

YSC3248: Parallel, Concurrent and Distributed Programming

Concurrent Skip Lists

Set Object Interface

- Collection of elements
- No duplicates
- Methods
 - add() a new element
 - remove() an element
 - contains() if element is present

Many are Cold but Few are Frozen

- Typically high % of contains() calls
- Many fewer add() calls
- And even fewer remove() calls
 - 90% contains()
 - 9% add()
 - 1% remove()
- Folklore?
 - Yes but probably mostly true

Concurrent Sets

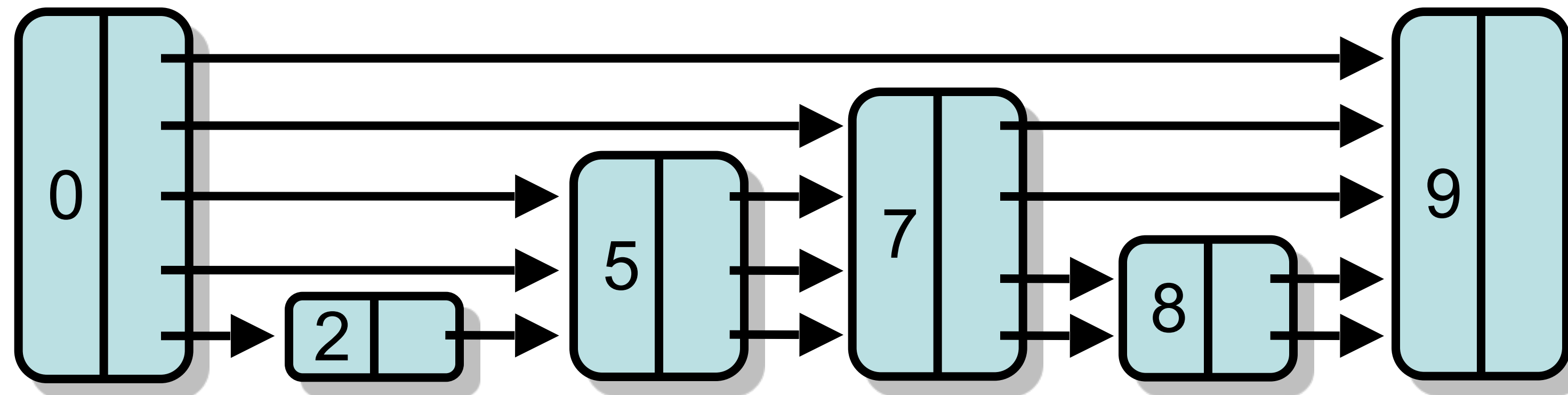
- Optimistic List, Lazy List
 - All have linear time (okay-ish)
- Any ideas on how we can do better?

Concurrent Sets

- Balanced Trees?
 - Red-Black trees, AVL trees, ...
- Problem: no one does this well ...
- ... because **rebalancing** after `add()` or `remove()` is a global operation

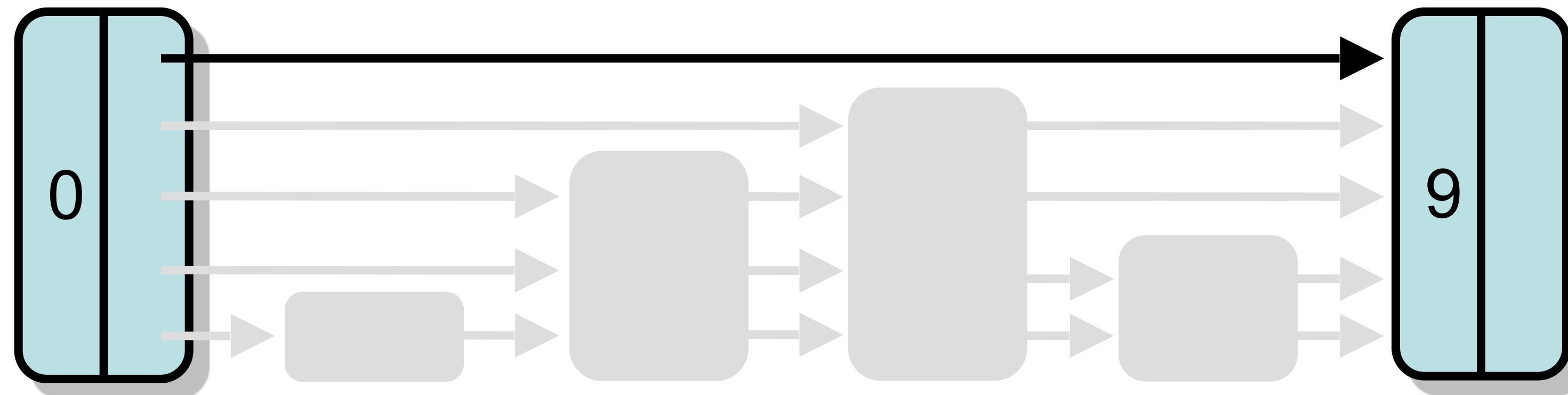
Skip Lists

- Probabilistic Data Structure
- No global rebalancing
- Logarithmic-time search



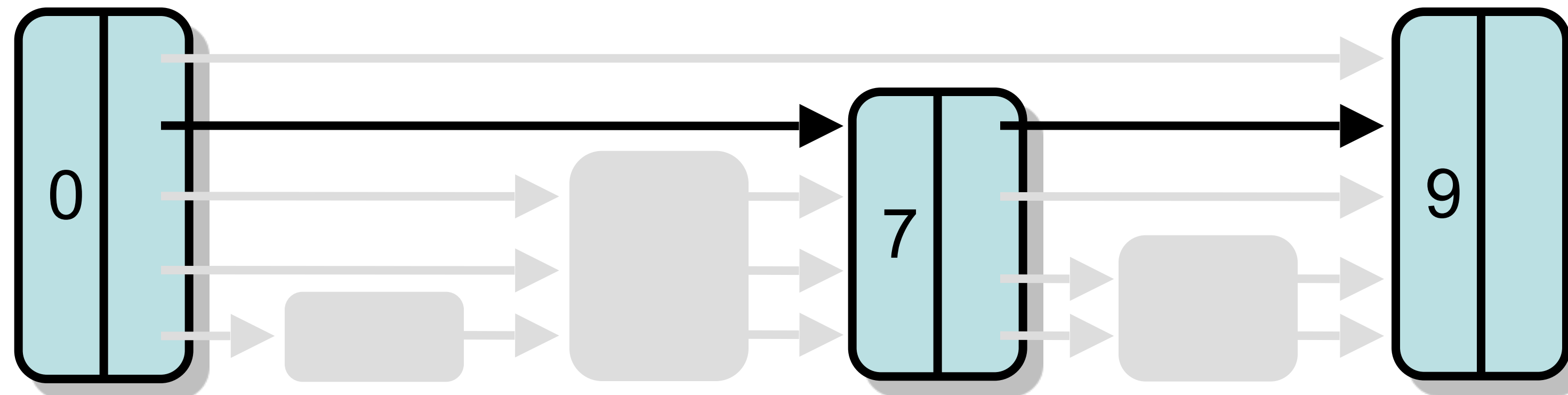
Skip List Property

- Each layer is sub-list of lower levels



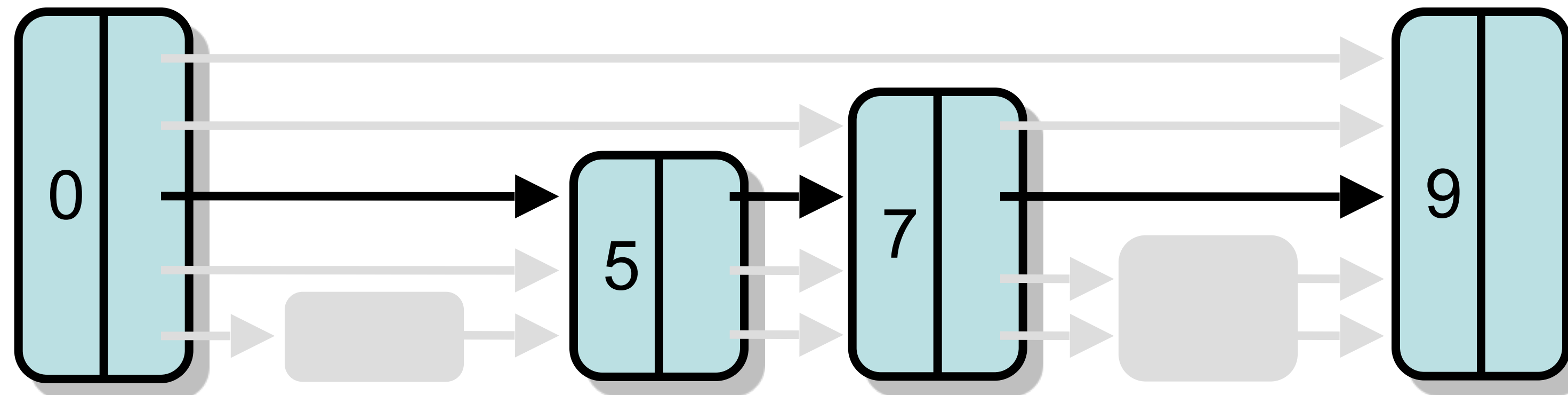
Skip List Property

- Each layer is sub-list of lower-levels



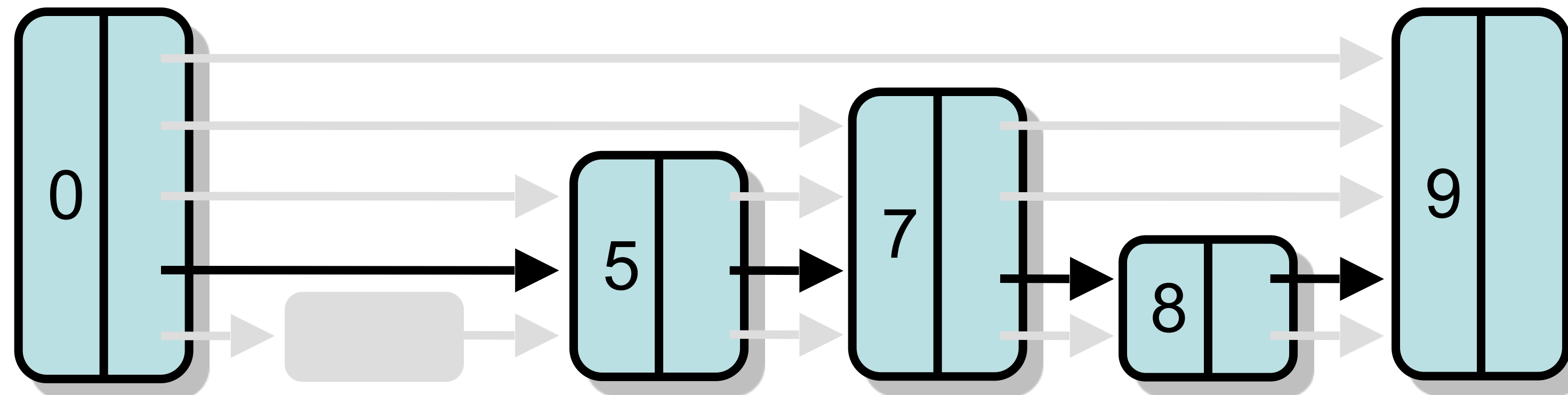
Skip List Property

- Each layer is sub-list of lower levels



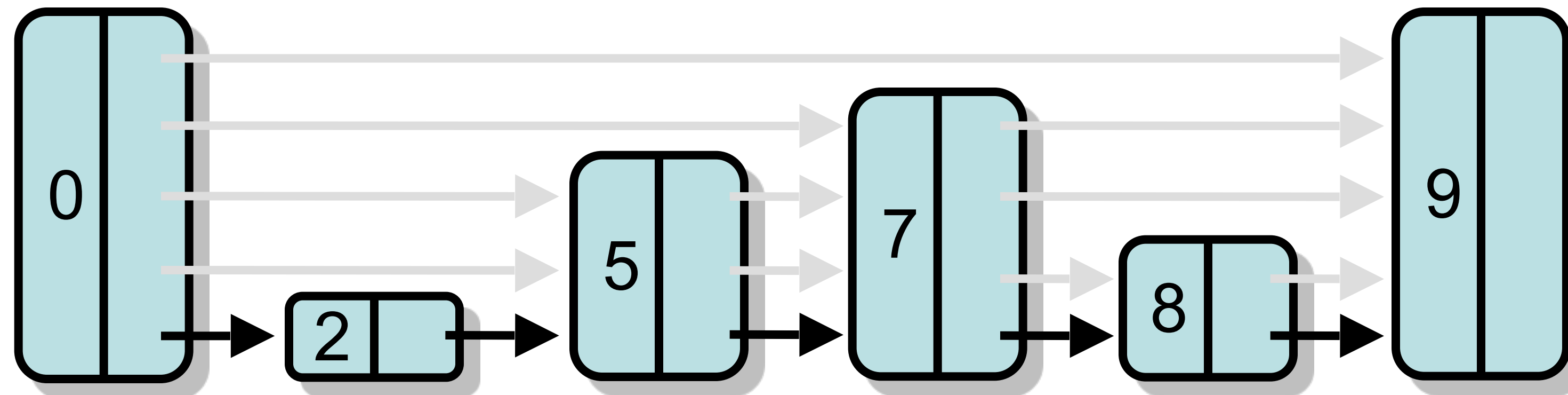
Skip List Property

- Each layer is sub-list of lower levels



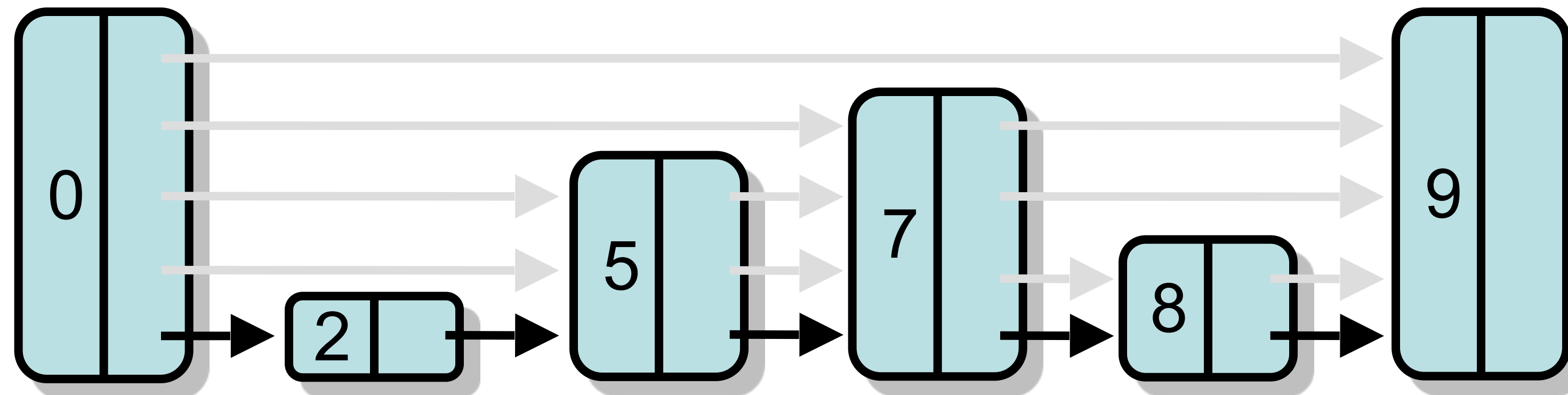
Skip List Property

- Each layer is sub-list of lower levels
- Lowest level is entire list

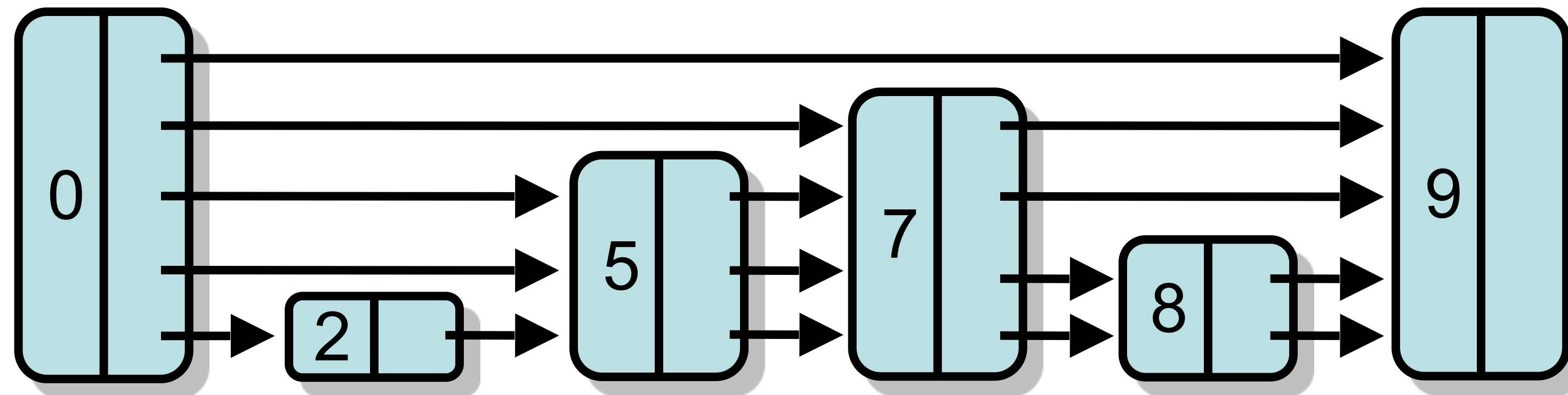
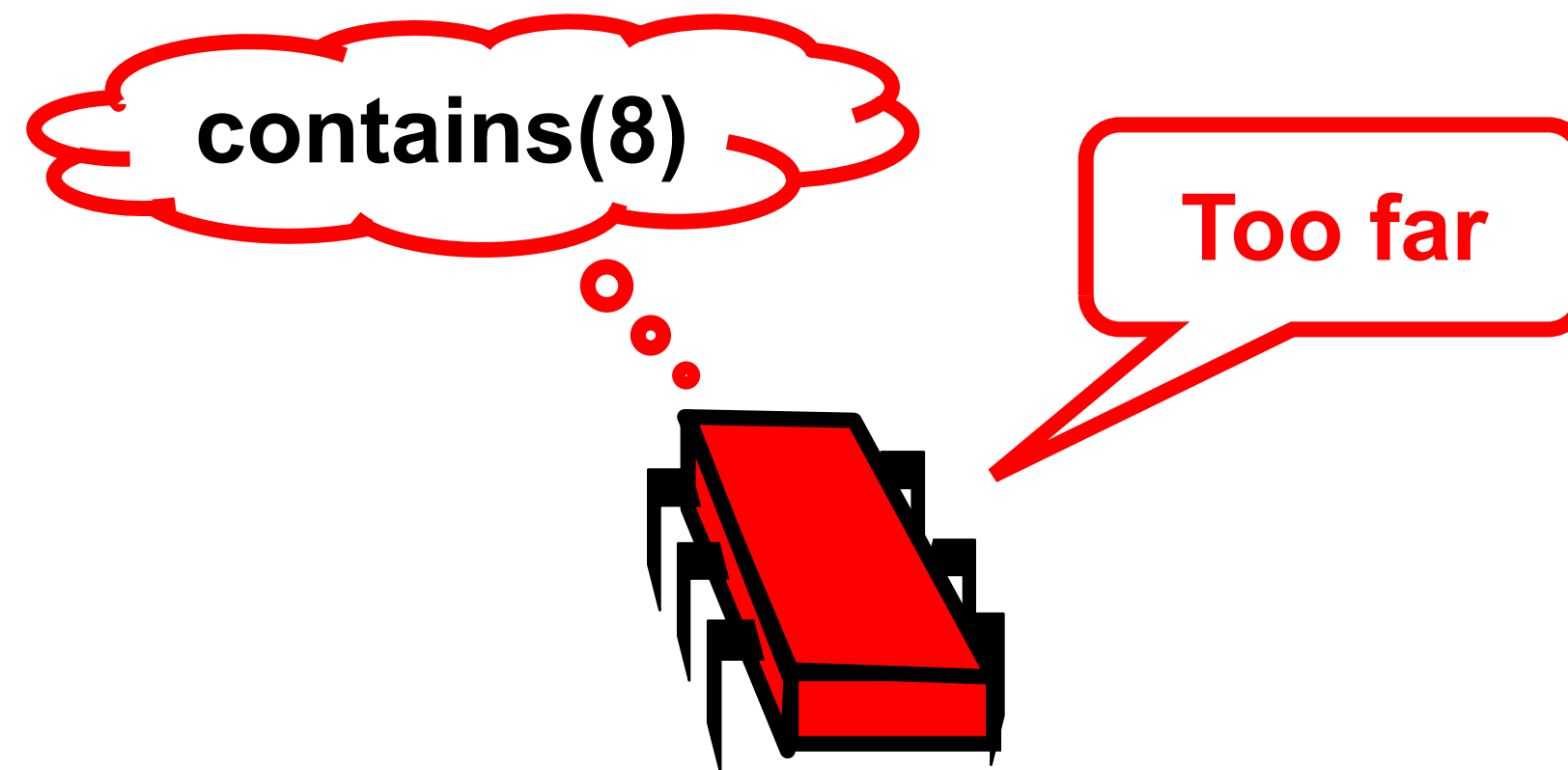


