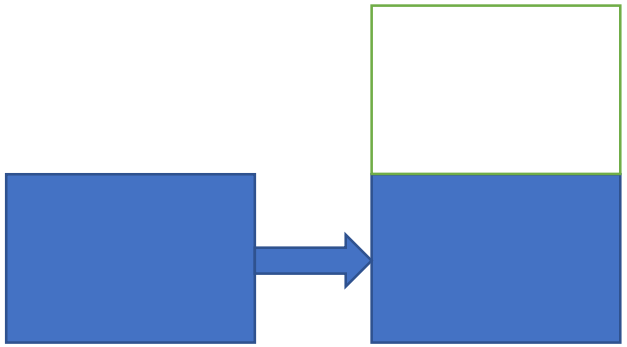
RCUArray: An RCU-like Parallel-Safe Distributed Resizable Array

By Louis Jenkins

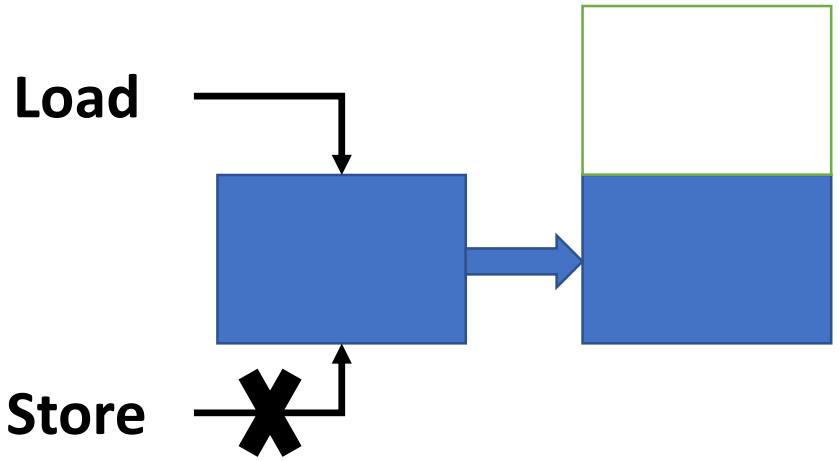
The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage



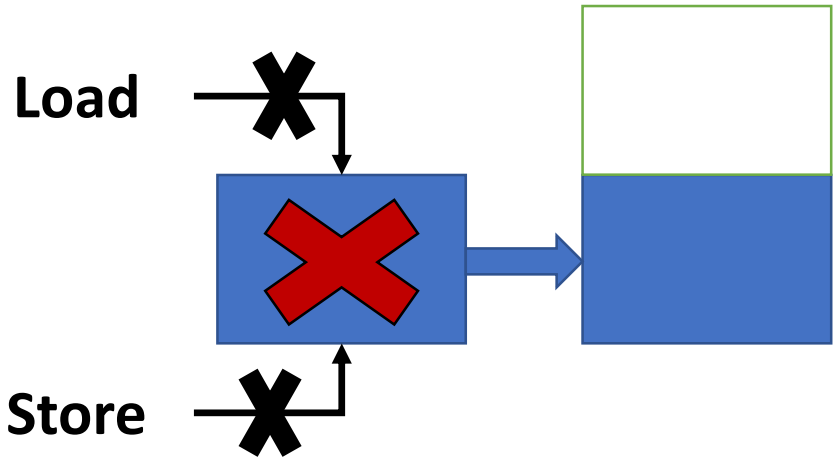
The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely



The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior



The Problem
Parallel-Safe Resizing

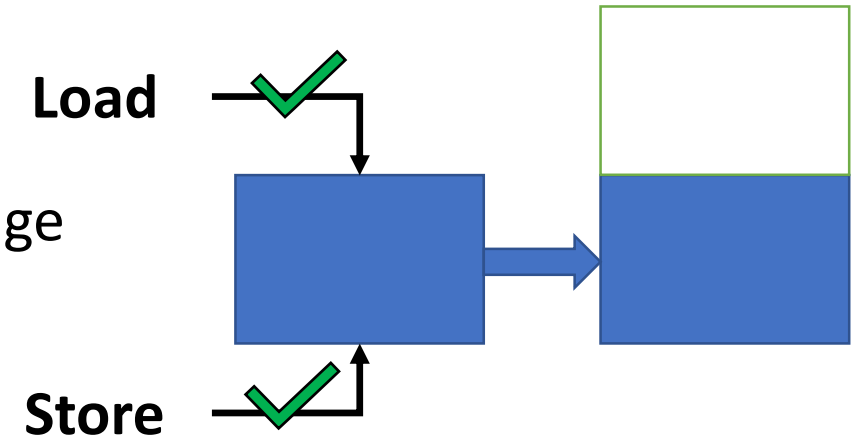
- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior
- Why not just synchronize access?
  - Not scalable

The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior
- Why not just synchronize access?
  - Not scalable
- What do we need?

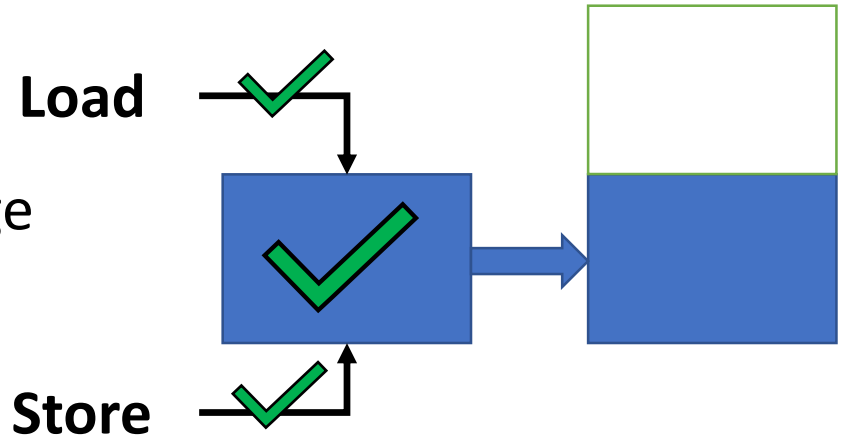
The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior
- Why not just synchronize access?
  - Not scalable
- What do we need?
  1. Allow concurrent access to both smaller and larger storage



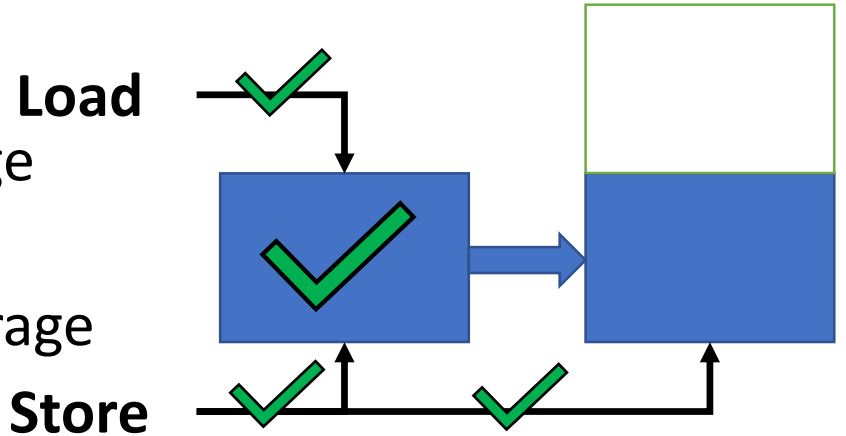
The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior
- Why not just synchronize access?
  - Not scalable
- What do we need?
  1. Allow concurrent access to both smaller and larger storage
  2. Ensure safe memory management of smaller storage



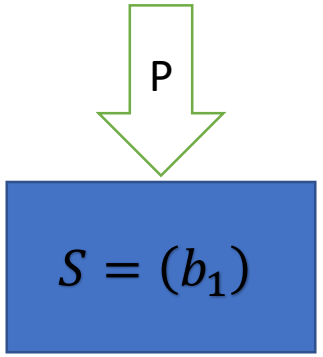
The Problem
Parallel-Safe Resizing

- Not inherently thread-safe to access memory while it is being resized
  - Memory has to be ‘moved’ from the smaller storage into larger storage
  - Concurrent loads and stores can result in undefined behavior
    - Stores after memory is moved can be lost entirely
    - Loads and Stores after the smaller storage is reclaimed can produce undefined behavior
- Why not just synchronize access?
  - Not scalable
- What do we need?
  1. Allow concurrent access to both smaller and larger storage
  2. Ensure safe memory management of smaller storage
  3. Ensure that stores to old memory are visible in larger storage



