Pipelining: Basic Concepts
Pipelining for instruction execution is similar to construction of factor assembly line for product manufacturing. The basic idea is to decompose the instruction execution process into a collection of smaller functions that can be independently performed by discrete subsystems in the processor implementation. An illustration of this decomposition into 4 parts is:

For pipelining, we will organized these discrete subsystems (which are called pipeline stages) implementing the instruction interpretation process into concurrently executing systems each operating on distinct instructions in the instruction stream (much like a factory assembly line).
Typical Non-Pipelined Execution

<table>
<thead>
<tr>
<th>Stage 0</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
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</thead>
<tbody>
<tr>
<td>I₀</td>
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</table>

Time to execute \( n \) instructions: \( 4nt \).
Idealized Pipelined Execution

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<thead>
<tr>
<th>Stage 3</th>
<th>Stage 2</th>
<th>Stage 1</th>
<th>Stage 0</th>
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</table>

Time to execute \( n \) instructions: \((3 + n)t\).

Steady state: \[ \frac{\text{Clock cycles for unpipelined execution}}{\text{Pipeline depth}} \]
Consider the presence of a branch instruction in the pipeline:

<table>
<thead>
<tr>
<th>Stage 3</th>
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<th>Stage 0</th>
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<tbody>
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<td>$I_3$</td>
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<td>$I_3$</td>
<td>$I_4$</td>
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<tr>
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<td>$I_4$</td>
<td>$I_{br}$</td>
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<tr>
<td></td>
<td></td>
<td>$I_{br}$</td>
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<td>$I_k$</td>
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<td>$I_{k+1}$</td>
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<td>$I_{k+2}$</td>
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<td></td>
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<td>$I_{k+3}$</td>
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</tbody>
</table>

Speedup from pipelinining = \( \frac{1}{1 + \text{Pipeline stall cycles per instruction}} \) \times \text{Pipeline depth}

Branch instructions introduce control hazards into the pipeline, negatively impacting performance. There are several types of hazards, namely control, data, and structural.
Pipeline Hazards

▶ **Structural Hazards**: arises from hardware resource conflicts. That is, when the hardware cannot service all the combinations of parallel use attempted by the stages in the pipeline.

▶ **Data Hazards**: arise when an instruction depends on the (data) results of another instruction that has not yet produced the desired/needed result.

▶ **Control Hazards**: arising from the presence of branches or other instructions in the pipeline that alter the sequential instruction flow.
Issue Description

Insufficient resources to service need.

Commonly arises when you have uneven service rates in the pipe stages.

Sometimes resources are not sufficiently duplicated: e.g., read/writes ports to the register file.

Possible Solutions

• Stall.

• Refactor pipeline or pipeline the pipe stage.

• Duplicate/split the resource (split I/D caches to alleviate memory pressure).

• Build instruction buffers to alleviate memory pressure.
Data Hazards

**Issue Description**

Early pipe stage attempts to read a data/operand value that has not yet been produced by an instruction in a later pipe stage.

This problem gets worse when we look at more complex out of order instruction execution.

**Possible Solutions**

- Stall.

- Data forwarding (allow earlier pipe stage to fetch incorrect data, but then overwrite the fetched result from the later pipe stage over the prematurely fetched data). Forwarding also called **bypassing** or **short-circuiting**.

- Sometimes forwarding is insufficient and we must use it and stalling to solve all data conflicts.
3 types of dependencies:

- *data dependencies* (or true data dependencies),
- *name dependencies*, and
- *control dependencies*.

Dependencies are artifacts of *programs*; hazards are artifacts of *pipeline organization*. Not all dependencies become hazards in the pipeline. That is, dependencies may turn into hazards within the pipeline depending on the architecture of the pipeline.
Data Dependencies

Assume that instruction $i$ executes before $j$, then:

An instruction $j$ is **data dependent** on instruction $i$ if:

- instruction $i$ produces a result that may be used by instruction $j$; or
- instruction $j$ is data dependent on instruction $k$, and instruction $k$ is data dependent on instruction $i$. 

Name Dependencies (not true dependencies)

Occurring when two instructions use the same register or memory location, but there is no flow in data between the instructions associated with that name.

There are 2 types of name dependencies between an instruction \( i \) that precedes instruction \( j \) in the execution order:

- **antidependence**: when instruction \( j \) writes a register or memory location that instruction \( i \) reads.

- **output dependence**: when instruction \( i \) and instruction \( j \) write the same register or memory location.

Because these are not true dependencies, the instructions \( i \) and \( j \) could potentially be executed in parallel if these dependencies are somehow removed (by using distinct register or memory locations).
Data Hazards

A hazard exists whenever there is a name or data dependence between two instructions and they are close enough that their overlapped execution would violate the program’s order of dependency.

