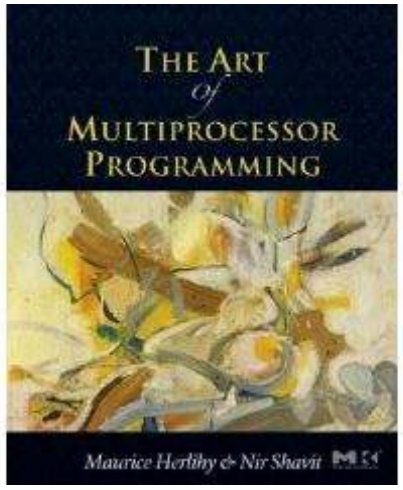
NON-BLOCKING DATA STRUCTURES AND TRANSACTIONAL MEMORY

Tim Harris, 28 November 2014

Lecture 8

- Problems with locks
- Atomic blocks and composition
- Hardware transactional memory
- Software transactional memory

Transactional Memory



Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

Our Vision for the Future

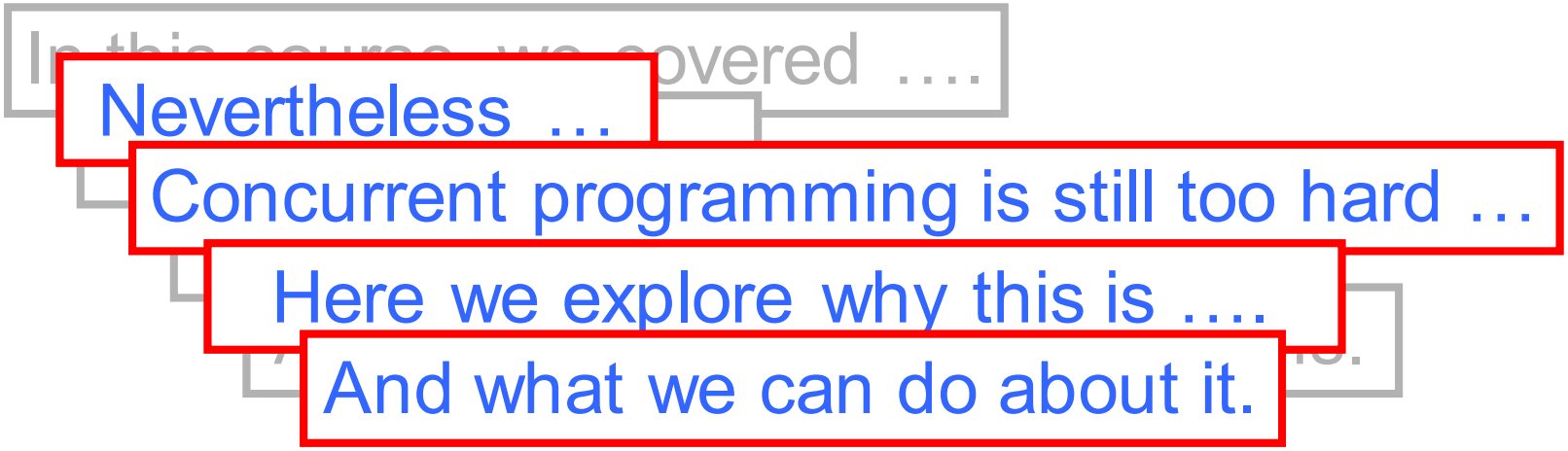
In this course, we covered ….

Best practices …

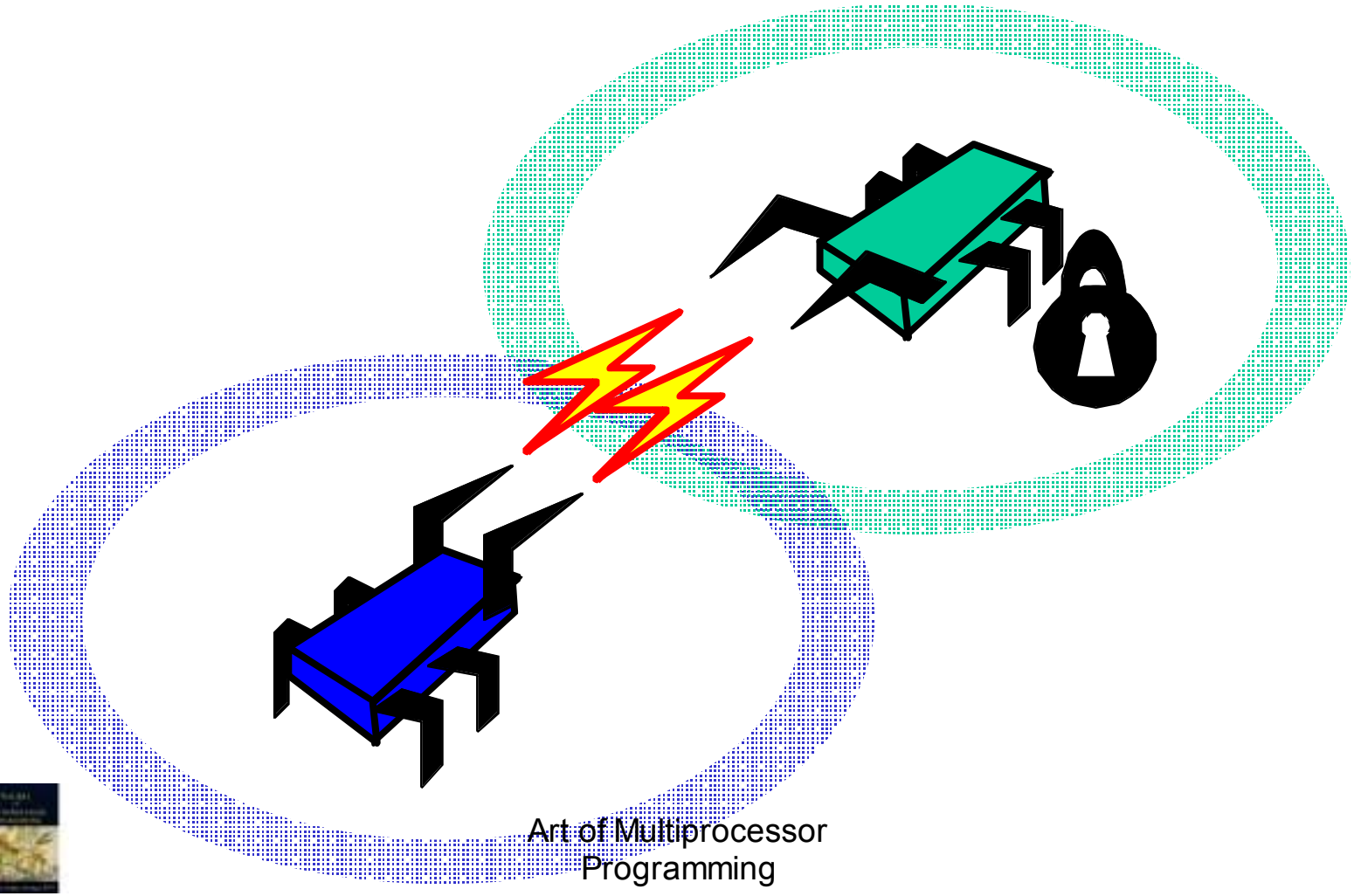
New and clever ideas …

And common-sense observations.

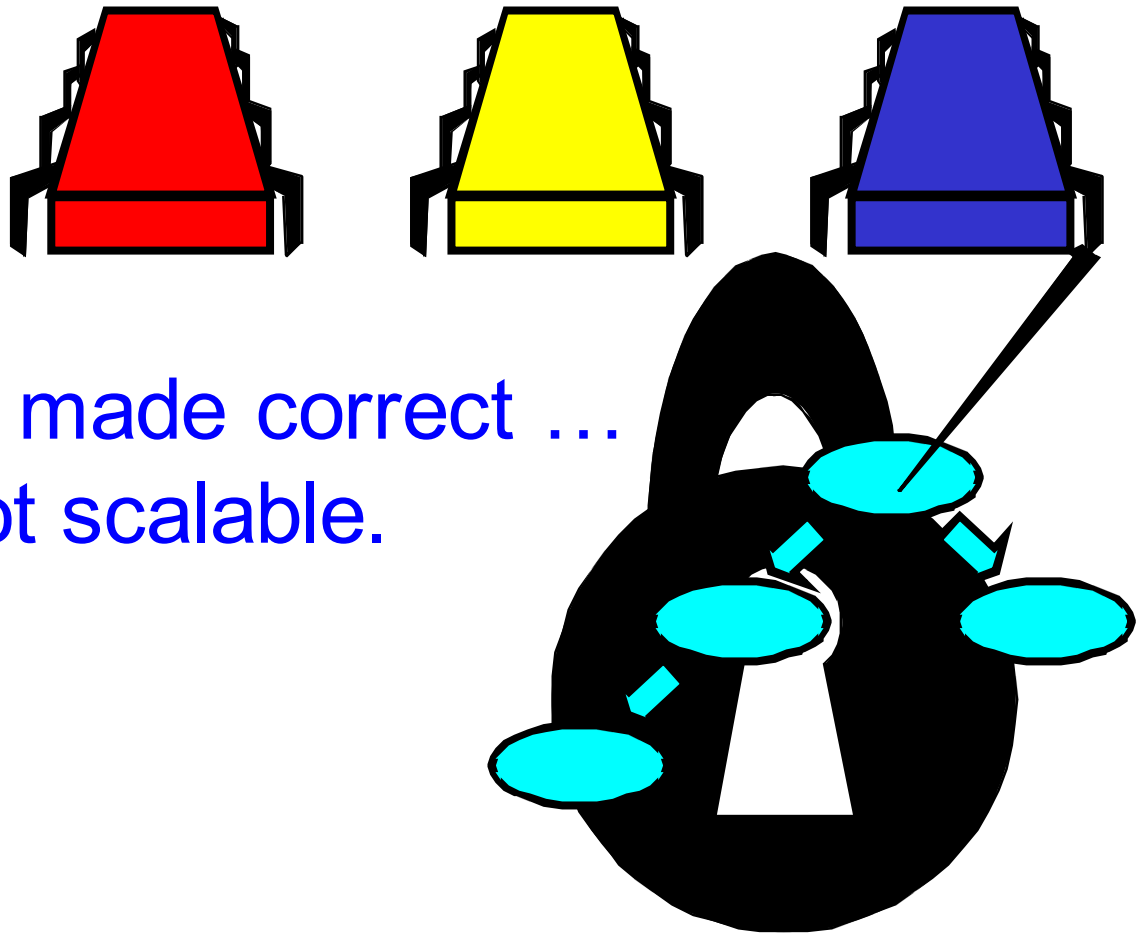
Our Vision for the Future



Locking



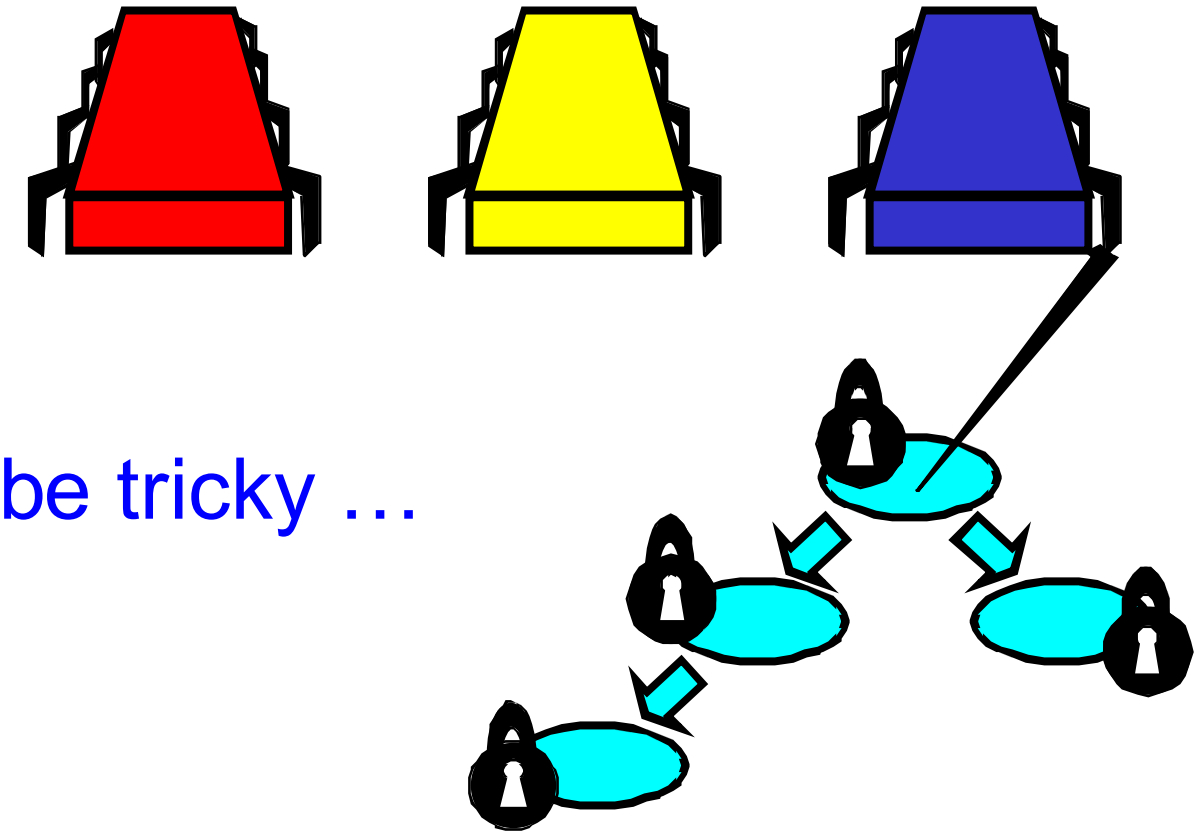
Coarse-Grained Locking



Easily made correct …

But not scalable.

