Everything You Always Wanted to Know about Synchronization but Were Afraid to Ask

Tudor David, Rachid Guerraoui, Vasileios Trigonakis

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

The multi-core revolution

- **Big challenges in hardware & software**
- Software
  - **scalability**: ↑ performance by ↑ number of cores

Synchronization is one of the biggest scalability bottlenecks

Synchronization

- Cannot always be avoided
  - not all applications embarrassingly parallel
- Synchronization is just an overhead
  - but guarantees correctness
- Scalability of synchronization
  - do not ↓ performance as the number of cores ↑

Scalability of synchronization is key to application scalability

Synchronization is difficult

- Tons of work
  - design of synchronization schemes [ISCA'89, TPDS'90, ASPLOS'91, TOCS'91, PPoPP'01, PODC'95, ICPP'06, SPAA'10, IPDPS'11, PPoPP'12, ATC'12, …]
  - fix synchronization bottlenecks [SOSP'89, HPCA'07, OSDI'99, OSDI'08, SOSP'09, APLOS'09, OSR'09, OSDI'10, …]
- Scalability issues?
  - hardware
  - usage of specific atomic operations
  - synchronization algorithm
  - application context
  - workload

Limited understanding of the behavior of synchronization

Take a step back

and perform a thorough analysis of synchronization on modern hardware

What is the main source of scalability problems in synchronization?

Answer

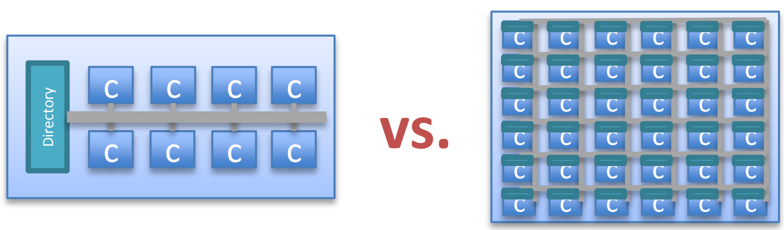
Scalability of synchronization is mainly a property of the hardware

Key observations

1. Crossing sockets is a killer

2. Sharing within a socket is necessary but not sufficient

3. Intra-socket uniformity matters



4. Loads & stores can be as expensive as atomic operations
5. Simple locks are powerful

…

Disclaimer ☺

We do not claim

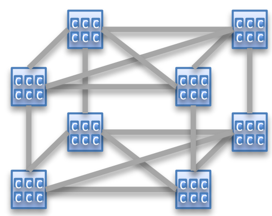
"Bad synchronization" in software
will scale **well** due to hardware

We claim

"Good synchronization" in software
might **not scale as expected** due to hardware

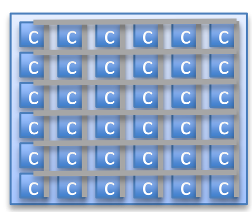
Analysis method

Hardware processors



Multi-sockets

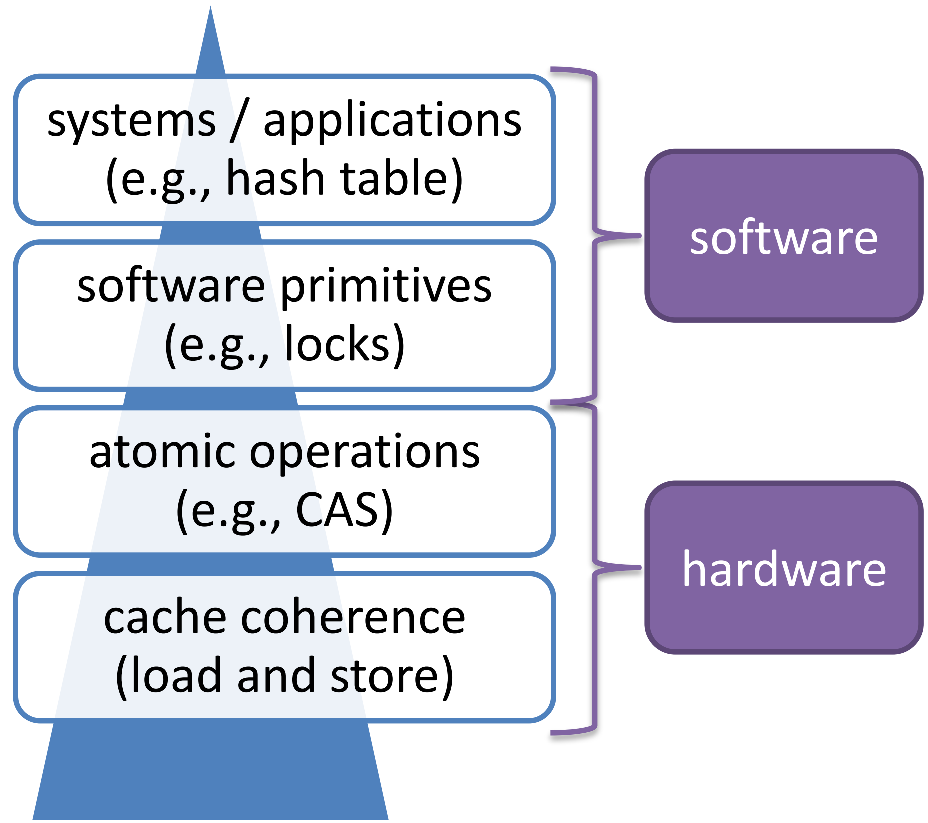
- AMD Opteron (4x 6172 - 48 cores)
- Intel Xeon (8x E7-8867L - 80 cores)



Single-sockets

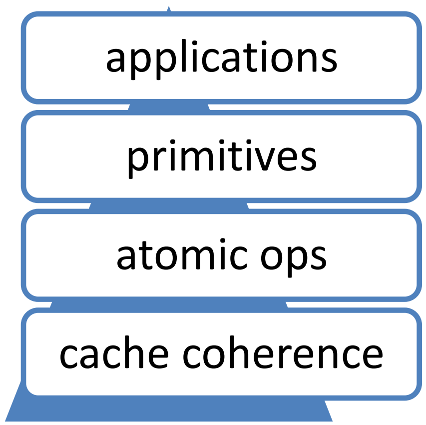
- Sun Niagara 2 (8 cores)
- Tilera TILE-Gx36 (36 cores)

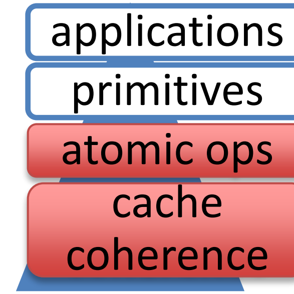
Synchronization layers



Outline

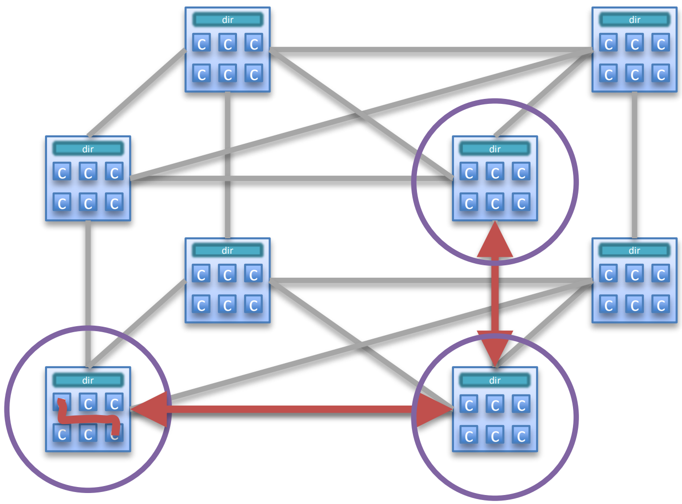
1. **Crossing sockets**
2. Sharing within a socket
3. Intra-socket uniformity
4. Atomic operations
5. Simple locks





