YSC4231: 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)

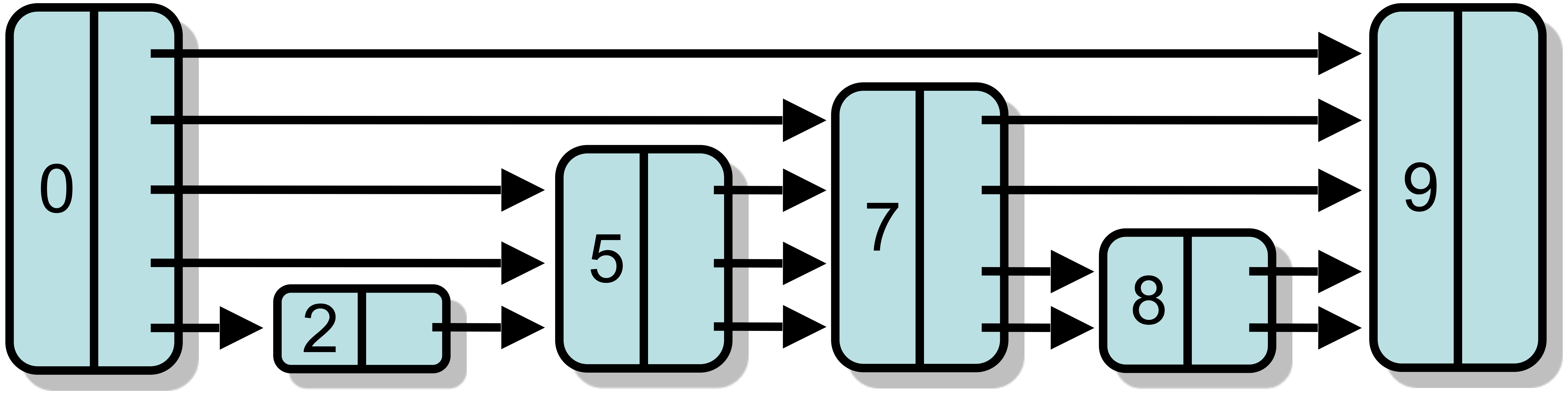
- Any ideas on how we can do better?

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

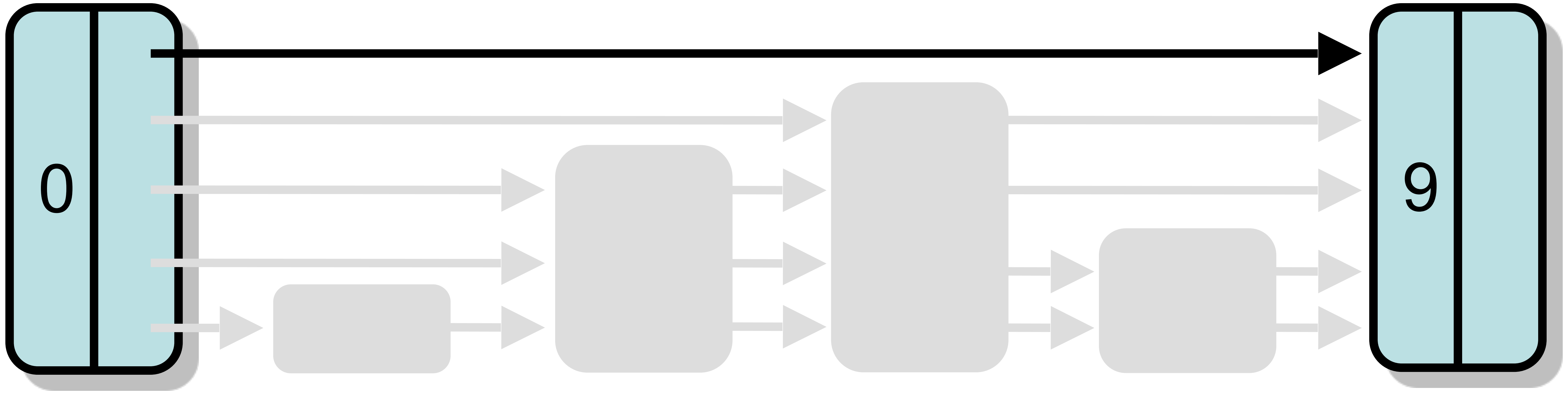
Skip Lists

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



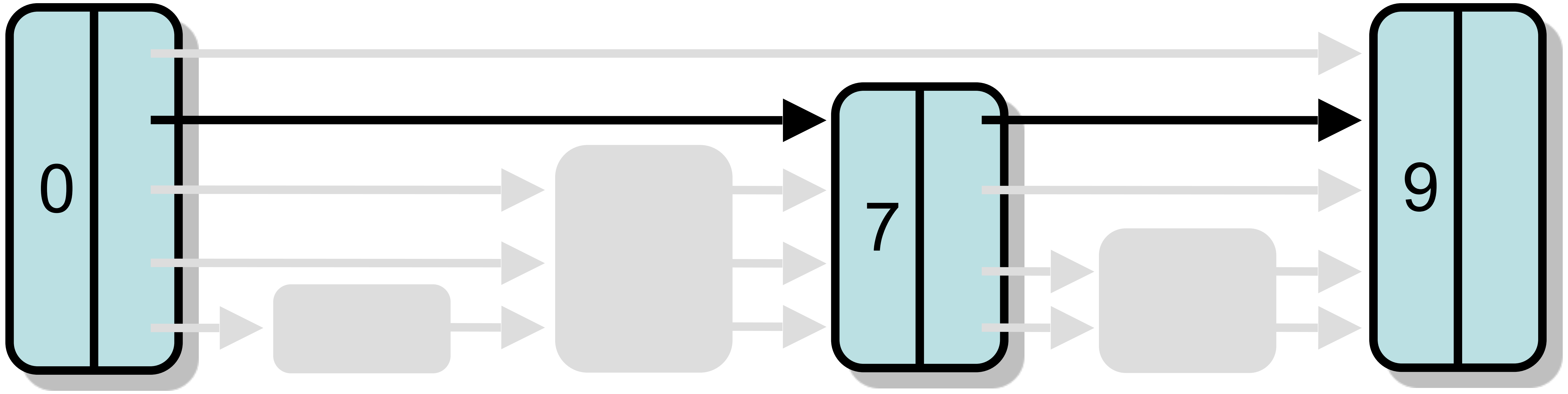
Skip List Property

- Each layer is sub-list of lower levels



Skip List Property

- Each layer is sub-list of lower-levels



Skip List Property

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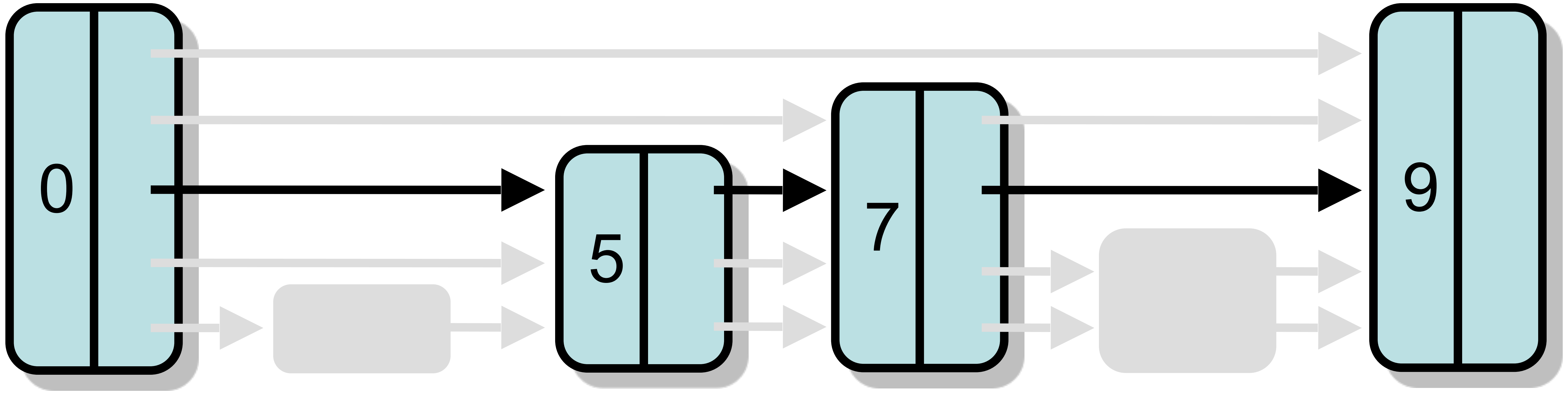

Skip List Property

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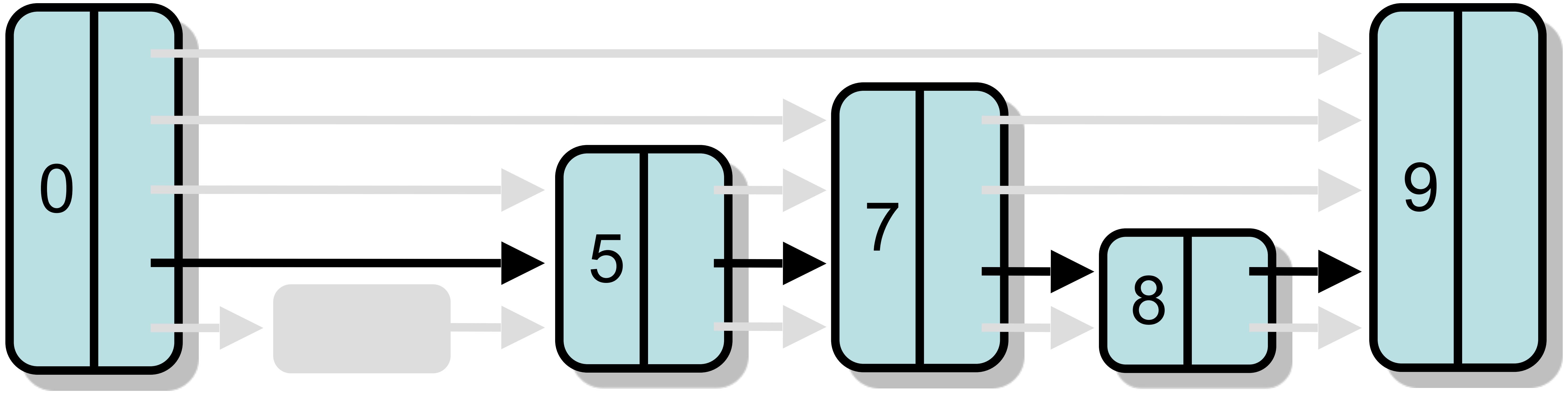
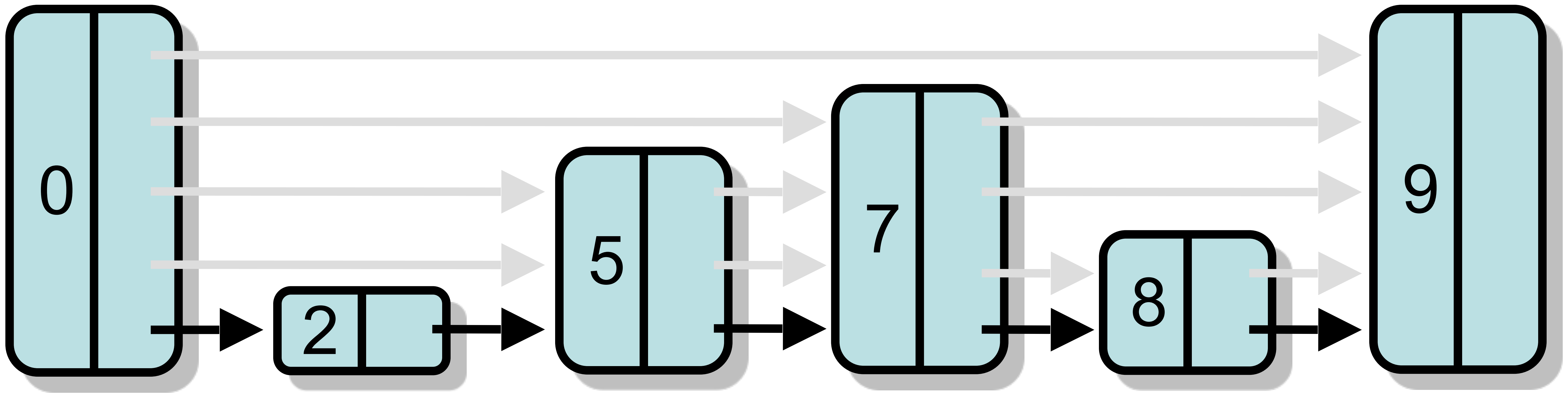