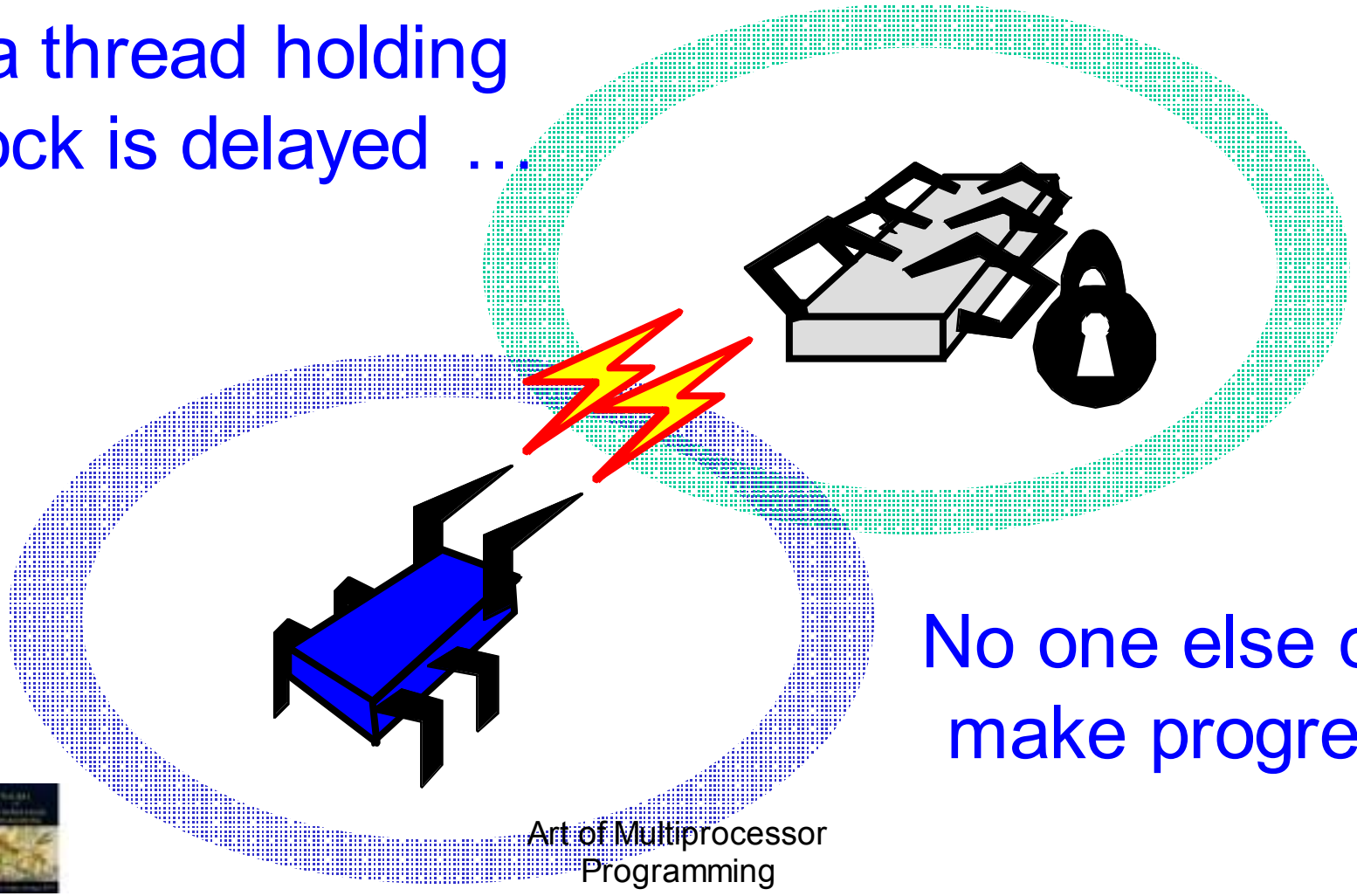
Fine-Grained Locking



Can be tricky …

Locks are not Robust

If a thread holding a lock is delayed …



No one else can make progress

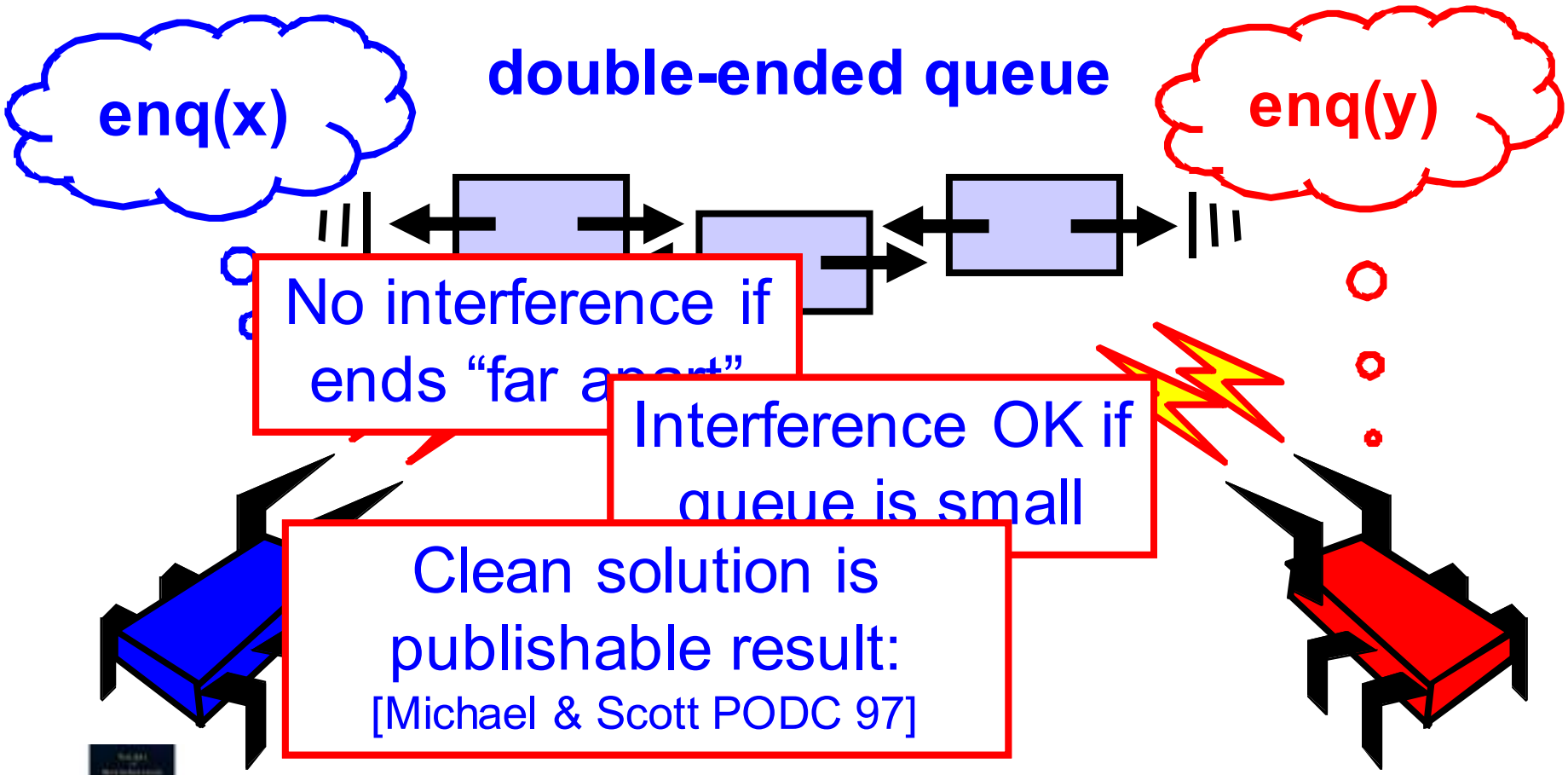
Locking Relies on Conventions

- Relation between
  - Locks and objects
  - Exists only in programmer's

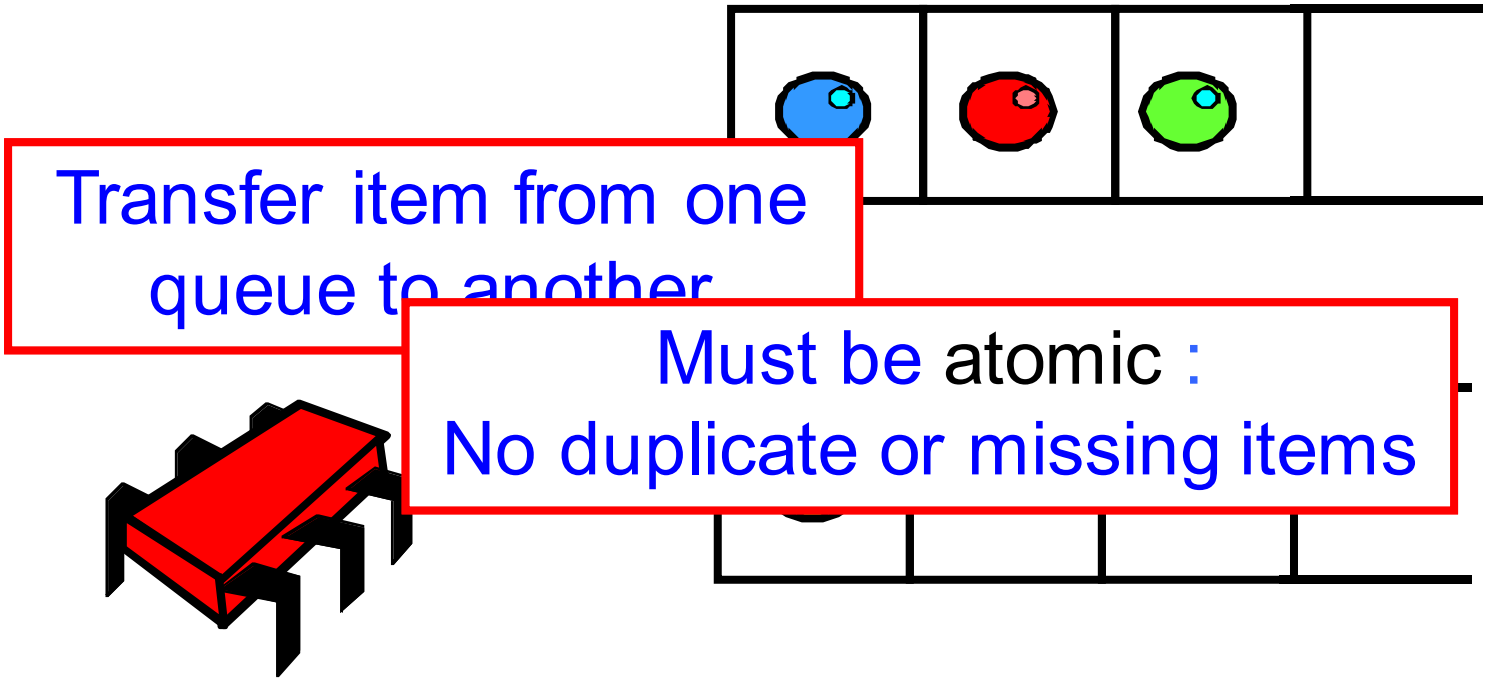
Actual comment from Linux Kernel
(hat tip: Bradley Kuszmaul)

```
/*
 * When a locked buffer is visible to the I/O layer
 * BH_Launder is set. This means before unlocking
 * we must clear BH_Launder, mb() on alpha and then
 * clear BH_Lock, so no reader can see BH_Launder set
 * on an unlocked buffer and then risk to deadlock.
 */
```

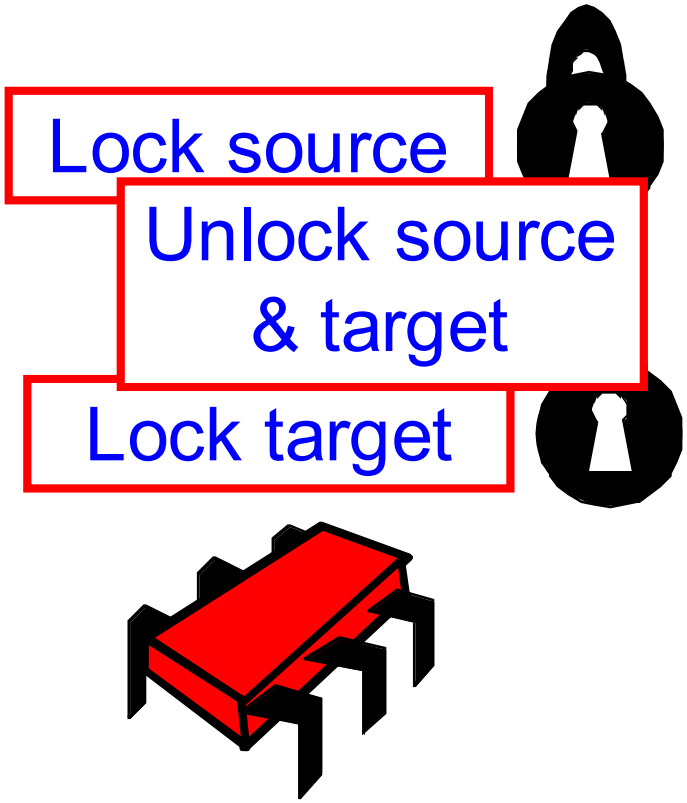
Simple Problems are hard

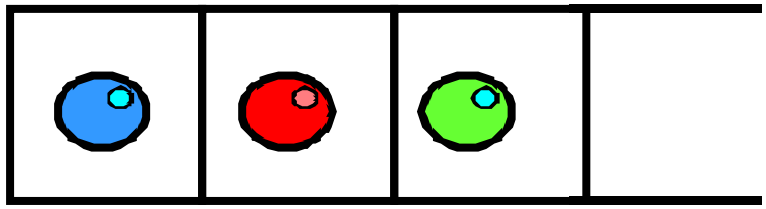


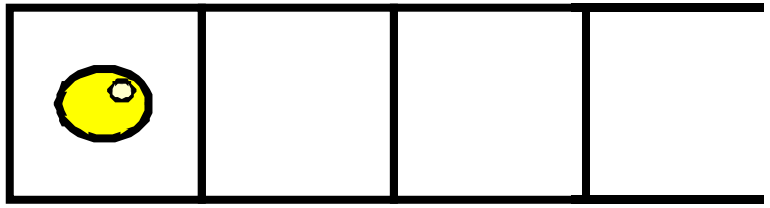
Locks Not Composable



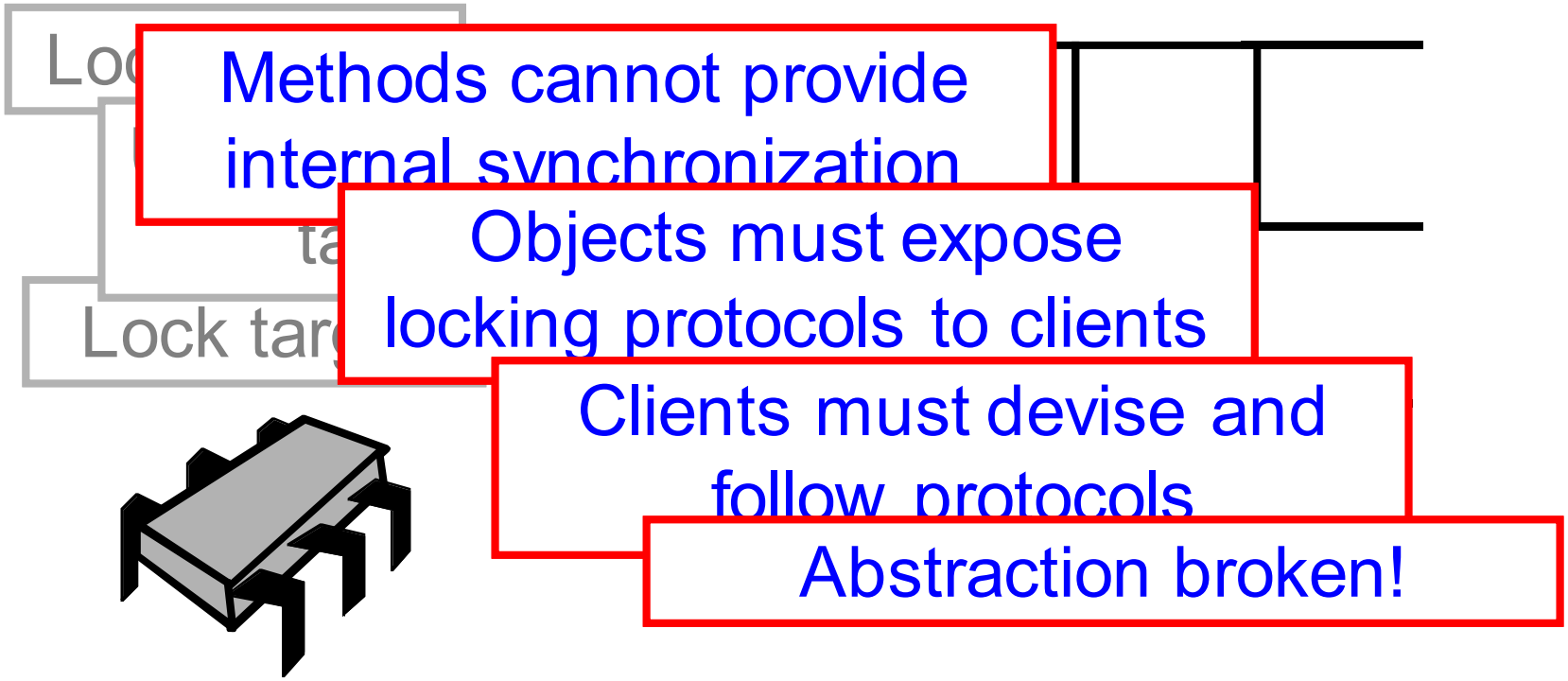
Locks Not Composable



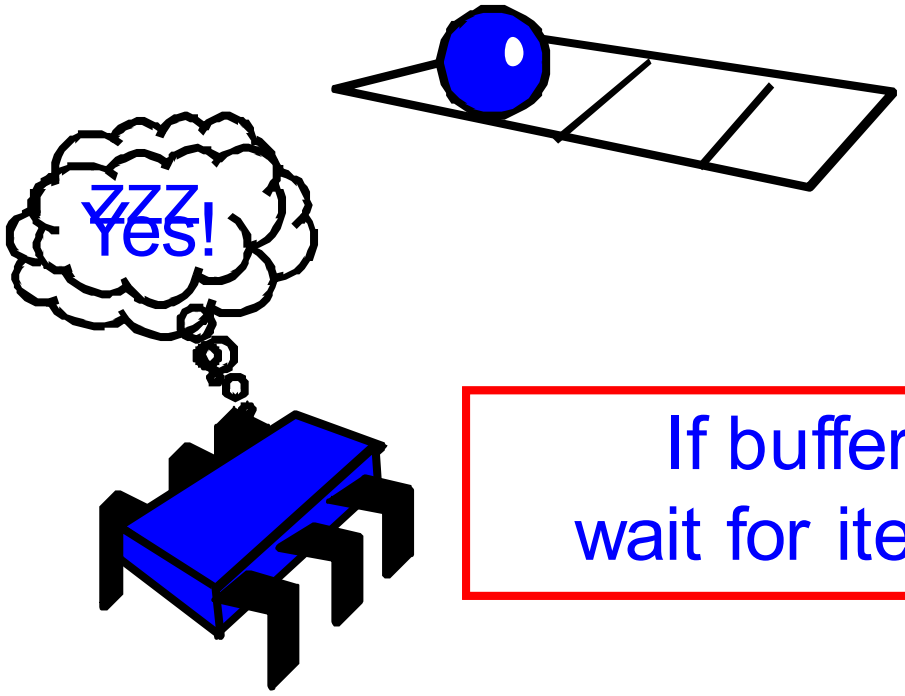




Locks Not Composable



Monitor Wait and Signal

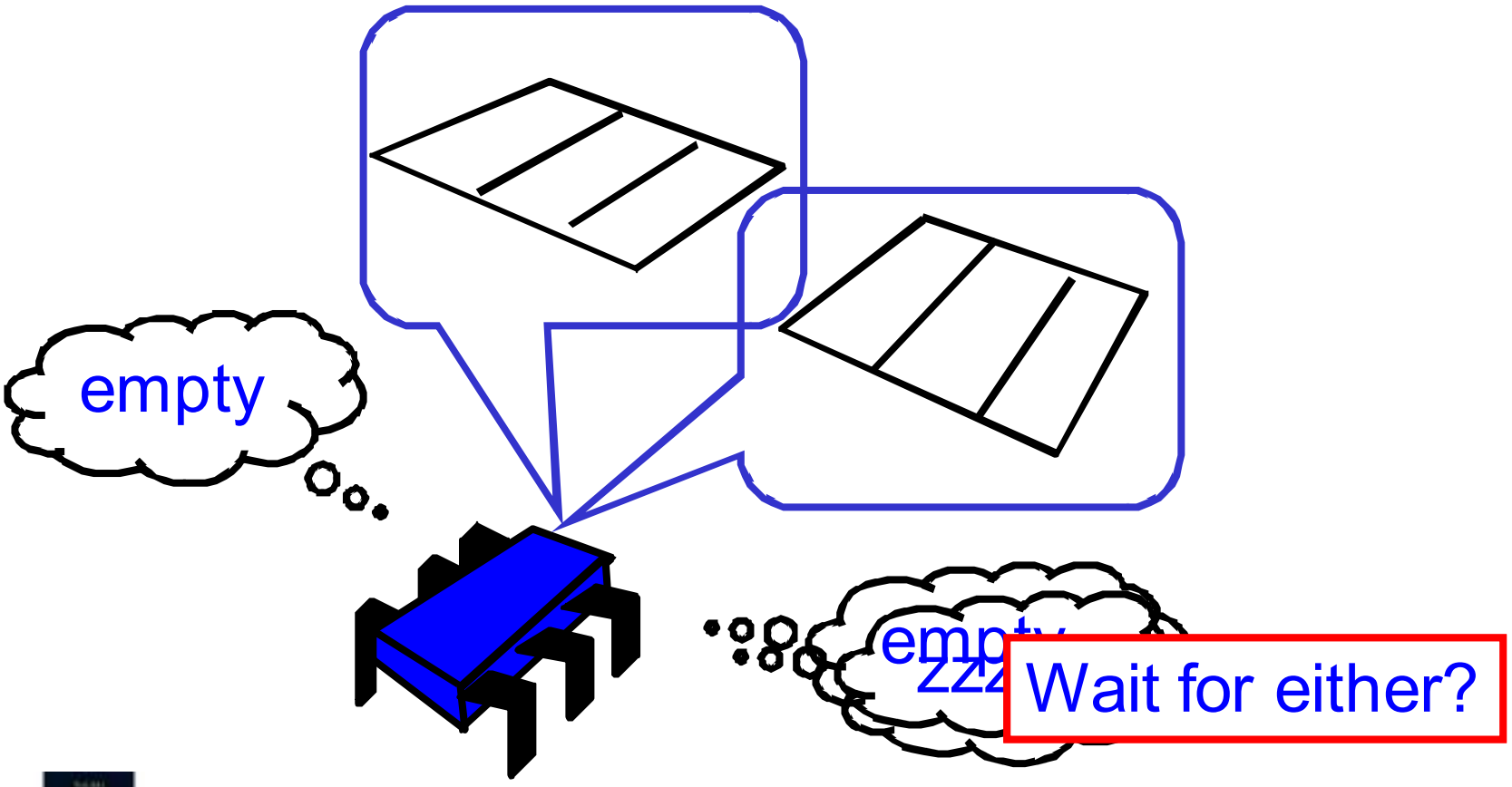


Empty

buffer

If buffer is empty,
wait for item to show up

Wait and Signal do not Compose



The Transactional Manifesto

- Current practice inadequate
  - to meet the multicore challenge
- Research Agenda
  - Replace **locking** with a **transactional** API
  - **Design** languages or libraries
  - **Implement** efficient run-time systems

Transactions

Block of code ….

