Issues with Lock Synchronization

- Priority Inversion
  - A lower-priority thread is preempted while holding a lock needed by higher-priority threads

- Convoying
  - Thread holding a lock is preempted, runs out of scheduling quantum, page faults, etc. while holding a lock needed by other threads

- Deadlock
  - Processes attempt to lock the same set of objects in different orders, cyclic dependence
Deadlock Example

- Concurrent Bank transfers

**Transfer 1 (from A to B)**
- Lock(A)
- Load(A)
- Lock(B) → locks A, fails to lock B
- Load(B)
- Calculate new value for A
- Calculate new value for B
- Write(A)
- Unlock(A)
- Write(B)
- Unlock(B)

**Transfer 2 (from B to A)**
- Lock(B)
- Load(B)
- Lock(A) → locks B, fails to lock A
- Load(A)
- Calculate new value for B
- Calculate new value for A
- Write(B)
- Unlock(B)
- Write(A)
- Unlock(A)
Issues with Lock Synchronization (Cont.)

- **Livelock**
  - Threads that need a lock are starved, unable to acquire it because other threads claim it before they get a chance

- **False inter-thread dependencies**
  - Conservative programming style can lead to thread serialization, even if it is not really needed

- **Performance problems**
  - Higher performance requires more fine-grain locking
  - Can lead to more overhead and more false dependencies
Back to Deadlock Example

Transfer 1 (from A to B)

Begin Transaction
Load(A)
Load(B)
Calculate new value for A
Calculate new value for B
Write(A)
Write(B)
End Transaction

Transfer 2 (from B to A)

Begin Transaction
Load(B)
Load(A)
Calculate new value for B
Calculate new value for A
Write(B)
Write(A)
End Transaction

- When there are no conflicts, both transactions complete successfully
- When there is a conflict (above), one transaction commits and the other aborts
Solution: Lock-Free Synchronization using Transactional Memory

- Transactional Memory
  - Allows programmers to define customized Read-Modify-Write operations that apply to multiple words of memory
  - Implemented by extending cache coherence protocols
- A Transaction is a finite sequence of instructions in a single thread that satisfies two conditions
  - Serializability
    - Transactions appear to execute serially
    - Instructions of one transaction do not interleave with another’s
    - Committed transactions are never observed to execute in different orders by different processors
  - Atomicity: All or nothing
    - Each transaction makes tentative changes to memory
    - When completed, a transaction commits (making changes permanent) or aborts (discarding changes) as a whole
Related Concept: Database Transactions

- Transactions are a widely used concept in database systems

- A database transaction satisfies the ACID properties:
  - Atomicity: Transaction is executed as a whole, or no part of it is executed (similar to last slide)
  - Consistency: If database is in a consistent state before transaction, it should be consistent after transaction
  - Isolation: Concurrent transactions will not interfere with each other’s execution. Intermediate changes by a transaction are not seen outside transaction until transaction is committed
  - Durability: After commit, a transaction’s changes are permanent even when system fails

- When a conflict occurs, some transactions are killed to allow others to commit
Transactional Memory Concepts

- **TM primitives**
  - **Load-Transactional (LT):** reads value of a shared memory location to a private register
  - **Load-Transactional-Exclusive (LTX):** reads value of a shared memory location to a private register with the intent to write
  - **Store-Transactional (ST):** Tentatively writes a value from a private register to a shared memory location

- **Read and write sets**
  - **Read set:** locations read by LT
  - **Write set:** locations accessed by LTX or ST
  - **Transaction’s data set:** Union of read and write sets
Changing A Transaction’s State

- COMMIT: Attempt to make transaction’s tentative changes permanent
  - A commit succeeds if no other transaction has updated any location in the transaction’s data set, and no other transaction has read any location in a transaction’s write set
  - If commit succeeds, all changes to write set are made visible to other threads
  - If commit fails, all tentative changes to write set are discarded
- ABORT: Discards all updates to a transaction’s write set
- VALIDATE: test current transaction status
  - Successful validate indicates current transaction hasn’t aborted (though it may abort later)
  - Unsuccessful validate indicates a transaction has aborted, discards the transaction’s tentative updates
Suggested Use for Transactions

- Instead of acquiring/releasing locks around critical section, a thread can:
  - Use LT or LTX to read from a set of locations
  - Use VALIDATE to check read values are consistent
  - Use ST to modify a set of locations
  - Use COMMIT to make changes permanent
  - If either VALIDATE or COMMIT fails, ABORT and restart

- Can be implemented in software, but hardware implementation is needed for good performance

