Towards a Scalable Non-Blocking Coding Style

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The Computer Revolution is Here

We already did the 0->1 cpu transition

Concurrent Programming is Now 'The Norm'

and very hard to do

We're doing the 1->2 cpu transition

Scalable Concurrent Programming

is even harder

Time to think about the 2->N cpu transition

Here is a different way of thinking about the problem

What is A Non-Blocking Algorithm?

- Formally:
  - Stopping one thread will not prevent global progress
- Less formally:
  - No thread 'locks' any resource
    - and then gets pre-empted by OS
    - Or blocked in I/O, etc
  - No 'critical sections', locks, mutexs, spin-locks, etc
- Individual threads might starve

XXX-Free Hierarchy

- **Wait**-Free Algorithms (the best)
  - All threads complete in finite count of steps
  - Low priority threads cannot block high priority threads
  - No priority inversion possible
- **Lock**-Free (this work)
  - Every successful step makes Global Progress
  - But individual threads may starve
    - Hence priority inversion is possible
  - No live-lock
- **Obstruction**-Free
  - A single thread in isolation completes in finite count of steps
  - Threads may block each other
    - Hence live-lock is possible

Motivation

- Multi-core is now almost unavoidable
- Larger core counts more common:
  - 8+ (X86), 64 (Sun/ Rock), 768 (Azul, more coming)
- Locking suffers serious contention issues
  - Amdahl's Law, etc
- Would like to write correct code without locks!
- Obstruction-free can live-lock
  - More prone with higher cpu count
  - Or higher thread count
- Wait-free algorithms behave the best
  - But tend to be ***slow***
  - And are ***very*** hard to code
    - Handful of people on the planet can write these

Scalable

- Most large-CPU count shared-memory hardware is:
  - Parallel-read, Independent-write
- Multiple CPUs reading the same location is fast
  - Free 'cache-hitting-loads'
- Multiple CPUs writing to the same location serialize
  - Speed limited to '1-cache-miss-per-write' or '1-memory-bus-update-per-write'
- Must avoid all CPUs writing same location for independent operations
  - i.e., no shared counters, single lock-words, etc
- Classic reader/writer lock chokes w/ >50 CPUs
  - Contention on single reader-count word limits scaling

Agenda

- Motivation
- **A Scalable Non-Blocking Coding Style**
- Example 1: BitVector
- Example 2: HashTable
- Example 3: Nearly FIFO Queue
- Summary

Parts we need...

- An Array to hold all Data
  - Fast parallel (scalable) access
- Atomic-update on single Array Words
  - java.util.concurrent.Atomic.*
  - “No spurious failure CAS”
- A Finite State Machine
  - Replicated per array word (or small set of words)
  - Use Atomic-Update to 'step' in the FSM
- Construct algorithm from many FSM 'steps'
  - Lock-Free: Each CAS makes progress
  - CAS success is local progress
  - CAS failure means another CAS succeeded (global progress, local starvation)

How Big is the Array?

- *Don't answer that: Make array growable*
  - Resize array as needed
  - Common operation for Collection classes
- Support array resize via State Machine
  - Really: array-copy while in use
  - All array words are independent
  - Copy is parallel, incremental, concurrent
- But mostly operate without a copy-in-progress
  - So the common situation is simple, fast

Concurrent Array Resize

- Copy old Array into a new larger Array
- The hard part during a resize operation:
  - Copy without losing any late-writes to old Array
- Fix: “mark” old Array words with no-more-updates flag
  - Payload still visible through the “mark”
- Updaters' of marked payload must
  copy then update in new array
- Readers' seeing mark must
  copy then read in new array

Atomic Update

- Need some form of Atomic-Update
  - `java.util.concurrent.atomic.*`
- Update 1 word IFF old-value is equal to expected-value
- Generally Compare-And-Swap (CAS, Azul/Sparc/X86) or Load-Linked / Store-Conditional (LL/SC, IBM)
- Common Hardware Limitations
  - LL/SC suffers from live-lock
  - Both CAS & LL/SC can suffer spurious failure on some hardware
    - Infinite spurious failures is live-lock(?)
    - Finite failures fixed with spin loop
  - Useful if CAS does not spuriously fail (e.g. Azul)
    - Especially at high CPU count
    - If 1000 CPUs attempt update, 1 should succeed

Atomic Update: Failure

- CAS failure returns old value on most (all?) hardware?
  - Old value is evidence CAS did not fail spuriously
  - The “witness” - the “proof of failure”
  - LL/SC never provides old value
- The witness not available **after** the CAS
  - Overwritten by another thread
- JDK API mistake: witness turned into a boolean
  - Hence failure-for-cause can not be distinguished from spurious-failure
- Hence must spin on CAS failure until see reason for failure
  - Report either CAS success OR
  - CAS failure-for-cause
- Spinning builds a “No spurious failure CAS”

Towards A Scalable Lock-Free Coding Style

- Big Array to hold Data
- Parallel, Scalable read access
- Concurrent writes via: CAS & Finite State Machine
  - No JMM issues during Finite State Machine updates
  - No **lock**s, no **volatile**
- Fast as a best-of-breed not-thread-safe implementation
  - But as correct as thread-safe implementations
  - *Much* faster than locking under heavy load
  - No indirections in common case
  - Directly reach main data array in 1 step
- Resize as needed
  - Copy Array to a larger Array on demand
  - Use State Machine to help copy
  - “Mark” old Array words to avoid missing late updates

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Example 1: BitVector

- Size: O(max element)
  - Auto-resizing
- Supports concurrent insert, remove, test&set
- Obvious implementation:
  - Array of 'long' - 64-bit payload words
  - Bit mask & shift accessors
- How to 'mark' payload?
  - Steal 1 bit out of 64
  - MOD 63 to select index words – this example only
    - (Actually: avoid slow MOD by moving every 64^{th} bit to recursive bitvector)
- Code up in SourceForge, high-scale-lib

Example 1: BitVector

- Basic get & test/set (using MOD)

```
boolean get( int x ) {
  long[] A = _A;
  int idx = x/63;
  if( idx >= A.length)
    return false;

  int old = A[idx];
  if( old < 0 )
    return copy(x).get(x);
  long mask = 1L <<(x%63);
  return (old & mask)!=0;
}
```

```
boolean test_set( int x ) {
  long[] A = _A;  // read once
  int idx = x/63;
  if( idx >= A.length )
    return grow(x);
  while( true ) {  // spin loop
    int old = A[idx];
    if( old < 0 )  // marked?
      return copy(x).test_set(x);
    long mask = 1L <<(x%63);
    if( (old & mask) != 0)
      return true;
    if( CAS(A[idx],old,old|mask))
      return false;
}
```

Example 1: BitVector

- Read Array once – it may change out from under us!

```
boolean get( int x ) {
  long[] A = _A;
  int idx = x/63;
  if( idx >= A.length)
    return false;

  int old = A[idx];
  if( old < 0 )
    return copy(x).get(x);
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    if( (old & mask) != 0)
      return true;
    if( CAS(A[idx],old,old|mask))
      return false;
}
```

Example 1: BitVector

- Out-of-bounds triggers resize

```
boolean get( int x ) {
  long[] A = _A;
  int idx = x/63;
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    if( (old & mask) != 0)
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    if( CAS(A[idx],old,old|mask))
      return false;
}
```

Example 1: BitVector

- 'Mark' triggers copy & retry

```
boolean get( int x ) {
  long[] A = _A;
  int idx = x/63;
  if( idx >= A.length)
    return false;

  int old = A[idx];
  if( old < 0 )
    return copy(x).get(x);
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    int old = A[idx];
    if( old < 0 )  // marked?
      return copy(x).test_set(x);
    long mask = 1L <<(x%63);
    if( (old & mask) != 0)
      return true;
    if( CAS(A[idx],old,old|mask))
      return false;
}
```

Example 1: BitVector

- Failed CAS must retry – BUT!
  - Means another thread made progress

```
boolean get( int x ) {
  long[] A = _A;
  int idx = x/63;
  if( idx >= A.length)
    return false;

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    long mask = 1L <<(x%63);
    if( (old & mask) != 0)
      return true;
    if( CAS(A[idx],old,old|mask))
      return false;
  }
```
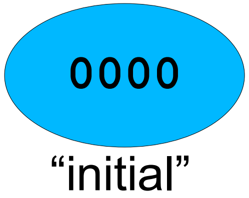
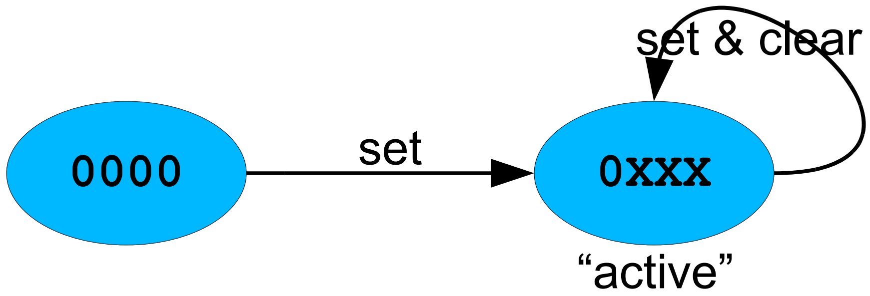

Example 1: BitVector

- Almost as fast as plain BitVector
  - Normal load & mask for get/set
  - Range check
  - Extra '<0' test (triggers copy & retry)
  - Set uses CAS spin-loop
- Copy: Sign-bit to stop further updates
  - Use CAS to set sign-bit
  - Then copy word to new array
  - Repeat operation on new array
- Finite State Machine!
  - per Array word
  - Hidden in the code
- Let's make the FSM obvious...

