NON-BLOCKING DATA STRUCTURES AND TRANSACTIONAL MEMORY

Tim Harris, 14 November 2013

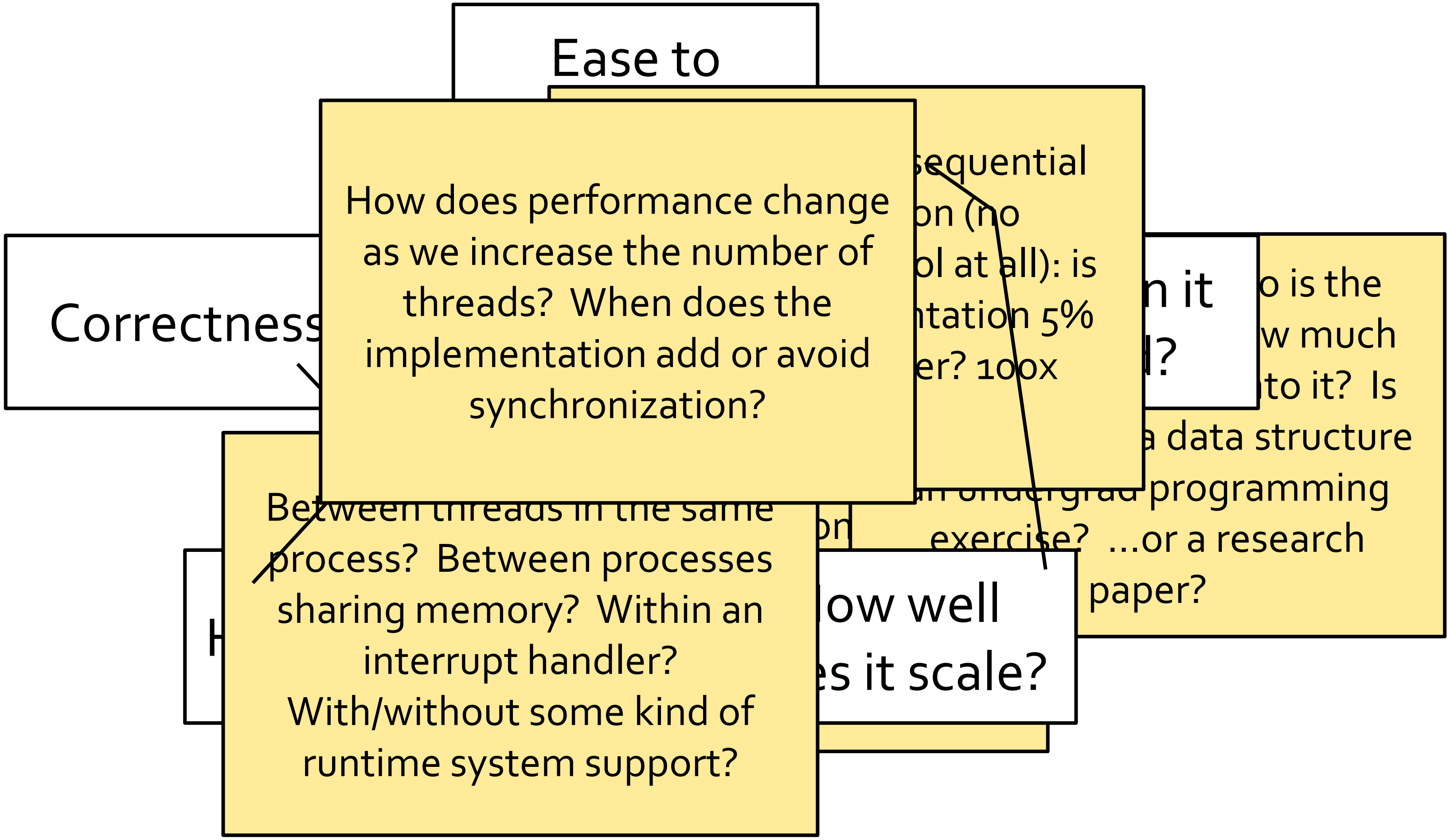
Lecture 6

- Introduction
- Amdahl’s law
- Basic spin-locks
- Queue-based locks
- Hierarchical locks
- Reader-writer locks
- Reading without locking
- Flat combining

Overview

- Building shared memory data structures
  - Lists, queues, hashtables, …
- Why?
  - Used directly by applications (e.g., in C/C++, Java, C#, …)
  - Used in the language runtime system (e.g., management of work, implementations of message passing, …)
  - Used in traditional operating systems (e.g., synchronization between top/bottom-half code)
- Why not?
  - Don't think of "threads + shared data structures" as a default/good/complete/desirable programming model
  - It's better to have shared memory and not need it…

What do we care about?



Ease to

Correctness

How does performance change as we increase the number of threads? When does the implementation add or avoid synchronization?

sequential
on (no
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w much
nto it? Is
a data structure
n undergrad programming
exercise? ...or a research
paper?

Between threads in the same process? Between processes sharing memory? Within an interrupt handler? With/without some kind of runtime system support?

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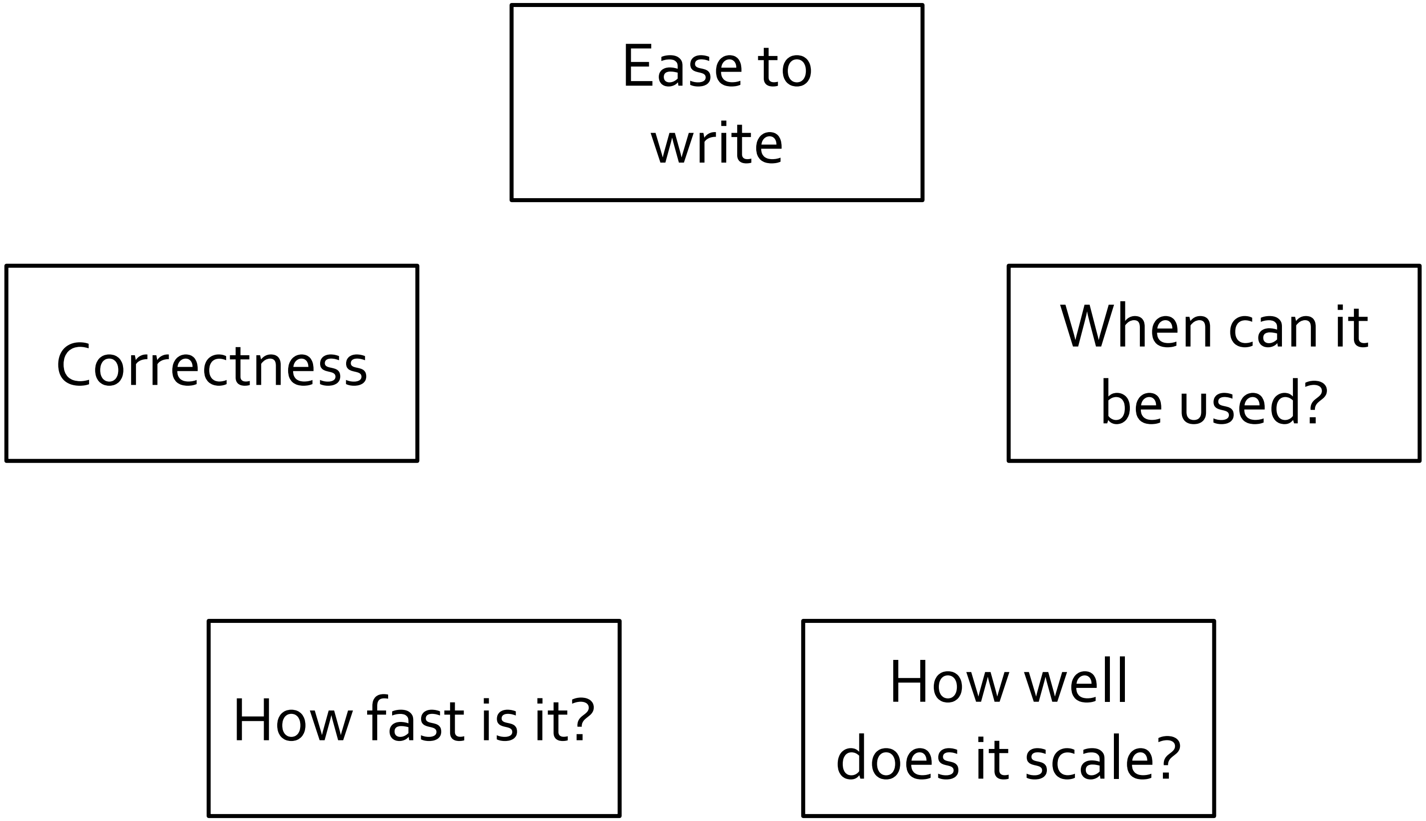
es it scale?

What do we care about?



Ease to write

Correctness

When can it be used?

How fast is it?

How well does it scale?

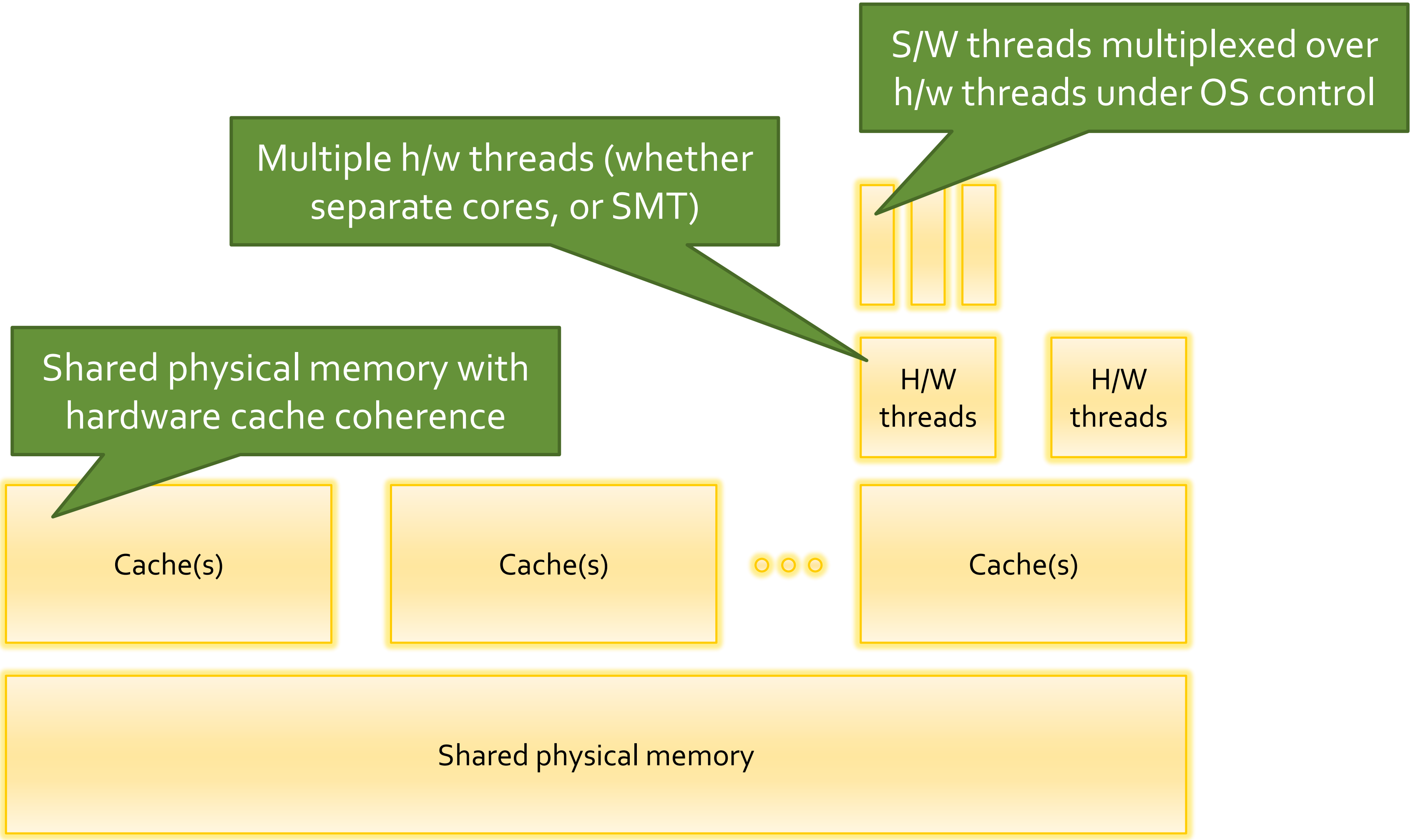
What do we care about?

1. Be explicit about goals and trade-offs
   - A benefit in one dimension often has costs in another
   - Does a perf increase prevent a data structure being used in some particular setting?
   - Does a technique to make something easier to write make the implementation slower?
   - Do we care? It depends on the setting
2. Remember, parallel programming is rarely a recreational activity
   - The ultimate goal is to increase perf (time, or resources used)
   - Does an implementation scale well enough to out-perform a good sequential implementation?

Suggested reading

- “The art of multiprocessor programming”, Herlihy & Shavit – excellent coverage of shared memory data structures, from both practical and theoretical perspectives
- “Transactional memory, 2nd edition”, Harris, Larus, Rajwar – recently revamped survey of TM work, with 350+ references
- “NOrec: streamlining STM by abolishing ownership records”, Dalessandro, Spear, Scott, PPoPP 2010
- “Simplifying concurrent algorithms by exploiting transactional memory”, Dice, Lev, Marathe, Moir, Nussbaum, Olszewski, SPAA 2010
- Intel “Haswelll” spec for SLE (speculative lock elision) and RTM (restricted transactional memory)

System model



S/W threads multiplexed over h/w threads under OS control

Multiple h/w threads (whether separate cores, or SMT)

Shared physical memory with hardware cache coherence

Three kinds of parallel hardware

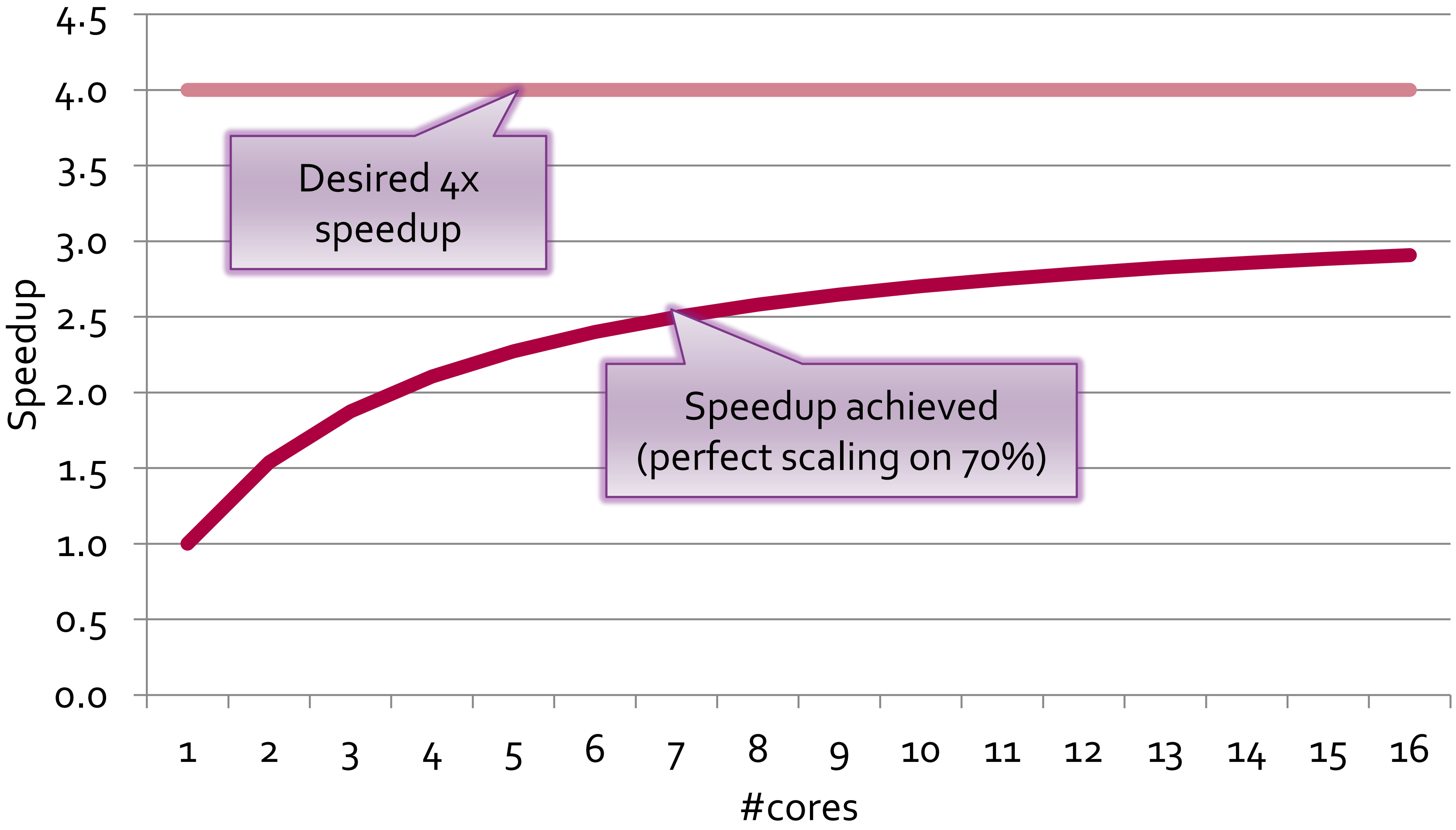
- Multi-threaded cores
  - Increase utilization of a core or memory b/w
  - Tolerate long latency operations
  - Peak ops/cycle fixed
- Multiple cores
  - Increase ops/cycle
  - Caches and off-chip resources don’t necessarily scale proportionately
- Multi-processor machines
  - Increase ops/cycle
  - Often scale cache & memory capacities and b/w proportionately
  - NUMA memory effects

Amdahl’s law

Amdahl’s law

- “Sorting takes 70% of the execution time of a sequential program. You replace the sorting algorithm with one that scales perfectly on multi-core hardware. On a machine with *n* cores, how many cores do you need to use to get a 4x speed-up on the overall algorithm?”

Amdahl's law, f=70%



Desired 4x speedup

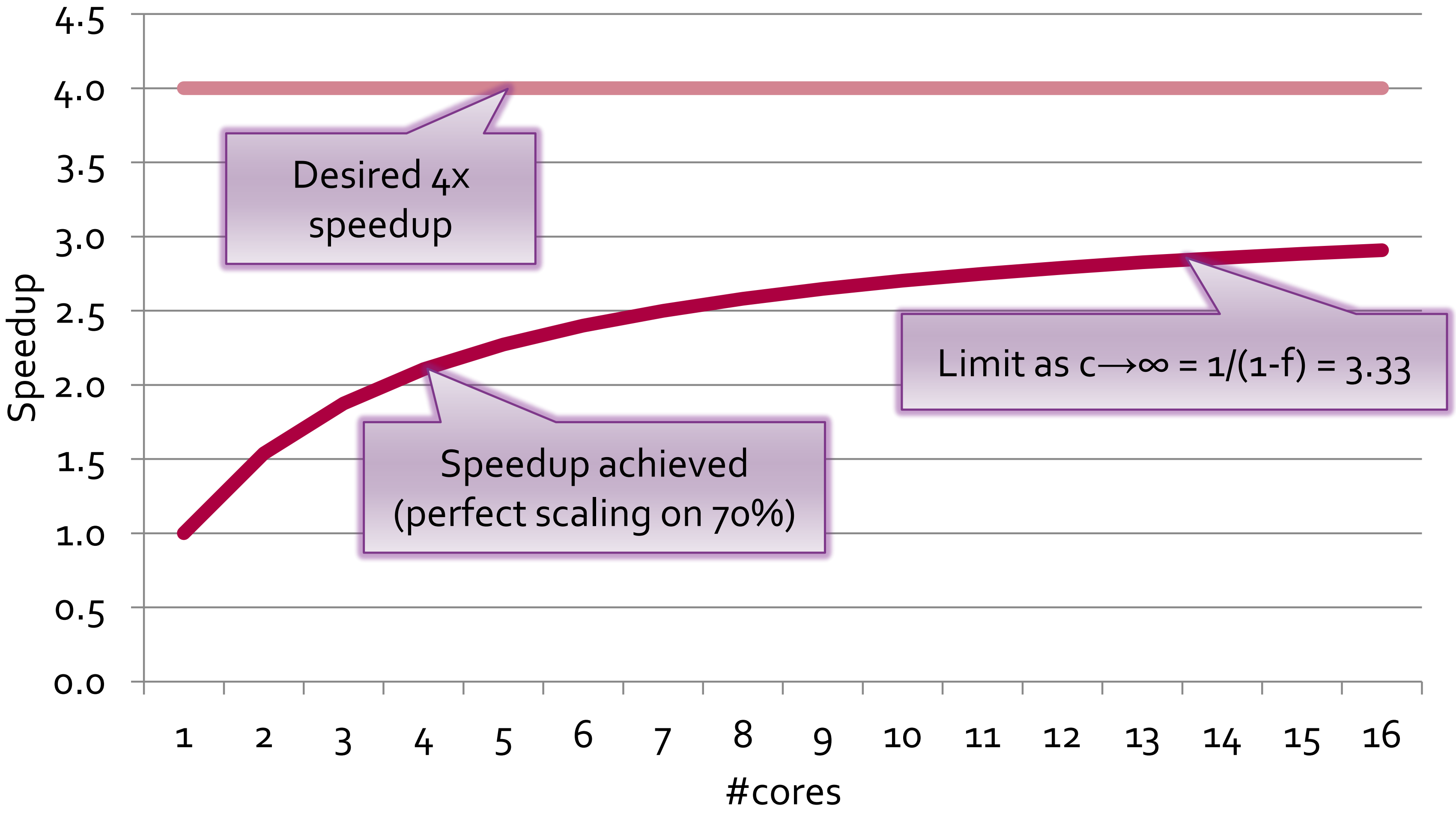
Speedup achieved (perfect scaling on 70%)

