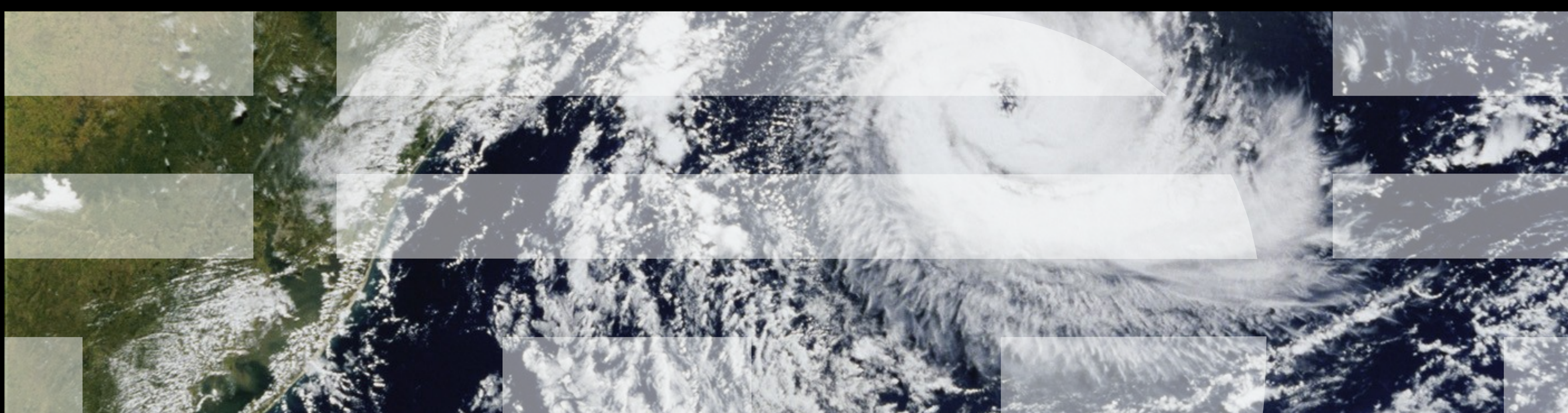
Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center
Member, IBM Academy of Technology
Linux Collaboration Summit, Napa Valley, CA, USA, March 27, 2014

# But What About Updates?

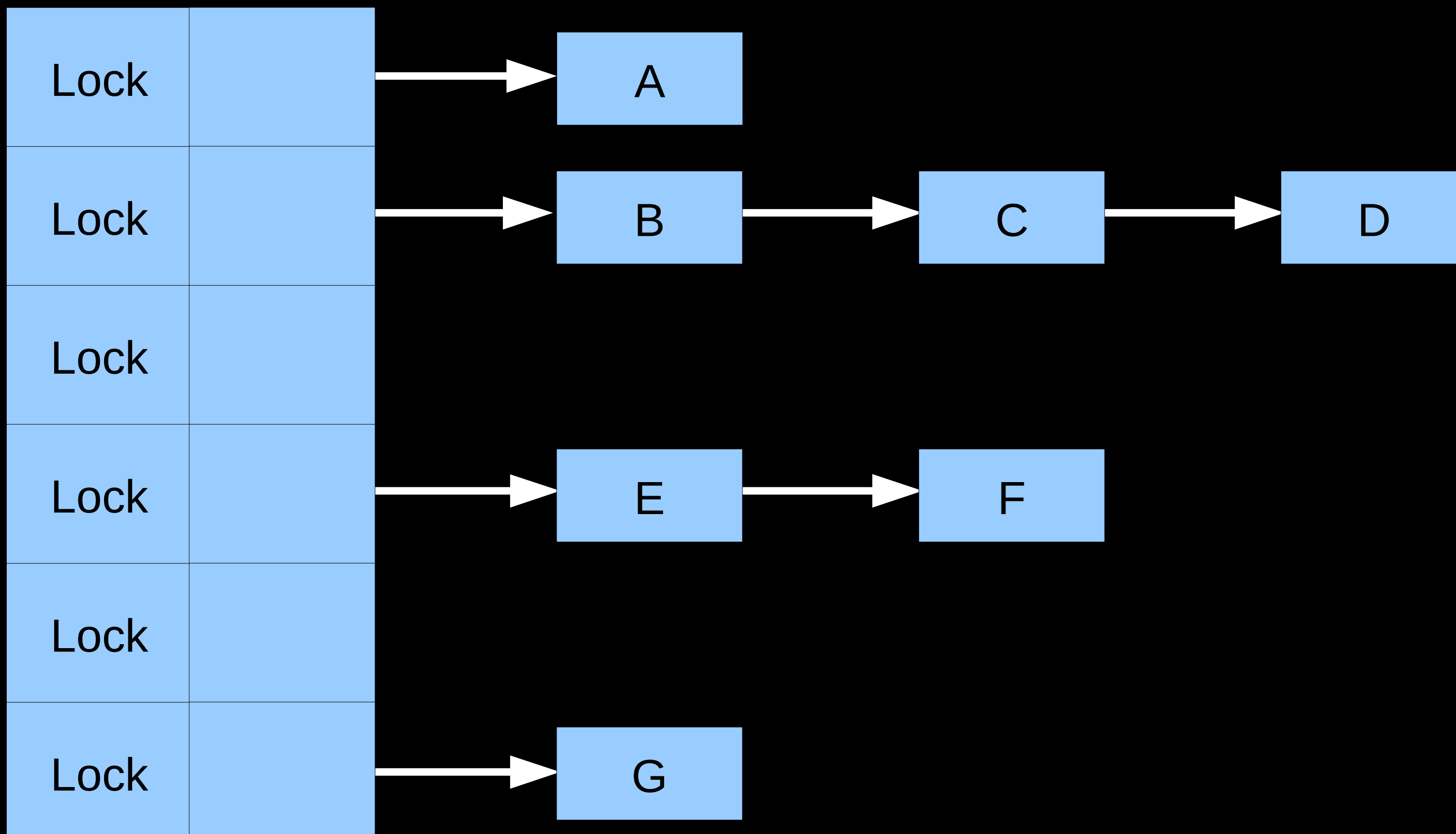


# Overview

- Aren't parallel updates a solved problem?
- Special cases for parallel updates
  - Split counters
  - Per-CPU/thread processing
  - Stream-based applications
  - Read-only traversal to location being updated
  - Hardware lock elision
- Possible additions to parallel-programming toolbox

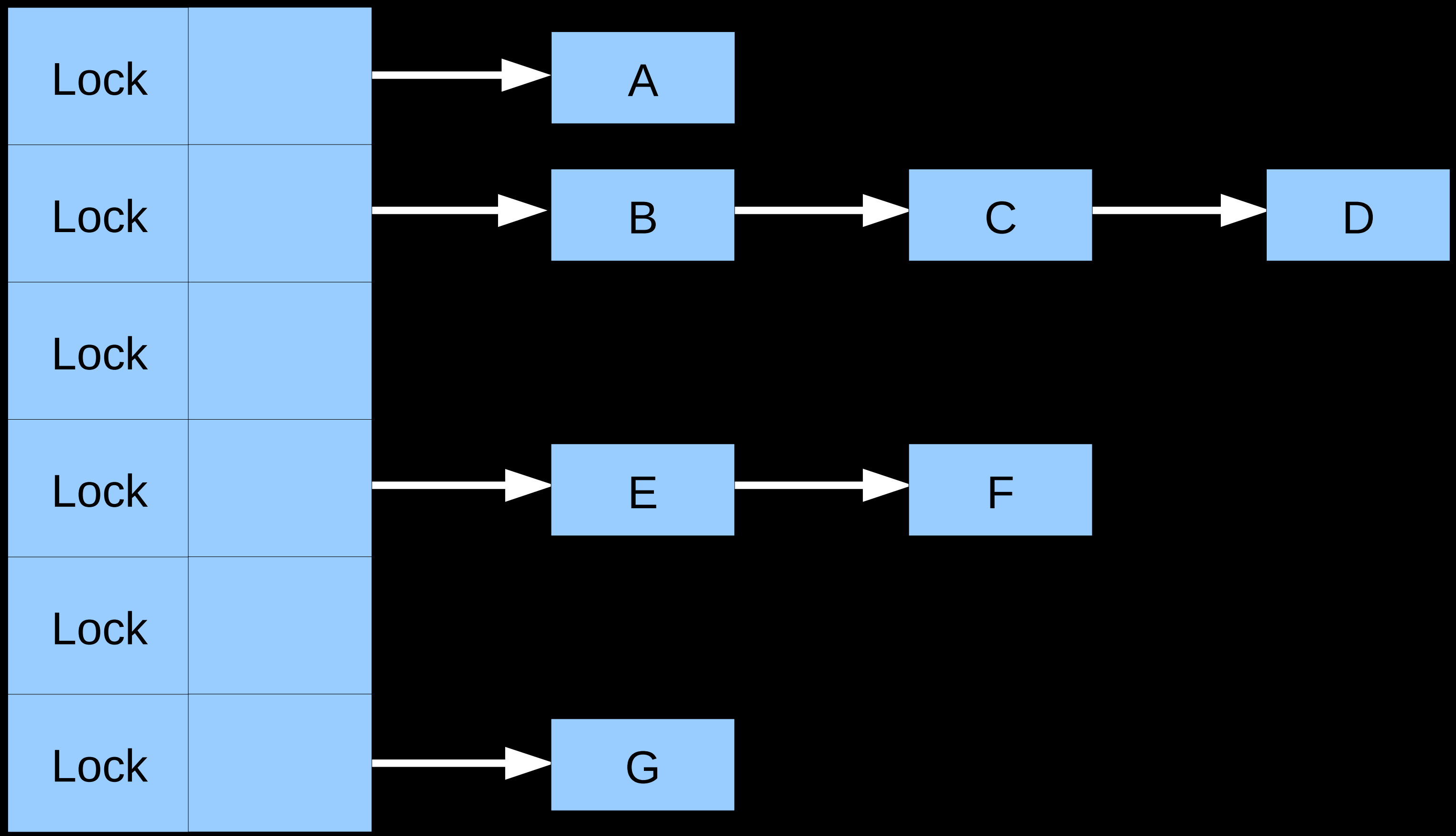
# Aren't Parallel Updates A Solved Problem?