BitVector State Machine

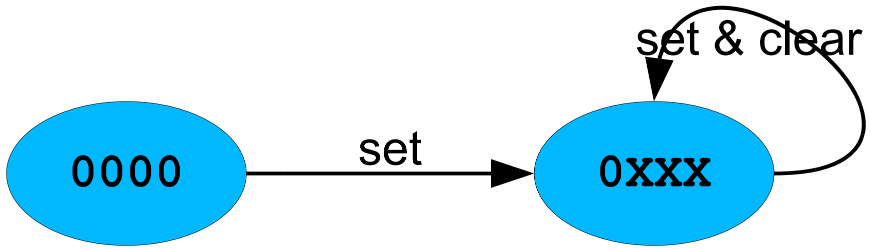


BitVector State Machine



A: Normal operations

BitVector State Machine

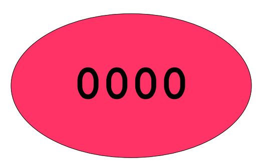


A: Normal operations

Out-of-Bounds set
triggers resize!

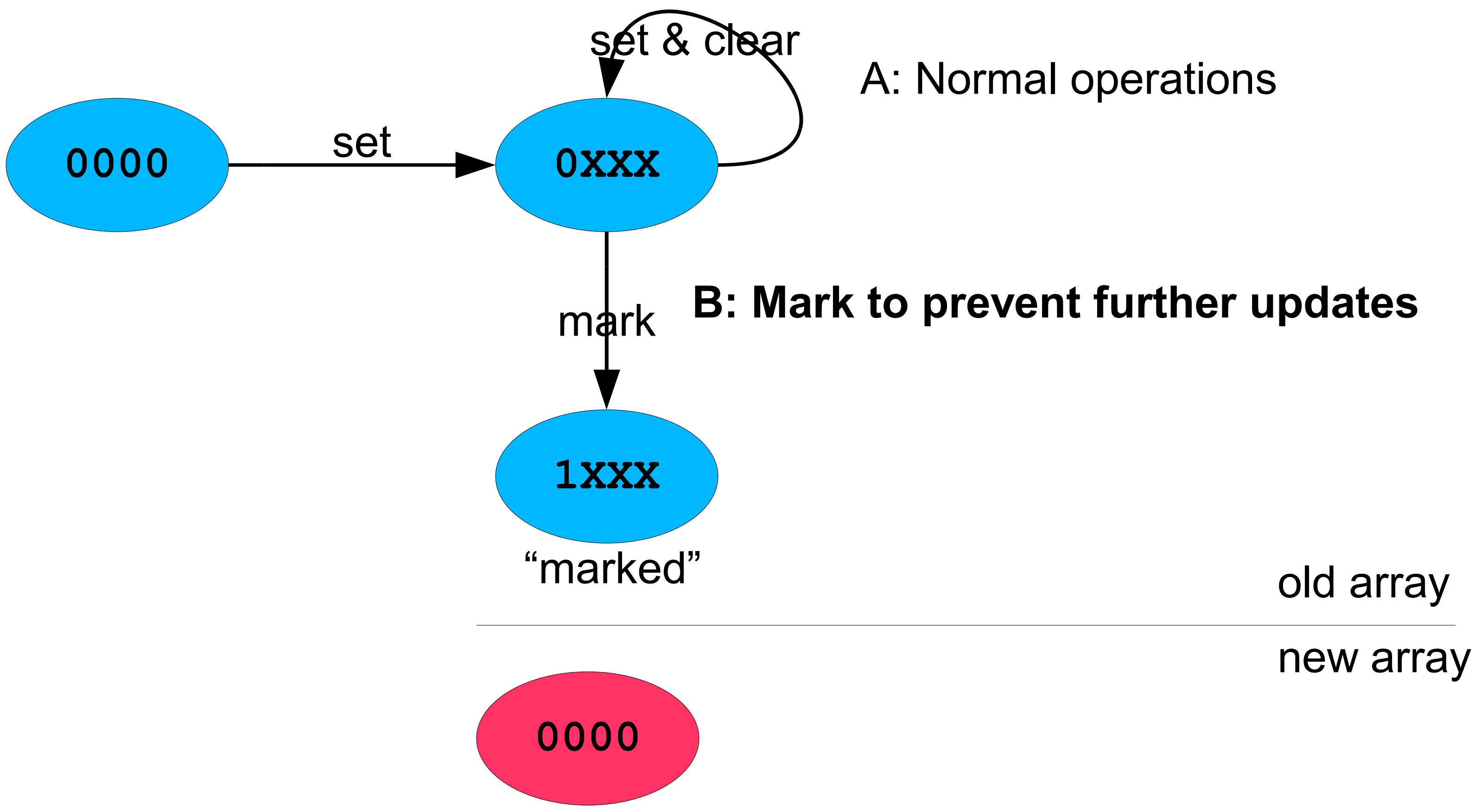
old array

new array

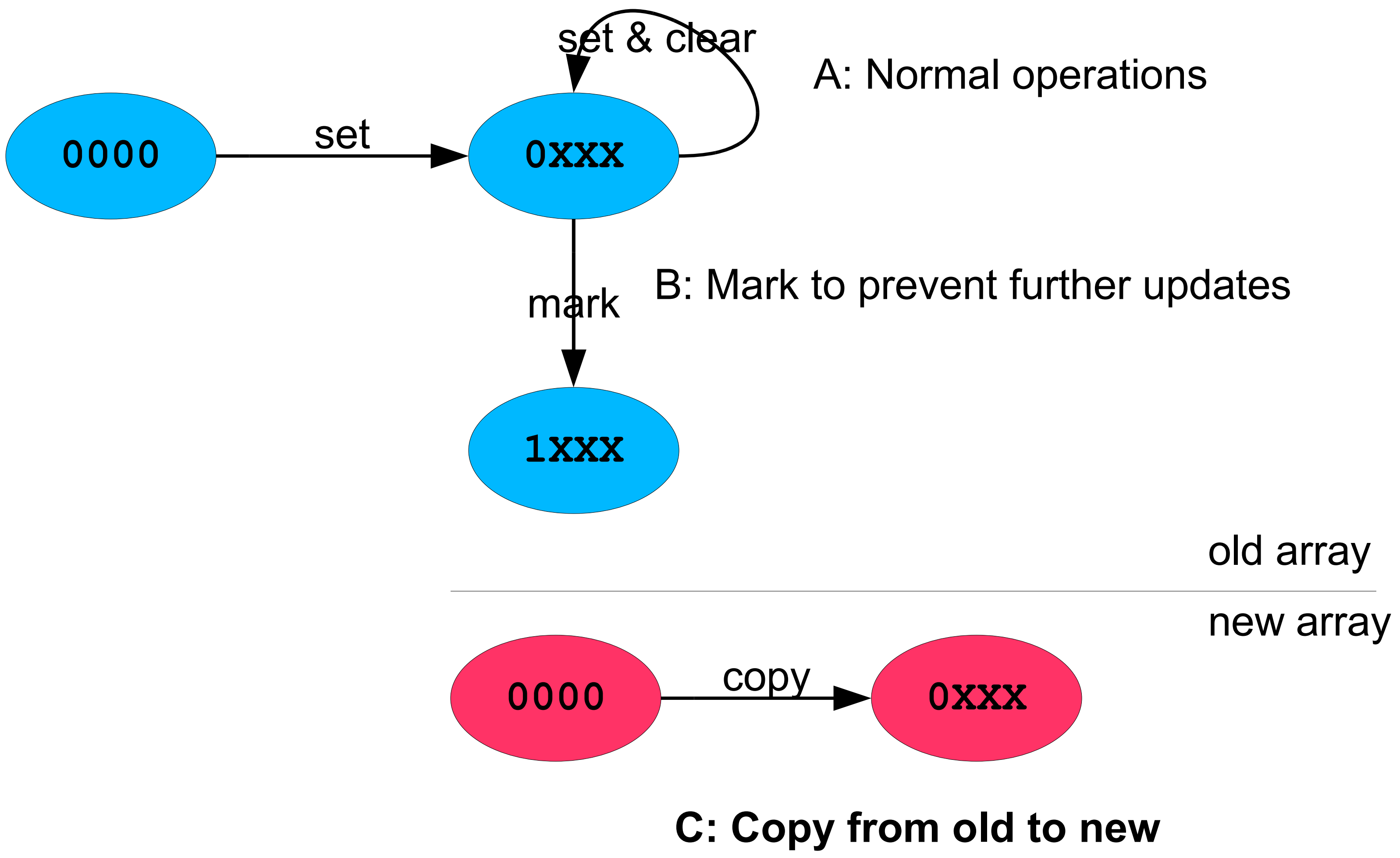


“initial”

