Superscalar Processors
Ch 13

Limitations, Hazards

Instruction Issue Policy

Register Renaming

Branch Prediction

Superscalar Processing (5)

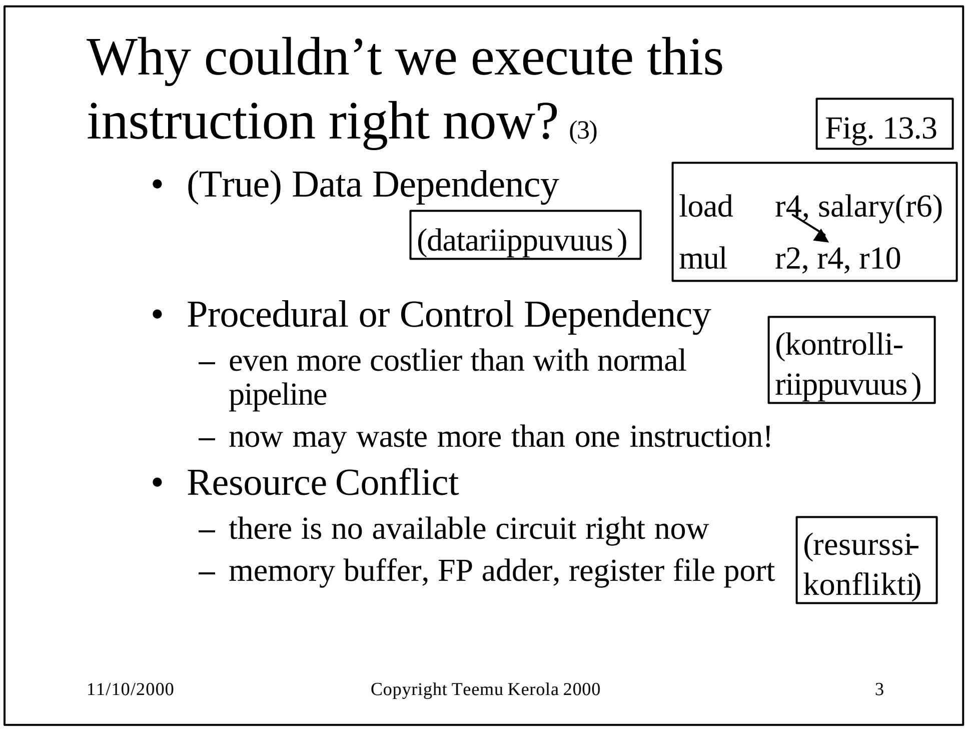
- Basic idea: more than one instruction completion per cycle
- Aimed at speeding up scalar processing
  - use multiple pipelines and not more phases

Fig. 13.2

- Many instructions in execution phase simultaneously
  - need parallelism also in earlier & later phases
- Multiple pipelines

Fig. 13.1

  - question: when can instruction be executed?
- Fetch many instructions at the same time
  - memory access must not be bottleneck



Why couldn't we execute this instruction right now? (3)

Fig. 13.3

- (True) Data Dependency

  (datariippuvuus)

```
load    r4, salary(r6)
mul     r2, r4, r10
```

- Procedural or Control Dependency

  (kontrolli-riippuvuus)
  - even more costlier than with normal pipeline
  - now may waste more than one instruction!
- Resource Conflict

  (resurssi-konflikti)
  - there is no available circuit right now
  - memory buffer, FP adder, register file port

