Path

IF

Issue

Mem

Int Mem

Mem

FP Add

FP Mul1

FP Mul2

FP Div

Op

D

S1

S2

#

Op

D

S1:v/ptr

S2:v/ptr

#

Op

D:F0

S1:v

S2:v

#

D answ

#

D answ

ReOrder Buffer (ROB)

Write Stage

#3 DIV F0,F2,F4
#4 ADDD F6,F0,F8
#5 SUBD F8,F10,F14
#6 MULD F6,F10,F8
Simple Tomasulo’s Algorithm

**Res. Station**

**Common Data Bus (CDB)**

**ReOrder Buffer (ROB)**

**Write Stage**

**Reg. Write Path**

**Op**
- D
- S1
- S2
- #

**Res.**
- 0:a
- 1:b
- 2:c
- 3:d
- 4:e
- 5:
- 6:
- 7:
- 8:e
- 9:

**Op**
- D:F0
- D: answ
- S1:v
- S1:v/ptr
- S2:v
- S2:v/ptr
- #
- #

**#3 DIV** F0,F2,F4
**#4 ADDD** F6,F0,F8
**#5 SUBD** F8,F10,F14
**#6 MULD** F6,F10,F8

**IF**
- Read operands
- Issue

**Mem**
- Issue
- Int
- Mem
- FP
- Add
- Mul1
- Mul2
- Div
- Mem

**Int Mem**

**Mem**

**FP**
- Add
- Mul1
- Mul2
- Div

**FP Add**

**FP Mul1**

**FP Mul2**

**FP Div**

**Int Mem**

**Mem**

**Write Stage**
Simple Tomasulo’s Algorithm

Res. Station

Common Data Bus (CDB)

Write Stage

ReOrder Buffer (ROB)

Reg. Write Path

IF

Issue

0:a
1:b
2:c
3:d
4:e
5:f
6:g
7:h
8:i
9:j

Op
D
S1
S2
#

Op
D
S1:v/ptr
S2:v
#

Op
D
S1:v
S2:v
#

Op
D:F0
S1:v
S2:v
#

Op
D:answ
#

Op
D:answ
#

#3 DIV F0,F2,F4
#4 ADDD F6,F0,F8
#5 SUBD F8,F10,F14
#6 MULD F6,F10,F8

#3 DIV
#4 ADD
#5 SUB
#6 MULD

#

#

9 8 7 6 5 4 3 2 1

9 8 7 6 5 4 3 2 1

123
Simple Tomasulo’s Algorithm

- **IF**
  - Read operands
  - Issue

- **Mem**
  - Int
  - Mem
  - FP Add
  - FP Mul1
  - FP Mul2
  - FP Div

- **Reg. Write Path**
  - 0: a
  - 1: b
  - 2: c
  - 3: d
  - 4: e
  - 5: f
  - 6: g
  - 7: h
  - 8: i
  - 9: j

- **Res. Station**

- **Common Data Bus (CDB)**
  - Int Mem
  - Mem

- **Write Stage**
  - ReOrder Buffer (ROB)

- **Path**
  - #3 DIV F0, F2, F4
  - #4 ADDD F6, F0, F8
  - #5 SUBD F8, F10, F14
  - #6 MULD F6, F10, F8

- **Op**
  - D
  - S1
  - S2
  - #

- **D**
  - D: F0
  - S1: v
  - S2: v
  - #
  - answ

- **124**
Simple Tomasulo’s Algorithm

#3 DIV F0,F2,F4
#4 ADDD F6,F0,F8
#5 SUBD F8,F10,F14
#6 MULD F6,F10,F8

Res. Station
Common Data Bus (CDB)
ReOrder Buffer (ROB)
Write Stage

Reg. Write Path

IF
Issue

Op
D
S1
S2
#

Op
D
S1:v/ptr
S2:v/ptr
#

Op
D:F0
S1:v
S2:v
#

D:answ
#
D:answ

Dept of Information Technology | www.it.uu.se
© Erik Hagersten | www.docs.uu.se/~eh
Simple Tomasulo’s Algorithm

- **IF** (Instruction Fetch)
- **Issue**
- **Res. Station**
- **Common Data Bus (CDB)**
- **Reg. Write Path**
- **Write Stage**
- **ReOrder Buffer (ROB)**

**Res. Station**

<table>
<thead>
<tr>
<th>Station</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>b/c</td>
</tr>
<tr>
<td>1</td>
<td>b</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
</tr>
<tr>
<td>5</td>
<td>b/c</td>
</tr>
<tr>
<td>6</td>
<td>#6</td>
</tr>
<tr>
<td>7</td>
<td>#5</td>
</tr>
<tr>
<td>8</td>
<td>#5</td>
</tr>
<tr>
<td>9</td>
<td>#5</td>
</tr>
</tbody>
</table>