Skip List Property

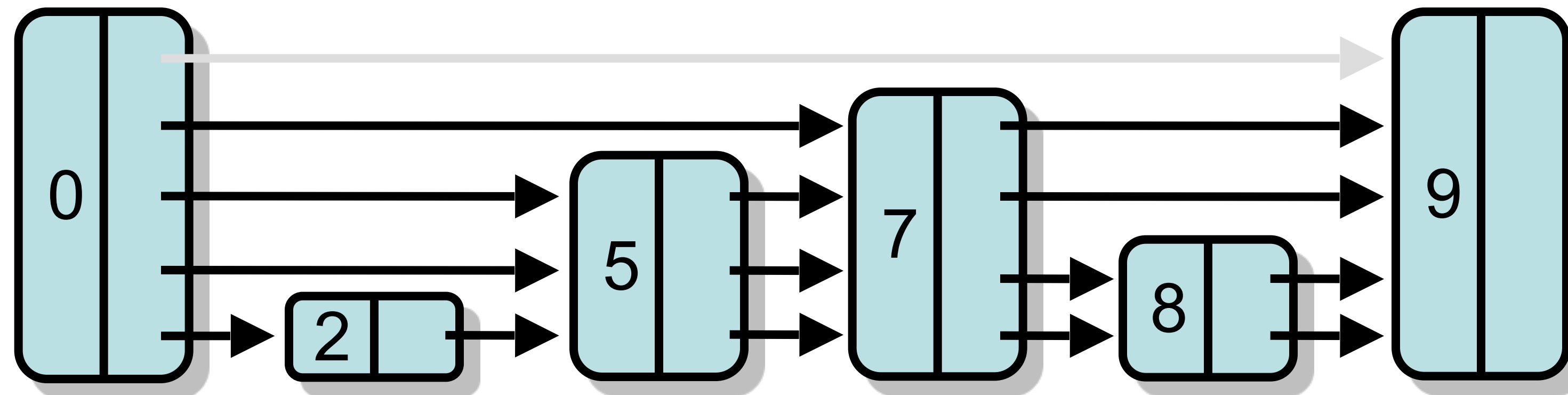
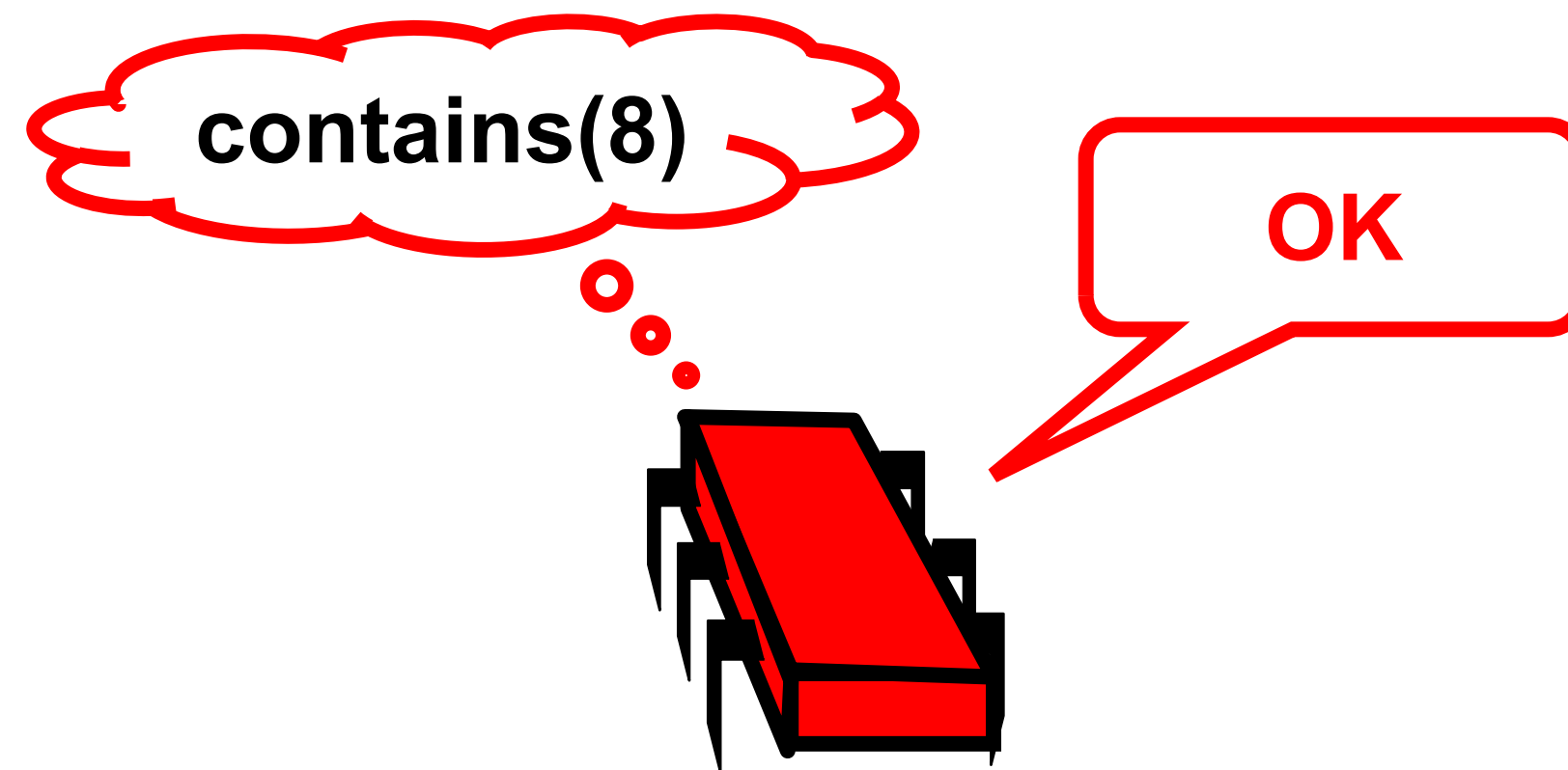
- Each layer is sub-list of lower levels
- Not easy to preserve in concurrent implementations ...



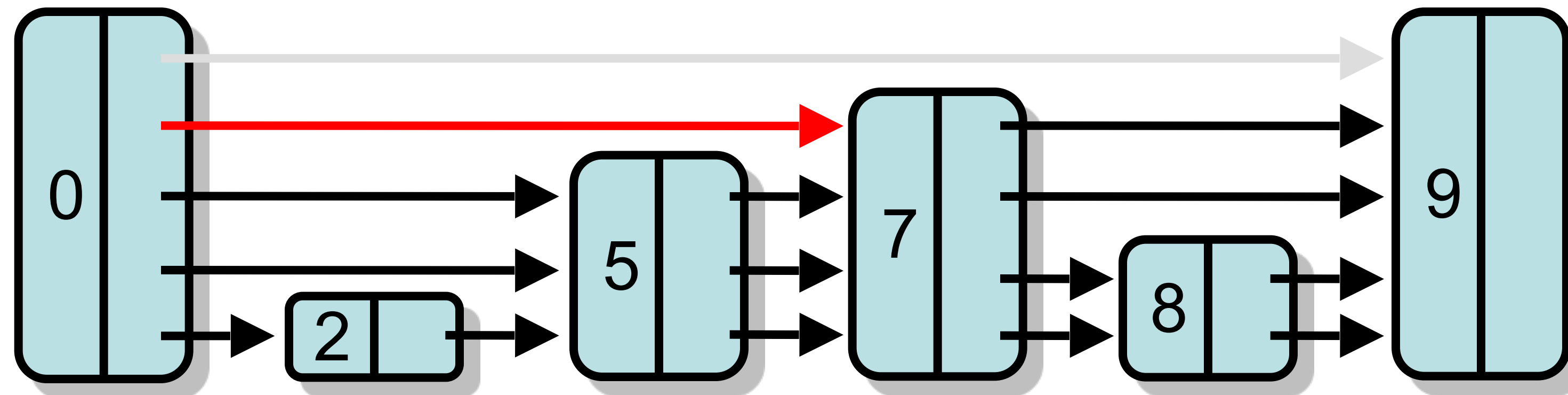
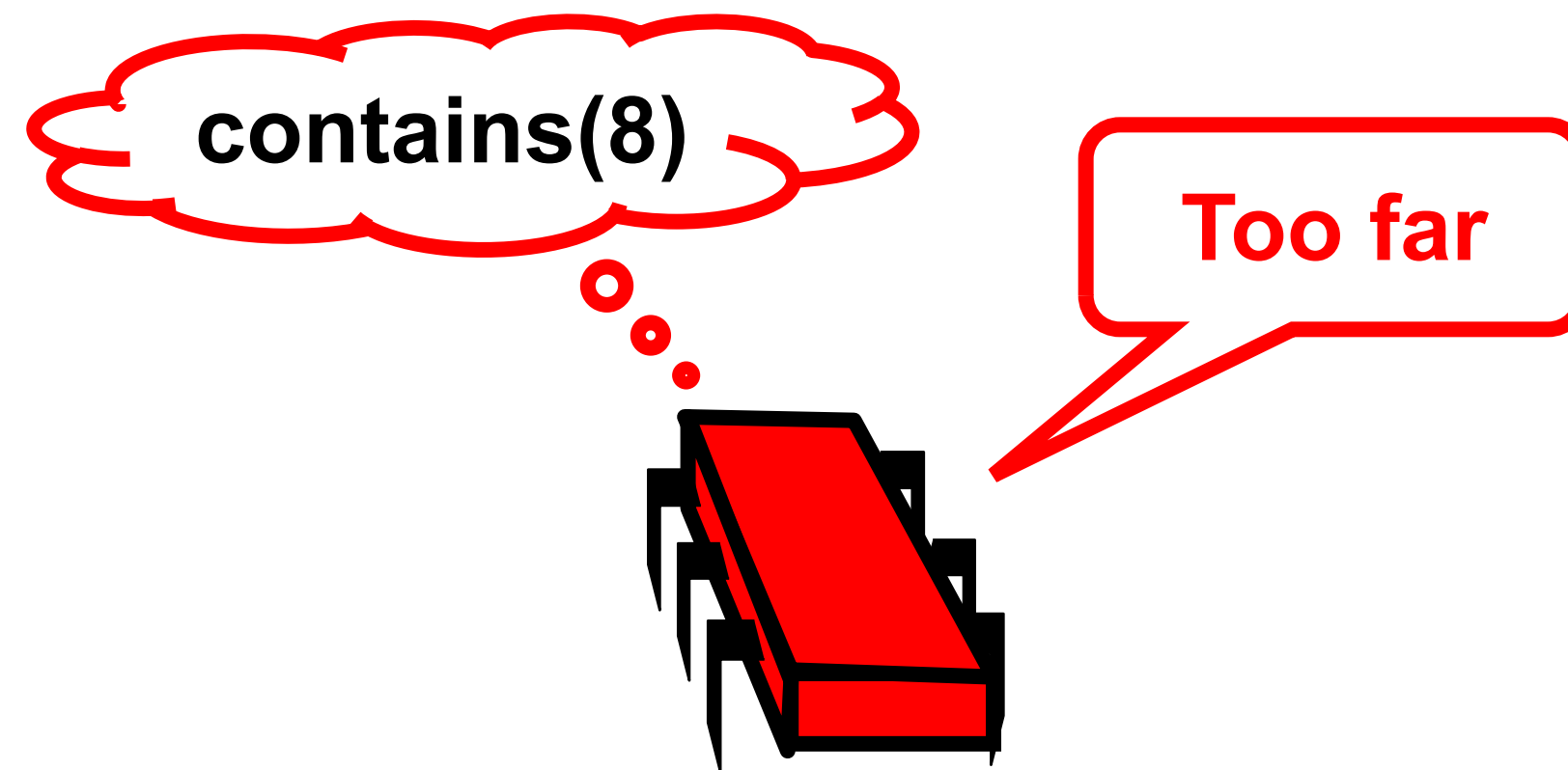
Search



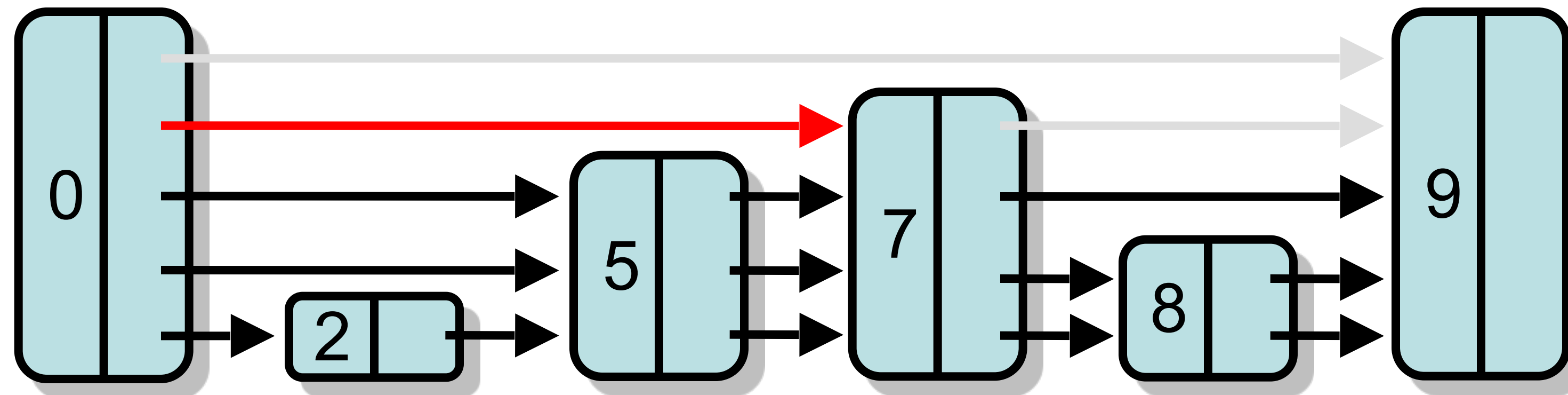
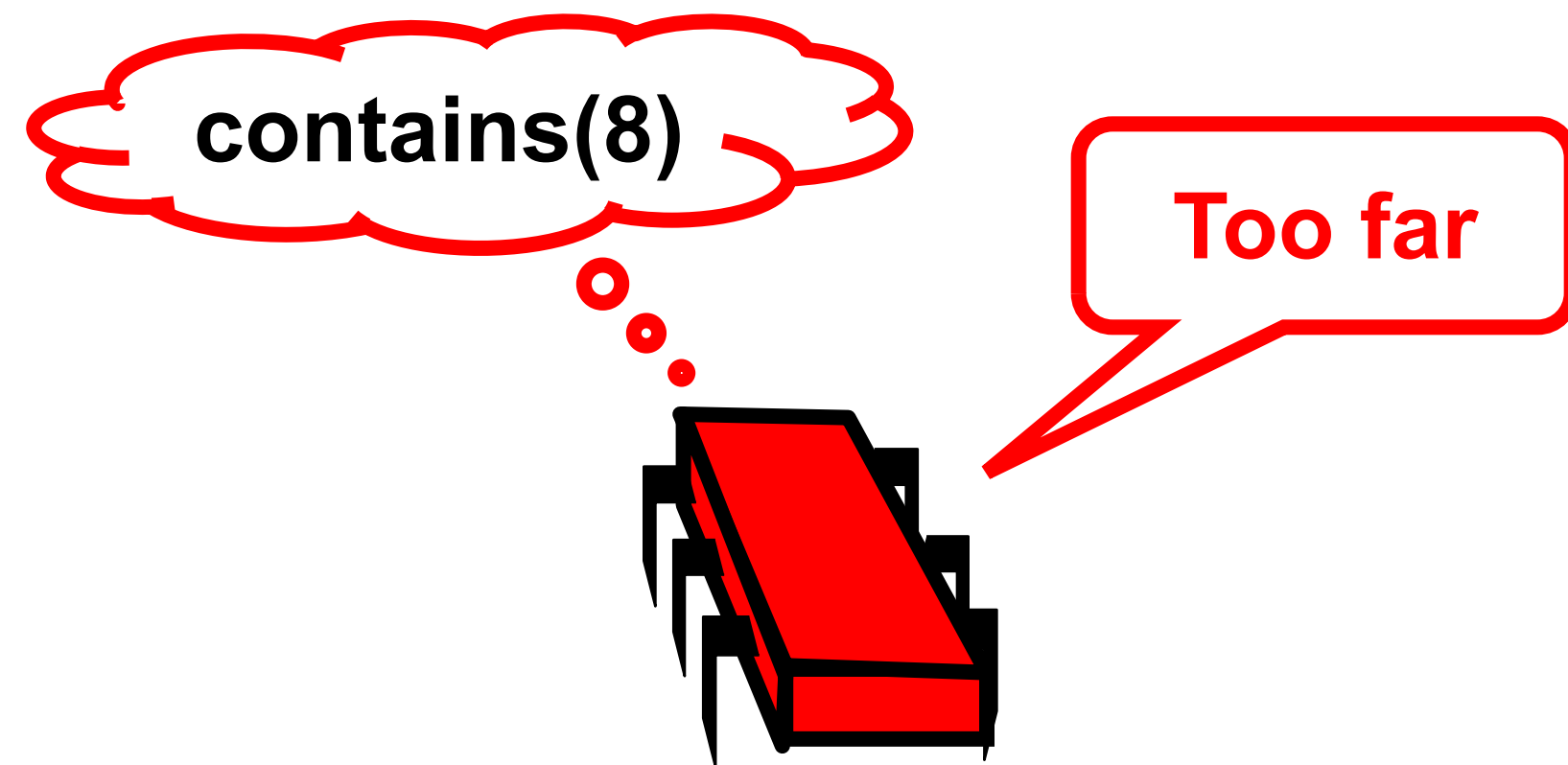
Search



