Locking Strategies: Coarse & Fine

CS 475, Fall 2019

Concurrent & Distributed Systems

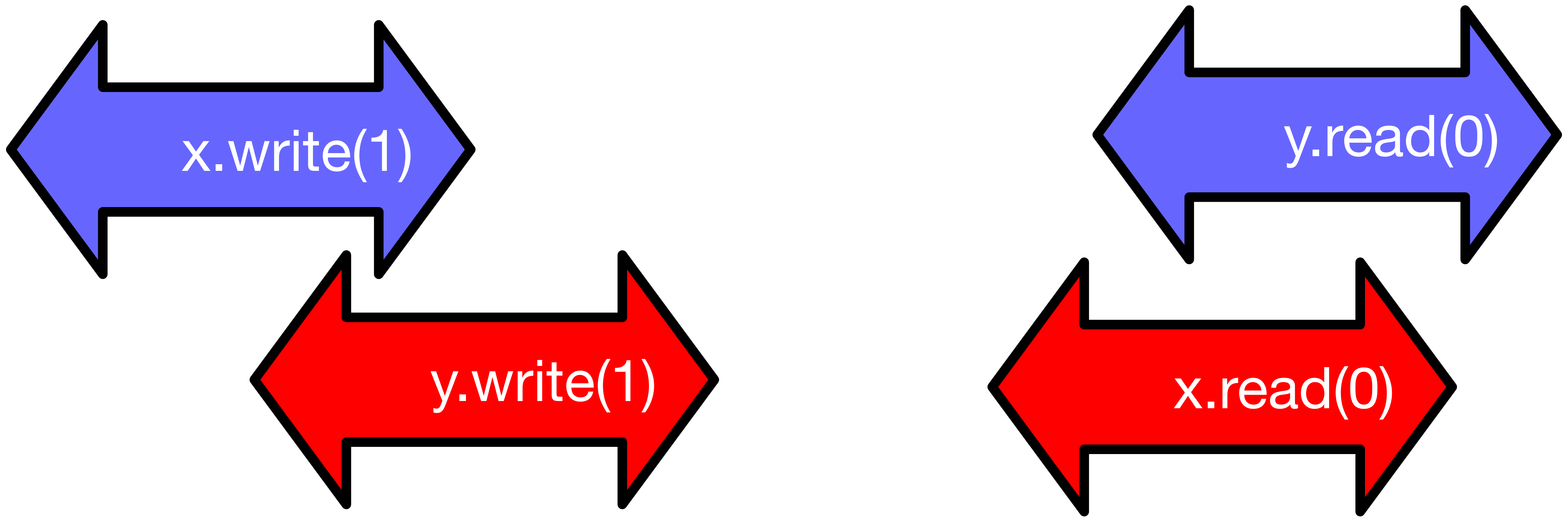
GEORGE MASON UNIVERSITY

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Sequential Consistency vs Linearizability

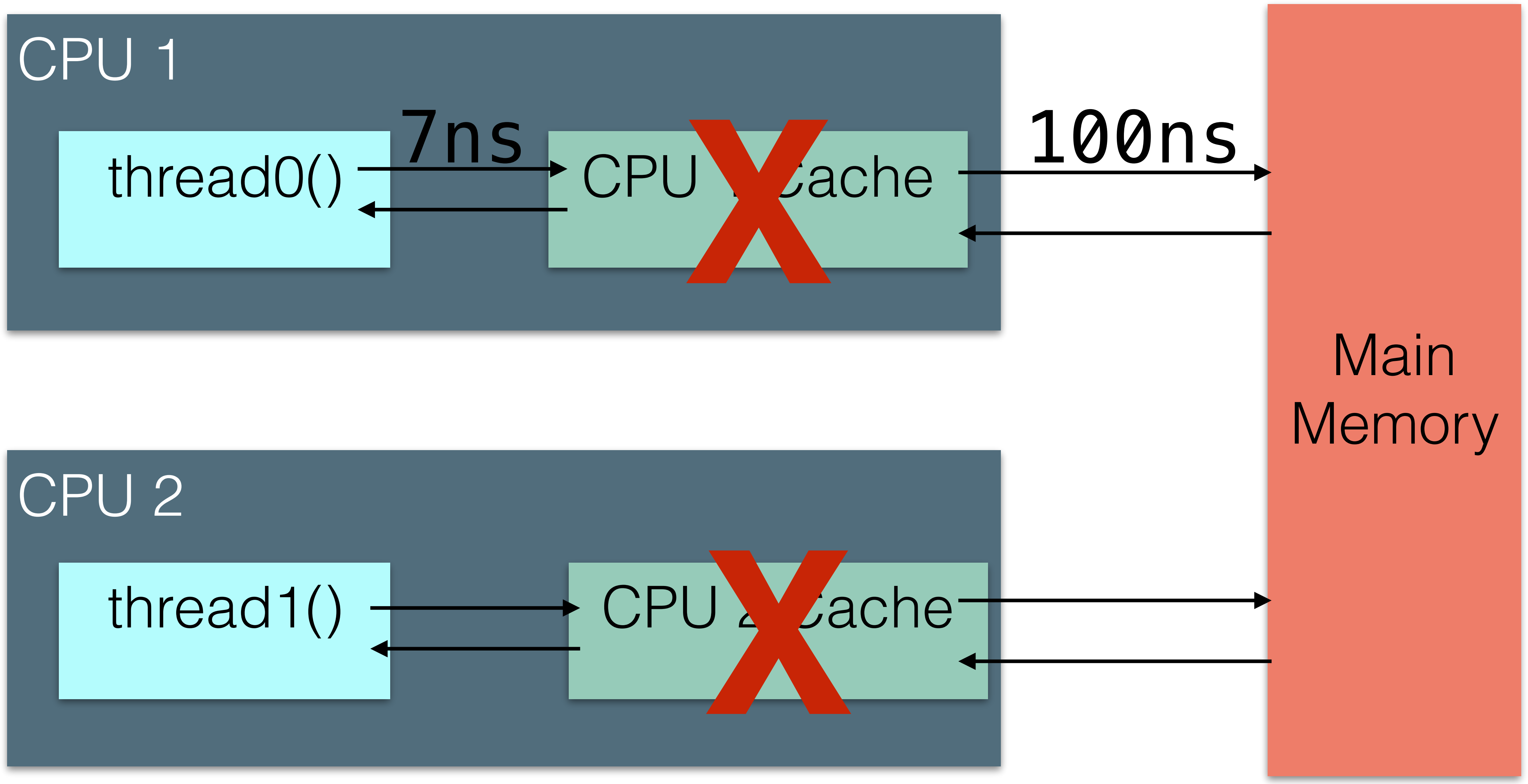
- Linearizability can be composed:
  - If p’s execution and q’s execution are both linearizable, then the combination must also be linearizable
- Sequential consistency can not be composed:
  - If p’s execution and q’s execution are both sequential, then the combination MAY also be sequential (but not guaranteed!)
- Why use sequential consistency?
  - Does not require global clock

The Flag Example



- Is this behavior really so wrong?
  – We can argue either way …

Volatile Keyword



Conditions

- When a thread is waiting for something to happen, it might want to release the lock and be notified when that thing has happened
  - Ex: while queue is full, release the lock to let someone else empty it
- This is what a *condition* does
- Key methods: *await*, *signal*

```
Condition condition = lock.newCondition();
lock.lock();
try{
   while(!property)
      condition.await();
}catch(InterruptedException e){
   //Application-dependent response, property may still be false
}
//at this point, property must be true and we have the lock again
```

```
condition.signal(); //wake up one thread await'ing
condition.signalAll(); //wake up all threads await'ing
```

Today

- Adding threads should not lower throughput - should increase throughput
  - Not possible if inherently sequential
  - How do we structure locks for faster performance?
  - First: wrap up discussion of read/write locks
  - Then: case study on a data structure
- Reading: H&S 9.1-9.5
- Note: HW1 coming up: https://www.jonbell.net/gmu-cs-475-fall-2019/homework-1/

Readers and Writers Problem

- Commonly called a read-write lock: data can be read by an unlimited number of threads at a time, written by at most one
- If a thread wants to write, nobody else can be reading (Alice + Bob with the billboards)
- High level approach:
  - Build on top of mutual exclusion locks with condition variables

Readers and Writers Lock

```
class ReadLock implements Lock{
   public void lock()
   {
      lock.lock();
      try{
         while(writer){
            condition.await();
         }
        readers++;
      } finally {
         lock.unlock();
      }
   }

   @Override
   public void unlock() {
      lock.lock();
      try{
         readers--;
         if(readers == 0)
            condition.signalAll();
      } finally{
         lock.unlock();
      }
   }
}
```

```
class WriteLock implements Lock{
   public void lock(){
      lock.lock();
      try{
         while(readers > 0 || writer)
            condition.await();
         writer =true;

      } finally{
         lock.unlock();
      }
   }

   @Override
   public void unlock() {
      writer = false;
      condition.signalAll();
   }
}
```

Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using queue locks
  - Easy to reason about
    - In simple cases
  - Standard Java model
    - Locks, Synchronized blocks and methods
- So, are we done?

Coarse-Grained Synchronization

- Sequential bottleneck
  - Threads “stand in line”
- Adding more threads
  - Does not improve throughput
  - Struggle to keep it from getting worse
- So why even use a multiprocessor?
  - Well, some apps inherently parallel …

Today:
Fine-Grained Synchronization

- Instead of using a single lock ..
- Split object into
  - Independently-synchronized components
- Methods conflict when they access
  - The same component …
  - At the same time

Linked List

- Illustrate this patterns…
- Using a list-based Set
  - Common application
  - Building block for other apps

Set Interface

- Unordered collection of items
- No duplicates
- Methods
  - `add(x)` put x in set
  - `remove(x)` take x out of set
  - `contains(x)` tests if x in set

List-Based Sets

```
public interface Set<T> {
 public boolean add(T x);
 public boolean remove(T x);
 public boolean contains(T x);
}
```

List-Based Sets

```
public interface Set<T> {
  public boolean add(T x);
  public boolean remove(T x);
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}
```

Add item to set

List-Based Sets

```
public interface Set<T> {
 public boolean add(T x);
 public boolean remove(T x);
 public boolean contains(Tt x);
}
```

Remove item from set

Art of Multiprocessor Programming

List-Based Sets

```
public interface Set<T> {
 public boolean add(T x);
 public boolean remove(T x);
 public boolean contains(T x);
}
```

Is item in set?

List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```

List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```

item of interest

List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```

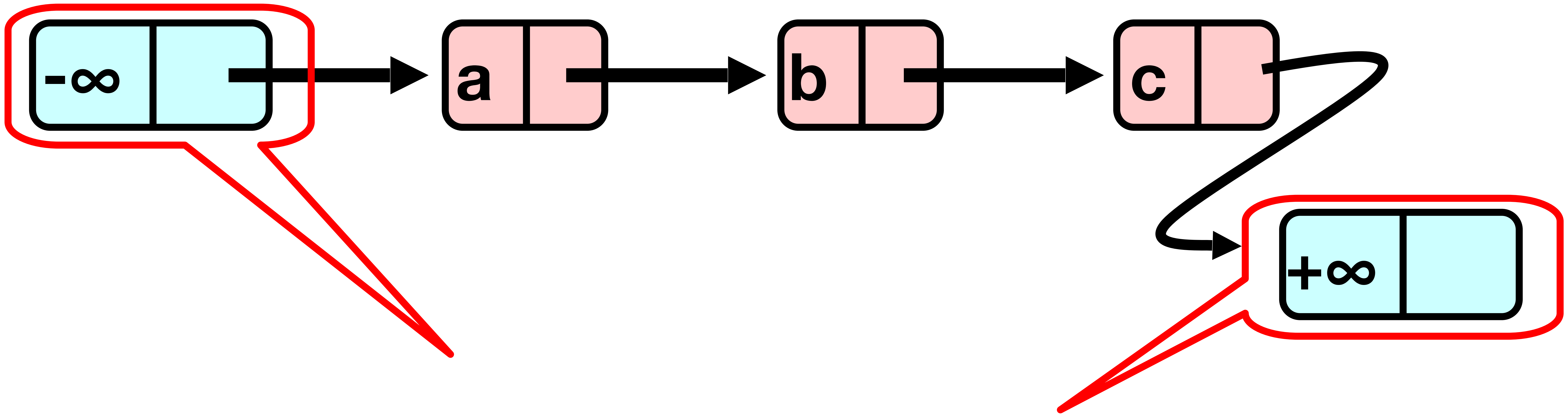
Usually hash code

List Node

```
public class Node {
 public T item;
 public int key;
 public Node next;
}
```

Reference to next node

The List-Based Set



Sorted with Sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Objects

- Invariant
  - Property that always holds
- Established because
  - True when object is **created**
  - Truth **preserved** by each method
    - Each **step** of each method

Specifically …

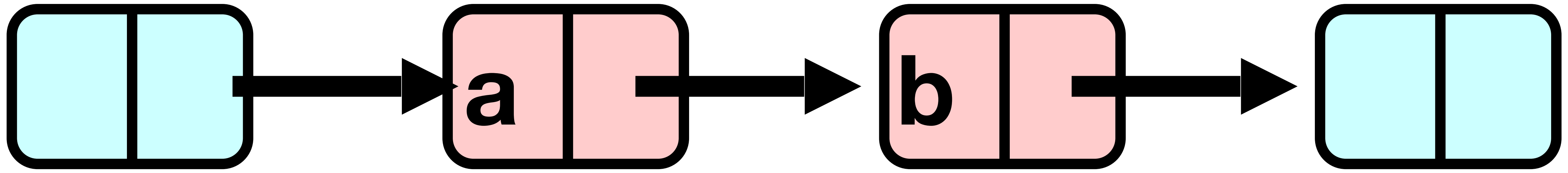
- Invariants preserved by
  - `add()`
  - `remove()`
  - `contains()`
- Most steps are trivial
  - Usually one step tricky
  - Often linearization point

Interference

- Invariants make sense only if
  - methods considered are the only way to modify the variables
- Language encapsulation helps
  - List nodes not visible outside class (private)
- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with **malloc()** & **free()** !
- Garbage-collection helps here

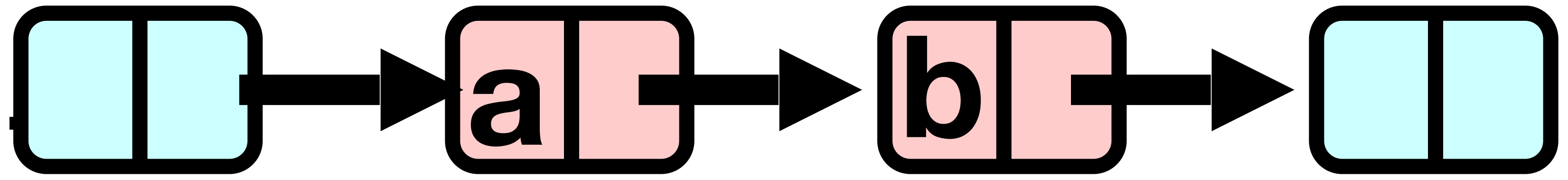
Abstract Data Types

- Our choice for how we store something concretely doesn't need to exactly match the abstract type that we expose
- Concrete representation



- Abstract Type
  - {a, b}

Abstract Data Types

- Meaning of representation given by abstraction map
  - S(

) = {a,b}

Representation Invariants

- Which abstract values are valid?
  - Is the set sorted?
  - Are there duplicates allowed in the set?
- Representation invariant
  - Characterizes legal concrete representation
  - Preserved by methods
  - Relied on by methods

Blame Game

- Rep invariant is a **contract**
- Suppose
  - **add()** leaves behind 2 copies of x in the concrete (list) type
  - **remove()** removes only 1 from the concrete (list) type
- Which one is incorrect?

Blame Game

- Suppose
  - **add()** leaves behind 2 copies of x in the concrete (list) type
  - **remove()** removes only 1 from the concrete (list) type
- Which one is incorrect?
  - If rep invariant says no duplicates
    - **add()** is incorrect
  - Otherwise
    - **remove()** is incorrect

Representation Invariants (partly)

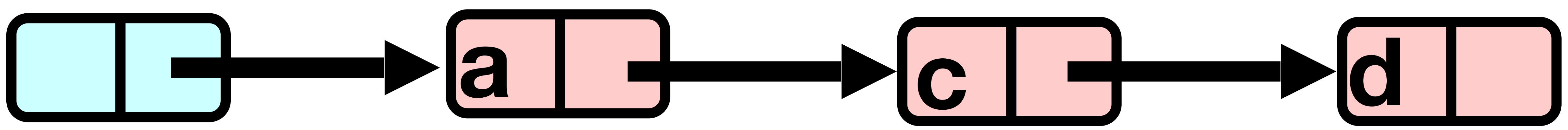
- For sentinel nodes:
  - tail reachable from head
- Sorted
- No duplicates

Abstraction Map

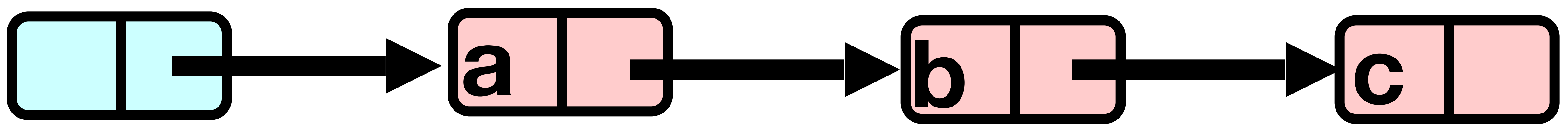
- S(head) =
  - { x | there exists a such that
    - a reachable from head and
    - a.item = x
  - }
  - (The set made from the head node in the list is the set of all x's such that the node holding x is reachable from the head)

Sequential List Based Set

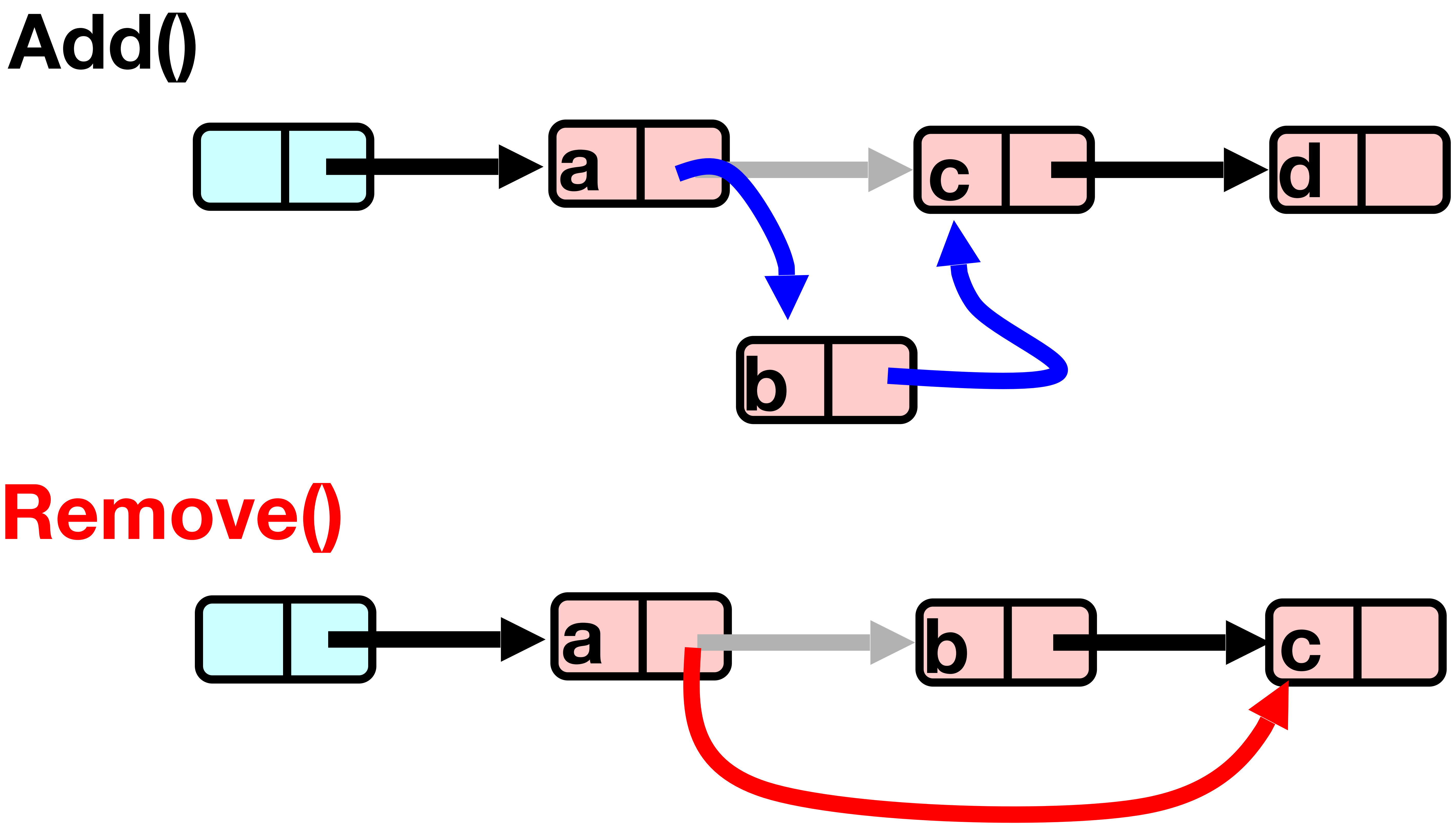
Add()



Remove()



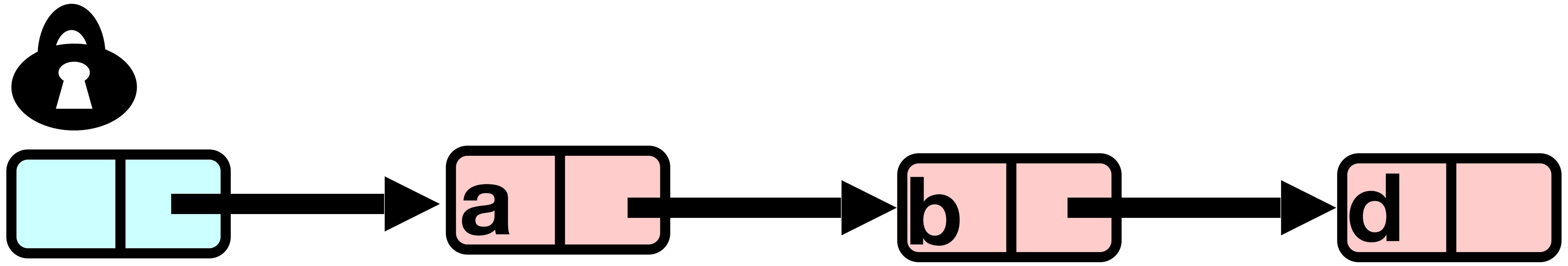
Sequential List Based Set



Coarse Grained Locking

```
public class CoarseLockedSet<T> {
 public synchronized boolean add(T x){ … }
 public synchronized boolean remove(T x){ … }
 public synchronized boolean contains(T x){ … }
}
```

Course Grained Locking



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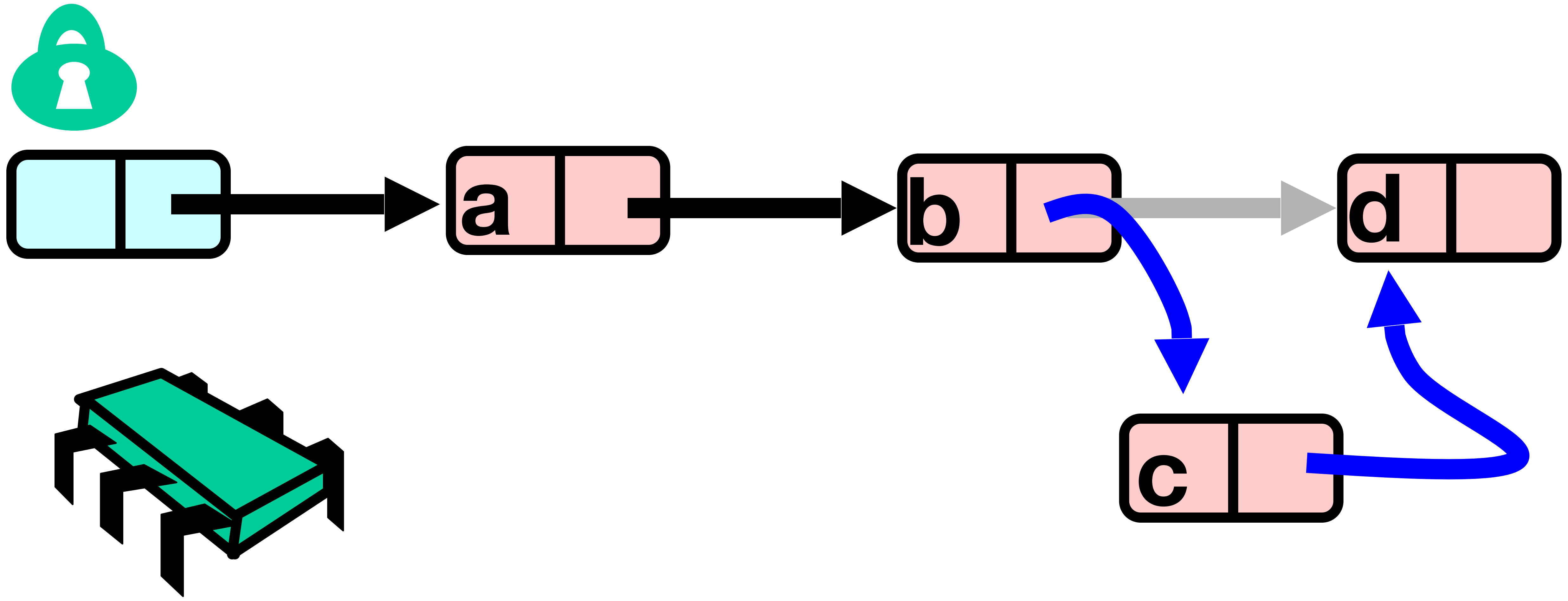

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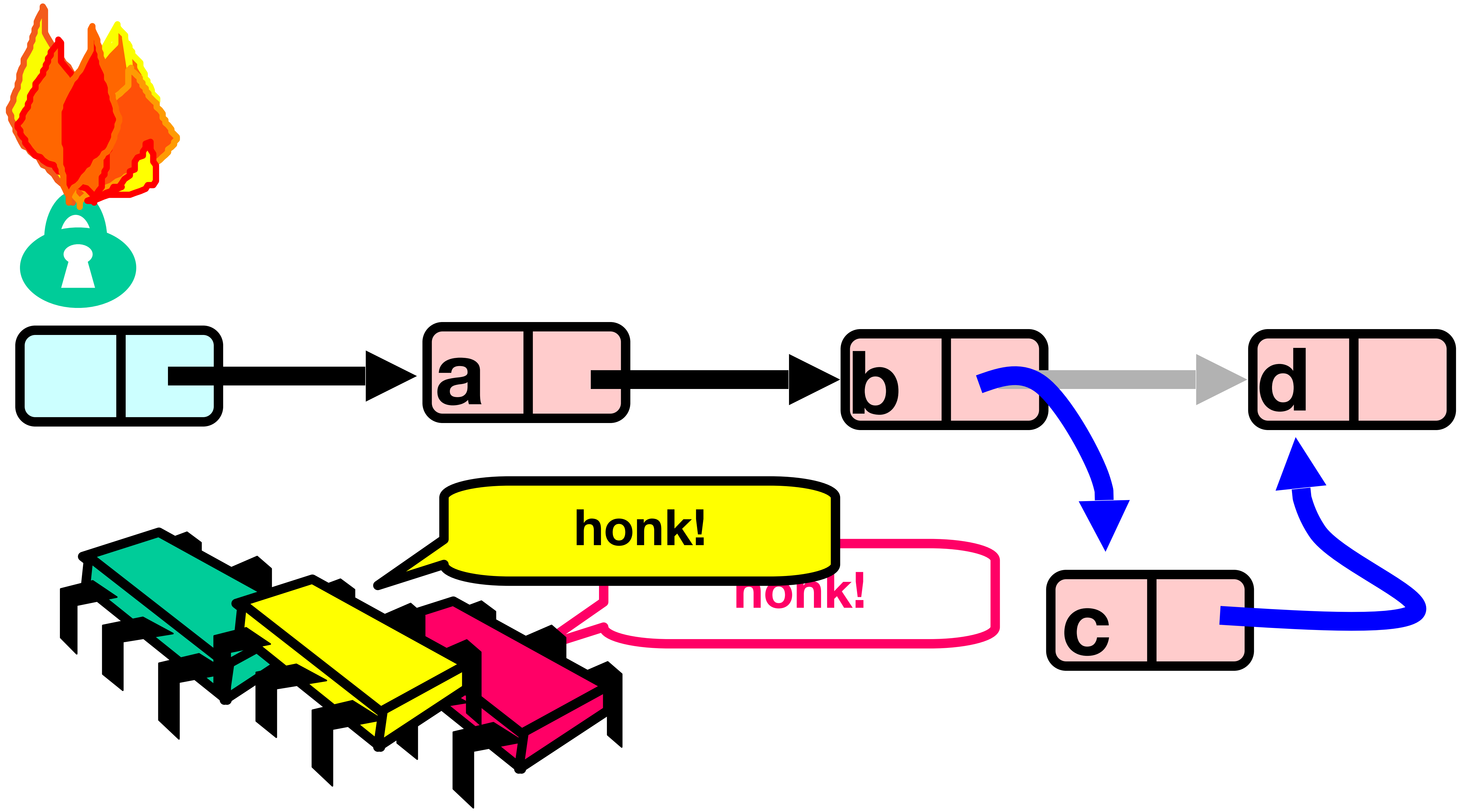


Simple but hotspot + bottleneck

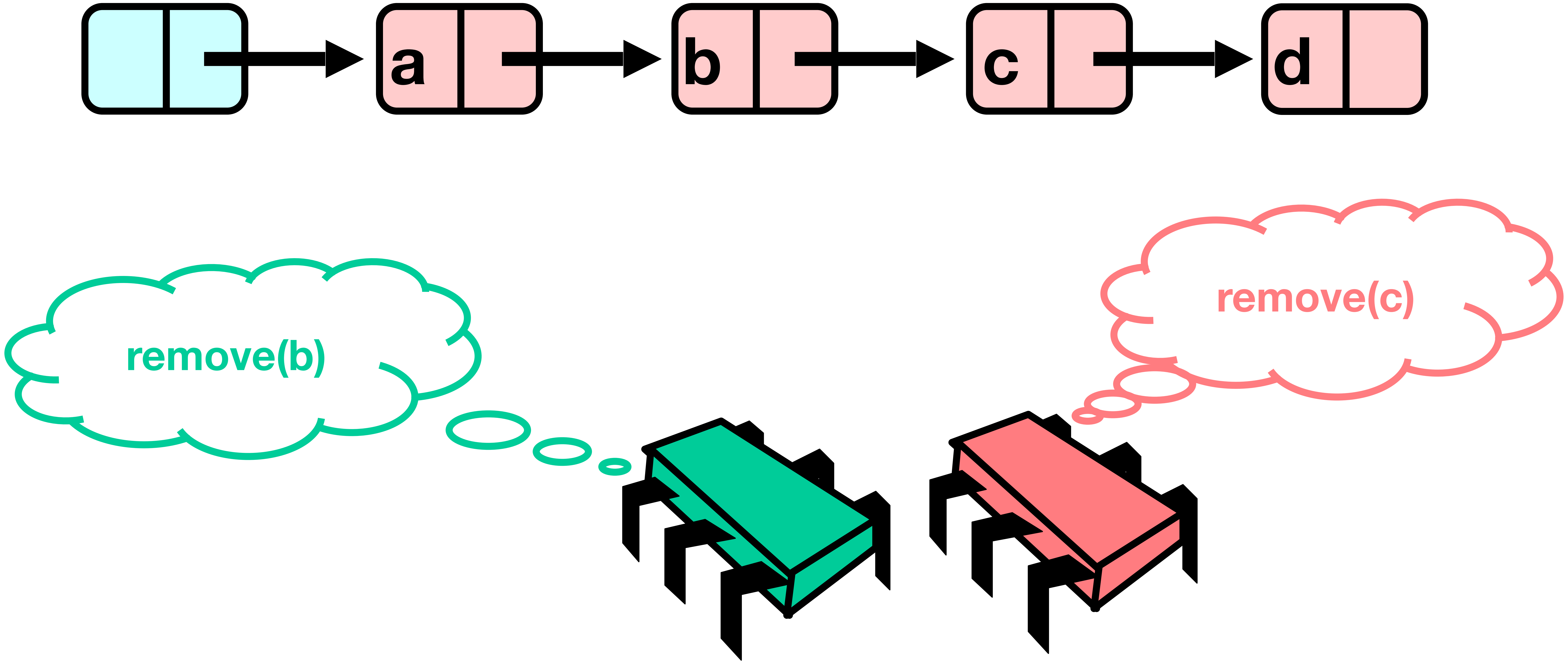
Coarse-Grained Locking

- Easy, same as the bigLock
  - “One lock to rule them all …”
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue

Fine-grained Locking

- Requires **careful** thought
  - "Do not meddle in the affairs of wizards, for they are subtle and quick to anger"
  - **Deadlocks ahead!**
- Split object into pieces
  - Each piece has own lock
  - Methods that work on disjoint pieces need not exclude each other

