In-order vs. Out-of-order Execution

In-order instruction execution

- instructions are fetched, executed & completed in compiler-generated order
- one stalls, they all stall
- instructions are **statically scheduled**

Out-of-order instruction execution

- instructions are fetched in compiler-generated order
- instruction completion may be in-order (today) or out-of-order (older computers)
- in between they may be executed in some other order
- independent instructions behind a stalled instruction can pass it
- instructions are **dynamically scheduled**

Dynamic Scheduling

Out-of-order processors:

- after instruction decode
  - check for **structural hazards**
    - an instruction can be issued when a functional unit is available
    - an instruction stalls if no appropriate functional unit
  - check for **data hazards**
    - an instruction can execute when its operands have been calculated or loaded from memory
    - an instruction stalls if operands are not available

Dynamic Scheduling

Out-of-order processors:

- don't wait for previous instructions to execute if this instruction does not depend on them
- ready instructions can execute before earlier instructions that are stalled, e.g., waiting for their data to be loaded from memory
  - when go around a **load** instruction that is stalled for a cache miss:
    - use **lockup-free caches** that allow instruction issue to continue while a miss is being satisfied
    - the load-use instruction still stalls

Dynamic Scheduling

in-order processors

`lw $3, 100($4)`	in execution, cache miss
`add $2, $3, $4`	waits until the miss is satisfied
`sub $5, $6, $7`	waits for the add

out-of-order processors

`lw $3, 100($4)`	in execution, cache miss
`sub $5, $6, $7`	can execute during the cache miss
`add $2, $3, $4`	waits until the miss is satisfied

Dynamic Scheduling

Out-of-order processors:

- ready instructions can execute before earlier instructions that are stalled, e.g., waiting for their branch condition to be computed
  - when go around a **branch** instruction:
    - the instructions that are issued from the predicted path are issued speculatively, called **speculative execution**
    - speculative instructions can execute (but not commit) before the branch is resolved
    - if the prediction was wrong, speculative instructions are flushed from the pipeline
    - if prediction is right, instructions are no longer speculative

Speculative Execution

Instruction **speculation**: executing an instruction before it is known that it should be executed

- all instructions that are fetched because of a prediction are speculative
- inorder pipeline:
  - branch is executed before the path
- out-of-order pipeline:
  - path can be executed before the branch
  - speculative instructions can be executed but not committed
  - getting rid of wrong-path instructions is not just a matter of flushing them from the pipeline

Speculative Execution

In addition, executing speculative instructions:

- must be safe (no additional exceptions) or must handle the exceptions after the instruction is no longer speculative
- must generate the same results