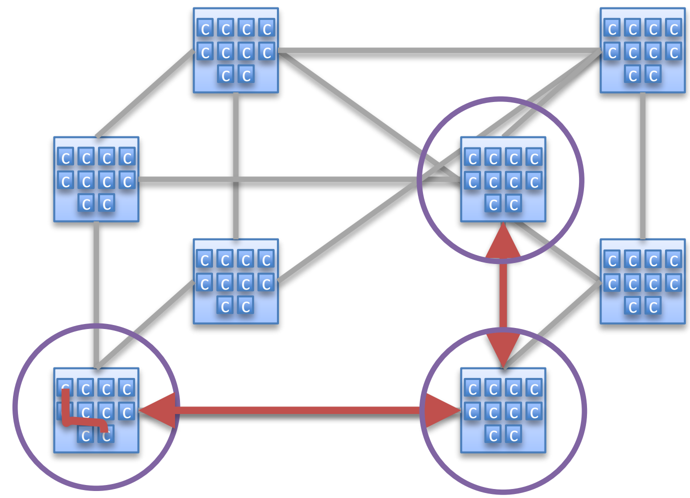
Distance on multi-sockets

Opteron



- Within socket: 40 ns
- Per hop: +40 ns
- Up to **3x** more

Xeon



- Within socket: 20 – 40 ns
- Per hop: +50 ns
- Up to **8x** more

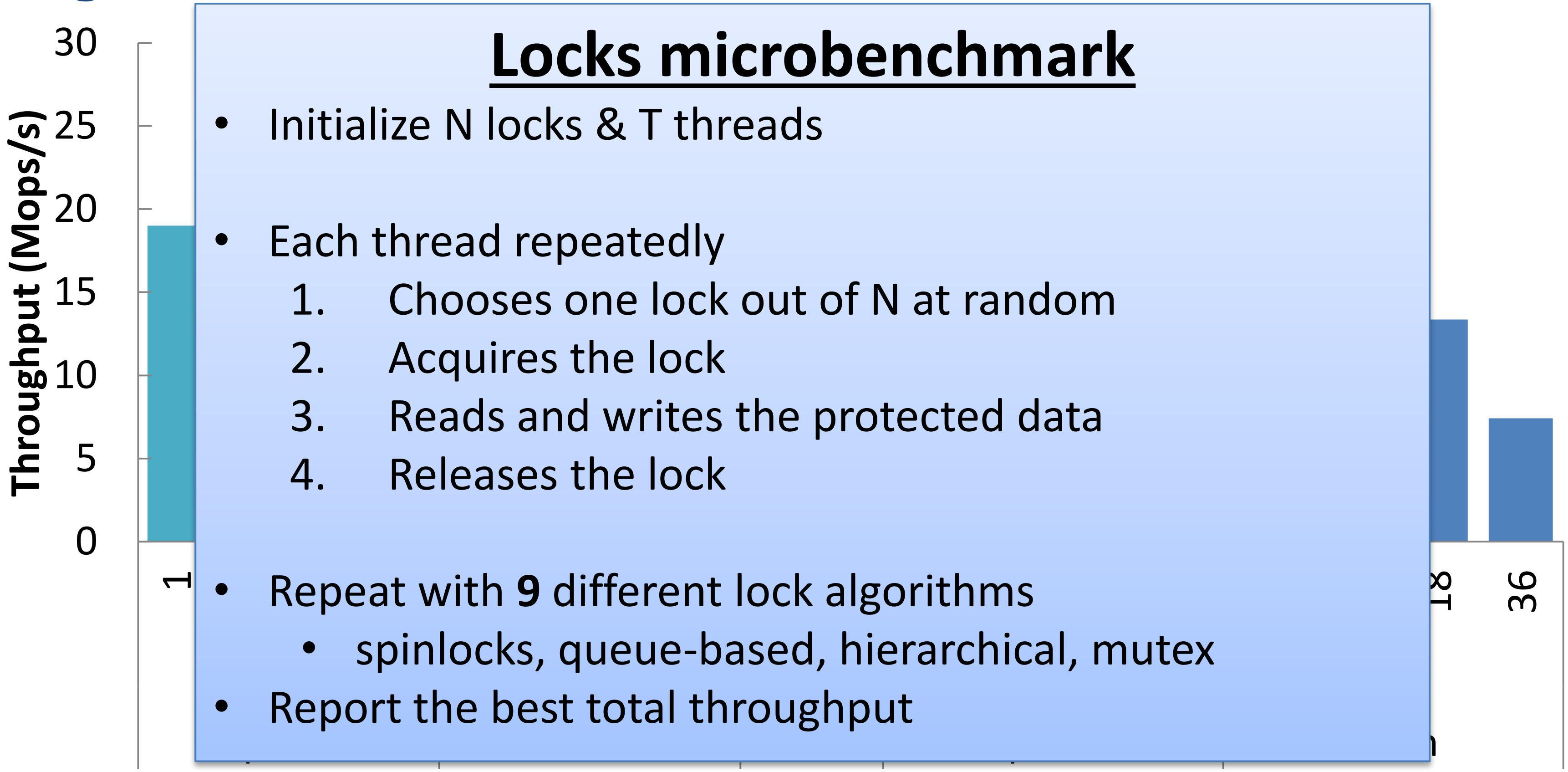
Crossing sockets is a killer: up to 8x more expensive

Locks on multi-sockets

** Each point is the best result out of 9 lock algorithms

High contention (4 locks)

Low contention (512 locks)



Locks microbenchmark

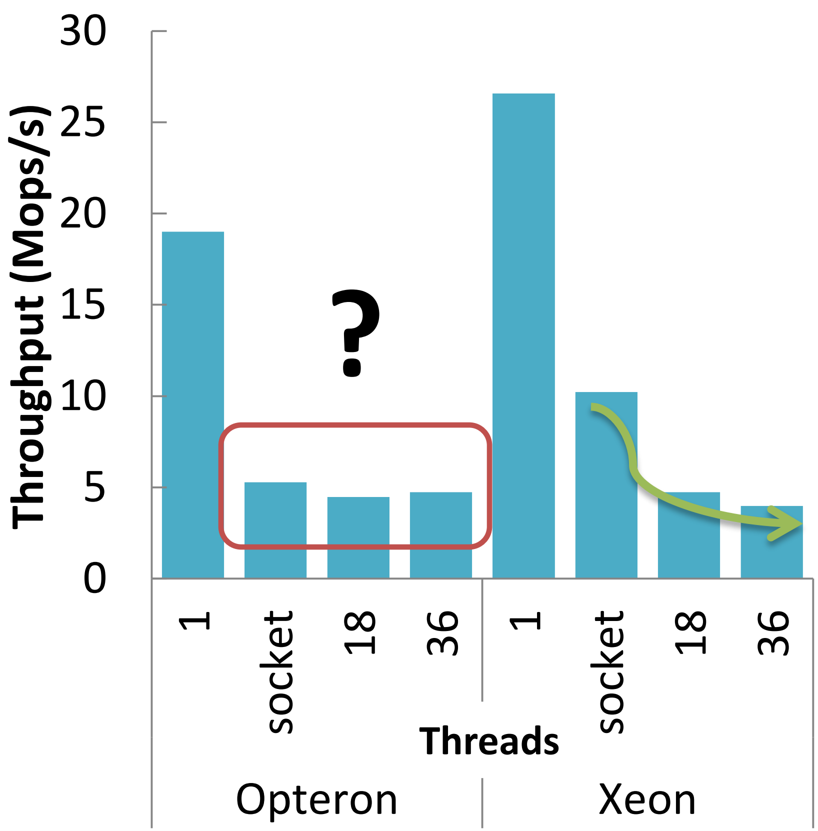
- Initialize N locks & T threads
- Each thread repeatedly
  1. Chooses one lock out of N at random
  2. Acquires the lock
  3. Reads and writes the protected data
  4. Releases the lock
- Repeat with **9** different lock algorithms
  - spinlocks, queue-based, hierarchical, mutex
- Report the best total throughput

applications
primitives
atomic ops
cache coherence

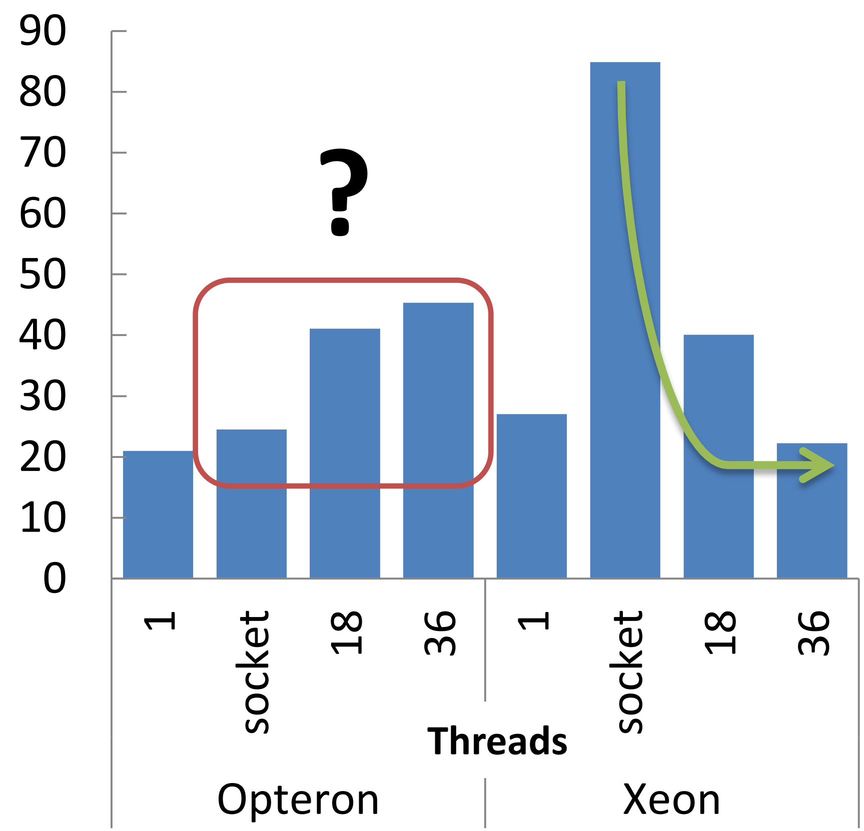
Locks on multi-sockets

** Each point is the best result out of 9 lock algorithms

High contention (4 locks)



