Lecture 9: Multiple Issue (Superscalar and VLIW)

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Example: Dynamic Scheduling in PowerPC 604 and Pentium Pro

- In-order Issue, Out-of-order execution, In-order Commit
Multiple Issue

\[ \text{CPI} = \text{CPI}_{\text{ideal}} + \text{Stalls}_{\text{structural}} + \text{Stalls}_{\text{RAW}} + \text{Stalls}_{\text{WAR}} + \text{Stalls}_{\text{WAW}} + \text{Stalls}_{\text{control}} \]

Προσοχή να διατηρούνται
1. Data flow
2. Exception Behavior

Έχουμε μελετήσει
θα μελετήσουμε σήμερα
Θα μελετήσουμε σε επόμενα μαθήματα

Δυναμικές δρομολόγησης  
εντολών (hardware)
• Scoreboard (ελάττωση RAW stalls)
• Register Renaming
  α) Tomasulo
  (ελάττωση WAR και WAW stalls)
  β) Reorder Buffer
• Branch prediction  
  (ελάττωση Control stalls)
• Multiple Issue (CPI < 1)
• Multithreading (CPI < 1)

Στατικές (software/compiler)
• Loop Unrolling
• Software Pipelining
• Trace Scheduling
Beyond CPI = 1

• Initial goal to achieve CPI = 1
• Can we improve beyond this?
• Two approaches
  • **Superscalar:**
    – varying no. instructions/cycle (1 to 8), i.e. 1-way, 2-way, ..., 8-way superscalar
    – scheduled by compiler (**statically scheduled**) or by HW (**dynamically scheduled**)
    – e.g. IBM PowerPC, Sun UltraSparc, DEC Alpha, HP 8000
    – The successful approach (to date) for general purpose computing
  • Anticipated success lead to use of **Instructions Per Clock** cycle (**IPC**) vs. CPI
Beyond CPI = 1

- Alternative approach
- **(Very) Long Instruction Words (V)L IW:**
  - fixed number of instructions (4-16)
  - scheduled by the compiler; put ops into wide templates
  - Currently found more success in DSP, Multimedia applications
  - Joint HP/Intel agreement in 1999/2000
  - Intel Architecture-64 (Merced/A-64) 64-bit address
  - Style: “Explicitly Parallel Instruction Computer (EPIC)”
Getting CPI < 1: Issuing Multiple Instructions/Cycle

- Superscalar DLX: 2 instructions, 1 FP & 1 anything else
  - Fetch 64-bits/clock cycle; Int on left, FP on right
  - Can only issue 2nd instruction if 1st instruction issues
  - More ports for FP registers to do FP load & FP op in a pair

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

- 1 cycle load delay expands to 3 instructions in SS
  - instruction in right half can’t use it, nor instructions in next slot
In-Order Superscalar Pipeline

- Fetch two instructions per cycle; issue both simultaneously if one is integer/memory and other is floating point.
- Same idea can be extended to wider issue by duplicating functional units (e.g. 4-issue UltraSPARC) but regfile ports and bypassing costs grow quickly.
Instructions in the instruction window are **free from control dependencies** due to branch prediction, and **free from name dependences** due to register renaming.

So, only *(true)* data dependences and structural conflicts remain to be solved.
Similar Technique: Superpipelined Machines

- **Machine issues instructions faster than they are executed**
- **Advantage**: increase in the number of instructions which can be in the pipeline at one time and hence the level of parallelism.
- **Disadvantage**: The larger number of instructions "in flight" (i.e. in some part of the pipeline) at any time, increases the potential for data and control dependencies to introduce stalls. Clock frequency is high.
Sequential ISA Bottleneck

Sequential source code

Superscalar compiler

Find independent operations

Schedule operations

Sequential machine code

Superscalar processor

Check instruction dependencies

Schedule execution

a = foo(b);

for (i=0, i<
Review: Unrolled Loop that Minimizes Stalls for Scalar

1 Loop: 
1. LD F0,0 (R1) 
2. LD F6,-8 (R1) 
3. LD F10,-16 (R1) 
4. LD F14,-24 (R1) 
5. ADDD F4,F0,F2 
6. ADDD F8,F6,F2 
7. ADDD F12,F10,F2 
8. ADDD F16,F14,F2 
9. SD 0 (R1),F4 
10. SD -8 (R1),F8 
11. SD -16 (R1),F12 
12. SUBI R1,R1,#32 
13. BNEZ R1,LOOP 
14. SD 8 (R1),F16  ; 8-32 = -24