Simple Fine-Grained Locking: Remove



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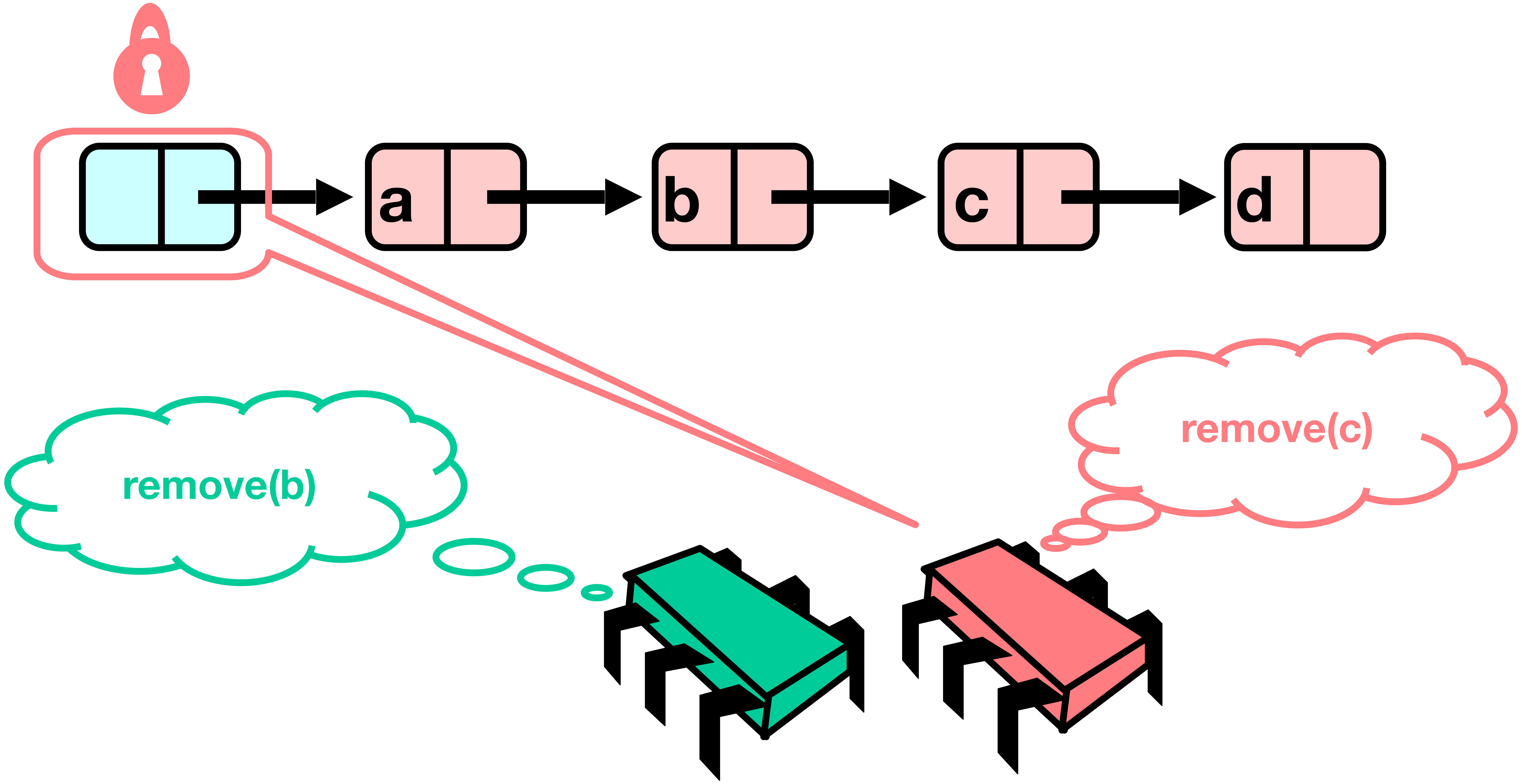

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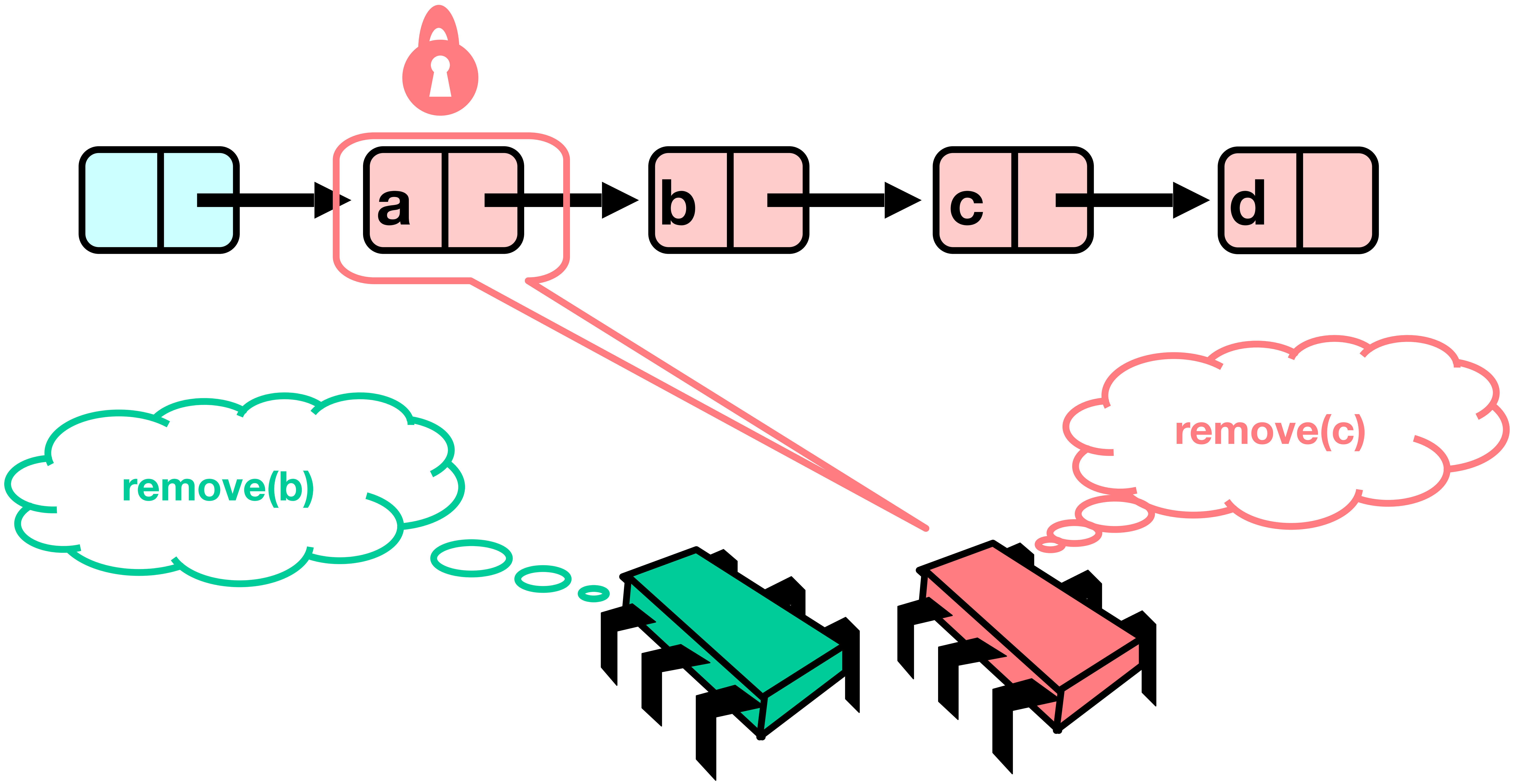

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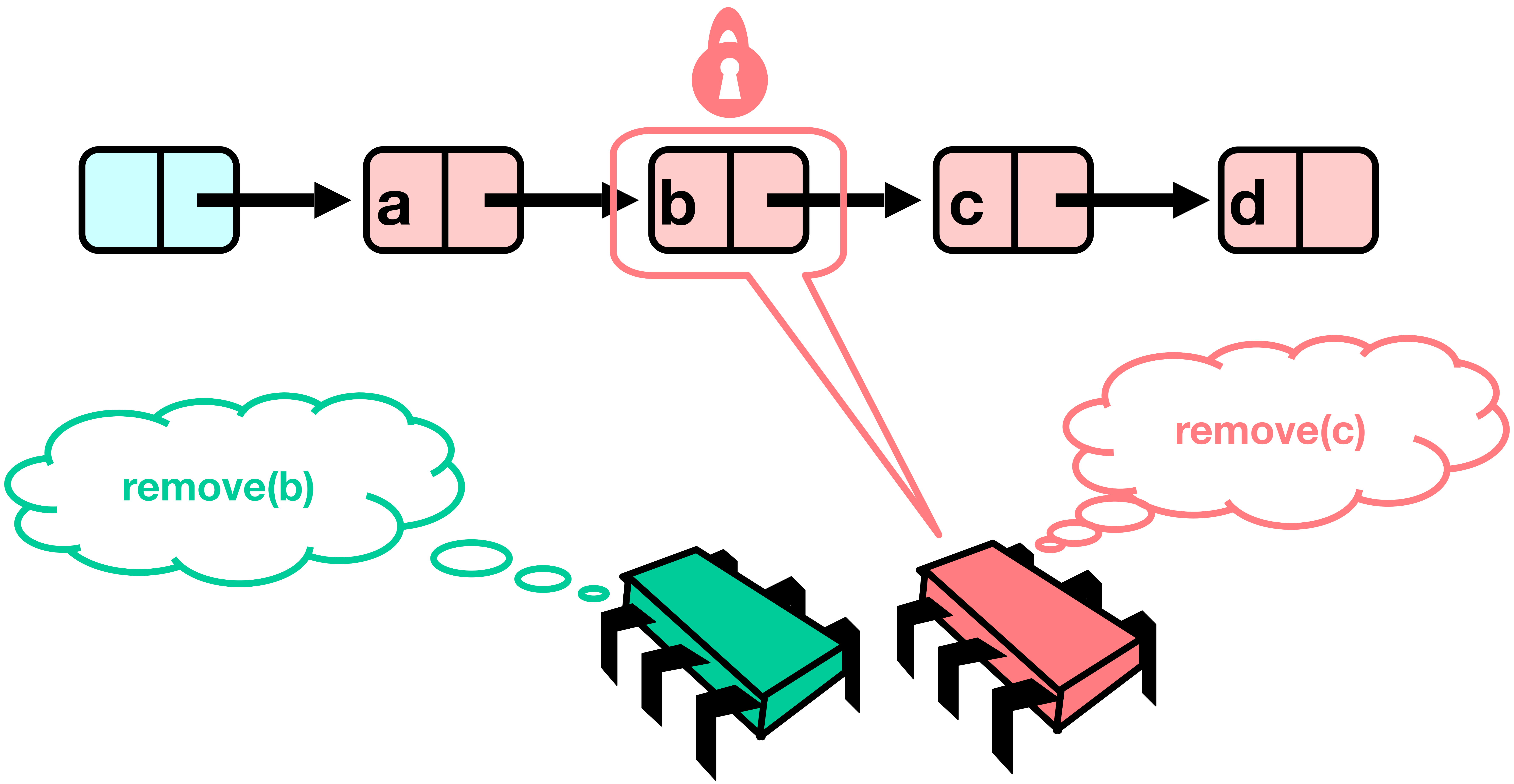

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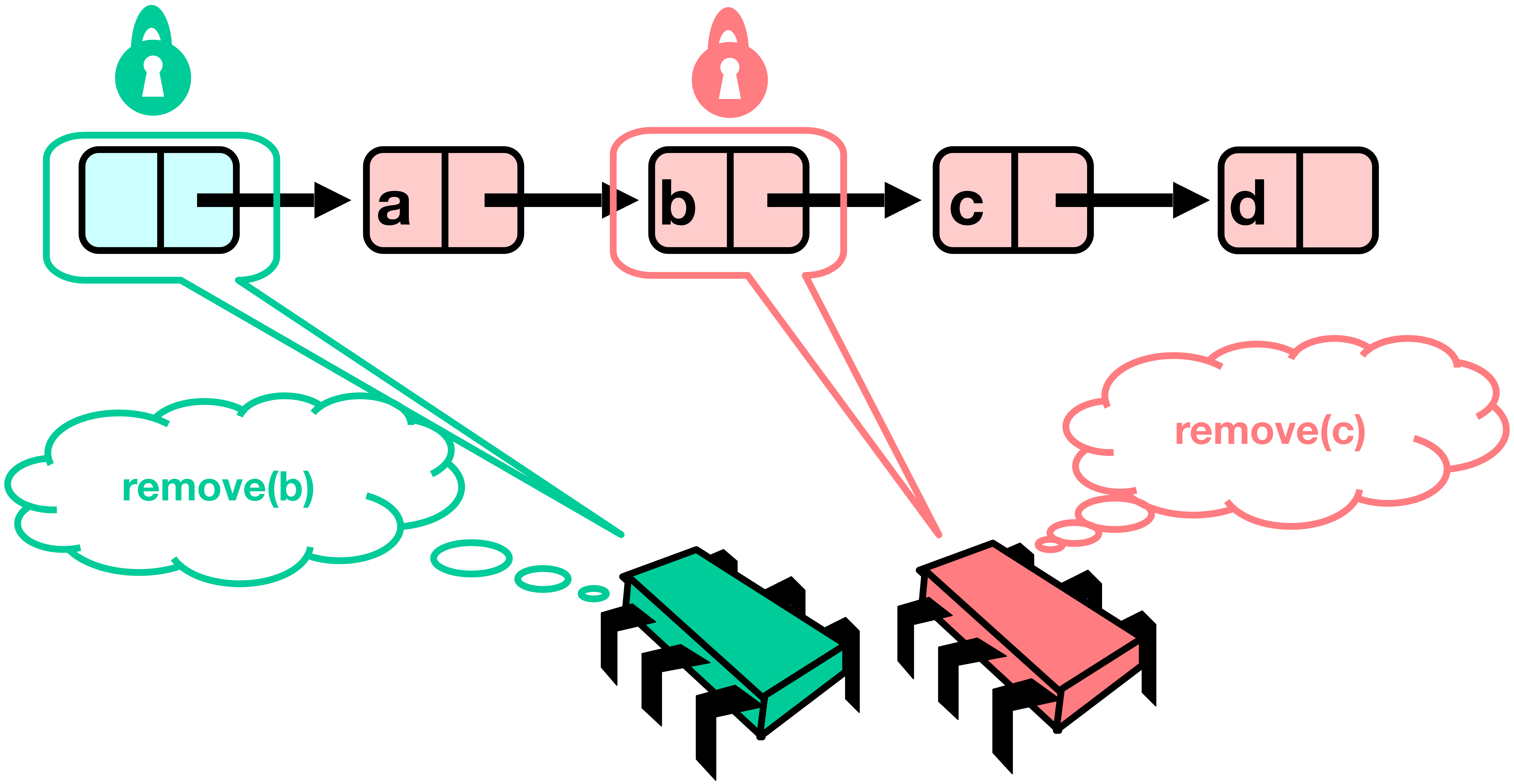

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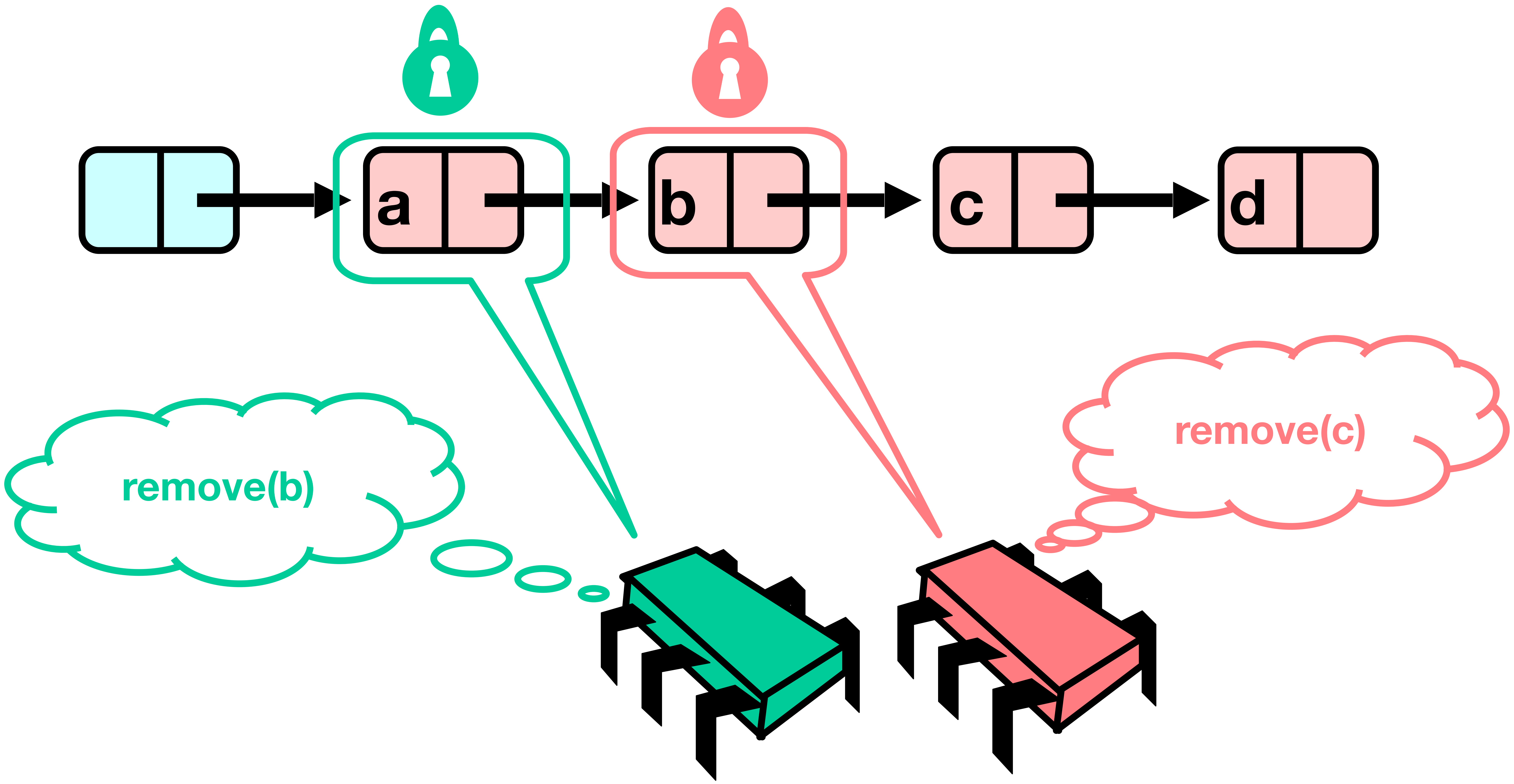

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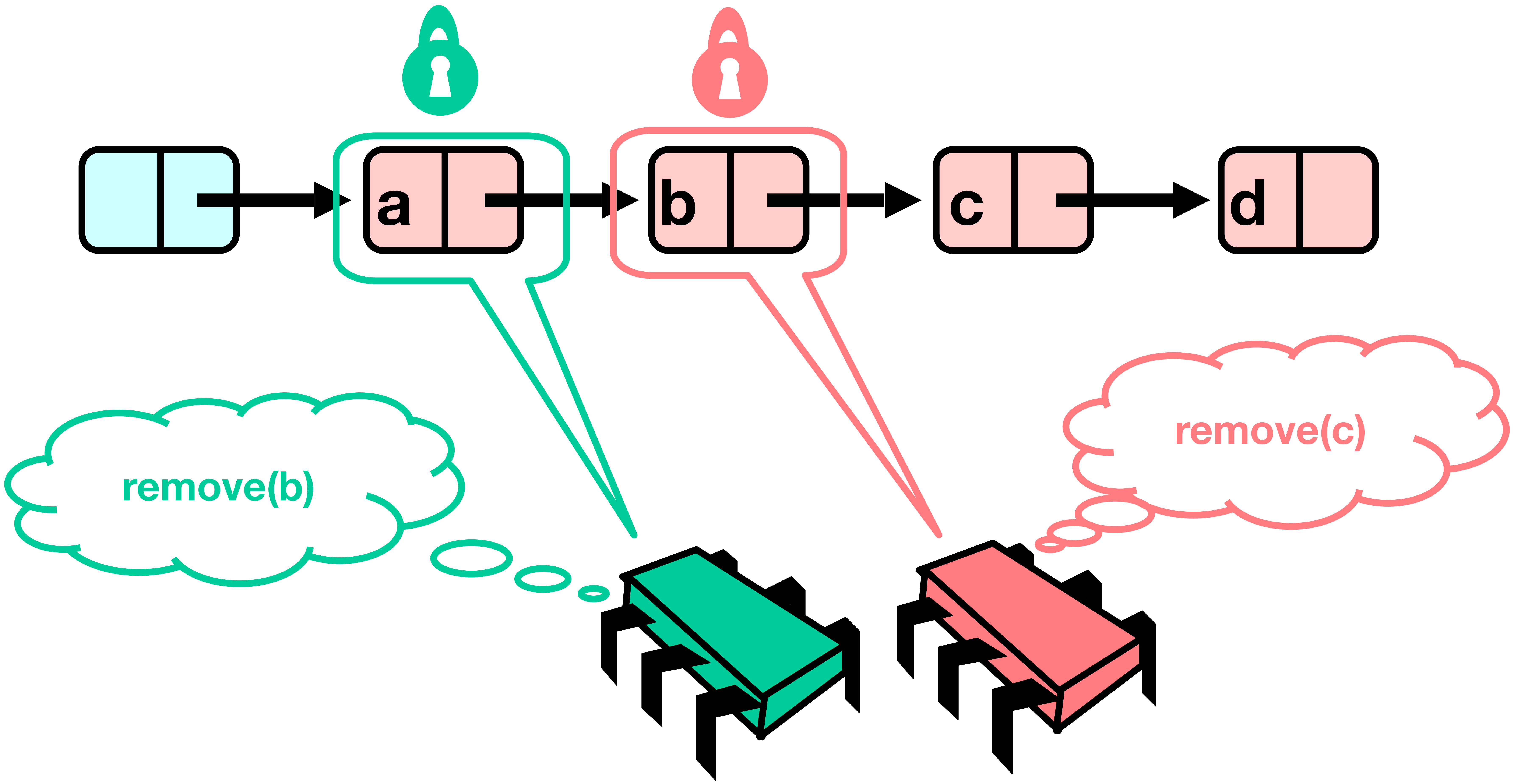
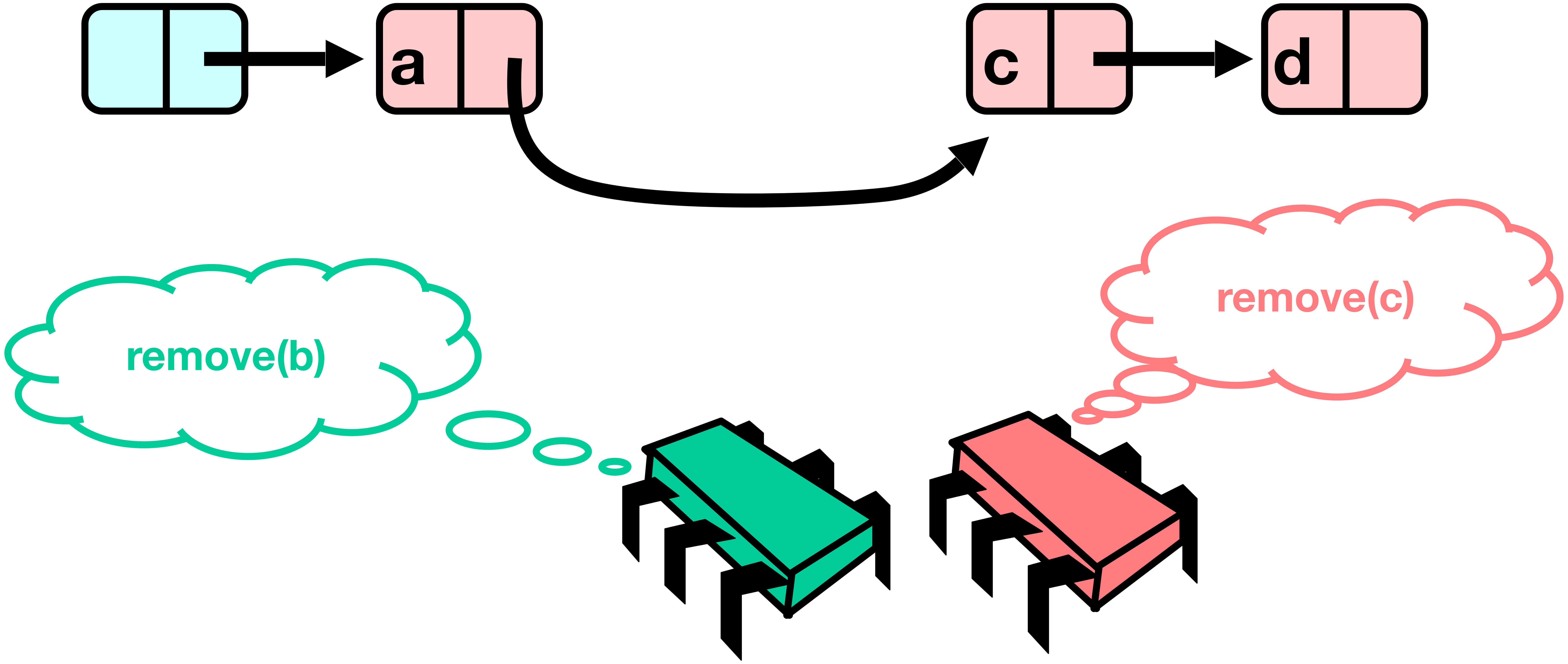


Uh, Oh



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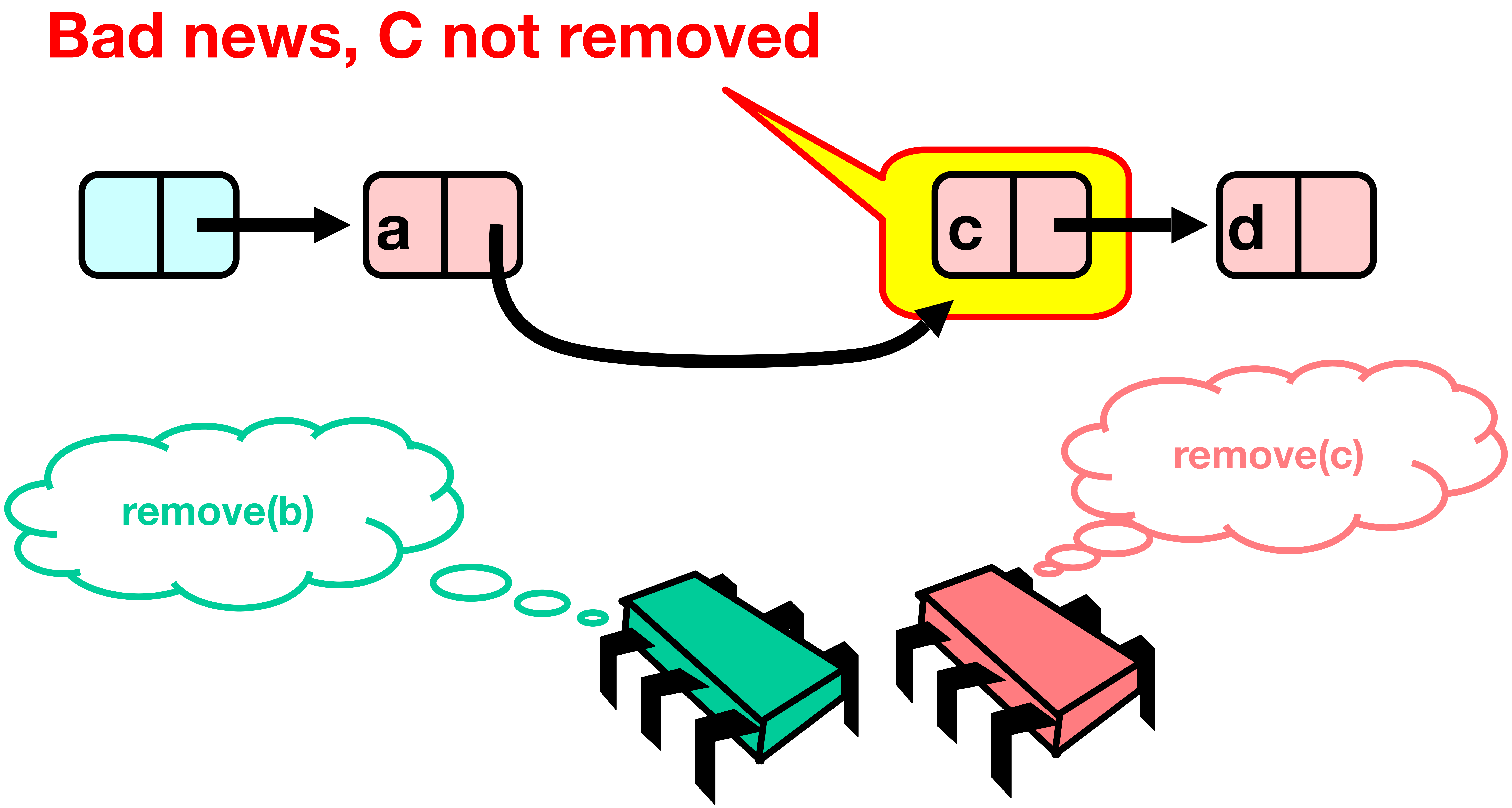
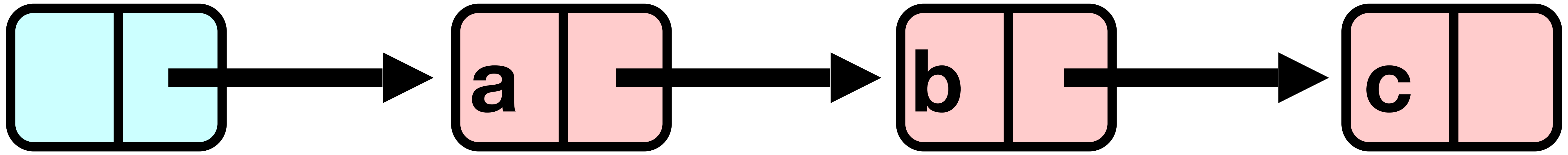
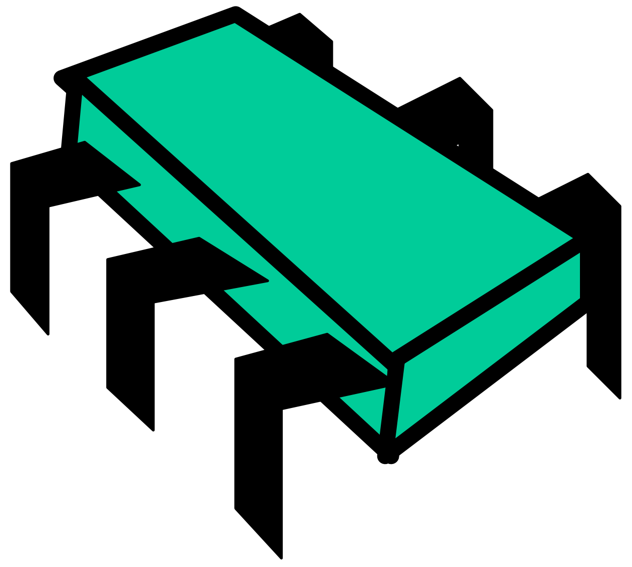


Hand-over-Hand locking





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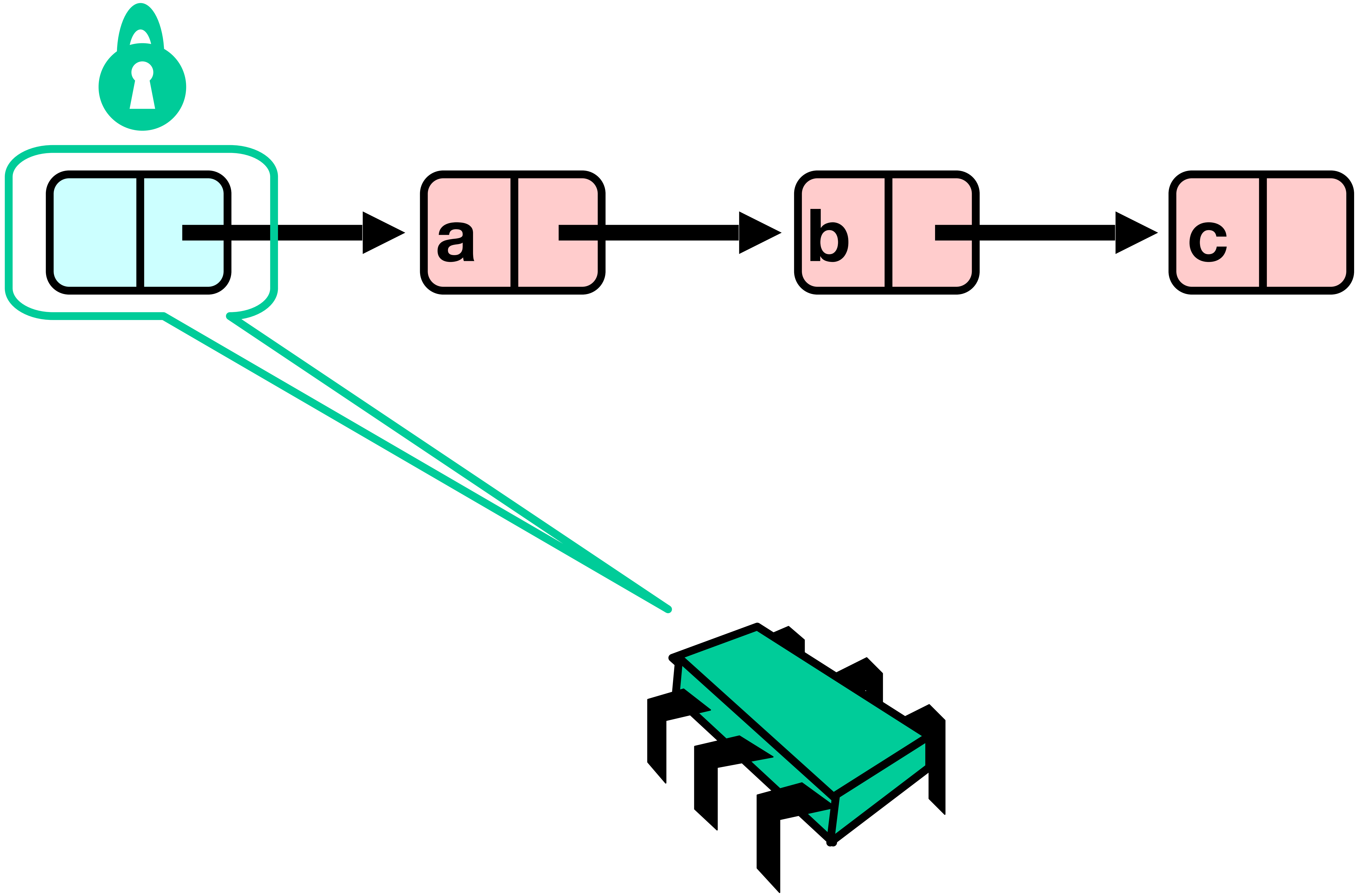

