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A Lock-Free Hash Table

Dr. Cliff Click
Chief JVM Architect & Distinguished Engineer
blogs.azulsystems.com/cliff
Azul Systems
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Hash Tables

- Constant-Time Key-Value Mapping
- Fast arbitrary function
- Extendable, defined at runtime
- Used for symbol tables, DB caching, network access, url caching, web content, etc
- Crucial for Large Business Applications
  - > 1MLOC
- Used in Very heavily multi-threaded apps
  - > 1000 threads

Popular Java Implementations

- Java's HashTable
  - Single threaded; scaling bottleneck
- HashMap
  - Faster but NOT multi-thread safe
- java.util.concurrent.HashMap
  - Striped internal locks; 16-way the default
- Azul, IBM, Sun sell machines >100cpus
- Azul has customers using all cpus in same app
- Becomes a scaling bottleneck!

A Lock-Free Hash Table

- No locks, even during table resize
  - No spin-locks
  - No blocking while holding locks
  - All CAS spin-loops bounded
  - Make progress even if other threads die....
- Requires atomic update instruction:
  CAS (Compare-And-Swap),
  LL/SC (Load-Linked/Store-Conditional, PPC only)
  or similar
- Uses sun.misc.Unsafe for CAS

A Faster Hash Table

- Slightly faster than j.u.c for 99% reads < 32 cpus
- Faster with more cpus (2x faster)
  - Even with 4096-way striping
  - 10x faster with default striping
- 3x Faster for 95% reads (30x vs default)
- 8x Faster for 75% reads (100x vs default)
- Scales well up to 768 cpus, 75% reads
  - Approaches hardware bandwidth limits

Agenda

- Motivation
- **“Uninteresting” Hash Table Details**
- State-Based Reasoning
- Resize
- Performance
- Q&A

Some “Uninteresting” Details

- Hashtable: A collection of Key/Value Pairs
- Works with any collection
- Scaling, locking, bottlenecks of the collection management responsibility of that collection
- Must be fast or O(1) effects kill you
- Must be cache-aware
- I'll present a sample Java solution
  - But other solutions can work, make sense

“Uninteresting” Details

- Closed Power-of-2 Hash Table
  - Reprobe on collision
  - Stride-1 reprobe: better cache behavior
- Key & Value on same cache line
- Hash memoized
  - Should be same cache line as K + V
  - But hard to do in pure Java
- No allocation on get() or put()
- Auto-Resize

Example get() code

```
idx = hash = key.hashCode();
while( true ) {         // reprobing loop
   idx &= (size-1);     // limit idx to table size
   k = get_key(idx);    // start cache miss early
   h = get_hash(idx);   // memoized hash
   if( k == key || (h == hash && key.equals(k)) )
      return get_val(idx);// return matching value
   if( k == null ) return null;
   idx++;               // reprobe
}
```

“Uninteresting” Details

- Could use prime table + MOD
  - Better hash spread, fewer reprobes
  - But MOD is 30x slower than AND
- Could use open table
  - put() requires allocation
  - Follow 'next' pointer instead of reprobe
  - Each 'next' is a cache miss
  - Lousy hash -> linked-list traversal
- Could put Key/Value/Hash on same cache line
- Other variants possible, interesting

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Ordering and Correctness

- How to show table mods correct?
  - put, putIfAbsent, change, delete, etc.
- Prove via: fencing, memory model, load/store ordering, “happens-before”?
- Instead prove* via state machine
- Define all possible {Key,Value} states
- Define Transitions, State Machine
- Show all states “legal”

*Warning: hand-wavy proof follows

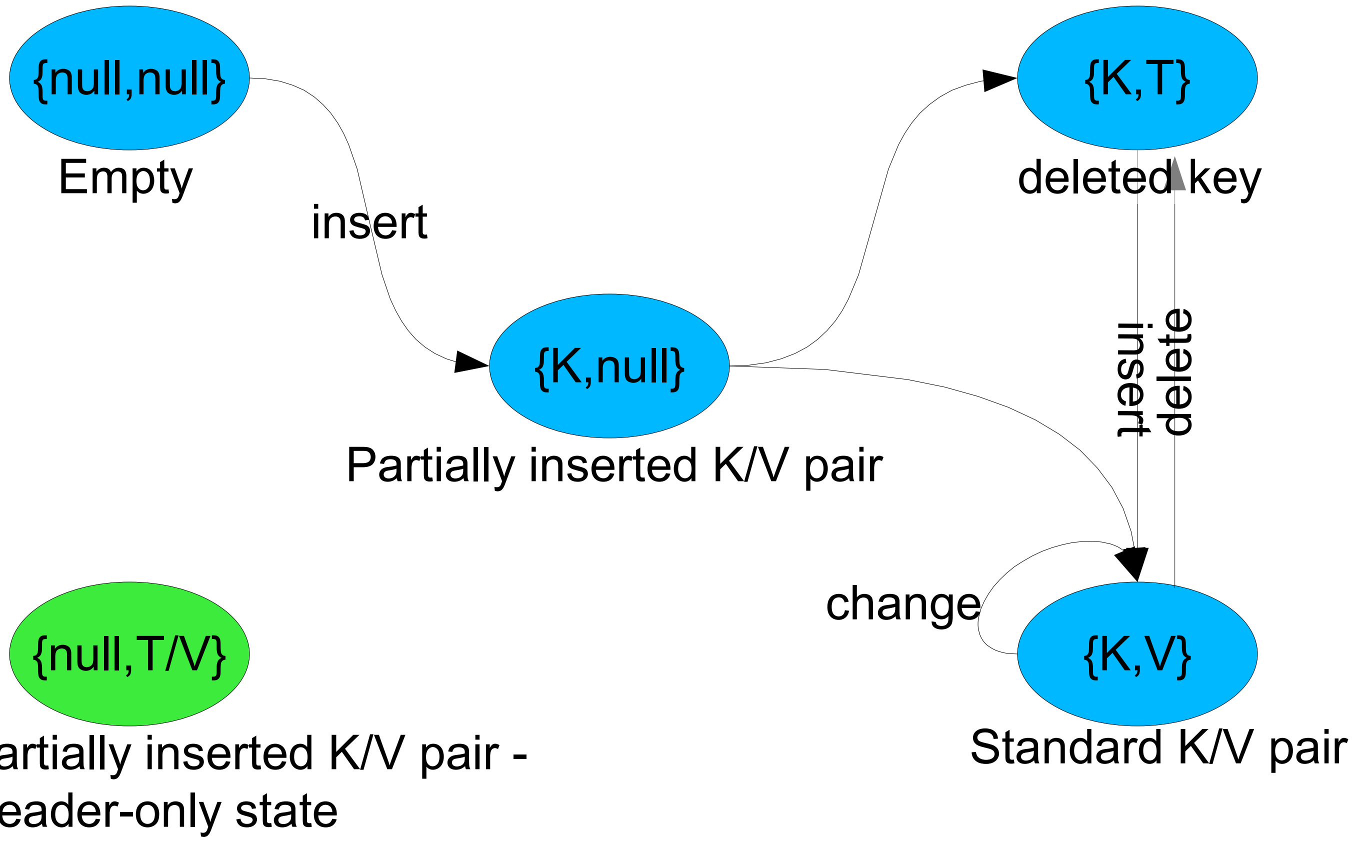
State-Based Reasoning

- Define all {Key,Value} states and transitions
- Don't Care about memory ordering:
  - get() can read Key, Value in any order
  - put() can change Key, Value in any order
  - put() must use CAS to change Key or Value
    - But not double-CAS
- No fencing required for correctness!
  - (sometimes stronger guarantees are wanted and will need fencing)
- Proof is simple!

