FOUNDATIONS OF CONCURRENT AND DISTRIBUTED SYSTEMS

– LINKED LISTS: LOCKING, LOCK-FREE, AND BEYOND –

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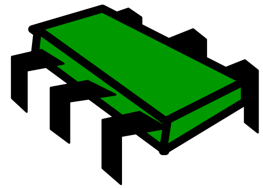
Today: Concurrent Objects

- Adding threads…
- Should **not lower throughput**
  - **Contention effects**
    - Mostly fixed by **queue locks**
  - **Overhead to acquire the lock:**
    - we look at **futex** a later lecture and briefly discuss queue locks.
- Should **increase throughput**
  - Not possible if inherently sequential
  - Surprising things are parallelizable

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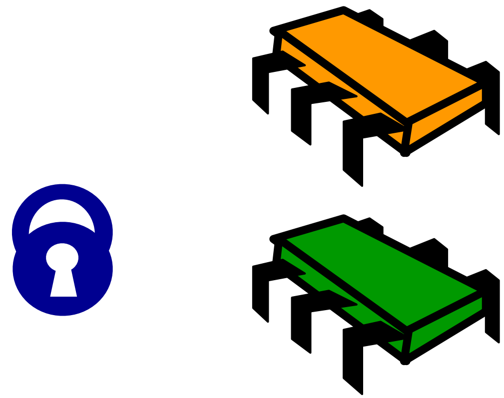

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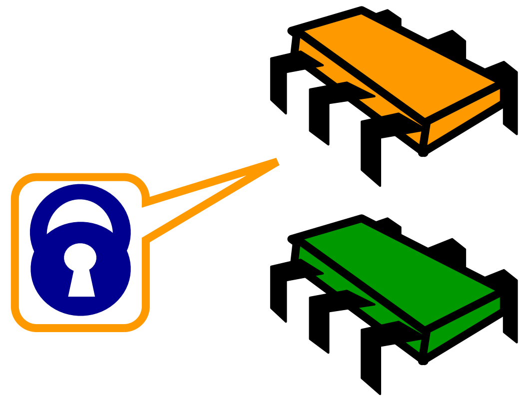

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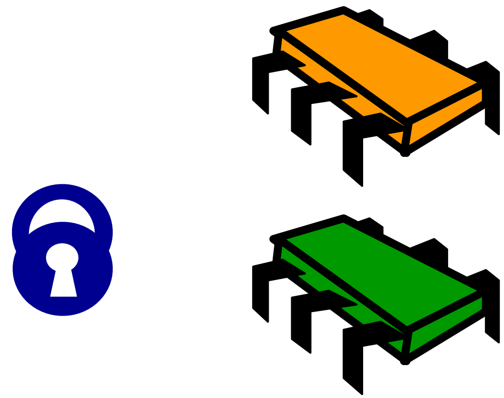

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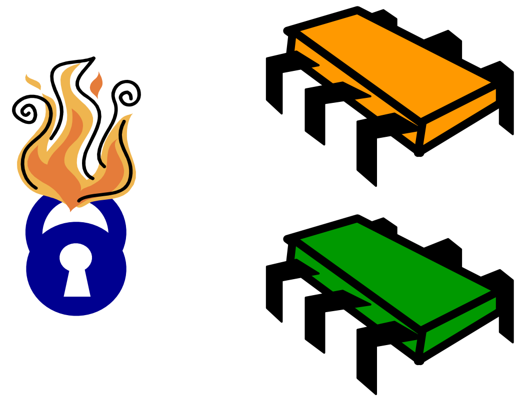

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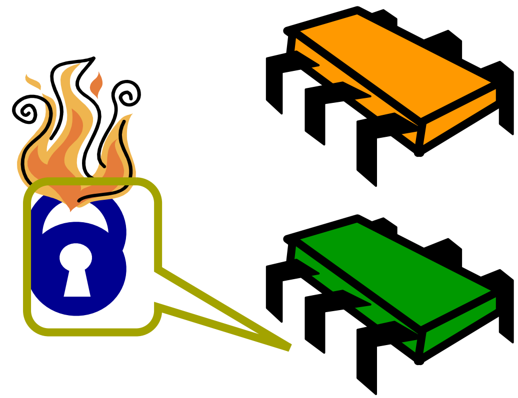

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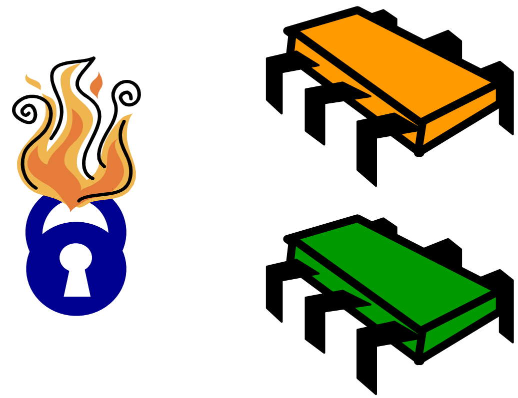

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Coarse-Grained Synchronization

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

Coarse-Grained Synchronization

- Sequential bottleneck
  - All 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 applications inherently parallel…

This Lecture

- Introduce four "patterns"
  - Bag of tricks
  - Methods that work more than once
- For highly-concurrent objects
- Goal
  - Concurrent access
  - More threads, more throughput

1. 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

2. Optimistic Synchronization

- Object = linked set of components
- Search without locking…
- If you find it, lock and check…
  - OK, we are done
  - Oops, try again
- Evaluation
  - Cheaper than locking
  - Mistakes are expensive

3. Lazy Synchronization

- Postpone hard work
- Removing components is tricky
  - Logical removal
    - Mark component to be deleted
  - Physical removal
    - Do what needs to be done

4. Lock-Free Synchronization

- Do not use locks at all
  - Use compareAndSet() and relatives…
- Advantages
  - Robust against asynchrony
- Disadvantages
  - Complex
  - Sometimes high overhead

Wait-Free Implementations

Definition: An object implementation is wait-free if every thread completes a method in a finite number of steps

No mutual exclusion

- Thread could halt in critical section

Lock-Free Implementations

Definition: An object implementation is lock-free if in an infinite execution infinitely often some method call finishes (obviously, in a finite number of steps)

No difference between lock-free and wait-free for finite executions

Example: Set Properties

- Collection of objects
- No duplicates
- Methods
  - add() a new object
  - remove() an object
  - Test if set contains() object

Set Interface

```
public interface Set {
  public boolean add(Object x);
  public boolean remove(Object x);
  public boolean contains(Object x);
}
```

Set Interface

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public interface Set {
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Add object to set

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public interface Set {
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```

Remove object from set

Set Interface

```
public interface Set {
  public boolean add(Object x);
  public boolean remove(Object x);
  public boolean contains(Object x);
}
```

Is object in set?

Linked List

- Illustrate these patterns…
- Using a list-based Set
  - Common data structure
  - Building block for other apps

List Node

```
public class Node {
  Object object;
  int key;
  Node next;
}
```

List Node

```
public class Node {
  Object object;
  int key;
  Node next;
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```

Object of interest

List Node

```
public class Node {
  Object object;
  int key;
  Node next;
}
```

Usually hash code

List Node