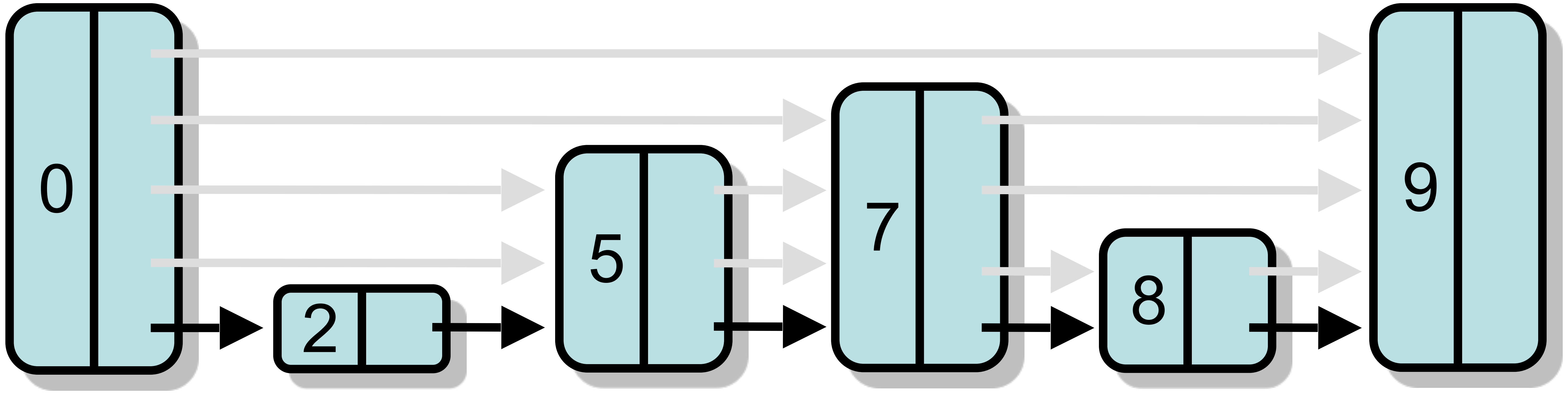
Skip List Property

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

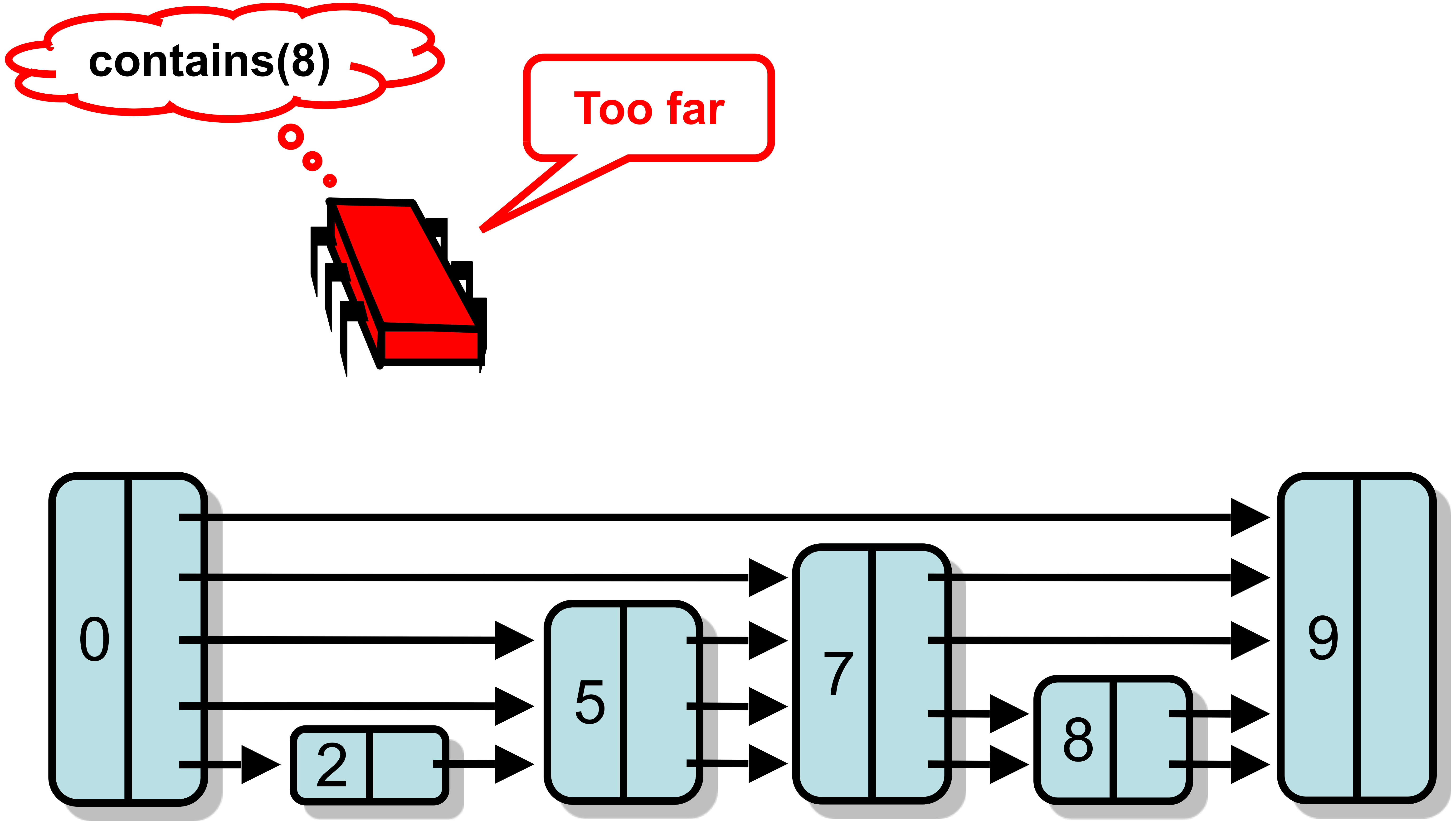


Skip List Property

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



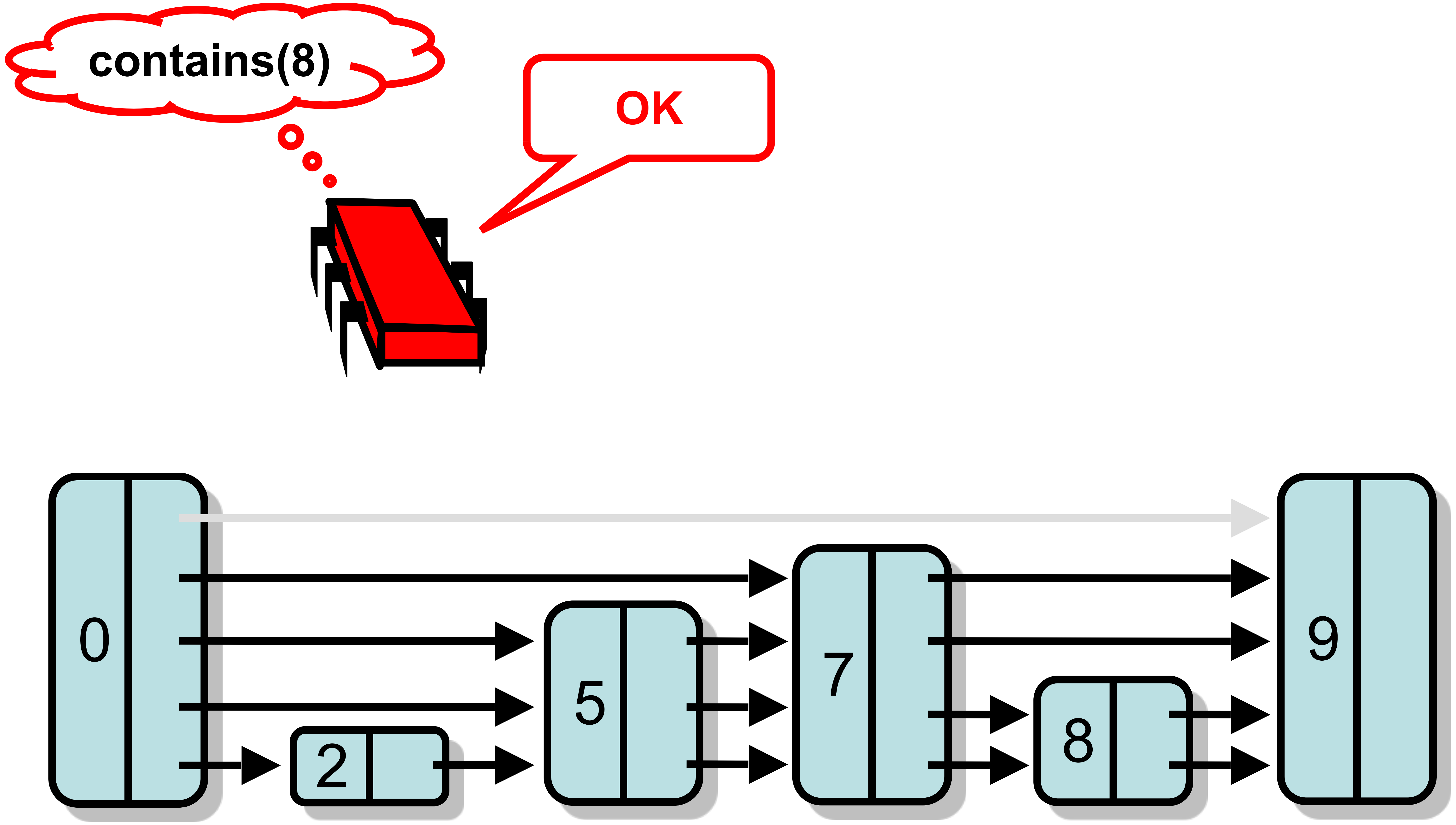
Search



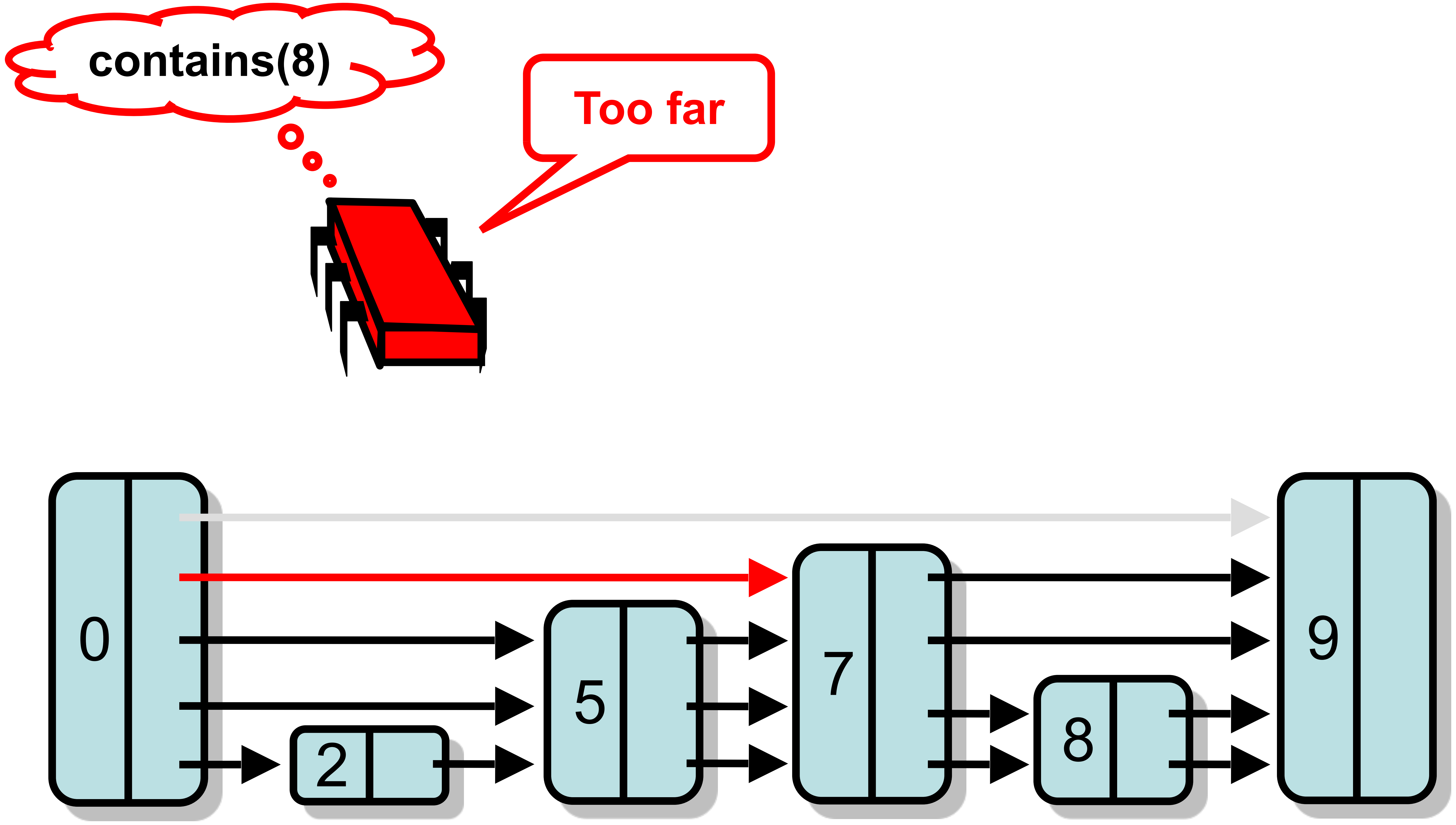
contains(8)

