Understanding Hardware Transactional Memory

Gil Tene, CTO & co-Founder, Azul Systems
@giltene

Agenda

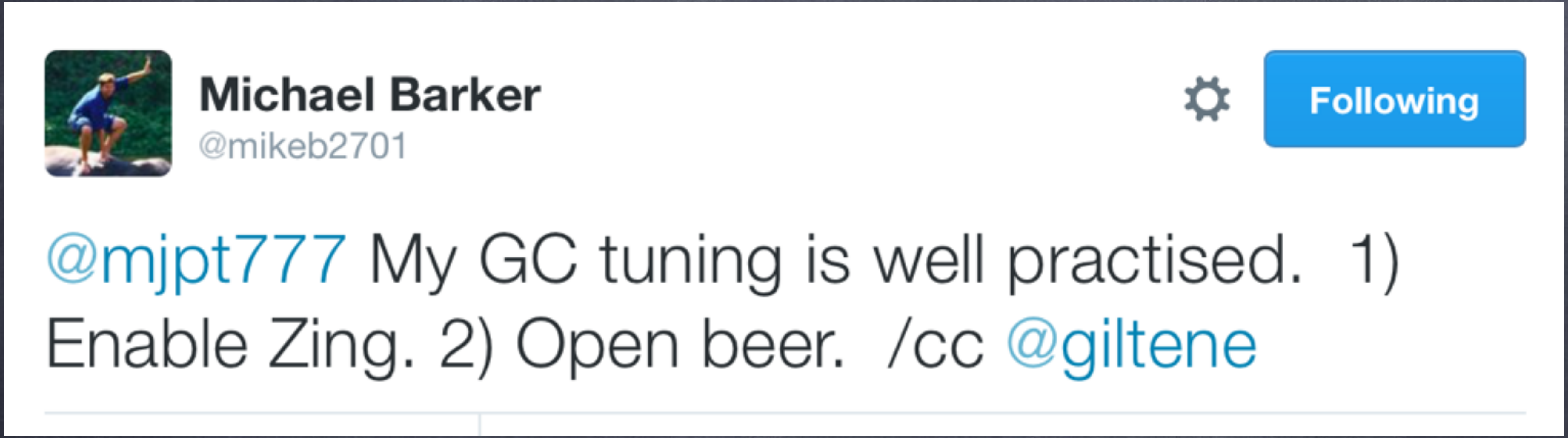
- Brief introduction
- What is Hardware Transactional Memory (HTM)?
- Cache coherence basics & how HTM works
- What it looks like from a runtime point of view
- Interesting coding considerations

About me: Gil Tene

- co-founder, CTO @Azul Systems
- Have been working on "think different" GC and runtime approaches since 2002
- Built world's 1st commercially shipping HTM system, along with JVM support for HTM
- A Long history building Virtual & Physical Machines, Operating Systems, Enterprise apps, etc...
- I also depress people by demonstrating how terribly wrong their latency measurements are…

* working on real-world trash compaction issues, circa 2004

As far as I am concerned GC is a solved problem



Michael Barker
@mikeb2701

@mjpt777 My GC tuning is well practised. 1) Enable Zing. 2) Open beer. /cc @giltene

Why does HTM matter now?

- Because it is (finally) here!
- HTM already available in the past
  - e.g. Azul Vega, since 2004
  - e.g. some later variants of Power architecture
  - e.g. some designs for SPARC
- But it is now here in commodity server chips
  - Intel TSX, on modern Intel Xeons
  - Already in E7-V3 (4+ sockets), E3-V4, E3-V5 (1 socket)
  - Coming (1H2016) in E5-26xx V4 (“Broadwell") chips
  - Most new servers will have HTM by 2H2016

What is HTM?

