Log-Based Transactional Memory

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Motivation

- Chip-multiprocessors/Multi-core/Many-core are here
  - "Intel has 10 projects in the works that contain four or more computing cores per chip" -- Paul Otellini, Intel CEO, Fall '05
- We must effectively program these systems
  - But programming with locks is challenging
  - "Blocking on a mutex is a surprisingly delicate dance"

    -- OpenSolaris, mutex.c

Locks are Hard

```
// WITH LOCKS
void move(T s, T d, Obj key){
  LOCK(s);
  LOCK(d);
  tmp = s.remove(key);
  d.insert(key, tmp);
  UNLOCK(d);
  UNLOCK(s);
}
```

Moreover

Coarse-grain locking limits concurrency

Fine-grain locking difficult

Thread 0

```
move(a, b, key1);
```

Thread 1

```
move(b, a, key2);
```

DEADLOCK!

Transactional Memory (TM)

- Programmer says
  - "I want this atomic"
- TM system
  - "Makes it so"

```
void move(T s, T d, Obj key){
  atomic {
   tmp = s.remove(key);
   d.insert(key, tmp);
  }
}
```

- Software TM (STM) Implementations
  - Currently slower than locks
  - Always slower than hardware?
- Hardware TM (HTM) Implementations
  - Leverage cache coherence & speculation
  - Fast
  - But hardware overheads and virtualization challenges

Goals for Transactional Memory

- Efficient Implementation
  - Make the common case fast
  - Can't justify expensive HW (yet)
- Virtualizing TM
  - Don't limit programming model
  - Allow transactions of any size and duration

Implementing TM

- Version Management
  - **new** values for commit
  - **old** values for abort
  - **Must keep both**
- Conflict Detection
  - Find read-write, write-read or write-write conflicts among concurrent transactions
  - Allows multiple readers **OR** one writer

Large state (must be precise)

Checked often (must be fast)

LogTM: Log-Based Transactional Memory

- Combined Hardware/Software Transactional Memory
  - Conservative hardware conflict detection
  - Software version management (with some hardware support)
- Eager Version Management
  - Stores new values in place
  - Stores old values in user virtual memory (the transaction log)
- Eager Conflict Detection
  - Detects transaction conflicts on each load and store

LogTM Publications

[HPCA 2006] LogTM: Log-based Transactional Memory

[ASPLOS 2006] Supporting Nested Transactional Memory in LogTM

[HPCA 2007] LogTM-SE: Decoupling Hardware Transactional Memory from Caches

[ISCA 2007] Performance Pathologies in Hardware Transactional Memory

Outline

- Introduction
- Background
- LogTM
- Implementing LogTM
- Evaluation
- Extending LogTM
- Related Work
- Conclusion

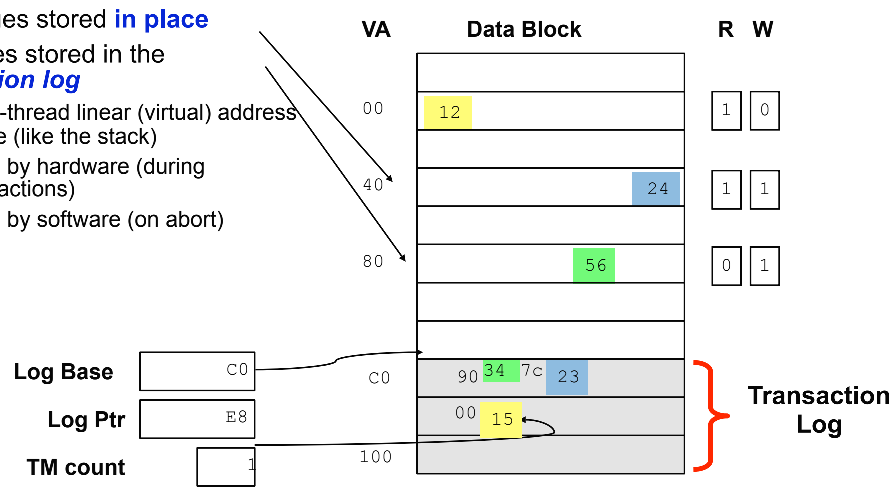
LOGTM

LogTM: Log-Based Transactional Memory

- Eager Software-Based Version Management
  - Store new values in place
  - Store old values in the transaction log
  - Undo failed transactions in software
- Eager All-Hardware Conflict Detection
  - Isolate new values
  - Fast conflict detection for all transactions

LogTM's Eager Version Management

- New values stored **in place**
- Old values stored in the ***transaction log***
  - A per-thread linear (virtual) address space (like the stack)
  - Filled by hardware (during transactions)
  - Read by software (on abort)



<example>

Eager Version Management Discussion

- Advantages:
  - No extra indirection (unlike STM)
  - Fast Commits
    - No copying
    - Common case
- Disadvantages
  - Slow/Complex Aborts
    - Undo aborting transaction
  - Relies on Eager Conflict Detection/Prevention

LogTM's Eager Conflict Detection

Requirements for Conflict Detection in LogTM:

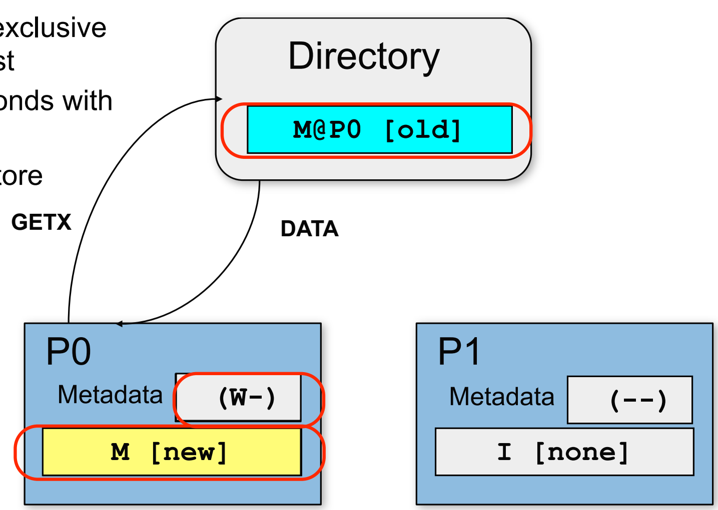
1. Transactions Must Be Well Formed
   - Each thread must obtain read isolation on all memory locations read and write isolation on all locations written
2. Isolation Must be Strict Two-Phase
   - Any thread that acquires read or write isolation on a memory location in a transaction must maintain that isolation until the end of the transaction
3. Isolation Must Be Released at the End of a Transaction
   - Because conflicts may prevent transactions from making progress, a thread completing a transaction must release isolation when it aborts or commits a transaction