**Common Data Bus (CDB)**

- **Int Mem**
- **Mem**
- **FP Add**
- **FP Mul1**
- **FP Mul2**
- **FP Div**

**ReOrder Buffer (ROB)**

- D: answ
- D: answ
- D
- #
- #
- #
- #
- #
- #
- #

**Instruction Example**

- #3 DIV F0,F2,F4
- #4 ADDD F6,F0,F8
- #5 SUBD F8,F10,F14
- #6 MULD F6,F10,F8

**Reg. Write Path**

- #3 DIV: F0, F2, F4
- #4 ADDD: F6, F0, F8
- #5 SUBD: F8, F10, F14
- #6 MULD: F6, F10, F8
Simple Tomasulo’s Algorithm

#3 DIV F0,F2,F4
#4 ADDD F6,F0,F8
#5 SUBD F8,F10,F14
#6 MULD F6,F10,F8

Common Data Bus (CDB)

Write Stage

ReOrder Buffer (ROB)

Reg. Write Path

IF

Res. Station

Op

D
S1:v/ptr
S2:v/ptr

#

Op

D
S1:v
S2:v

#

D
answ
#

D
answ

Op

D:F0
S1:v
S2:v

#

127
Tomasulo’s: What is going on?

1. Read Register:
   - Rename DestReg to the Res. Station location

2. Wait for all dependencies at Res. Station

3. After Execution
   a) Put result in Reorder Buffer (ROB)
   b) Broadcast result on CDB to all waiting instructions
   c) Rename DestReg to the ROB location

4. When all preceeding instr. have arrived at ROB:
   - Write value to DestReg
Dynamic Scheduling Past Branches

Schedule speculative instructions past branches

```
LD
ADD
SUB
ST

"Predict taken"

>=? 0

LD
ADD
SUB
ST

>1?

LD
ADD
SUB
ST

<2?

LD
ADD
SUB
ST
```

"Predict taken"

“Predict taken”

"Predict taken"

=0?

=0?

Schedule speculative instructions past branches

"Predict taken"
Dynamic Scheduling Past Branches

LD ADD SUB ST

>=0?

LD ADD SUB ST

>1?

LD ADD SUB ST

<2?

Wrong Prediction!!!

Do not commit!

Wrong Prediction!!!

Do not commit!
Summing up Tomasulo’s

- Out-of-order (O-O-O) execution
- In order commit
  - Allows for speculative execution (beyond branches)
  - Allows for precise exceptions
- Distributed implementation
  - Reservation stations – wait for RAW resolution
  - Reorder Buffer (ROB)
  - Common Data Bus “snoops” (CDB)
- "Register renaming" avoids WAW, WAR
- Costly to implement (complexity and power)
Dealing with Exceptions

Erik Hagersten
Uppsala University
Sweden
Exception handling in pipelines

Example: Page fault from TLB

Must restart an instruction that causes an exception (interrupt, trap, fault) "precise interrupts"

(...as well as all instructions following it.)

A solution (in-order...):

1. Force a trap instruction into the pipeline
2. Turn off all writes for the faulting instruction
3. Save the PC for the faulting instruction
   - to be used in return from exception
   - may need to save multiple PC values
Guaranteeing the execution order

Exceptions may be generated in another order than the instruction execution order

<table>
<thead>
<tr>
<th>Pipeline stage</th>
<th>Problem causing exception</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>Page fault on instruction fetch; misaligned memory access; memory protection violation</td>
</tr>
<tr>
<td>ID</td>
<td>Undefined or illegal opcode</td>
</tr>
<tr>
<td>EX</td>
<td>Arithmetic exception</td>
</tr>
<tr>
<td>MEM</td>
<td>Page fault on data access; misaligned memory access; memory protection violation</td>
</tr>
<tr>
<td>WB</td>
<td>none</td>
</tr>
</tbody>
</table>

Example sequence:

lw    (e.g., page fault in MEM)
add   (e.g., page fault in IF)
FP Exceptions

Example:

DIVF F0,F2,F4 24 cycles
ADDF F10,F10,F8 3 cycles
SUBF F12,F12,F14 3 cycles

SUBF may generate a trap before DIVF has completed!!
Revisiting Exceptions:

A pipeline implements precise interrupts iff:

- All instructions before the faulting instruction can complete
- All instructions after (and including) the faulting instruction must not change the system state and must be restartable

ROB helps the implementation in O-O-O execution
HW support for [static] speculation and improved ILP