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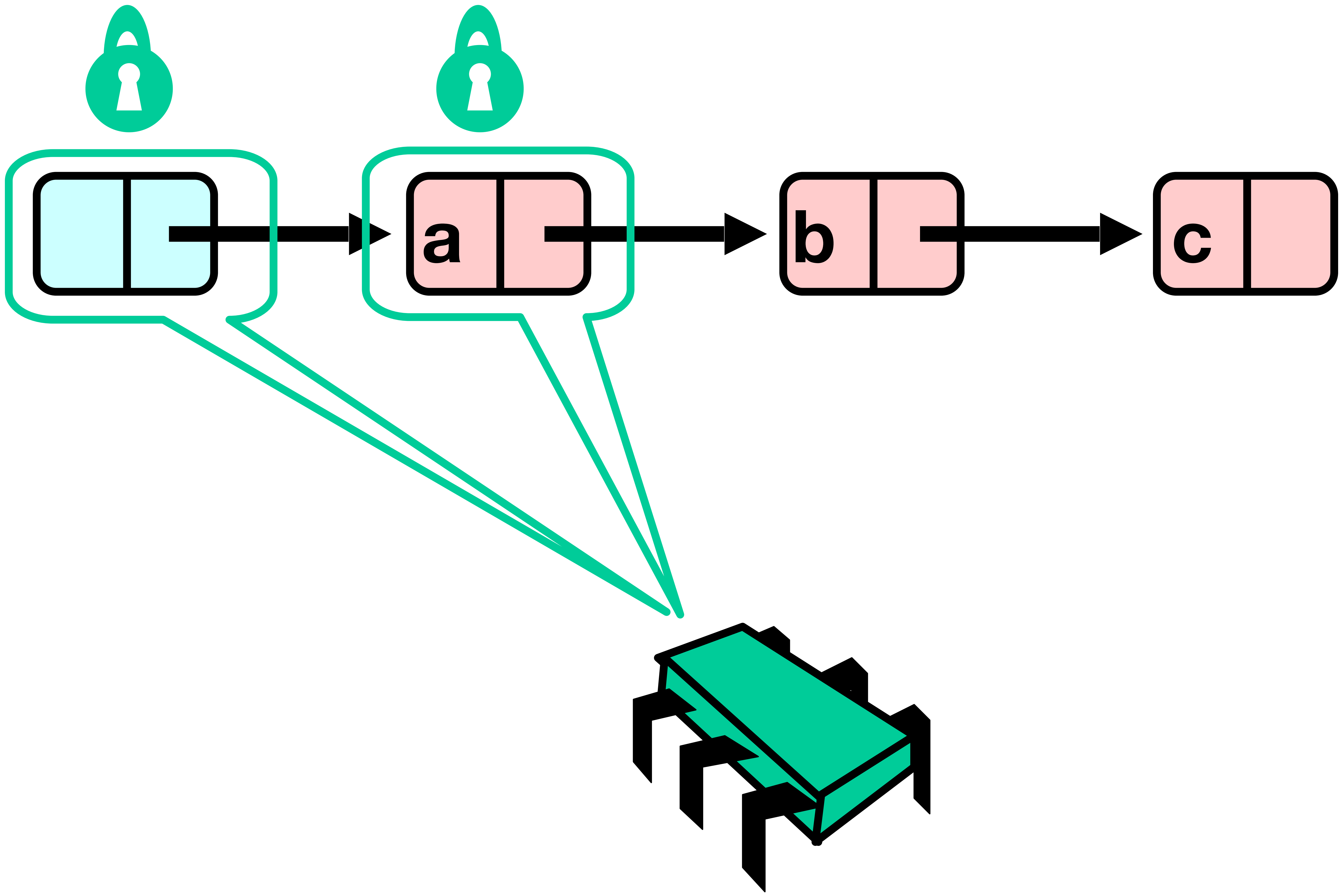

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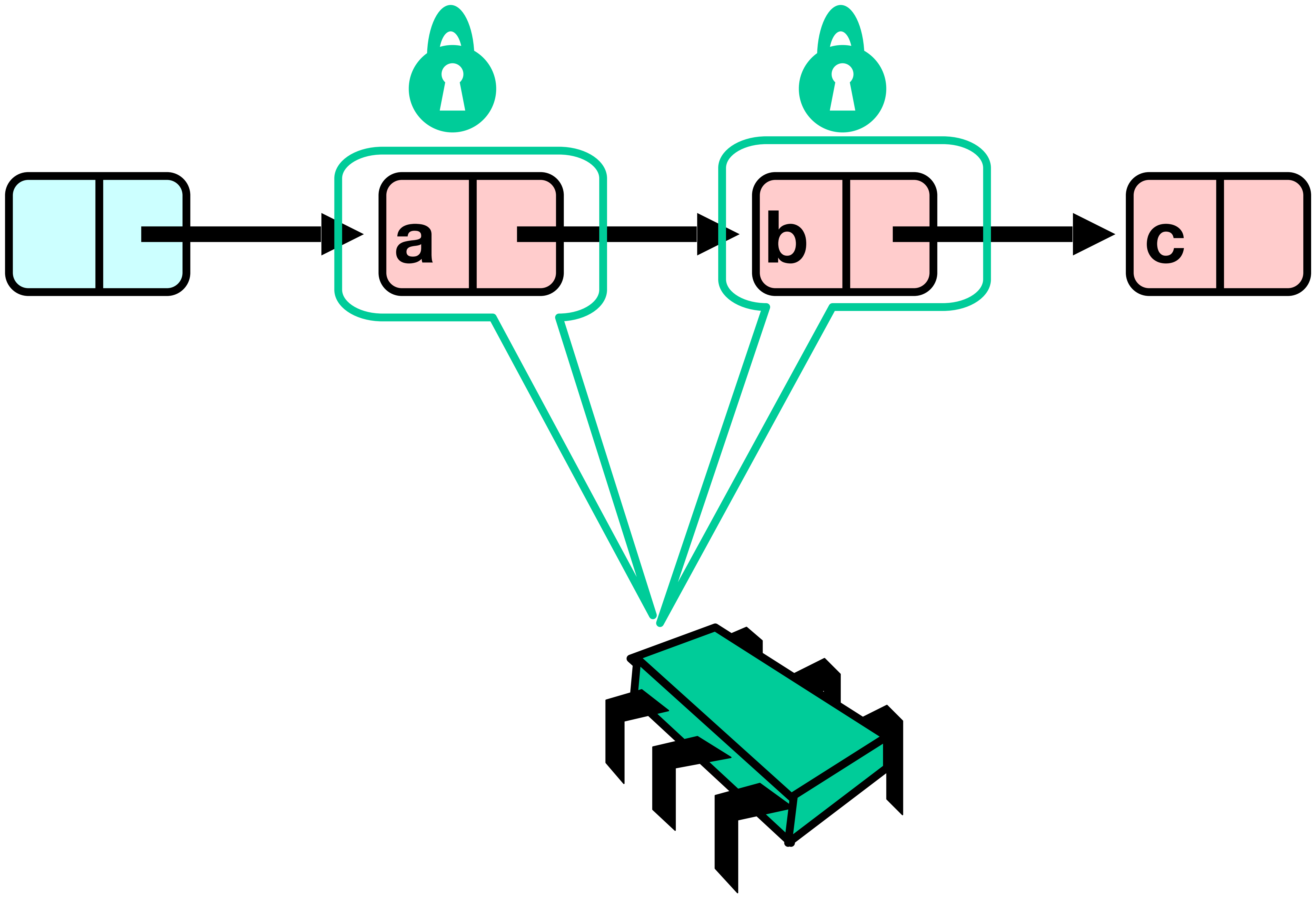

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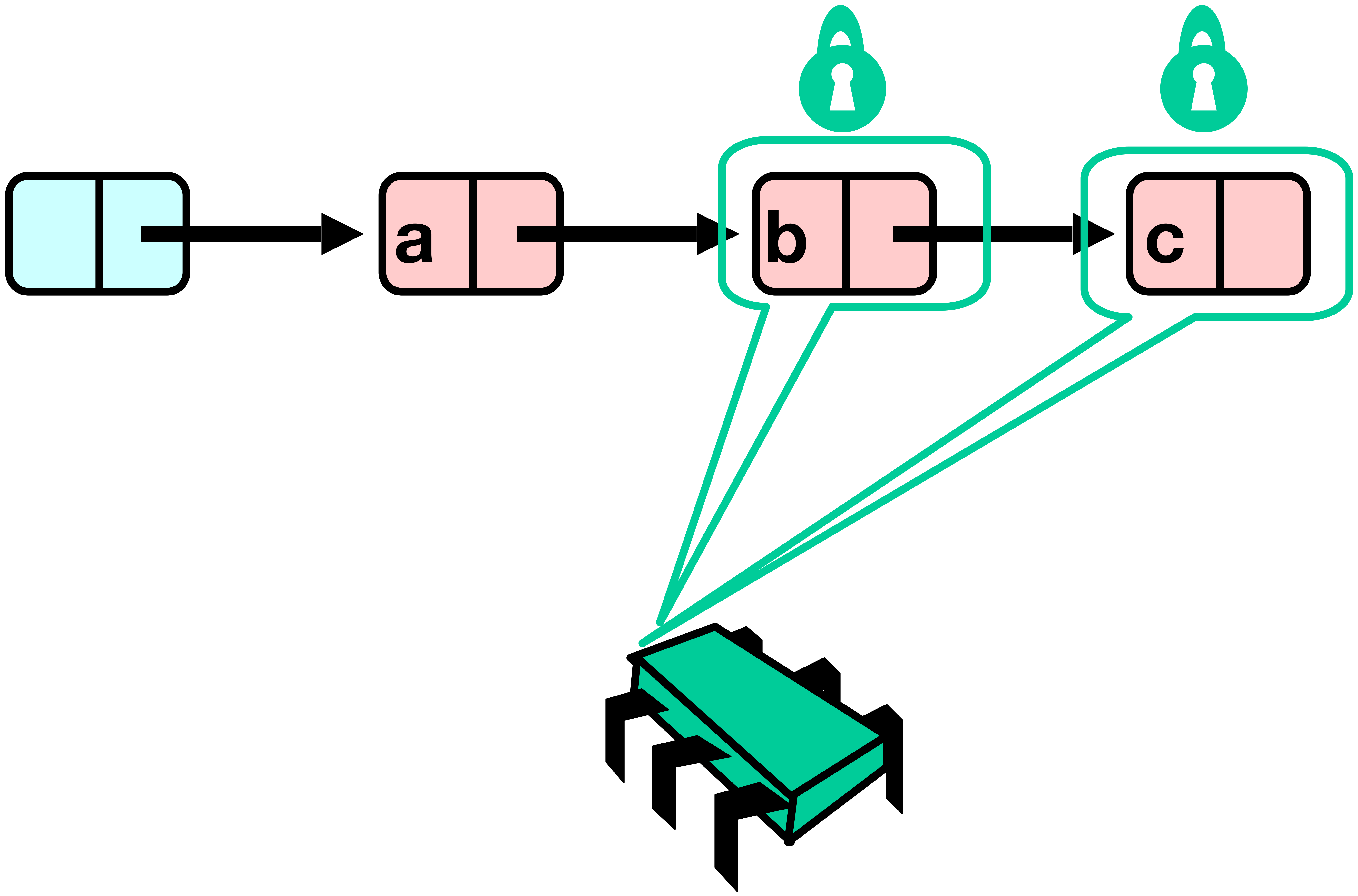
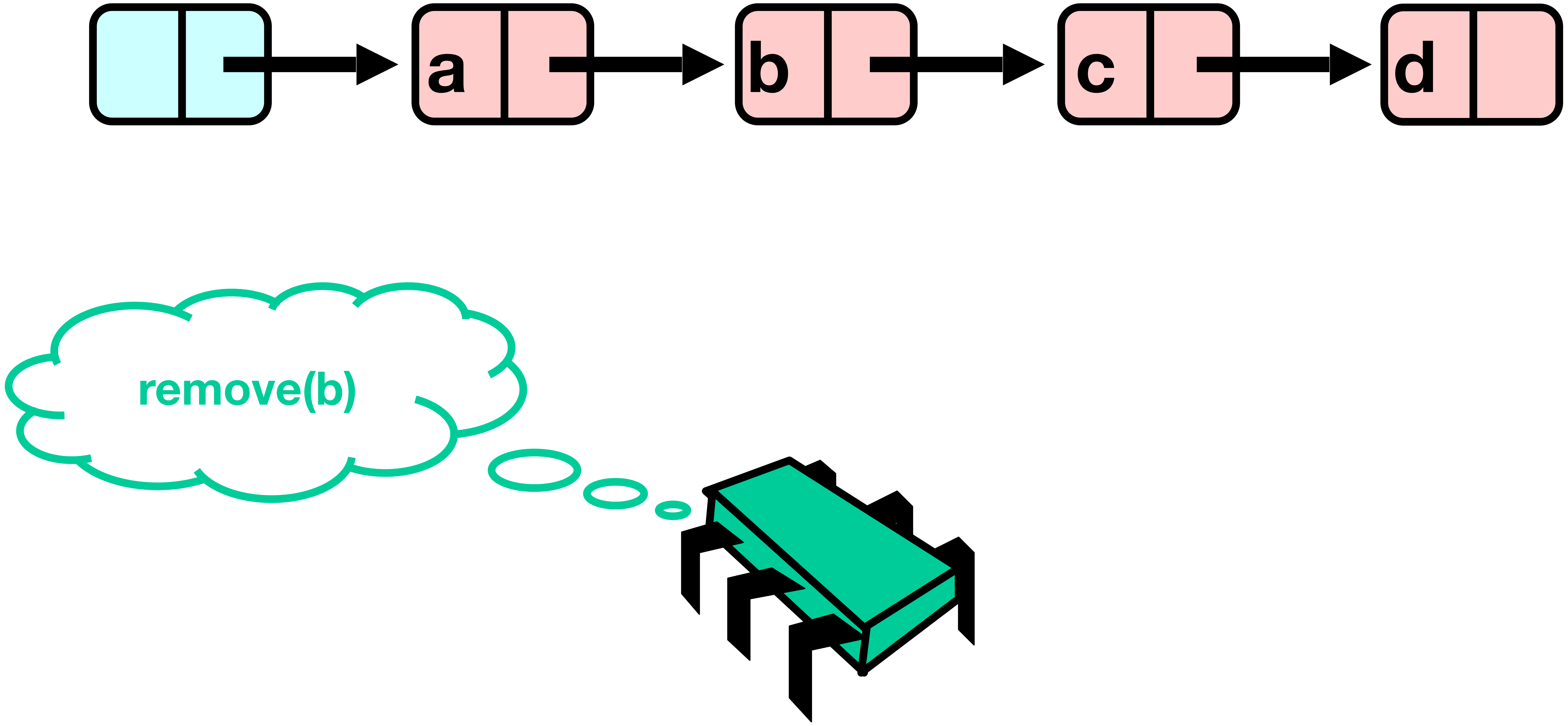


Removing a Node



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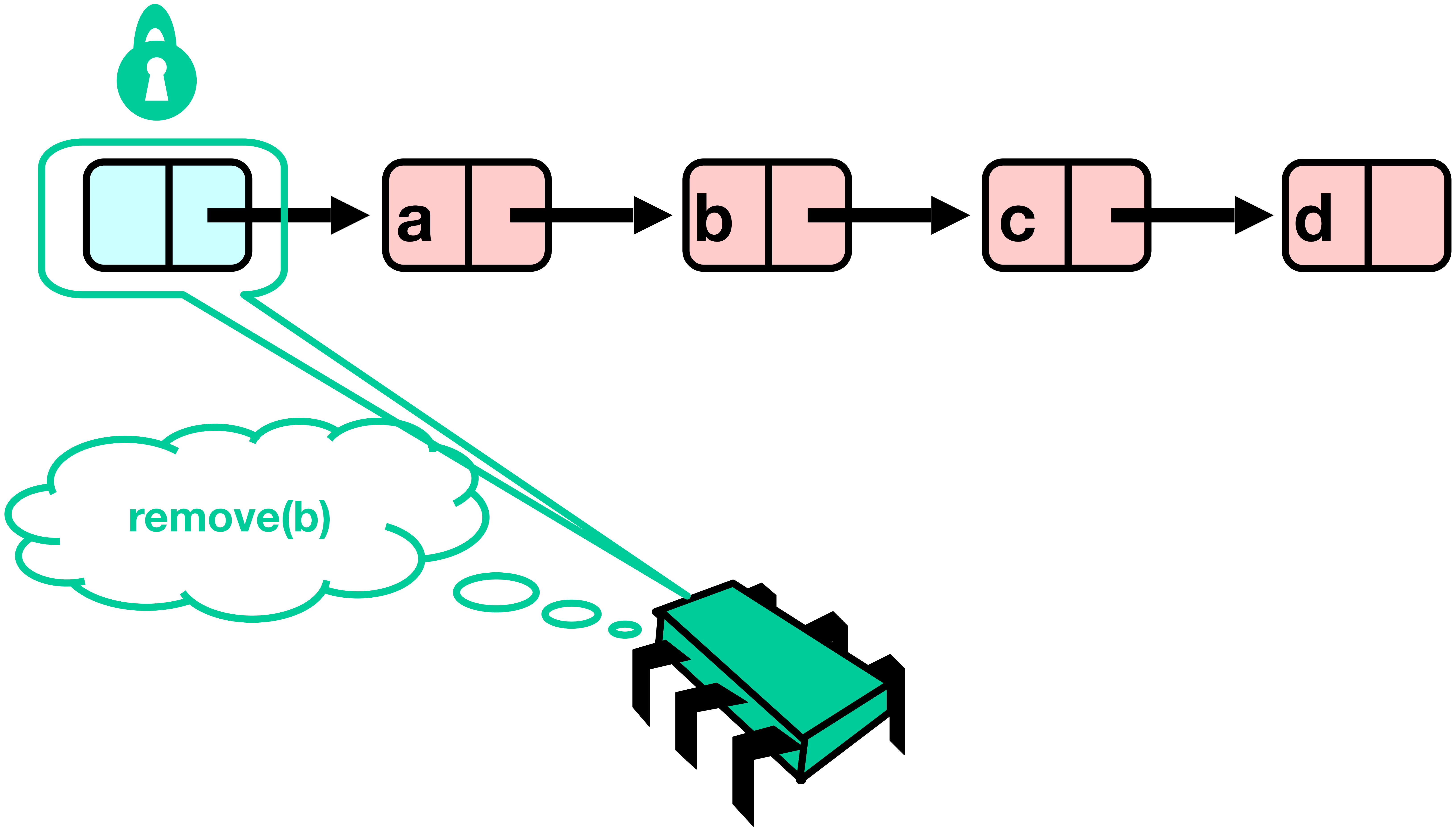

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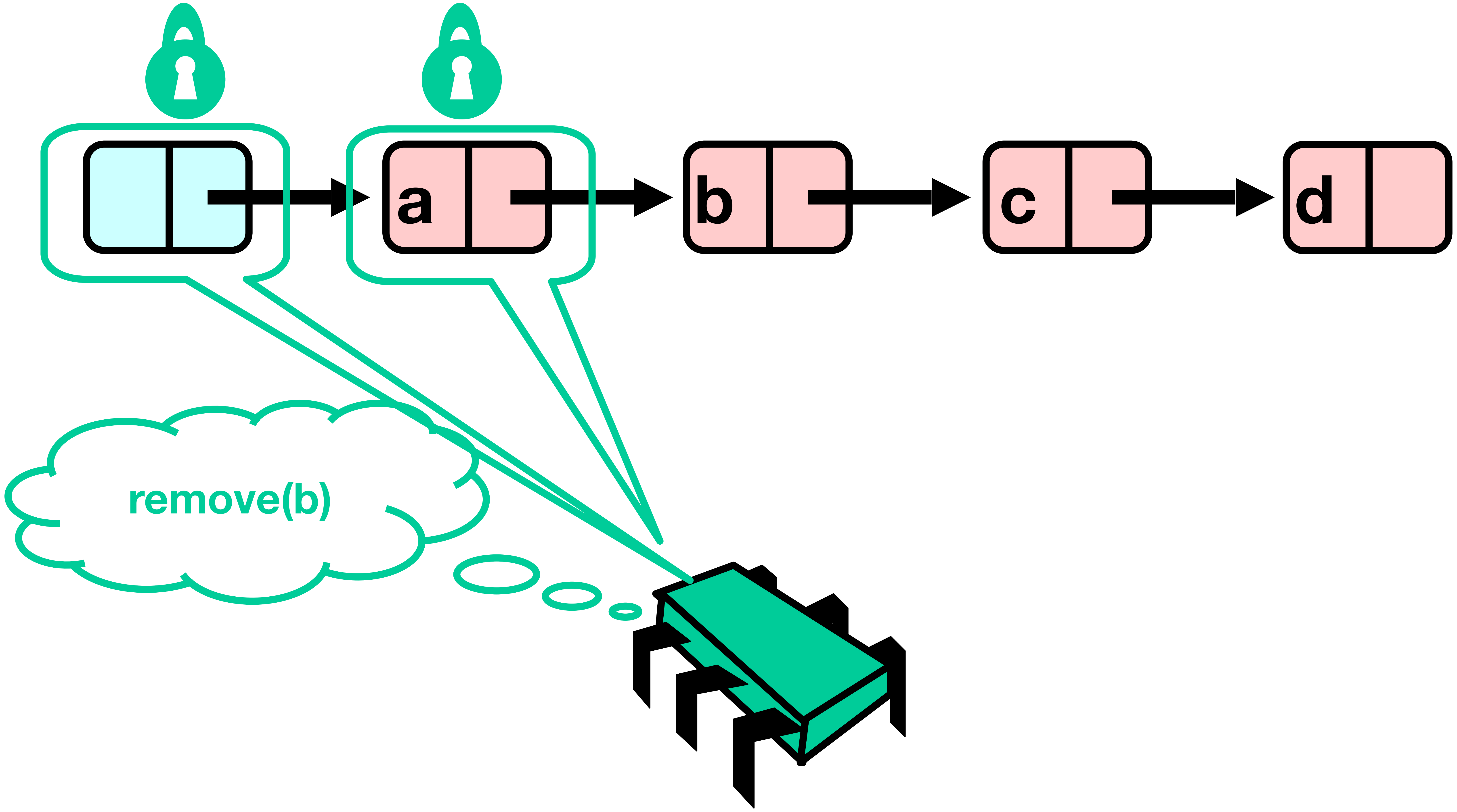

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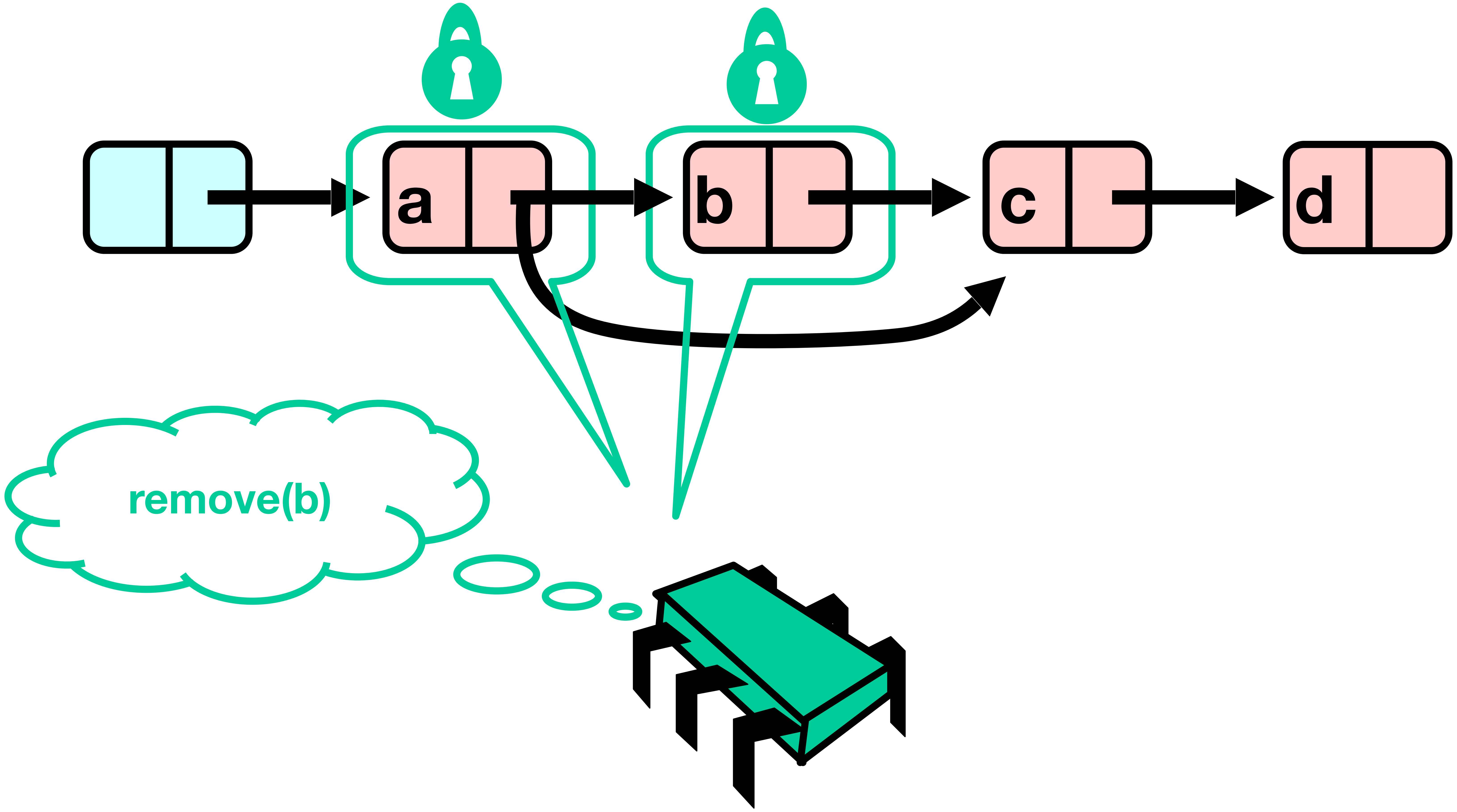

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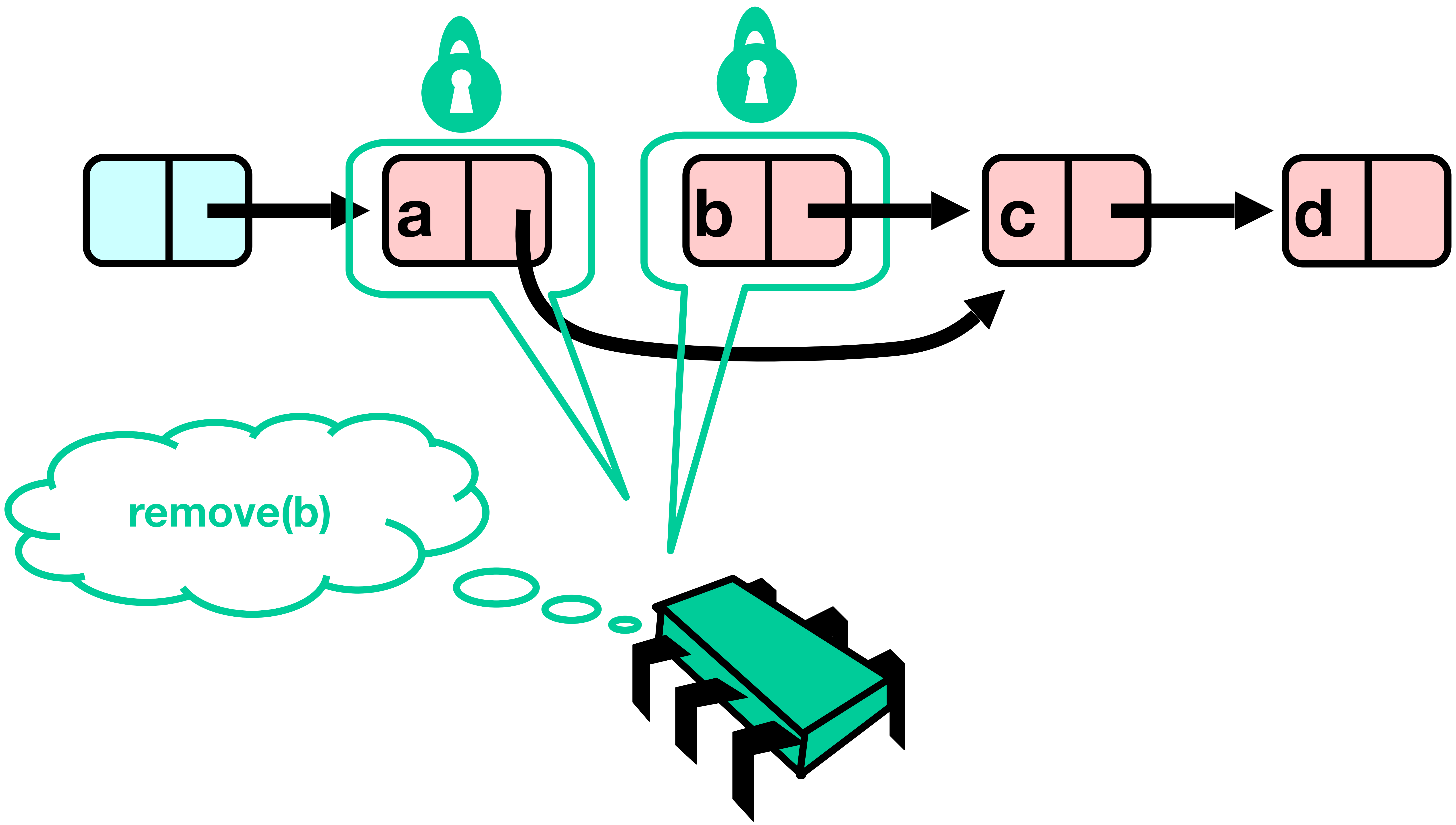

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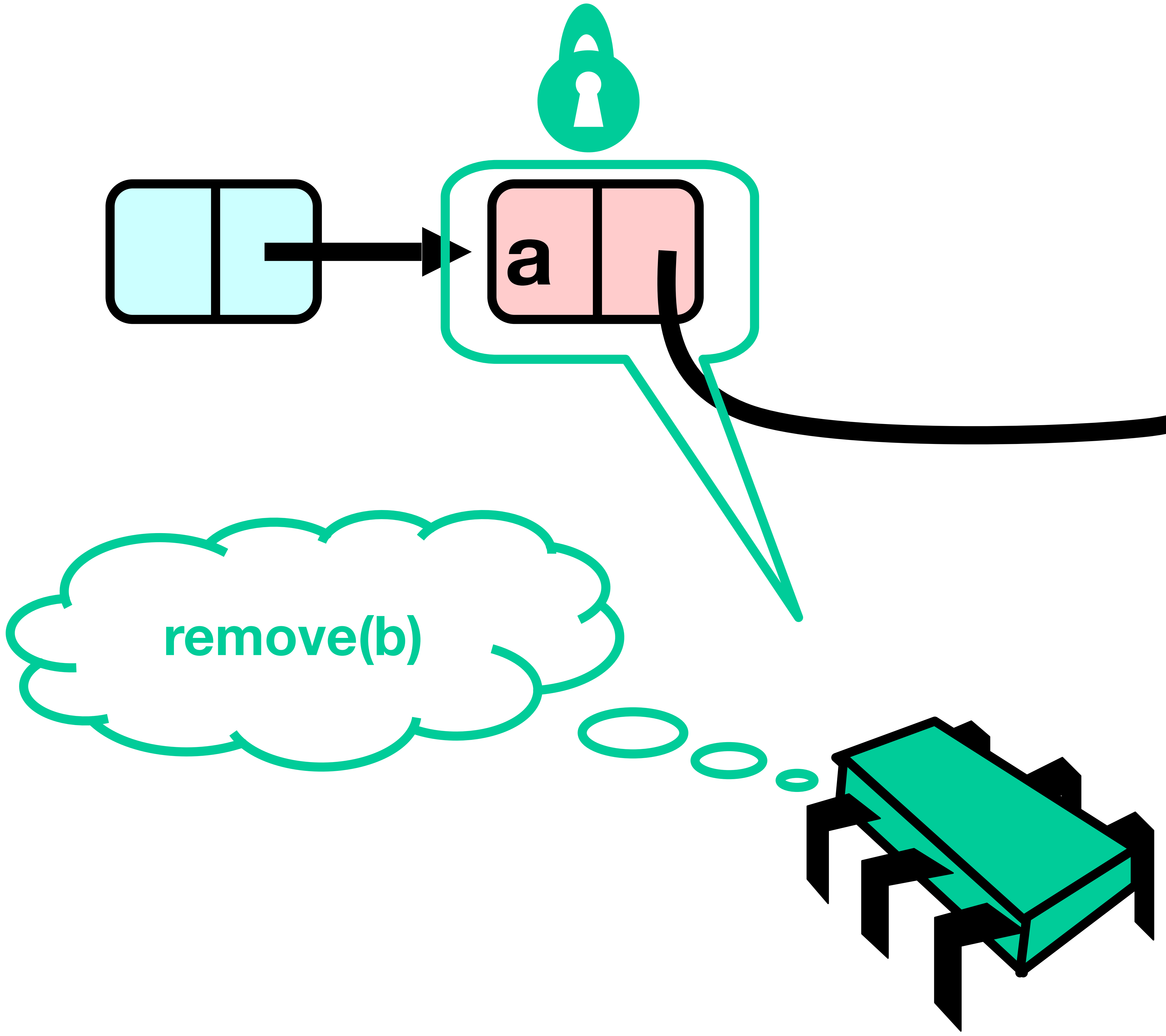
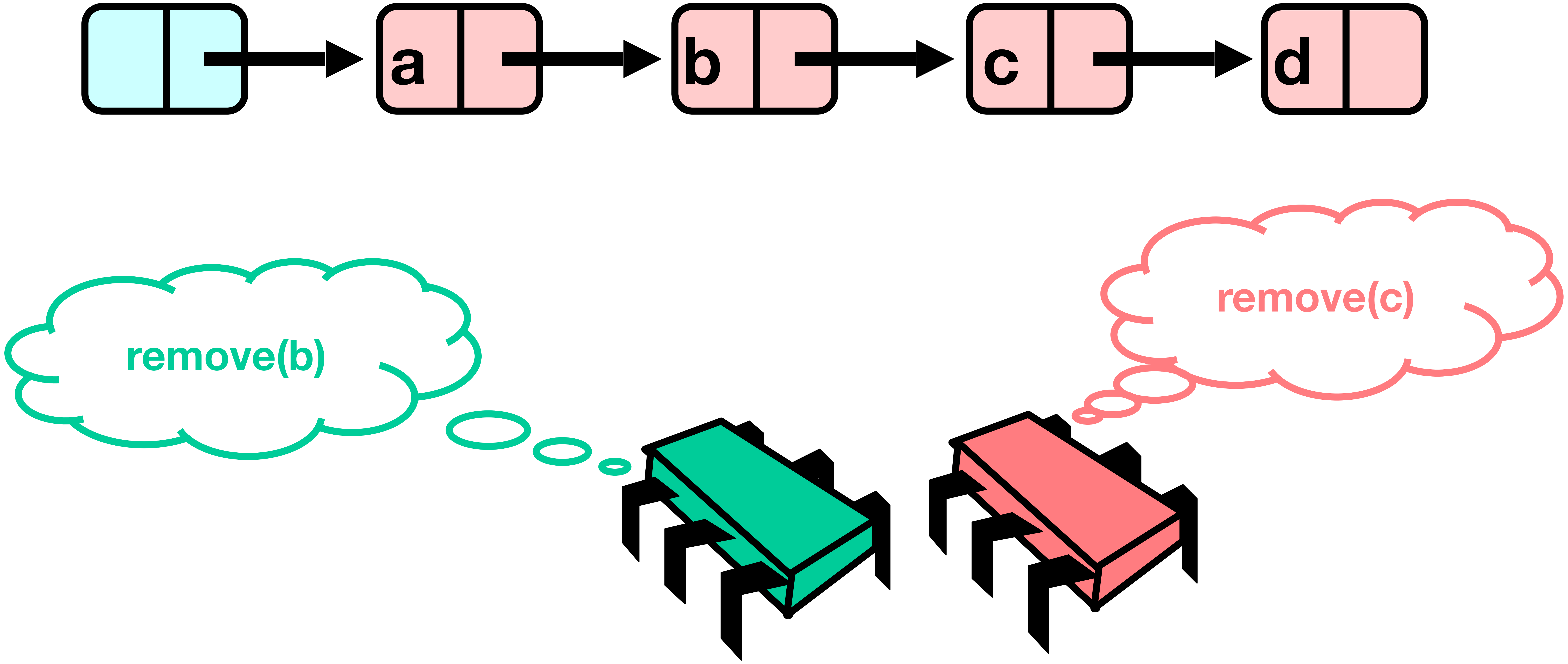


Why do we need to always hold 2 locks?