BitVector State Machine



BitVector State Machine



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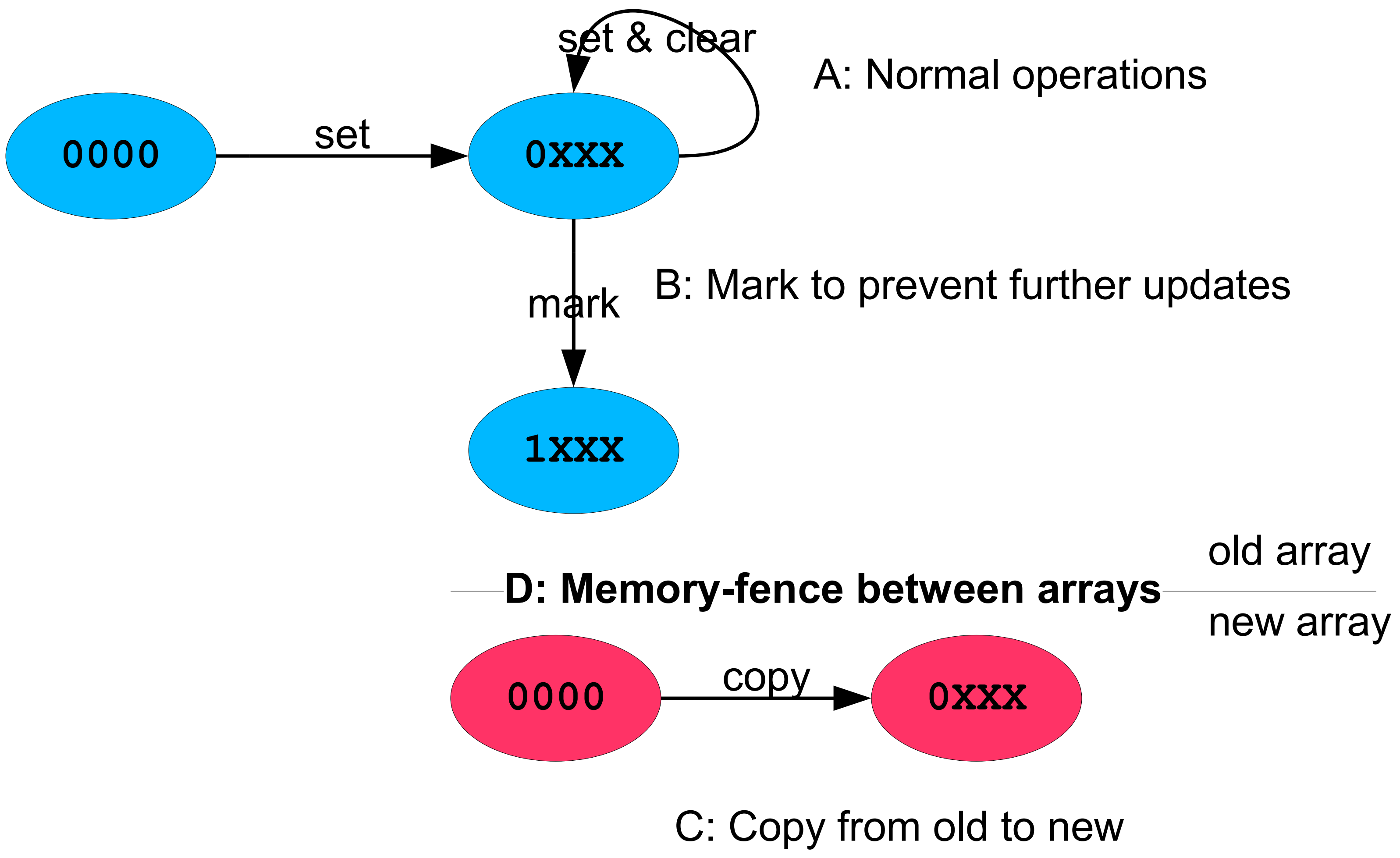

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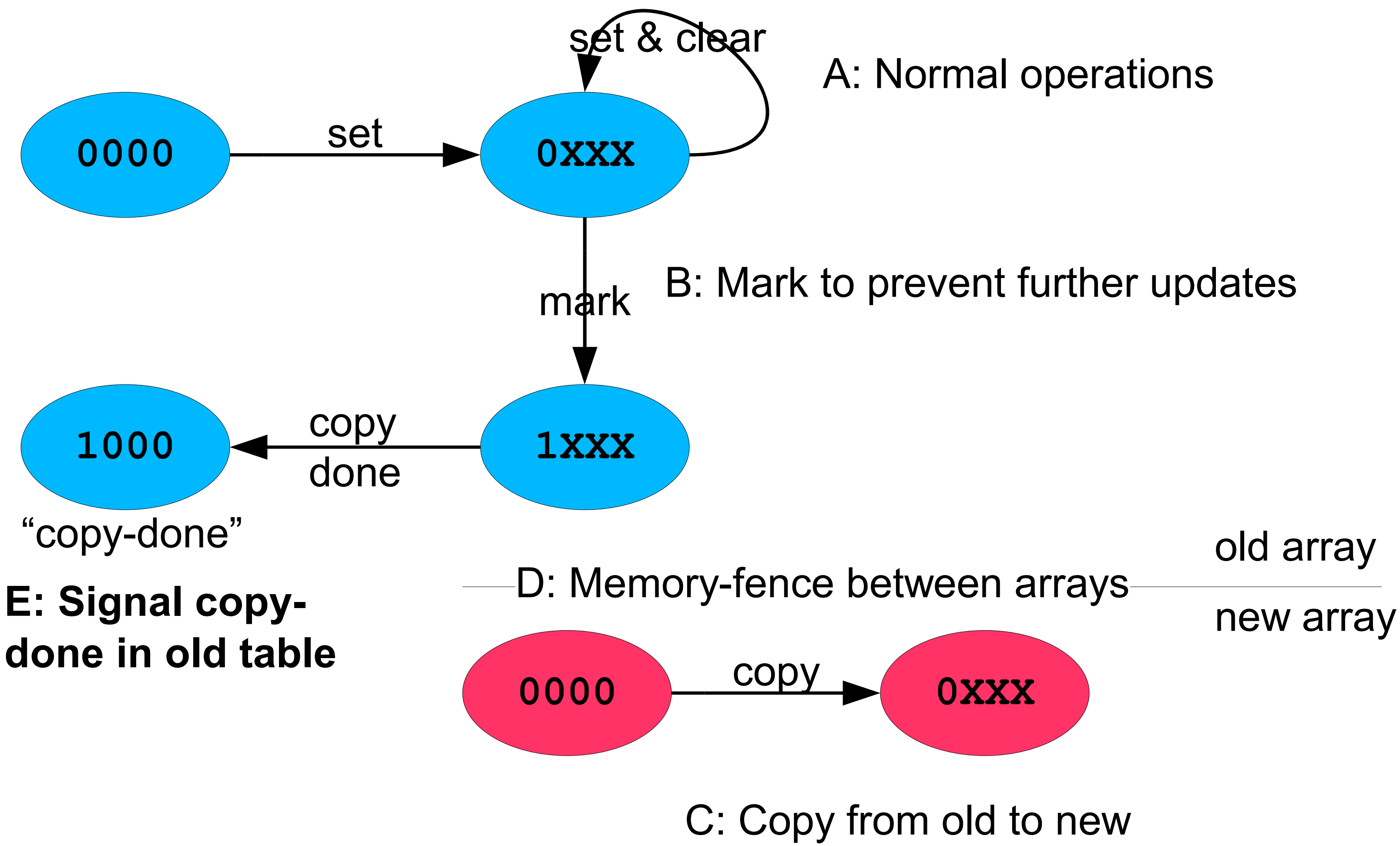

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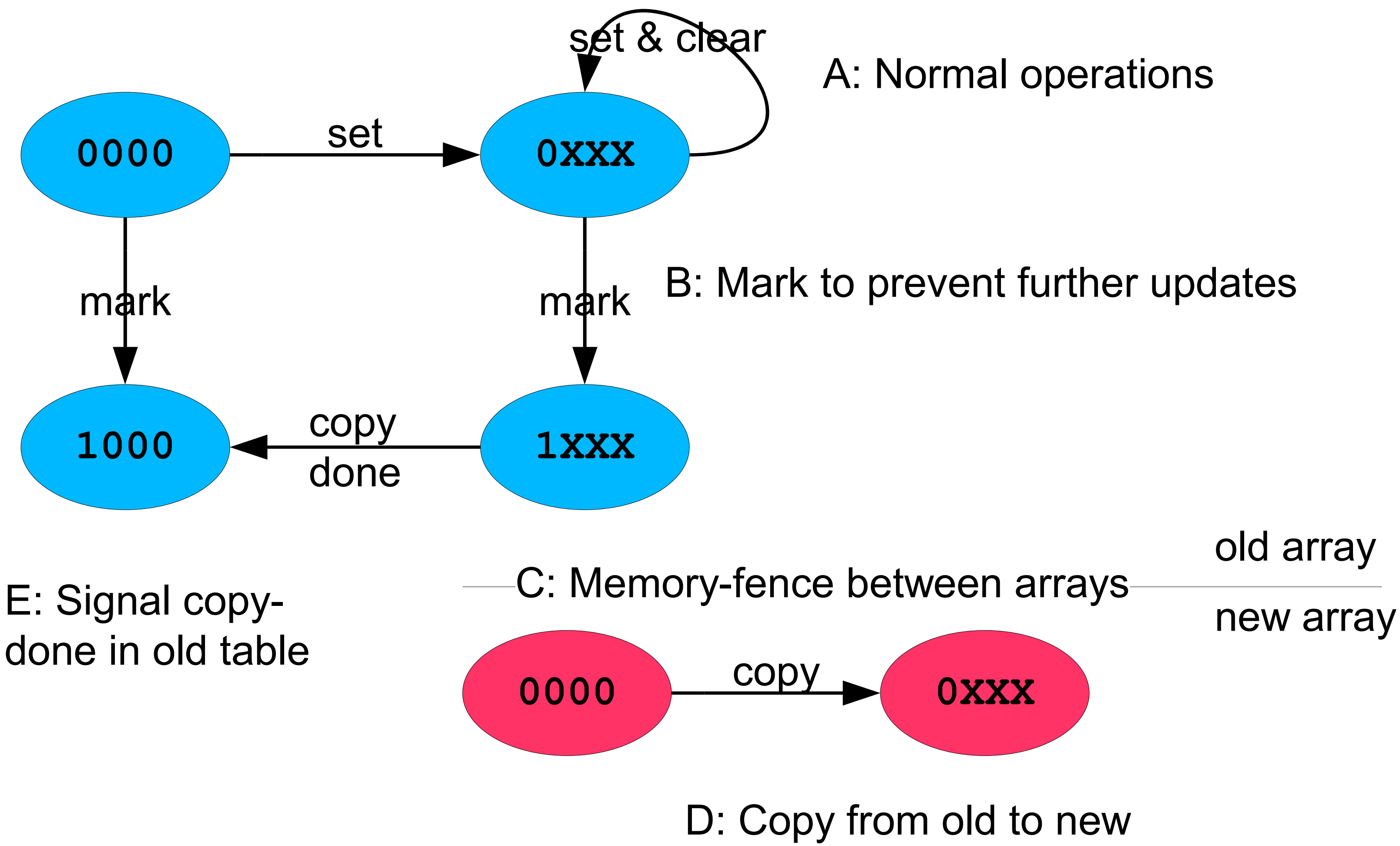