Erik Hagersten
Uppsala University
Sweden
**Very Long Instruction Word (VLIW)**

- Independent functional units with no hazard detection

Compiler is responsible for instruction scheduling

<table>
<thead>
<tr>
<th>Mem ref 1</th>
<th>Mem ref 2</th>
<th>FP op 1</th>
<th>FP op 2</th>
<th>Int op/branch</th>
<th>Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD F0,0(R1)</td>
<td>LD F6,-8(R1)</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>1</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>LD F14,-24(R1)</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>2</td>
</tr>
<tr>
<td>LD F18,-32(R1)</td>
<td>LD F22,-40(R1)</td>
<td>ADDD F4,F0,F2</td>
<td>ADDD F8,F6,F2</td>
<td>NOP</td>
<td>3</td>
</tr>
<tr>
<td>LD F26,-48(R1)</td>
<td>NOP</td>
<td>ADDD F12,F10,F2</td>
<td>ADDD F16,F14,F2</td>
<td>NOP</td>
<td>4</td>
</tr>
<tr>
<td>NOP</td>
<td>NOP</td>
<td>ADDD F20,F18,F2</td>
<td>ADDD F24,F22,F2</td>
<td>NOP</td>
<td>5</td>
</tr>
<tr>
<td>SD 0(R1), F4</td>
<td>SD -8(R1), F8</td>
<td>ADDD F28,F26,F2</td>
<td>NOP</td>
<td>NOP</td>
<td>6</td>
</tr>
<tr>
<td>SD -16(R1), F12</td>
<td>SD -24(R1), F8</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>7</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td>SD -40(R1),F24</td>
<td>NOP</td>
<td>NOP</td>
<td>SUBI R1,R1,#48</td>
<td>8</td>
</tr>
<tr>
<td>SD 0(R1),F28</td>
<td>NOP</td>
<td>NOP</td>
<td>NOP</td>
<td>BNEZ R1,LOOP</td>
<td>9</td>
</tr>
</tbody>
</table>
Limits to VLIW

Difficult to exploit parallelism
- $N$ functional units and $K$ "dependent" pipeline stages implies $NxK$ independent instructions to avoid stalls

Memory and register bandwidth

Code size

No binary code compatibility

But, ... simpler hardware
- short schedule
- high frequency
HW support for static speculation

- Move LD up and ST down. But, how far?
  - Normally not outside of the basic block!

- These techniques will allow larger moves and increase the effective size of a basic block
  - Removing branches: predicate execution
  - Move LD above ST: hazard detection
  - Move LD above branch
## Compiler speculation

The compiler moves instructions before a branch so that they can be executed before the branch condition is known.

Advantage: creates longer schedulable code sequences => more ILP can exploited

Example: 
if (A == 0) then A = B; else A = A+4;

<table>
<thead>
<tr>
<th>Non speculative code</th>
<th>Speculative code</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW R1,0(R3)</td>
<td>LW R1,0(R3)</td>
</tr>
<tr>
<td>BNEZ R1,L1</td>
<td>LW R14,0(R2)</td>
</tr>
<tr>
<td>LW R1,0(R2)</td>
<td>BEQZ R1,L3</td>
</tr>
<tr>
<td>J L2</td>
<td>ADD R14,R14,4</td>
</tr>
<tr>
<td>L1: ADD R1,R1,4</td>
<td>L3: SW 0(R3),R14</td>
</tr>
<tr>
<td>L2: SW 0(R3),R1</td>
<td></td>
</tr>
</tbody>
</table>

What about exceptions?

- Move past BR
  - + reg rename

---

Dept of Information Technology | www.it.uu.se
© Erik Hagersten | www.docs.uu.se/∼eh
Speculative instructions

Moving a LD up, may make it *speculative*
- Moving past a branch
- Moving past a ST (that may be to the same address)

**Issues:**
- Non-intrusive
- Correct exception handling (again)
- Low overhead
- Good prediction
Example: Moving LD above a branch

LD.s R1, 100(R2) ; “Speculative LD” to R1
.... ; set “poison bit” in R1 if exception
BRNZ R7, #200
...
LD.chk R1 ; Get exception if poison bit of R1 is set

Good performance if the branch is not taken
Example: Moving LD above a ST

LD.a R1, 100(R2); “advanced LD”
; create entry in the ALAT <addr,reg>

....
ST  R7, 50(R3); invalidate entry if ALAT addr match
...
LD.c R1; Redo LD if entry in ALAT invalid
; remove entry in ALAT

ALAT (advanced load address table) is an associative data structure storing tuples of: <addr, dest-reg>
Conditional execution

- Removes the need for some branches 😊
- Conditional Instructions
  - Conditional register move
    
    \[\text{CMOVZ R1, R2, R3} \quad \text{;move R2 to R1 if (R3 == 0)}\]
  - Compare-and-swap (atomics memory operations later)
    
    \[\text{CAS R1, R2, R3} \quad \text{;swap R2 and mem(R1) if (mem(R1)== R3)}\]
  - Avoiding a branch makes the basic block larger!!!
    