Amdahl’s law, f=70%

$$MaxSpeedup(f, c) = \frac{1}{(1 - f) + {}^{f}/_{c}}$$

f = fraction of code speedup applies to
c = number of cores used

Amdahl's law, f=70%

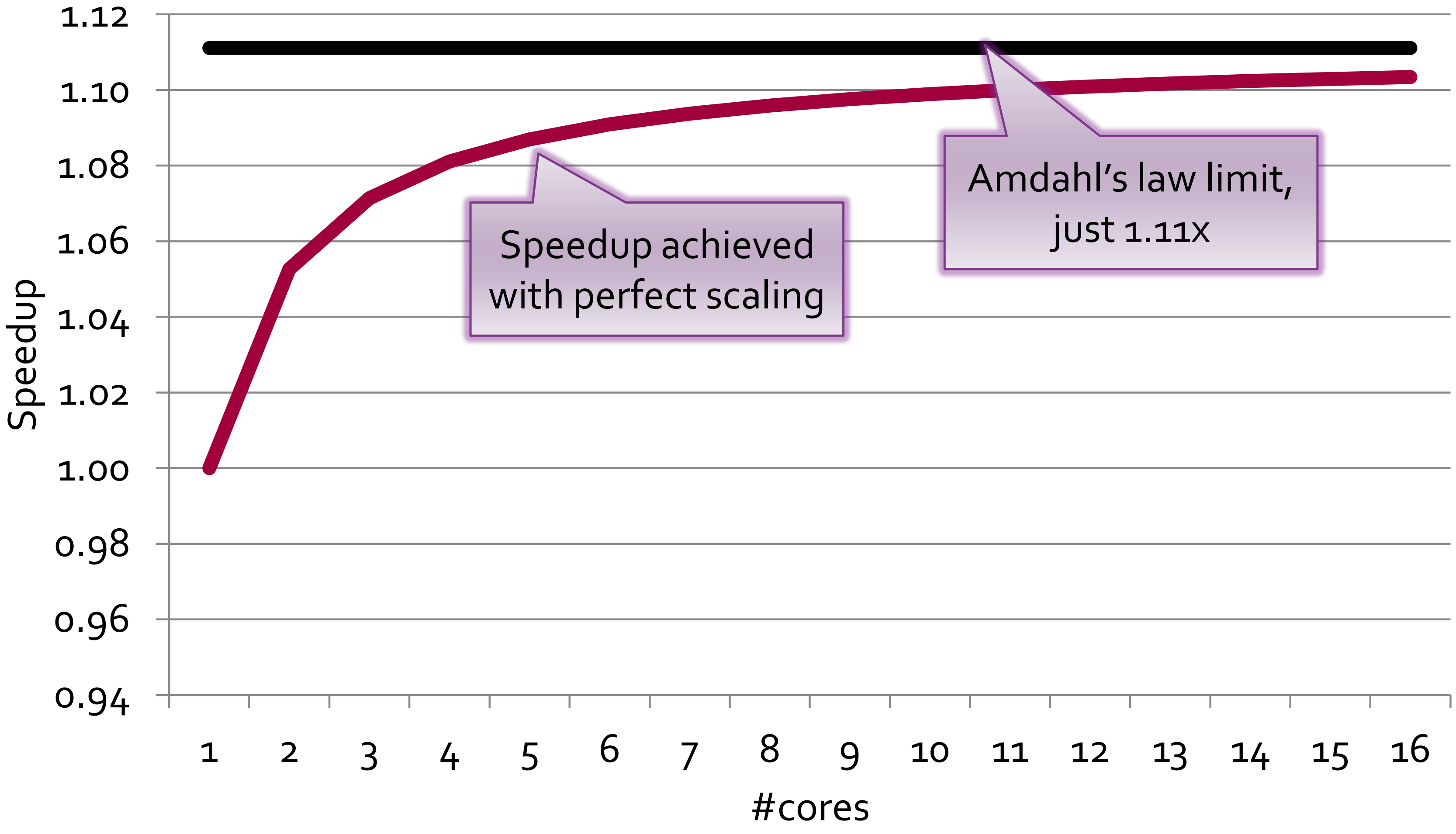


Desired 4x speedup

Limit as c→∞ = 1/(1-f) = 3.33

Speedup achieved (perfect scaling on 70%)

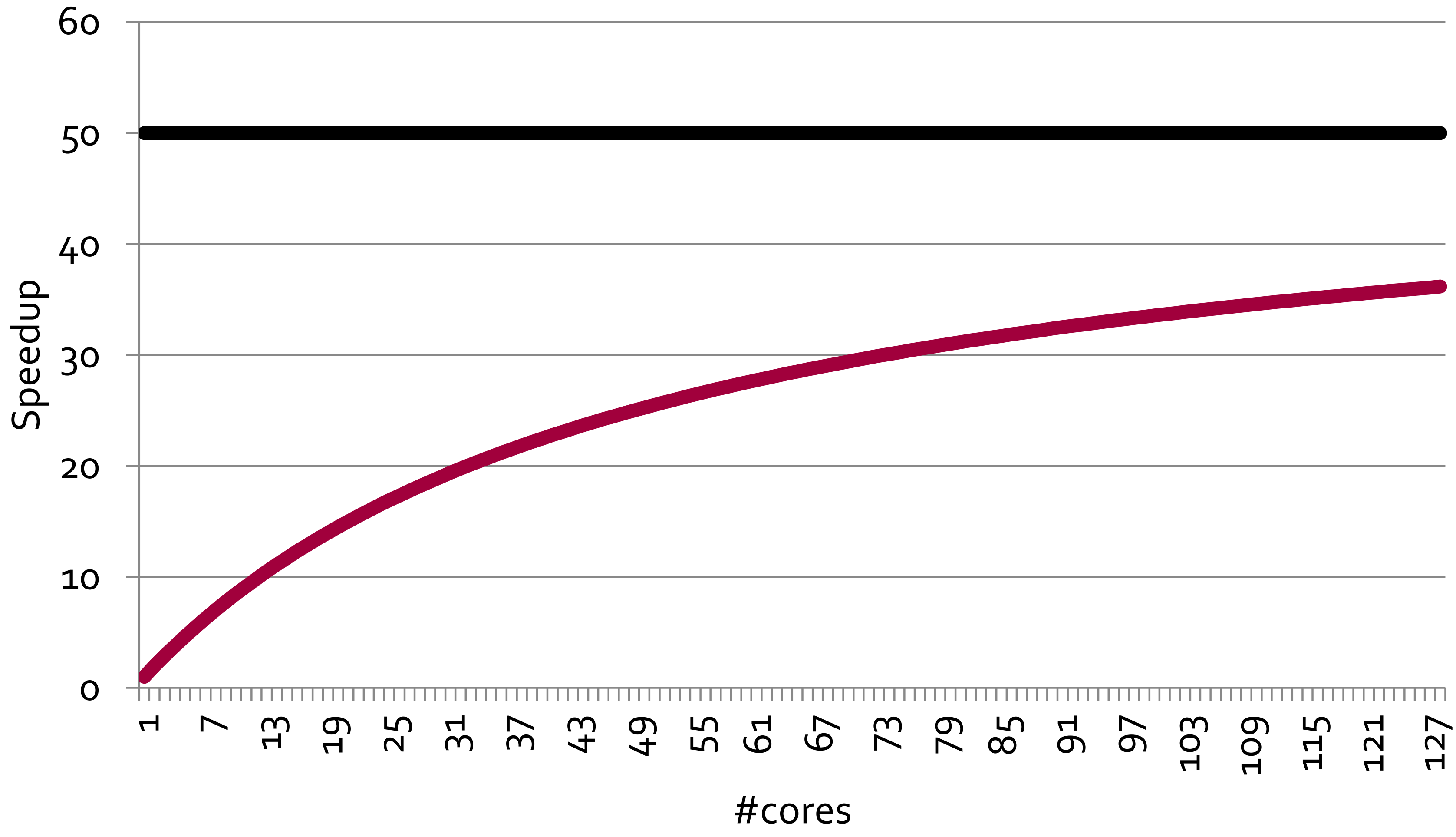
Amdahl's law, f=10%



Speedup achieved with perfect scaling

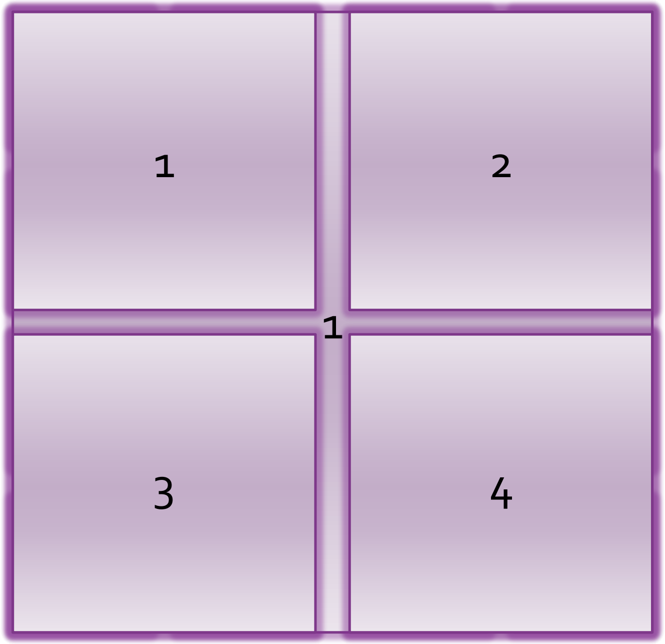
Amdahl's law limit, just 1.11x

Amdahl's law, f=98%

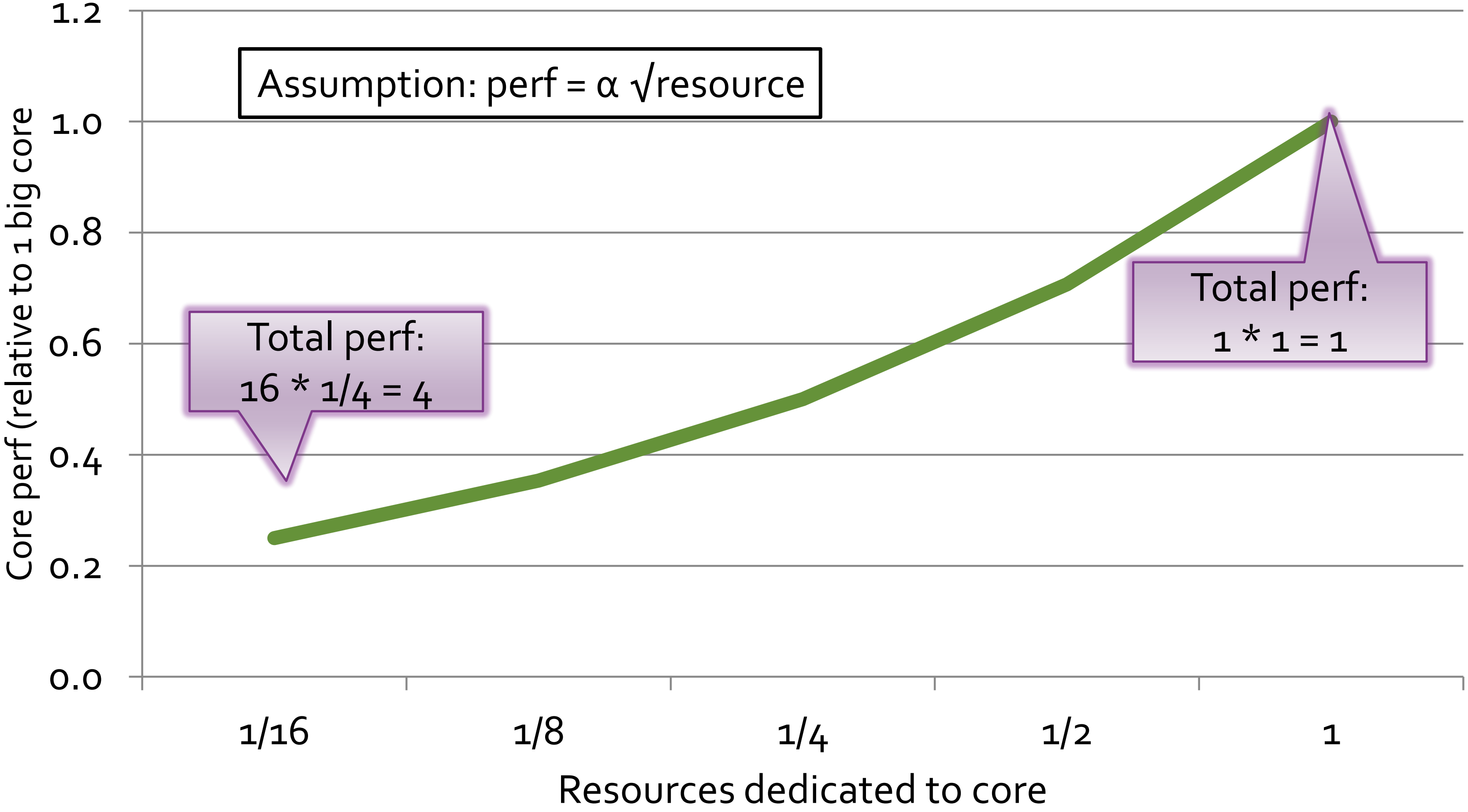


Amdahl’s law & multi-core

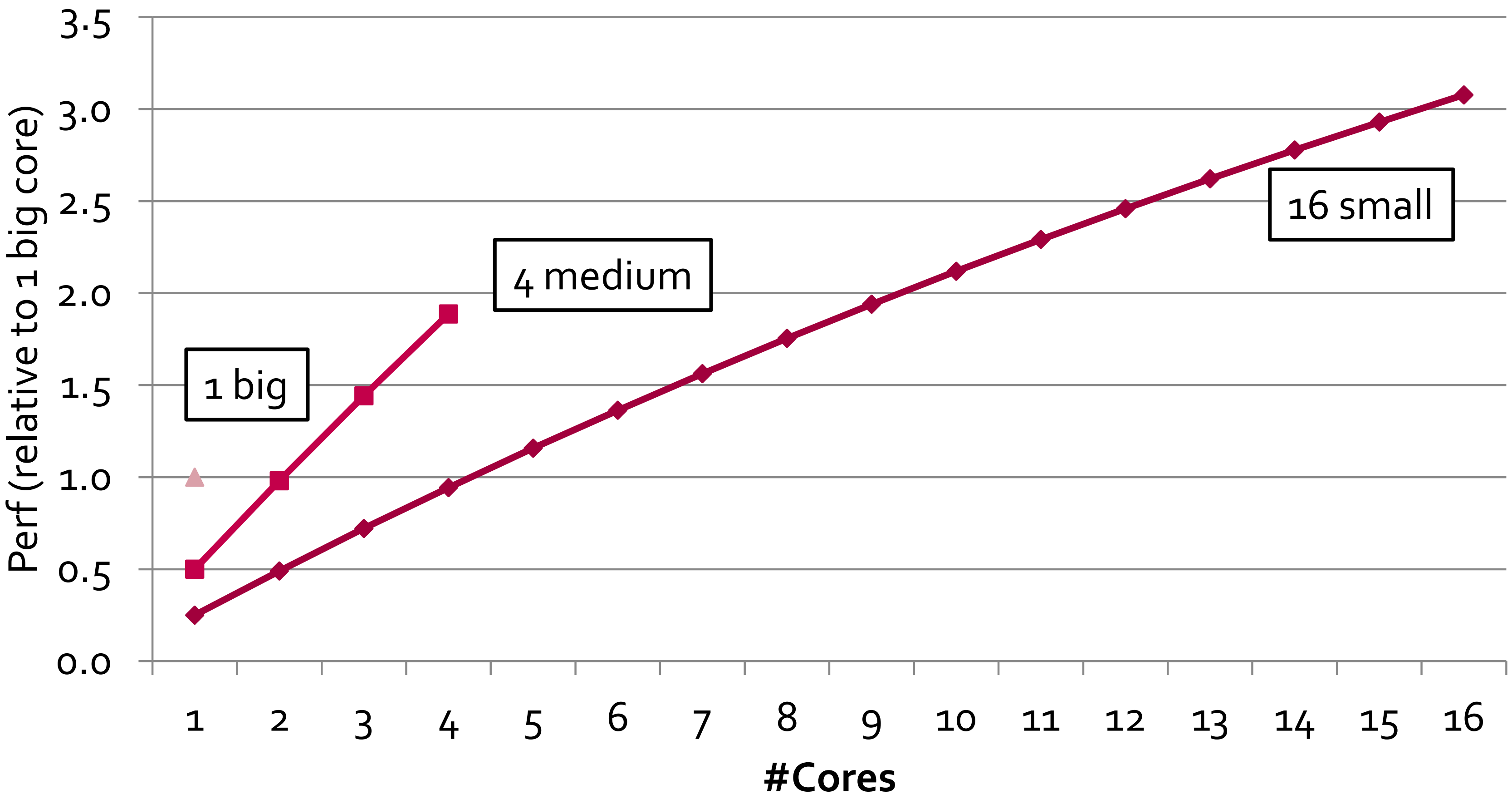
Suppose that the same h/w budget (space or power) can make us:



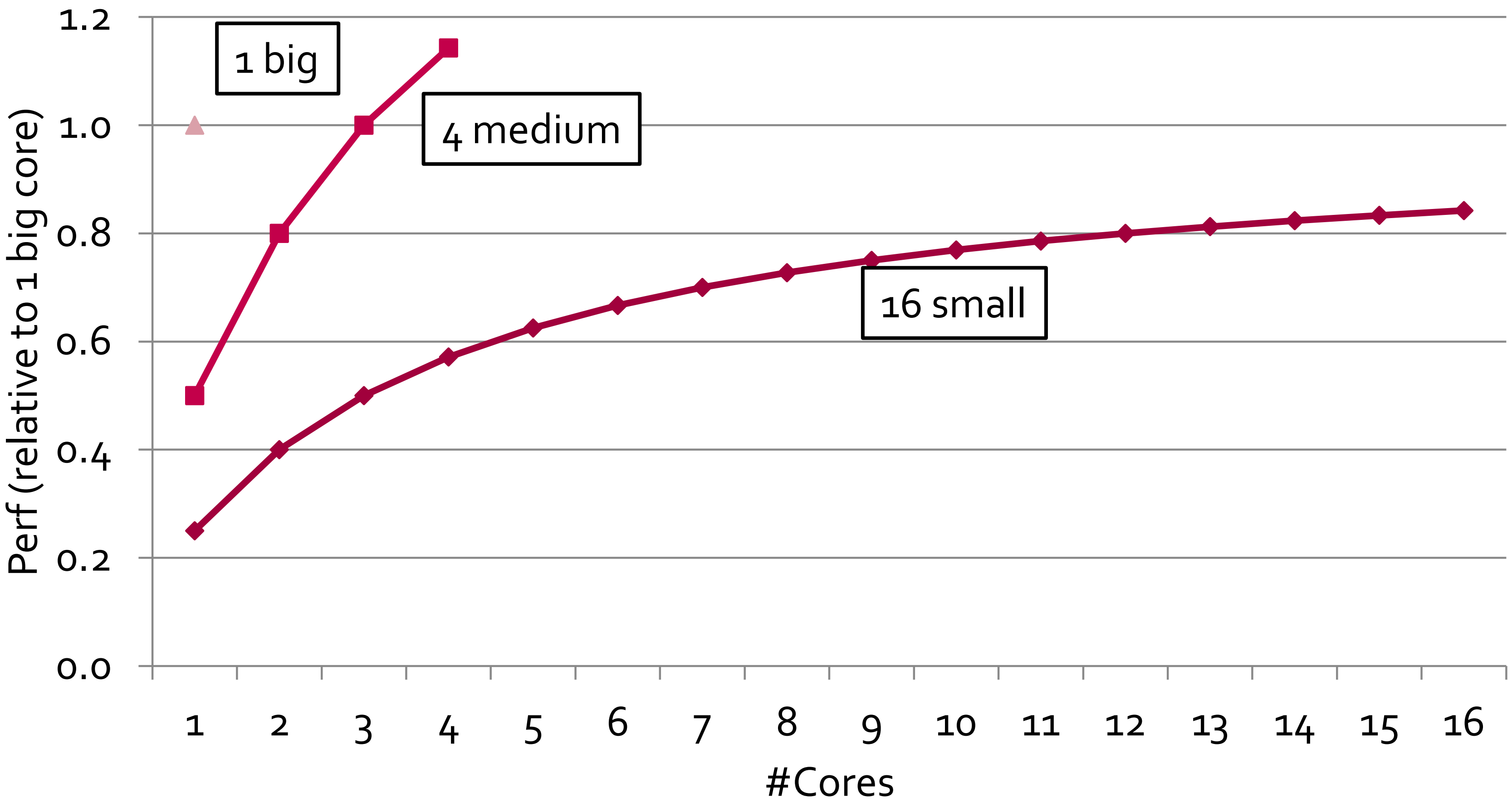
Perf of big & small cores



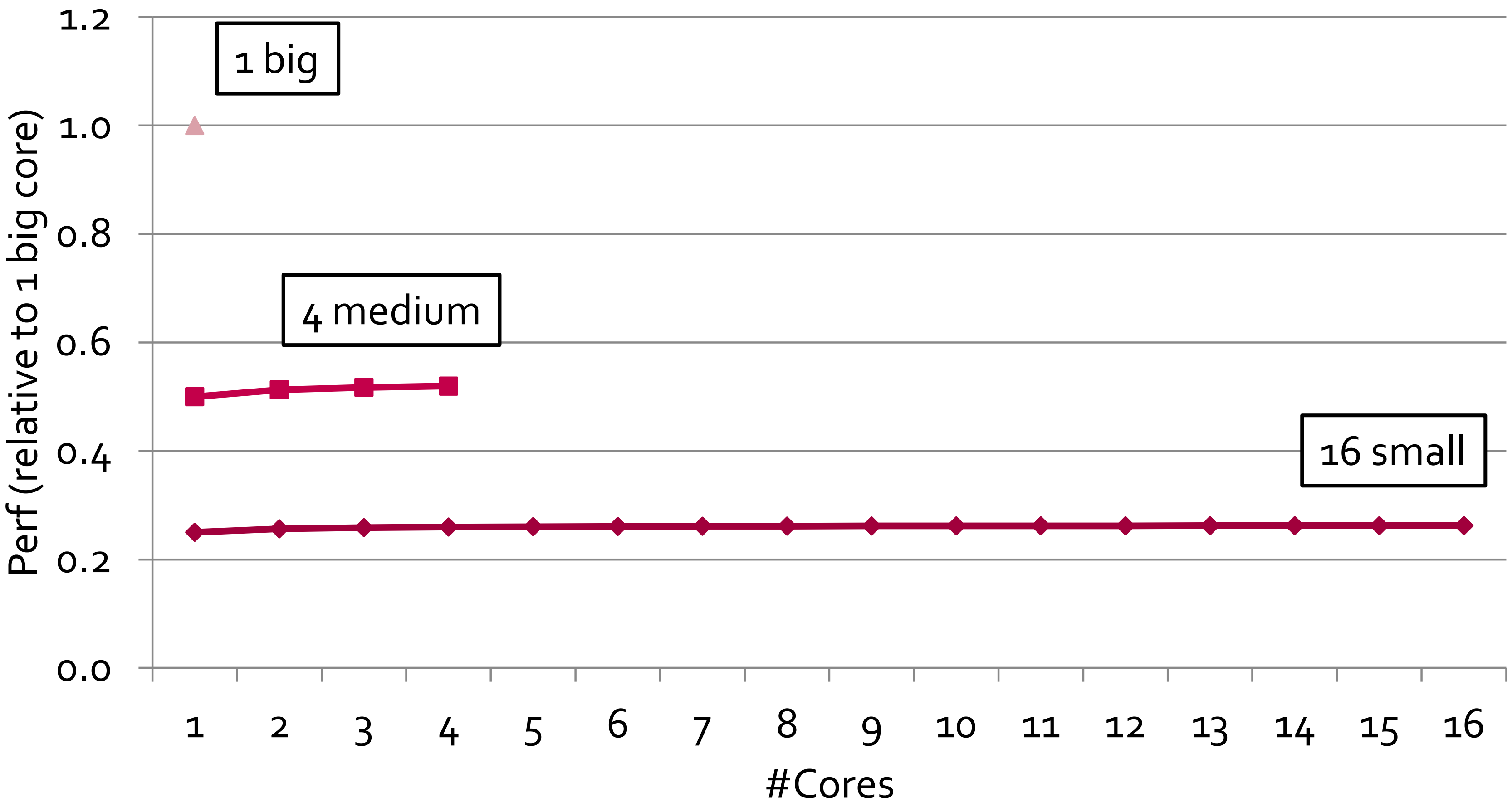
Amdahl's law, f=98%



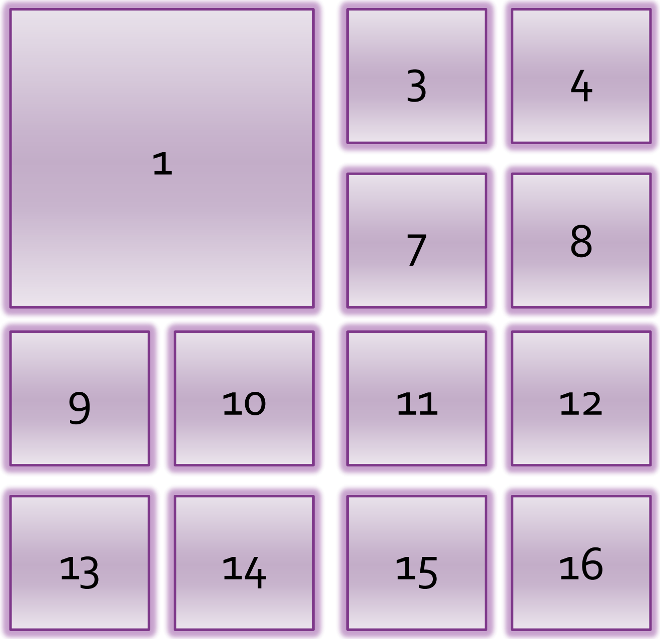
Amdahl’s law, f=75%



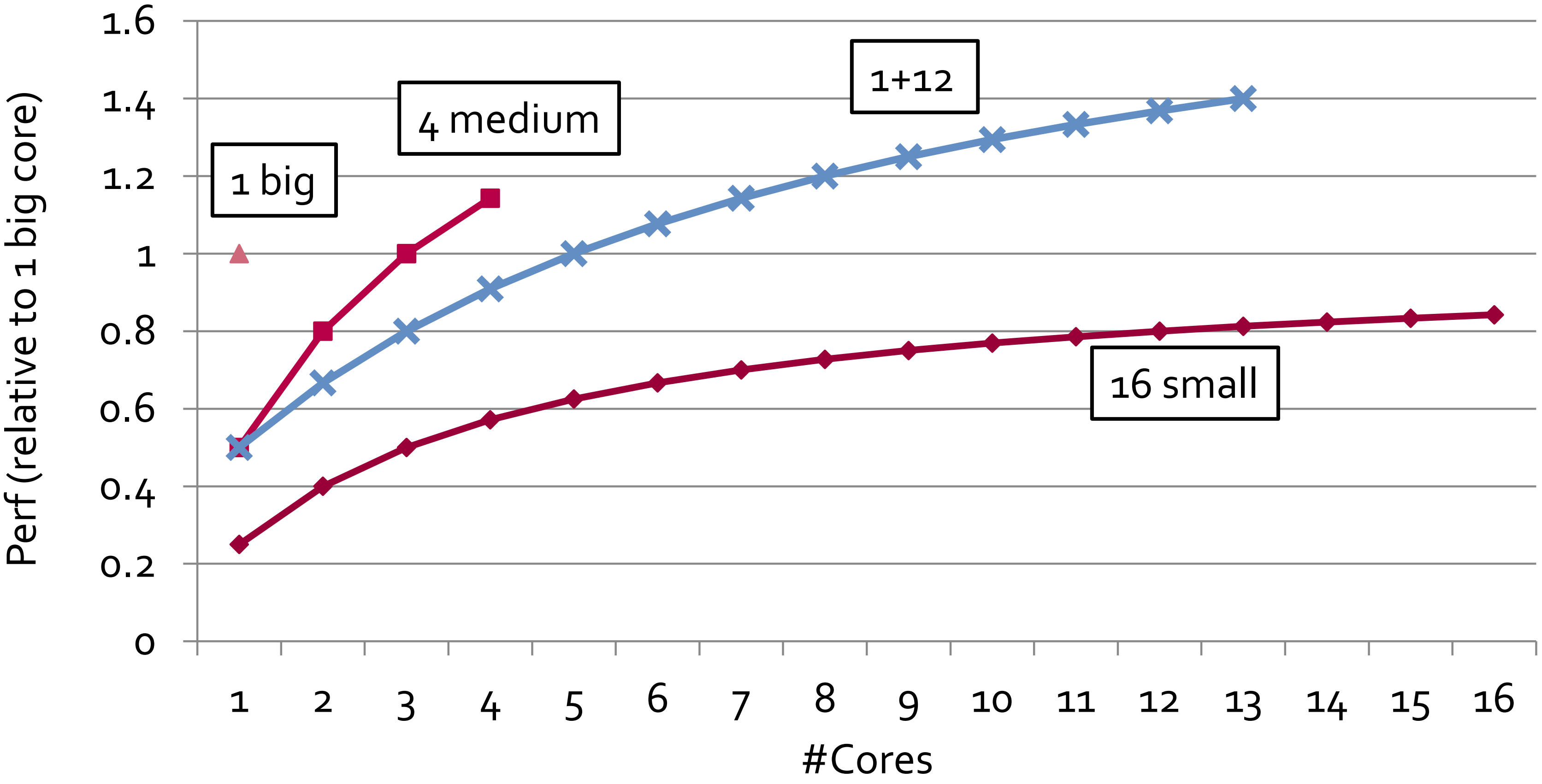
Amdahl’s law, f=5%



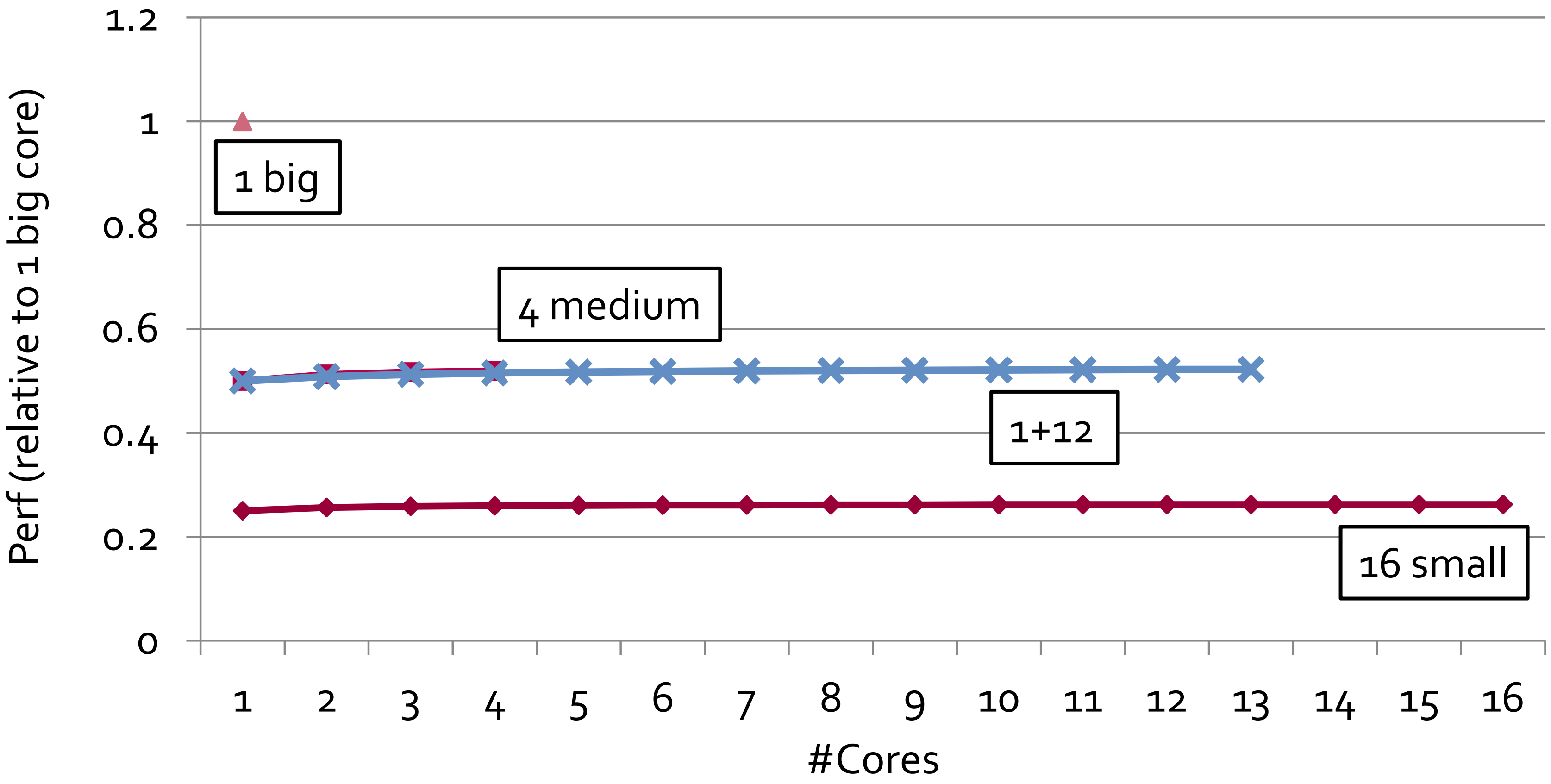
Asymmetric chips



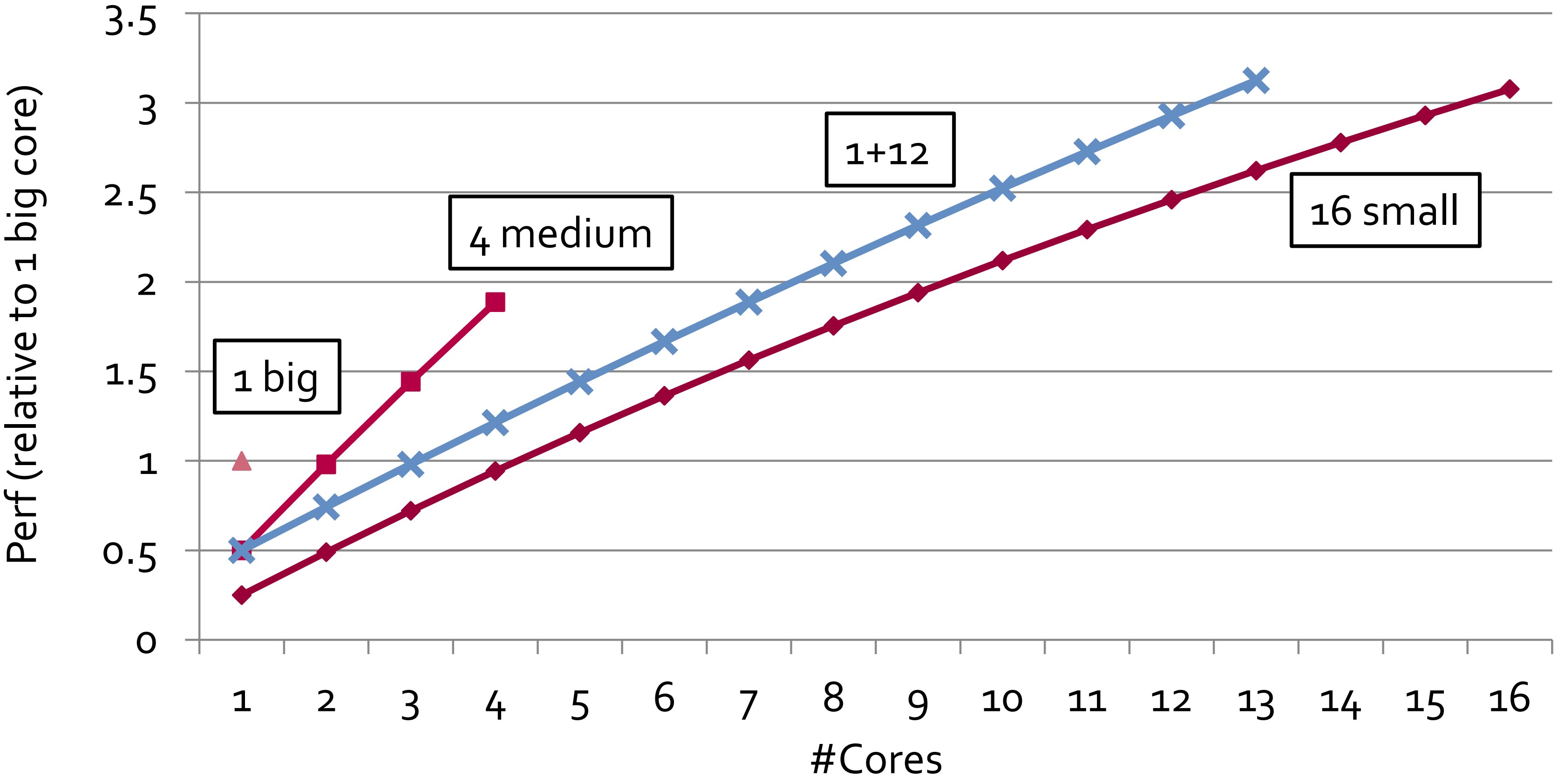
Amdahl's law, f=75%



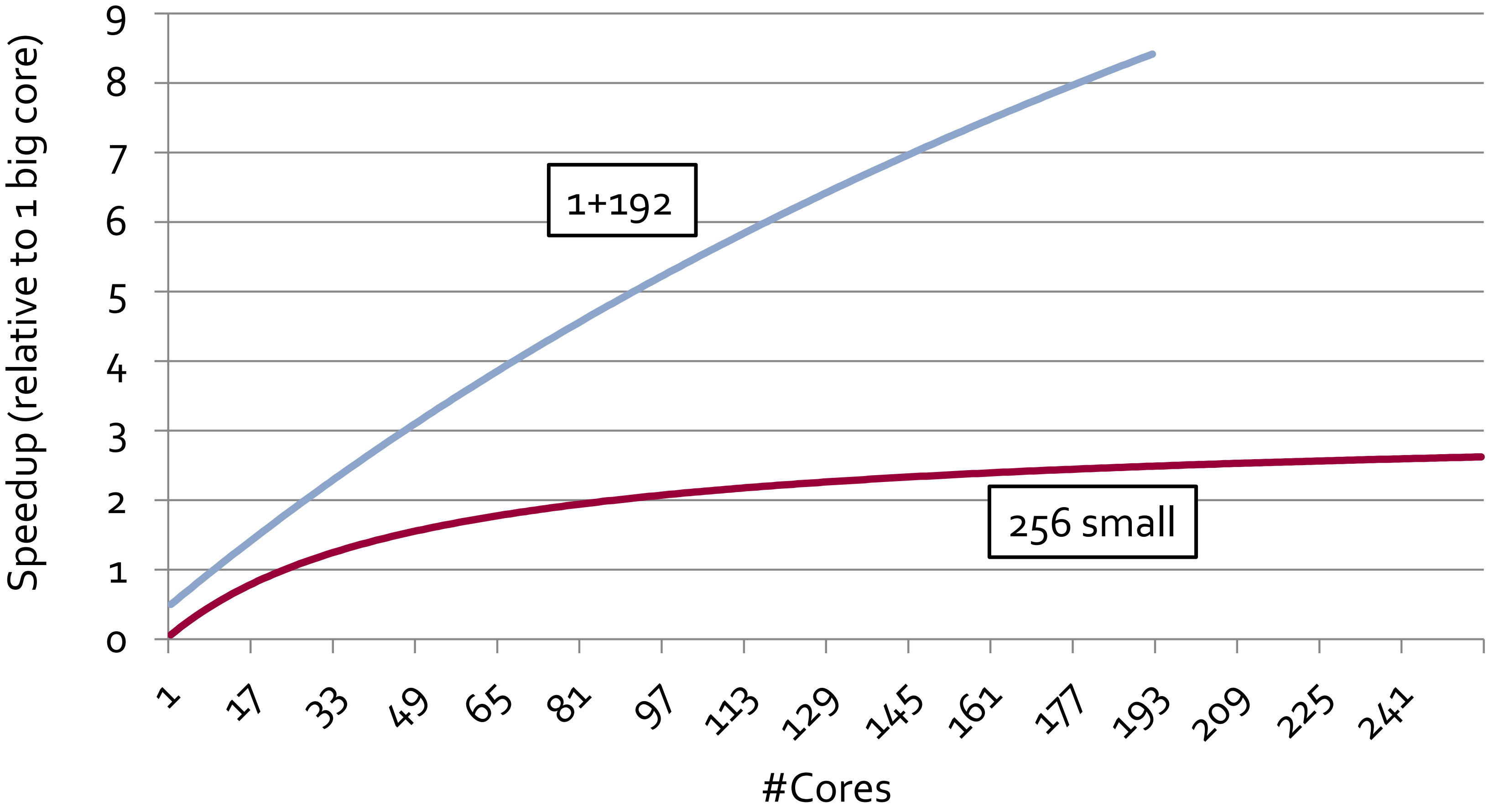
Amdahl's law, f=5%



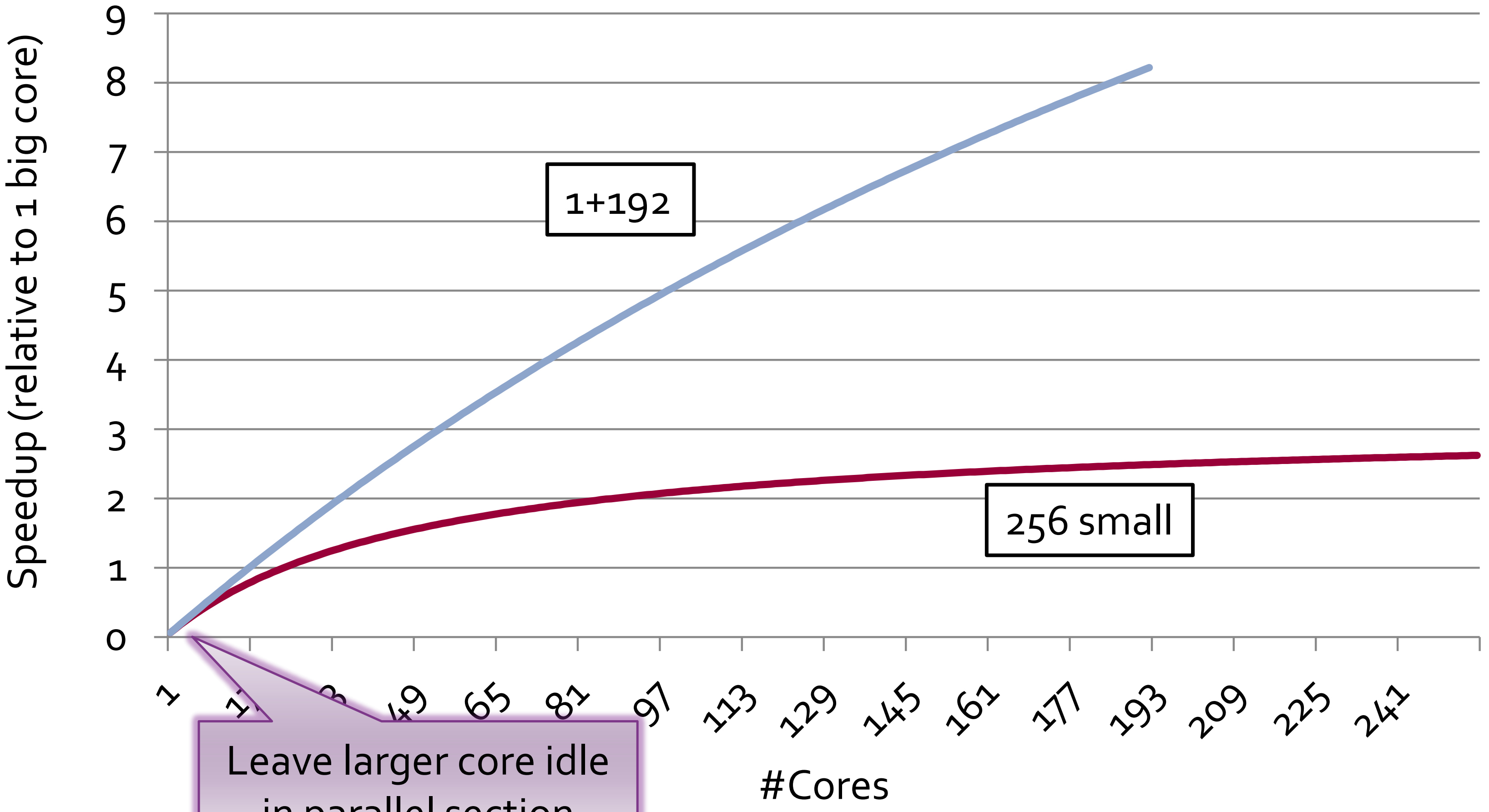
Amdahl’s law, f=98%



Amdahl's law, f=98%



Amdahl's law, f=98%



Leave larger core idle in parallel section

Basic spin-locks

Test and set (pseudo-code)

```
bool testAndSet(bool *b) {
  bool result;
  atomic {
    result = *b;
    *b = TRUE;
  }
  return result;
}
```

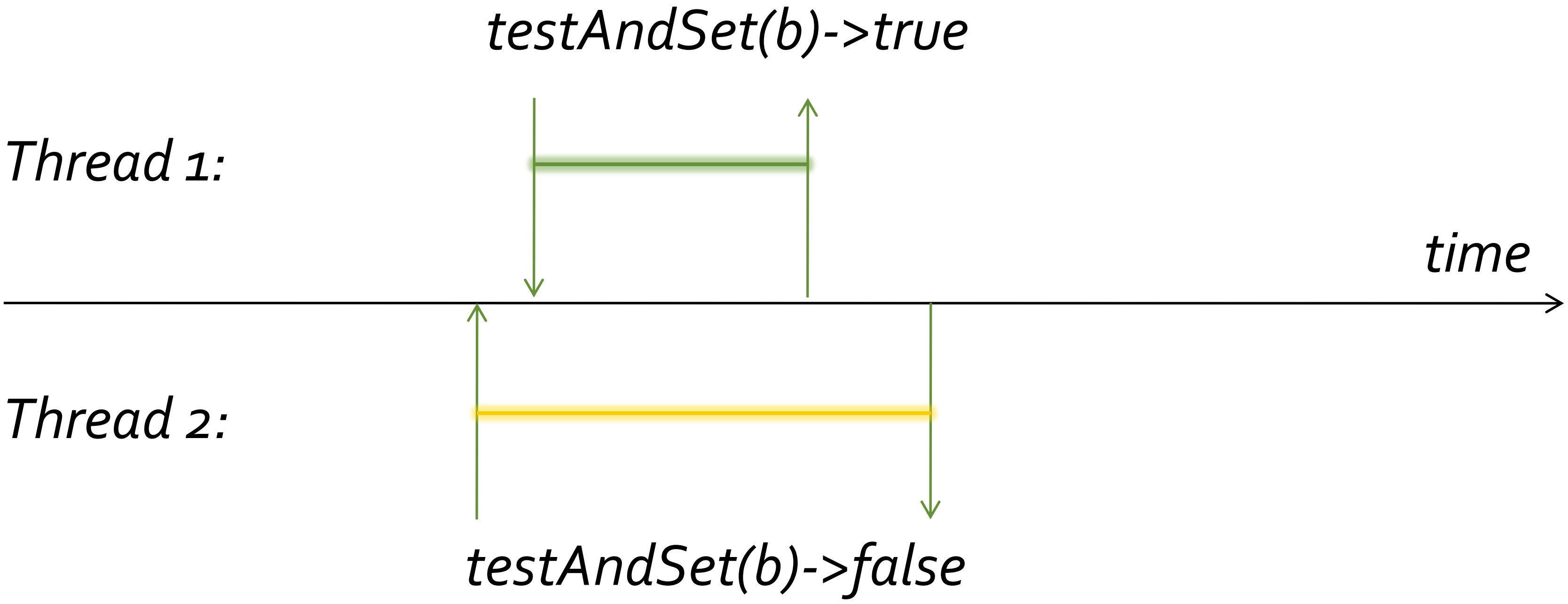
Pointer to a location holding a boolean value (TRUE/FALSE)