Valid States

- A Key slot is:
  - null – empty
  - K – some Key; can never change again
- A Value slot is:
  - null – empty
  - T – tombstone
  - V – some Values
- A state is a {Key,Value} pair
- A transition is a successful CAS

State Machine



Example put(key,newval) code:

```
idx = hash = key.hashCode();
while( true ) {         // Key-Claim stanza
   idx &= (size-1);
   k = get_key(idx);    // State: {k,?}
   if( k == null &&     // {null,?} -> {key,?}
       CAS_key(idx,null,key) )
     break;             // State: {key,?}
   h = get_hash(idx);   // get memoized hash
   if( k == key || (h == hash && key.equals(k)) )
     break;             // State: {key,?}
   idx++;               // reprobe
}
```

Example put(key,newval) code

```
// State: {key,?}
oldval = get_val(idx);  // State: {key,oldval}
// Transition: {key,oldval} -> {key,newval}
if( CAS_val(idx,oldval,newval) ) {
  // Transition worked
  ...                         // Adjust size
} else {
  // Transition failed; oldval has changed
  // We can act "as if" our put() worked but
  // was immediately stomped over
}
return oldval;
```

Some Things to Notice

- Once a Key is set, it never changes
  - No chance of returning Value for wrong Key
  - Means Keys leak; table fills up with dead Keys
    - Fix in a few slides...
- No ordering guarantees provided!
  - Bring Your Own Ordering/Synchronization
- Weird {null,V} state meaningful but uninteresting
  - Means reader got an empty key and so missed
    - But possibly prefetched wrong Value

Some Things to Notice

- There is no machine-wide coherent State!
- Nobody guaranteed to read the same State
  - Except on the same CPU with no other writers
- No need for it either
- Consider degenerate case of a single Key
- Same guarantees as:
  - single shared global variable
  - many readers & writers, no synchronization
  - i.e., darned little

A Slightly Stronger Guarantee

- Probably want “happens-before” on Values
  - java.util.concurrent provides this
- Similar to declaring that shared global 'volatile'
- Things written into a Value before put()
  - Are guaranteed to be seen after a get()
- Requires st/st fence before CAS'ing Value
  - “free” on Sparc, X86
- Requires ld/ld fence after loading Value
  - “free” on Azul

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Resizing The Table

- Need to resize if table gets full
- Or just re-probing too often
- Resize copies live K/V pairs
  - Doubles as cleanup of dead Keys
  - Resize (“cleanse”) after any delete
  - Throttled, once per GC cycle is plenty often
- Alas, need fencing, 'happens before'
- Hard bit for concurrent resize & put():
  - Must not drop the last update to old table

Resizing

- Expand State Machine
- Side-effect: mid-resize is a valid State
- Means resize is:
  - Concurrent – readers can help, or just read&go
  - Parallel – all can help
  - Incremental – partial copy is OK
- Pay an extra indirection while resize in progress
  - So want to finish the job eventually
- Stacked partial resizes OK, expected

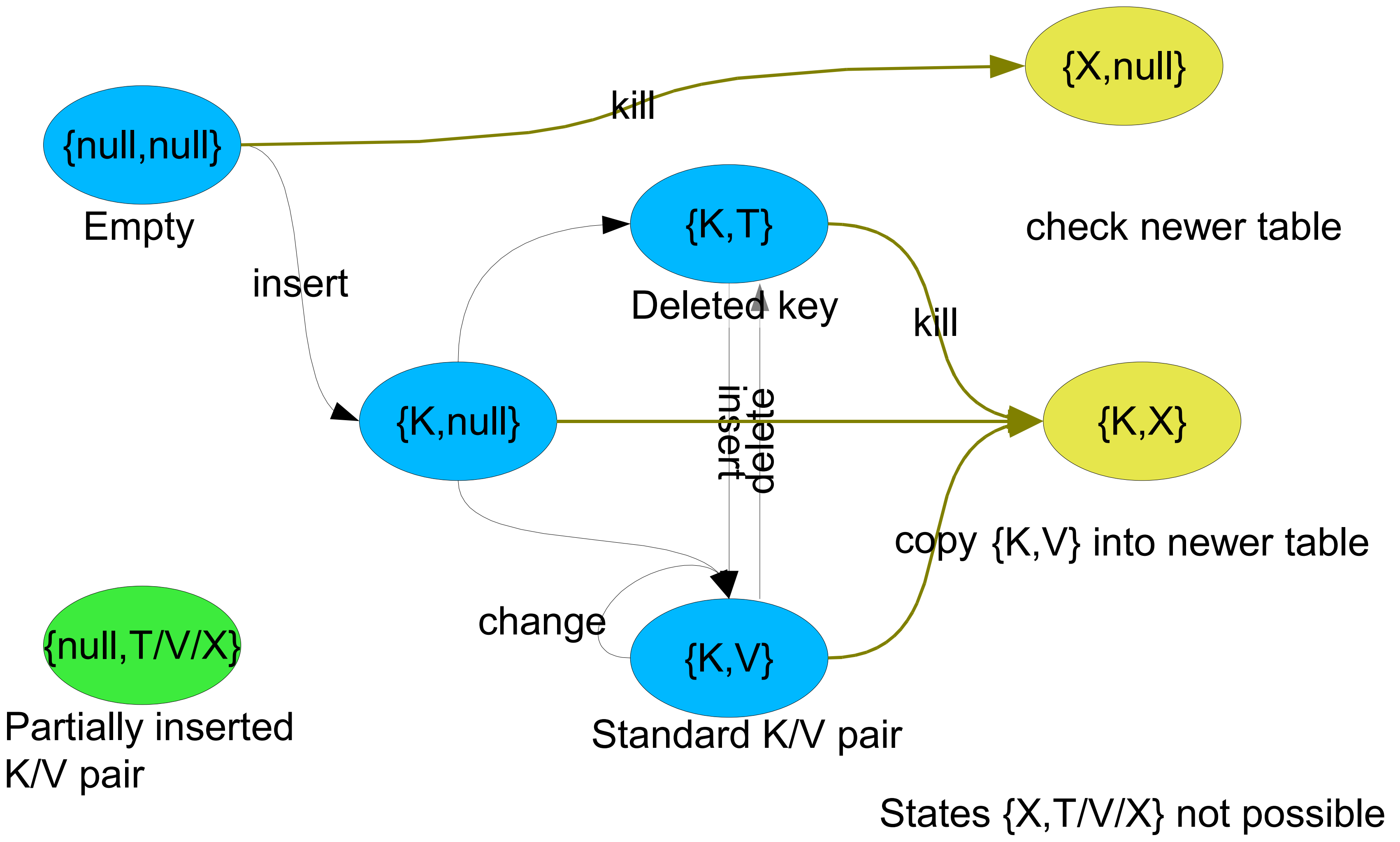
get/put during Resize

- get() works on the old table
  - Unless see a sentinel
- put() or other mod *must* use new table
- Must check for new table every time
  - Late writes to old table 'happens before' resize
- Copying K/V pairs is independent of get/put
- Copy has many heuristics to choose from:
  - All touching threads, only writers, unrelated background thread(s), etc