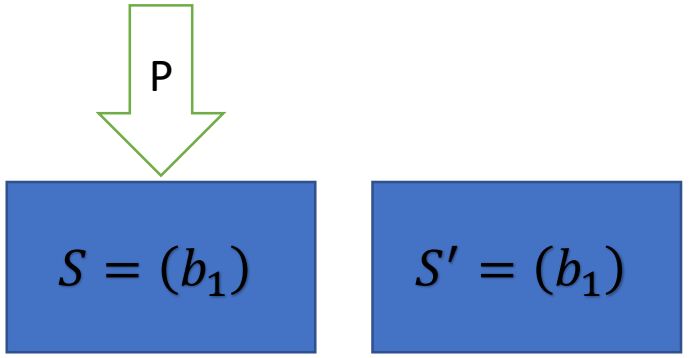
Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s



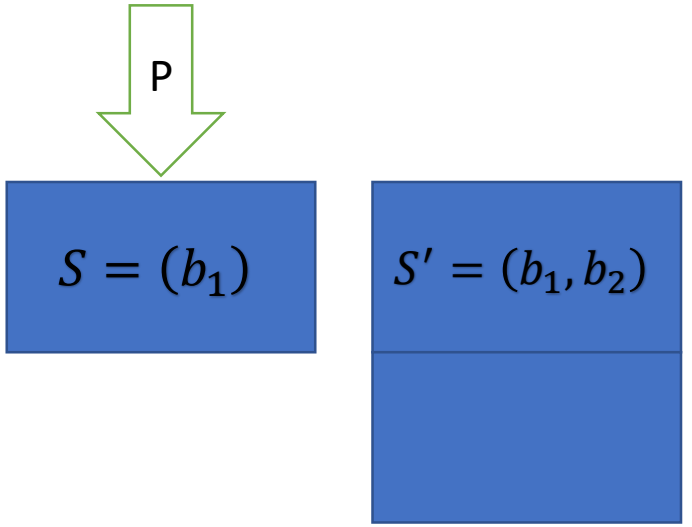
Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'



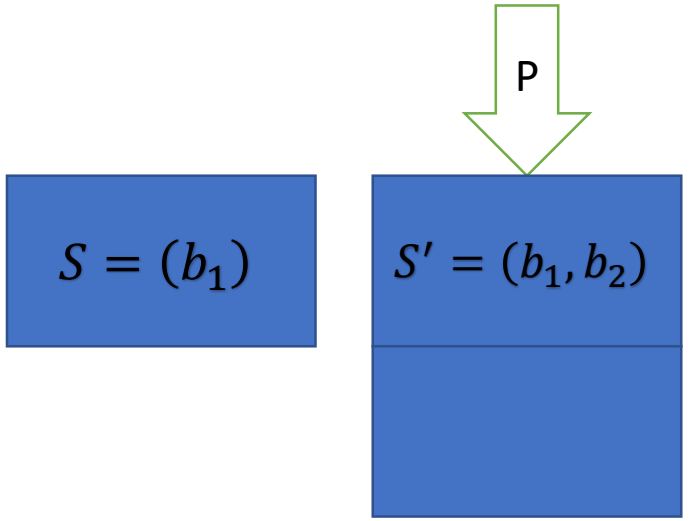
Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s'…



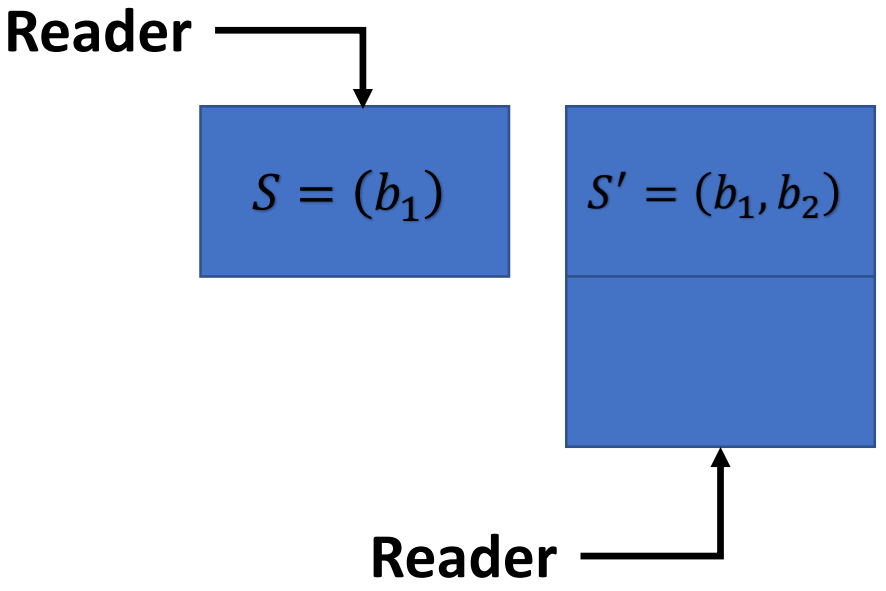
Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s', s' becomes new current snapshot



Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s', s' becomes new current snapshot
- Not always applicable in all situations
  - Must be safe to access *at least* two different snapshots of the same data



Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s', s' becomes new current snapshot
- Not always applicable in all situations
  - Must be safe to access *at least* two different snapshots of the same data

Read-Copy-Update

- Readers Concurrent with Readers

Reader-Writer Locks

- Readers Concurrent With Readers

Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s', s' becomes new current snapshot
- Not always applicable in all situations
  - Must be safe to access *at least* two different snapshots of the same data

Read-Copy-Update	**Reader-Writer Locks**
• Readers Concurrent with Readers	• Readers Concurrent With Readers
• Writers Mutually Exclusive with Writers	• Writers Mutually Exclusive with Writers

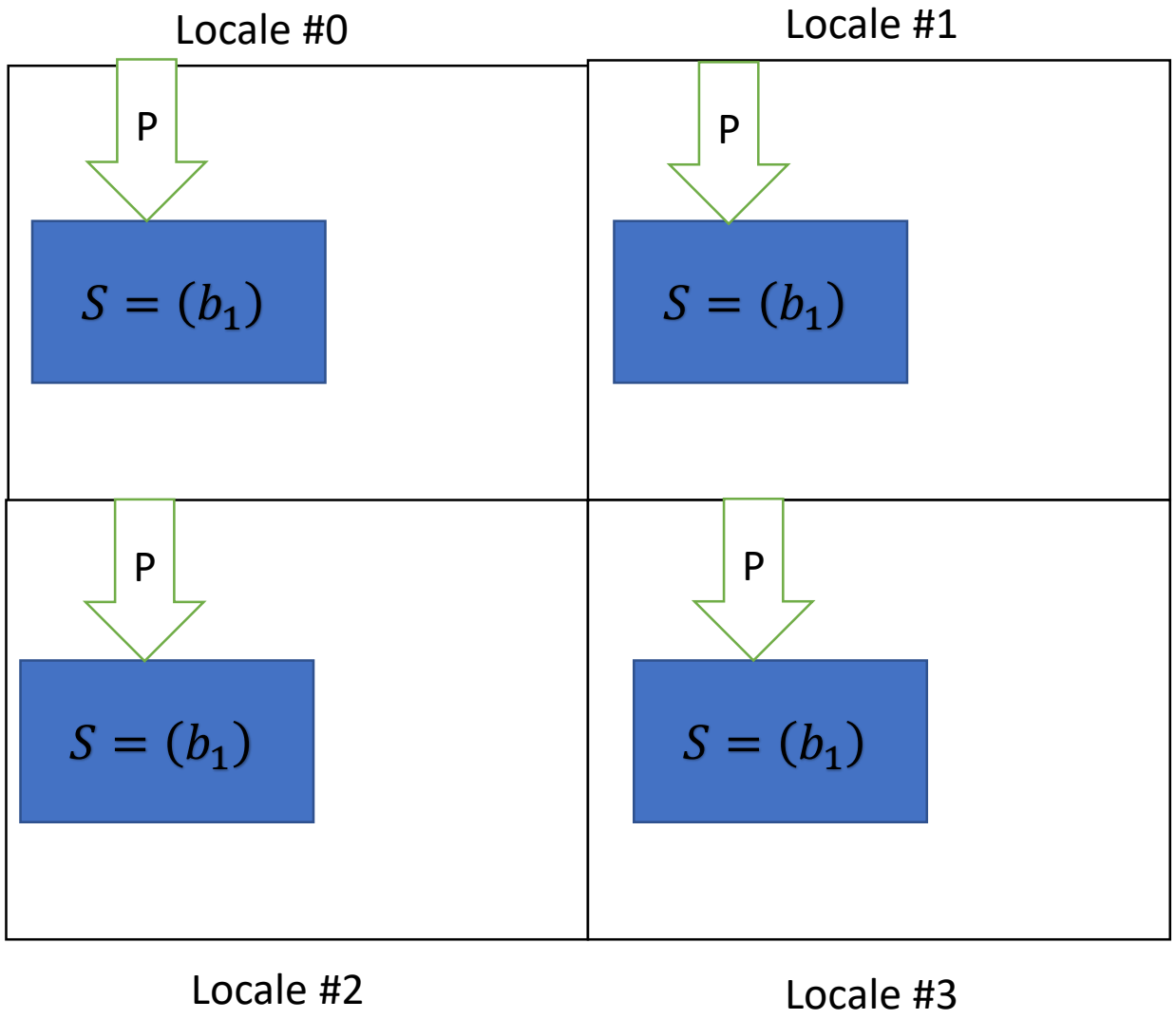
Read-Copy-Update (RCU)

