Synchronization on Multi-Core CPUs

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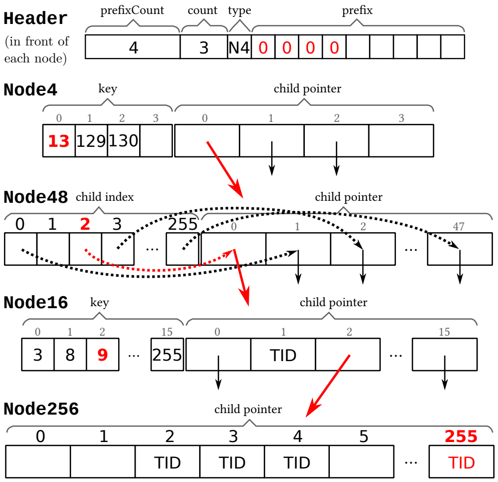
Introduction

- this course focuses on high-level concurrency control protocols (logical transaction isolation)
- any implementation of these protocols must also deal with low-level synchronization (thread safety)
- many data structures must thread-safe: index structures, tuple storage, job queues, buffer management data structures, etc.
- low-level synchronization often decides how well a program scales on multi-core CPUs

Case Study: The Adaptive Radix Tree (ART)

- order-preserving index for in-memory database systems
- originally designed for high single-threaded performance



Lock Coupling

- very easy to apply to ART
- modifications only change 1 node and (sometimes) its parent
- can use read/write locks to allow for more concurrency

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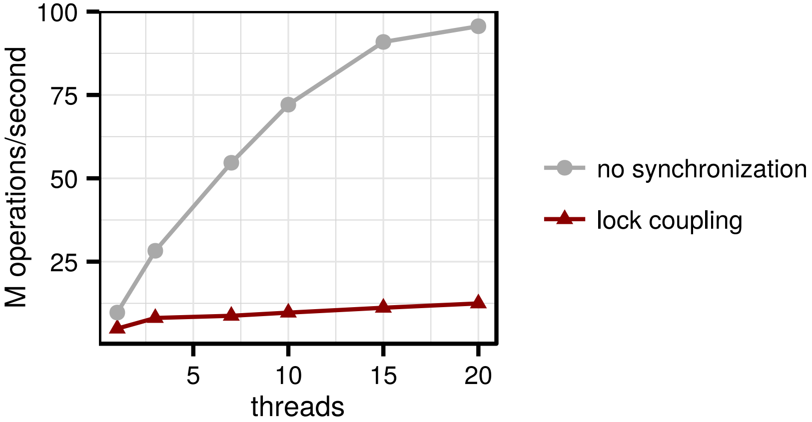
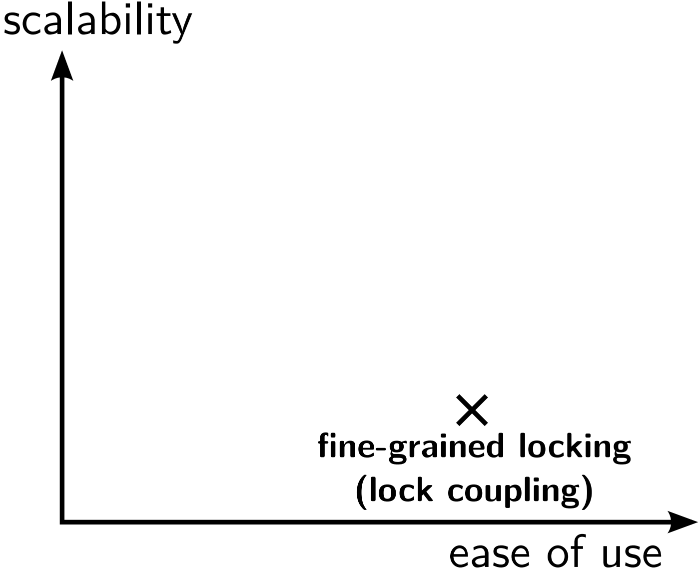
  readLock(node)
  if parent != null
    unlock(parent)
  // check if prefix matches, may increment level
  if !prefixMatches(node, key, level)
    unlock(node)
    return null  // key not found
  // find child
  nextNode = node.findChild(key[level])
  if isLeaf(nextNode)
    value = getLeafValue(nextNode)
    unlock(node)
    return value  // key found
  if nextNode == null
    unlock(node)
    return null  // key not found
  // recurse to next level
  return lookup(key, nextNode, level+1, node)
```

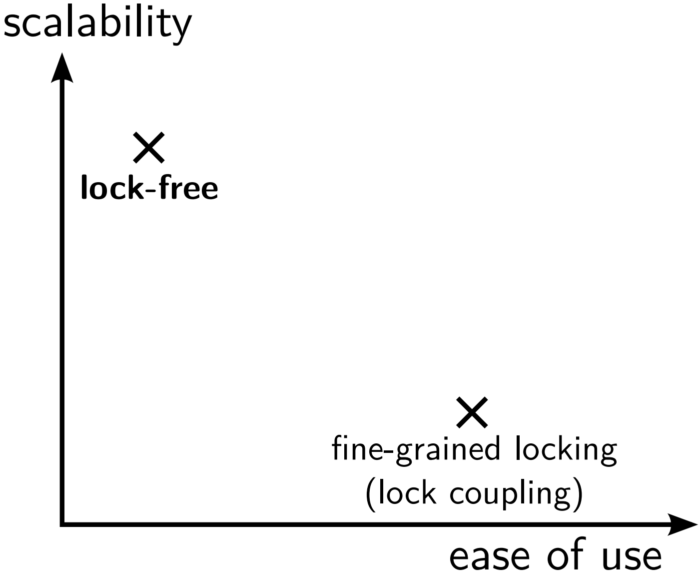
