Chapter 5: Multiprocessors (Thread-Level Parallelism)– Part 2

Introduction

> What is a parallel or multiprocessor system?

> Why parallel architecture?

> Performance potential

> Flynn classification

Communication models

Architectures

Centralized sharedmemory

Distributed sharedmemory

Parallel programming

Synchronization

Memory consistency models

Memory Consistency Model - Motivation

Example shared-memory program

Initially all locations = 0

Processor 1	Processor 2
Data = 23	while (Flag != 1) {;}
Flag = 1	… = Data

Execution (only shared-memory operations)

Processor 1	Processor 2
Write, Data, 23	
Write, Flag, 1	
	Read, Flag, 1
	Read, Data, ___

Memory Consistency Model: Definition

Memory consistency model

Order in which memory operations will appear to execute

$\Rightarrow$ What value can a read return?

Affects ease-of-programming and performance

The Uniprocessor Model

Program text defines total order = *program order*

Uniprocessor model

    Memory operations appear to execute one-at-a-time in program order

    $\Rightarrow$ Read returns value of last write

BUT uniprocessor hardware

    Overlap, reorder operations

Model maintained as long as

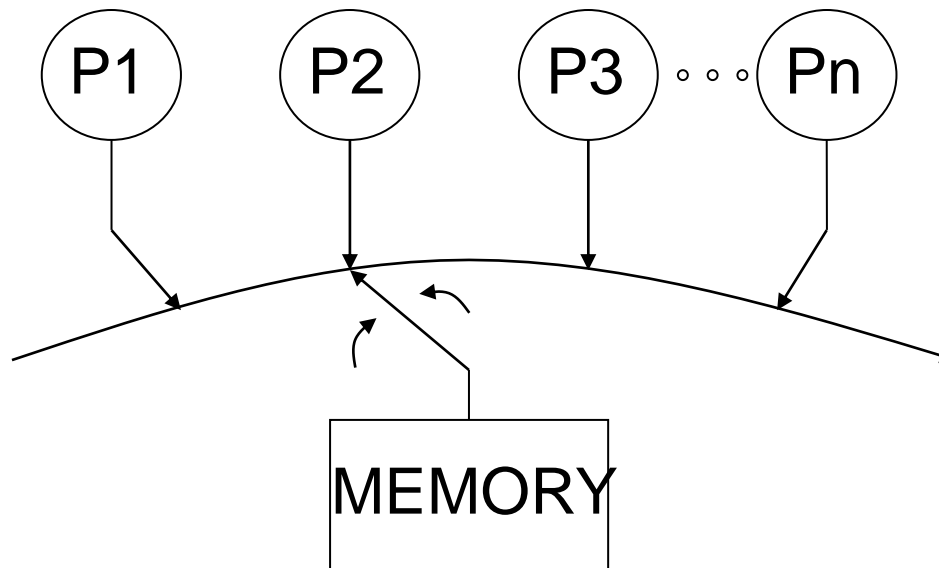   maintain control and data dependences

$\Rightarrow$ Easy to use + high performance

Implicit Memory Model

Sequential consistency (SC) [Lamport]

Result of an execution appears as if

- All operations executed in some sequential order (i.e., atomically)
- Memory operations of each process in program order

Understanding Program Order – Example 1

Initially Flag1 = Flag2 = 0

P1   P2
Flag1 = 1   Flag2 = 1
if (Flag2 == 0)   if (Flag1 == 0)
    critical section   *critical section*

Execution:

P1   P2
(Operation, Location, Value)   *(Operation, Location, Value)*
Write, Flag1, 1   Write, Flag2, 1

Read, Flag2, 0   Read, Flag1, ____

Understanding Program Order – Example 1

P1   P2
Write, Flag1, 1   Write, Flag2, 1
    ↓   ↓
Read, Flag2, 0   Read, Flag1, ~~0~~
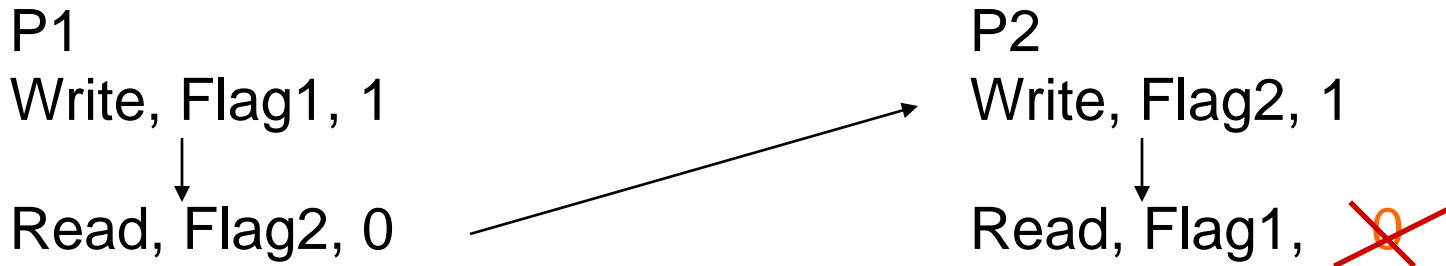
Can happen if