Atomic: appears to happen instantaneously

Serializable: all appear to happen in one-at-a-time

Commit: takes effect (atomically)

Abort: has no effect (typically restarted)

Atomic Blocks

```
atomic {
  x.remove(3);
  y.add(3);
}

atomic {
  y = null;
}
```

Atomic Blocks

```
atomic {
  x.remove(3);
  y.add(3);
}

atomic {
  y = null;
}
```

No data race

A Double-Ended Queue

```
public void LeftEnq(item x) {
  Qnode q = new Qnode(x);
  q.left = left;
  left.right = q;
  left = q;
}
```

Write sequential Code

A Double-Ended Queue

```
public void LeftEnq(item x)
 atomic {
  Qnode q = new Qnode(x);
  q.left = left;
  left.right = q;
  left = q;
 }
}
```

A Double-Ended Queue

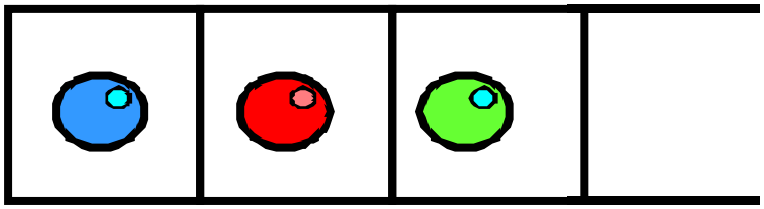
```
public void LeftEnq(item x) {
  atomic {
    Qnode q = new Qnode(x);
    q.left = left;
    left.right = q;
    left = q;
  }
}
```

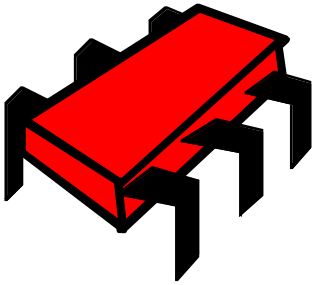
Enclose in atomic block

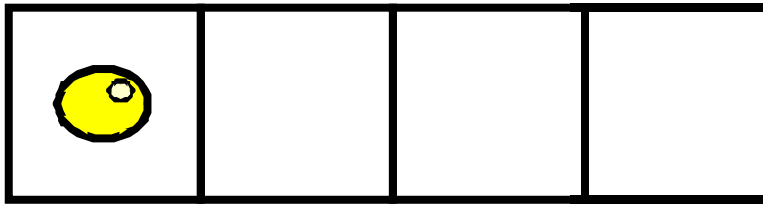
Warning

- Not always this simple
  - Conditional waits
  - Enhanced concurrency
  - Complex patterns
- But often it is…

Composition?



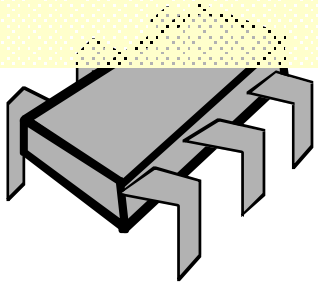


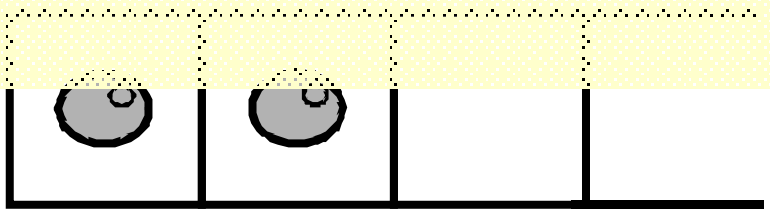


Composition?

```
public void Transfer(Queue<T> q1, q2)
{
 atomic {
  T x = q1.deq();
  q2.enq(x);
 }
}
```

Trivial or what?





Conditional Waiting

```
public T LeftDeq() {
 atomic {
  if (left == null)
   retry;
  …

 }
}
```

Roll back transaction and restart when something changes

Composable Conditional Waiting

```
atomic {
  x = q1.deq();
} orElse {
  x = q2.deq();
}
```

Run 1st method. If it retries

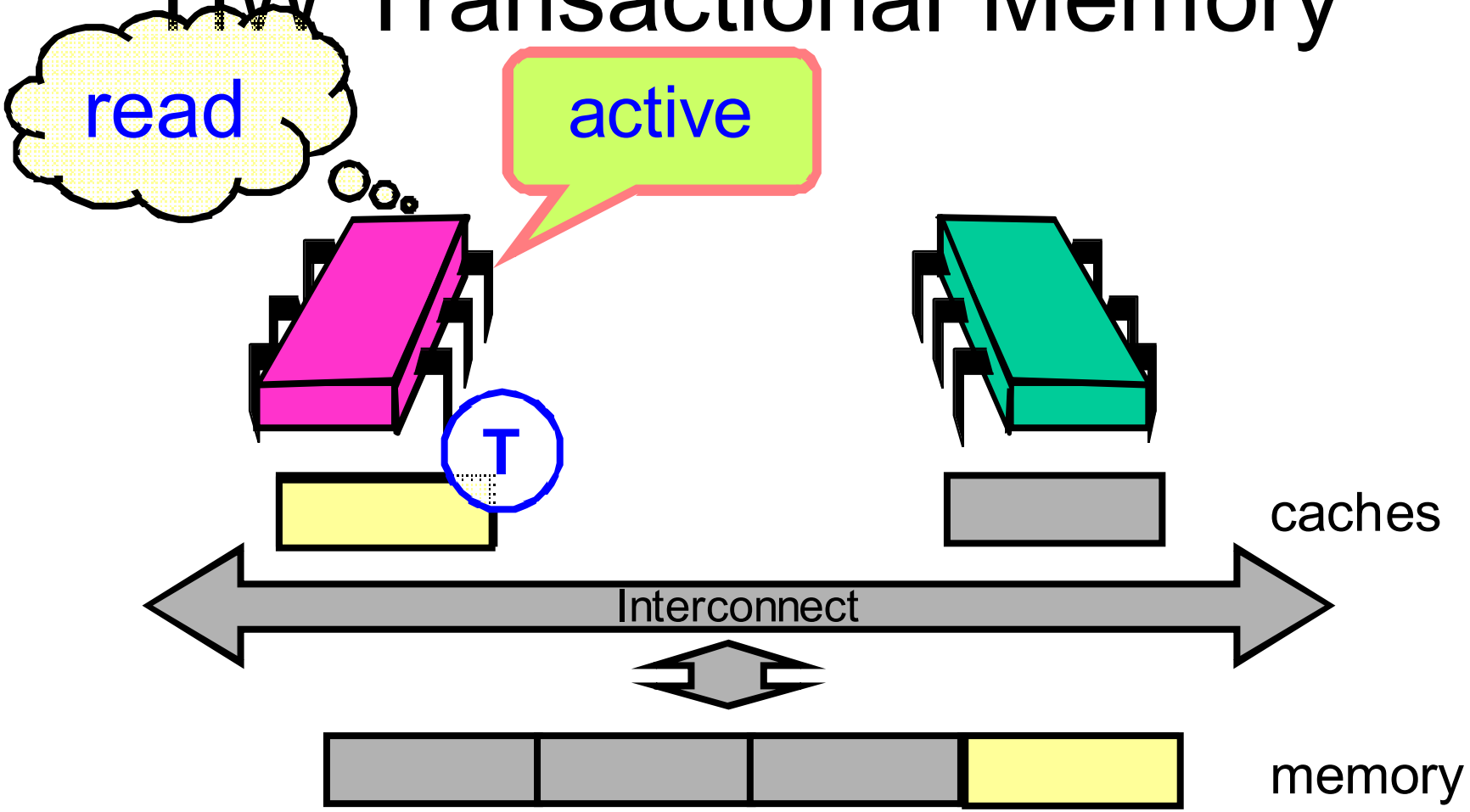
Run 2nd method. If it retries …

Entire statement retries

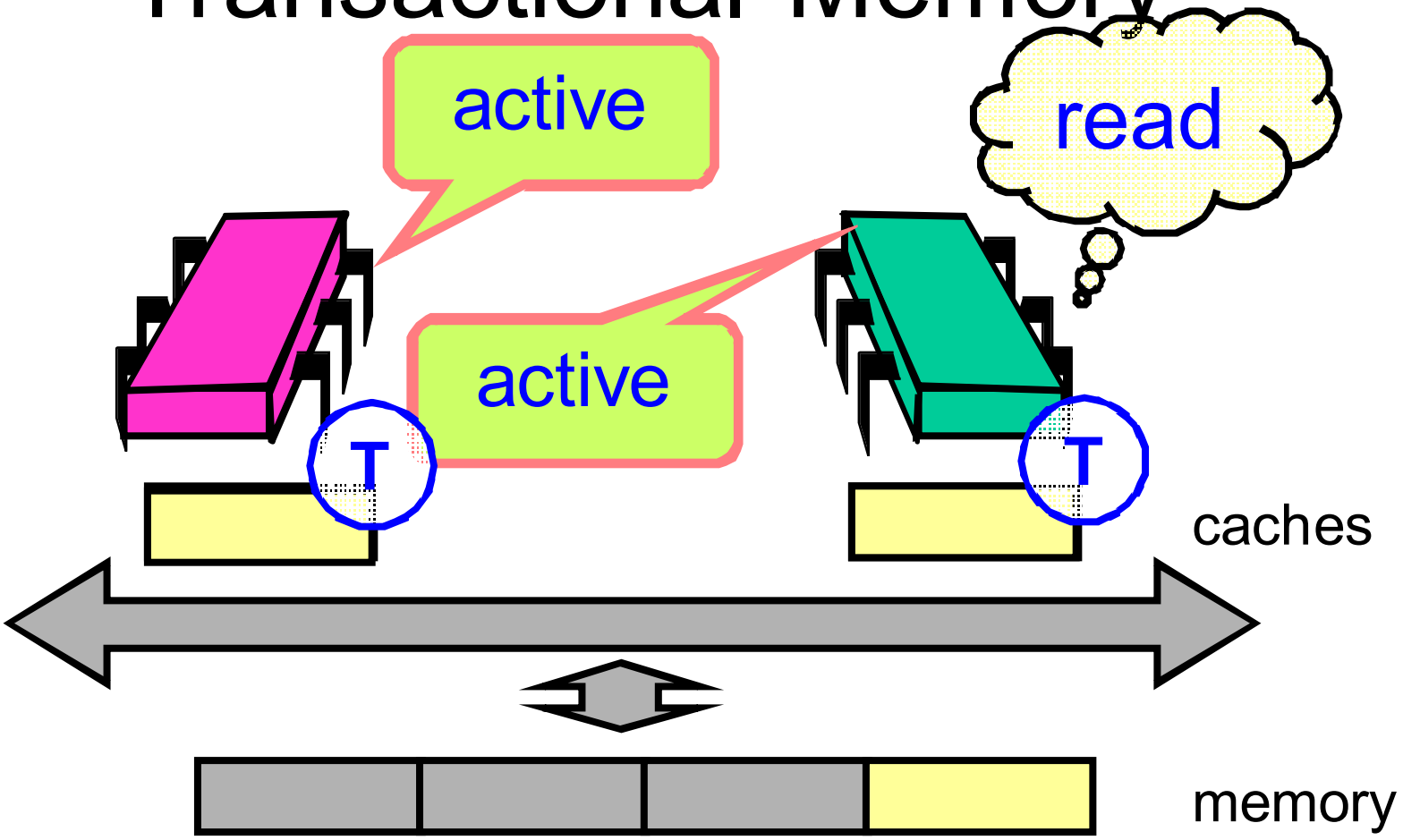
Hardware Transactional Memory

- Exploit Cache coherence
- Already almost does it
  - Invalidation
  - Consistency checking
- Speculative execution
  - Branch prediction = optimistic synch!