14 clock cycles, or 3.5 per iteration
### Loop Unrolling in Superscalar

<table>
<thead>
<tr>
<th>Integer instruction</th>
<th>FP instruction</th>
<th>Clock cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD F0,0(R1)</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>LD F6,-8(R1)</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>ADDD F4,F0,F2</td>
<td>3</td>
</tr>
<tr>
<td>LD F14,-24(R1)</td>
<td>ADDD F8,F6,F2</td>
<td>4</td>
</tr>
<tr>
<td>LD F18,-32(R1)</td>
<td>ADDD F12,F10,F2</td>
<td>5</td>
</tr>
<tr>
<td>SD 0(R1),F4</td>
<td>ADDD F16,F14,F2</td>
<td>6</td>
</tr>
<tr>
<td>SD -8(R1),F8</td>
<td>ADDD F20,F18,F2</td>
<td>7</td>
</tr>
<tr>
<td>SD -16(R1),F12</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>SD -24(R1),F16</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>SUBI R1,R1,#40</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>BNEZ R1,LOOP</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

- Unrolled 5 times to avoid delays
- 12 clocks, or 2.4 clocks per iteration (1.5X)
SS Advantages and Challenges

- The potential advantages of a SS processor versus a vector or VLIW processor are their ability to extract some parallelism from less structured code (i.e. no loops) and their ability to easily cache all forms of data.

- While Integer/FP split is simple for the HW, get CPI of 0.5 only for programs with:
  - Exactly 50% FP operations
  - No hazards

- If more instructions issue at same time, greater difficulty of decode and issue
  - Even 2 way-scalar => examine 2 opcodes, 6 register specifiers, & decide if 1 or 2 instructions can issue
Example Processor: Intel Core2
All in one: 2-way SS +OoO+Branch Prediction+Reorder Buffer(Speculation)

Show read cycle for clarification

<table>
<thead>
<tr>
<th>Iteration number</th>
<th>Instructions</th>
<th>Issues at clock number</th>
<th>Executes at clock number</th>
<th>Read access at clock number</th>
<th>Write CDB at clock number</th>
<th>Commits at clock number</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LD R2,0(R1)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>First issue</td>
</tr>
<tr>
<td>1</td>
<td>DADDIU R2,R2,#1</td>
<td>1</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>Wait for LW</td>
</tr>
<tr>
<td>1</td>
<td>SD R2,0(R1)</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td>7</td>
<td>Wait for DADDIU</td>
</tr>
<tr>
<td>1</td>
<td>DADDIU R1,R1,#8</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>Commit in order</td>
</tr>
<tr>
<td>1</td>
<td>BNE R2,R3,LOOP</td>
<td>3</td>
<td>7</td>
<td></td>
<td></td>
<td>8</td>
<td>Wait for DADDIU</td>
</tr>
<tr>
<td>2</td>
<td>LD R2,0(R1)</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>No execute delay</td>
</tr>
<tr>
<td>2</td>
<td>DADDIU R2,R2,#1</td>
<td>4</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>10</td>
<td>Wait for LW</td>
</tr>
<tr>
<td>2</td>
<td>SD R2,0(R1)</td>
<td>5</td>
<td>6</td>
<td></td>
<td></td>
<td>10</td>
<td>Wait for DADDIU</td>
</tr>
<tr>
<td>2</td>
<td>DADDIU R1,R1,#8</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>11</td>
<td>11</td>
<td>Commit in order</td>
</tr>
<tr>
<td>2</td>
<td>BNE R2,R3,LOOP</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
<td>11</td>
<td>Wait for DADDIU</td>
</tr>
<tr>
<td>3</td>
<td>LD R2,0(R1)</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>12</td>
<td>Earliest possible</td>
</tr>
<tr>
<td>3</td>
<td>DADDIU R2,R2,#1</td>
<td>7</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>13</td>
<td>Wait for LW</td>
</tr>
<tr>
<td>3</td>
<td>SD R2,0(R1)</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
<td>13</td>
<td>Wait for DADDIU</td>
</tr>
<tr>
<td>3</td>
<td>DADDIU R1,R1,#8</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>14</td>
<td>14</td>
<td>Executes earlier</td>
</tr>
<tr>
<td>3</td>
<td>BNE R2,R3,LOOP</td>
<td>9</td>
<td>13</td>
<td></td>
<td></td>
<td>14</td>
<td>Wait for DADDIU</td>
</tr>
</tbody>
</table>