LogTM's Conflict Detection in Practice

- LogTM detects conflicts using coherence
  - Requesting processor issues coherence request to memory system
  - Coherence mechanism forwards to other processor(s)
  - Responding processor *detects* conflict using local state & informs requesting processor of conflict
- Requesting processor *resolves* conflict (discussed later)

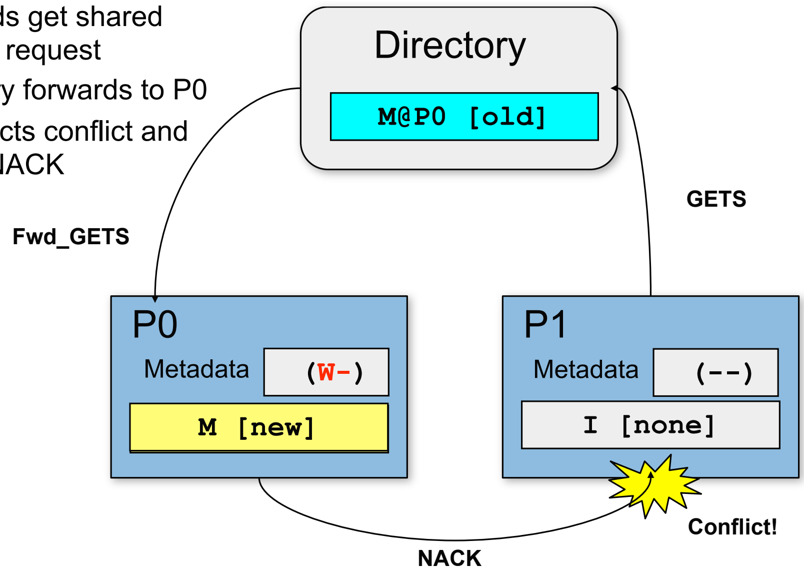
Example Implementation (LogTM-Dir)

- P0 store
  - P0 sends get exclusive (GETX) request
  - Directory responds with data (old)
  - P0 executes store



Example Implementation (LogTM-Dir)

- In-cache transaction conflict
  - P1 sends get shared (GETS) request
  - Directory forwards to P0
  - P1 detects conflict and sends NACK



Conflict Resolution

- Conflict Resolution
  - Can wait risking deadlock
  - Can abort risking livelock
  - Wait/abort transaction at requesting or responding proc?
- LogTM resolves conflicts at requesting processor
  - Requesting can wait (using coherence nacks/retries)
  - But must abort if deadlock is possible
- Requester Stalls Policy
  - Logically order transactions with timestamps
  - On conflict notification, wait unless already causing an older transaction to wait

LogTM API

User	System/Library	Low-Level
begin_transaction() commit_transaction() abort_transaction()	Initialize_logtm_transactions() Register_abort_handler(void (*) handler)	Undo_log_entry() Complete_abort_with_restart() Complete_abort_wo_restart()

IMPLEMENTING LOGTM

Version Management Trade-offs

- Hardware vs. Software Register Checkpointing
- Implicit vs. Explicit Logging
- Buffered vs. Direct Logging
- Logging Granularity
- Logging Location

Compiler-Supported Software Logging

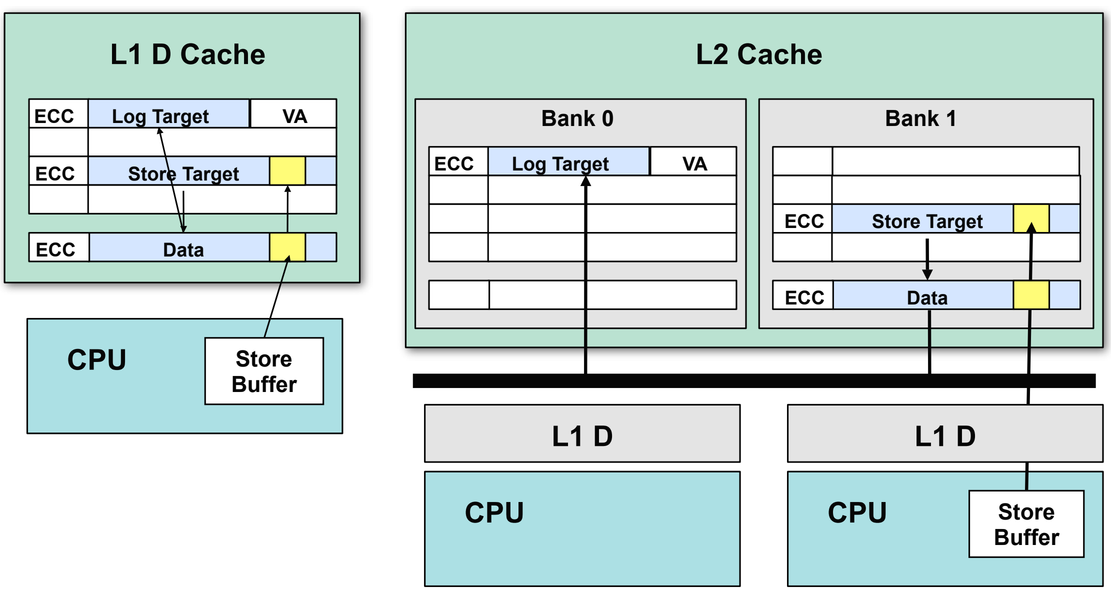
- Software Register Checkpointing
  - Compiler generates instructions to save registers to transaction log
- Software-only logging
  - Compiler generates instructions to save old values and to the transaction log

- Lowest implementation cost
  - All-software version management
- High overhead
  - Slow to start transactions (save registers)
  - Slow writes (extra load & instructions)

In-Cache Hardware Logging

- Hardware Register Checkpointing
  - Bulk save architectural registers (like USIII)
- Hardware Logging
  - Hardware saves old values and virtual address to memory at the first level of writeback cache
- Best Performance
  - Little or no logging-induced delay
  - Single-cycle transaction begin/commit
- Complex implementation
  - Shadow register file
  - Buffering and forwarding logic in caches