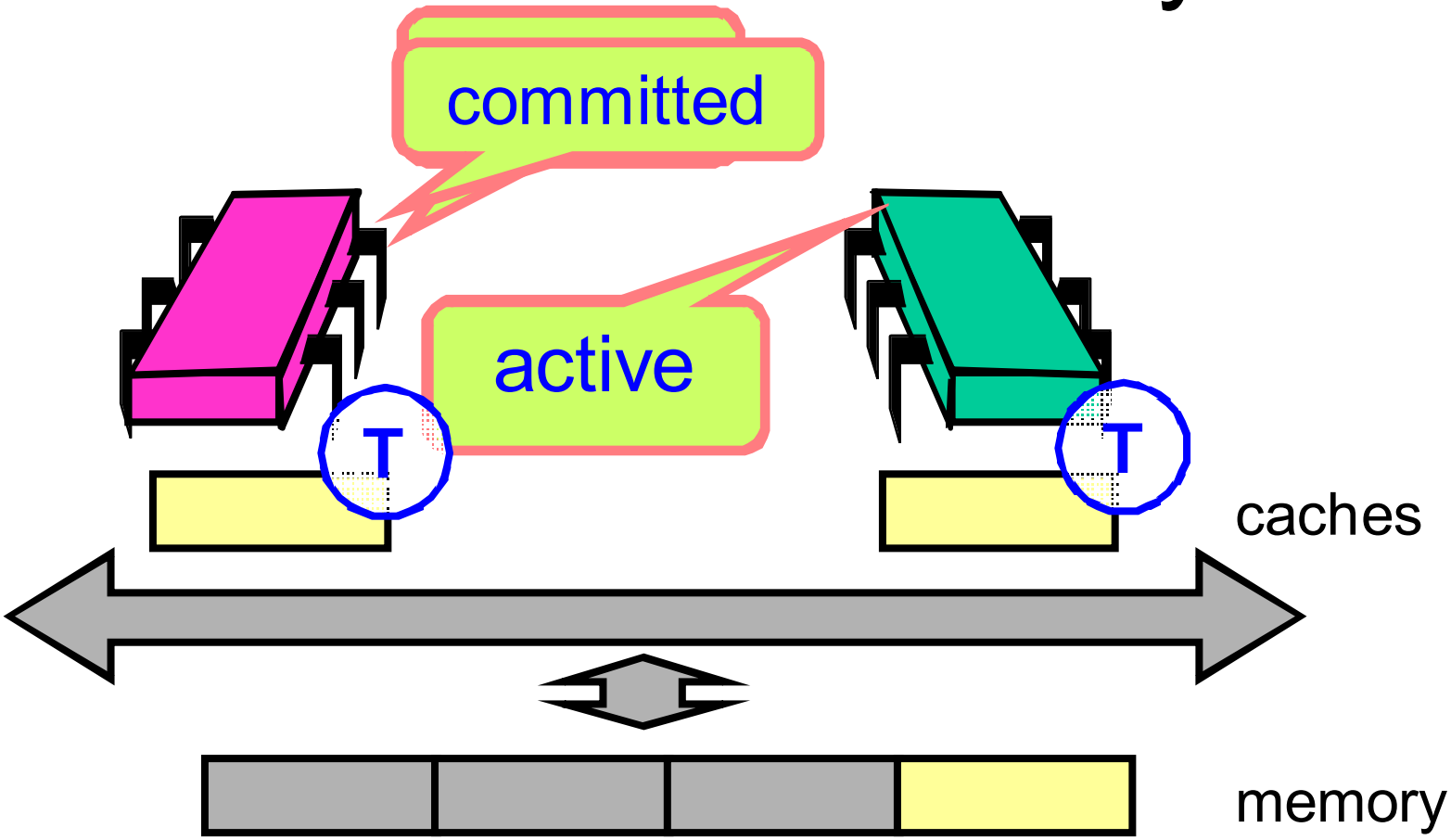
HW Transactional Memory



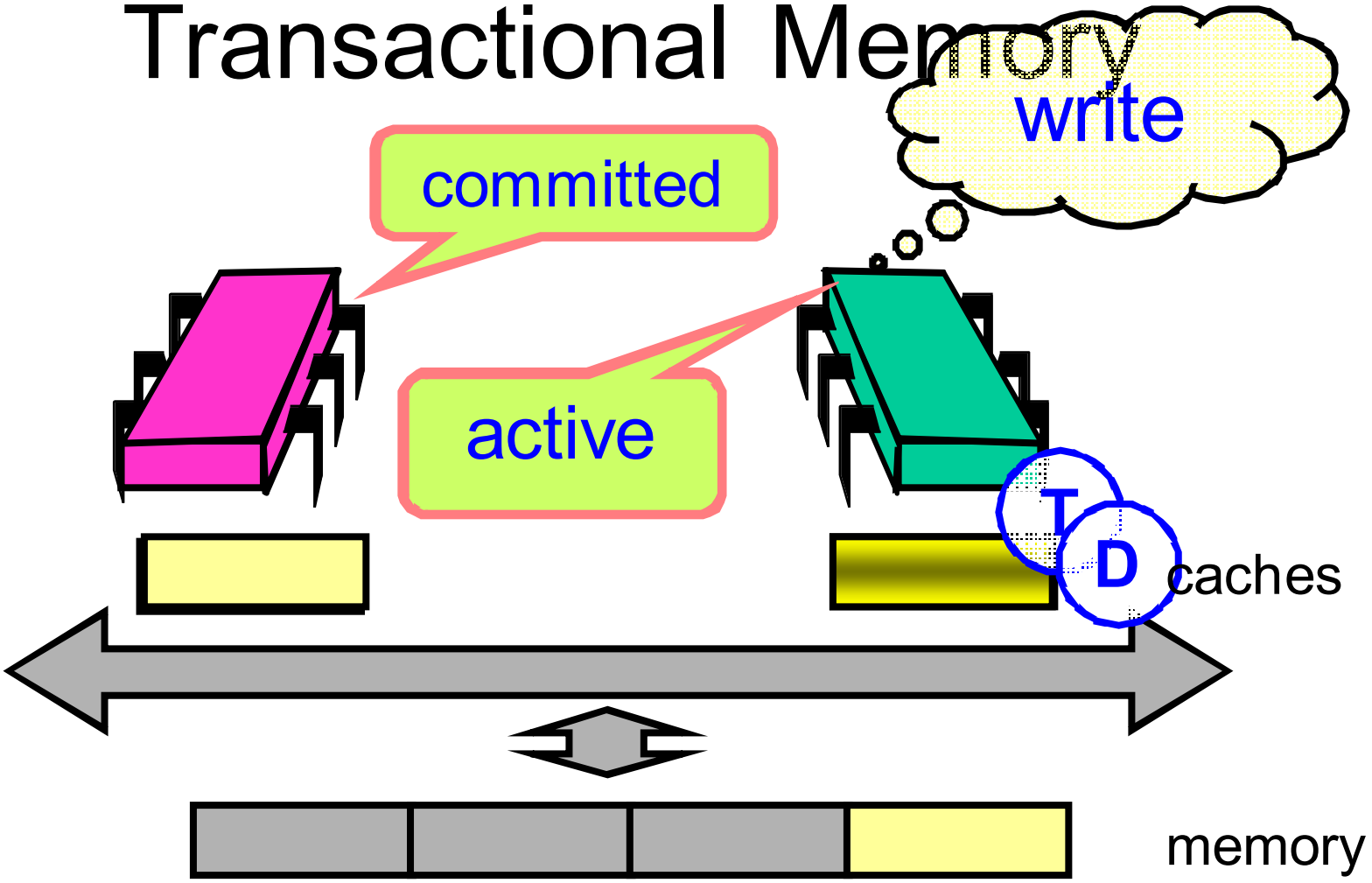
Transactional Memory

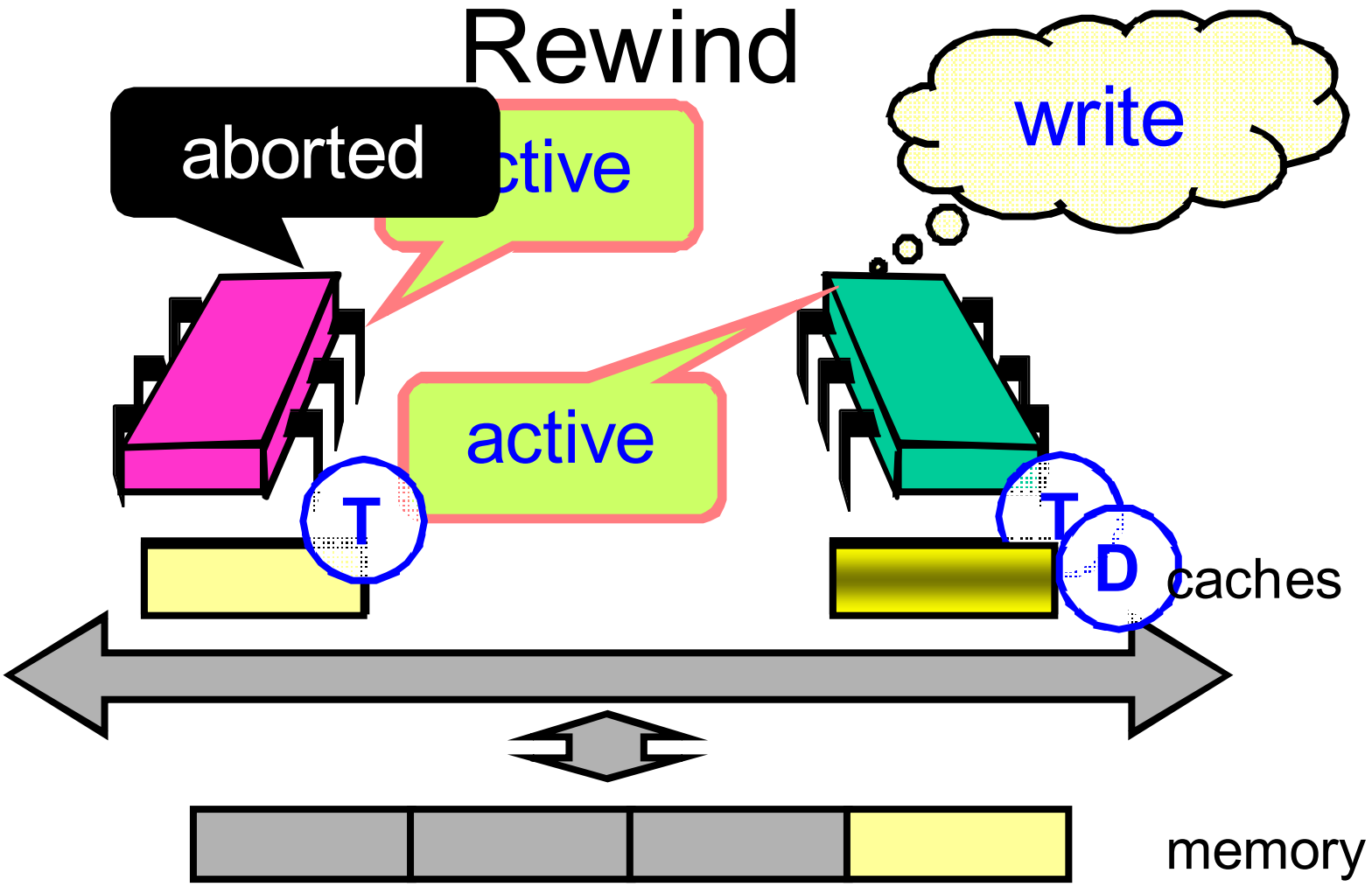


Transactional Memory



Transactional Memory




Rewind
aborted
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write
active
T
T
D
caches
memory

Transaction Commit

- At commit point
  - If no cache conflicts, we win.
- Mark transactional entries
  - Read-only: valid
  - Modified: dirty (eventually written back)
- That's all, folks!
  - Except for a few details …

Not all  and 

- Limits to
  - Transactional cache size
  - Scheduling quantum
- Transaction cannot commit if it is
  - Too big
  - Too slow
  - Actual limits platform-dependent

HTM Strengths & Weaknesses

- Ideal for lock-free data structures

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- Practical proposals have limits on
  - Transaction size and length
  - Bounded HW resources
  - Guarantees vs best-effort

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- Ideal for lock-free data structures
- Practical proposals have limits on
  - Transaction size and length
  - Bounded HW resources
  - Guarantees vs best-effort
- On fail
  - Diagnostics essential
  - Try again in software?

Compos

Locks don't compose, transactions do.

Composition necessary for Software Engineering.

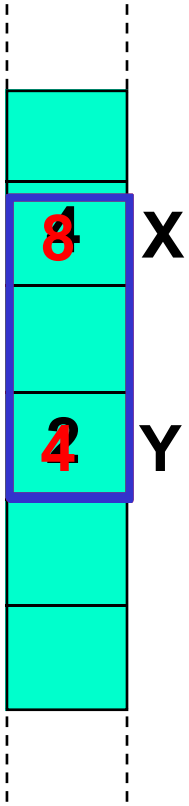
But practical HTM doesn't ***really*** support composition!

Why we need STM

Transactional Consistency

- Memory Transactions are collections of reads and writes executed atomically
- They should maintain *consistency*
  - *External*: with respect to the interleavings of other transactions (*linearizability*).
  - *Internal*: the transaction itself should operate on a consistent state.

External Consistency



Application Memory

Invariant x = 2y

Transaction A:
Write x
Write y

Transaction B:
Read x
Read y
Compute z = 1/(x-y) = 1/2

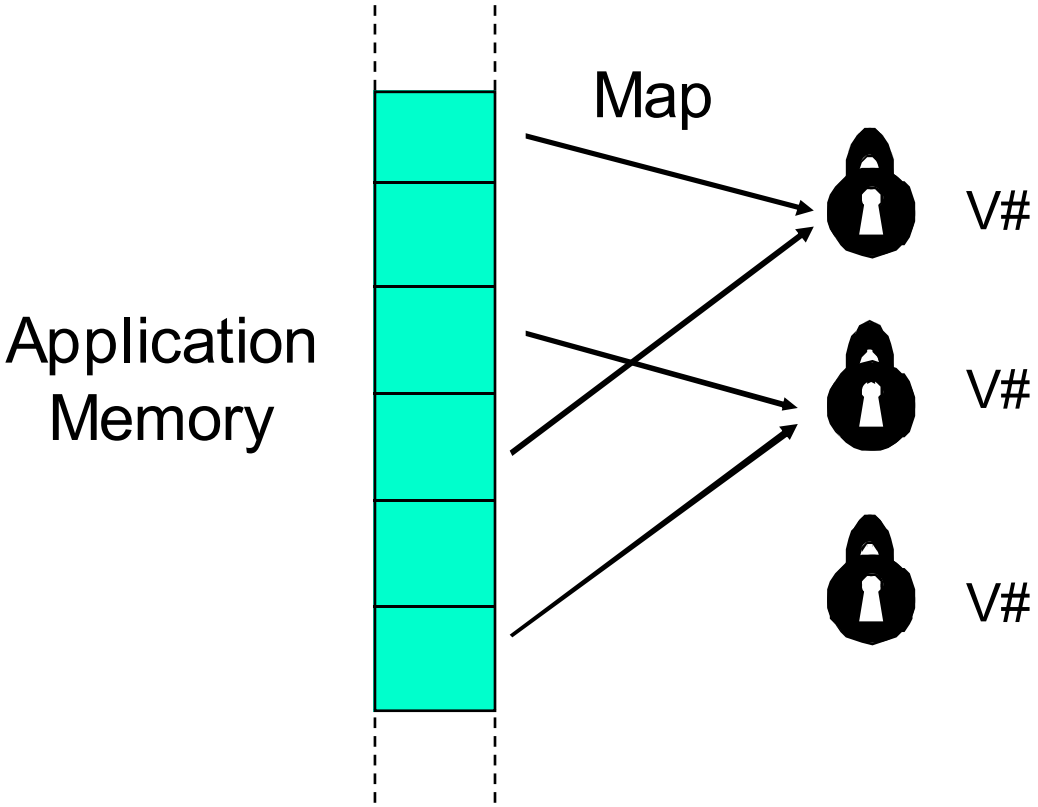
A Simple Lock-Based STM

- STMs come in different forms
  - Lock-based
  - Lock-free
- Here : a simple lock-based STM
- Lets start by Guaranteeing External Consistency

Synchronization

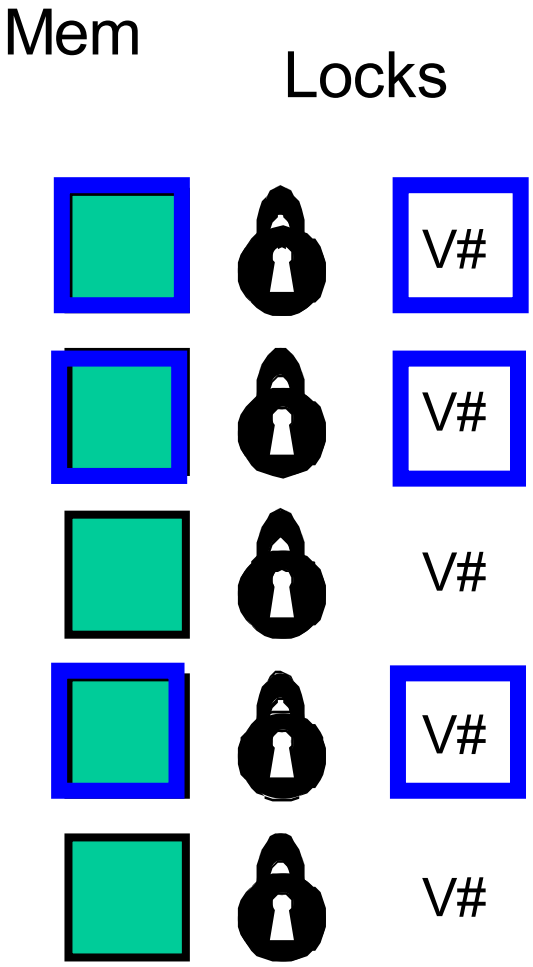
- Transaction keeps
  - **Read set**: locations & values read
  - **Write set**: locations & values to be written
- Deferred update
  - Changes installed at commit
- Lazy conflict detection
  - Conflicts detected at commit

STM: Transactional Locking



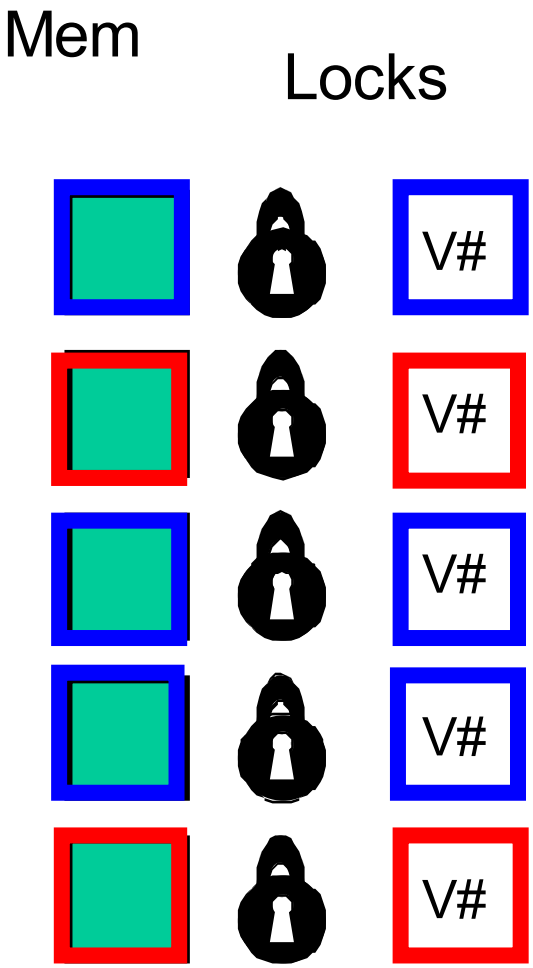
Array of version #s & locks

Reading an Object



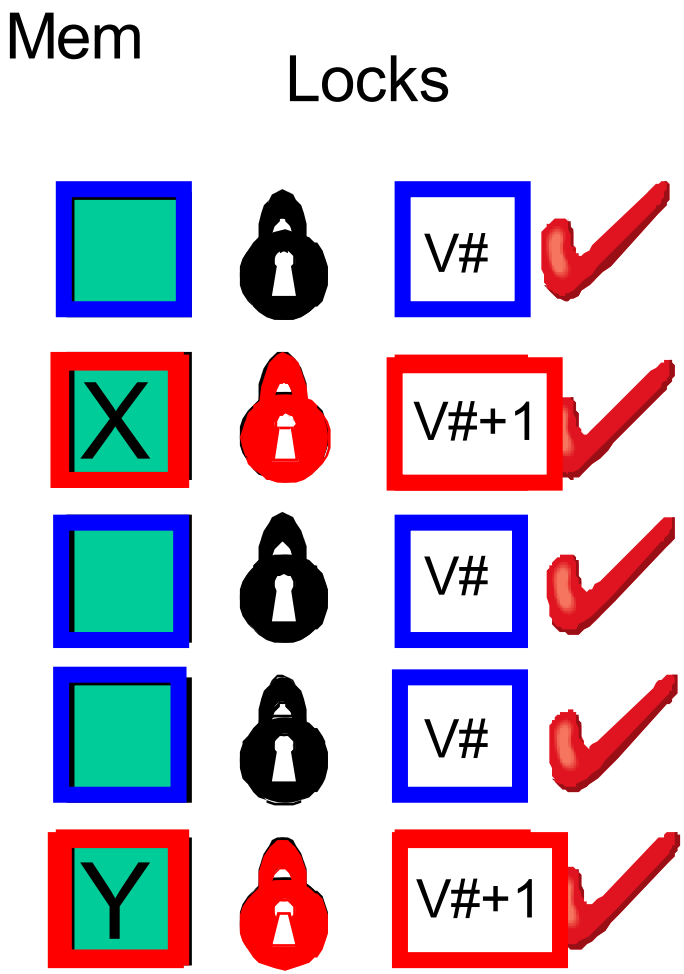
Add version numbers & values to read set

To Write an Object



Add version numbers & new values to write set

To Commit



Acquire write locks

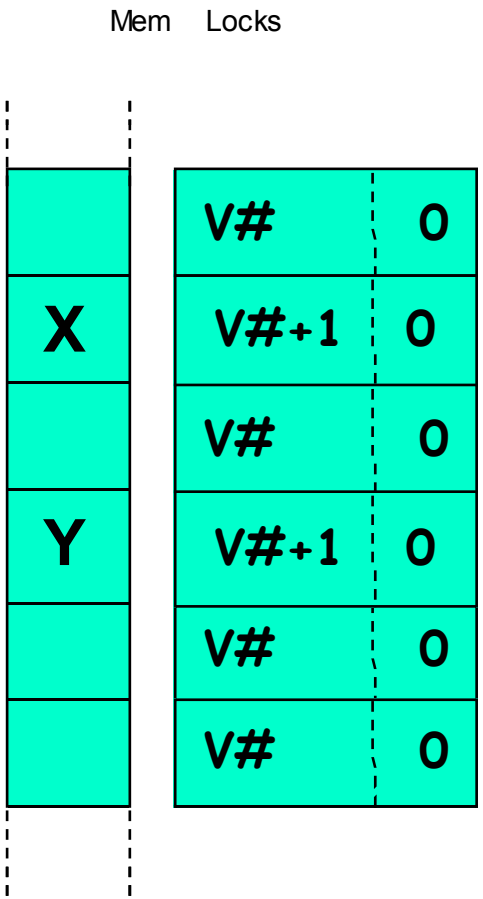
Check version numbers unchanged

Install new values

Increment version numbers

Unlock.

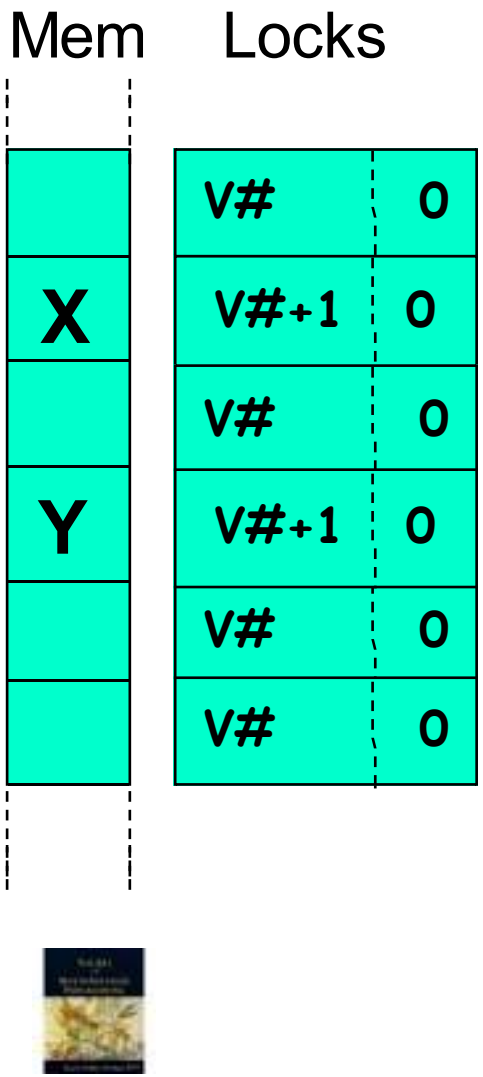
Encounter Order Locking (Undo Log)



1. To Read: load lock + location
2. Check unlocked add to Read-Set
3. To Write: lock location, store value
4. Add old value to undo-set
5. Validate read-set v#'s unchanged
6. Release each lock with v#+1

Quick read of values freshly written by the reading transaction

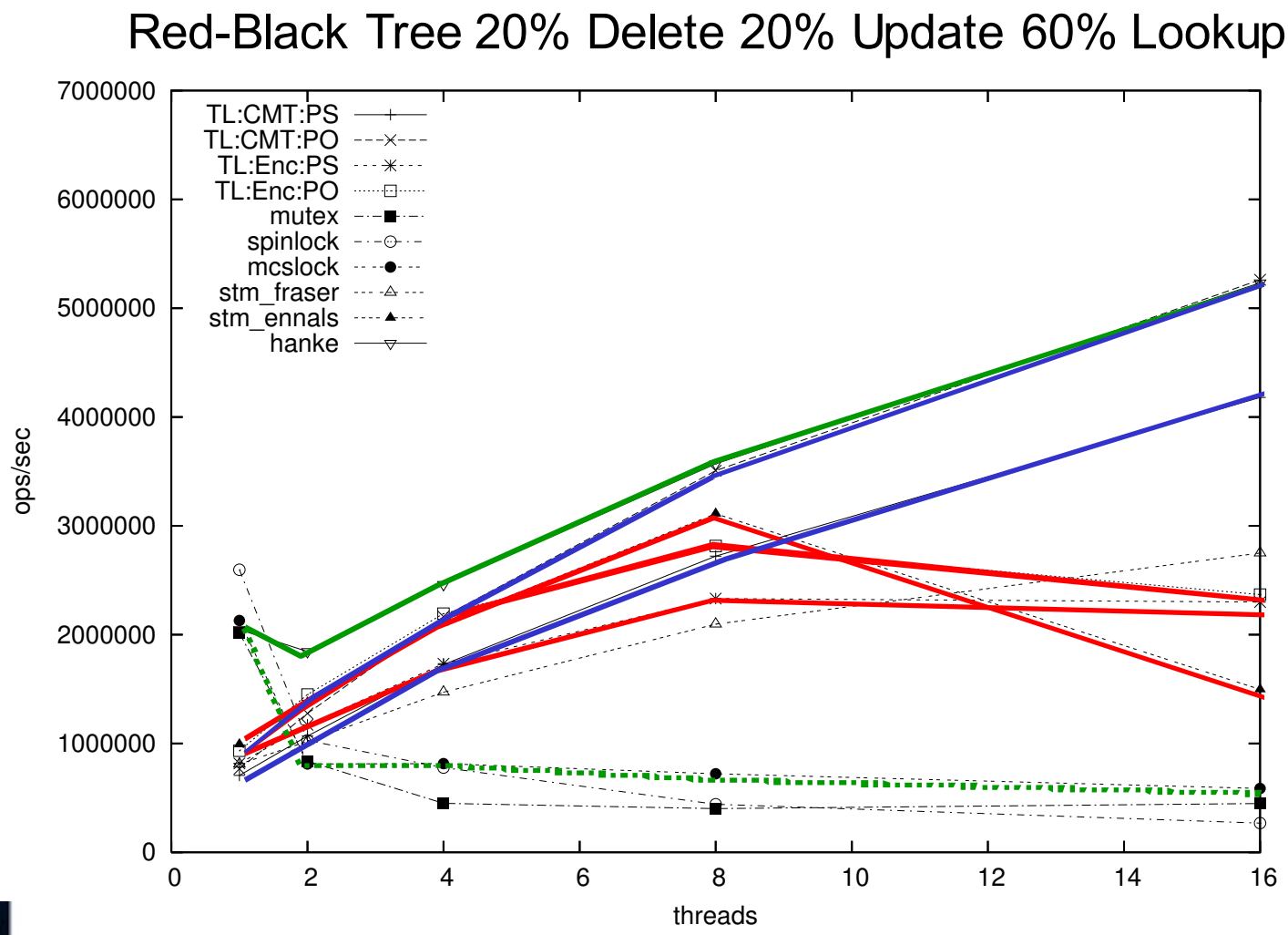
Commit Time Locking (Write Buff)