```
public class Node {
  Object object;
  int key;
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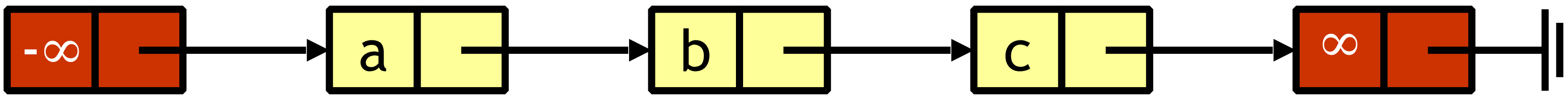
}
```

Reference to next node

The List-Based Set



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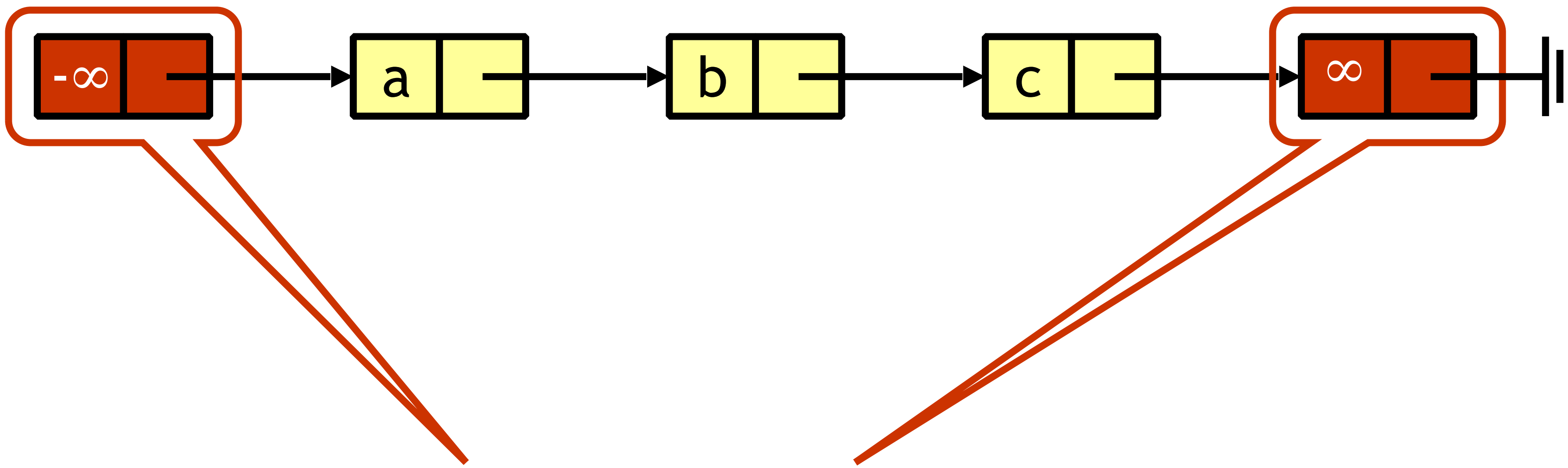


Ordered + sentinel nodes
(min & max possible keys)

Reasoning about Concurrent Data Structures

- Identify invariants
  - Properties that always holds
- True when object is created
- Truth preserved by each method
  - add(), remove(), contains()
  - Each step of each method
- Most steps are trivial
  - Usually one step tricky
  - Often linearization point

Interference

- Proof that invariants are preserved works if methods considered are the only modifiers
- Language encapsulation helps
  - List nodes not visible outside class
- Freedom from interference needed even for removed nodes
  - Some algorithms traverse removed nodes
  - Careful with malloc() and free()!
  - Garbage-collection helps here

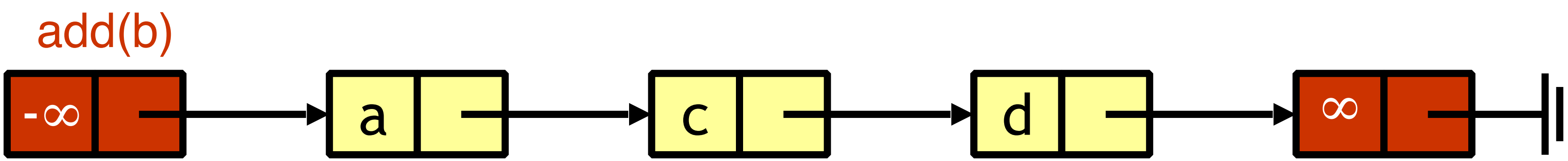
Blame Game

- Suppose
  - add() leaves behind 2 copies of x
  - remove() removes only 1
- Which one is incorrect?
  - If invariant says no duplicates
    - add() is incorrect
  - Otherwise
    - remove() is incorrect

Set Invariant (Partly)

- Sentinel nodes
  - Tail reachable from head
- Sorted
- No duplicates

Sequential List Based Set