New State: 'use new table' Sentinel

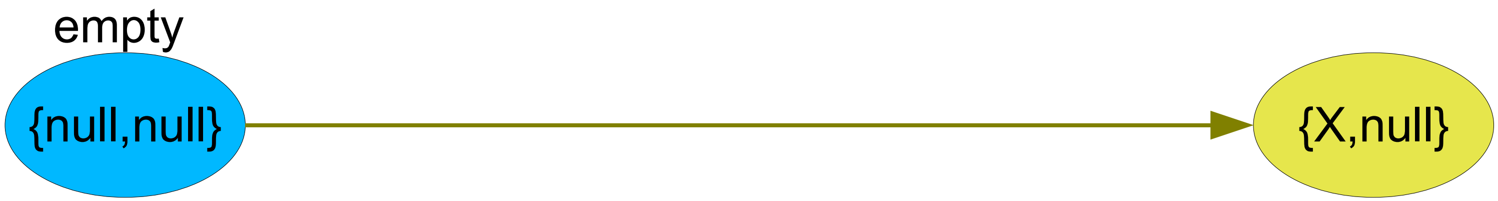
- X: sentinel used during table-copy
  - Means: not in old table, check new
- A Key slot is:
  - null, K
  - X – 'use new table', not any valid Key
  - null → K OR null → X
- A Value slot is:
  - null, T, V
  - X – 'use new table', not any valid Value
  - null → {T,V}* → X