# Parallel-Processing Workhorse: Hash Tables




**Perfect partitioning leads to perfect performance and stunning scalability!**

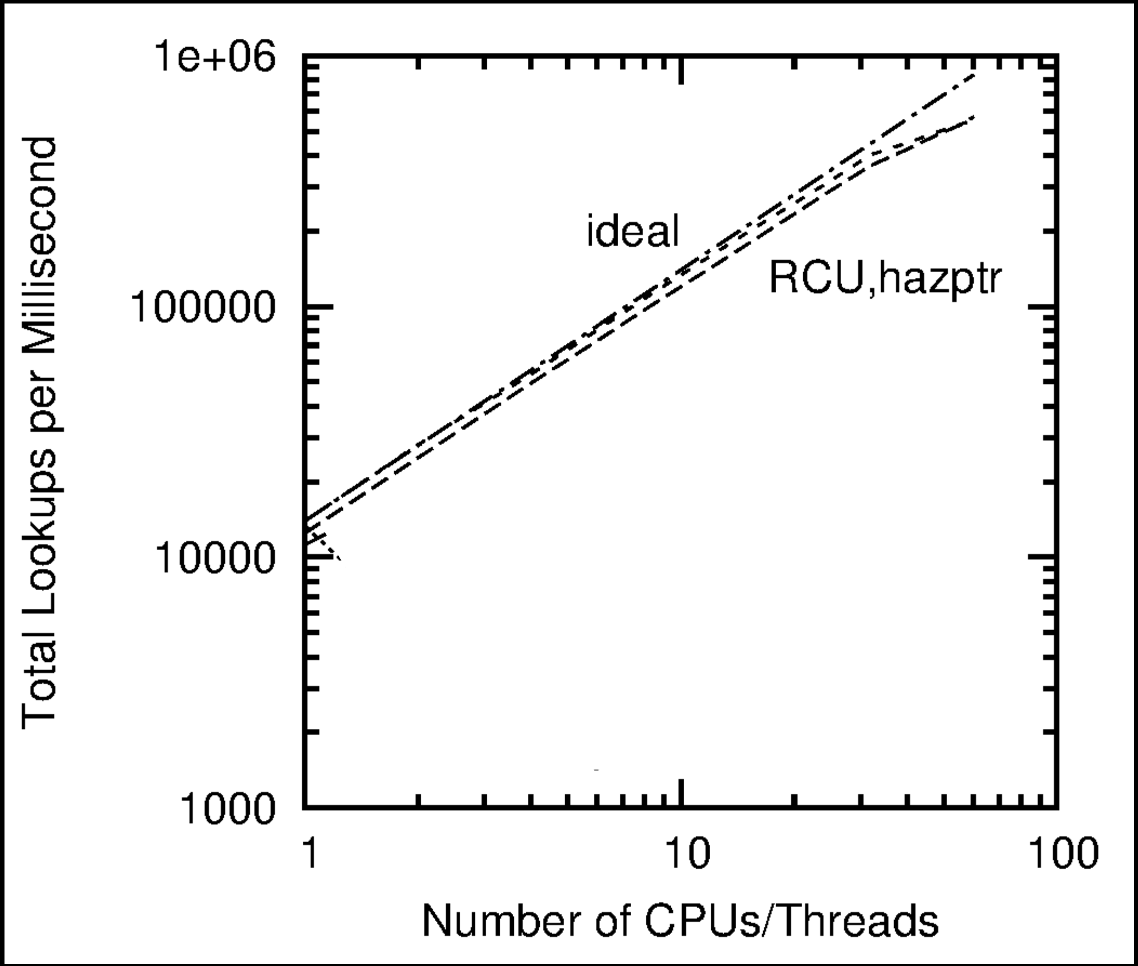
# Parallel-Processing Workhorse: Hash Tables