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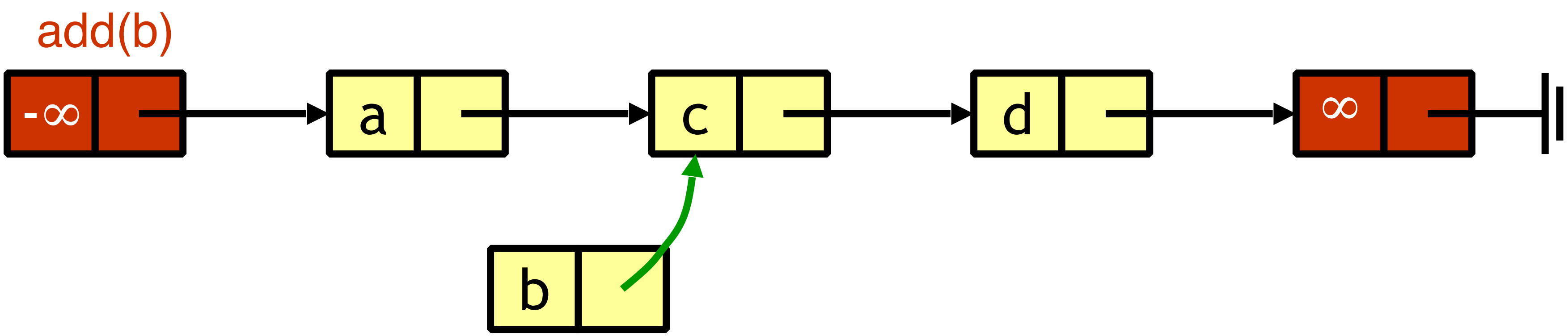

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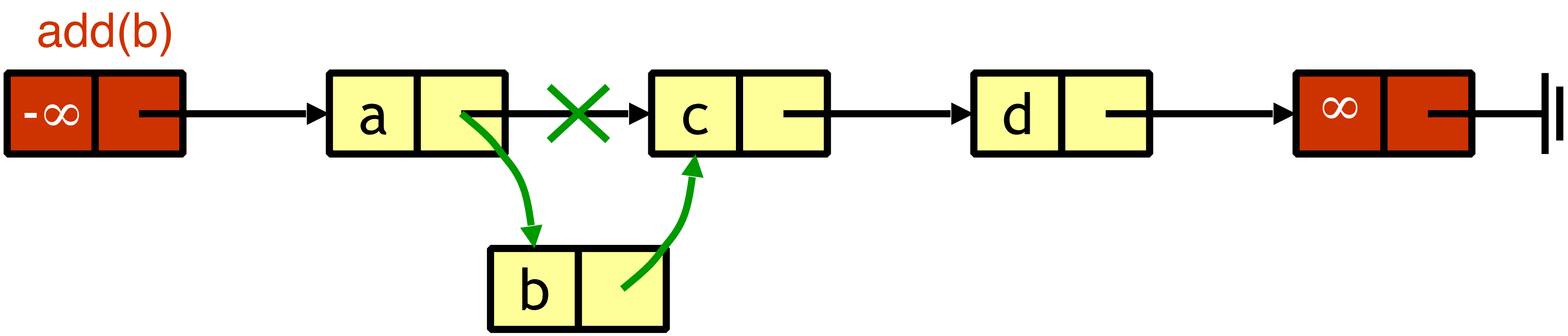
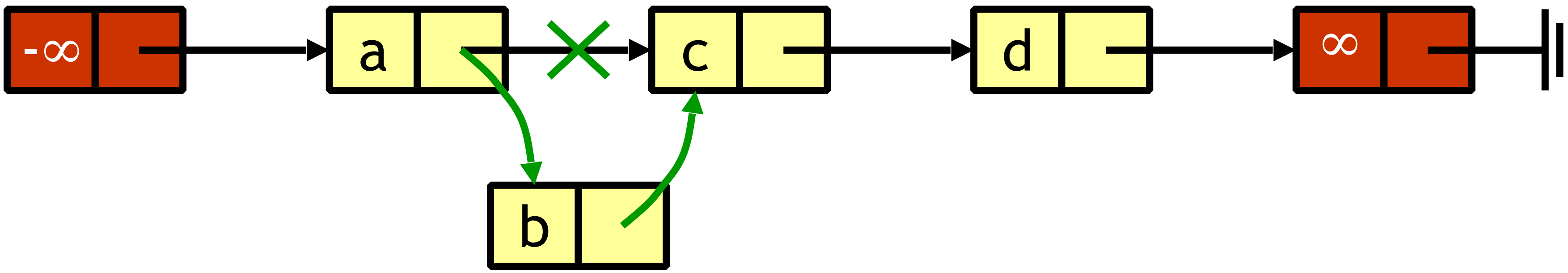
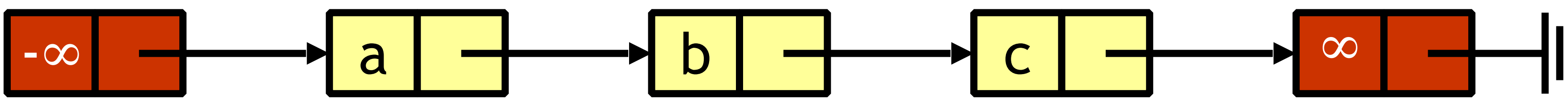


Sequential List Based Set

add(b)



remove(b)



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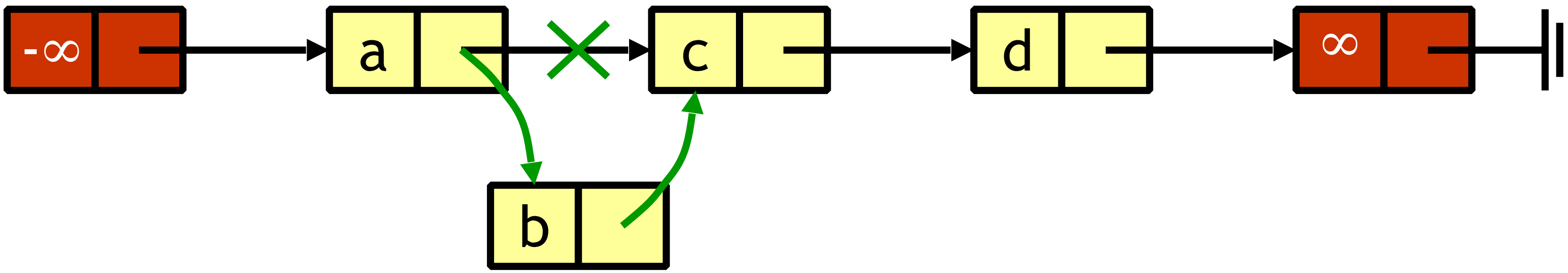

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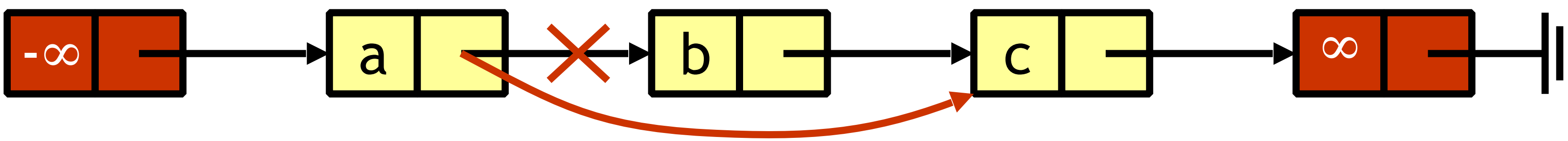
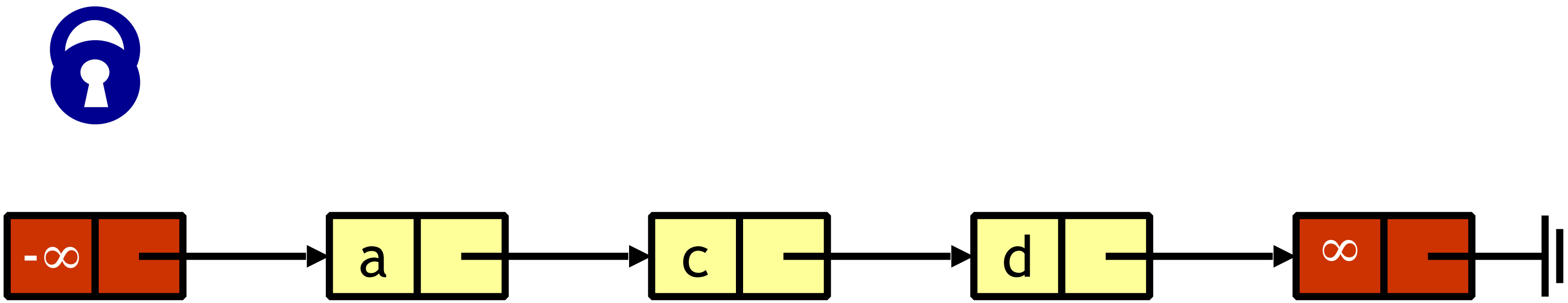


Coarse-Grained Locking



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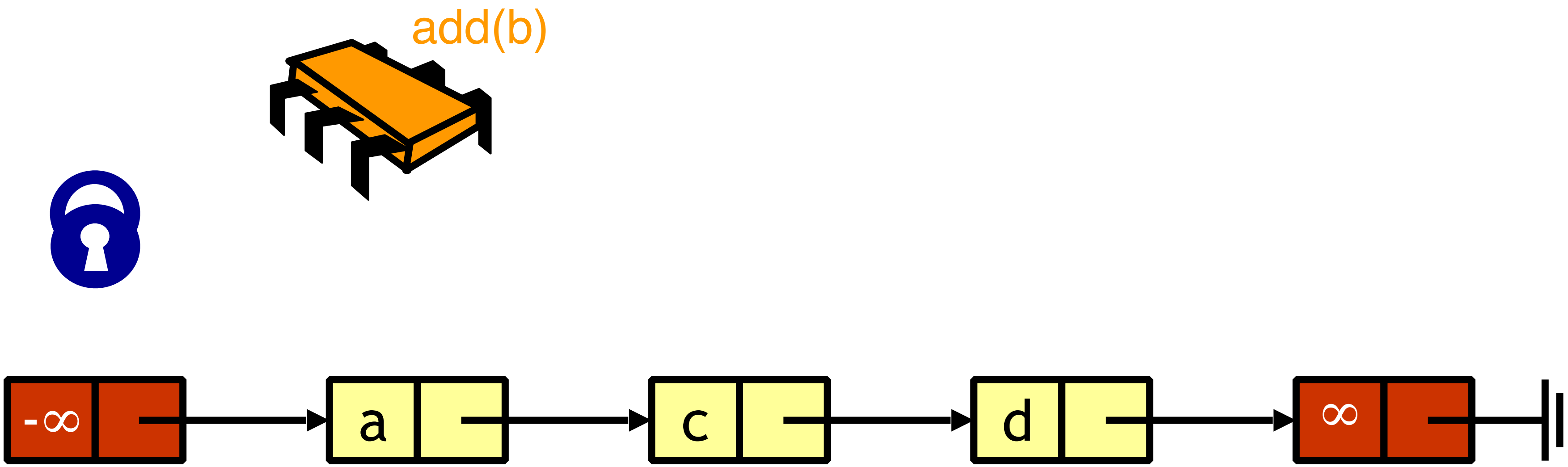

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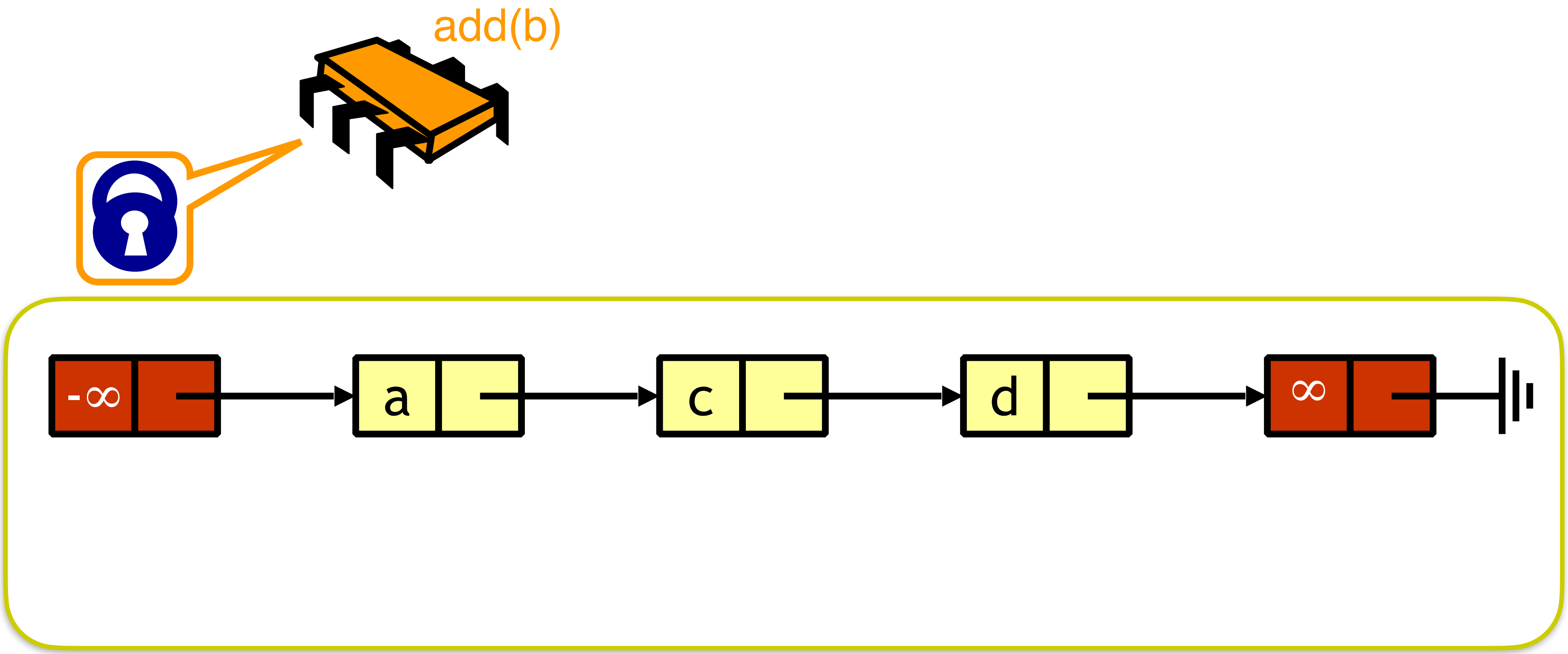

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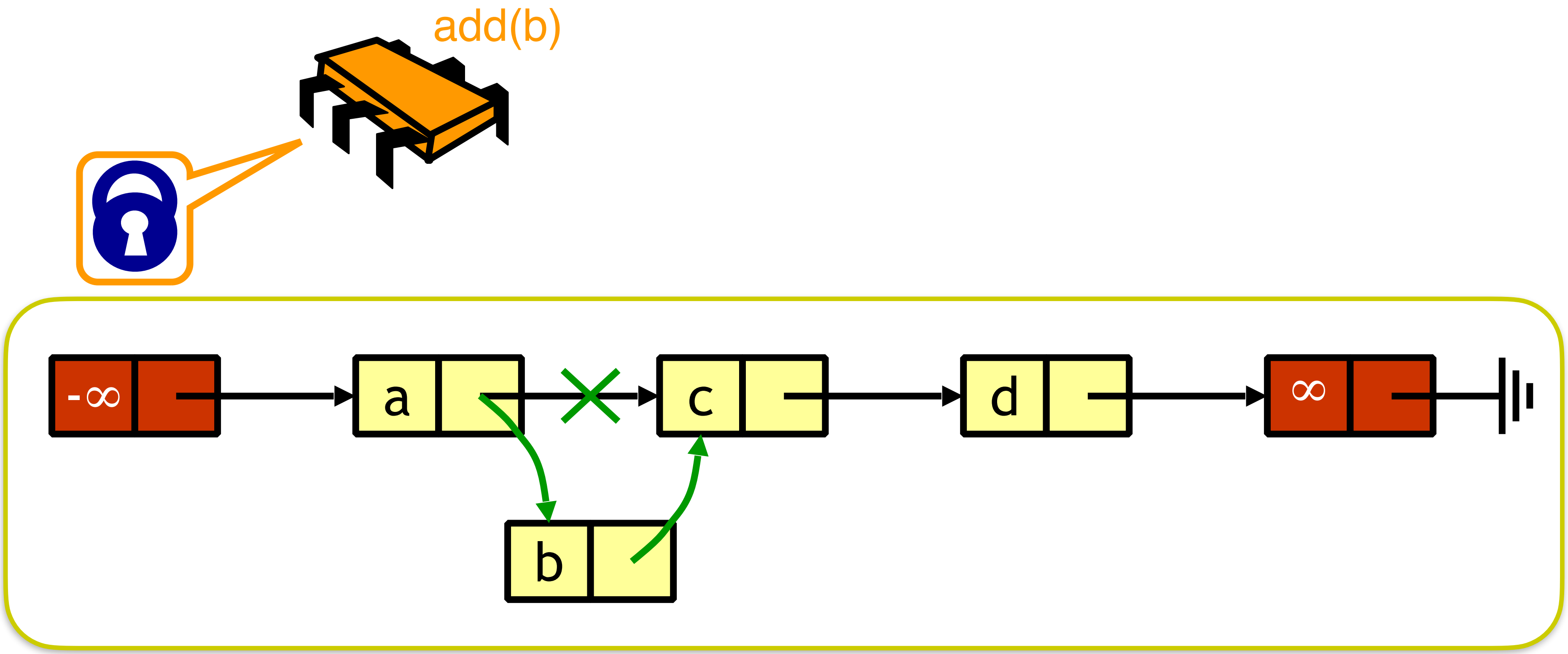

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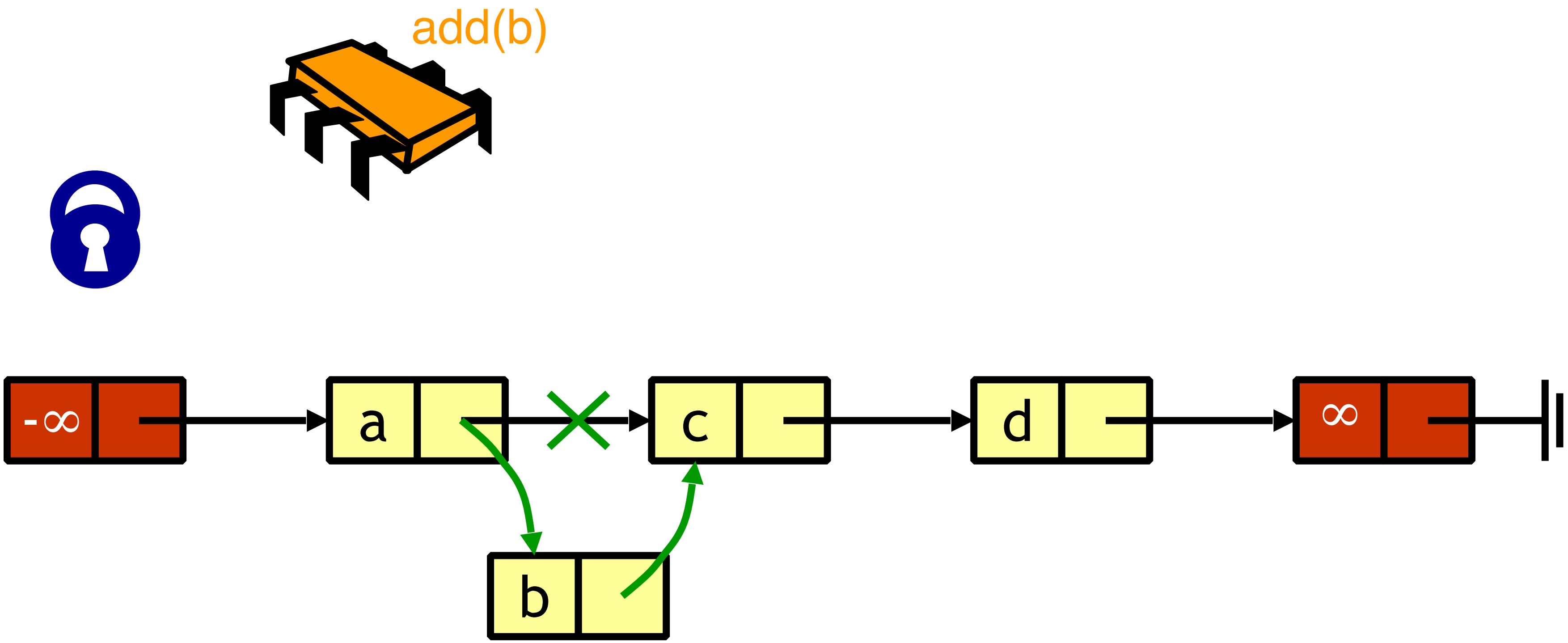

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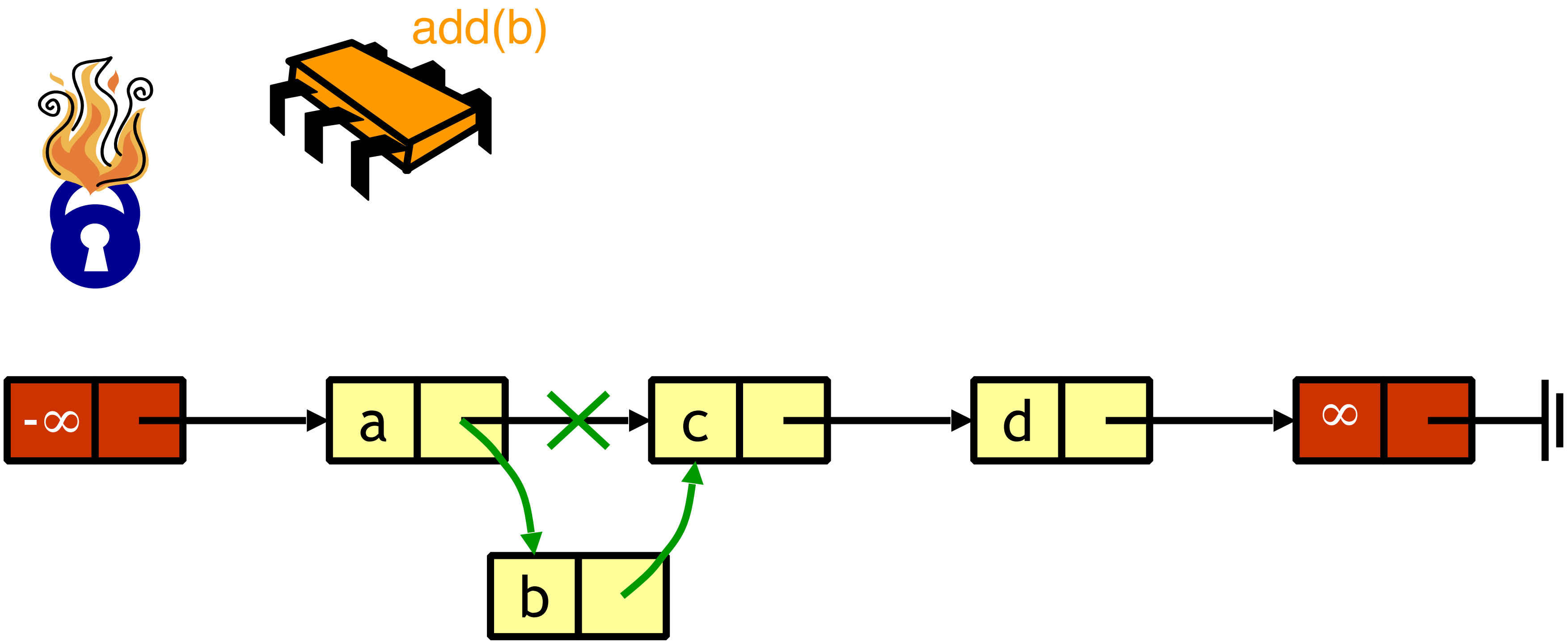


Simple but hotspot + bottleneck

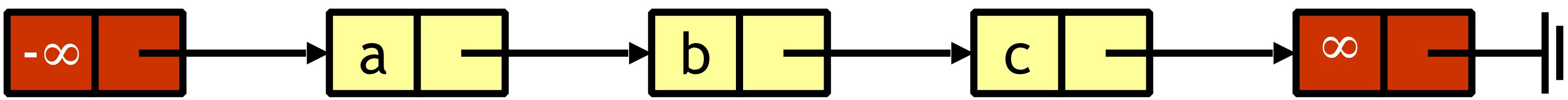
1. Coarse-Grained Locking

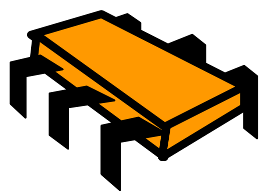
- Easy, same as synchronized methods
  - "One lock to rule them all…"
- Simple, clearly correct
  - Deserves respect!
- Works poorly with contention
  - Queue locks help