Low contention (512 locks)

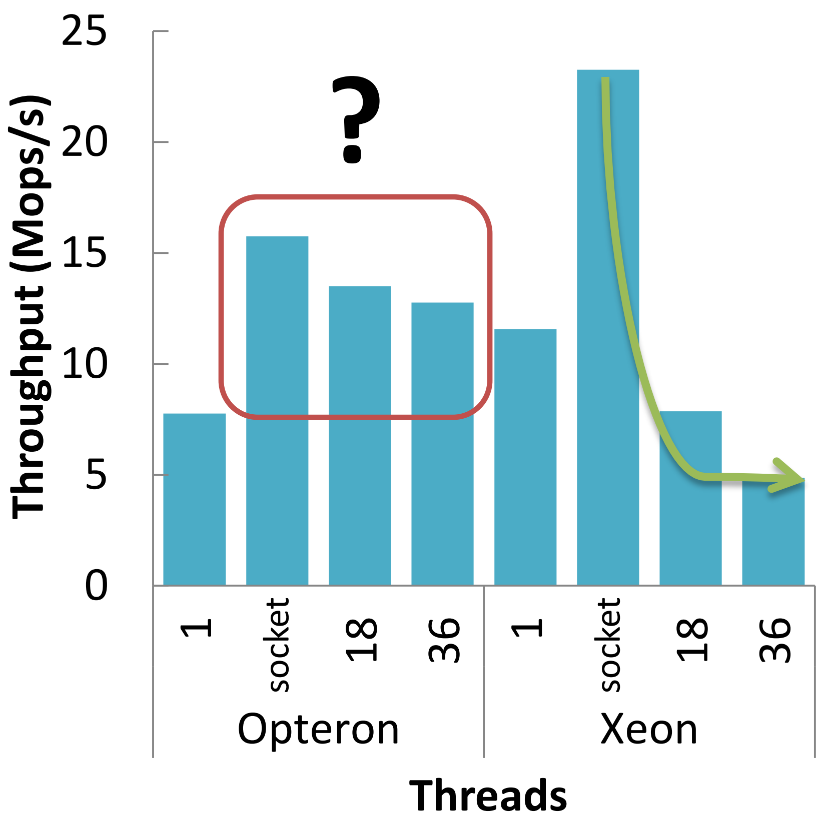


Crossing sockets is a killer: big decrease in performance

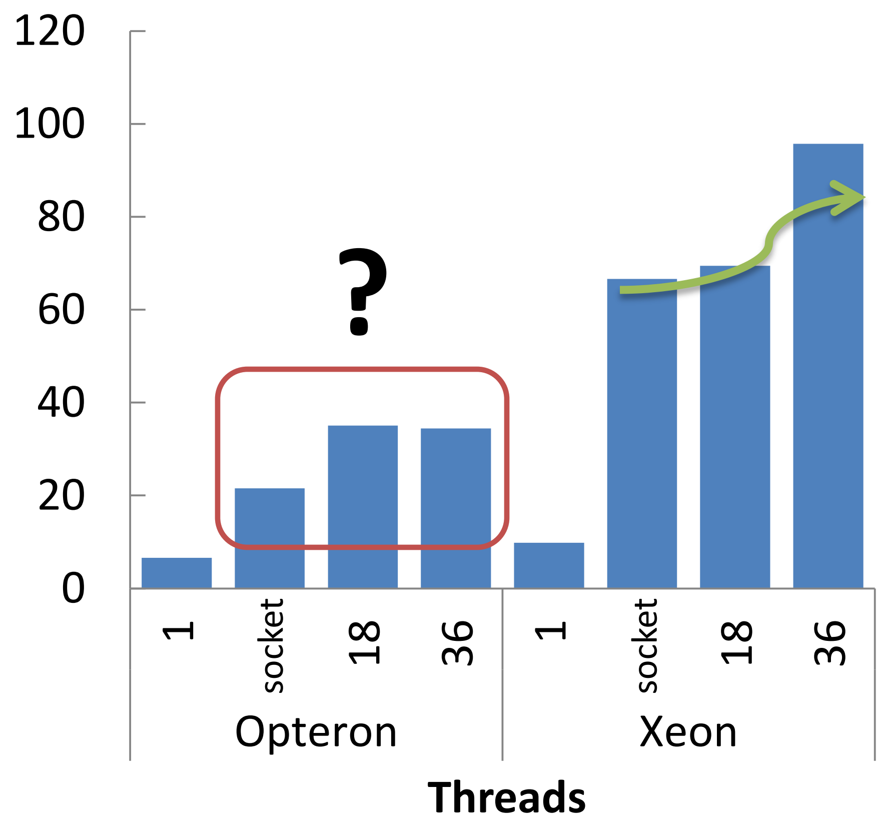
Hash table on multi-sockets

** Each point is the best result taken by any out of 9 lock algorithms

High contention (12 buckets)



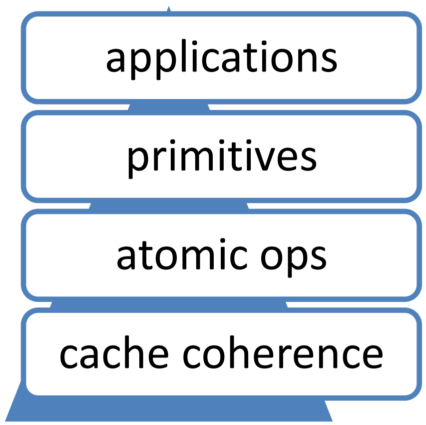
Low contention (512 buckets)

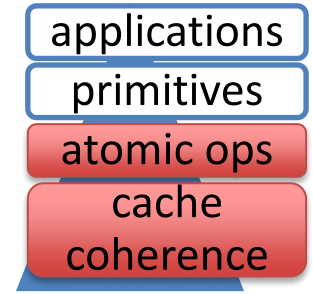


Crossing sockets is a killer

Outline

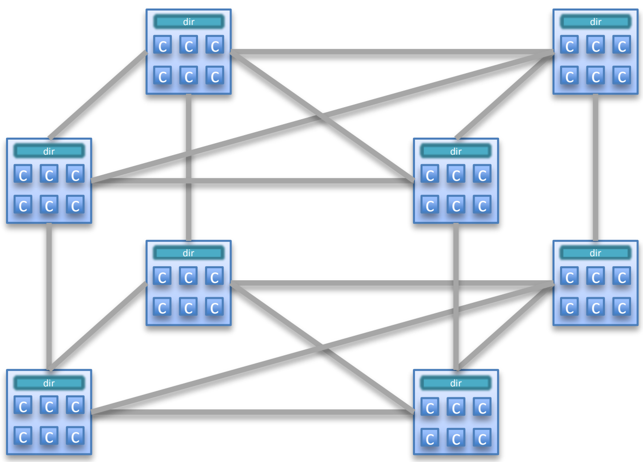
1. Crossing sockets
2. **Sharing within a socket**
3. Intra-socket uniformity
4. Atomic operations
5. Simple locks