- Synchronization strategy that favors performance of readers over writers
  - **Read** the current snapshot s
  - **Copy** s to create s'
  - **Update** applied to s', s' becomes new current snapshot
- Not always applicable in all situations
  - Must be safe to access *at least* two different snapshots of the same data

Read-Copy-Update	**Reader-Writer Locks**
• Readers Concurrent with Readers	• Readers Concurrent With Readers
• Writers Mutually Exclusive with Writers	• Writers Mutually Exclusive with Writers
• Readers Concurrent with Writers	• Readers Mutually Exclusive with Writers

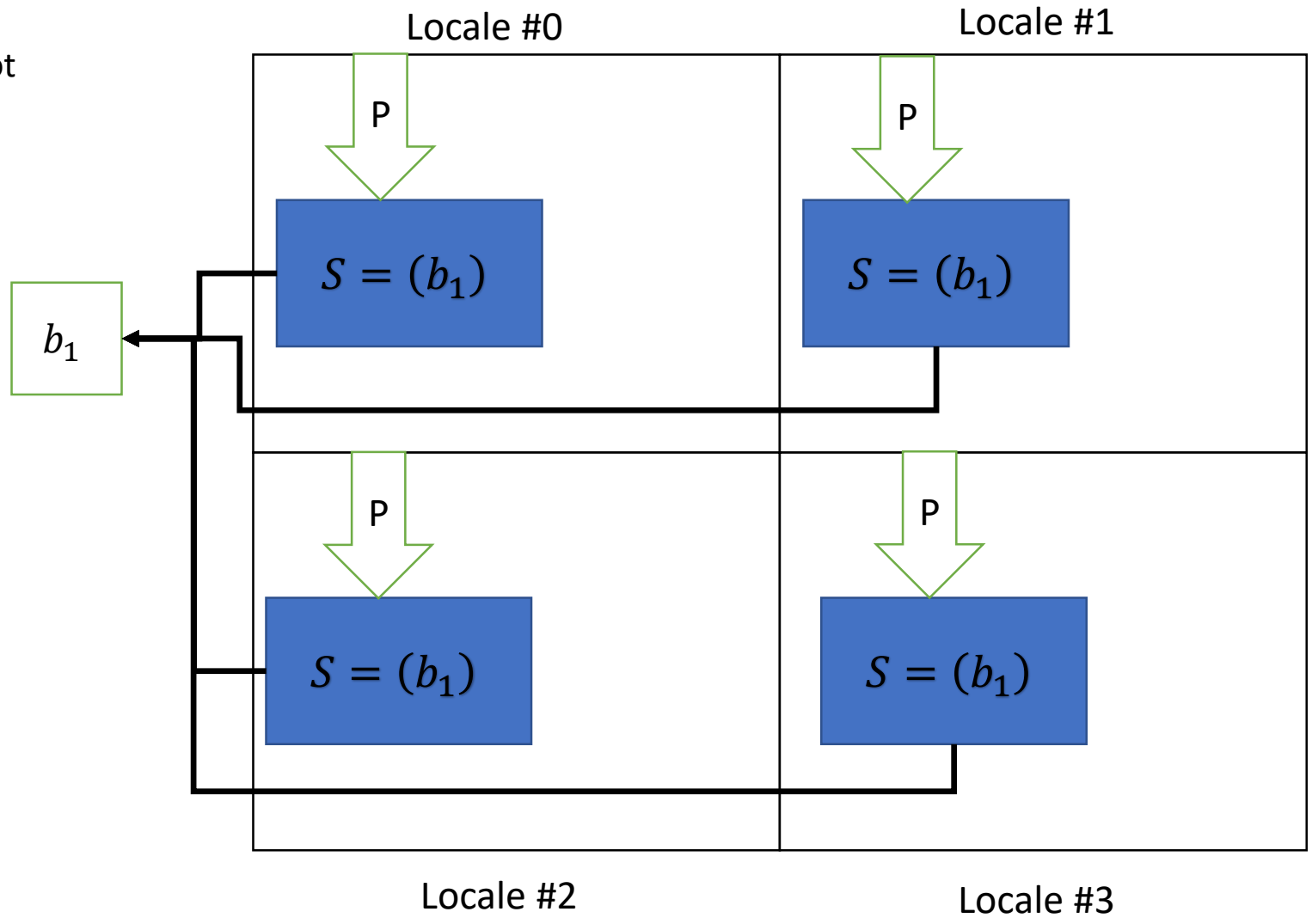
Distributed RCU

- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot



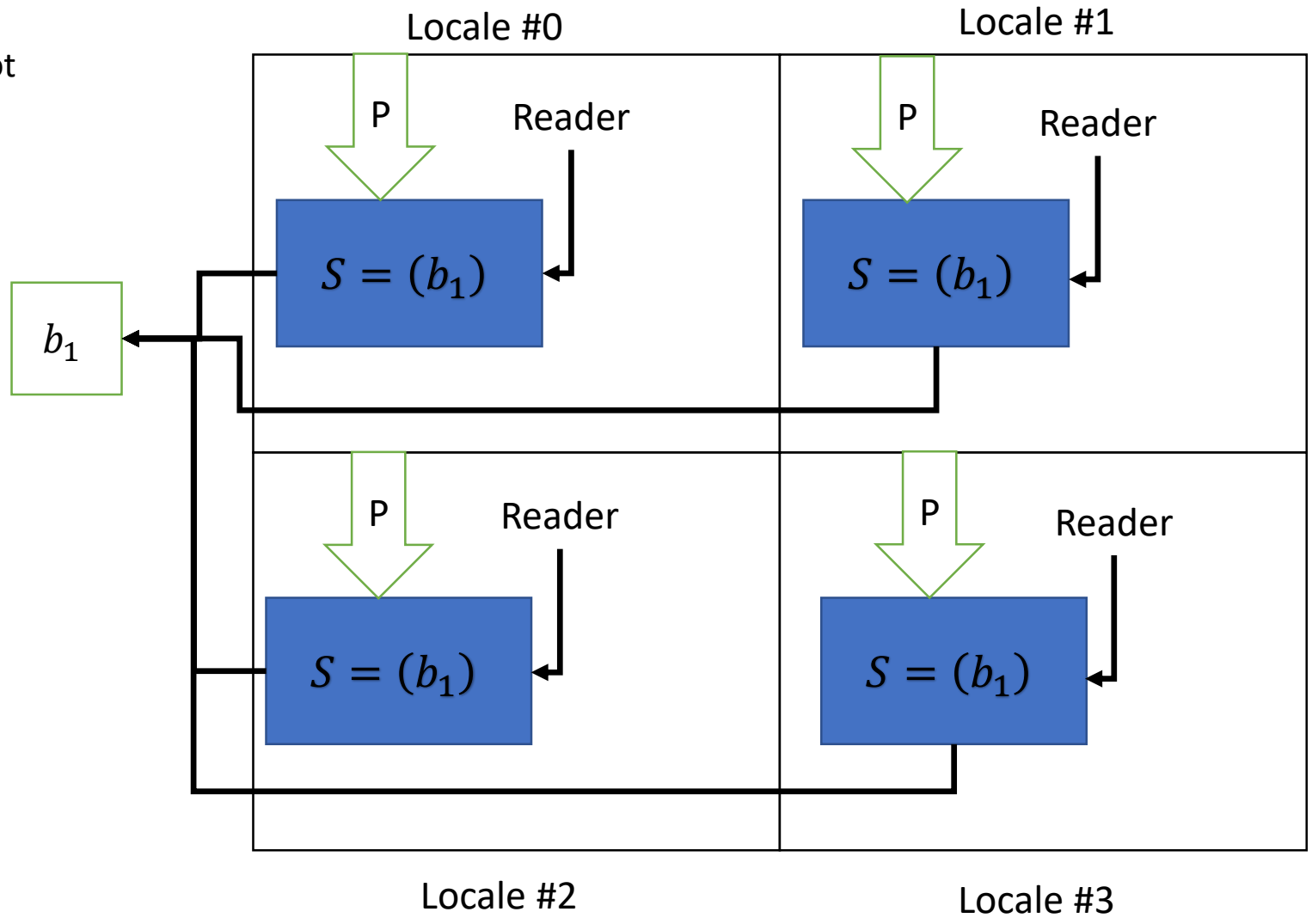
Distributed RCU

- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot
  - All local snapshots point to the same block



