Transactional Memory

Architectural Support for Practical Parallel Programming

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The Era of Multi-core Chips

- Diminishing returns from single-core chips
  - Wire delays, memory latency, power consumption, complexity, …
- Multi-core chips are the scalable alternative
  - Modular, fault-tolerant, memory-level parallelism …
  - All processor vendors are building CMPs
- But, we how do we program them?
  - Correct & fast parallel programming is a black art

Urgent: make parallel programming the common case

What Makes Parallel Programming Hard?

1. Finding independent tasks
2. Mapping tasks to threads
3. Defining & implementing synchronization protocol
4. Race conditions & deadlock avoidance
5. Memory model
6. Portable & predictable performance
7. Scalability
8. Locality management
9. Composing parallel tasks
10. Recovering from errors

11. And, of course, all the single thread issues…

Example: Java 1.4 HashMap

- Fundamental data structure
  - Map: Key → Value

```
public Object get(Object key)  {
   int idx = hash(key);                          // Compute hash
   HashEntry e = buckets[idx];                   // to find bucket
   while (e != null)  {                          // Find element in
  bucket
      if (equals(key, e.key))
        return e.value;
      e = e.next;
    }
   return null;
 }
```

- Not thread safe (no lock overhead when not needed)

Synchronized HashMap

- Java 1.4 solution: synchronized layer
  - Convert any map to thread-safe variant
  - Explicit locking – user specifies blocking

```
public Object get(Object key)
      {
        synchronized (mutex)  // mutex guards all accesses to map m
          {
            return m.get(key);
          }
      }
```

- Coarse-grain synchronized HashMap:
  - Thread-safe, easy to program
  - Limits concurrency → poor scalability
    - E.g., 2 threads can't access disjoint hashtable elements

ConcurrentHashMap

- Java 5 solution: Complete redesign

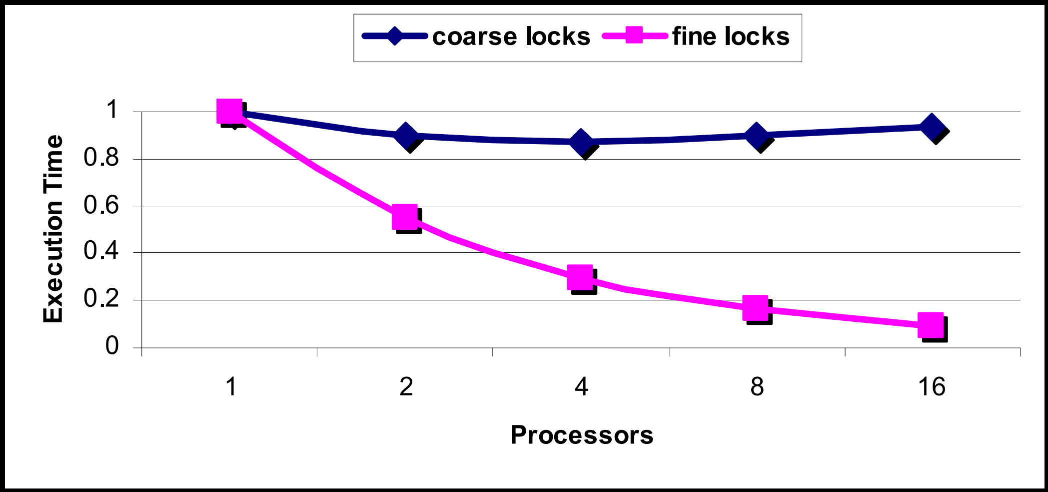
```
public Object get(Object key) {
   int hash = hash(key);
   // Try first without locking...
   Entry[] tab = table;
   int index = hash & (tab.length - 1);
   Entry first = tab[index];
   Entry e;

   for (e = first; e != null; e = e.next) {
     if (e.hash == hash && eq(key, e.key)) {
       Object value = e.value;
       if (value != null)
         return value;
       else
         break;
     }
   }
   …
```

```
   …
   // Recheck under synch if key not there or
    interference
   Segment seg = segments[hash &
    SEGMENT_MASK];
   synchronized(seg) {
     tab = table;
     index = hash & (tab.length - 1);
     Entry newFirst = tab[index];
     if (e != null || first != newFirst) {
       for (e = newFirst; e != null; e = e.next) {
         if (e.hash == hash && eq(key, e.key))
           return e.value;
       }
     }
     return null;
   }
 }
```