Too far

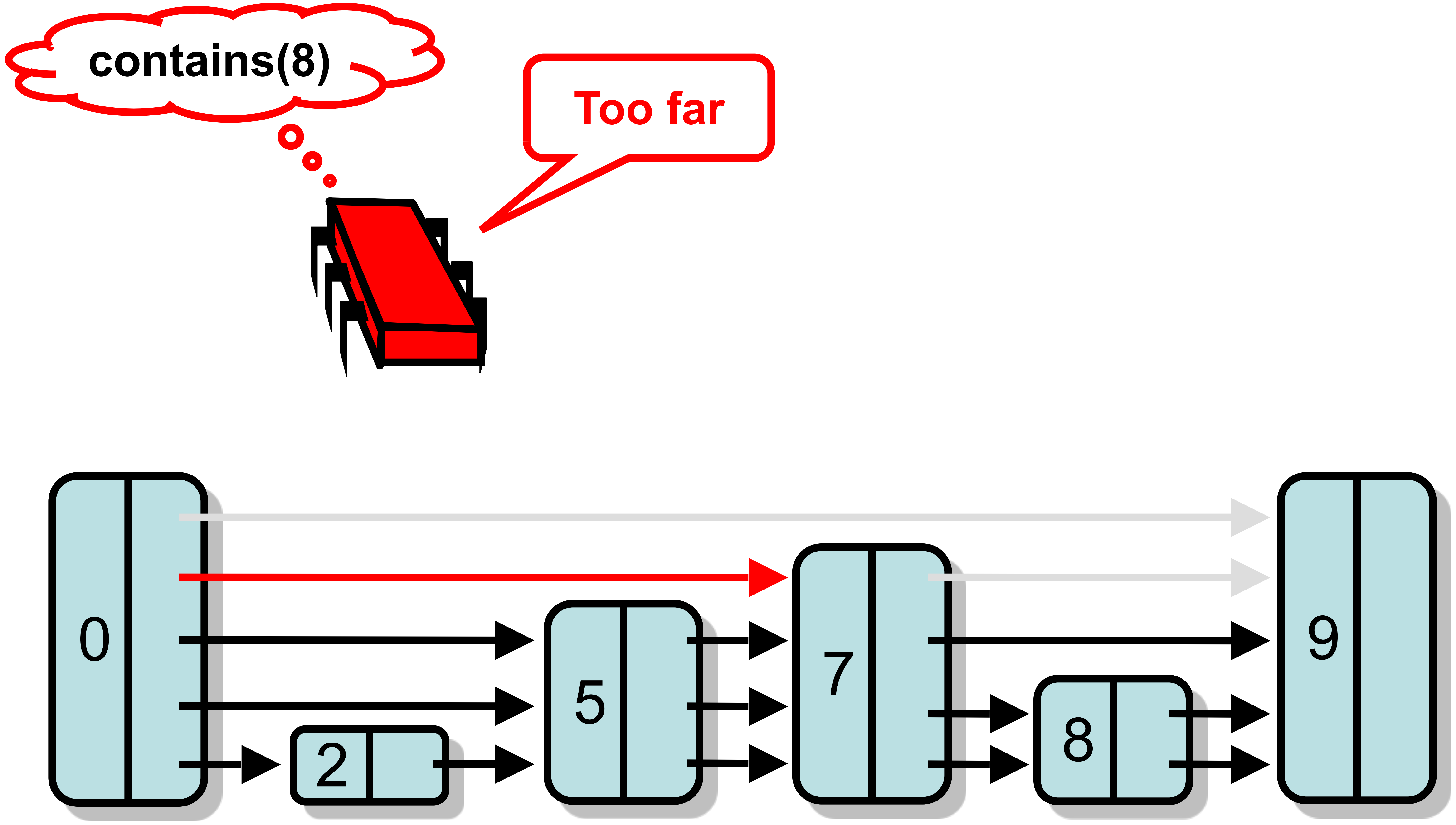
Search



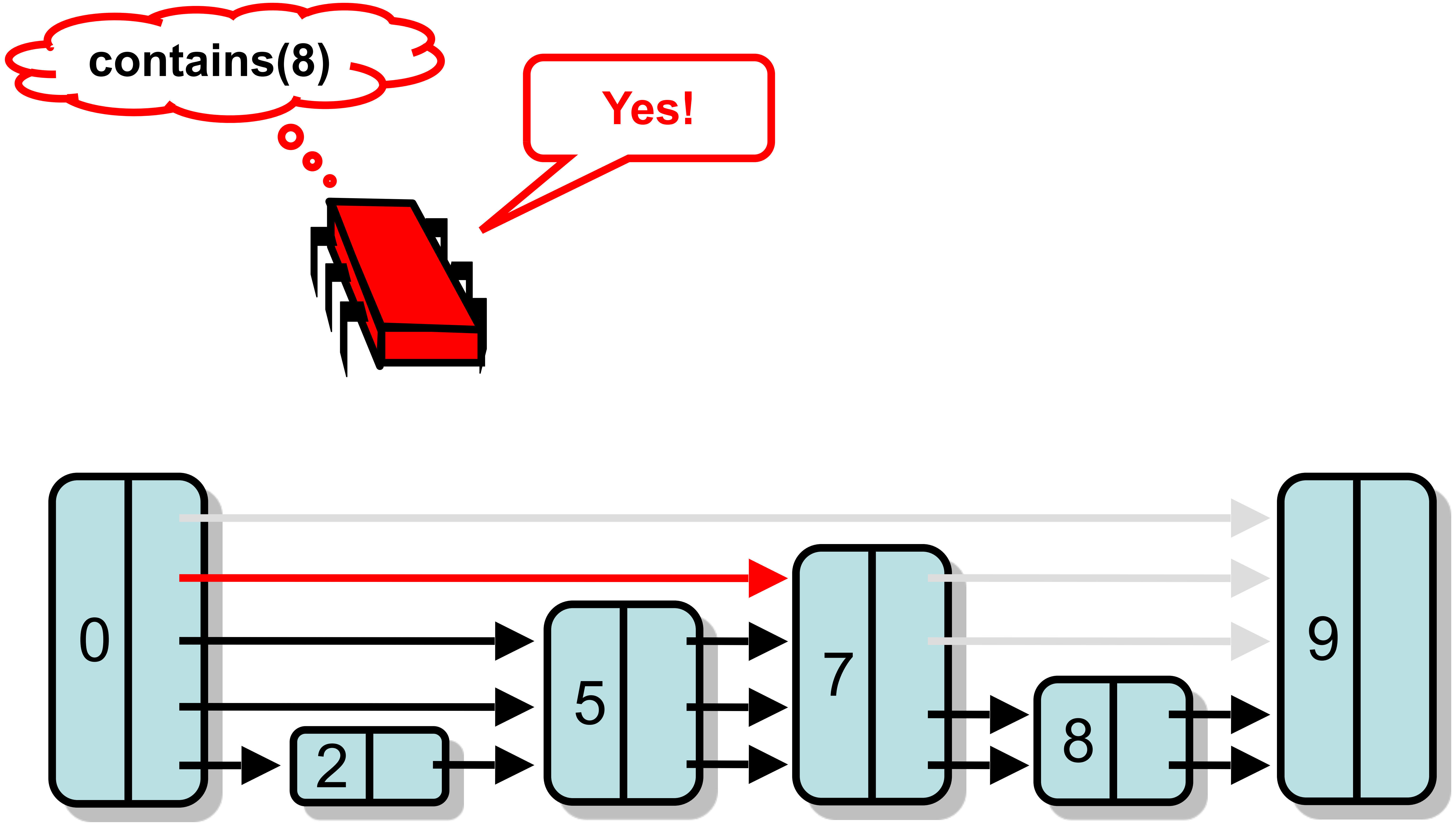
Search



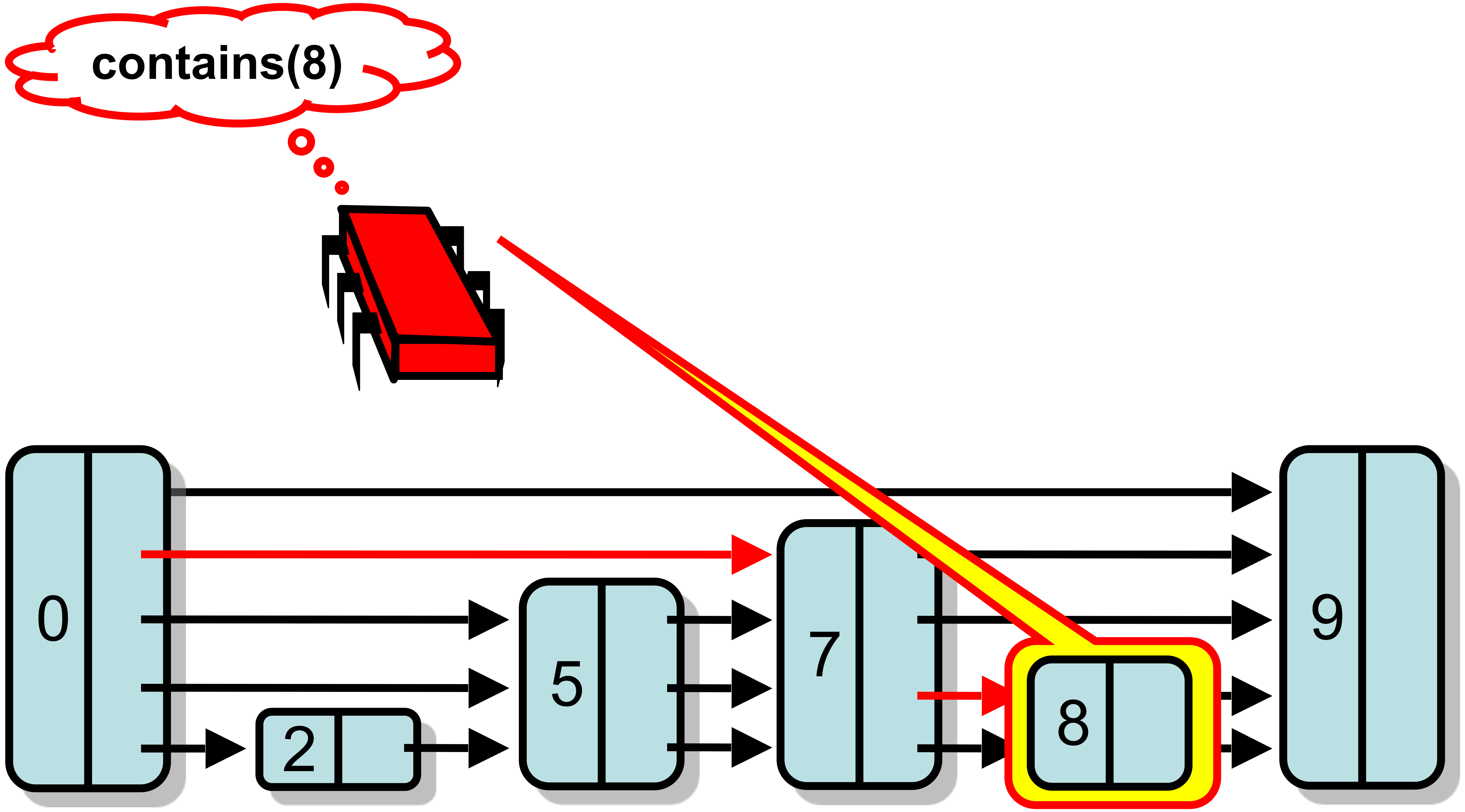
Search



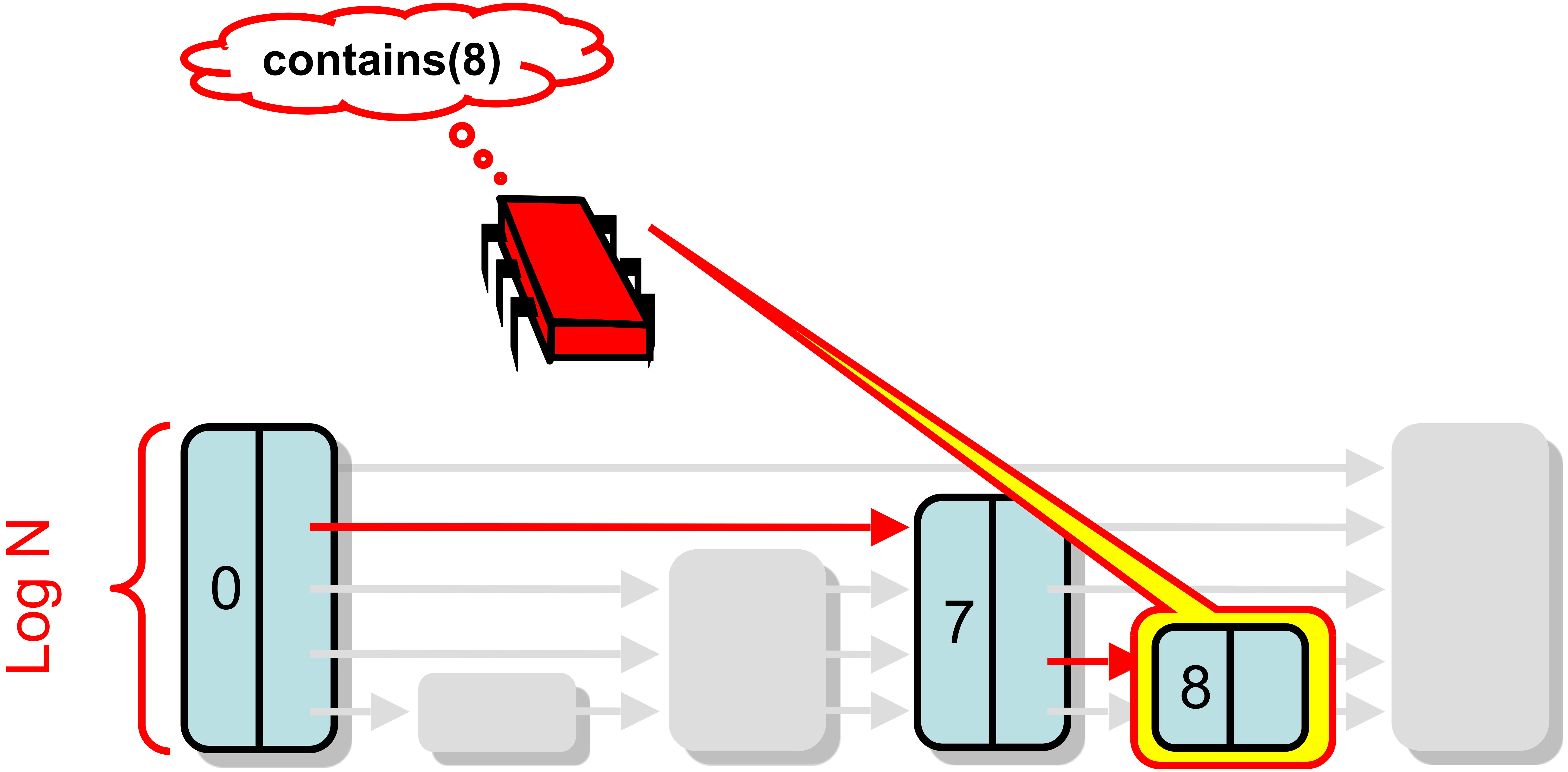
Search



Search

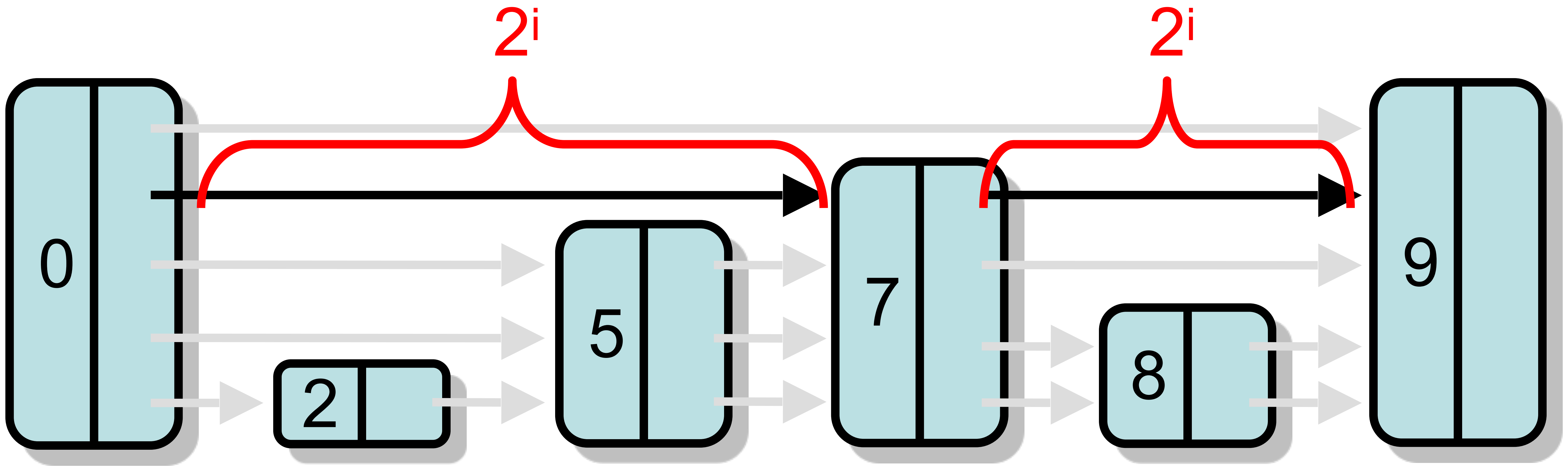


Logarithmic



Why Logarthimic

- 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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```

