Microcoding, an effective technique to manage control unit complexity, invented in era when logic (tubes), main memory (magnetic core), and ROM (diodes) used different technologies.

Difference between ROM and RAM speed motivated additional complex instructions.

Technology advances leading to fast SRAM made technology assumptions invalid.

Complex instructions sets impede parallel and pipelined implementations.

Load/store, register-rich ISAs (pioneered by Cray, popularized by RISC) perform better in new VLSI technology.
“Iron Law” of Processor Performance

\[
\text{Time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Time}}{\text{Cycle}}
\]

- Instructions per program depends on source code, compiler technology, and ISA
- Cycles per instructions (CPI) depends on ISA and μarchitecture
- Time per cycle depends upon the μarchitecture and base technology

<table>
<thead>
<tr>
<th>Microarchitecture</th>
<th>CPI</th>
<th>cycle time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcoded</td>
<td>&gt;1</td>
<td>short</td>
</tr>
<tr>
<td>Single-cycle unpipelined</td>
<td>1</td>
<td>long</td>
</tr>
<tr>
<td>Pipelined</td>
<td>1</td>
<td>short</td>
</tr>
</tbody>
</table>
Classic 5-Stage RISC Pipeline

This version designed for regfiles/memories with synchronous reads and writes.
CPI Examples

Microcoded machine
7 cycles 5 cycles 10 cycles
Inst 1 Inst 2 Inst 3

3 instructions, 22 cycles, CPI=7.33

Unpipelined machine

Inst 1 Inst 2 Inst 3

3 instructions, 3 cycles, CPI=1

Pipelined machine

Inst 1
Inst 2
Inst 3

3 instructions, 3 cycles, CPI=1
5-stage pipeline CPI≠5!!!
Instructions interact with each other in pipeline

- An instruction in the pipeline may need a resource being used by another instruction in the pipeline
  \[ \rightarrow \textit{structural hazard} \]

- An instruction may depend on something produced by an earlier instruction
  - Dependence may be for a data value
    \[ \rightarrow \textit{data hazard} \]
  - Dependence may be for the next instruction’s address
    \[ \rightarrow \textit{control hazard (branches, exceptions)} \]

- Handling hazards generally introduces bubbles into pipeline and reduces ideal CPI > 1
Pipeline CPI Examples

Measure from when first instruction finishes to when last instruction in sequence finishes.

- **Inst 1**
  - **Inst 2**
  - **Inst 3**

  3 instructions finish in 3 cycles
  CPI = \( \frac{3}{3} = 1 \)

- **Inst 1**
  - **Inst 2**
  - **Bubble**
  - **Inst 3**

  3 instructions finish in 4 cycles
  CPI = \( \frac{4}{3} = 1.33 \)

- **Inst 1**
  - **Bubble 1**
  - **Inst 2**
  - **Bubble 2**
  - **Inst 3**

  3 instructions finish in 5 cycles
  CPI = \( \frac{5}{3} = 1.67 \)
Resolving Structural Hazards

- Structural hazard occurs when two instructions need same hardware resource at same time
  - Can resolve in hardware by stalling newer instruction till older instruction finished with resource
- A structural hazard can always be avoided by adding more hardware to design
  - E.g., if two instructions both need a port to memory at same time, could avoid hazard by adding second port to memory
- Classic RISC 5-stage integer pipeline has no structural hazards by design
  - Many RISC implementations have structural hazards on multi-cycle units such as multipliers, dividers, floating-point units, etc., and can have on register writeback ports
Types of Data Hazards

Consider executing a sequence of register-register instructions of type:

\[ r_k \leftarrow r_i \text{ op } r_j \]

Data-dependence

\[ r_3 \leftarrow r_1 \text{ op } r_2 \quad \text{Read-after-Write} \]
\[ r_5 \leftarrow r_3 \text{ op } r_4 \quad \text{(RAW) hazard} \]

Anti-dependence

\[ r_3 \leftarrow r_1 \text{ op } r_2 \quad \text{Write-after-Read} \]
\[ r_1 \leftarrow r_4 \text{ op } r_5 \quad \text{(WAR) hazard} \]

Output-dependence

\[ r_3 \leftarrow r_1 \text{ op } r_2 \quad \text{Write-after-Write} \]
\[ r_3 \leftarrow r_6 \text{ op } r_7 \quad \text{(WAW) hazard} \]
Three Strategies for Data Hazards

- **Interlock**
  - Wait for hazard to clear by holding dependent instruction in issue stage

- **Bypass**
  - Resolve hazard earlier by bypassing value as soon as available

- **Speculate**
  - Guess on value, correct if wrong
**Interlocking Versus Bypassing**

\[ \begin{align*}
\text{add } & x_1, \ x_3, \ x_5 \\
\text{sub } & x_2, \ x_1, \ x_4
\end{align*} \]

Instruction interlocked in decode stage

Bypass around ALU with no bubbles
Example Bypass Path

Fetch

Inst. Register

Instruction Cache

Decode

EXecute

Memory

Writeback

ALU

Data Cache

Registers

Imm

Store

Inst.