2 issues/cycle & 2 commits/cycle otherwise reorder buffer will overflow
Alternative Solutions

• Very Long Instruction Word (VLIW)
• Explicitly Parallel Instruction Computing (EPIC)
• Simultaneous Multithreading (SMT), next lecture
• Multi-core processors, ~last lecture

• **VLIW**: tradeoff instruction space for simple decoding
  – The long instruction word has room for many operations
  – By definition, all the operations the compiler puts in the long instruction word are independent => execute in parallel
  – E.g., 2 integer operations, 2 FP ops, 2 Memory refs, 1 branch
    » 16 to 24 bits per field => 7*16 or 112 bits to 7*24 or 168 bits wide
    » Intel Itanium 1 and 2 contain 6 operations per instruction packet
  – Need compiling technique that schedules across several branches
VLIW: Very Long Instruction Word

- Multiple operations packed into one instruction
- Each operation slot is for a fixed function
- Constant operation latencies are specified
- Architecture requires guarantee of:
  - Parallelism within an instruction => no cross-operation RAW check
  - No data use before data ready => no data interlocks
VLIW Compiler Responsibilities

- Schedule operations to maximize parallel execution
- Guarantees intra-instruction parallelism
- Schedule to avoid data hazards (no interlocks)
  - Typically separates operations with explicit NOPs

In a VLIW (also called Very Large Instruction Word) processor, several operations that can be executed in parallel are placed on a single instruction word.

```
<table>
<thead>
<tr>
<th>Instruction 1</th>
<th>op_1</th>
<th>op_2</th>
<th>op_3</th>
<th>op_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruction 2</td>
<td>op_1</td>
<td>Ø</td>
<td>op_3</td>
<td>op_4</td>
</tr>
<tr>
<td>Instruction 3</td>
<td>Ø</td>
<td>op_2</td>
<td>op_3</td>
<td>Ø</td>
</tr>
</tbody>
</table>
```

VLIW architectures rely on compile-time detection of parallelism.
- The compiler analyzes the program and detects operations to be executed in parallel.

After one instruction has been fetched all the corresponding operations are issued in parallel.
- No hardware is needed for run-time detection of parallelism.

The instruction window problem disappears: the compiler can potentially analyze the whole program to detect parallel operations.
Typical VLIW processor

(a) A typical VLIW processor and instruction format

(b) VLIW execution with degree \( m = 3 \)

**Figure 4.14** The architecture of a very long instruction word (VLIW) processor and its pipeline operations. (Courtesy of Multiflow Computer, Inc., 1987)
Loop Unrolling in VLIW

<table>
<thead>
<tr>
<th>Memory reference 1</th>
<th>Memory reference 2</th>
<th>FP operation 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></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>LD F10,-16(R1)</td>
<td>LD F14,-24(R1)</td>
<td></td>
<td></td>
<td></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></td>
<td>3</td>
</tr>
<tr>
<td>LD F26,-48(R1)</td>
<td>ADDD F12,F10,F2</td>
<td>ADDD F16,F14,F2</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>ADDD F20,F18,F2</td>
<td>ADDD F24,F22,F2</td>
<td></td>
<td></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></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>SD -16(R1),F12</td>
<td>SD -24(R1),F16</td>
<td></td>
<td></td>
<td>SUBI R1,R1,#48</td>
<td>7</td>
</tr>
<tr>
<td>SD -32(R1),F20</td>
<td>SD -40(R1),F24</td>
<td></td>
<td></td>
<td>BNEZ R1,LOOP</td>
<td>8</td>
</tr>
<tr>
<td>SD -48(R1),F28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