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 {
  …
  }
```

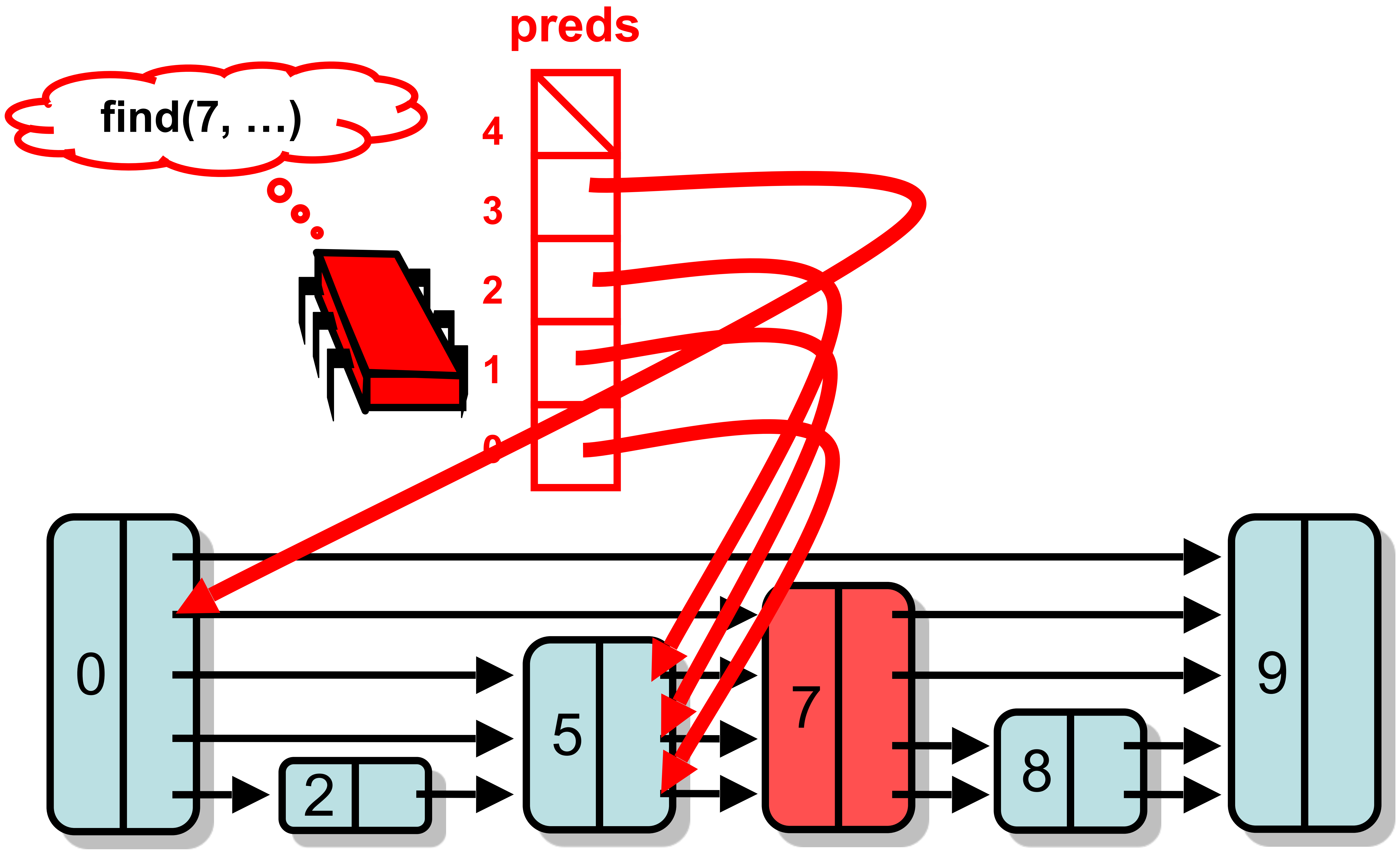
Object sought

return predecessors

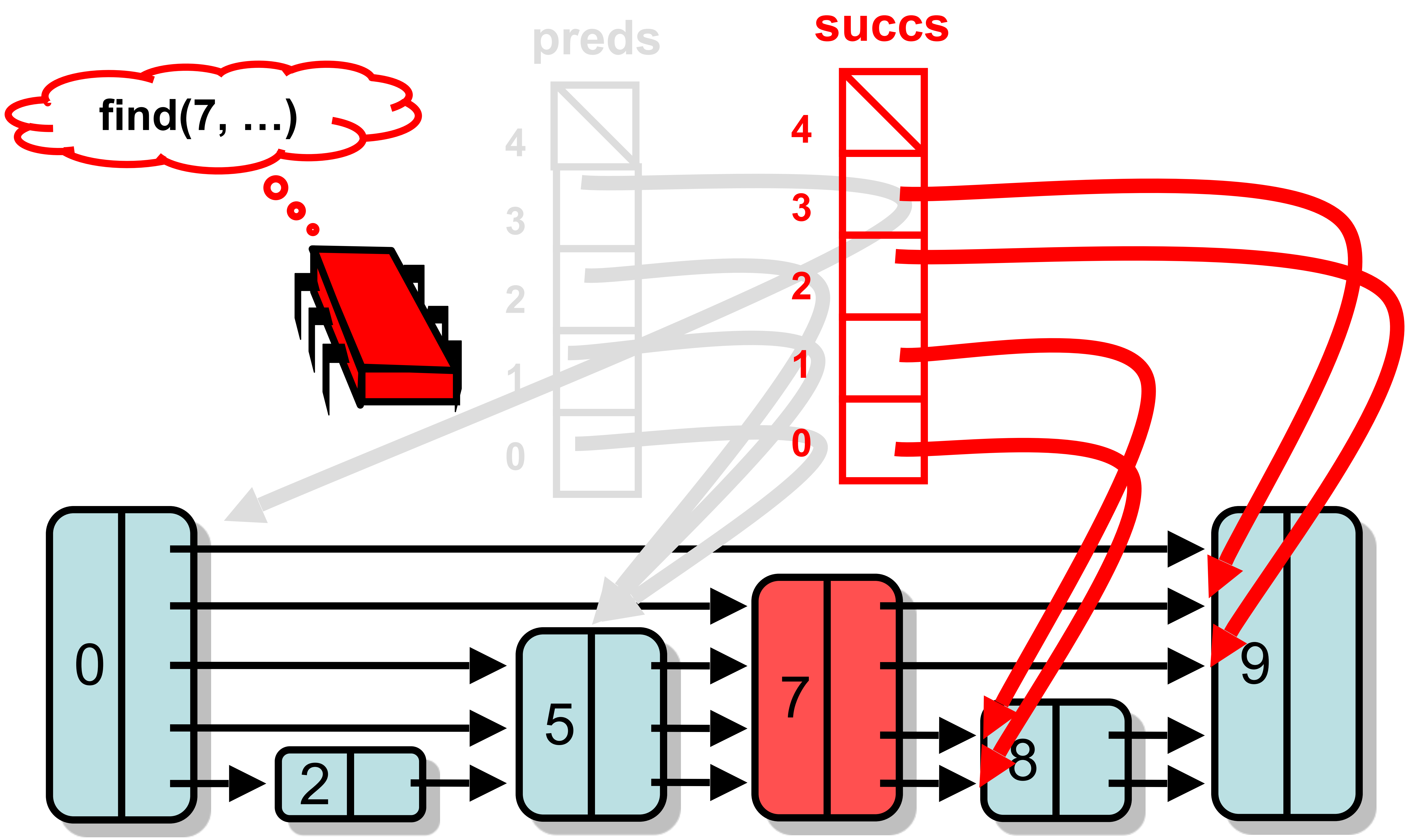
return successors

object height
(-1 if not there)

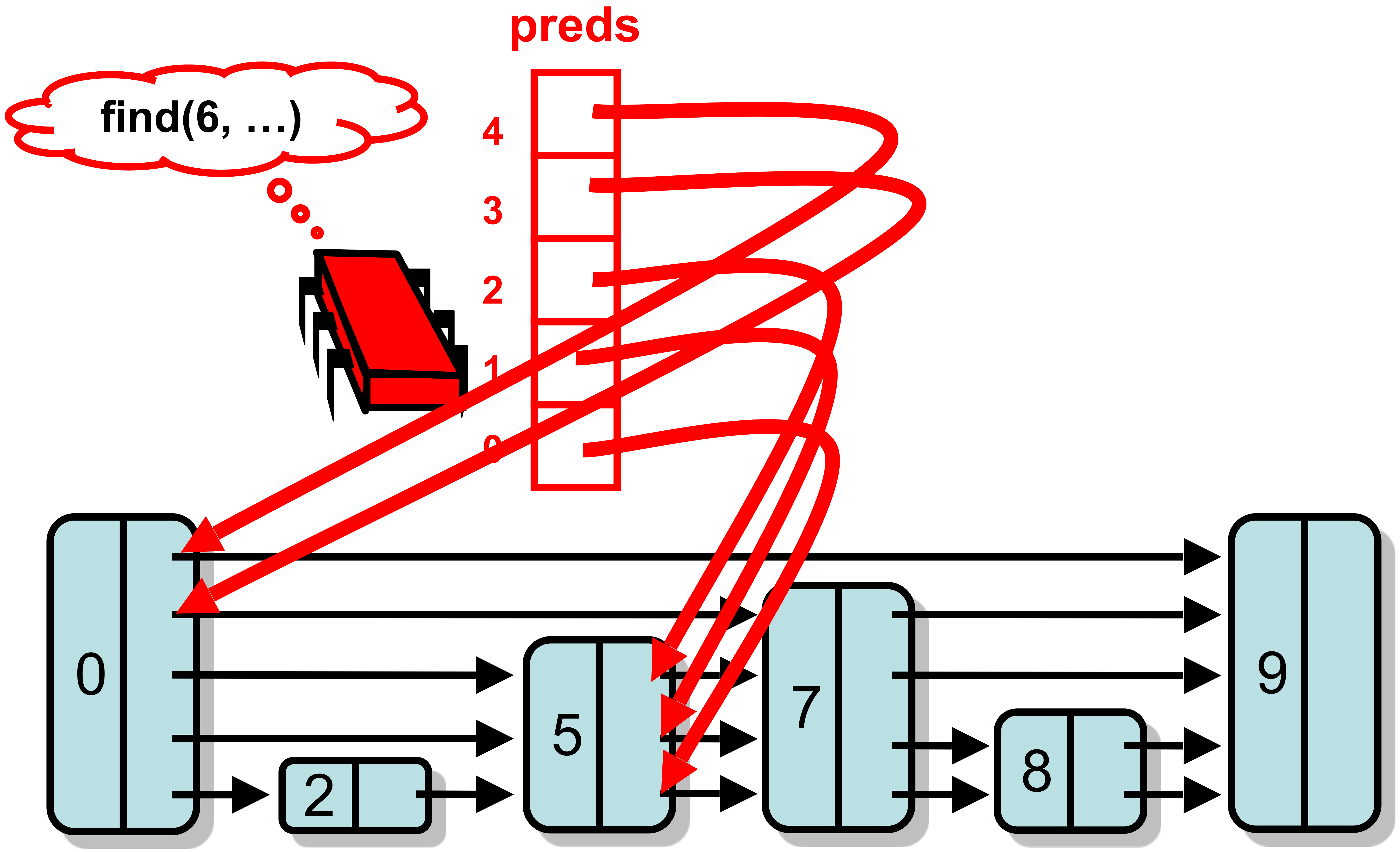
Successful Search



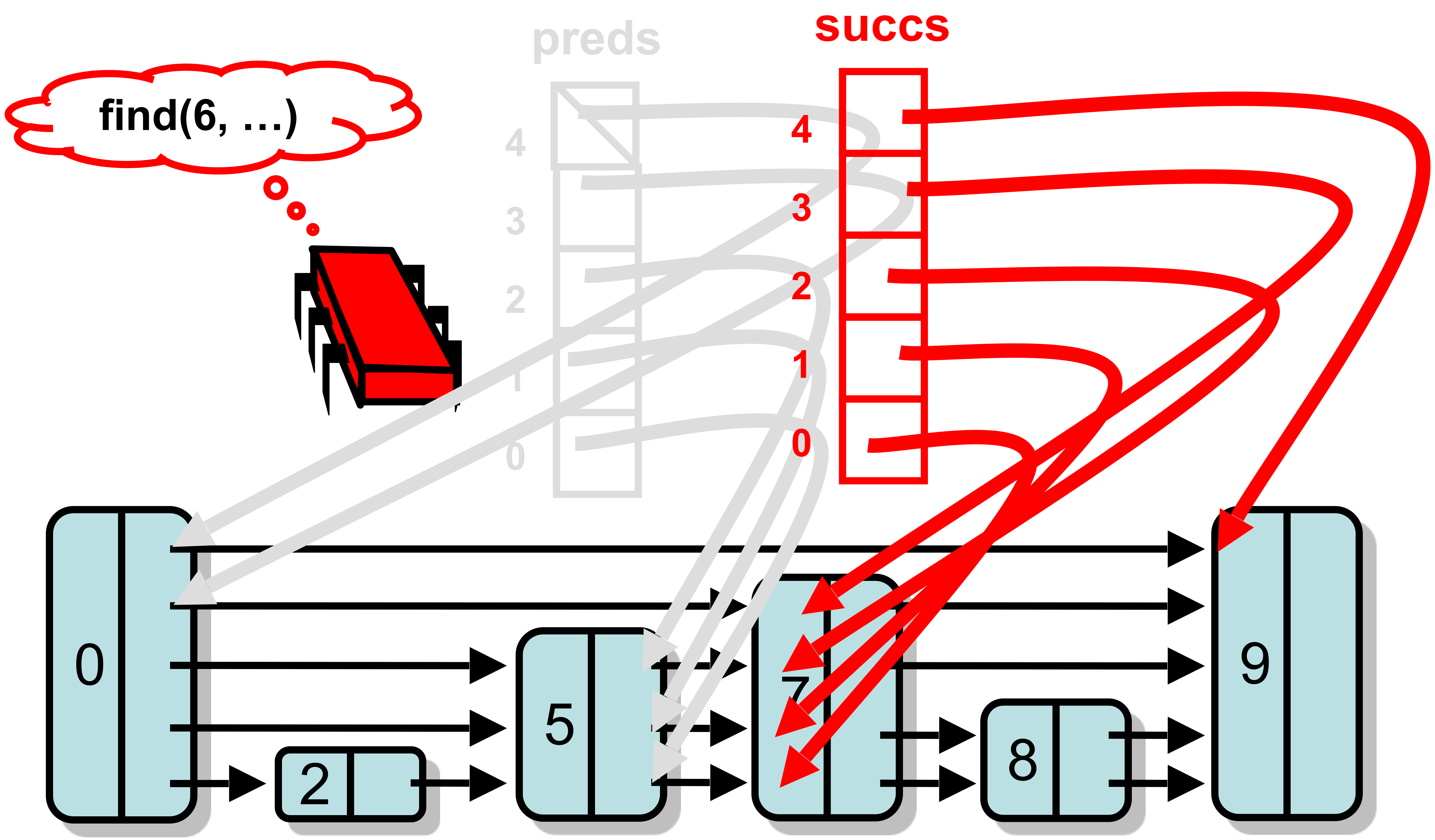
Successful Search



Unsuccessful Search



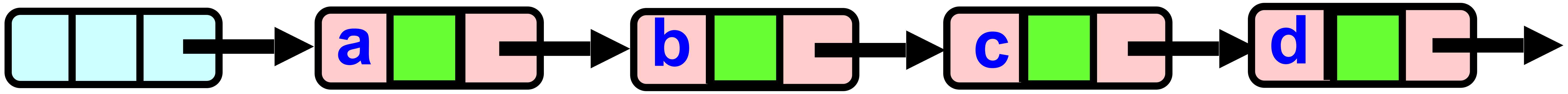
Unsuccessful Search



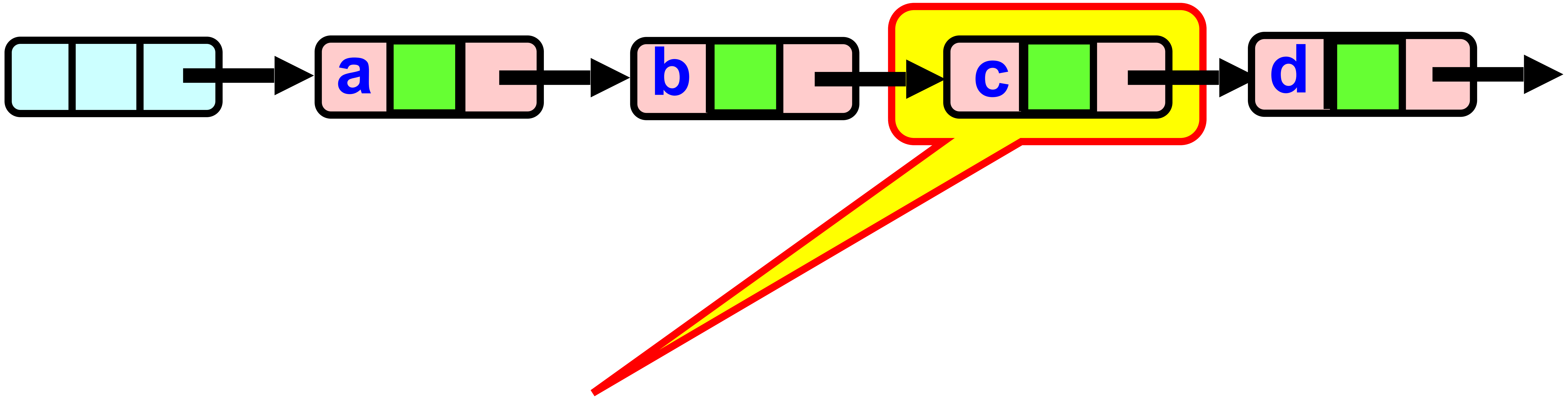
Lazy Skip List

- 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

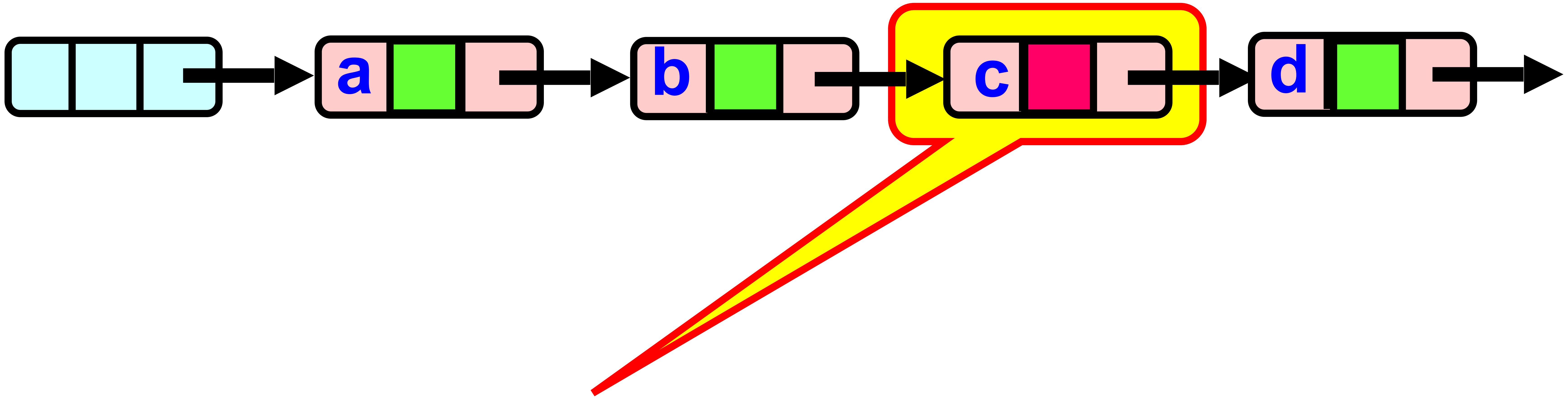


Review: Lazy List Remove



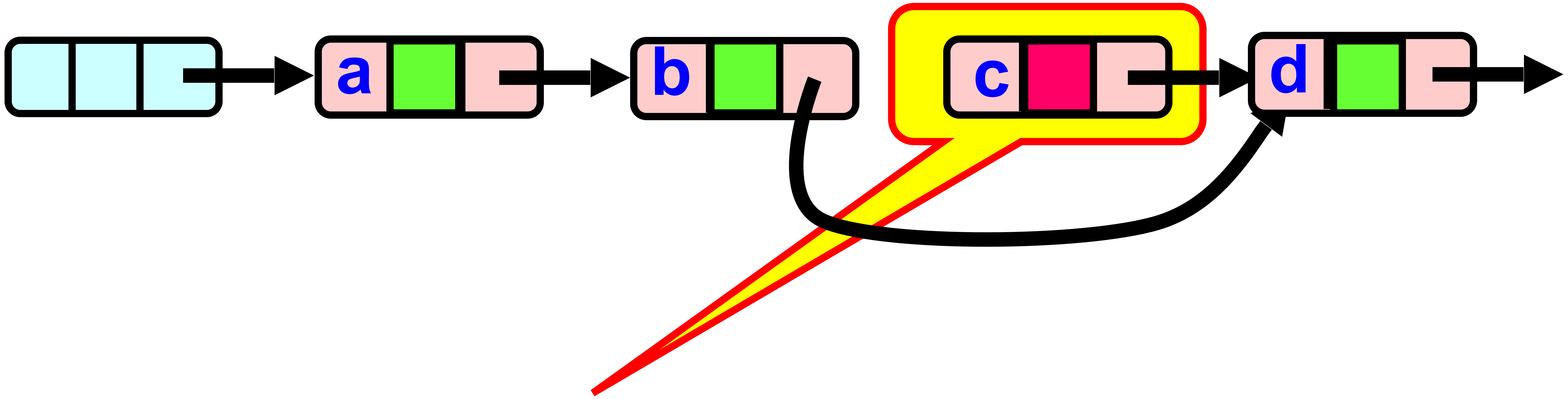
Present in list

Review: Lazy List Remove



Logically deleted

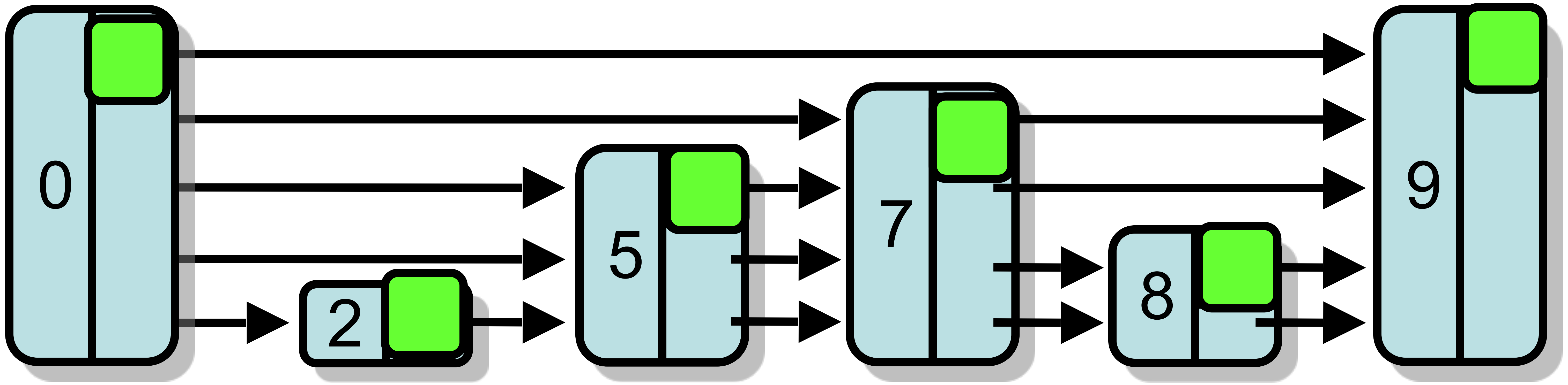
Review: Lazy List Remove



Physically deleted

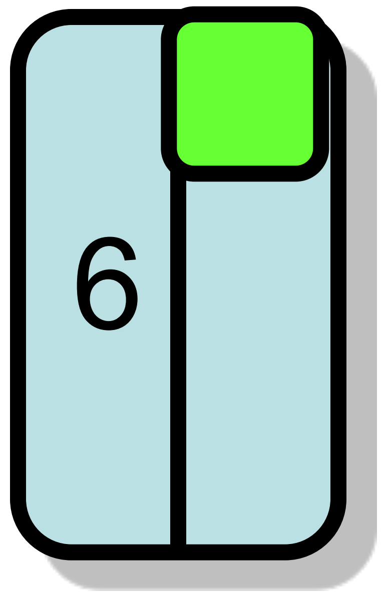
Lazy Skip Lists

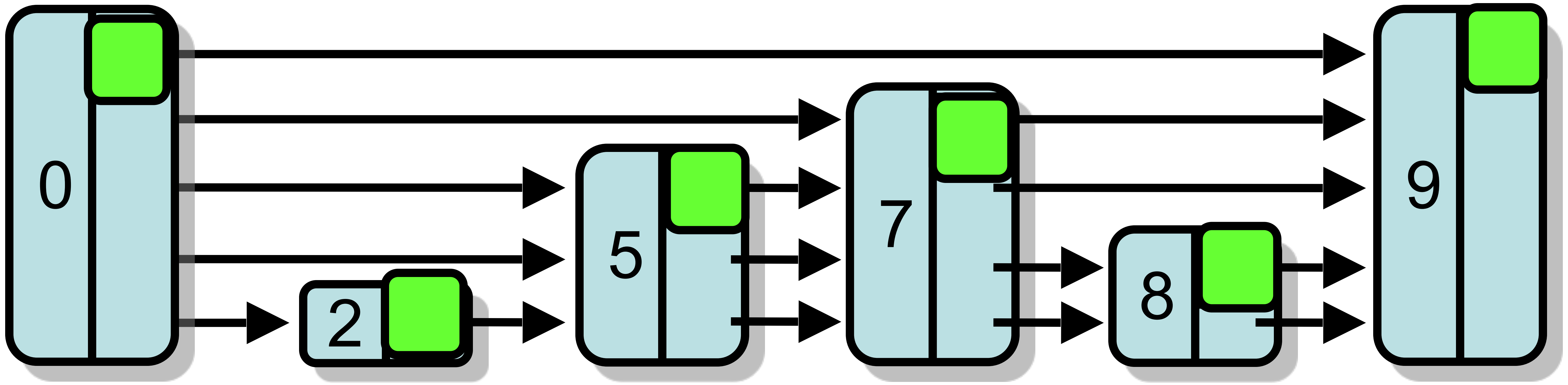
- Use a mark bit for logical deletion



add(6)