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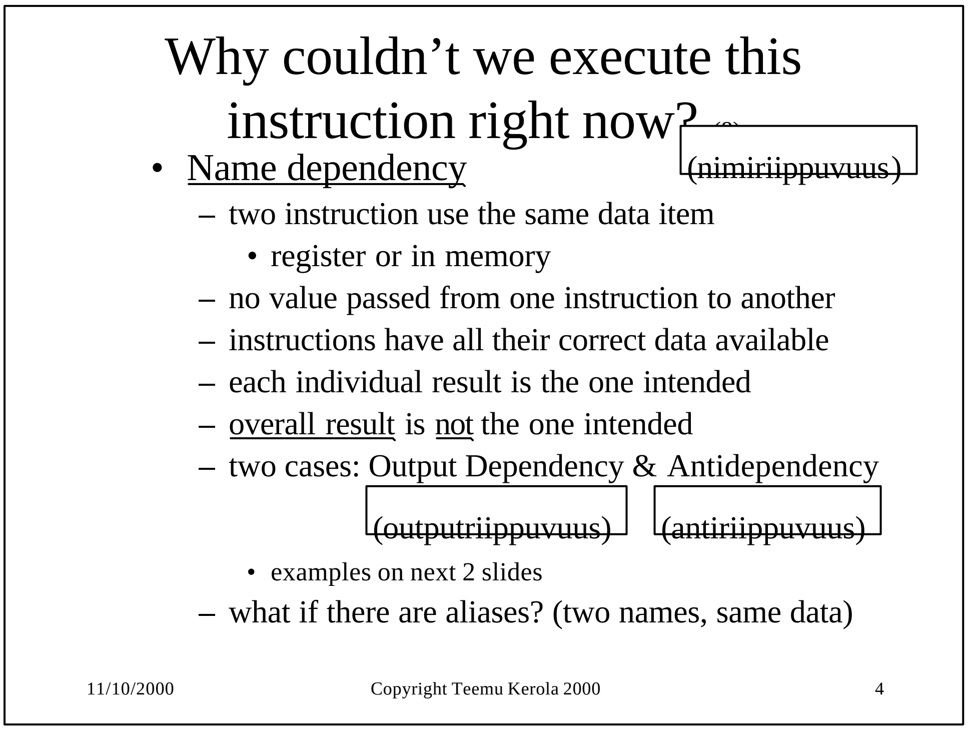

Why couldn't we execute this instruction right now? (3)

- <u>Name dependency</u> (nimiriippuvuus)
  - two instruction use the same data item
    - register or in memory
  - no value passed from one instruction to another
  - instructions have all their correct data available
  - each individual result is the one intended
  - <u>overall result</u> is <u>not</u> the one intended
  - two cases: Output Dependency & Antidependency

    (outputriippuvuus) (antiriippuvuus)
    - examples on next 2 slides
  - what if there are aliases? (two names, same data)

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Output Dependency? (1)

- Some earlier instruction has not yet finished writing from the same location that we want to write to
- Need to preserve order

```
read   r1, sum
add    r2, r1, r3
add    r1, r4, r5
```

Want to have sum of r4 and r5 in r1

Antidependency (1)

Some earlier instruction has not yet finished reading from the same location that we want to write to
Need to preserve order

```
mv     r2, r1
add    r1, r4, r5
```

Want to have original value of r1 in r2

Machine Parallelism (2)

- Instruction-level parallelism
  - How much parallelism is there
  - Theoretical maximum
- Machine parallelism
  - How much parallelism is achieved by any specific machine or architecture?
  - At most as much as instruction-level parallelism
    - dependencies?
    - physical resources?
    - not optimized (stupid) design?

Superscalar Processor

Fig. 13.6

- Instruction dispatch
  - get next available executable instruction from instruction stream
- Window of execution
  - all instructions that are considered to be issued
- Instruction issue
  - allow instruction to start execution
  - execution and completion phase should continue now with no stalls
- Instruction reorder and commit (retiring)
  - hopefully all system state changes here!
  - last chance to change order or abandon results

Instruction Dispatch

- Whenever there are both
  - – available slots in window of execution
  - – ready instructions from prefetch or branch prediction buffer