Read the current contents of the location b points to…

…set the contents of *b to TRUE

Test and set

- Suppose two threads use it at once



Test and set lock

lock: FALSE

FALSE => lock available
TRUE => lock held

```
void acquireLock(bool *lock) {
   while (testAndSet(lock)) {
     /* Nothing */
   }
}
```

Each call tries to acquire the lock, returning TRUE if it is already held

```
void releaseLock(bool *lock) {
  *lock = FALSE;
}
```

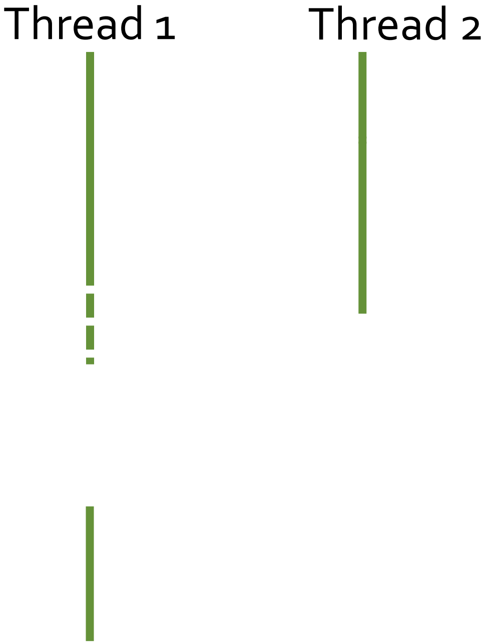
NB: all this is pseudo-code, assuming SC memory

Test and set lock

lock: TRUE

```
void acquireLock(bool *lock) {
   while (testAndSet(lock)) {
     /* Nothing */
   }
}
```

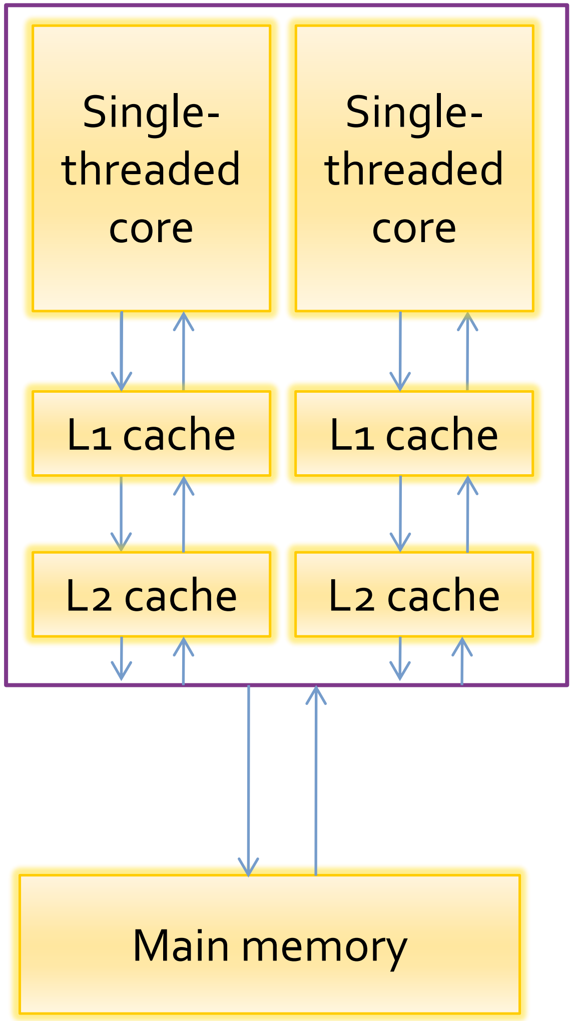
```
void releaseLock(bool *lock) {
  *lock = FALSE;
}
```



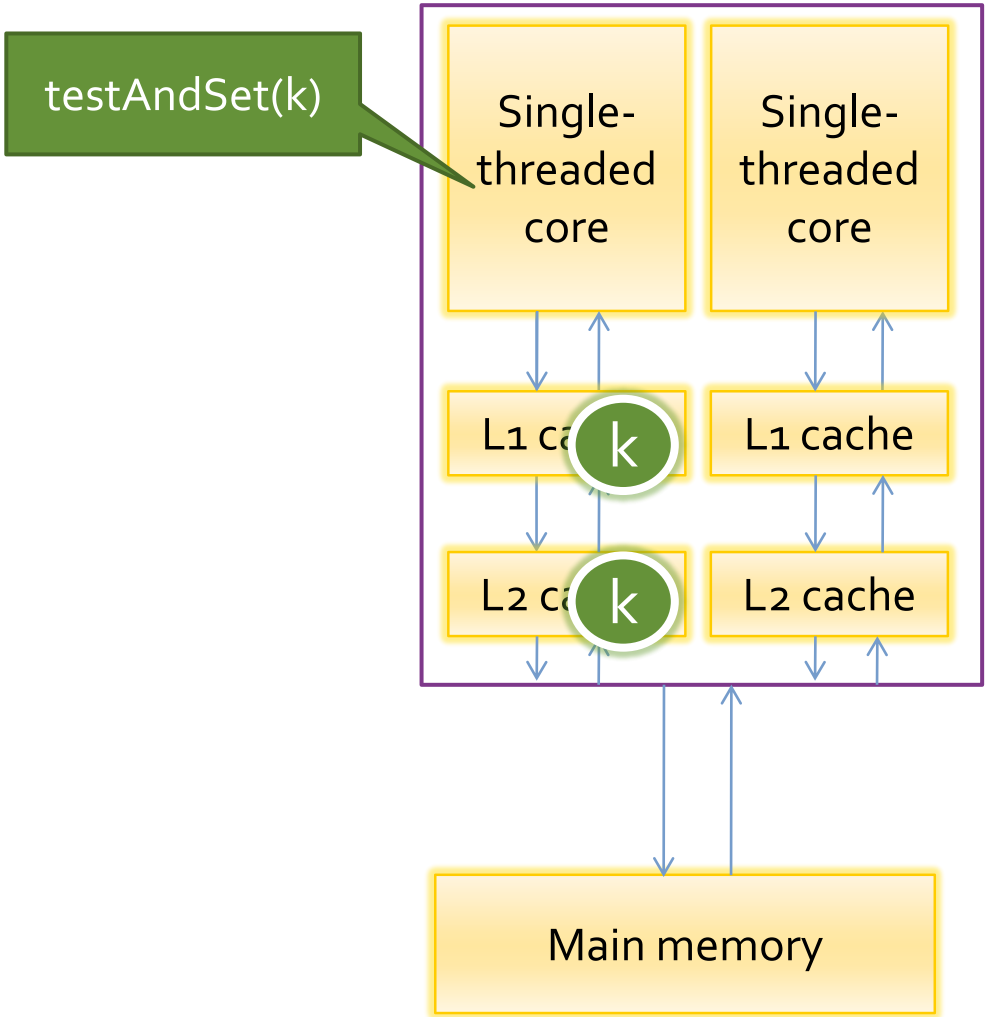
What are the problems here?

testAndSet implementation causes contention

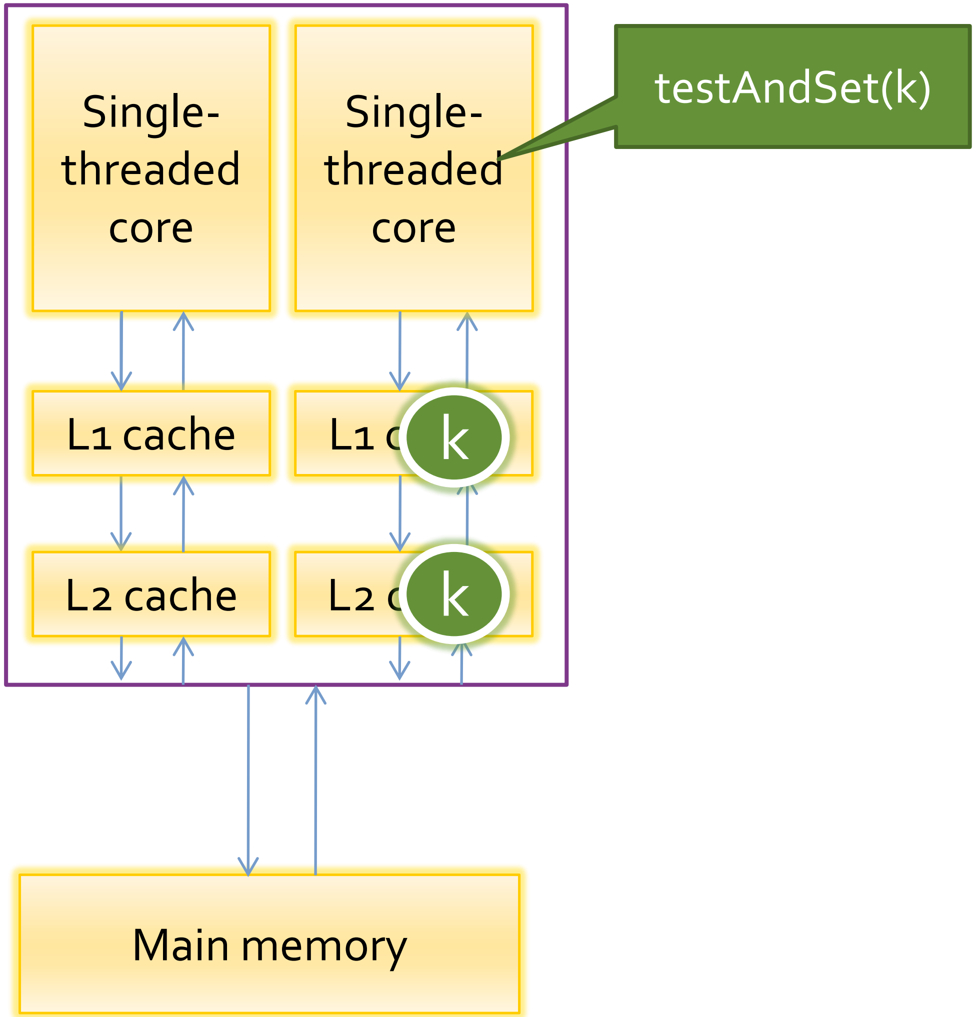
Contention from testAndSet



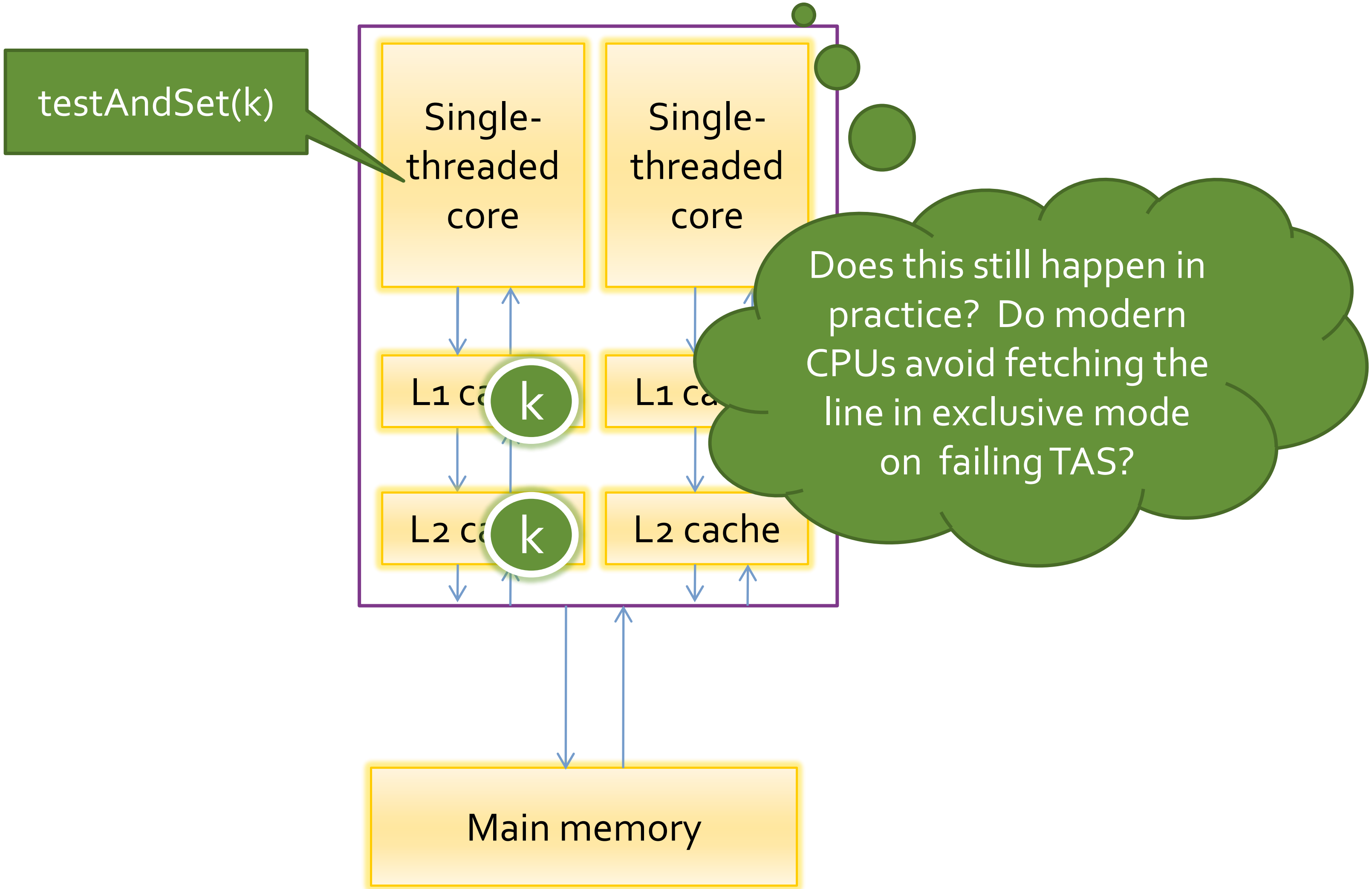
Multi-core h/w – separate L2



Multi-core h/w – separate L2



Multi-core h/w – separate L2



Does this still happen in practice? Do modern CPUs avoid fetching the line in exclusive mode on failing TAS?

What are the problems here?

testAndSet implementation causes contention

No control over locking policy

Only supports mutual exclusion: not reader-writer locking

Spinning may waste resources while waiting

General problem

- No logical conflict between two failed lock acquires
- Cache protocol introduces a physical conflict
- For a good algorithm: only introduce physical conflicts if a logical conflict occurs
  - In a lock: successful lock-acquire & failed lock-acquire
  - In a set: successful insert(10) & failed insert(10)
- But not:
  - In a lock: two failed lock acquires
  - In a set: successful insert(10) & successful insert(20)
  - In a non-empty queue: enqueue on the left and remove on the right

Test and test and set lock

lock: FALSE

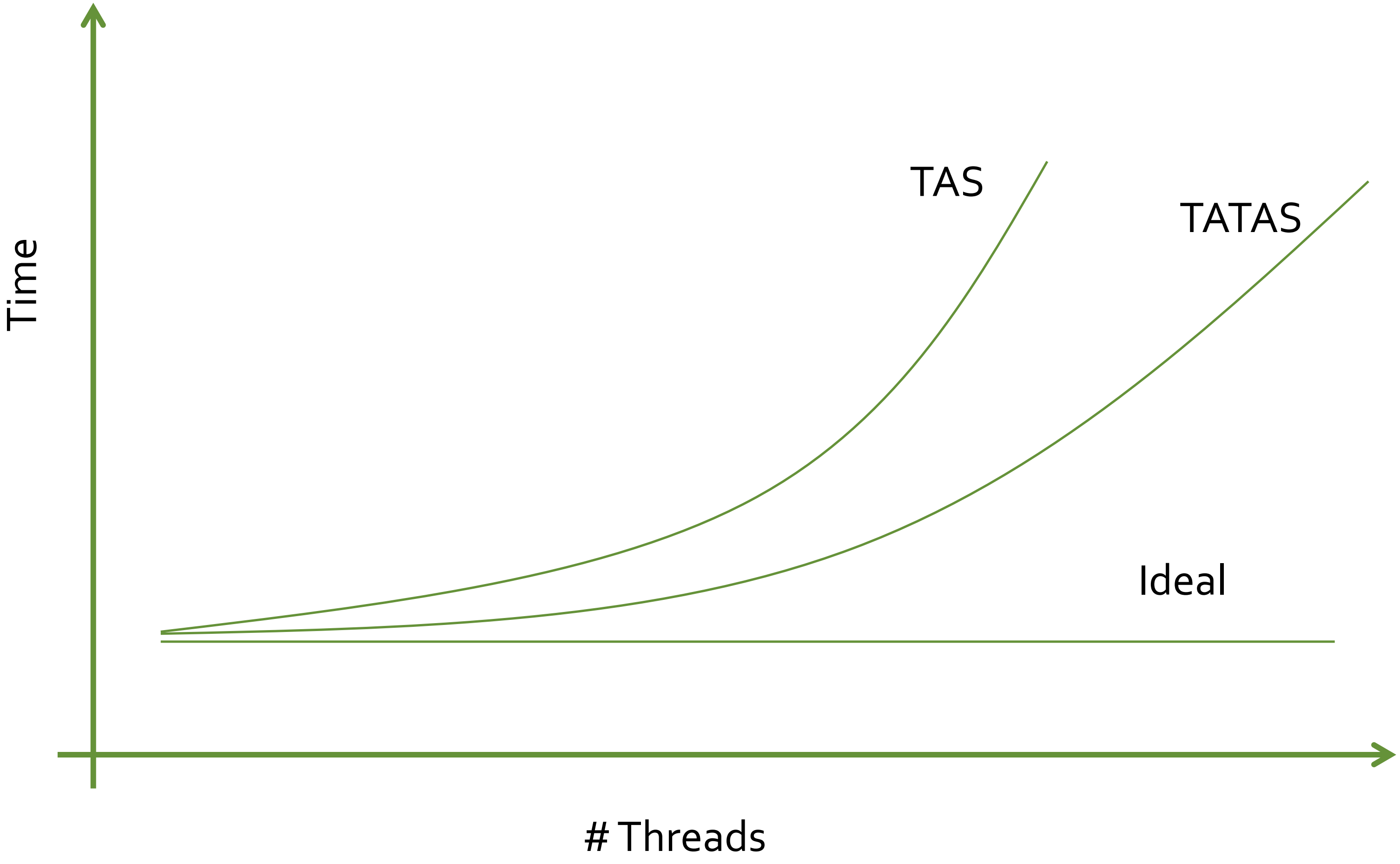
FALSE => lock available
TRUE => lock held

```
void acquireLock(bool *lock) {
  do {
    while (*lock) { }
  } while (testAndSet(lock));
}
```

Spin while the lock is held… only do testAndSet when it is clear

```
void releaseLock(bool *lock) {
   *lock  = FALSE;
}
```

Performance

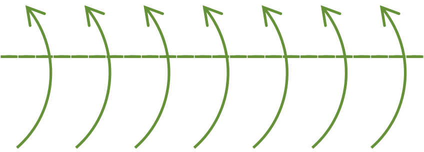


Based on Fig 7.4, Herlihy & Shavit, “The Art of Multiprocessor Programming”

Stampedes

lock: TRUE

```
void acquireLock(bool *lock) {
  do {
    while (*lock) { }
  } while (testAndSet(lock));
}
```



```
void releaseLock(bool *lock) {
   *lock = FALSE;
}
```

Back-off algorithms

1. Start by spinning, watching the lock for "*c*" iterations
2. If the lock does not become free, spin locally for "*s*" *(without watching the lock)*

What should "c" be?
What should "s" be?