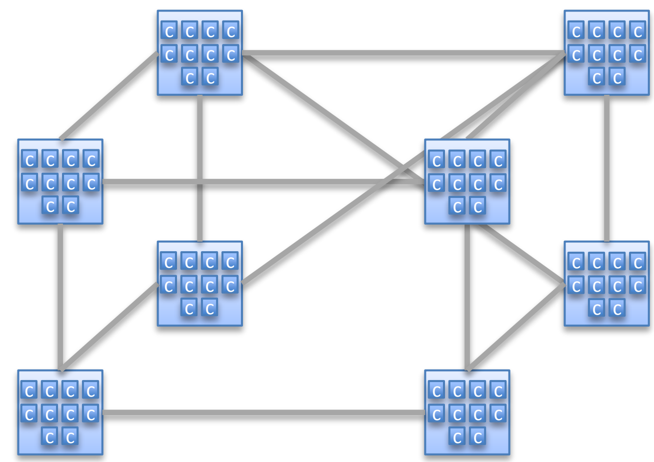
Coherence on multi-sockets

Opteron

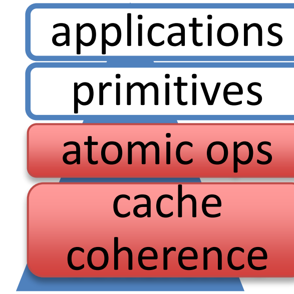


Incomplete directory

Xeon

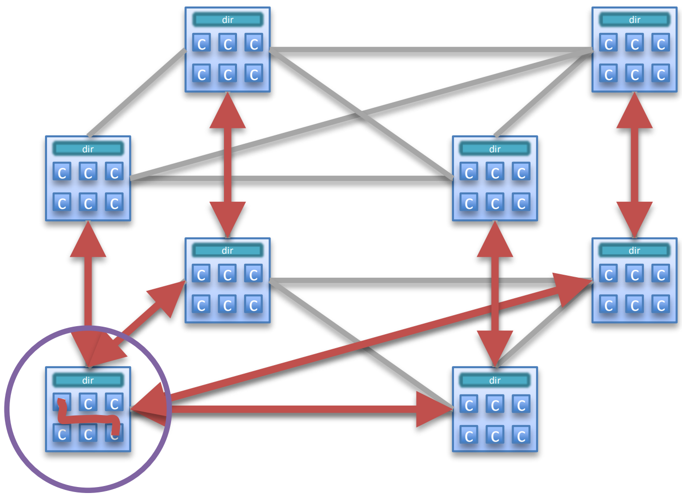


Broadcast requests



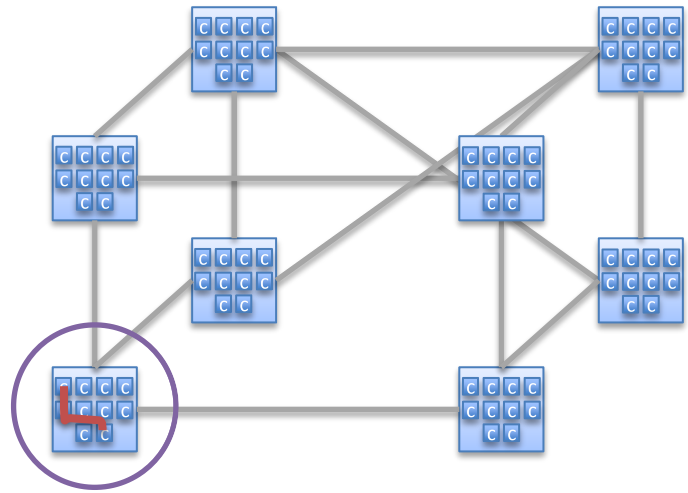
Locality on multi-sockets

Opteron



- **Within socket: 40 ns**
- Data within a socket
  - served locally (40 ns)
  - broadcast (**120 ns**)

Xeon

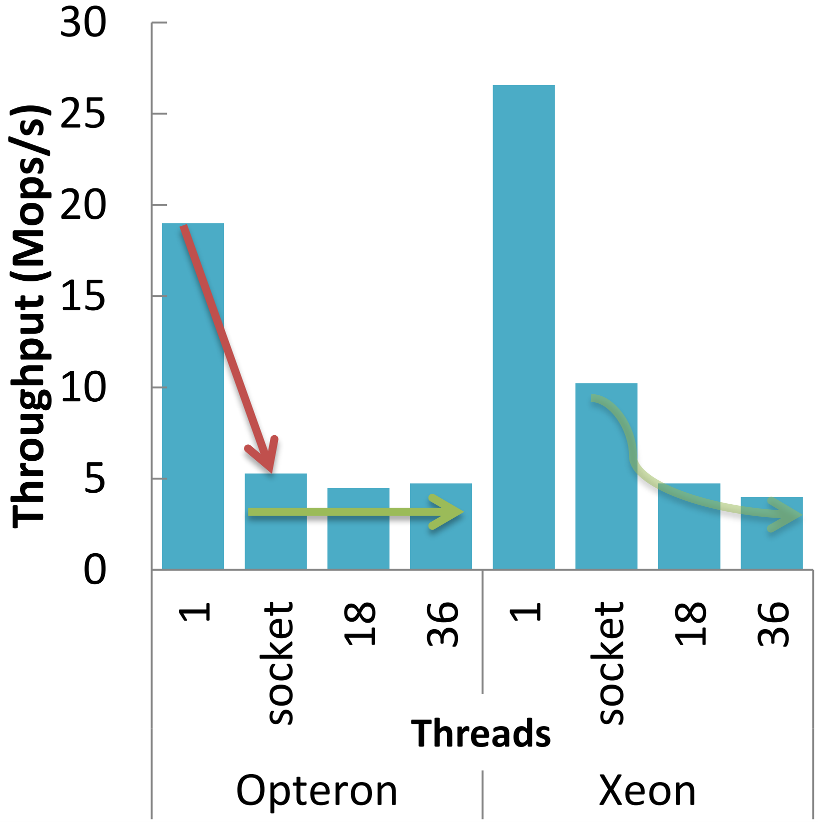


- **Within socket: 20 – 40 ns**
- Data within a socket
  - served by the LLC (20 – 40 ns)

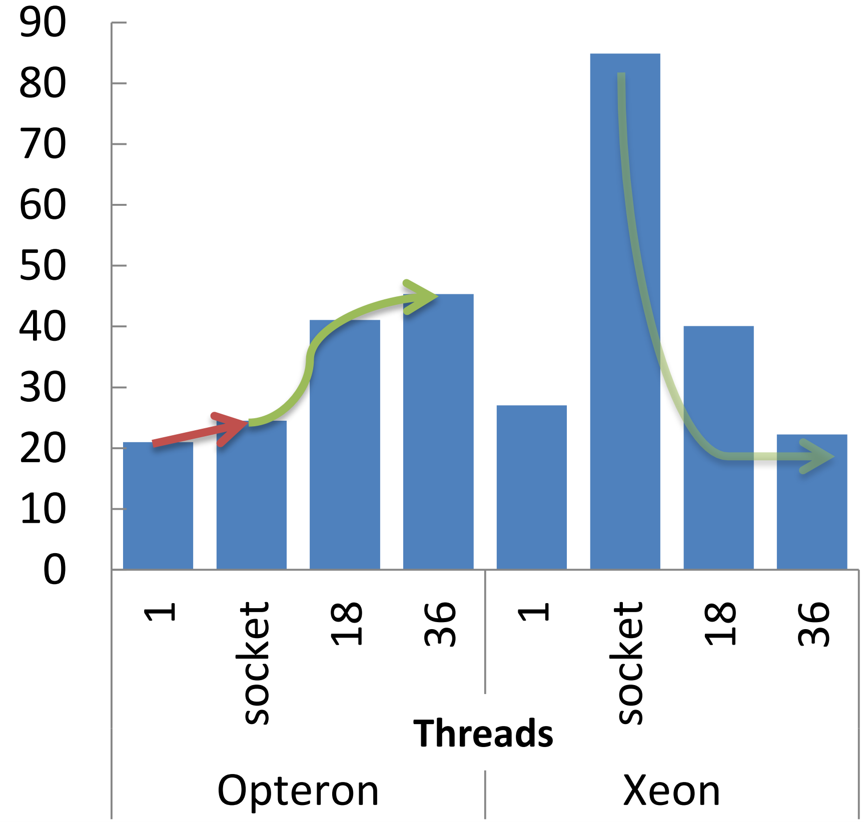
Sharing within a socket is necessary but not sufficient

Locks on multi-sockets

High contention (4 locks)