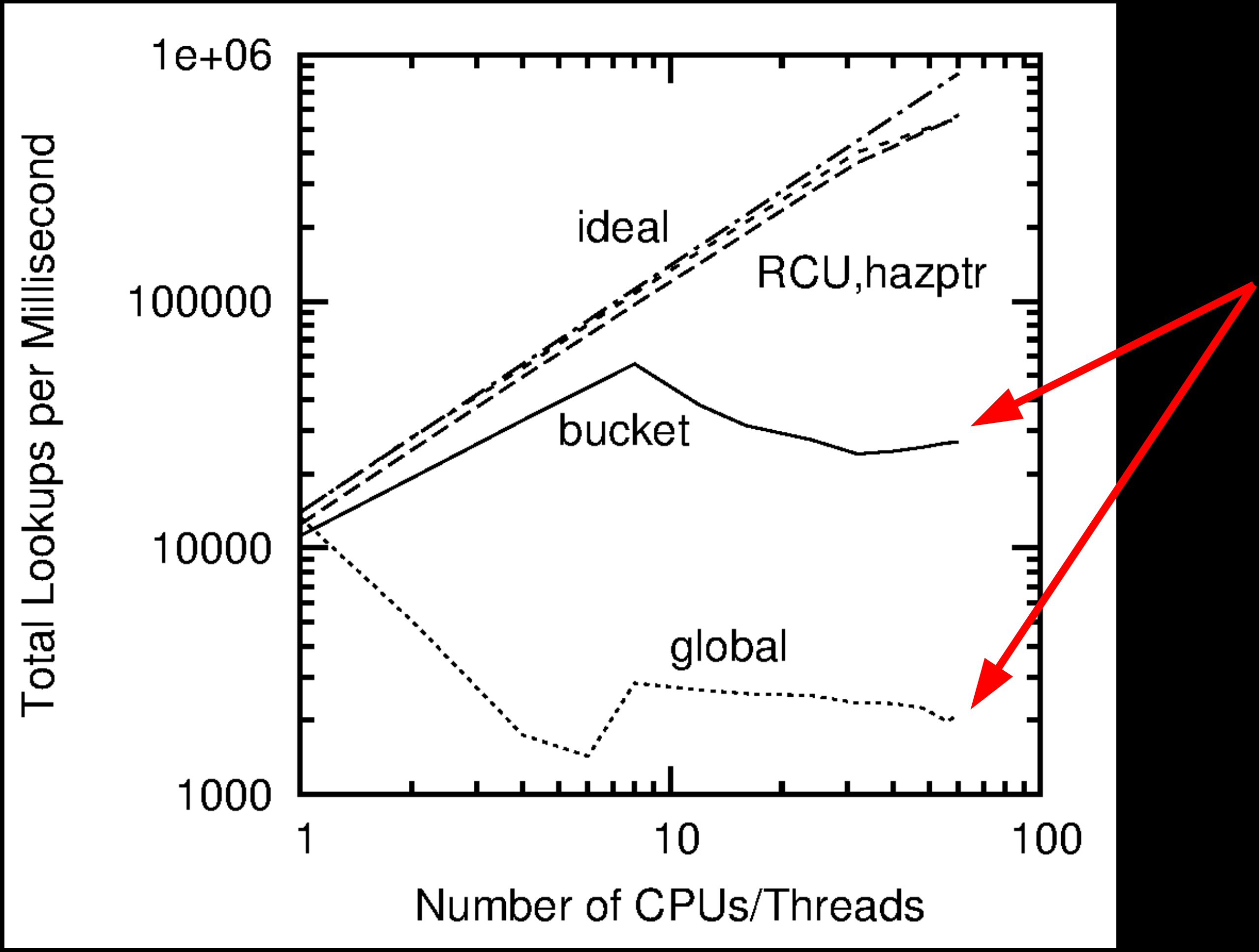

**Perfect partitioning leads to perfect performance and stunning scalability!**

**In theory, anyway...**

# Read-Mostly Workloads Scale Well: Hash Table

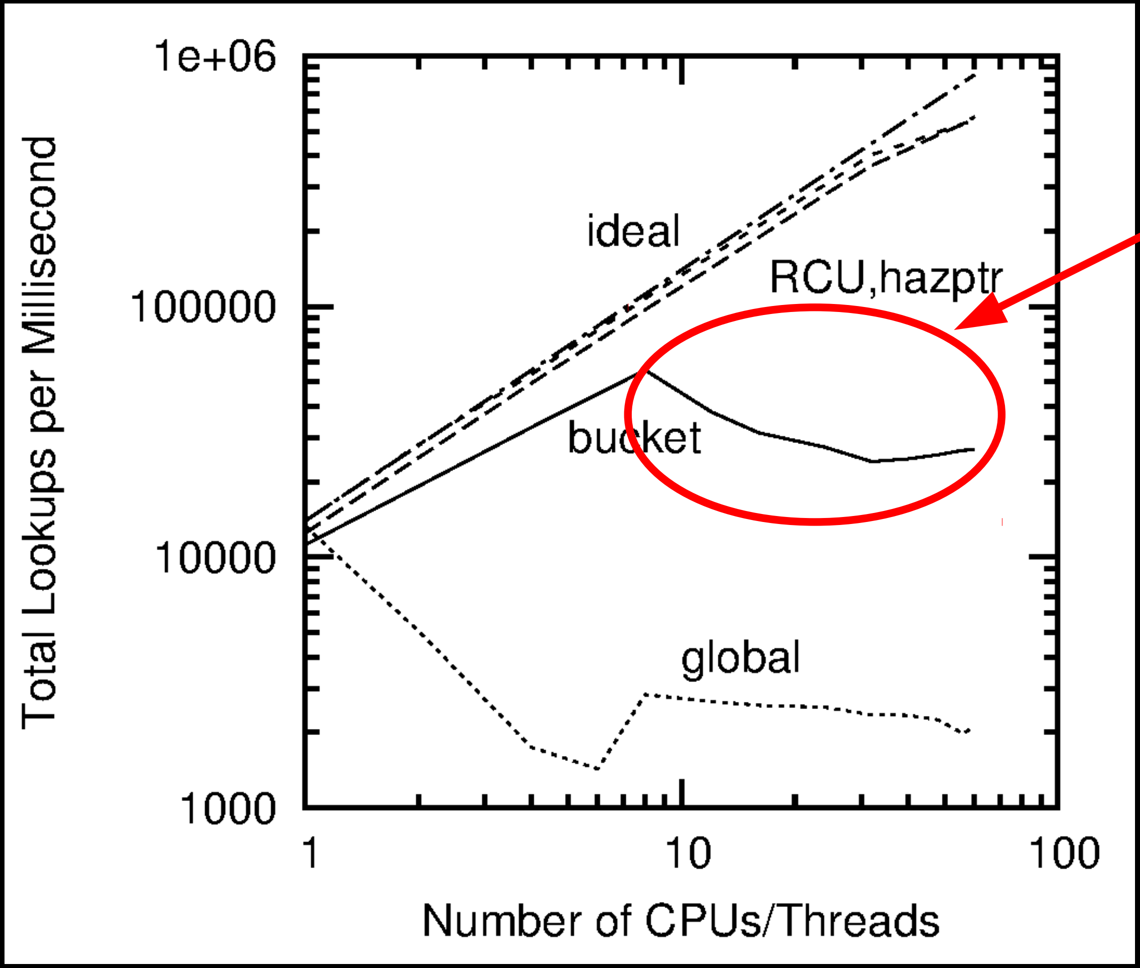


# Update-Heavy Workloads, Not So Much...

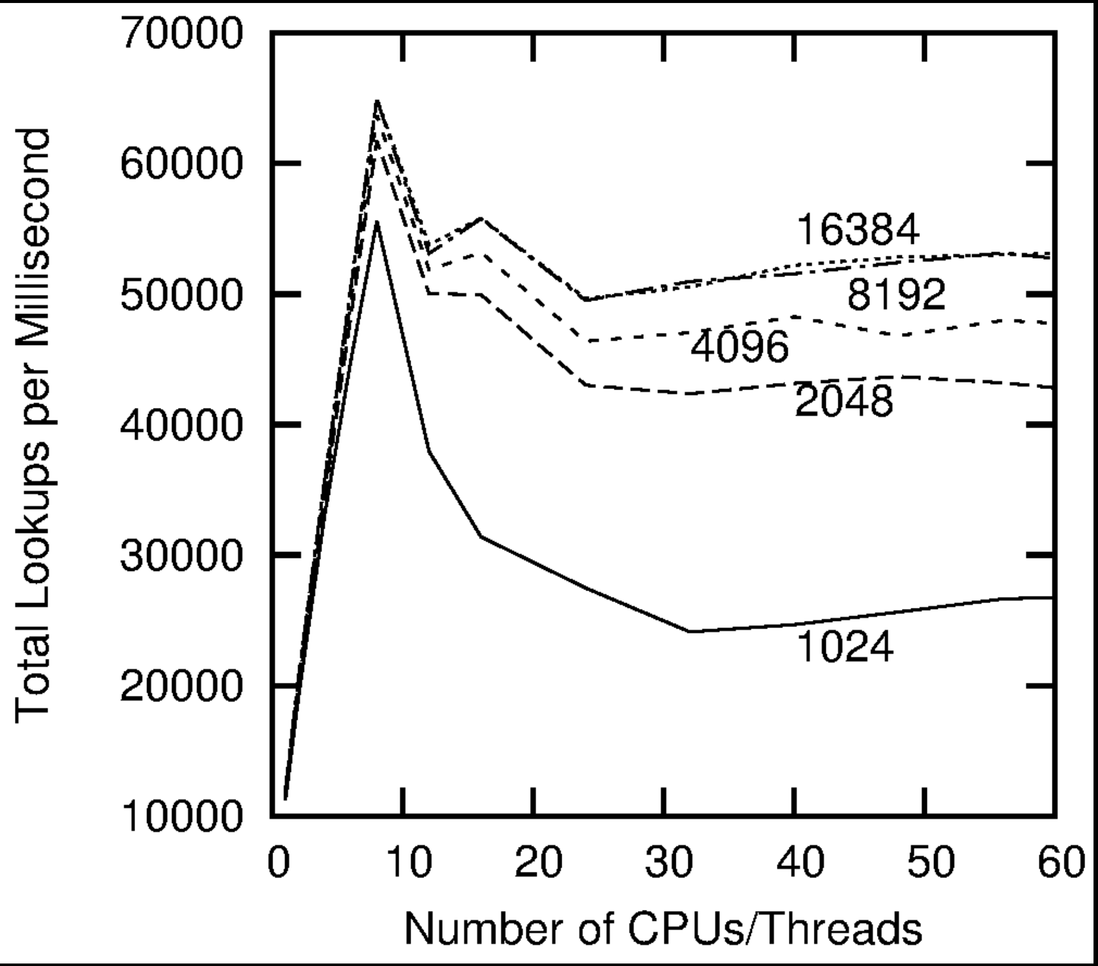



And the horrible thing? Updates are all locking ops!

# But Hash Tables Are Partitionable!  What is Wrong?



# But Hash Tables Are Partitionable!  # of Buckets?

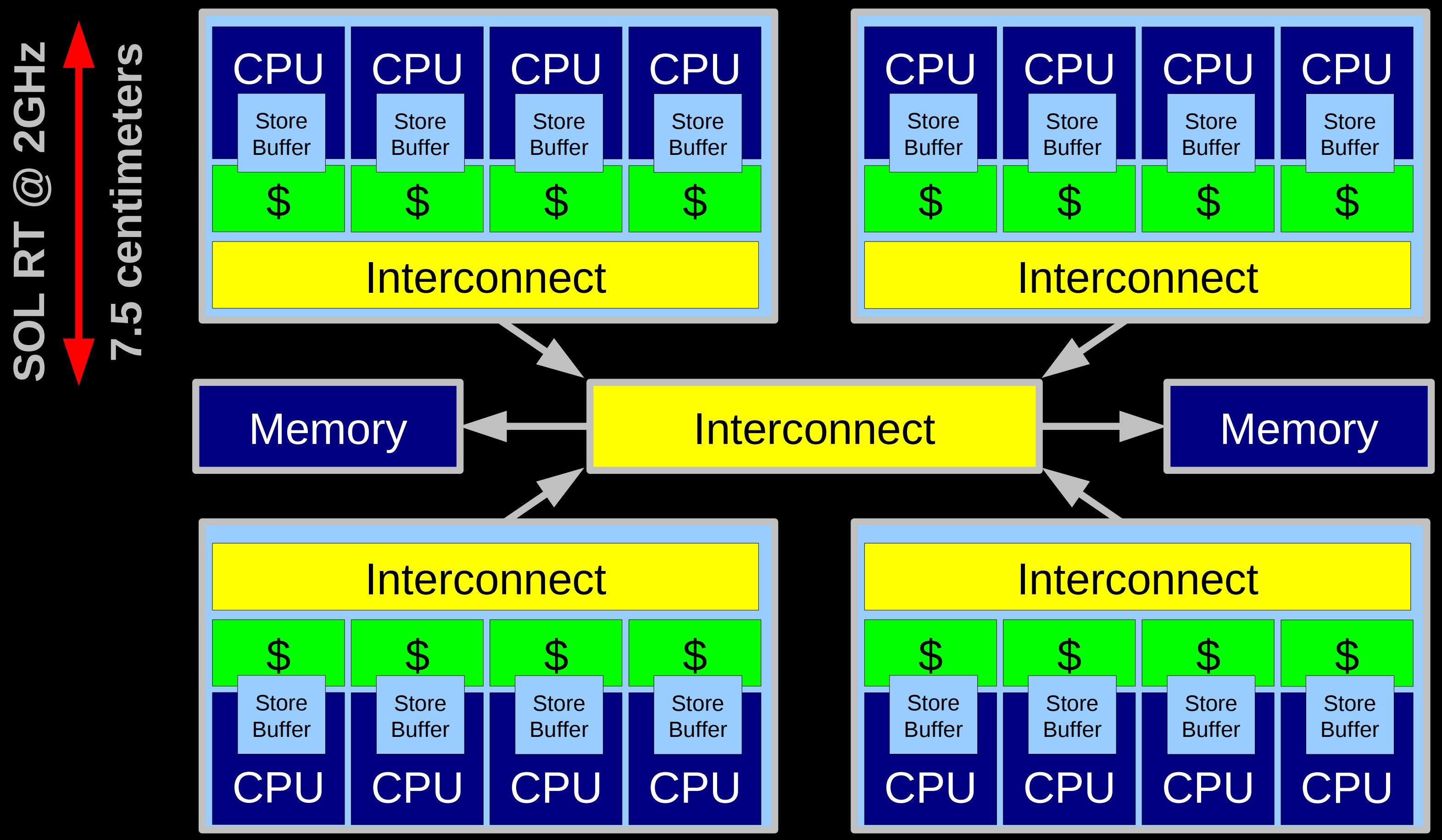



Some improvement, but...

# But Hash Tables Are Partitionable!  What is Wrong?

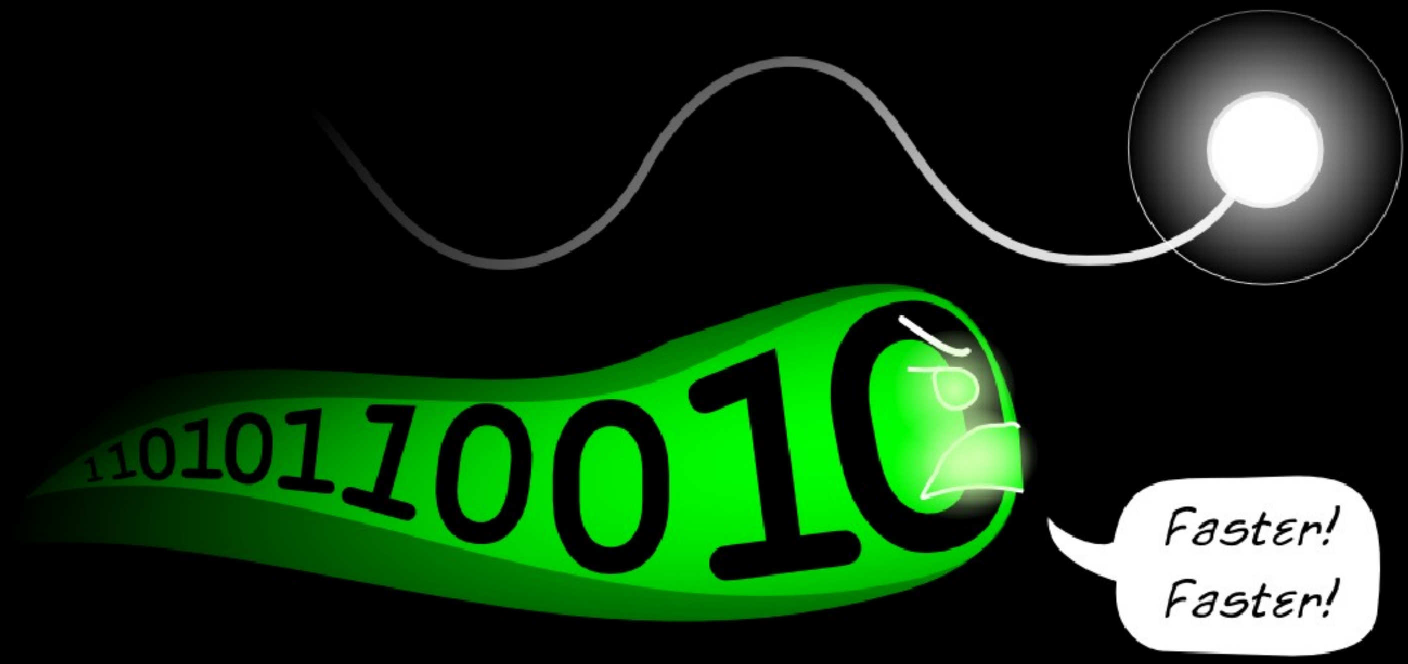
- NUMA effects:
  - First eight CPUs on one socket, ninth on another
  - No hash-bucket locality in workload: partitioned data, but not workload
  - High cache-miss overhead: Buckets pass from one socket to the other