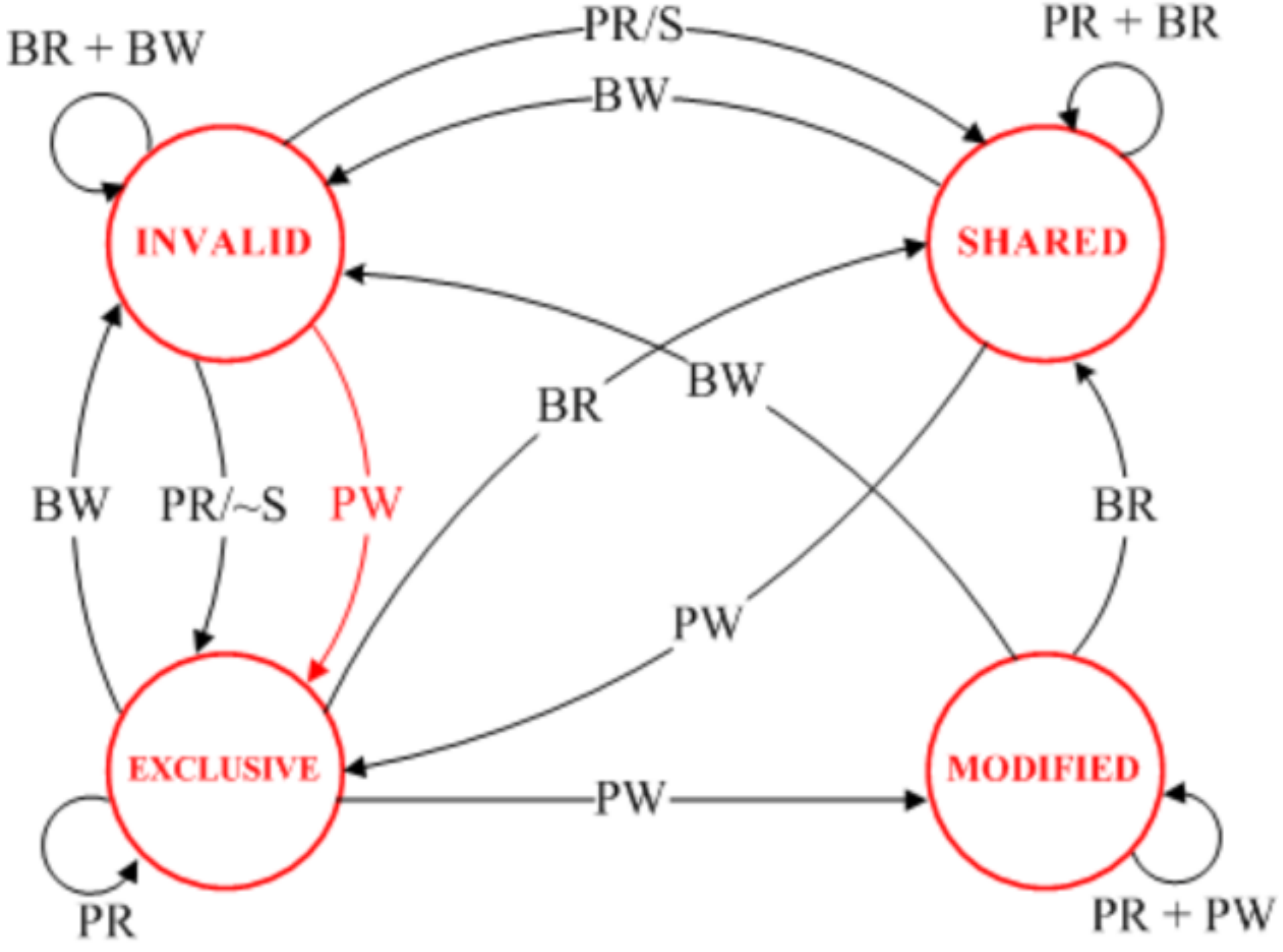
What is HTM?

(For the kind of HTM I will be talking about…)

- Can be thought of as "Speculative Multi-Address Atomicity"
- Transaction starts and ends with explicit instructions
- No special load or store instructions
- All memory operations in a successfully completed transaction appear to execute atomically (to other threads)
- Transactions may abort. All memory operations in an aborted transaction appear "to have never happened"