1. To Read: load lock + location
2. Location in write-set? (Bloom Filter)
3. Check unlocked add to Read-Set
4. To Write: add value to write set
5. Acquire Locks
6. Validate read/write v#'s unchanged
7. Release each lock with v#+1

Hold locks for very short duration

COM vs. ENC High Load



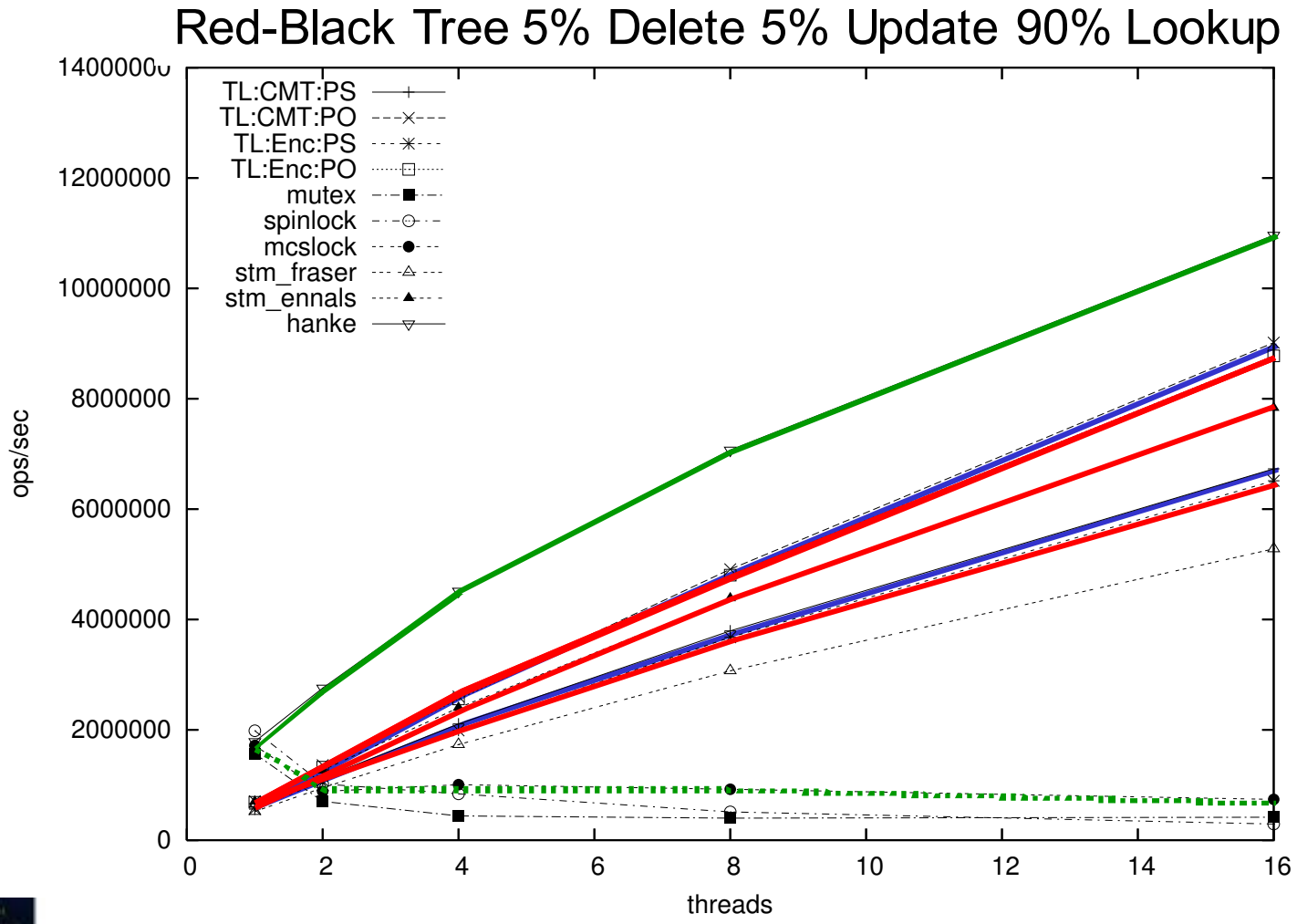
Hand

COM

ENC

MCS

COM vs. ENC Low Load



Hand

COM

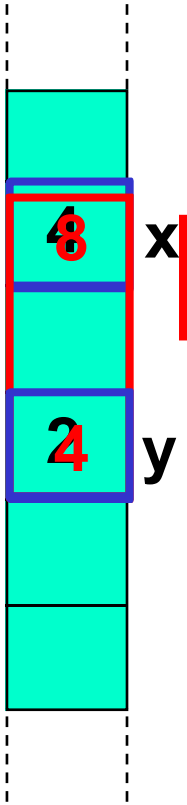
ENC

MCS

Problem: Internal Inconsistency

- A Zombie is an active transaction destined to abort.
- If Zombies see inconsistent states bad things can happen

Internal Consistency



Invariant: x = 2y

Transaction A: reads x = 4

Transaction B: writes
8 to x, 16 to y, aborts A)

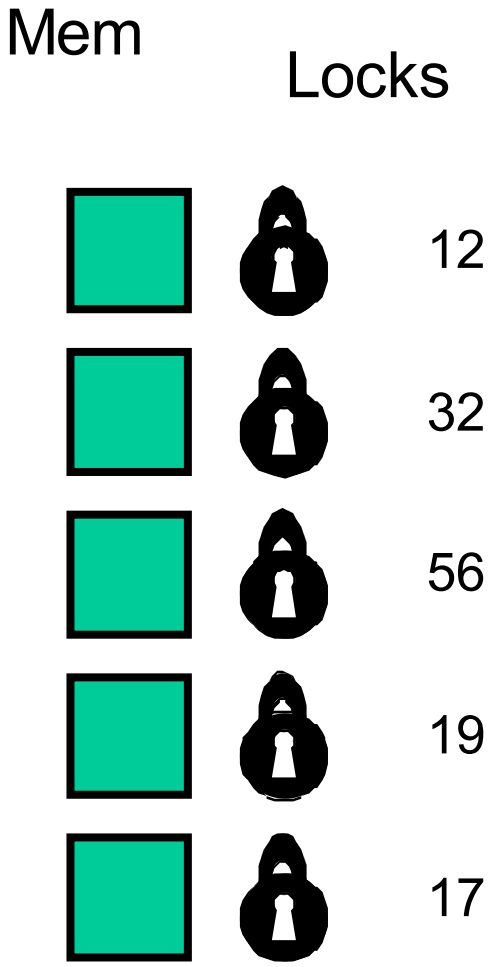
Transaction A: (zombie)
reads y = 4
computes 1/(x-y)

Divide by zero FAIL!

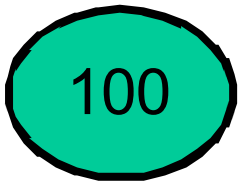
Solution: The Global Clock (The TL2 Algorithm)

- Have one shared global clock
- Incremented by (small subset of) writing transactions
- Read by all transactions
- Used to validate that state worked on is always consistent

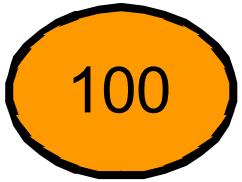
Read-Only Transactions



Copy version clock to local read version clock

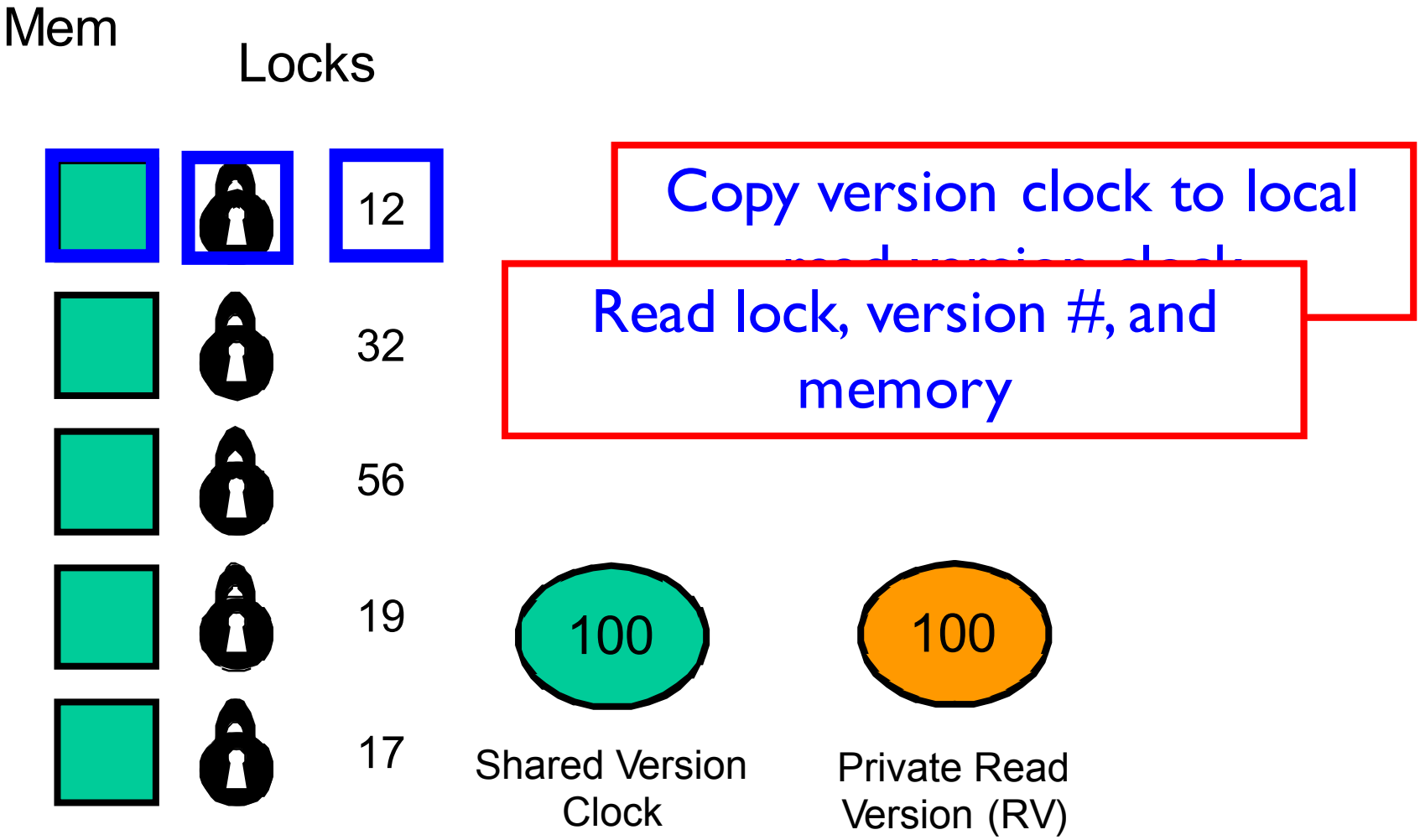


Shared Version Clock

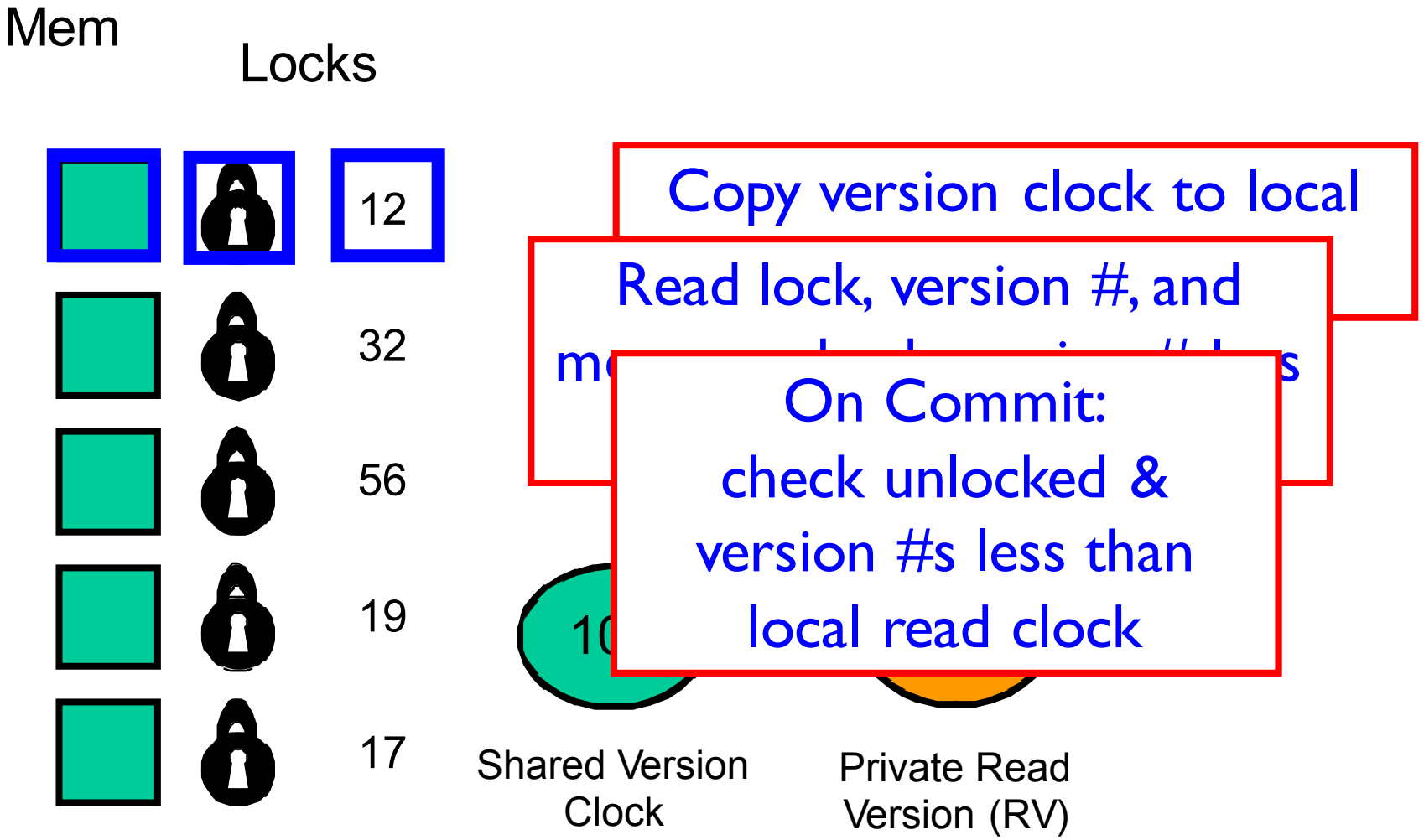


Private Read Version (RV)

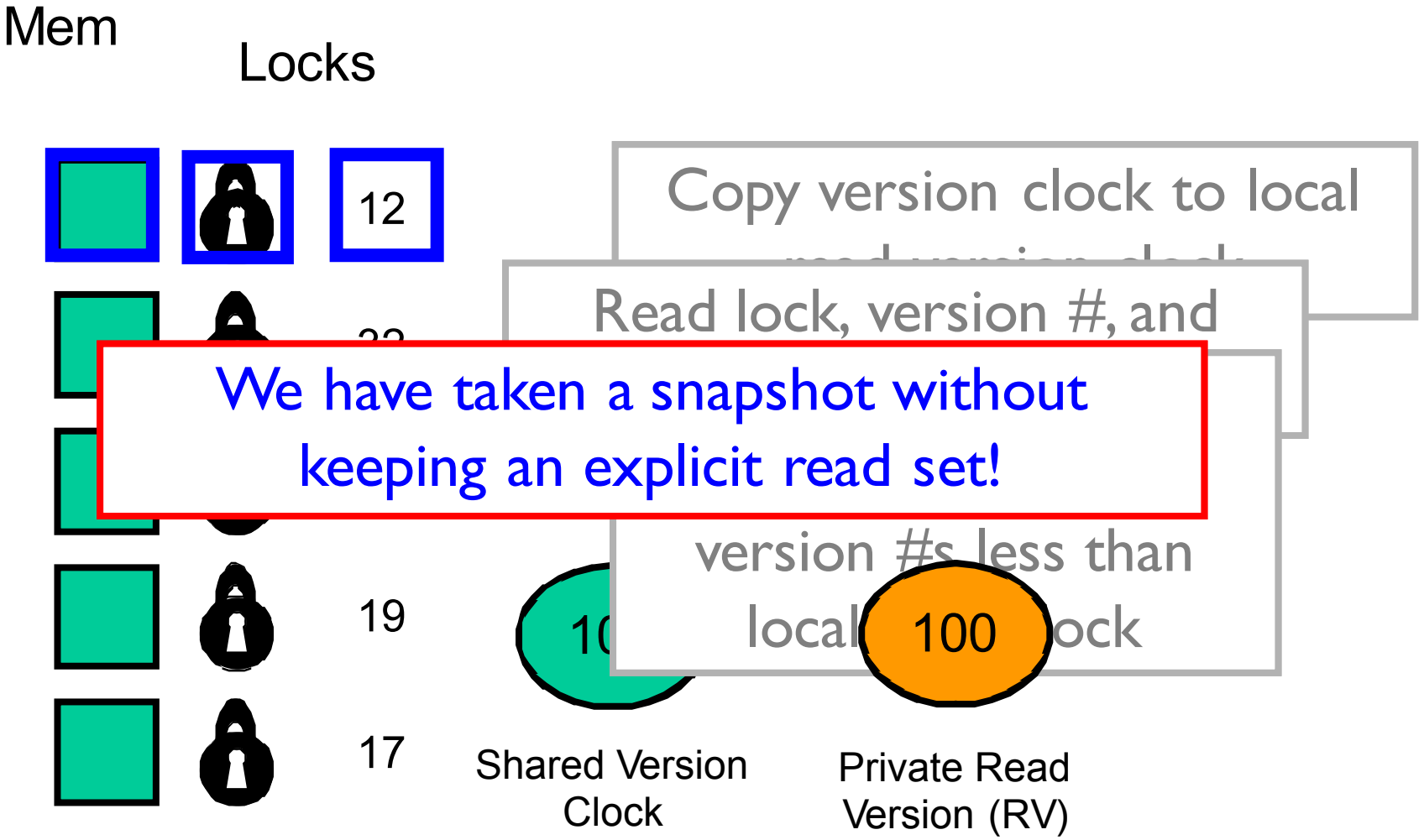
Read-Only Transactions



Read-Only Transactions

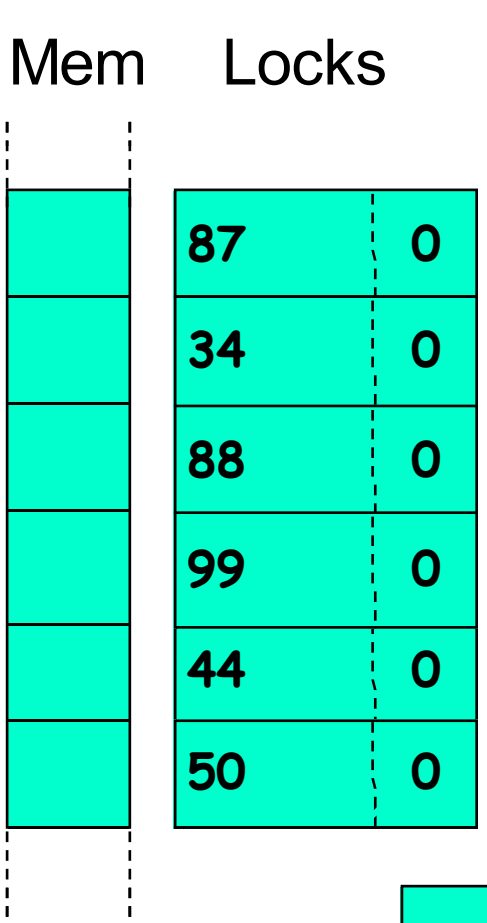


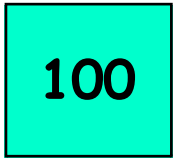
Read-Only Transactions

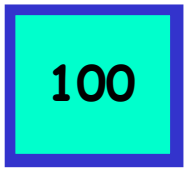


We have taken a snapshot without keeping an explicit read set!