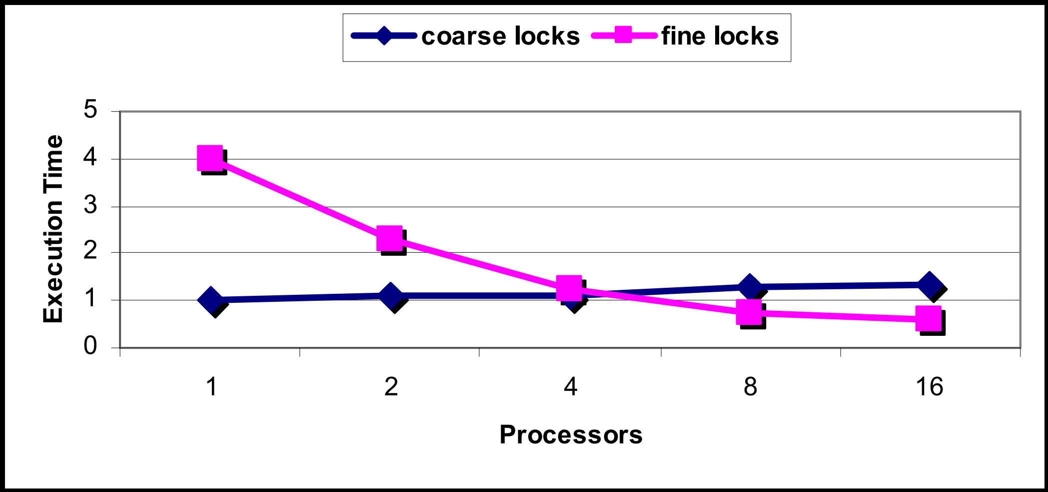
Fine-grain locking & concurrent reads: complicated & error prone

Quantitative Example

Hash-Table



Balanced Tree



Locks are Simply Broken

- Performance – correctness tradeoff
  - Coarse-grain locks: serialization
  - Fine-grain locks: deadlocks, livelocks, races, …
- Cannot easily compose lock-based code
- No failure atomicity
- User’s specification ≠ implementation
  - Makes programming & tuning difficult

Outline

- Motivation
- Transactional Memory
  - Motivation, use & performance example
- Transactional Coherence & Consistency (TCC)
  - Architecture model, implementation, advanced features
- Performance evaluation
  - SpecJBB2000
- Conclusions & current work

Transactional Memory (TM)

- Programmer specifies large, atomic tasks [Herlihy'93]
  - atomic { some_work; }
  - Multiple objects, unstructured control-flow, …
  - Declarative approach; system implements details
- Transactional memory provides
  - Atomicity: all or nothing
  - Isolation: writes not visible until transaction commits
  - Consistency: serializable commit order
- Performance through optimistic concurrency [Kung'81]
  - Execute in parallel assuming independent transactions
  - If conflicts detected, abort & re-execute one transaction
    - Conflict = two transactions read-write same data

Transactional HashMap

- Transactional layer via an ‘atomic’ construct
  - Ensure all operations are atomic
  - Implicit atomic directive – system finds concurrency

```
public Object get(Object key)
  {
    atomic                          // System guarantees atomicity
      {
        return m.get(key);
      }
  }
```

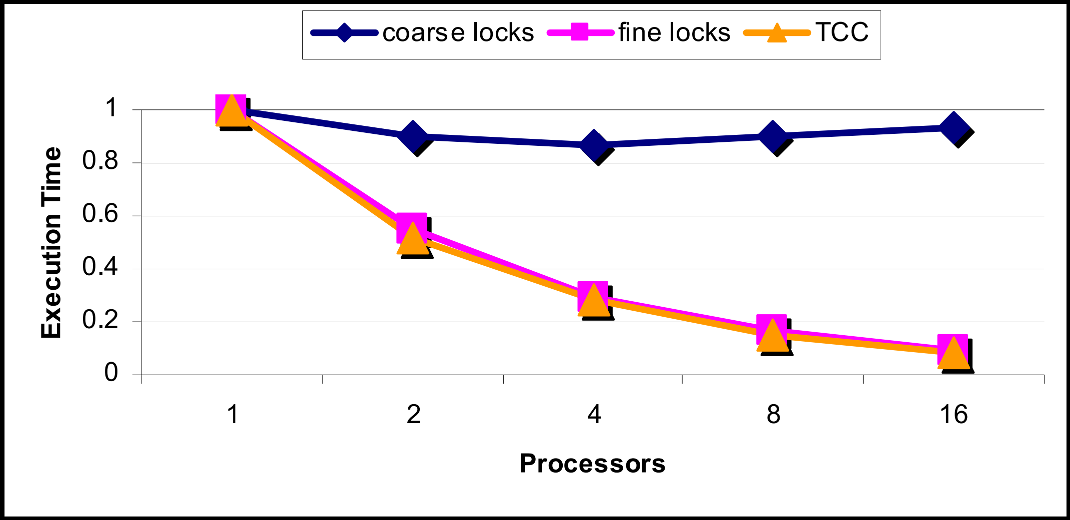
- Transactional HashMap
  - Thread-safe, easy to program, good performance