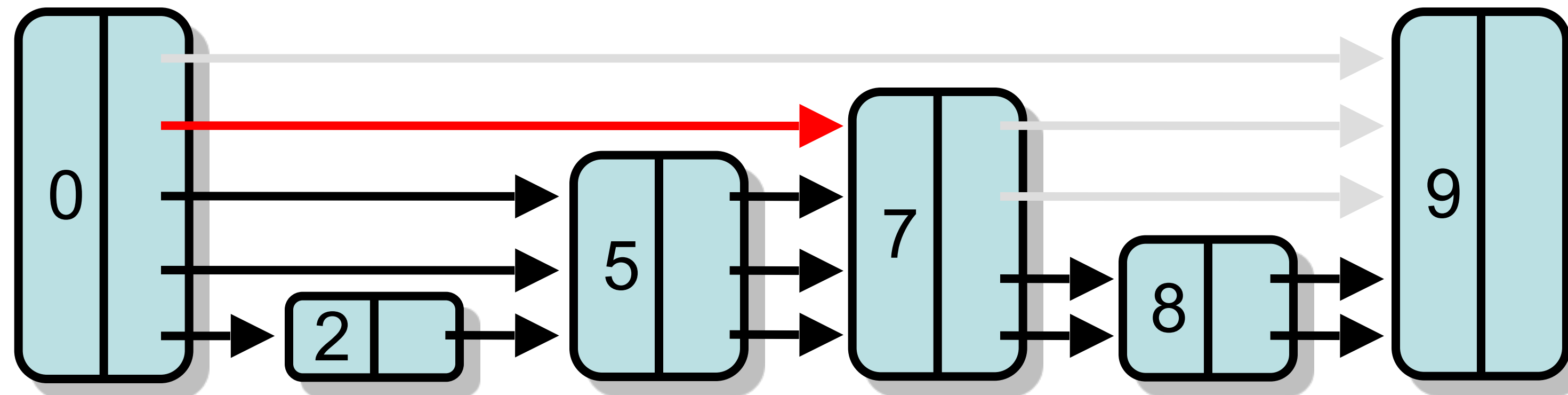
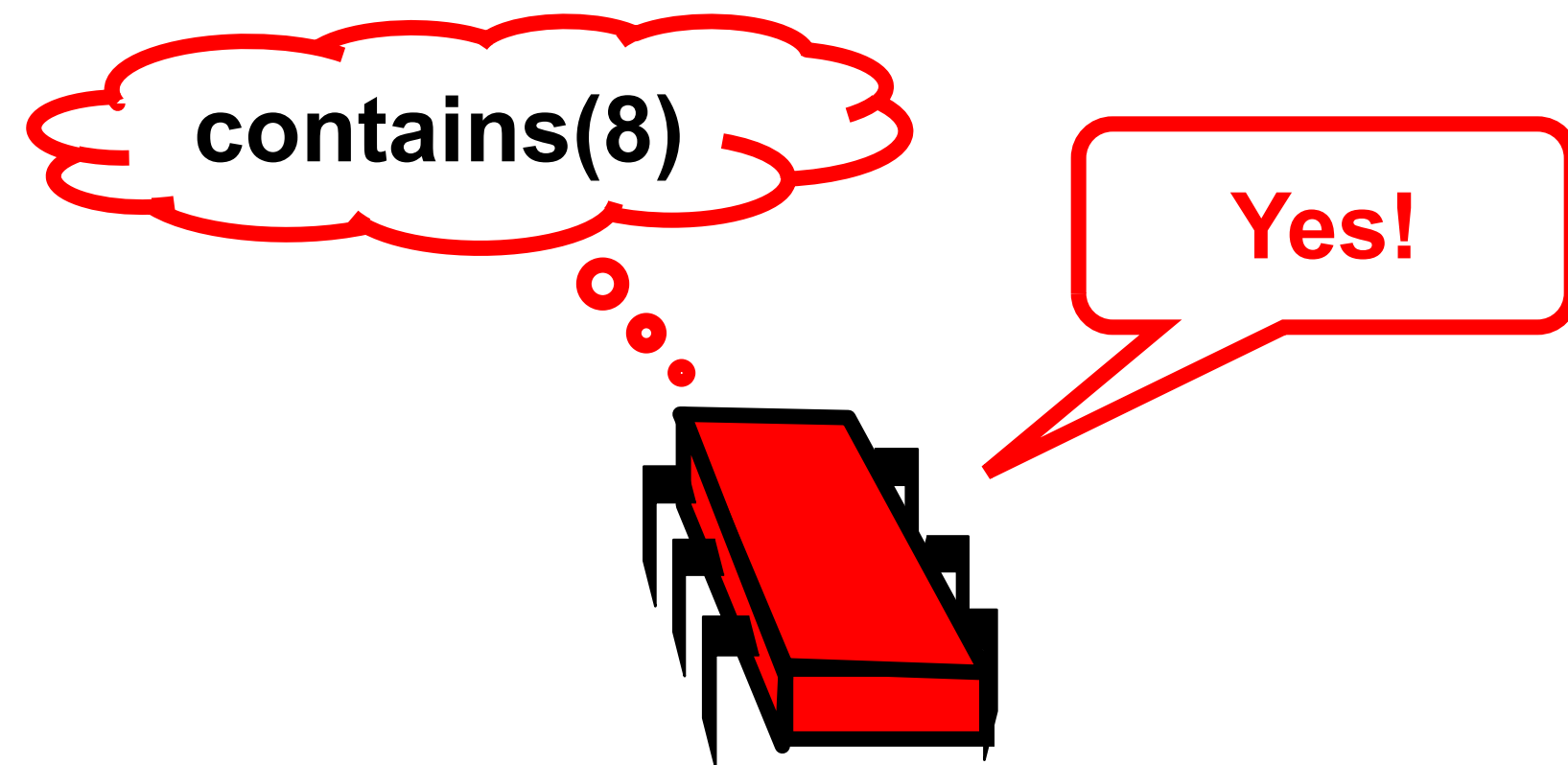
Search



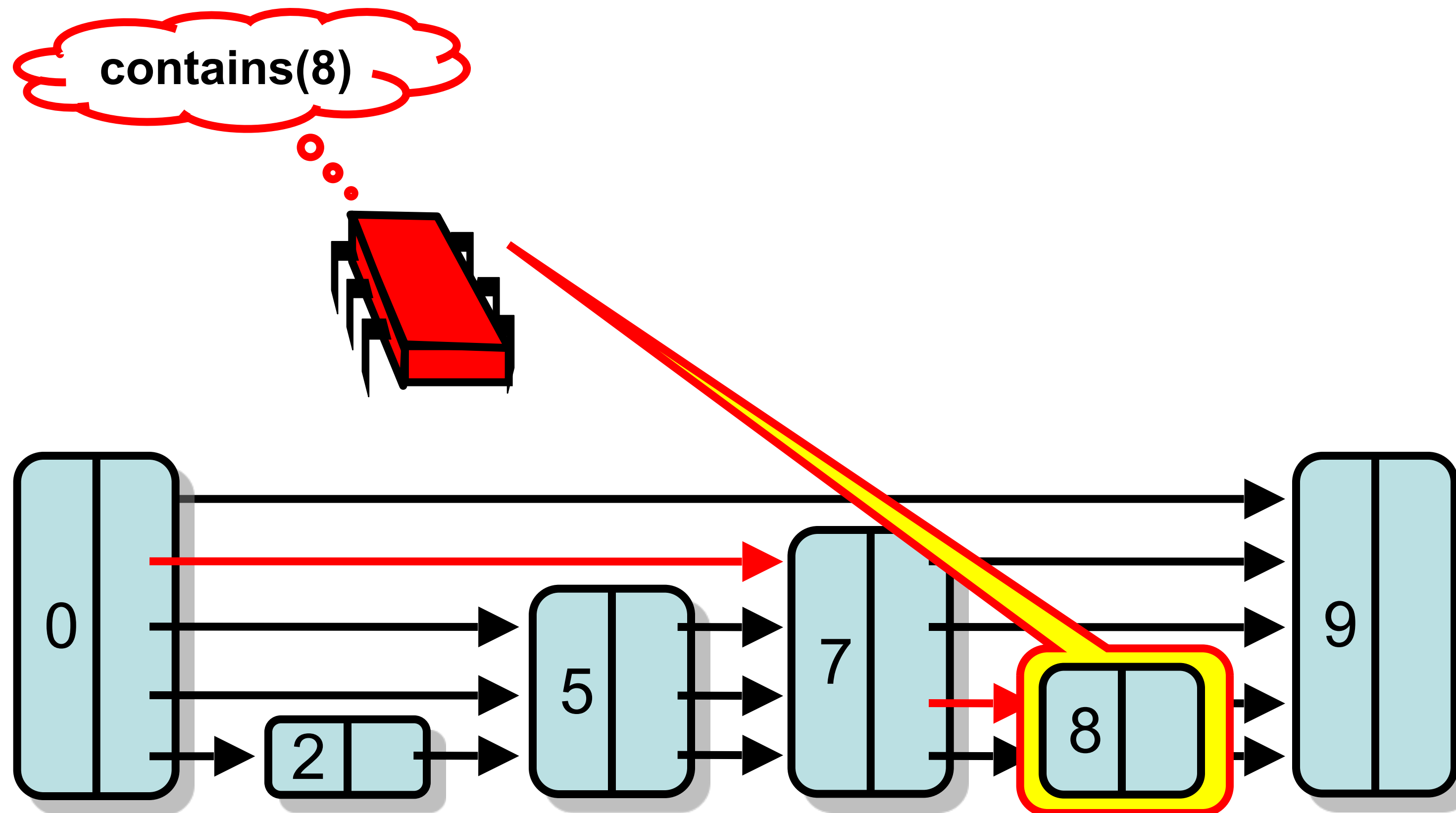
Search



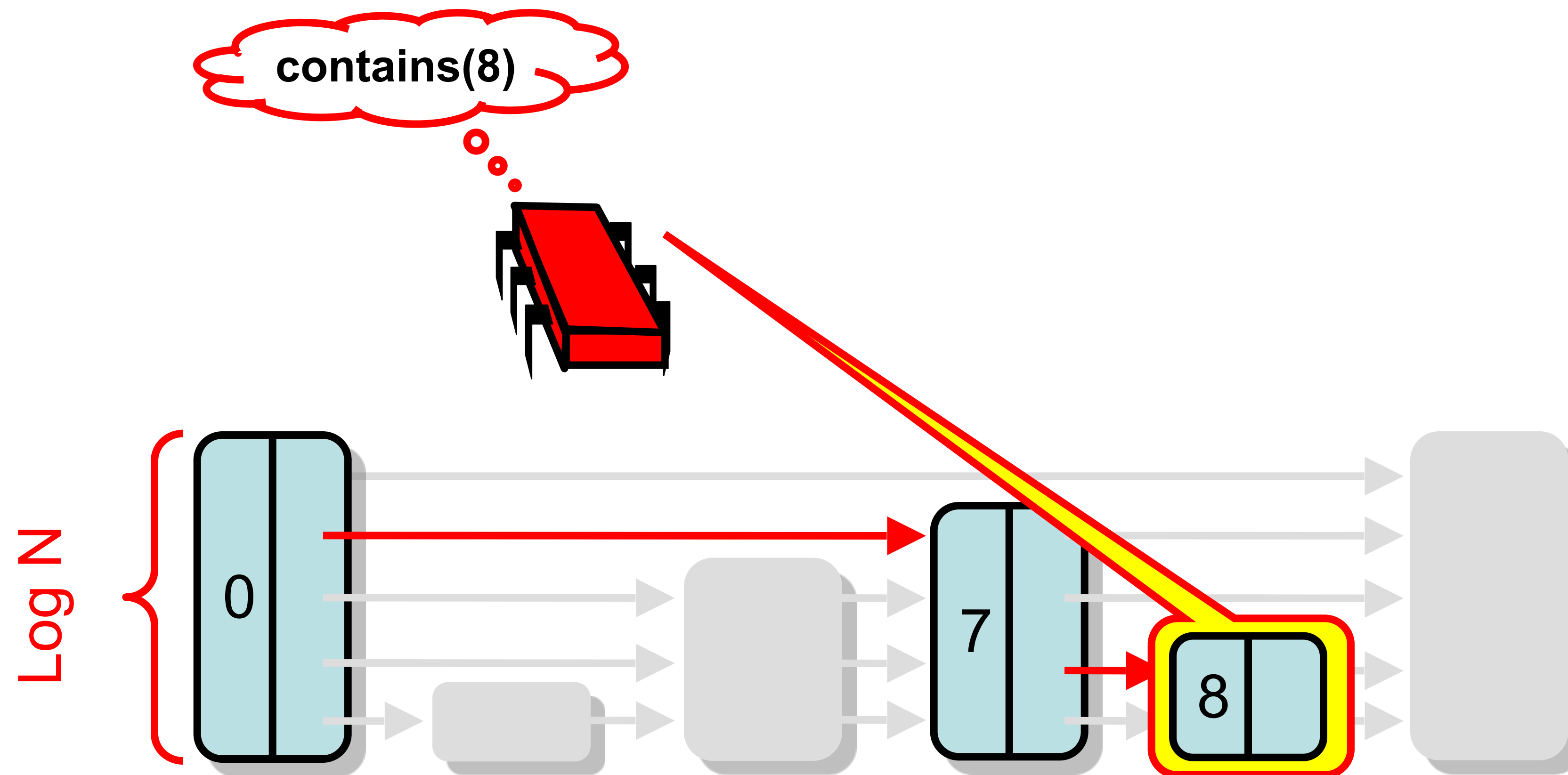
Search



Search

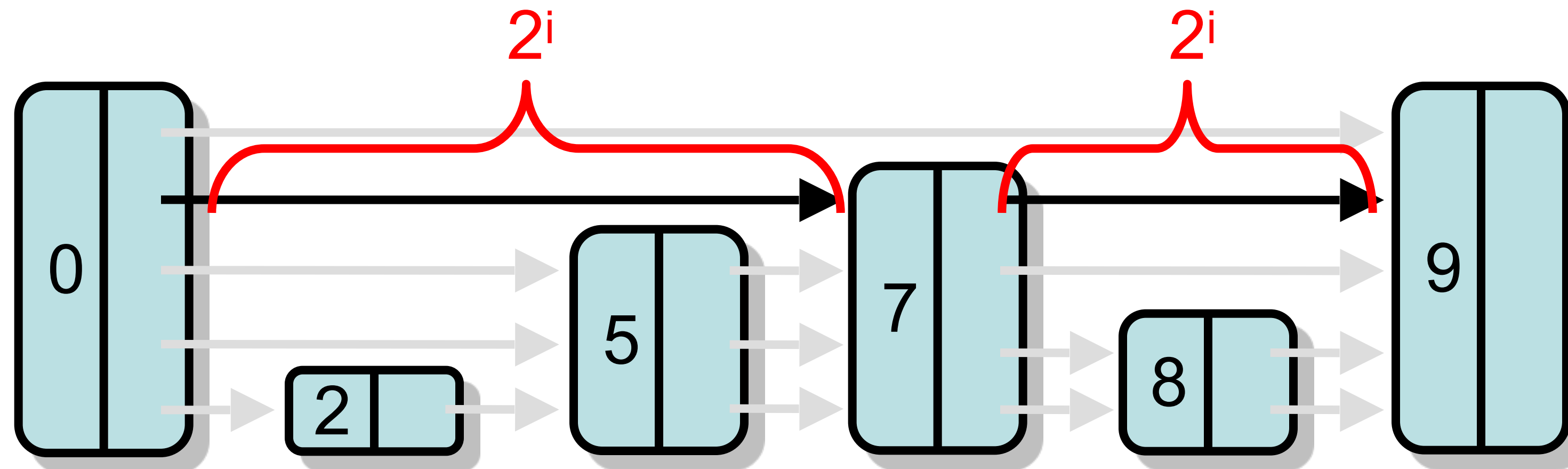


Logarithmic



Why Logarithmic

- Property: Each pointer at layer i jumps over roughly 2^i nodes
- Pick node heights randomly so property guaranteed probabilistically



Sequential Find

```
def find(x: T, preds: Array[Node[T]], succs: Array[Node[T]]): Int {  
  ...  
}
```

Sequential Find

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def find(x: T, preds: Array[Node[T]], succs: Array[Node[T]]): Int {  
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**object height
(-1 if not there)**

Sequential Find

```
def find(x: T, preds: Array[Node[T]], succs: Array[Node[T]]): Int {  
  ...  
}
```

Object sought

**object height
(-1 if not there)**

Sequential Find

```
def find(x: T, preds: Array[Node[T]], succs: Array[Node[T]]) : Int {  
  ...  
}
```

Object sought

return predecessors

object height
(-1 if not there)

Sequential Find

```
def find(x: T, preds: Array[Node[T]], succs: Array[Node[T]]) : Int {  
  ...  
}
```