Possible data hazards:

- RAW (read after write)
- WAW (write after write)
- WAR (write after read)

RAR (read after read) is not a hazard.
Control Hazards

Issue Description
The presence of a (conditional) branch alters the sequential flow of instructions and it is not known where to continue until the branch outcome is resolved (general in one of the later stages of the pipeline).

Possible Solutions
- Stall until the branch is resolved.
- **Delayed branch**: Redefine the runtime behavior of branches to take affect only after the partially fetched/executed instructions flow through the pipeline.
- **Branch prediction**: Predict (statically or dynamically) the outcome of the branch and fetch there. Next slide.
**Static:** Continue fetching instructions following the branch and design the pipeline so that instructions following the branch can be run safely\(^1\) through the pipe stages and *flush the pipeline* if the branch is taken.

**Static:** Similar to above, except fetch at branch destination and flush if branch not taken.

**Dynamic:** Track branch instruction behavior using a *branch-prediction buffer* (or *branch history table*) and use it to predict\(^2\) the direction of the branch. Continue fetching at the predicted location.

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\(^1\)The instructions following the branch do not cause changes to the visible machine state, or the changes made can easily be undone.

\(^2\)There are numerous mechanisms to implement the branch-prediction buffer. Simple ones are 1-bit or 2-bit predictors; more complex techniques are also possible.
An example 2-bit (dynamic) predictor
Effectiveness of dynamic prediction

SPECG89 benchmarks

Frequency of mispredictions

- NASA7: 1%
- Matrix300: 0%
- Tomcatv: 1%
- Doduc: 5%
- Spice: 9%
- Fppp: 9%
- Gcc: 12%
- Espresso: 5%
- Eqnott: 18%
- Li: 10%

4096 entries: 2 bits per entry
Unlimited entries: 2 bits per entry
Additional Comments on Branch Prediction

► Branch Target Buffers (storing either the dest addr or the actual dest instr)
► Local and Global Predictors (correlating branch predictor)
► Tournament Predictors
Lecture break; continue next class
Characterizations of Exceptions

1. Synchronous vs asynchronous: asynchronous triggered by external devices; usually can be handled after completion of current instruction.

2. User requested vs coerced: examples of user requested: invoke O/S, trace instr execution, breakpoint.

3. Maskable vs nonmaskable: mask controls whether the hardware responds to the exception or not.

4. Within vs between instrs: exceptions that occur within (during) an instruction execution is more difficult to process if restart of the interrupted instr stream is required.

5. Resume vs terminate: terminate is easier as the system does not have to save a restart state.
Precise Exceptions

A precise exception occurs when the machine completes all instructions preceding the interrupting instruction and does not (visibly) execute any instructions following the faulting instruction. The machine can thus be restarted at the interrupting instruction.

Some architectural features make precise exceptions impossible to realize: specifically the delayed branch.

Some machines operate in 2 modes: a **fast mode** without precise exceptions and a **slow mode** with precise exceptions. Of course any machine with **non-precise exceptions of restartable events** must have some mechanism to capture the partial state and resume/finish executing the from the imprecise state so that proper execution occurs.
Multicycle Operation

EX
Integer unit

EX
FP/integer multiply

EX
FP adder

EX
FP/integer divider

IF | ID
---|---
MEM | WB
Implementation Support for Multicycle Operation

FIGURE 3.44  A pipeline that supports multiple outstanding FP operations.
Latency: the number of intervening cycles between an instruction that produces a result and an instruction that uses the result.

Initiation interval (or repeat interval): the number of cycles that must elapse between issuing two operations of a given type.

Warning, lots of forward references here; we will define the hazard taxonomy (RAW, WAW, WAR) and dependencies and types of data dependencies.
1. Long running unpipelined units (e.g., FP divides) can cause structural hazards
2. With a varying num of cycles for different instructions, multi-ported register files are required
3. WAW hazards are now possible (WAR hazards are avoided if register read occurs prior to instr dispatch
4. Out-of-order exceptions can happen
5. Long latencies increase frequency of RAW hazards
Out-of-Order Execution

Allowing instructions to finish from the pipeling before earlier instructions with longer execution steps are finished.

How to manage exceptions in the slow instructions?

history file: track the original values of registers to they can be restored when interrupt/exception occurs.

future file: capture register changes in a future file and commit in order of instruction completion.

Allow imprecise exceptions, save enough pipeline state to restart only the incompleted instructions.

Delay schedule instructions for execution until you can guarantee that forward instructions will not cause a restartable exception.
Dynamically Scheduled Pipelines

Hardware schedules instructions to reduce stalls due to hazards.

Two main techniques: a scheduling **Scoreboard** and **Tomasulo**’s algorithm.

**Scoreboarding**: use a centralized scoreboard to record instructions and the data/registers to be read/written by them that are in flight. Details in this appendix.

**Tomasulo**: distributed mechanism.
Tomasulo: SuperScalar w/ Speculation