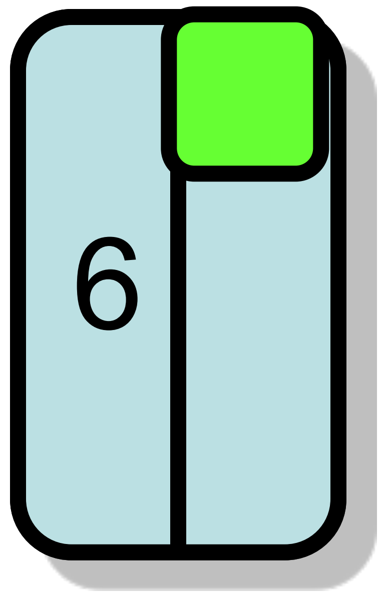
- Create node of (random) height 4

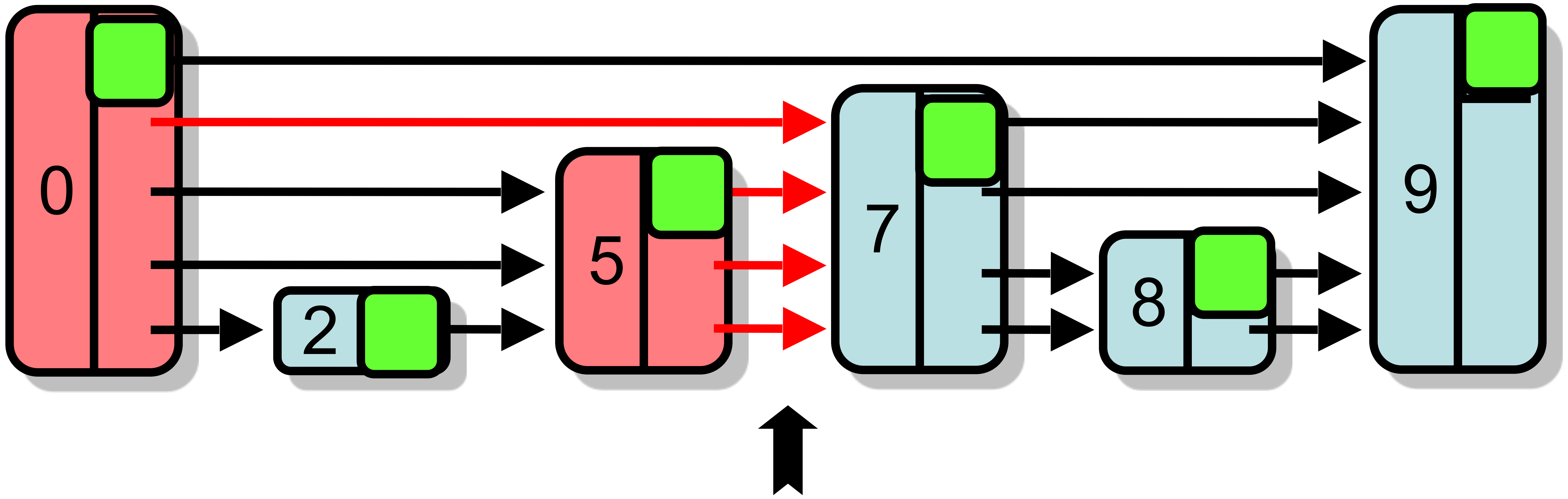




add(6)

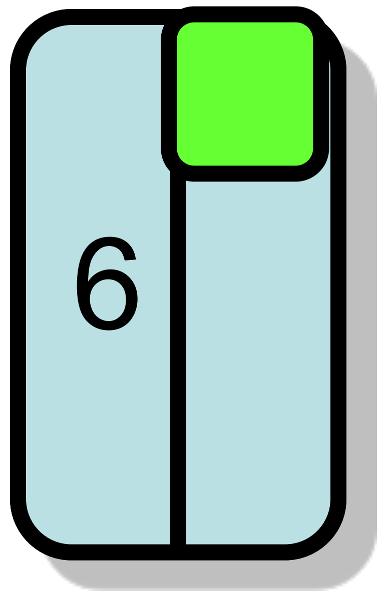
- **find()** predecessors

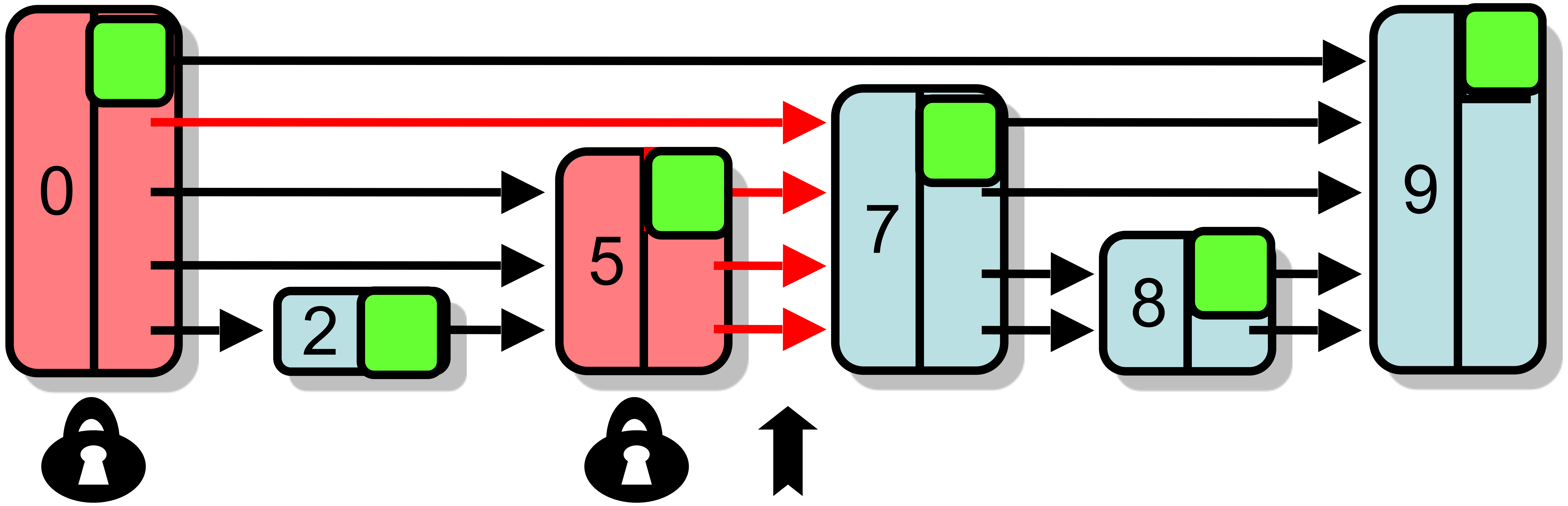




add(6)

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

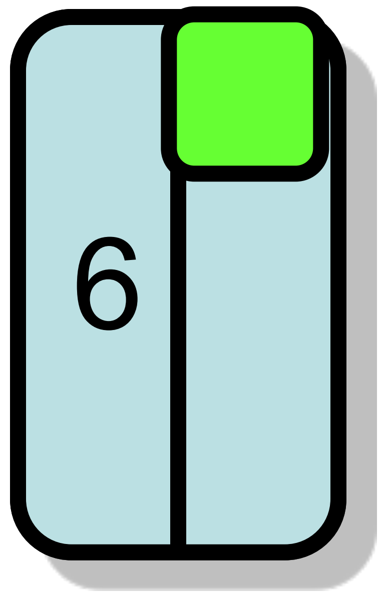


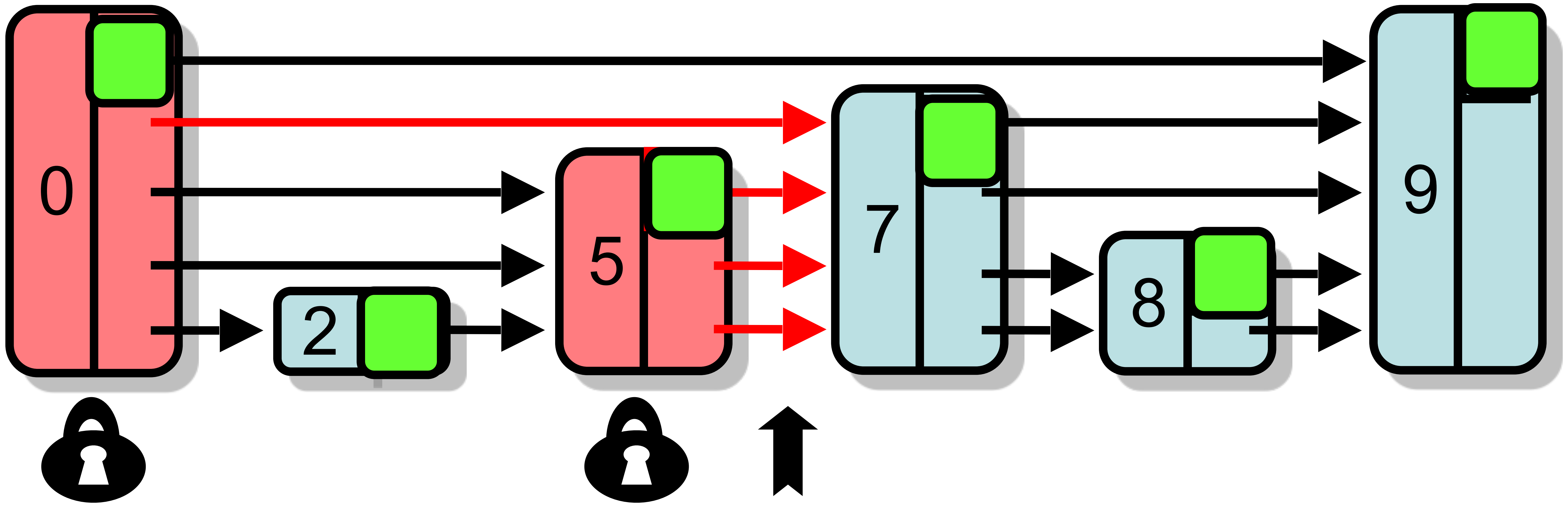


add(6)

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

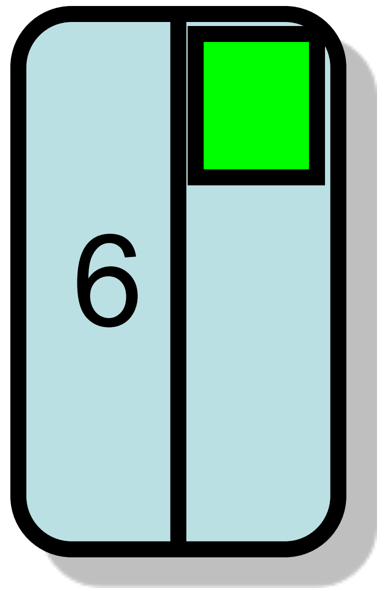
} **Optimistic approach**

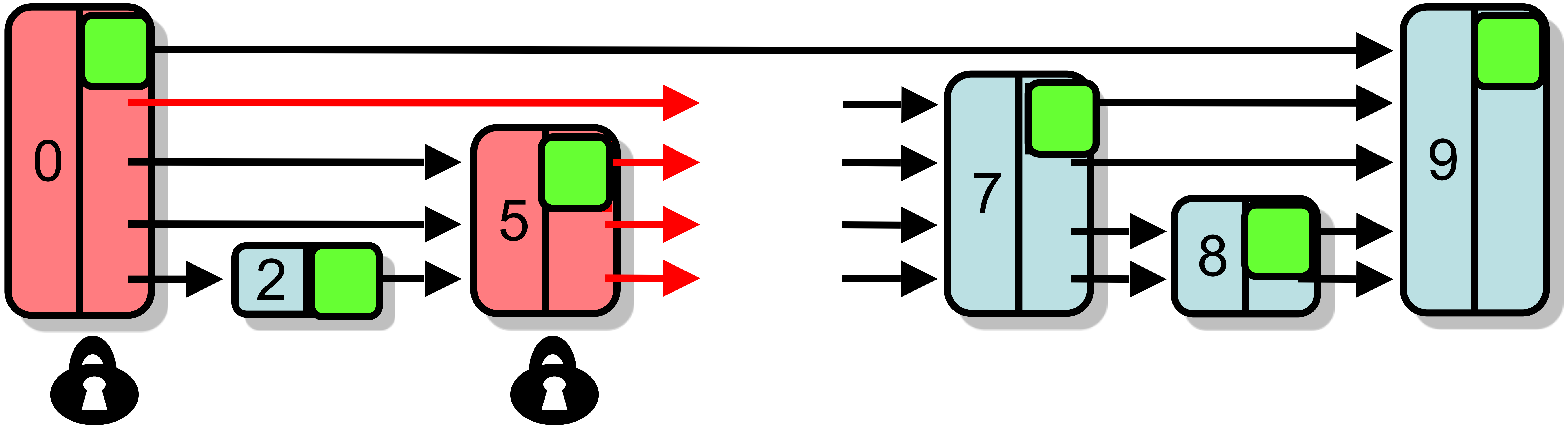




add(6)

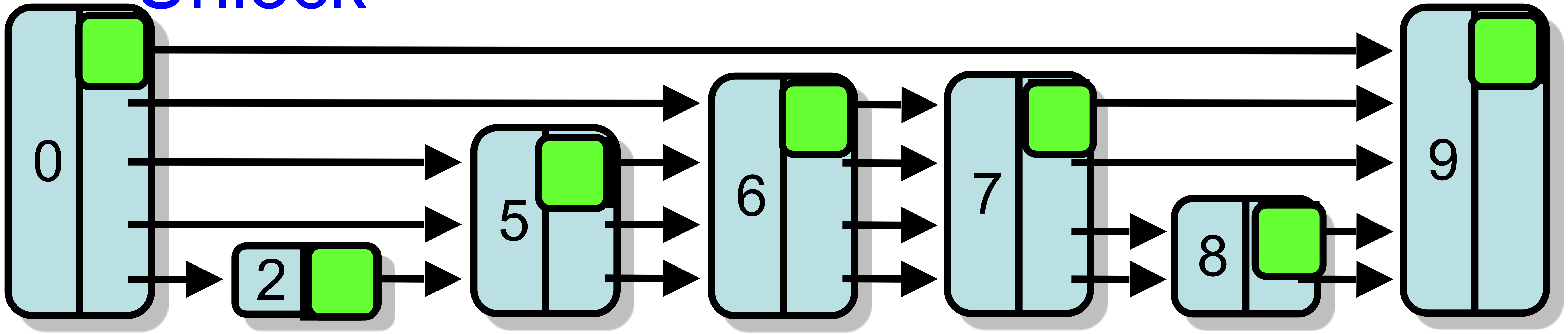
- **find()** predecessors
- Lock them
- Validate
- Splice



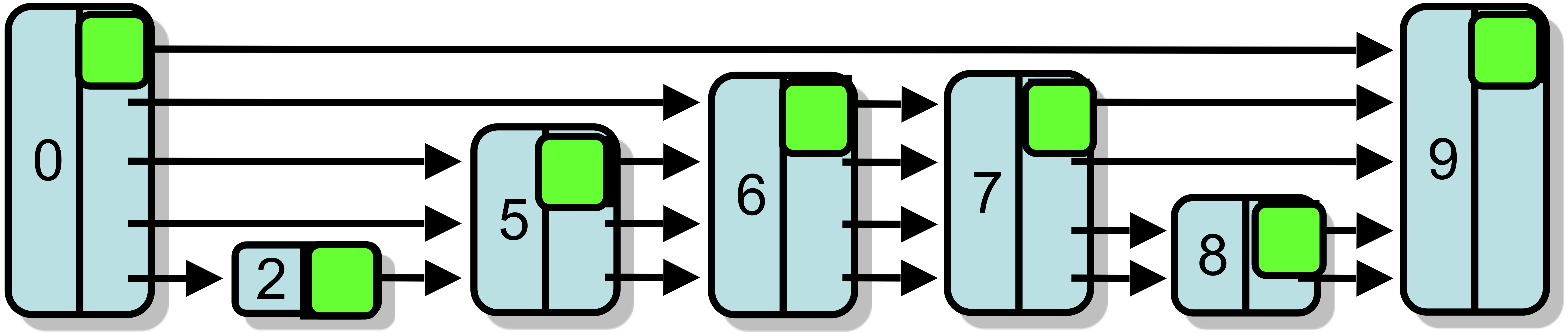


add(6)

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

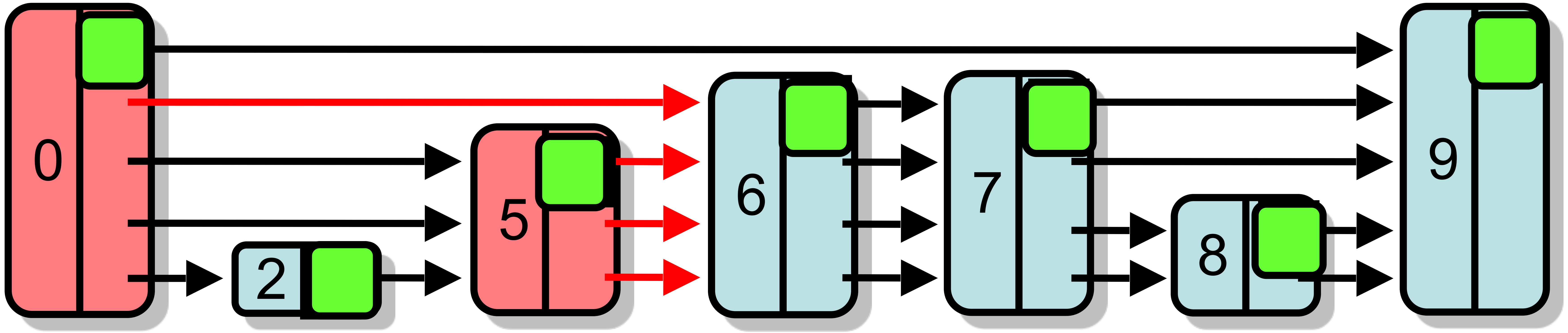


remove(6)



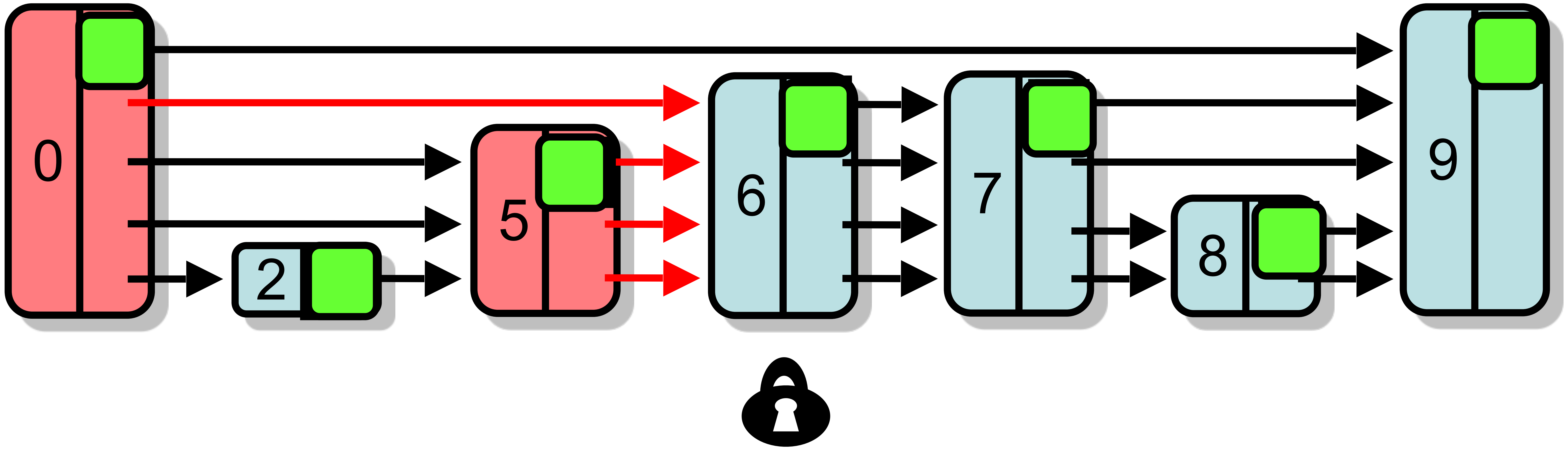
remove(6)

- **find()** predecessors



remove(6)

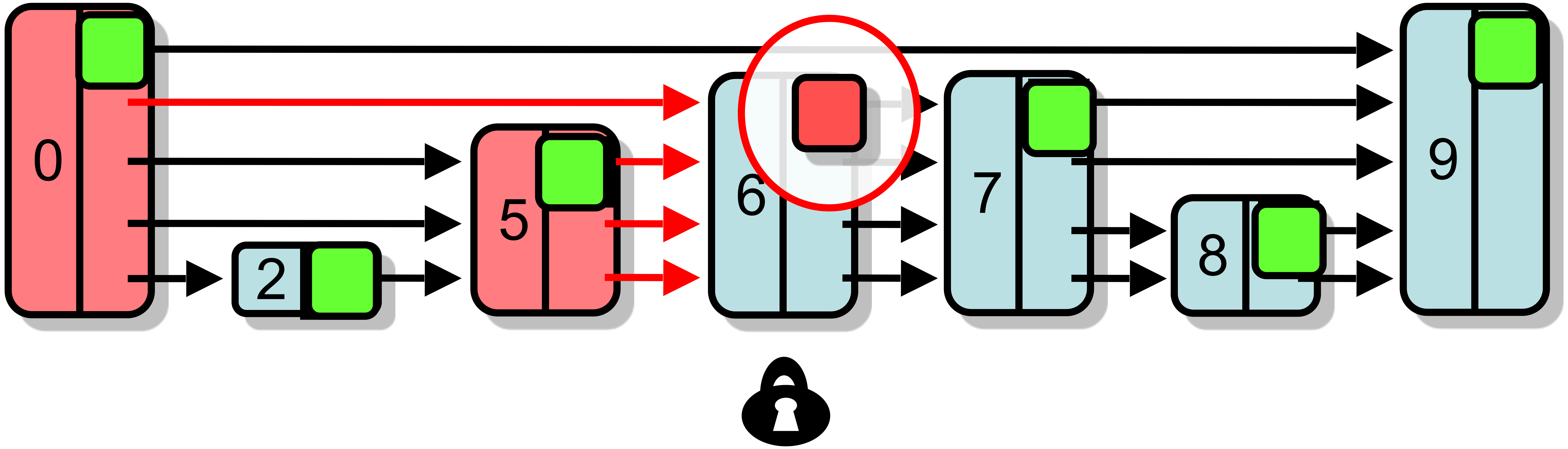
- **find()** predecessors
- Lock victim