Performance of Lock Coupling




scalability
fine-grained locking
(lock coupling)
ease of use

Lock-free ART?

- non-blocking data structures are extremely difficult to design, to implement, and to debug
- every non-trivial lock-free data structure is a research contribution
- non-blocking data structures add significant overhead
  - Bw-tree: extra delta records in front of each node
  - Split-ordered list (state-of-the-art lock-free hash table): dummy nodes
- a hypothetical lock-free ART variant would
  - require significant changes to the data structure (path compression is a major issue)
  - likely be slower than the methods presented in the following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Hardware Transactional Memory

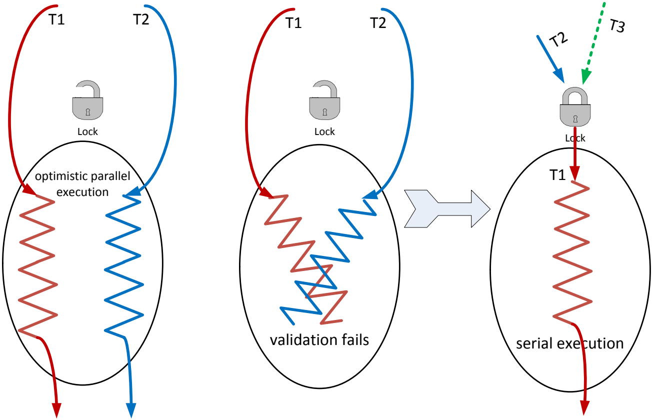
- Intel's Haswell microarchitecture introduced hardware support in mainstream CPUs
- (only guarantees in-memory atomicity and isolation, but not durability)

Interface to HTM: Intel Transactional Synchronization Extensions (TSX)

- Restricted Transactional Memory (RTM):
  - XBEGIN: begin
  - XEND: commit
  - XABORT: rollback
- Hardware Lock Elision (HLE):
  - XACQUIRE prefix: "acquire" lock speculatively
  - XRELEASE prefix: release lock speculatively
  - prefix is ignored on older CPUs

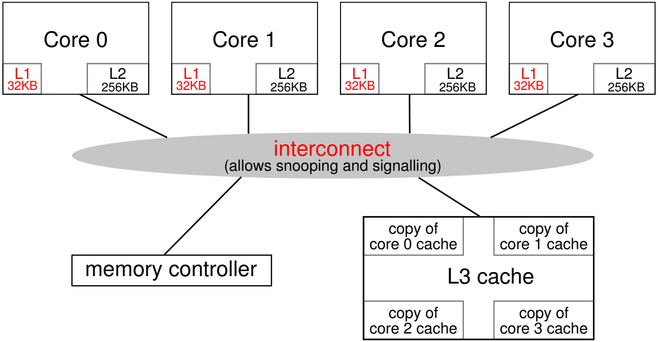
Hardware Lock Elision

- elide lock on first try optimistically
- start HTM transaction instead
- if a conflict happens, the lock is actually acquired



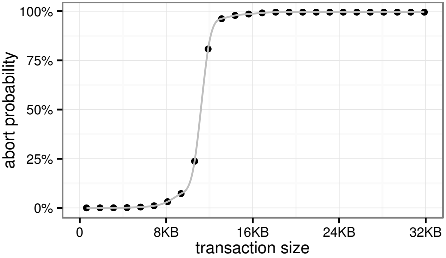
How Does the CPU implement HTM?