Concurrent Removes



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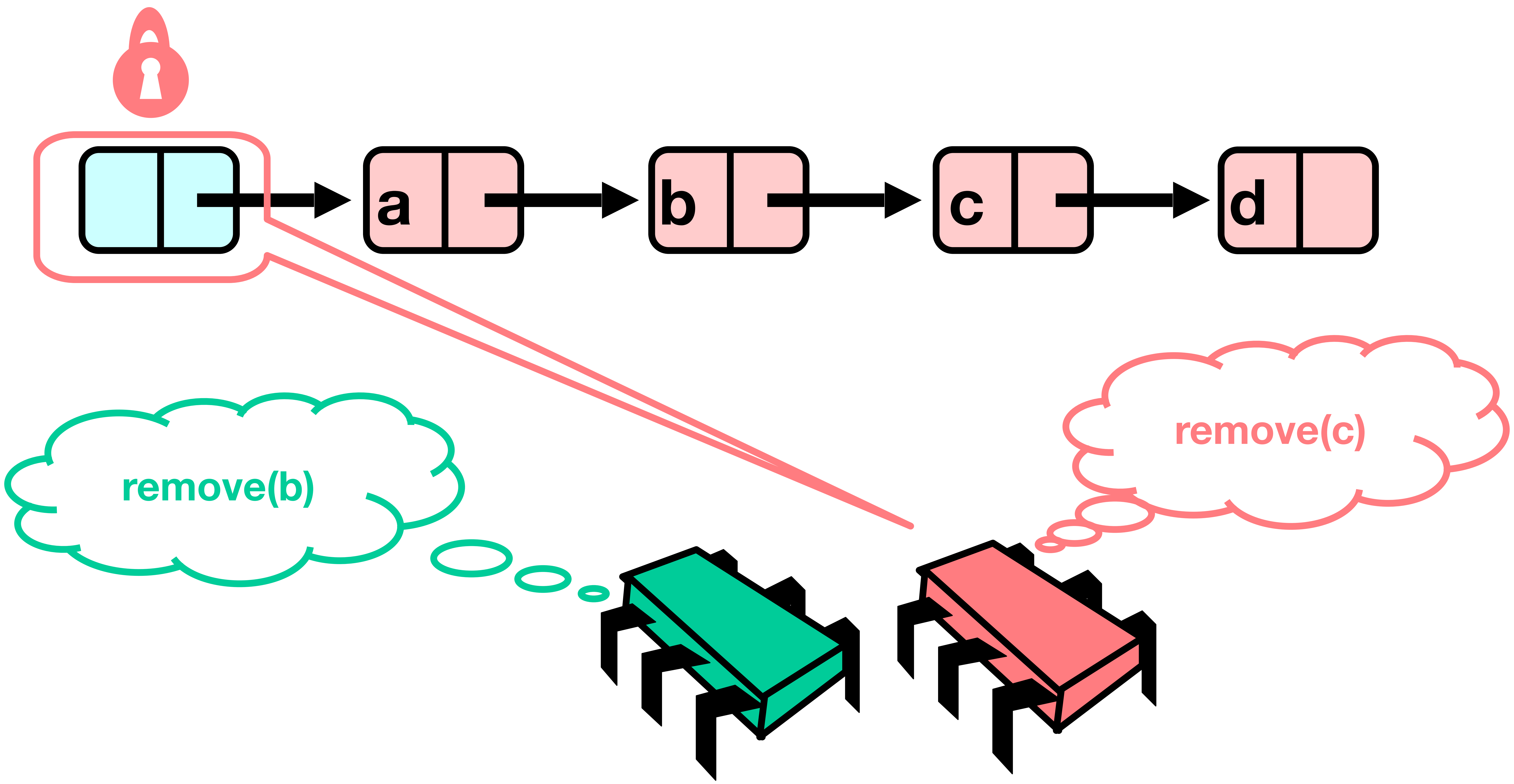

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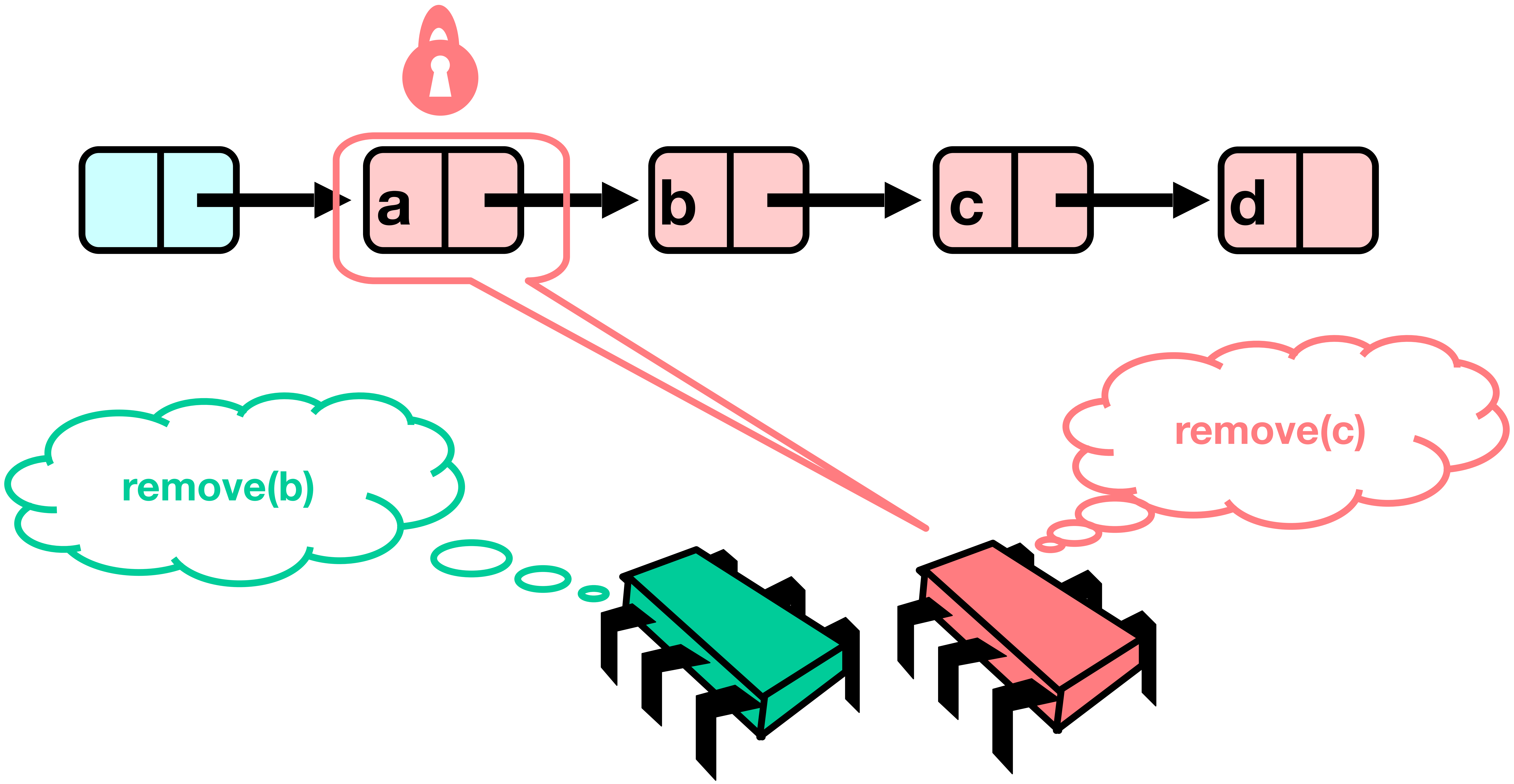

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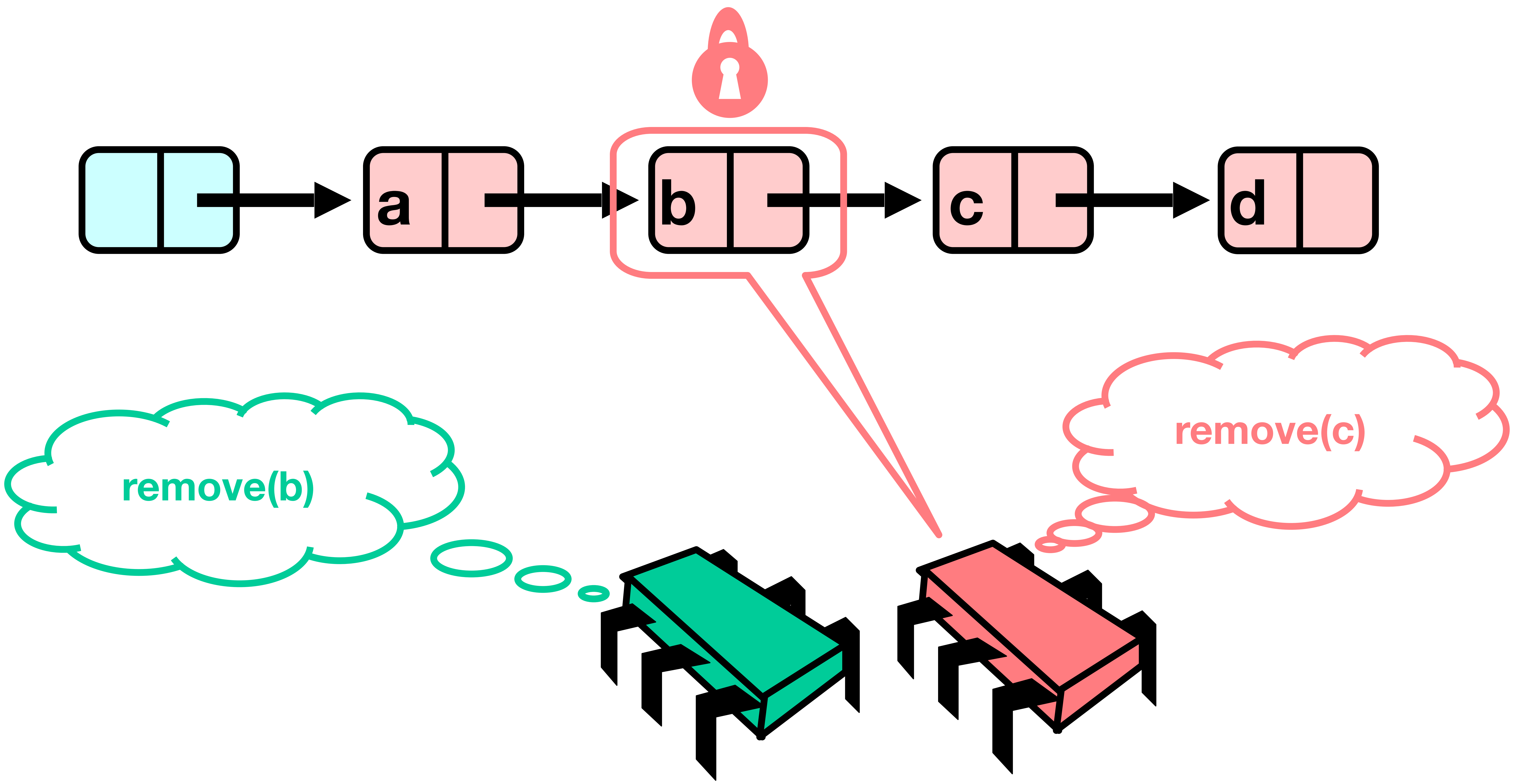

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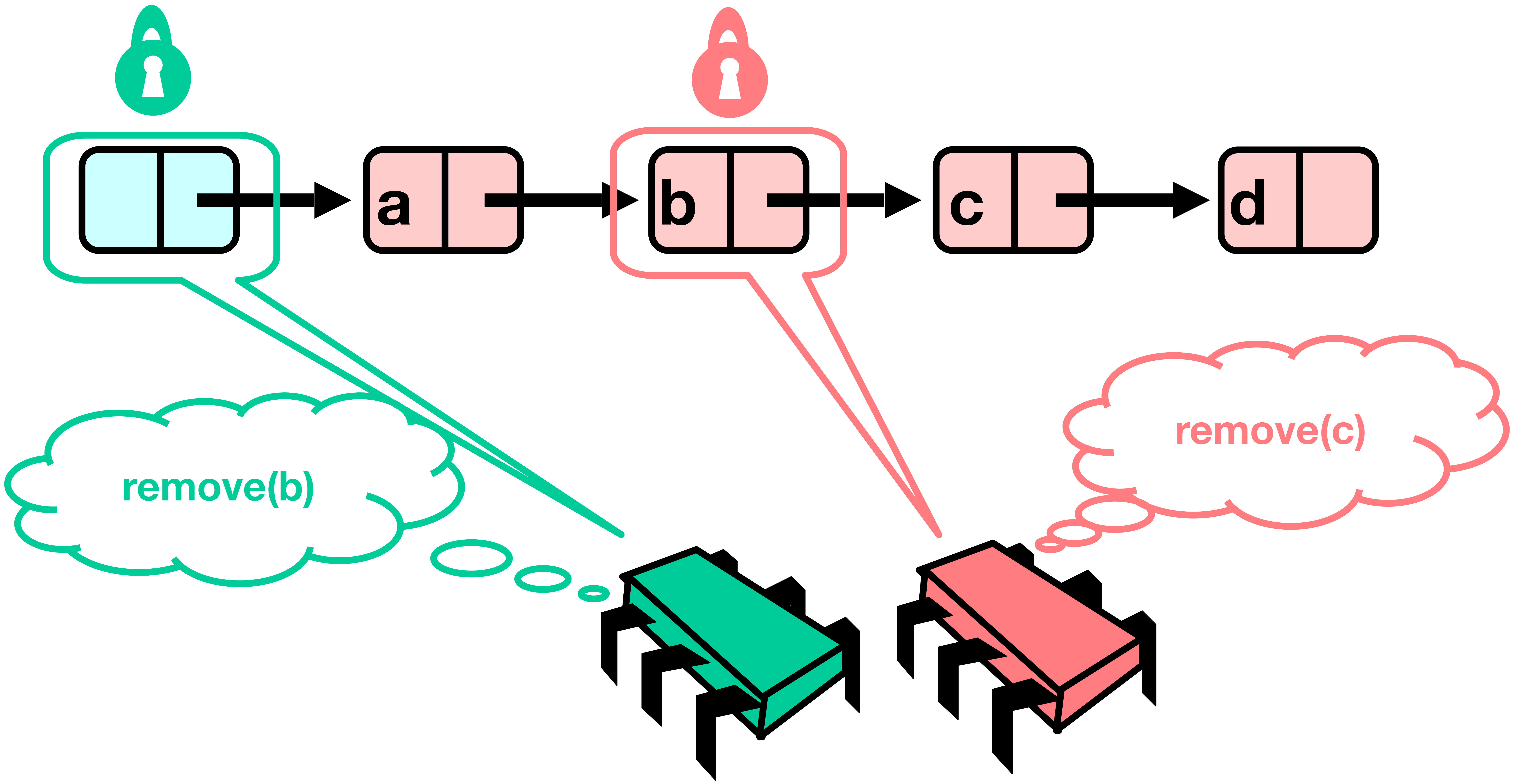

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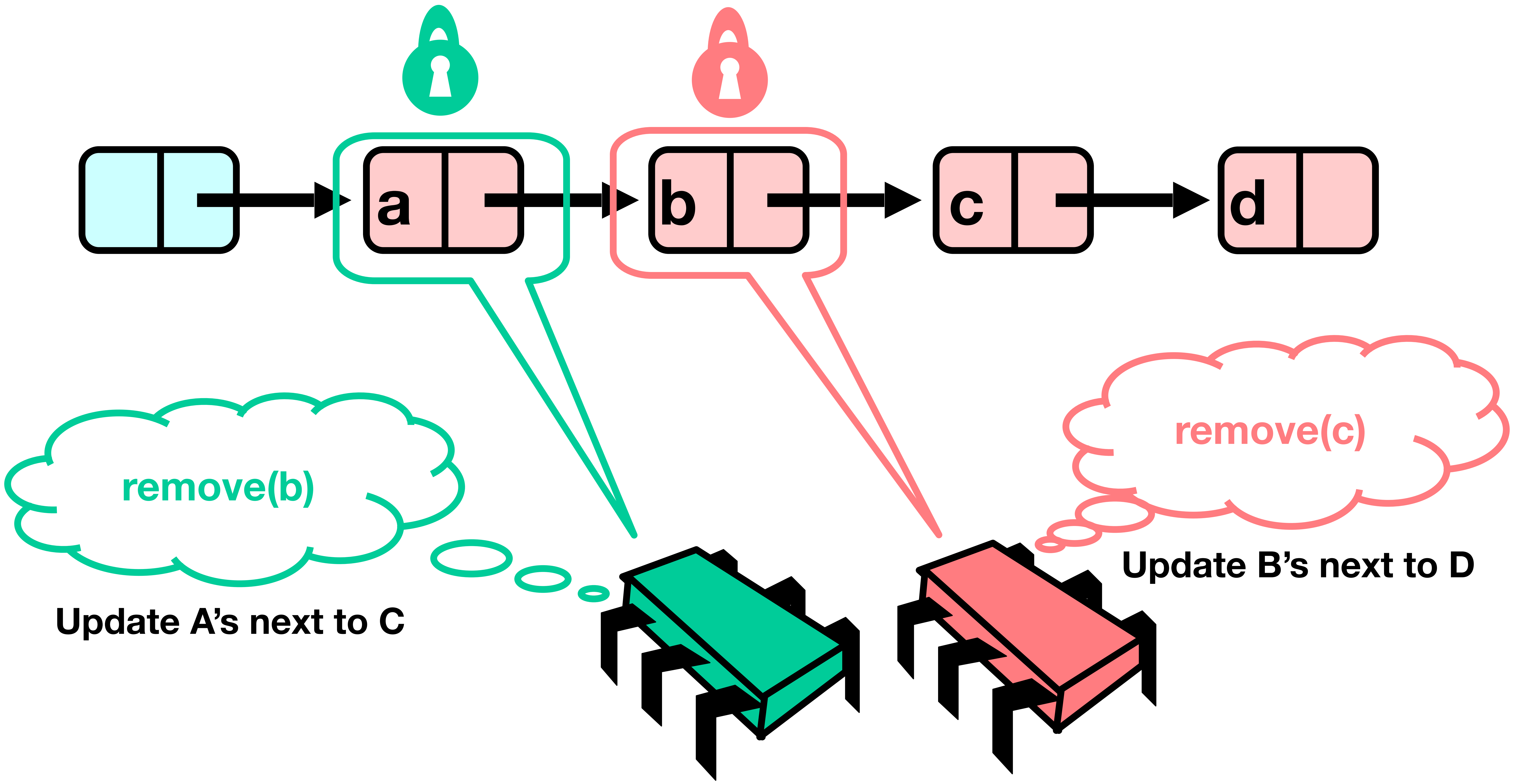

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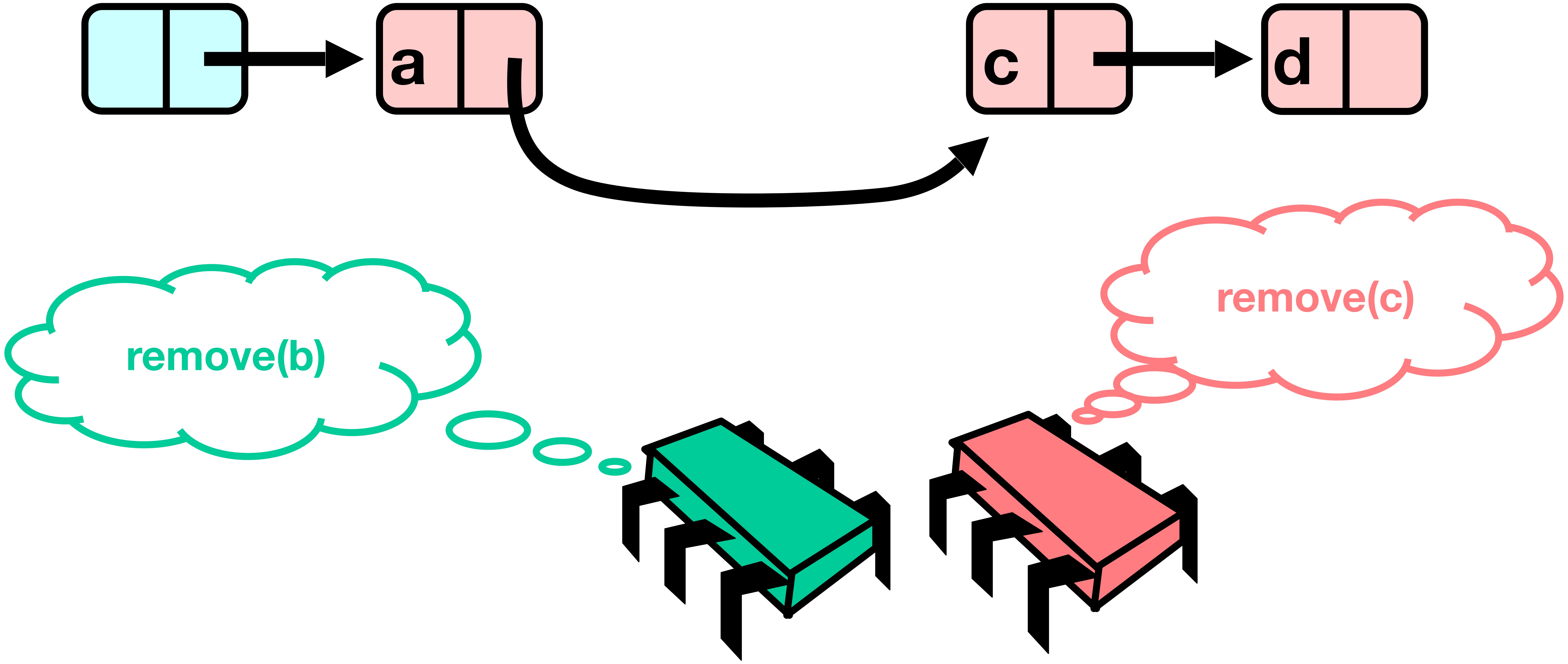

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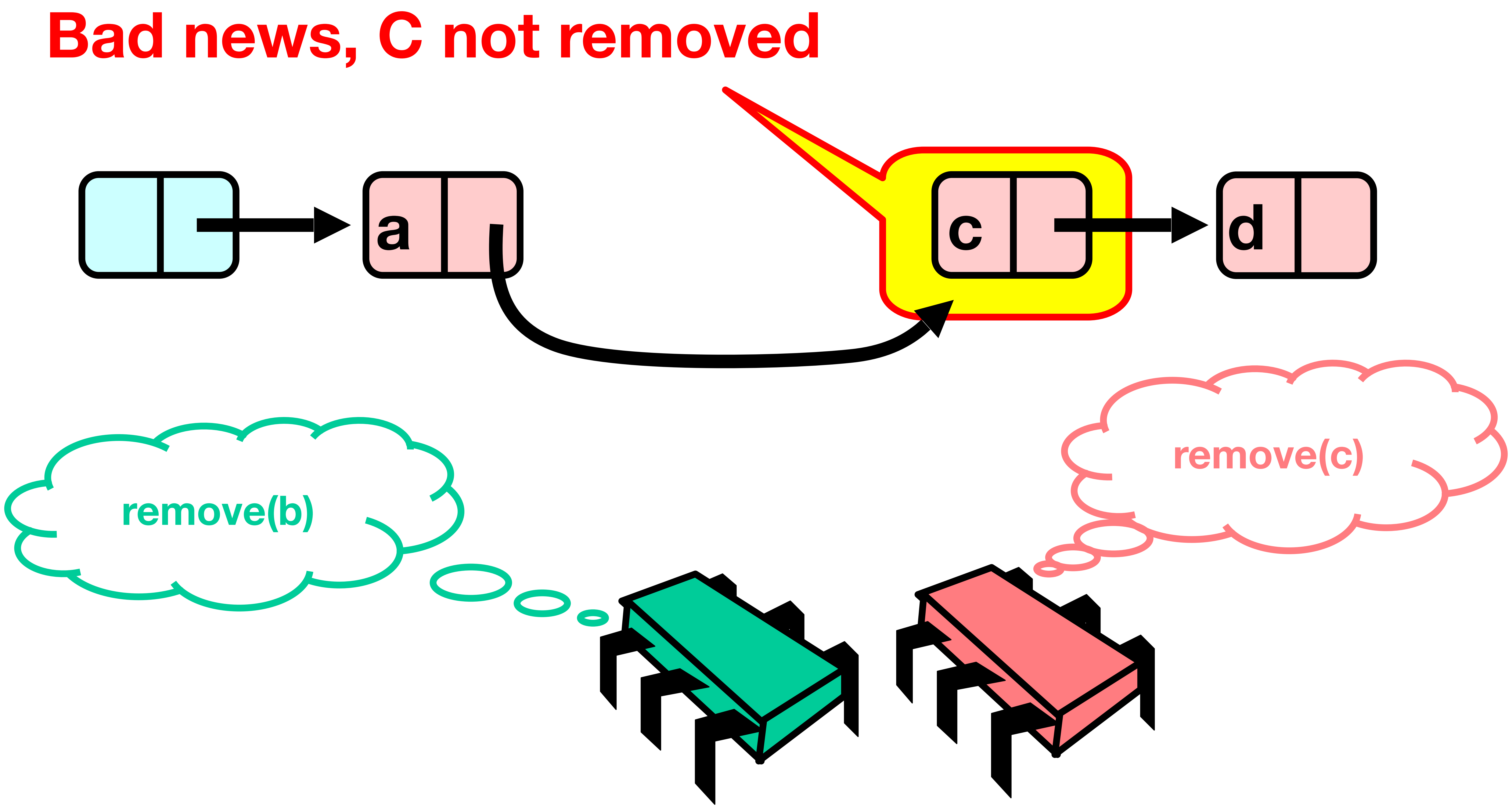
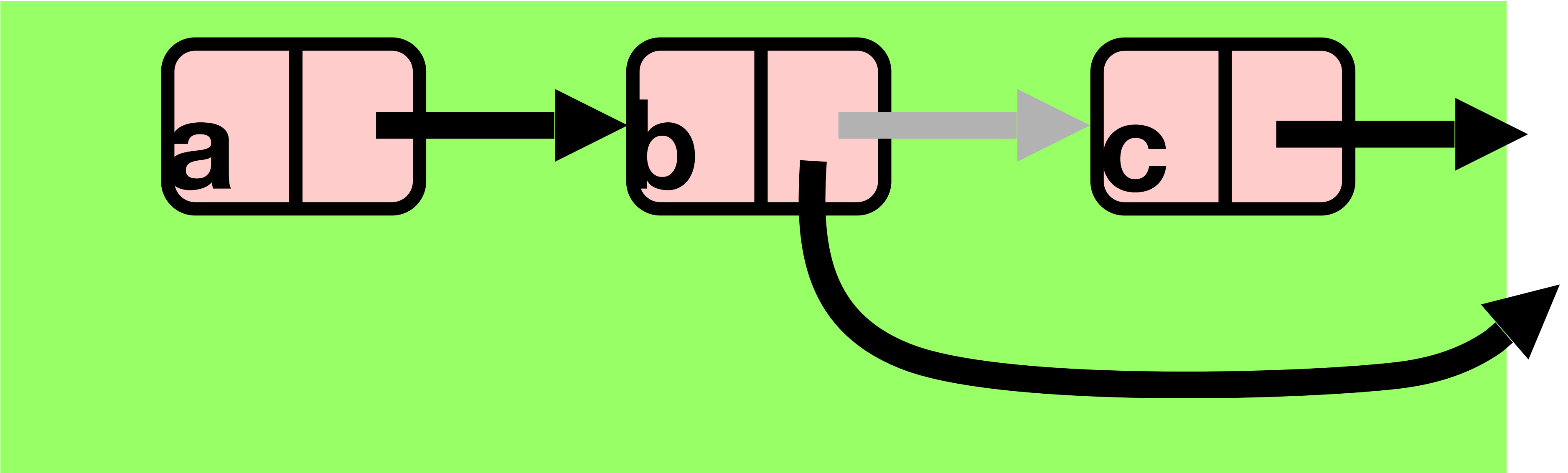
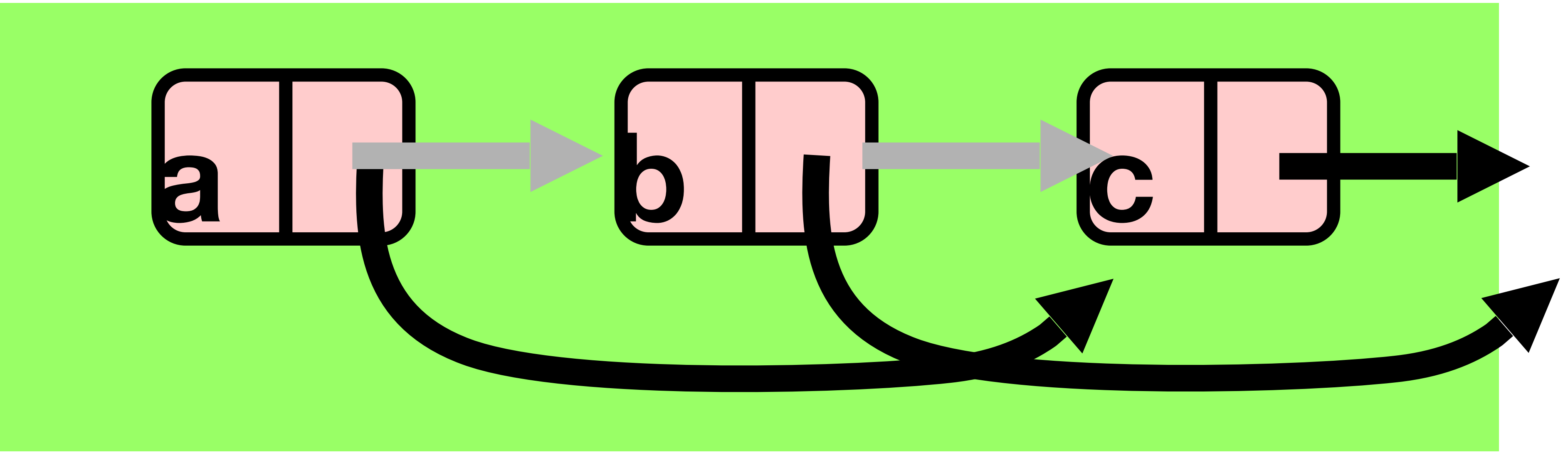