Register

Writeback

PC

B

A
[Assumes data written to registers in a W cycle is readable in parallel D cycle (dotted line). Extra write data register and bypass paths required if this is not possible.]
Value Speculation for RAW Data Hazards

- Rather than wait for value, can guess value!

- So far, only effective in certain limited cases:
  - Branch prediction
  - Stack pointer updates
  - Memory address disambiguation
Control Hazards

What do we need to calculate next PC?

- For Unconditional Jumps
  - Opcode, PC, and offset

- For Jump Register
  - Opcode, Register value, and offset

- For Conditional Branches
  - Opcode, Register (for condition), PC and offset

- For all other instructions
  - Opcode and PC (and have to know it’s not one of above)
Control flow information in pipeline

Fetch

PC known

Decode

Op opcode, offset known

EXecute

Branch condition, Jump register value known

Memory

Writeback

Instruction Cache

Inst. Register

ALU

Data Cache

Store

Registers

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RISC-V Unconditional PC-Relative Jumps

[ Kill bit turns instruction into a bubble ]

PC fetch

Instruction Cache

Inst. Register

PC decode

Add

Kill

FKill

Jump?

PCJumpSel

Fetch

Decode

EXecute

[ Kill bit turns instruction into a bubble ]
Pipelining for Unconditional PC-Relative Jumps

Example:

```
F D X M W
F D X M W
j target
```

```
D X M W
D X M W
bubble
```

target: add x1, x2, x3
Branch Delay Slots

- Early RISCs adopted idea from pipelined microcode engines, and changed ISA semantics so instruction *after* branch/jump is always executed before control flow change occurs:
  
  - 0x100 j target
  - 0x104 add x1, x2, x3 // Executed before target
  - ...  
  - 0x205 target: xori x1, x1, 7

- Software has to fill delay slot with useful work, or fill with explicit NOP instruction
Post-1990 RISC ISAs don’t have delay slots

- Encodes microarchitectural detail into ISA
  - c.f. IBM 650 drum layout

- Performance issues
  - Increased I-cache misses from NOPs in unused delay slots
  - I-cache miss on delay slot causes machine to wait, even if delay slot is a NOP

- Complicates more advanced microarchitectures
  - Consider 30-stage pipeline with four-instruction-per-cycle issue

- Better branch prediction reduced need
  - Branch prediction in later lecture
RISC-V Conditional Branches

PCSel  FKill  Branch?  DKill  Cond?

Fetch  Decode  EXecute

Instruction Cache  Inst. Register  ALU
Pipelining for Conditional Branches

beq x1, x2, target

bubble

bubble

target: add x1, x2, x3
Pipelining for Jump Register

- Register value obtained in execute stage

```
F D X M W  jr x1
F D X M W  bubble
F D X M W  bubble
F D X M W  target: add x5, x6, x7
```
Why instruction may not be dispatched every cycle in classic 5-stage pipeline \((\text{CPI}>1)\)

- Full bypassing may be too expensive to implement
  - typically all frequently used paths are provided
  - some infrequently used bypass paths may increase cycle time and counteract the benefit of reducing CPI

- Loads have two-cycle latency
  - Instruction after load cannot use load result
  - MIPS-I ISA defined load delay slots, a software-visible pipeline hazard (compiler schedules independent instruction or inserts NOP to avoid hazard). Removed in MIPS-II (pipeline interlocks added in hardware)
    - MIPS: “Microprocessor without Interlocked Pipeline Stages”

- Jumps/Conditional branches may cause bubbles
  - kill following instruction(s) if no delay slots

*Machines with software-visible delay slots may execute significant number of NOP instructions inserted by the compiler.*

*NOPs reduce CPI, but increase instructions/program!*
Traps and Interrupts

In class, we’ll use following terminology

- **Exception**: An unusual internal event caused by program during execution
  - E.g., page fault, arithmetic underflow

- **Trap**: Forced transfer of control to supervisor caused by exception
  - Not all exceptions cause traps (c.f. IEEE 754 floating-point standard)