Example Execution: Read Only Trans





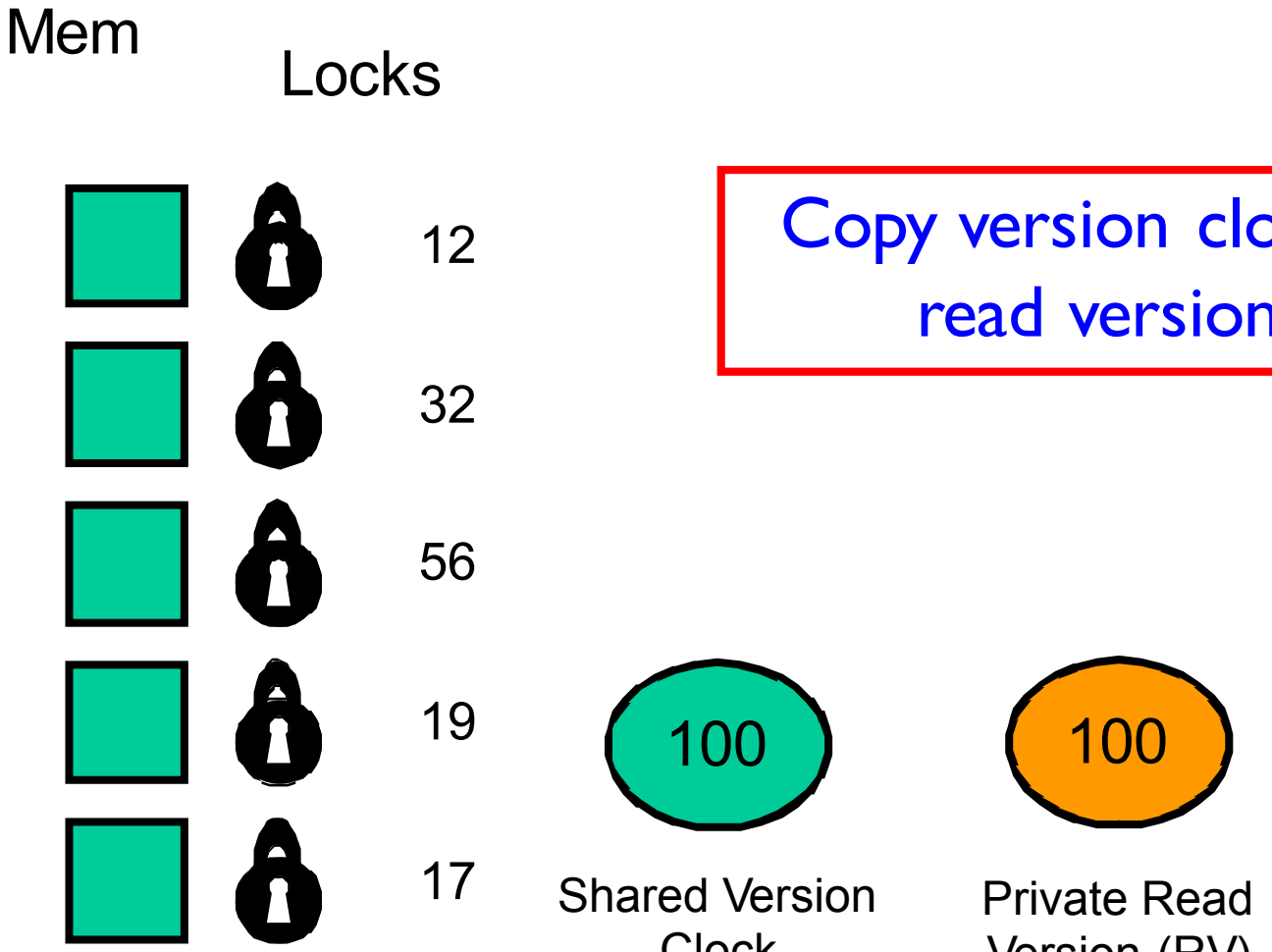


Shared Version Clock

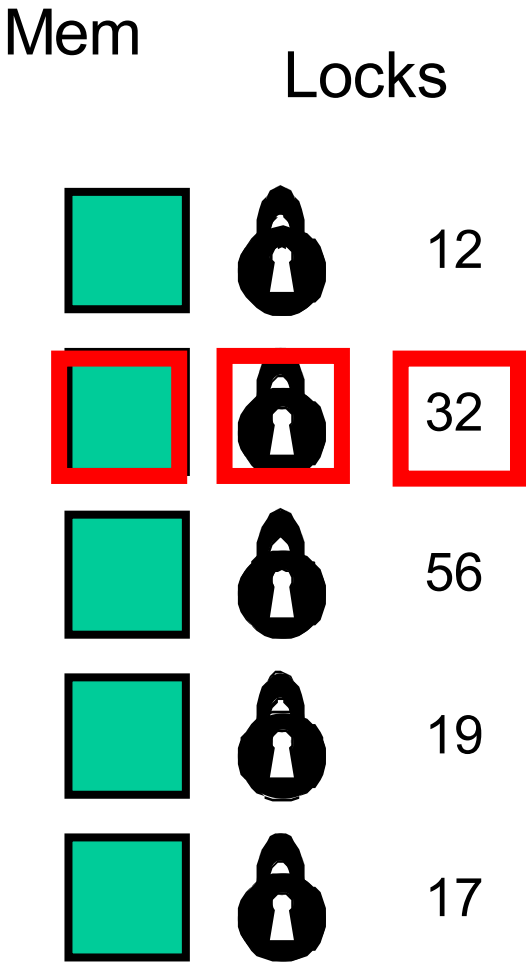
1. RV ← Shared Version Clock
2. On Read: read lock, read mem, read lock: check unlocked, unchanged, and v# <= RV
3. Commit.

Reads form a snapshot of memory.
No read set!

Ordinary (Writing) Transactions

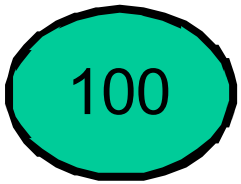


Ordinary Transactions

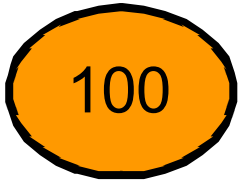


Copy version clock to local read version clock

On read/write, check:
Unlocked & version # < RV
Add to R/W set

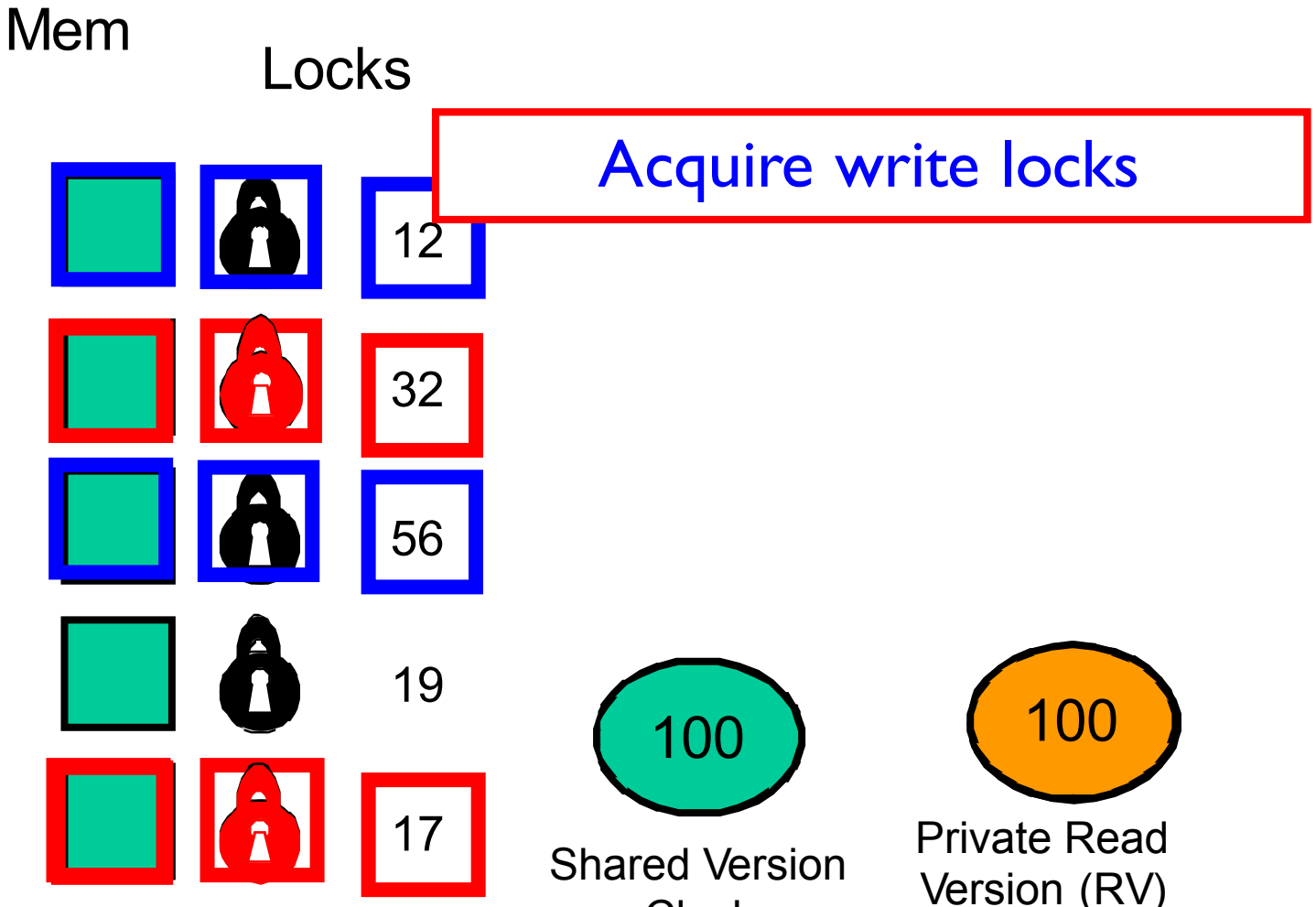


Shared Version Clock

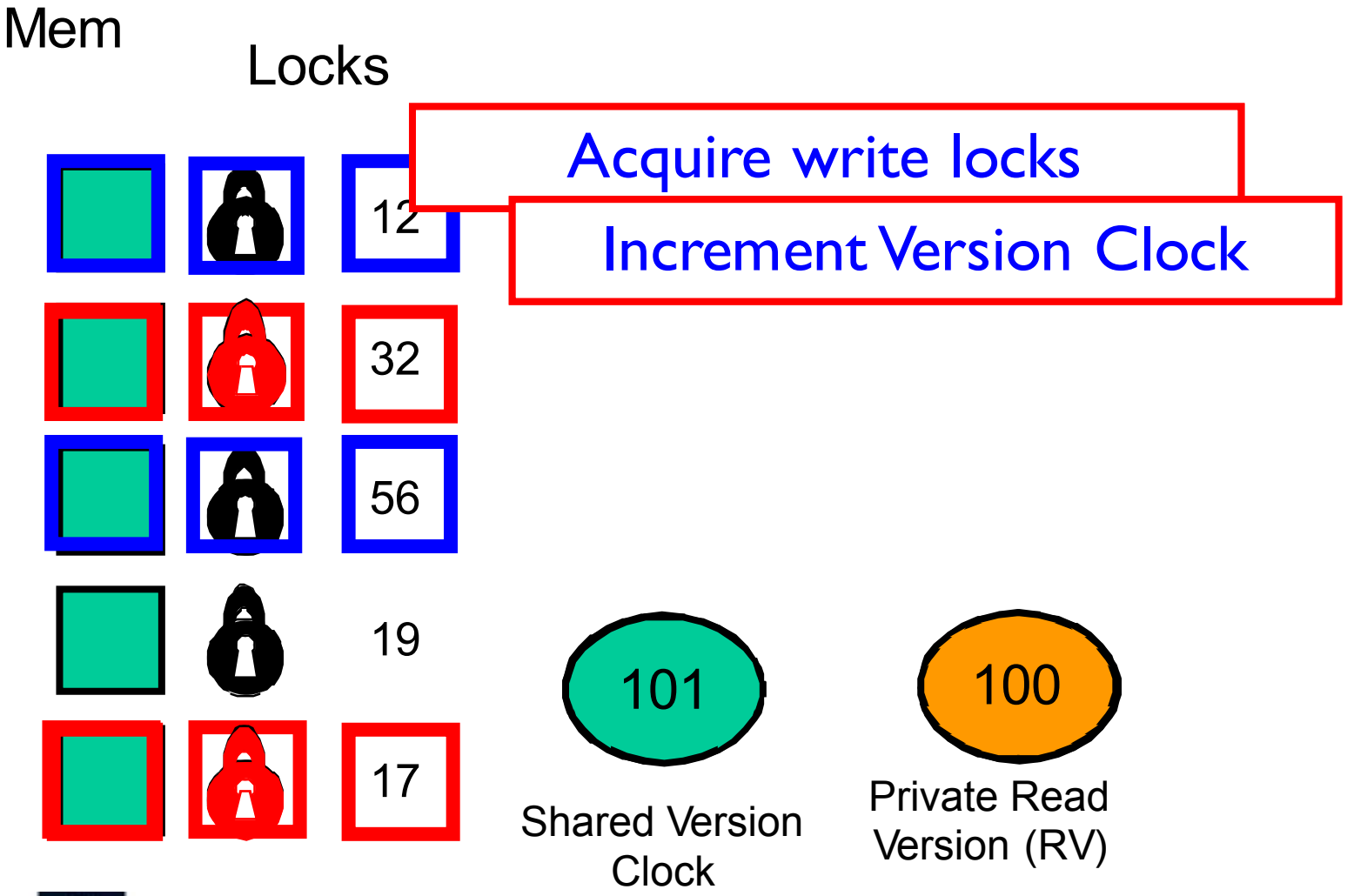


Private Read Version (RV)

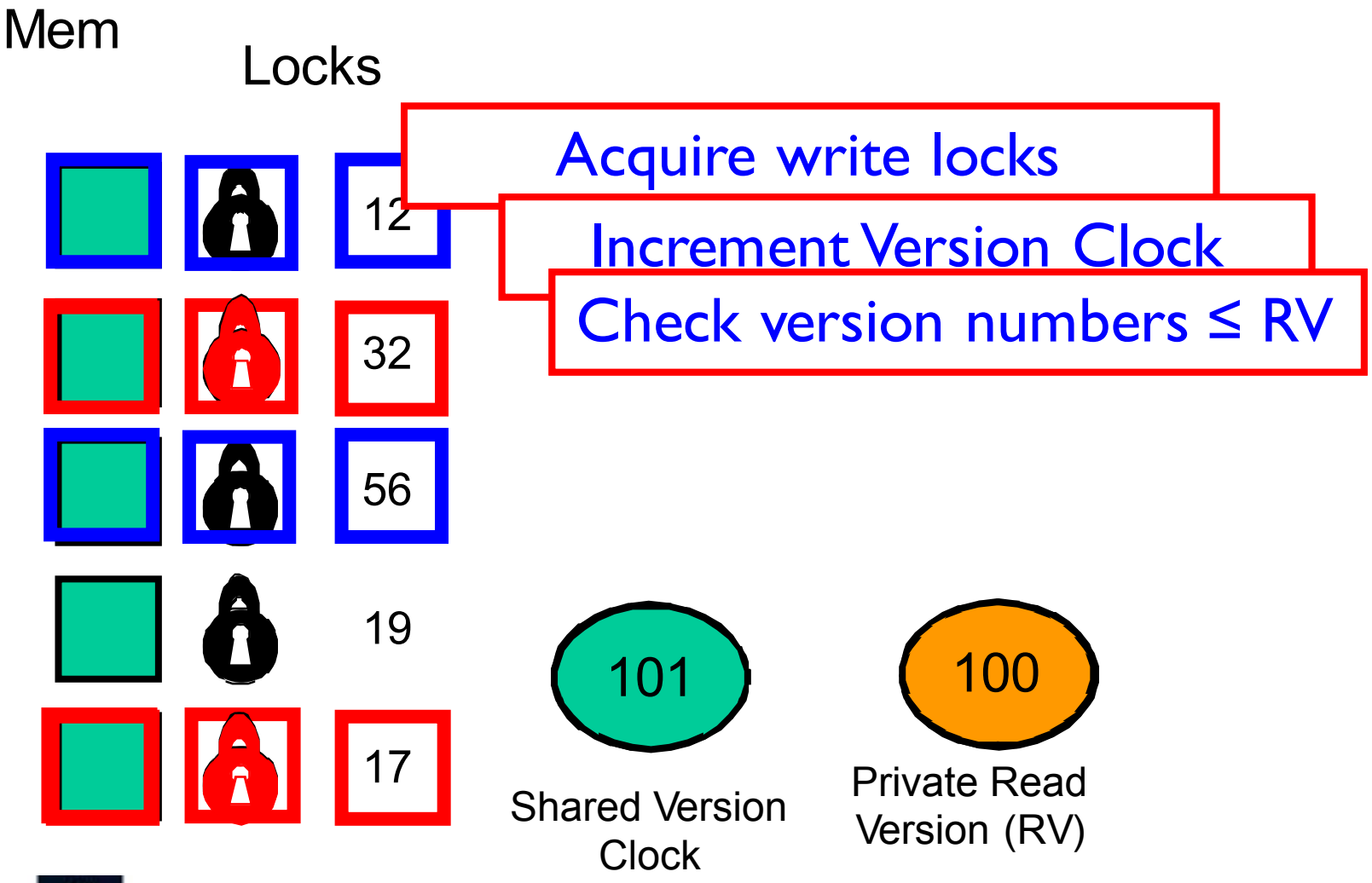
On Commit


Mem
Locks
Acquire write locks
12
32
56
19
17
100
Shared Version Clock
100
Private Read Version (RV)