Window of Execution

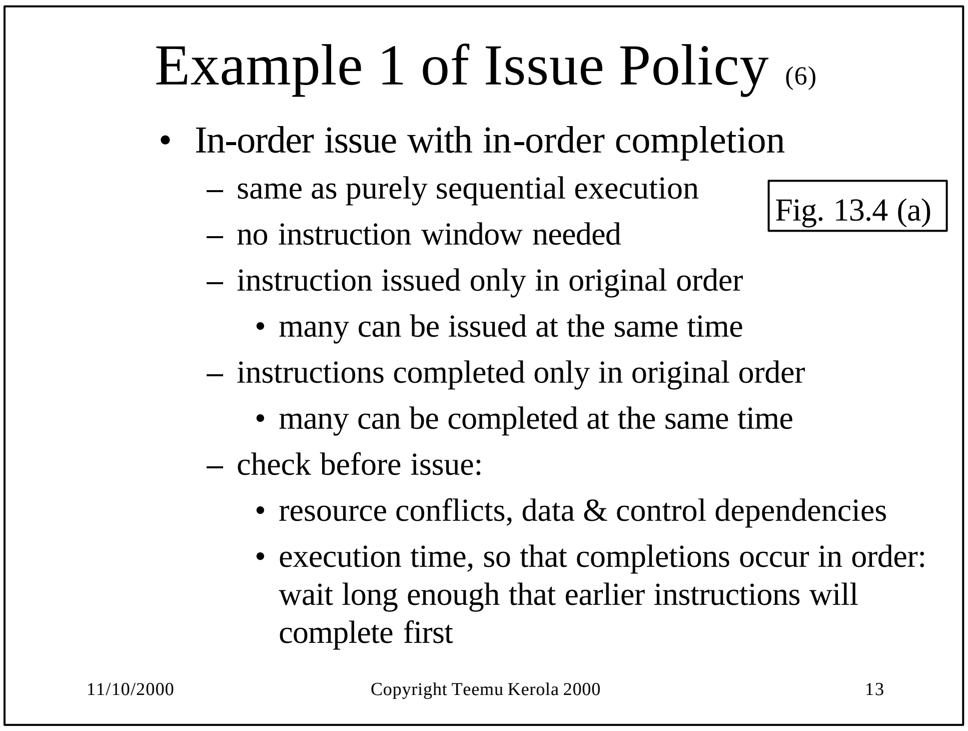
- Bigger is better
  - – easier to find a good candidate that can be issued right now
  - – more work to figure out all dependencies
  - – too small value will limit machine parallelism significantly
    - E.g., 6th instruction could be issued,
      but only 4 next ones are even considered

Instruction Issue

- Select next instruction(s) for execution
- Check first everything so that execution can proceed with no stalls (stopping) to the end
  - resource conflicts
  - data dependencies
  - control dependencies
  - output dependencies
  - antidependencies

Instruction Issue Policies (3)

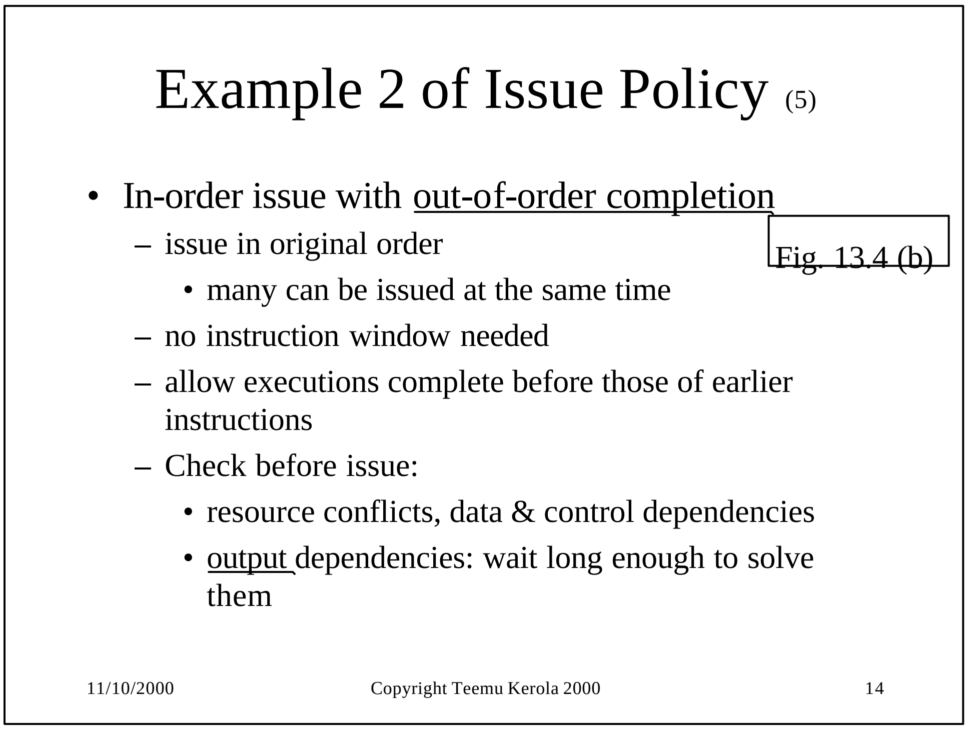
- Instruction fetch policy
  - constraints on how many instructions are considered to be dispatched at a time
    - 2 instructions fetched and decoded at a time $\Rightarrow$ both must be dispatched before next 2 fetched
- Instruction execution policy
  - constraints on which order dispatched instructions may start execution
- Completion policy
  - constraints the order of completions