# Hardware Structure and Laws of Physics

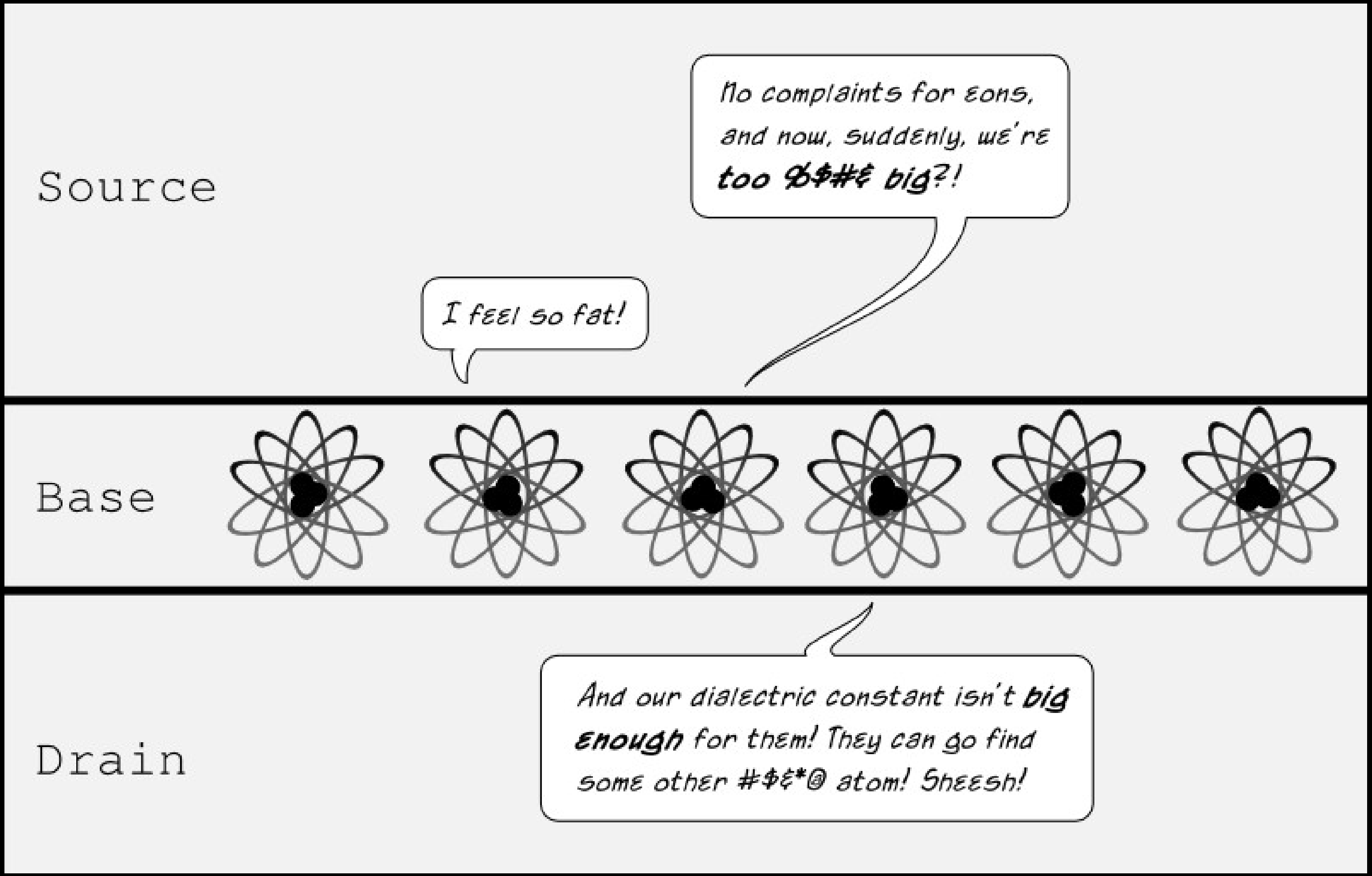



**Electrons move at 0.03C to 0.3C in transistors and, so need locality of reference**

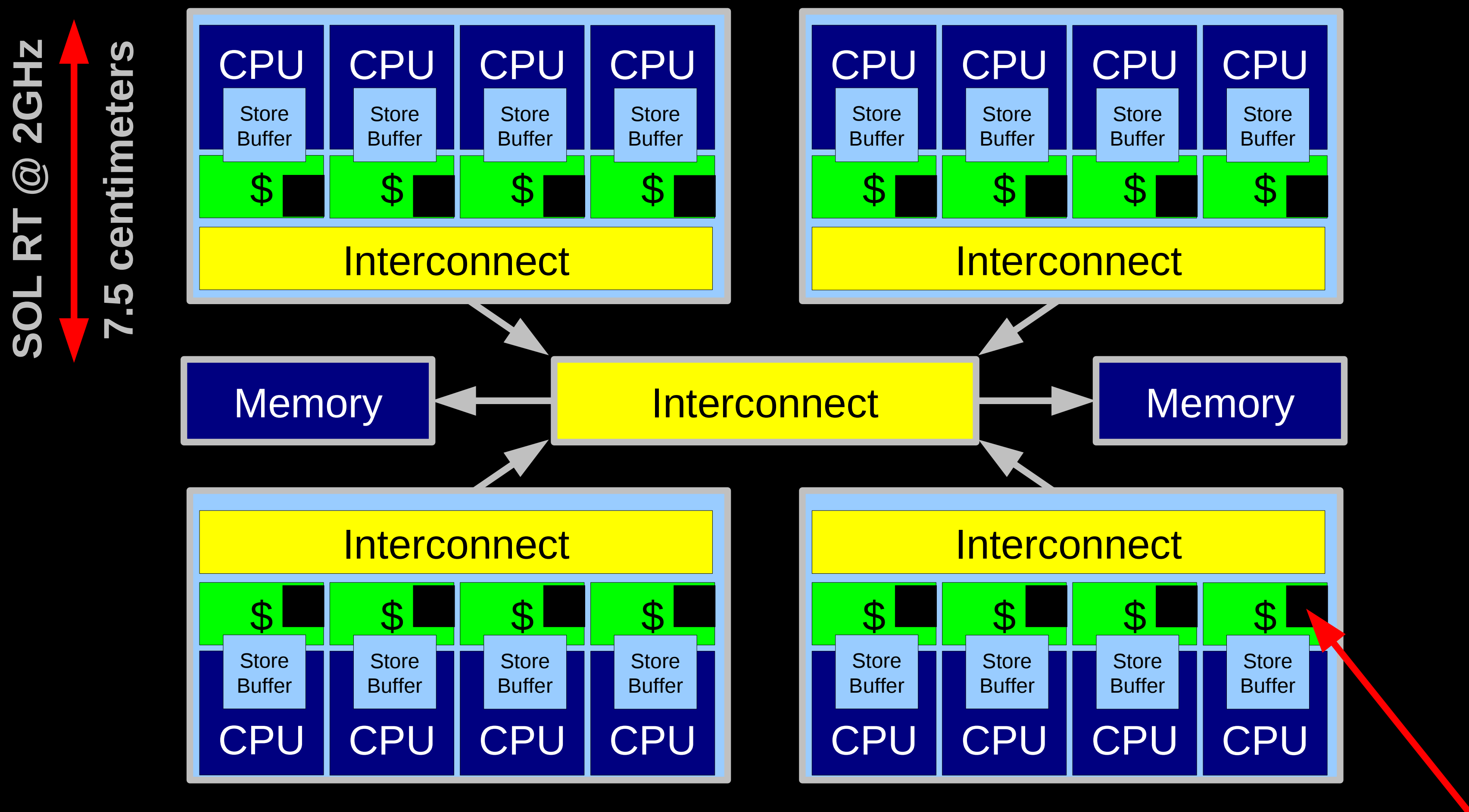
# Problem With Physics #1: Finite Speed of Light