Time spent wathcing “c”

- Lower values:
  - Less time to build up a set of threads that will stampede
  - Less contention in the memory system, if remote reads incur a cost
  - Risk of a delay in noticing when the lock becomes free if we are not watching
- Higher values:
  - Less likelihood of a delay between a lock being released and a waiting thread noticing

Local spinning time “s”

- Lower values:
  - More responsive to the lock becoming available
- Higher values:
  - If the lock doesn’t become available then the thread makes fewer accesses to the shared variable

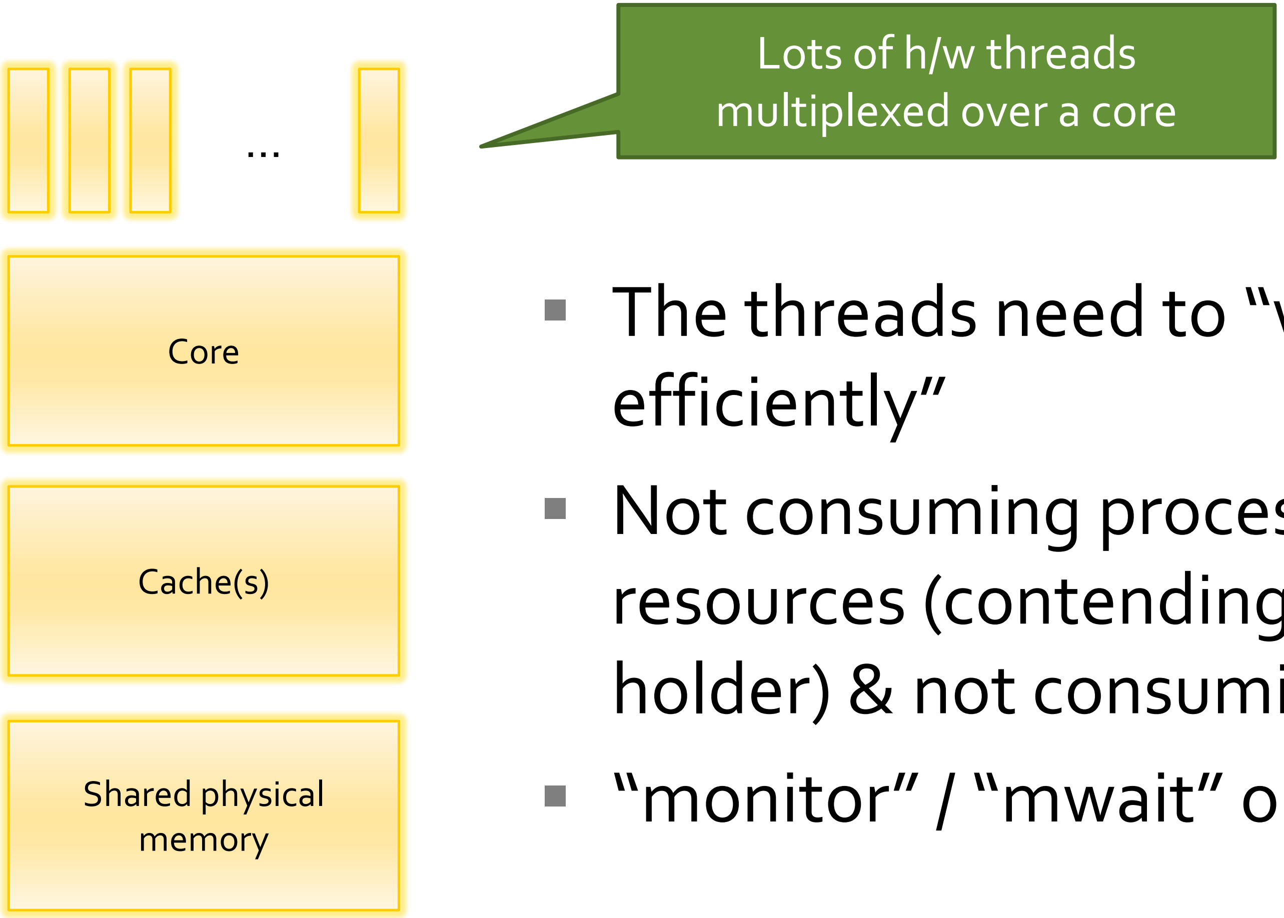
Methodical approach

- For a given workload and performance model:
  - What is the best that could be done (i.e. given an “oracle” with perfect knowledge of when the lock becomes free)?
  - How does a practical algorithm compare with this?
- Look for an algorithm with a bound between its performance and that of the oracle
- “Competitive spinning”

Rule of thumb

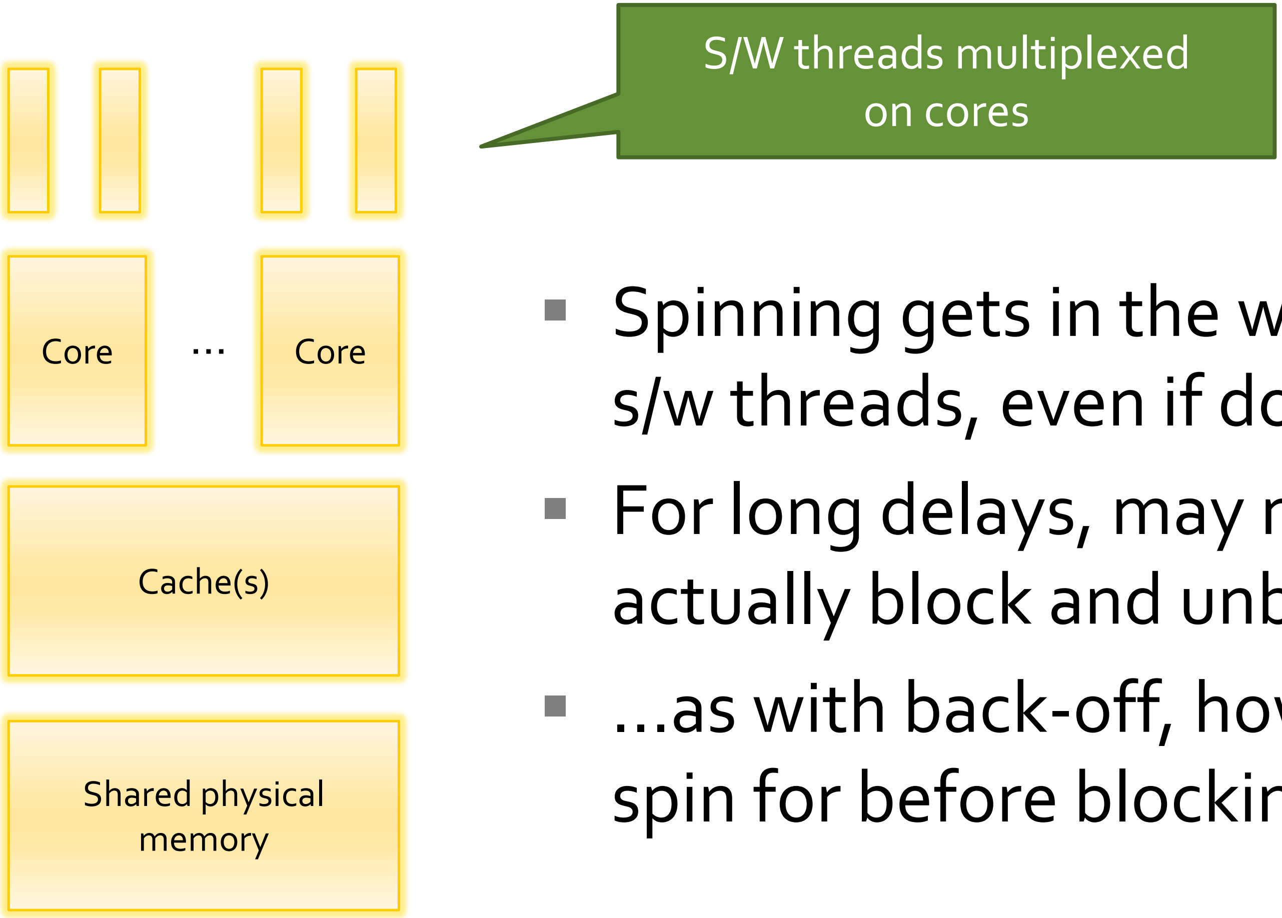
- Spin for a duration that’s comparable with the shortest back-off interval
- Exponentially increase the per-thread back-off interval (resetting it when the lock is acquired)
- Use a maximum back-off interval that is large enough that waiting threads don’t interfere with the other threads’ performance

Systems problems



- The threads need to “wait efficiently”
- Not consuming processing resources (contending with lock holder) & not consuming power
- “monitor” / “mwait” operations

Systems problems



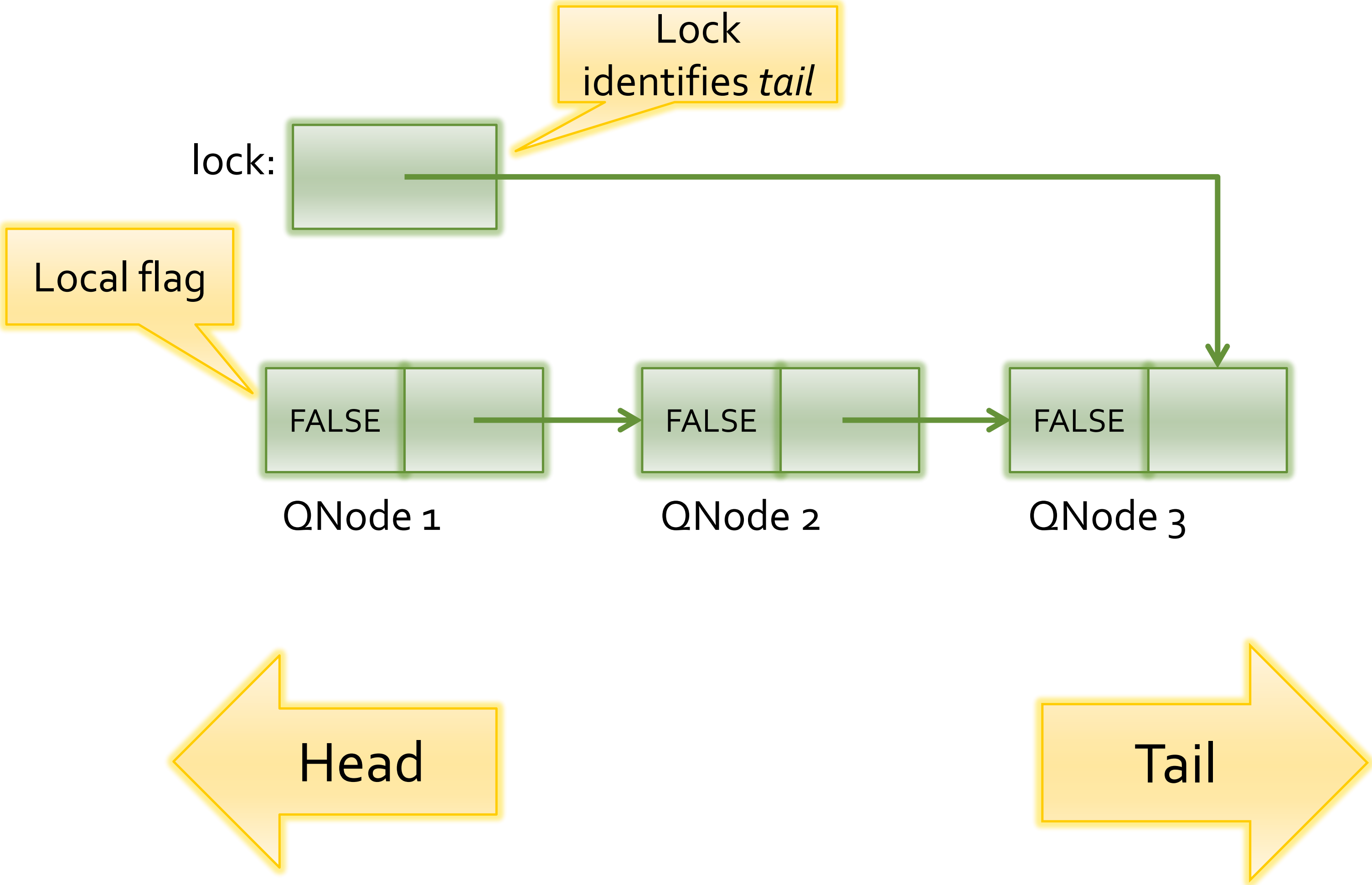
- Spinning gets in the way of other s/w threads, even if done efficiently
- For long delays, may need to actually block and unblock
- …as with back-off, how long to spin for before blocking?

Queue-based locks

Queue-based locks

- Lock holders queue up: immediately provides FCFS behavior
- Each spins *locally* on a flag in their queue entry: no remote memory accesses while waiting
- A lock release wakes the next thread directly: no stampede

MCS locks



Lock identifies *tail*

lock:

Local flag

FALSE

FALSE

FALSE

QNode 1

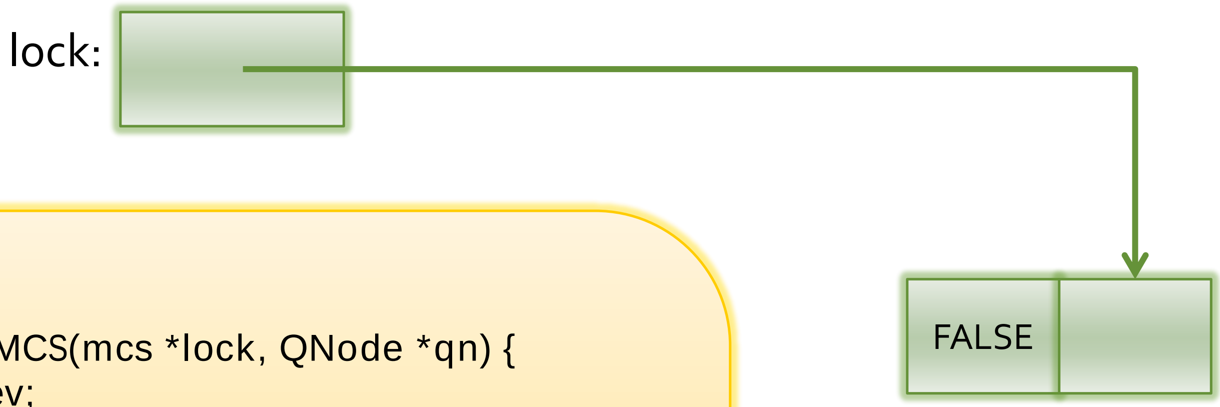
QNode 2

QNode 3

Head

Tail

MCS lock acquire



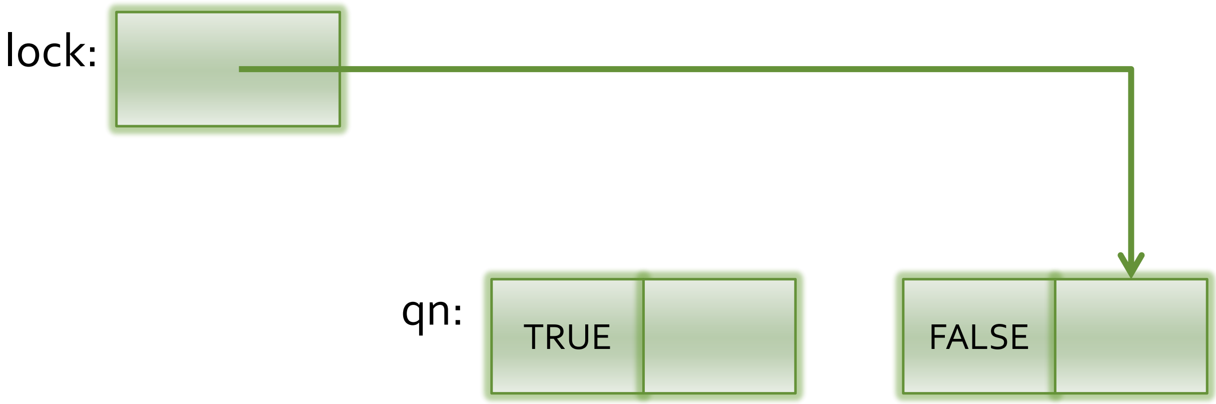
```
void acquireMCS(mcs *lock, QNode *qn) {
  QNode *prev;
  qn->flag = false;
  qn->next = NULL;
  while (true) {
     prev = lock->tail;
     /* Label 1 */
     if (CAS(&lock->tail, prev, qn)) break;
  }
  if (prev != NULL) {
    prev->next = qn; /* Label 2 */
    while (!qn->flag) { } // Spin
} }
```

Find previous tail node

Atomically replace “prev” with “qn” in the lock itself

Add link within the queue

MCS lock release



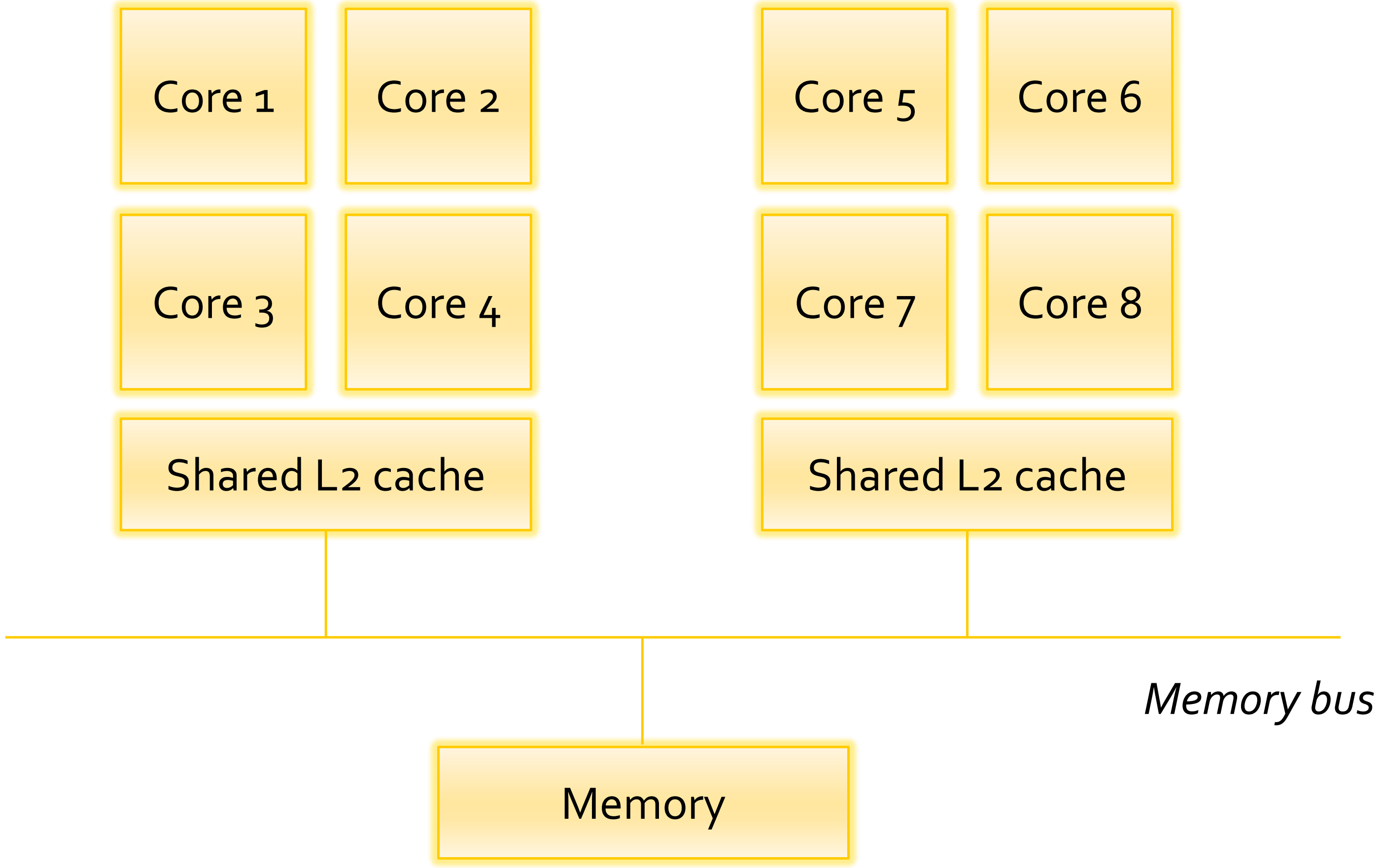
```
void releaseMCS(mcs *lock, QNode *qn) {
  if (lock->tail = qn) {
     if (CAS(&lock->tail, qn, NULL)) return;
  }
  while (qn->next == NULL) { }
  qn->next->flag = TRUE;
}
```

If we were at the tail then remove us

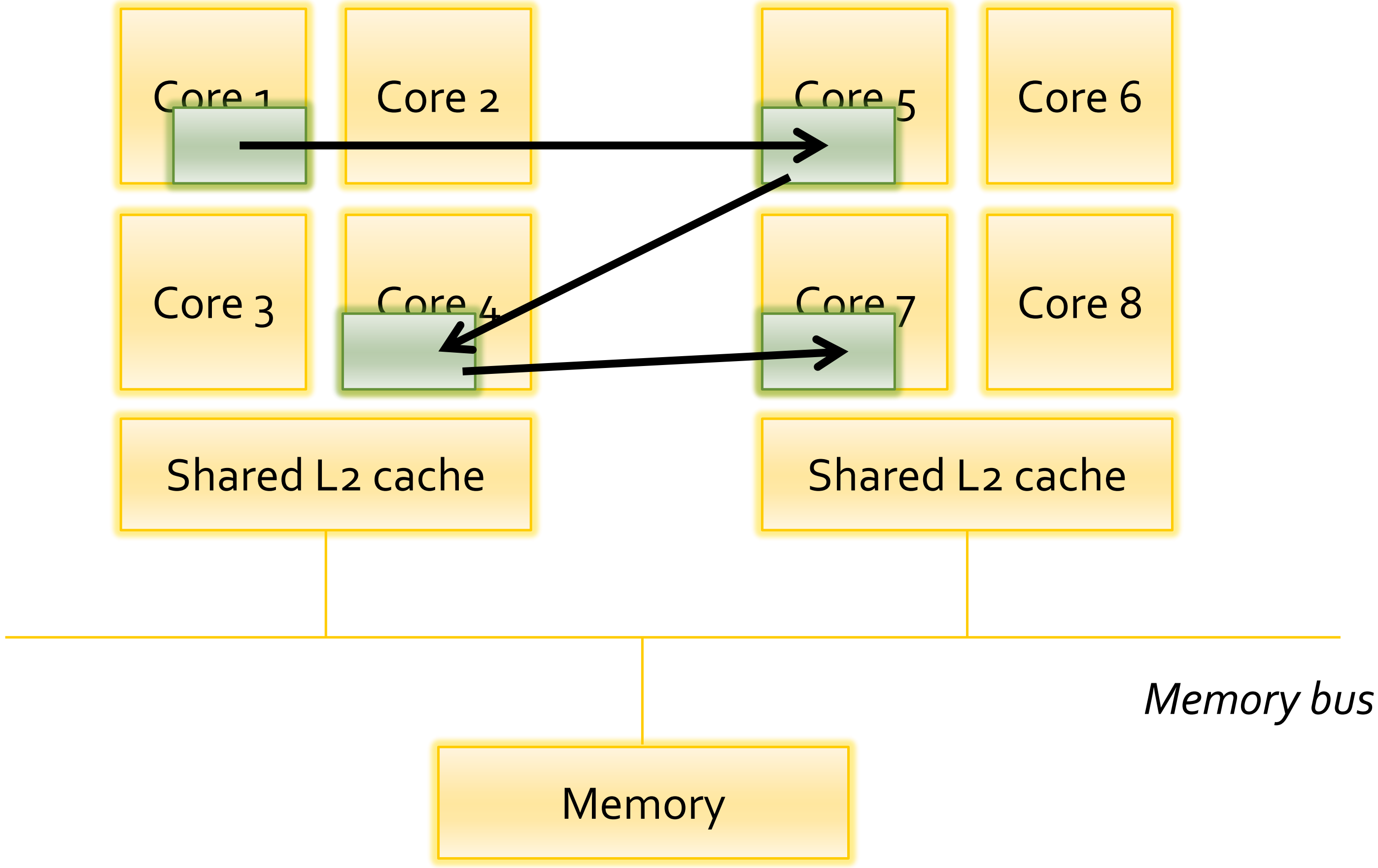
Wait for next lock holder to announce themselves; signal them