Resize - motivation

- Triggered by adding larger element
- **Copy** each word before get/put
- Pay indirection even after **copy**
  - Visit old table, fence, operate on new table
- So need to **copy** all words eventually, and then
- **Promote**: make new array **the** top-level array
  - No more indirection
- **Policy**? How to copy all words?
  - Visiting threads can “copy some words”
  - Or background threads copy, or only-writers, etc
  - Good standard engineering, nothing special

Resize – Copy Mechanics

- Helper: any thread copying words it does not directly need
- Helpers CAS-up a "promise to copy" counter
  - Atomic-increment by fixed N (e.g. 16 words)
- Helpers **copy** words via State Machine
- Helpers atomic-increment "done work" counter
  - On transition to "copy-done" state
- Promote new Array when "done work" == A.length
- What If: Helper stalled? (promises but never copies)
  - Allow helpers to "double-promise"!
  - Worst case: each thread can complete entire copy
- Eventually, copy completes & array promotes

Coding Style Elements

- Large array for parallel read & update
  - No JMM issues for read or update (no lock, no volatile)
- State Machine per-array-word
  - Successful CAS is FSM transition
  - Failed CAS causes retry
    - (but another thread made progress)
- 'Mark' payload words to stop 'late updates'
- Array copy for Resize
  - Copy is parallel, incremental, concurrent
  - Copy part of State Machine
  - Unrelated threads can make progress during resize
  - Fence between old and new tables

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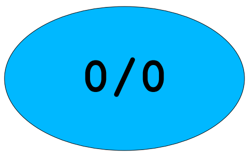
Example 2: HashTable

- Array of K/V Pairs
  - Keys in even slots, Values odd slots
  - CAS each word separately, but FSM spans both words
  - Value can also be 'Tombstone'
  - Key & Value both start as **null**
- Mark payload by 'boxing' values
- Copy on resize, or to flush stale keys
- Supports concurrent insert, remove, test, resize
- Linear scaling on Azul to 768 CPUs
  - More than billion reads/sec simultaneous with
  - More than 10million updates/sec
- Code up in SourceForge, high-scale-lib
  - Passes Java Compatibility Kit (JCK) for ConcurrentHashMap

"Uninteresting" Details

- Good, standard engineering – nothing special
- Closed Power-of-2 Hash Table
  - Reprobe on collision
  - Stride-1 reprobe: better cache behavior
  - (complicated argument about 2^n vs prime goes here)
- 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

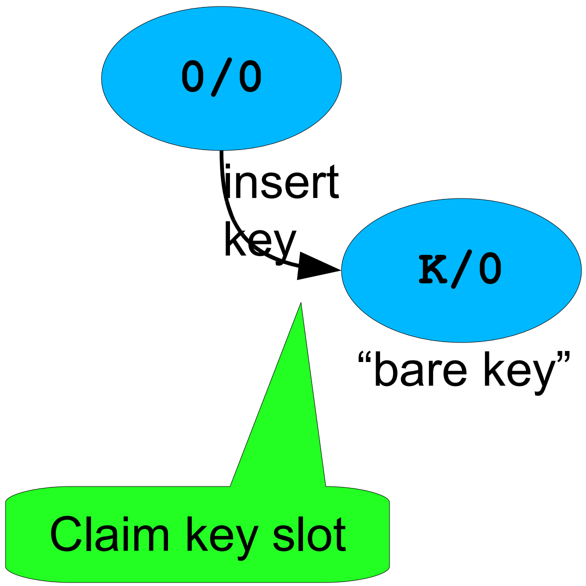
HashTable State Machine



“initial”

- Inserting K/V pair
- Already probed table, missed
- Found proper empty K/V slot
- Ready to claim slot for this Key

HashTable State Machine



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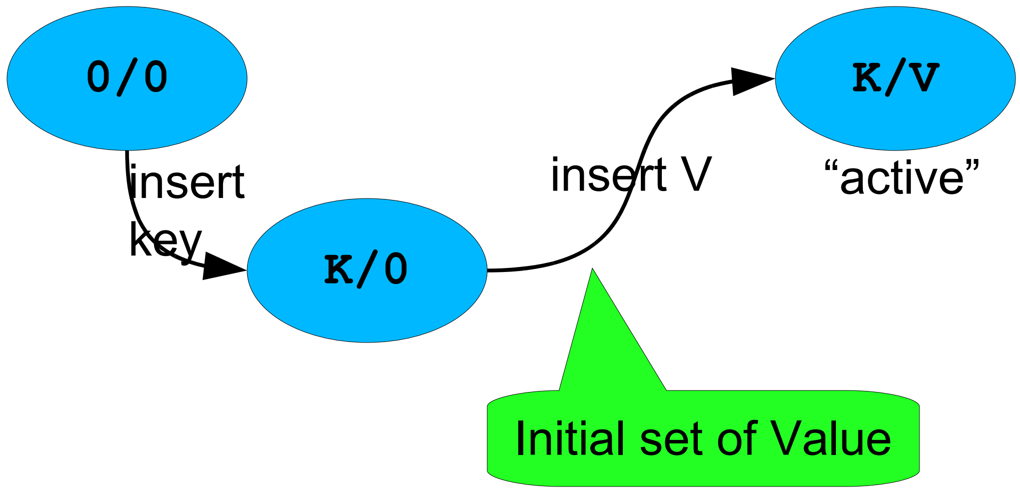

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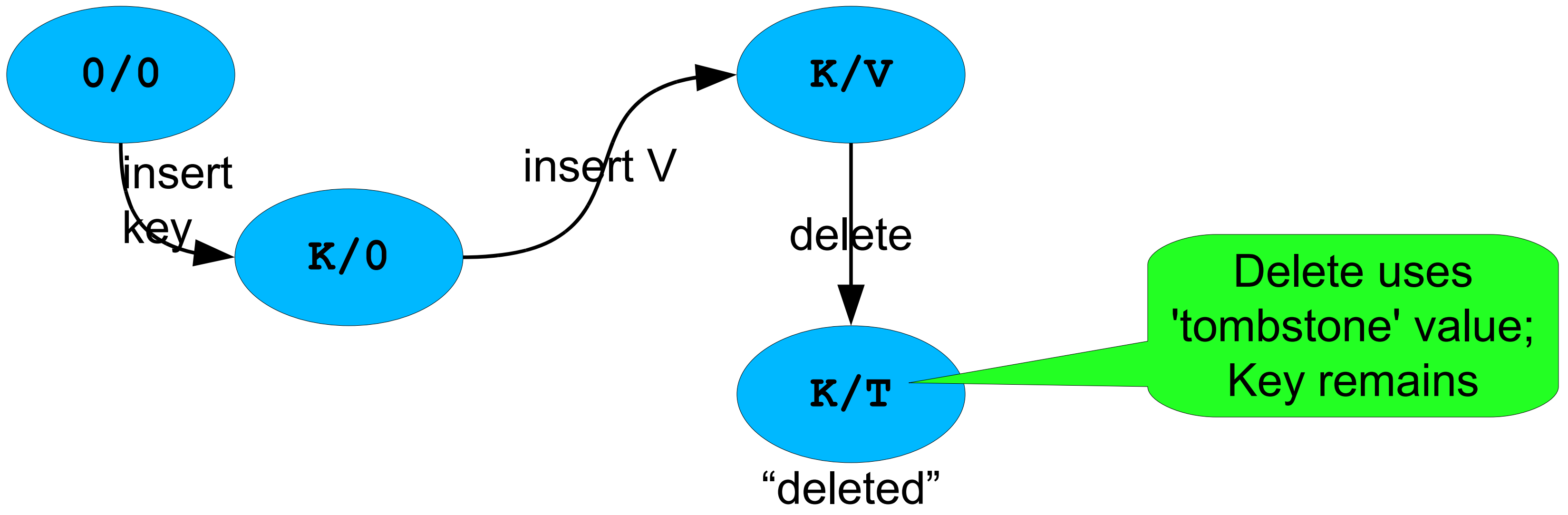