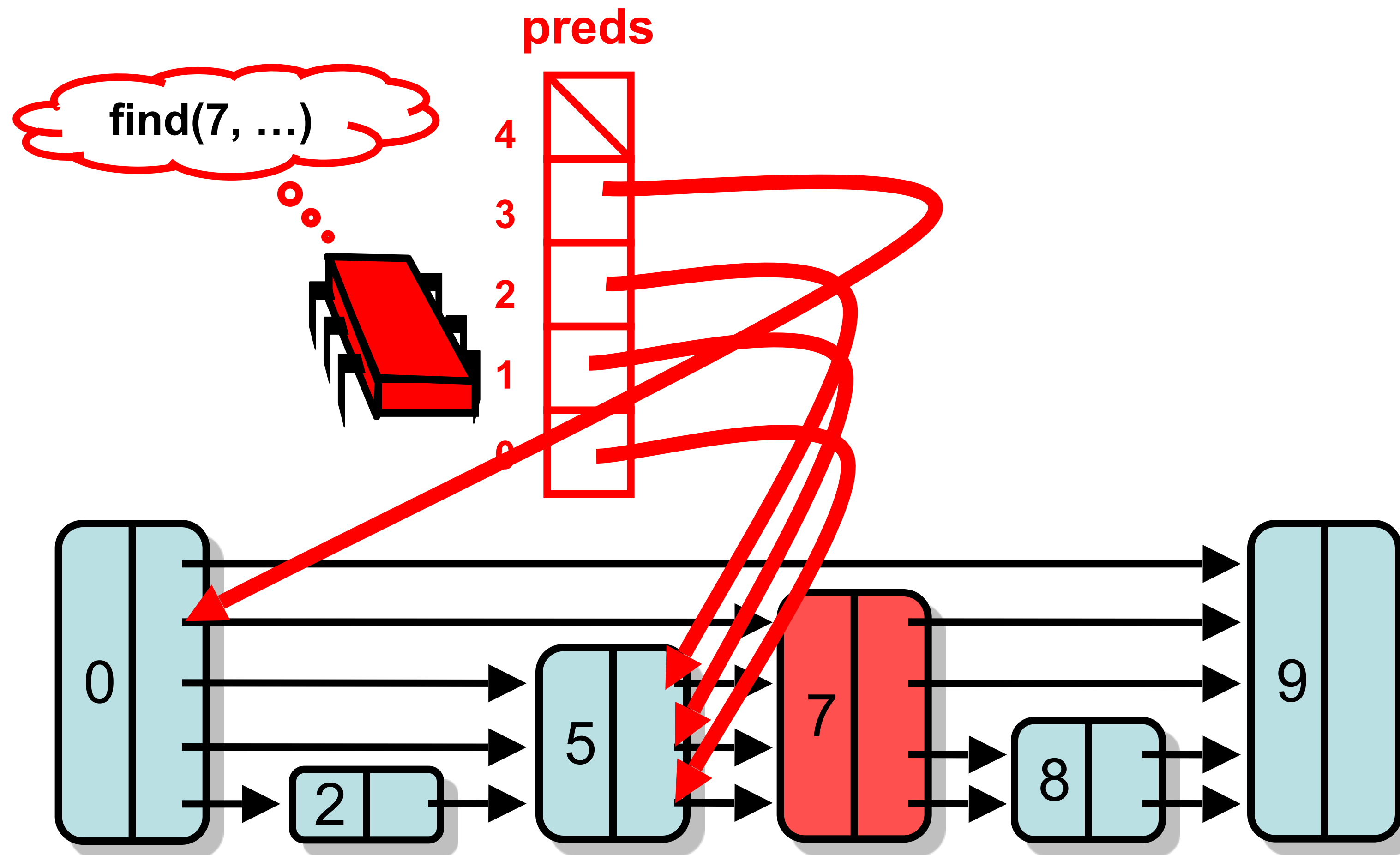
Object sought

return predecessors

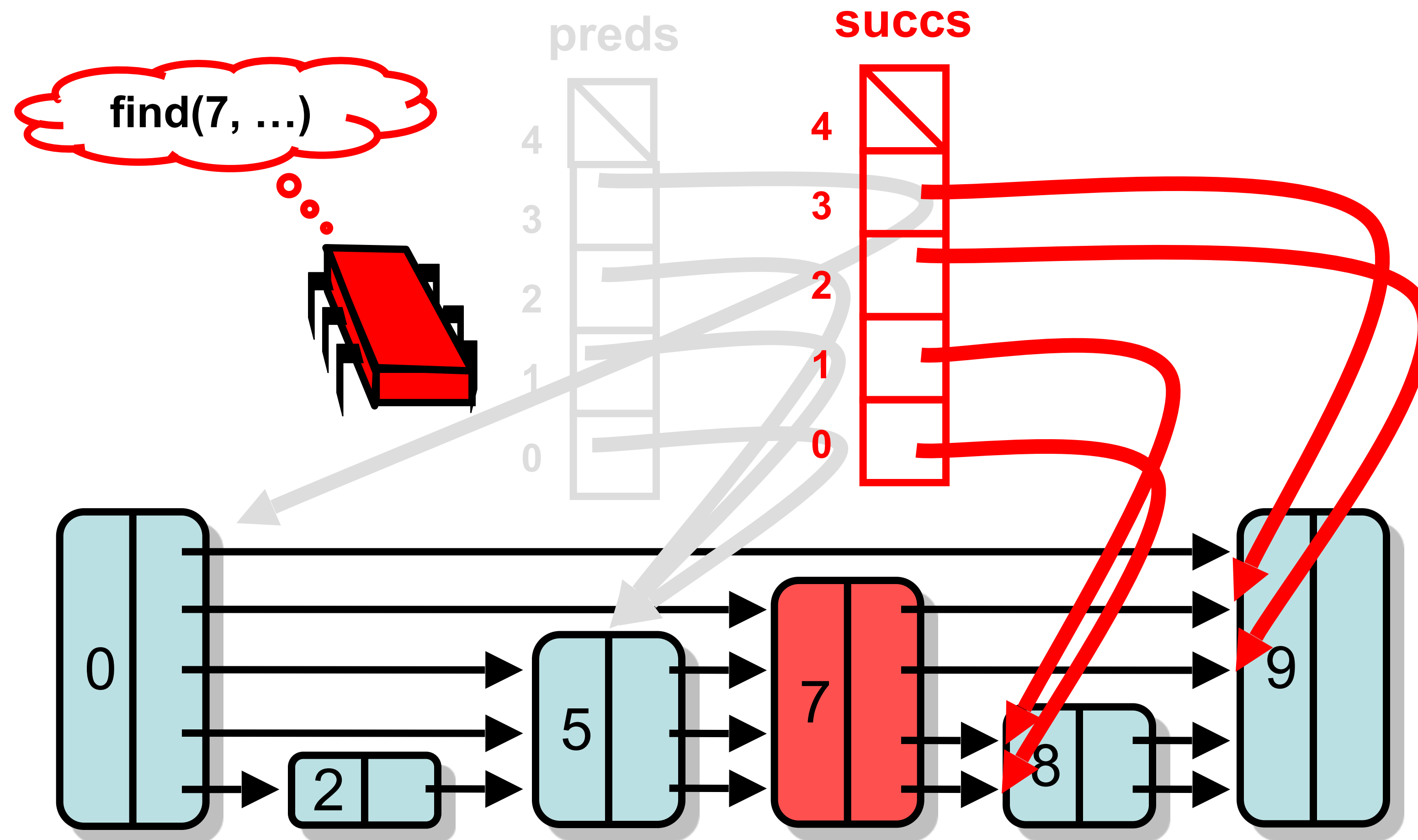
return successors

**object height
(-1 if not there)**

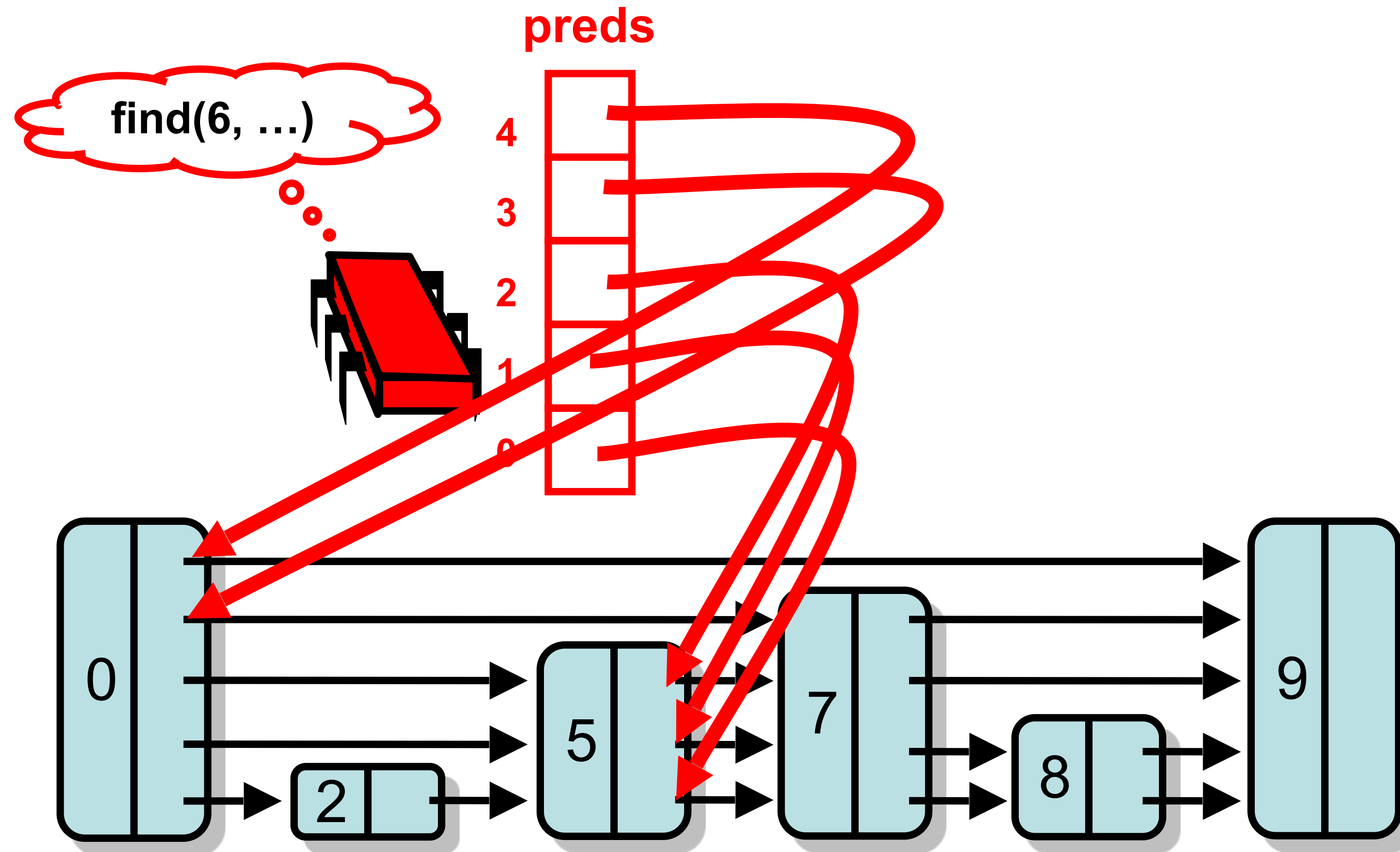
Successful Search



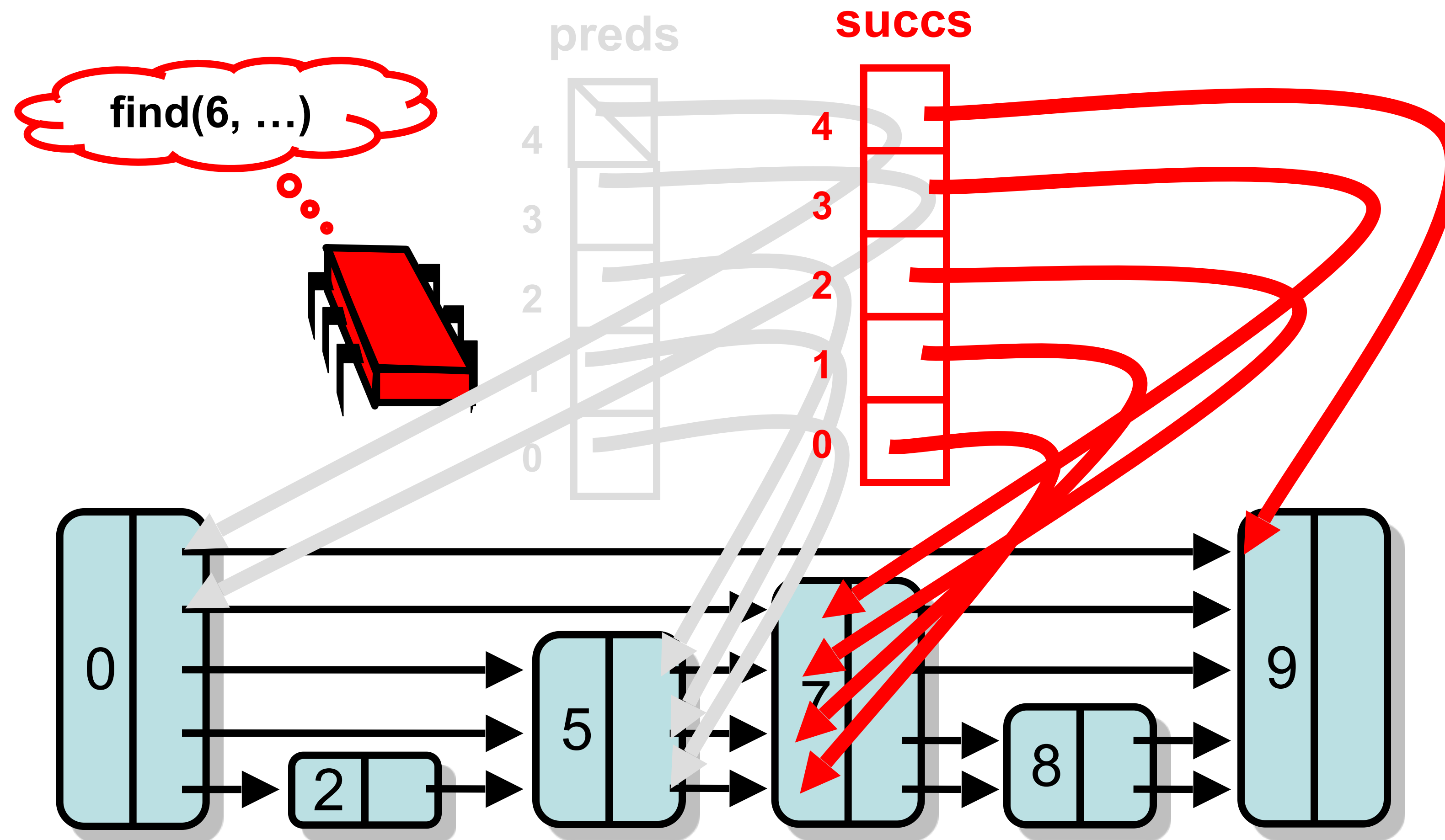
Successful Search



Unsuccessful Search



Unsuccessful Search

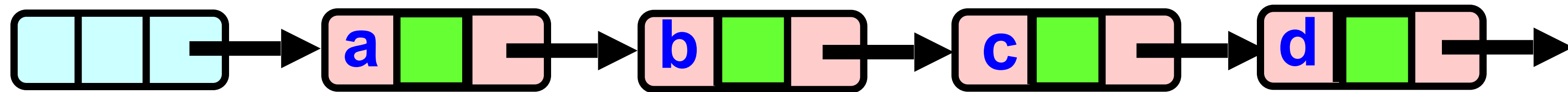


An Example (Sequential)

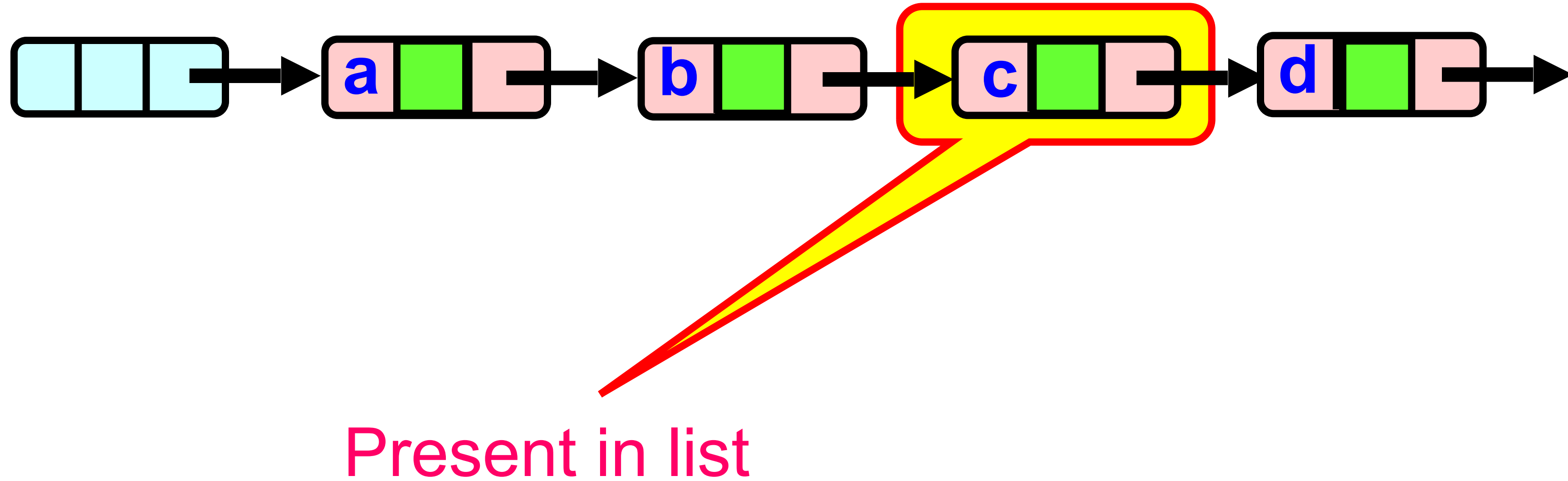
Lazy Skip List

- Mix blocking and non-blocking techniques:
 - Use optimistic-lazy locking for add() and remove()
 - Wait-free contains()
- Remember: typically lots of contains() calls but few add() and remove()

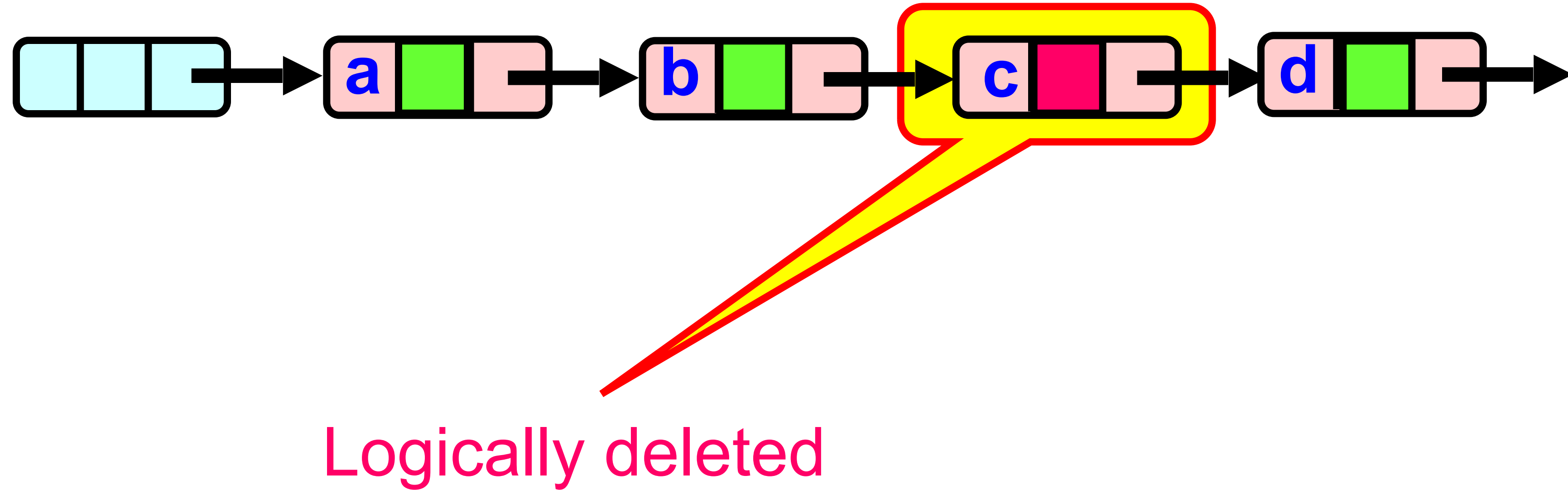
Review: Lazy List Remove



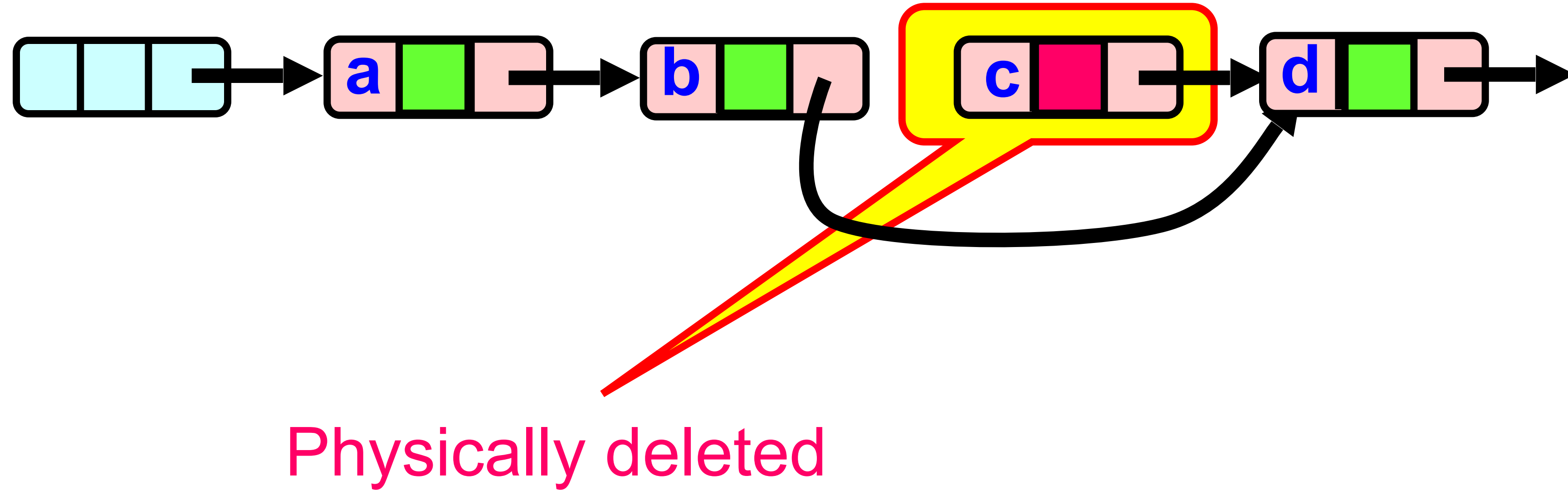
Review: Lazy List Remove



Review: Lazy List Remove

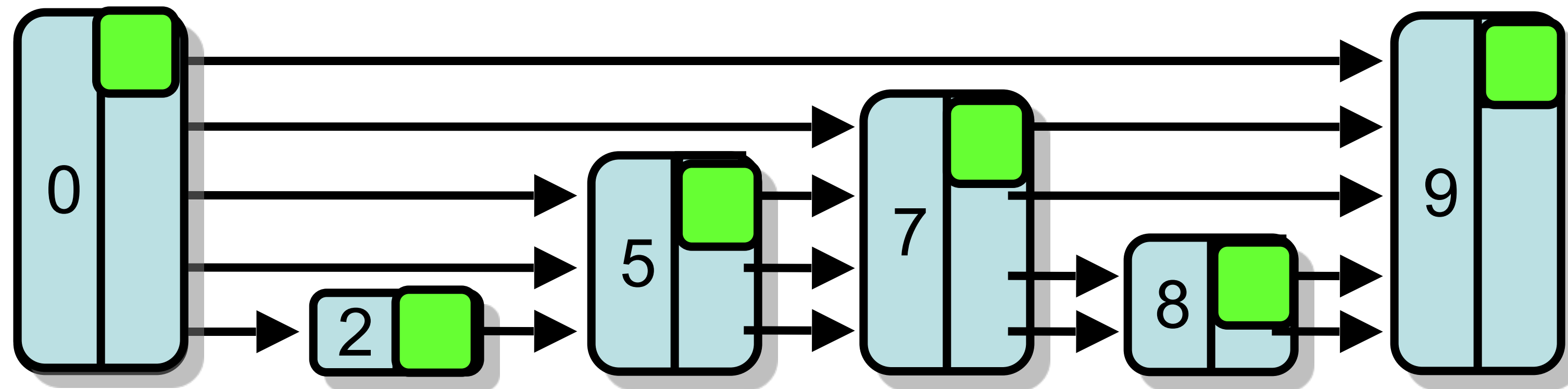


Review: Lazy List Remove



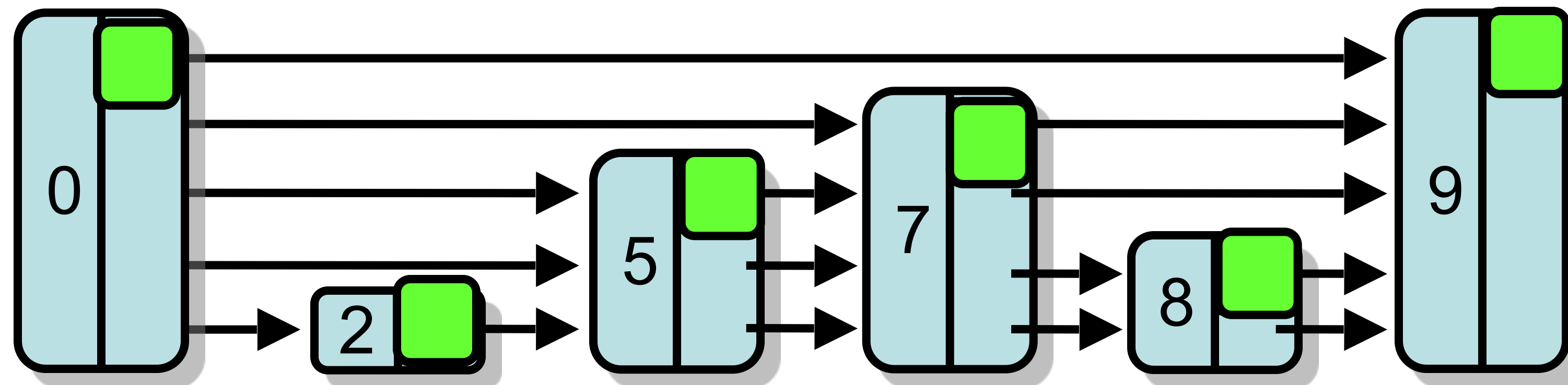
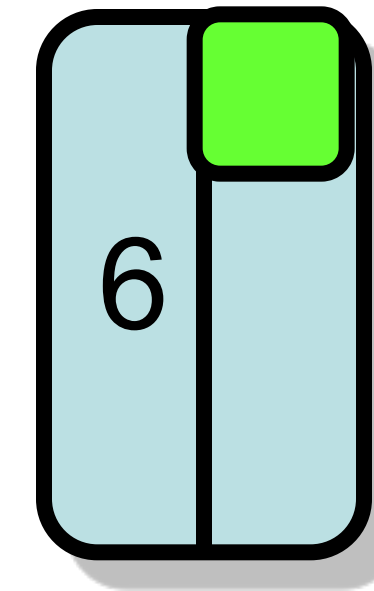
Lazy Skip Lists