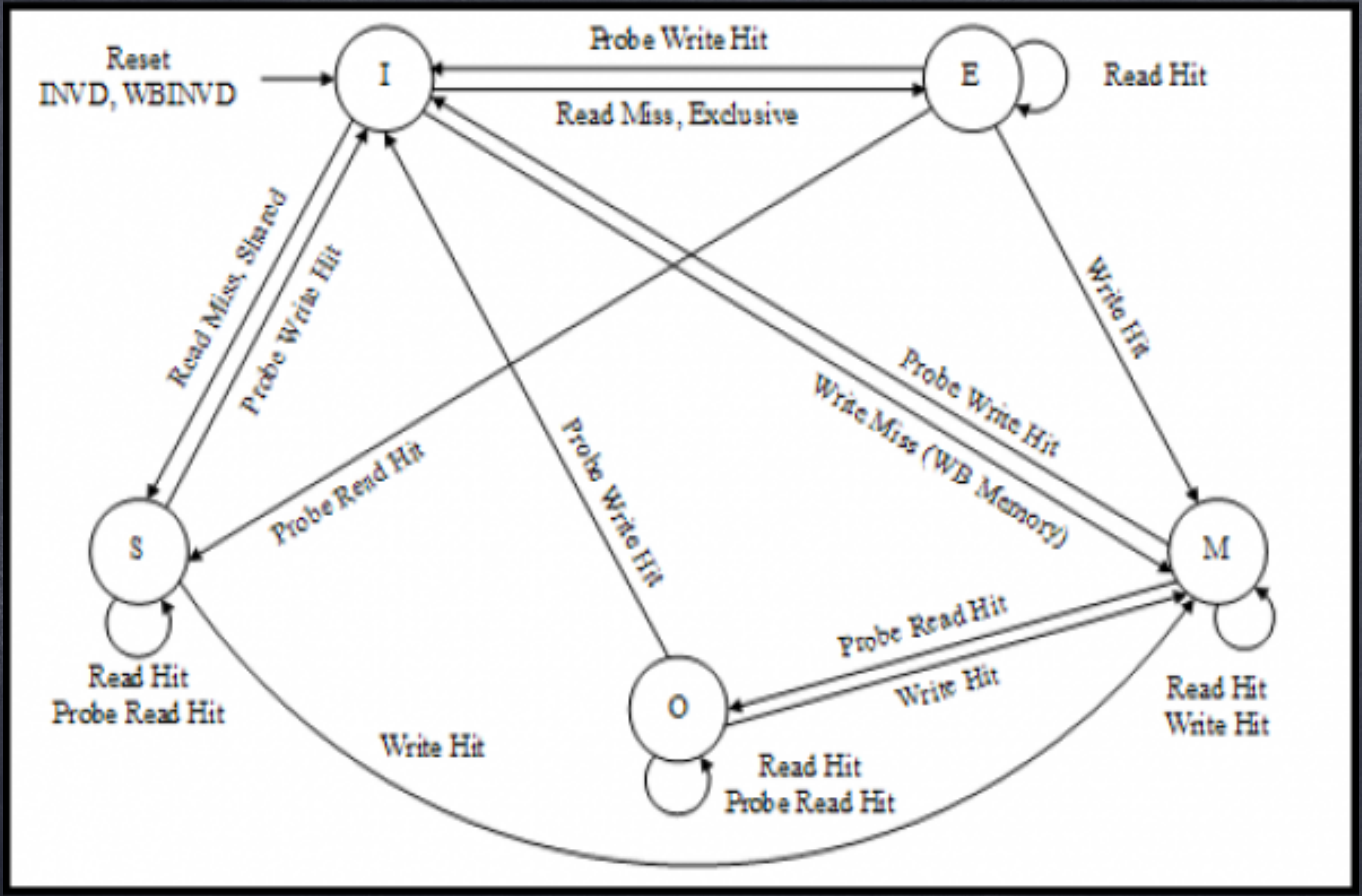
Cache Coherence

Protocols can be messy



PR = processor read
PW = processor write
S/~S = shared/NOT shared

BR = observed bus read
BW = observed bus write


Reset
INVD, WBINVD
I
Probe Write Hit
Read Miss, Exclusive
E
Read Hit
Read Miss, Shared
Probe Write Hit
Write Hit
Probe Write Hit
Write Miss (WB Memory)
Probe Read Hit
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M
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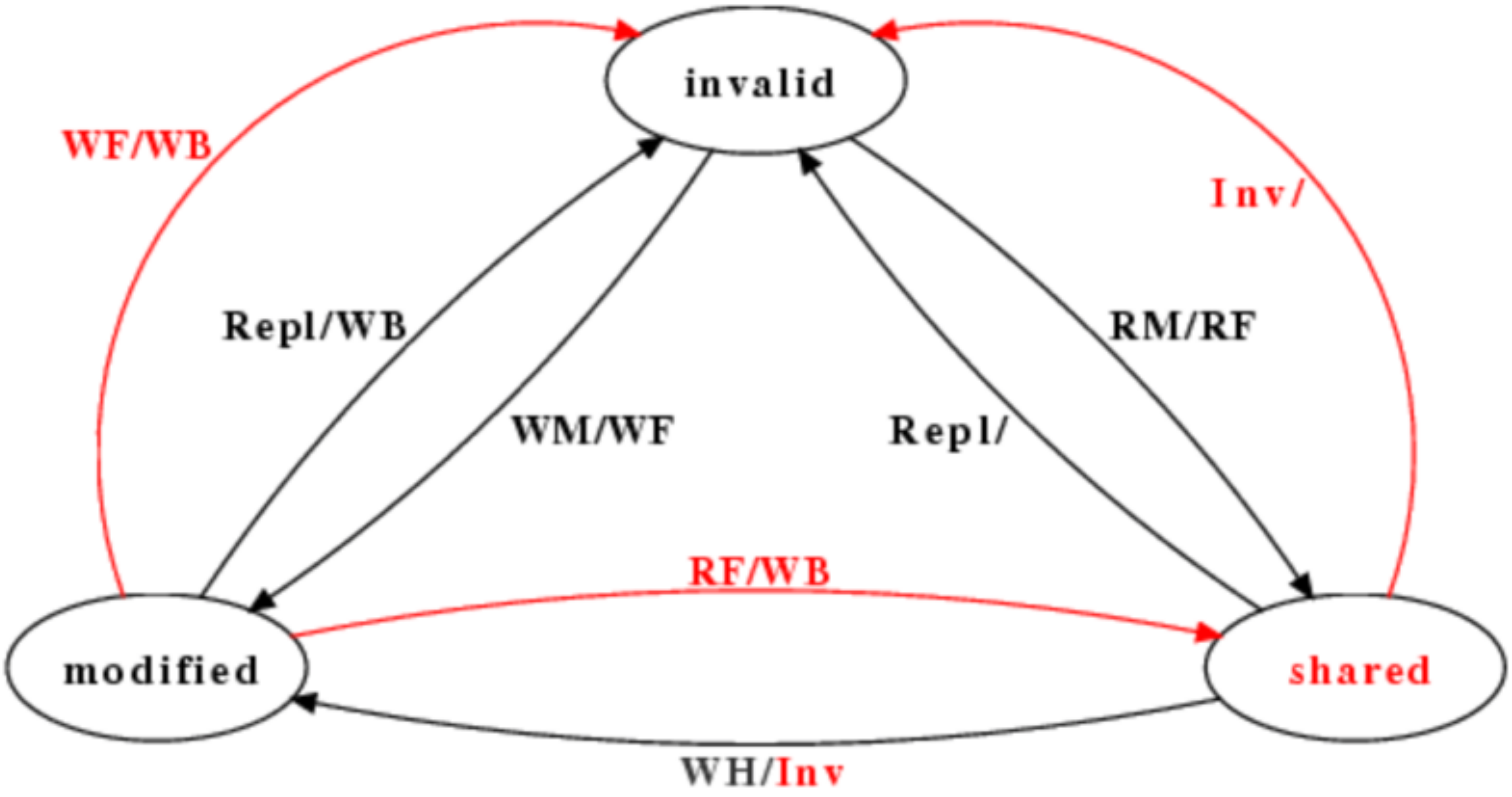
Probe Read Hit



MSI Coherence Protocol States and Transitions

But conceptually it’s not that messy…

Cache line state from an individual CPU's point of view

I
- I don't have it
  (Invalid)

S
- I have a copy (and someone else may, too)
  (Shared)

E
- I have the only copy
  (Exclusive)

M
- I have the only copy, and I've changed it
  (Modified)

Cache line state from an individual CPU’s point of view

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HTM builds on existing cache coherence

Conceptual cache line state additions for HTM

- Line was accessed during speculation:
  - Line was read from during speculation
  - Line was modified during speculation
- When transaction completes, clear all speculation tracking state
- Losing track of a line that was accessed during speculation aborts the transaction
- Aborts invalidate speculatively modified lines

What can make the cache "lose track" of a line?

