**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**

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 because they are waiting for their data to be loaded from memory
  1. 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

Out-of-order processors:

2. 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
- in-order pipeline:
  - branch is executed before the path
- out-of-order pipeline:
  - path can be executed before the branch
  - but not committed!

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