Transactional Memory: Performance

- Concurrent read operations
  - Basic locks do not permit multiple readers
    - Need reader-writer locks $\Rightarrow$ more complex
  - Automatically allows multiple concurrent readers
- Concurrent access to disjoint data
  - Users have to manually perform fine-grain locking
    - Difficult and error prone
    - Not modular
  - Automatically provides fine-grain locking

Performance Revisited

HashMap



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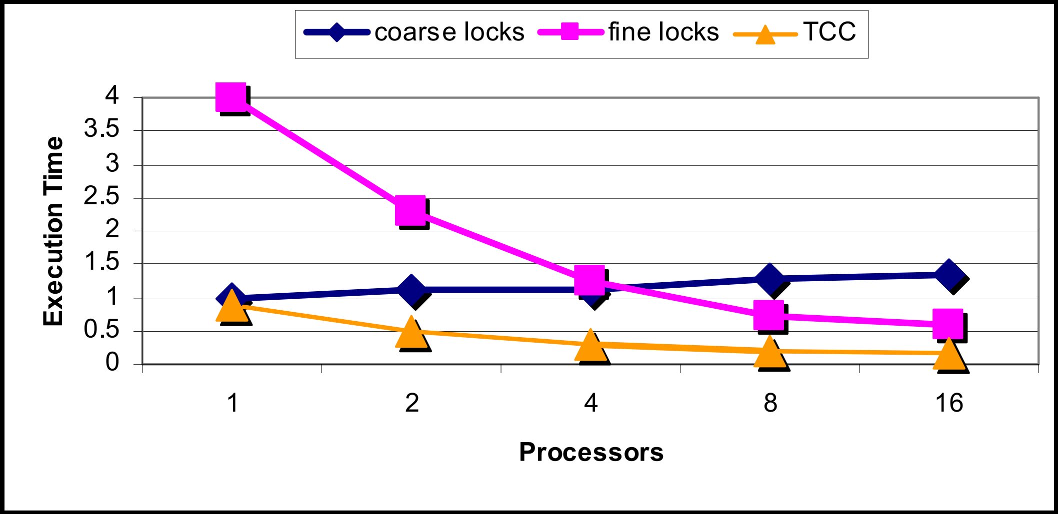

Transactional Memory Benefits

- As easy to use as coarse-grain locks
- Scale as well as fine-grain locks
  - No performance correctness tradeoff
  - Automatic read-read & fine-grain concurrency
- Composition:
  - Safe & scalable composition of software modules
- Failure atomicity & recovery

Does TM help with all the Parallel Programming Issues?

- ☒ Finding independent tasks
- ☒ Mapping tasks to threads
- ☑ Defining & implementing synchronization protocol
- ☑ Race conditions & deadlock avoidance
- ≈ Memory model
- ☑ Composing parallel tasks
- ☒ Portable & predictable performance
- ≈ Scalability
- ☒ Locality management
- ☑ Recovering from errors

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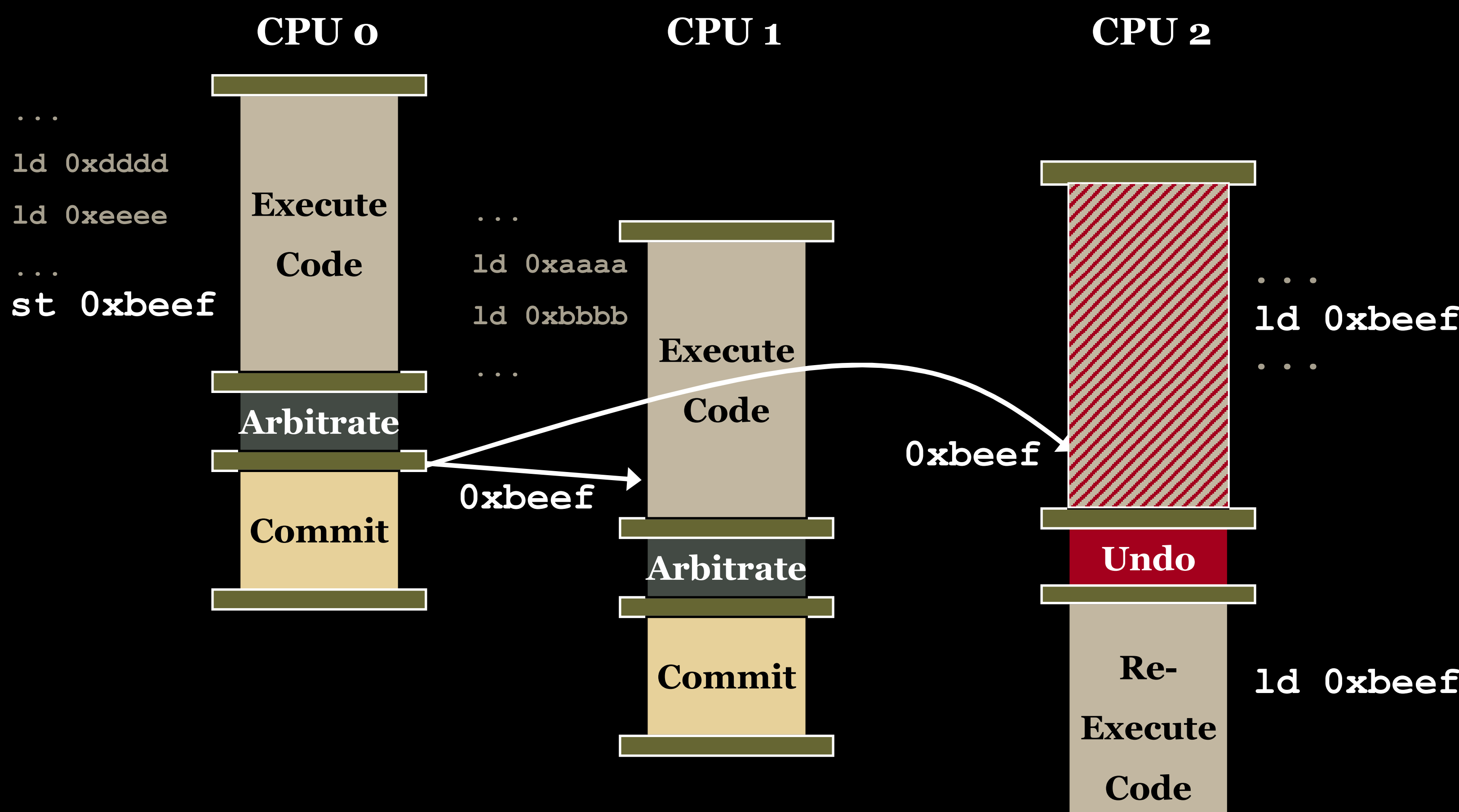
The Stanford Transactional Coherence/Consistency Project