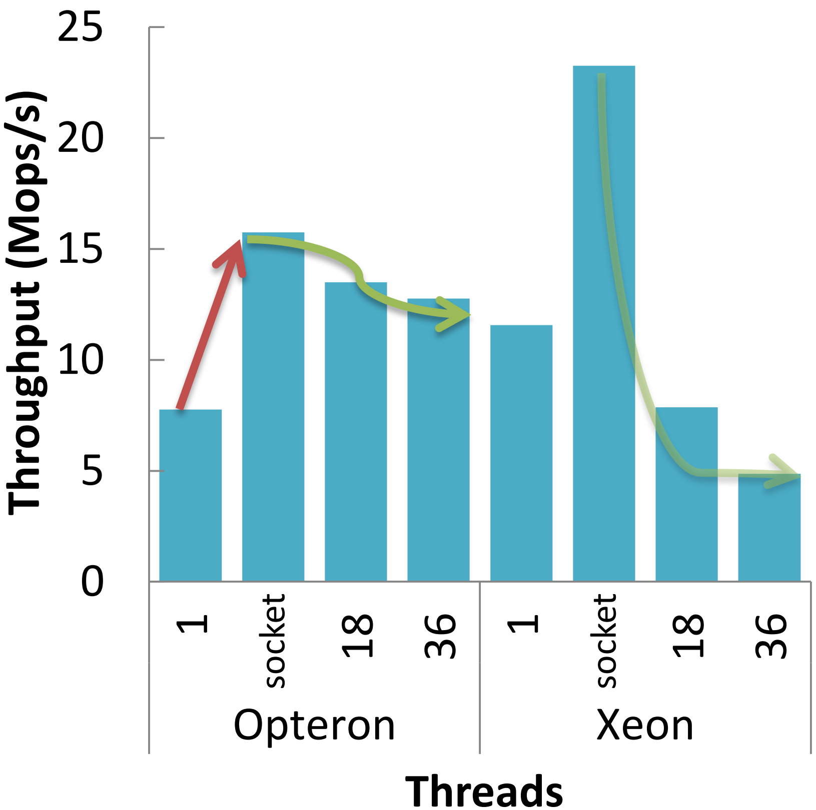
Low contention (512 locks)



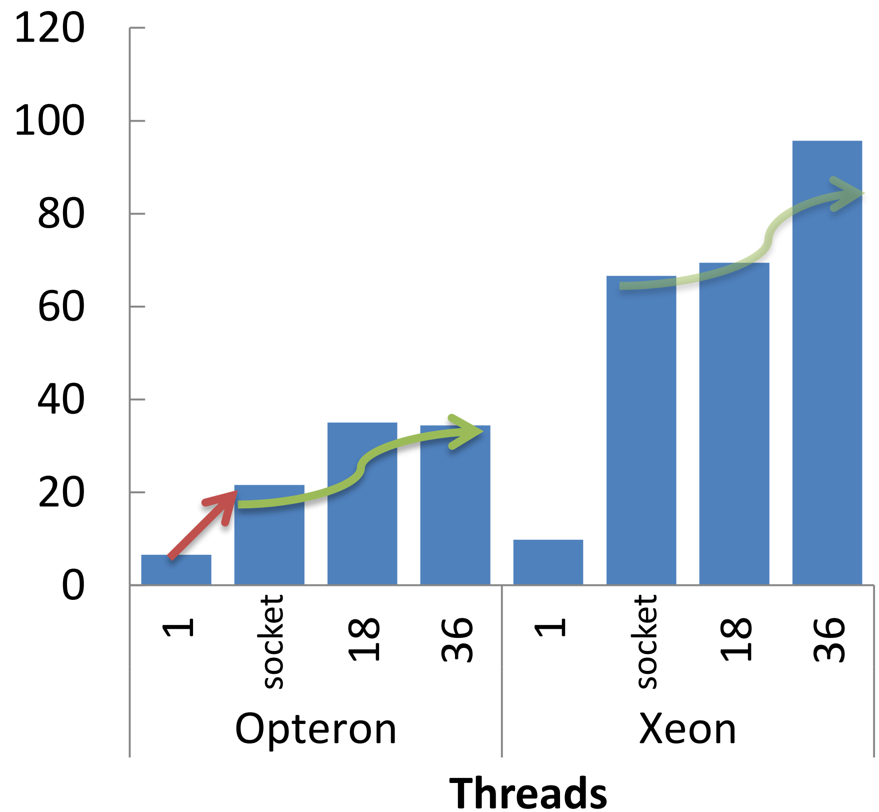
Sharing within a socket is not sufficient

Hash table on multi-sockets

High contention (12 buckets)



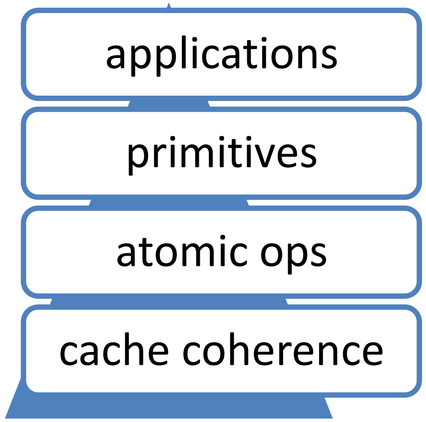
Low contention (512 buckets)

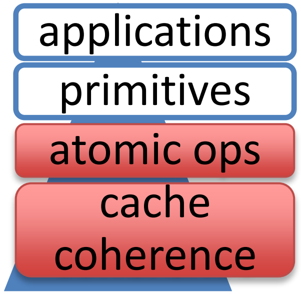


Sharing within a socket is necessary but not sufficient

Outline

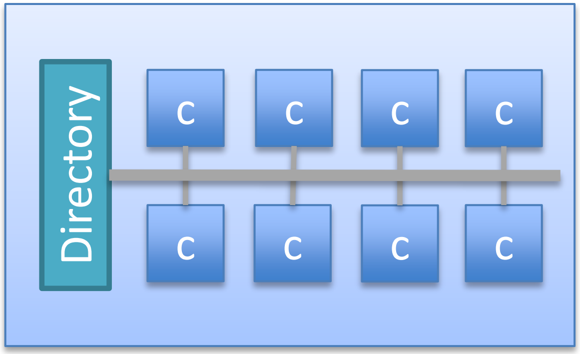
1. Crossing sockets
2. Sharing within a socket
3. **Intra-socket uniformity**
4. Atomic operations
5. Simple locks





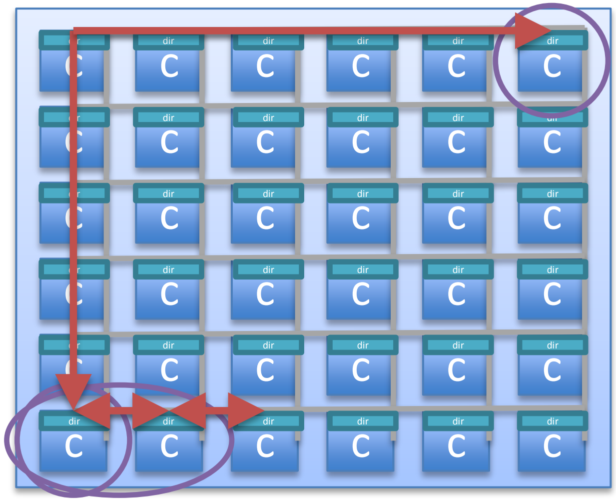
Distance on single-sockets

Niagara



- Uniform: 23 ns

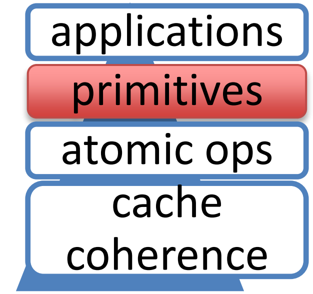
Tilera



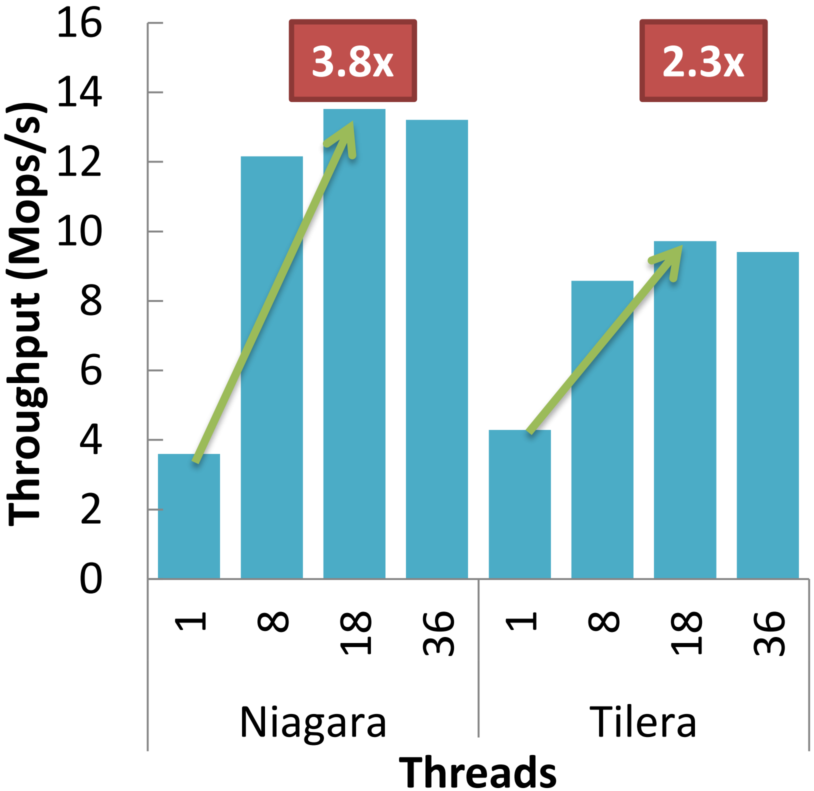
- 1 hop: 40 ns
- Per hop: +2 ns
- Up to **0.5x** more