# Problem With Physics #2: Atomic Nature of Matter

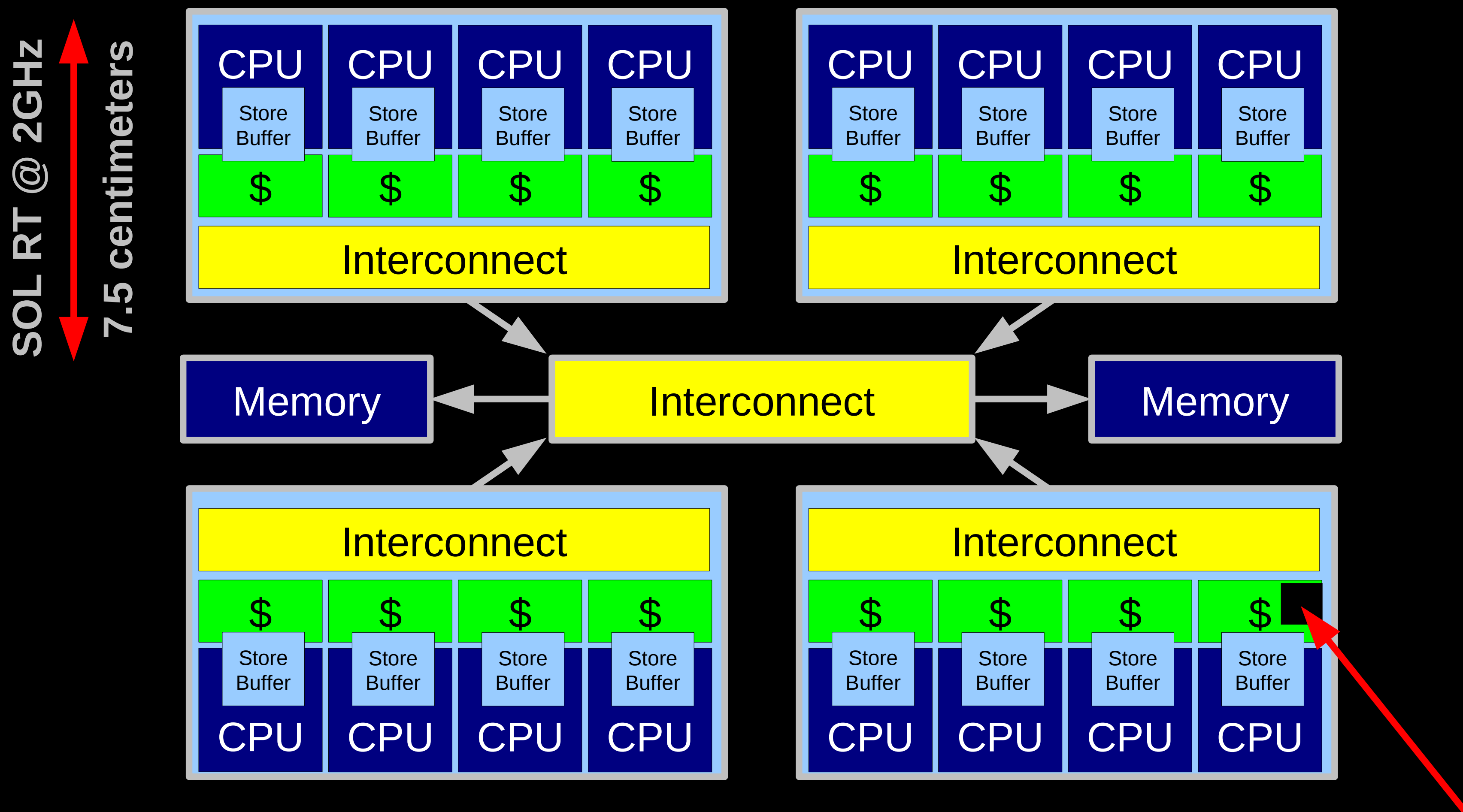


# Read-Only Accesses Dodge The Laws of Physics!!!




Read-only data remains replicated in all caches

# Updates, Not So Much...




**Read-only data remains replicated in all caches, but each update destroys other replicas!**

# But Hash Tables Are Partitionable!  What is Wrong?

- NUMA effects:
  - First eight CPUs on one socket, ninth on another
  - No hash-bucket locality in workload: partitioned data, but not workload
  - High cache-miss overhead: Buckets pass from one socket to the other
- Can avoid NUMA effects:
  - Partition hash buckets over NUMA nodes
    - Just like distributed systems do: See Dynamo paper
  - Use tree instead of hash table and do range partitioning
  - Do range partitioning across multiple hash tables, one per socket
  - If moderate number of updates and lots of memory, replicate hash table, one instance per socket
  - Minimize update footprint: Fine-grained locking
    - But if you tune your hash tables properly, this buys you little
  - Hardware transactional memory: Avoid locking overhead
    - More on this later in this presentation

# Update-Heavy Workloads Painful for Parallelism!!! But There Are Some Special Cases...

# But There Are Some Special Cases

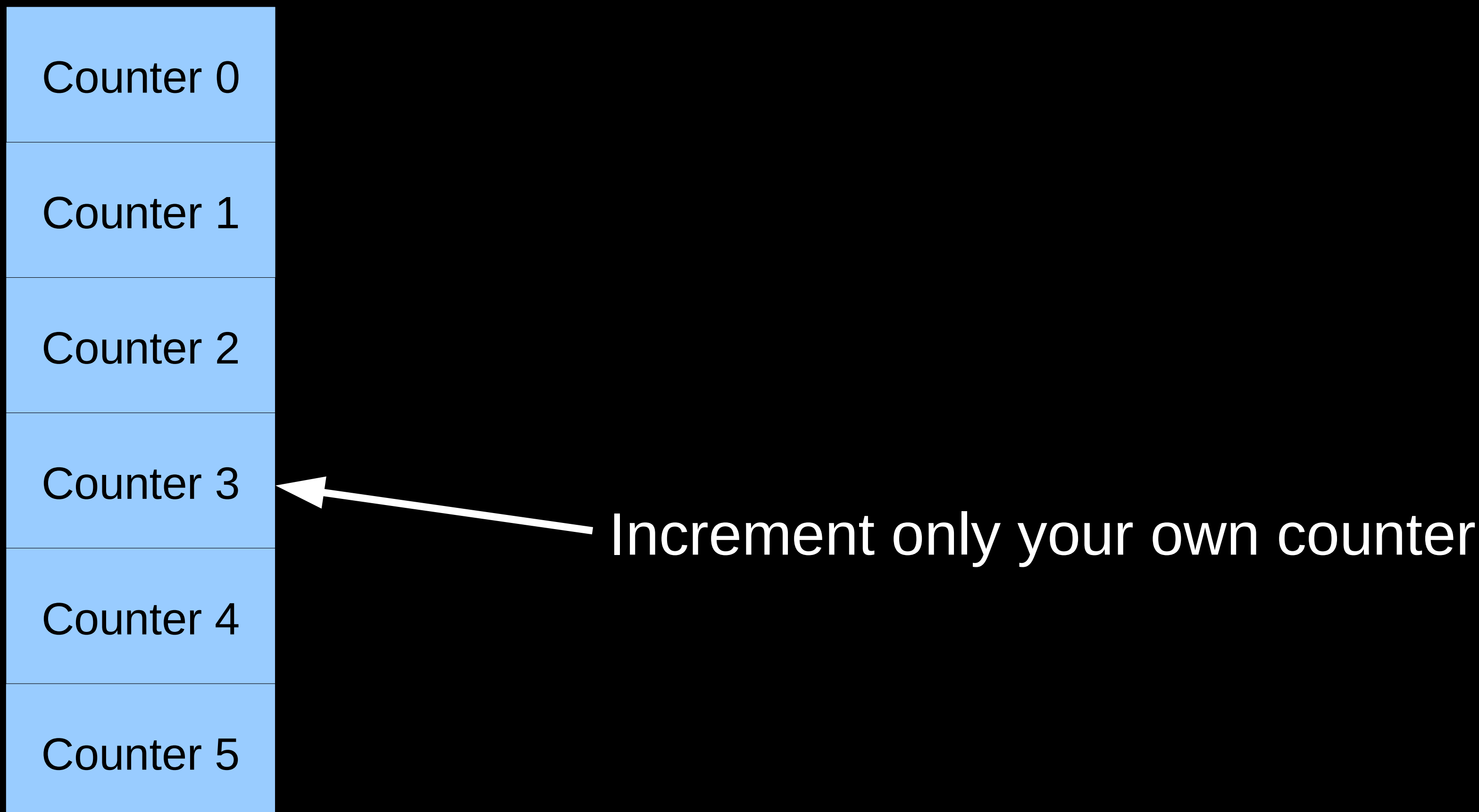
- Split counters (used for decades)
- Per-CPU/thread processing (perfect partitioning)
  - Huge number of examples, including the per-thread/CPU stack
  - But not everything can be perfectly partitioned
- Stream-based applications
- Read-only traversal to location being updated
- Hardware lock elision

# Split Counters

# Split Counters

- Have a per-CPU/thread counter: DEFINE_PER_CPU(u32, ctr);
- For updates, CPU/thread non-atomically updates its own counter
- For reads, sum all the counters
- Rely on commutative and associative laws of addition
- Plus rely on short-term inaccuracy permitted for statistical counters
- Constant work done for updates, linear scaling, great performance

# Split Counters Diagram



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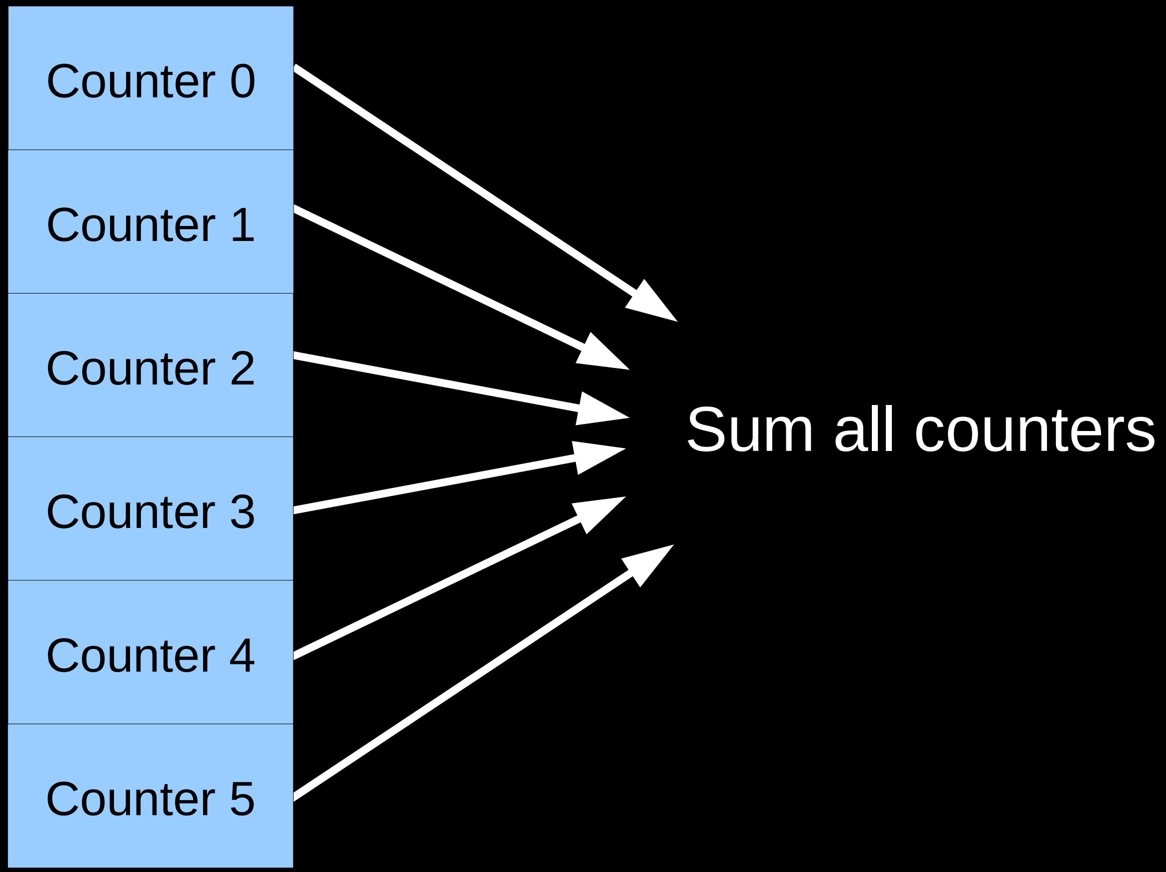
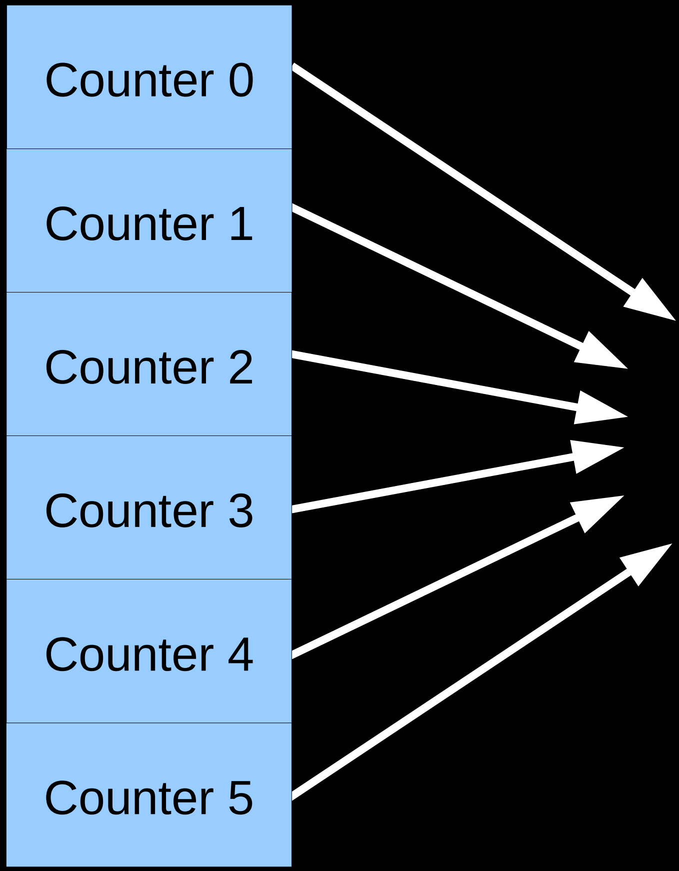