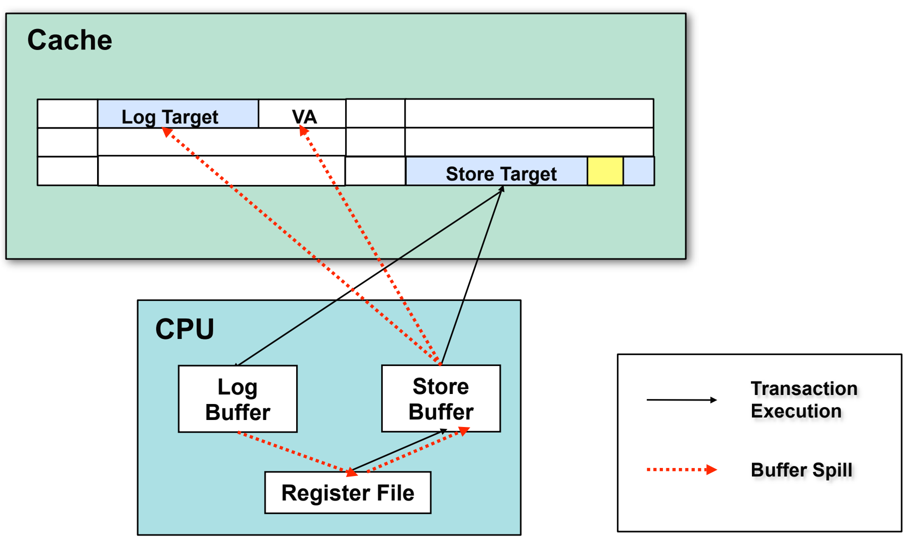
In-Cache Hardware Logging



Hardware/Software Hybrid Buffered Logging

- Hardware Register Checkpointing
  - Bulk save architectural registers (like USIII)
- Buffered Logging
  - Hardware saves old values and virtual address to a small buffer
- Good Performance
  - Little or no logging-induced delay for small transactions
  - Single-cycle transaction begin/commit
  - Reduces processor-to-cache memory traffic
- Less-complex implementation
  - Shadow register file
  - No changes to caches

Hardware/Software Hybrid Buffered Logging

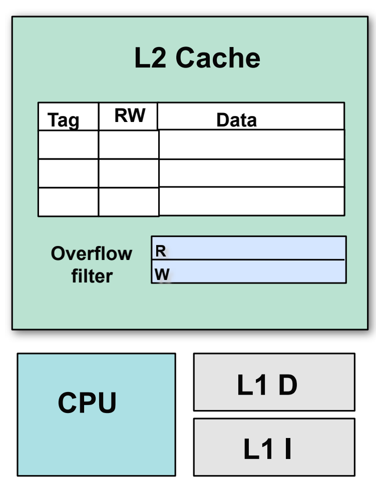


Implementing Conflict Detection

- Existing cache coherence mechanisms can support conflict detection for cached data by adding an R (read) W (write) bit to each cache line
- Challenges for detecting conflicts on un-cached data differ for broadcast and directory systems
- Broadcast
  - Easy to find all possible conflicts
  - Hard to filter false conflicts
- Directory
  - Hard to find all possible conflicts
  - Easy to filter false conflicts

LogTM-Bcast

- Adds a Bloom Filter to track memory blocks touched in a transaction, then evicted from the cache
- Allows any number of addresses to be added to the filter
- Detects all true conflicts
- Allows some false conflicts



LogTM-Dir

- Extends a standard MESI directory with sticky states
- The directory continues to forward coherence traffic for a memory location to processors that touch that location in a transaction then evict it from the cache
- Removes most false conflicts with a single overflow bit per cache

Sticky States

Directory State

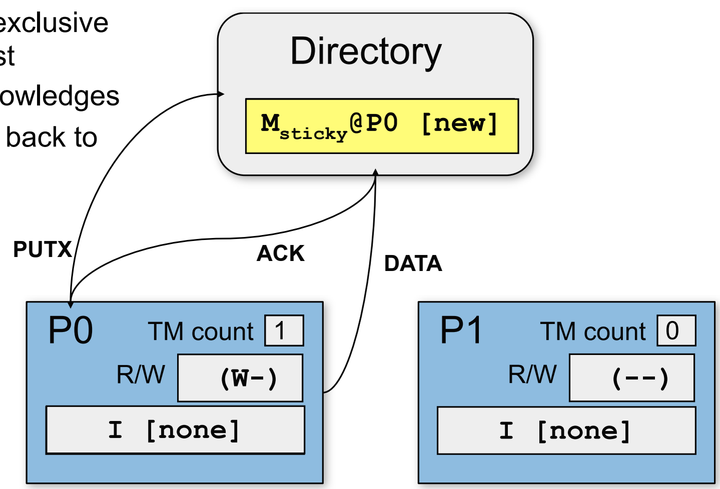
Cache State	M	S	I
M	M		
E	E		
S		S	
I	Sticky-M	Sticky-S	I

LogTM-Dir Conflict Detection w/ Cache Overflow

- At overflow at processor P0
  - Set P0's overflow bit (1 bit per processor)
  - Allow writeback, but set directory state to Sticky@P0
- At (potential) conflicting request by processor P1
  - Directory forwards P1's request to P0.
  - P0 tells P1 "no conflict" if overflow is reset
  - But asserts conflict if set (w/ small chance of false positive)
- At transaction end (commit or abort) at processor P0
  - Reset P0's overflow bit
- Clean sticky states lazily on next access

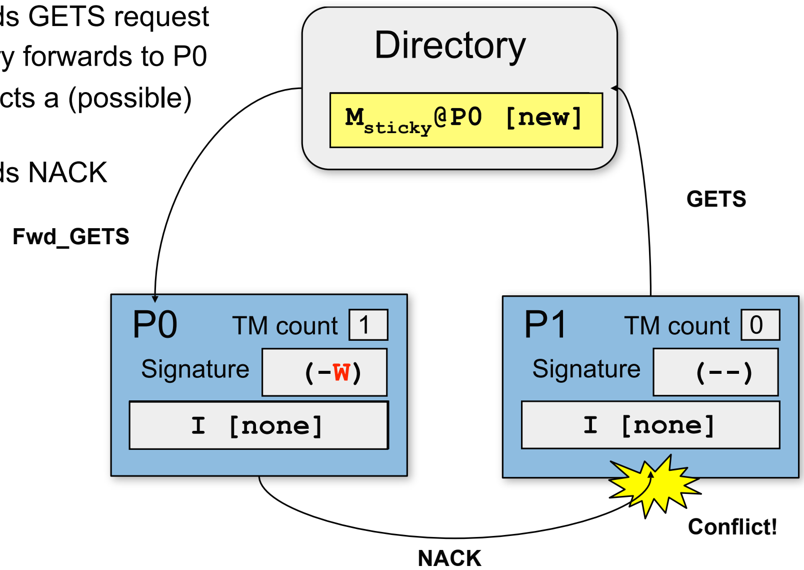
LogTM-Dir

- Cache overflow
  - P0 sends put exclusive (PUTX) request
  - Directory acknowledges
  - P0 writes data back to memory