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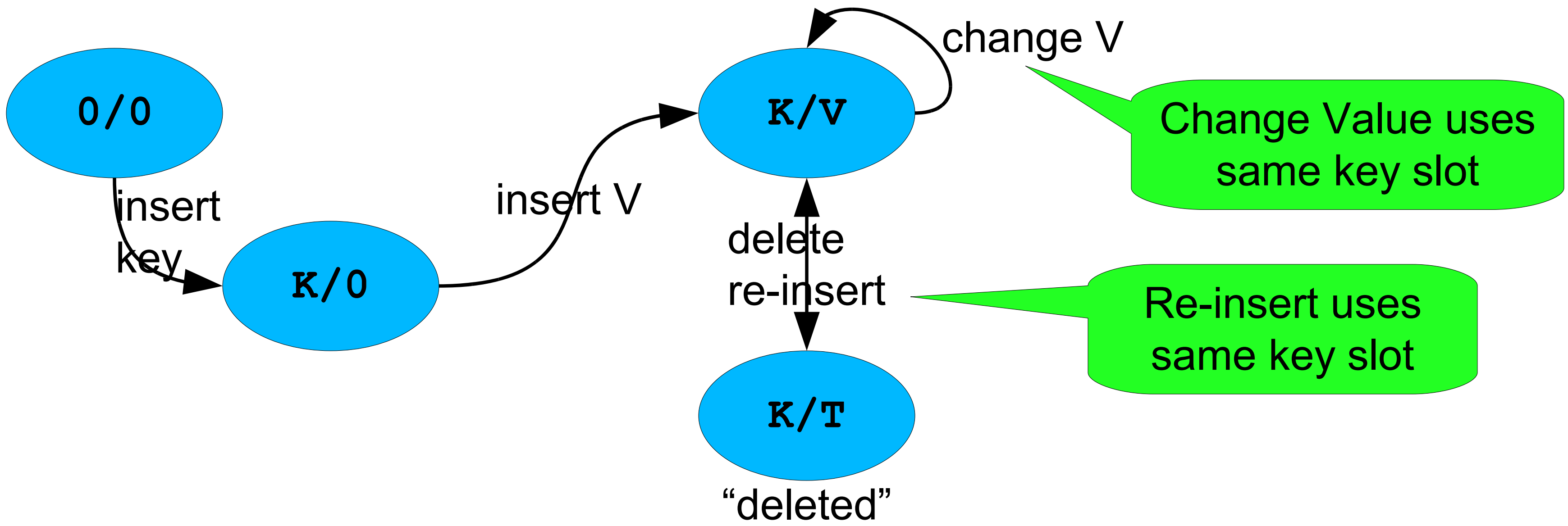

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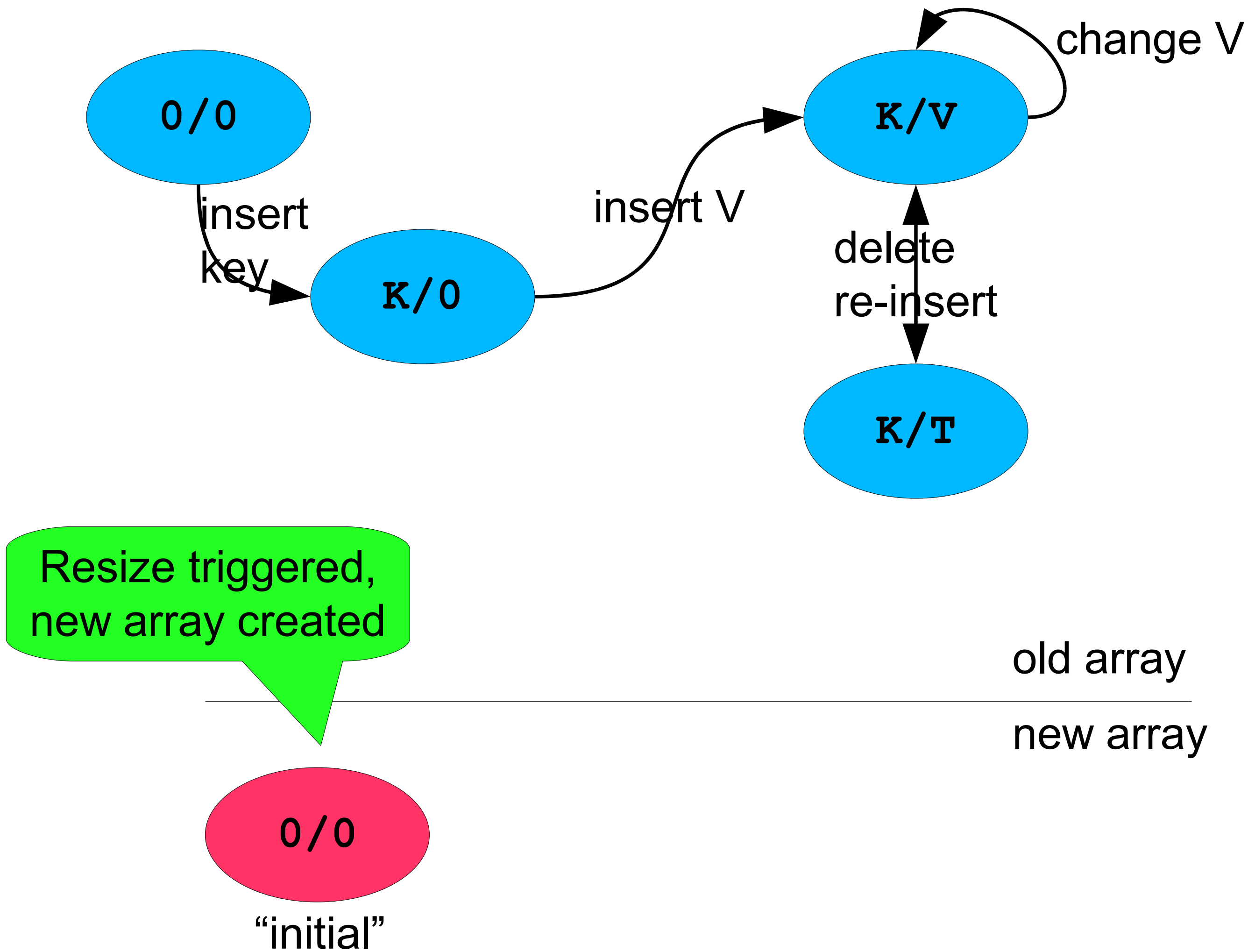

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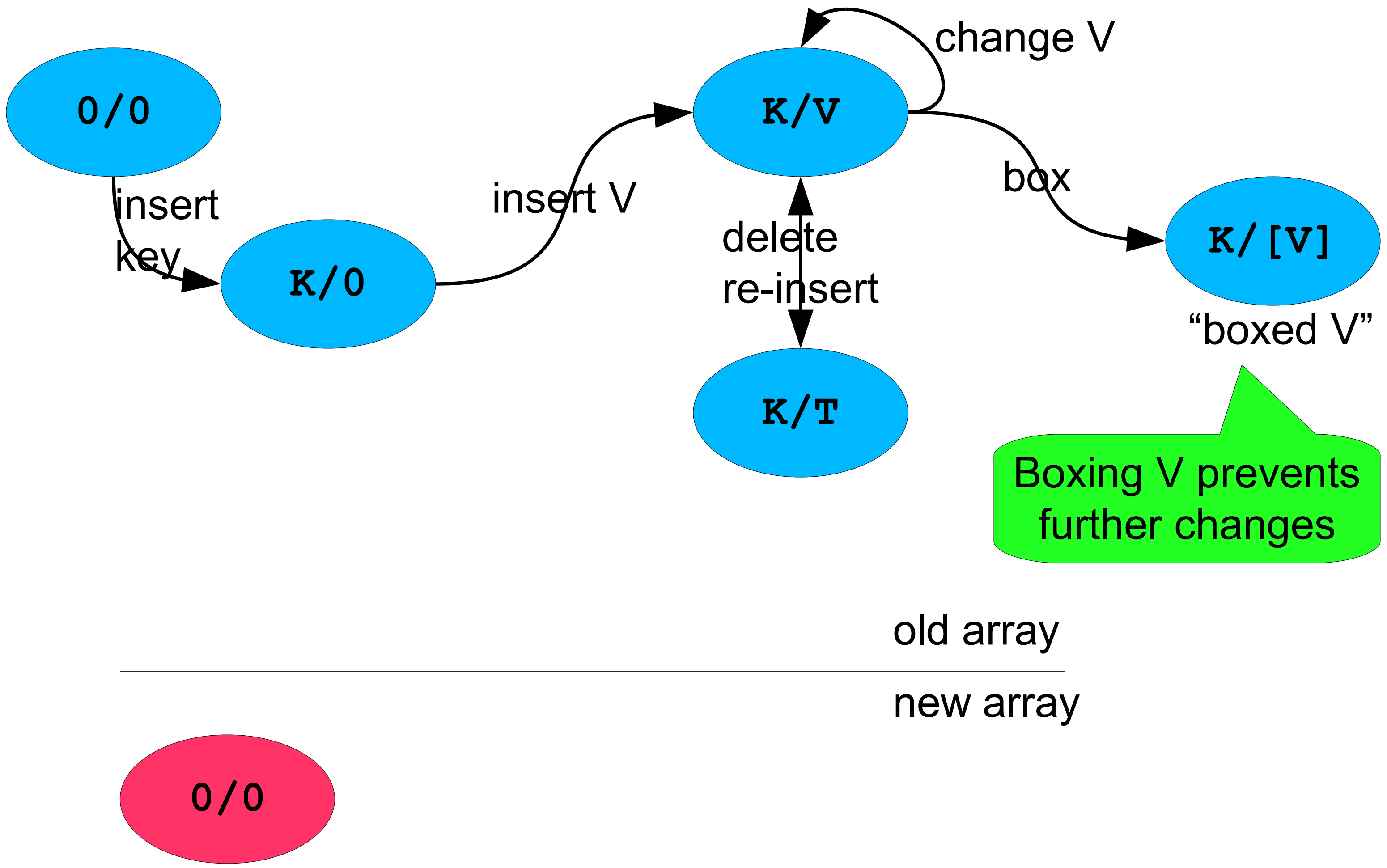