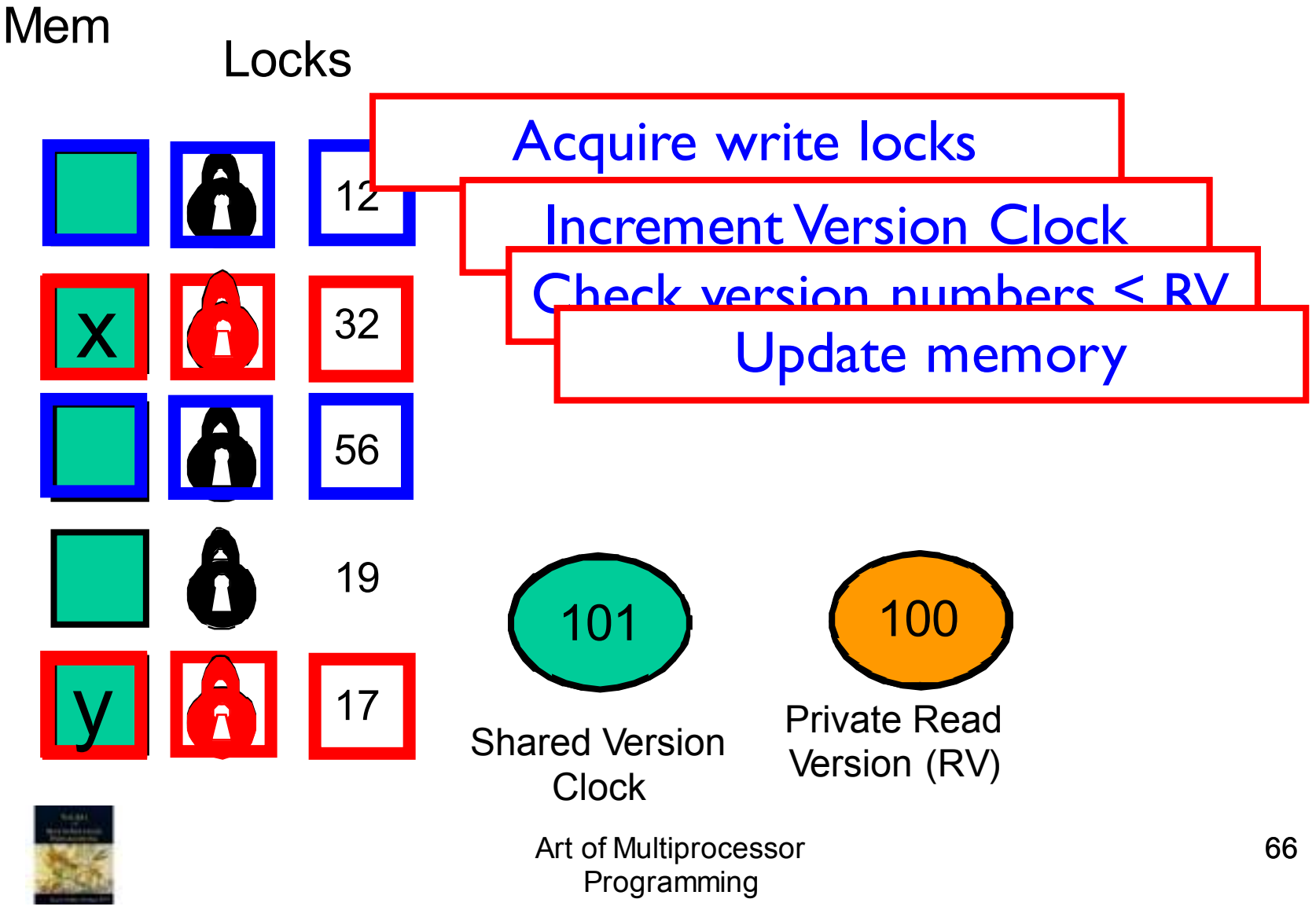
On Commit


Mem
Locks
Acquire write locks
Increment Version Clock
12
32
56
19
17
101
Shared Version Clock
100
Private Read Version (RV)

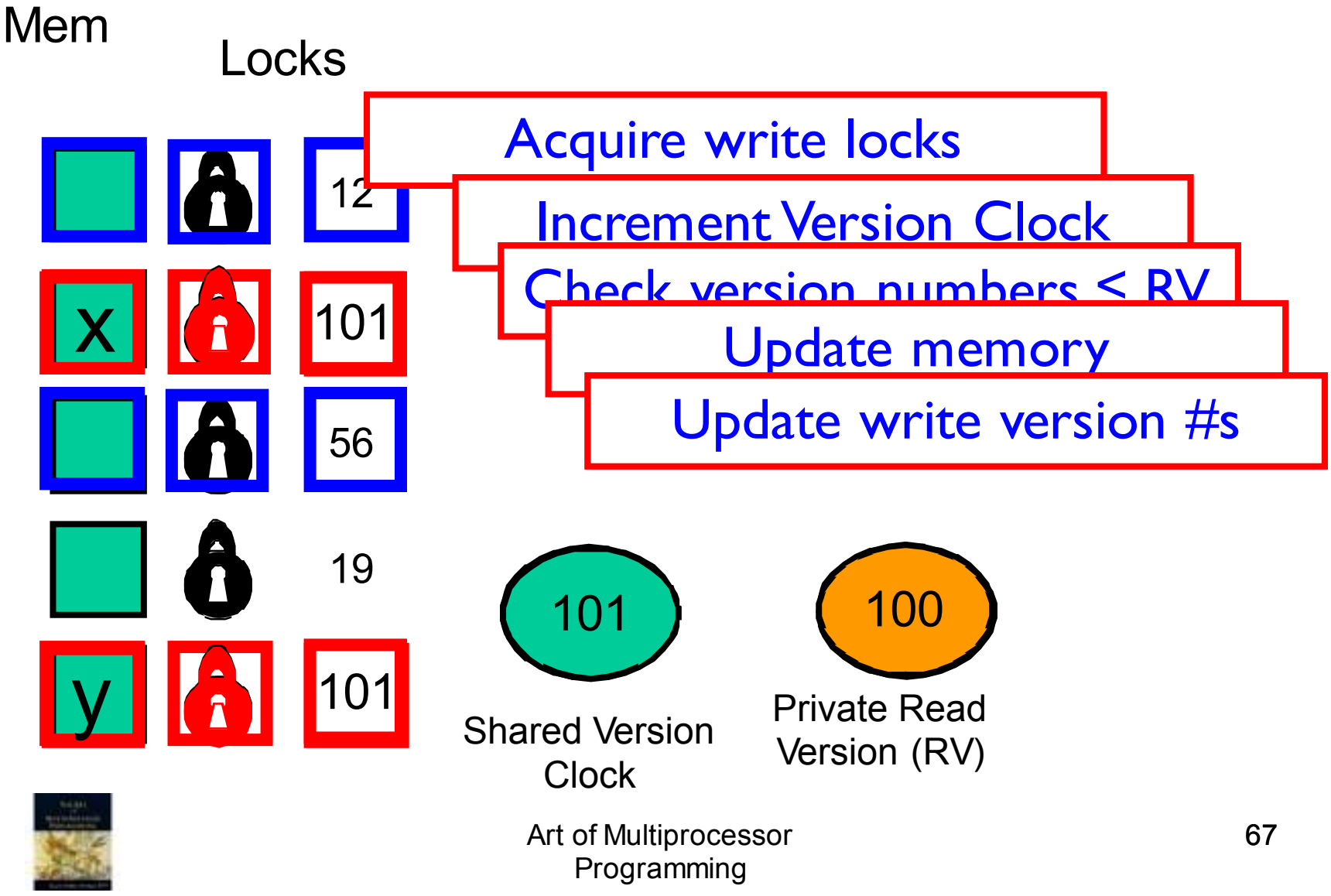
On Commit


Mem
Locks
12
32
56
19
17
Acquire write locks
Increment Version Clock
Check version numbers ≤ RV
101
Shared Version Clock
100
Private Read Version (RV)

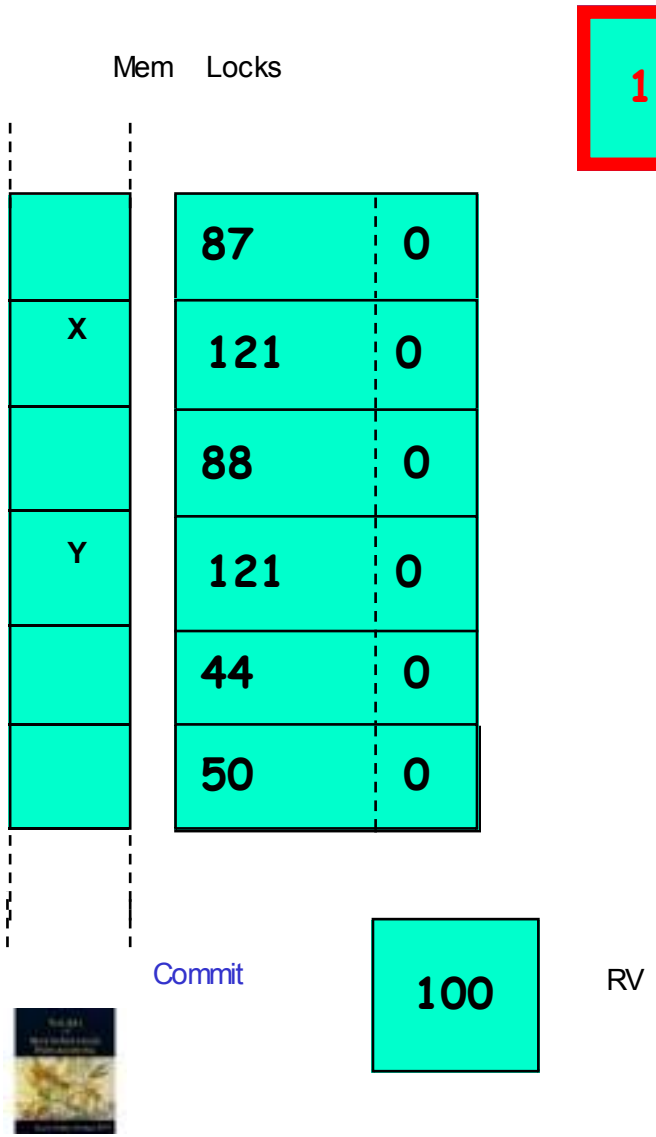
On Commit


Mem
Locks
12
x
32
56
19
y
17
Acquire write locks
Increment Version Clock
Check version numbers ≤ RV
Update memory
101
Shared Version Clock
100
Private Read Version (RV)

On Commit


Mem
Locks
12
x
101
56
19
y
101
Acquire write locks
Increment Version Clock
Check version numbers ≤ RV
Update memory
Update write version #s
101
Shared Version Clock
100
Private Read Version (RV)

Example: Writing Trans



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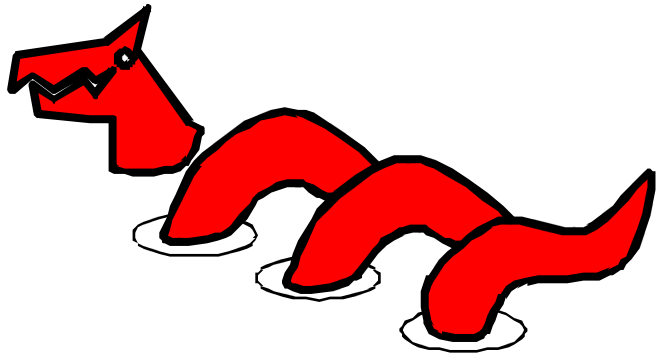
Shared Version Clock

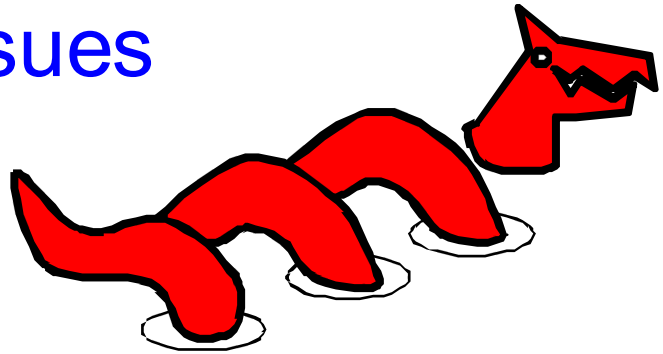
1. RV ← Shared Version Clock
2. On Read/Write: check unlocked and v# <= RV then add to Read/Write-Set
3. Acquire Locks
4. WV = F&I(VClock)
5. Validate each v# <= RV
6. Release locks with v# ← WV

Reads+Inc+Writes =serializable

TM Design Issues

- Implementation choices
- Language design issues
- Semantic issues





Granularity

- Object
  - managed languages, Java, C#, …
  - Easy to control interactions between transactional & non-trans threads
- Word
  - C, C++, …
  - Hard to control interactions between transactional & non-trans threads

Direct/Deferred Update

- *Deferred*
  - modify private copies & install on commit
  - Commit requires work
  - Consistency easier
- *Direct*
  - Modify in place, roll back on abort
  - Makes commit efficient
  - Consistency harder

Conflict Detection

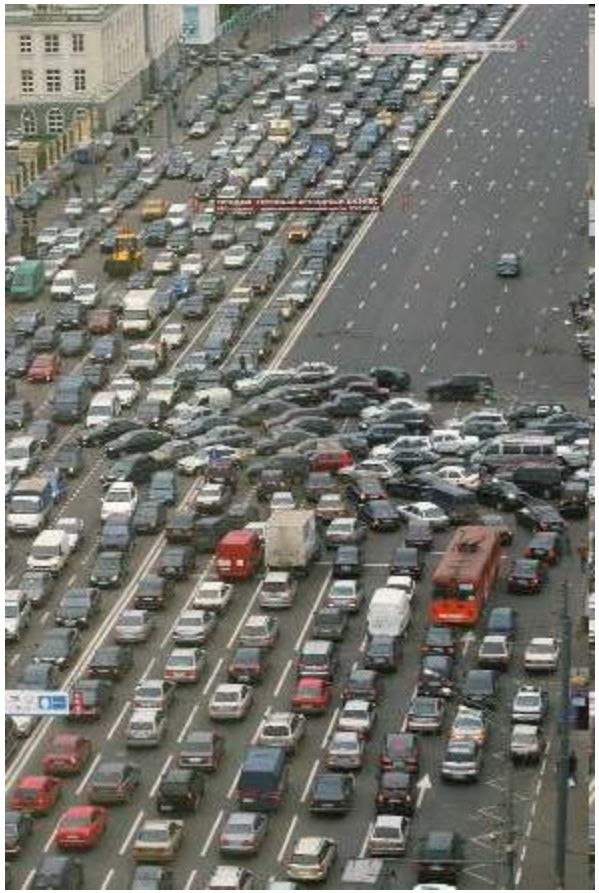
- Eager
  - Detect before conflict arises
  - “Contention manager” module resolves
- Lazy
  - Detect on commit/abort
- Mixed
  - Eager write/write, lazy read/write …

Conflict Detection

- Eager detection may abort transactions that could have committed.
- Lazy detection discards more computation.

Contention Management & Scheduling

- How to resolve conflicts?
- Who moves forward and who rolls back?
- Lots of empirical work but formal work in infancy



Contention Manager Strategies

- Exponential backoff
- Priority to
  - Oldest?
  - Most work?
  - Non-waiting?
- None Dominates
- But needed anyway

Judgment of Solomon

I/O & System Calls?

- Some I/O revocable
  - Provide transaction-safe libraries
  - Undoable file system/DB calls
- Some not
  - Opening cash drawer
  - Firing missile

I/O & System Calls

- One solution: make transaction irrevocable
  - If transaction tries I/O, switch to irrevocable mode.
- There can be only one …
  - Requires serial execution
- No explicit aborts
  - In irrevocable transactions

Exceptions

```
int i = 0;
try {
  atomic {
    i++;
    node = new Node();
  }
} catch (Exception e) {
  print(i);
}
```

Exceptions

Throws OutOfMemoryException!

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int i = 0;
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Exceptions

Throws OutOfMemoryException!