  - But bottleneck still an issue

2. Fine-grained Locking

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

Hand-over-Hand Locking





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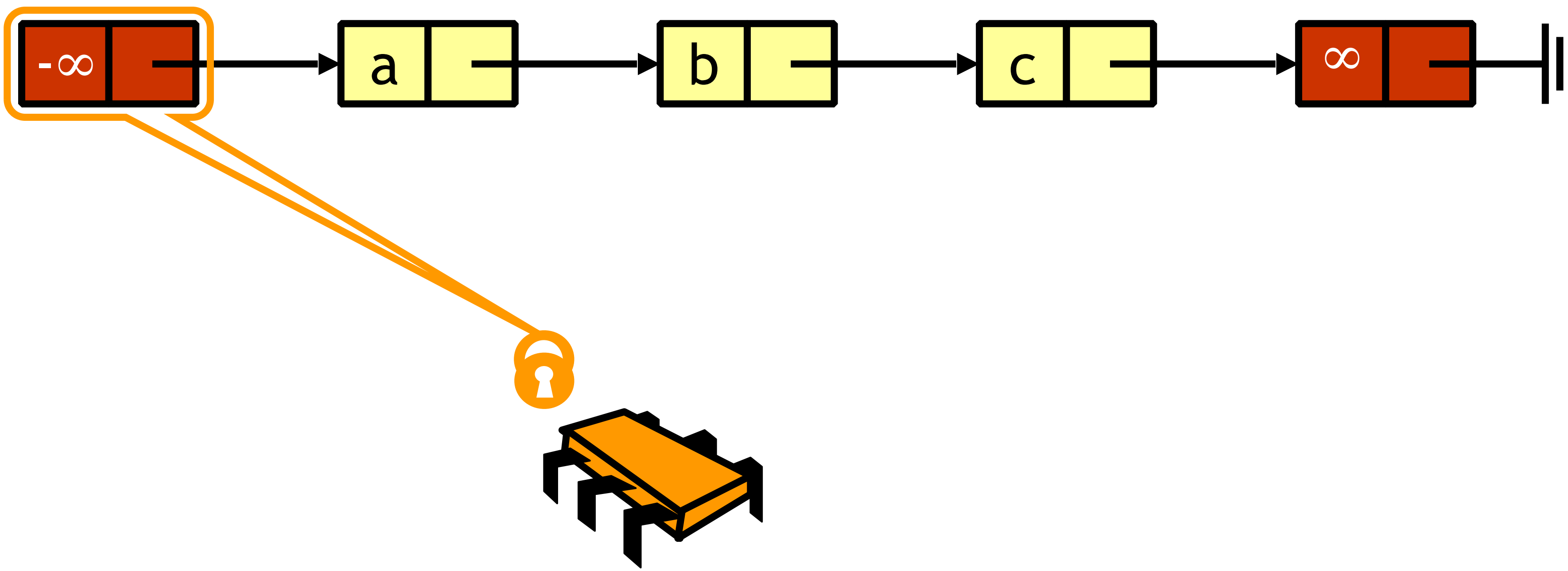

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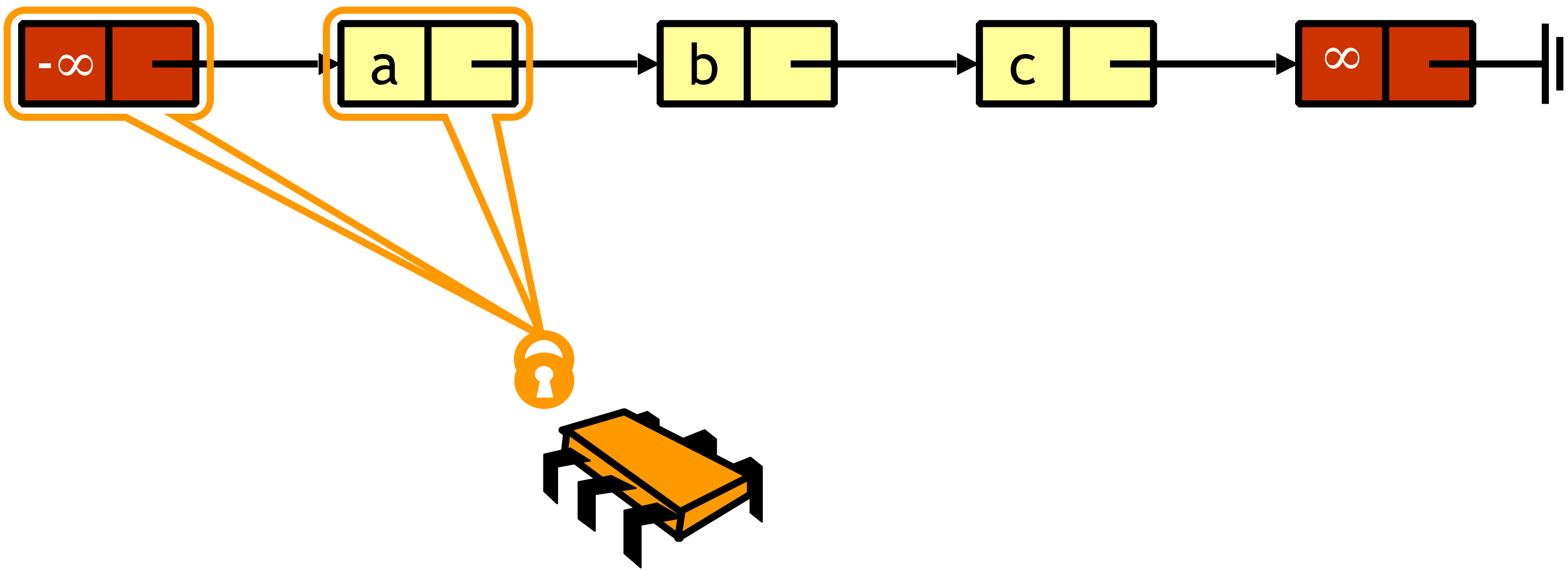

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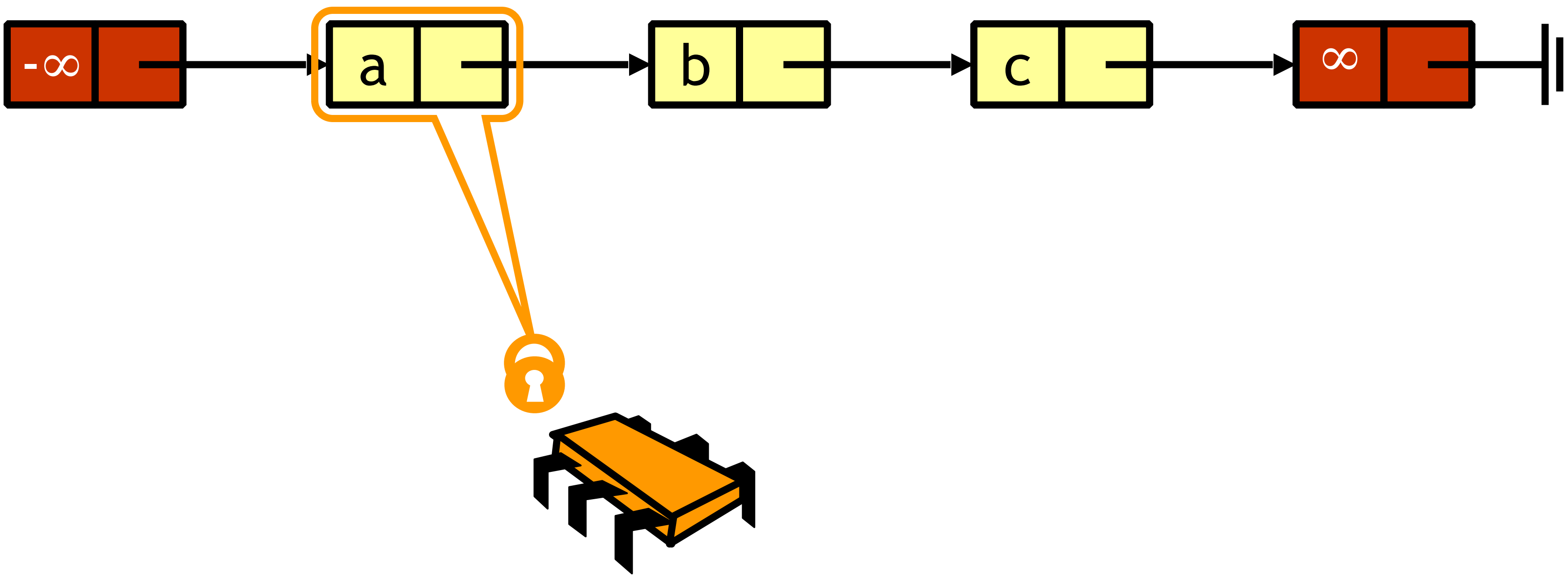

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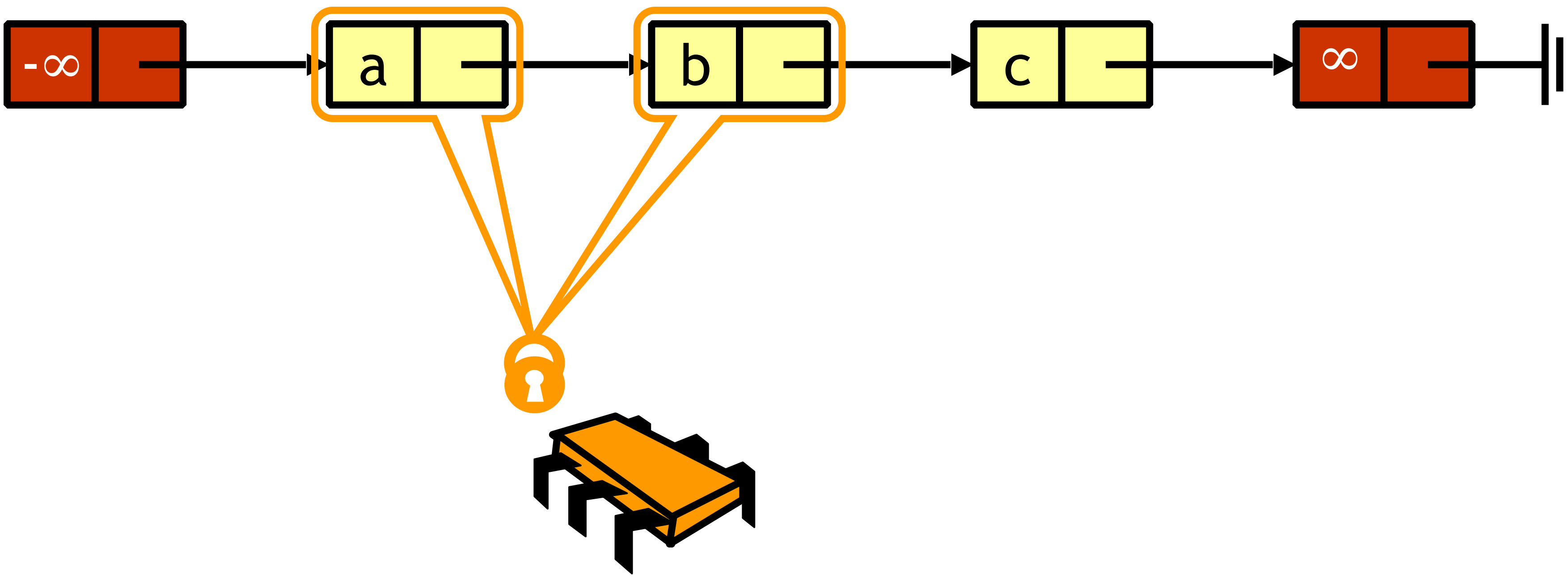

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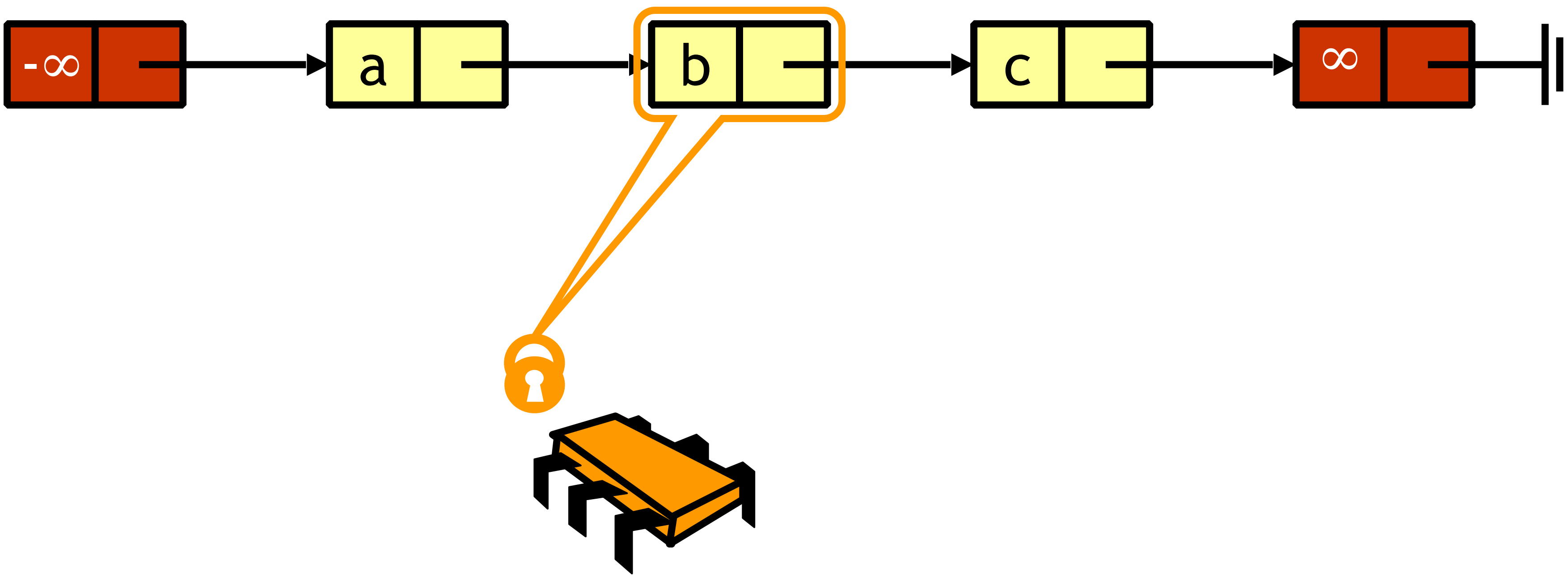

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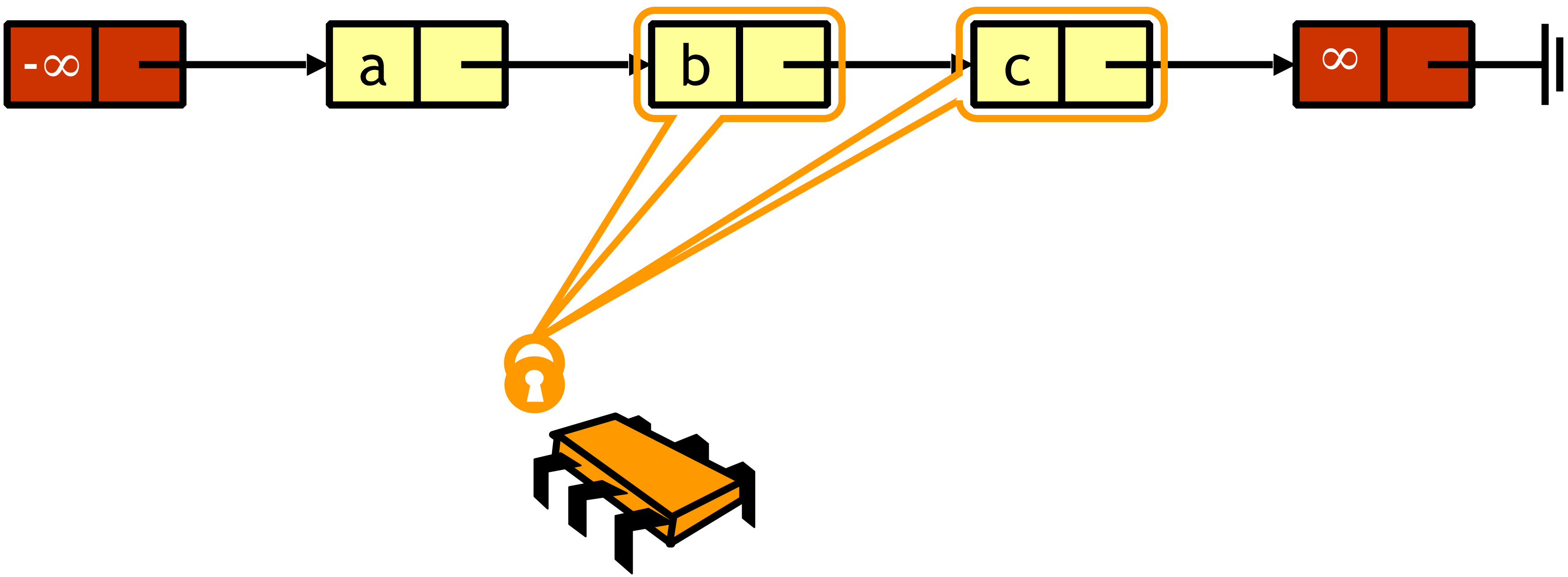

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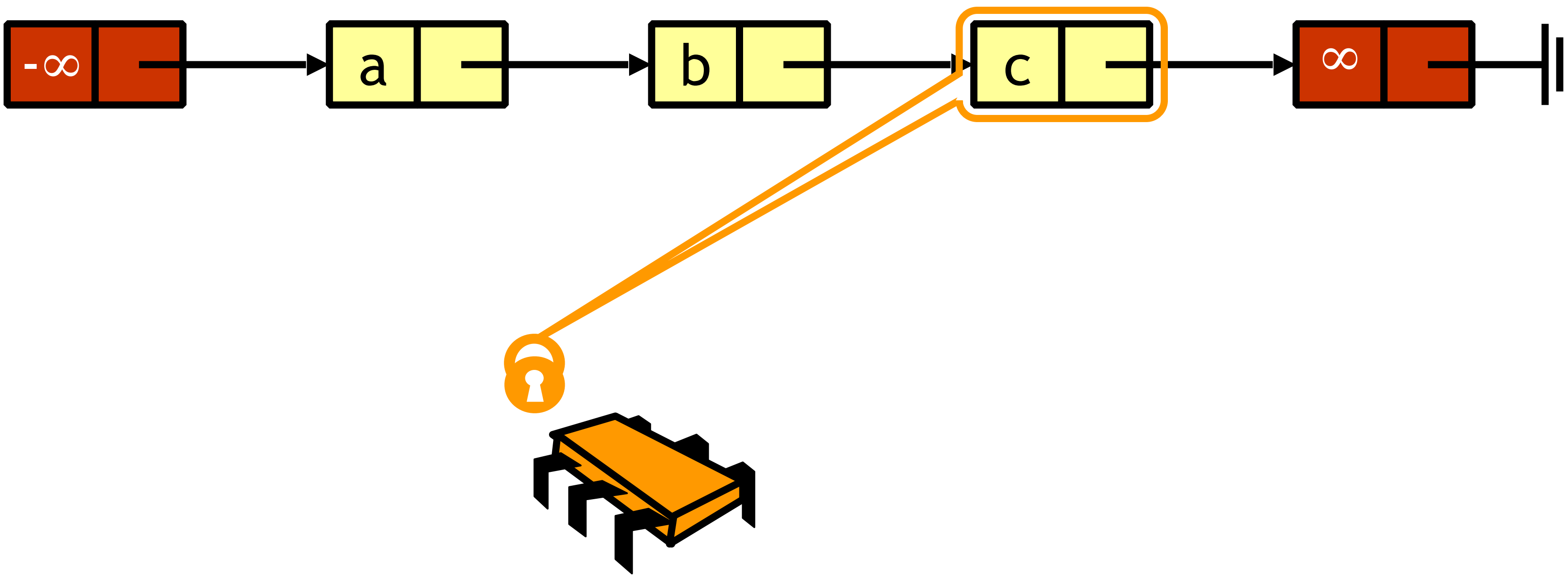

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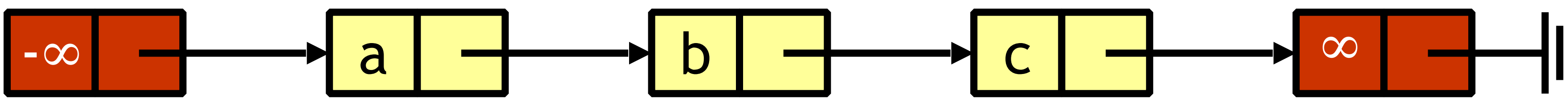

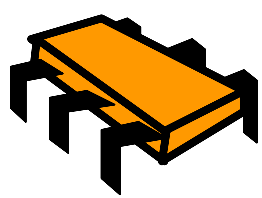

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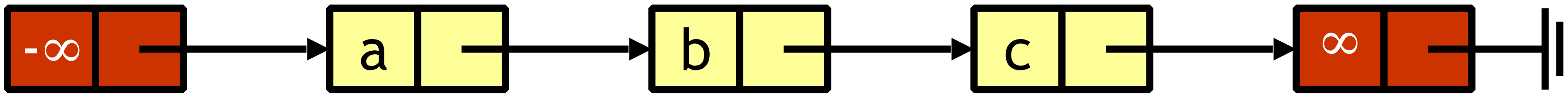

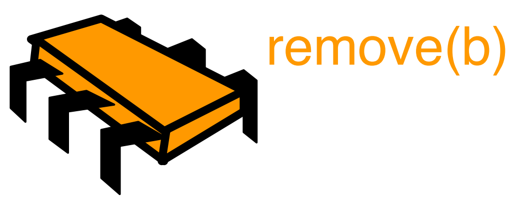

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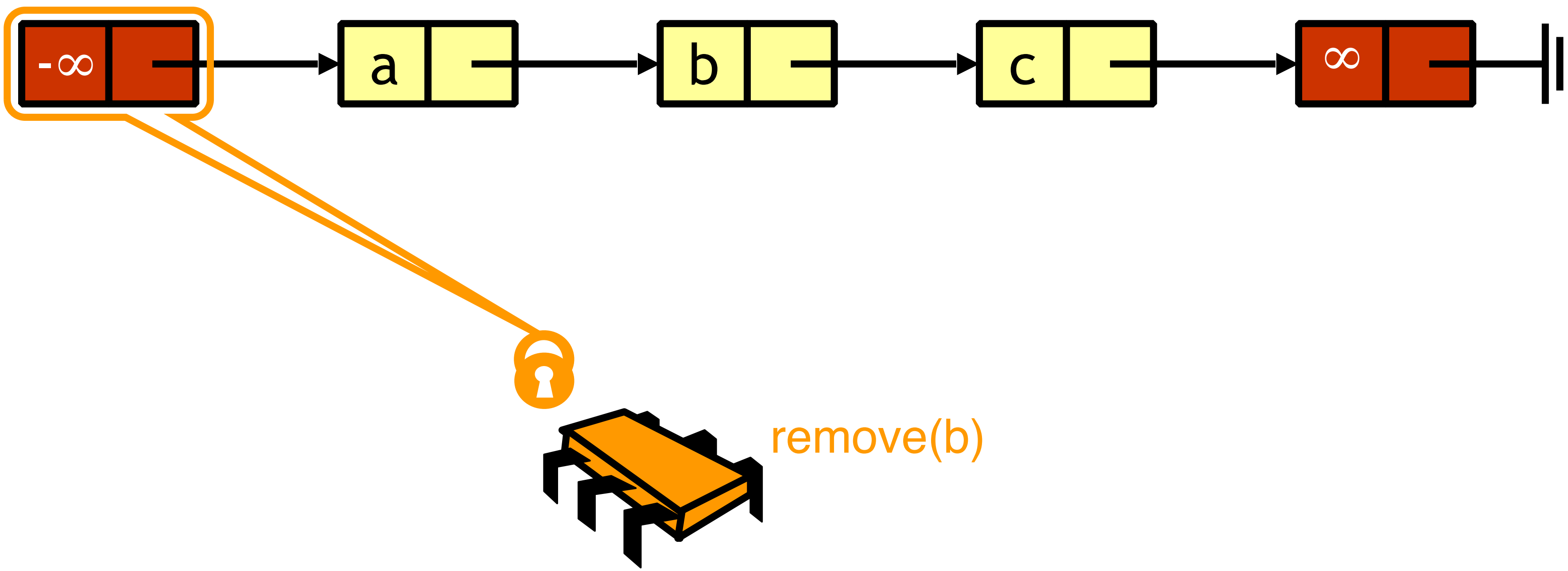

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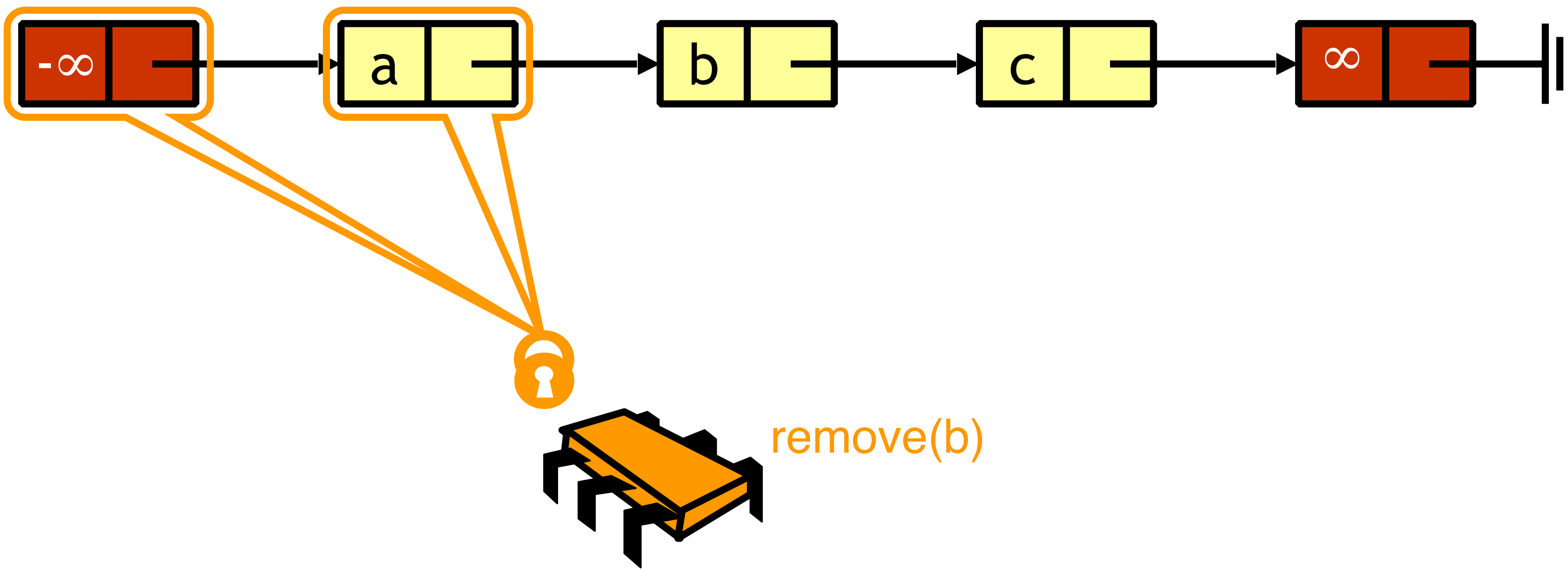

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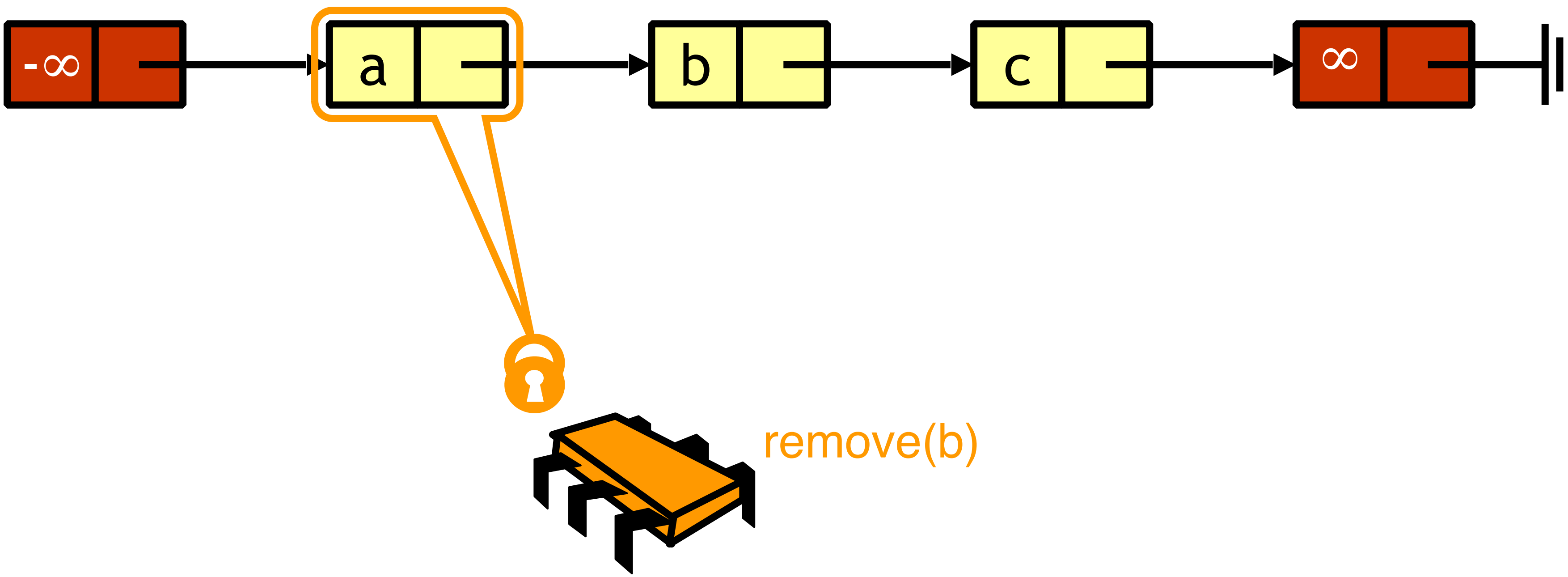

