Memory Consistency Models

- Formal specification of how the memory system will appear to the programmer
- Places restrictions on the value that can be returned by a "read" operation in a shared memory program execution
  - "Read" should return the value of the last "Write" to the same location
  - For uniprocessor, "last" is defined by program order
  - For a multiprocessor, not clear how to define "last write"

- Why do we care?
  - Programmability
  - Performance
  - Portability

Sequential Consistency

- An extension of uniprocessor "program order"
- A multiprocessor is sequentially consistent if
  - Result of any execution is the same as if the operation of all processors were executed in some sequential order
  - Operation of each processor appear in this sequence in the order specified by its program

- Advantage
  - Simple and intuitive programming model

- Disadvantages
  - Prevents many hardware optimizations (e.g., write buffers)
  - Prevents many compiler optimizations (e.g., code motion)
- Example programs: Figure 4

Implementing Sequential Consistency

- Need to maintain two requirements
  - Program order
  - Atomicity for memory operations
- SC restricts some common optimizations, even in the absence of caches
- Architectures without caches
  - Write Buffers with bypassing (Fig 5a)
  - Overlapping write operations (Fig 5b)
  - Non-blocking read operations (Fig 5c)

Relaxed Memory Models

- Can relax either:
  - Program order requirement
  - Write atomicity requirement
- Relaxing program order requirement
  - Write to a following read
  - Two writes
  - Read to a following read or write
- Relaxing write atomicity requirement
  - Can a read return the value of another processor’s write before the write is visible to all processors
- Can a processor read the value of its own previous write before it is made visible to all other processors
- Figure 8 summarizes all relaxed models, Figure 9 shows some systems with relaxed models
Relaxing Write to Read Program Order

- IBM 370
- Total Store Order (TSO), implemented in SPARC V8
- Processor Consistency (PC)
- All techniques allow a read to be reordered with respect to previous writes from the same processor
- Enable write buffers
- Techniques differ on when to allow a read to return the value of a write (Figure 8)
- Figure 10 shows example of how techniques are different

Relaxing Write to Read & Write Program Orders

- Partial Store Order (PSO), implemented in SPARC V8
- Writes to different locations from the same processor can be pipelined or overlapped
  - Writes allowed to reach memory or other caches out of program order
  - A processor can read the value of its own write early
  - A processor is prohibited from reading another processor’s write until it is visible to all other processors

Relaxing All Program Orders

- Relax program order between all operations to a different location
- A read or write may be reordered with respect to a following read or write to a different location
- Allows non-blocking reads (lock-free caches, speculative execution)
- Allows almost all compiler optimizations
- Examples
  - Weak Ordering (WO)
  - Release Consistency (RCpc, PCsc)
  - DEC Alpha
  - PowerPC
  - Relaxed Memory Order (RMO) in SPARC V9

Weak Ordering (WO)

- Classifies memory operations into two categories
  - Data operations
  - Synchronization operations
- To enforce program order between operations, programmer needs to specify synchronization operation
- Intuition: reordering data operations in between synchronization operations would not affect correctness
- Writes appear atomic to programmer

Reading Assignment