- Another CPU wants to write to it
  - Other CPU would need it "exclusive"
  - It would first need to invalidate it in this cache
- Another CPU wants to read from it
  - Cache line would need to be in "shared" state here
  - If it were in speculatively modified state: abort
- Capacity related self-eviction
  - E.g. current Xeons: 32KB, 8 way set associative

That’s it…. For memory.

CPU state. E.g. Intel TSX

- In addition to memory transactionality, CPU architectural state is maintained
    - On abort, PC moves to location provided in XBEGIN
    - EAX is changed to indicate abort information
    - All other architecture state remains the same as it was before XBEGIN was executed

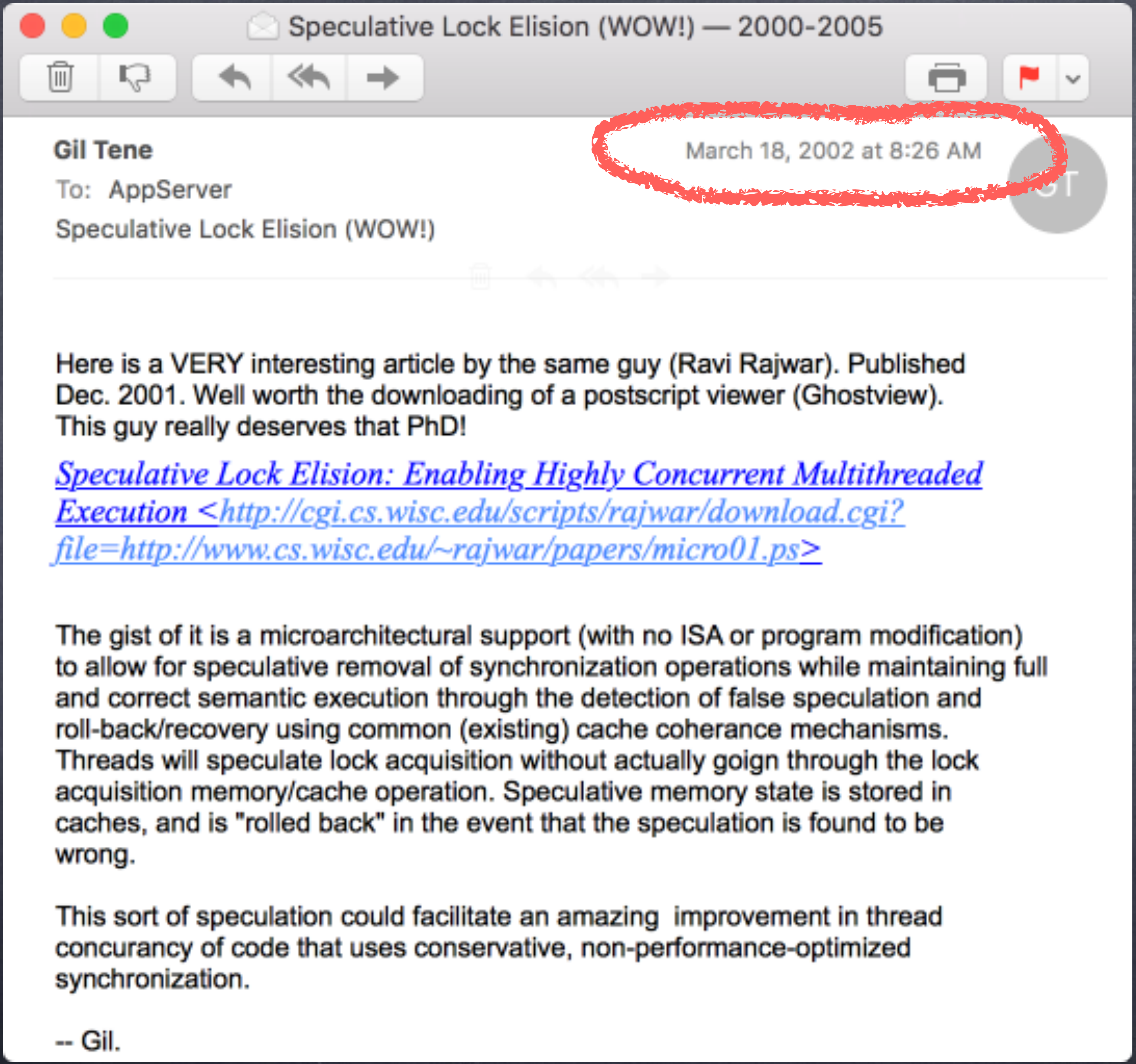
So when can you do with HTM?

Well, transact on memory, of course…

Speculative Lock Elision

2001 PhD. thesis by Ravi Rajwar

** An independent work on a somewhat similar lock serialization avoidance concept by Jose F. Martinez and Josep Torrellas, UIUC, also published in 2001



Speculative Lock Elision (WOW!) — 2000-2005

Gil Tene

March 18, 2002 at 8:26 AM

To: AppServer

Speculative Lock Elision (WOW!)

Here is a VERY interesting article by the same guy (Ravi Rajwar). Published Dec. 2001. Well worth the downloading of a postscript viewer (Ghostview). This guy really deserves that PhD!