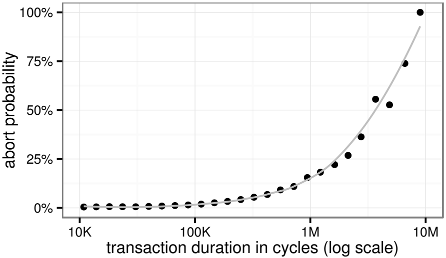
- local L1 cache (32KB) serves as a buffer for transactional writes and for tracking transactional reads at cache line granularity (64 bytes)
- cache coherency protocol is used to detect conflicts



Limitations of Haswell's HTM

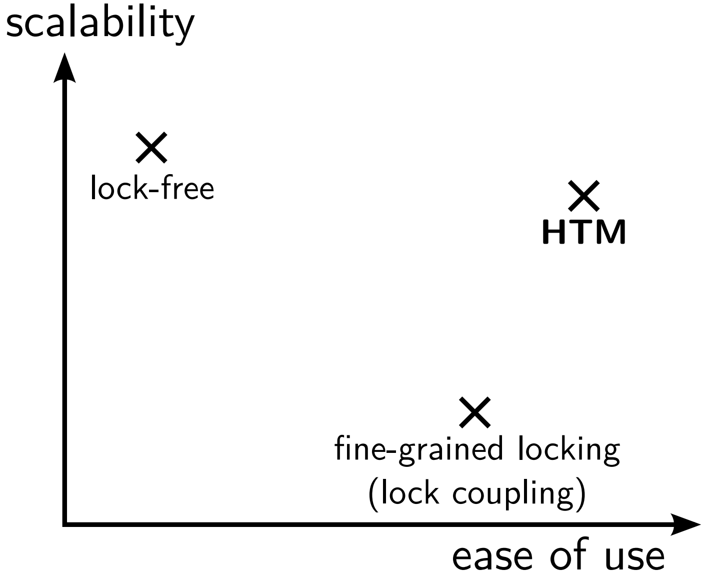
- size (32KB) and associativity (8-way) of L1 cache limit transaction size
- interrupts, context switches limit transaction duration
- certain (rarely used) instructions always cause abort





Hardware Transactional Memory (HTM)

+ very easy to use (with coarse-grained, elided locks)
+ often scales well
− requires special (not yet widespread) hardware support
− sometimes hard to predict/debug behavior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Optimistic Lock Coupling (1)

- add lock and version to each node
- write:
  - acquire lock (exclude other writers)
  - increment version when unlocking
  - do not acquire locks for nodes that are not modified (traverse like a reader)
- read:
  - do not acquire locks, proceed optimistically
  - detect concurrent modifications through versions (and restart if necessary)
  - can track changes across multiple nodes (lock coupling)

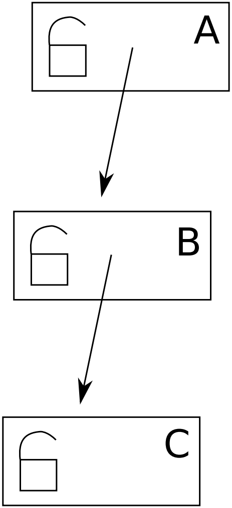
Optimistic Lock Coupling (2)

traditional **optimistic**

1. lock node A
2. search node A

3. lock node B
4. unlock node A
5. search node B

6. lock node C
7. unlock node B
8. search node C