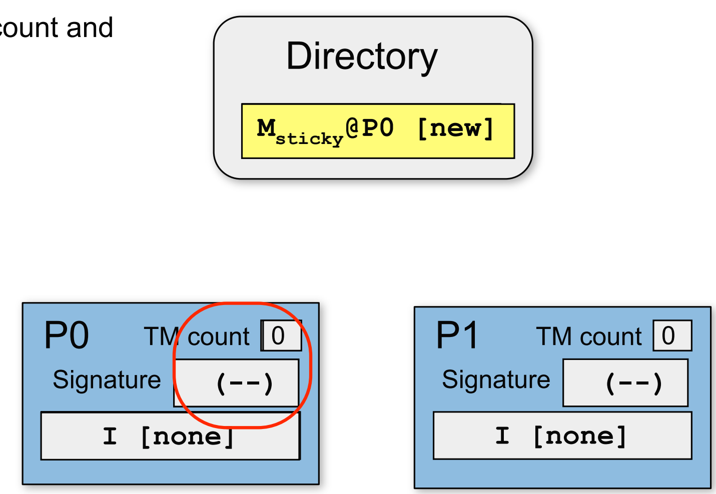
LogTM-Dir

- Out-of-cache conflict
  - P1 sends GETS request
  - Directory forwards to P0
  - P0 detects a (possible) conflict
  - P0 sends NACK



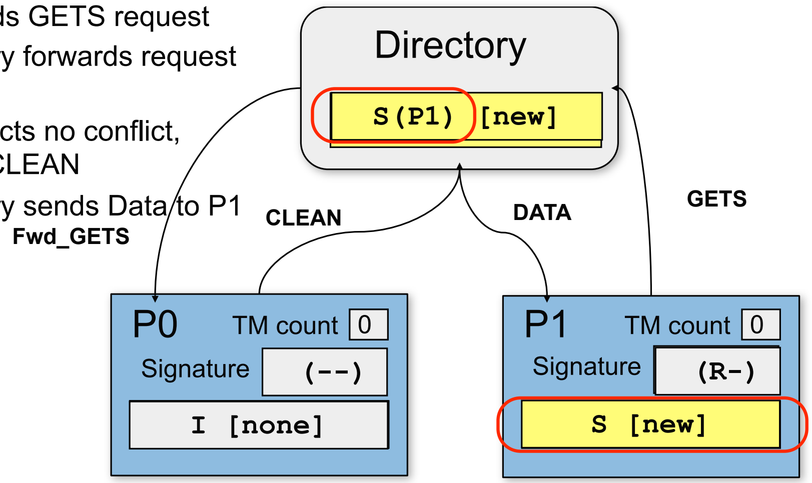
LogTM-Dir

- Commit
  - P0 clears TM count and
  - Signature



LogTM-Dir

- Lazy cleanup
  - P1 sends GETS request
  - Directory forwards request to P0
  - P0 detects no conflict, sends CLEAN
  - Directory sends Data to P1



EVALUATION

System Model

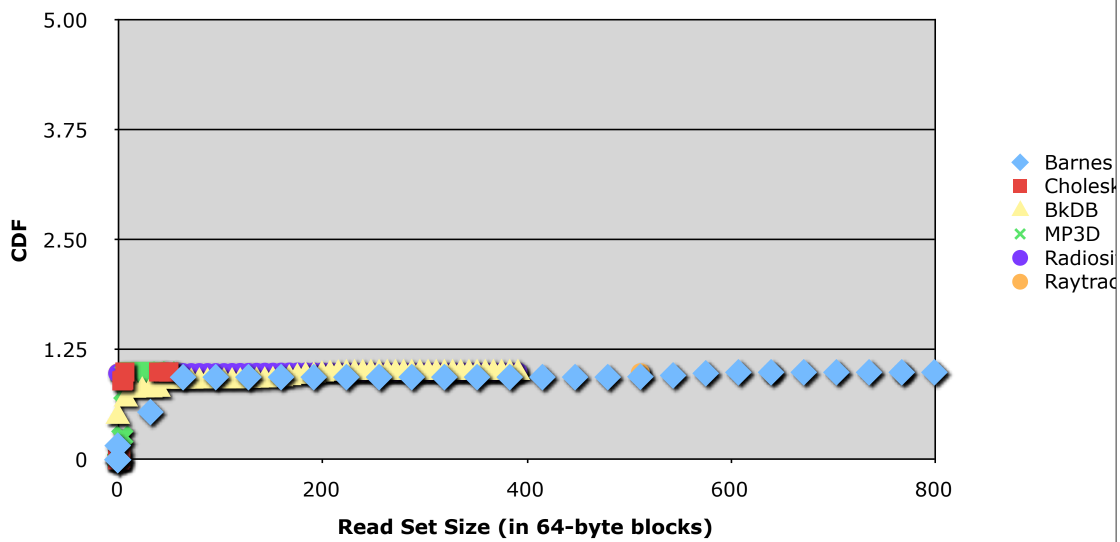
- LogTM-Dir
- In-Cache Hardware Logging & Hybrid Buffered Logging

Component	Settings
Processors	32, 1 GHz, single-issue, in-order, non-memory IPC=1
L1 Cache	16 kB 4-way split, 1-cycle latency
L2 Cache	4 MB 4-way unified, 12-cycle latency
Memory	4 GB, 80-cycle latency
Directory	Full-bit-vector sharers list, directory cache, 6-cycle latency
Interconnection Network	Hierarchical switch topology, 14-cycle link latency