Speculative Lock Elision: Enabling Highly Concurrent Multithreaded Execution <http://cgi.cs.wisc.edu/scripts/rajwar/download.cgi?file=http://www.cs.wisc.edu/~rajwar/papers/micro01.ps>

The gist of it is a microarchitectural support (with no ISA or program modification) to allow for speculative removal of synchronization operations while maintaining full and correct semantic execution through the detection of false speculation and roll-back/recovery using common (existing) cache coherance mechanisms. Threads will speculate lock acquisition without actually goign through the lock acquisition memory/cache operation. Speculative memory state is stored in caches, and is "rolled back" in the event that the speculation is found to be wrong.

This sort of speculation could facilitate an amazing improvement in thread concurancy of code that uses conservative, non-performance-optimized synchronization.

-- Gil.

Using HTM under the hood in a JVM

A trip down transactional memory lane

Speculative Locking: Breaking the Scale Barrier

UNBOUND COMPUTE™

Gil Tene, VP Technology, CTO

Ivan Posva, Senior Staff Engineer

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Multi-threaded Java Apps can Scale

New JVM capabilities improve multi-threaded application scalability.

How can this affect the way you code?

Speculative locking reduces effects of Amdahl's law

Agenda

Why do we care?

Lock contention vs. Data contention

Transactional execution of `synchronized {…}`

Measurements

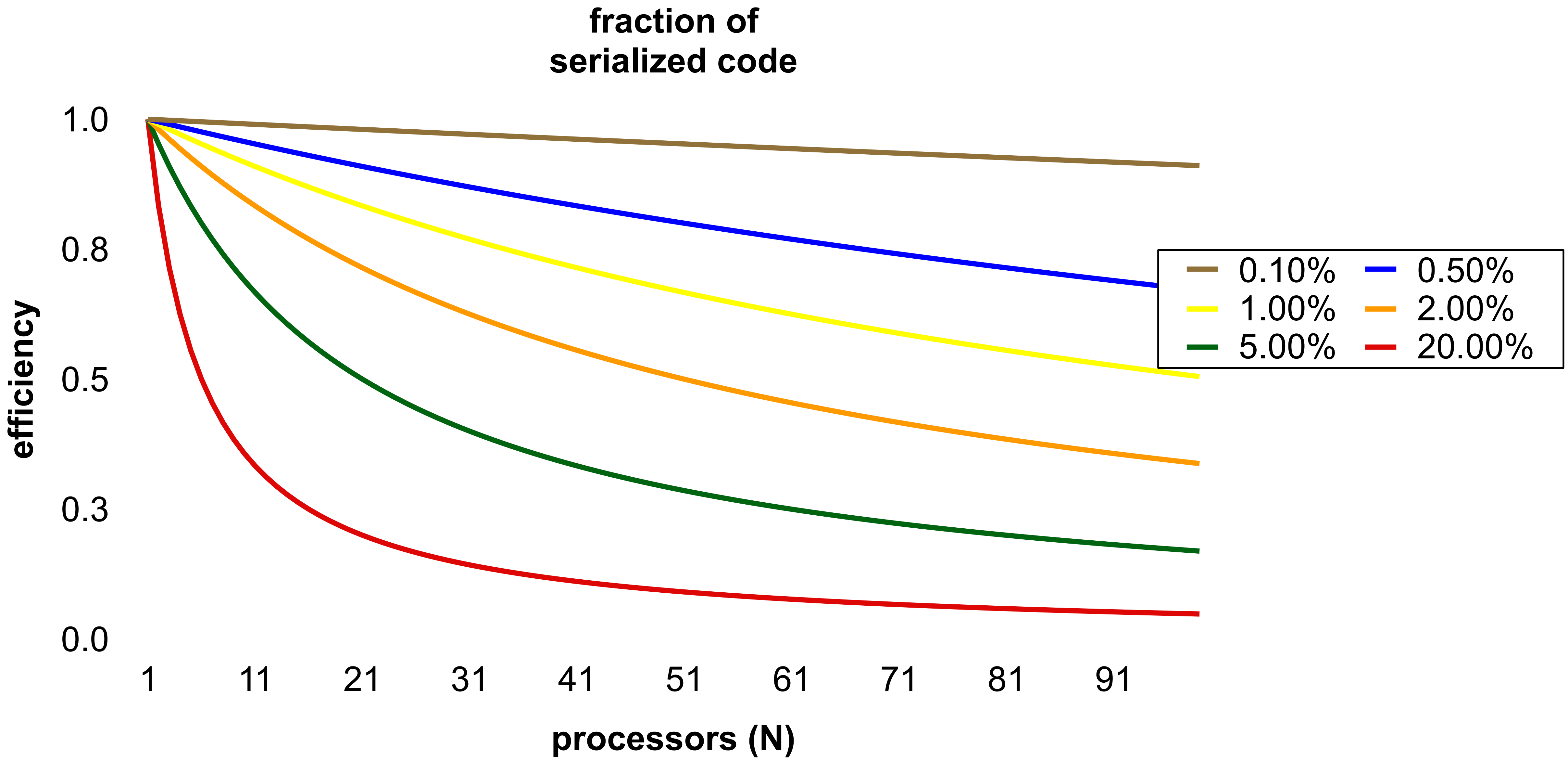
Effects on how you code for contention

Summary

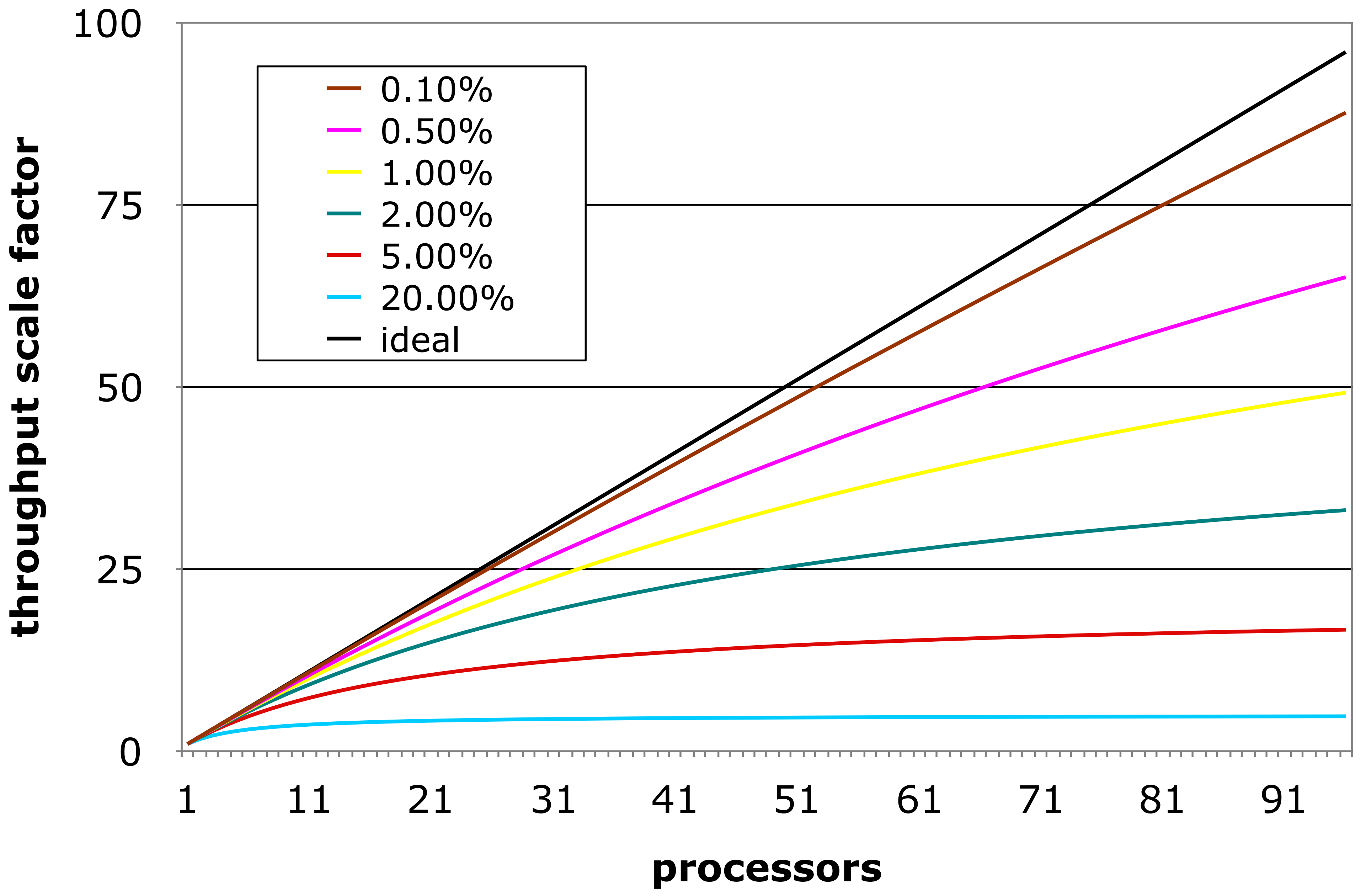
Amdahl's Law

Serialized portions of program limit scale

- efficiency = 1/(N*q + (1-q))
  - N = # of concurrent threads
  - q = fraction of serialized code



Amdahl’s Law Effect on Throughput



Amdahl's Law Example

- The theoretical limit is usually intuitive