Problem

- To delete node c
  - Swing node b's next field to d



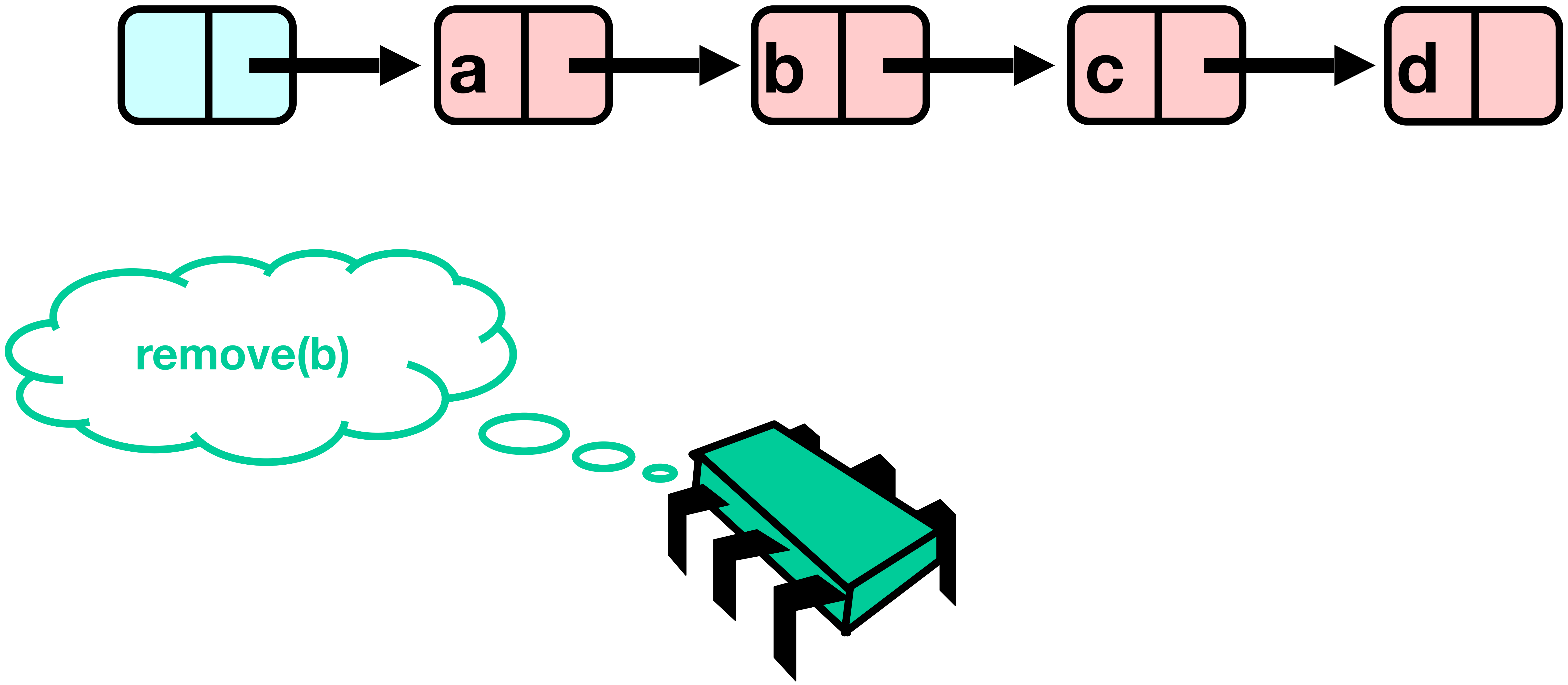
- Problem is,
  - Someone deleting b concurrently could direct a pointer to c



Insight

- If a node is locked
  - No one can delete node's successor
- If a thread locks:
  - Node to be deleted
  - And its predecessor
  - Then it works

Hand-Over-Hand Again



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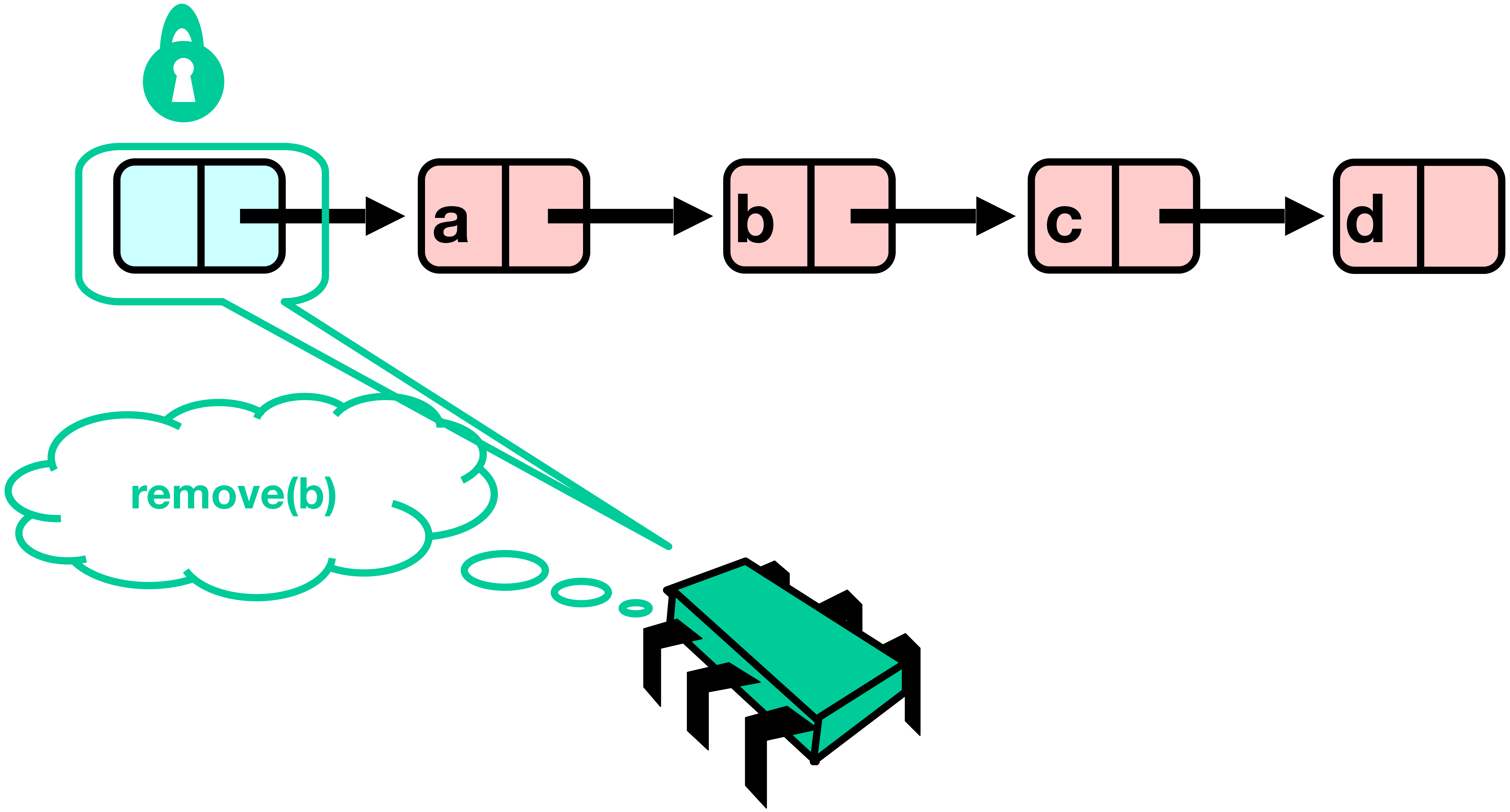

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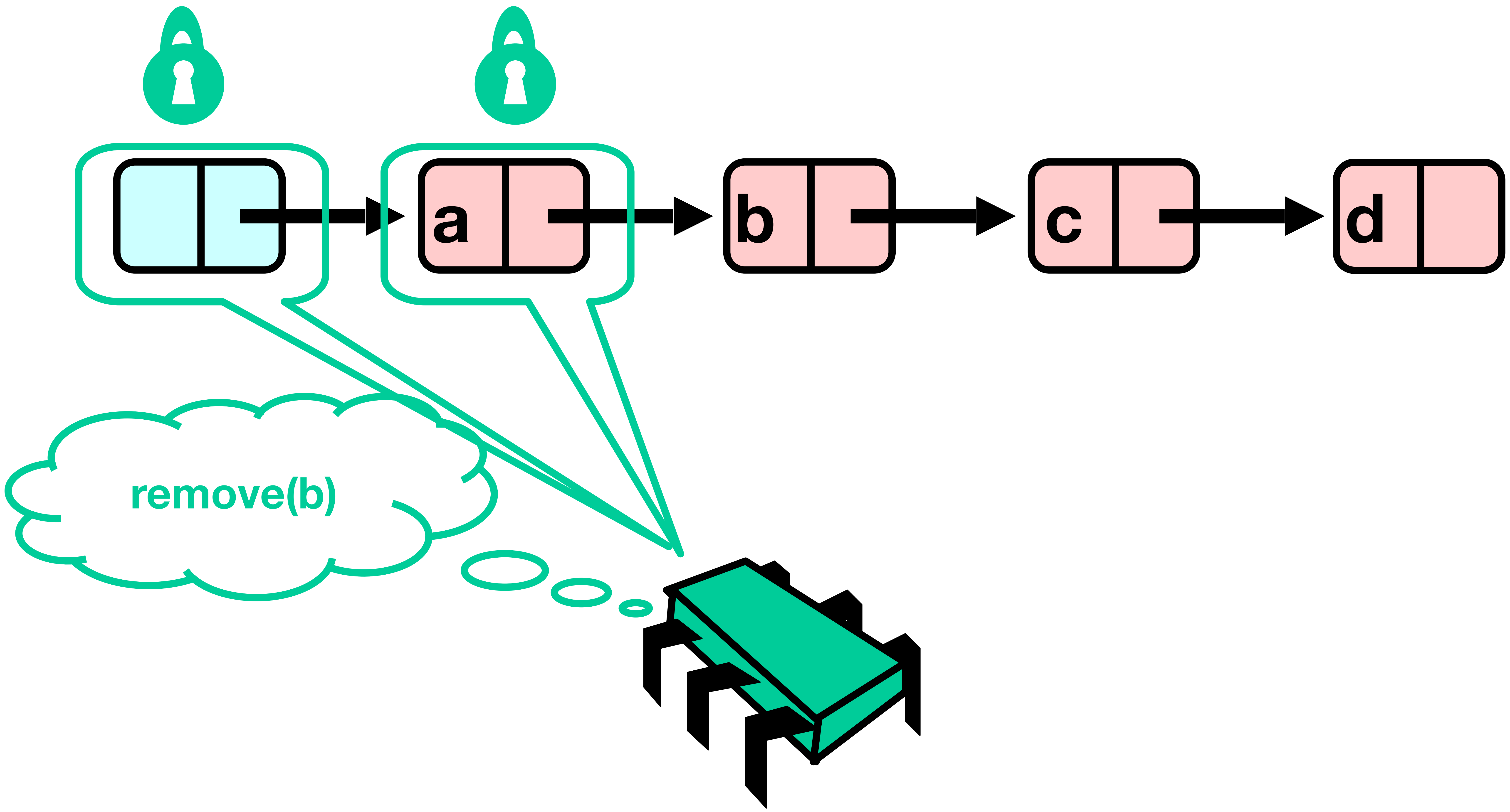

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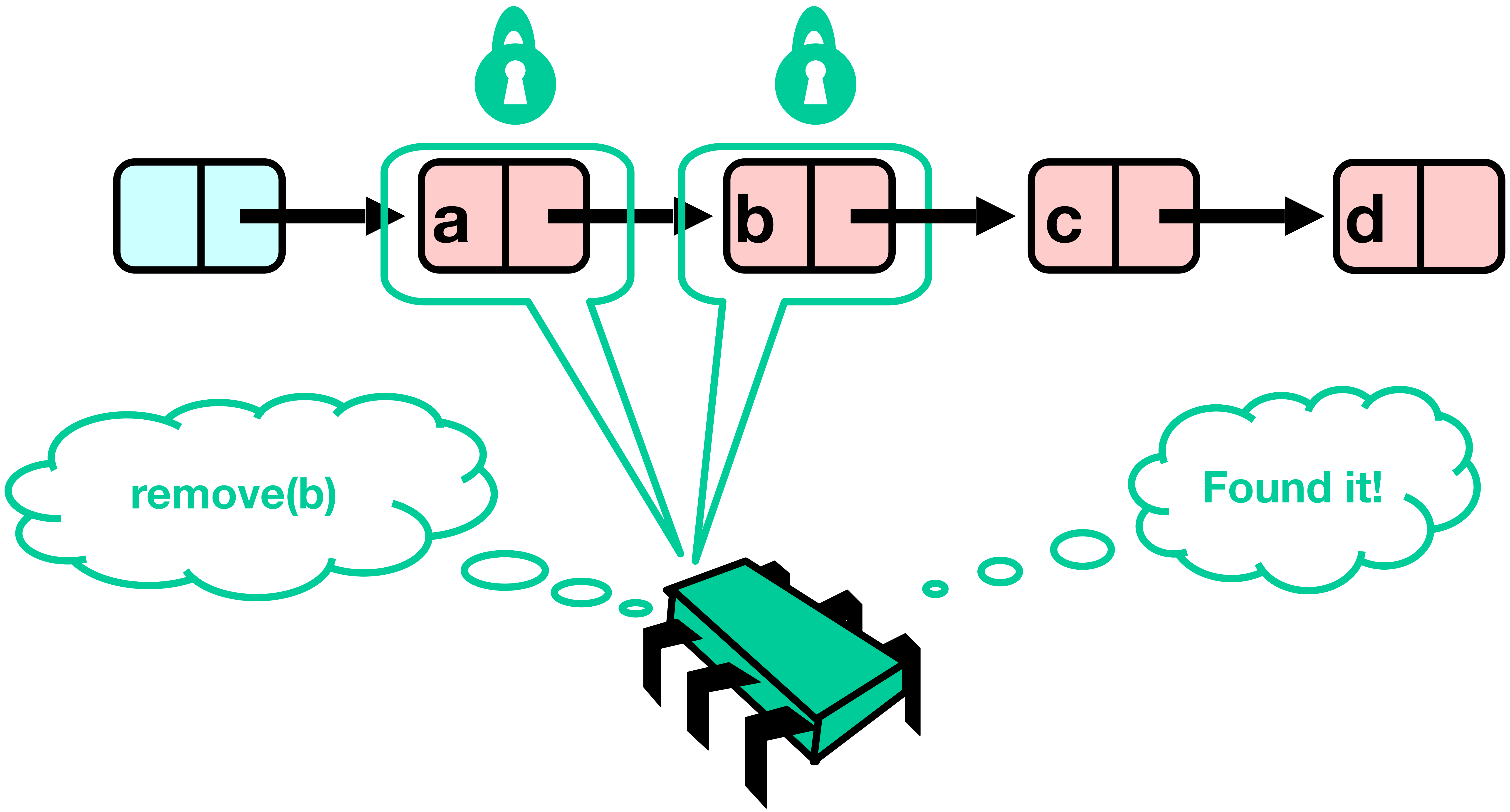

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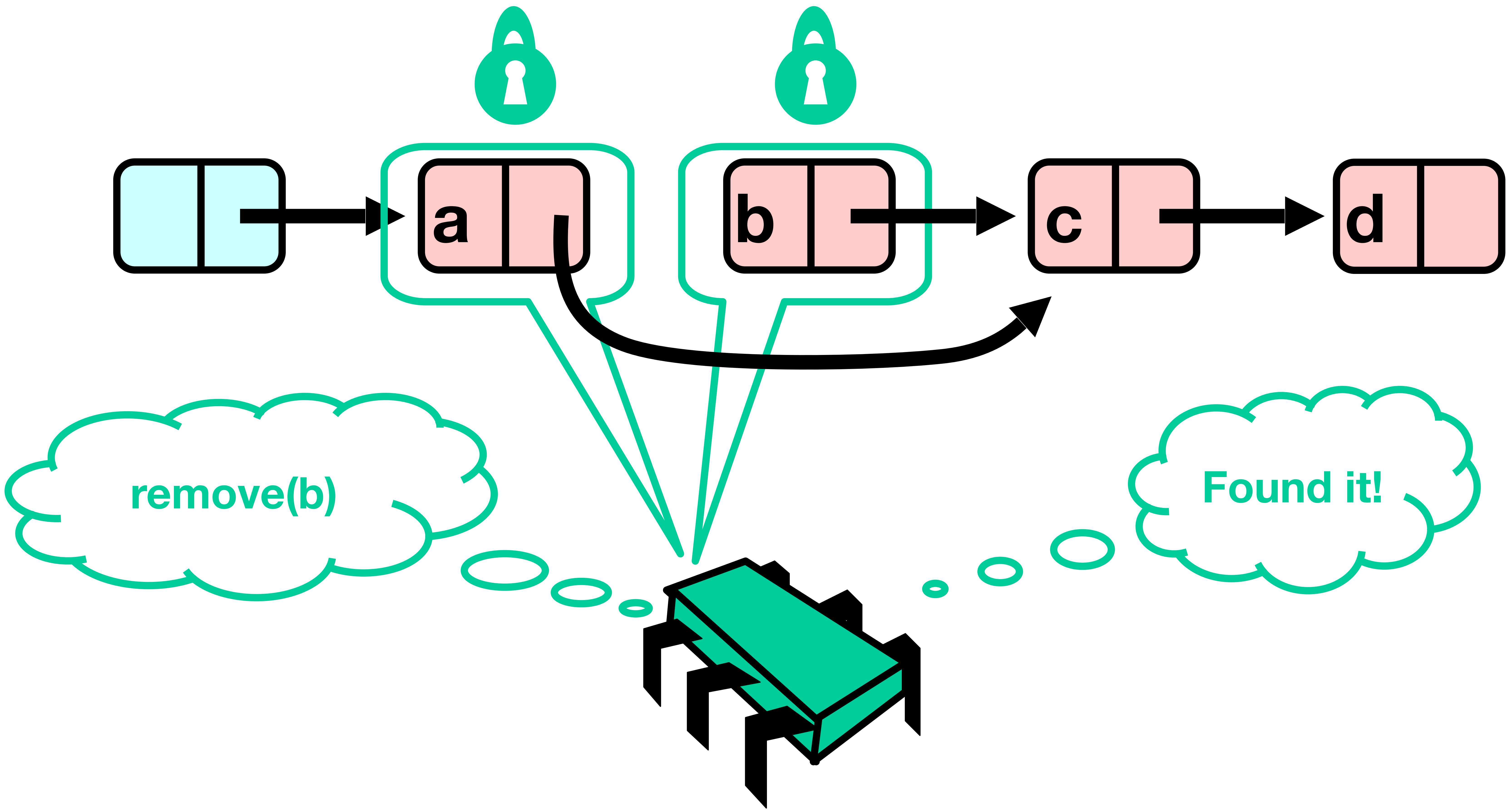

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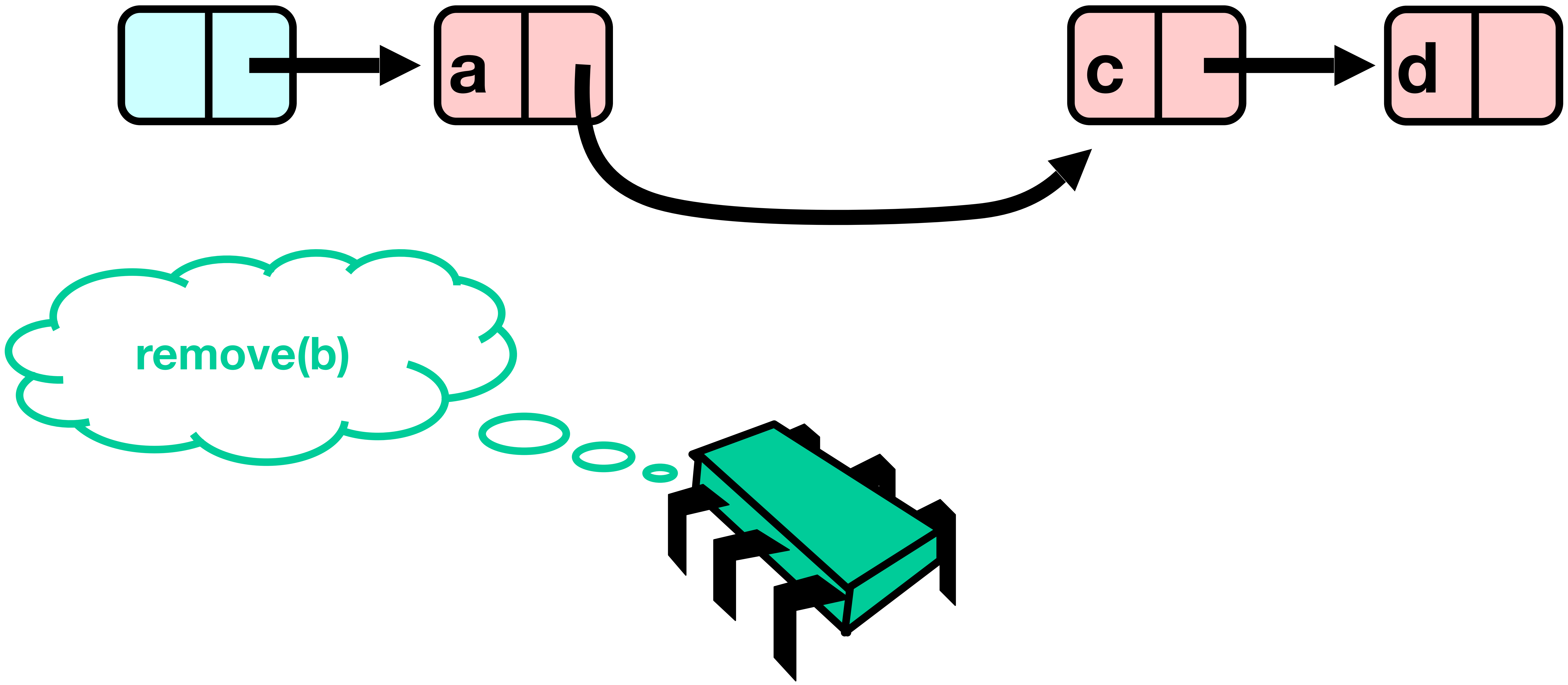
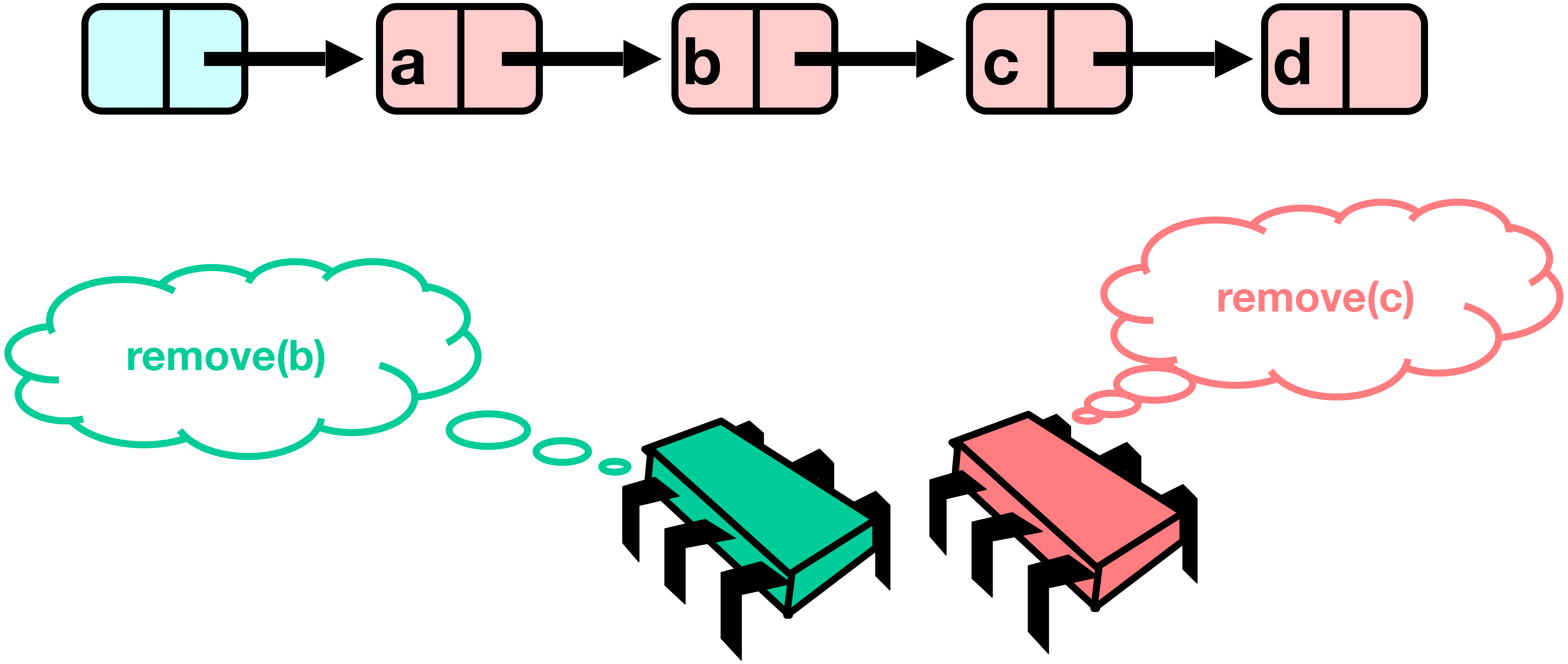


Removing a Node



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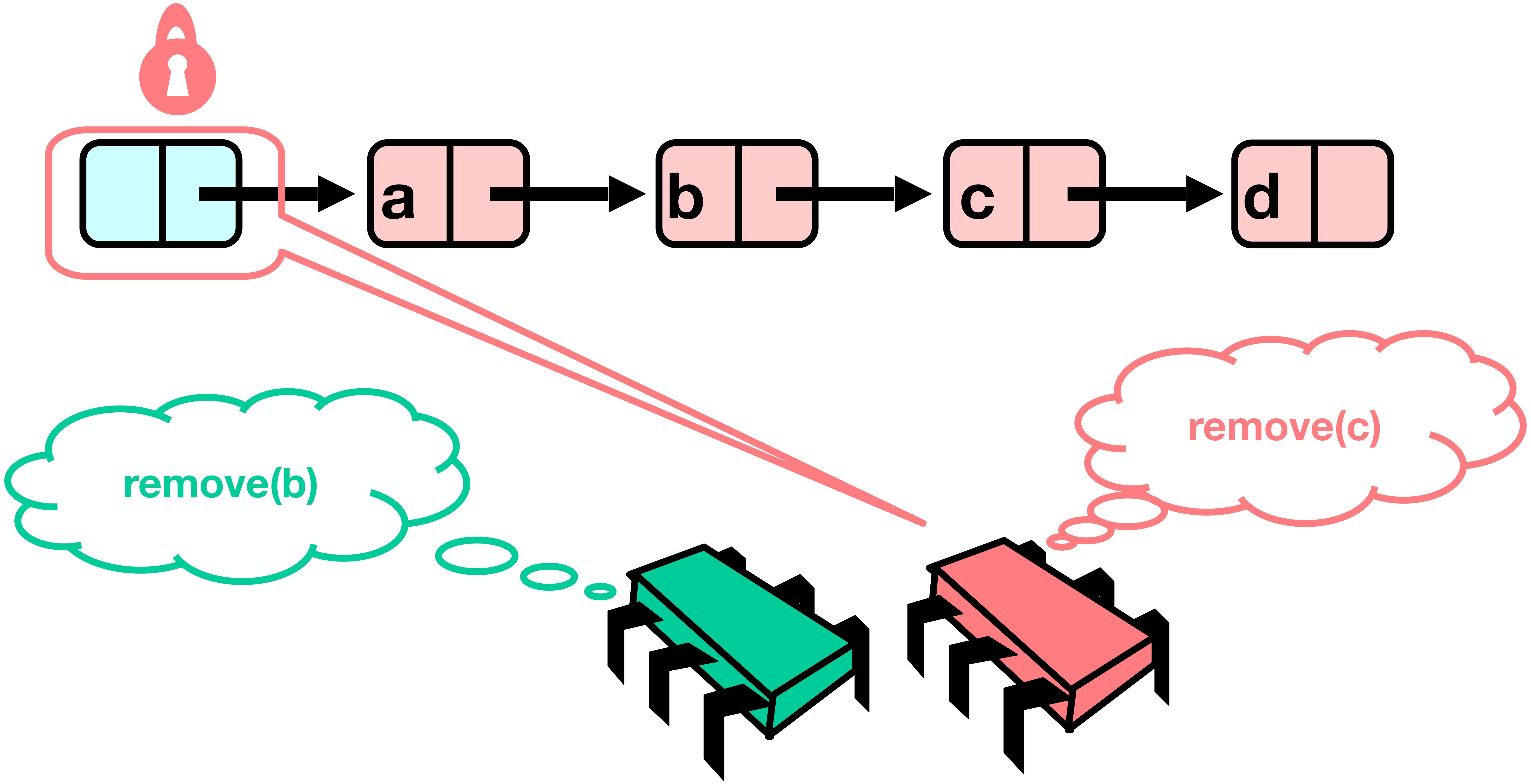
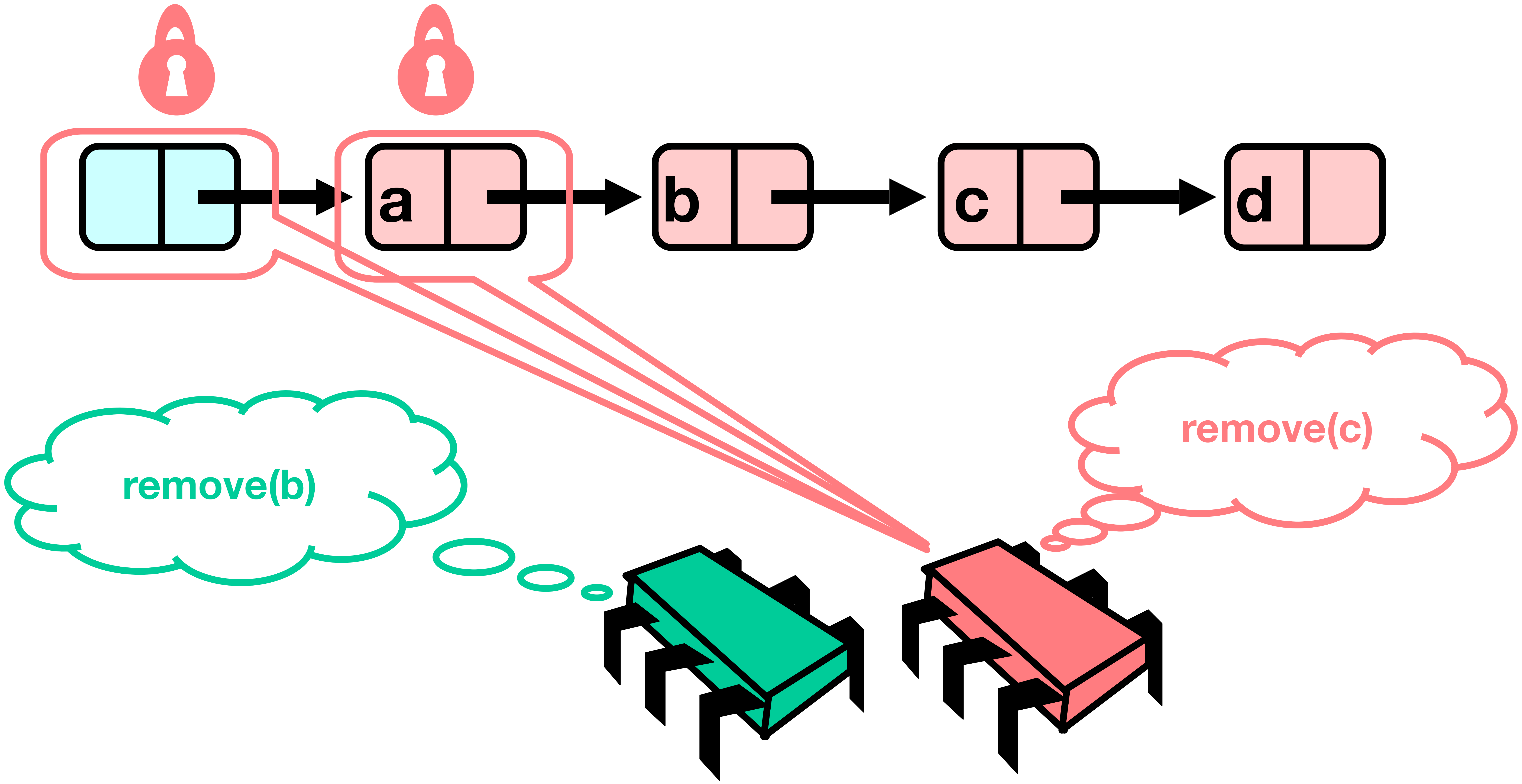
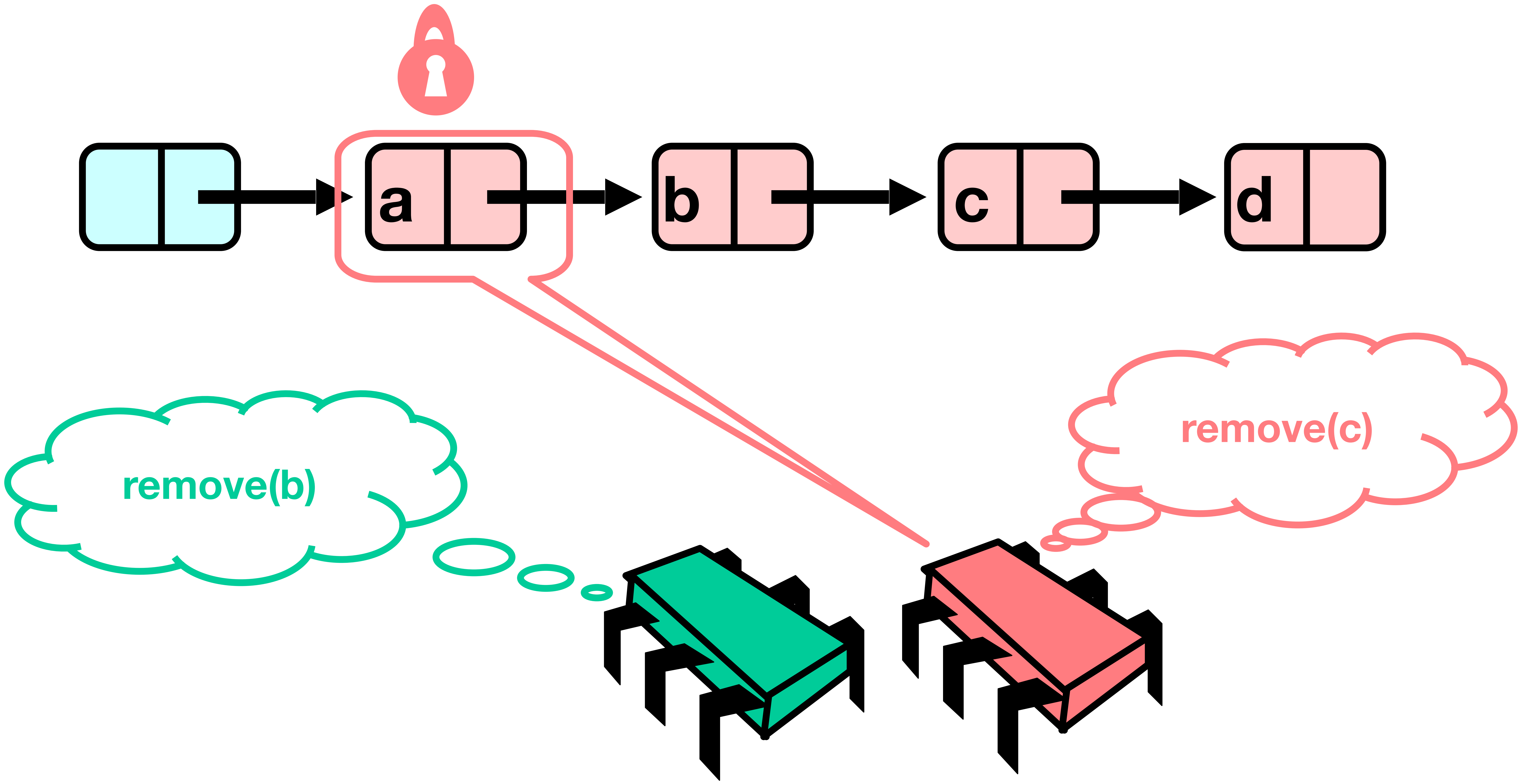