    ➔ More instructions for the code scheduler to play with
- Predicate execution
  - A more generalized technique
  - Each instruction executed if the associated 1-bit predicate REG is 1.
Predicate example

IF R1 > R2 then
   LD R7, 100(R1)
   ADD R1, R1, #1
else
   LD R7, 100(R2)
   ADD R2, R2, #1
end

5 instr executed in "then path"
2 branches
Predicate example

IF R1 > R2 then
   LD R7, 100(R1)
   ADD R1, R1, #1
else
   LD R7, 100(R2)
   ADD R2, R2, #1
end

Using Predicates

...{IF R1 > R2 then P6=1; P7=0
   else P6=0; P7=1} ;one instr!
P6: LD R7, 100(R1)
P6: ADD R1, R1, #1
P7: LD R7, 100(R2)
P7: ADD R2, R2, #1

Standard Technique

CGT R3, R1, R2
BRNZ R3, else
LD R7, 100(R1)
ADD R1, R1, #1
BR end
else:
LD R7, 100(R2)
ADD R2, R2, #1
end:

5 instr executed in "then path"
2 branches

One instruction sets the two predicate Regs
Each instr. in the "then" guarded by P6
Each instr. in the "else" guarded by P7
→ One basic block
→ Fewer total instr

5 instr executed in "then path"
0 branch
HW vs. SW speculation

Advantages:

- Dynamic runtime disambiguation of memory addresses
- Dynamic branch prediction is often better than static which limits the performance of SW speculation.
- HW speculation can maintain a precise exception model

Main disadvantage:

- Complex implementation and extensive need of hardware resources (conforms with technology trends)
Example: IA64 and Itanium(I)

Erik Hagersten
Uppsala University
Sweden
Little of everything

- VLIW
- Advanced loads supported by ALAT
- Load speculation supported by predication
- Dynamic branch prediction
- ”All the tricks in the book”
Itanium instructions

- Instruction bundle (128 bits)
  - (5 bits) template (identifies I types and dependencies)
  - 3 x (41 bits) instruction

- Can issue up to two bundles per cycle (6 instr)
- The “Type” specifies if the instr. are independent

- Latencies:

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-LD</td>
<td>1</td>
</tr>
<tr>
<td>FP-LD</td>
<td>9</td>
</tr>
<tr>
<td>Pred branch</td>
<td>0-3</td>
</tr>
<tr>
<td>Misspred branch</td>
<td>0-9</td>
</tr>
<tr>
<td>I-ALU</td>
<td>0</td>
</tr>
<tr>
<td>FP-ALU</td>
<td>4</td>
</tr>
</tbody>
</table>
Itanium Registers

- 128 65-bit GPR (w/ poison bit)
- 128 82-bit FP REGS
- 64 1-bit predicate REGS
- 8 64-bit branch registers
- A bunch of CSRs (control/status registers)
Dynamic register window

Explicit Regs
(seen by the instructions)

Physical Regs

64

127
Dynamic register window for GPRs

Explicit Regs (seen by main)

- Physical Regs: 127
- Unused: 63
- Dyn. main: 63
- Global: 31
- 0

- Physical Regs: 127
- Unused: 63
- Dyn. main: 63
- Global: 31
- 0
Calling Procedure A

Procedure!!! (....not processes)

Explicit Regs (seen by main)
Explicit Regs (seen by proc A)

Physical Regs

Unused

Input

Dyn. main

Output

Input

Global

Global

Global

0

0

31

31

63

63

127

85

63

54

10

10

54

54

...not processes...
Calling Procedure B
(automatic passing of parameters)
Register Stack Engine (RSE)

- Saves and restores registers to memory on register spills
- Implemented in hardware
- Works in the background
- Gives the illusion of an unlimited register stack

- This is similar to SPARC and UCB’s RISC
Register rotation: FP and GPRs

- Used in software pipelining
- Register renaming for each iteration
- Removes the need for prologue/epilogue
- RSE (register stack engine)
What is the alternative?

- VLIW was meant to simplify HW
- Itanium has 230 M transistors and consumes 130W?
- Will it scale with technology?
- Other alternatives:
  - Increase cache size,
  - Increase the frequency, or,
  - Run more than one thread/chip (More about this during “Future Technologies”)