remove(6)

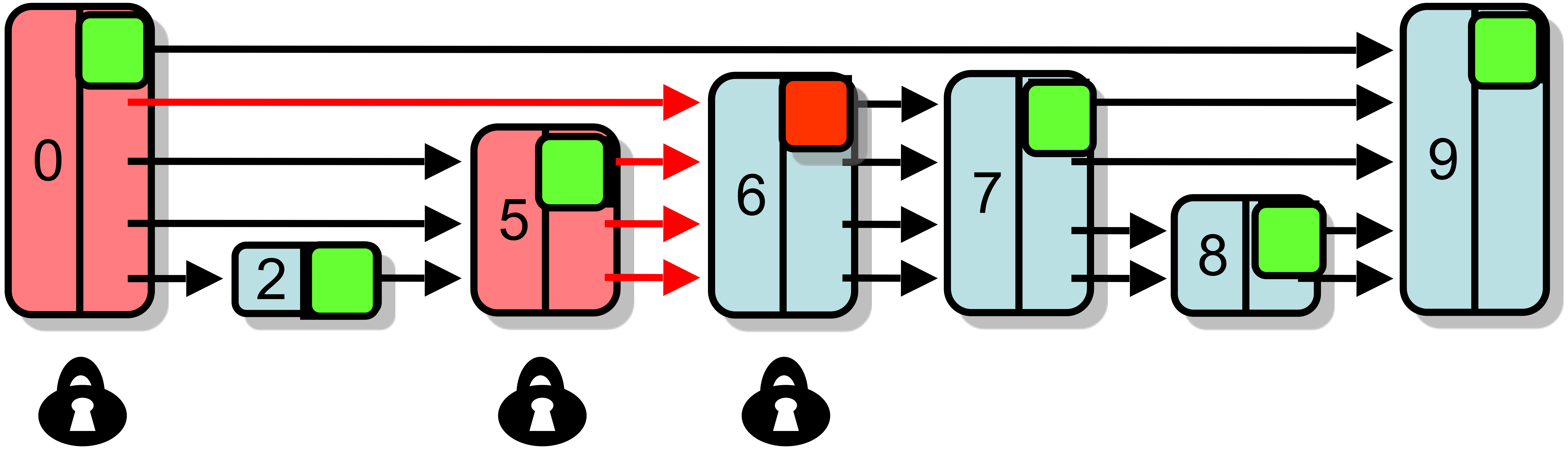
- **find()** predecessors
- Lock victim
- Set mark (if not already set)

Logical remove…



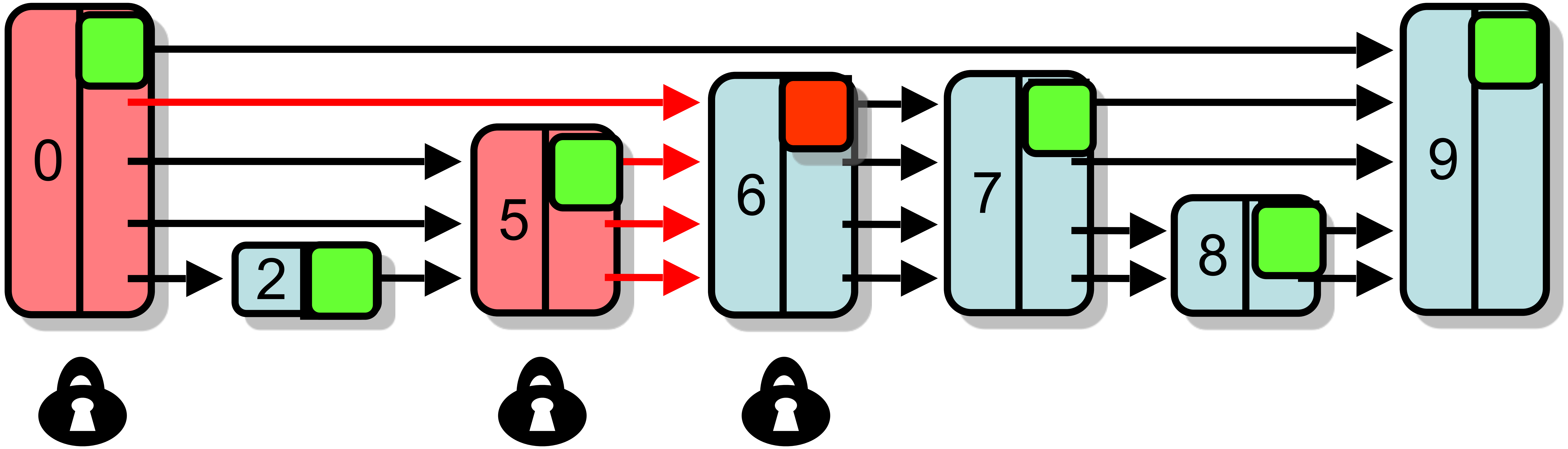
remove(6)

- **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



remove(6)

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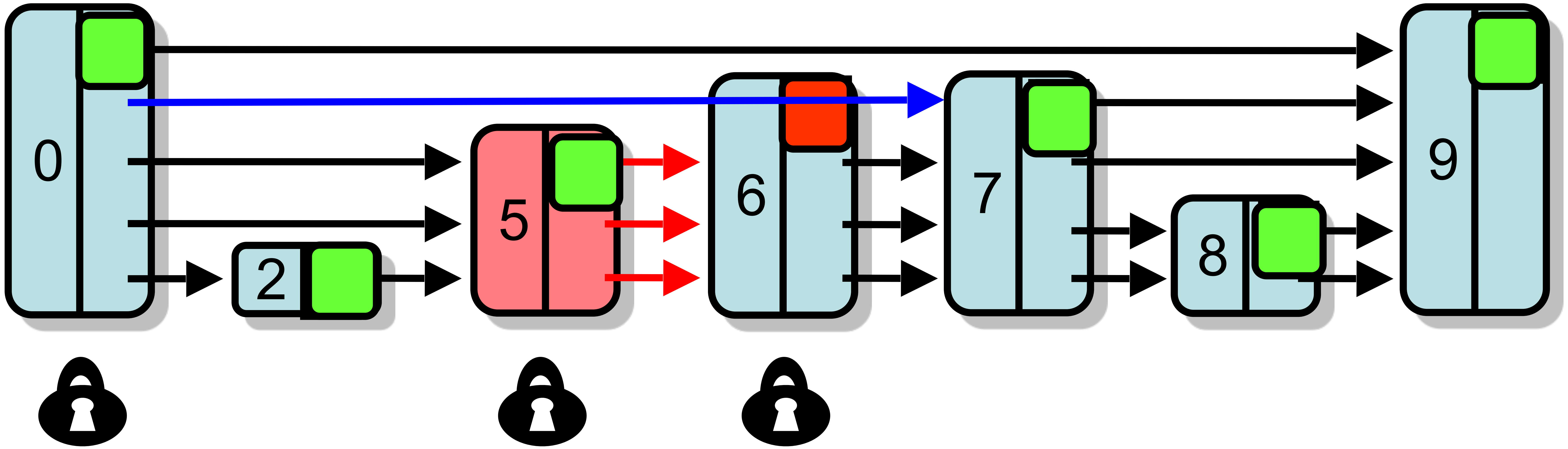

remove(6)

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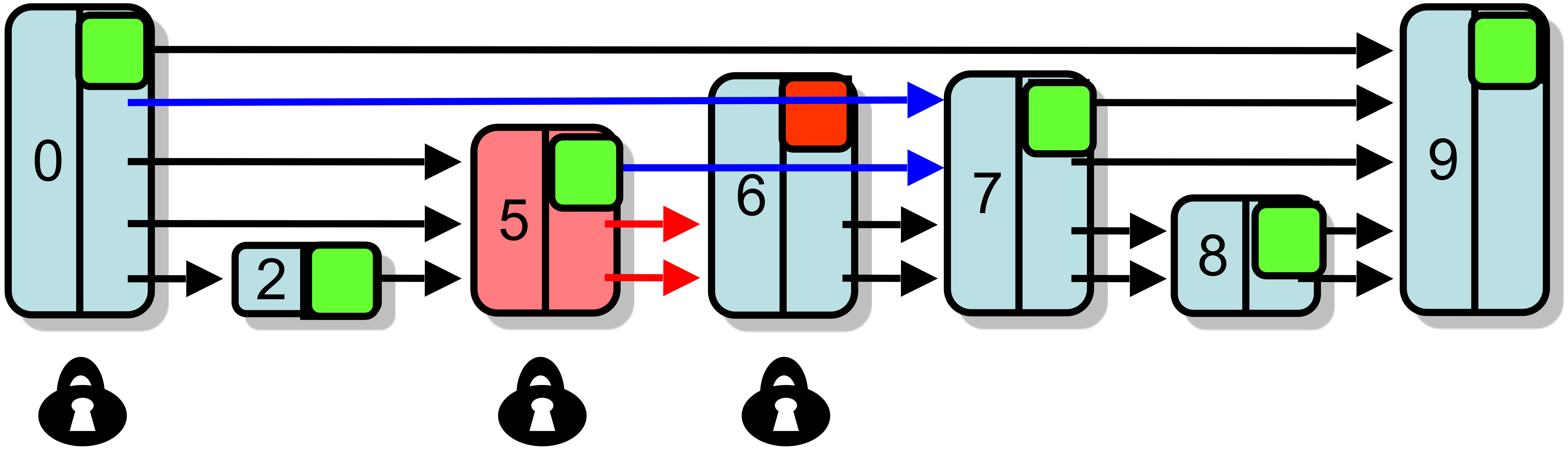
- Lock predecessors (ascending order) & validate
- Physically remove



remove(6)

- **find()** predecessors
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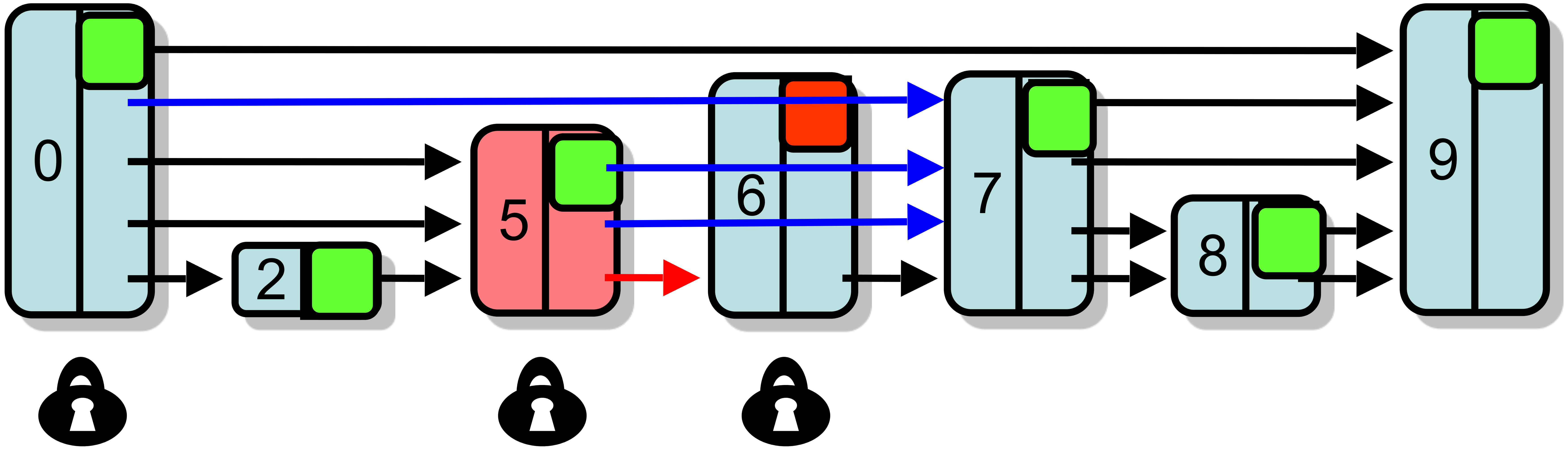
- Physically remove



remove(6)

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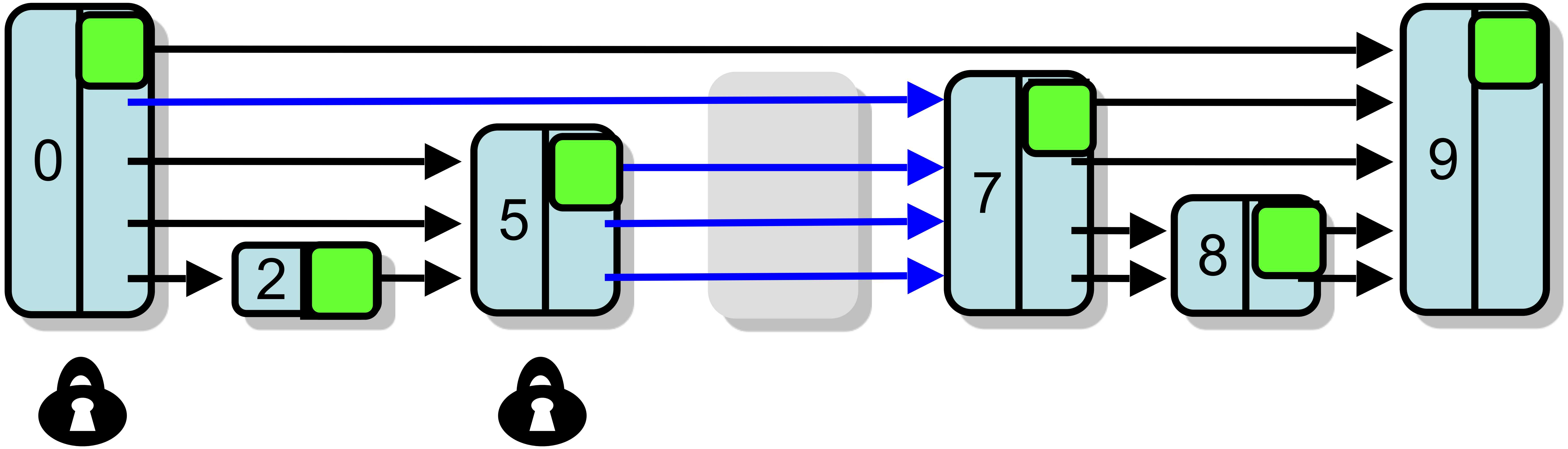
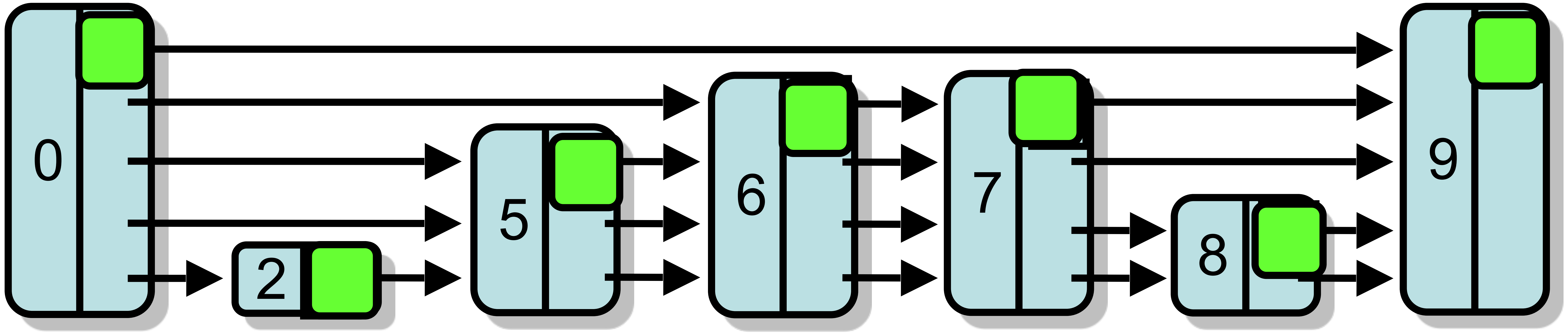
- Physically remove



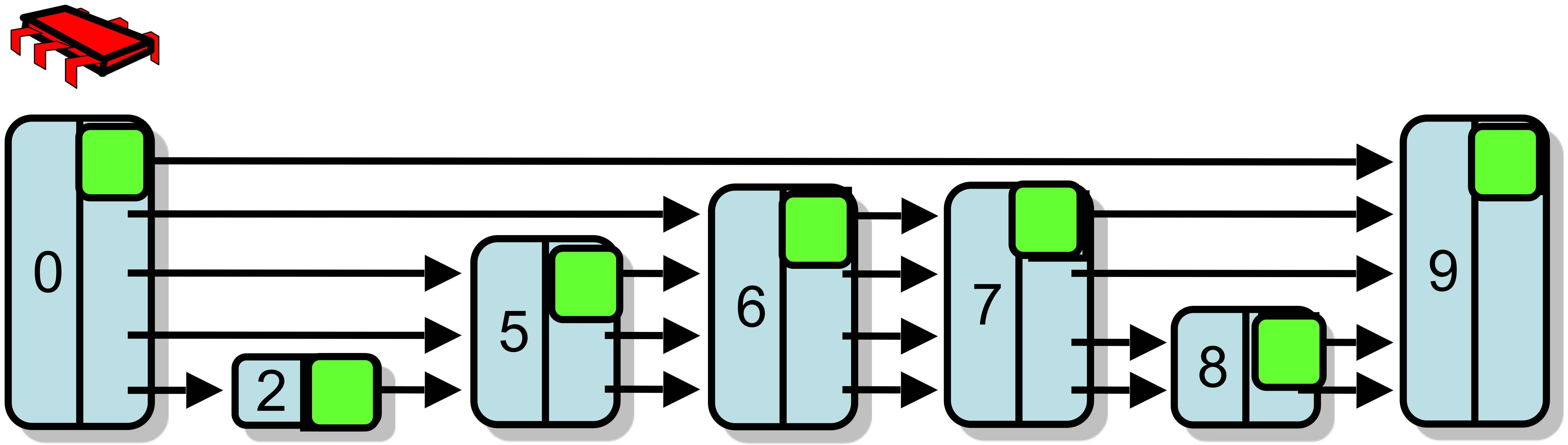
contains(8)

- **find()** & not marked



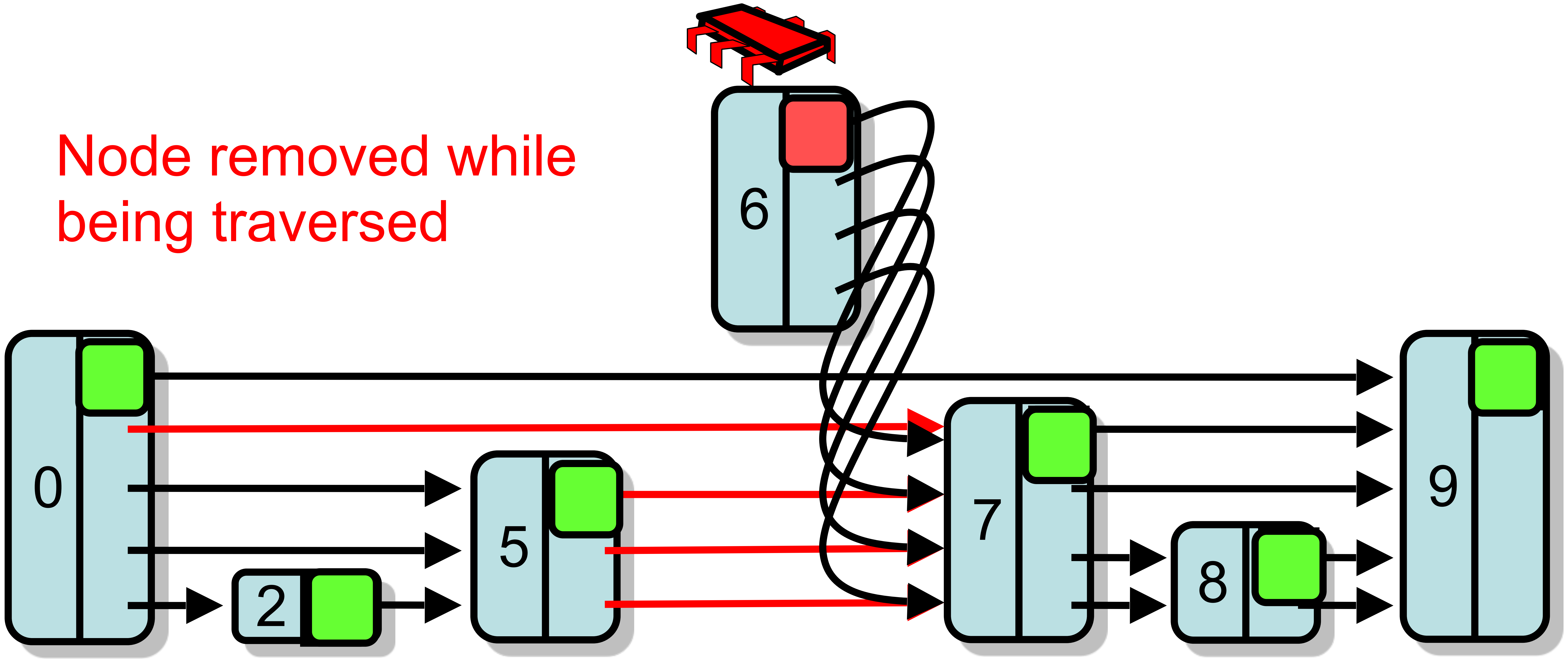
contains(8)