- Use a mark bit for logical deletion



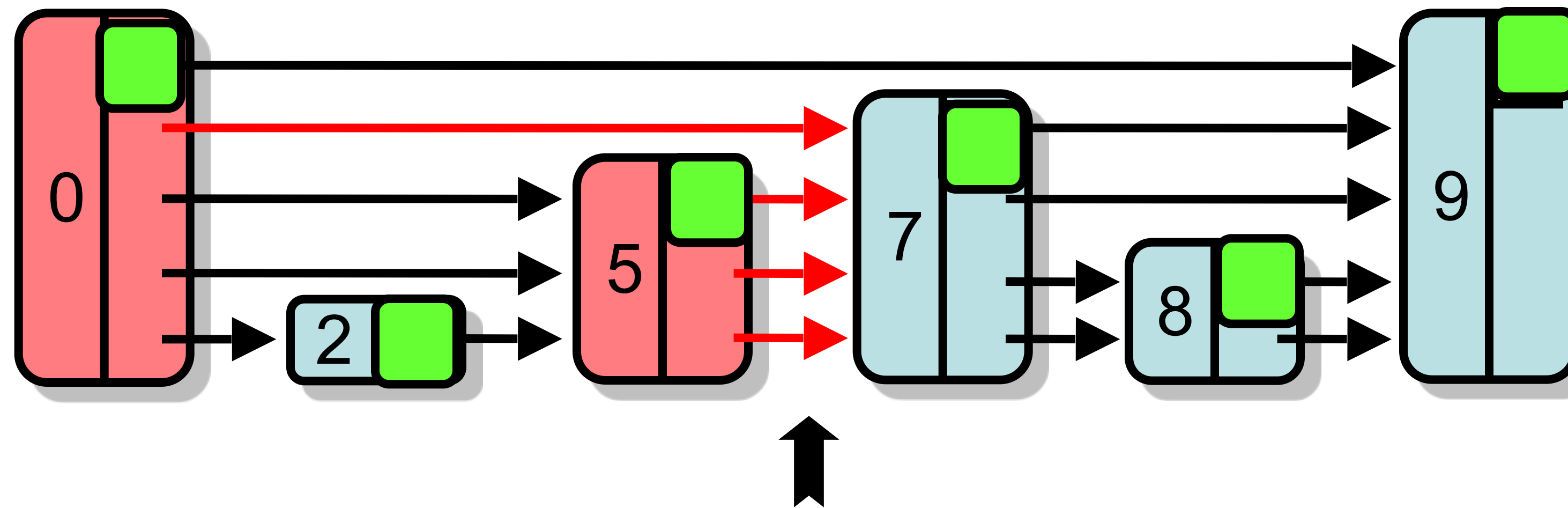
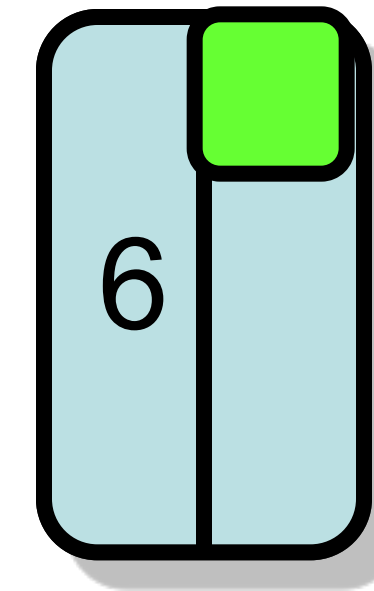
add(6)

- Create node of (random) height 4



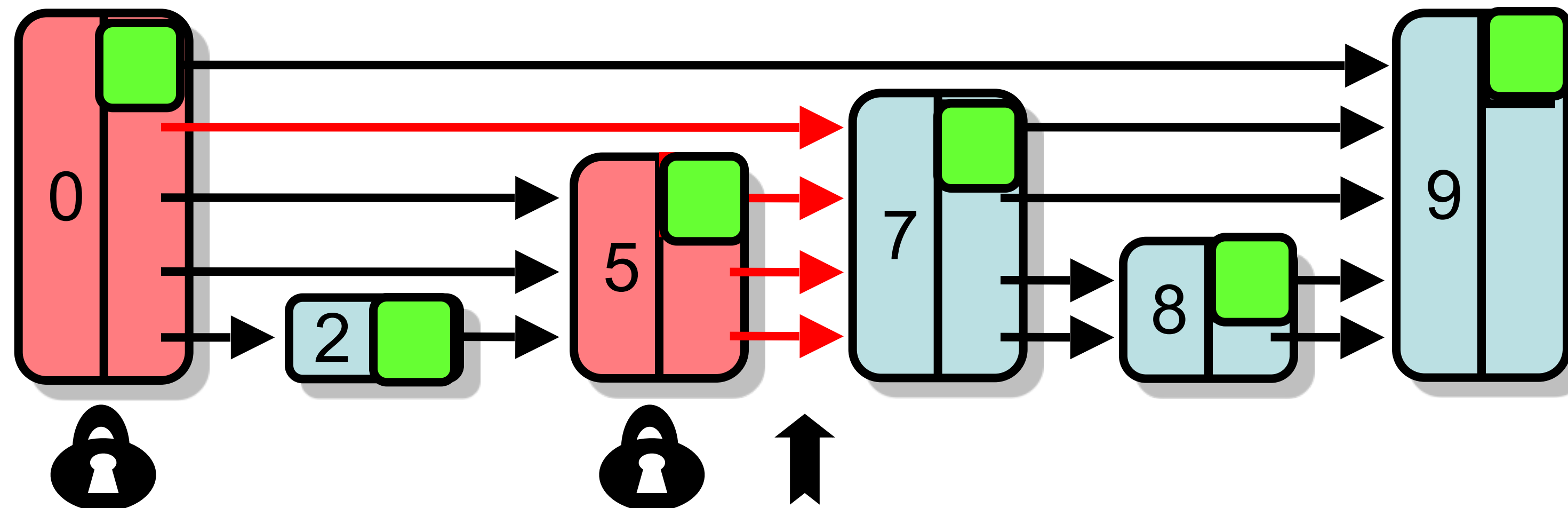
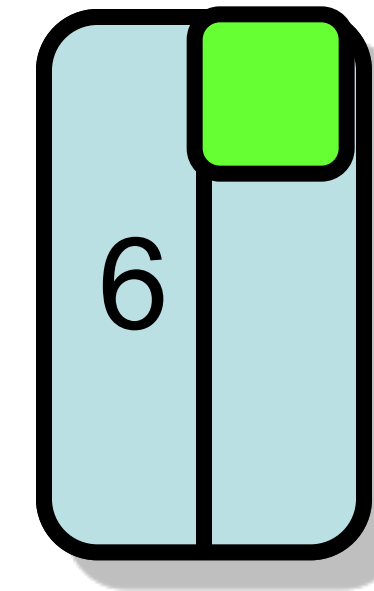
add(6)

- **find()** predecessors



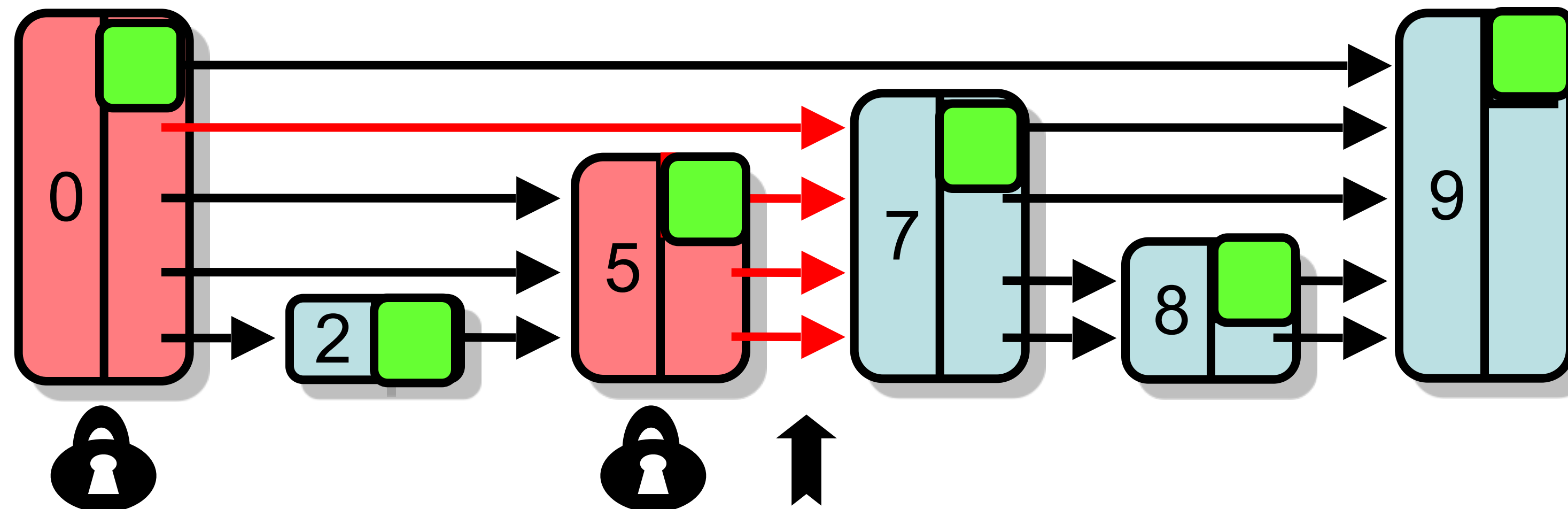
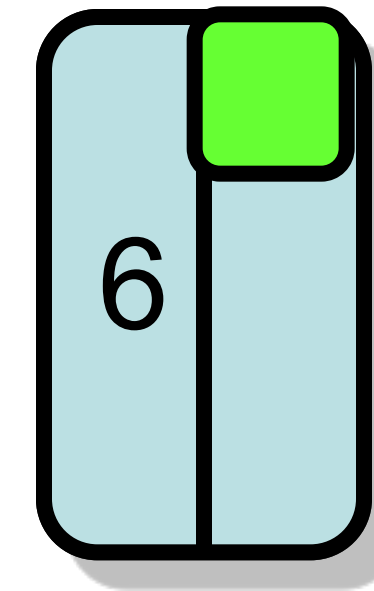
add(6)

- **find()** predecessors
- Lock them



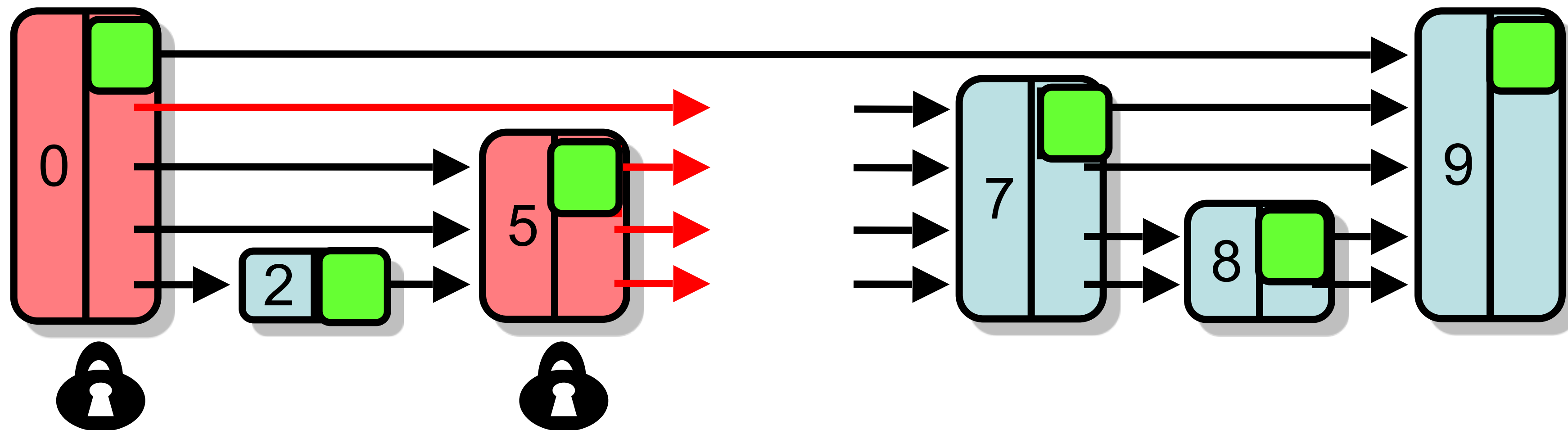
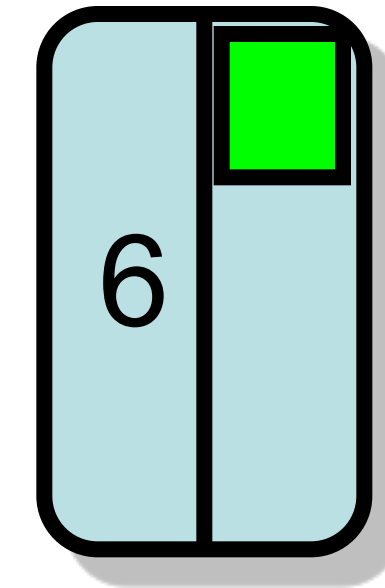
add(6)

- **find()** predecessors
 - Lock them
 - Validate
- } **Optimistic approach**



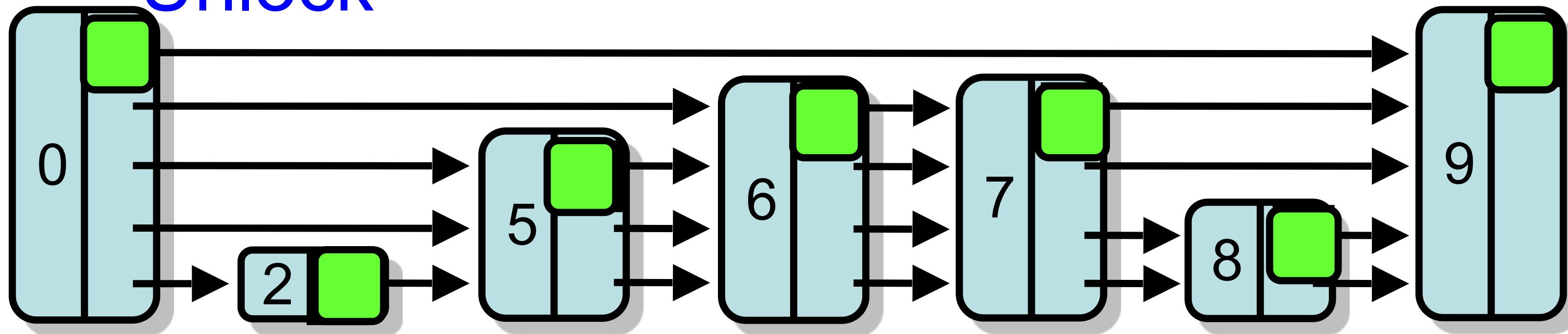
add(6)

- **find()** predecessors
- Lock them
- Validate
- Splice

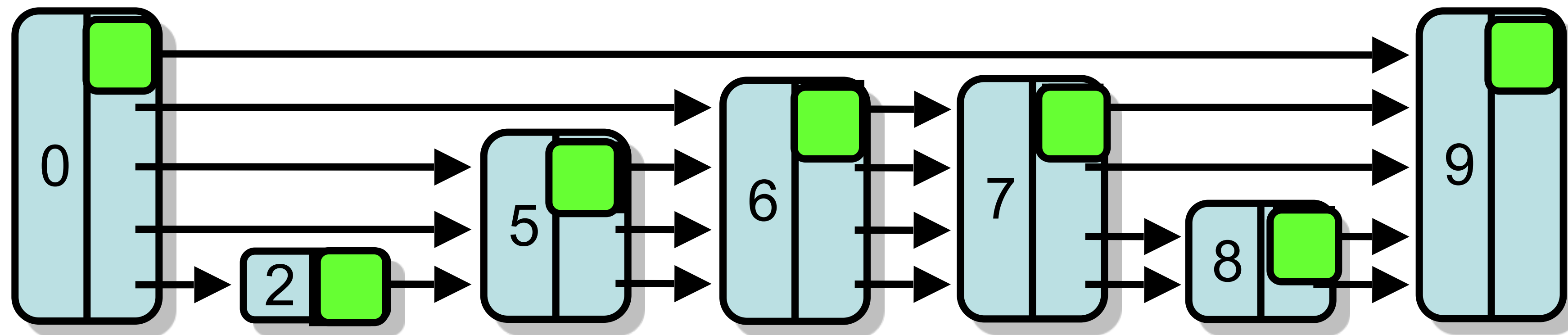


add(6)

- **find()** predecessors
- Lock them
- Validate
- Splice
- Unlock

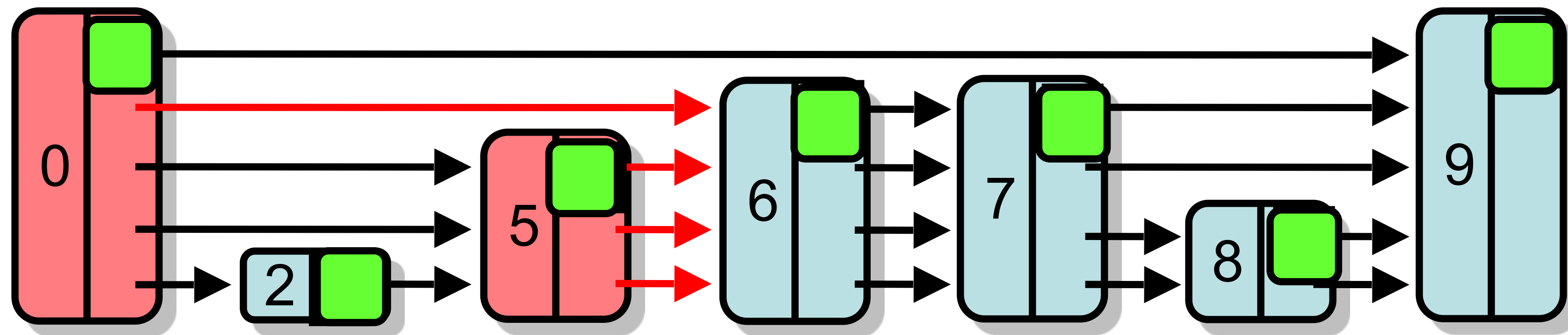


remove(6)