- A hardware-assisted TM implementation
  - Avoids ≥2x overhead of software-only implementation
  - Semantically correct TM implementation
  - Does not require recompilation of base libraries
- A system that uses TM for coherence & consistency
  - All transactions, all the time
  - Use TM to replace MESI coherence
    - Other proposals build TM on top of MESI
  - Sequential consistency at the transaction level
    - Address the memory model challenge as well
- Research on applications, TM languages,TM system issues, TM architectures, TM prototypes,…

TCC Execution Model



Transactional coherence/consistency with non-blocking guarantees

See [ISCA'04] for details

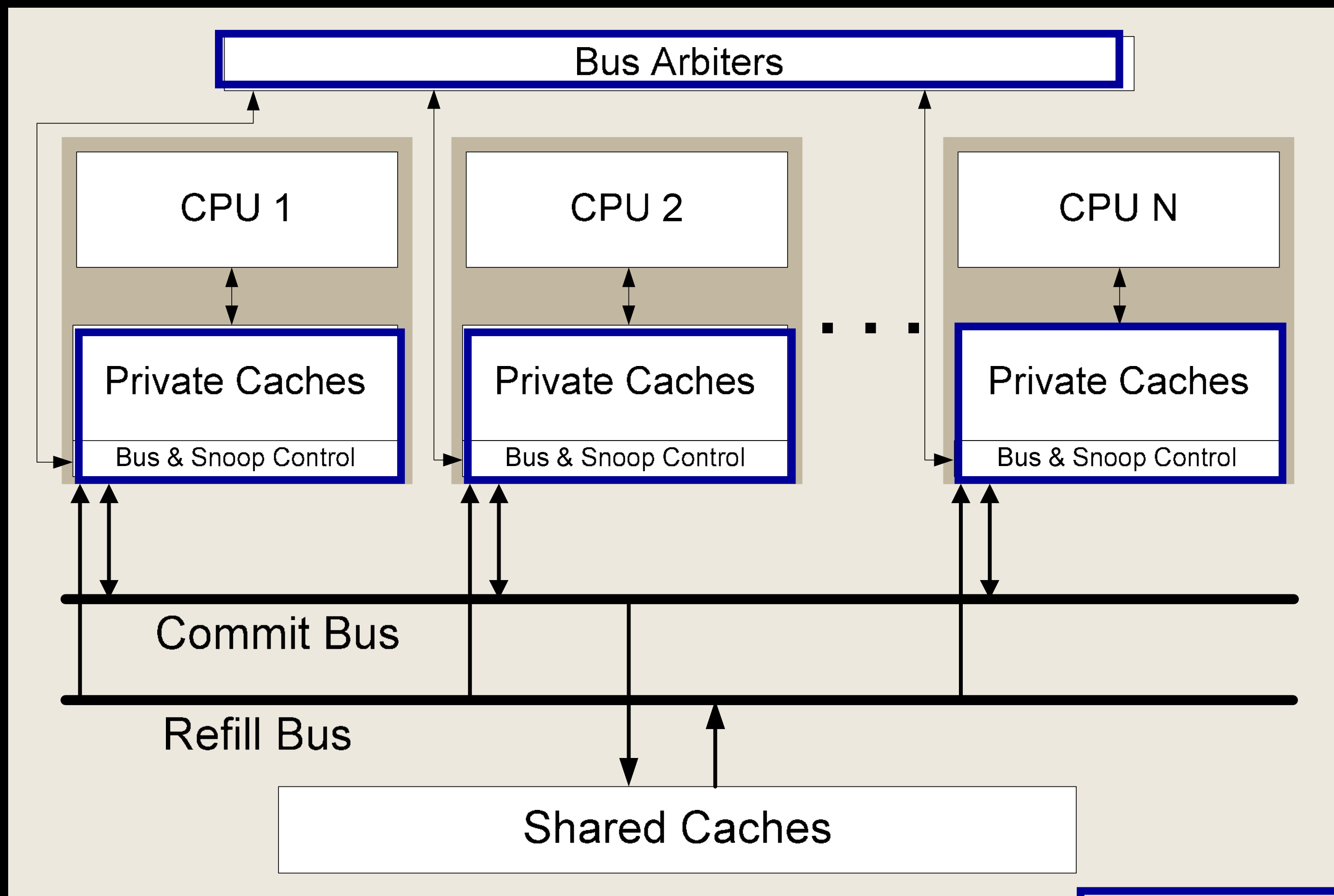
TCC Implementation

- TM implementation requirements