- Write buffers with read bypassing

- Overlap, reorder write followed by read in h/w or compiler

- Allocate Flag1 or Flag2 in registers

Understanding Program Order - Example 2

Initially A = Flag = 0

P1
A = 23;
Flag = 1;

P2
while (Flag != 1) {;}
... = A;

P1
Write, A, 23
Write, Flag, 1

P2
Read, Flag, 0

Read, Flag, 1
Read, A, ____

Understanding Program Order - Example 2

Initially A = Flag = 0

P1	P2
A = 23;	while (Flag != 1) {;}
Flag = 1;	... = A;

P1	P2
Write, A, 23	Read, Flag, 0
Write, Flag, 1	
	Read, Flag, 1
	Read, A, ~~0~~

Can happen if

Overlap or reorder writes or reads in hardware or compiler
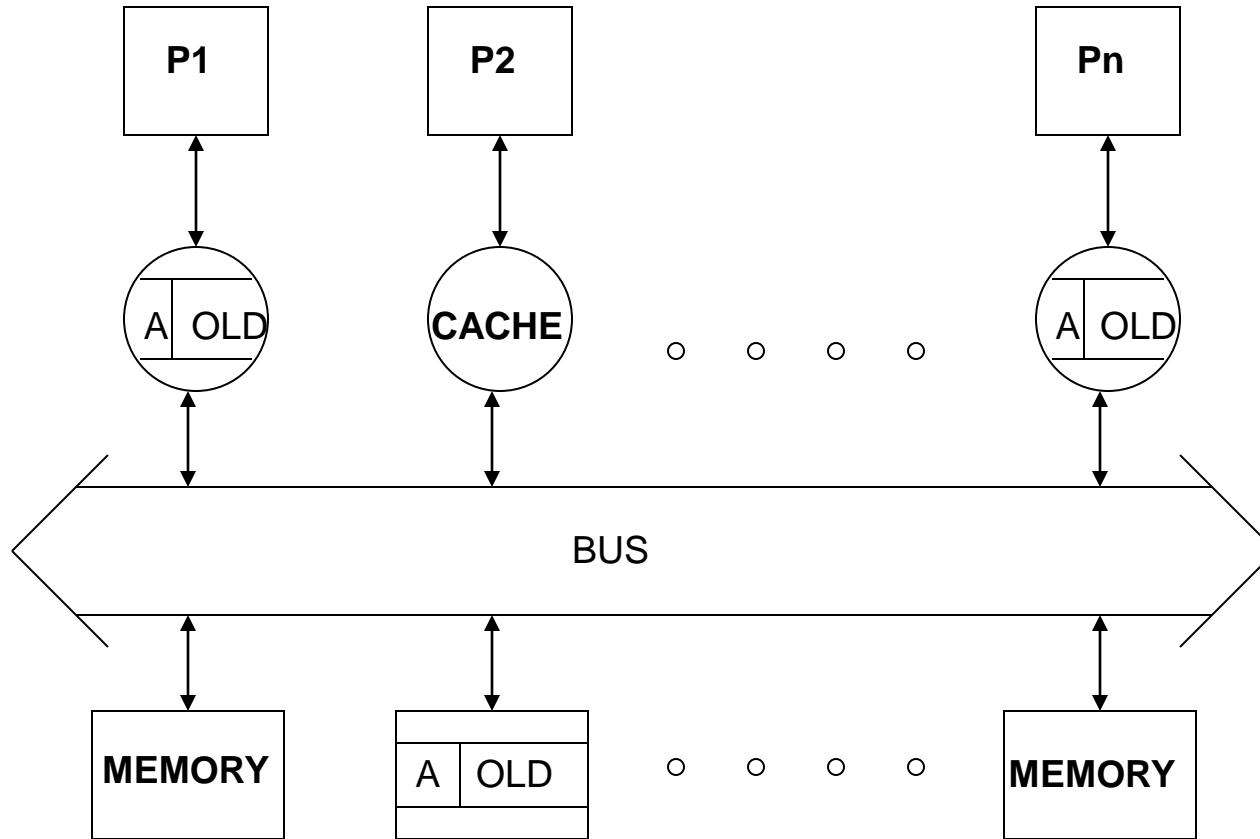
Understanding Program Order: Summary

SC limits program order relaxation:

       Write $\rightarrow$ Read

       Write $\rightarrow$ Write

       Read $\rightarrow$ Read, Write

Understanding Atomicity

A mechanism needed to propagate a write to other copies

$\Rightarrow$ Cache coherence protocol

Cache Coherence Protocols

How to propagate write?

