

Instruction-Level Parallelism (ILP)

- Pipelining: executing multiple instructions in parallel
- To increase ILP
 - Deeper pipeline
 - Less work per stage \Rightarrow shorter clock cycle
 - Multiple issue
 - Replicate pipeline stages \Rightarrow multiple pipelines
 - Start multiple instructions per clock cycle
 - $CPI < 1$, so use Instructions Per Cycle (IPC)
 - E.g., 4GHz 4-way multiple-issue
 - 16 BIPS, peak $CPI = 0.25$, peak $IPC = 4$
 - But dependencies reduce this in practice

Multiple Issue

- Static multiple issue
 - Compiler groups instructions to be issued together
 - Packages them into “issue slots”
 - Compiler detects and avoids hazards
- Dynamic multiple issue
 - CPU examines instruction stream and chooses instructions to issue each cycle
 - Compiler can help by reordering instructions
 - CPU resolves hazards using advanced techniques at runtime

Speculation

- “Guess” what to do with an instruction
 - Start operation as soon as possible
 - Check whether guess was right
 - If so, complete the operation
 - If not, roll-back and do the right thing
- Common to static and dynamic multiple issue
- Examples
 - Speculate on branch outcome
 - Roll back if path taken is different
 - Speculate on load
 - Roll back if location is updated

Compiler/Hardware Speculation

- Compiler can reorder instructions
 - e.g., move load before branch
 - Can include “fix-up” instructions to recover from incorrect guess
- Hardware can look ahead for instructions to execute
 - Buffer results until it determines they are actually needed
 - Flush buffers on incorrect speculation

Speculation and Exceptions

- What if exception occurs on a speculatively executed instruction?
 - e.g., speculative load before null-pointer check
- Static speculation
 - Can add ISA support for deferring exceptions
- Dynamic speculation
 - Can buffer exceptions until instruction completion (which may not occur)

Static Multiple Issue

- Compiler groups instructions into “issue packets”
 - Group of instructions that can be issued on a single cycle
 - Determined by pipeline resources required
- Think of an issue packet as a very long instruction
 - Specifies multiple concurrent operations
 - \Rightarrow Very Long Instruction Word (VLIW)

Scheduling Static Multiple Issue

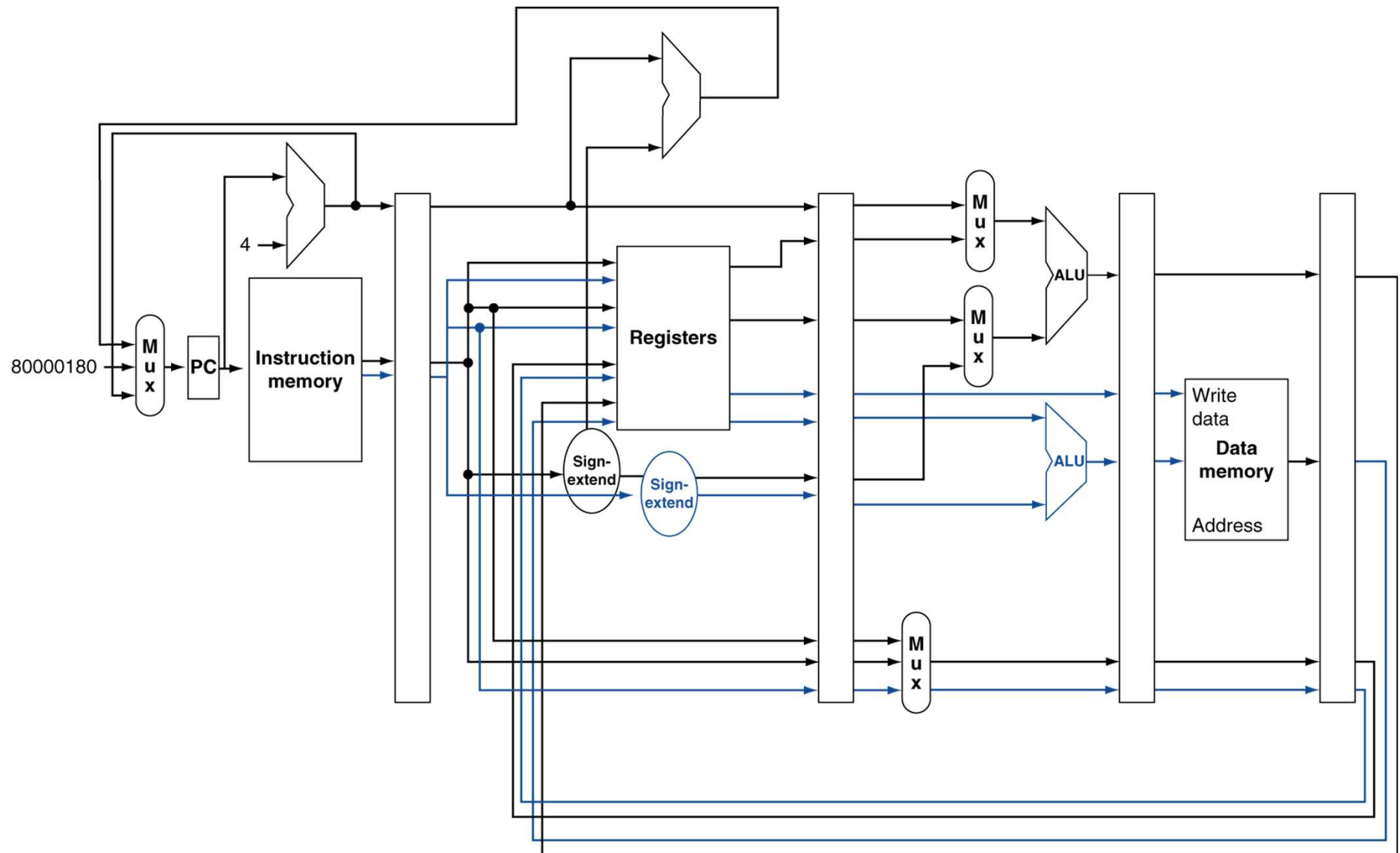
- Compiler must remove some/all hazards
 - Reorder instructions into issue packets
 - No dependencies with a packet
 - Possibly some dependencies between packets
 - Varies between ISAs; compiler must know!
 - Pad with nop if necessary