Uniformity is expected to scale better

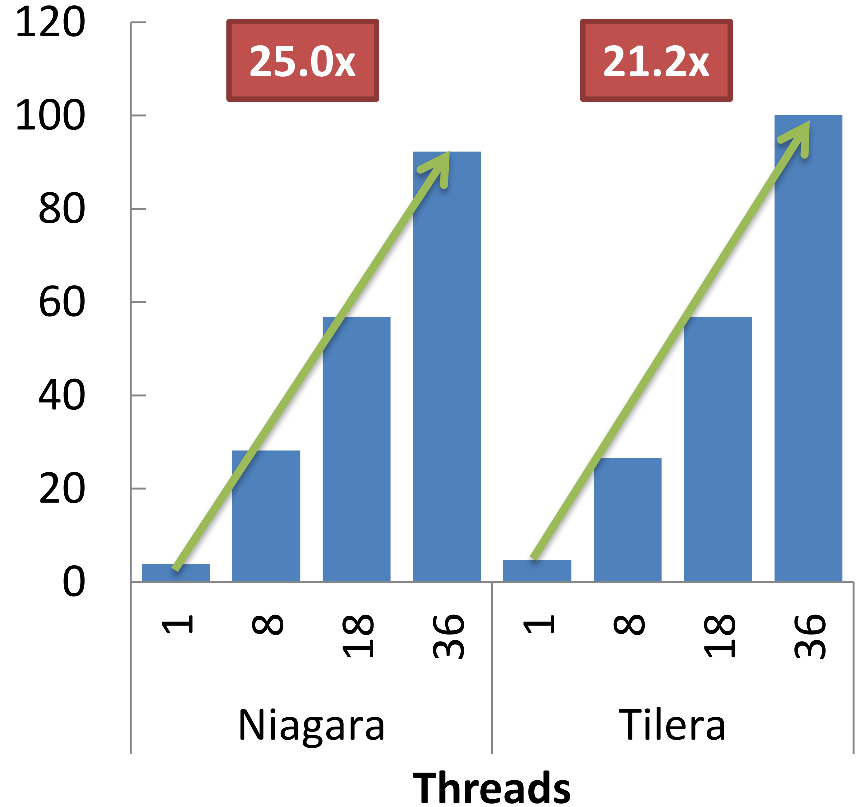
Locks on single-sockets



High contention (4 locks)

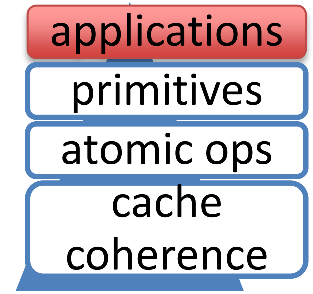


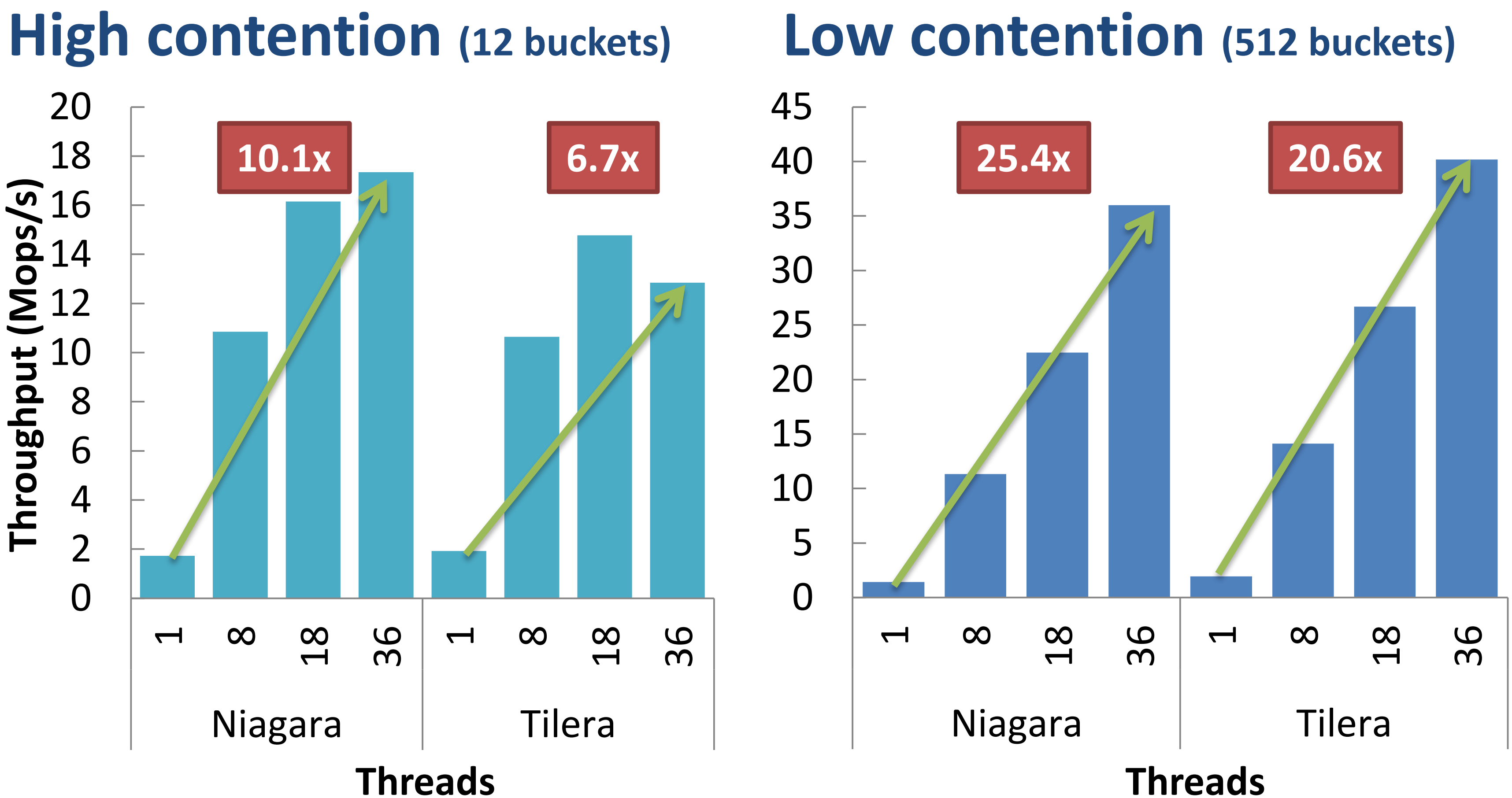
Low contention (512 locks)



Uniformity leads to up to 70% higher scalability

Hash table on single-sockets

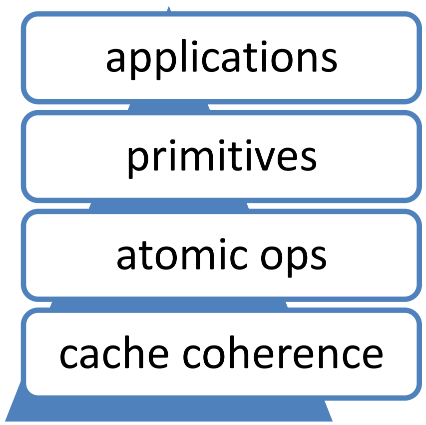




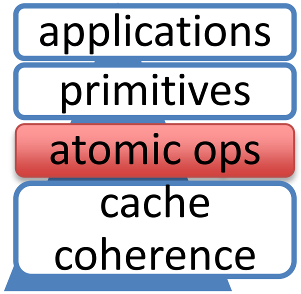
Uniformity leads to up to 50% higher scalability