Invalidate -- Remove old copies from other caches

Update -- Update old copies in other caches to new values

Understanding Atomicity - Example 1

Initially A = B = C = 0

P1	P2	P3	P4
A = 1;	A = 2;	while (B != 1) {;}	while (B != 1) {;}
B = 1;	C = 1;	while (C != 1) {;}	while (C != 1) {;}
		tmp1 = A;	tmp2 = A;

Understanding Atomicity - Example 1

Initially A = B = C = 0

P1	P2	P3	P4
A = 1;	A = 2;	while (B != 1) {;}	while (B != 1) {;}
B = 1;	C = 1;	while (C != 1) {;}	while (C != 1) {;}
		tmp1 = A; ~~1~~	tmp2 = A; ~~2~~

Can happen if updates of A reach P3 and P4 in different order

Coherence protocol must serialize writes to same location
    (Writes to same location should be seen in same order by all)

Understanding Atomicity - Example 2

Initially A = B = 0

P1	P2	P3
A = 1	while (A != 1) ;	while (B != 1) ;
	B = 1;	tmp = A

P1	P2	P3
Write, A, 1		
	Read, A, 1	
	Write, B, 1	
		Read, B, 1
		Read, A, ~~0~~

Can happen if read returns new value before all copies see it

SC Summary

SC limits

Program order relaxation:

Write $\rightarrow$ Read

Write $\rightarrow$ Write

Read $\rightarrow$ Read, Write

When a processor can read the value of a write

Unserialized writes to the same location

Alternative

(1) Aggressive hardware techniques proposed to get SC w/o penalty
using speculation and prefetching

But compilers still limited by SC

(2) Give up sequential consistency

Use relaxed models

Classification for Relaxed Models

Typically described as system optimizations - system-centric

Optimizations

> Program order relaxation:

>> Write $\rightarrow$ Read

>> Write $\rightarrow$ Write

>> Read $\rightarrow$ Read, Write

> Read others' write early

> Read own write early

All models provide safety net

All models maintain uniprocessor data and control dependences, write serialization

Some System-Centric Models

Relaxation:	W →R Order	W →W Order	R →RW Order	Read Others' Write Early	Read Own Write Early	Safety Net
IBM 370	✔					serialization instructions
TSO	✔				✔	RMW
PC	✔			✔	✔	RMW
PSO	✔	✔			✔	RMW, STBAR
WO	✔	✔	✔		✔	synchronization
RCsc	✔	✔	✔		✔	release, acquire, nsync, RMW
RCpc	✔	✔	✔	✔	✔	release, acquire, nsync, RMW
Alpha	✔	✔	✔		✔	MB, WMB
RMO	✔	✔	✔		✔	various MEMBARs
PowerPC	✔	✔	✔	✔	✔	SYNC

System-Centric Models: Assessment

System-centric models provide higher performance than SC

BUT 3P criteria

   Programmability?

        Lost intuitive interface of SC

   Portability?

        Many different models

   Performance?

        Can we do better?

   Need a higher level of abstraction

An Alternate Programmer-Centric View

One source of consensus

Programmers need SC to reason about programs

But SC not practical today

How about the next best thing…

A Programmer-Centric View

Specify memory model as a contract

    System gives sequential consistency

    IF programmer obeys certain rules

+ Programmability

+ Performance

+ Portability

The Data-Race-Free-0 Model: Motivation

Different operations have different semantics

P1	P2
A = 23;	while (Flag != 1) {;}
B = 37;	… = B;
Flag = 1;	… = A;

Flag = Synchronization; A, B = Data

Can reorder data operations

Distinguish data and synchronization

Need to

- Characterize data / synchronization

- Prove characterization allows optimizations w/o violating SC

Data-Race-Free-0: Some Definitions

Two operations conflict if

- – Access same location

- – At least one is a write

(Consider SC executions $\Rightarrow$ global total order)

Two conflicting operations race if

- From different processors

- Execute one after another (consecutively)

P1	P2
Write, A, 23	
Write, B, 37	
	Read, Flag, 0
Write, Flag, 1	
	Read, Flag, 1
	Read, B, ___
	Read, A, ___

Races usually "synchronization," others "data"

Can optimize operations that *never race*

Data-Race-Free-0 (DRF0) Definition

Data-Race-Free-0 Program

    All accesses distinguished as either synchronization or data

    All races distinguished as synchronization

        (in any SC execution)

Data-Race-Free-0 Model

    Guarantees SC to data-race-free-0 programs

It is widely accepted that data races make programs hard to debug

    independent of memory model (even with SC)

Distinguishing/Labeling Memory Operations

Need to distinguish/label operations at all levels

- High-level language
- Hardware

Compiler must translate language label to hardware label

Java: volatiles, synchronized

C++: atomics

Hardware: fences inserted before/after synchronization

Data-Race-Free Summary

The idea

    Programmer writes data-race-free programs

    System gives SC

For programmer

    Reason with SC

    Enhanced portability

For hardware and compiler

    More flexibility

Finally, convergence on hardware and software sides

    (BUT still many problems…)