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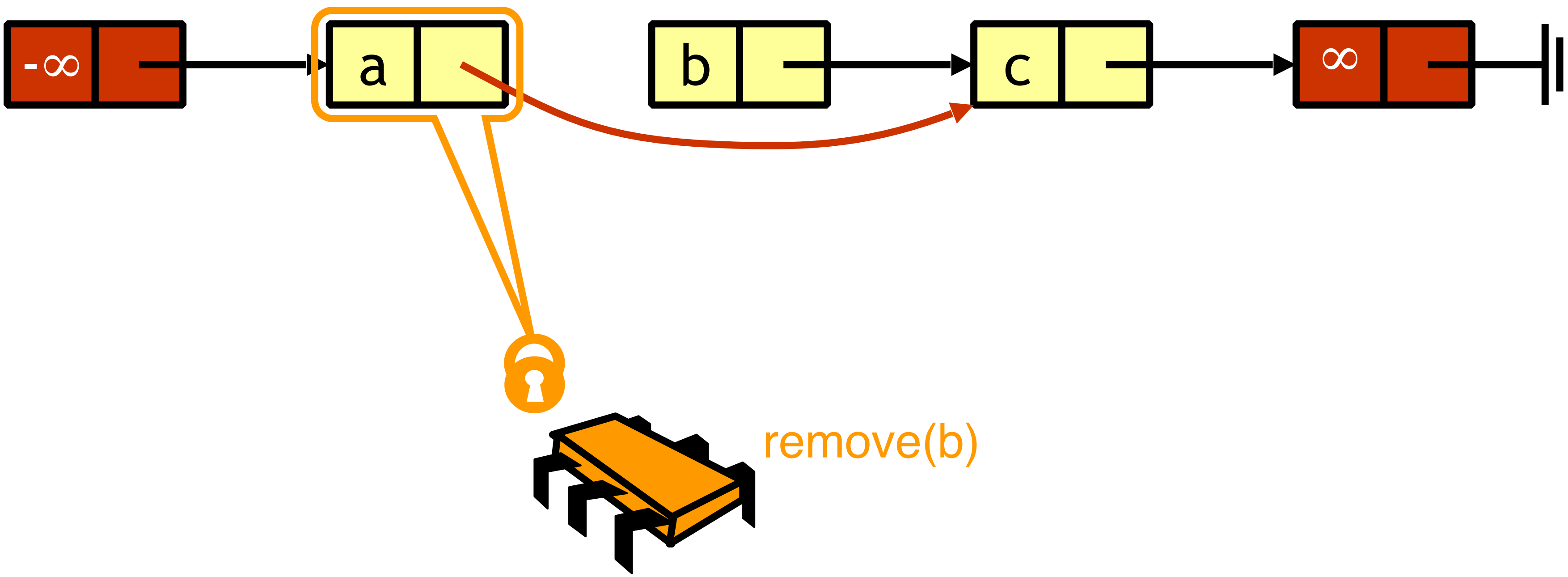

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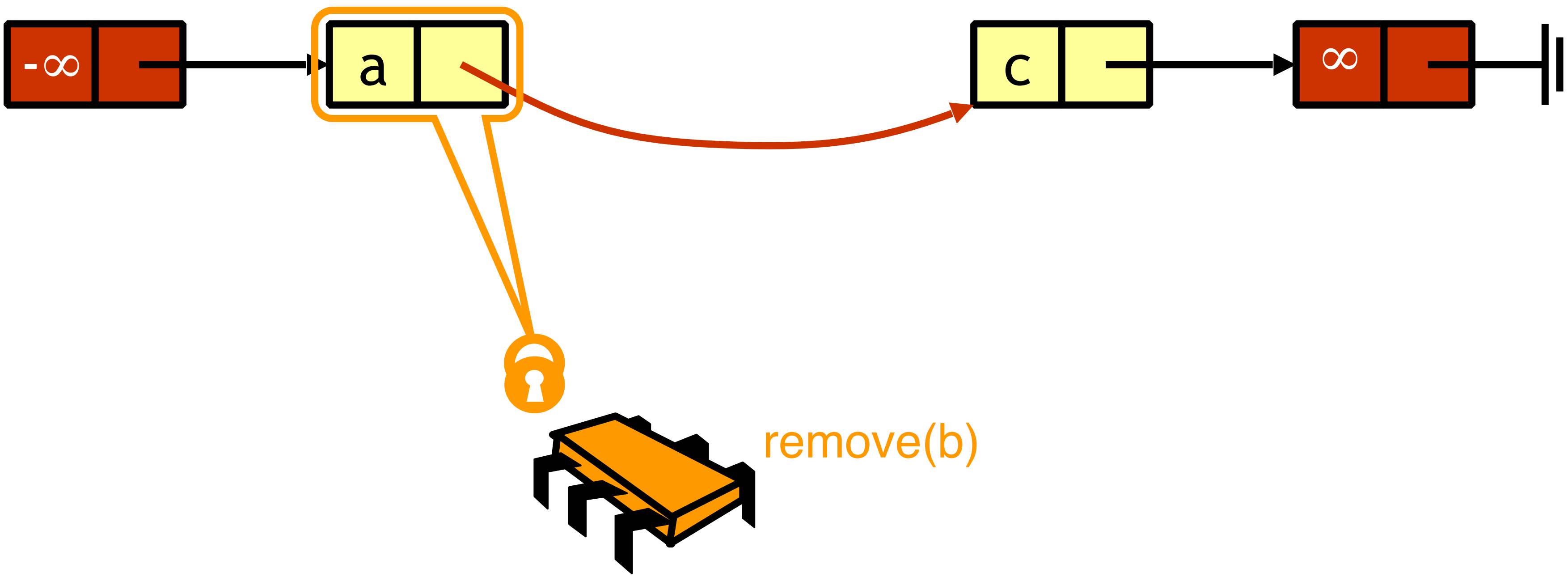

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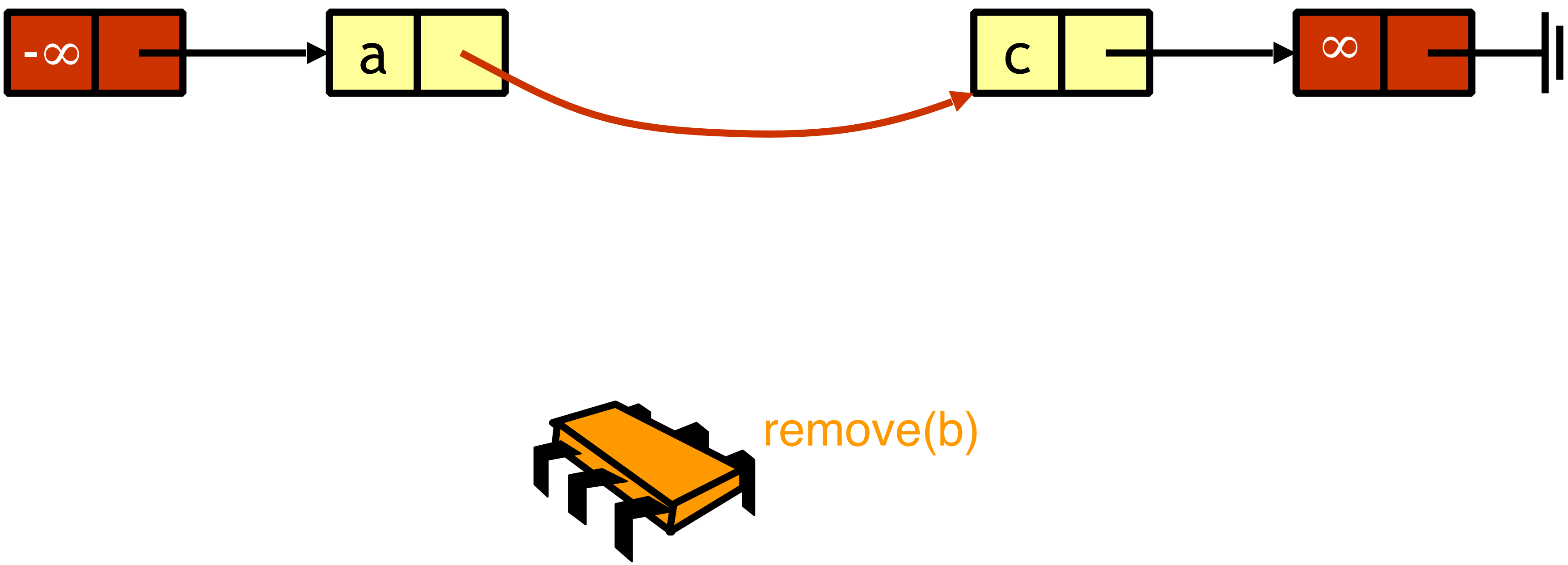

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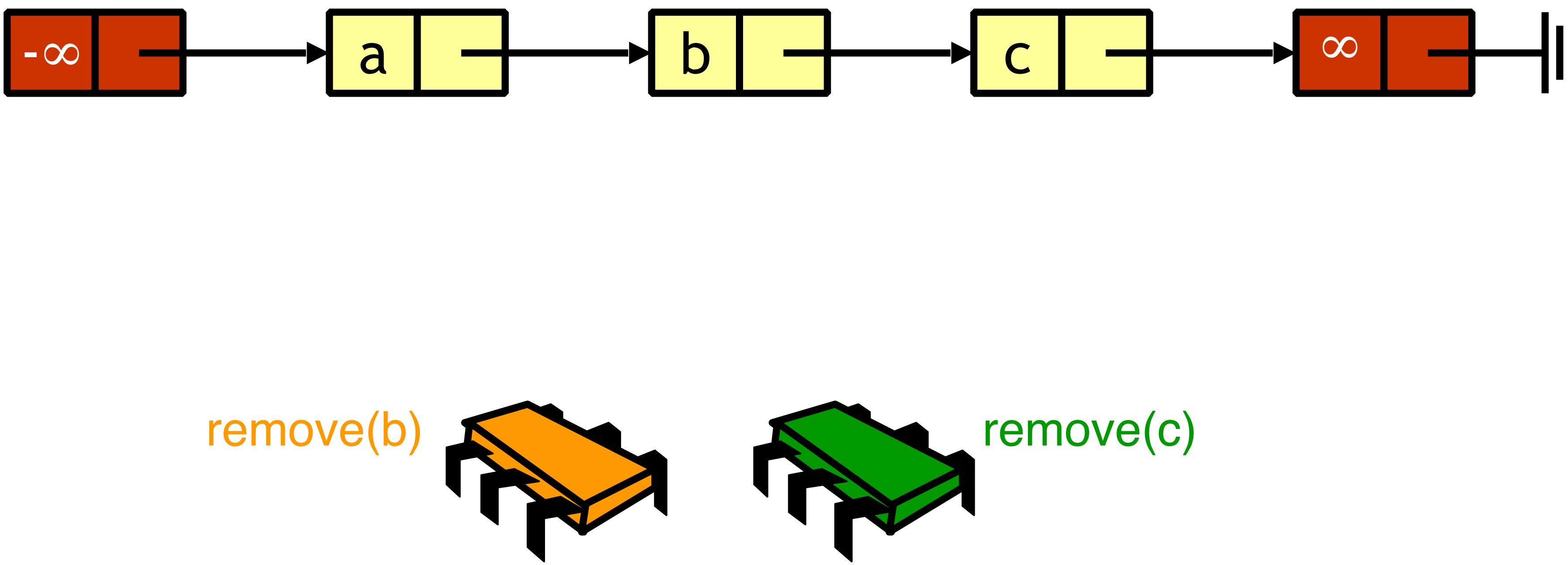

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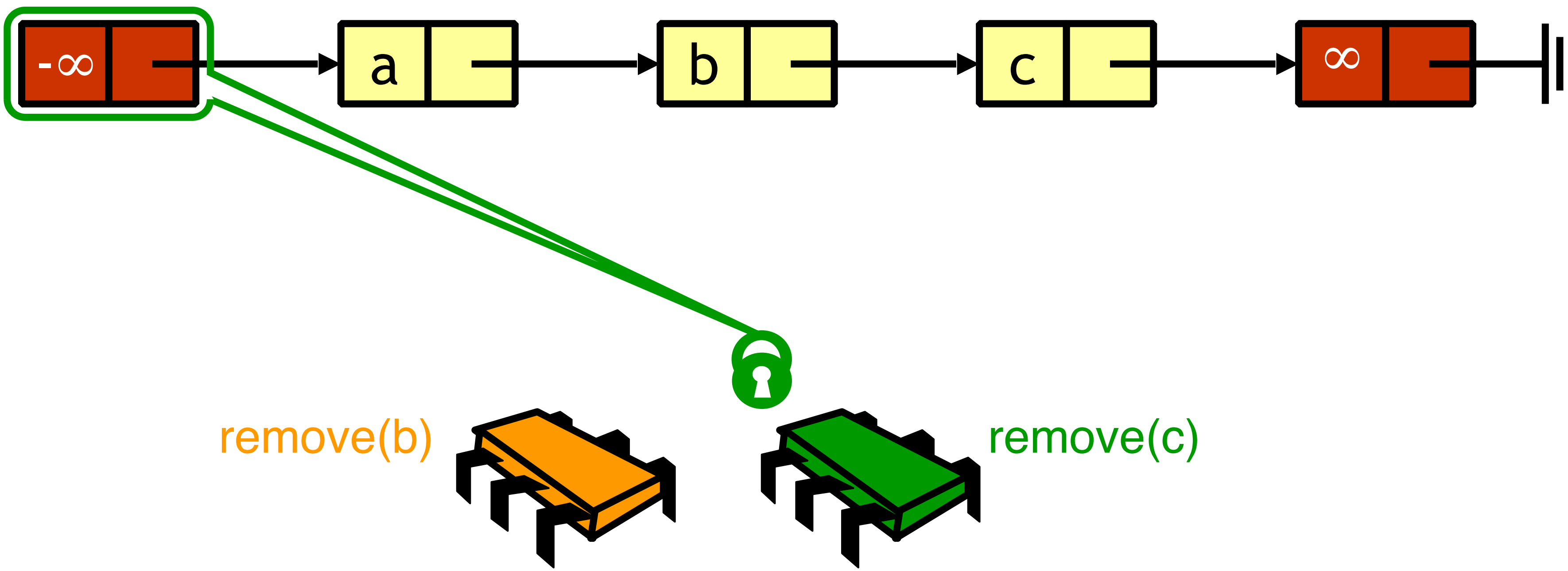

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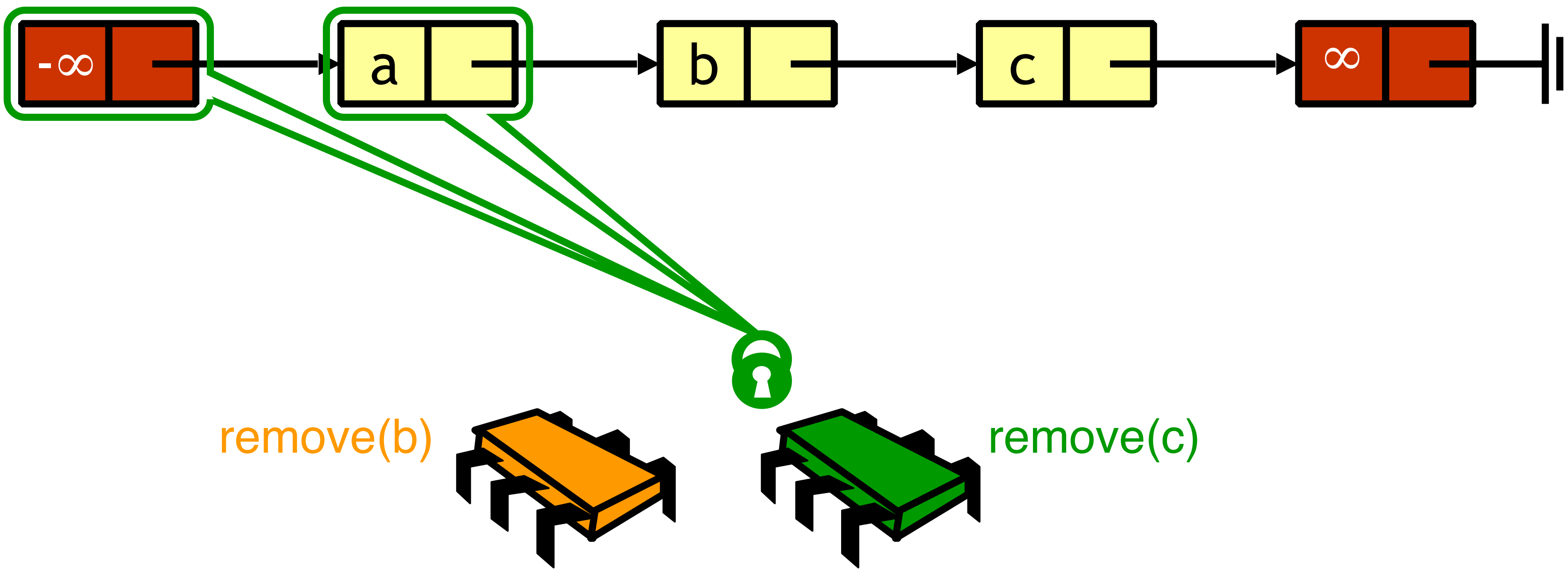

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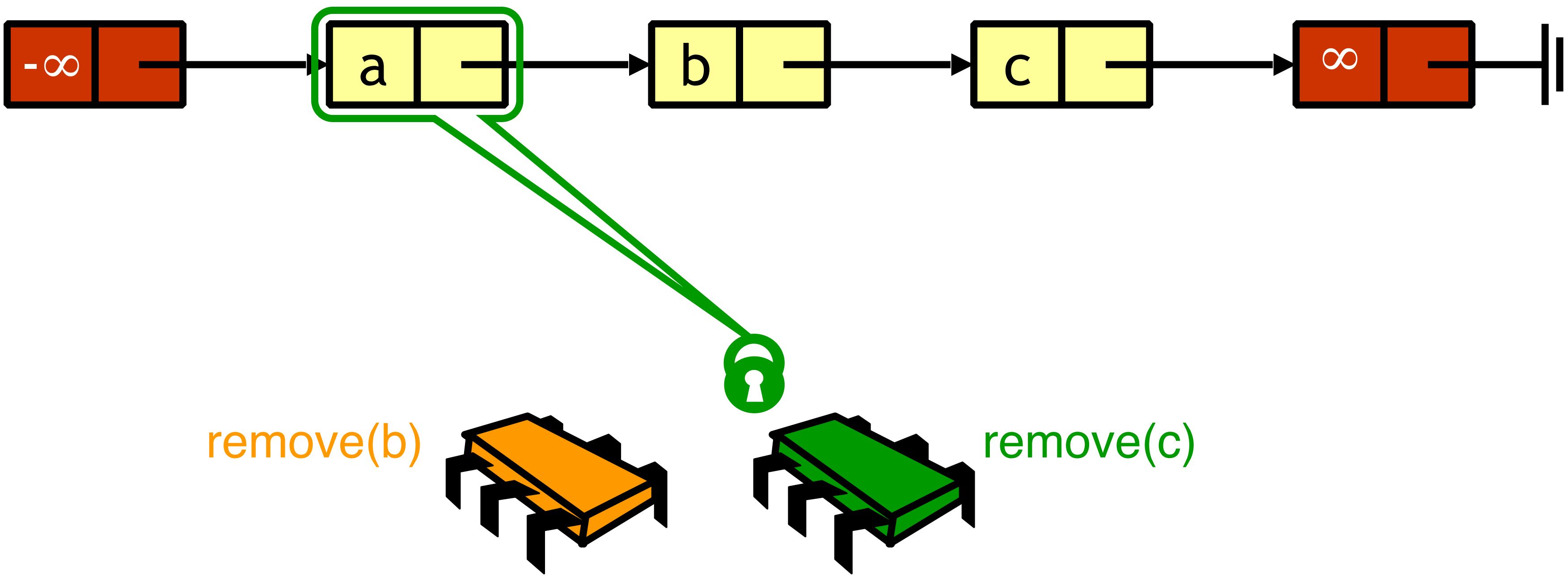

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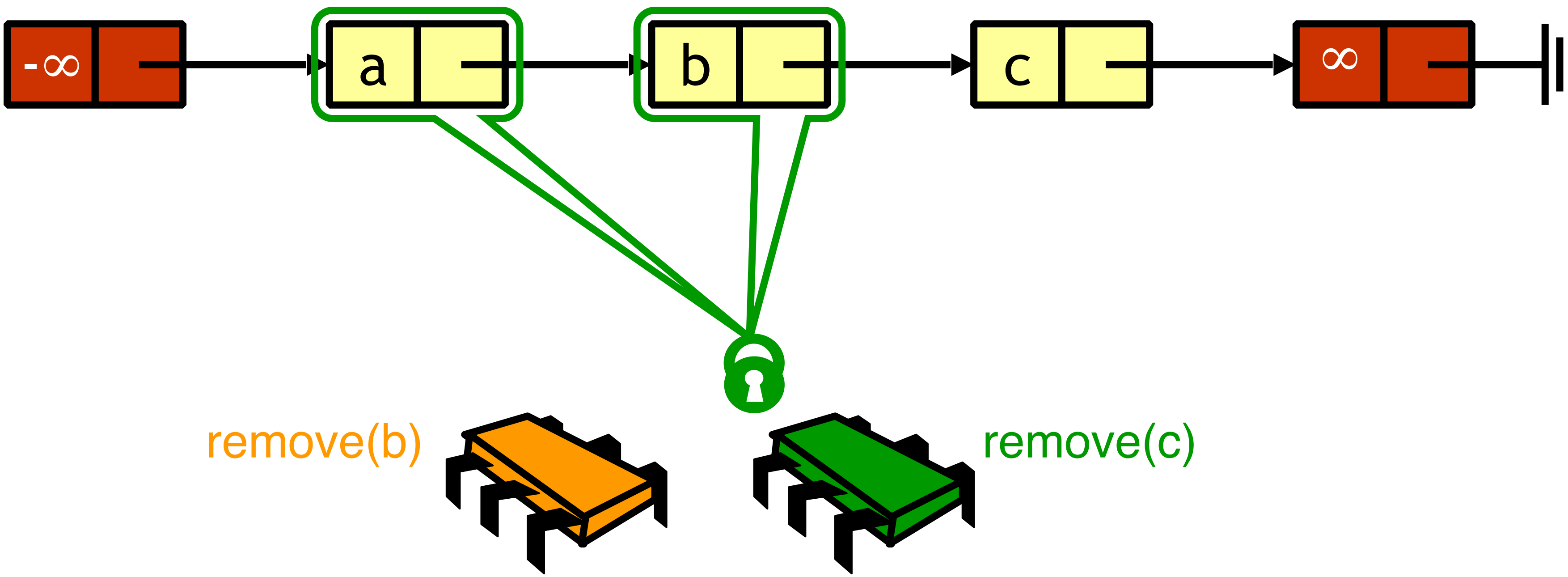

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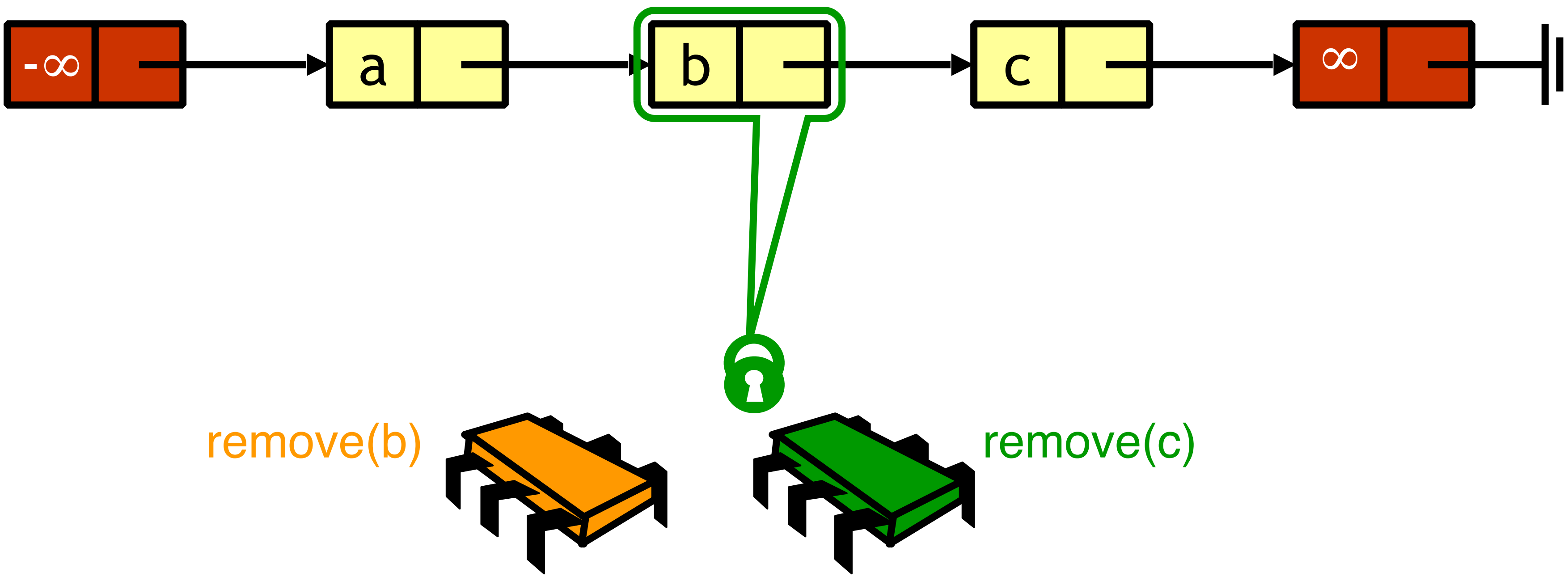

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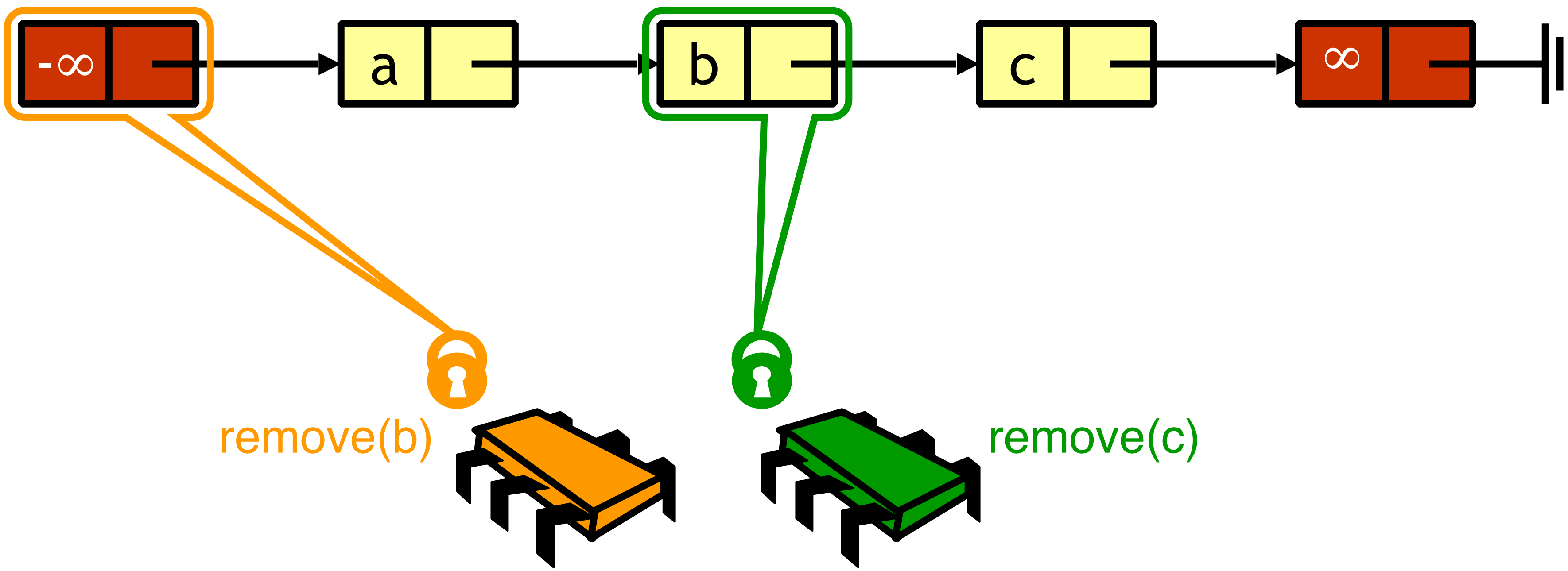

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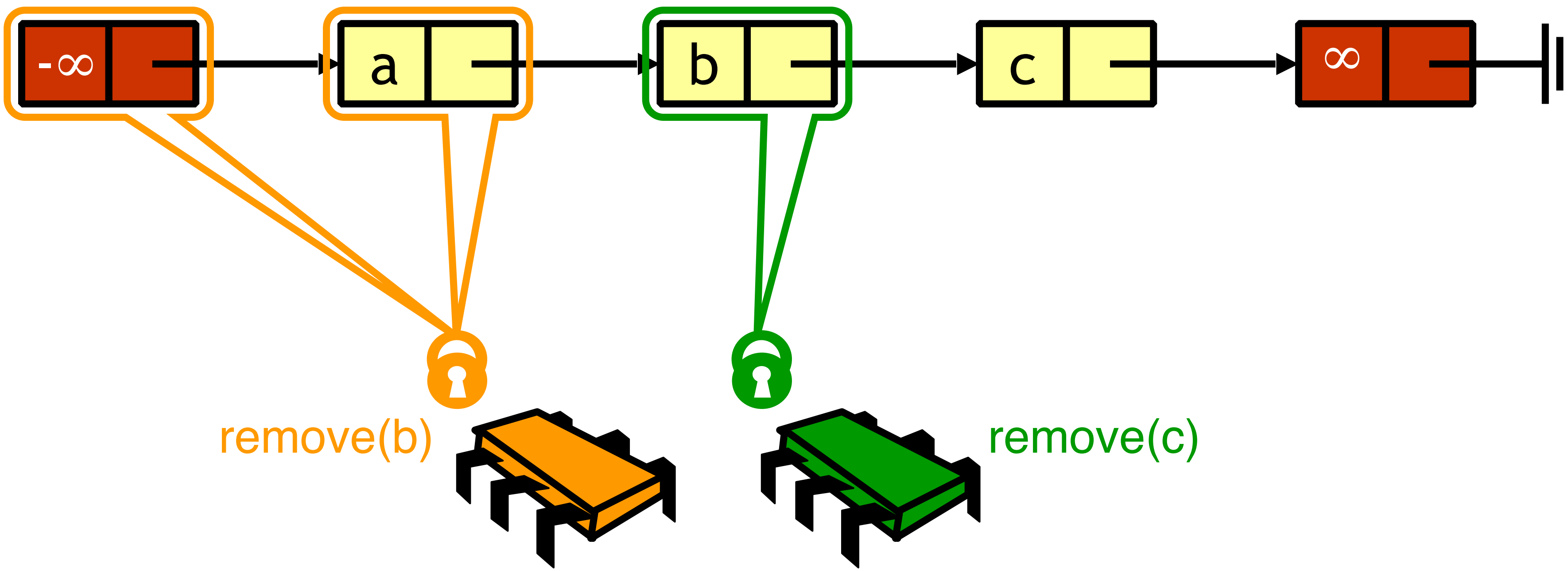

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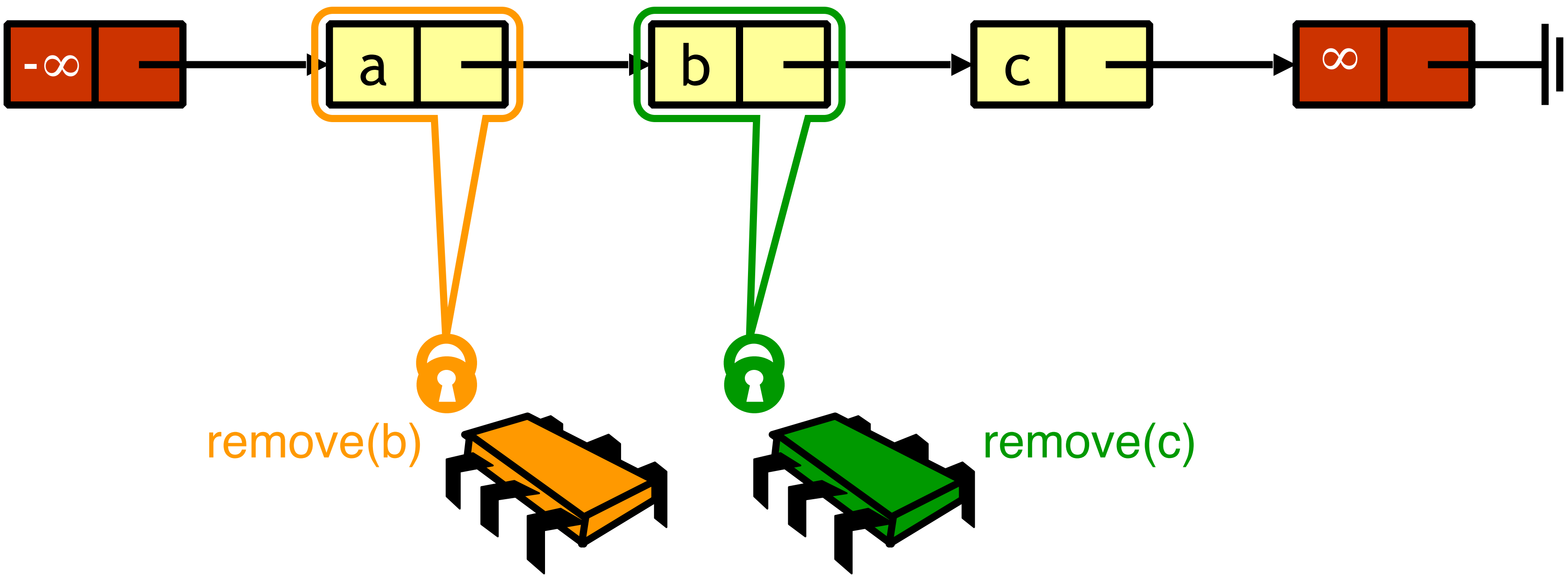

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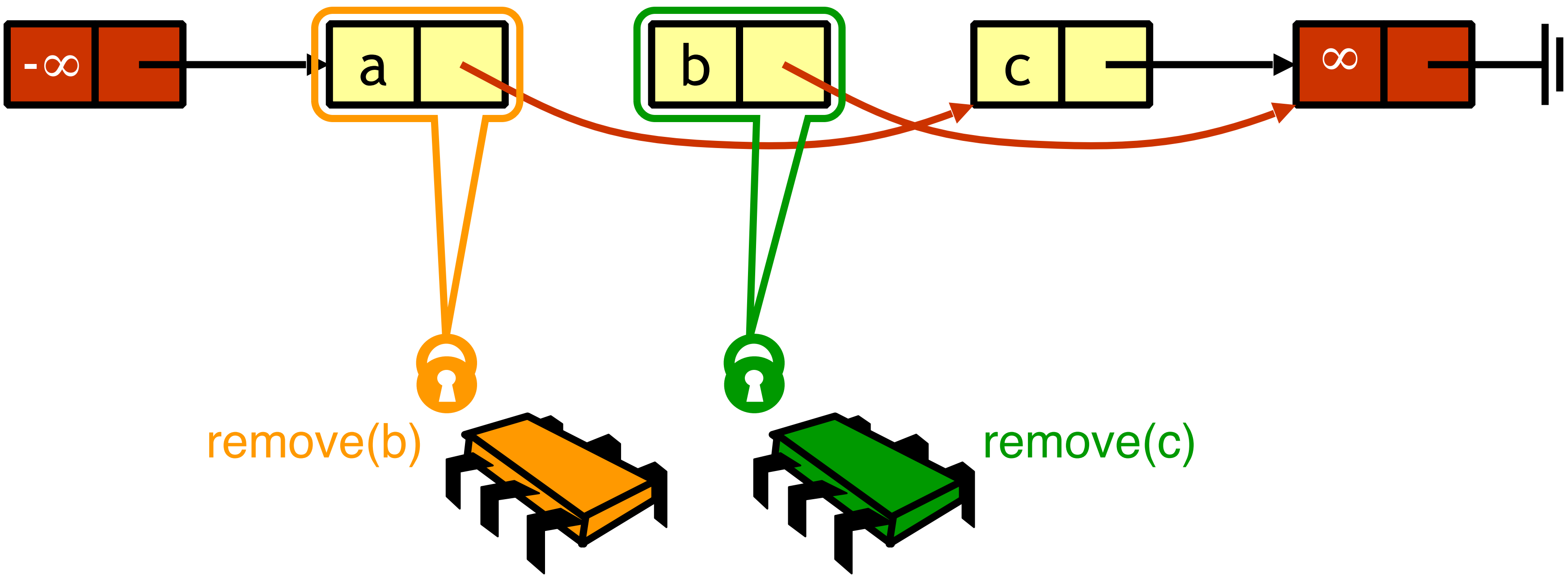

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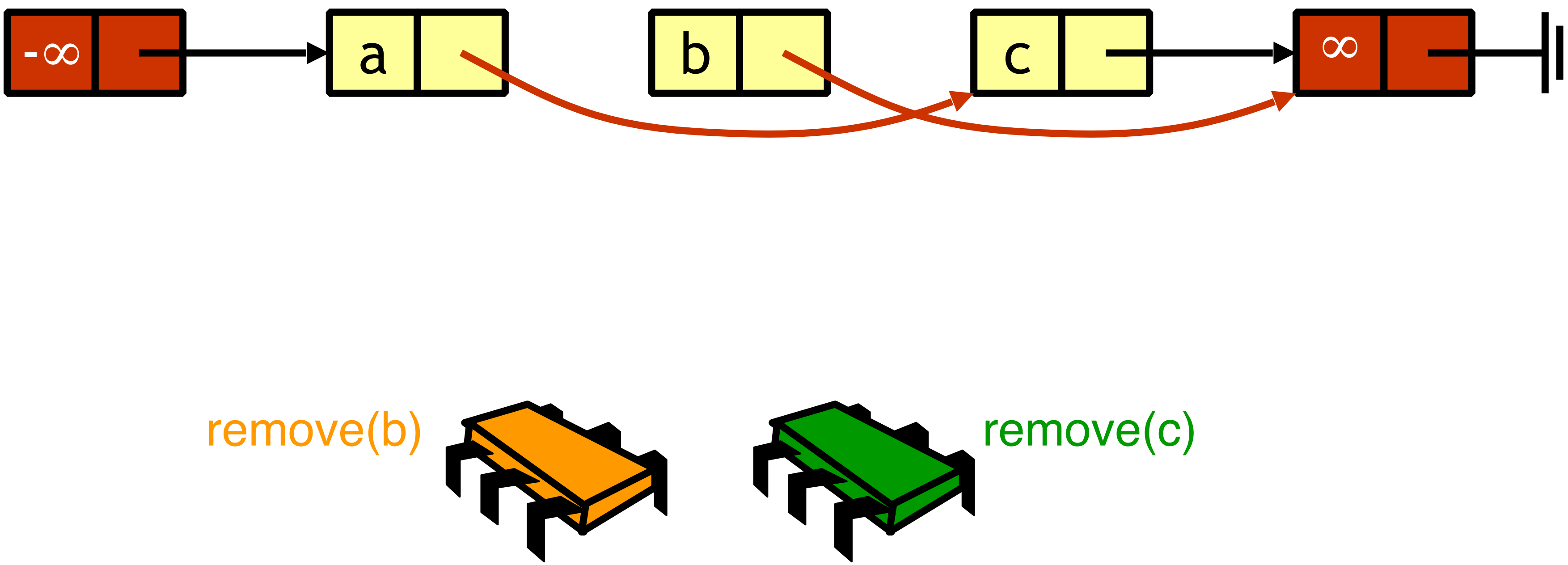