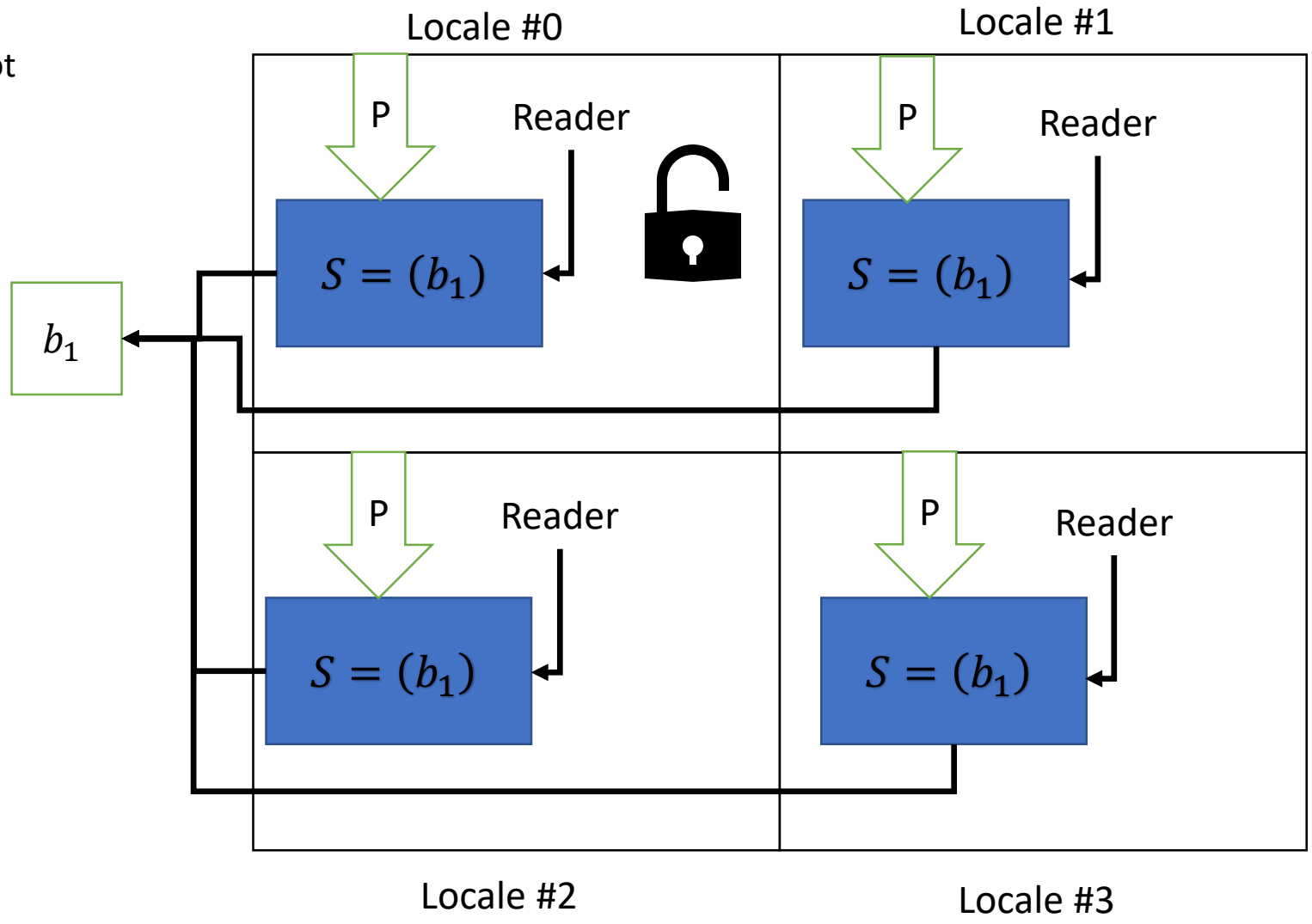
Distributed RCU

- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot
  - All local snapshots point to the same block
- Reader Concurrency
  - Readers will read from local snapshot only
  - All readers regardless of node will see same block
  - All stores to b_1 are seen by any snapshot or node



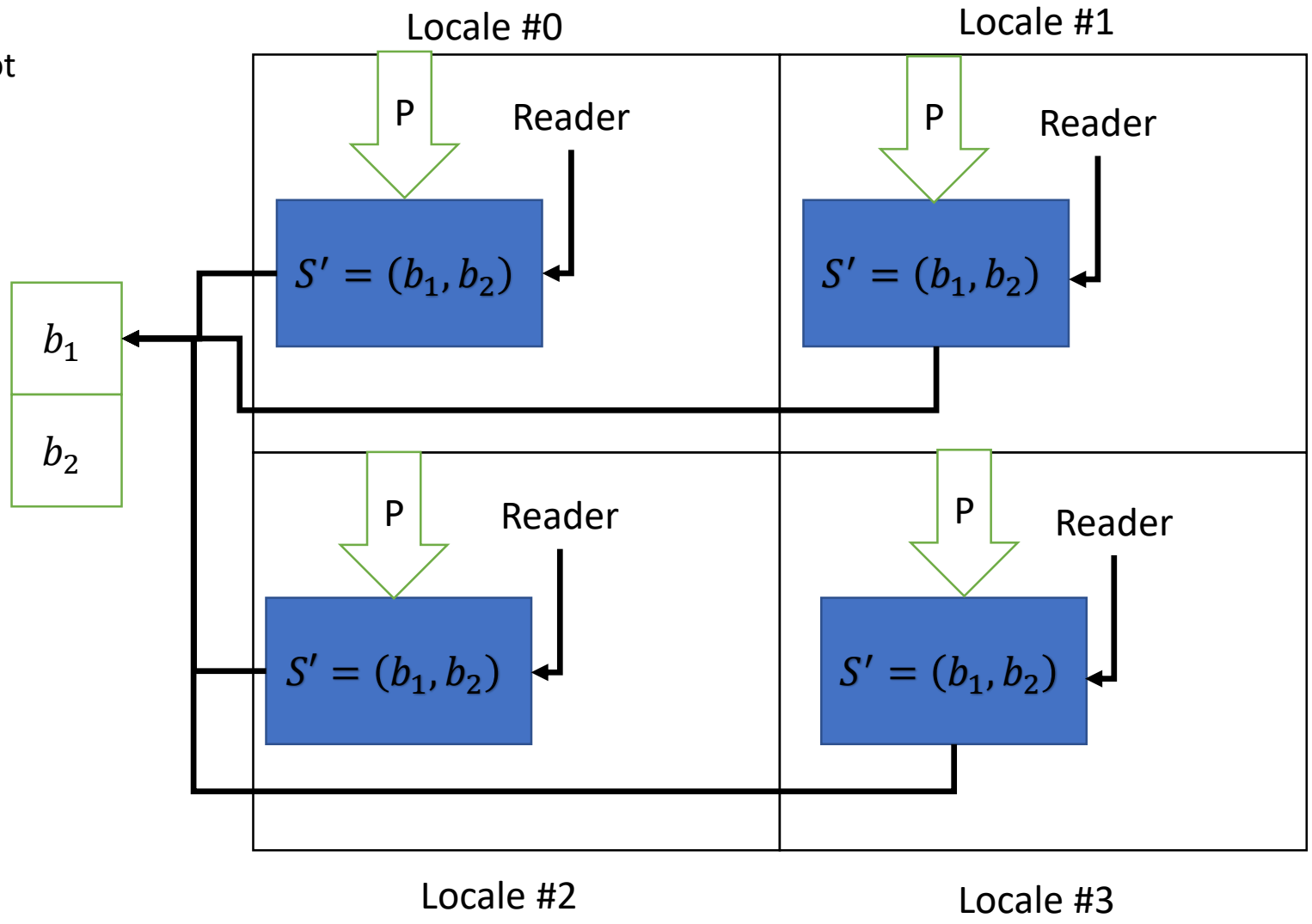
Distributed RCU

- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot
  - All local snapshots point to the same block
- Reader Concurrency
  - Readers will read from local snapshot only
  - All readers regardless of node will see same block
  - All stores to b_1 are seen by any snapshot or node
- Writer Mutual Exclusion
  - Use a distributed lock