  - Manage multiple data versions <u>atomic commit</u> or <u>abort</u>
  - Track read-set and write-set for <u>conflict detection</u>

- TCC implementation approach
  - Lazy version management using cache as write buffer
    - Transaction updates merge with memory at commit
    - Good fault tolerance & faster aborts compared to eager
  - Optimistic conflict detection
    - Detect conflicts when one transaction commits
    - Built-in forward progress guarantees
  - Commit also implements coherence/consistency

See [PACT'06] tutorial for alternatives

Example CMP Environment



TCC support

Similar implementations for other CMP, SMP, cc-NUMA systems

CMP Architecture for TCC

Transactionally Read Bits:

`ld 0xdeadbeef`

Transactionally Written Bits:

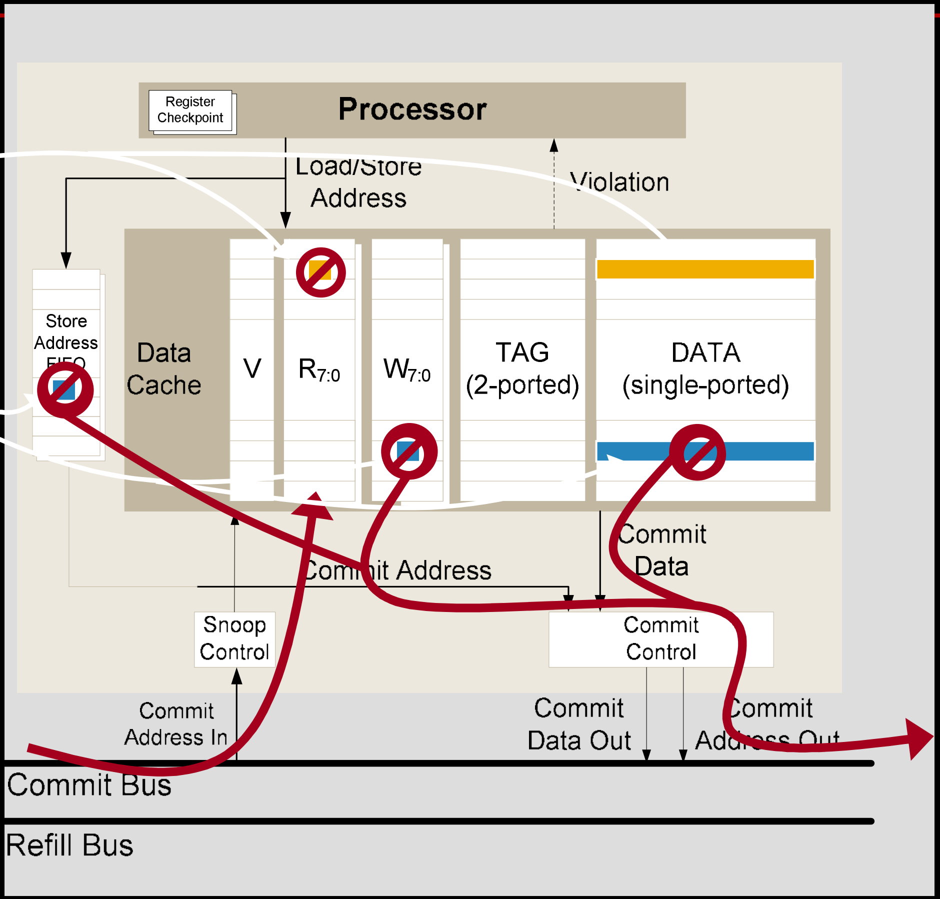
`st 0xcafebabe`

Commit:

Read pointers from Store Address FIFO, flush addresses with W bits set

Violation Detection:

Compare incoming address to R bits



Other implementations

See [PACT'05] for details

- Write-back, multi-level caches, directory-based with 2-phase commit
- Hybrid HW/SW approach

Virtualization of TCC Hardware [ASPLOS'06]

- Key observation: most transactions are small
  - They fit easily in L1 and L2 caches (see [HPCA'06])
- Space virtualization (cache overflow)
  - Switch to OS-based TM using virtual memory
    - Page-granularity, copies/diffs for versioning and conflicts
    - Transactions can use HW, OS, or both
  - Can handle overflows and paging
- Time virtualization (interrupts, quanta expiration)
  - Short transactions are aborted (faster than virtualization)
  - Interrupts deferred till next transaction commits
    - Otherwise, abort an transaction & reuse

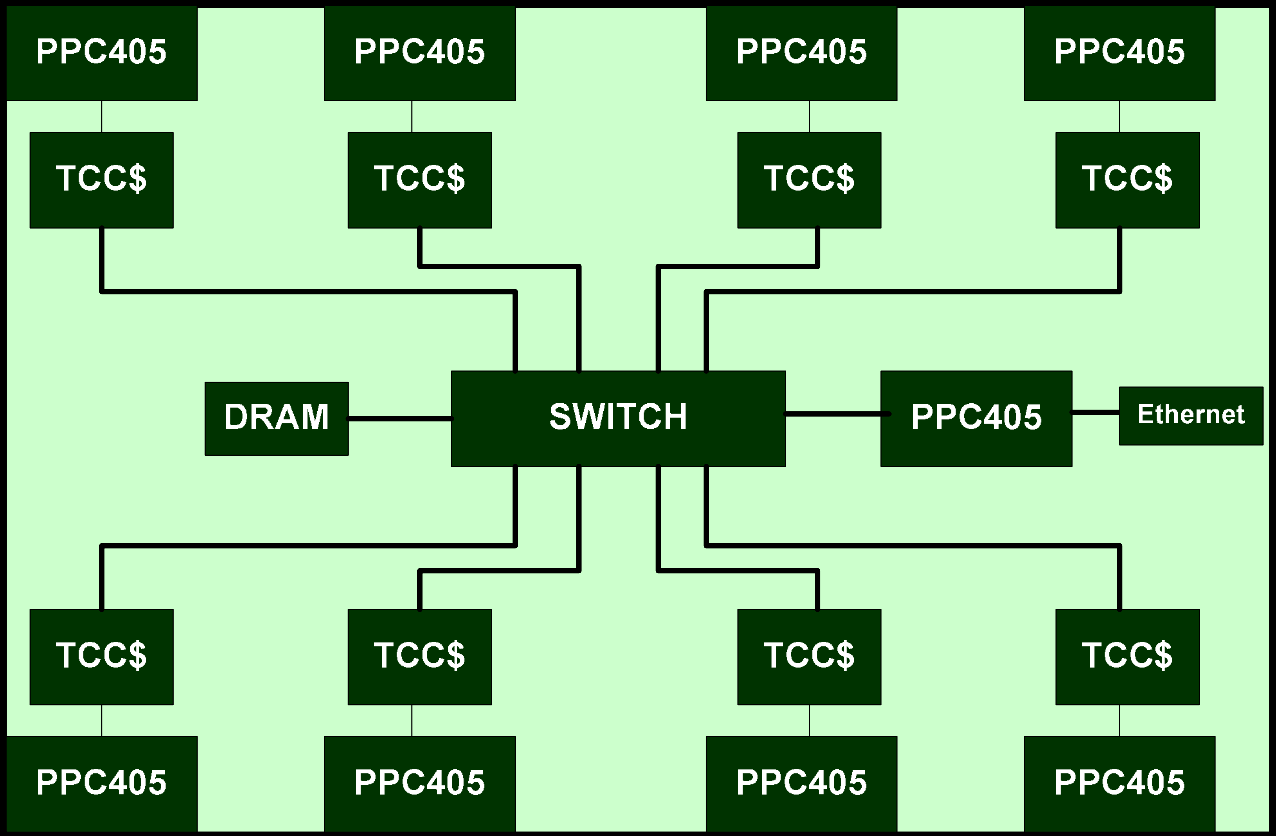
Support for PL & OS Functionality [ISCA'06]

- Challenging issues
  - Interaction with library-based software, I/O, exceptions, & system calls within transactions, error handling, schedulers, conditional synchronization, memory allocators, …
- Defined complete TM semantics at the ISA level
  - Two-phase commit
  - Transactional handlers for commit/abort/violations
    - All interesting events switch to software handlers
  - Nested transactions (closed and open)
    - Closed: independent rollback & restart for nested transactions
    - Open: independent atomicity and isolation for nested transactions
- Demonstrate TM interaction with rich PL & OS functionality
  - See [ISCA'06] and [PLDI'06] for details