# Split Counters Diagram




Sum all counters

While they continue changing

**It is possible to avoid the O(n) behavior on reads, see Bare Metal talk.**

# Split Counters: What If You Need Them To Keep Still?

```
DEFINE_PER_CPU(count);
br_read_lock();
this_cpu_inc(count);
br_read_unlock();

sum = 0;
br_write_lock();
for_each_possible_cpu(cpu)
       sum += per_cpu(count, cpu);
br_write_unlock();
```

# Split Counters: What If You Need Them To Keep Still?

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```

**Yes, the read lock guard updates and the write lock guards reads.**
**This is why we now have lglocks (local-global locks)**

# Perfect Partitioning

# Perfect Partitioning

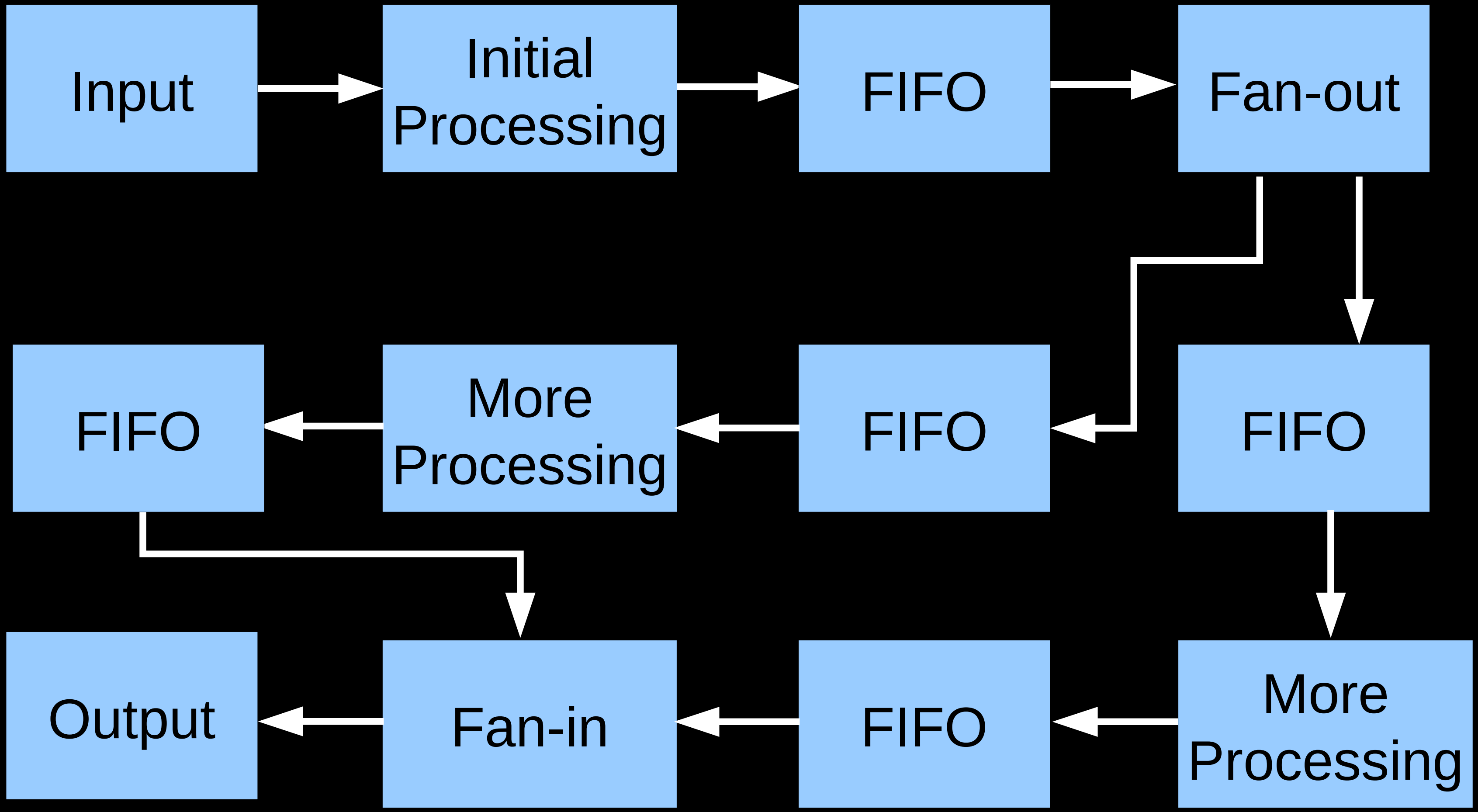
- Sharded lists
  - Given element in partition, modified only by CPUs in that partition
    - Partition by key range
    - Partition by hashed value (favorite of Google, Amazon, …)
    - Forward update to CPU in the corresponding partition, see next section
  - Set as special case of list
  - Very fast for heavy update workloads, still suffer read-write misses
- Localized caches
  - For example, per-socket cache
  - Blazing lookup speed!!!
  - But beware of memory footprint and cache miss rates!
- Per-CPU atomics help userspace per-CPU partitioning
  - http://www.linuxplumbersconf.org/2013/ocw//system/presentations/1695/original/LPC%20-%20PerCpu%20Atomics.pdf
- Honorable mention: Queued locking

# Stream-Based Applications

# Stream-Based Applications

- Adrian Sutton of LMAX presented this at linux.conf.au 2013:
  - http://www.youtube.com/watch?v=UvE389P6Er4
  - http://lca2013.linux.org.au/schedule/30168/view_talk
  - http://mechanical-sympathy.blogspot.com/
- Only two threads permitted to access a given location
- Use fixed-array circular FIFOs to pipe data between data-processing stages (represented by individual threads/CPUs)
  - Confining a processing stage to a single socket is not a bad plan. ;-)
- Get nearly uniprocessor performance, especially for heavy-weight processing

# Example Stream-Based Application



# Read-Only Traversal To Location Being Updated

# Read-Only Traversal To Update Location

- Consider a radix tree
- Classic locking methodology would:
  - Lock root
  - Use fragment of key to select descendant
  - Lock descendant
  - Unlock root
  - Repeat
- The lock contention on the root is not going to be pretty!

# Better Read-Only Traversal To Update Location

- Improved locking methodology might:
  - rcu_read_lock()
  - Traversal:
    - Start at root without locking
    - Use fragment of key to select descendant
    - Repeat until update location is reached
    - Acquire locks on update location
    - Do consistency checks, retry from start if inconsistent
  - Carry out update
  - rcu_read_unlock()
- Eliminates contention on root node!
- But need some sort of consistency-checks mechanism...
  - Sequence locking
  - “Deleted” flags on individual data elements

# Sequence-Locked Read-Only Traversal

- for (;;)
  - rcu_read_lock()
  - seq = read_seqbegin(&myseq)
  - Start at root without locking
  - Use fragment of key to select descendant
  - Repeat until update location is reached
  - Acquire locks on update location
  - If (!read_seqretry(&myseq, seq))
    - break
  - Release locks on update location and rcu_read_unlock()
- Carry out update
- Release locks on update location and rcu_read_unlock()

# Sequence-Locked Read-Only Traversal

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  - If (!read_seqretry(&myseq, seq))
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  - Release locks on update location and rcu_read_unlock()
- Carry out update
- Release locks on update location and rcu_read_unlock()
- But tree-shape updates must write_seqcount_begin

**dcache does something sort of like this, see d_move().**

# Deletion-Flagged Read-Only Traversal

- for (;;)
  - rcu_read_lock()
  - Start at root without locking
  - Use fragment of key to select descendant
  - Repeat until update location is reached
  - Acquire locks on update location
  - If update location's deleted flag is not set:
    - break
  - Release locks on update location and rcu_read_unlock()
- Carry out update
- Release locks on update location and rcu_read_unlock()

**Could dcache do something like this?**

# Read-Only Traversal To Location Being Updated

- Focus contention on portion of structure being updated
- Of course, full partitioning is better!
- But why not automate read-only traversal?