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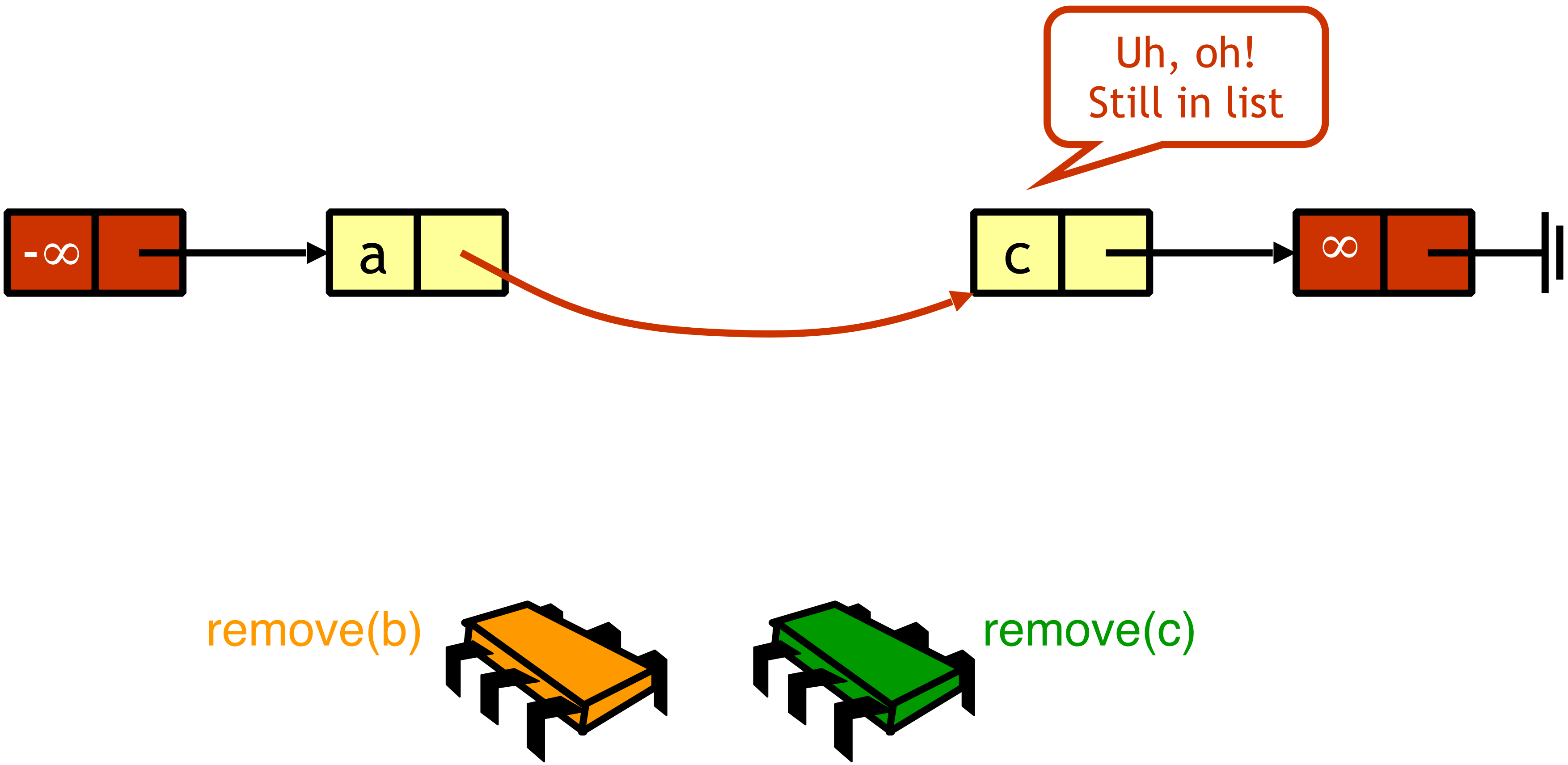
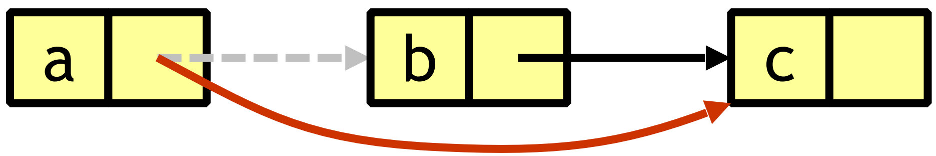
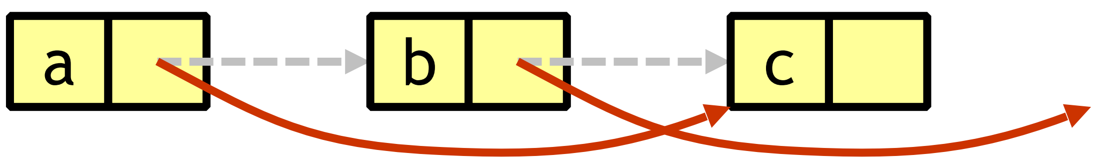


Problem

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



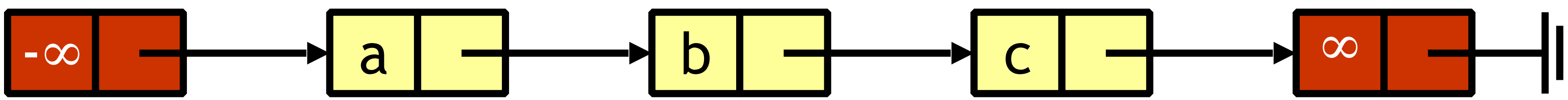
- Problem is
  - Someone could delete c concurrently

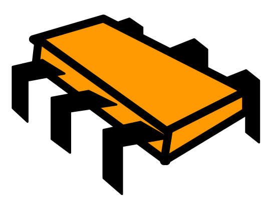


Insight

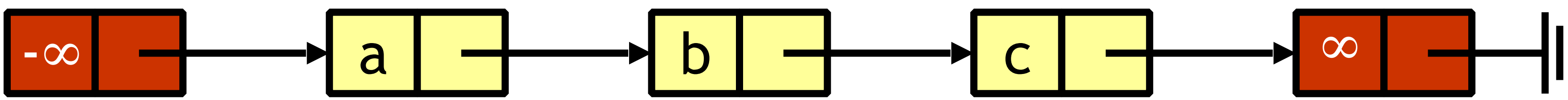
- If a node is locked
  - No one can delete node’s successor
- If a thread locks
  - The node to be deleted
  - And its predecessor
  - Then it works

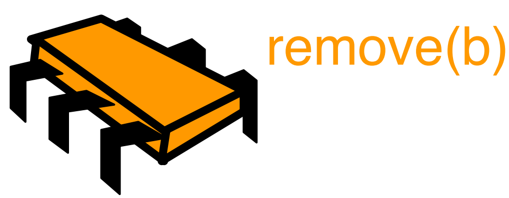
Hand-over-Hand Again





Hand-over-Hand Again





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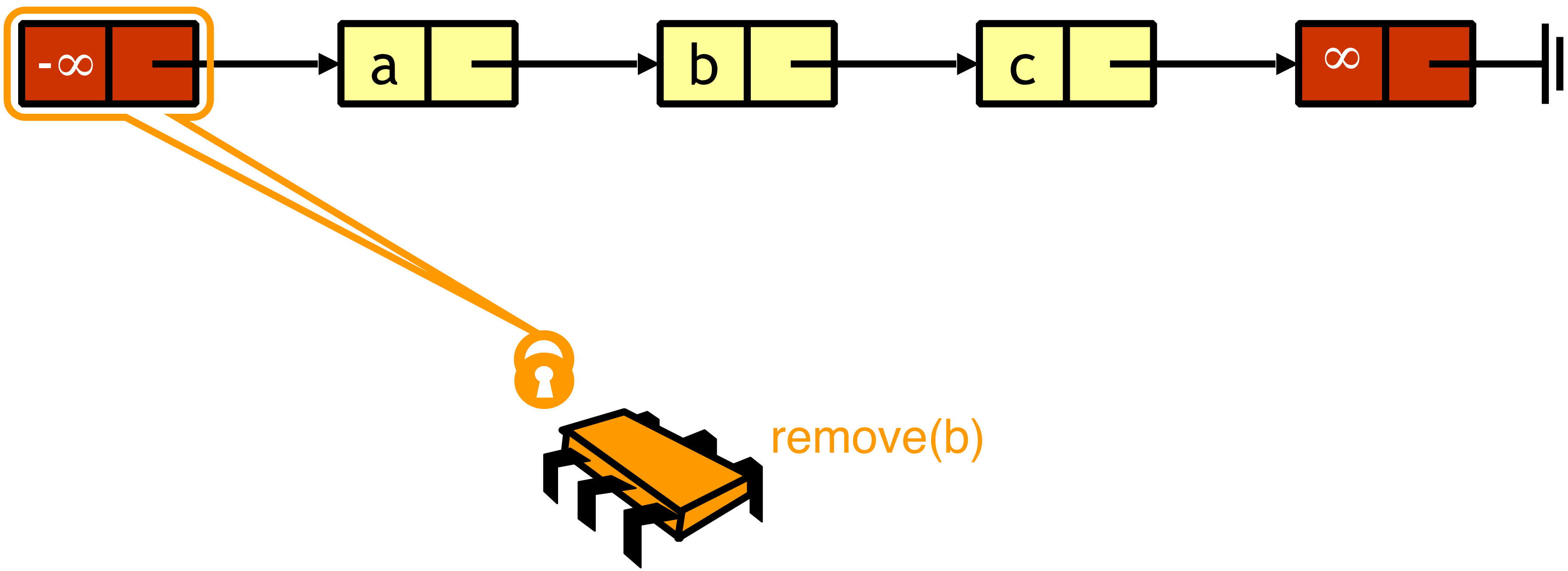

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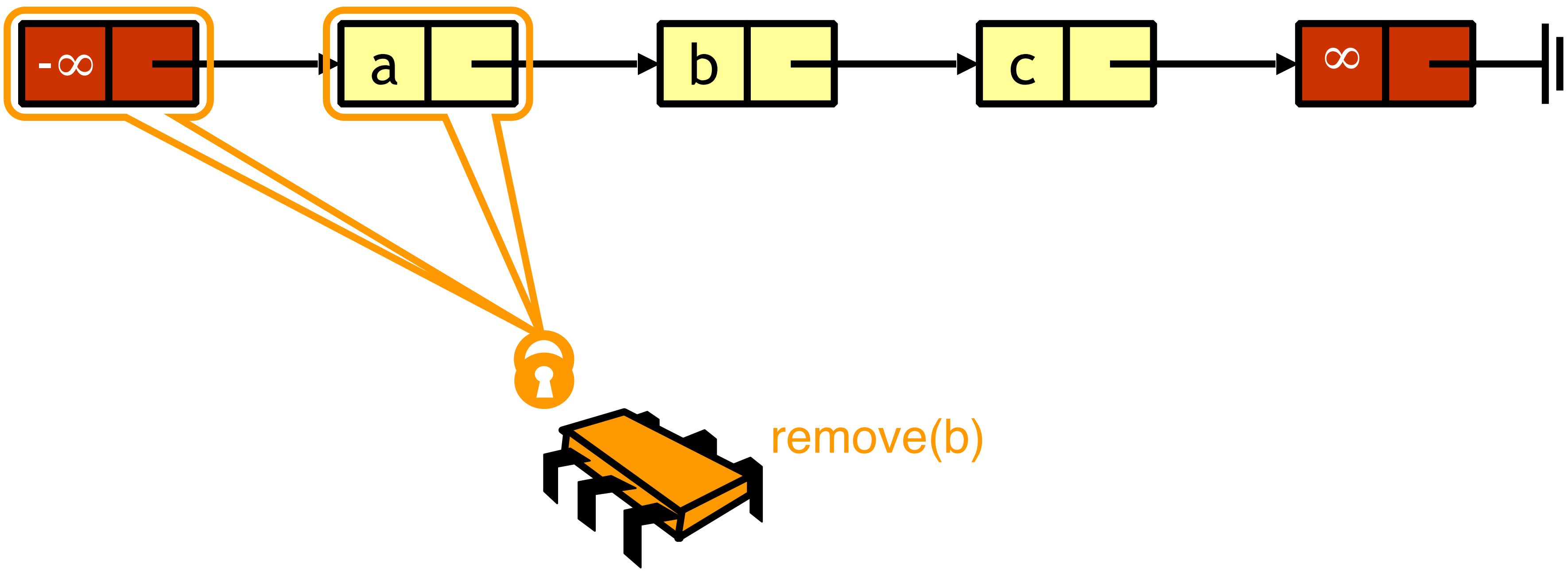

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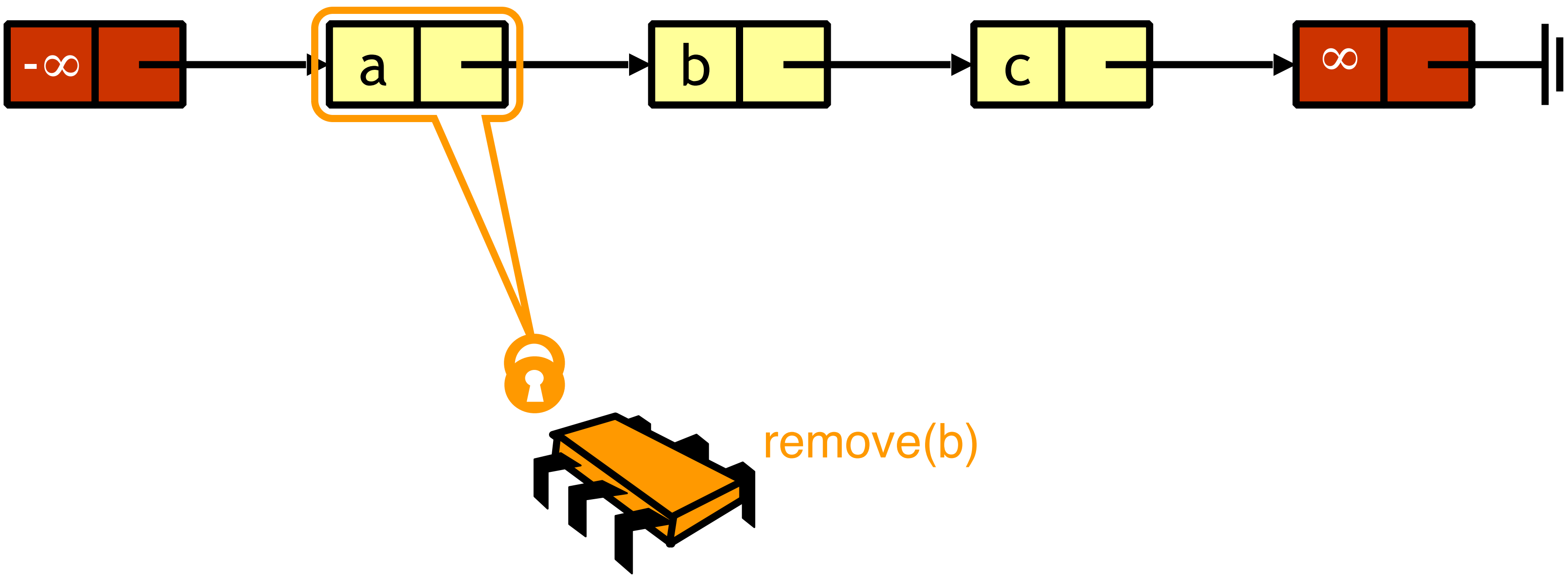

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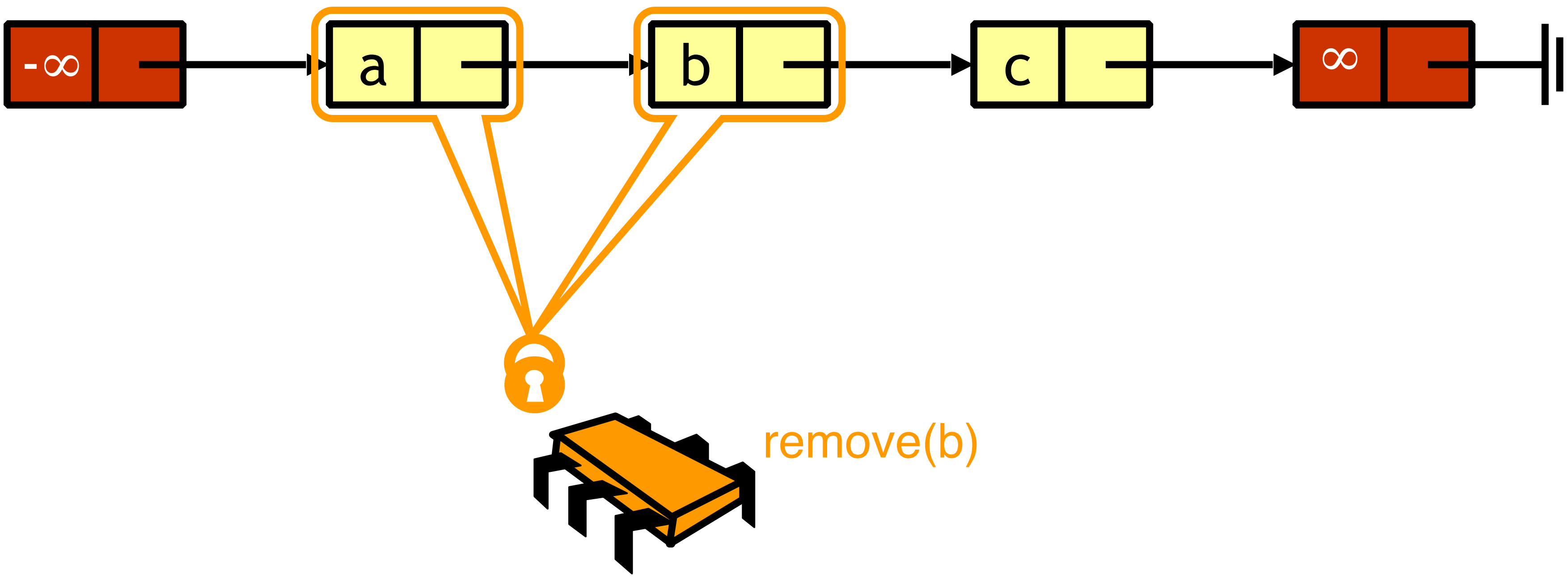

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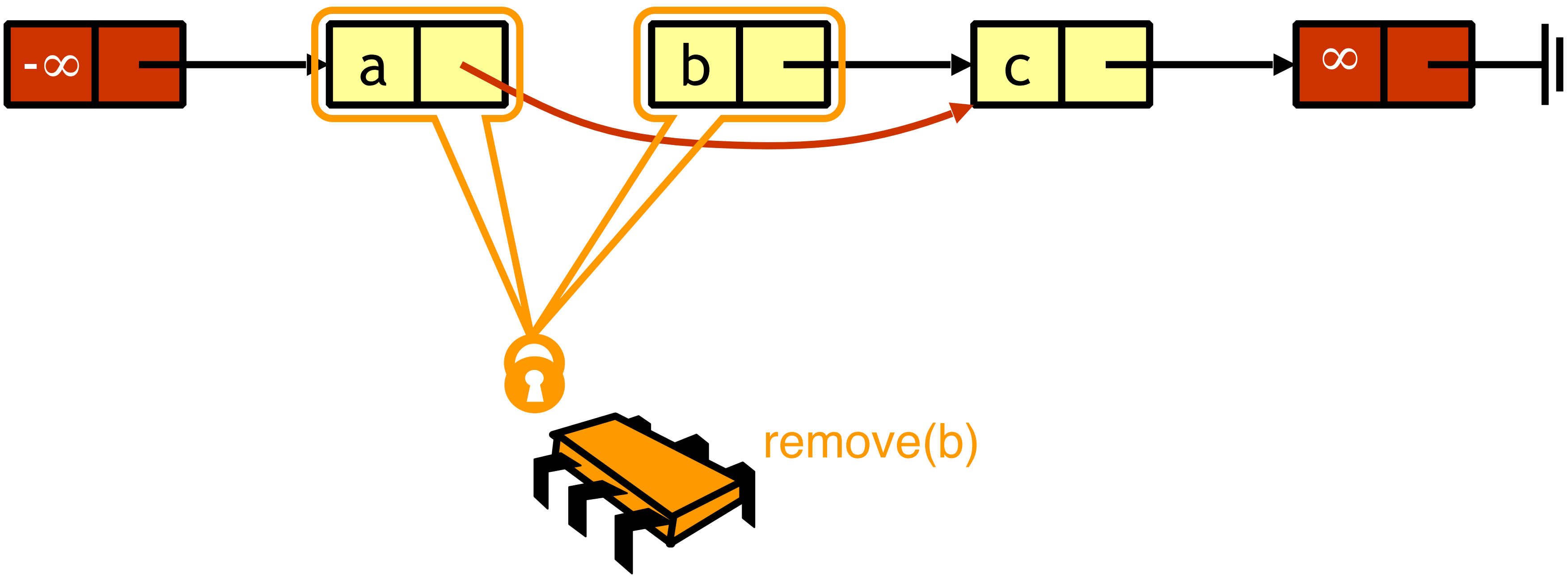

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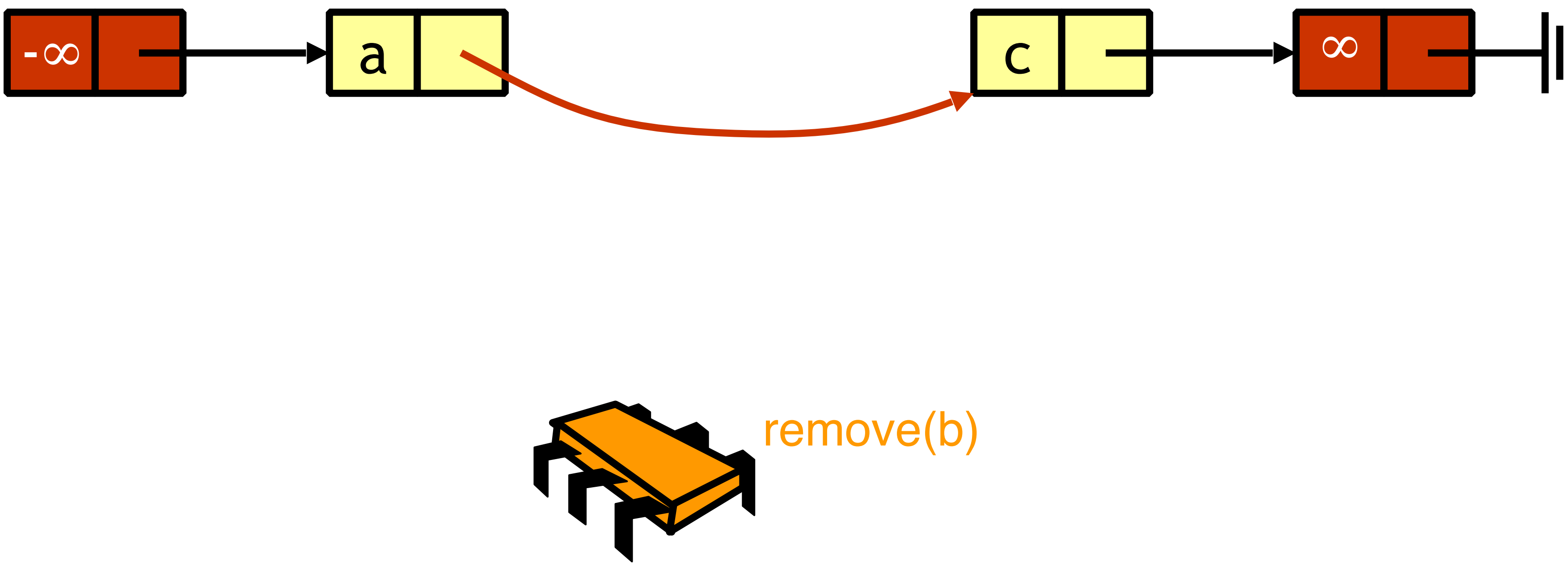

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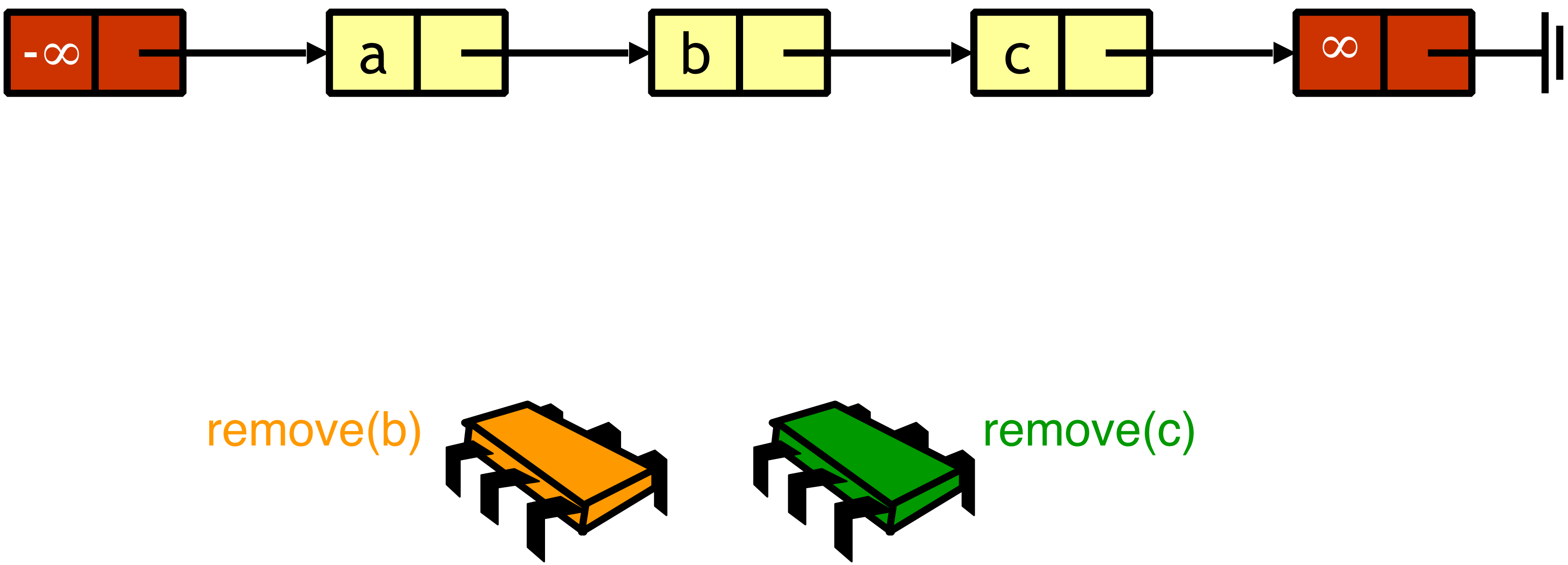

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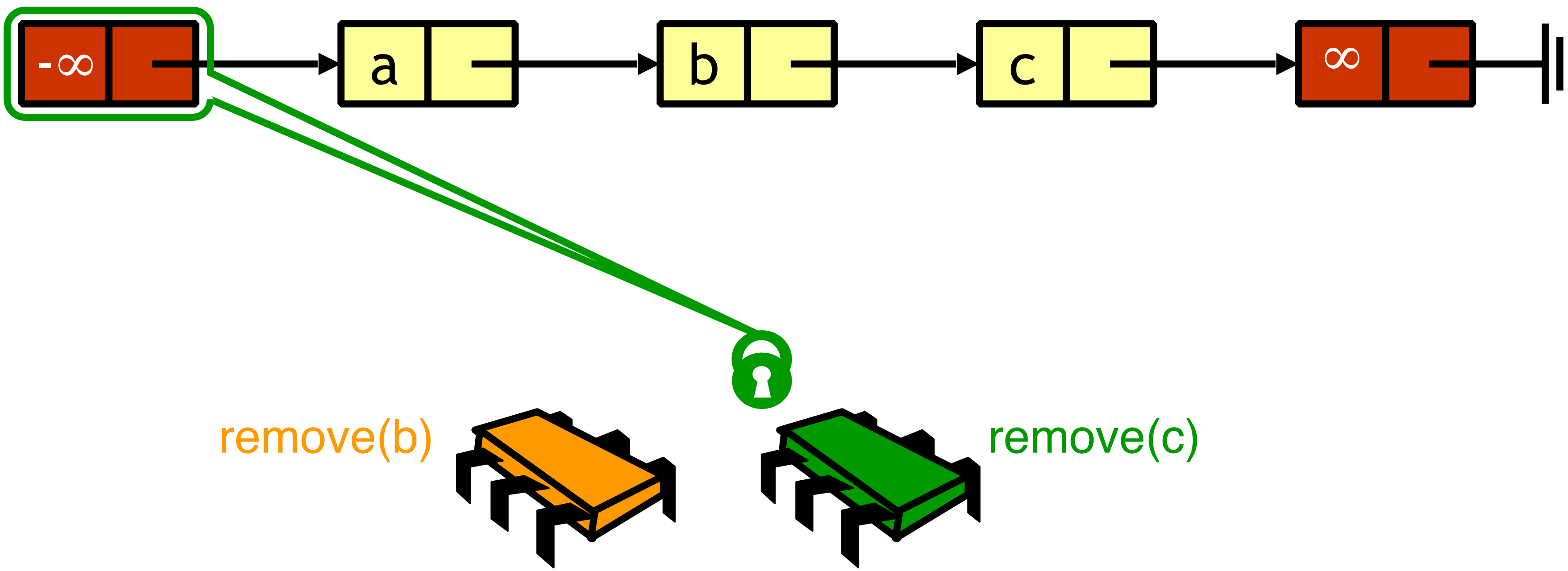