Example 1 of Issue Policy (6)

Fig. 13.4 (a)

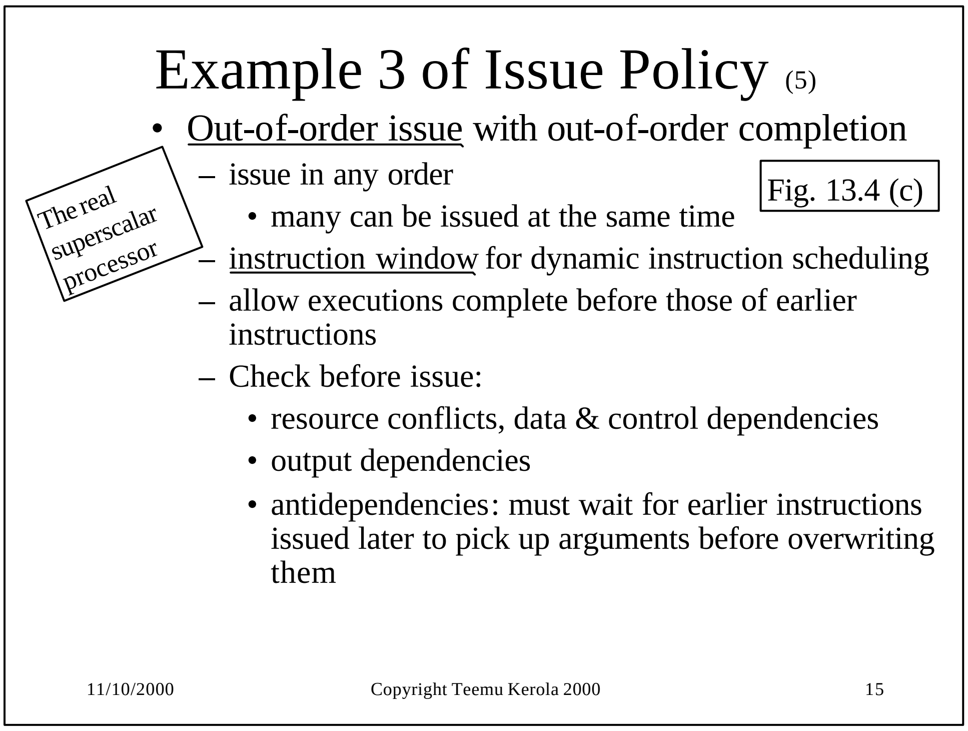
- In-order issue with in-order completion
  - same as purely sequential execution
  - no instruction window needed
  - instruction issued only in original order
    - many can be issued at the same time
  - instructions completed only in original order
    - many can be completed at the same time
  - check before issue:
    - resource conflicts, data & control dependencies
    - execution time, so that completions occur in order: wait long enough that earlier instructions will complete first



Example 2 of Issue Policy (5)

Fig. 13.4 (b)

- In-order issue with out-of-order completion
  - issue in original order
    - many can be issued at the same time
  - no instruction window needed
  - allow executions complete before those of earlier instructions
  - Check before issue:
    - resource conflicts, data & control dependencies
    - output dependencies: wait long enough to solve them



Example 3 of Issue Policy (5)

The real superscalar processor

Fig. 13.4 (c)