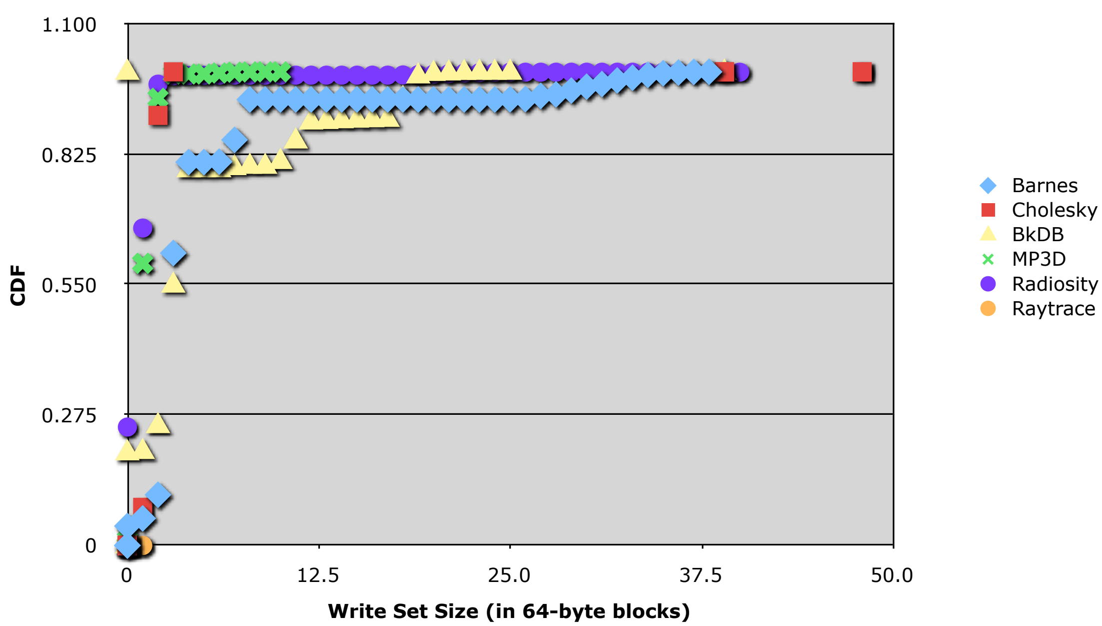
Benchmarks

Benchmark	**Synchronization**	**Inputs**
Shared Counter	Counter lock	2500 cycle random think time
B-Tree	Transactions only	9-ary tree, 5 levels deep
Barnes	Locks on tree nodes	512 bodies
Cholesky	Task queue locks	14
Berkeley DB (BkDB)	Locks on object lists	512 operations
MP3D	Locks	4096 molecules
Radiosity	Task queue locks	Large room
Raytrace	Work list and counter locks	Car