Unrolled 7 times to avoid delays
7 results in 9 clocks, or 1.3 clocks per iteration (1.8X vs SS)
Average: 2.5 ops per clock, 50% efficiency
Note: Need more registers in VLIW (15 vs. 6 in SS)
Advantages of VLIW

Compiler prepares fixed packets of multiple operations that give the full "plan of execution"

- dependencies are determined by compiler and used to schedule according to function unit latencies
- function units are assigned by compiler and correspond to the position within the instruction packet ("slotting")
- compiler produces fully-scheduled, hazard-free code => hardware doesn't have to "rediscover" dependencies or schedule
Disadvantages of VLIW

• Object-code compatibility
  – have to recompile all code for every machine, even for two machines in same generation

• Object code size
  – instruction padding wastes instruction memory/cache
  – loop unrolling/software pipelining replicates code

• Scheduling variable latency memory operations
  – caches and/or memory bank conflicts impose statically unpredictable variability
  – As the issue rate and number of memory references becomes large, this synchronization restriction becomes unacceptable

• Knowing branch probabilities
  – Profiling requires an significant extra step in build process

• Scheduling for statically unpredictable branches
  – optimal schedule varies with branch path
What if there are no loops?

- Branches limit basic block size in control-flow intensive irregular code
- Difficult to find ILP in individual basic blocks

Basic block
Trace Scheduling [Fisher, Ellis]

- **Trace selection:** Pick string of basic blocks, a *trace*, that represents most frequent branch path
- Use profiling feedback or compiler heuristics to find common branch paths
- **Trace Compaction:** Schedule whole “trace” at once. Packing operations to few wide instructions.
- Add fixup code to cope with branches jumping out of trace
- Effective to certain classes of programs
- Key assumption is that the trace is much more probable than the alternatives
Intel Itanium, EPIC IA-64

- EPIC is the style of architecture (cf. CISC, RISC)
  - Explicitly Parallel Instruction Computing (really just VLIW)
- IA-64 (Intel Itanium architecture) is Intel’s chosen ISA (cf. x86, MIPS)
  - IA-64 = Intel Architecture 64-bit
  - An object-code-compatible VLIW
- Merced was first Itanium implementation (cf. 8086)
  - First customer shipment expected 1997 (actually 2001)
  - McKinley, second implementation shipped in 2002
  - Recent version, Poulson, eight cores, 32nm, 2012

- Different instruction format than VLIW architectures using with indicators
- Support for SW speculation
Eight Core Itanium “Poulson” [Intel 2012]

- 8 cores
- 1-cycle 16KB L1 I&D caches
- 9-cycle 512KB L2 I-cache
- 8-cycle 256KB L2 D-cache
- 32 MB shared L3 cache
- 544mm² in 32nm CMOS
- Over 3 billion transistors

- Cores are 2-way multithreaded
- 6 instruction/cycle fetch
  - Two 128-bit bundles (3 instrs/bundle)
- Up to 12 instrs/cycle execute
IA-64 Registers

- 128 General Purpose 64-bit Integer Registers
- 128 General Purpose 82-bit Floating Point Registers
- 64 1-bit Predicate Registers
- 8 64-bit Branch Registers

Register stack mechanism: GPRs “rotate” to reduce code size for software pipelined loops
  - Rotation is a simple form of register renaming allowing one instruction to address different physical registers on each procedure call
## Execution Units

<table>
<thead>
<tr>
<th>Execution unit slot</th>
<th>Instruction type</th>
<th>Instruction description</th>
<th>Example instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-unit</td>
<td>A</td>
<td>Integer ALU</td>
<td>add, subtract, and, or, compare</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>Non-ALU integer</td>
<td>integer and multimedia shifts, bit tests, moves</td>
</tr>
<tr>
<td>M-unit</td>
<td>A</td>
<td>Integer ALU</td>
<td>add, subtract, and, or, compare</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>Memory access</td>
<td>Loads and stores for integer/FP registers</td>
</tr>
<tr>
<td>F-unit</td>
<td>F</td>
<td>Floating point</td>
<td>Floating-point instructions</td>
</tr>
<tr>
<td>B-unit</td>
<td>B</td>
<td>Branches</td>
<td>Conditional branches, calls, loop branches</td>
</tr>
<tr>
<td>L + X</td>
<td>L + X</td>
<td>Extended</td>
<td>Extended immediates, stops and no-ops</td>
</tr>
</tbody>
</table>
IA-64 Instruction Format