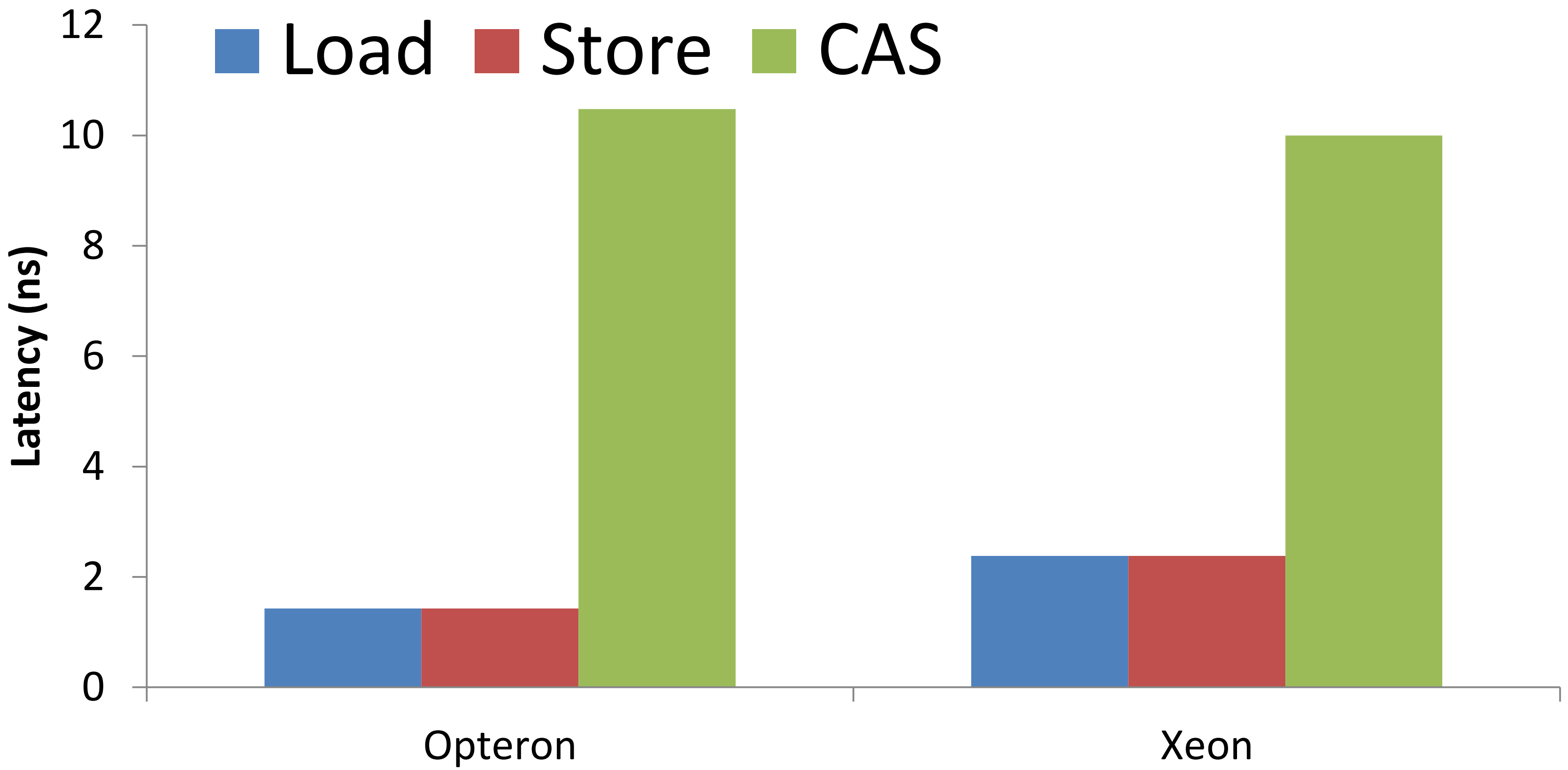
Outline

1. Crossing sockets
2. Sharing within a socket
3. Intra-socket uniformity
4. **Atomic operations**
5. Simple locks



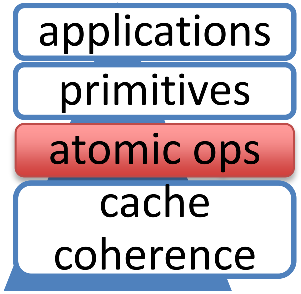
Atomic ops on local data

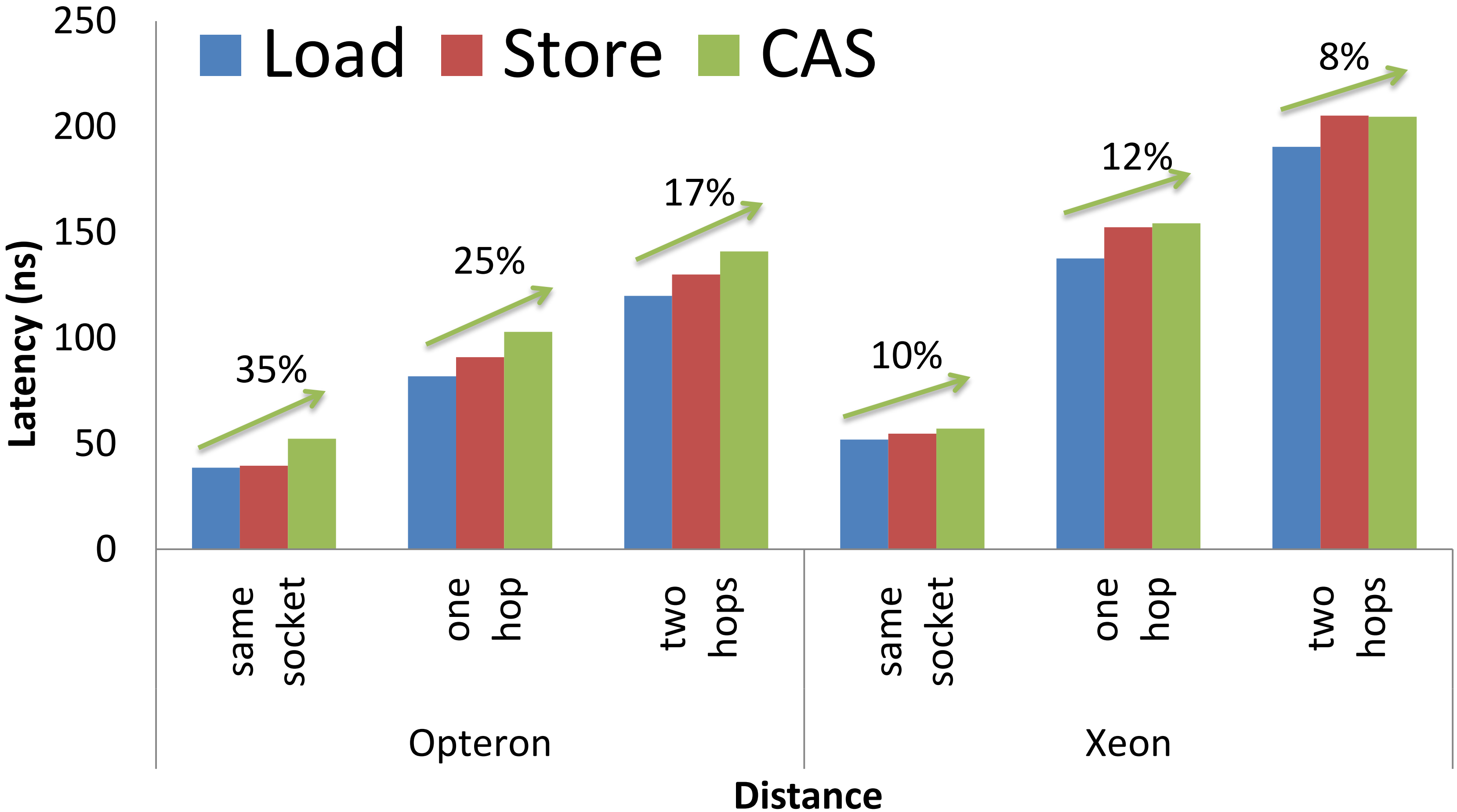




CAS: an order of magnitude more expensive on local data

Atomic ops on multi-sockets

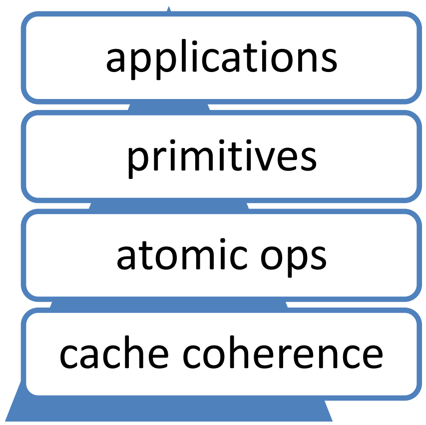




Loads and stores can be as expensive as atomic operations

Outline

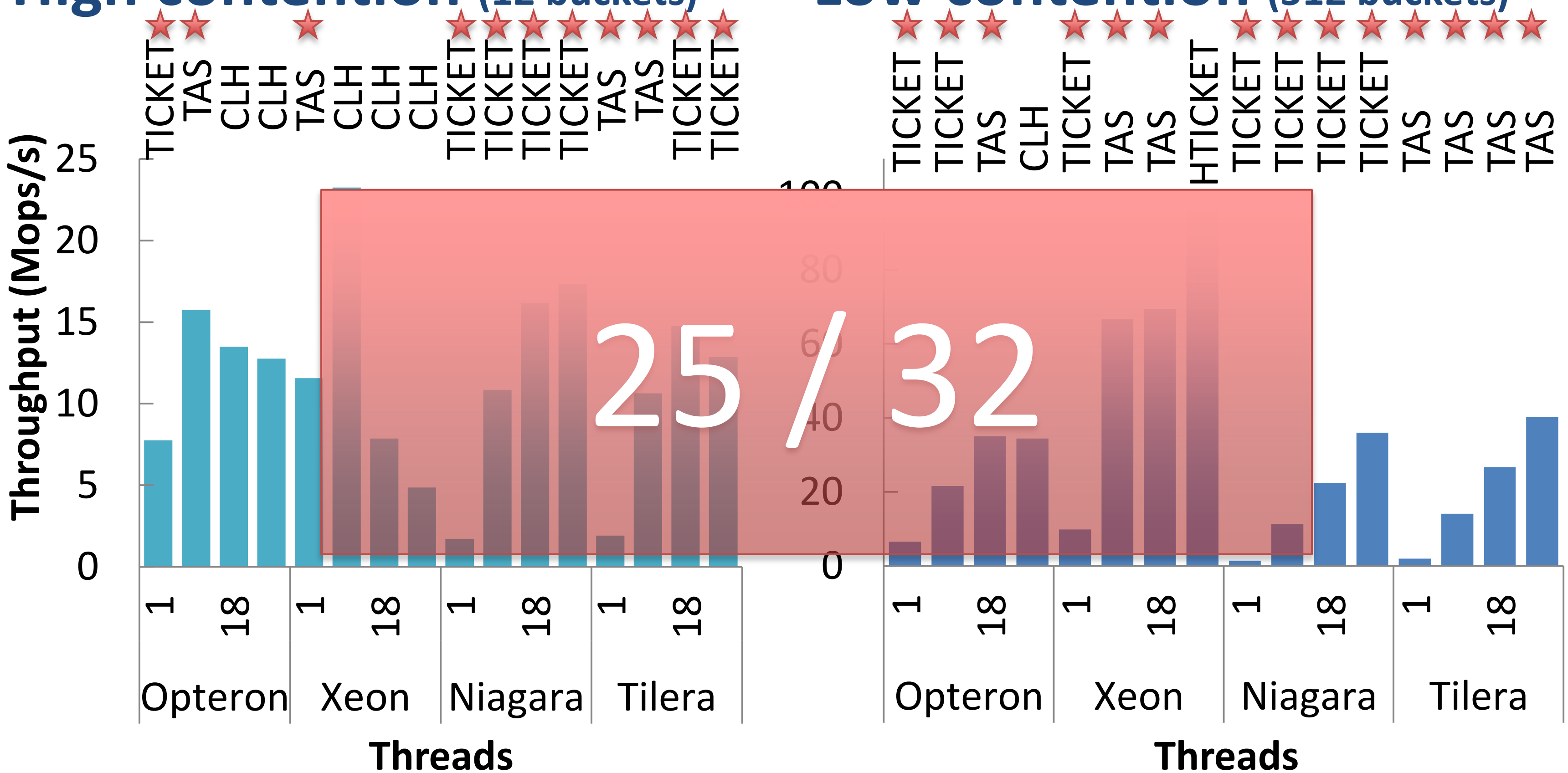
1. Crossing sockets
2. Sharing within a socket
3. Intra-socket uniformity
4. Atomic operations
5. **Simple locks**



Hash table – best locks

applications
primitives
atomic ops
cache coherence

High contention (12 buckets)   Low contention (512 buckets)



Simple locks are powerful

Lessons learned

1. **Crossing sockets is a killer**

   → up to 8x more expensive communication

2. **Sharing within a socket is necessary but not sufficient**

   → up to 3x more expensive communication