- **Interrupt**: An external event outside of running program, which causes transfer of control to supervisor

- Traps and interrupts usually handled by same pipeline mechanism
History of Exception Handling

- (Analytical Engine had overflow exceptions)
- First system with traps was Univac-I, 1951
  - Arithmetic overflow would either
    - 1. trigger the execution a two-instruction fix-up routine at address 0, or
    - 2. at the programmer's option, cause the computer to stop
  - Later Univac 1103, 1955, modified to add external interrupts
    - Used to gather real-time wind tunnel data
- First system with I/O interrupts was DYSEAC, 1954
  - Had two program counters, and I/O signal caused switch between two PCs
  - Also, first system with DMA (direct memory access by I/O device)
  - And, first mobile computer (two tractor trailers, 12 tons + 8 tons)
Asynchronous Interrupts

- An I/O device requests attention by asserting one of the *prioritized interrupt request lines*

- When the processor decides to process the interrupt
  - It stops the current program at instruction $I_i$, completing all the instructions up to $I_{i-1}$ (*precise interrupt*)
  - It saves the PC of instruction $I_i$ in a special register (EPC)
  - It disables interrupts and transfers control to a designated interrupt handler running in the kernel mode
Interrupt Handler

- Saves EPC before enabling interrupts to allow nested interrupts ⇒
  - need an instruction to move EPC into GPRs
  - need a way to mask further interrupts at least until EPC can be saved
- Needs to read a *status register* that indicates the cause of the interrupt
- Uses a special indirect jump instruction ERET (*return-from-environment*) which
  - enables interrupts
  - restores the processor to the user mode
  - restores hardware status and control state
Synchronous Trap

- A synchronous trap is caused by an exception on a particular instruction

- In general, the instruction cannot be completed and needs to be restarted after the exception has been handled
  - requires undoing the effect of one or more partially executed instructions

- In the case of a system call trap, the instruction is considered to have been completed
  - a special jump instruction involving a change to a privileged mode
Exception Handling 5-Stage Pipeline

- How to handle multiple simultaneous exceptions in different pipeline stages?
- How and where to handle external asynchronous interrupts?
Exception Handling 5-Stage Pipeline

PC<br>Inst. Mem<br>D<br>Decode<br>E<br>M<br>Data Mem<br>W

Select Handler PC<br>Kill F Stage<br>Kill D Stage<br>Kill E Stage

PC address Exception<br>Illegal Opcode<br>Overflow<br>Data address Exceptions<br>Asynchronous Interrupts

Illegal Opcode<br>Overflow<br>Data address Exceptions

Commit Point<br>Kill Writeback<br>EPC
Exception Handling 5-Stage Pipeline

- Hold exception flags in pipeline until commit point (M stage)

- Exceptions in earlier pipe stages override later exceptions *for a given instruction*

- Inject external interrupts at commit point (override others)

- If exception at commit: update Cause and EPC registers, kill all stages, inject handler PC into fetch stage
Speculating on Exceptions

- **Prediction mechanism**
  - Exceptions are rare, so simply predicting no exceptions is very accurate!

- **Check prediction mechanism**
  - Exceptions detected at end of instruction execution pipeline, special hardware for various exception types

- **Recovery mechanism**
  - Only write architectural state at commit point, so can throw away partially executed instructions after exception
  - Launch exception handler after flushing pipeline

- Bypassing allows use of uncommitted instruction results by following instructions
Issues in Complex Pipeline Control

- Structural conflicts at the execution stage if some FPU or memory unit is not pipelined and takes more than one cycle
- Structural conflicts at the write-back stage due to variable latencies of different functional units
- Out-of-order write hazards due to variable latencies of different functional units
- How to handle exceptions?
Complex In-Order Pipeline

- Delay writeback so all operations have same latency to W stage
  - Write ports never oversubscribed (one inst. in & one inst. out every cycle)
  - Stall pipeline on long latency operations, e.g., divides, cache misses
  - Handle exceptions in-order at commit point

How to prevent increased writeback latency from slowing down single cycle integer operations? Bypassing
In-Order Superscalar Pipeline

- Fetch two instructions per cycle; issue both simultaneously if one is integer/memory and other is floating point
- Inexpensive way of increasing throughput, examples include Alpha 21064 (1992) & MIPS R5000 series (1996)
- Same idea can be extended to wider issue by duplicating functional units (e.g. 4-issue UltraSPARC & Alpha 21164) but regfile ports and bypassing costs grow quickly
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