Node 6 removed while traversed



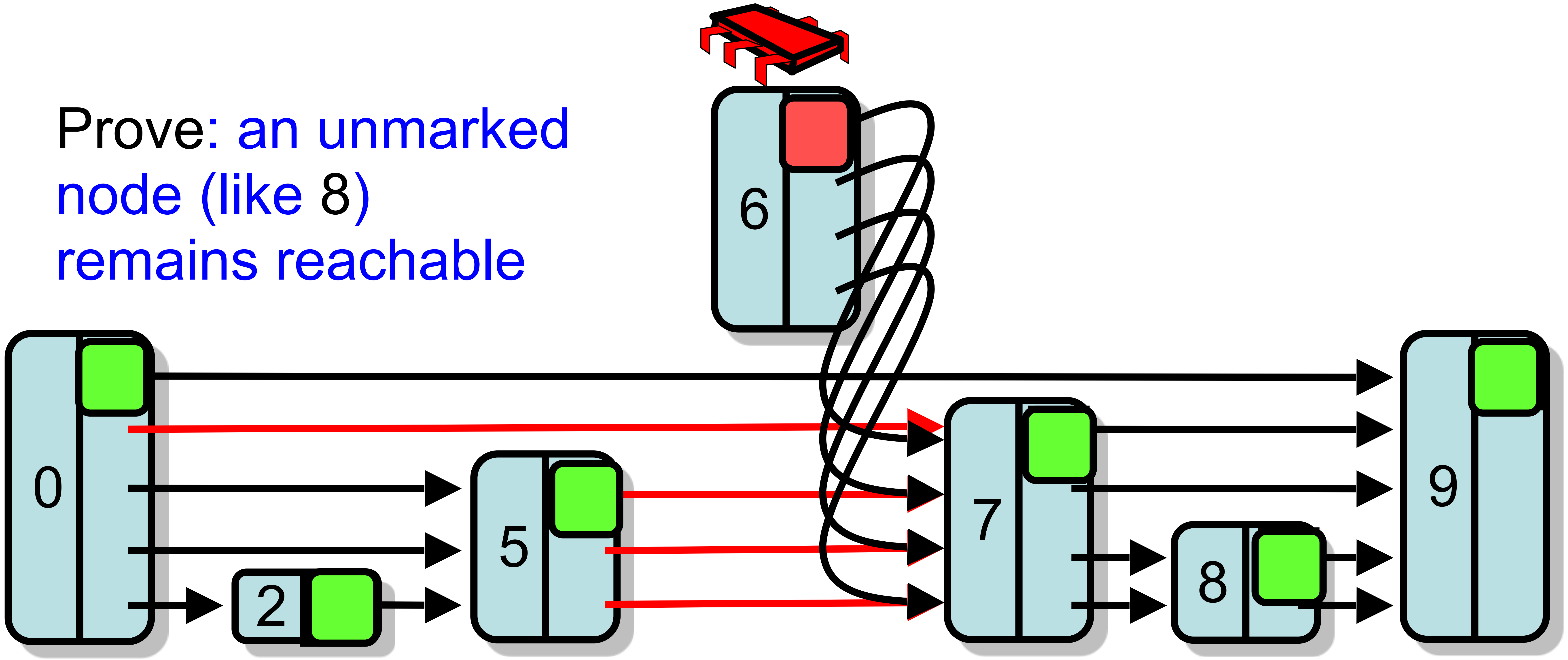
contains(8)

Node removed while being traversed



contains(8)

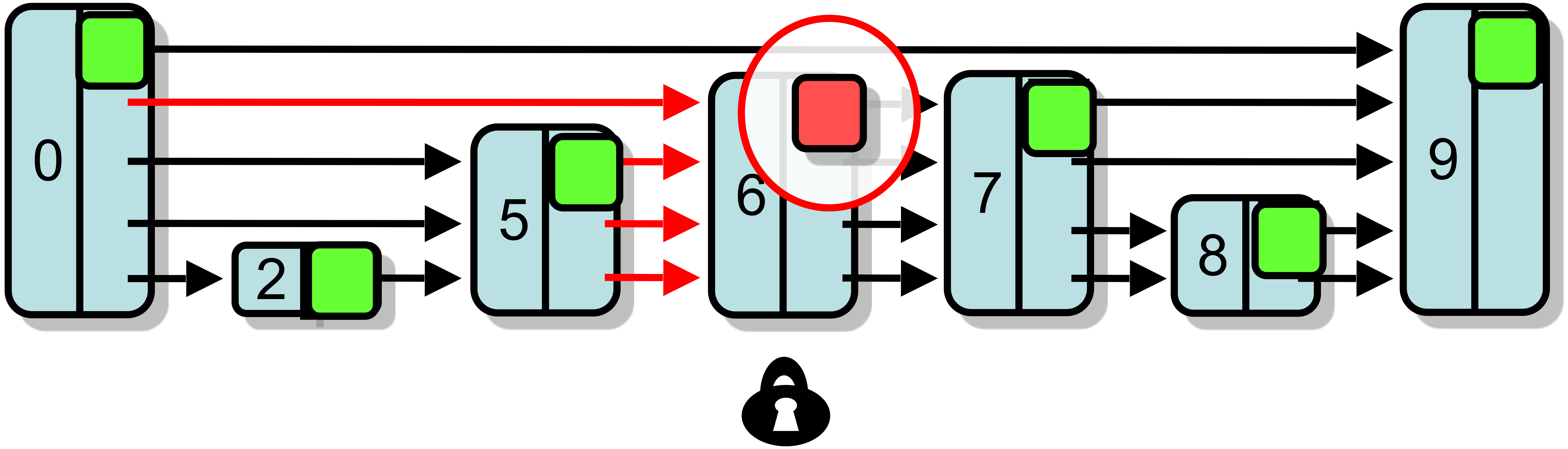
Prove: an unmarked node (like 8) remains reachable



remove(6): Linearization

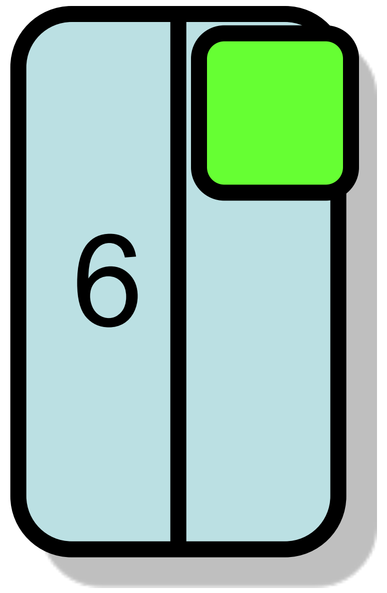
- Successful remove happens when bit is set

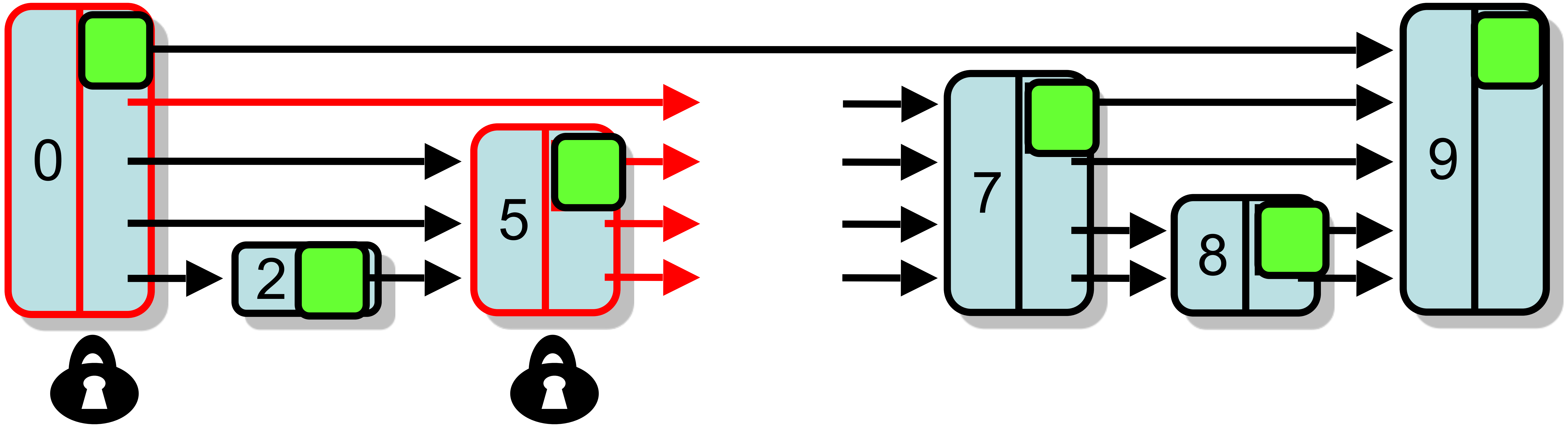
Logical remove…



Add: Linearization

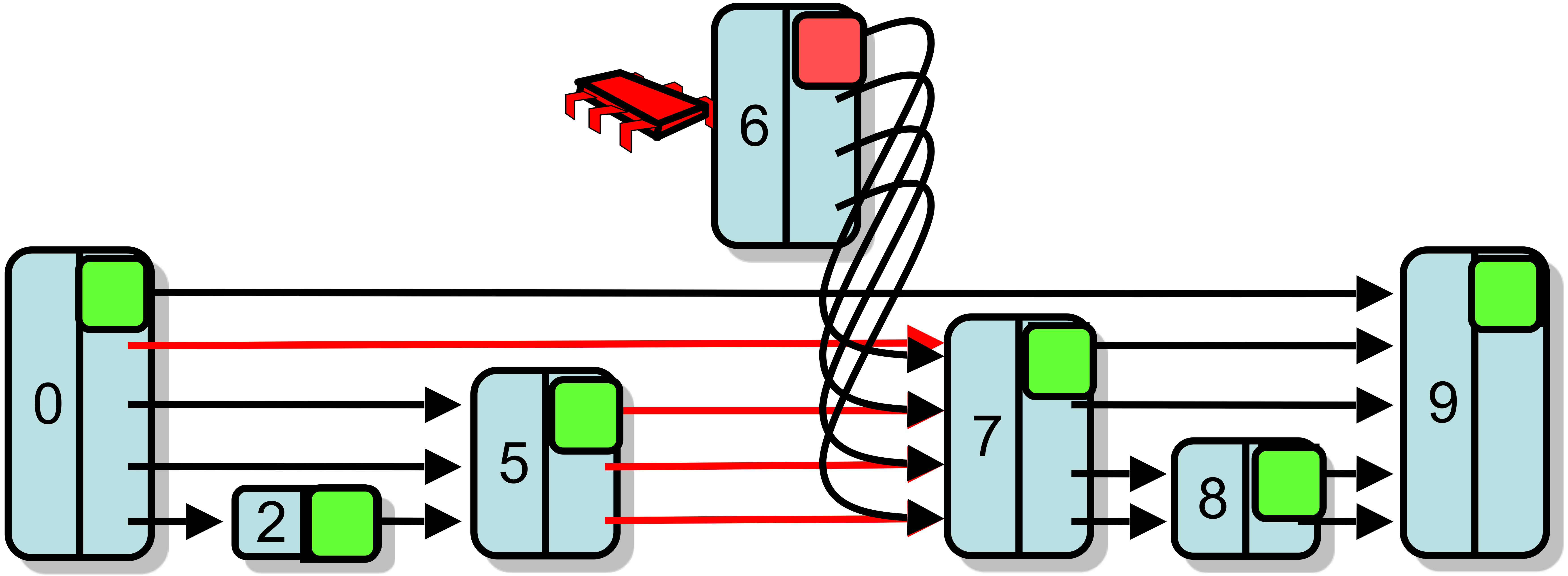
- Successful add() at point when fully linked
- Add fullyLinked bit to indicate this
- Bit tested by contains()





contains(7): Linearization

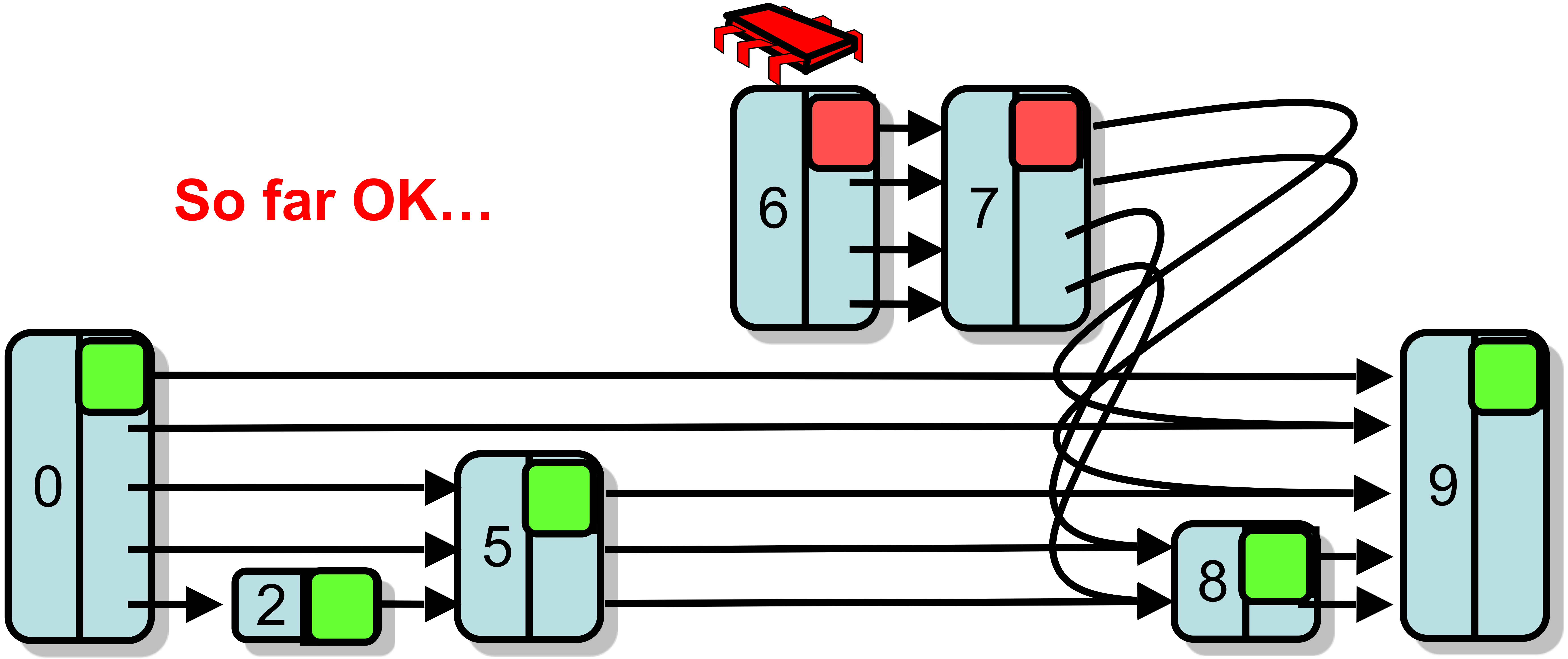
- When fully-linked unmarked node found
- Pause while fullyLinked bit unset



contains(7): Linearization

- When do we linearize unsuccessful Search?

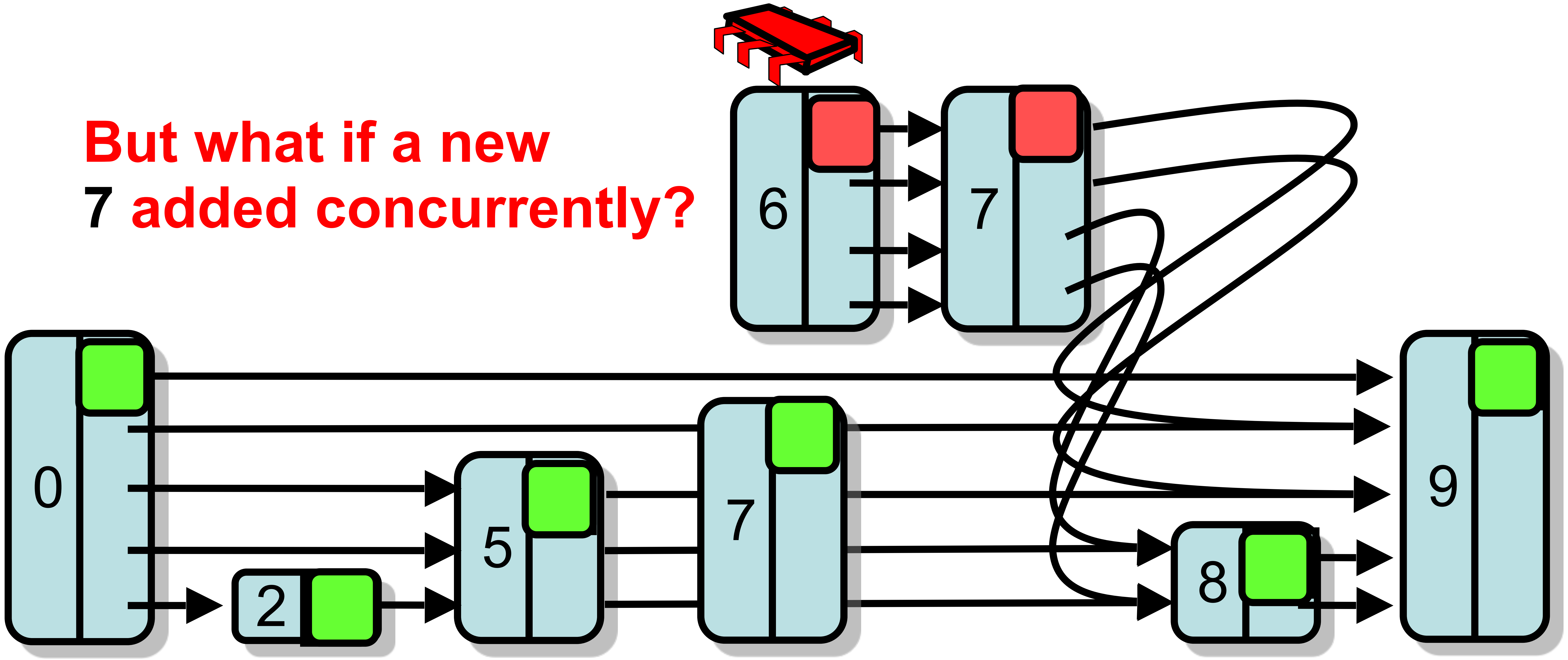
So far OK…



contains(7): Linearization

- When do we linearize unsuccessful Search?

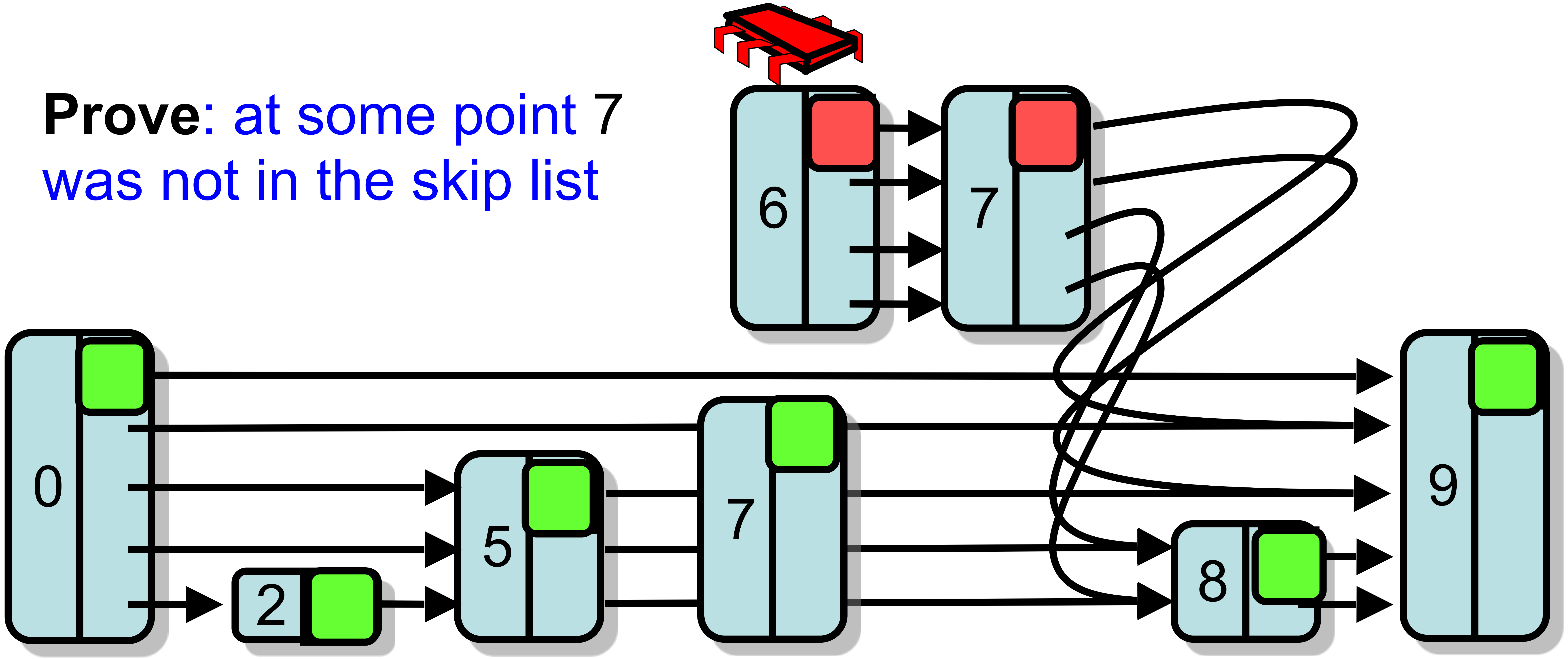
But what if a new