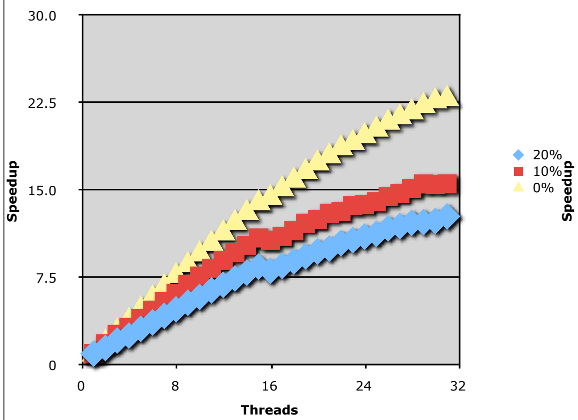
Read Set Size



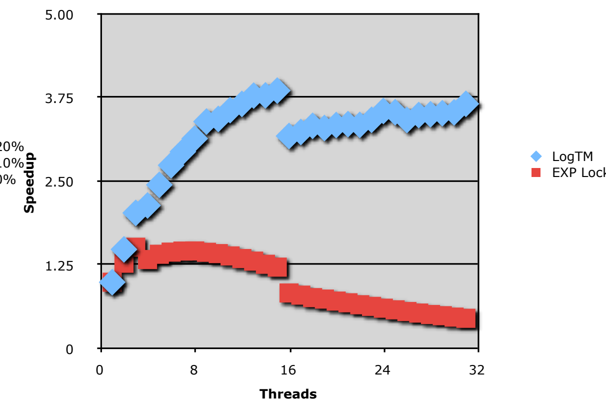
Write Set Size



Microbenchmark Scalability

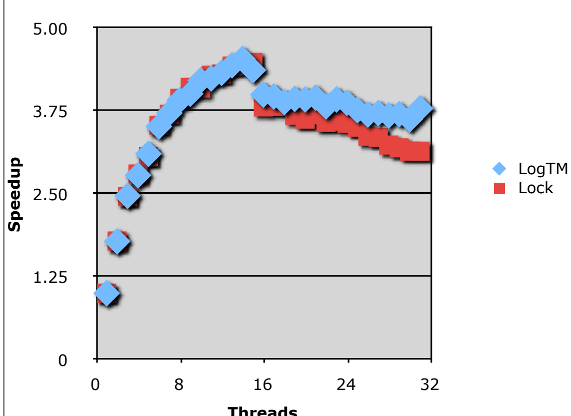


Btree 0%, 10% and 20% Updates

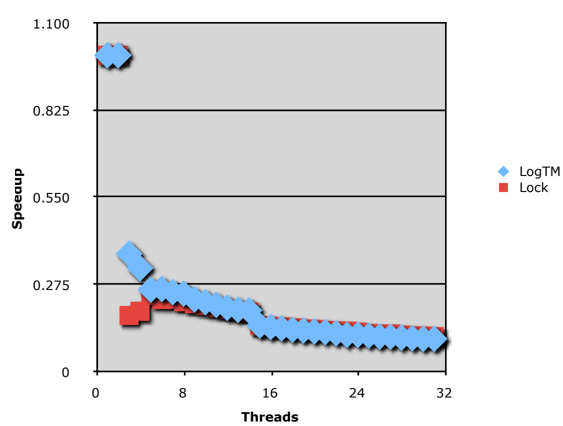


Shared Counter: LogTM vs. Locks

Benchmark Scalability

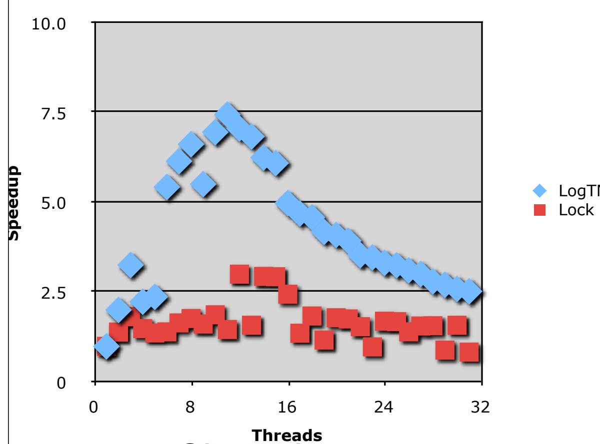


Barnes

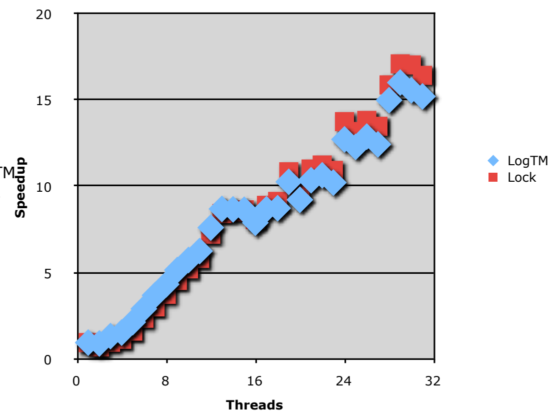


BkDB

Benchmark Scalability

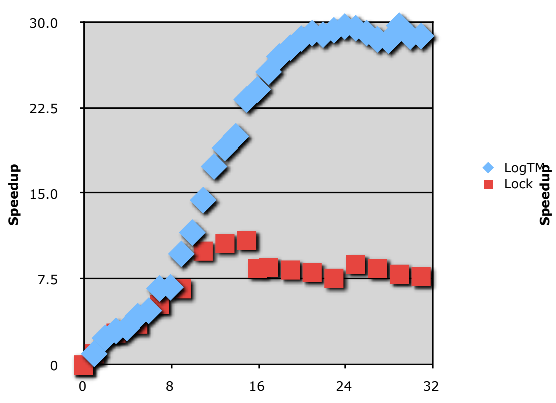


Cholesky

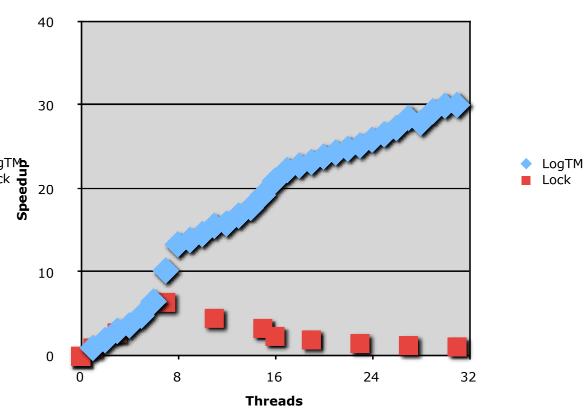


MP3D

Benchmark Scalability



Radiosity



Raytrace

Scalability Summary

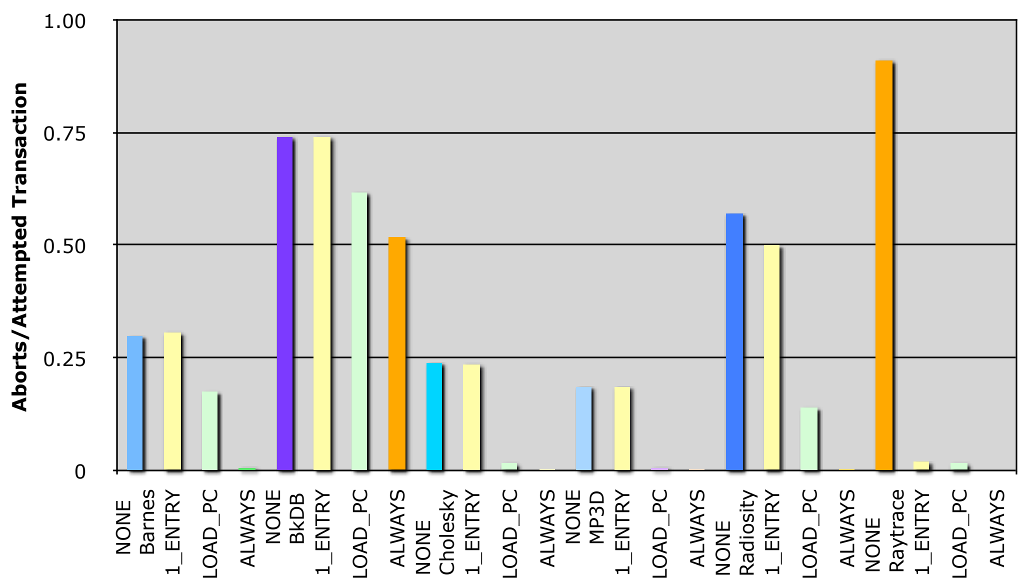
- Benchmarks scale as well or better using LogTM transactions
  - Performance is better for all benchmarks
- LogTM improves the scalability of some benchmarks, but not others
- Abort rates are low

- Next:
  - Write set prediction
  - Buffered Logging
  - Log Granularity

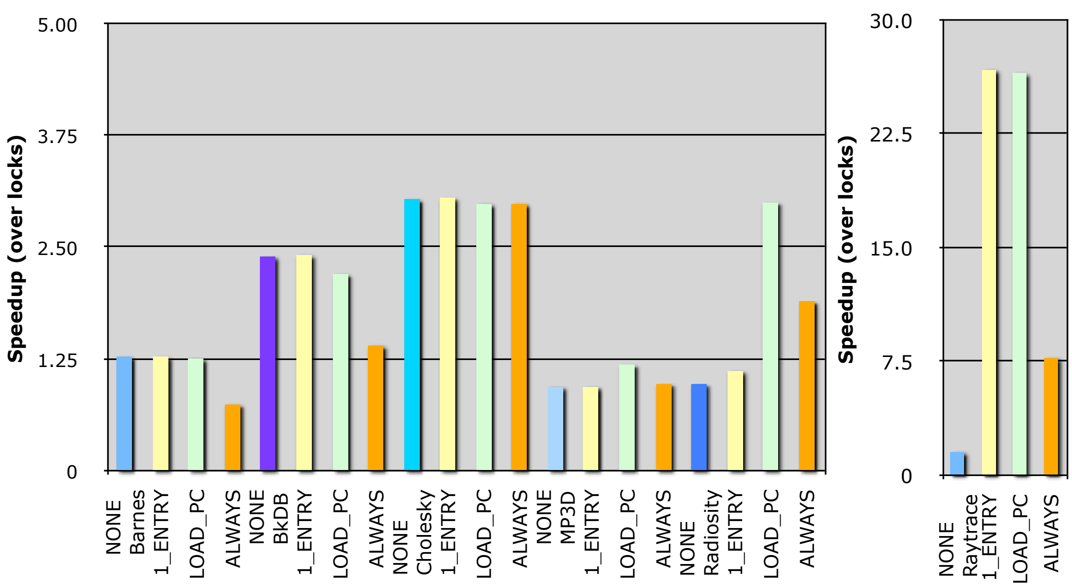
Write Set Prediction

- Predicts if the target of each load will be modified in this transaction
- Eagerly acquires write isolation
- Reduces “waits for” cycles that force aborts in LogTM
- Four Predictors:
  - **None** -- Never predict
  - **1-Entry** -- Remembers a single address
  - **Load PC** -- History based on PC of load instruction
  - **Always** -- Acquire write isolation for all loads and stores