State Machine – old table

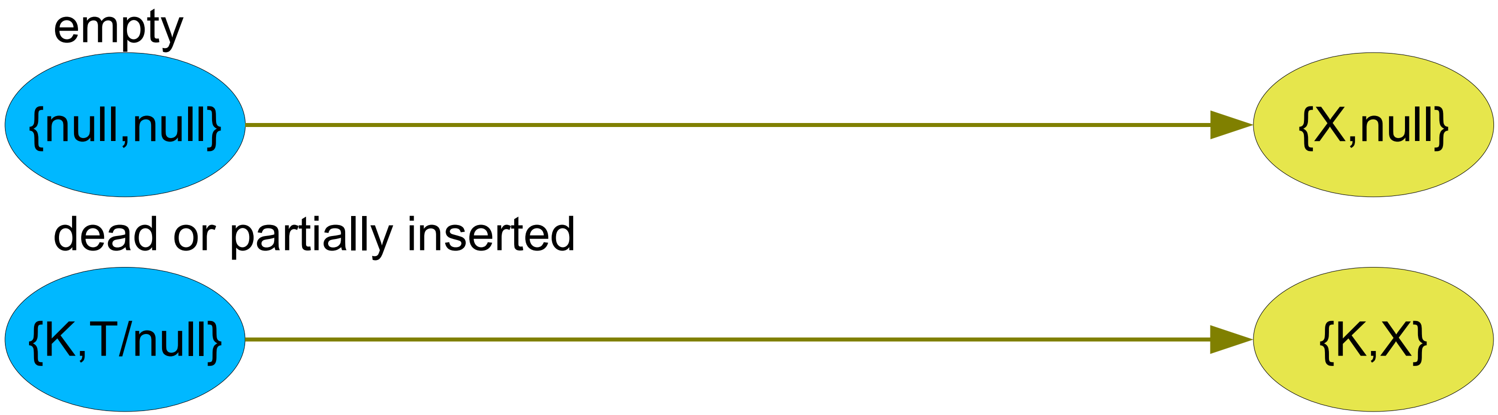


States {X,T/V/X} not possible

State Machine: Copy One Pair



State Machine: Copy One Pair



empty

{null,null}

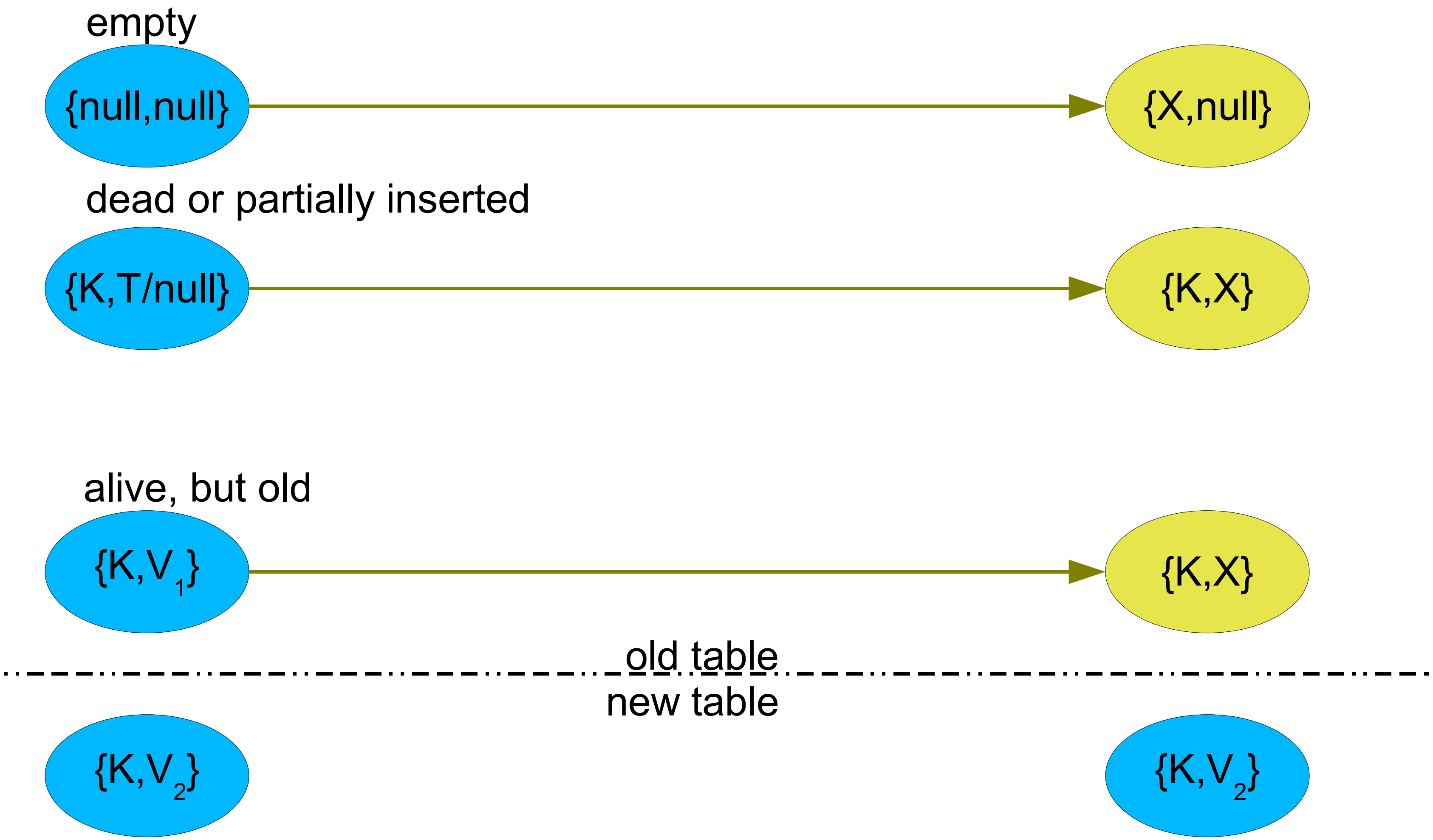
{X,null}

dead or partially inserted

{K,T/null}

{K,X}

State Machine: Copy One Pair



empty

{null,null}

{X,null}

dead or partially inserted

{K,T/null}

{K,X}

alive, but old

$\{K,V_1\}$

{K,X}

old table

new table

$\{K,V_2\}$

$\{K,V_2\}$

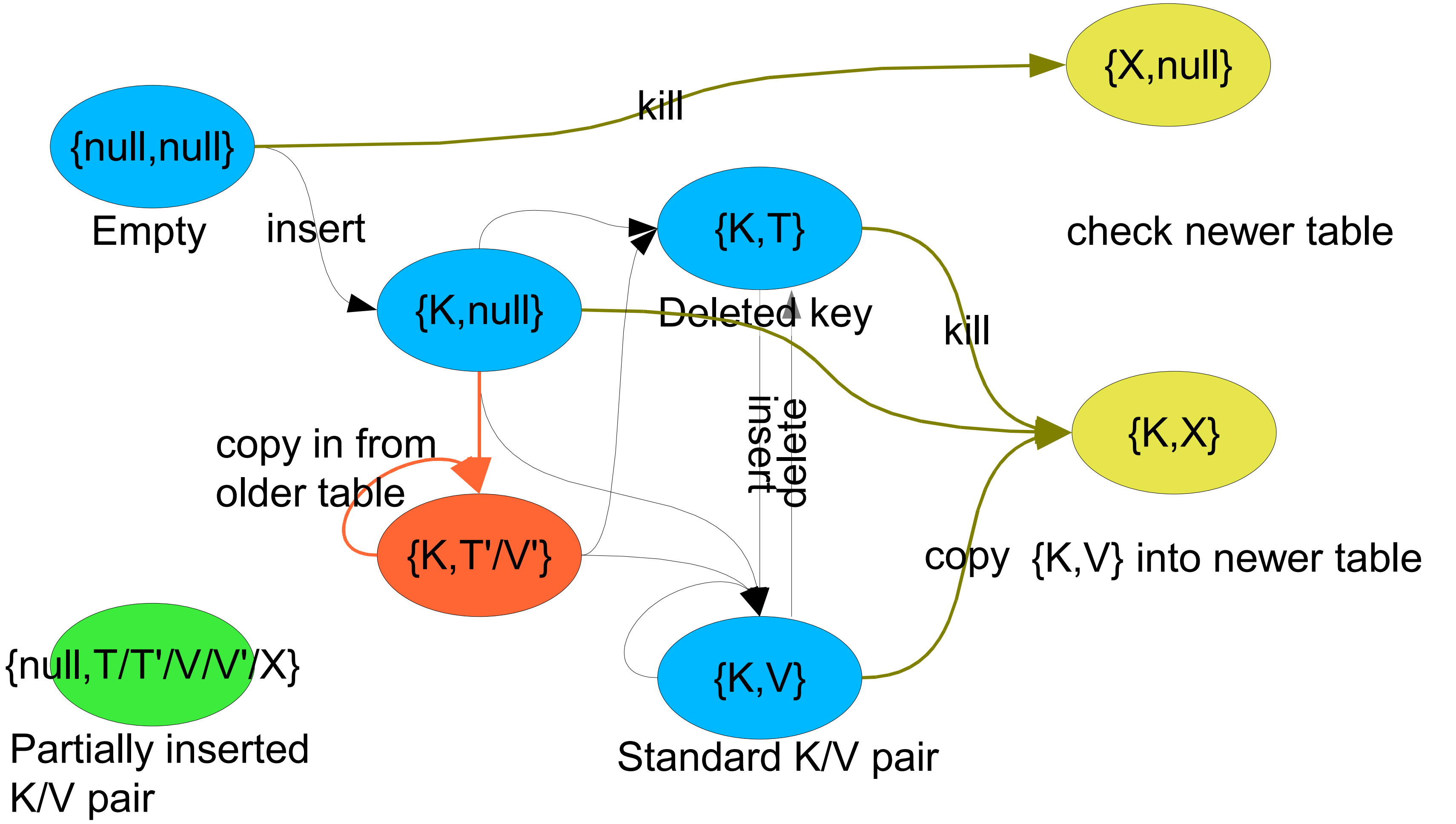
Copying Old To New

- New States V', T' – primed versions of V,T
  - Prime'd values in new table copied from old