MIPS with Static Dual Issue

- Two-issue packets
 - One ALU/branch instruction
 - One load/store instruction
 - 64-bit aligned
 - ALU/branch, then load/store
 - Pad an unused instruction with nop

Address	Instruction type	Pipeline Stages						
n	ALU/branch	IF	ID	EX	MEM	WB		
n + 4	Load/store	IF	ID	EX	MEM	WB		
n + 8	ALU/branch		IF	ID	EX	MEM	WB	
n + 12	Load/store		IF	ID	EX	MEM	WB	
n + 16	ALU/branch			IF	ID	EX	MEM	WB
n + 20	Load/store			IF	ID	EX	MEM	WB

MIPS with Static Dual Issue



Hazards in the Dual-Issue MIPS

- More instructions executing in parallel
- EX data hazard
 - Forwarding avoided stalls with single-issue
 - Now can't use ALU result in load/store in same packet
 - `add $t0, $s0, $s1`
`load $s2, 0($t0)`
 - Split into two packets, effectively a stall
- Load-use hazard
 - Still one cycle use latency, but now two instructions
- More aggressive scheduling required

Scheduling Example

- Schedule this for dual-issue MIPS

```
Loop: lw    $t0, 0($s1)      # $t0=array element
      addu  $t0, $t0, $s2    # add scalar in $s2
      sw    $t0, 0($s1)      # store result
      addi  $s1, $s1, -4     # decrement pointer
      bne   $s1, $zero, Loop # branch $s1!=0
```

	ALU/branch	Load/store	cycle
Loop:	<code>nop</code>	<code>lw \$t0, 0(\$s1)</code>	1
	<code>addi \$s1, \$s1, -4</code>	<code>nop</code>	2
	<code>addu \$t0, \$t0, \$s2</code>	<code>nop</code>	3
	<code>bne \$s1, \$zero, Loop</code>	<code>sw \$t0, 4(\$s1)</code>	4

- $IPC = 5/4 = 1.25$ (c.f. peak $IPC = 2$)

Loop Unrolling

- Replicate loop body to expose more parallelism
 - Reduces loop-control overhead
- Use different registers per replication
 - Called “register renaming”
 - Avoid loop-carried “anti-dependencies”
 - Store followed by a load of the same register
 - Aka “name dependence”
 - Reuse of a register name

Loop Unrolling Example

	ALU/branch	Load/store	cycle
Loop:	addi \$s1 , \$s1, -16	lw \$t0 , 0(\$s1)	1
	nop	lw \$t1 , 12(\$s1)	2
	addu \$t0 , \$t0 , \$s2	lw \$t2 , 8(\$s1)	3
	addu \$t1 , \$t1 , \$s2	lw \$t3 , 4(\$s1)	4
	addu \$t2 , \$t2 , \$s2	sw \$t0 , 16(\$s1)	5
	addu \$t3 , \$t4 , \$s2	sw \$t1 , 12(\$s1)	6
	nop	sw \$t2 , 8(\$s1)	7
	bne \$s1 , \$zero, Loop	sw \$t3 , 4(\$s1)	8

- $IPC = 14/8 = 1.75$
 - Closer to 2, but at cost of registers and code size

Dynamic Multiple Issue

- “Superscalar” processors
- CPU decides whether to issue 0, 1, 2, ... each cycle
 - Avoiding structural and data hazards
- Avoids the need for compiler scheduling
 - Though it may still help
 - Code semantics ensured by the CPU