- Template bits describe grouping of these instructions with others in adjacent bundles
- Each group contains instructions that can execute in parallel

128-bit instruction bundle (41*3+5)

bundle $j-1$  bundle $j$  bundle $j+1$  bundle $j+2$

group $i-1$  group $i$  group $i+1$  group $i+2$
<table>
<thead>
<tr>
<th>Template</th>
<th>Slot 0</th>
<th>Slot 1</th>
<th>Slot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>M</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>1</td>
<td>M</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>I</td>
<td>I</td>
</tr>
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</tr>
<tr>
<td>4</td>
<td>M</td>
<td>L</td>
<td>X</td>
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<tr>
<td>5</td>
<td>M</td>
<td>L</td>
<td>X</td>
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<td>M</td>
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<td>I</td>
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<td>10</td>
<td>M</td>
<td>M</td>
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<td>B</td>
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<td>23</td>
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<td>M</td>
<td>B</td>
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<tr>
<td>24</td>
<td>M</td>
<td>F</td>
<td>B</td>
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<tr>
<td>25</td>
<td>M</td>
<td>F</td>
<td>B</td>
</tr>
<tr>
<td>26</td>
<td>M</td>
<td>F</td>
<td>B</td>
</tr>
</tbody>
</table>
IA-64 Basic Architecture

- Registers (both integer and floating point) are 64-bit.
- Predicate registers are 1-bit.
- 8 or more functional units.
**IA-64 Predicated Execution**

Problem: Mispredicted branches limit ILP

Solution: Eliminate hard to predict branches with predicated execution

- Almost all IA-64 instructions can be executed conditionally under predicate
- Instruction becomes NOP if predicate register false

---

**Predication**

b0: Inst 1
    Inst 2
    br a==b, b2 *if*

b1: Inst 3 *else*
    Inst 4
    br b3

b2: Inst 5 *then*
    Inst 6

b3: Inst 7
    Inst 8

Four basic blocks

Inst 1
Inst 2
p1 = a!=b, p2 = a==b
(p1) Inst 3 || (p2) Inst 5
(p1) Inst 4 || (p2) Inst 6
Inst 7
Inst 8

One basic block

---

*Mahlke et al, ISCA95: On average >50% branches removed*
Branch Predication

- **Branch predication** is an aggressive compilation technique to generate code with higher degree of instruction level parallelism.
- It lets operations from both branches of a conditional branch to be executed in parallel, to increase the amount of parallel operations.
- In this way, branches are eliminated and replaced by conditional execution.
  - Hardware support is needed, as implemented in the IA-64 architecture.

**The idea is:** let instructions from both branches go on in parallel, before the branch condition has been evaluated. The hardware takes care that only those corresponding to the right branch will be finally committed.
Branch Predication Example

For a branch instruction, the compiler assigns a predicate to each of the two following instruction paths.

For a VLIW machine, the instructions may be arranged as follows:

<table>
<thead>
<tr>
<th>Instruction 1</th>
<th>Instruction 2</th>
<th>Instruction 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;P₁&gt; Instruction 4</td>
<td>&lt;P₂&gt; Instruction 7</td>
<td>&lt;P₁&gt; Instruction 5</td>
</tr>
<tr>
<td>&lt;P₁&gt; Instruction 5</td>
<td>&lt;P₂&gt; Instruction 8</td>
<td>&lt;P₁&gt; Instruction 6</td>
</tr>
<tr>
<td>&lt;P₁&gt; Instruction 6</td>
<td>&lt;P₂&gt; Instruction 9</td>
<td>&lt;P₂&gt; Instruction 9</td>
</tr>
</tbody>
</table>

CPU can execute instructions from different paths concurrently, but only the correct path will finally be committed.