  - Non-prime in new table is recent put()
    - “happens after” any prime'd value
  - Prime allows 2-phase commit
  - Engineering: wrapper class (Java), steal bit (C)
- Must be sure to copy late-arriving old-table write
- Attempt to copy atomically
  - May fail & copy does not make progress
  - But old, new tables not damaged

New States: Prime'd

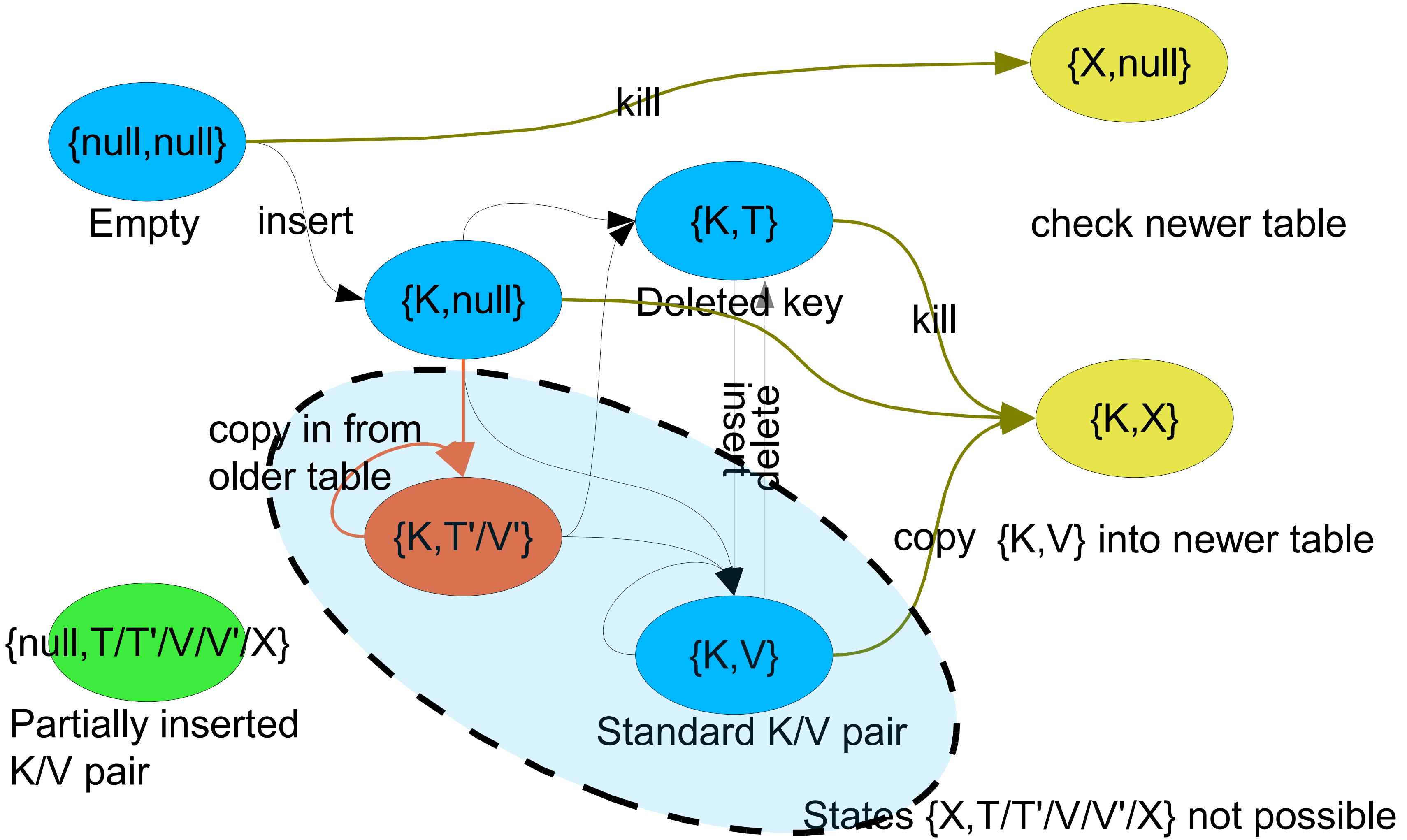
- A Key slot is:
  - null, K, X
- A Value slot is:
  - null, T, V, X
  - T',V' – primed versions of T & V
    - Old things copied into the new table
    - “2-phase commit”
  - null → {T',V'}* → {T,V}* → X
- State Machine again...