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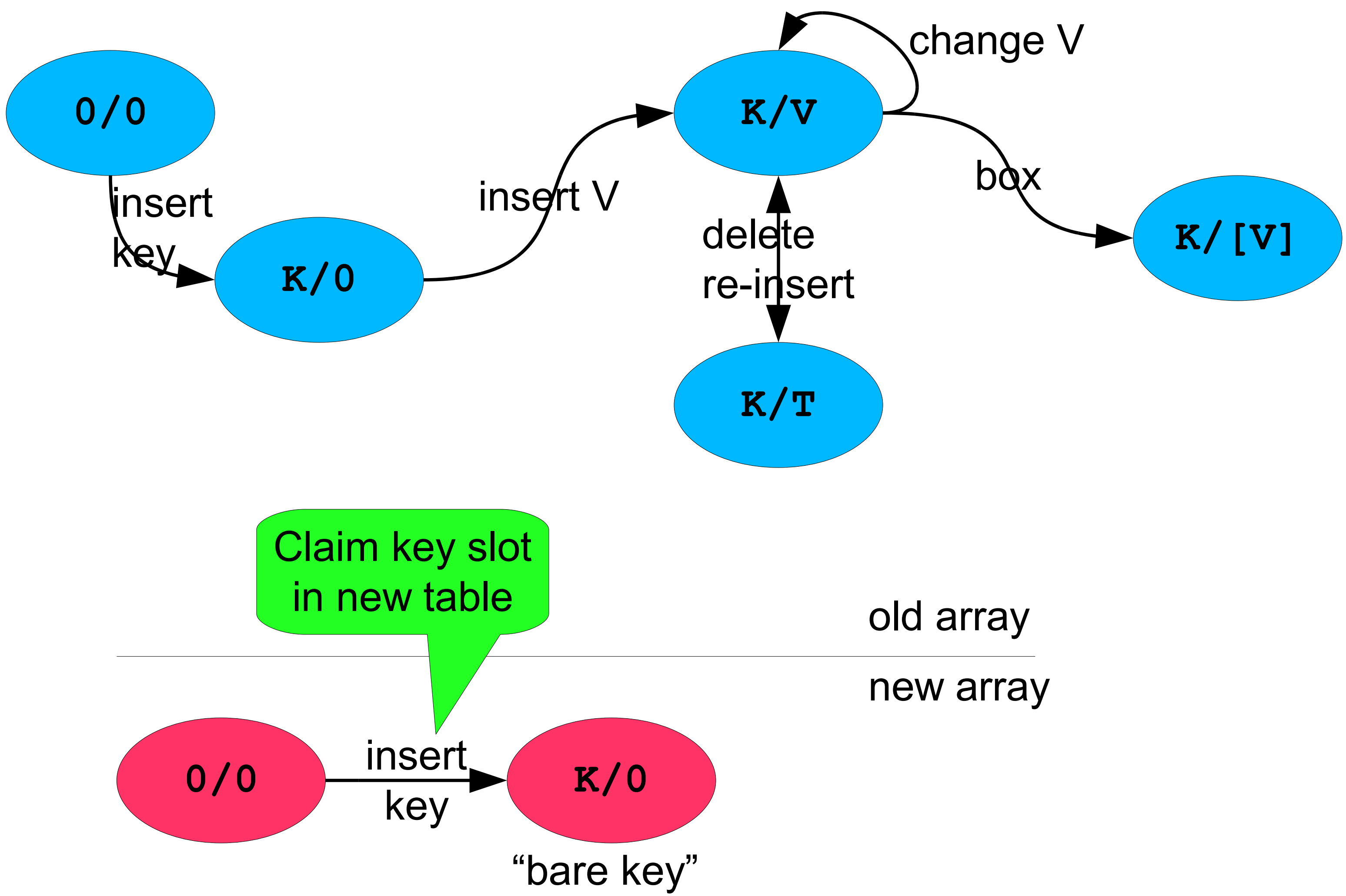

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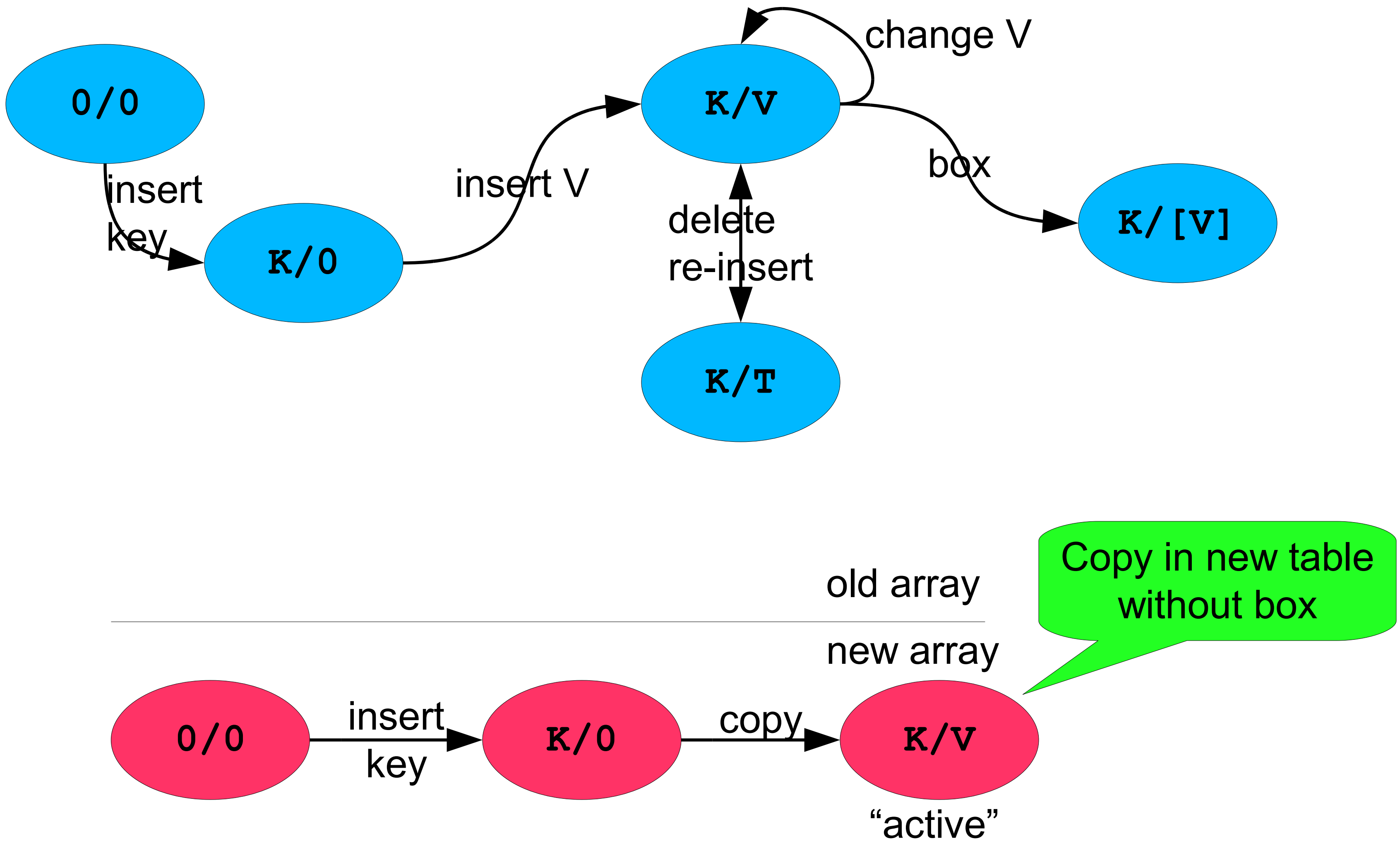

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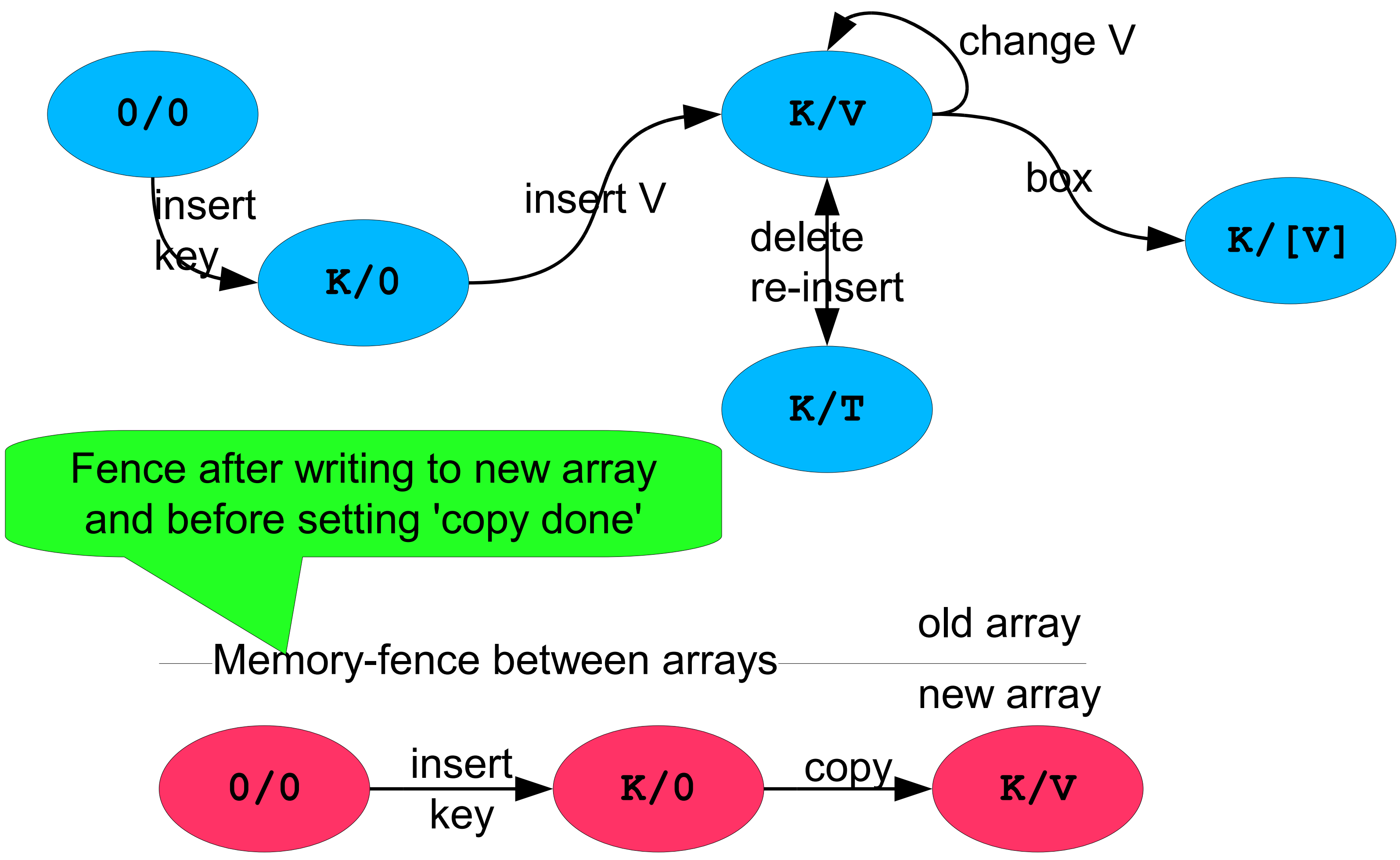