Dynamic Pipeline Scheduling

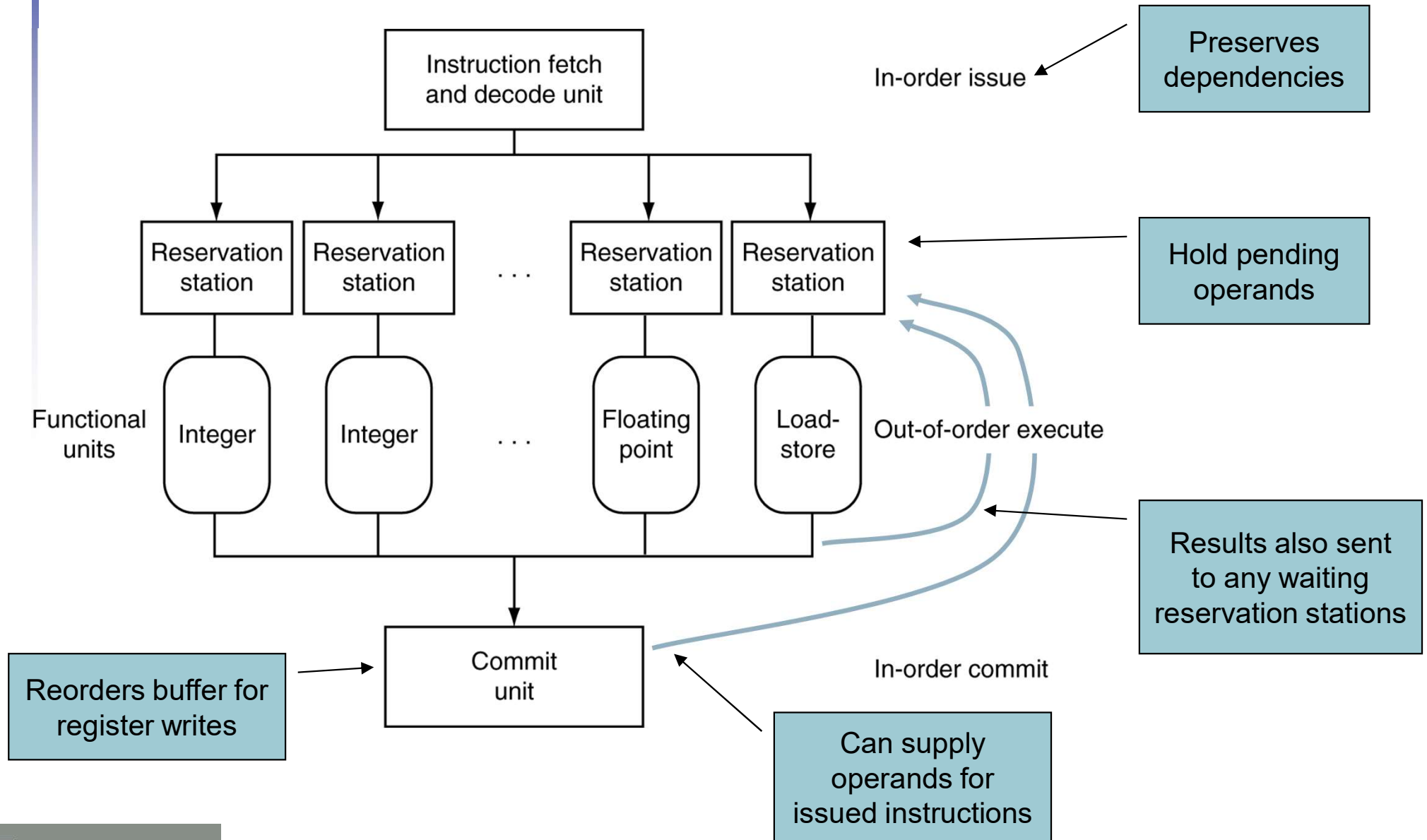
- Allow the CPU to execute instructions out of order to avoid stalls
 - But commit result to registers in order

- Example

```
lw      $t0, 20($s2)
addu    $t1, $t0, $t2
sub      $s4, $s4, $t3
slti    $t5, $s4, 20
```

- Can start sub while addu is waiting for lw

Dynamically Scheduled CPU



Register Renaming

- Reservation stations and reorder buffer effectively provide register renaming
- On instruction issue to reservation station
 - If operand is available in register file or reorder buffer
 - Copied to reservation station
 - No longer required in the register; can be overwritten
 - If operand is not yet available
 - It will be provided to the reservation station by a function unit
 - Register update may not be required

Speculation

- Predict branch and continue issuing
 - Don't commit until branch outcome determined
- Load speculation
 - Avoid load and cache miss delay
 - Predict the effective address
 - Predict loaded value
 - Load before completing outstanding stores
 - Bypass stored values to load unit
 - Don't commit load until speculation cleared

Why Do Dynamic Scheduling?

- Why not just let the compiler schedule code?
- Not all stalls are predicable
 - e.g., cache misses
- Can't always schedule around branches
 - Branch outcome is dynamically determined
- Different implementations of an ISA have different latencies and hazards

Does Multiple Issue Work?

The BIG Picture

- Yes, but not as much as we'd like
- Programs have real dependencies that limit ILP
- Some dependencies are hard to eliminate
 - e.g., pointer aliasing
- Some parallelism is hard to expose
 - Limited window size during instruction issue
- Memory delays and limited bandwidth
 - Hard to keep pipelines full
- Speculation can help if done well