Hierarchical locks

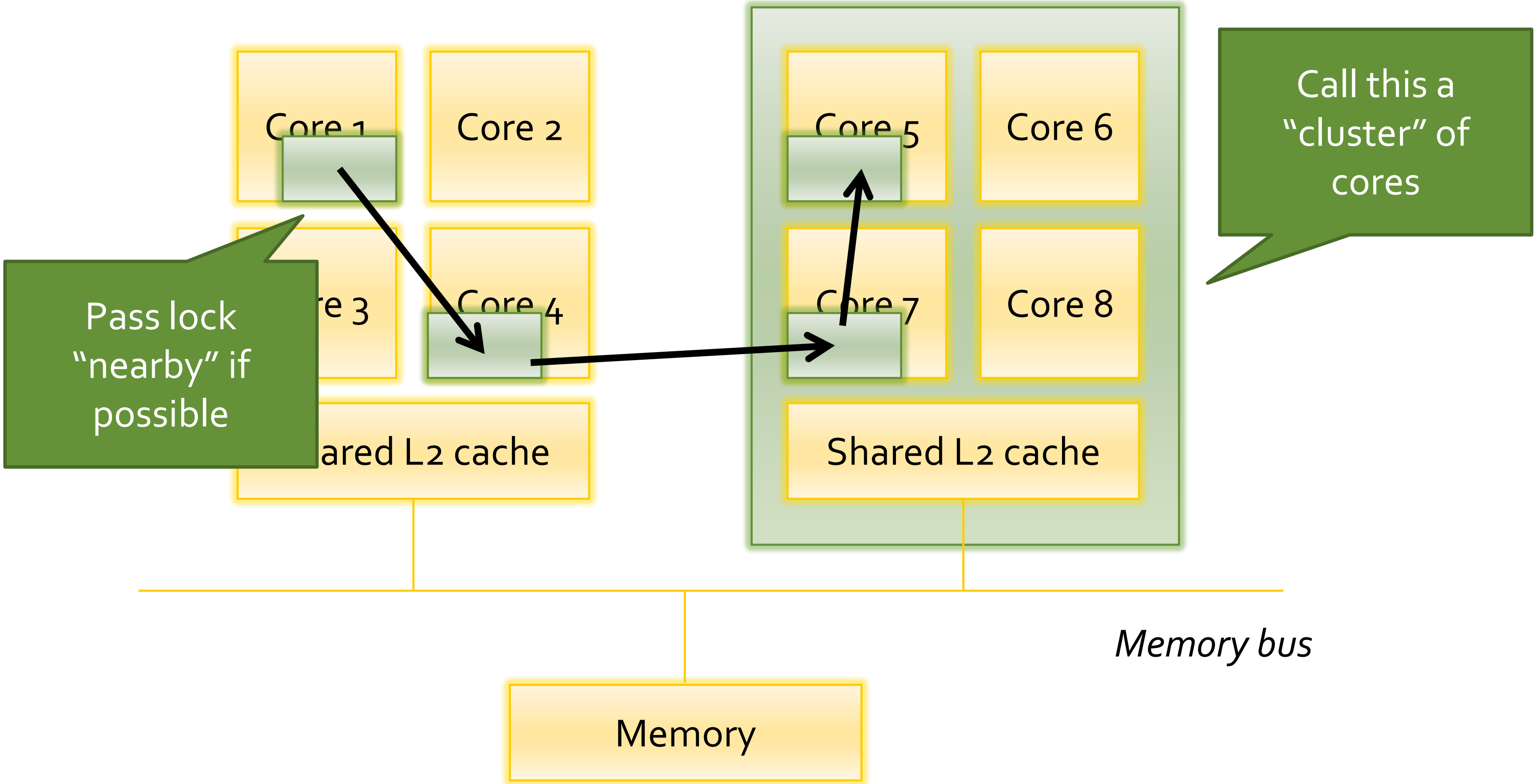
Hierarchical locks



Hierarchical locks



Hierarchical locks



Pass lock "nearby" if possible

Call this a "cluster" of cores

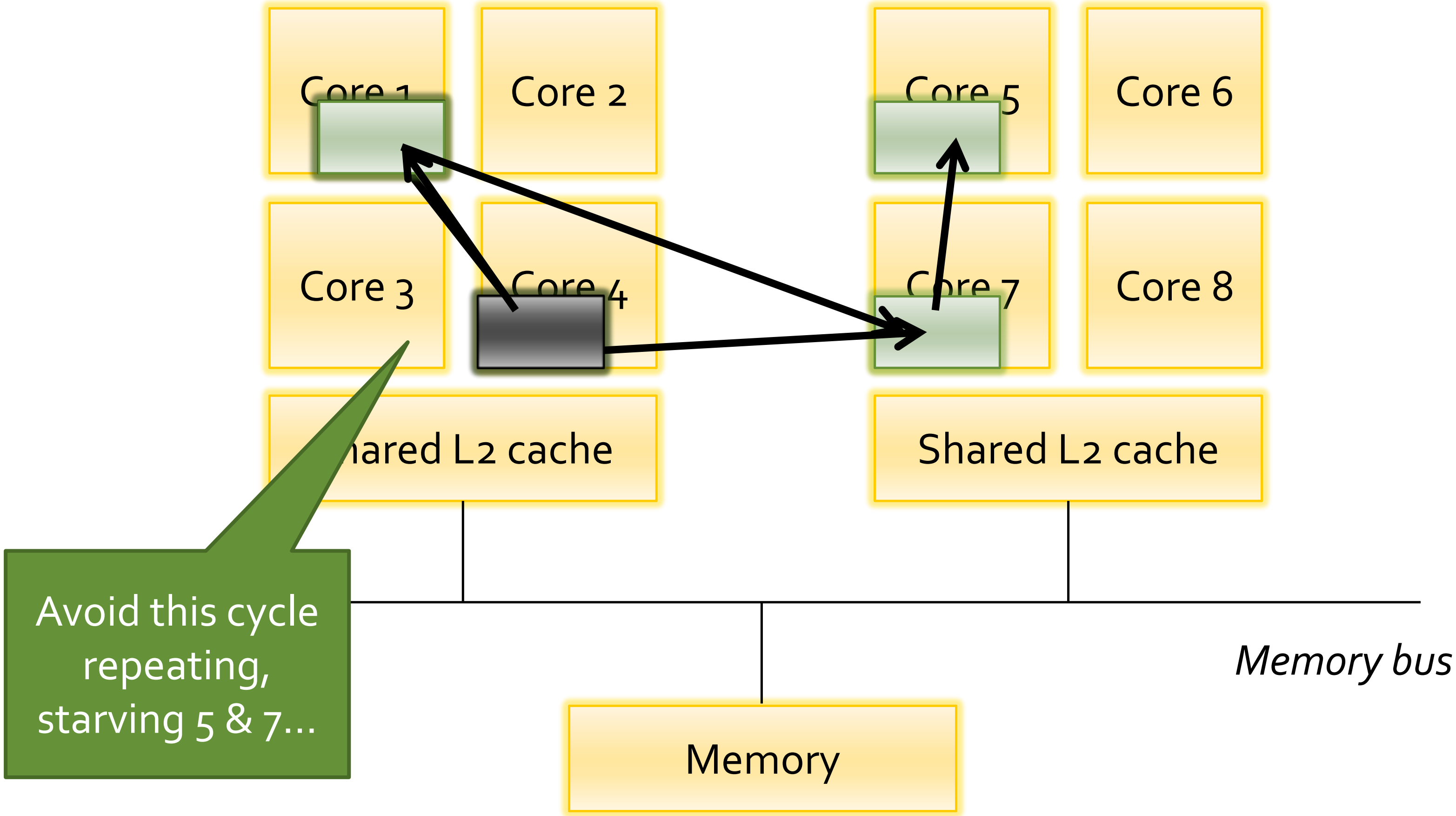
Hierarchical TATAS with backoff

lock: -1

-1 => lock available
n => lock held by cluster n

```
void acquireLock(bool *lock) {
  do {
    holder = *lock;
    if (holder != -1) {
       if (holder == MY_CLUSTER) {
          BackOff(SHORT);
       } else {
          BackOff(LONG);
       }
    }
  } while (!CAS(lock, -1, MY_CLUSTER));
}
```

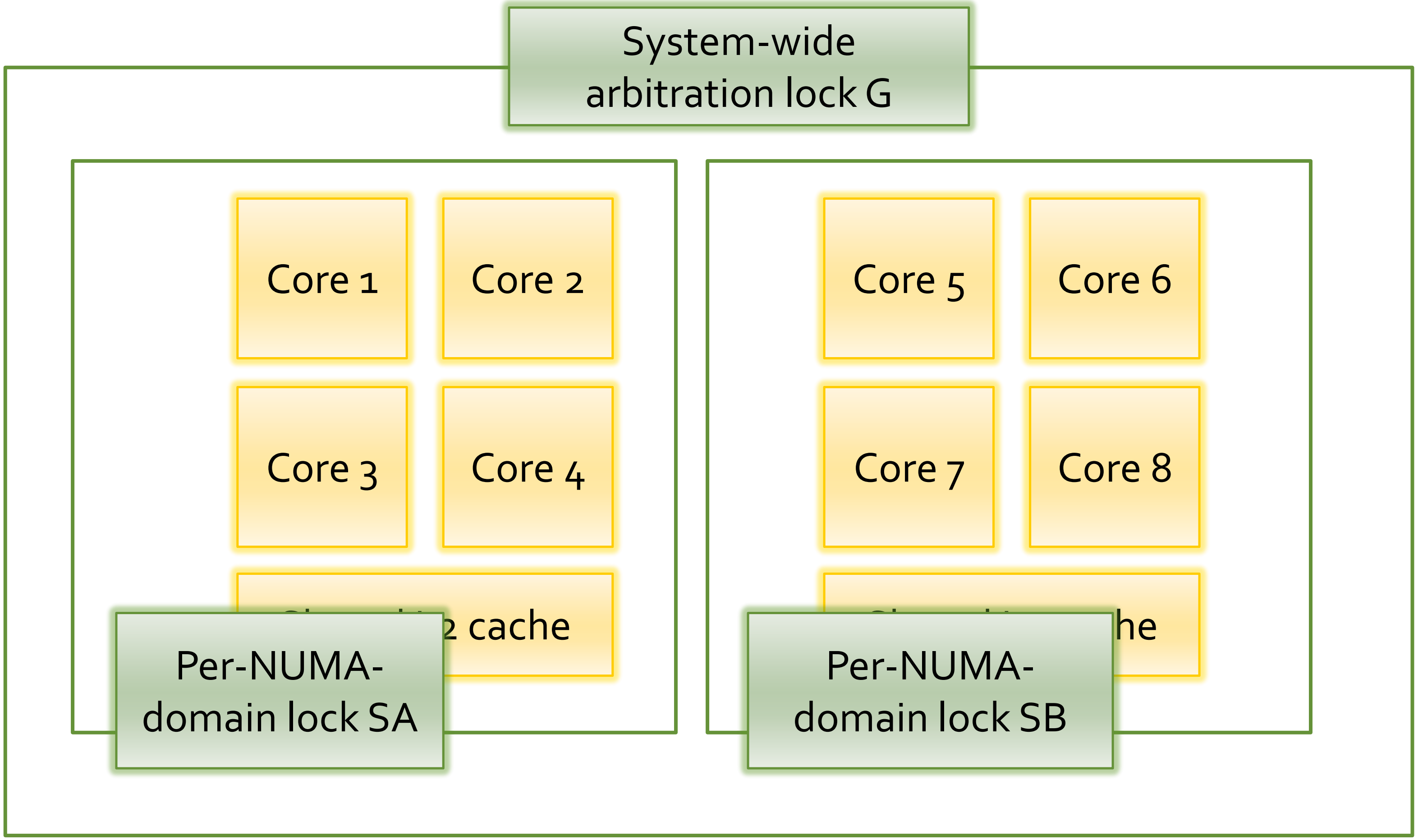
Hierarchical locks



Avoid this cycle repeating, starving 5 & 7…

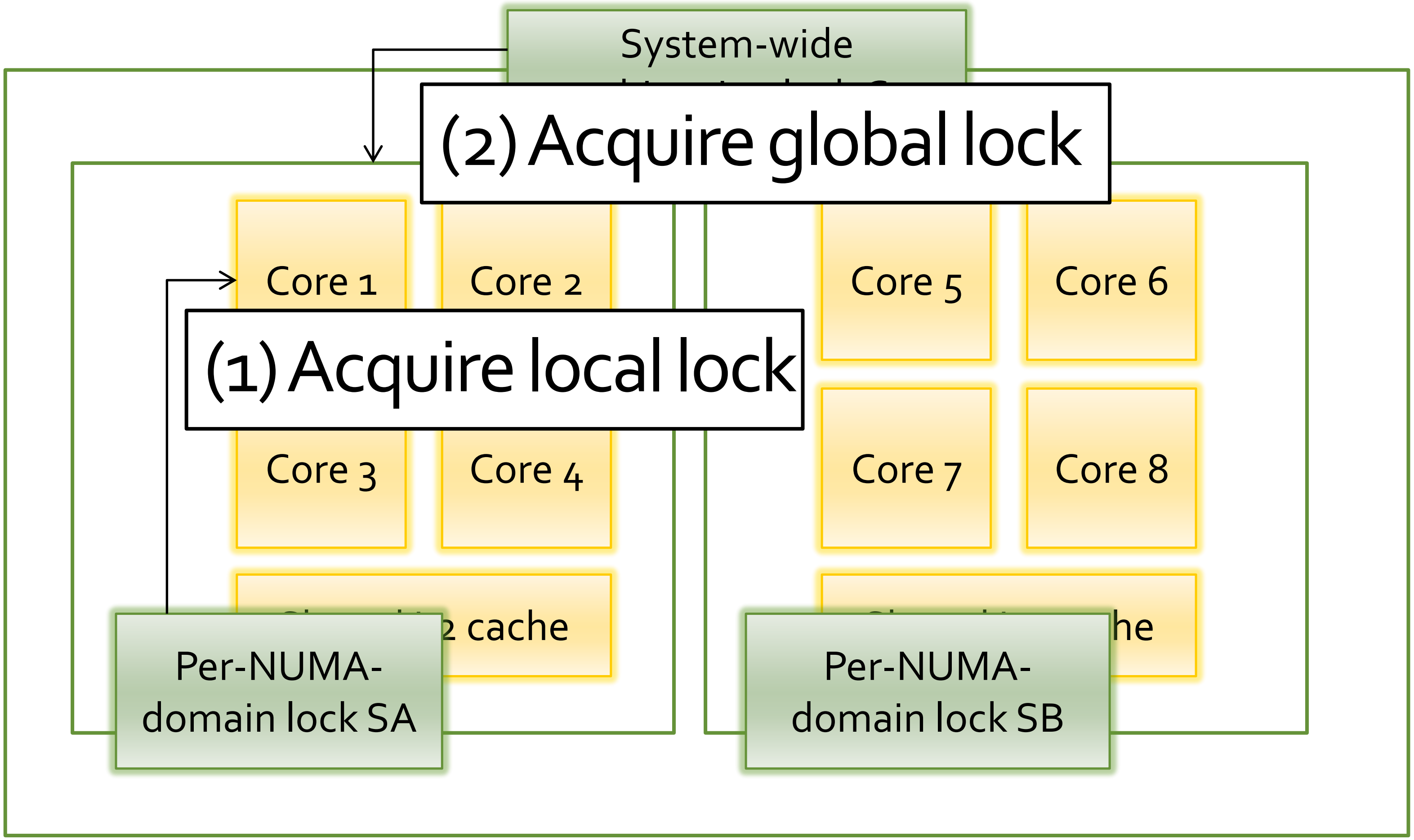
Lock cohorting

- "Lock Cohorting: A General Technique for Designing NUMA Locks", Dice *et al* PPoPP 2012



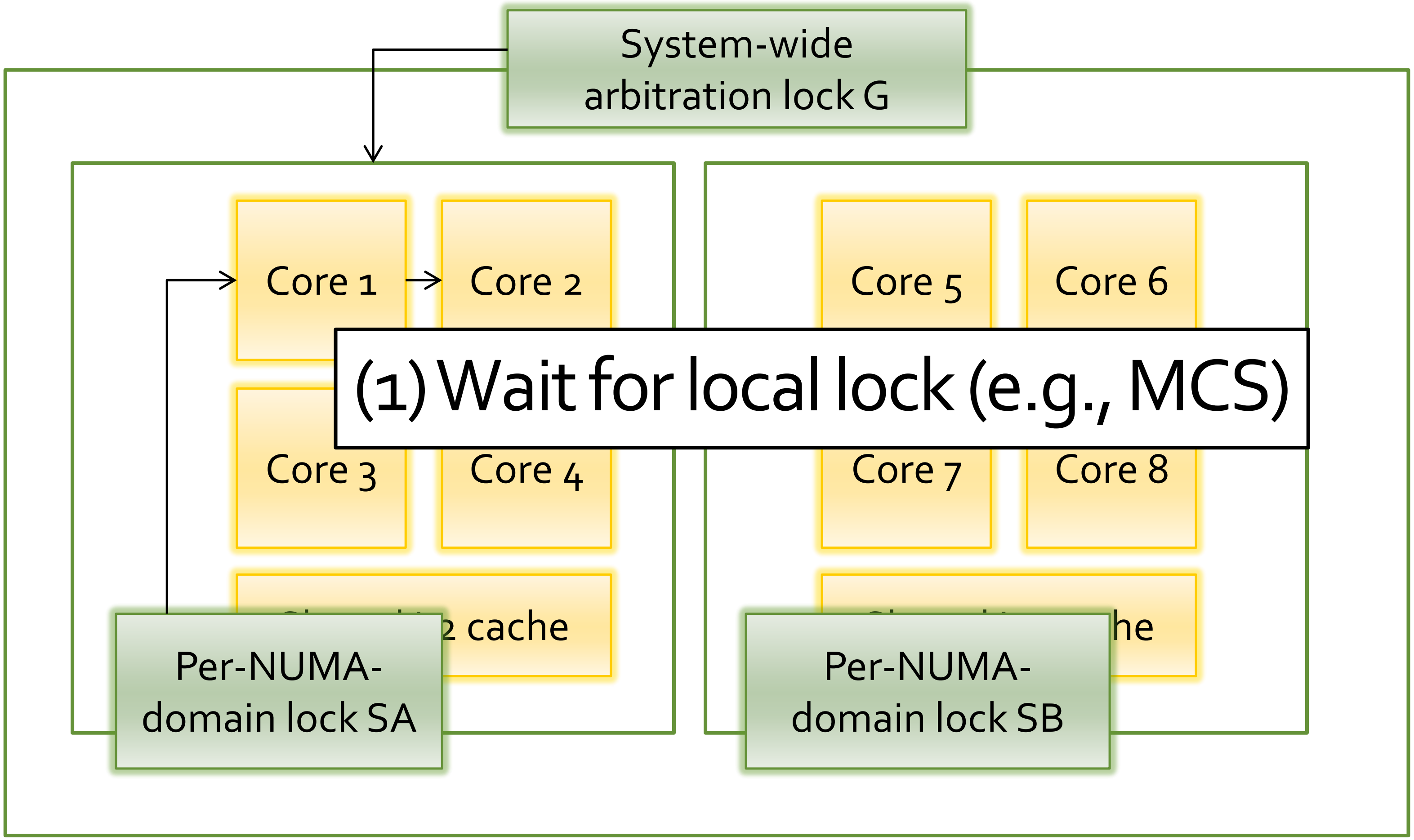
Lock cohorting

- Lock acquire, uncontended



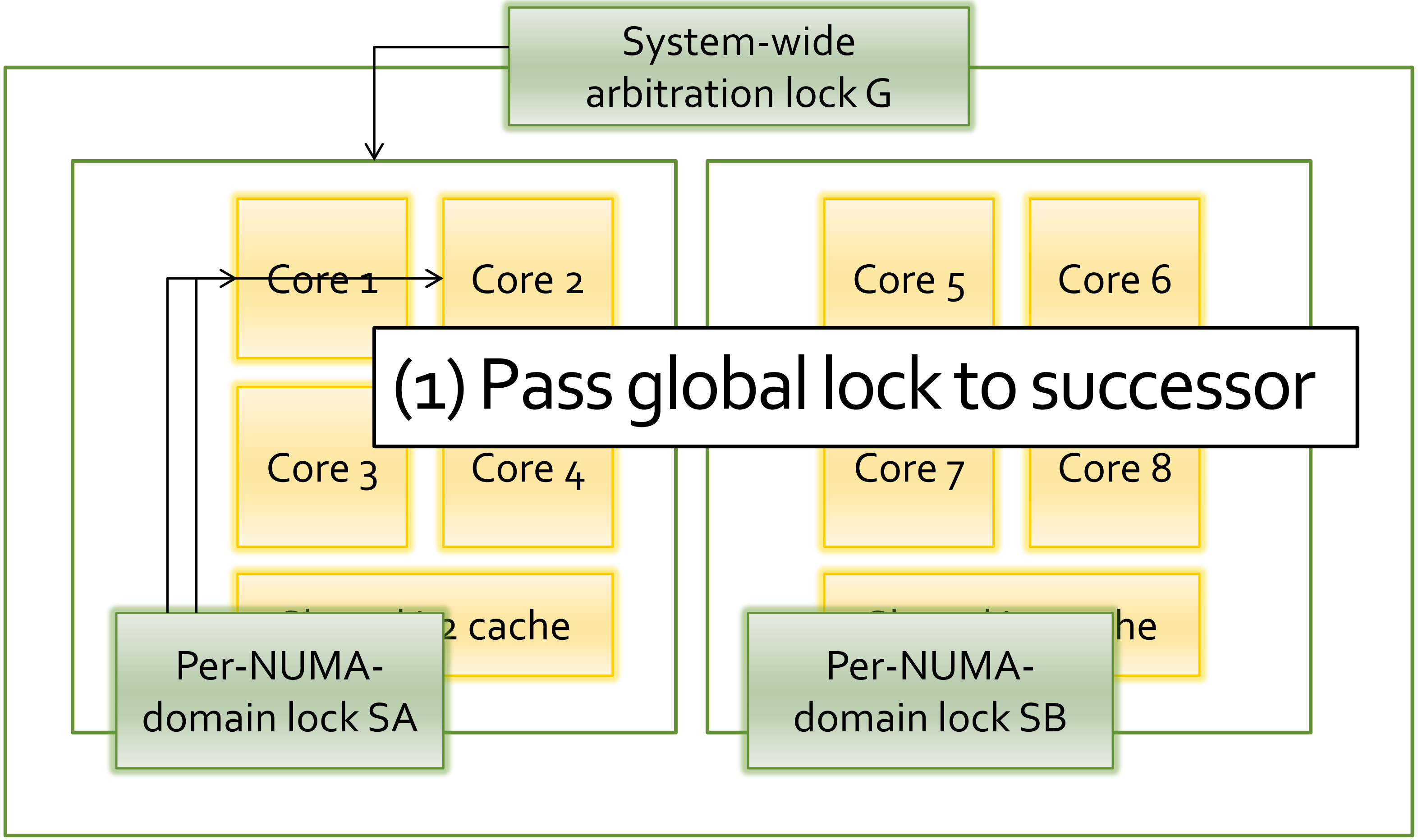
Lock cohorting

- Lock acquire, contended



Lock cohorting

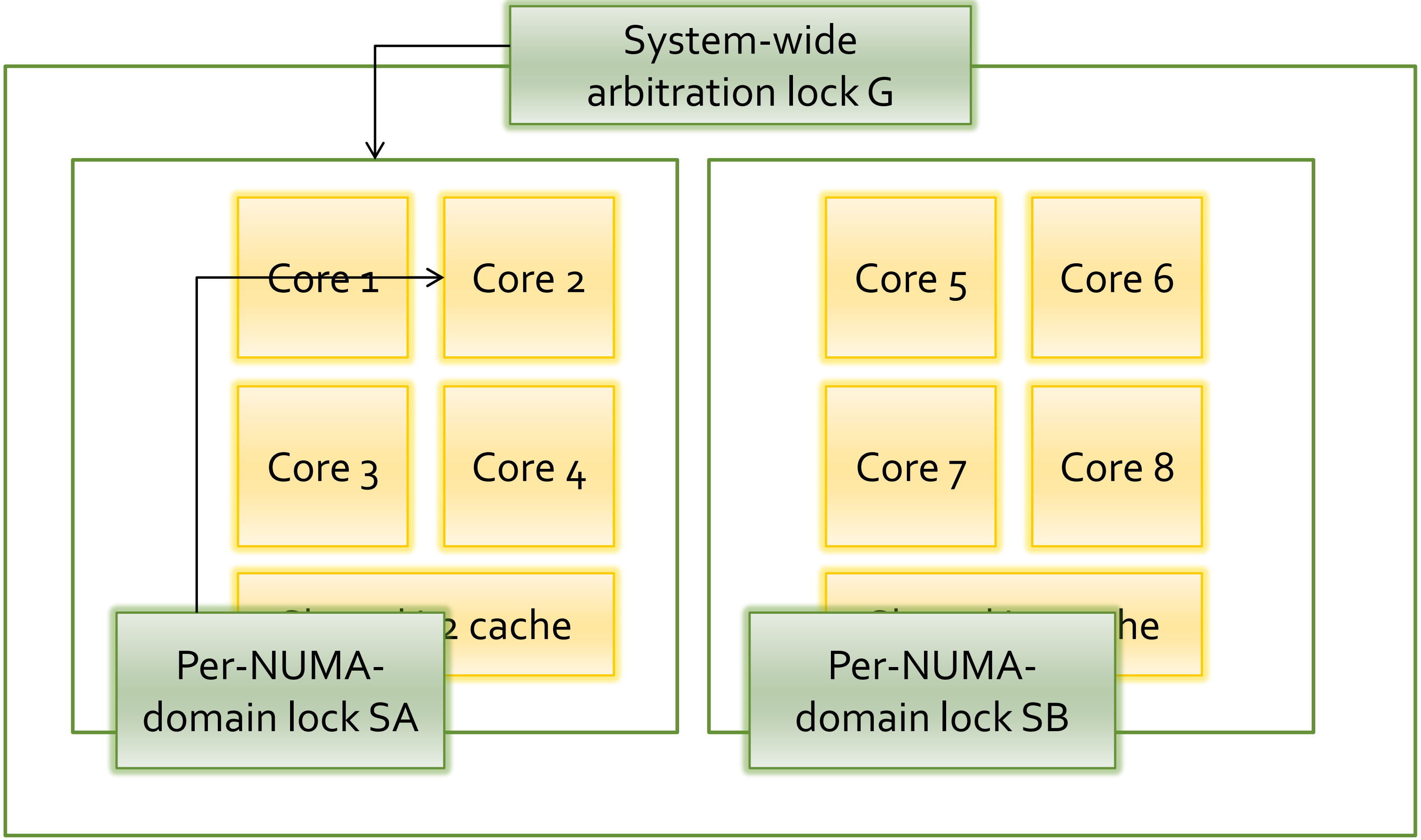
- Lock release, with successor



(1) Pass global lock to successor

Lock cohorting, requirements

- Global: “thread oblivious” (acq one thread, release another)
- Local lock: “cohort detection” (can test for successors)