  - Assume 10% serialization
  - At best you can do 10x the work of 1 CPU
- Efficiency drops are dramatic and may be less intuitive
  - Assume 10% Serialization
  - 10 CPUs will not scale past a speedup of 5.3x (Eff. 0.53)
  - 16 CPUs will not scale past a speedup of 6.4x (Eff. 0.48)
  - 64 CPUs will not scale past a speedup of 8.8x (Eff. 0.14)
  - 99 CPUs will not scale past a speedup of 9.2x (Eff. 0.09)
  - …
  - It will take a whole lot of inefficient CPUs to [never] reach a 10x

Agenda

Why do we care?

Lock contention vs. Data contention

Transactional execution of `synchronized {…}`

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Lock Contention vs. Data Contention

- Lock contention:

  An attempt by one thread to acquire a lock when another thread is holding it

- Data contention:

  An attempt by one thread to atomically access data when another thread expects to manipulate the same data atomically

Data Contention in a Shared Data Structure

- Readers do not contend
- Readers and writers don’t always contend
- Even writers may not contend with other writers

Synchronization and Locking

Locks are typically very conservative

- Need synchronization for correct execution
  - Critical sections, shared data structures
- Intent is to protect against data contention
- Can't easily tell in advance
  - That's why we lock…
- Lock contention >= Data contention
  - In reality: lock contention >>= Data contention

Database Transactions

The industry has already solved a similar problem

- Semantics of potential failure exposed to the application
- Transactions: atomic group of DB commands
  - All or nothing
  - From “**`BEGIN TRANSACTION`**” to “**`COMMIT`**”
- Data contention results in a rollback
  - Leaves no trace
- Application can re-execute until successful
- Optimistic concurrency does scale

Agenda

Why do we care?