- Out-of-order issue with out-of-order completion
  - issue in any order
    - many can be issued at the same time
  - instruction window for dynamic instruction scheduling
  - allow executions complete before those of earlier instructions
  - Check before issue:
    - resource conflicts, data & control dependencies
    - output dependencies
    - antidependencies: must wait for earlier instructions issued later to pick up arguments before overwriting them

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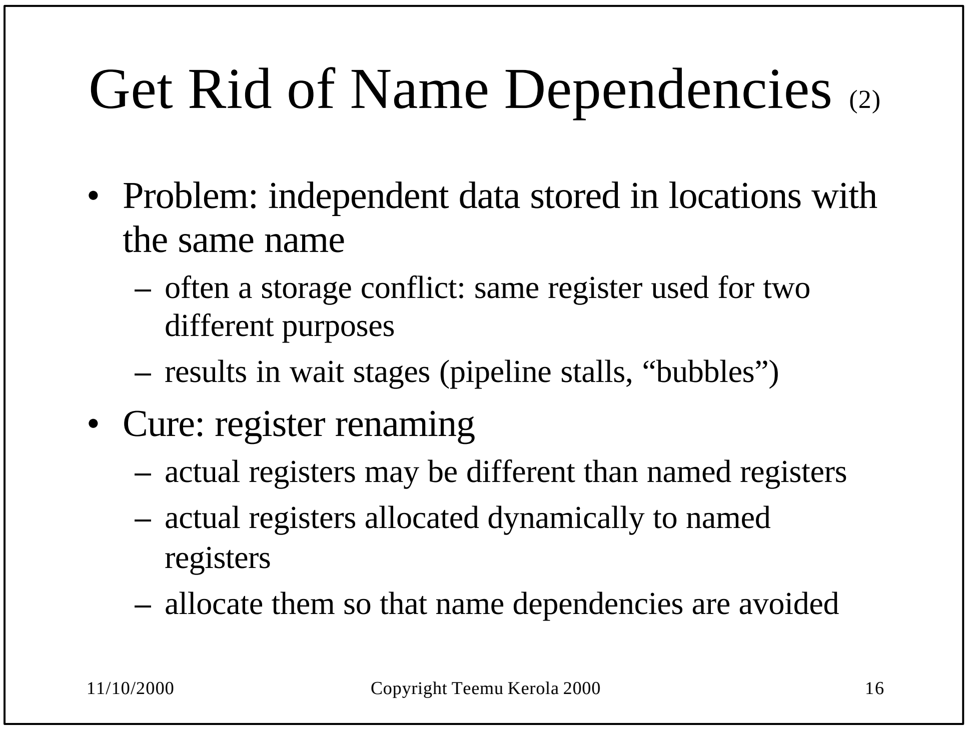

Get Rid of Name Dependencies (2)

- Problem: independent data stored in locations with the same name
  - often a storage conflict: same register used for two different purposes
  - results in wait stages (pipeline stalls, “bubbles”)
- Cure: register renaming
  - actual registers may be different than named registers
  - actual registers allocated dynamically to named registers
  - allocate them so that name dependencies are avoided

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Register Renaming (3)

Output dependency: I3 can not complete before I1 has completed first:

Antidependency: I3 can not complete before I2 has read value from R3:

```
R3:=R3 + R5;     (I1)
R4:=R3 + 1;      (I2)
R3:=R5 + 1;      (I3)
R7:=R3 + R4;     (I4)
```

Rename registers to hardware registers R3a, R3b, R3c, R4b, R5a, R7b

No name dependencies now:

```
R3b:=R3a + R5a   (I1)
R4b:=R3b + 1     (I2)
R3c:=R5a + 1     (I3)
R7b:=R3c + R4b   (I4)
```

- Drawback: need more registers
- Why R3a & R3b?