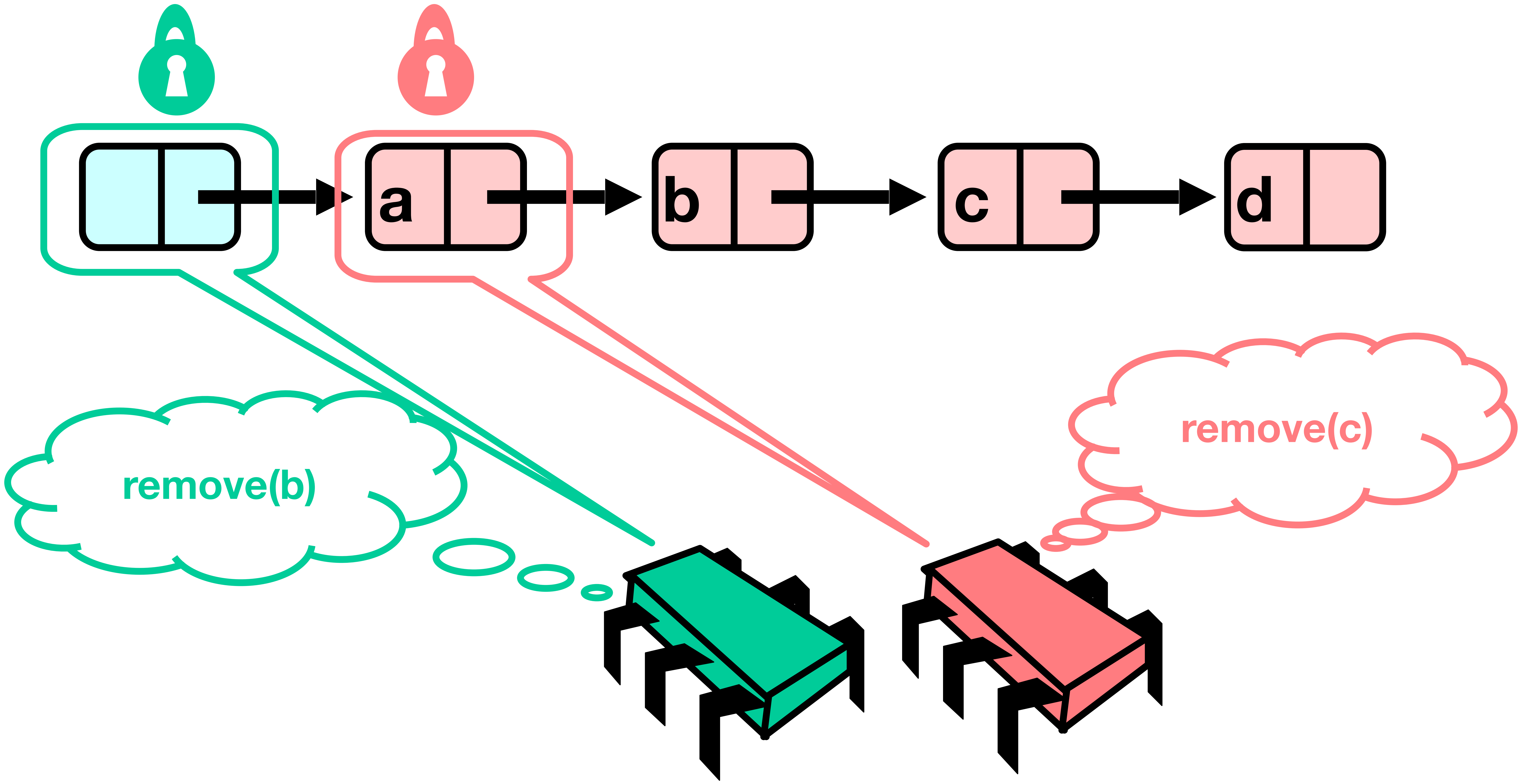
Removing a Node



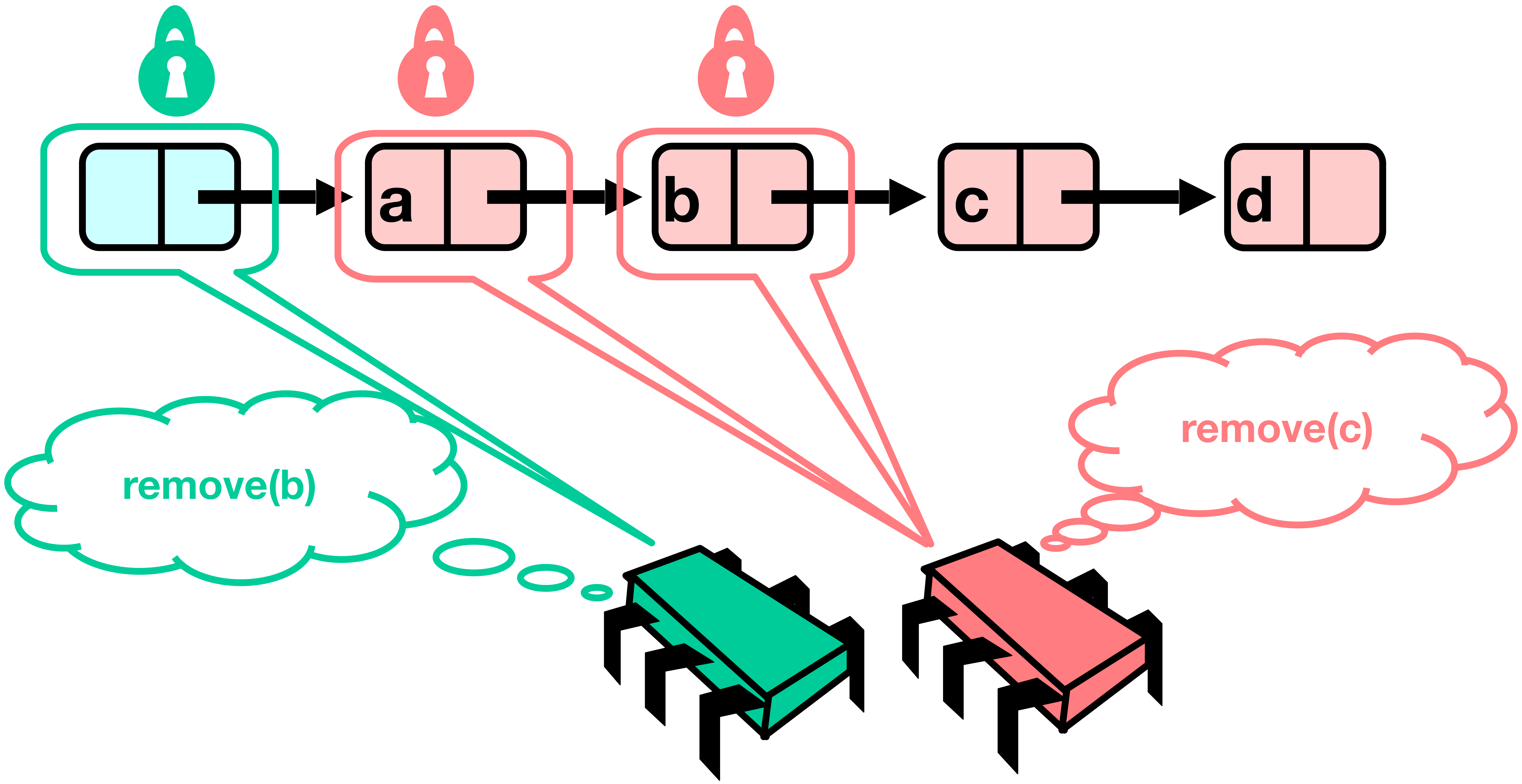
Removing a Node



Removing a Node



Removing a Node



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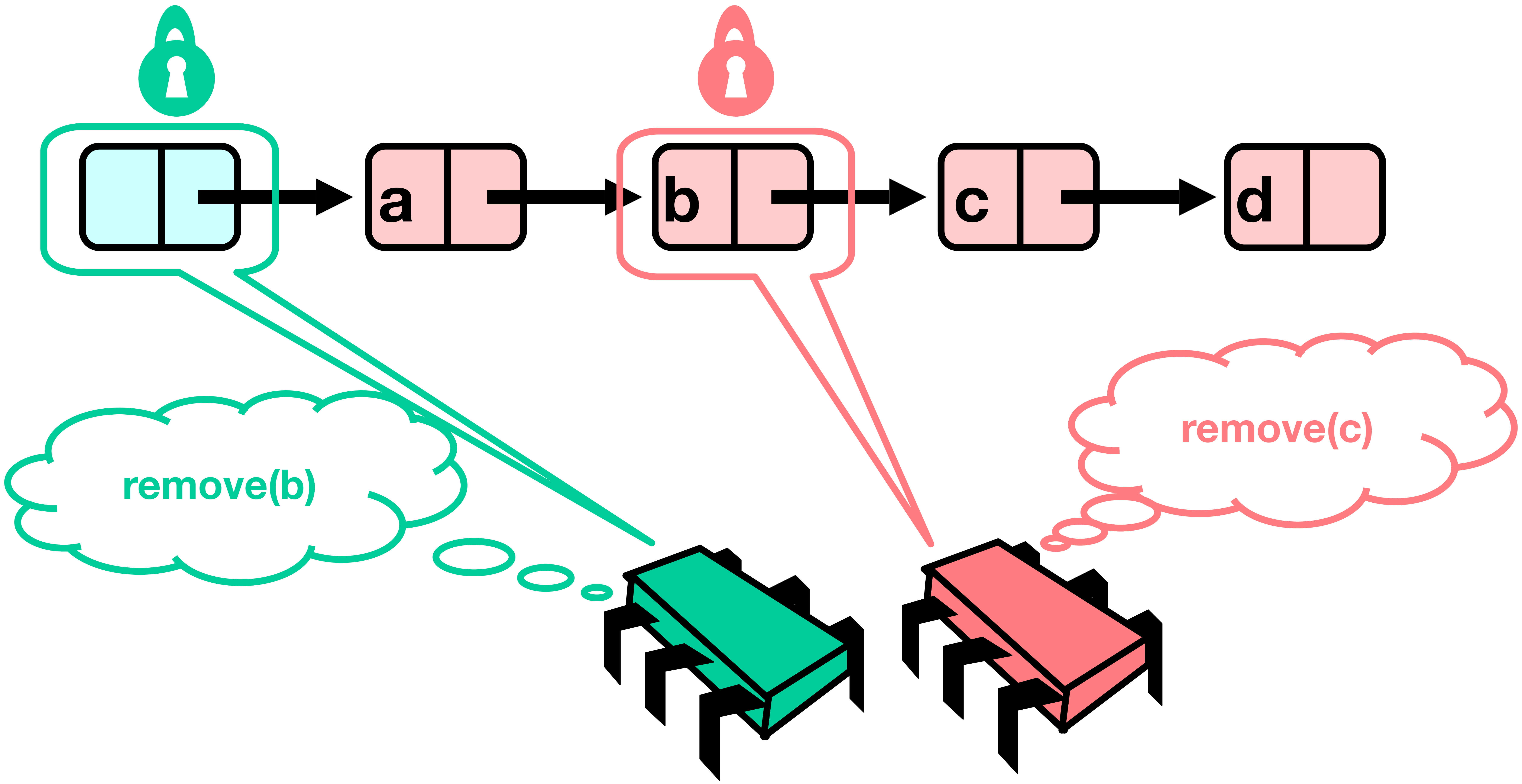
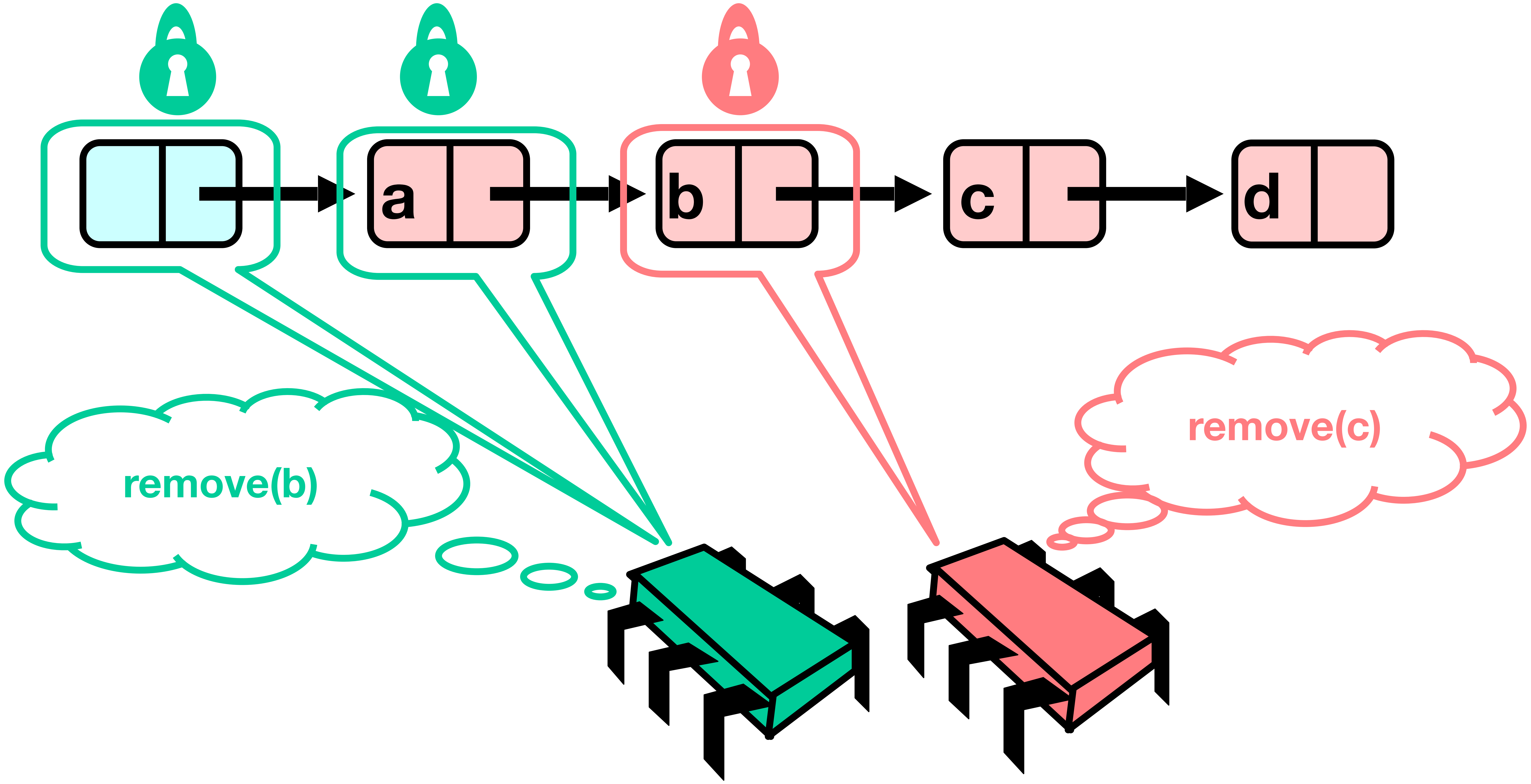
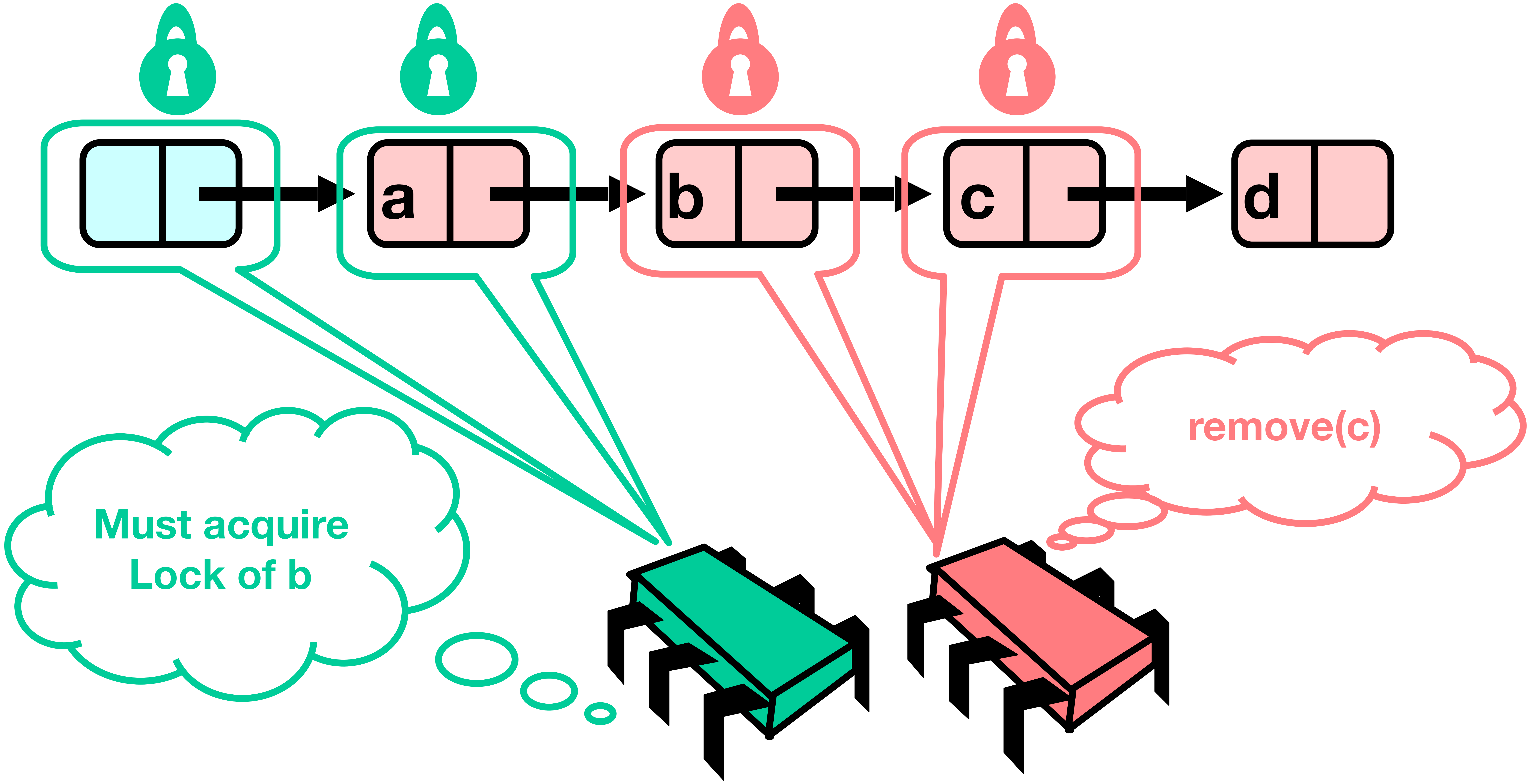