Reader-writer locks

Reader-writer locks (TATAS-like)

lock: 0

-1 => Locked for write
0 => Lock available
+n => Locked by n readers

```
void acquireWrite(int *lock) {
   do {
     if ((*lock == 0) &&
        (CAS(lock, 0, -1))) {
      break;
   } while (1);
}
```

```
void acquireRead(int *lock) {
   do {
      int oldVal = *lock;
      if ((oldVal >= 0) &&
         (CAS(lock, oldVal, oldVal+1))) {
           break;
   }} while (1);
}
```

```
void releaseWrite(int *lock) {
  *lock = 0;
}
```

```
void releaseRead(int *lock) {
  FADD(lock, -1); // Atomic fetch-and-add
}
```

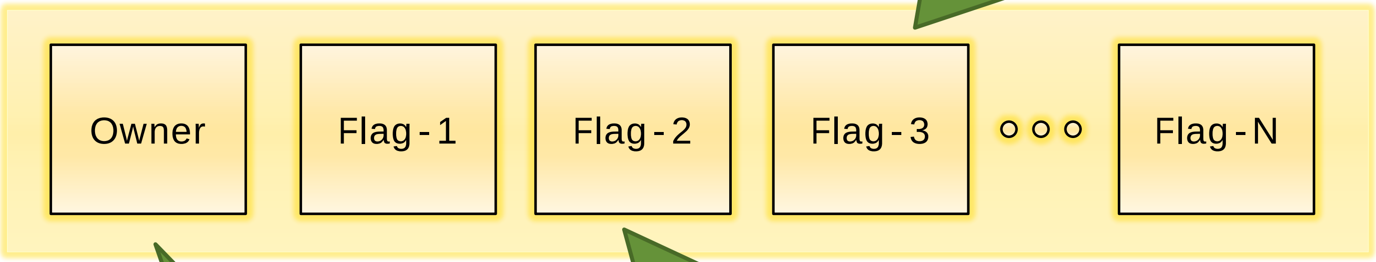
The problem with readers

```
int readCount() {
    acquireRead(lock);
    int result = count;
    releaseRead(lock);
    return result;
}
```

```
void incrementCount() {
    acquireWrite(lock);
    count++;
    releaseWrite(lock);
}
```

- Each acquireRead fetches the cache line holding the lock in exclusive mode
    - Again: acquireRead are not logically conflicting, but this introduces a physical confliect
- The time spent managing the lock is likely to vastly dominate the actual time looking at the counter
- Many workloads are read-mostly…

Keeping readers separate



Acquire write on core i:
CAS the owner from 0 to i

…then spin until all of the flags are clear

Acquire read on core i: set own flag to true…

…then check that the owner is 0
(if not then clear own flag and wait)

Keeping readers separate

- With care, readers do not need to synchronize with other readers
  - Extend the flags to be whole cache lines
  - Pack multiple locks flags for the same thread onto the same line
  - Exploit the cache structure in the machine: Dice & Shavit’s TLRW byte-lock
- If “N” threads is very large..
  - Dedicate the flags to specific important threads
  - Replace the flags with ordinary multi-reader locks
  - Replace the flags with per-NUMA-domain multi-reader locks

Other locking techniques

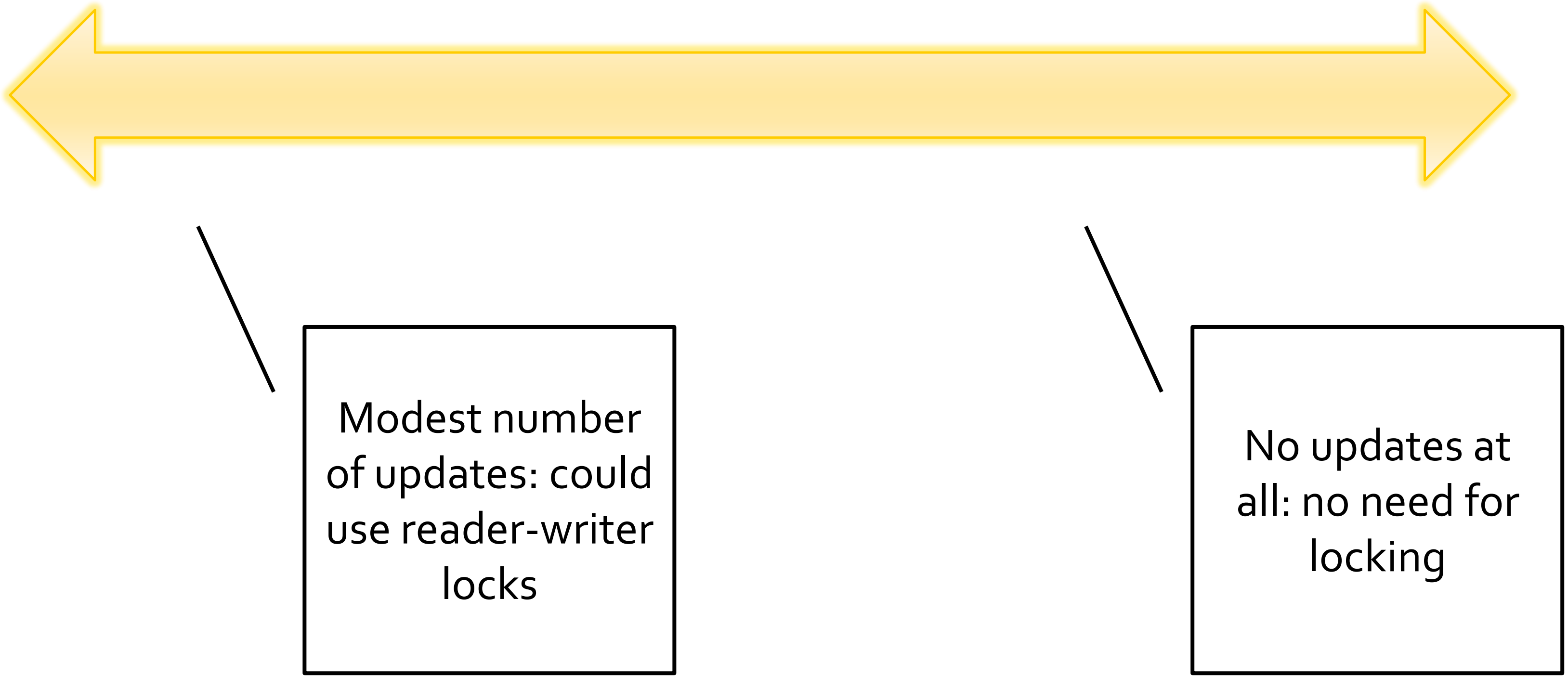
- Affinity
  - Allow one thread fast access to the lock
  - "One thread" – e.g., previous lock holder
  - "Fast access" – e.g., with fewer / no atomic CAS operations
  - Mike Burrows "Implementing unnecessary mutexes" (Do the assumptions hold? How slow is an uncontended CAS on a modern machine? Are these techniques still useful?)
- Inflation
  - Start out with a simple lock for likely-to-be-uncontended use
  - Replace with a "proper" lock if contended
  - David Bacon (thin locks), Agesen *et al* (meta-locks)
  - Motivating example: standard libraries in Java

Where are we

- Amdahl’s law: to scale to large numbers of cores, we need critical sections to be rare and/or short
- A lock implementation may involve updating a few memory locations
- Accessing a data structure may involve only a few memory locations too
- If we try to shrink critical sections then the time in the lock implementation becomes proportionately greater
- So:
  - try to make the cost of the operations in the critical section lower, or
  - try to write critical sections correctly without locking

Reading without locking

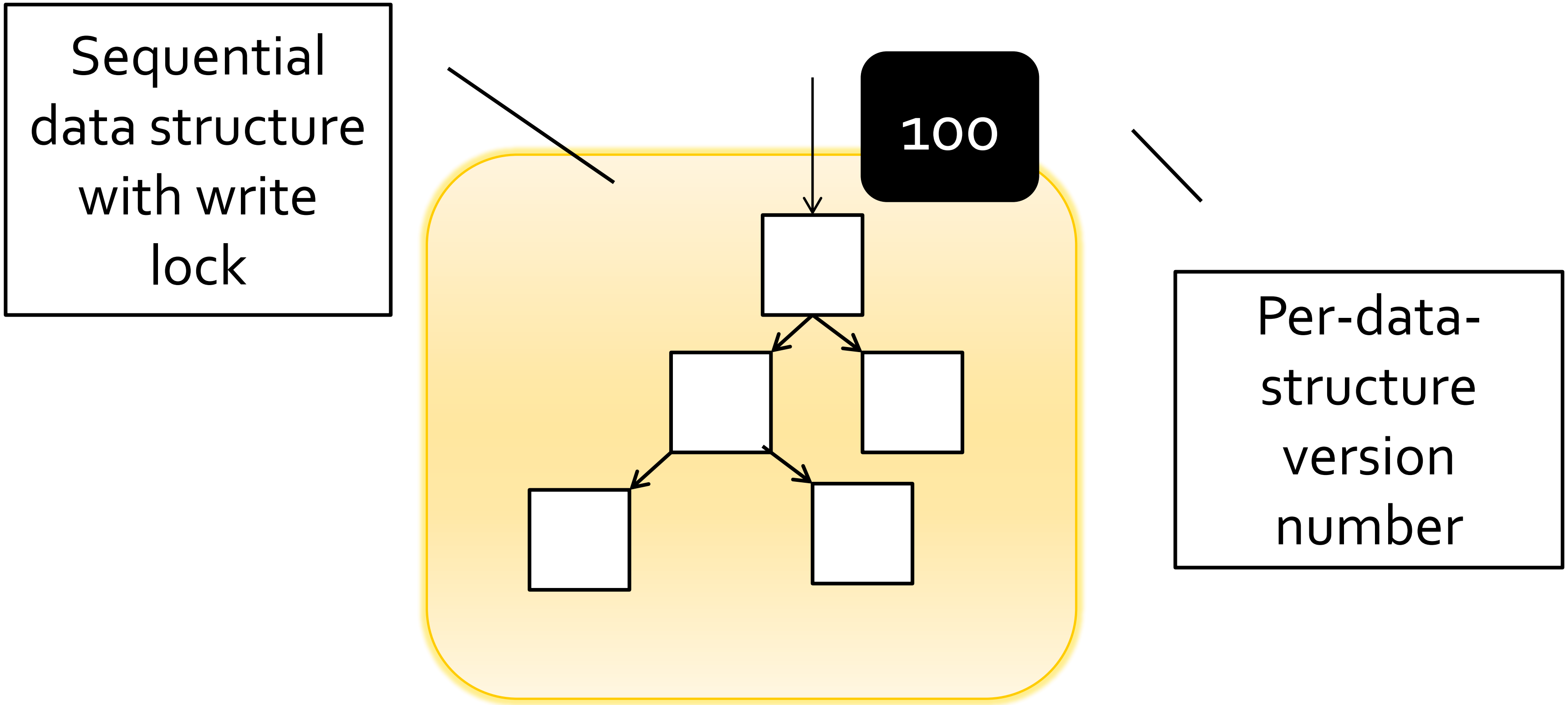
What if updates are very rare



Modest number of updates: could use reader-writer locks

No updates at all: no need for locking

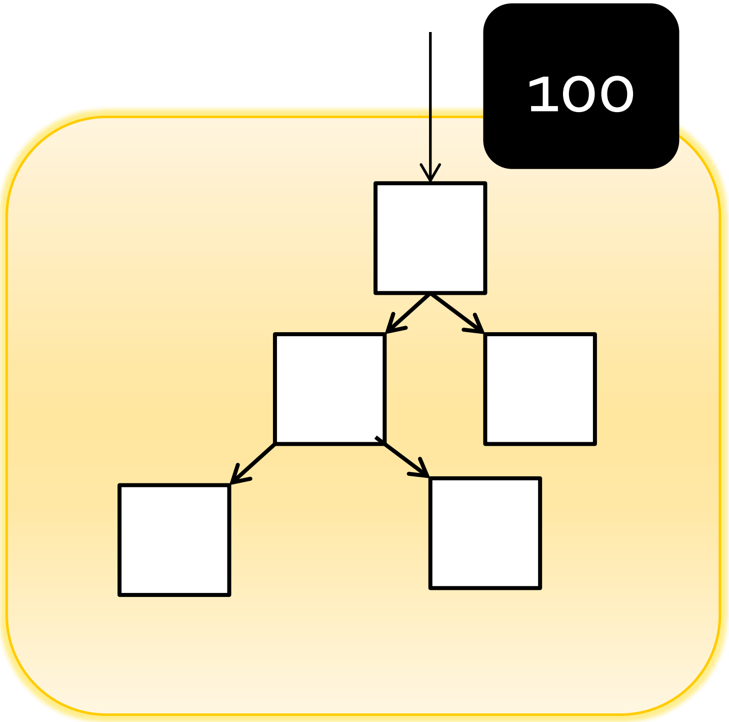
Version numbers



Sequential data structure with write lock

Per-data-structure version number

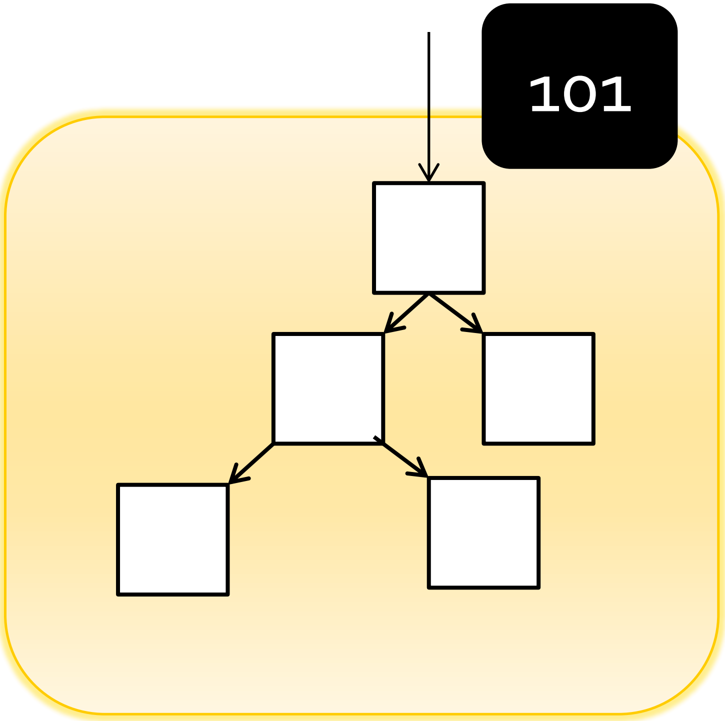
Version numbers: writers



Version numbers: writers

Writers:

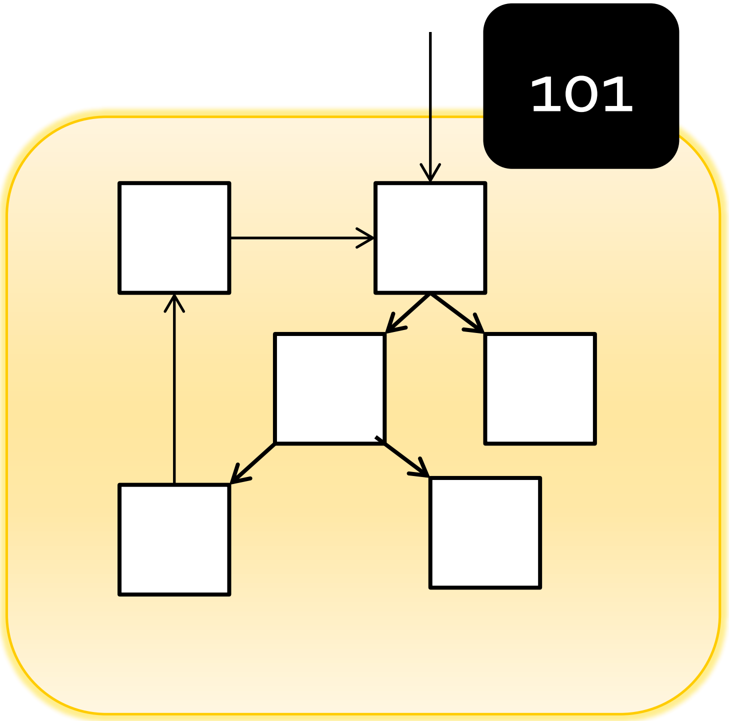
1. Take write lock
2. Increment version number



Version numbers: writers

Writers:

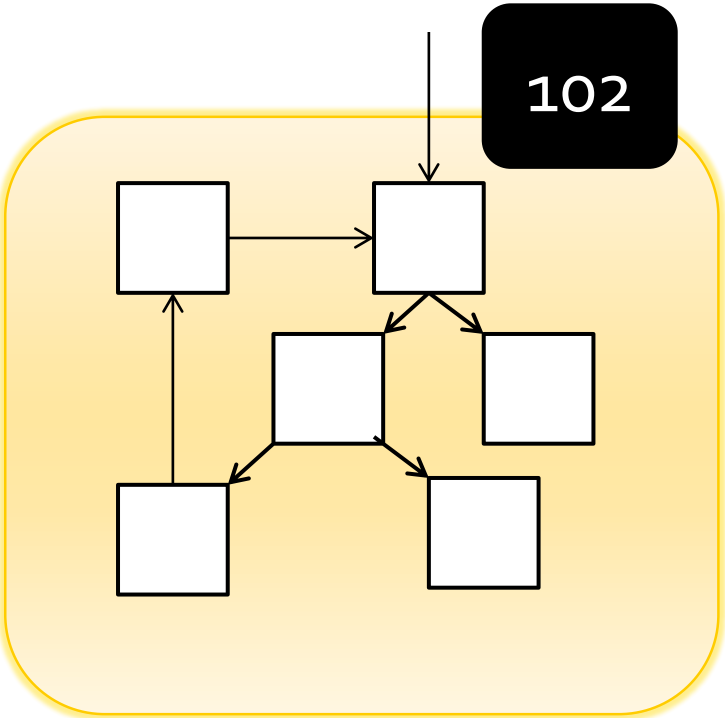
1. Take write lock
2. Increment version number
3. Make update



Version numbers: writers

Writers:

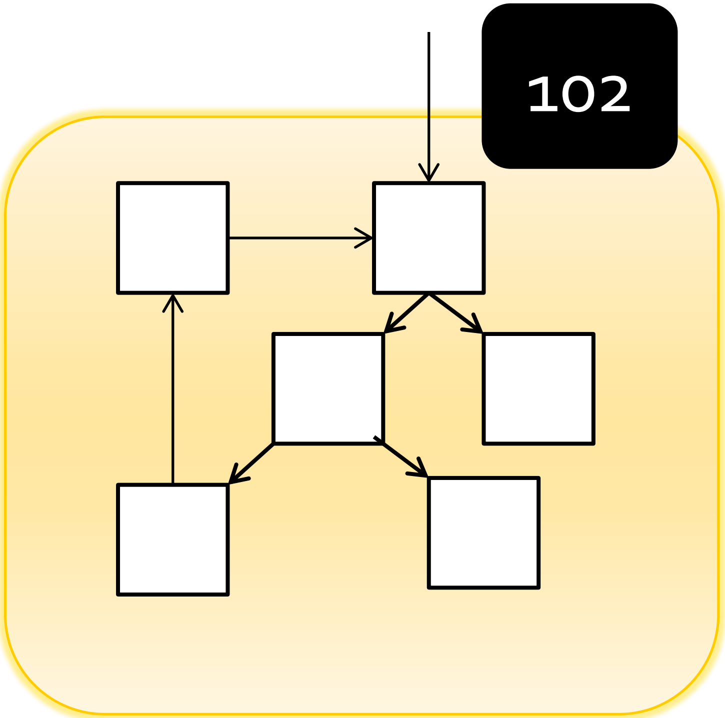
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock



Version numbers: readers

Writers:

1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock



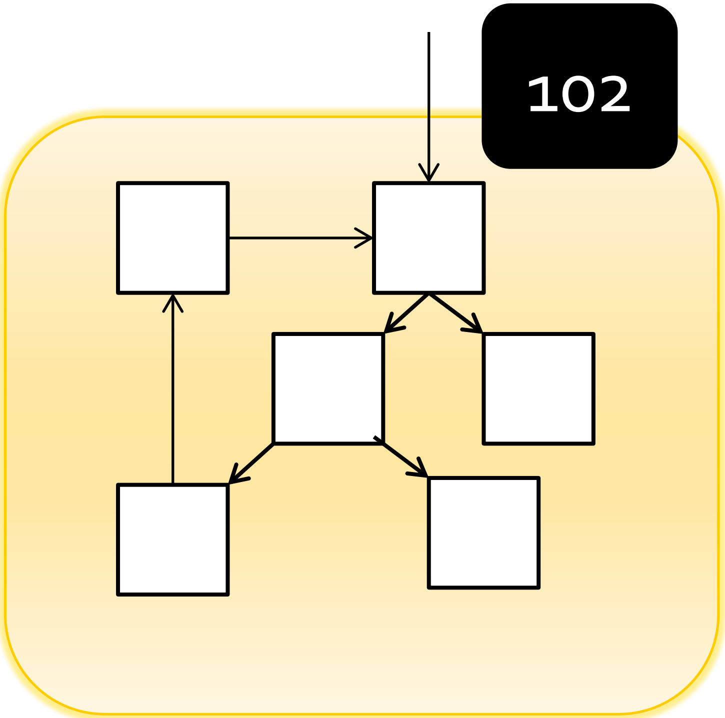
Readers:

1. Wait for version number to be even

Version numbers: readers

Writers:

1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock



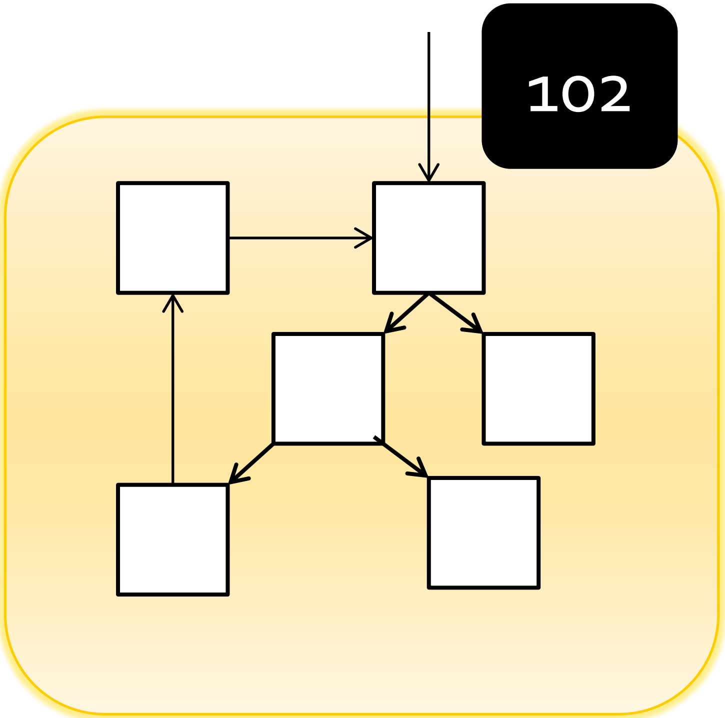
Readers:

1. Wait for version number to be even
2. Do operation

Version numbers: readers

Writers:

1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock



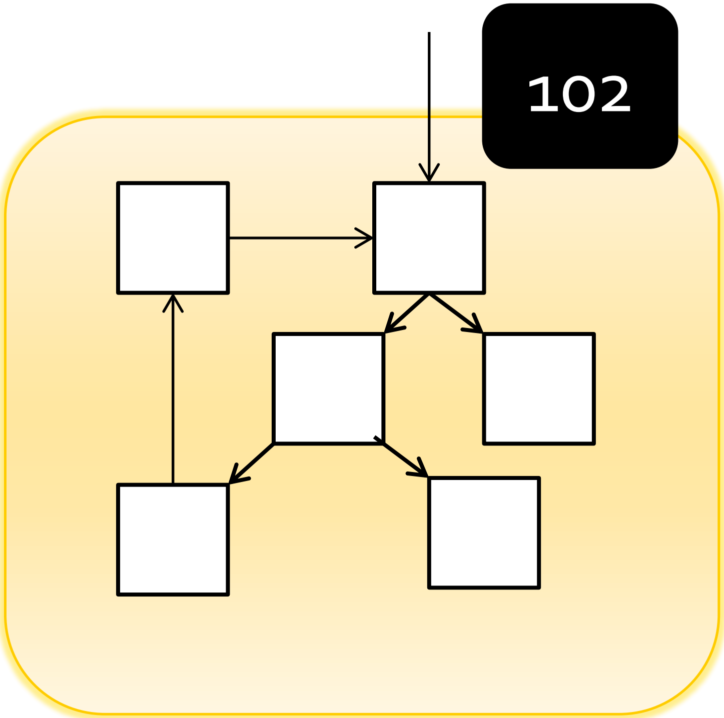
Readers:

1. Wait for version number to be even
2. Do operation
3. Has the version number changed?
4. No? Go to 1

Why do we need the two steps?