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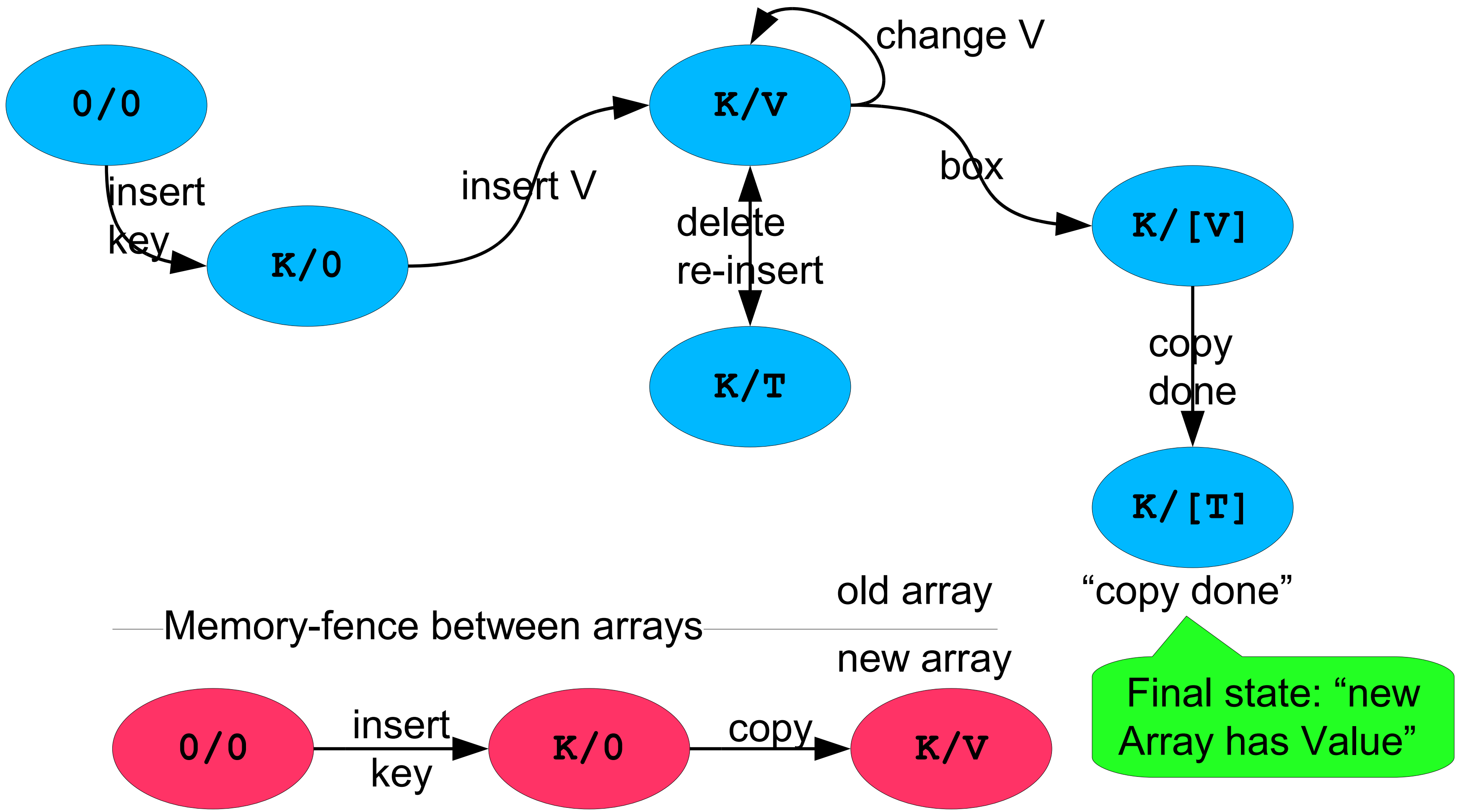

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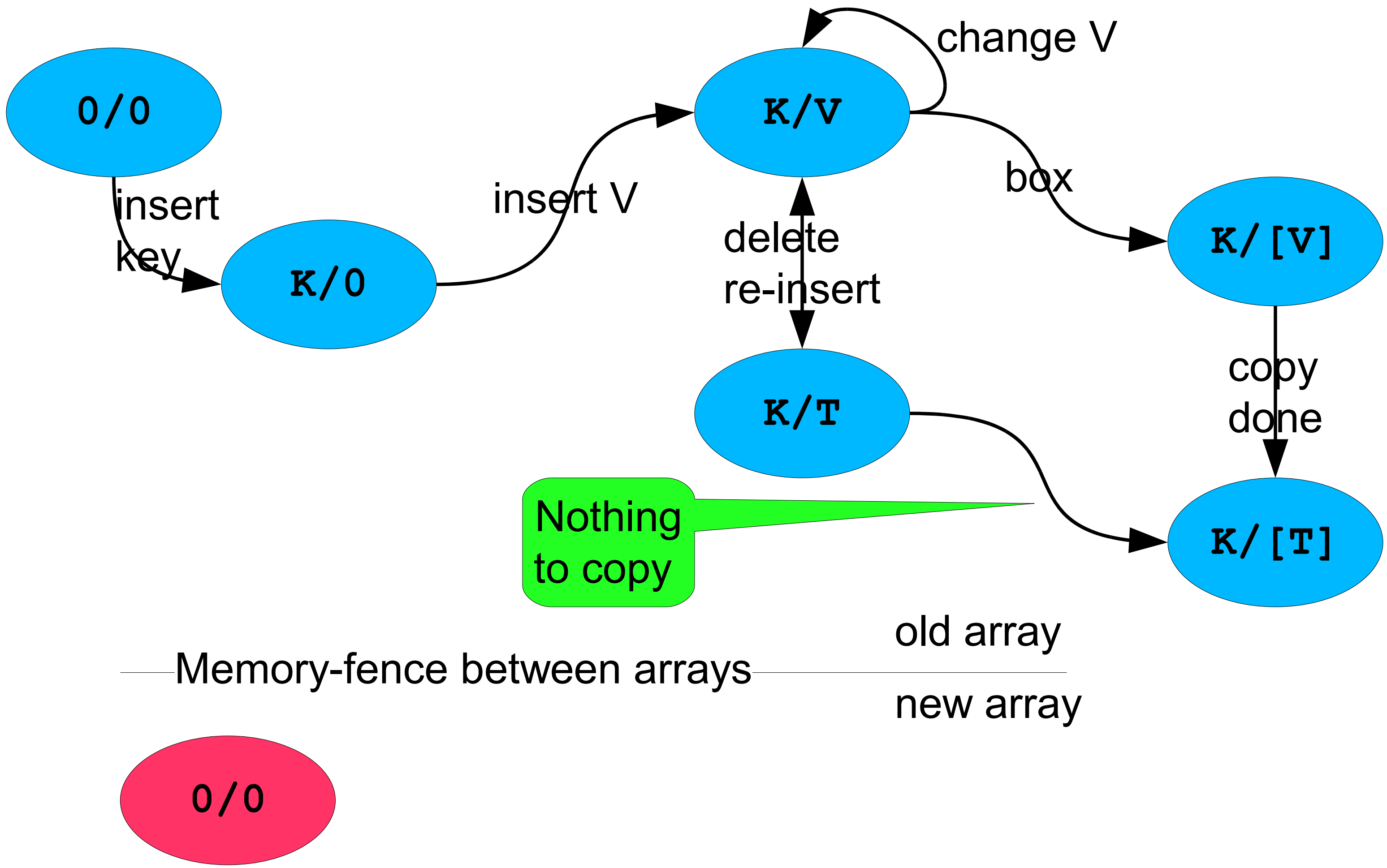