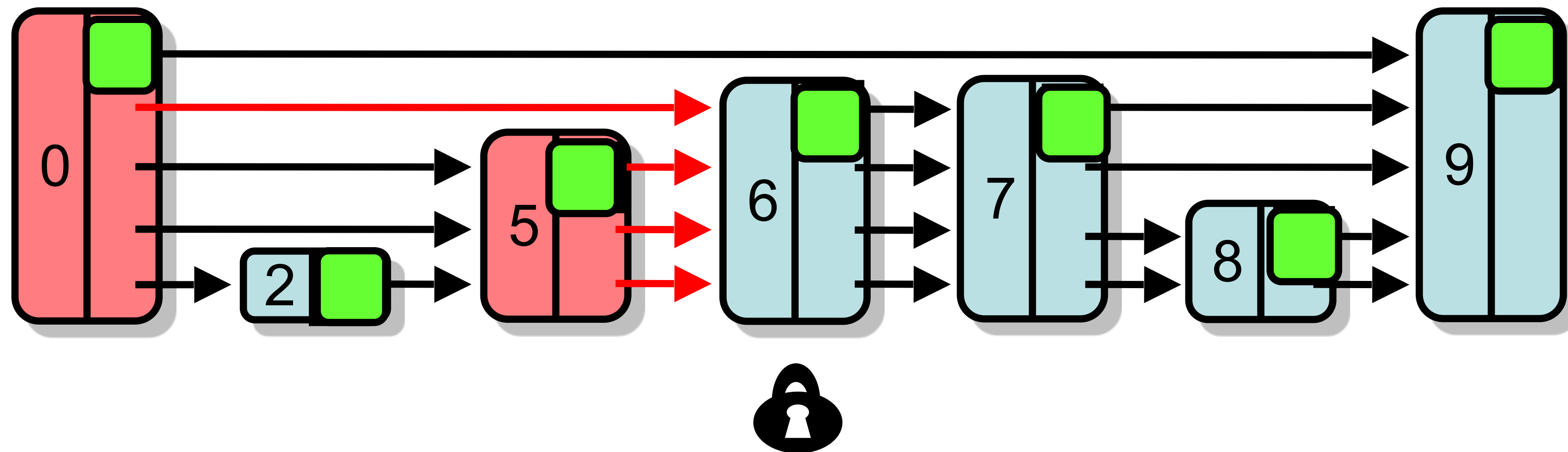
remove(6)

- **find()** predecessors



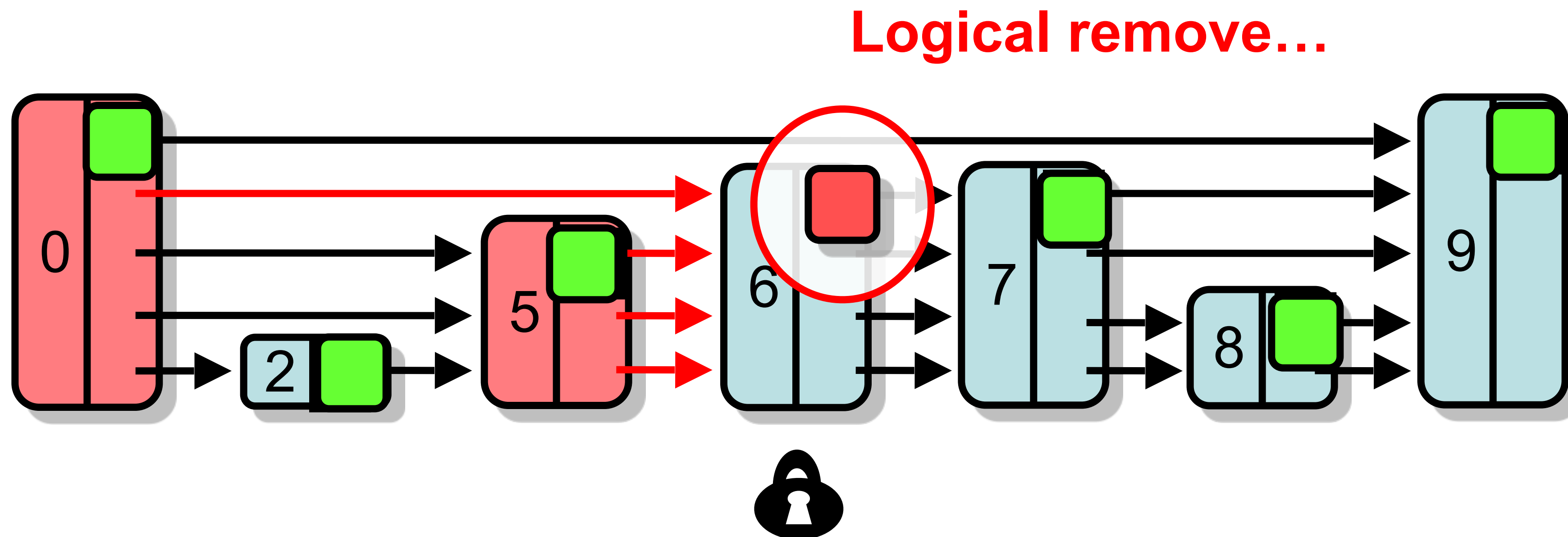
remove(6)

- **find()** predecessors
- Lock victim



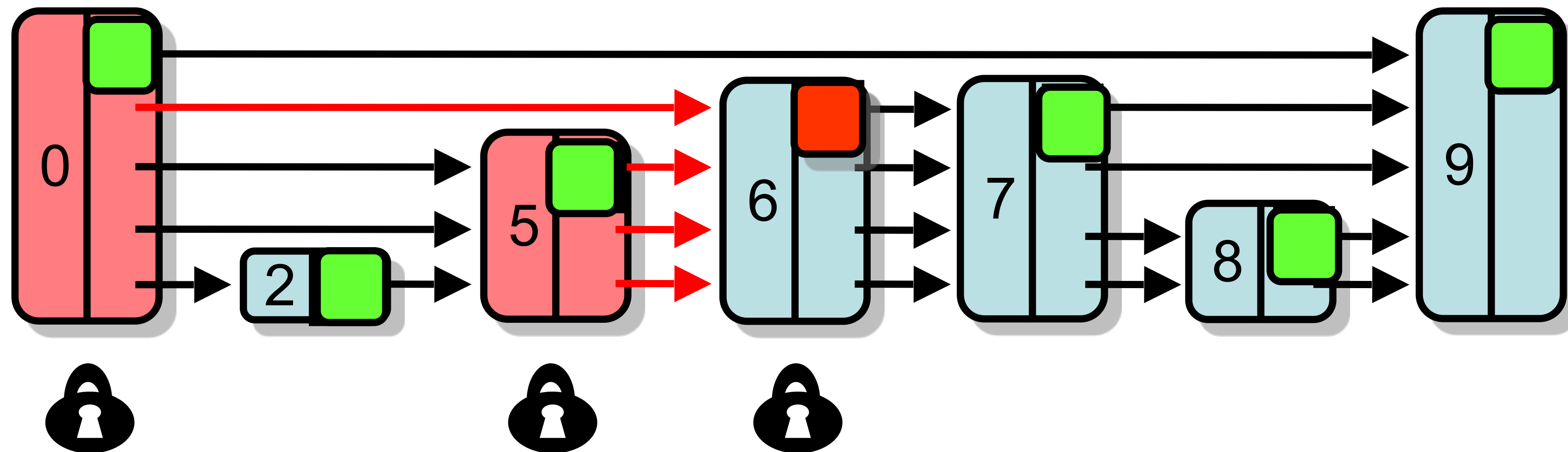
remove(6)

- **find()** predecessors
- Lock victim
- Set mark (if not already set)



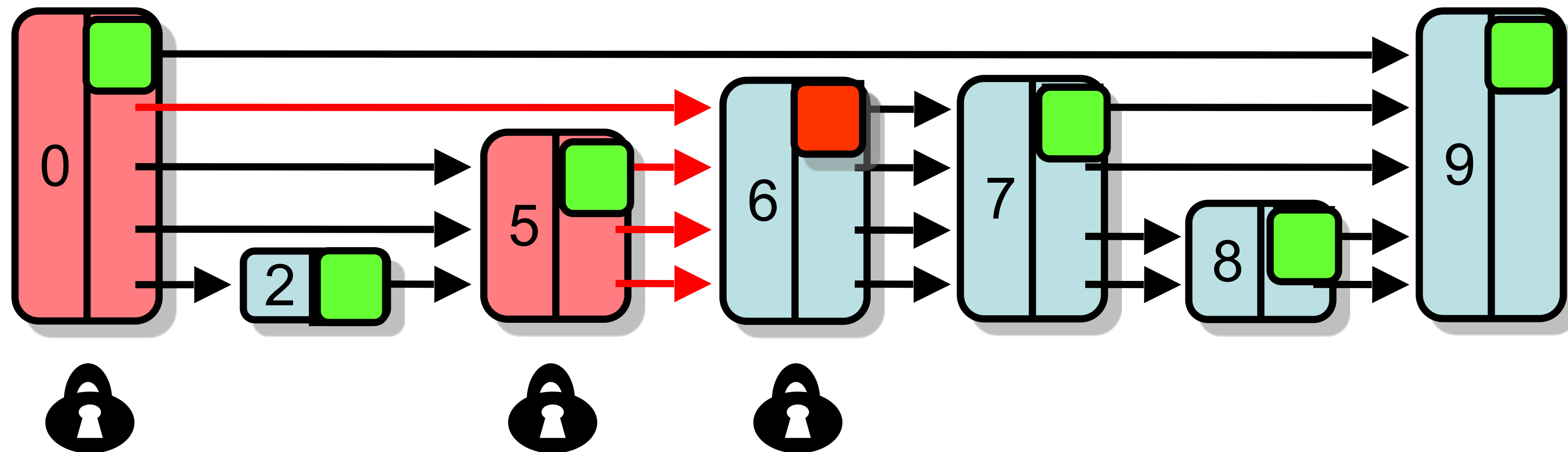
remove(6)

- **find()** predecessors
- Lock victim
- Set mark (if not already set)
- Lock predecessors (ascending order) & validate



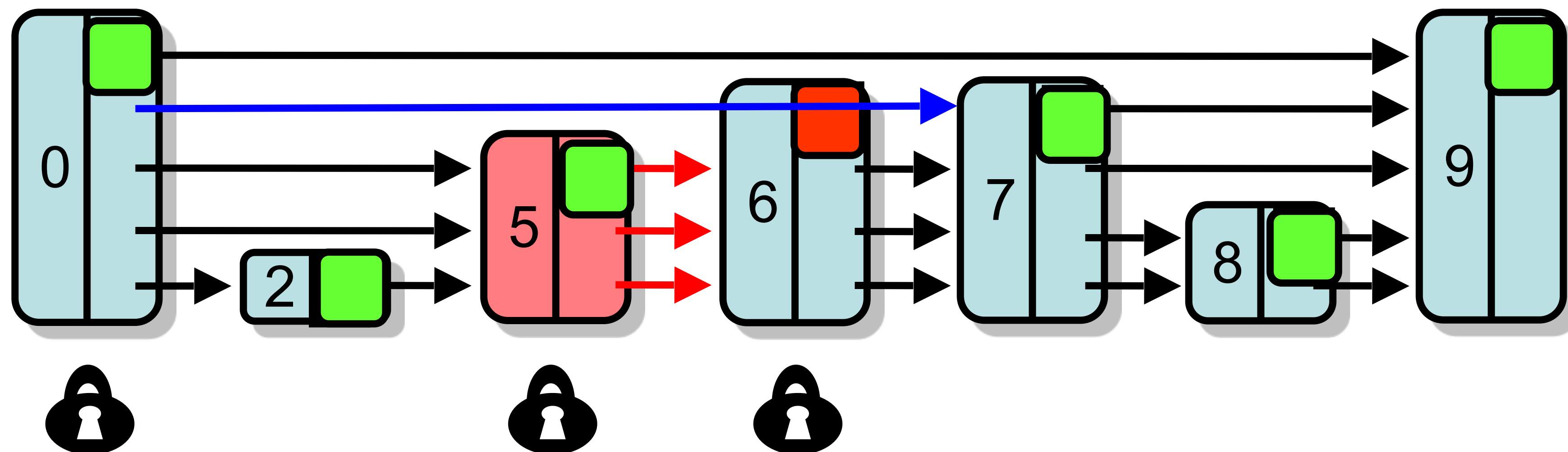
remove(6)

- **find()** predecessors
- Lock victim
- Set mark (if not already set)
- Lock predecessors (ascending order) & validate
- Physically remove



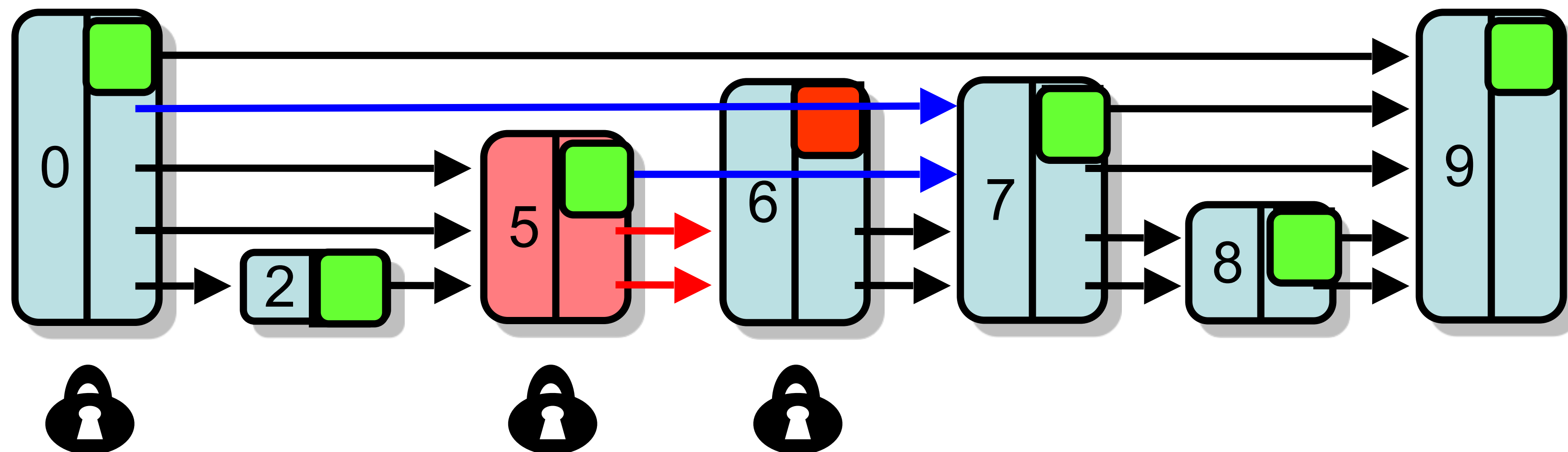
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- Lock victim
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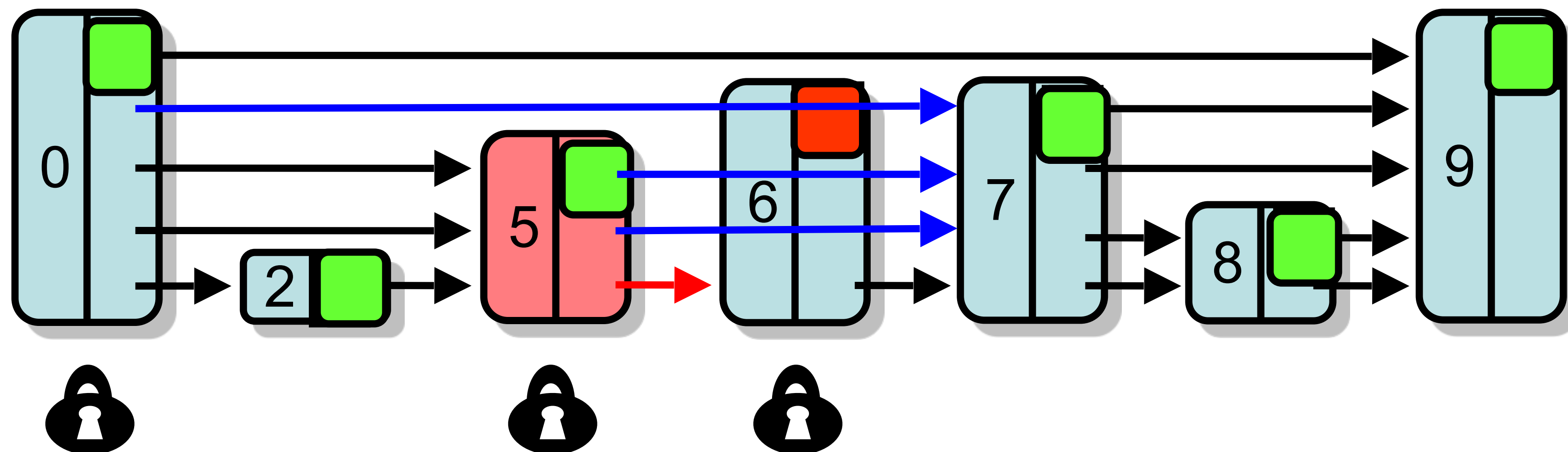
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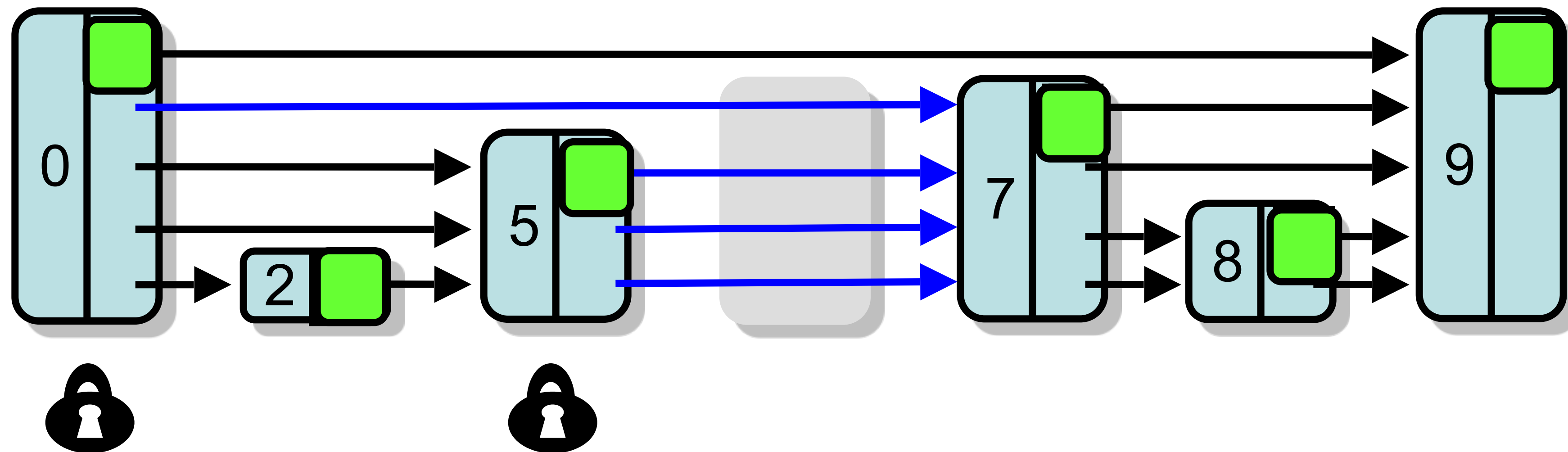
remove(6)

- **find()** predecessors
- Lock victim
- Set mark (if not already set)
- Lock predecessors (ascending order) & validate
- Physically remove