State Machine – new table

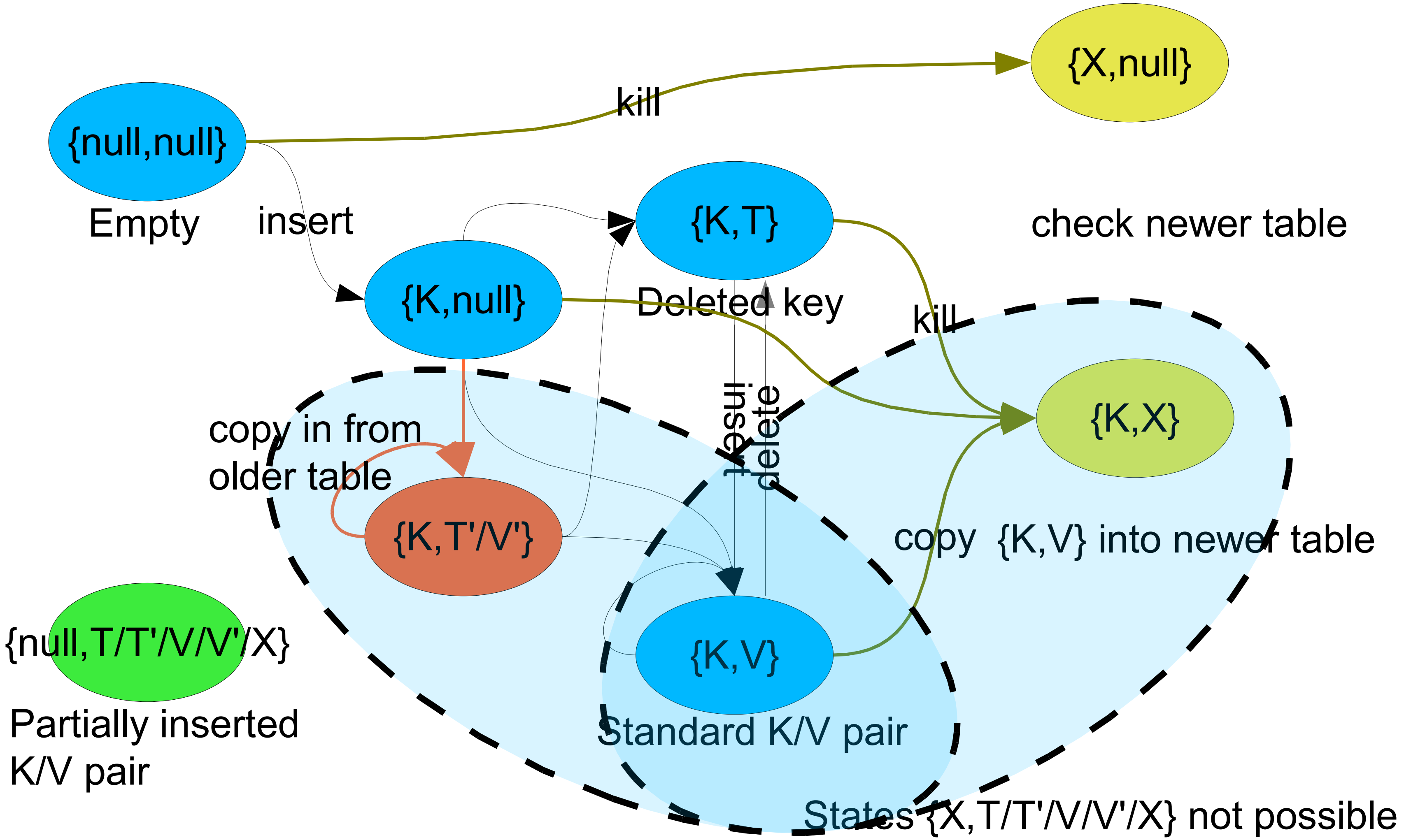


States {X,T/T'/V/V'/X} not possible

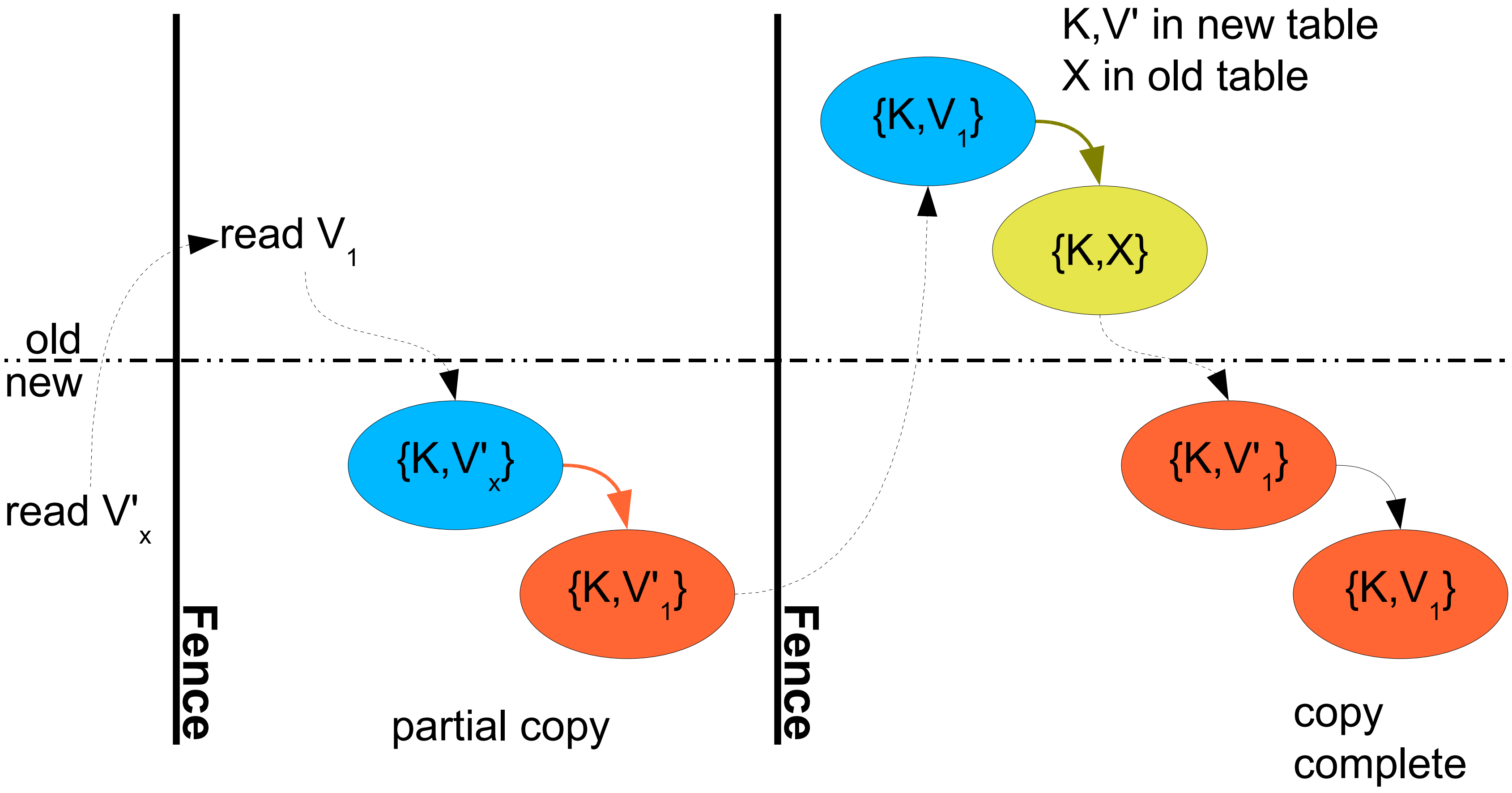
State Machine – new table



State Machine – new table



State Machine: Copy One Pair



Some Things to Notice

- Old value could be V or T
  - or V' or T' (if nested resize in progress)
- Skip copy if new Value is not prime'd
  - Means recent put() overwrote any old Value
- If CAS into new fails
  - Means either put() or other copy in progress
  - So this copy can quit
- **Any** thread can see **any** state at **any** time
  - And CAS to the next state

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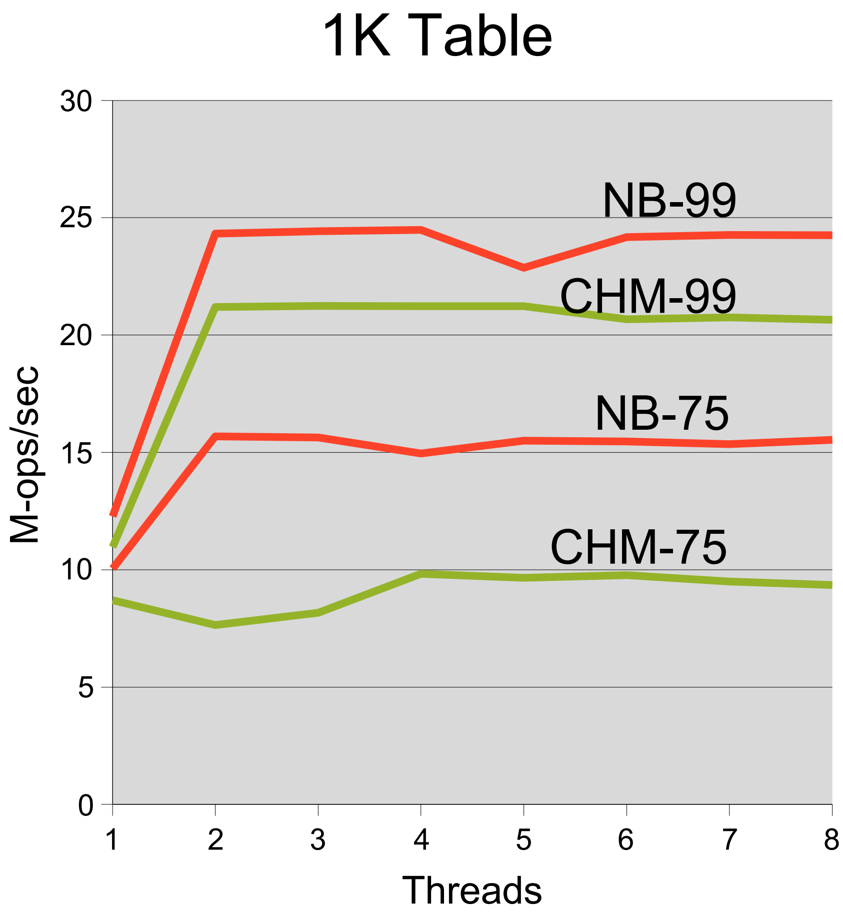
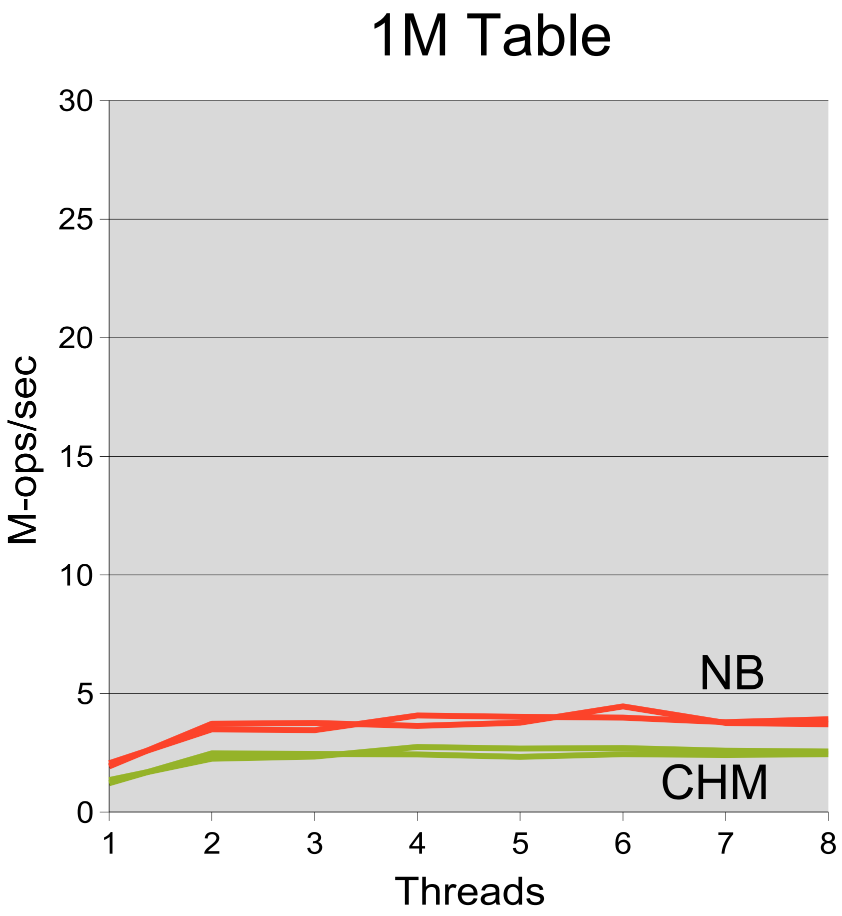
Microbenchmark