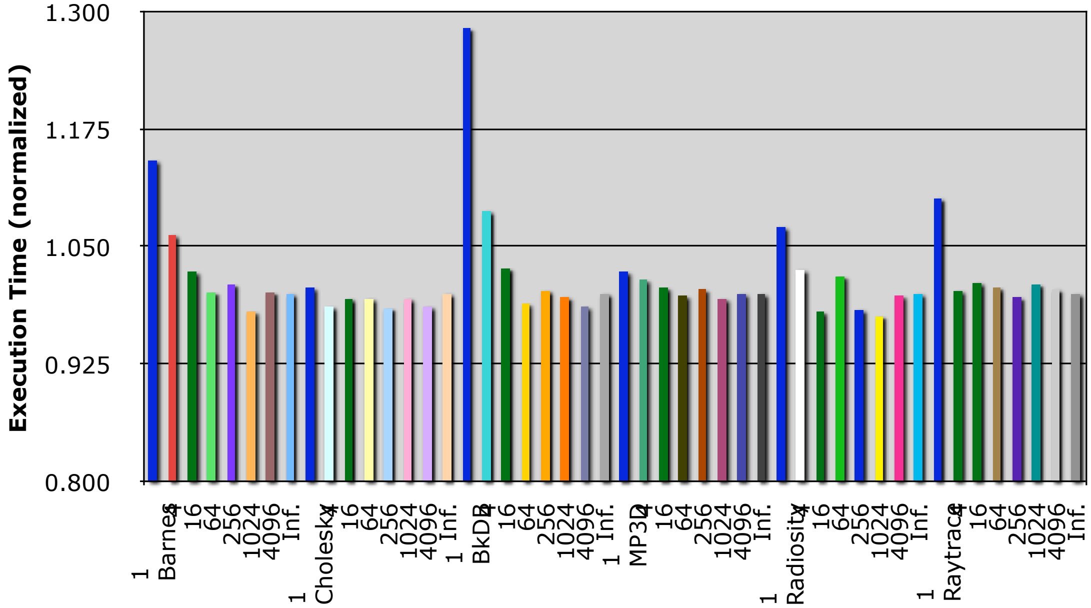
Abort Rate with Write Set Prediction



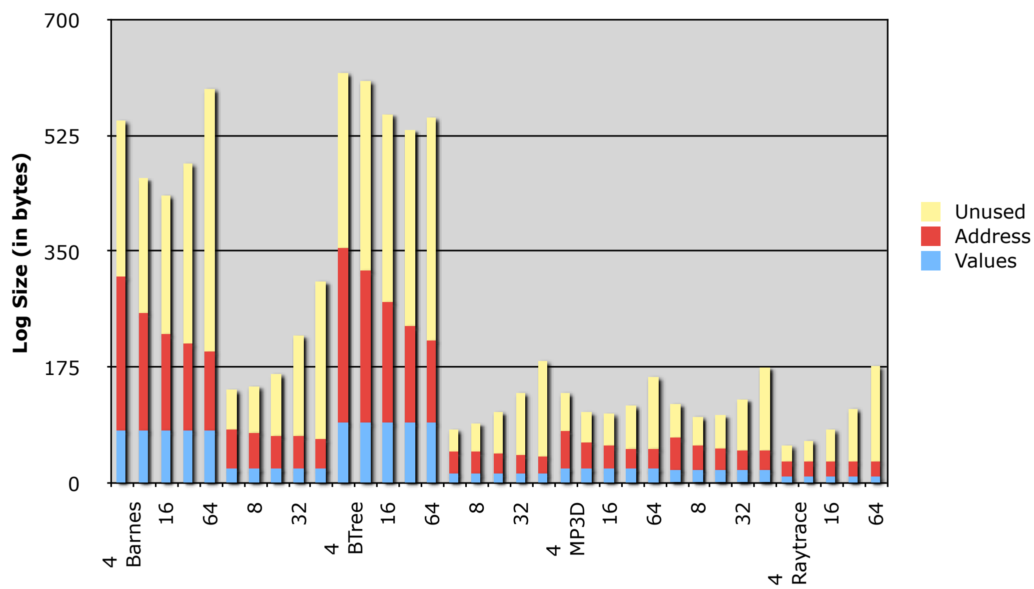
Performance Impact of WSP



Impact of Buffer-Spill Stalls



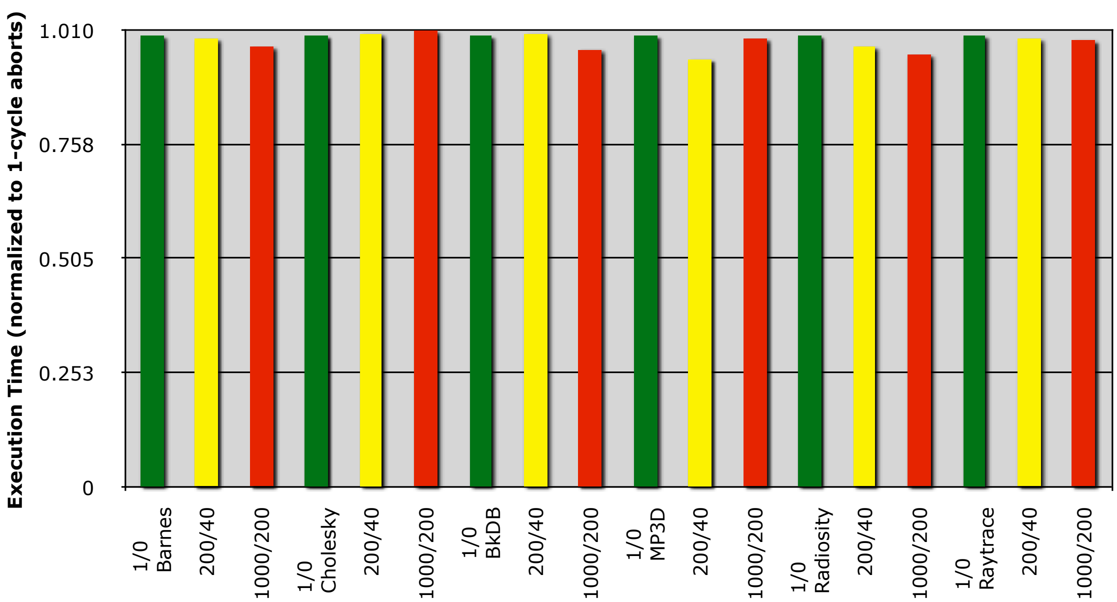
Log Granularity



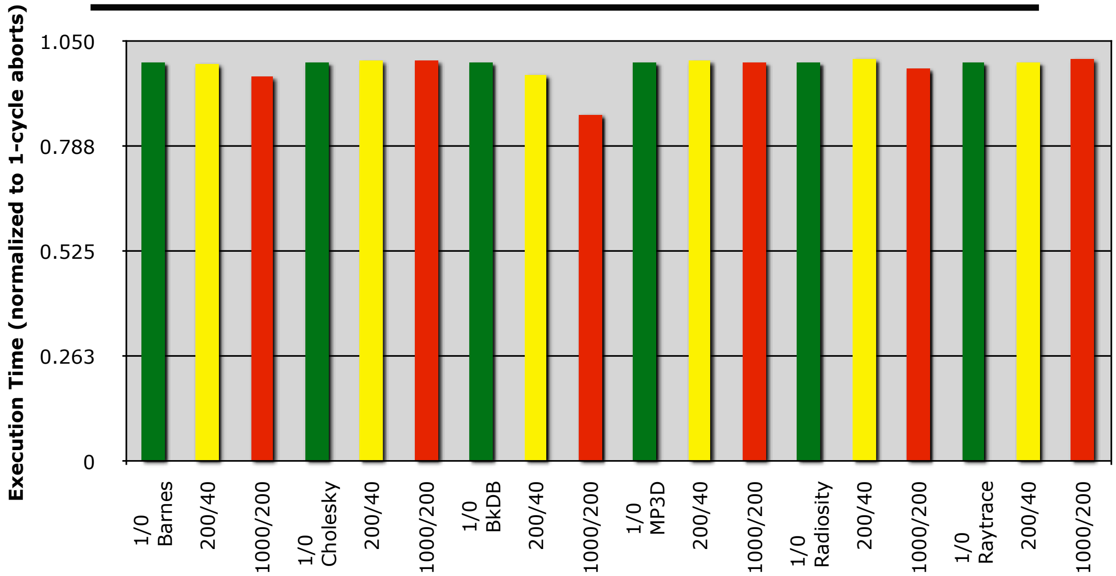
Modeling Abort Penalty

- Abort penalty
  - Delays coherence requests
  - Delays transaction restart
- Penalty consists of:
  - Trap overhead (constant)
  - Rollback overhead (per log entry)
- Measured performance for 3 settings:
  - Ideal -- single-cycle abort
  - Medium -- 200 cycle trap, 40-cycle per undo record
  - Slow -- 1000 cycle trap, 200-cycle per undo record

Sensitivity to Abort Penalty (no WSP)



Sensitivity to Abort Penalty (with WSP)



EXTENDING LOGTM

Extending LogTM

- Supporting Nesting in LogTM
  - Support nested VM by segmenting the transaction log
  - Non-transactional escape actions facilitate OS interactions
- Virtualizing Conflict Detection with Signatures LogTM-Signature Edition (LogTM-SE) tracks read and write sets with signatures (like Bloom Filters)
  - Supports thread switching and paging by saving, restoring and manipulating signatures

RELATED WORK

Related Work

- Hardware Support for Database Transactions
- Early Transactional Memory Systems
- Hardware TM (HTM)
- Software TM (STM)
- Hybrid TM
- TM Virtualization

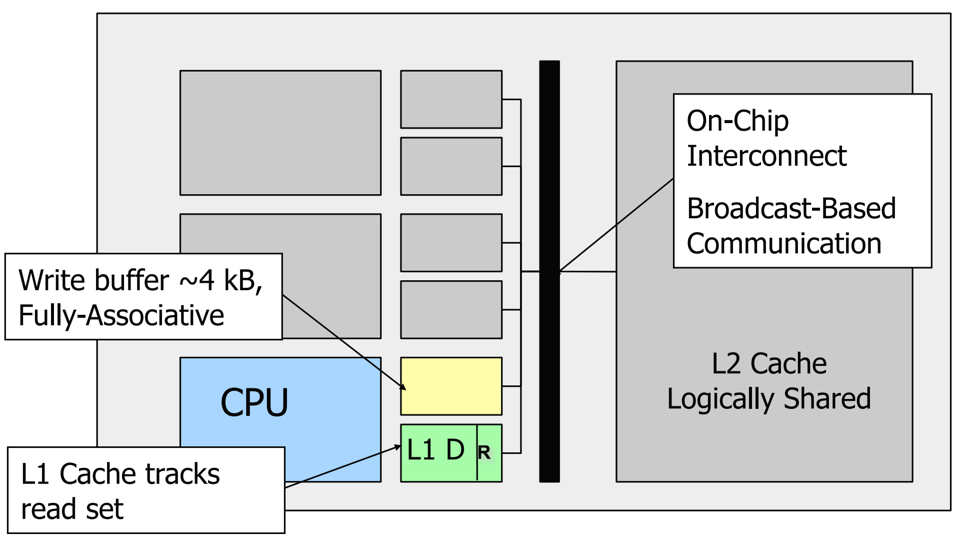
Early Transactional Memory Systems

- Hardware Support for Database Transactions
  - 801 Storage System
    - Database-like transactions on 1-level store (memory and disk)
    - Transactions are durable
- Early HTM
  - Knight
    - used transactions to parallelize code written in ‘mostly functional’ languages
  - Herlihy and Moss
    - First HTM
    - Implementation based on a separate transaction cache
    - Transactions limited to cached data

Unbounded Transactional Memory

- Uses Eager VM and Eager CD
- Supports unbounded transactions in hardware
- Complex hardware