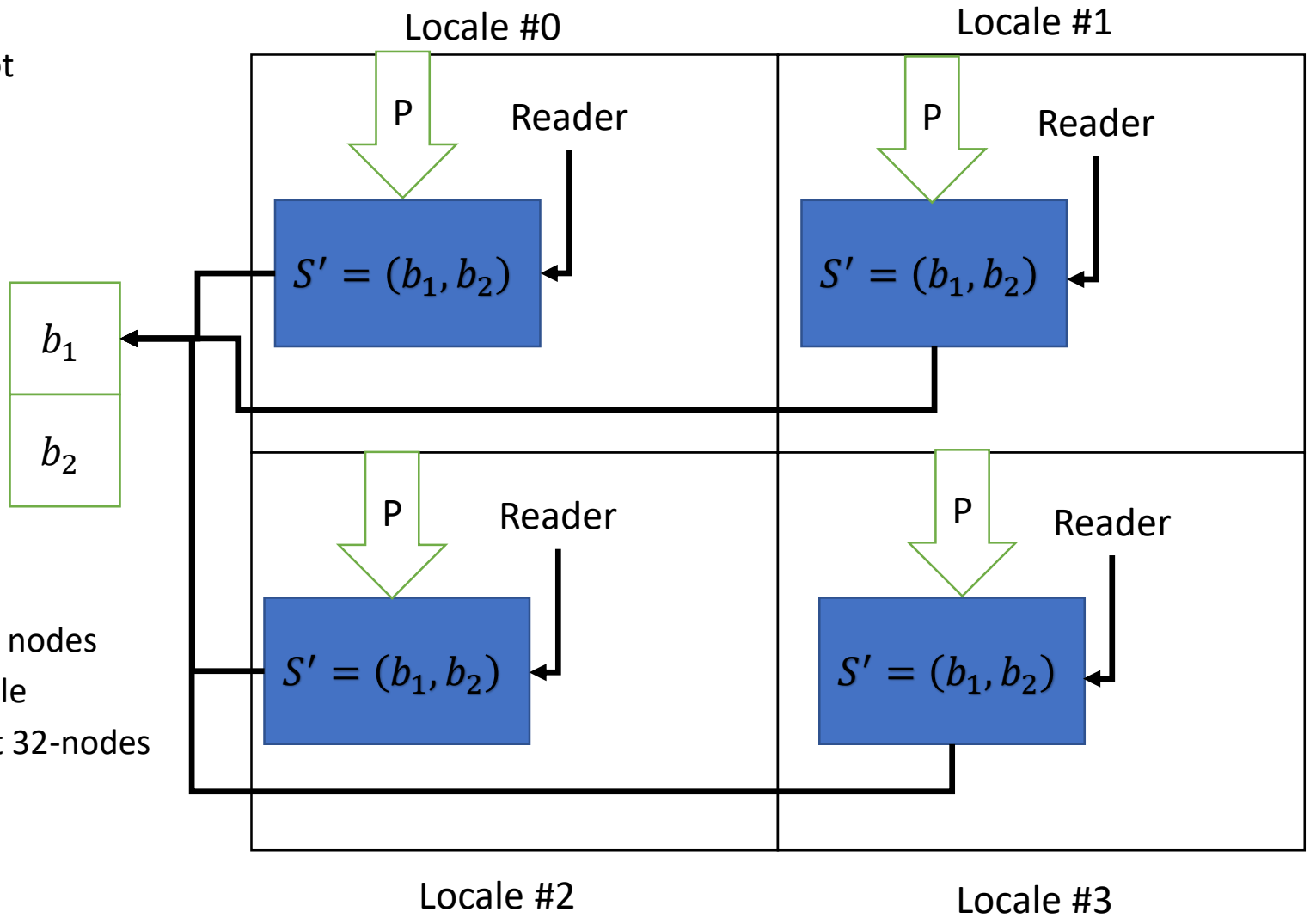
Distributed RCU

- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot
  - All local snapshots point to the same block
- Reader Concurrency
  - Readers will read from local snapshot only
  - All readers regardless of node will see same block
  - All stores to b_1 are seen by any snapshot or node
- Writer Mutual Exclusion
  - Use a distributed lock
  - Perform each update local to each node

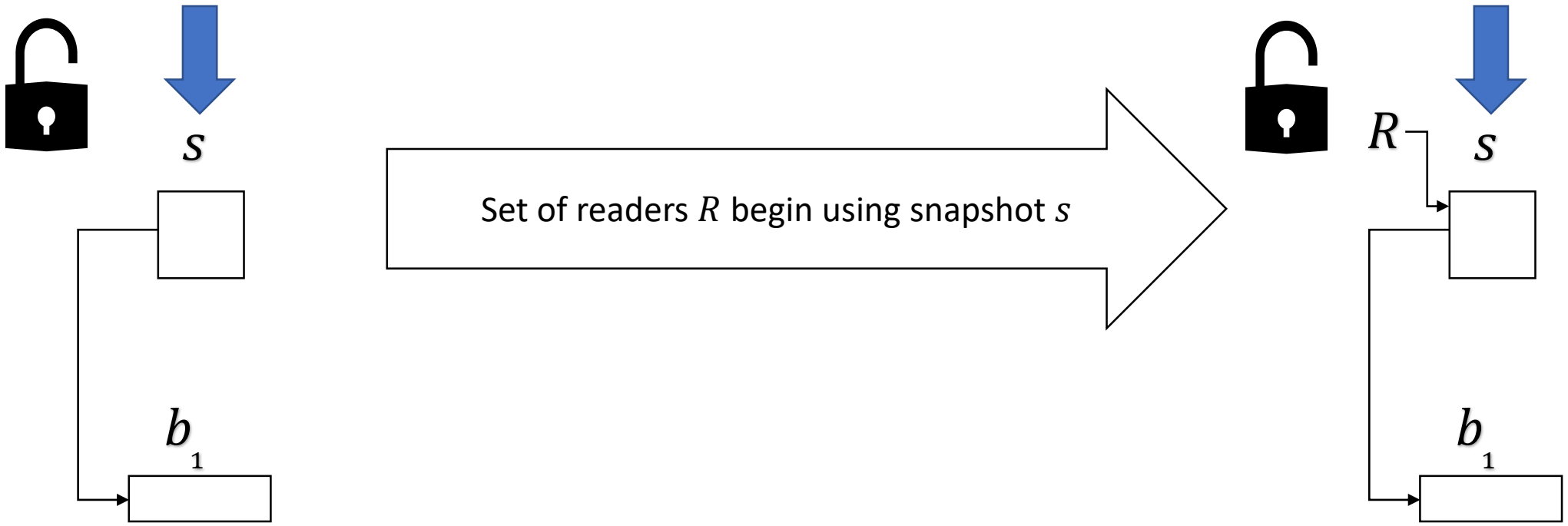


Distributed RCU

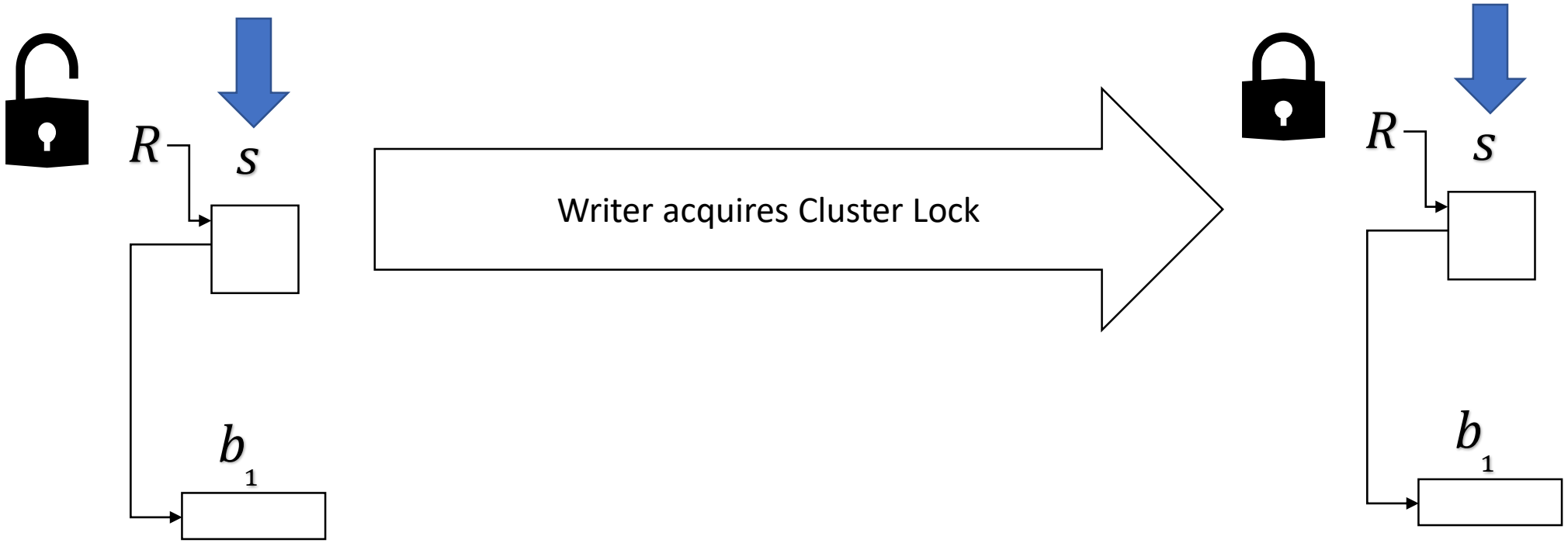
- Privatization and Snapshots
  - Each node in the cluster has its own local snapshot
  - All local snapshots point to the same block
- Reader Concurrency
  - Readers will read from local snapshot only
  - All readers regardless of node will see same block
  - All stores to b_1 are seen by any snapshot or node
- Writer Mutual Exclusion
  - Use a distributed lock
  - Perform each update local to each node
- Results
  - Fast and parallel-safe loads/stores across multiple nodes
  - Allow for loads and stores to be immediately visible
  - 40x faster resizing than naïve Block Distribution at 32-nodes