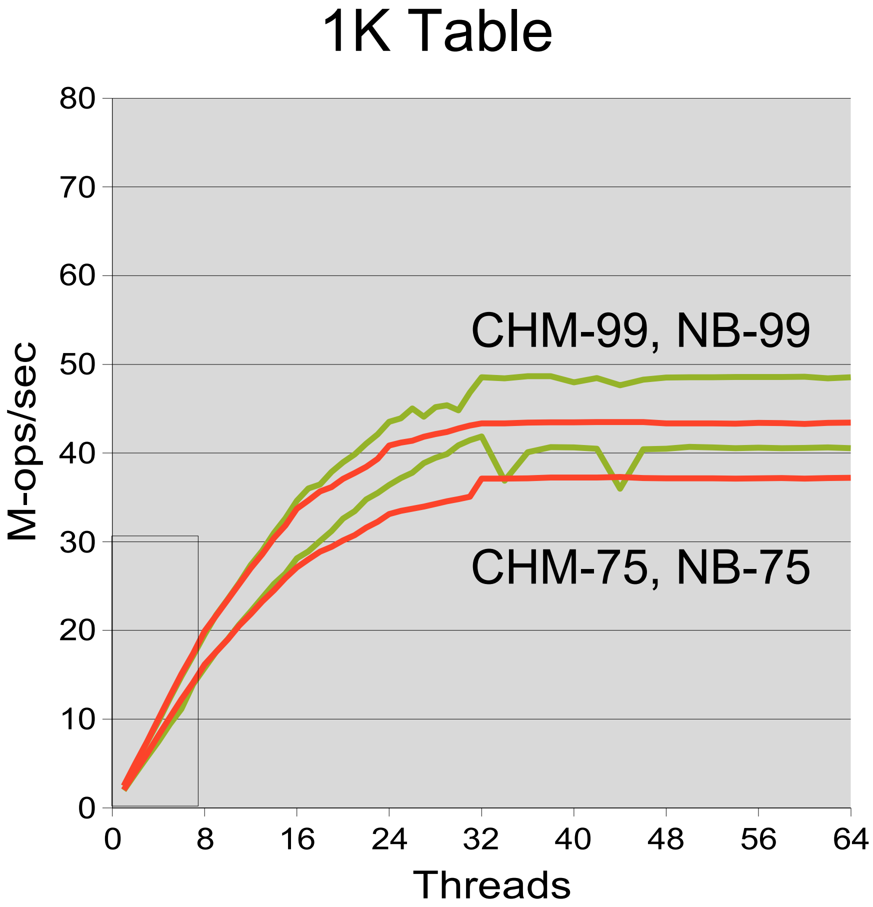
- Measure insert/lookup/remove of Strings
- Tight loop: no work beyond HashTable itself and test harness (mostly RNG)
- “Guaranteed not to exceed” numbers
- All fences; full ConcurrentHashMap semantics
- Variables:
  - 99% get, 1% put (typical cache) vs 75 / 25
  - Dual Athalon, Niagara, Azul Vega1, Vega2
  - Threads from 1 to 800
  - NonBlocking vs 4096-way ConcurrentHashMap
  - 1K entry table vs 1M entry table