Lock contention vs. Data contention

Transactional execution of **`synchronized {…}`**

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Summary

There is no spoon.

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What does **`synchronized`** mean?

- It does not actually mean:

  grab lock, execute block, release lock

- It does mean:

  execute block atomically in relation to other blocks synchronizing on the same object

- It can be satisfied by the more conservative:

  execute block atomically in relation to all other threads

- That looks a lot like a transaction

"The Java Language Specification", "The Java Virtual Machine Specification", JSR133

Transactional execution of `synchronized {…}`

- Two basic requirements
  - Detect data contention within the block
  - Roll back `synchronized` block on data contention

- `synchronized` can run concurrently
  - JVM can use hardware transactional memory to detect data contention
  - JVM must rolls back `synchronized` blocks that encounter data contention

Transactional execution of **`synchronized {…}`**

- The JVM maintains the semantic meaning of:
  execute block atomically in relation to all other threads
- Uncontended **`synchronized`** blocks run just as fast as before
- Data contended **`synchronized`** blocks still serialize execution
- **`synchronized`** blocks without data contention can execute in parallel

Transactional execution of `synchronized {…}`

- It's all transparent!
- No changes to Java code
  - The VM handles everything
- Nested `synchronized` blocks
  - Roll back to outermost transactional `synchronized`
- Reduces serialization
- Amdahl's Law now only reflects data contention
  - Desire to reduce data contention

Implementation in a JVM

How does it fit in the current locking schemes?

- Thin locks handle uncontended `synchronized` blocks
  - Most common case
  - Uses CAS, no OS interaction
- Thick locks handle data contended `synchronized` blocks
  - Blocks in the OS
- Transactional monitors handle contended `synchronized` blocks that have no data contention
  - Execute `synchronized` blocks in parallel
  - Uses HW transactional memory support

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Transactional **`synchronized {…}`**