Superscalar Implementation (6)

Fig. 13.6

- Fetch strategy
  - prefetch, branch prediction
- Dependency check logic
  - forwarding circuits to transfer dependency data directly instead via registers or memory
- Multiple functional units (pipelines)
- Effective memory hierarchy to service many memory accesses simultaneously
- Logic to issue multiple instruction simultaneously
- Logic to commit instruction in correct order

Overall Gain from Superscalar Implementation

- See the effect of ...
  - renaming ⇒ right graph
  - window size ⇒ color of vertical bar
  - out-of-order issue ⇒ "base" machine
  - duplicated
    - data cache access ⇒ "+ld/st"
    - ALU ⇒ "ALU"
    - both ⇒ "both"
- Max speed-up about 4

Fig. 13.5

Example: PowerPC 601 Architecture (2)

- General RISC organization
  - instruction formats Fig. 10.9
  - 3 execution units Fig. 13.10
- Logical view Fig. 13.11
  - 4 instruction window for issue
  - each execution unit picks up next one for it whenever there is room for new instruction
  - integer instructions issued only when 1st in queue

PowerPC 601 Pipelines (4)

- Instruction pipelines Fig. 13.12
  - all state changes in final “Write Back” phase
  - up to 3 instruction can be dispatched at the same time, and issued right after that in each pipeline if no dependencies exist
    - dependencies solved by stalls
  - ALU ops place their result in one of 8 condition code field in condition register
    - up to 8 separate conditions active concurrently

PowerPC 601 Branches (4)

- Zero cycle branches
  - – branch target addresses computed already in lower dispatch buffers
    - before dispatch or issue!
  - – Easy: unconditional branches (jumps) or branch on already resolved condition code field
  - – otherwise
    - conditional branch backward: guess taken
    - conditional branch forward: guess not taken
    - if speculation ends up wrong, cancel conditional instructions in pipeline before write-back
    - speculate only on one branch at a time

PowerPC 601 Example

- Conditional branch example
  - – Original C code Fig. 13.13 (a)
  - – Assembly code Fig. 13.13 (b)
    - predict branch <u>not taken</u>
  - – Correct branch prediction Fig. 13.14 (a)
  - – Incorrect branch prediction Fig. 13.14 (b)

PowerPC 620 Architecture

- 6 execution units [Fig. 4.25]
- Up to 4 instructions dispatched simultaneously
- Reservation stations to store dispatched instructions and their arguments [HePa96] Fig. 4.49
  - kind of rename registers also!

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PowerPC 620 Rename Registers (7)

- Rename registers to store results not yet committed [HePa96] Fig. 4.49
  - normal uncompleted and speculative instructions
  - 8 int and 12 FP extra rename registers
    - in same register file as normal registers
  - results copied to normal registers at commit
  - information on what to do at commit is in completion unit in reorder buffers
- Instruction completes (commits) from completion unit reorder buffer once all previous instructions are committed
  - max 4 instructions can commit at a time

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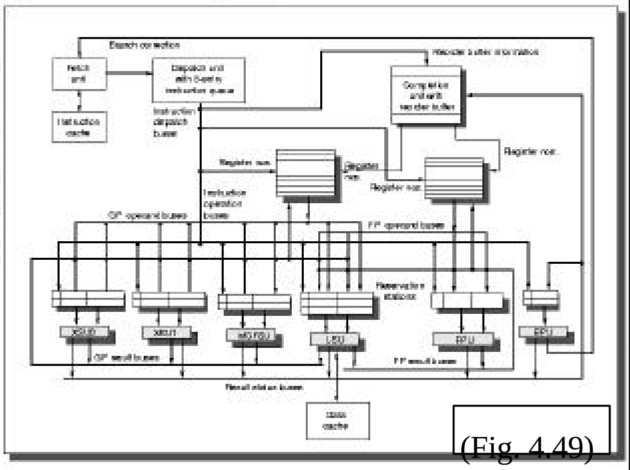
PowerPC 620 Speculation

- Speculation on branches
  - 256-entry branch target buffer
    - two-way set-associative
  - 2048-entry branch history table
    - used when branch target buffer misses
  - speculation on max 4 unresolved branches

End of Chapter 13: Superscalar --



(Fig. 4.49)

FIGURE 4.49 The PowerPC 620 has six different functional units, each with its own reservation stations and a 16-

(Hennessy-Patterson, Computer Architecture, 2nd Ed, 1996)