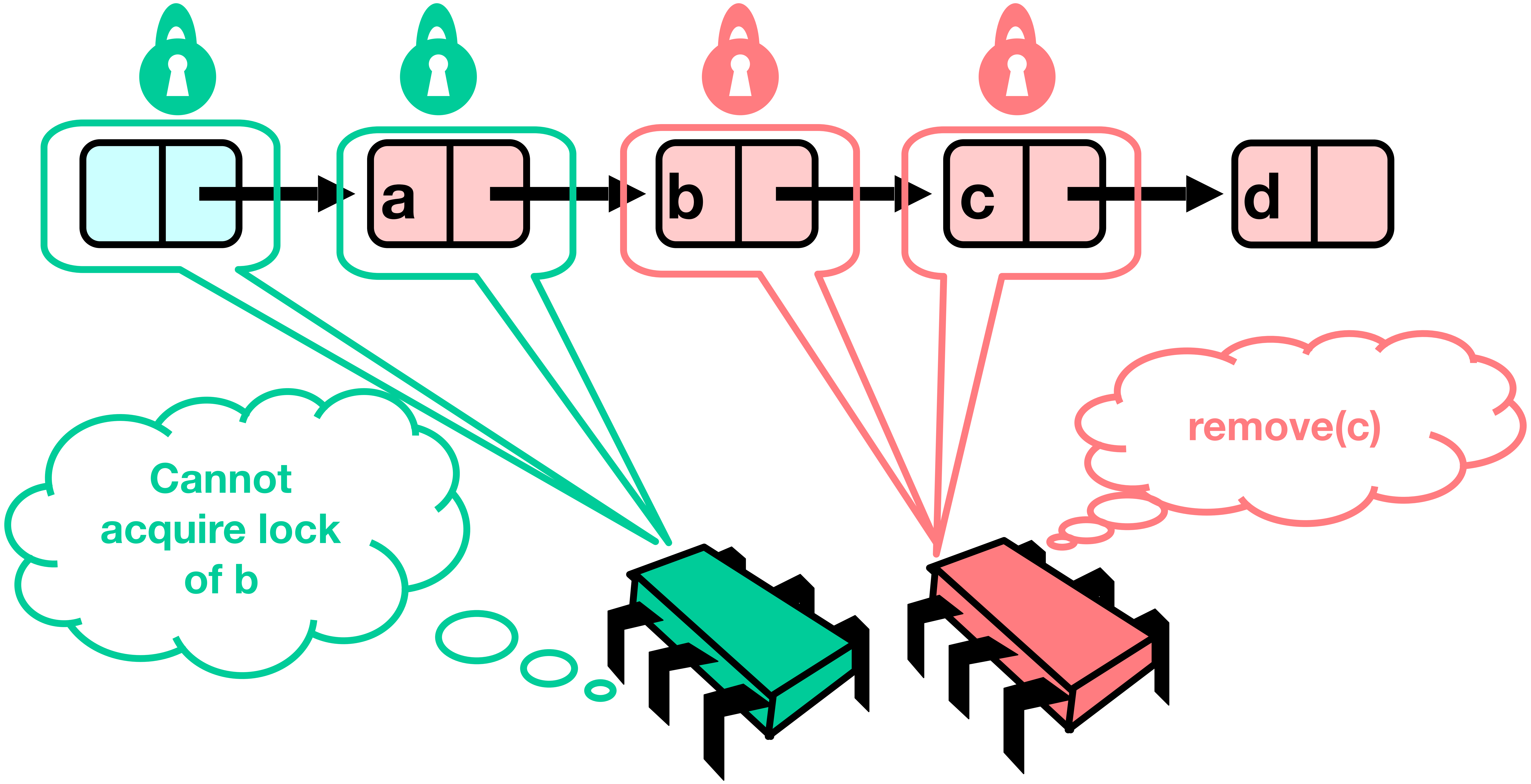
Removing a Node



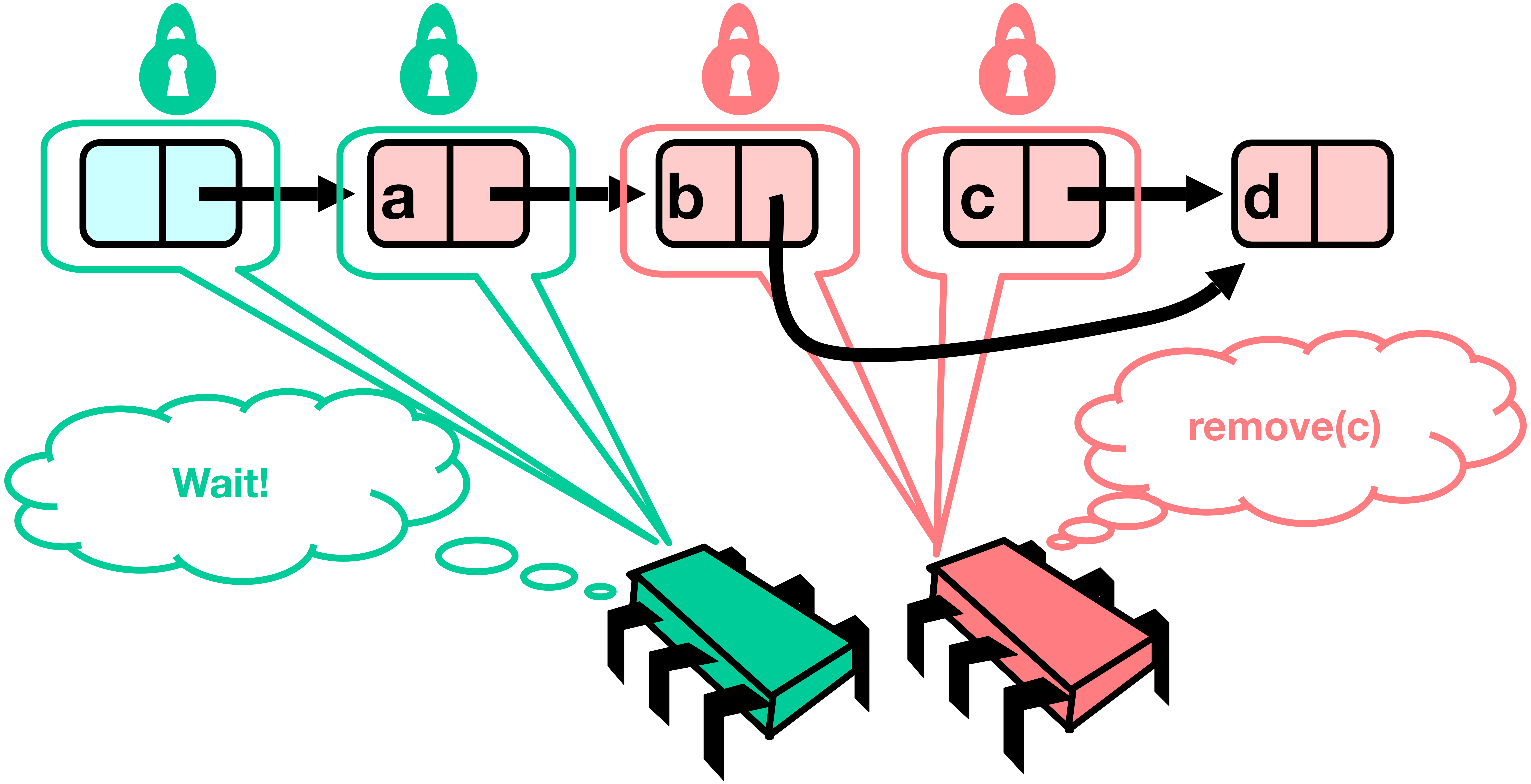
Removing a Node



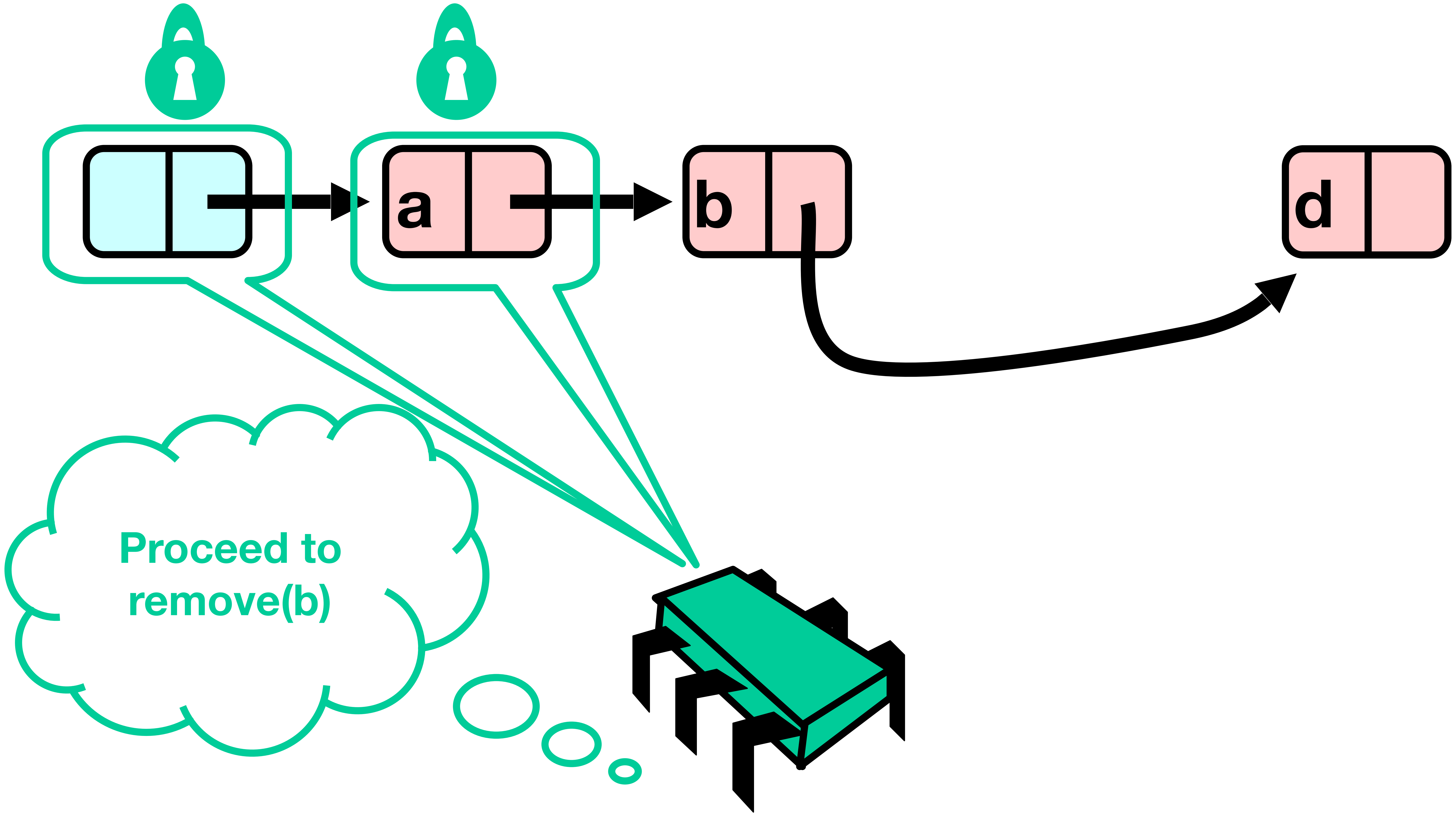
Removing a Node



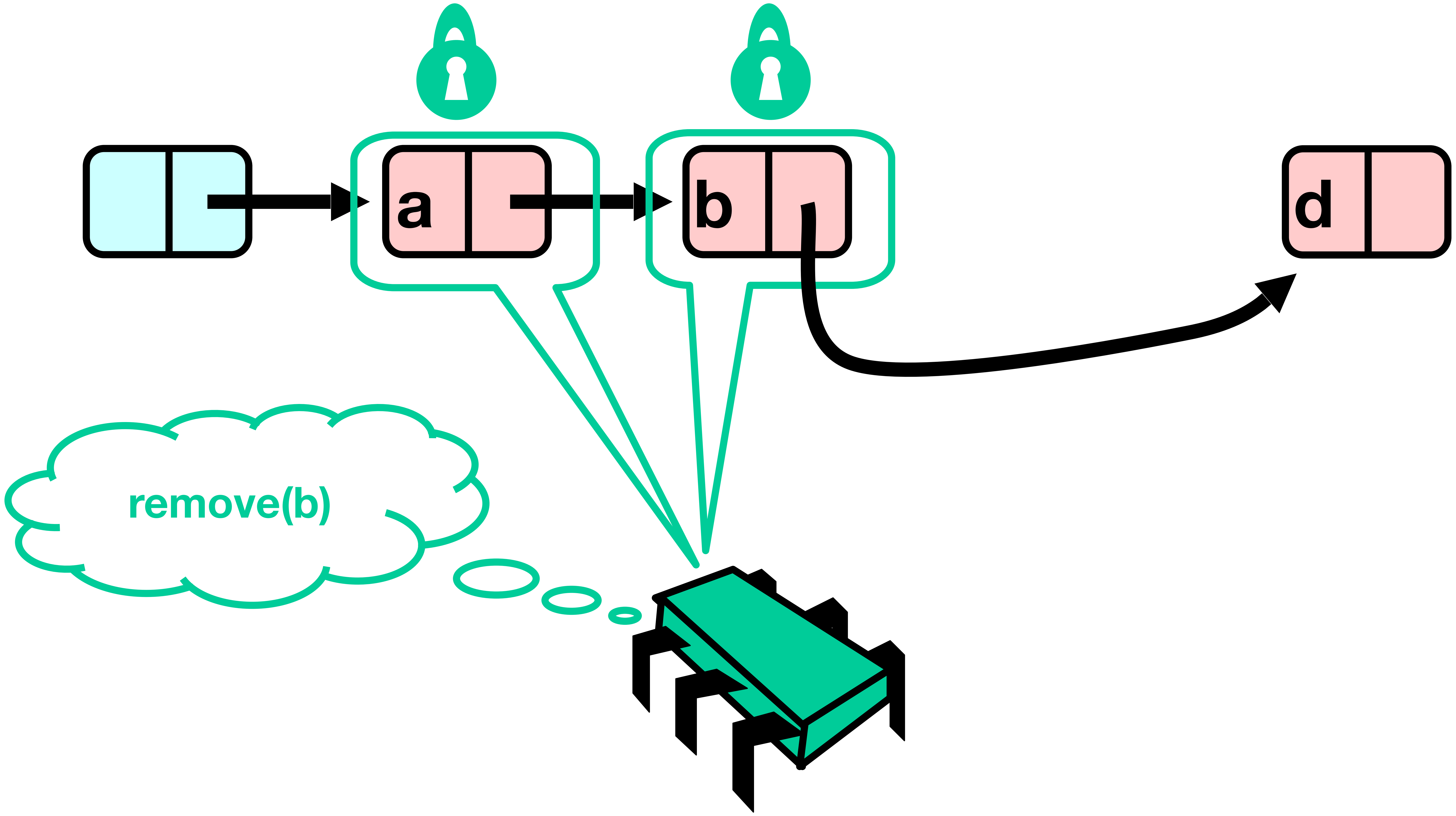
Removing a Node



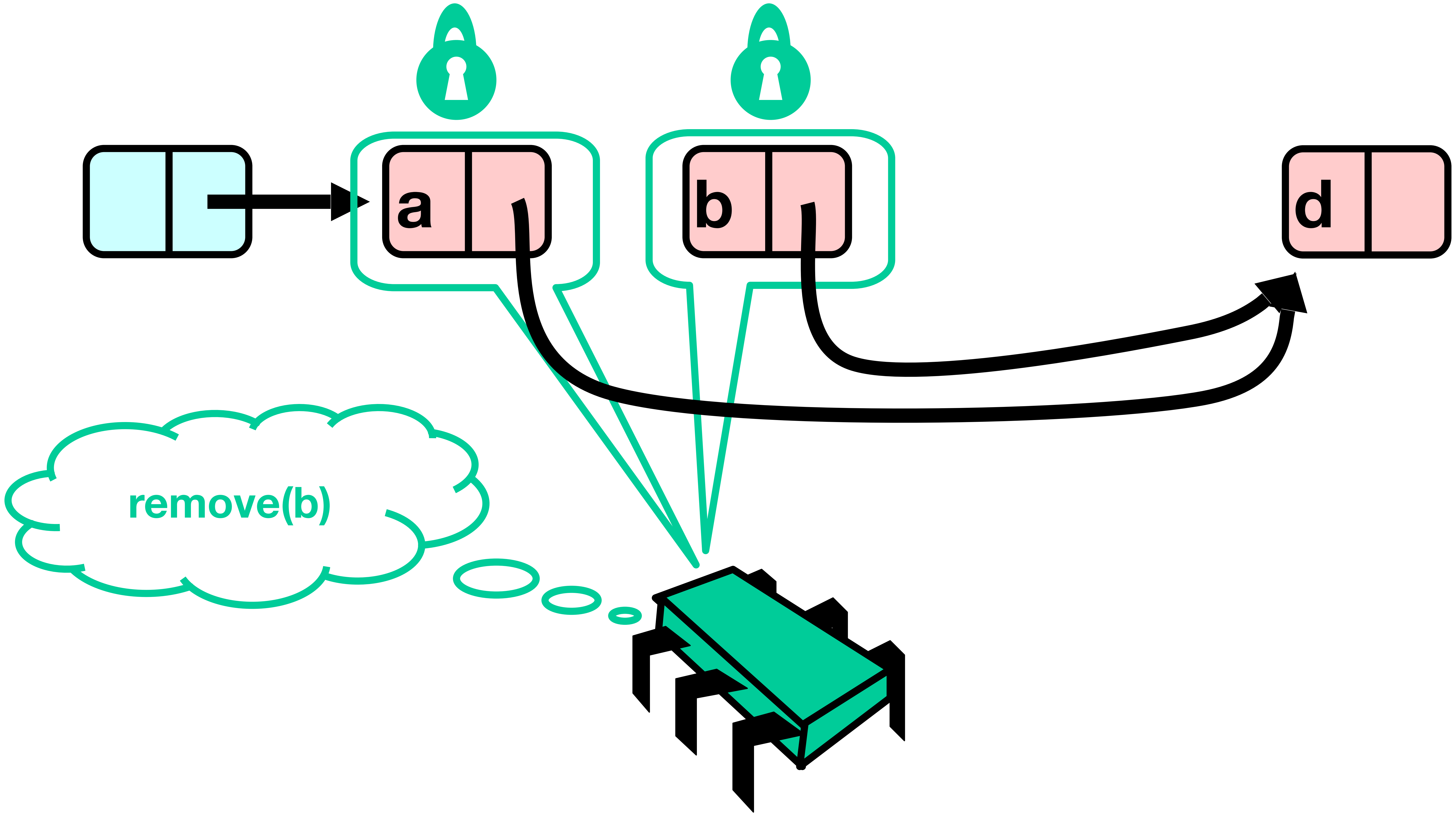
Removing a Node



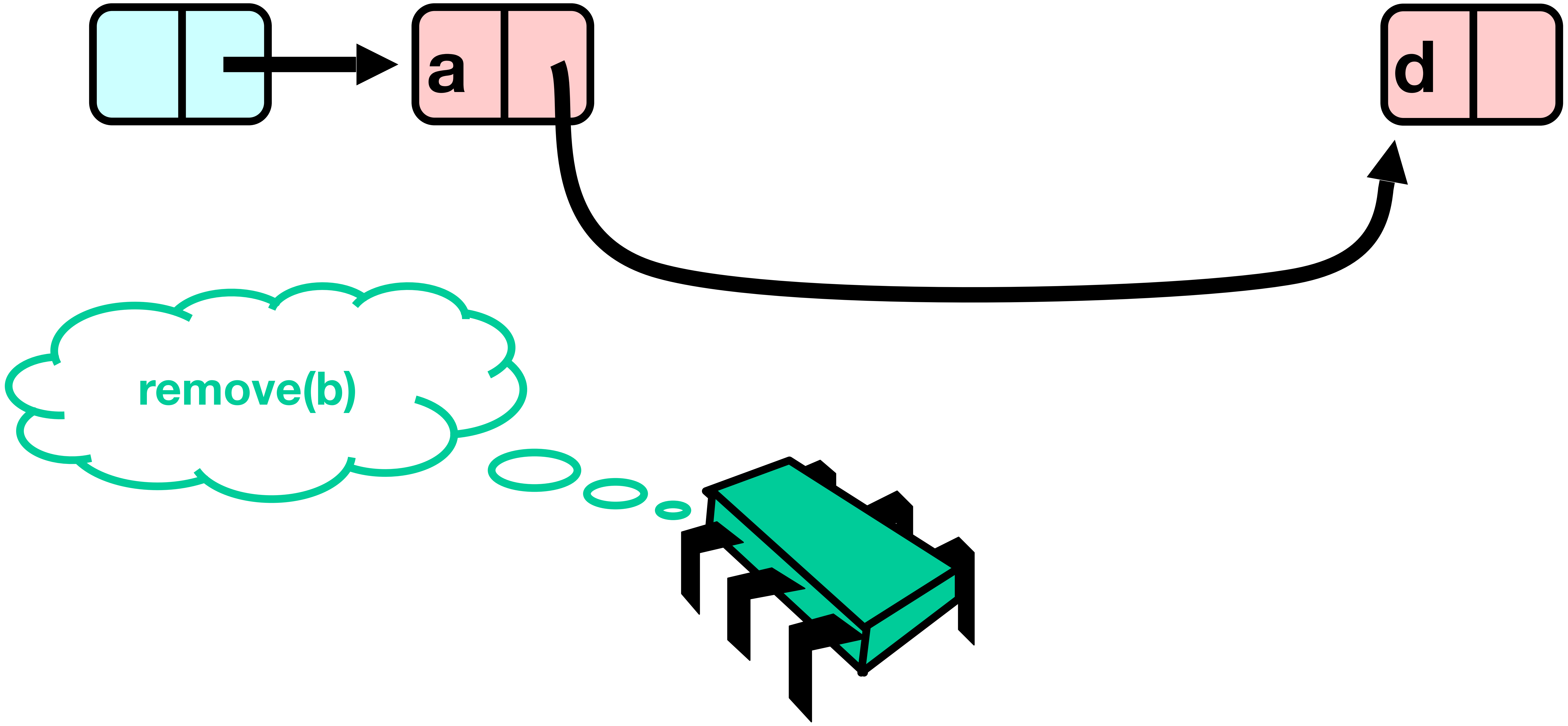
Removing a Node



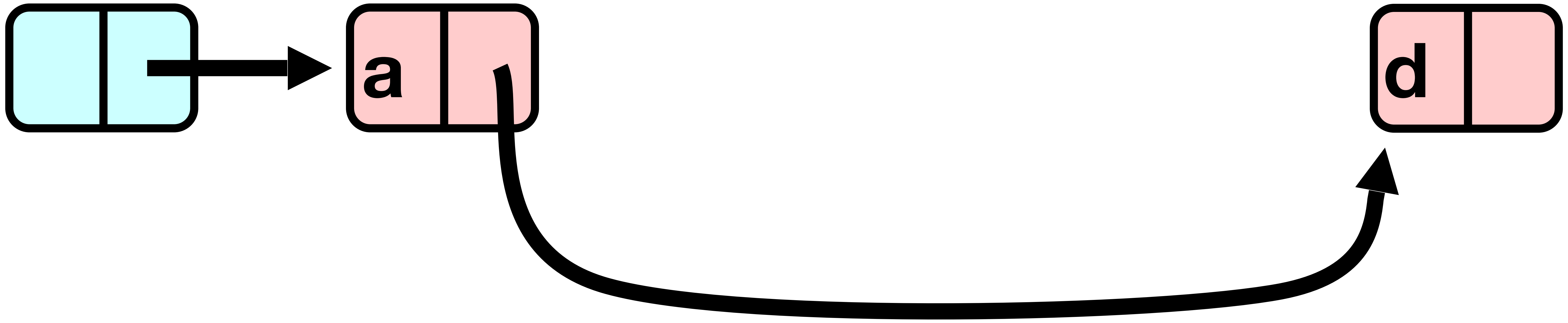
Removing a Node



Removing a Node



Removing a Node



Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   …
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Key used to order node

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
   ...
 } finally {
  currNode.unlock();
  predNode.unlock();
 }}
```

Predecessor and current nodes

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
  ...
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Make sure locks released

Remove method

```
public boolean remove(Item item) {
 int key = item.hashCode();
 Node pred, curr;
 try {
  ...
 } finally {
  curr.unlock();
  pred.unlock();
 }}
```

Everything else

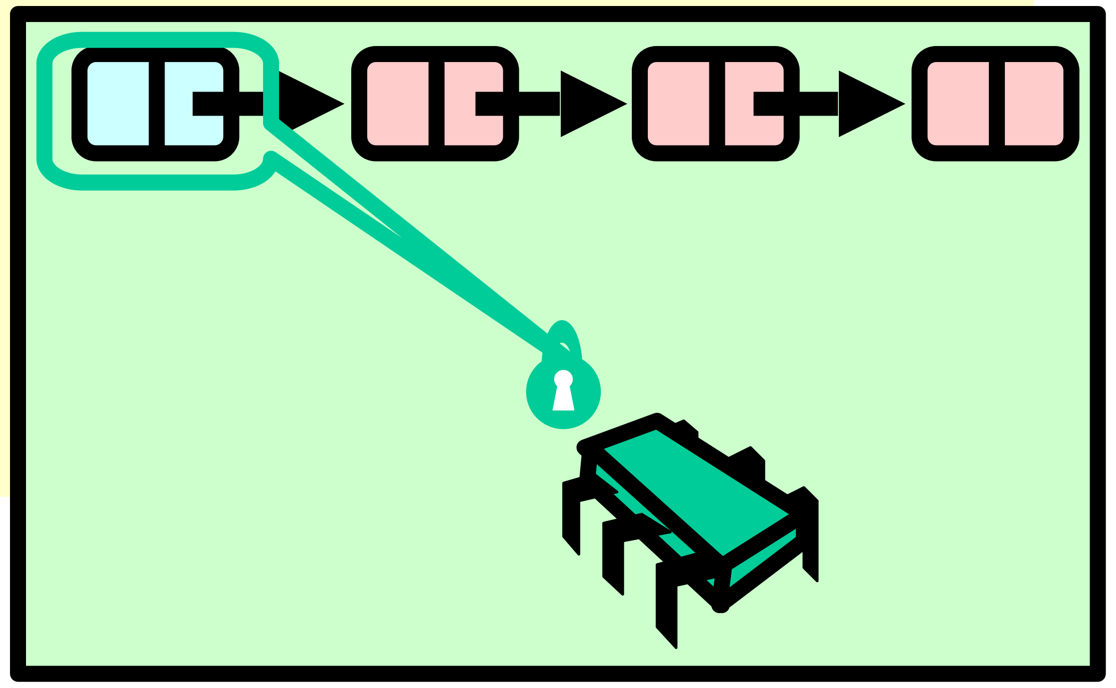
Remove method

```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 …
} finally { … }
```

Remove method

lock pred == head

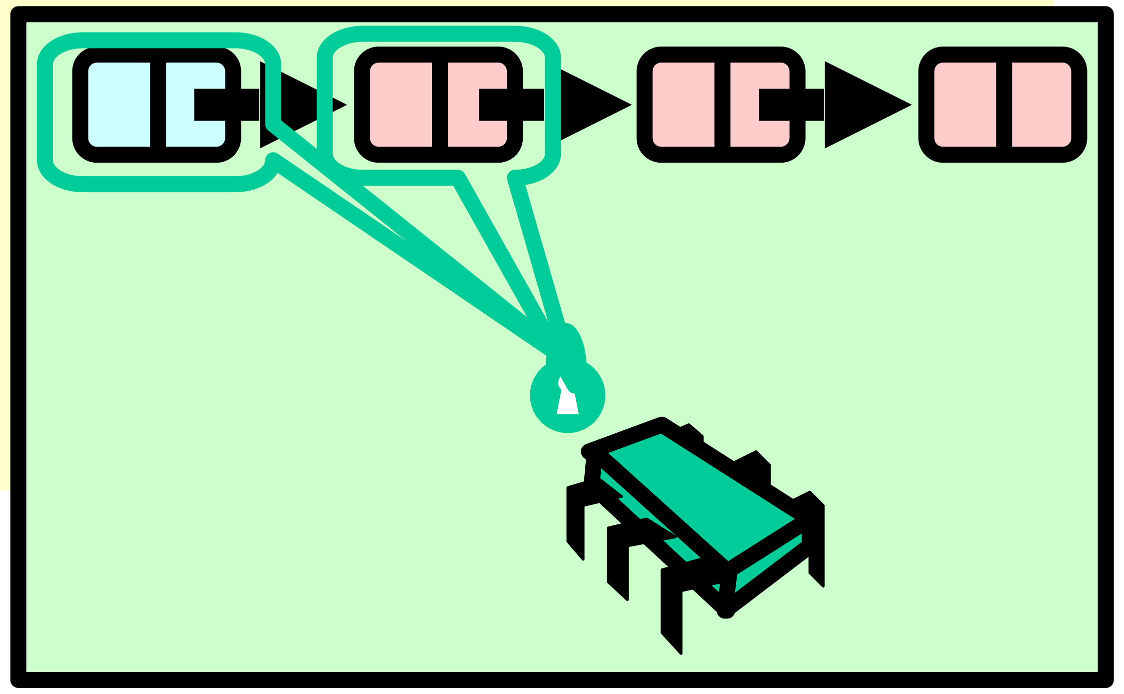
```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 ...
} finally { ... }
```



Remove method

```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 ...
} finally { ... }
```

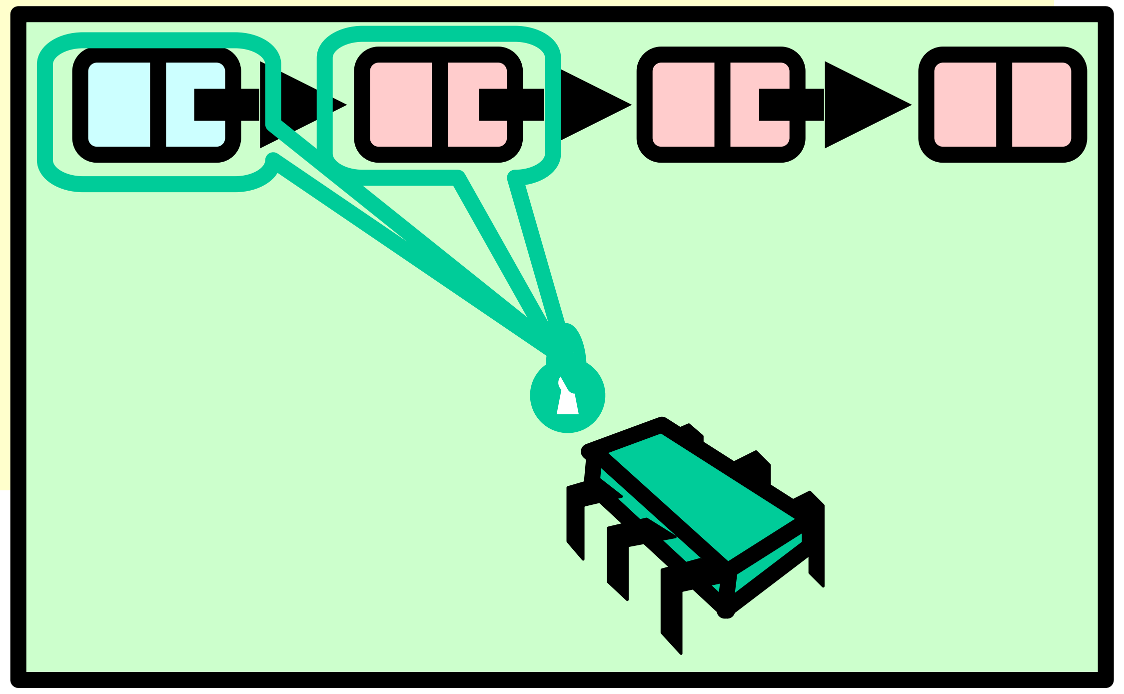
Lock current



Remove method

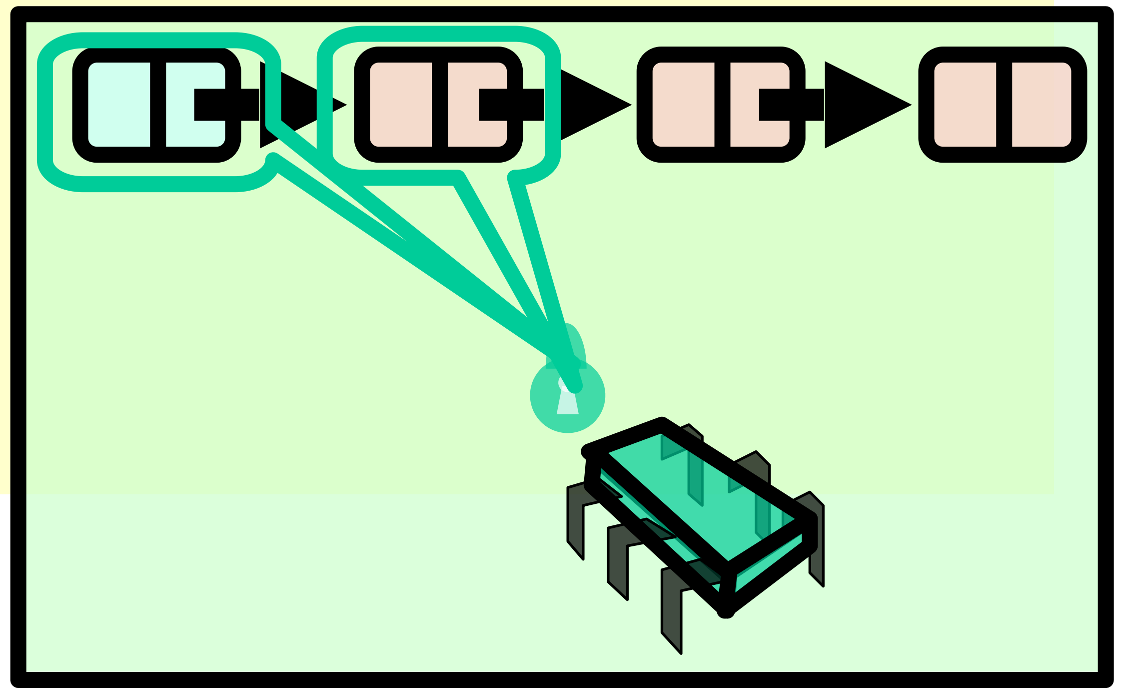
```
try {
 pred = this.head;
 pred.lock();
 curr = pred.next;
 curr.lock();
 ...
} finally { … }
```

Traversing list



Remove: searching

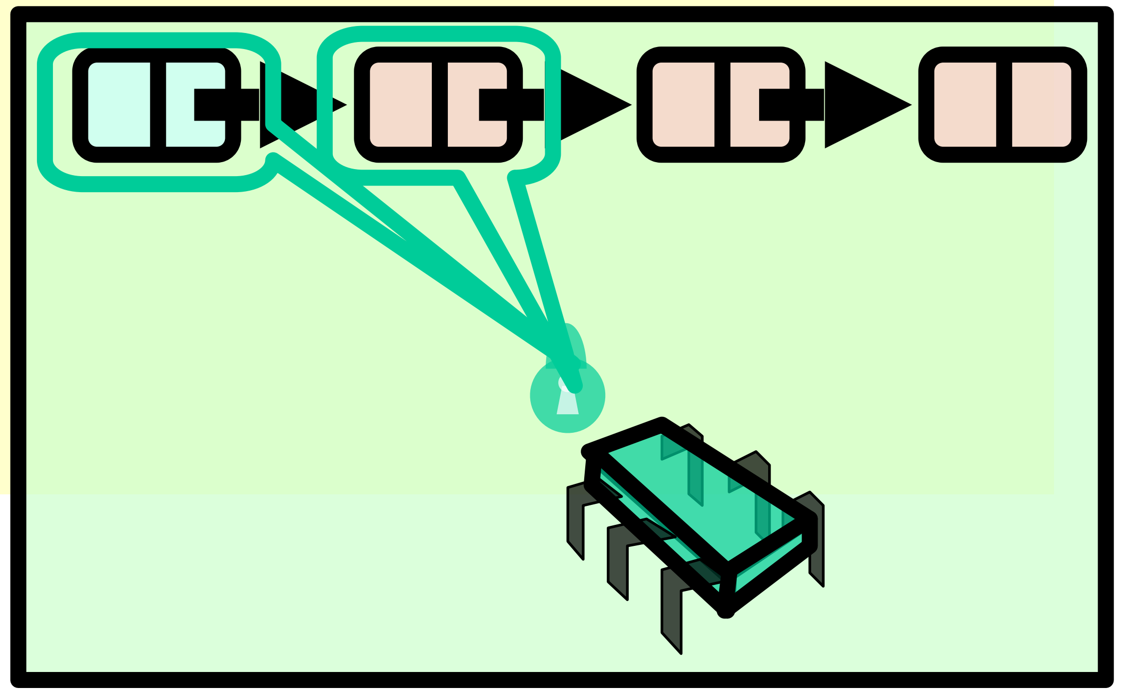
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

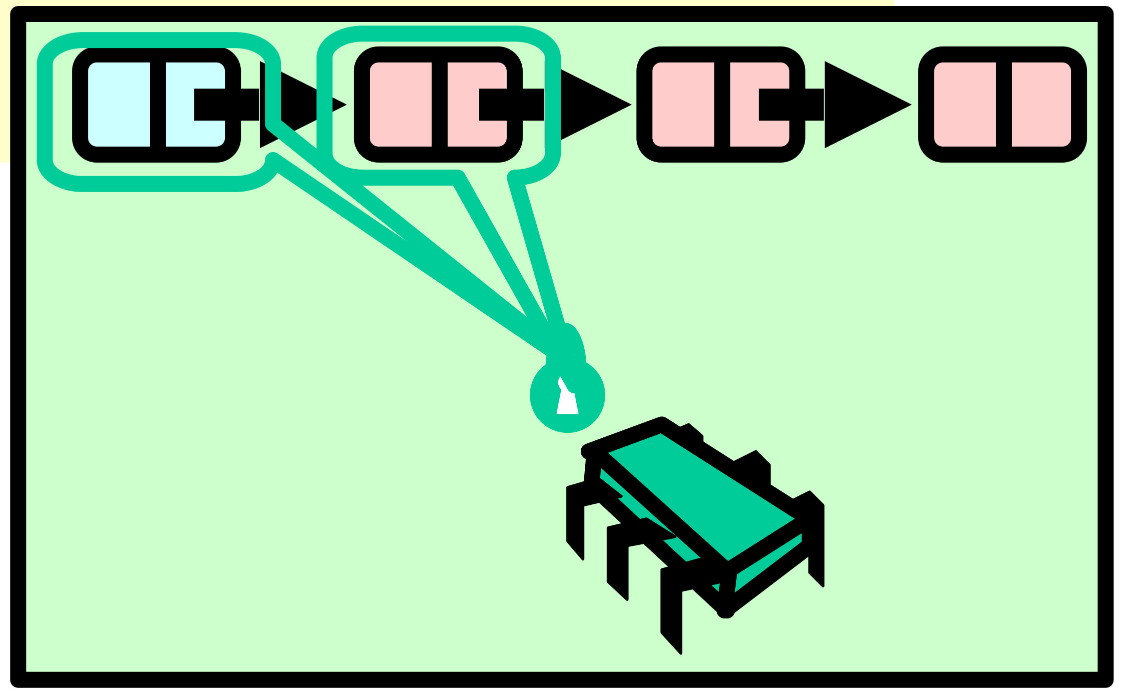
Search key range



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

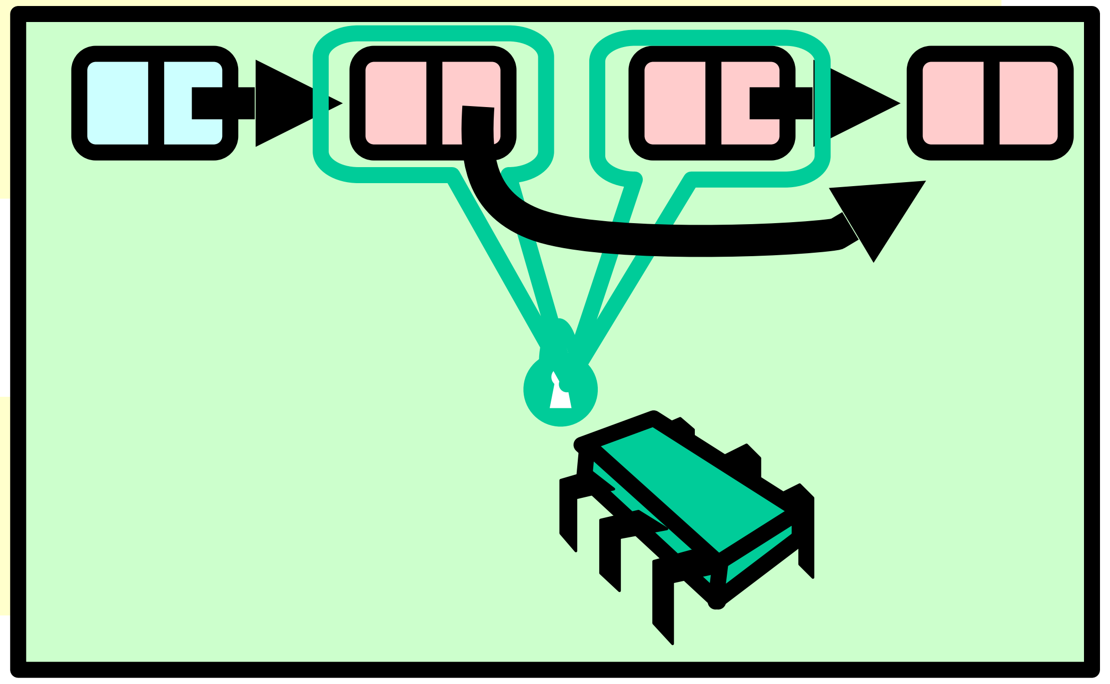
At start of each loop: curr and pred locked



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

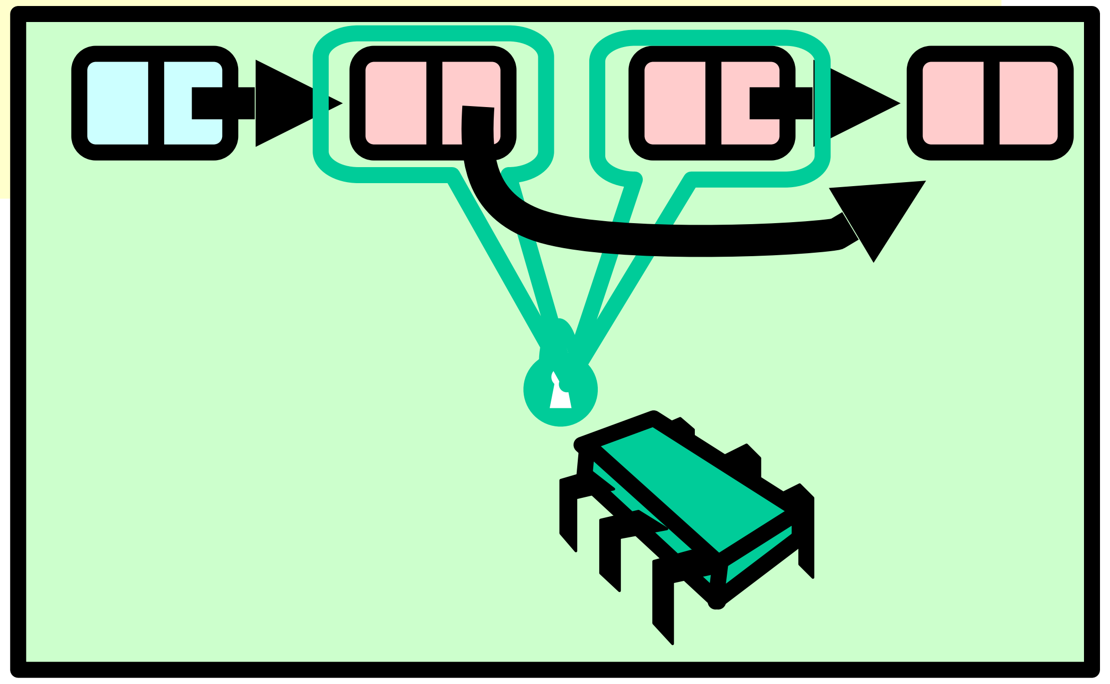
If item found, remove node



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

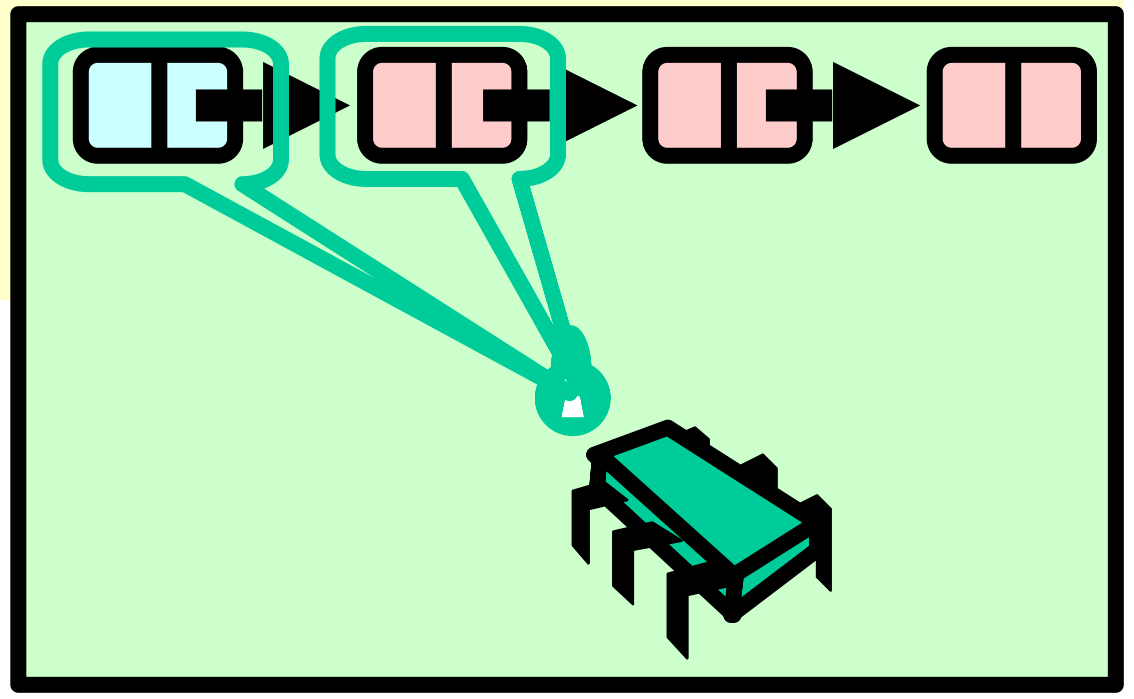
If node found, remove it



Remove: searching

Unlock predecessor

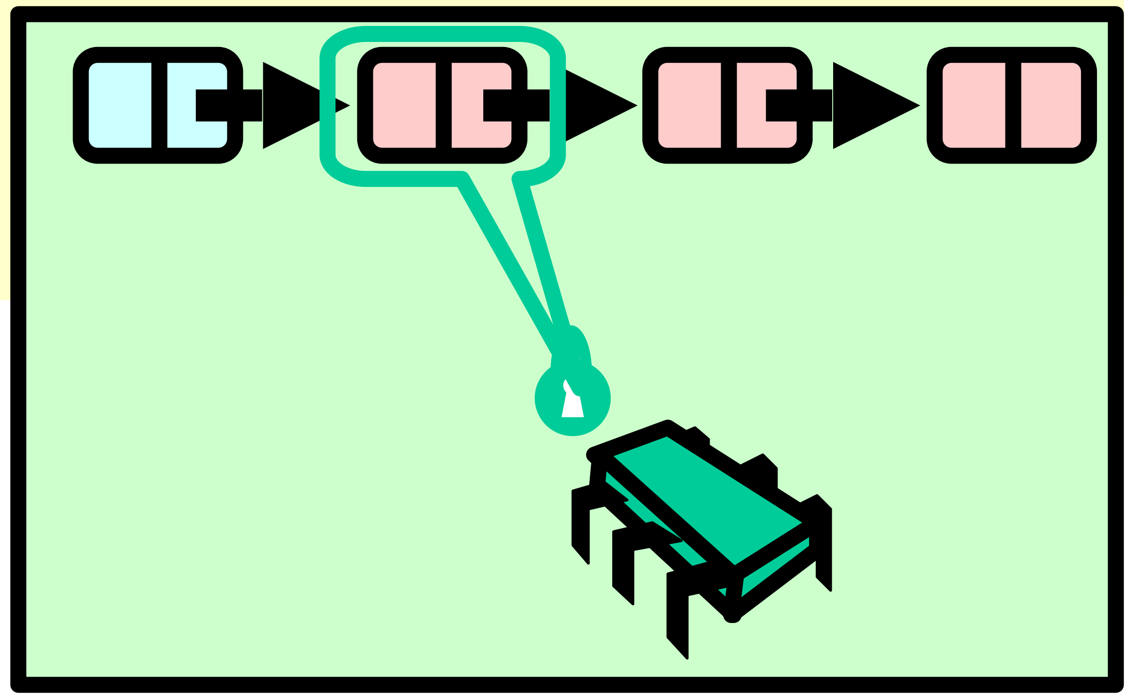
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

Only one node locked!

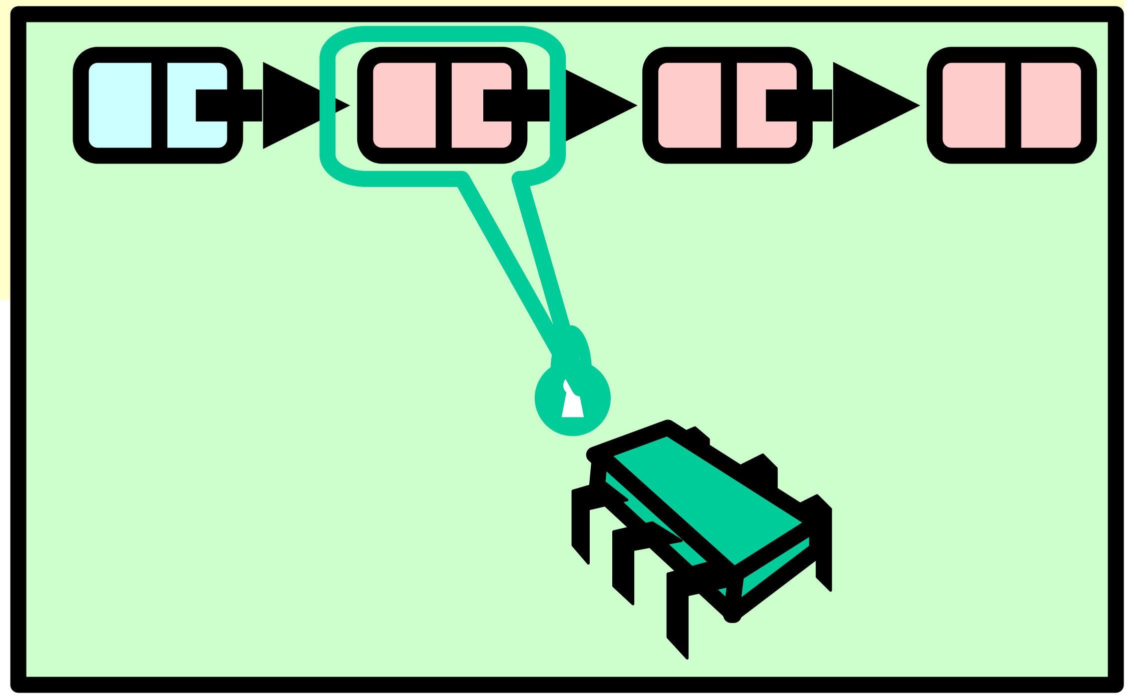
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

demote current

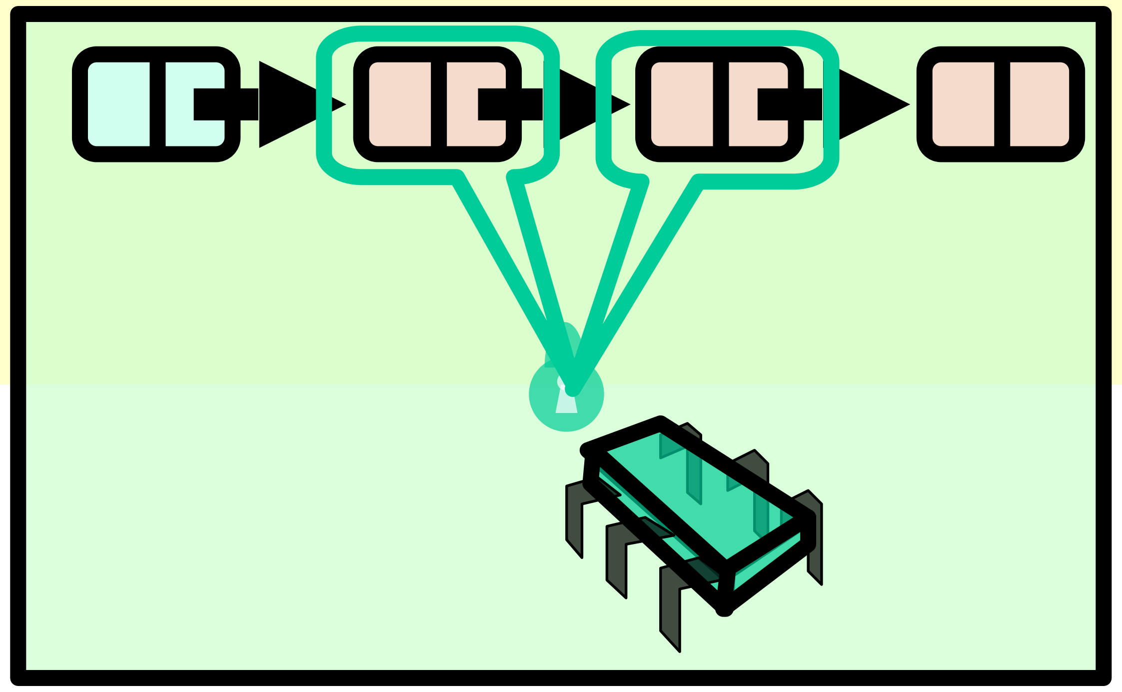
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```



Remove: searching

Find and lock new current

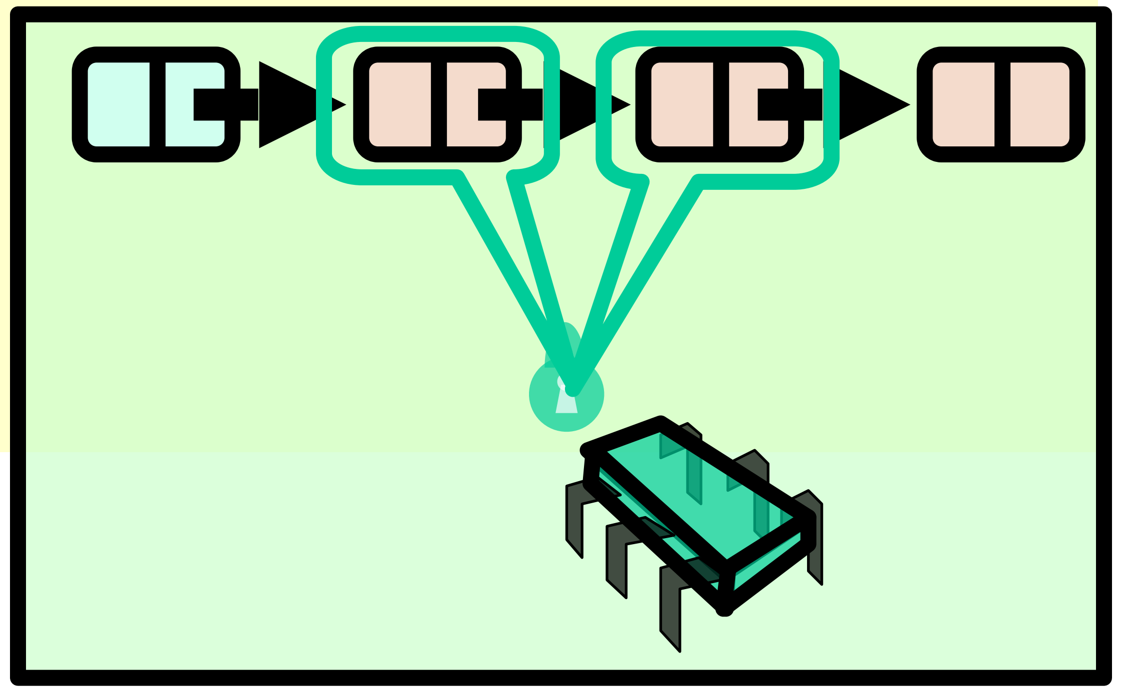
```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = currNode;
  curr = curr.next;
  curr.lock();
}
return false;
```



Remove: searching

Lock invariant restored

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = currNode;
  curr = curr.next;
  curr.lock();
}
return false;
```