  - Pointer and state bits for each line in memory
  - Hardware state machine for transaction rollback
  - Global virtual address space

Transactional Memory Coherence and Consistency (TCC)



Bulk

- Encodes read and write sets in signatures (like bloom filters)
- Like TCC, uses lazy VM and lazy CD
- Can detect conflicts for non-cached data

Hybrid Transactional Memory

- Combines HTM and STM
- Executes small transactions in hardware, large transactions in software
- Allows program execution on existing hardware (without HTM support)

Transaction Virtualization

- Virtual Transactional Memory (VTM)
  - Rajwar and Herlihy
  - Adds a virtualization mechanism to limited HTM (e.g. Herlihy and Moss TM)
  - Implements CD and VM for transactions that exceed hardware capabilities in micro-code
- Page-granularity Transaction Virtualization
  - PTM -- Chuang et al.
  - XTM -- Chung et al.

HTM Virtualization Mechanisms

	Before Virtualization				After Virtualization					
	$Miss	Commit	Abort	$Eviction	$Miss	Commit	Abort	$Eviction	Paging	Thread Switch
UTM	-	-	-	H	H	H	HC	H	H	H
VTM	-	-	-	S	S	SC	S	S	S	SWV
UnrestrictedTM	-	-	-	A	B	B	B	B	AS	AS
XTM	-	-	-	ASC	-	SCV	S	SC	SC	AS
XTM-g	-	-	-	SC	-	SCV	S	SC	SC	AS
PTM-Copy	-	-	-	SC	S	S	SC	SC	S	S
PTM-Select	-	-	-	S	H	S	S	S	S	S
LogTM-SE	-	-	SC	-	-	S	SC	-	S	S

Shaded = virtualization event
- = handled in simple HW
H = complex hardware

S = handled in software
A = abort transaction
C = copy values

W = walk cache
V = validate read set
B = block other transactions

Conclusion

- TM can make parallel programs faster and easier to write
- LogTM provides:
  - Hardware/Software Implementation
    - Simple, flexible hardware
  - Software-Based Eager Version Management
    - Makes the common case (commit) fast
    - Reduces hardware complexity
  - Hardware-Based Eager Conflict Detection
    - Allows blocking to reduce wasted work

Thanks to my Collaborators

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