9. unlock node B



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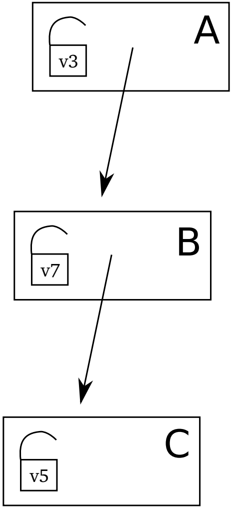

Optimistic Lock Coupling (2)

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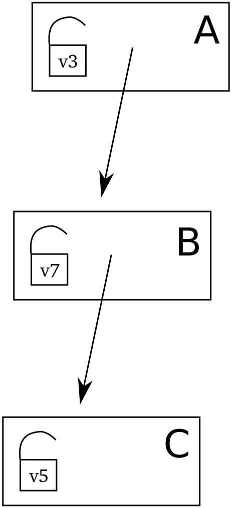

optimistic

1. read version v3
2. search node A

Optimistic Lock Coupling (2)

traditional

1. lock node A
2. search node A
3. lock node B
4. unlock node A
5. search node B
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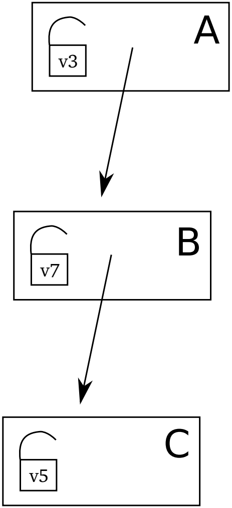


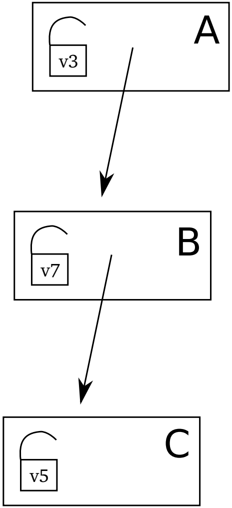
optimistic

1. read version v3
2. search node A
3. read version v7
4. re-check version v3
5. search node B

Optimistic Lock Coupling (2)

traditional

1. lock node A
2. search node A
3. lock node B
4. unlock node A
5. search node B
6. lock node C
7. unlock node B
8. search node C
9. unlock node B



optimistic

1. read version v3
2. search node A
3. read version v7
4. re-check version v3
5. search node B
6. read version v5
7. re-check version v7
8. search node C
9. re-check version v5

Optimistic Lock Coupling (3)

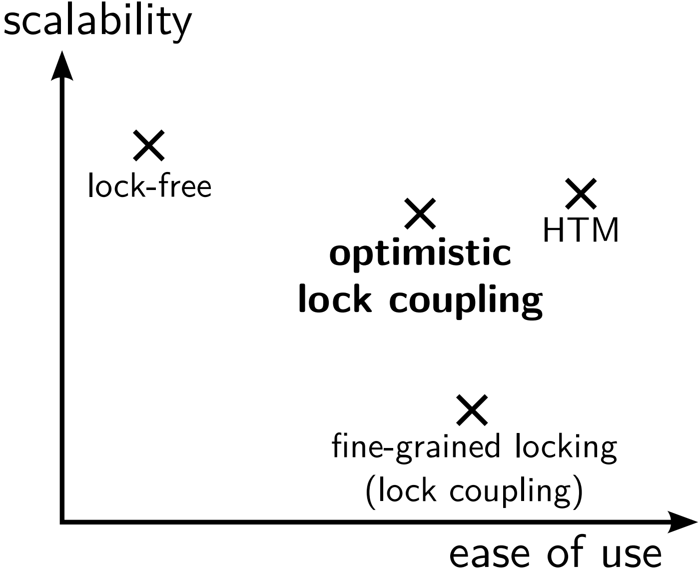
```
lookup(key, node, level, parent)
   readLock(node)
   if parent != null
      unlock(parent)
   // check if prefix matches, may increment level
   if !prefixMatches(node, key, level)
      unlock(node)
      return null  // key not found
   // find child
   nextNode = node.findChild(key[level])

   if isLeaf(nextNode)