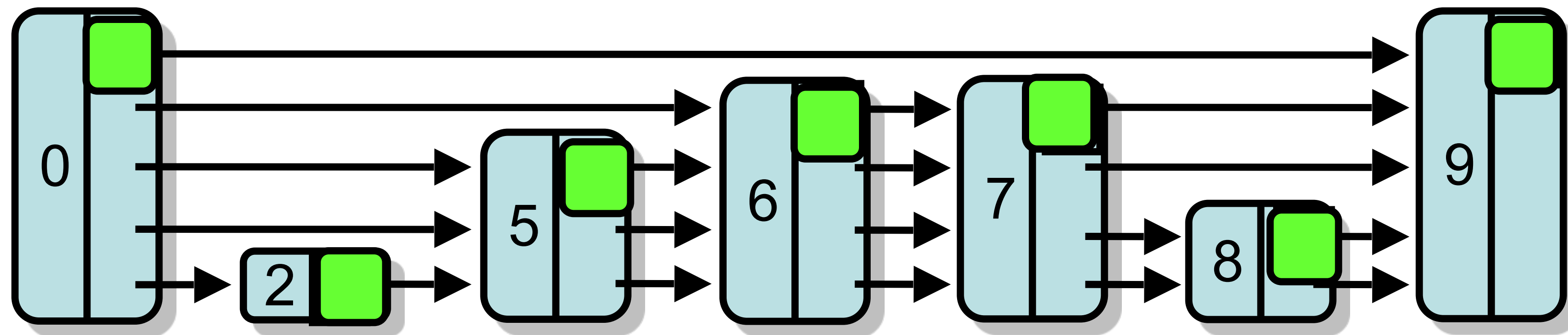
remove(6)

- **find()** predecessors
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- Lock predecessors (ascending order) & validate
- Physically remove



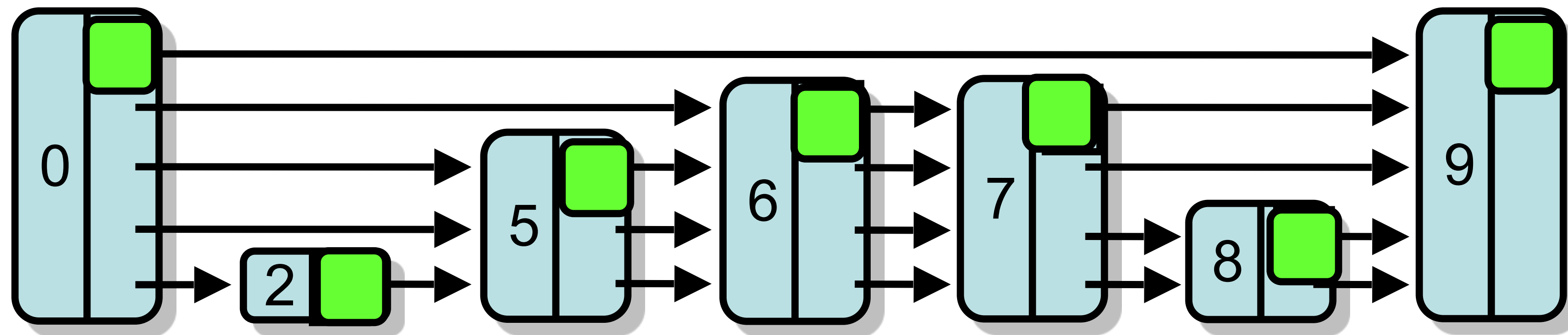
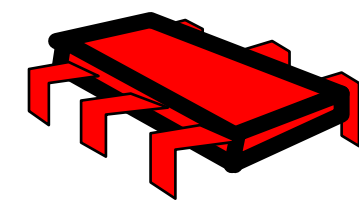
contains(8)

- **find()** & not marked



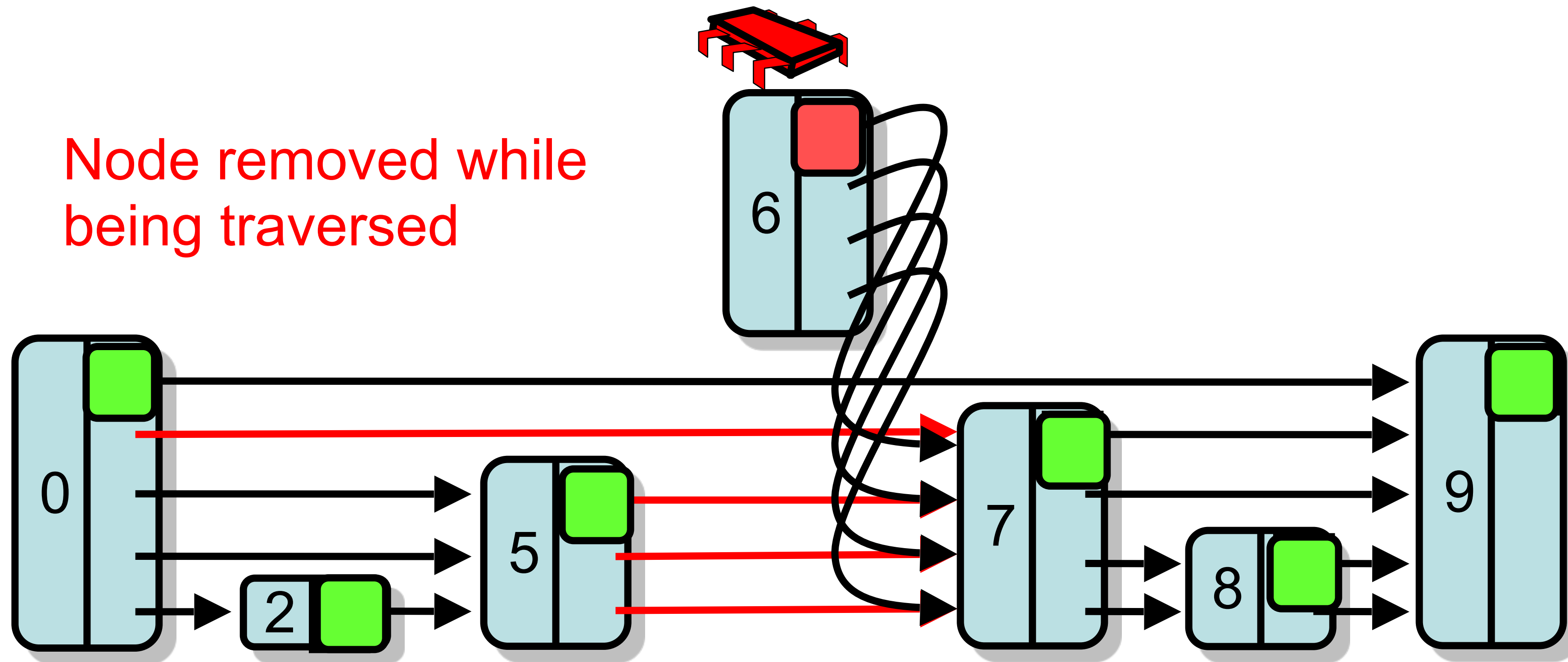
contains(8)

Node 6 removed while traversed



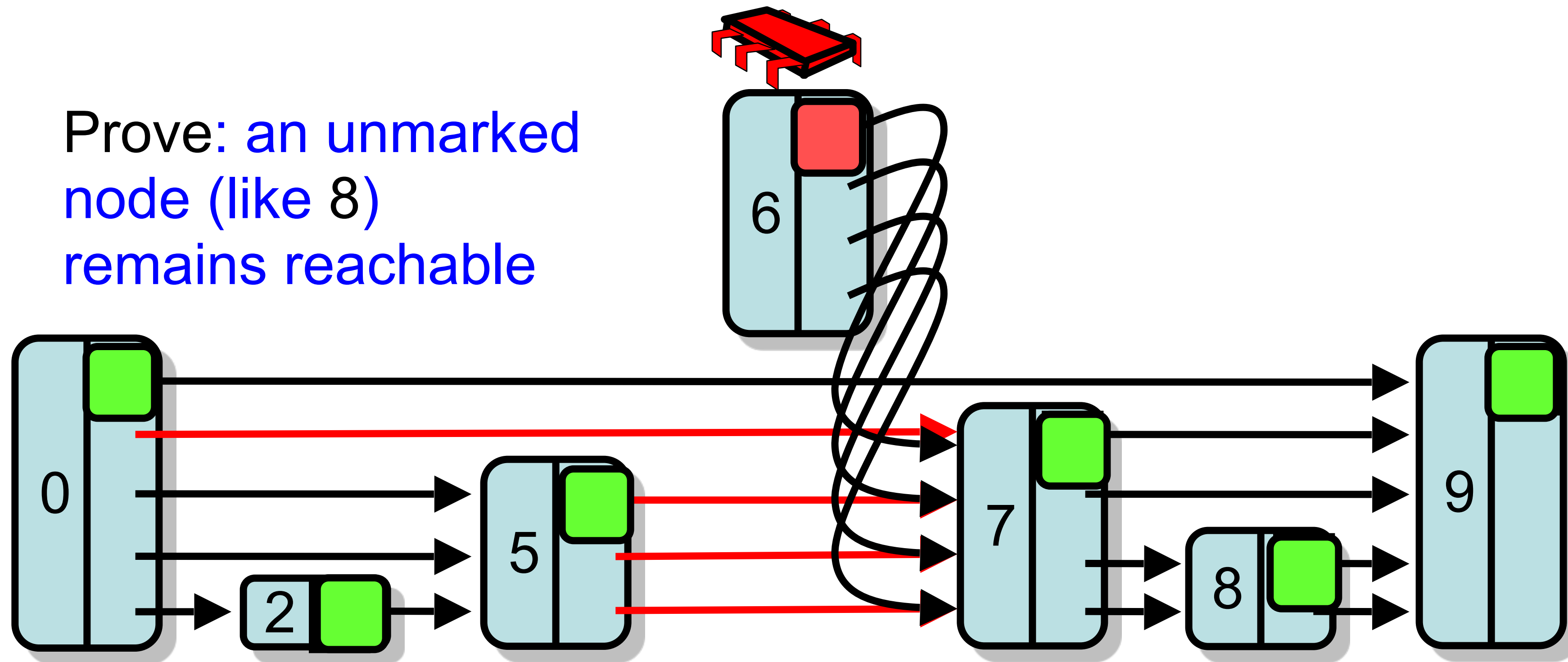
contains(8)

Node removed while
being traversed



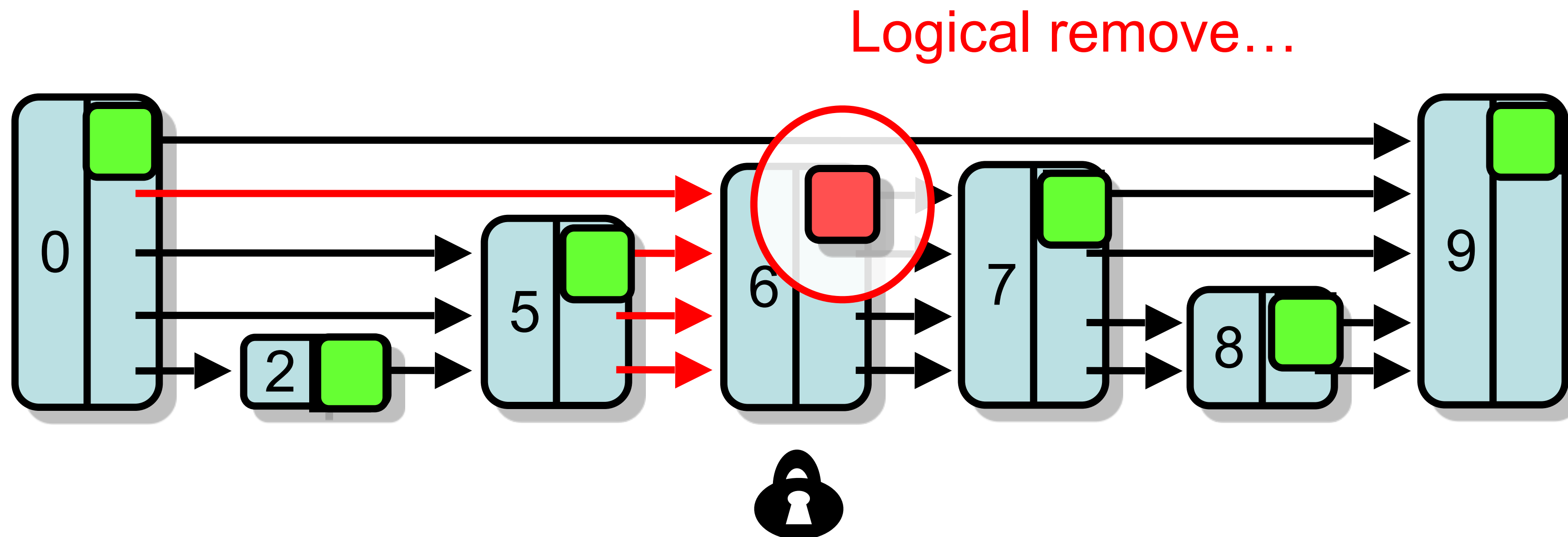
contains(8)

Prove: an unmarked
node (like 8)
remains reachable



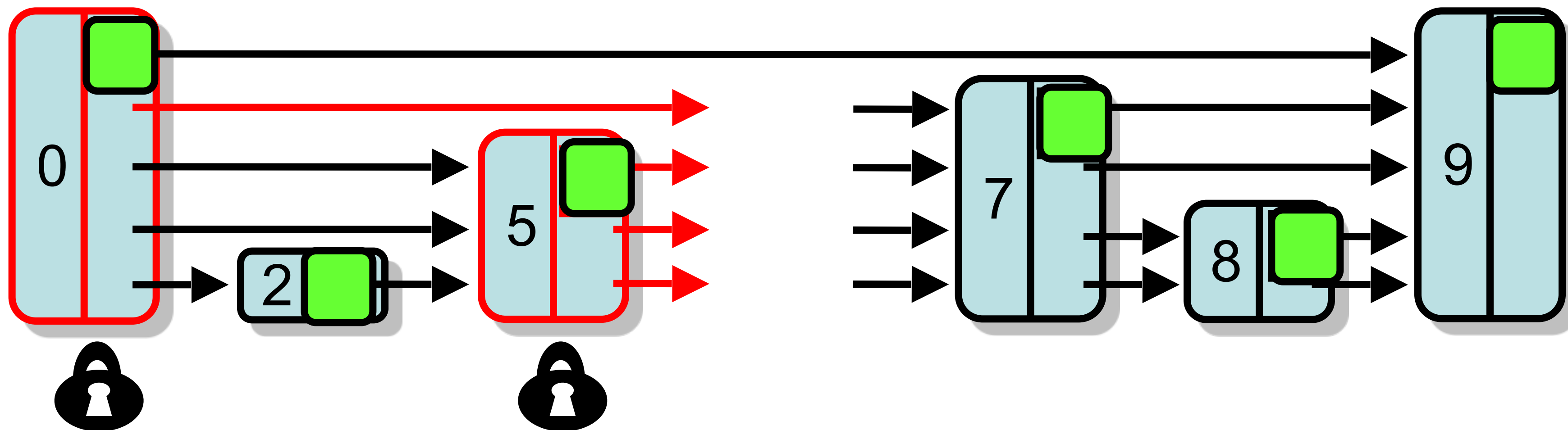
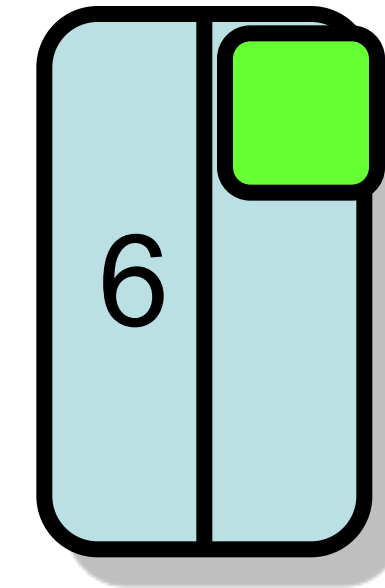
remove(6): Linearization

- Successful remove happens when bit is set



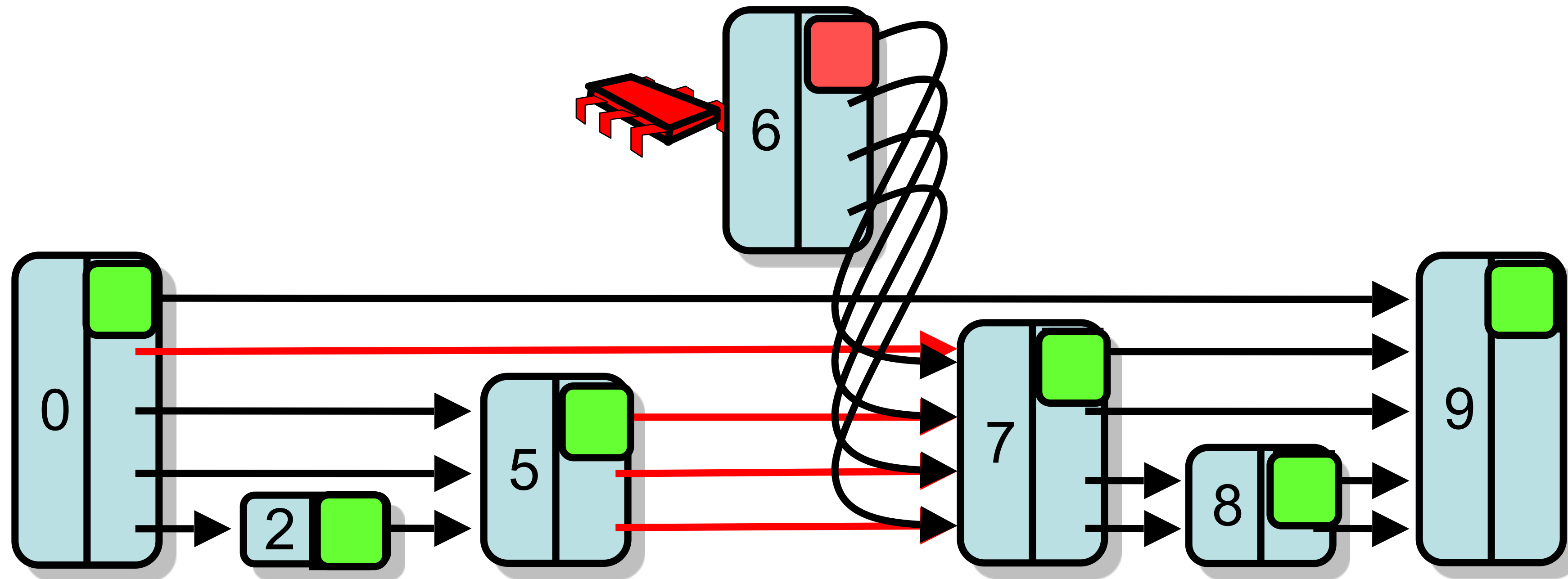
Add: Linearization

- Successful add() at point when fully linked
- Add fullyLinked bit to indicate this
- Bit tested by contains()