# Hardware Lock Elision

# Hardware Lock Elision

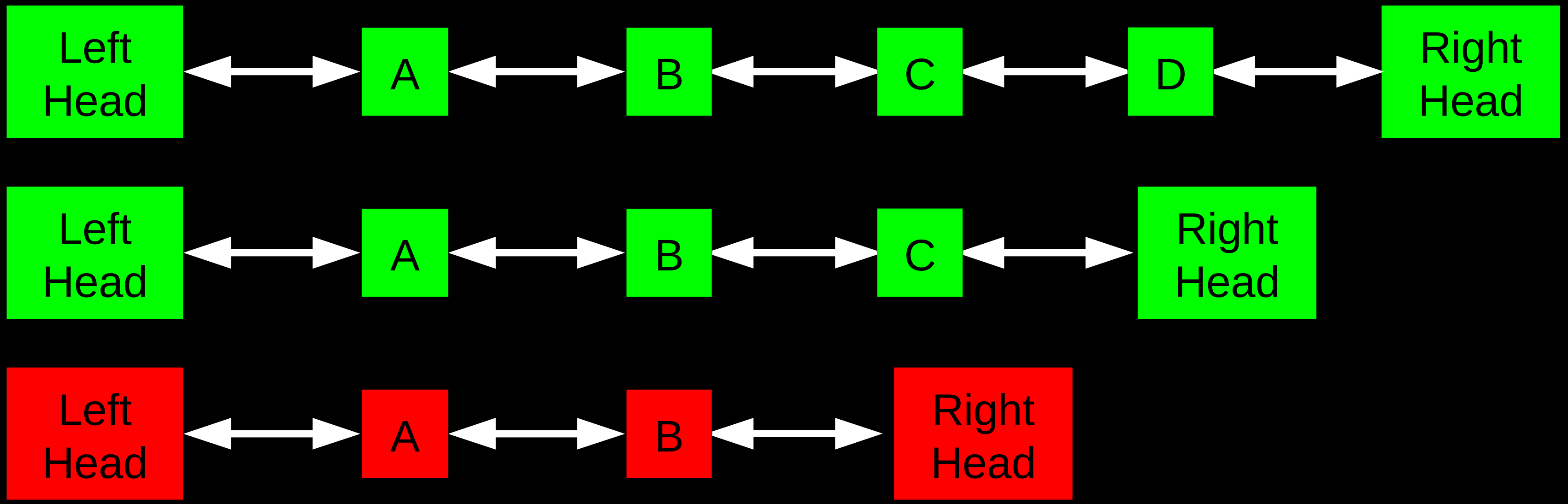
- If two lock-based critical sections have no conflicting accesses, why serialize them?
  - Conflicting access: concurrent accesses to the same location, at least one of which is a write
- Recent hardware from IBM and Intel supports this notion
  - Andi Kleen's ACM Queue article: http://queue.acm.org/detail.cfm?id=2579227
  - http://www.power.org/documentation/power-isa-version-2-07/
  - http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html
- Good results for some benchmarks on smallish systems:
  - http://pcl.intel-research.net/publications/SC13-TSX.pdf

# Is Hardware Lock Elision The Silver Bullet?

- Some drawbacks:
  - Must have software fallback (aside from small mainframe transactions)
    - Not a cure-all for lock-based deadlocks
    - However, in some cases, might allow coarser locking
  - Still must avoid conflicting accesses
    - “Some restructuring may be required”
    - Even when the software does not care about the conflicts
  - Critical section's data references must fit into cache
  - Critical section cannot contain irrevocable operations (like syscalls)
  - “Lemming effect”: self-perpetuating software fallback
  - Does not repeal the laws of physics
    - Speed of light and size of atoms remain the same :-)
  - Does not match the 2005 hype (but what would?)
- No silver bullet, but promising for a number of cases

# Hardware Lock Elision: Toy Example

- Toy problem: Create a dequeue that can operate in parallel
  - Difficult to create lock-based dequeue that is parallel at both ends
  - Problem: Level of concurrency varies with dequeue state



# Hardware Lock Elision: Toy Example

- Toy problem: Create a dequeue that can operate in parallel
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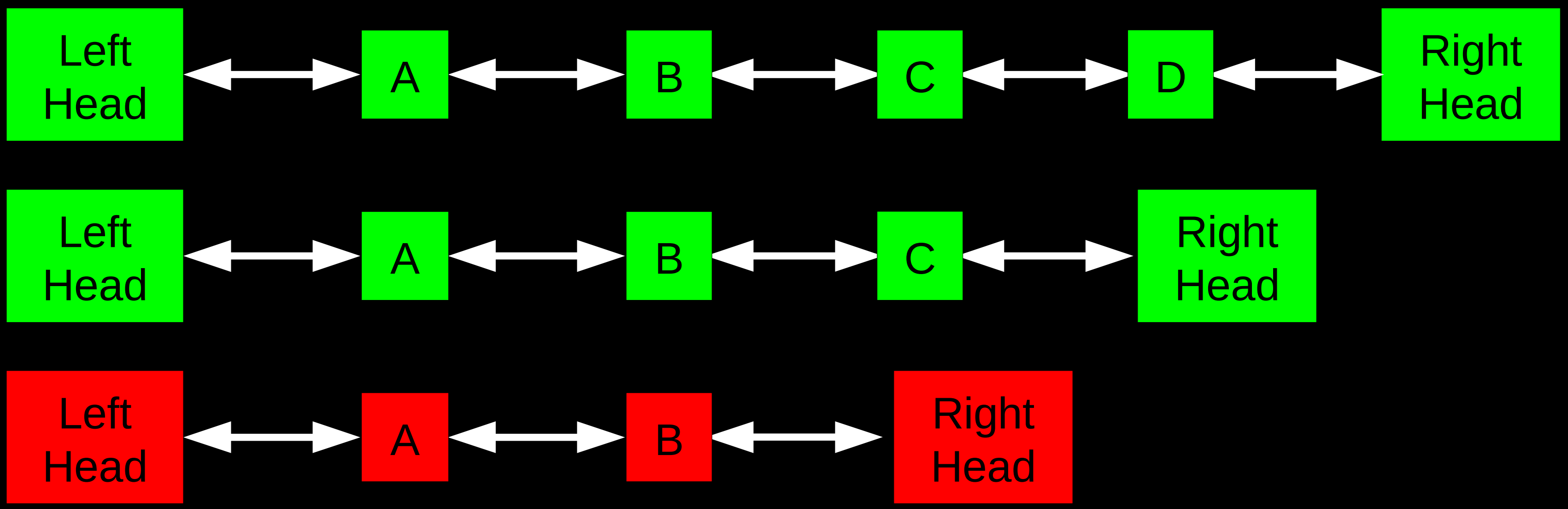
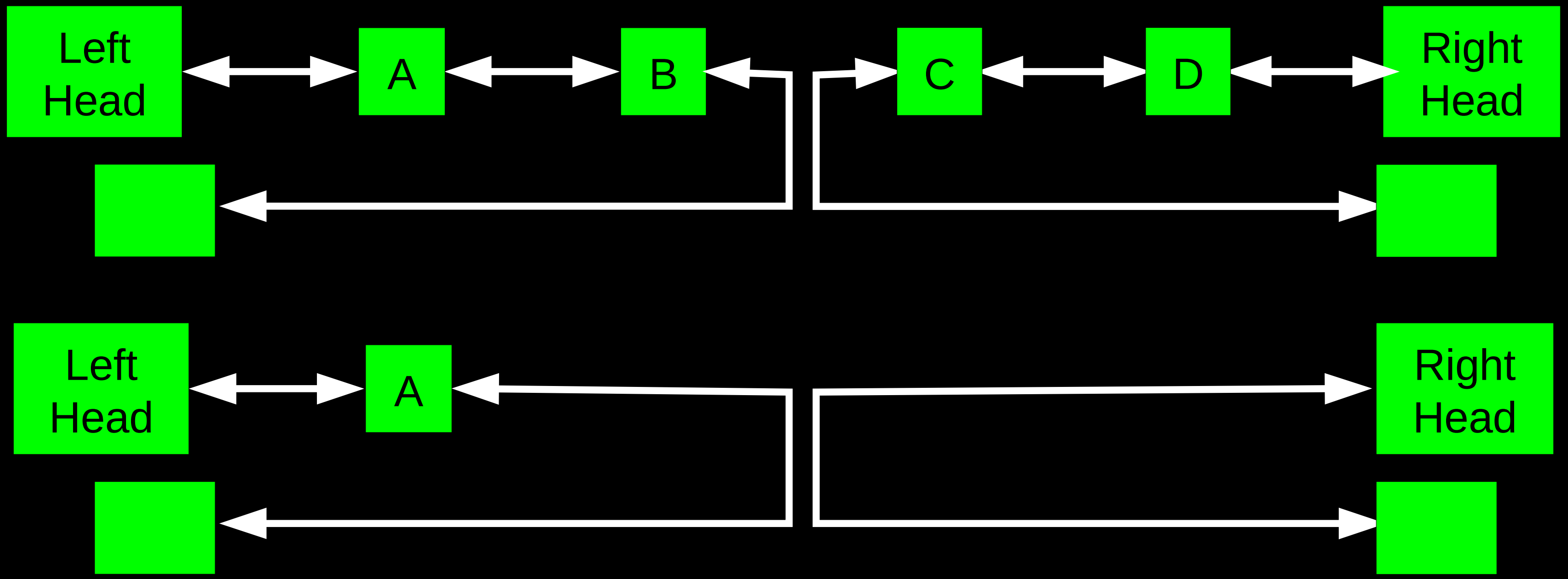
  - But is this really a hard problem?



# Hardware Lock Elision: Lock-Based Solution

- Use two lock-based dequeues
  - Can always insert concurrently: grab dequeue's lock
  - Can always remove concurrently unless one or both are empty
    - If yours is empty, grab both locks in order!



# Hardware Lock Elision: Lock-Elision Solution

- But lock elision is even easier:
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- But lock elision is even easier:
  - One dequeue protected by one lock!
  - The hardware automatically runs parallel when it is safe to do so
- However, there are some drawbacks (as always):
  - I/O, system calls, and other irrevocable operations defeat elision
  - Old hardware defeats elision
    - Though I am sure that both Intel and IBM would be more than happy to sell you some new hardware!
  - In many cases, restructuring required to avoid conflicting accesses
  - Hardware limitations (cache geometry, etc.) can defeat elision
  - Moderate levels of contention result in single-threaded execution even if the dequeue is full enough to enable concurrent operation

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  - Hardware limitations (cache geometry, etc.) can defeat elision
  - Moderate levels of contention result in single-threaded execution even if the dequeue is full enough to enable concurrent operation
- But why are you putting everything through one dequeue???

# Hardware Lock Elision: Potential Game Changers

What must happen for HTM to take over the world?

# Hardware Lock Elision: Potential Game Changers

- Forward-progress guarantees
  - Mainframe is a start, but larger sizes would be helpful
- Transaction-size increases
- Improved debugging support
  - Gottschich et al: “But how do we really debug transactional memory?”
- Handle irrevocable operations (unbuffered I/O, syscalls, ...)
- Weak atomicity

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- Weak atomicity – but the Linux-kernel RCU maintainer and weak-memory advocate ***would*** say that...