Writers:

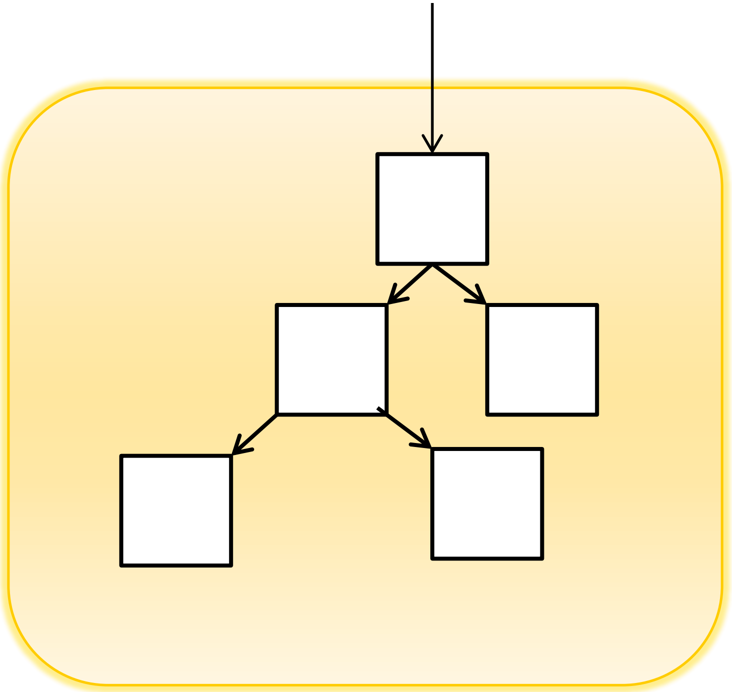
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock



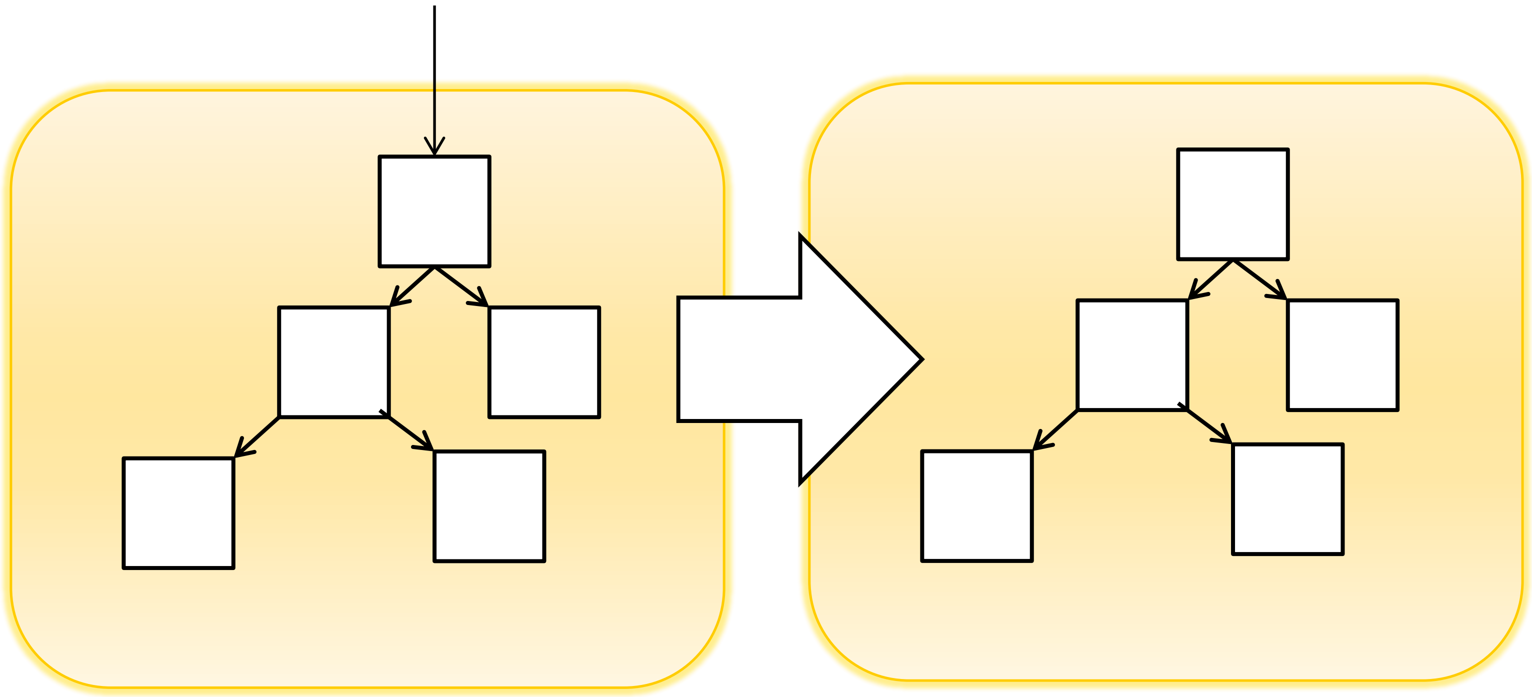
Readers:

1. Wait for version number to be even
2. Do operation
3. Has the version number changed?
4. No? Go to 1

Read-Copy-Update (RCU)

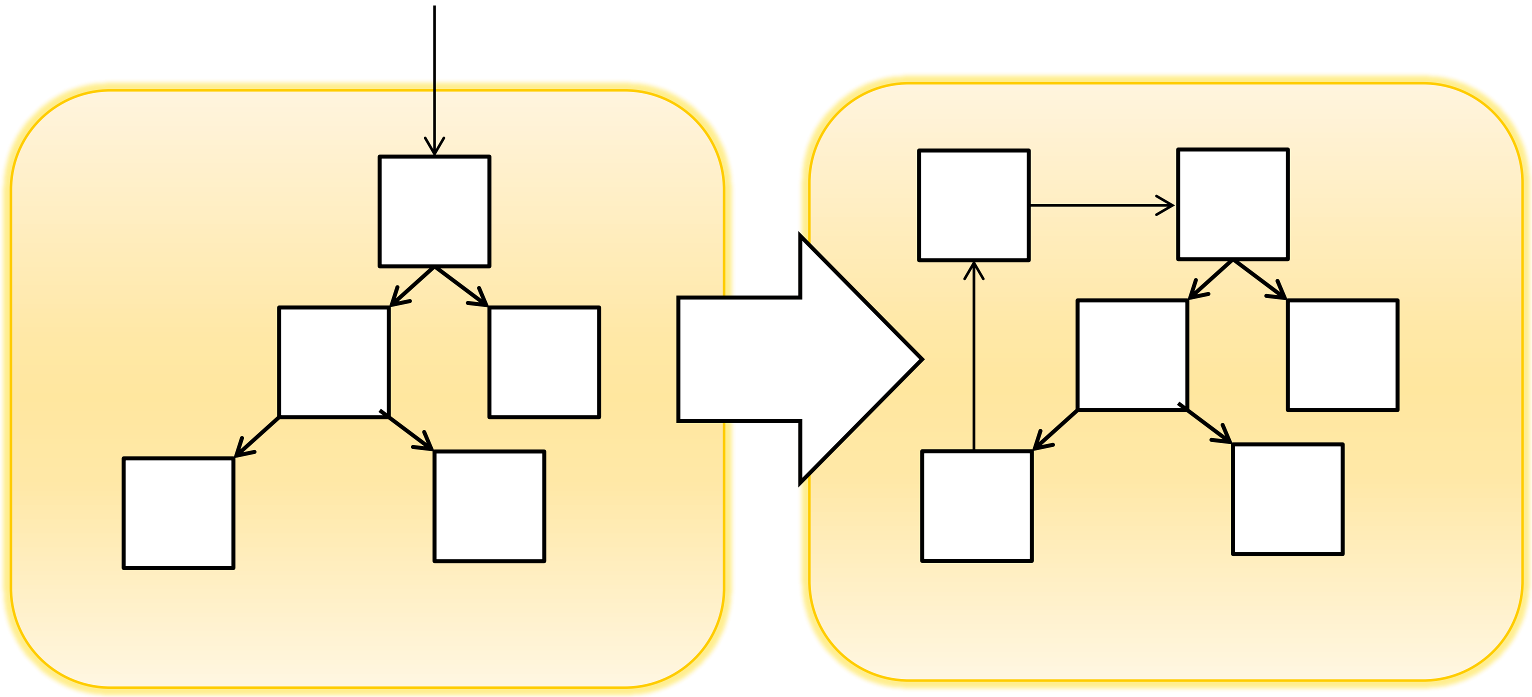


Read-Copy-Update (RCU)



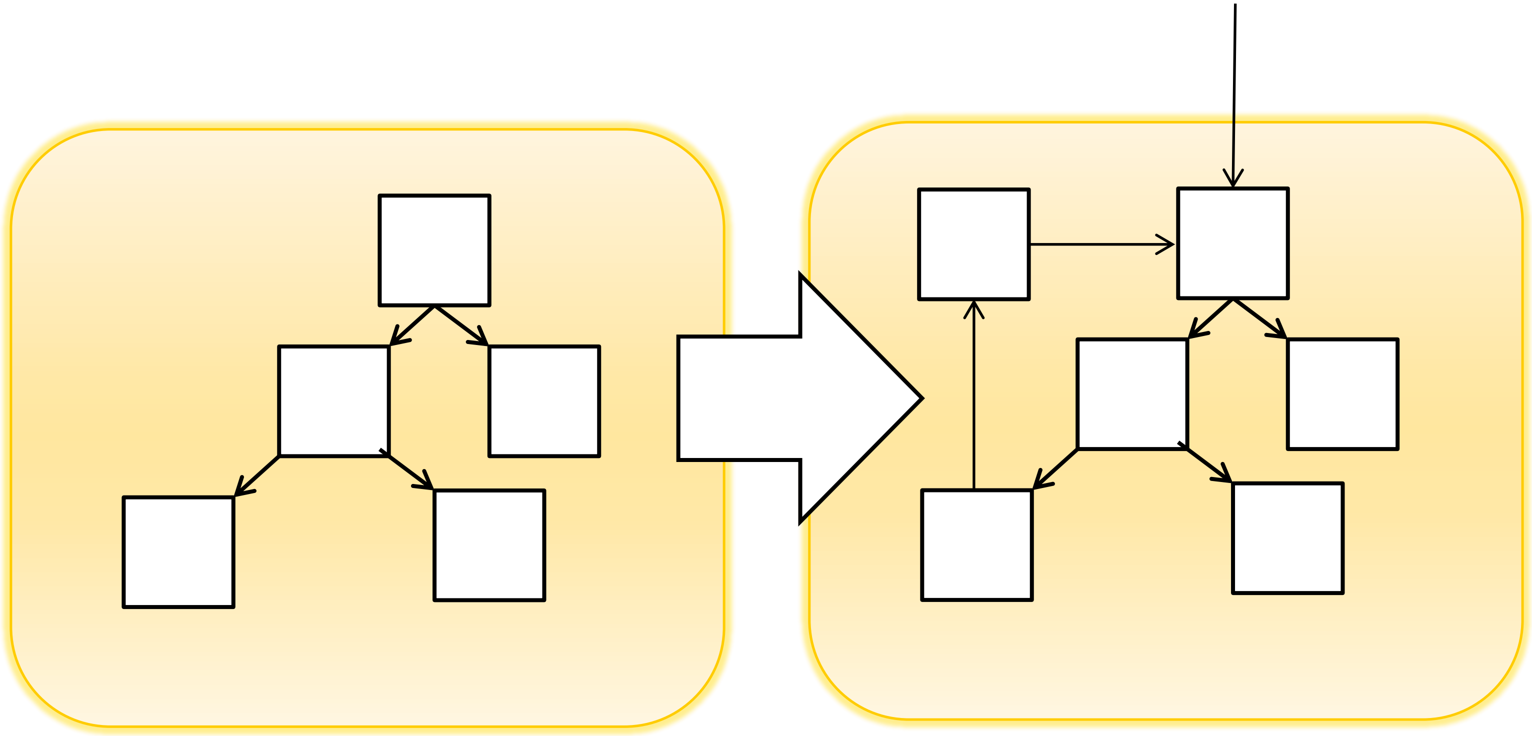
1. Copy existing structure

Read-Copy-Update (RCU)



1. Copy existing structure
2. Update copy

Read-Copy-Update (RCU)



1. Copy existing structure
2. Update copy
3. Install copy with CAS on root pointer

Read-Copy-Update (RCU)

- Use locking to serialize updates (typically)
  - …but allow readers to operate concurrently with updates
- Ensure that readers don’t go wrong if they access data mid-update
  - Have data structures reachable via a single root pointer: update the root pointer rather than updating the data structure in-place
  - Ensure that updates don’t affect readers – e.g., initializing nodes before splicing them into a list, and retaining “next” pointers in deleted nodes
  - Exact semantics offered can be subtle (ongoing research direction)
- Memory management problems common with lock-free data structures

When will these techniques be effective?

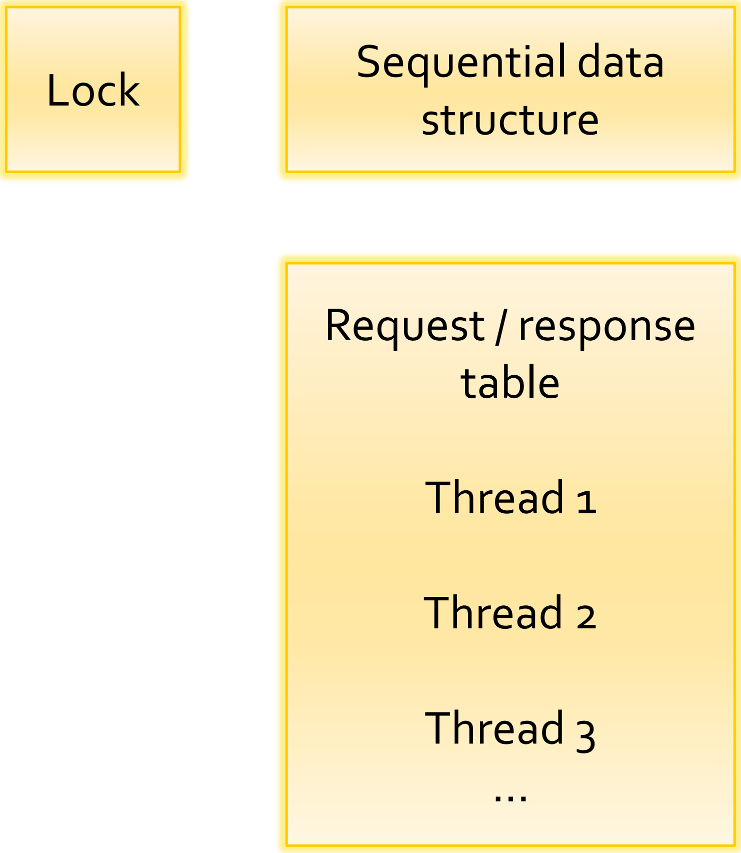
- Update rate low
  - So the need to serialize updates is OK
- Readers behaviour is OK mid-update
  - E.g., structure small enough to clone, rather than update in place
  - Readers will be OK until a version number check (not enter endless loops etc.)
- Deallocation or re-use of memory can be controlled

Flat combining

Flat combining

- "Flat Combining and the Synchronization-Parallelism Tradeoff", Hendler *et al*
- Intuition:
  - Acquiring and releasing a lock involves numerous cache line transfers on the interconnect
  - These may take hundreds of cycles (e.g., between cores in different NUMA nodes)
  - The work protected by the lock may involve only a few memory accesses…
  - …and these accesses may be likely to hit in the cache of the previous lock holder (but miss in your own)
  - So: if a lock is not available, request that the current lock holder does the work on your behalf

Flat combining



Lock

Sequential data structure

Request / response table

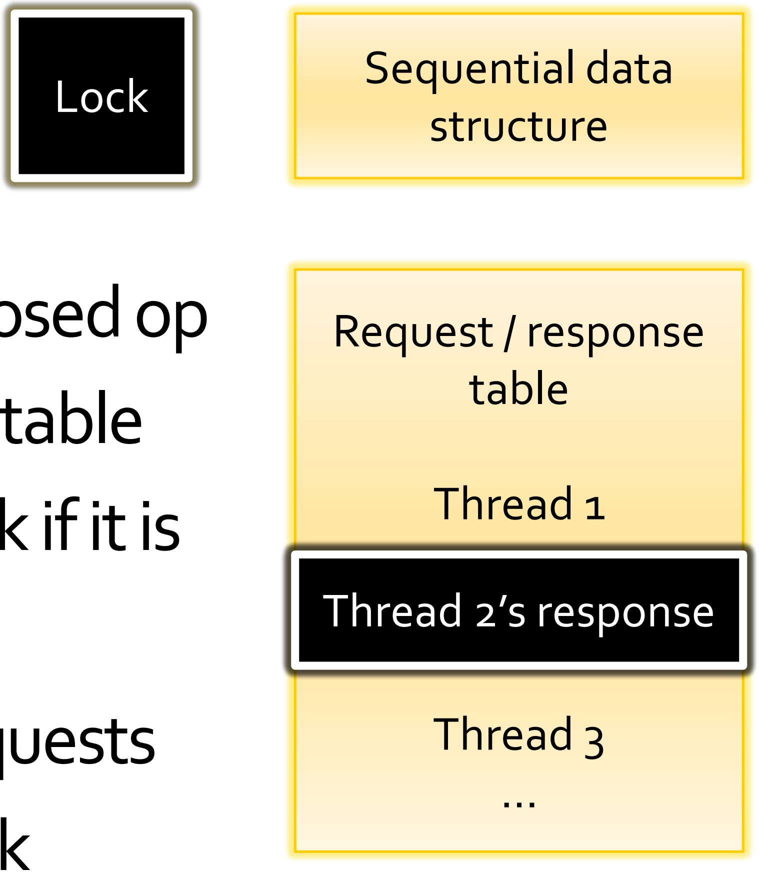
Thread 1

Thread 2

Thread 3

…

Flat combining: uncontended acquire



Lock

Sequential data structure

Request / response table

Thread 1

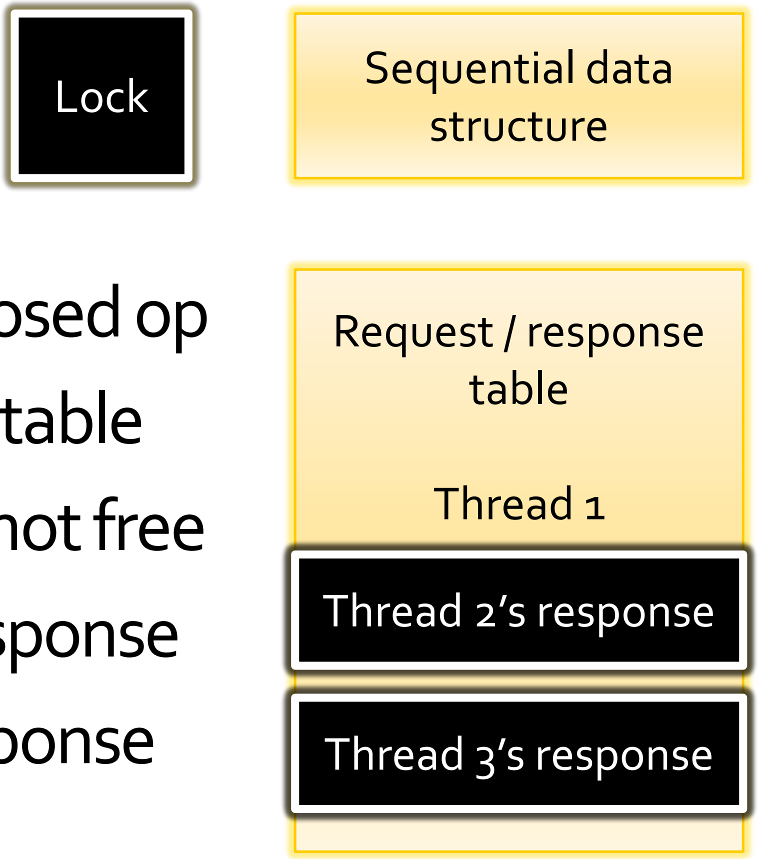
Thread 2’s response

Thread 3

…

1. Write proposed op to req/resp table
2. Acquire lock if it is free
3. Process requests
4. Release lock
5. Pick up response

Flat combining: contended acquire



Lock

Sequential data structure

Request / response table

Thread 1

Thread 2’s response

Thread 3’s response

1. Write proposed op to req/resp table
2. See lock is not free
3. Wait for response
4. Pick up response