TM Programming with TCC

- Basic approaches
  - Sequential algorithms: use TM for thread-level speculation
  - Parallel algorithm: use TM for non-blocking synchronization
- C-based programming
  - OpenMP extensions for transactional programming
  - Familiar, high-level model for C programmers
- Java-based programming with Atomos [PLDI'06]
  - Replaces synchronized and volatile with atomic
  - Transaction-based conditional waiting
    - Removed wait, notify, and notifyAll
    - Watch sets for efficient implementation
  - Nested transactions, violation handlers, …
- Other work
  - Performance feedback & tuning environment [ICS'05]
  - TM programming with Python

ATLAS: the 1st TM Hardware Prototype



- 8-core TCC system on BEE2 board (aka RAMP-Red)
  - 100MHz; runs Linux OS
  - 100x faster than a simulator

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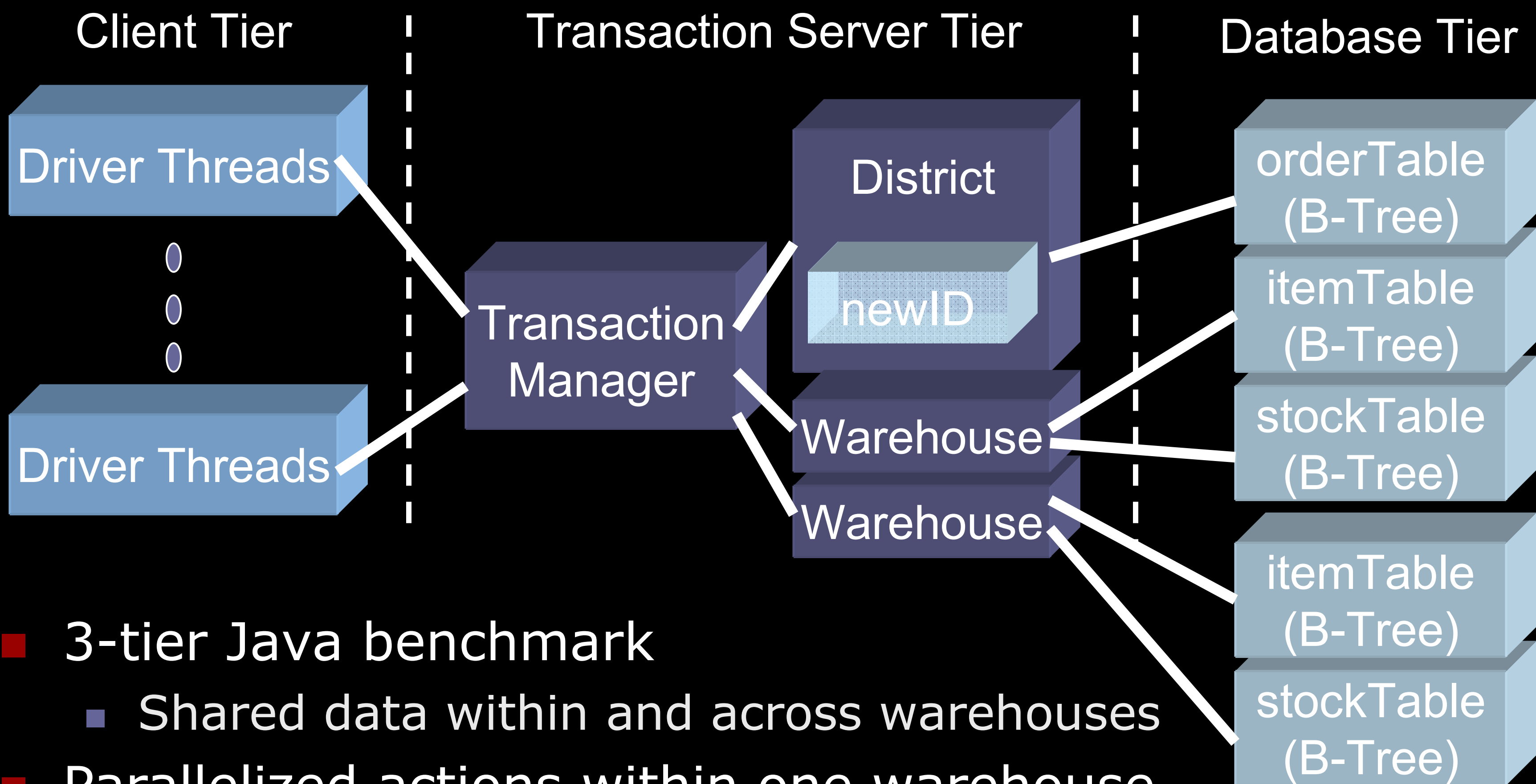
TM Example: SPECjbb2000