      value = getLeafValue(nextNode)
      unlock(node)
      return value  // key found
   if nextNode == null
      unlock(node)
      return null  // key not found
   // recurse to next level
   return lookup(key, nextNode, level+1, node)
```

```
lookupOpt(key, node, level, parent, versionParent)
   version = readLockOrRestart(node)
   if parent != null
      readUnlockOrRestart(parent, versionParent)
   // check if prefix matches, may increment level
   if !prefixMatches(node, key, level)
      readUnlockOrRestart(node, version)
      return null  // key not found
   // find child
   nextNode = node.findChild(key[level])
   checkOrRestart(node, version)
   if isLeaf(nextNode)
      value = getLeafValue(nextNode)
      readUnlockOrRestart(node, version)
      return value  // key found
   if nextNode == null
      readUnlockOrRestart(node, version)
      return null  // key not found
   // recurse to next level
   return lookupOpt(key, nextNode, level+1, node, version)
```

Optimistic Lock Coupling (4)

+ can easily be applied to most data structures (no modifications necessary)
+ scales well
+ low overhead
− can lead to (unnecessary) aborts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Read-Optimized Write EXclusion (ROWEX) (1)

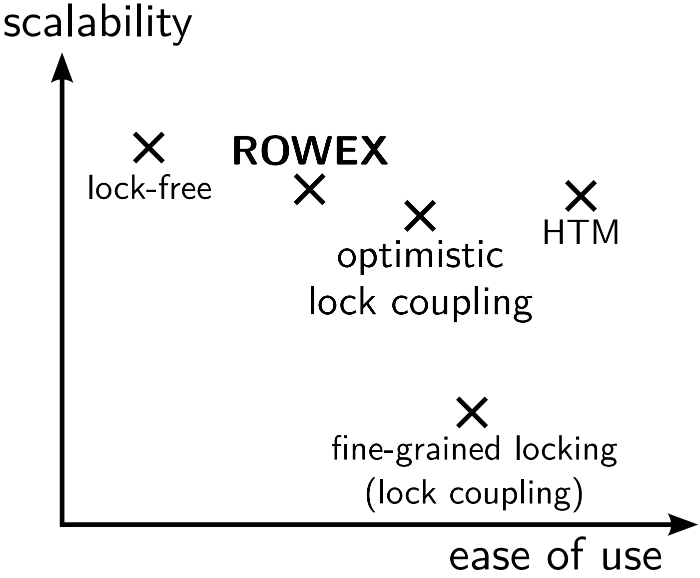
- add lock to each node
- write:
  - acquire lock (excludes writers)
  - make sure than any modification leaves the tree in a state safe for readers
