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 shared memory
Distributed shared memory
Parallel programming
Synchronization

Memory consistency models
Example shared-memory program

Initially all locations = 0

<table>
<thead>
<tr>
<th>Processor 1</th>
<th>Processor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data = 23</td>
<td>while (Flag != 1) {;}</td>
</tr>
<tr>
<td>Flag = 1</td>
<td>… = Data</td>
</tr>
</tbody>
</table>

Execution (only shared-memory operations)

<table>
<thead>
<tr>
<th>Processor 1</th>
<th>Processor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Write, Data, 23</td>
<td></td>
</tr>
<tr>
<td>Write, Flag, 1</td>
<td></td>
</tr>
</tbody>
</table>

Read, Flag, 1

Read, Data, ___
Memory Consistency Model: Definition

Memory consistency model

Order in which memory operations will appear to execute
⇒ 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**

![Diagram of processes P1, P2, P3, ..., Pn communicating with memory]

MEMORY
Understanding Program Order – Example 1

Initially $\text{Flag1} = \text{Flag2} = 0$

P1
Flag1 = 1
if (Flag2 == 0)
    \text{critical section}

P2
Flag2 = 1
if (Flag1 == 0)
    \text{critical section}

Execution:

P1
$(\text{Operation, Location, Value})$
Write, Flag1, 1
Read, Flag2, 0

P2
$(\text{Operation, Location, Value})$
Write, Flag2, 1
Read, Flag1, ___
Understanding Program Order – Example 1

P1
Write, Flag1, 1
Read, Flag2, 0

P2
Write, Flag2, 1
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
Initially $A = \text{Flag} = 0$

P1

A = 23;
Flag = 1;

P1

Write, A, 23
Write, Flag, 1

P2

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

P2

Read, Flag, 0
Read, Flag, 1
Read, A, ____
**Understanding Program Order - Example 2**

Initially $A = Flag = 0$

P1
\[
A = 23;
\]
\[
Flag = 1;
\]

P1

Write, $A$, 23
Write, $Flag$, 1

P2

while ($Flag != 1$) {;
... = $A$;

P2

Read, $Flag$, 0
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
A mechanism needed to propagate a write to other copies

⇒ 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 $A = B = C = 0$

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A = 1$;</td>
<td>$A = 2$;</td>
<td>while ($B != 1$) {}</td>
<td>while ($B != 1$) {}</td>
</tr>
<tr>
<td>$B = 1$;</td>
<td>$C = 1$;</td>
<td>while ($C != 1$) {}</td>
<td>while ($C != 1$) {}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tmp1 = A;</td>
<td>tmp2 = A;</td>
</tr>
</tbody>
</table>
### Understanding Atomicity - Example 1

Initially $A = B = C = 0$

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A = 1;$</td>
<td>$A = 2;$</td>
<td>while ($B != 1$) {}</td>
<td>while ($B != 1$) {}</td>
</tr>
<tr>
<td>$B = 1;$</td>
<td>$C = 1;$</td>
<td>while ($C != 1$) {}</td>
<td>while ($C != 1$) {}</td>
</tr>
<tr>
<td>tmp1 = A;</td>
<td></td>
<td></td>
<td>tmp2 = A;</td>
</tr>
</tbody>
</table>

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

A = 1

while (A != 1) ;

B = 1;

P2

P3

while (B != 1) ;

tmp = A

P1

Write, A, 1

P2

Read, A, 1

Write, B, 1

P3

Read, B, 1

Read, A, ❌

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 → Read
Write → Write
Read → 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

<table>
<thead>
<tr>
<th>Relaxation:</th>
<th>W → R Order</th>
<th>W → W Order</th>
<th>R → RW Order</th>
<th>Read Others’ Write Early</th>
<th>Read Own Write Early</th>
<th>Safety Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBM 370</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>serialization instructions</td>
</tr>
<tr>
<td>TSO</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>RMW</td>
</tr>
<tr>
<td>PC</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>RMW</td>
</tr>
<tr>
<td>PSO</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>RMW, STBAR</td>
</tr>
<tr>
<td>WO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>synchronization</td>
</tr>
<tr>
<td>RCsc</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>release, acquire, nsync, RMW</td>
</tr>
<tr>
<td>RCpc</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>release, acquire, nsync, RMW</td>
</tr>
<tr>
<td>Alpha</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>MB, WMB</td>
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<tr>
<td>RMO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>various MEMBARs</td>
</tr>
<tr>
<td>PowerPC</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>SYNC</td>
</tr>
</tbody>
</table>
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

\[
\begin{align*}
\text{P1} & : & A &= 23; & \text{while} \ (\text{Flag} \neq 1) \ \{ ; \} \\
\text{P2} & : & B &= 37; & \ldots &= B; \\
& & \text{Flag} &= 1; & \ldots &= A; \\
& & \text{Flag} &= \text{Synchronization}; & A, B &= \text{Data}
\end{align*}
\]

Can reorder data operations

Distinguish data and synchronization

Need to

- Characterize data / synchronization
- Prove characterization allows optimizations w/o violating SC
Two operations conflict if

- Access same location
- At least one is a write
Data-Race-Free-0: Some Definitions (Cont.)

(Consider SC executions ⇒ global total order)

Two conflicting operations race if

– From different processors
– Execute one after another (consecutively)

P1
Write, A, 23
Write, B, 37
Write, Flag, 1

P2
Read, Flag, 0
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…)