3. **Intra-socket uniformity matters**

   → up to 70% higher scalability

4. **Loads & stores can be as expensive as atomic operations**

   → 8 - 35% more expensive on non-locally cached data

5. **Simple locks are powerful**

   → better in 25 out of 32 data-points on a hash table

Scalability of synchronization is mainly a property of the hardware

Analysis' space & limitations

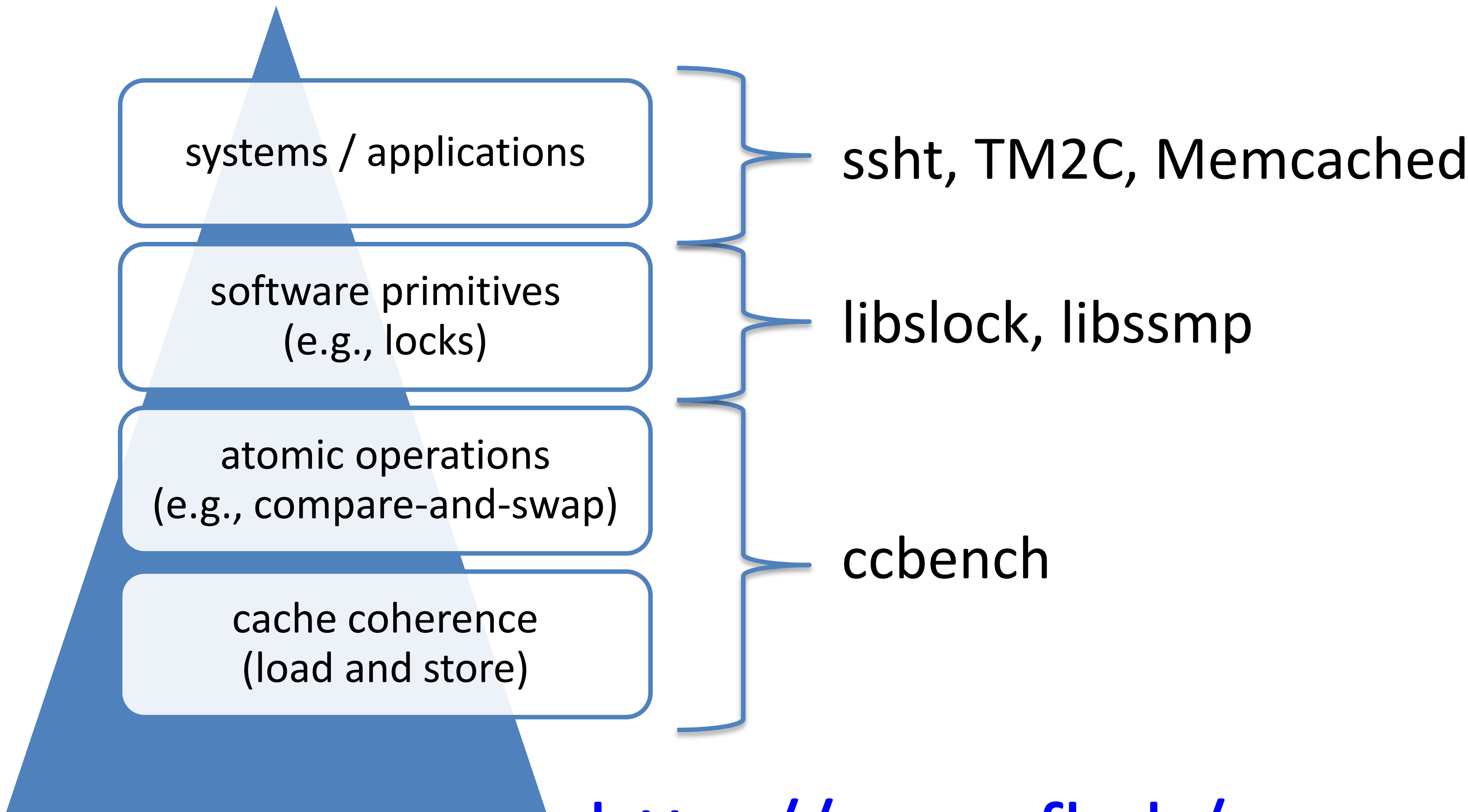
synchronization schemes

- locks
- message passing
- lock-free
- combiner approaches
- …

AMD intel ORACLE Sun microsystems TILERA IBM ARM

hardware platforms

SSYNC synchronization suite



http://go.epfl.ch/ssync

applications
primitives
atomic ops
cache coherence

Thanks!

1. Crossing sockets is a killer
2. Sharing within a socket is necessary but not sufficient
3. Intra-socket uniformity matters
4. Loads & stores can be as expensive as atomic operations
5. Simple locks are powerful

Scalability of synchronization is mainly a property of the hardware

http://go.epfl.ch/ssync