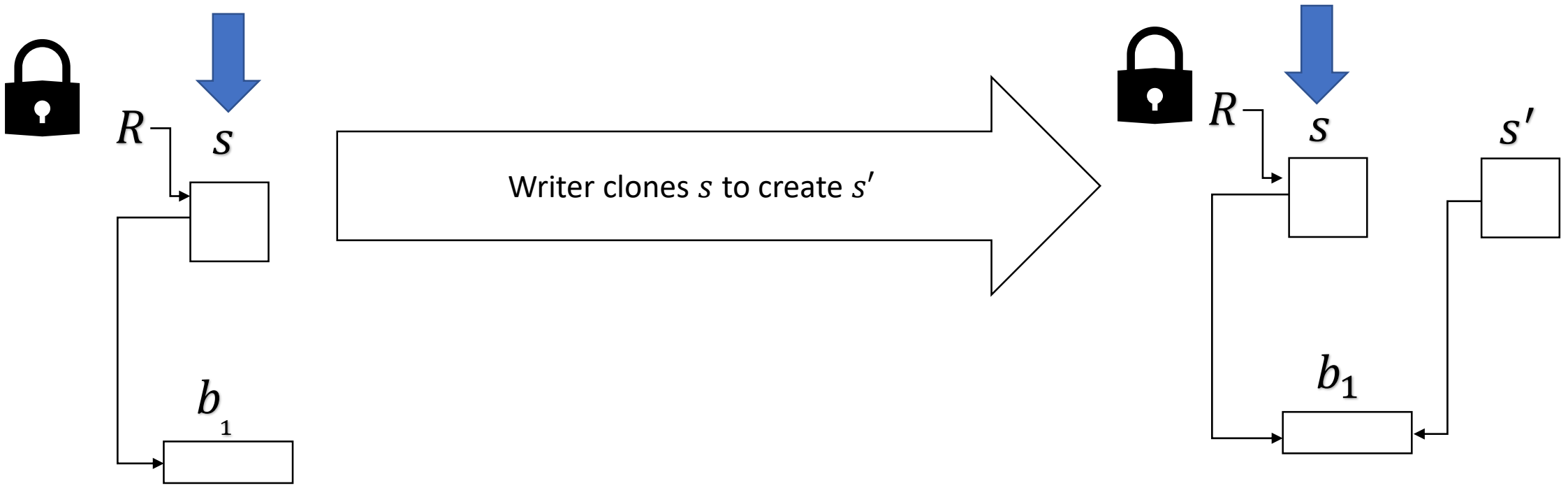
RCUArray – Resizing Example



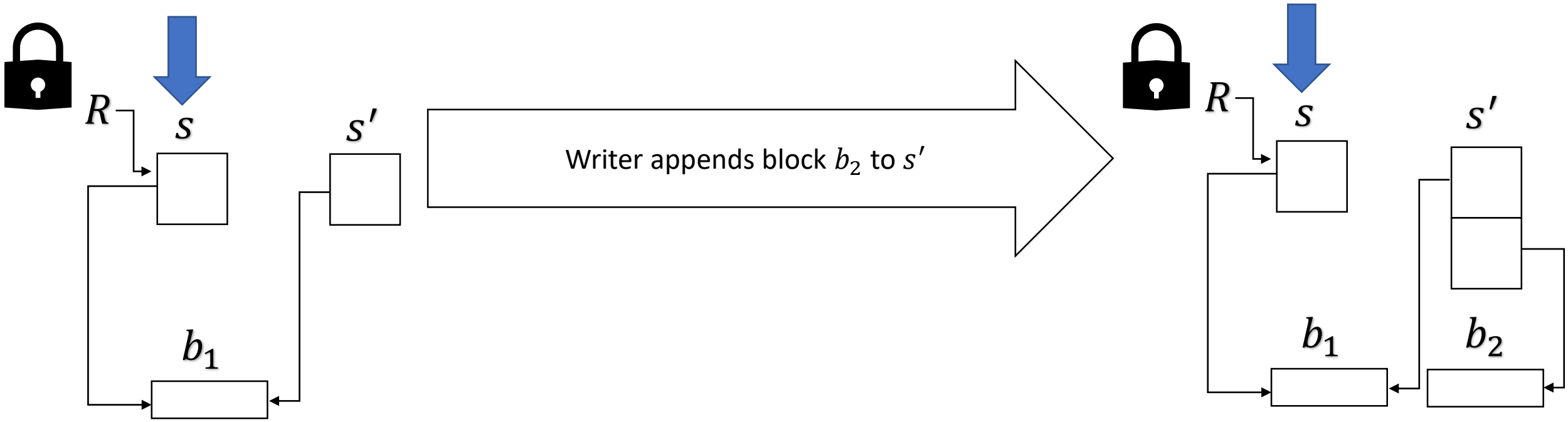
RCUArray – Resizing



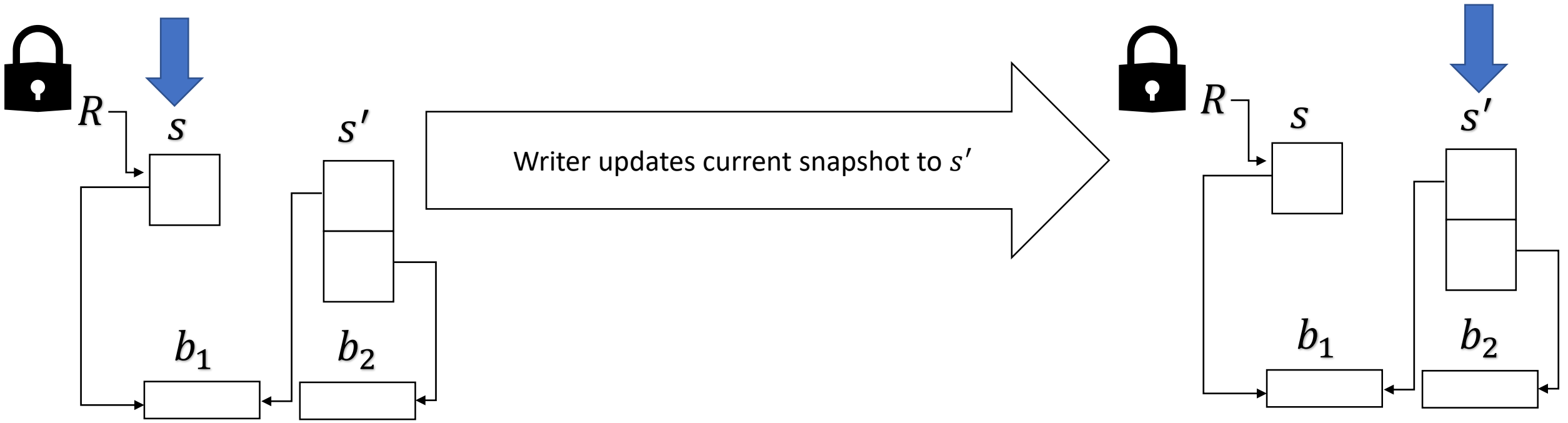
RCUArray – Resizing



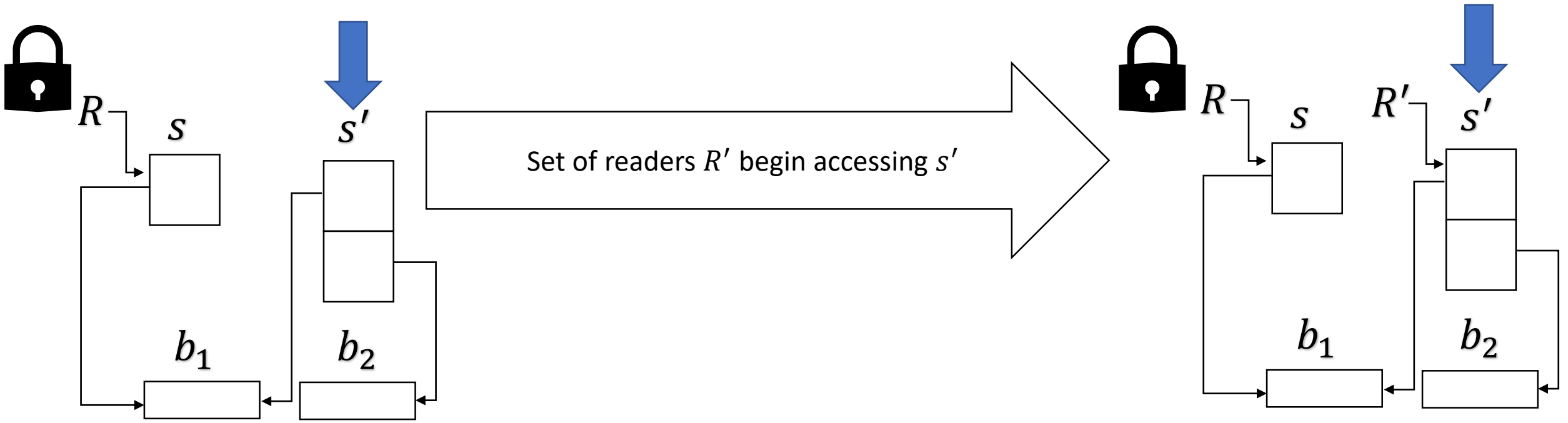
RCUArray – Resizing



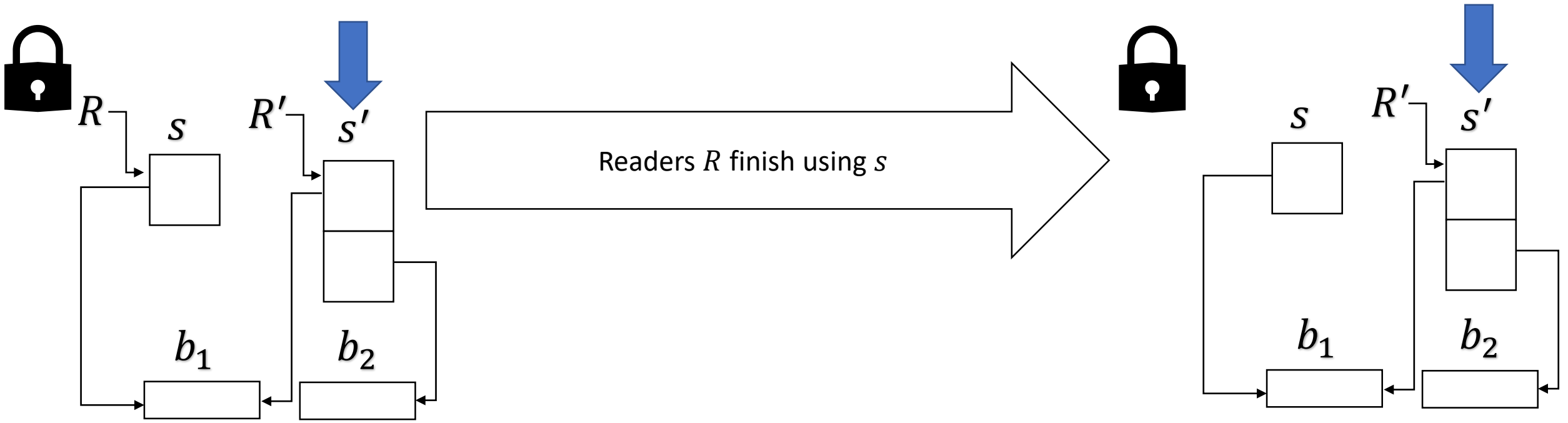
RCUArray – Resizing



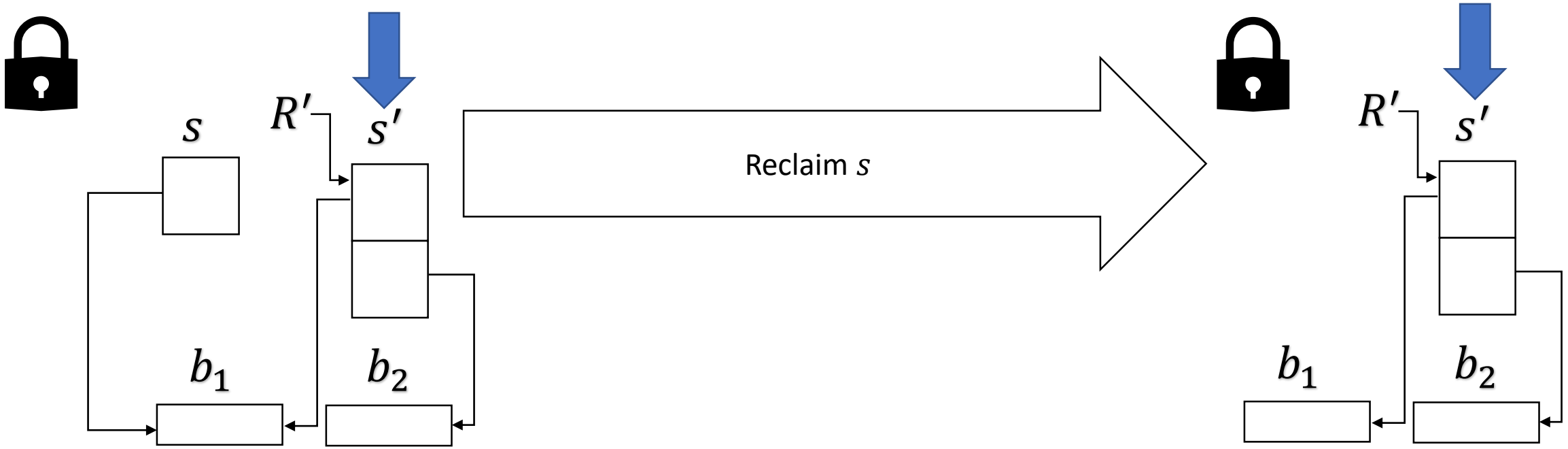
RCUArray – Resizing



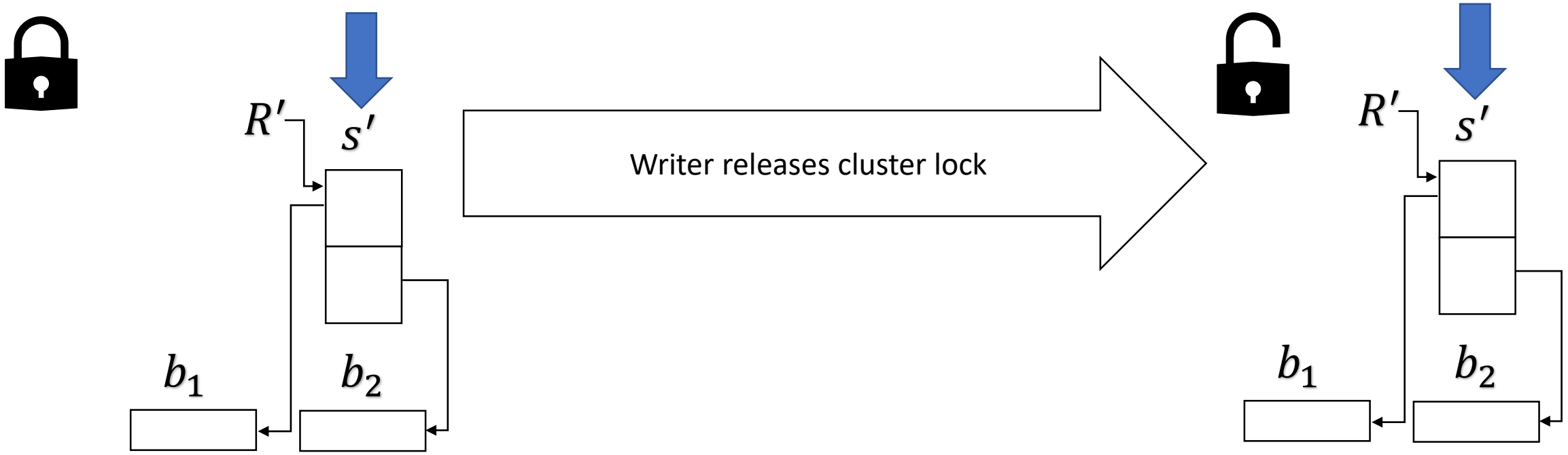
RCUArray – Resizing



RCUArray – Resizing



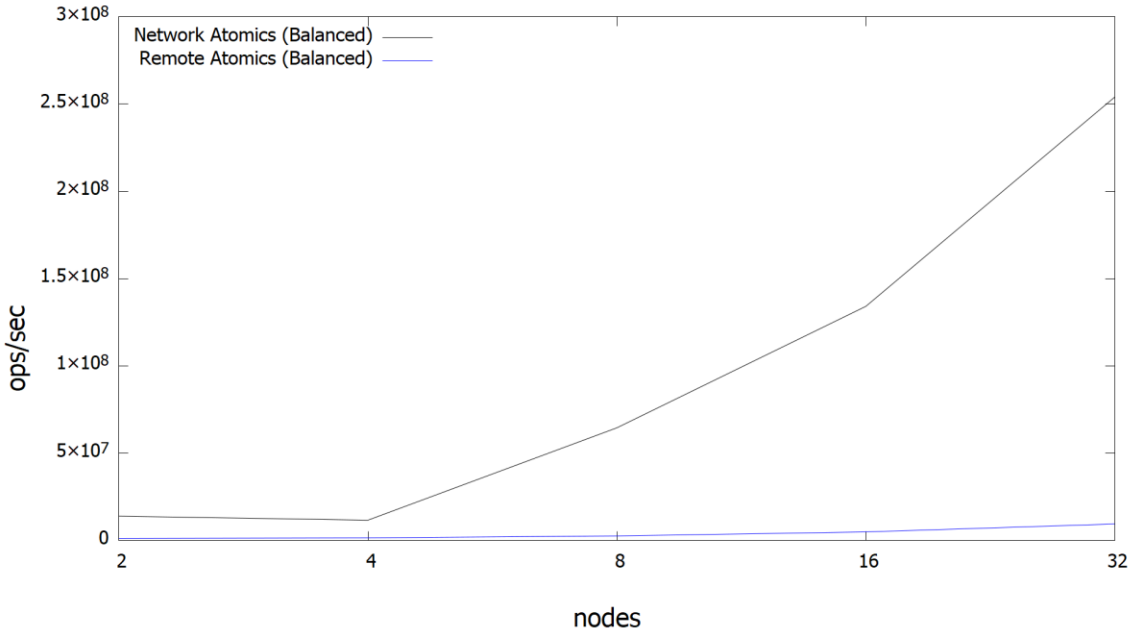
RCUArray – Resizing



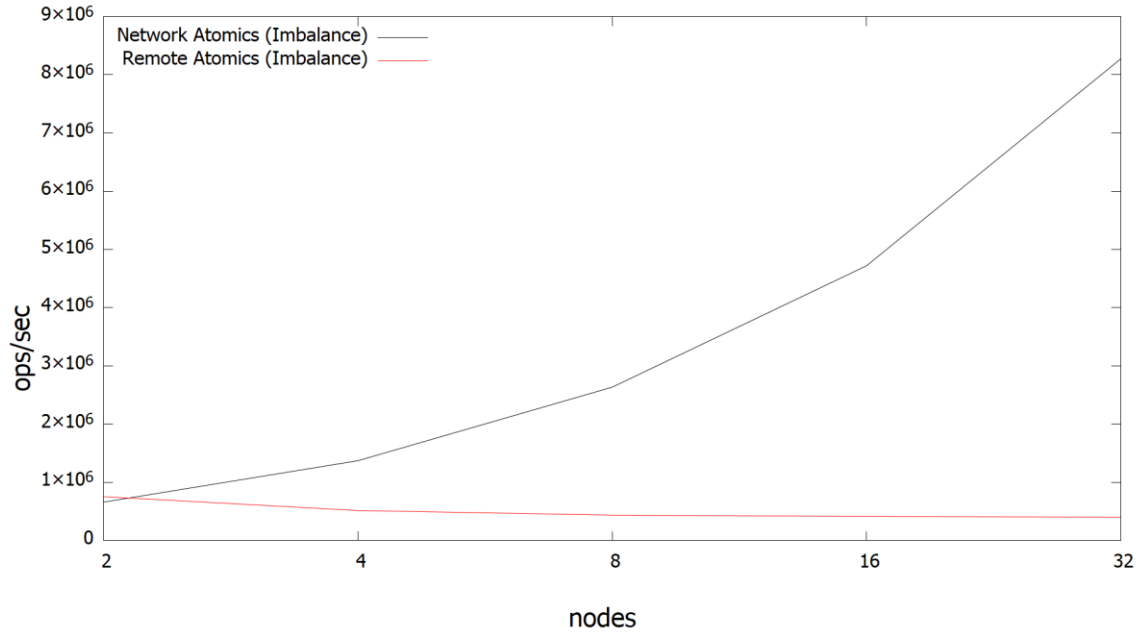
Network Atomics vs Remote Execution Atomics

- In Chapel, pointers to potentially remote memory are widened to 128-bits