Remove: searching

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
 return false;
```

Otherwise, not present

Why does this work?

- To remove node e
  - Must lock e
  - Must lock e's predecessor
- Therefore, if you lock a node
  - It can't be removed
  - And neither can its successor

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

- **pred** reachable from **head**
- **curr** is **pred.next**
- So **curr.item** is in the set

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

Linearization point if item is present

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Node locked, so no other thread can remove it ….

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
}
return false;
```

Item not present

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

- **pred** reachable from **head**
- **curr** is **pred.next**
- **pred.key <** key
- key < **curr.key**

Why remove() is linearizable

```
while (curr.key <= key) {
  if (item == curr.item) {
   pred.next = curr.next;
   return true;
  }
  pred.unlock();
  pred = curr;
  curr = curr.next;
  curr.lock();
 }
 return false;
```

Linearization point

Adding Nodes

- To add node e
  - Must lock predecessor
  - Must lock successor
- Neither can be deleted
  - (Is successor lock actually required?)

Same Abstraction Map

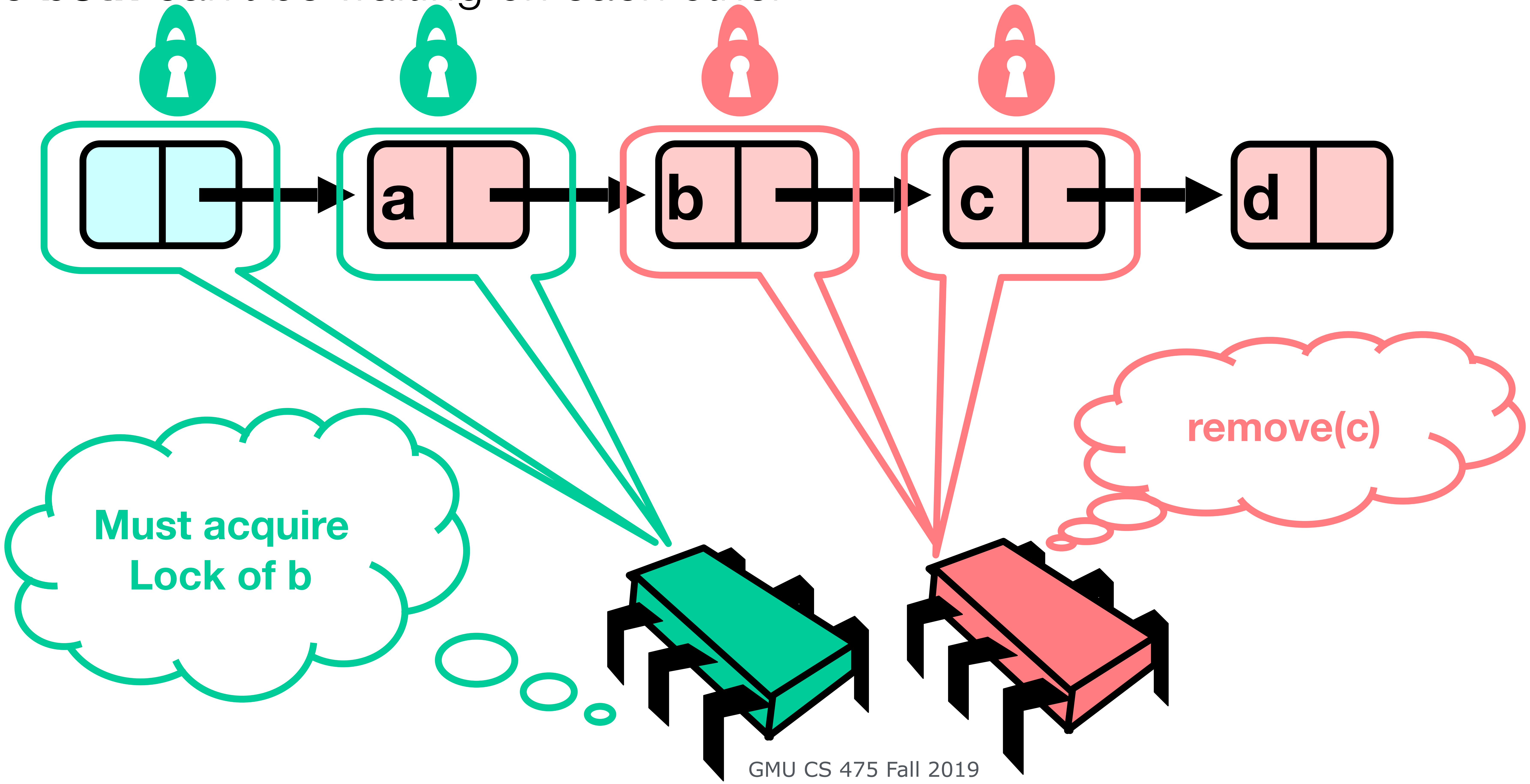
- S(head) =
  - { x | there exists a such that
    - a reachable from head and
    - a.item = x
  - }

Representation Invariant

- Easy to check that
  - tail always reachable from head
  - Nodes sorted, no duplicates

Why doesn't it deadlock?

- Deadlock occurs with at least 2 threads, where each thread wants the lock that the other has
- HOWEVER: each thread always acquires locks in same order (left to right)
- Hence **both** can't be waiting on each other

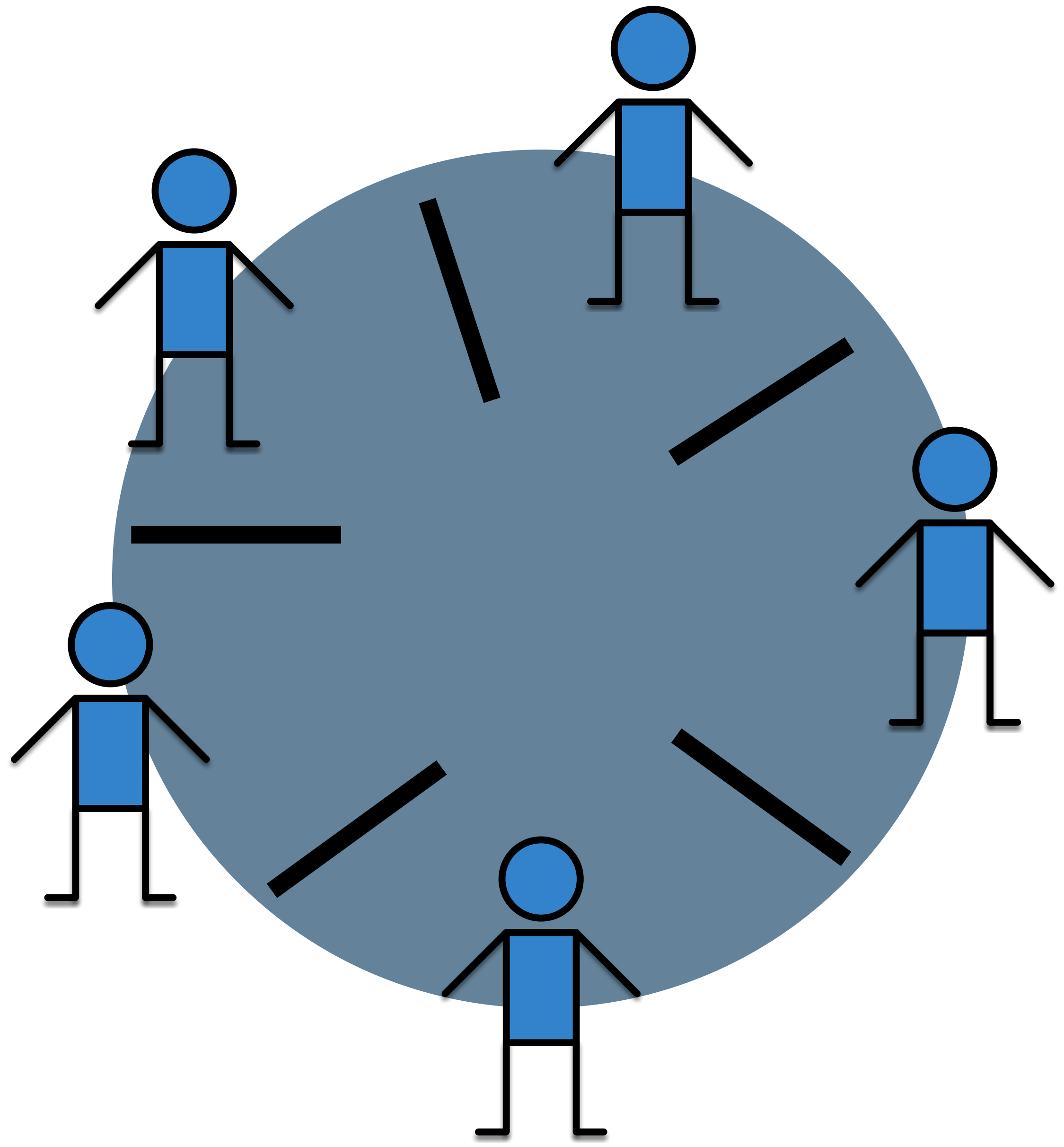


Drawbacks

- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Long chain of acquire/release
  - Inefficient

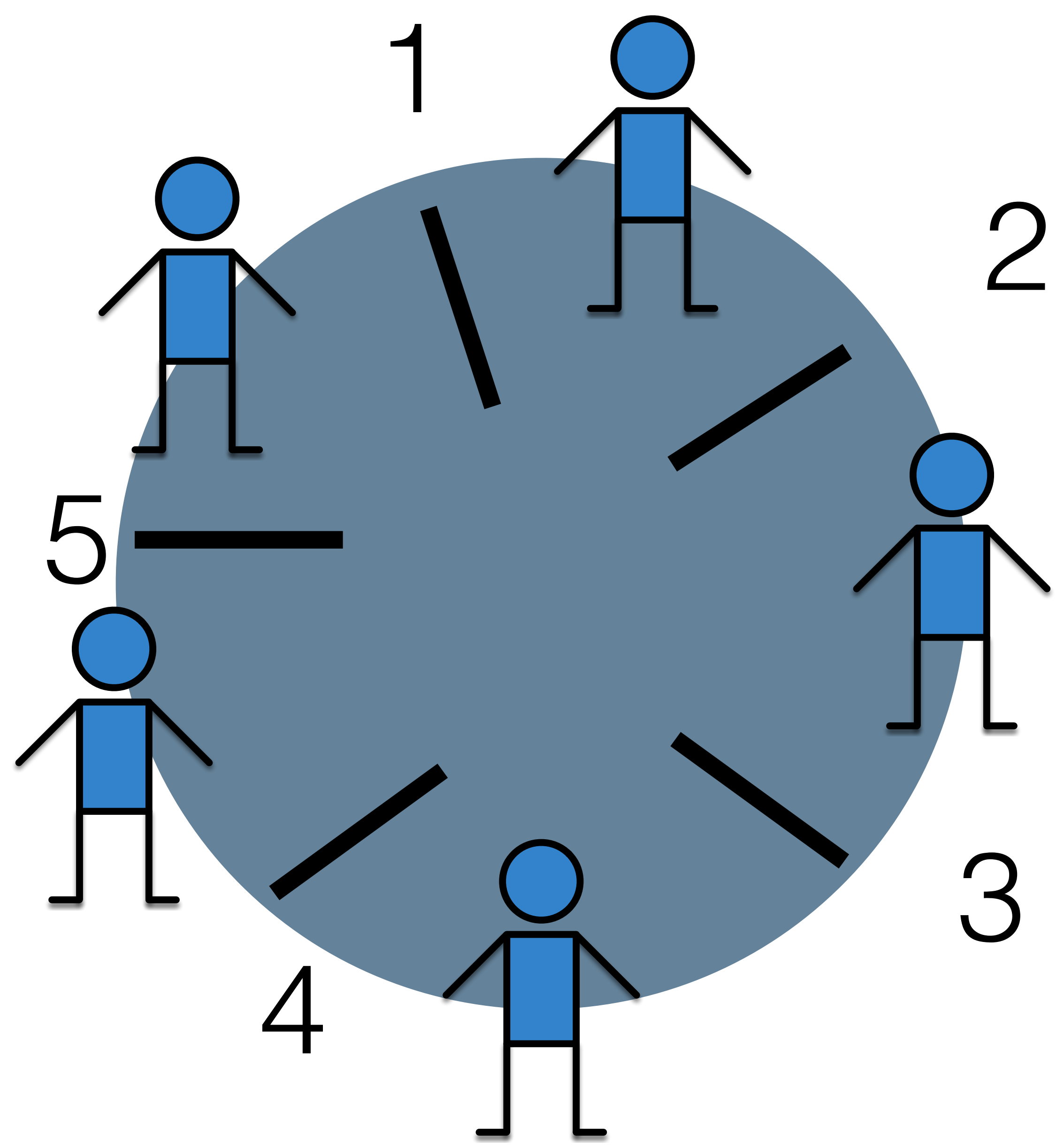
Dining Philosophers

- N philosophers seated around a circular table
  - One chopstick between each philosopher (N chopsticks)
  - A philosopher picks up both chopsticks next to him to eat
  - Philosophers may not pick up both chopsticks at the same time
- How do they all eat without deadlocking or starving?

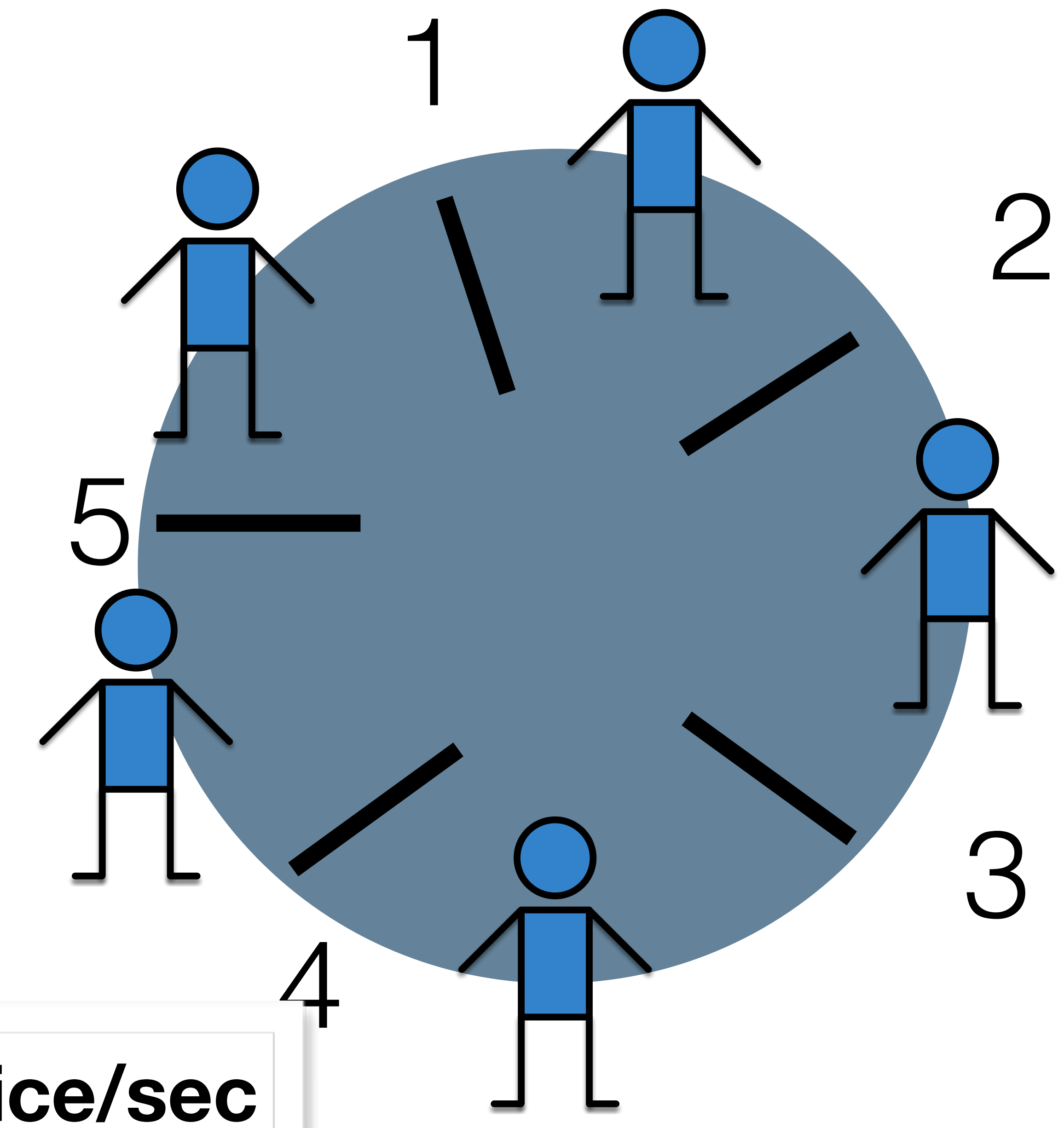


Dining Philosophers

- Give each chopstick a lock
- Is this enough?
- Could deadlock!
- Actual solutions:
  - Pick up one chopstick, wait for the other for N msec, otherwise put down what you have, wait, and try again
  - Only allow 4 philosophers to pick up chopsticks at once
  - Even # seats pick up right chopstick, odd # seats pick up left



Dining Philosophers



- Give each chopstick a lock
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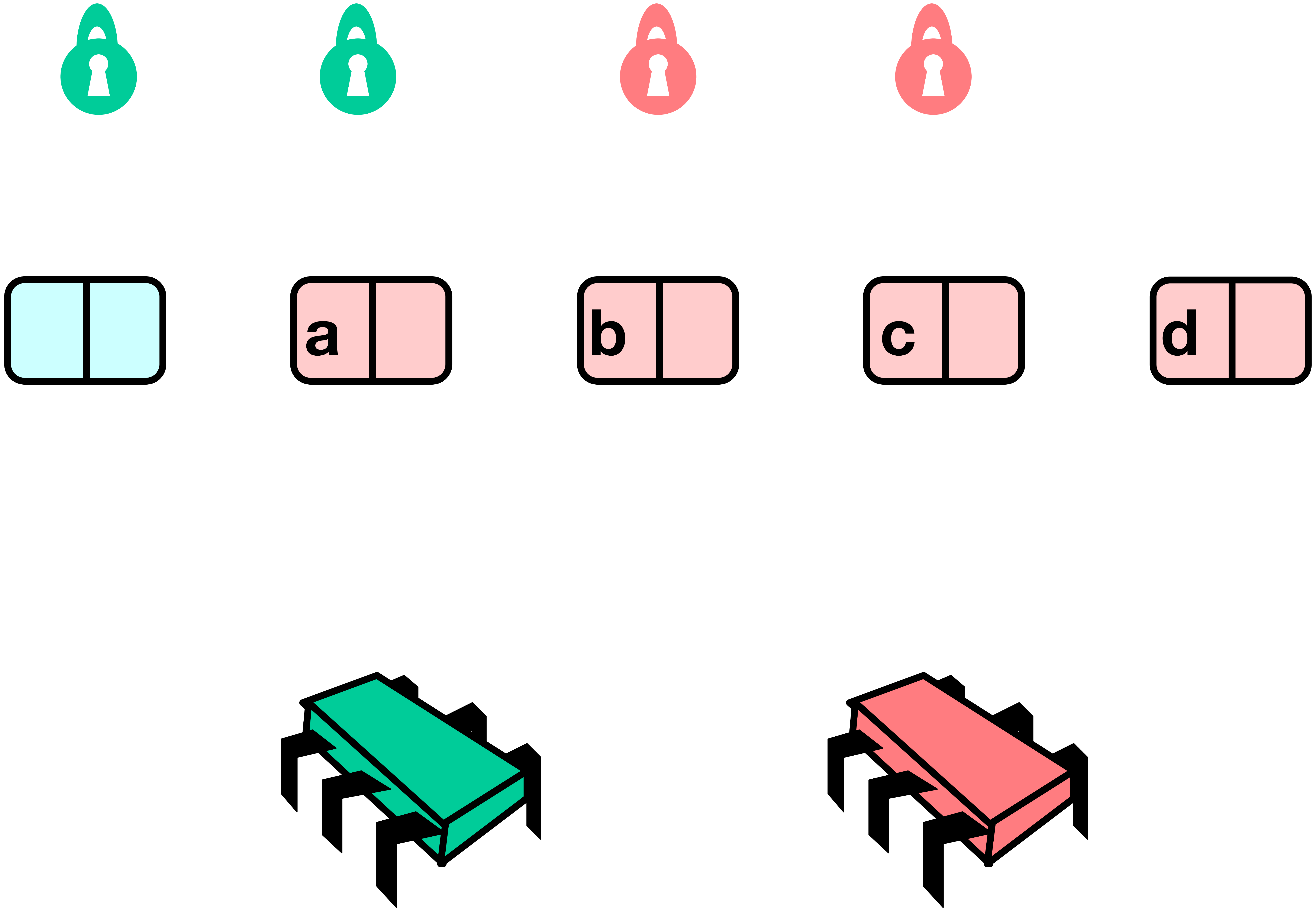
  - Pick up one chopstick, wait for the other for N msec, otherwise put down what you have, wait, and try again
  - Only allow 4 philosophers to pick up chopsticks at once
  - Even # seats pick up right chopstick, odd # seats pick up left

1,450 grains of rice/sec

5,431,616 grains of rice/sec

12,450,856 grains of rice/sec


a
b
c
d