- Hardware support implies limited transaction size
  - May trap to software on overflow
Hardware Implementation Guidelines

- Non-transactional operations use the same caches, cache controllers, and coherence protocols that they would’ve used in the absence of TM.
- Custom hardware support restricted to L1 caches and instructions that communicate with them.
- Committing or aborting a transaction is a local operation to the cache, doesn’t require communicating with other threads or writing data back to memory.
Example Implementation

- Extends Write-Once snooping coherence protocol

- Each processor maintains two caches
  - Regular cache for non-transactional operations (direct-mapped)
  - Transactional cache for transactional operations (fully associative)
    - Similar to Jouppi’s Victim cache
    - Holds all tentative writes without propagating them to other processors or memory unless the transaction commits

- Cache Line States: Paper Tables 1 and 2
  - XCOMMIT lines contain old data, XABORT lines contain tentatively modified data
  - On Commit, XCOMMIT entries discarded, XABORT entries change to NORMAL
  - On Abort, XABORT entries discarded, XCOMMIT entries change to normal

- Bus transactions: Paper Table 3
Example Implementation: Processor Actions

- Processor maintains two flags
  - Transaction active (TACTIVE): Whether a transaction is in progress
  - Transaction status (TSTATUS): Whether transaction is active or aborted

- Non-transactional operations behave like original coherence protocol

- Transactional operations issued by aborted transaction cause no bus cycles, may return arbitrary values

- VALIDATE inst. returns TSTATUS flag
  - If false, sets TACTIVE to false and TSTATUS to true

- ABORT inst. sets TSTATUS to true and TACTIVE to false

- COMMIT returns TSTATUS, sets TSTATUS to true and TACTIVE to false
Example Implementation:
Processor Actions (Cont.)

- **LT issued by active transaction**
  - Probe Transactional cache for an XABORT entry and return its value.
  - If hit to NORMAL entry, it changes to XABORT, and an XCOMMIT entry is allocated
  - If no NORMAL or XABORT entries exist in transactional cache, issue T_READ cycle on bus. When it completes successfully, set up one XABORT and one XCOMMIT entry in transactional cache
  - If T_READ returns BUSY, abort transaction (TSTATUS ← false, drop all XABORT entries, set XCOMMIT entries to NORMAL)

- **LTX issued by active transaction**
  - Uses T_RFO on miss (instead of T_READ)
  - Change cache state to RESERVED if T_RFO succeeds

- **ST issued by active transaction**
  - Similar to LTX except that it updates the XABORT entry’s data
Example Implementation: Cache Actions

- Both regular and transactional caches snoop bus
  - Ignore all requests for addresses not in the cache

- Regular cache actions
  - READ or T_READ: If state is VALID, return value. If state is RESERVED or DIRTY, return value and reset state to VALID
  - RFO or T_RFO: return data and invalidate own line

- Transactional cache actions
  - Acts like regular cache if TSTATUS is false or a request is non-transactional (READ or RFO), except that it ignores entries with transactional tags other than NORMAL
  - T_READ: If state is VALID, return value
  - All other transactional operations: Return BUSY

- Memory responds to WRITE requests
  - responds to READ, T_READ, RFO or T_RFO when no caches do
Performance Evaluation

- Alternatives
  - Test-and-test-and-set (TTS)
  - Spin locks with exponential backoff
  - MCS software queuing (similar to last class’s paper)
  - Hardware queuing: QOSB
    - Add a processor to hardware queue of waiters for a line
    - Allows processor to spin on locally-cached shadow version of line
    - When line is released by processor at head of queue, it is transferred to next waiting processor in queue
  - Load_Linked/Store_Conditional (LL/SC)
    - Load location first (with intent to store)
    - Store a new value only if no updates have occurred to location since load_linked

- Performance in Paper figures 4, 5, 6
Implementation Issues

- Some disadvantages of original technique
  - Uses separate, fully-associative transactional cache
  - Transactional cache size limits transaction length
  - Many implementation details not discussed

- Data version management
  - Need to store old and new data modified by a transaction
  - If using one cache, need to store new data or old data elsewhere

- LogTM
  - Stores new values in cache, old value in per-thread log in virtual memory
    - On commit (common case), log is discarded
    - On abort, old values restored from log by software

- Will TM be successful in making parallel programming easier?
Reading Assignment

- Arthur Veen, "Dataflow Machine Architecture," ACM Computing Surveys, 1986 (Read sections 1, 2, 3 and skim the rest of the paper)
- Gregory Papadopoulos and David Culler, "Monsoon: An Explicit Token-Store Architecture," ISCA, 1990 (Read)