7 added concurrently?



contains(7): Linearization

- When do we linearize unsuccessful Search?

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



Coding Time!

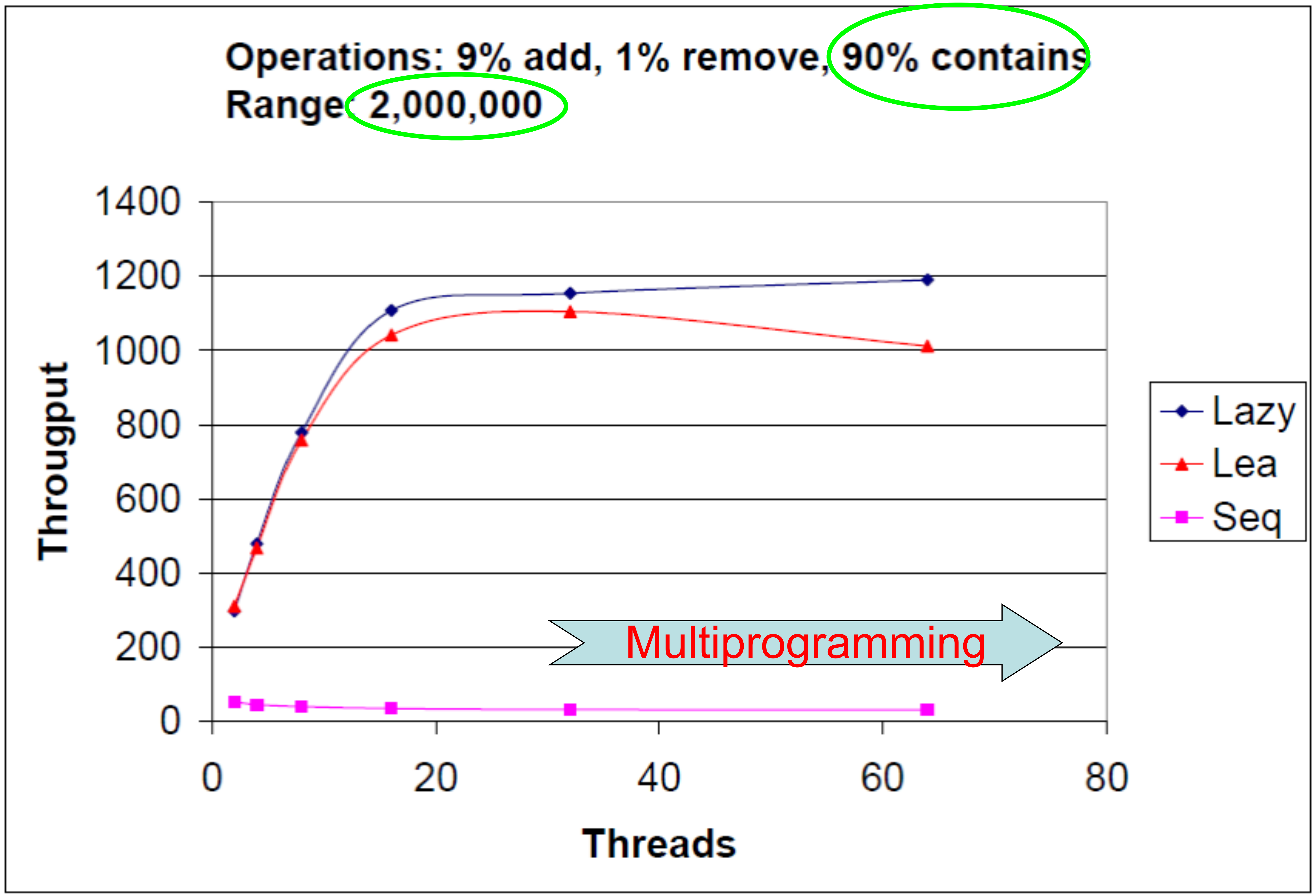
- Design a benchmark suite for concurrent set implementations allowing arbitrary numbers of threads and operations.

- Use the ideas from the previous lectures.

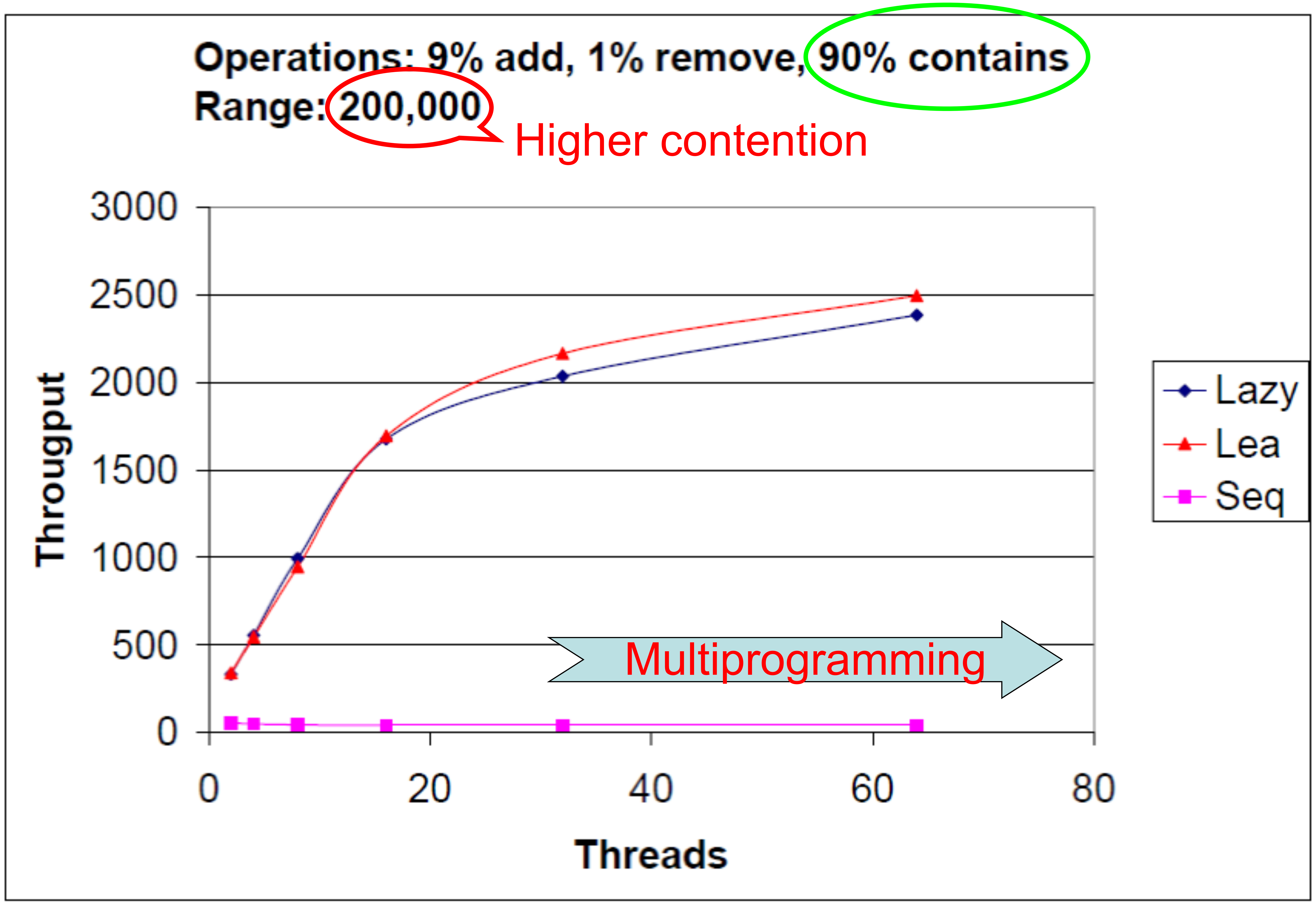
- Implement it for *optimistic lists*, *lazy lists* and *lazy skip-lists* and determine the winner!

- Also, let’s add Java’s concurrent set implementation (by Doug Lea) into the mix

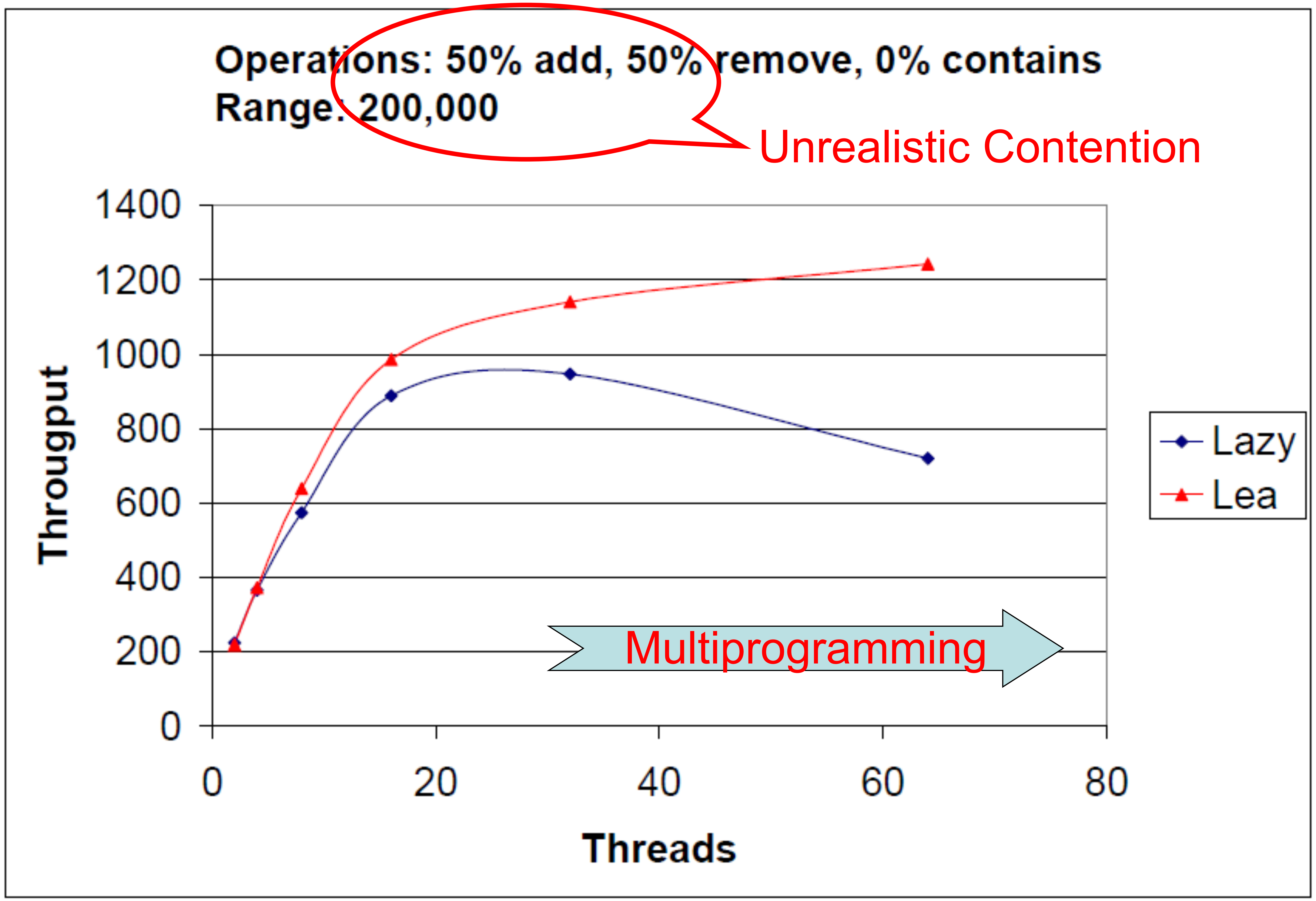
Lazy Skip List: Performance



Lazy Skip List: Performance



Lazy Skip List: Performance



Unrealistic Contention

Multiprogramming

Summary

- Lazy Skip List
  - Optimistic fine-grained Locking

- Performs as well as the lock-free solution in “common” cases

- This is how you implement a concurrent set.

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