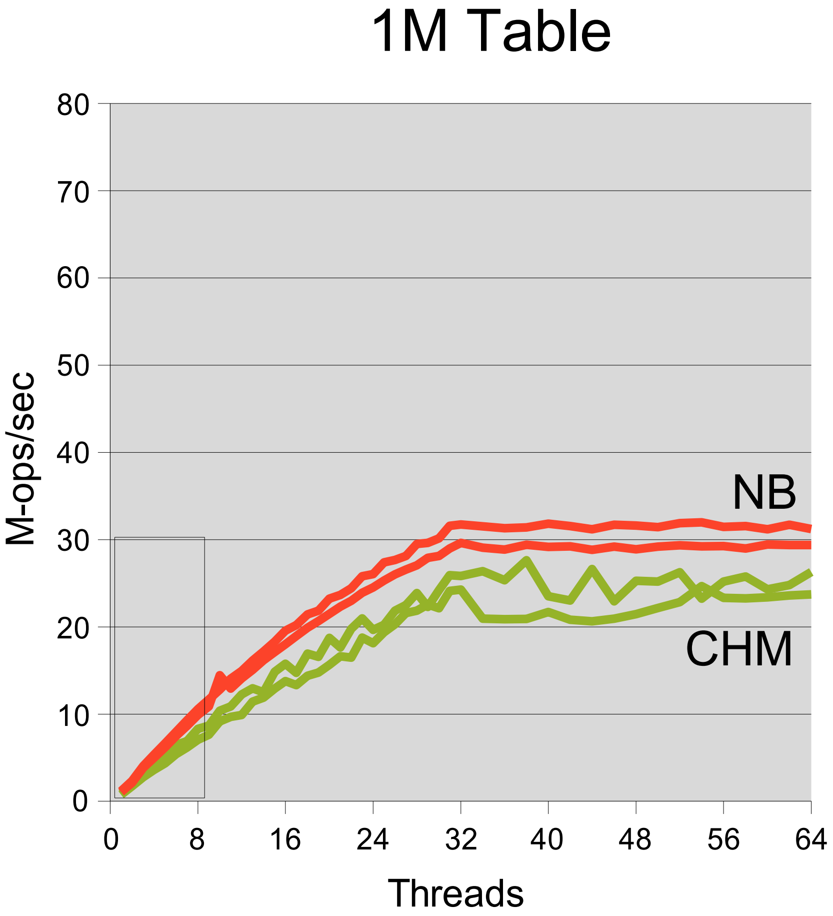
AMD 2.4GHz – 2 (ht) cpus



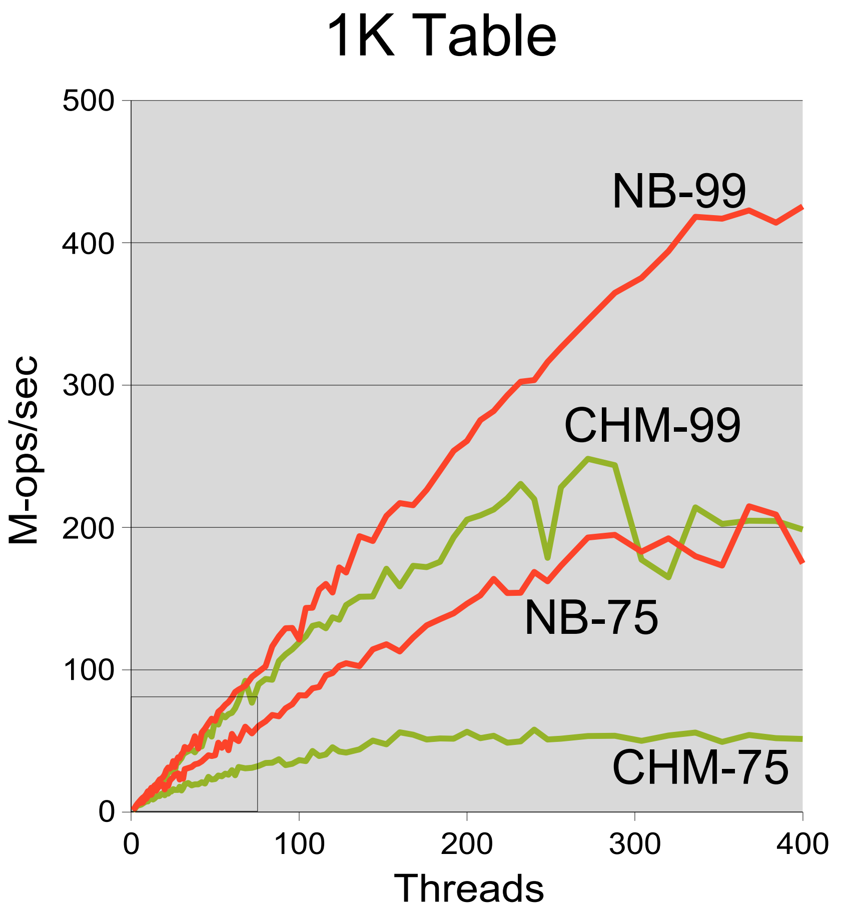


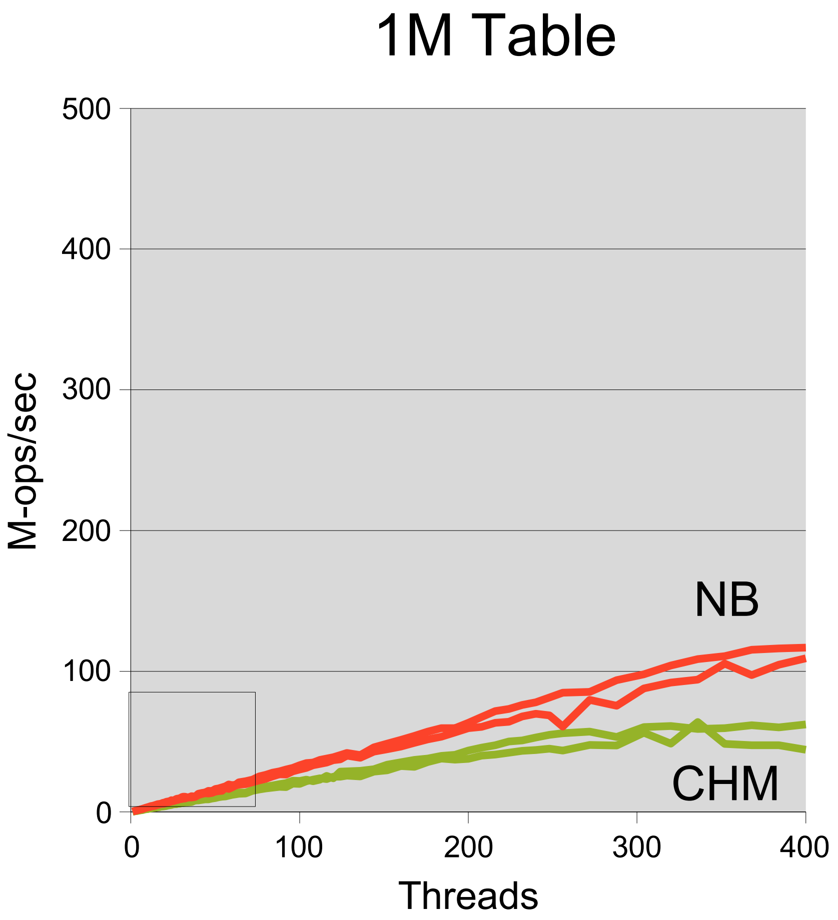
Niagara – 8x4 cpus



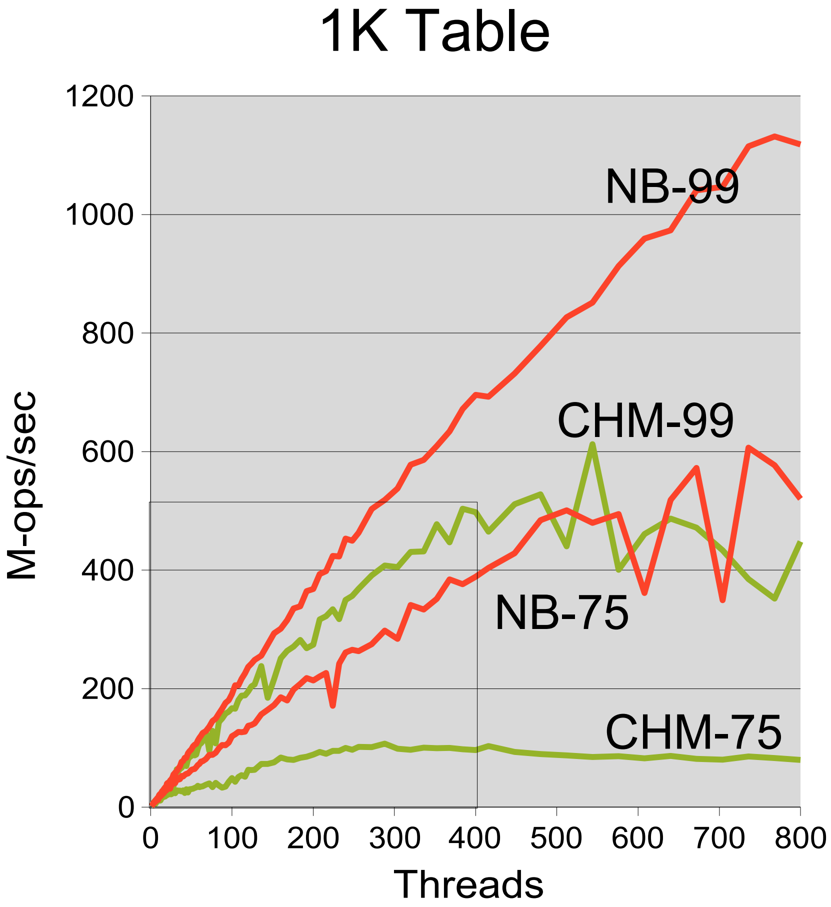


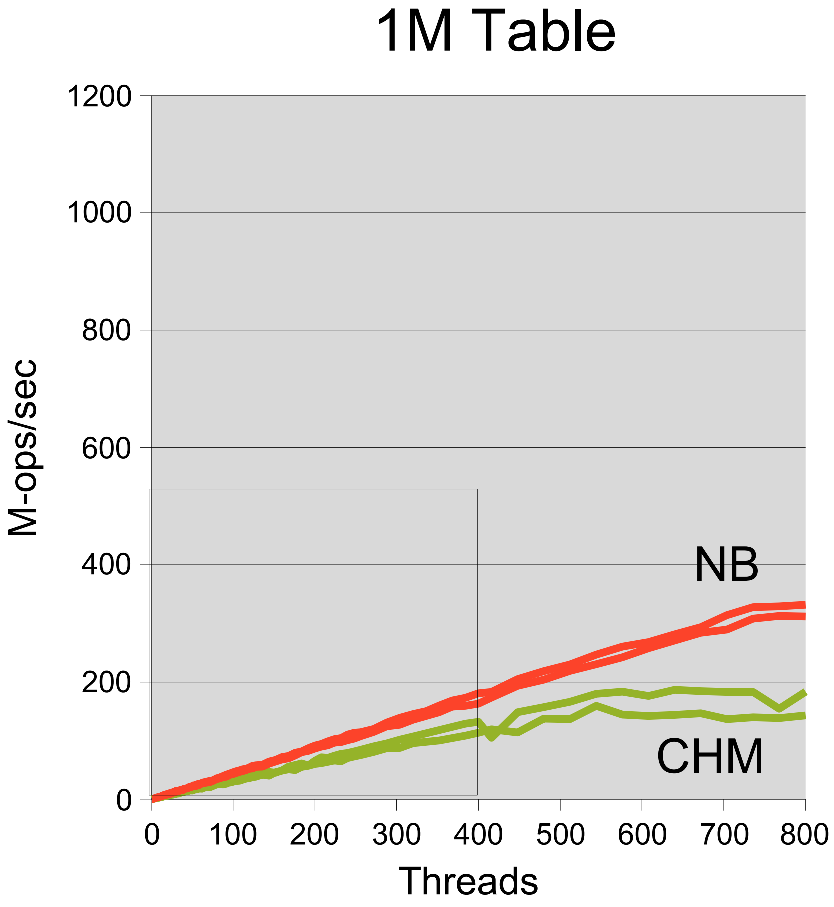
Azul Vega1 – 384 cpus





Azul Vega2 – 768 cpus





Summary

- A faster lock-free HashTable
- Faster for more CPUs
- Much faster for higher table modification rate
- State-Based Reasoning:
  - No ordering, no JMM, no fencing
- **Any** thread can see **any** state at **any** time
  - Must assume values change at each step
- State graphs **really** helped coding & debugging
- Resulting code is small & fast

Summary

- Obvious future work:
  - Tools to check states
  - Tools to write code
- Seems applicable to other data structures as well
  - Concurrent append j.u.Vector
  - Scalable near-FIFO work queues
- Code & Video available at:

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