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- Handle irrevocable operations (unbuffered I/O, syscalls, ...)
- Weak atomicity:  It is not just me saying this!
  - Herlihy et al: “Software Transactional Memory for Dynamic-Sized Data Structures”
  - Shavit: “Data structures in the multicore age”
  - Haas et al: “How FIFO is your FIFO queue?”
  - Gramoli et al: “Democratizing transactional memory”
- With these additions, much greater scope possible

# Special Cases For Parallel Updates: Summary

- There is currently no silver bullet:
  - Split counters
    - Extremely specialized
  - Per-CPU/thread processing
    - Not all algorithms can be efficiently partitioned
  - Stream-based applications
    - Specialized
  - Read-only traversal to location being updated
    - Great for small updates to large data structures, but limited otherwise
  - Hardware lock elision
    - Some good potential, and some potential limitations
- Linux kernel: Good progress by combining approaches
- Lots of opportunity for collaboration and innovation

# Possible Additions To Parallel-Programming Toolbox

# Possible Additions To Parallel-Programming Toolbox

- OpLog for update-mostly operations
  - http://pdos.csail.mit.edu/papers/sbw-phd-thesis.pdf
  - Each CPU/thread maintains a timestamped operation log
  - Updates can cancel
  - Read operations force updates to be applied, as do some updates
  - Prototyped for Linux-kernel rmap with good results
- The scalable commutativity rule
  - http://www.read.seas.harvard.edu/~kohler/pubs/clements13scalable.pdf
  - Operations that cannot commute imply scalability bottleneck
    - fork()/exec() does not commute with other threads' address-space, file-descriptor, or signal-state operations – a combined fork()/exec(), e.g., posix_spawn(), would commute (but good luck getting apps to use it!)
    - “Lowest available FD” rule limits multithreaded open/close performance
  - Excellent guide for future API design
  - Similar to http://paulmck.livejournal.com/16478.html
    - But way more complete and precise

# Summary

# Summary

- We are farther along with read-mostly methods than with update-heavy methods
- But there are some good approaches for update-heavy workloads for some special cases
  - Split counters
  - Per-CPU/thread processing
  - Stream-based applications
  - Read-only traversal to location being updated
  - Hardware lock elision
  - Some recent research might prove practical
- We can expect specialization for update-heavy workloads
  - Though generality would be nice if feasible!

# To Probe Deeper (1/4)

- Hash tables:
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Chapter 10
- Spit counters:
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Chapter 5
  - http://events.linuxfoundation.org/sites/events/files/slides/BareMetal.2014.03.09a.pdf
- Perfect partitioning
  - Candide et al: “Dynamo: amazon's highly available key-value store”
    - http://doi.acm.org/10.1145/1323293.1294281
  - McKenney: “Is Parallel Programming Hard, And, If So, What Can You Do About It?”
    - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 6.5
  - McKenney: “Retrofitted Parallelism Considered Grossly Suboptimal”
    - https://www.usenix.org/conference/hotpar12/retro%EF%AC%81tted-parallelism-considered-grossly-sub-optimal
  - McKenney et al: “Experience With an Efficient Parallel Kernel Memory Allocator”
    - http://www.rdrop.com/users/paulmck/scalability/paper/mpalloc.pdf
  - Bonwick et al: “Magazines and Vmem: Extending the Slab Allocator to Many CPUs and Arbitrary Resources”
    - http://static.usenix.org/event/usenix01/full_papers/bonwick/bonwick_html/
  - Turner et al: “PerCPU Atomics”
    - http://www.linuxplumbersconf.org/2013/ocw//system/presentations/1695/original/LPC%20-%20PerCpu%20Atomics.pdf

# To Probe Deeper (2/4)

- Stream-based applications:
  - Sutton: “Concurrent Programming With The Disruptor”
    - http://www.youtube.com/watch?v=UvE389P6Er4
    - http://lca2013.linux.org.au/schedule/30168/view_talk
  - Thompson: “Mechanical Sympathy”
    - http://mechanical-sympathy.blogspot.com/
- Read-only traversal to update location
  - Arcangeli et al: “Using Read-Copy-Update Techniques for System V IPC in the Linux 2.5 Kernel”
    - https://www.usenix.org/legacy/events/usenix03/tech/freenix03/full_papers/arcangeli/arcangeli_html/index.html
  - Corbet: “Dcache scalability and RCU-walk”
    - https://lwn.net/Articles/419811/
  - Xu: “bridge: Add core IGMP snooping support”
    - http://kerneltrap.com/mailarchive/linux-netdev/2010/2/26/6270589
  - Howard: “A Relativistic Enhancement to Software Transactional Memory”
    - http://www.usenix.org/event/hotpar11/tech/final_files/Howard.pdf
  - McKenney et al: “URCU-Protected Hash Tables”
    - http://lwn.net/Articles/573431/

# To Probe Deeper (3/4)

- Hardware lock elision: Overviews
  - Kleen: "Scaling Existing Lock-based Applications with Lock Elision"
    - http://queue.acm.org/detail.cfm?id=2579227
- Hardware lock elision: Hardware description
  - POWER ISA Version 2.07
    - http://www.power.org/documentation/power-isa-version-2-07/
  - Intel® 64 and IA-32 Architectures Software Developer Manuals
    - http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html
  - Jacobi et al: "Transactional Memory Architecture and Implementation for IBM System z"
    - http://www.microsymposia.org/micro45/talks-posters/3-jacobi-presentation.pdf
- Hardware lock elision: Evaluations
  - http://pcl.intel-research.net/publications/SC13-TSX.pdf
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 16.3
- Hardware lock elision: Need for weak atomicity
  - Herlihy et al: "Software Transactional Memory for Dynamic-Sized Data Structures"
    - http://research.sun.com/scalable/pubs/PODC03.pdf
  - Shavit et al: "Data structures in the multicore age"
    - http://doi.acm.org/10.1145/1897852.1897873
  - Haas et al: "How FIFO is your FIFO queue?"
    - http://dl.acm.org/citation.cfm?id=2414731
  - Gramoli et al: "Democratizing transactional programming"
    - http://doi.acm.org/10.1145/2541883.2541900

# To Probe Deeper (4/4)

- Possible future additions
  - Boyd-Wickizer: “Optimizing Communications Bottlenecks in Multiprocessor Operating Systems Kernels”
    - http://pdos.csail.mit.edu/papers/sbw-phd-thesis.pdf
  - Clements et al: “The Scalable Commutativity Rule: Designing Scalable Software for Multicore Processors”
    - http://www.read.seas.harvard.edu/~kohler/pubs/clements13scalable.pdf

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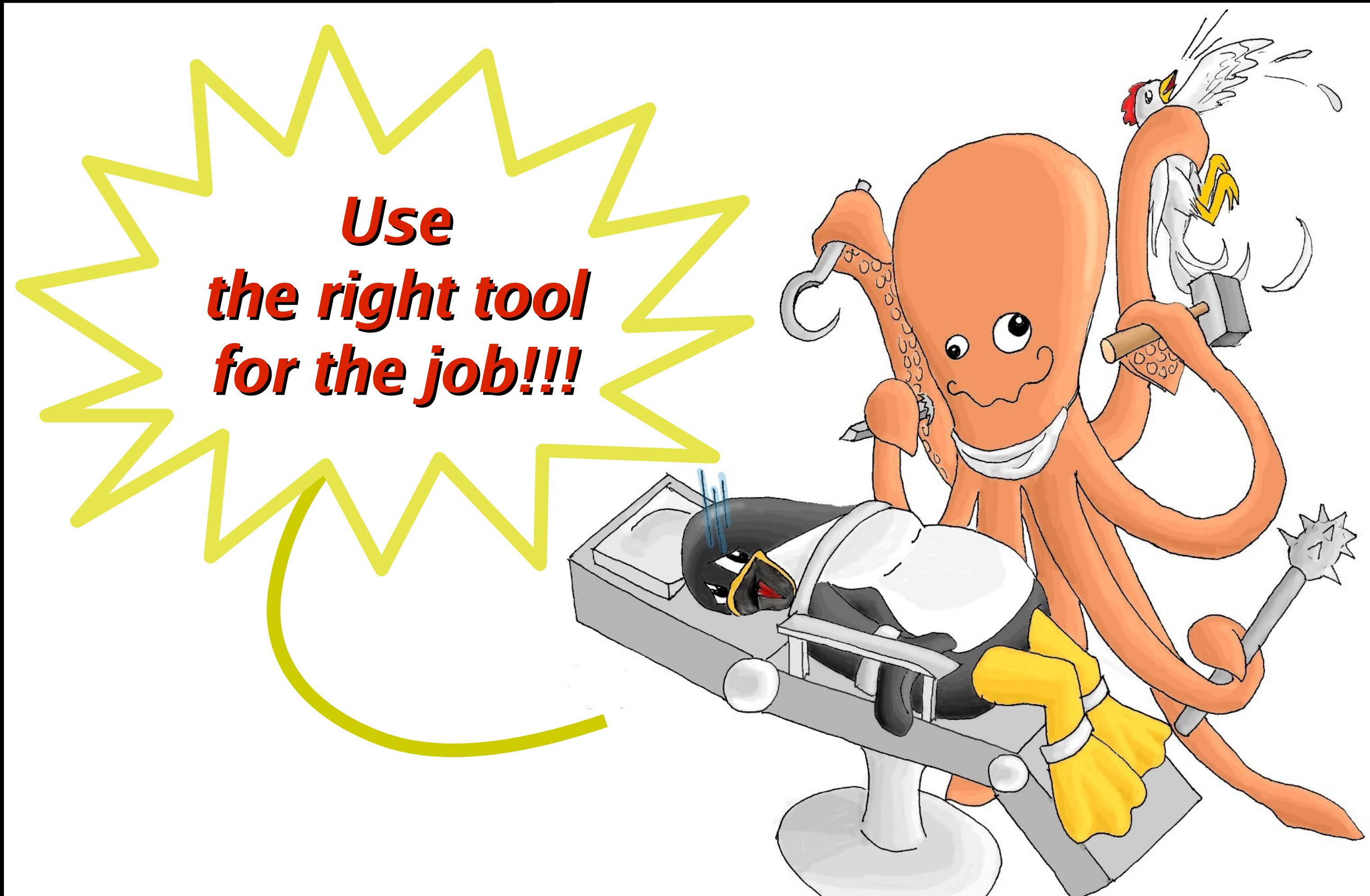


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