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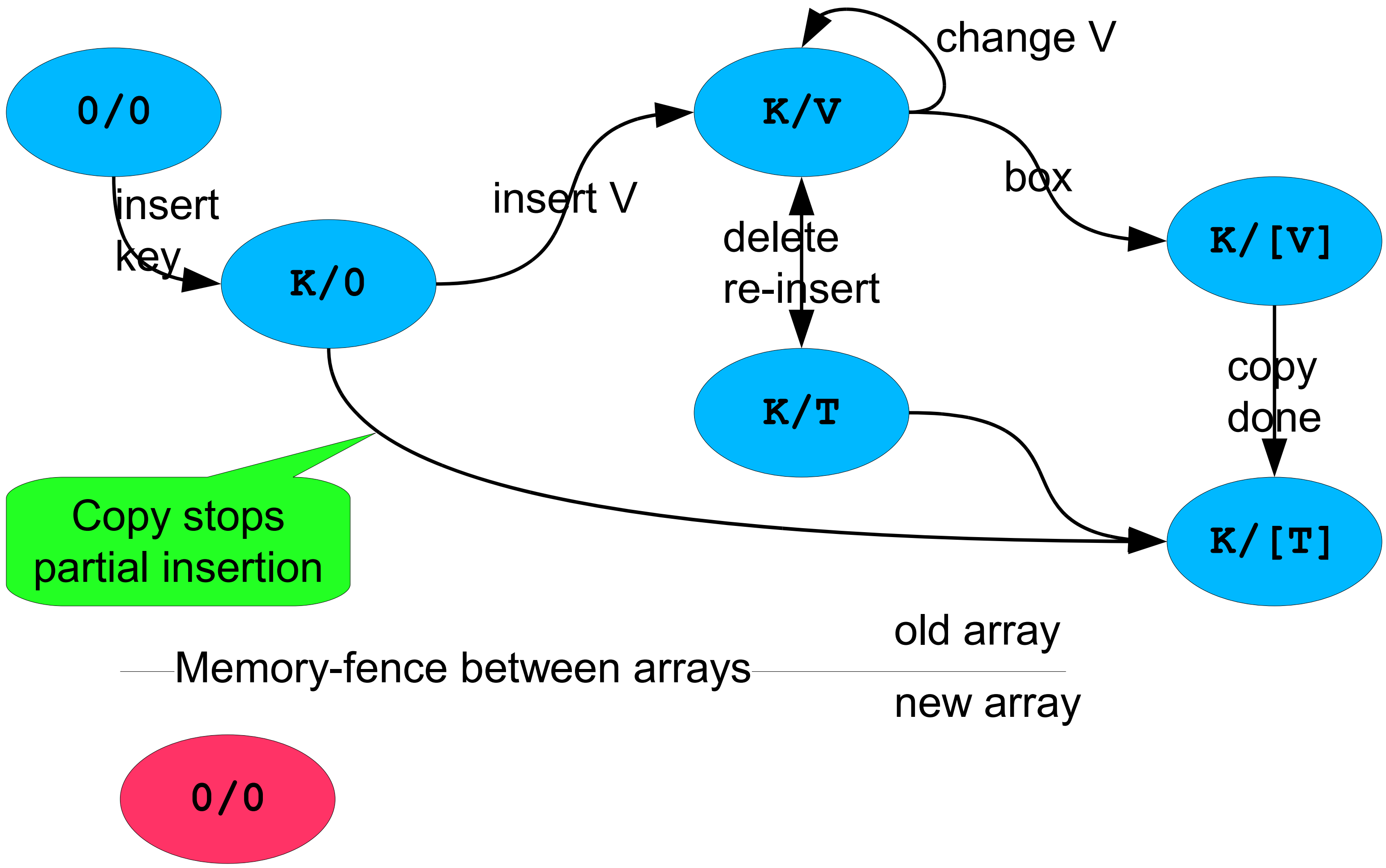

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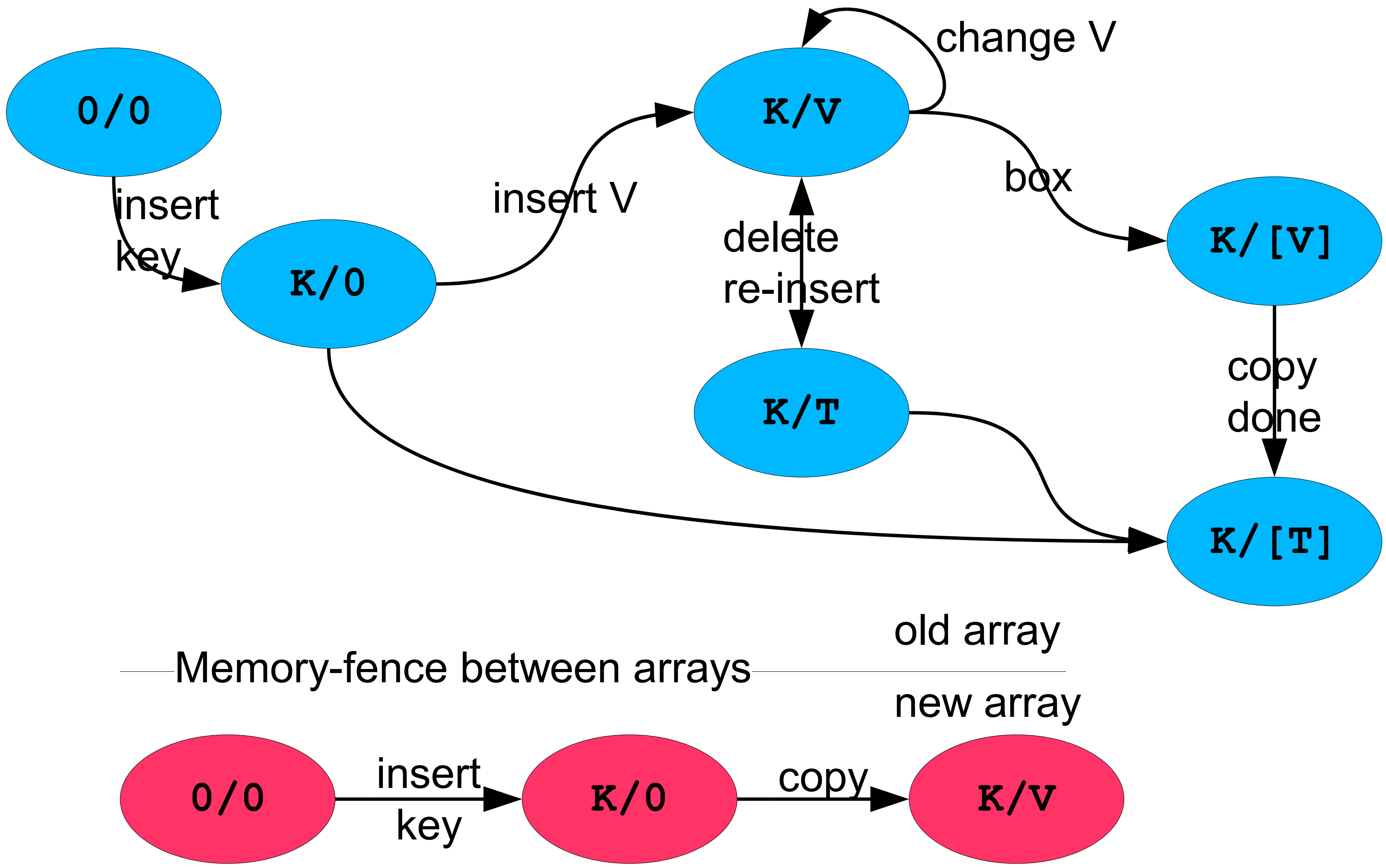

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Example 3: Nearly FIFO Queue

- Concurrent near-FIFO Queue
  - e.g. producer / consumer worklist
  - Producers & consumers are large thread pools
- Scaling bottleneck:
  - Locking or single word CAS on push & pop
- Could stripe Queue:
  - Many short Queues
  - Select random Queue
  - Many different locks or many different words to CAS
    - Less contention
  - Pick at random to push or pop
  - Must search all queues for not-full or not-empty

Example 3: Nearly FIFO Queue

- 1000's of CPUs need 1000's of Queues
  - Stripe Ad-Absurdum
  - Queues get ever-smaller
  - Get down to Queues of 1 entry
- Single-entry Queue: either full or empty
  - Implement as a single word
  - Either **null** or value
- Need 1000's of single-entry Queues
  - Array of single word Queues
- Producers start @ random index
  - Search for **null**, CAS down value
- Consumers start @ random index
  - Search for value, CAS down **null**

Example 3: Nearly FIFO Queue

- Nearly FIFO:
  - Consumers *must* advance scan point
  - Or might neglect tasks left in other slots
  - Means every value in array gets visited eventually
- Tricky bit: correct array size for efficiency
  - Too small, table gets full, producers spin uselessly
  - Too large, table is mostly empty, consumers scan uselessly
- Array copy & promote is easier:
  - Risk: late insert in old array just prior to promote abandons value
  - Consumers fill old array with 'tombstone'
  - Promote when old array is entire 'stoned
- Still need feedback mechanisms on P/C threadpools

Example 3: Nearly FIFO Queue

- Work in progress, no code yet...
- But out of time anyways ;-)
- Nice idea, hope it pans out

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Summary

- Lock-Free
- Highly scalable (proven scalable to ~1000 CPUs)
- Use large array for data
  - Allows fast parallel-read
  - Allows parallel, incremental, concurrent copy
- Use Finite State Machine to control writes
  - FSM-per-word
  - Successful CAS advances FSM
  - Failed CAS retries
- During copy, FSM includes words from both arrays

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THANK YOU

Dr. Cliff Click, Distinguished Engineer

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