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int i = 0;
try {
  atomic {
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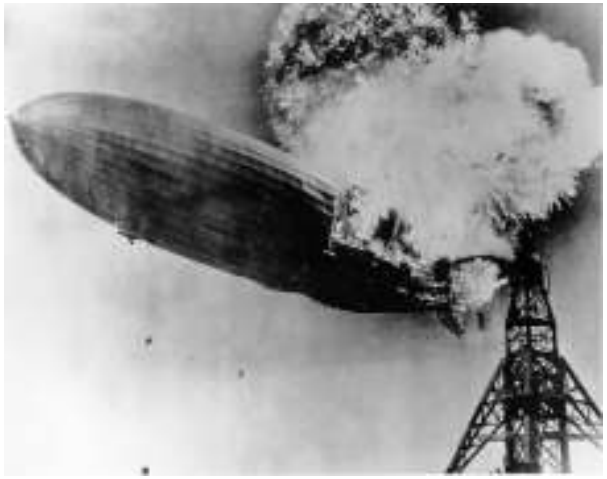
  print(i);
}
```

What is printed?

Unhandled Exceptions

- Aborts transaction
  - Preserves invariants
  - Safer
- Commits transaction
  - Like locking semantics
  - What if exception object refers to values modified in transaction?



Nested Transactions

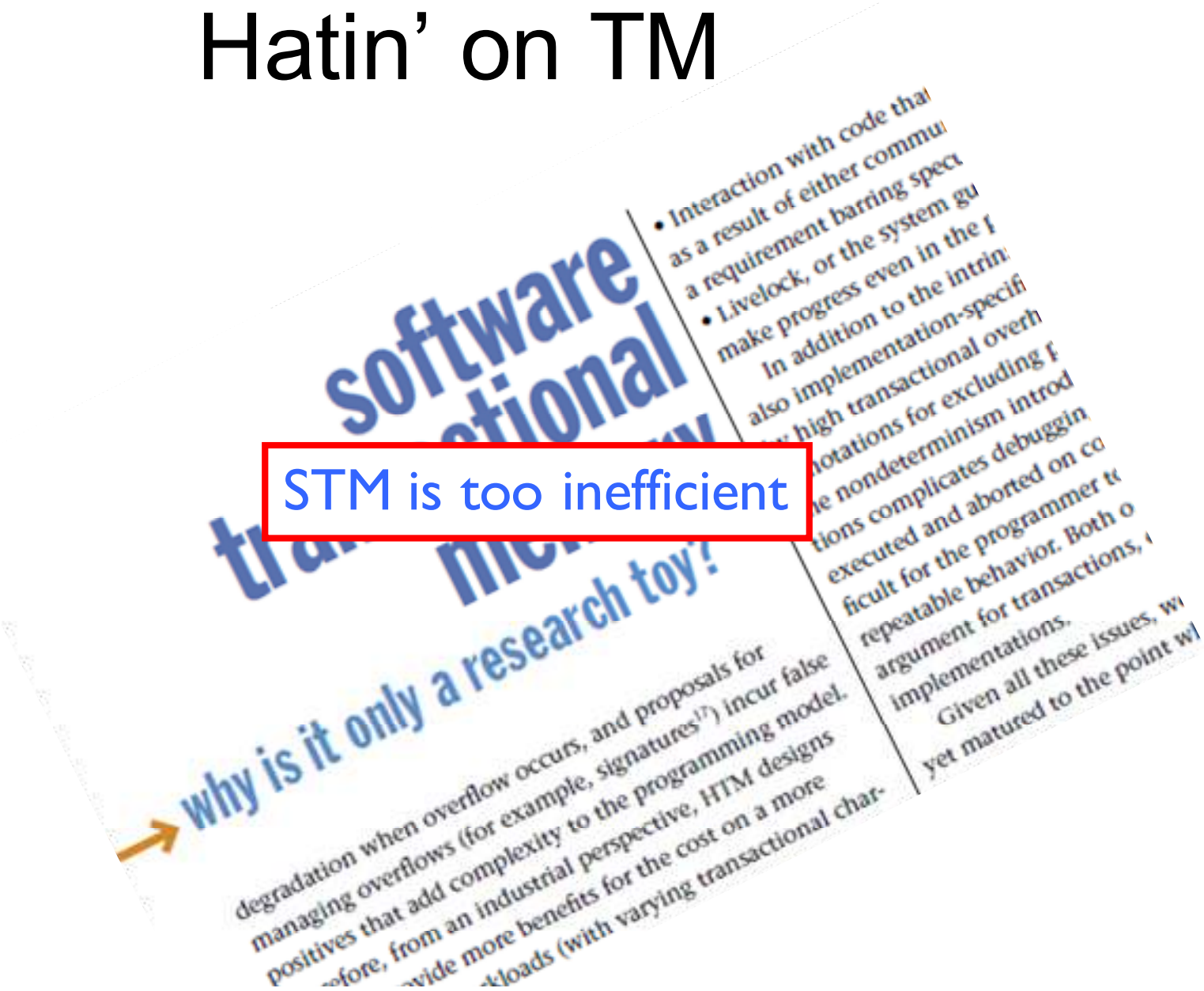
```
atomic void foo() {
  bar();
}

atomic void bar() {
 …
}
```

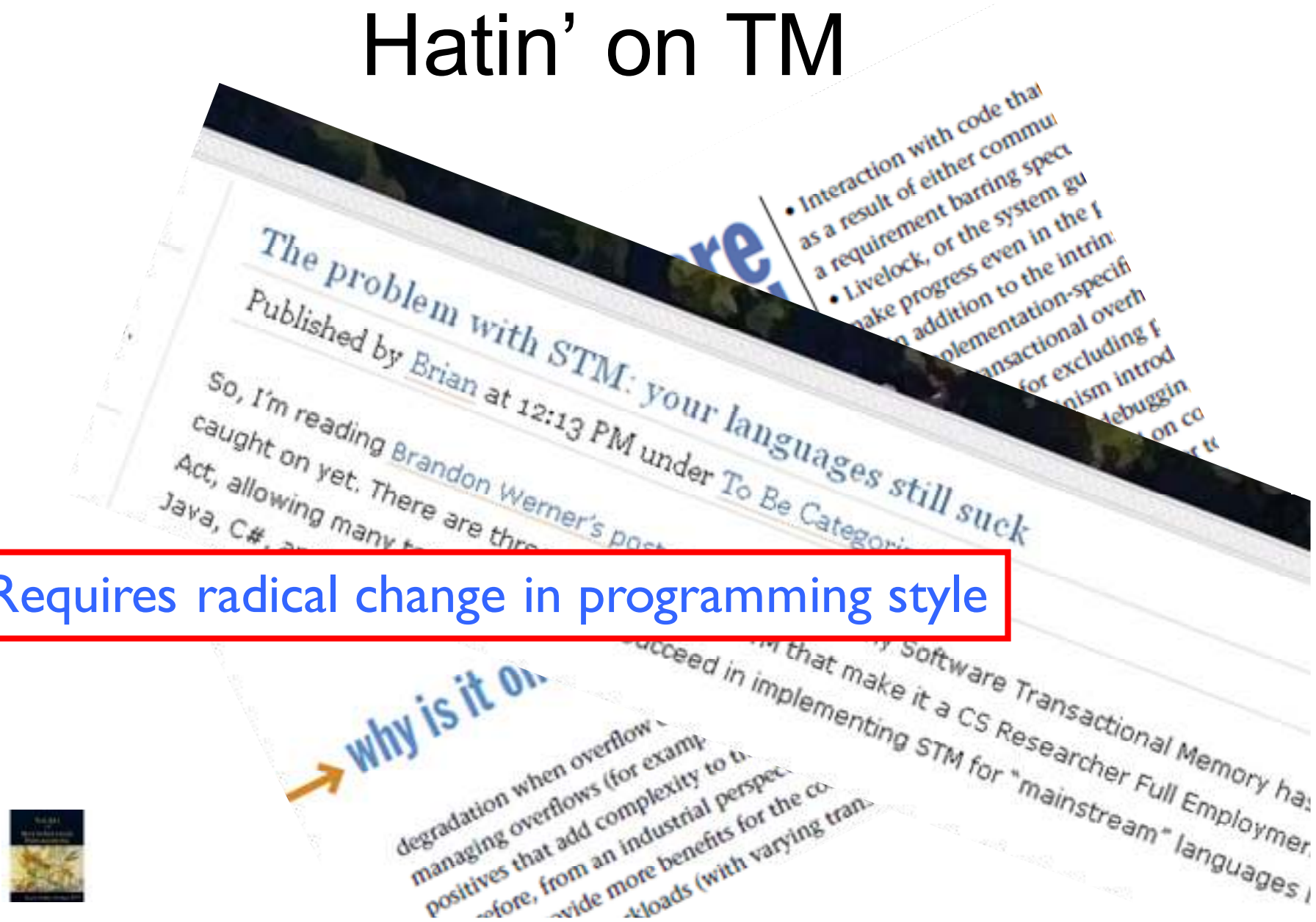
Nested Transactions

- Needed for modularity
  - Who knew that cosine() contained a transaction?
- Flat nesting
  - If child aborts, so does parent
- First-class nesting
  - If child aborts, partial rollback of child only

Hatin' on TM

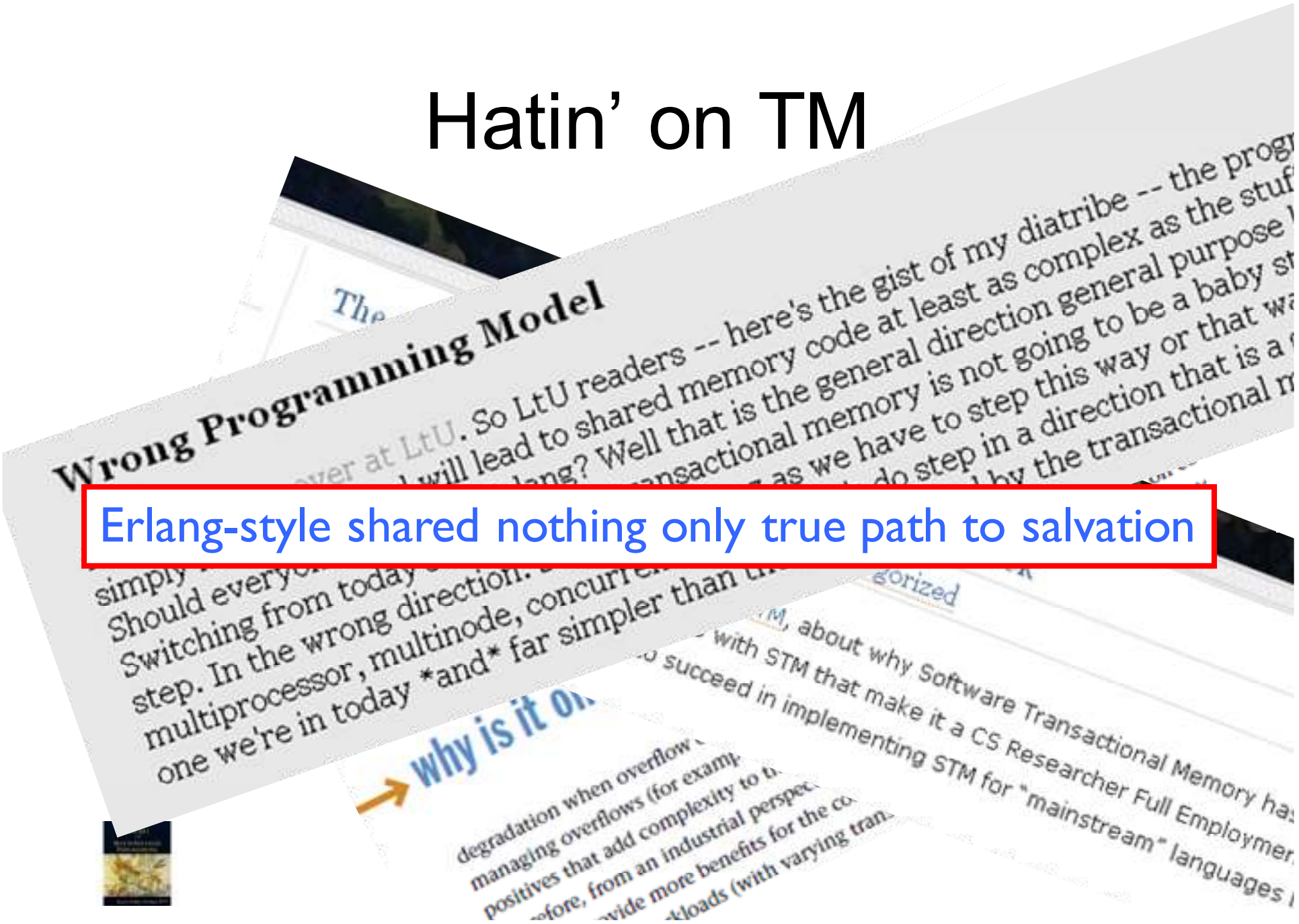

software
why is it only a research toy?
STM is too inefficient
degradation when overflow occurs, and proposals for
managing overflows (for example, signatures[17]) incur false
positives that add complexity to the programming model.
efore, from an industrial perspective, HTM designs
ovide more benefits for the cost on a more
kloads (with varying transactional char-
• Interaction with code tha
as a result of either commu
a requirement barring spec
• Livelock, or the system gu
make progress even in the
In addition to the intrin
also implementation-specifi
high transactional overh
notations for excluding
e nondeterminism introd
tions complicates debuggin
executed and aborted on co
ficult for the programmer t
repeatable behavior. Both o
argument for transactions,
implementations.
Given all these issues, w
yet matured to the point w

Hatin' on TM

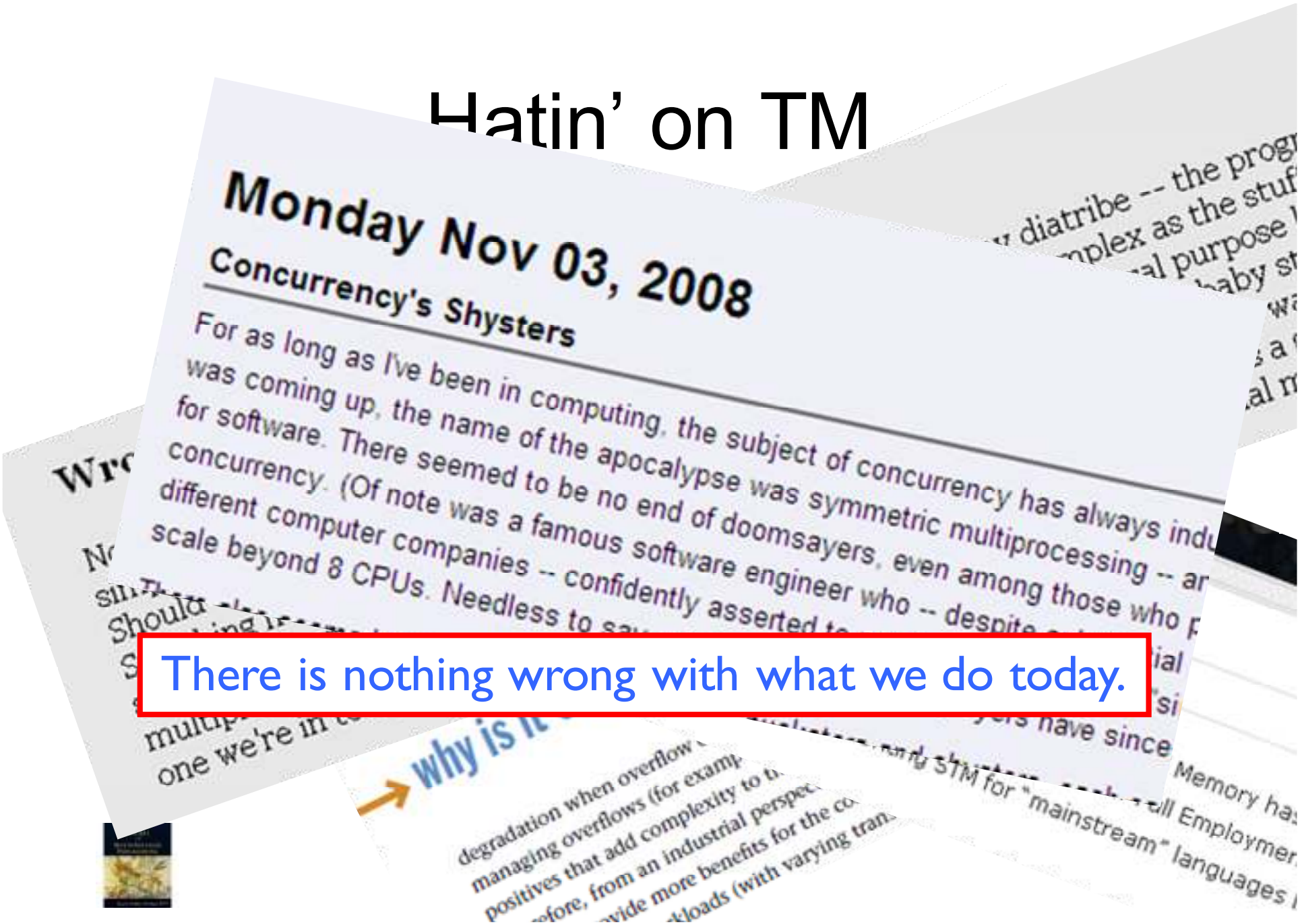


Requires radical change in programming style

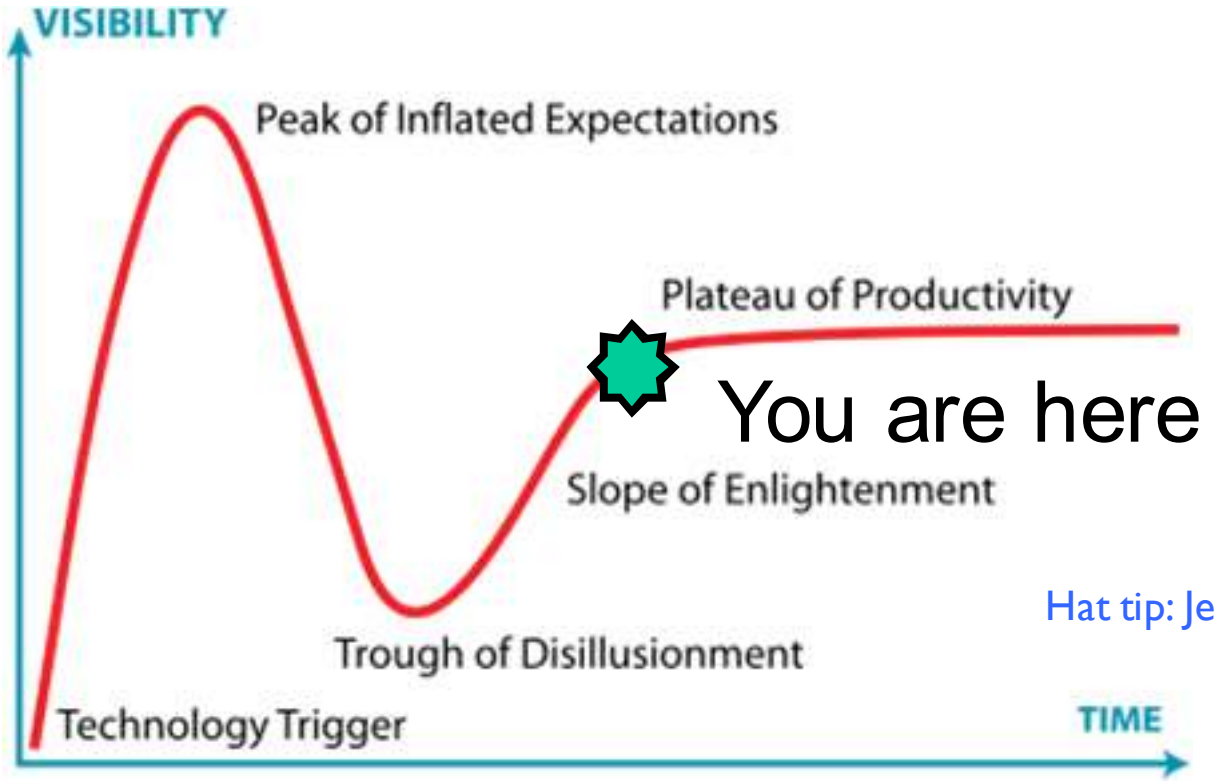
Hatin' on TM


Wrong Programming Model
Erlang-style shared nothing only true path to salvation

Hatin' on TM


Monday Nov 03, 2008
Concurrency's Shysters
For as long as I've been in computing, the subject of concurrency has always
was coming up, the name of the apocalypse was symmetric multiprocessing --
for software. There seemed to be no end of doomsayers, even among those who
concurrency. (Of note was a famous software engineer who -- despite
different computer companies -- confidently asserted
scale beyond 8 CPUs. Needless to
There is nothing wrong with what we do today.
why is it
degradation when overflow
managing overflows (for
positives that add complexity to
efore, from an industrial
vide more benefits for the
kloads (with varying
have since
STM for "mainstream" languages
Memory
Employmer

Gartner Hype Cycle



Hat tip: Jeremy Kemp

I, for one, Welcome our new Multicore Overlords …

- Multicore forces us to rethink almost everything

I, for one, Welcome our new Multicore Overlords …

- Multicore forces us to rethink almost everything
- Standard approaches too complex

I, for one, Welcome our new Multicore Overlords …

- Multicore forces us to rethink almost everything
- Standard approaches won't scale
- Transactions might make life simpler…

I, for one, Welcome our new Multicore Overlords …

- Multicore forces us to rethink almost everything
- Standard approaches won't sca
- Transactions might …
- Multicore programming

  Plenty more to do…

  Maybe ***you*** will save us…

Thanks ! תודה