

## 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