Measurements

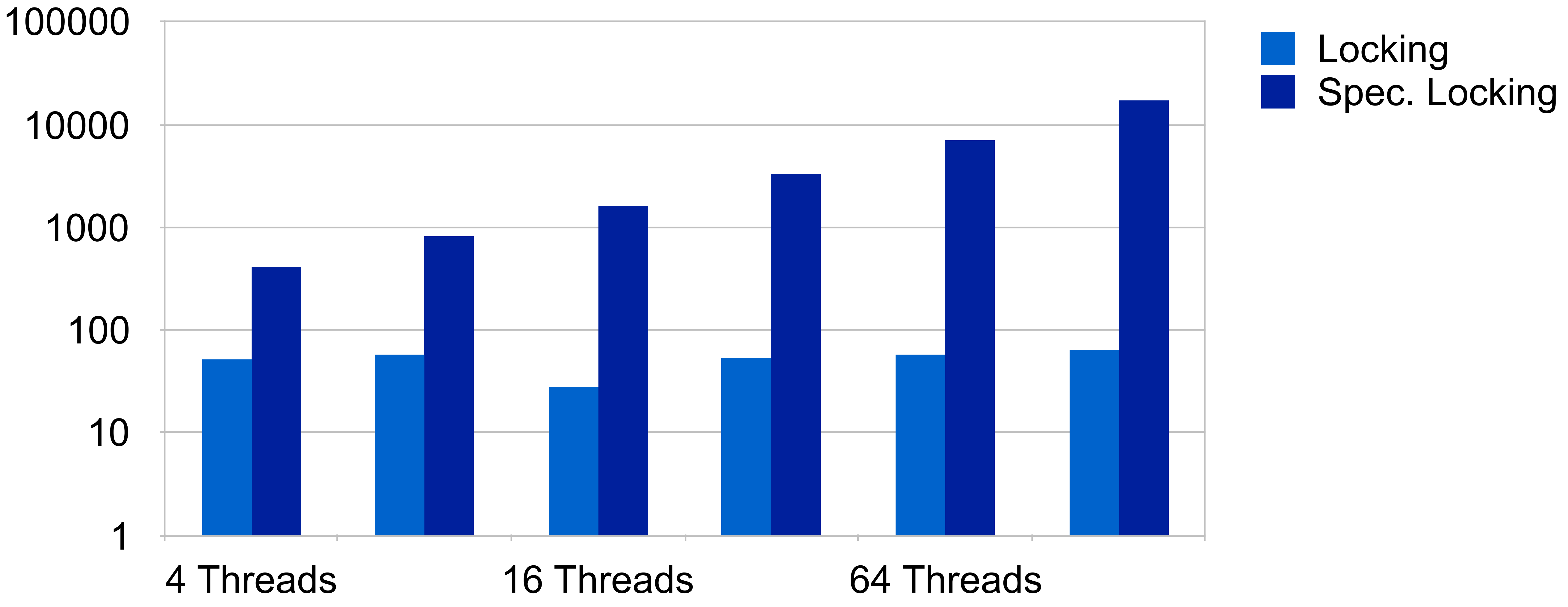
Effects on how you code for contention

Summary

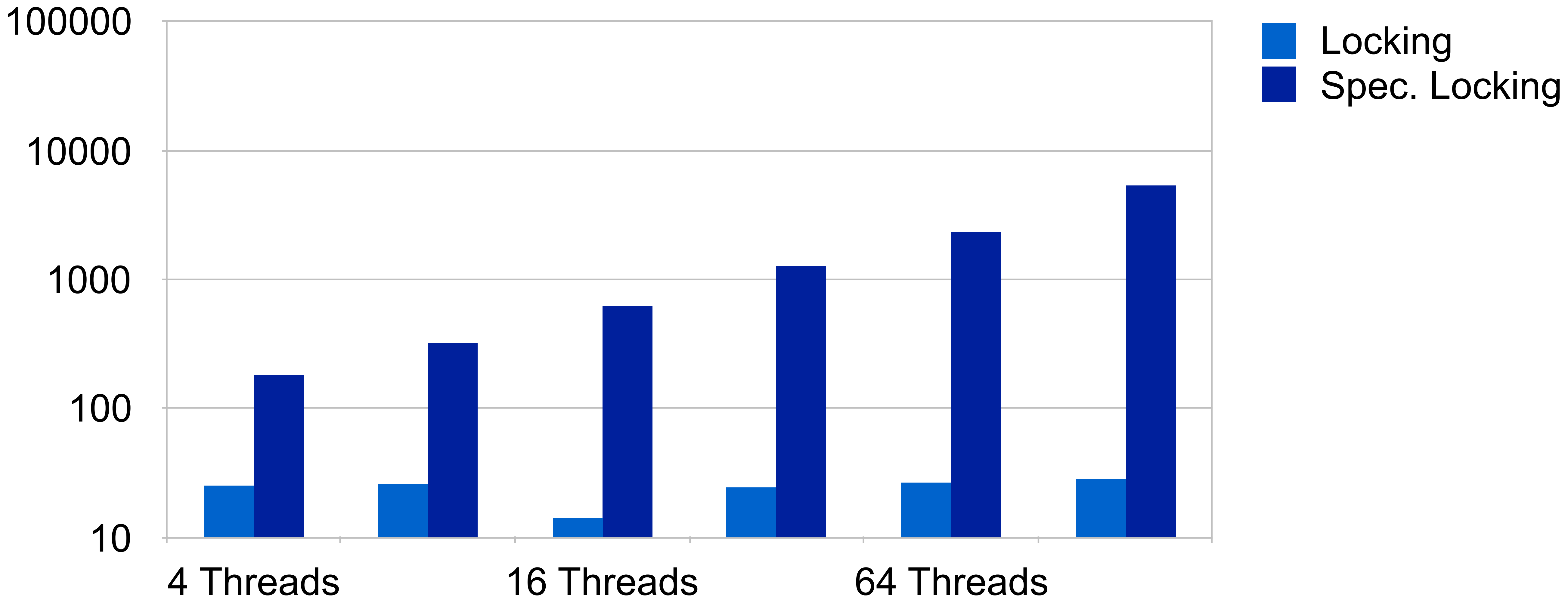
Data Contention and Hashtables

- Examples of no data contention in a Hashtable
  - 2 readers
  - 1 reader, 1 writer, different hash buckets
  - 2 writers, different hash buckets
- Examples of data contention in a Hashtable
  - 1 reader, 1 writer in same hash bucket
  - 2 writers in same hash bucket

Measurements: Hashtable (0% writes)



Measurements: Hashtable (5% writes)



Agenda

Why do we care?

Lock contention vs. Data contention

Transactional `synchronized {…}`

Measurements

Effects on how you code for contention

Summary

Minimizing Data Contention 1

```
private Object table[];
private int    size;

public synchronized void put(Object key, Object val) {
  …
  // missed, insert into table
  table[idx] = new HashEntry(key, val, table[idx]);
  size++; // writer data contention
}

public synchronized int size() {
  return size;
}
```

Minimizing Data Contention 2

```
private Object table[];
private int    sizes[];

public synchronized void put(Object key, Object val) {
  …
  // missed, insert into table
  table[idx] = new HashEntry(key, val, table[idx]);
  sizes[idx]++; // reduced writer data contention
}

public synchronized int size() {
  int size = 0;
  for (int i=0; i<sizes.length; i++) size += sizes[i];
  return size;
}
```

Minimizing Data Contention 3

```
private Object table[];
private int    sizes[];
private int cachedSize;

public synchronized void put(Object key, Object val) {
  …
  // missed, insert into table
  table[idx] = new HashEntry(key, val, table[idx]);
  sizes[idx]++;
  cachedSize = -1; // clear the cache
}

public synchronized int size() {
  if (cachedSize < 0) { // reduce size recalculation
    cachedSize = 0;
    for (int i=0; i<sizes.length; i++)
      cachedSize += sizes[i];
  }
  return cachedSize;
}
```

Minimizing Data Contention 4

```
private Object table[];
private int    sizes[];
private int cachedSize;

public synchronized void put(Object key, Object val) {
  …
  // missed, insert into table
  table[idx] = new HashEntry(key, val, table[idx]);
  sizes[idx]++;
  if (cachedSize >= 0) cachedSize = -1; // avoid contention
}

public synchronized int size() {
  if (cachedSize < 0) {
    cachedSize = 0;
    for (int i=0; i<sizes.length; i++)
      cachedSize += sizes[i];
  }
  return cachedSize;
}
```

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Why do we care?

Lock contention vs. Data contention

Transactional **`synchronized {…}`**

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Summary

- Hardware Transactional Memory is here!
- Expect speculative use for locking and synchronization in libraries and runtimes
    - JVMs, CLR, …
    - POSIX mutexes, semaphores, etc.
- It may be useful for some other cool stuff…

Q&A