- read:
  - simply proceed without observing locks or versions

Read-Optimized Write EXclusion (ROWEX) (2)

+ scales well
+ reads are non-blocking (always successful and there are no restarts)
+ easier to implement than lock-free data structures
− more difficult to implement than Optimistic Lock Coupling (requires modifications to the underlying data structure)

Synchronizing ART with ROWEX

- local modifications:
  - make key and child pointer accesses atomic (`std::atomic`)
  - make `Node4` and `Node16` unsorted and append-only
- grow/shrink a node:
  - lock node and its parent
  - create new node and copy entries
  - set parent pointer to the new node
- path compression:
  - modify prefix atomically
  - add `level` field to each node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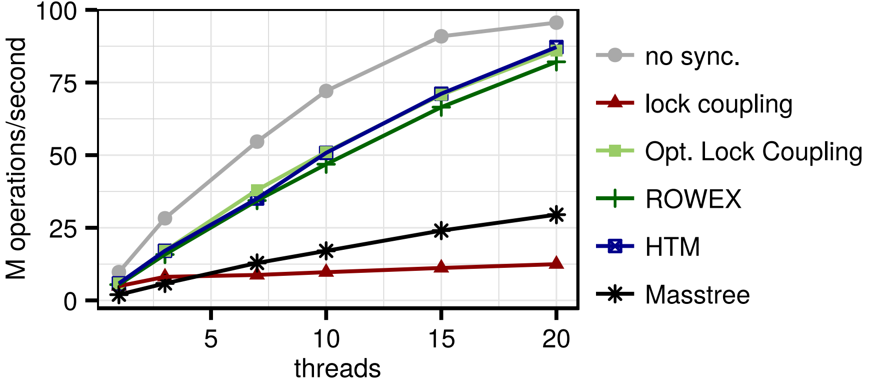
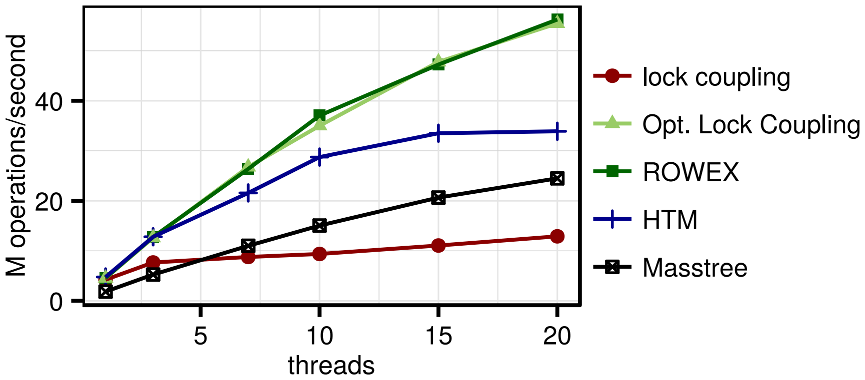
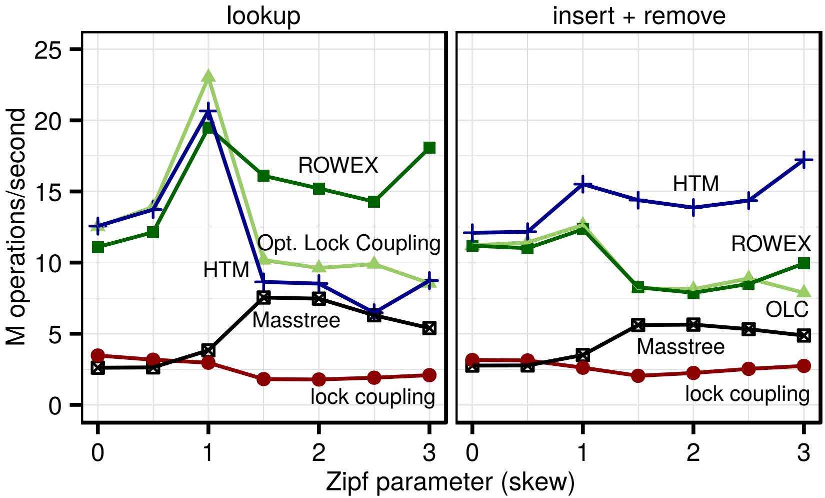
Lookup (50M 8B Integers)



Insert (50M 8B Integers)



Lookup/Insert/Remove the Same Key (High Contention, 2 threads)



Summary

- traditional fine-grained locking does not scale for tree-like index structures
- locks are fine if they are only acquired by writers and only on nodes that are modified
- Optimistic Lock Coupling is a highly practical alternative to the lock-free paradigm

Source: `https://github.com/flode/ARTSynchronized`

Paper: `http://db.in.tum.de/~leis/papers/artsync.pdf`