- 3-tier Java benchmark
  - Shared data within and across warehouses
- Parallelized actions within one warehouse
  - Orders, payments, delivery updates, etc on shared data

Sequential Code for NewOrder

```
TransactionManager::go() {
      // 1. initialize a new order transaction
      newOrderTx.init();
      // 2. create unique order ID
      orderId = district.nextOrderId(); // newID++
      order = createOrder(orderId);
      // 3. retrieve items and stocks from warehouse
      warehouse = order.getSupplyWarehouse();
      item = warehouse.retrieveItem();   // B-tree search
      stock = warehouse.retrieveStock(); // B-tree search
      // 4. calculate cost and update node in stockTable
      process(item, stock);
      // 5. record the order for delivery
      district.addOrder(order); // B-tree update
      // 6. print the result of the process
      newOrderTx.display();
}
```

- Non-trivial code with complex data-structures
  - Fine-grain locking ➔ difficult to get right
  - Coarse-grain locking ➔ no concurrency

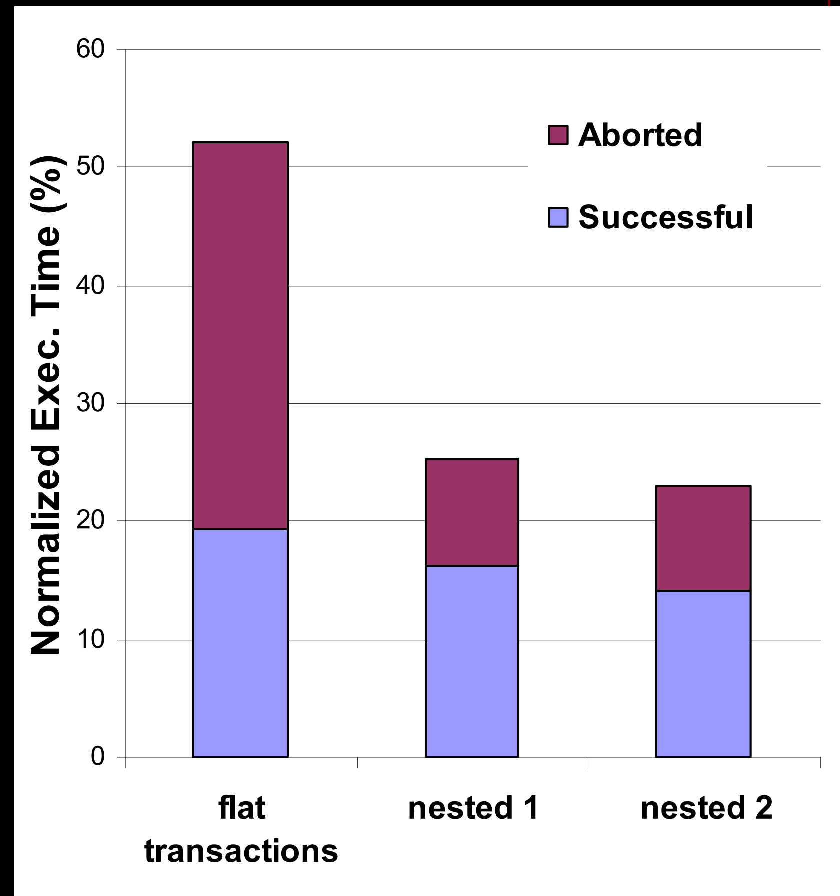
TM Code for NewOrder

```
TransactionManager::go() {
    atomic { // begin transaction
        // 1. initialize a new order transaction
        // 2. create a new order with unique order ID
        // 3. retrieve items and stocks from warehouse
        // 4. calculate cost and update warehouse
        // 5. record the order for delivery
        // 6. print the result of the process
    } // commit transaction
}
```

- Whole NewOrder as one atomic transaction
  - 2 lines of code changed
- Also tried nested transactional versions
  - To reduce frequency & cost of violations
  - 2 to 4 additional lines of code

TM Performance for SpecJBB2000

- Simulated TM CMP
  - Stanford's TCC architecture
- Speedup over sequential
  - Flat transactions: 1.9x
    - Code similar to coarse locks
    - Frequent aborted transactions due to dependencies
  - Nested transactions: 3.9-4.2x
    - Reduced abort cost OR
    - Reduced abort frequency
- See [WTW'06] for details



Conclusions

- Transactional Memory (TM)
  - Simple code that scales well on parallel systems
  - Easy to compose, fault recovery, …
- Transactional Coherence and Consistency
  - An efficient hardware-based TM
  - Uses TM to provide coherence & consistency model
- Current research focus
  - Hybrid & scalable TM implementations
  - Language and application development work
  - Operating system and error recovery support
  - System-level transactions

Questions?

- Further information and papers available at

http://tcc.stanford.edu