Transactional Memory

Issues with Lock Synchronization

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

- **Conveying**
  - 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

Deadlock Example

- **Concurrent Bank transfers**
  - Transfer 1 (from A to B)
    - Lock(A)
    - Load(A)
    - Lock(B) \(\rightarrow\) locks A, fails to lock B
    - Load(B)
    - Calculate new value for A
    - Calculate new value for B
    - Write(A)
    - Write(B)
    - Unlock(A)
    - Unlock(B)
  - Transfer 2 (from B to A)
    - Lock(B)
    - Load(B)
    - Lock(A) \(\rightarrow\) locks B, fails to lock A
    - Load(A)
    - Calculate new value for B
    - Calculate new value for A
    - Write(B)
    - Write(A)
    - Unlock(B)
    - 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

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 satisfy two conditions
    - **Serializability**
      - 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 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 is not seen outside transaction until transaction is committed.
  - Durability: After commit, 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 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 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: 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
  - 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

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)
    - Stores 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)