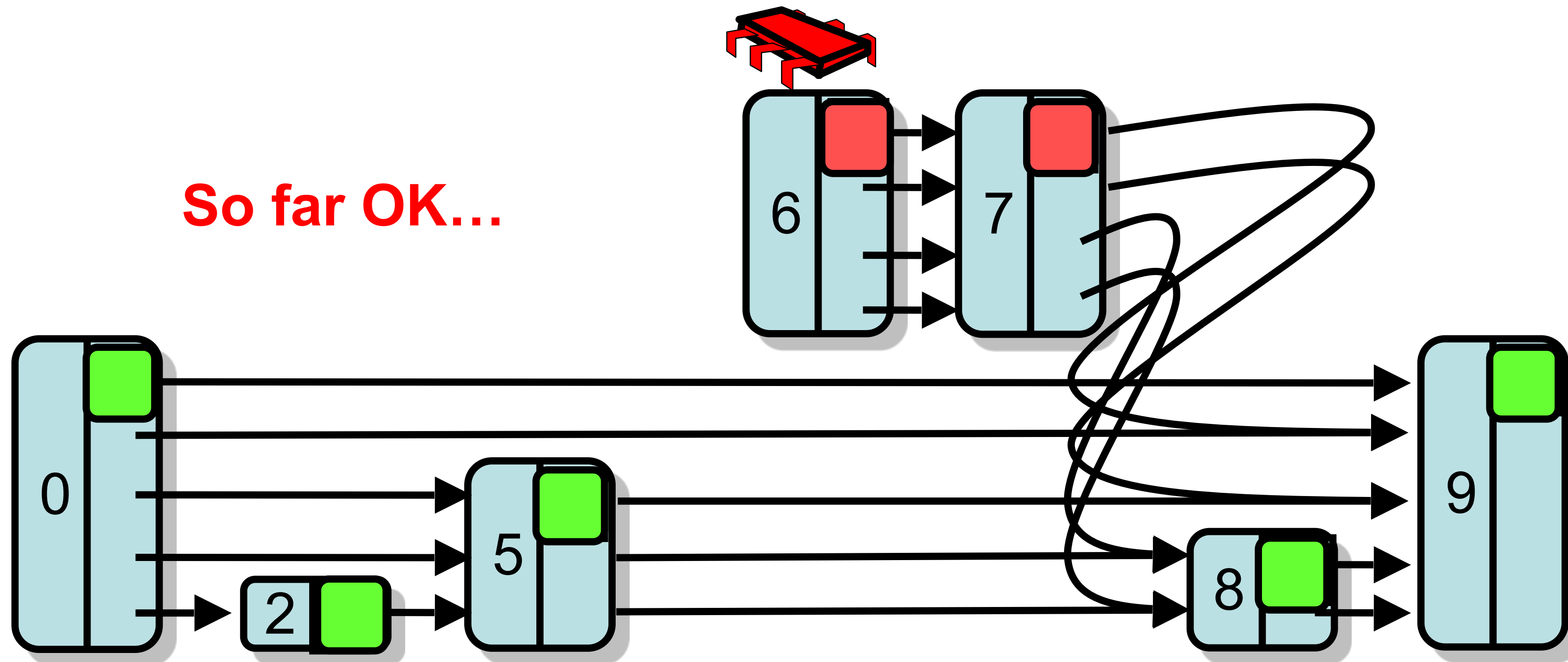
contains(7): Linearization

- When fully-linked unmarked node found
- Pause while fullyLinked bit unset



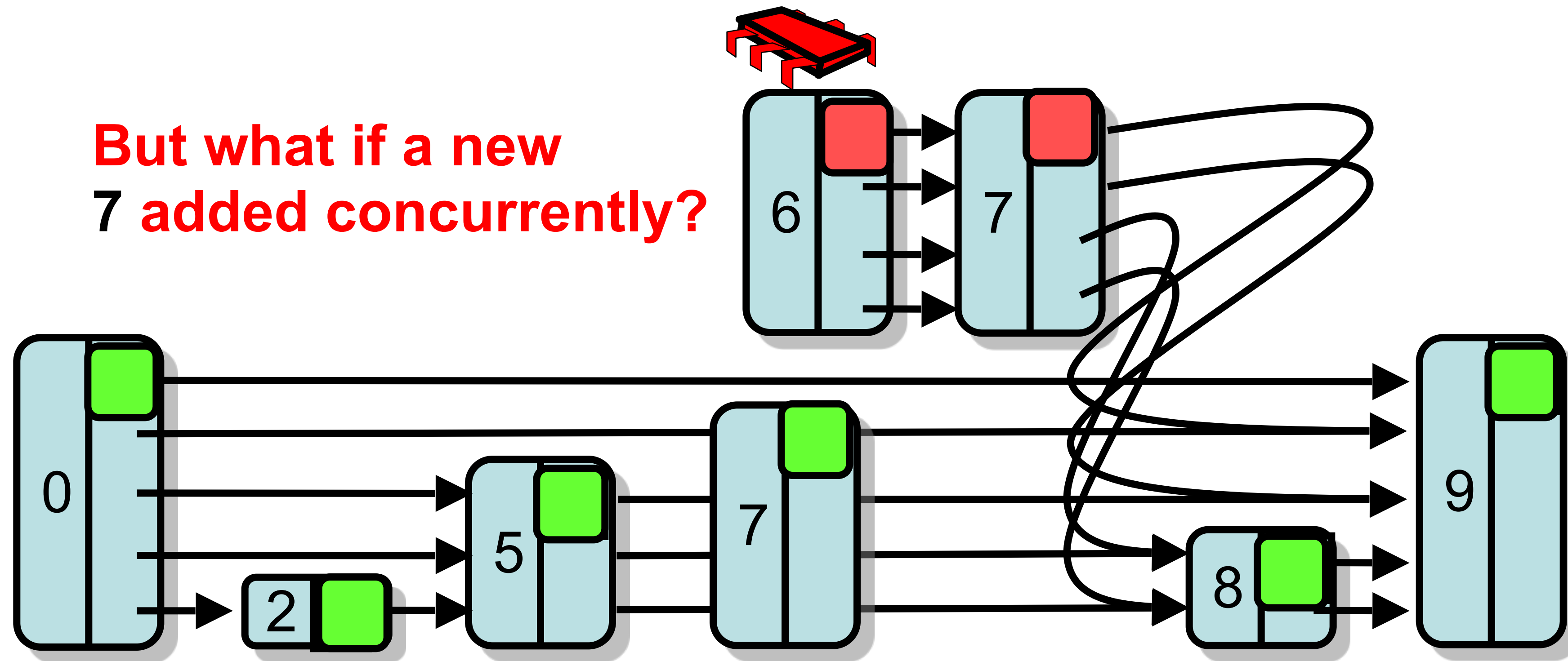
contains(7): Linearization

- When do we linearize unsuccessful Search?



contains(7): Linearization

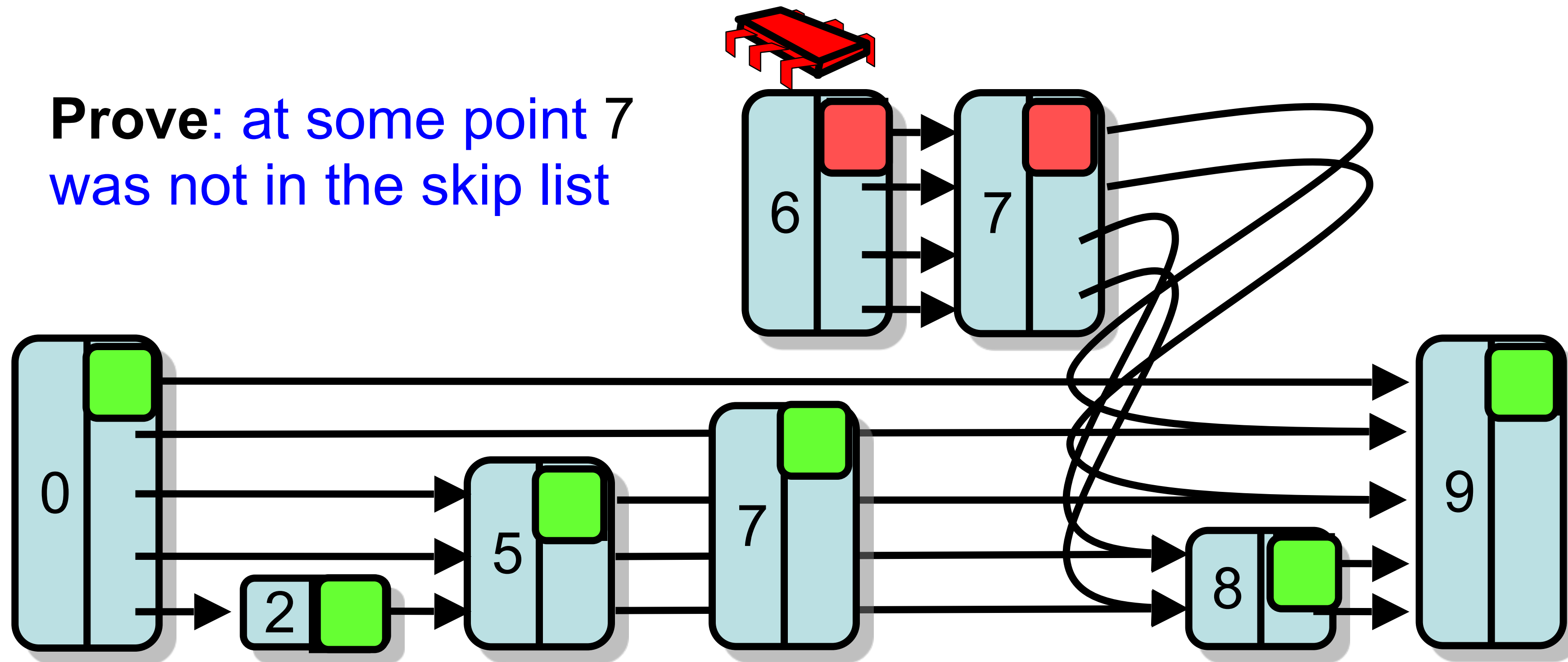
- When do we linearize unsuccessful Search?



contains(7): Linearization

- When do we linearize unsuccessful Search?

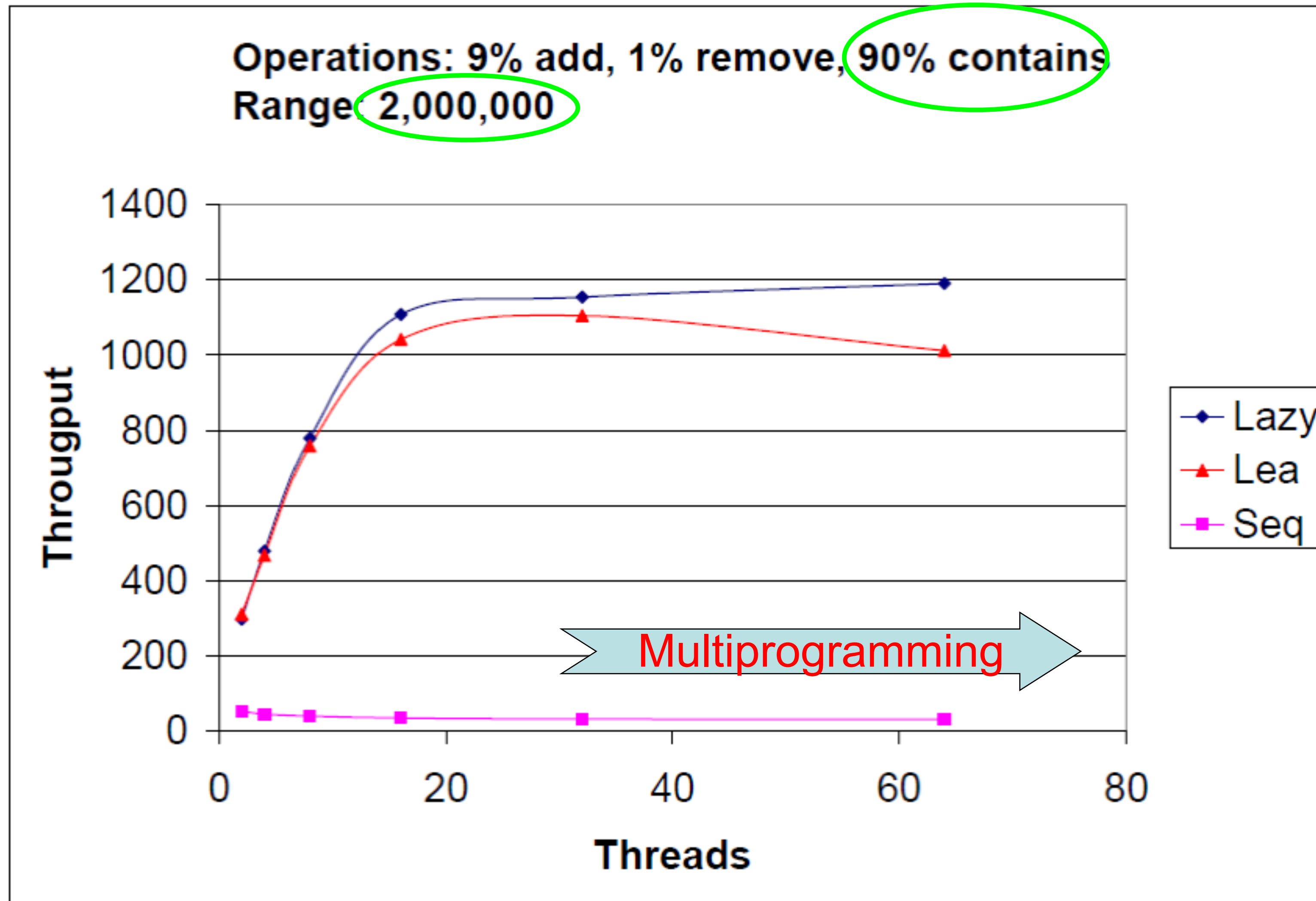
Prove: at some point 7 was not in the skip list



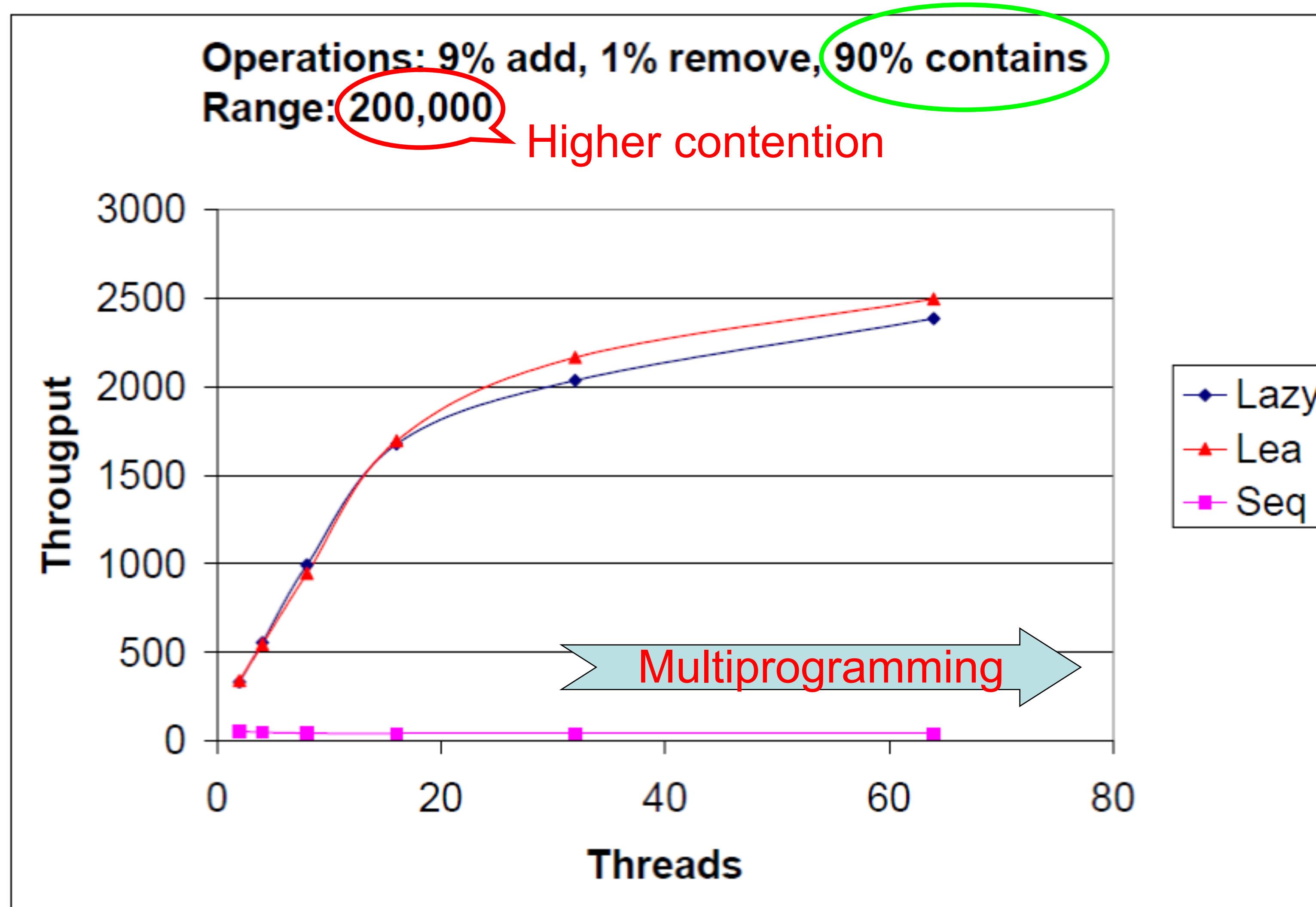
Coding Time!

- Design a benchmark suite for concurrent set implementations allowing arbitrary numbers of threads and operations.
- Use the ideas from the previous lectures.
- Implement it for *optimistic lists*, *lazy lists* and *lazy skip-lists* and determine the winner!
- Also, let's add Java's concurrent set implementation (by Doug Lea) into the mix

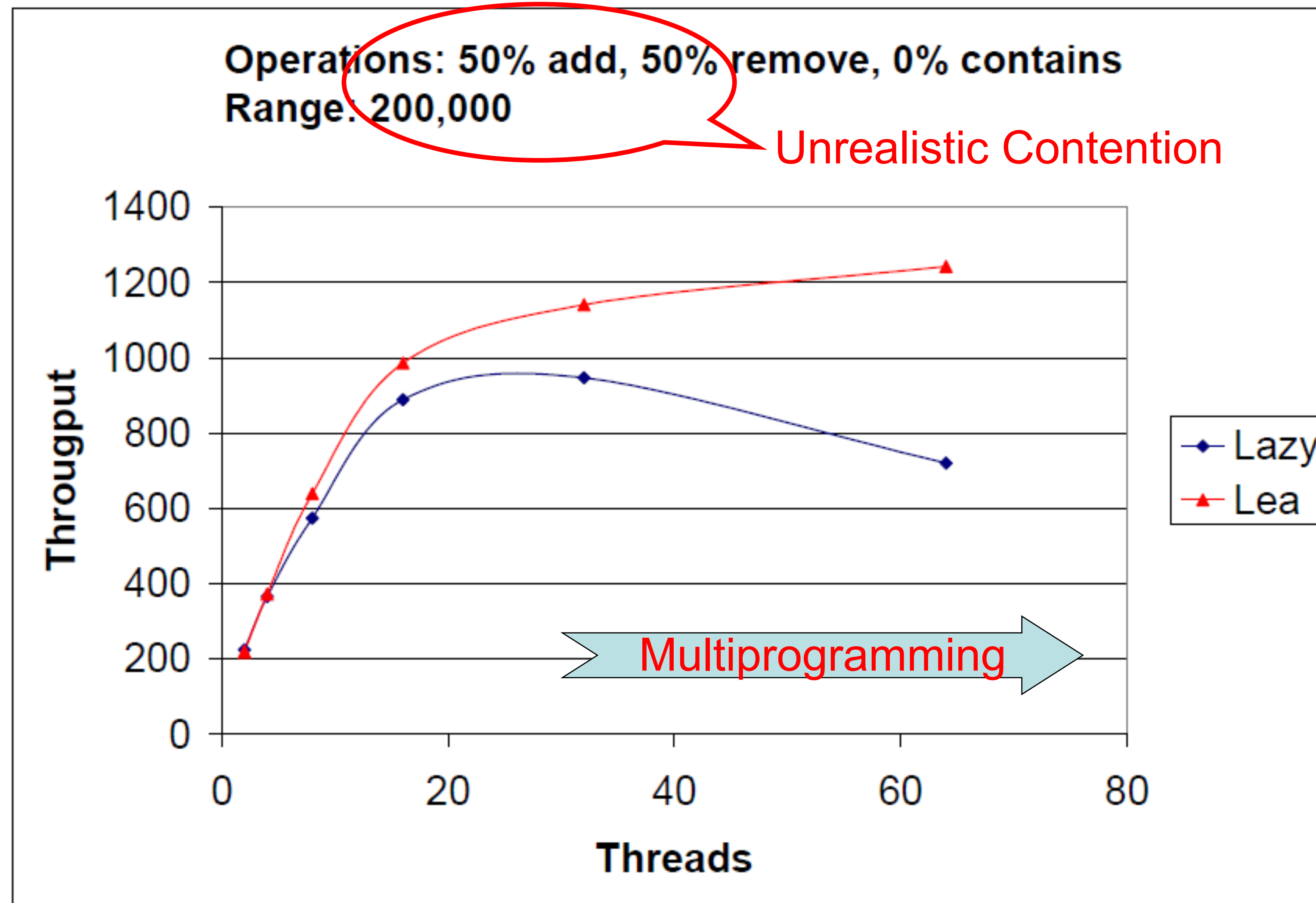
Lazy Skip List: Performance



Lazy Skip List: Performance



Lazy Skip List: Performance



Summary

- Lazy Skip List
 - Optimistic fine-grained Locking
- Performs as well as the lock-free solution in “common” cases
- Simple

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