  - 64-bit Address, 32-bit Locale id, 32-bit Sub-locale id (NUMA)
- Cray's Aeries NIC only supports 64-bit network atomic operations
  - Atomics via remote execution proves to be significantly slower than network atomics
  - Distributed wait-free algorithms can scale with network atomics
    - Must have a low constant bounds in inter-node communications

Network Execution 26x faster (32 Nodes)

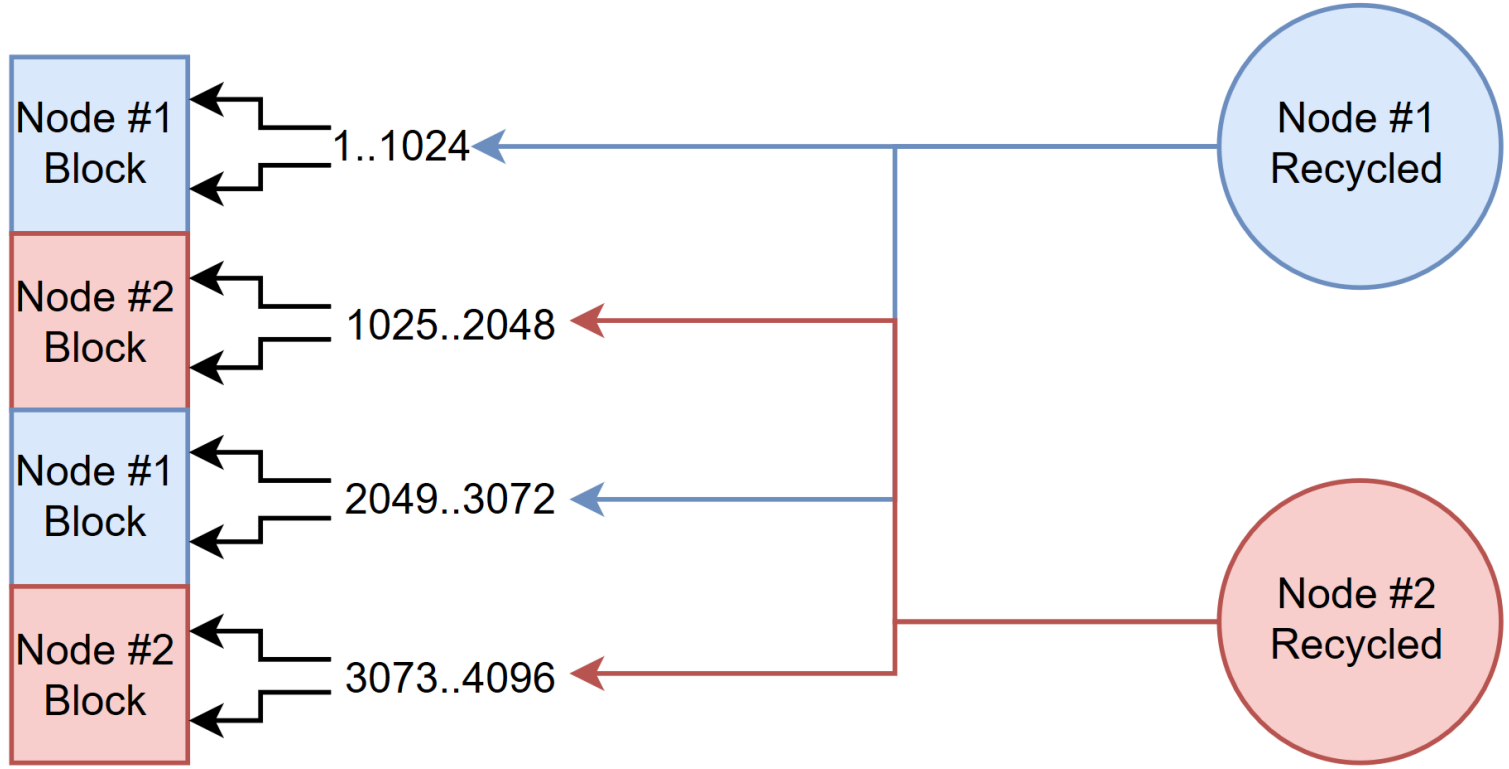


Network Execution 20x faster (32 Nodes)



RCUArray as a Dynamic Heap

- Replacing Wide Pointers
  - Blocks have locality information
  - 64-bits vs 128-bits
  - Network Atomics
- Recycling Memory
  - Each node recycles indices to local blocks
- Dynamic Heap
  - Parallel-Safe and Fast Resizing
  - Distributed across multiple locales
  - Great as a per data-structure heap



Conclusion

- Chapel makes RCU easier…
  - Lot of abstraction and language constructs
    - Privatization
    - Parallel remote tasks
  - Including Distributed RCU…
- RCUArray as a distribution
  - Exploring implementation under Domain map Standard Interface (DSI)
- Memory Management Related Efforts
  - Current efforts to add Quiescent State-Based “Garbage Collector” into language
    - 75% finished runtime changes… but on hold
  - Plans to introduce a Epoch-Based “Garbage Collector” as a Chapel module…