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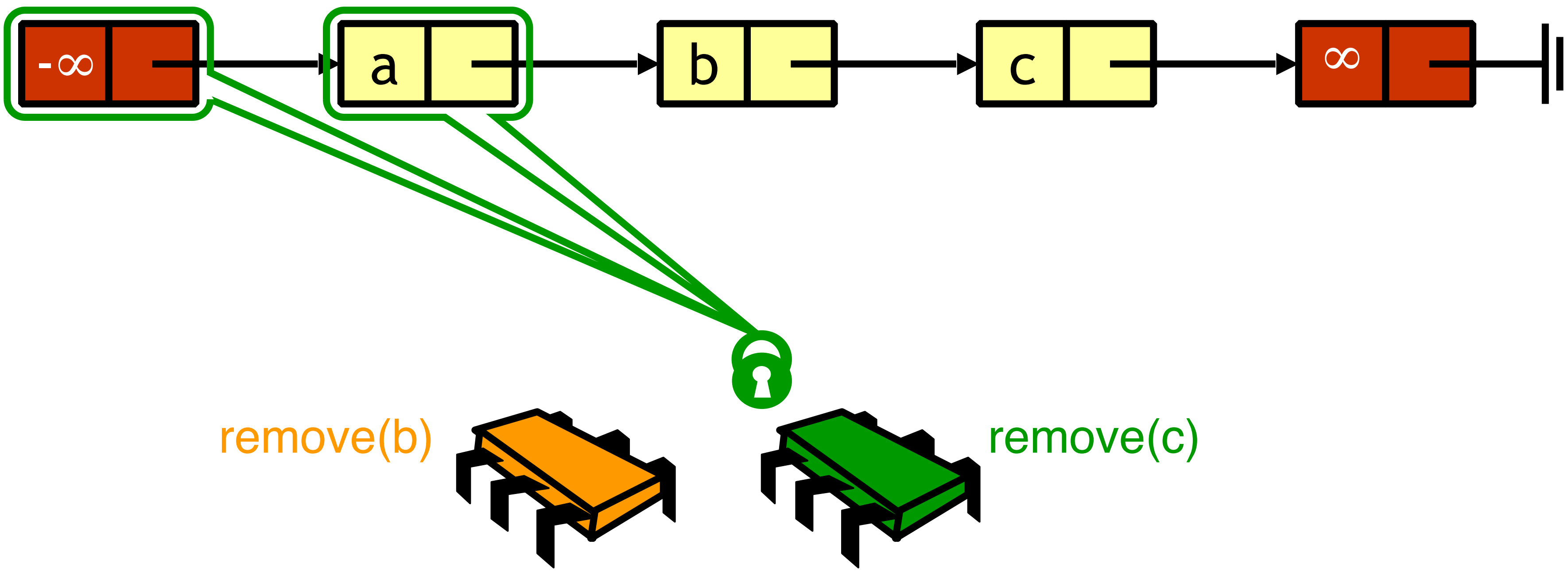

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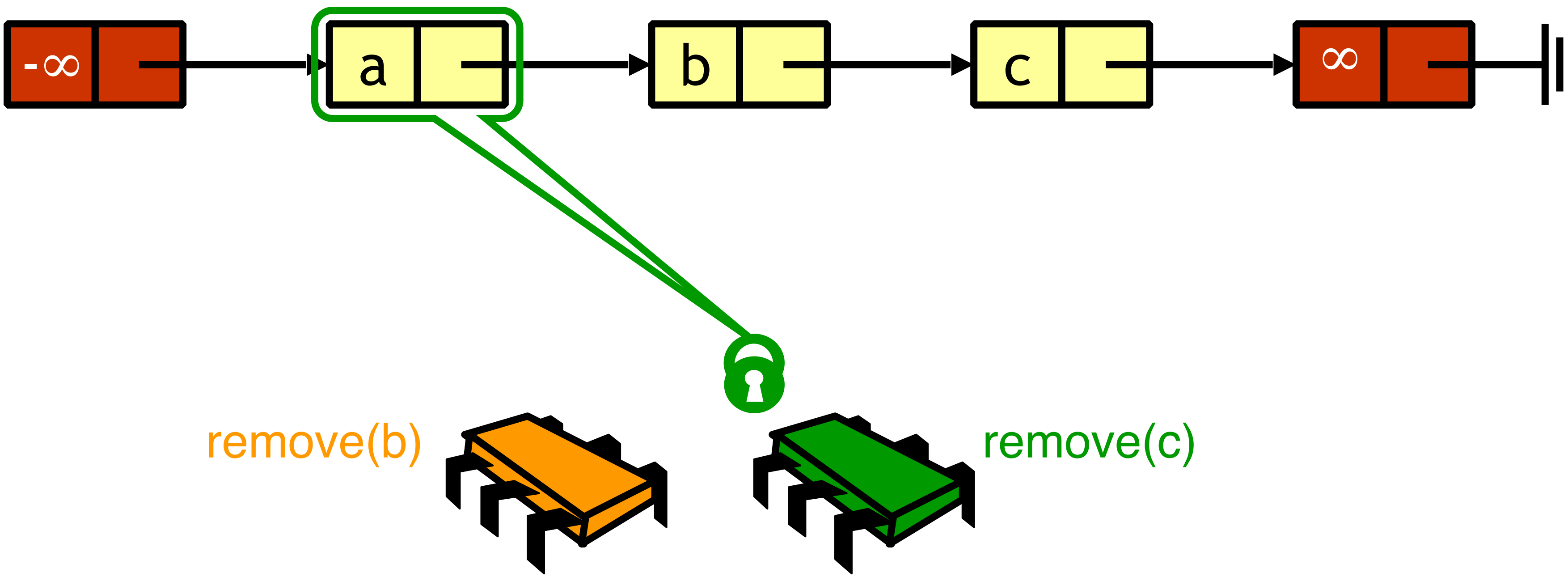

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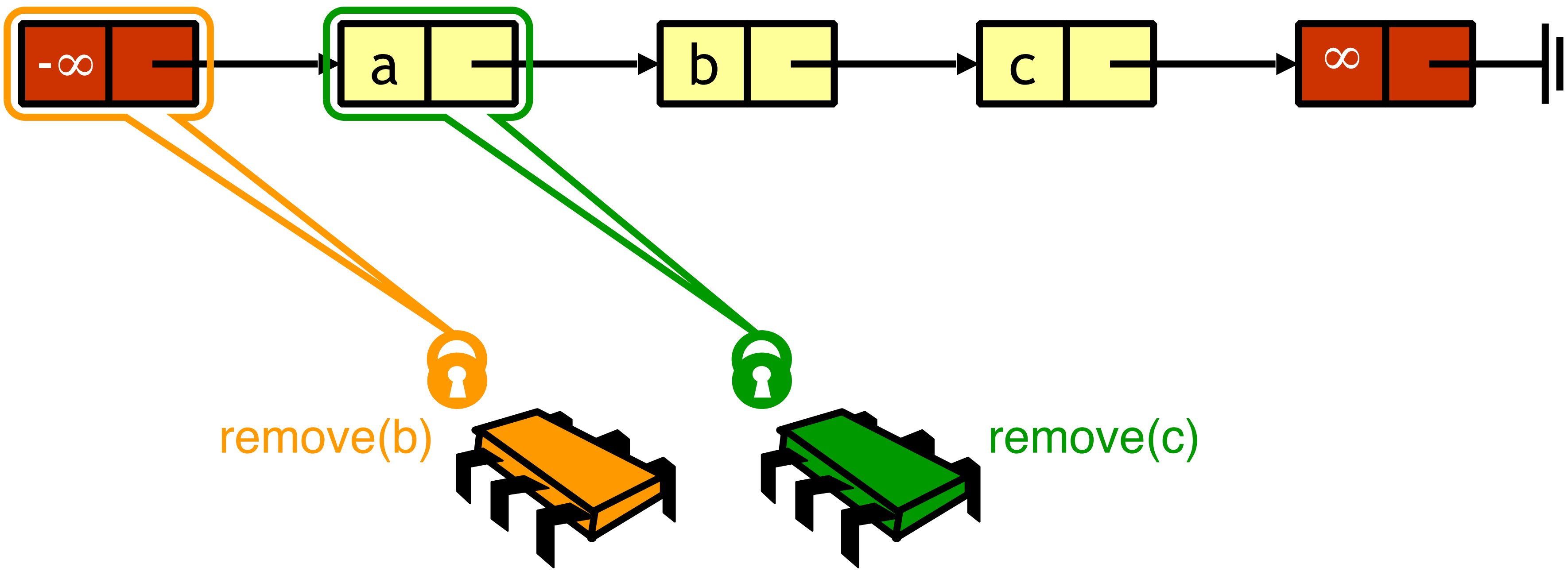

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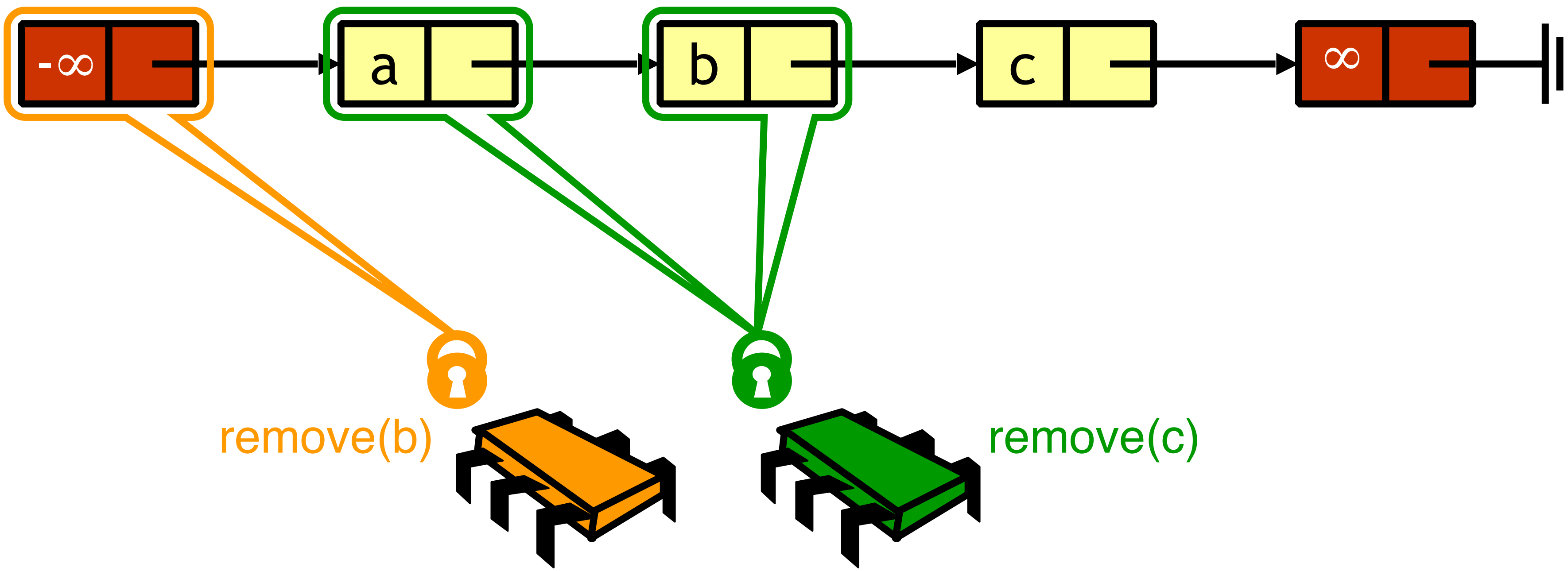

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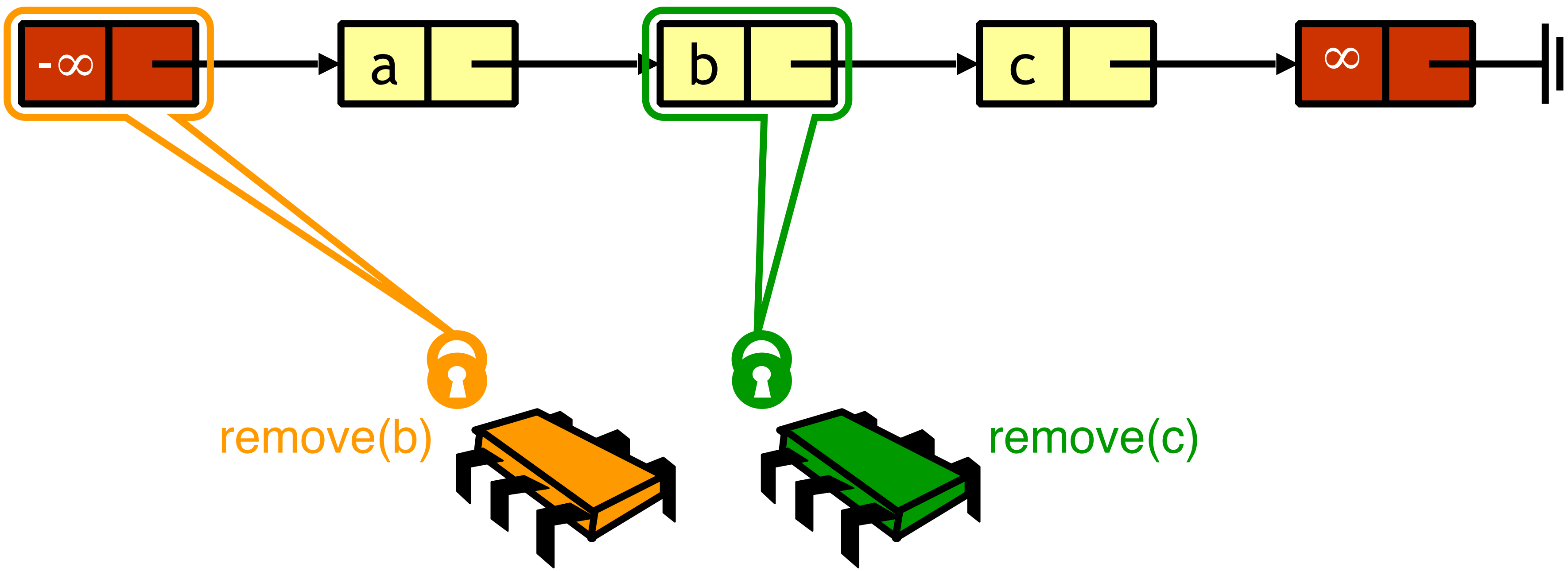

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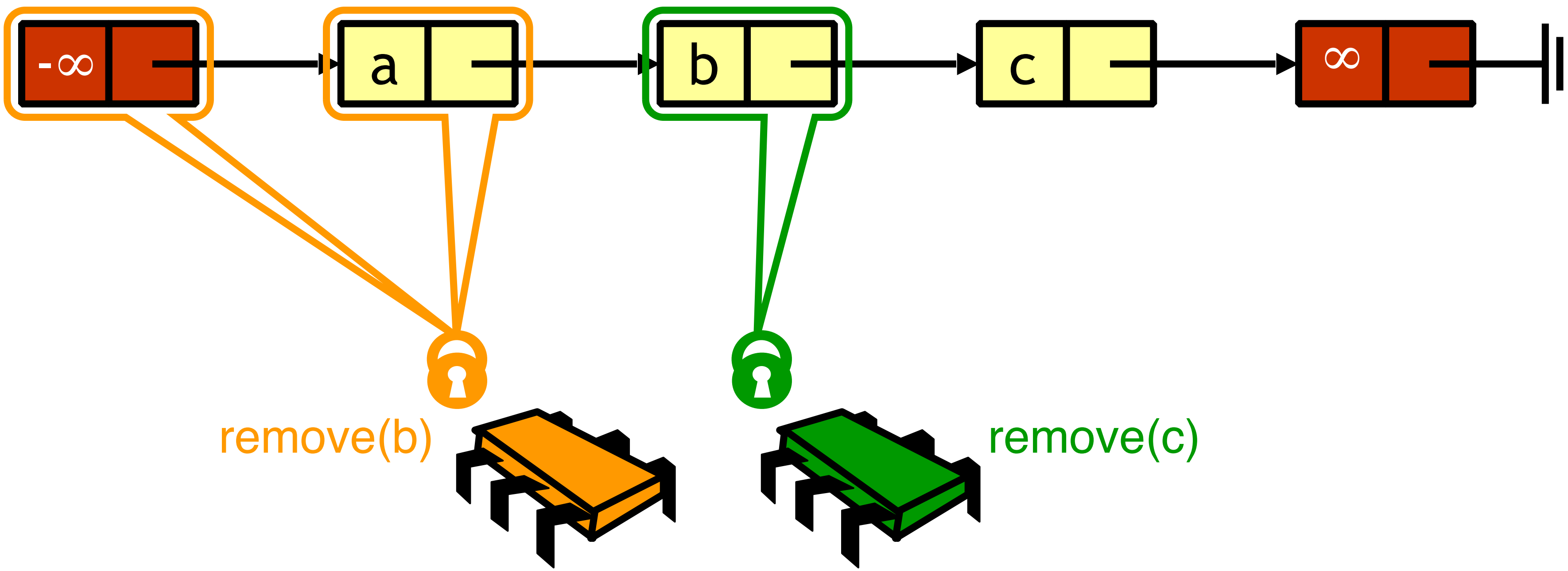

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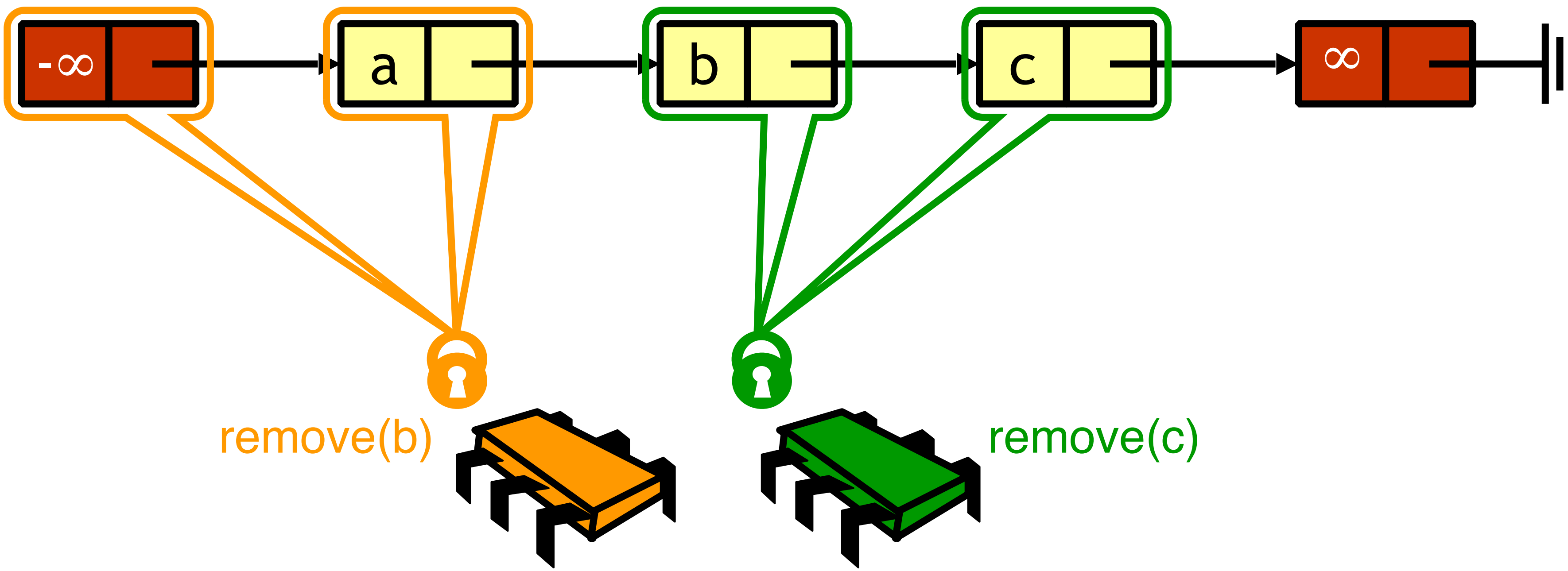

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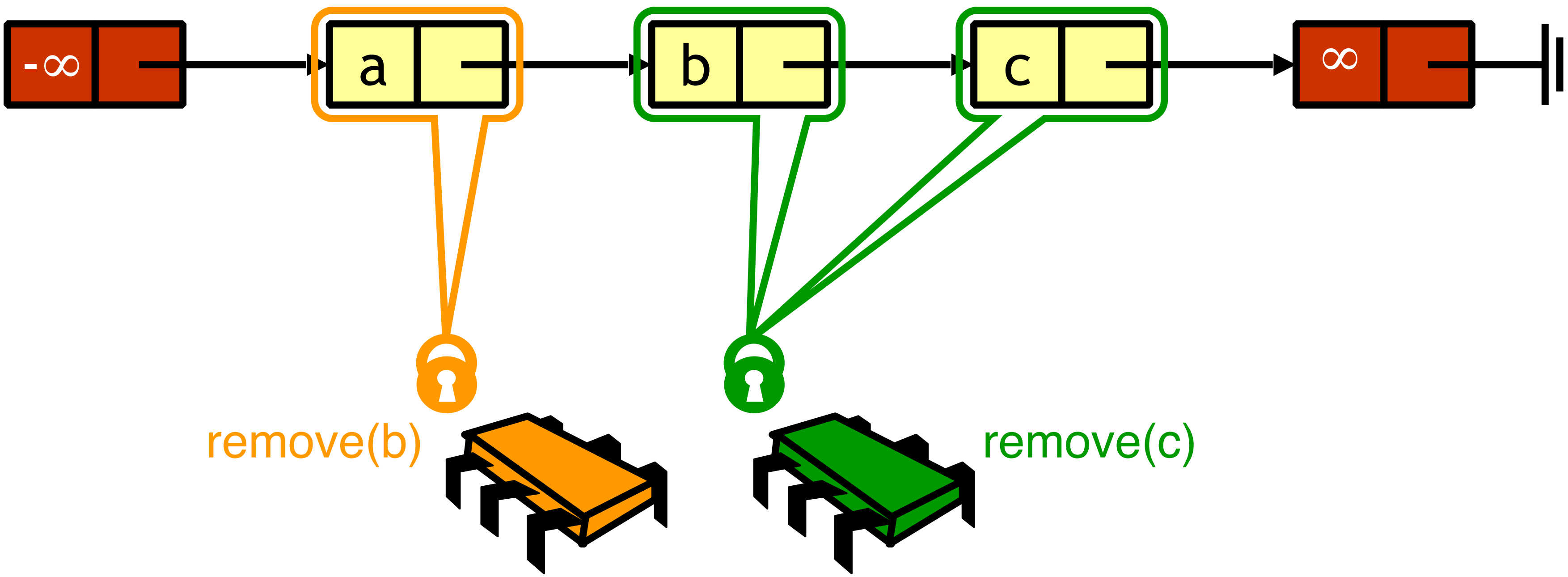

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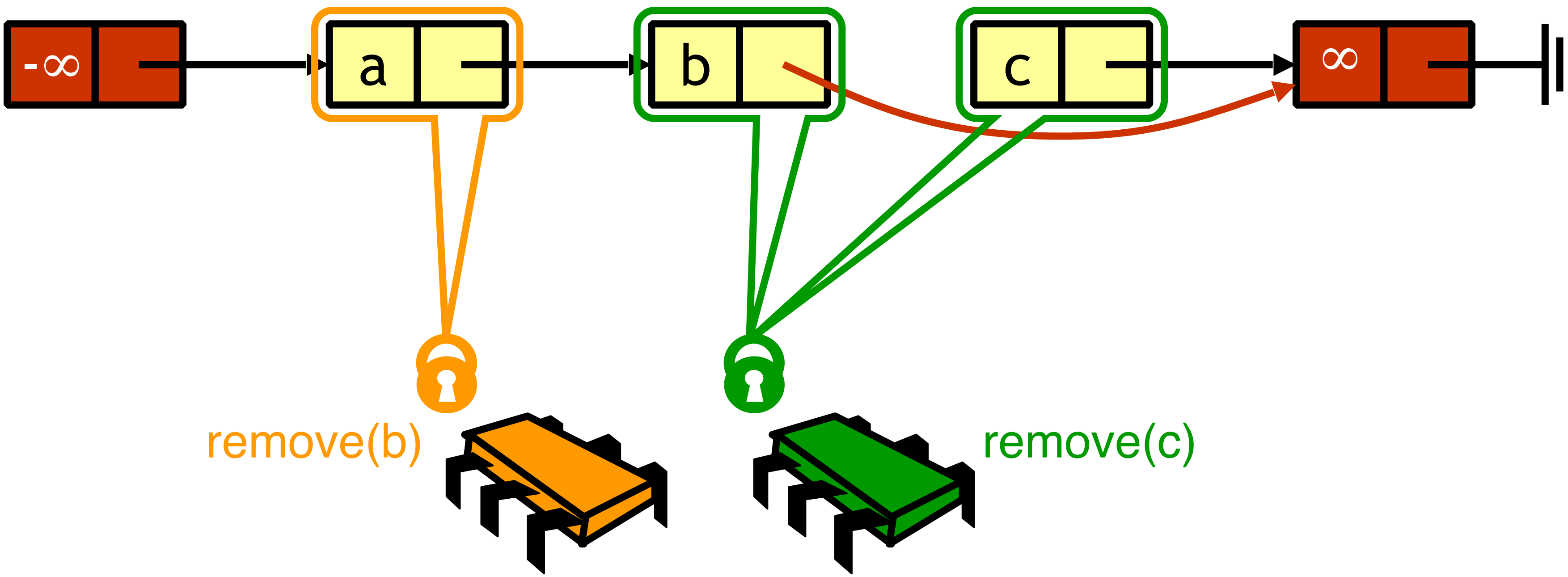

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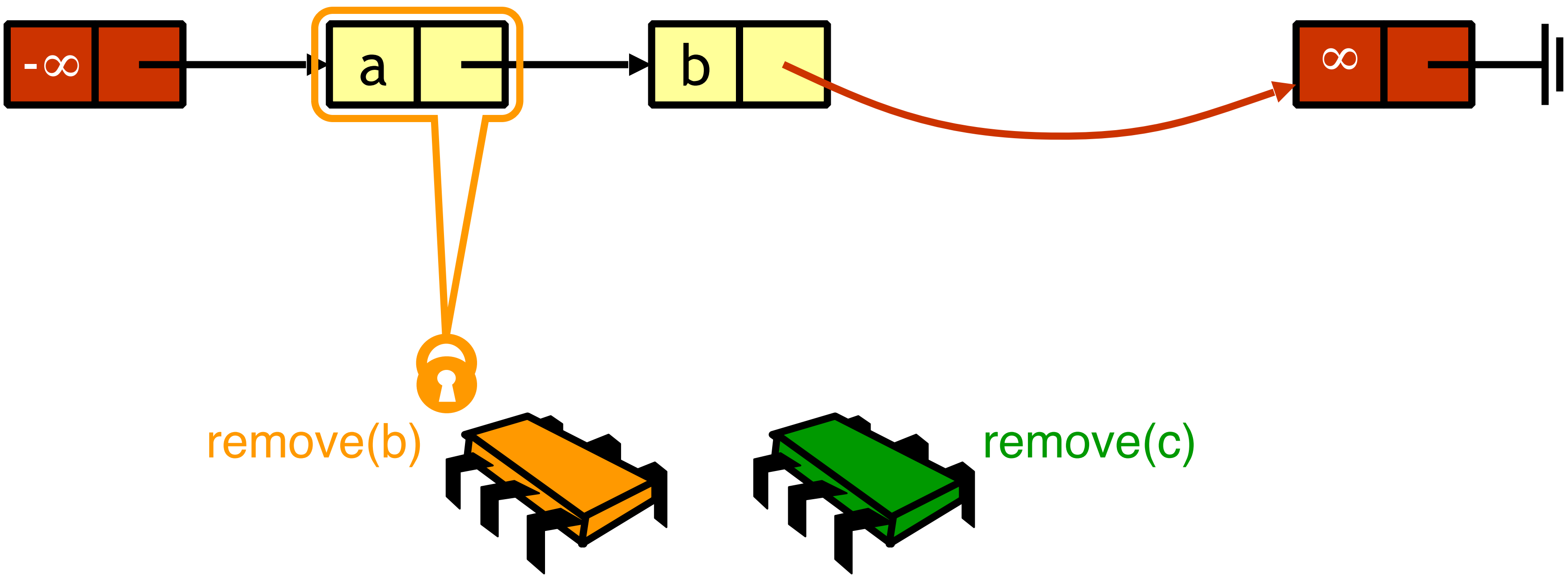

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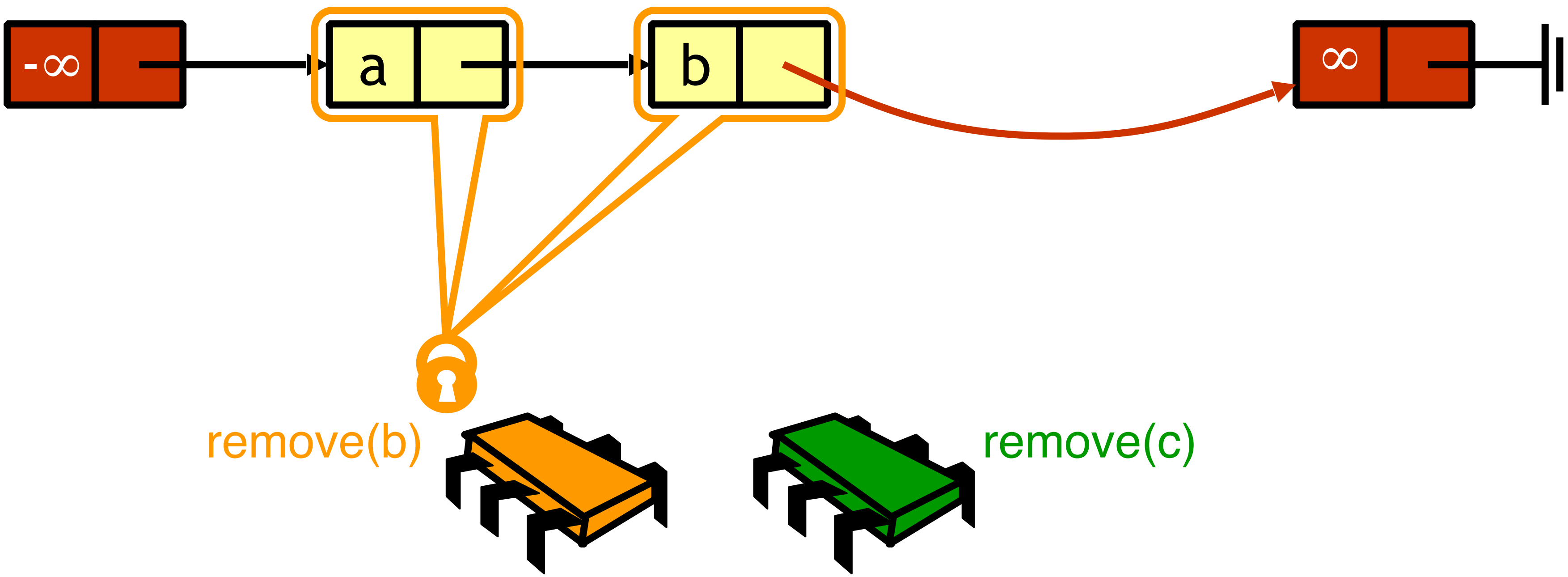

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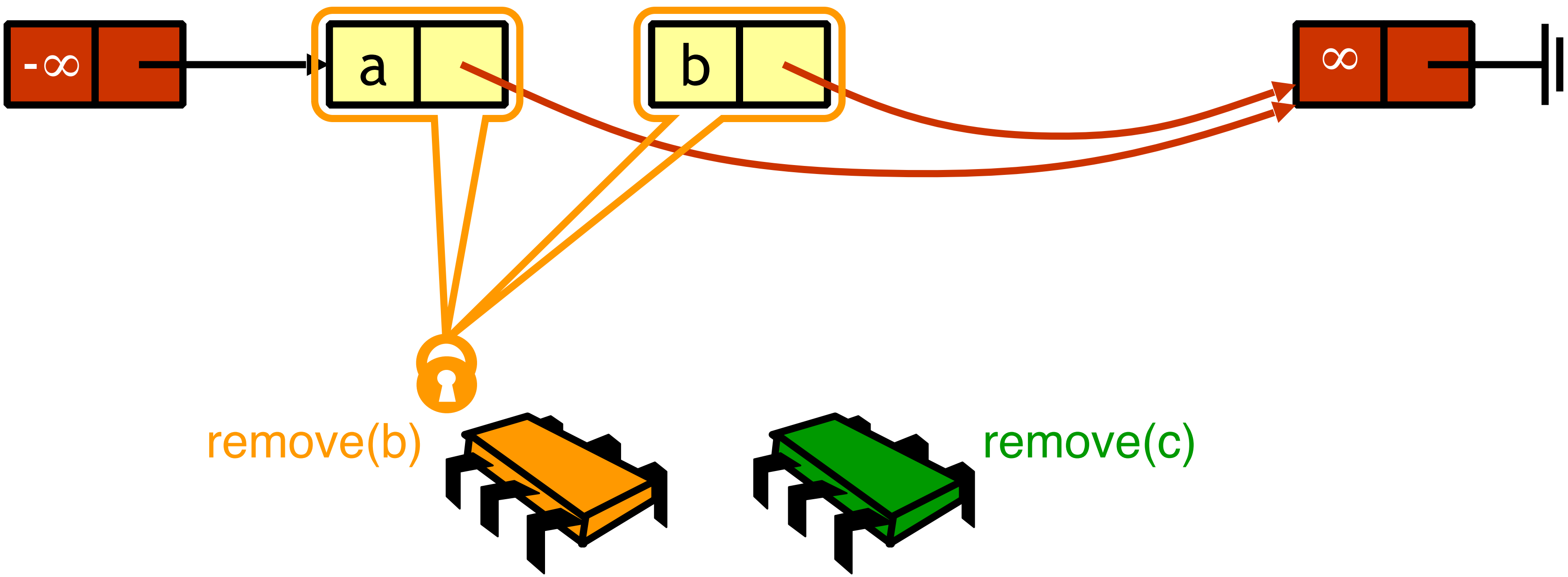

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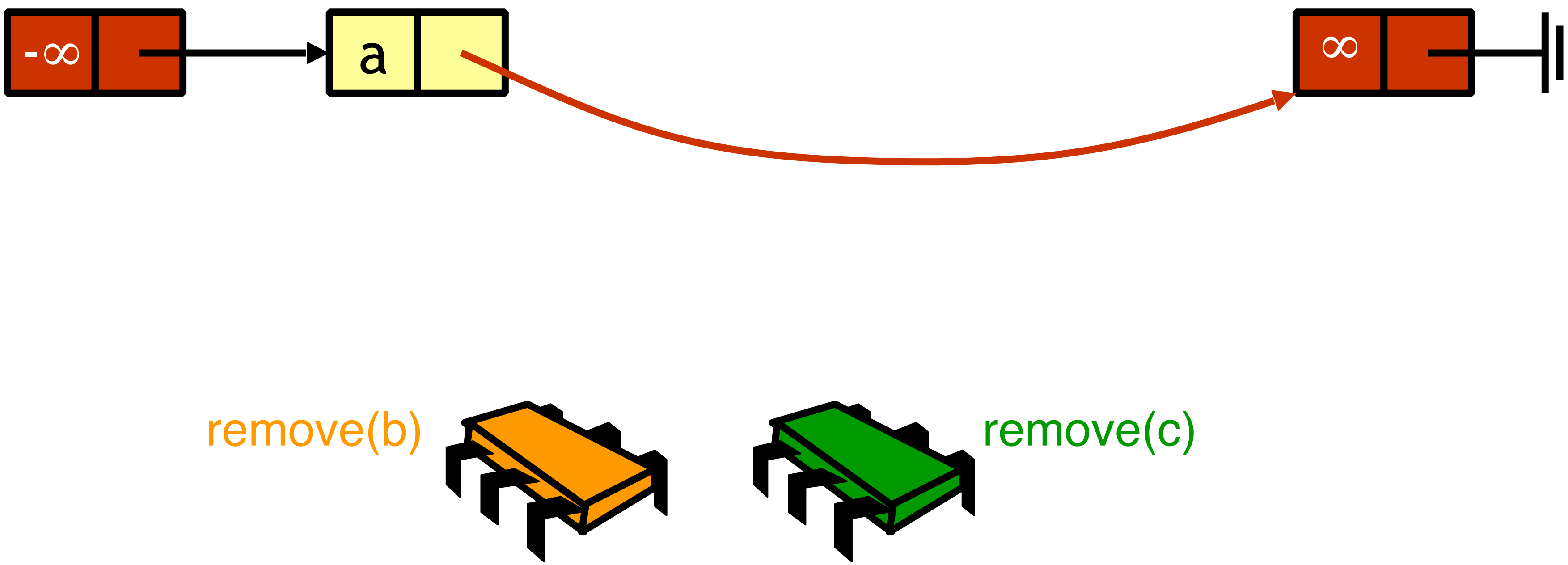


Remove

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

Remove

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

Key used to order node

Remove

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

Predecessor and current nodes

Remove

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

Make sure locks released

Remove

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

Everything else

Remove

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

Remove

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

Lock previous

Remove

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

Lock current

Remove

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

Traverse the list

Remove: Searching

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

Remove: Searching

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

Search key range (curr and pred locked)

Remove: Searching

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

If node found, remove it

Remove: Searching

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

Unlock predecessor and demote current (only one node locked!)

Remove: Searching

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

Find and lock new current

Remove: Searching

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

Otherwise not present

Adding Nodes

- To add node b
  - Lock predecessor
  - Lock successor
- Neither can be deleted

Drawbacks

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

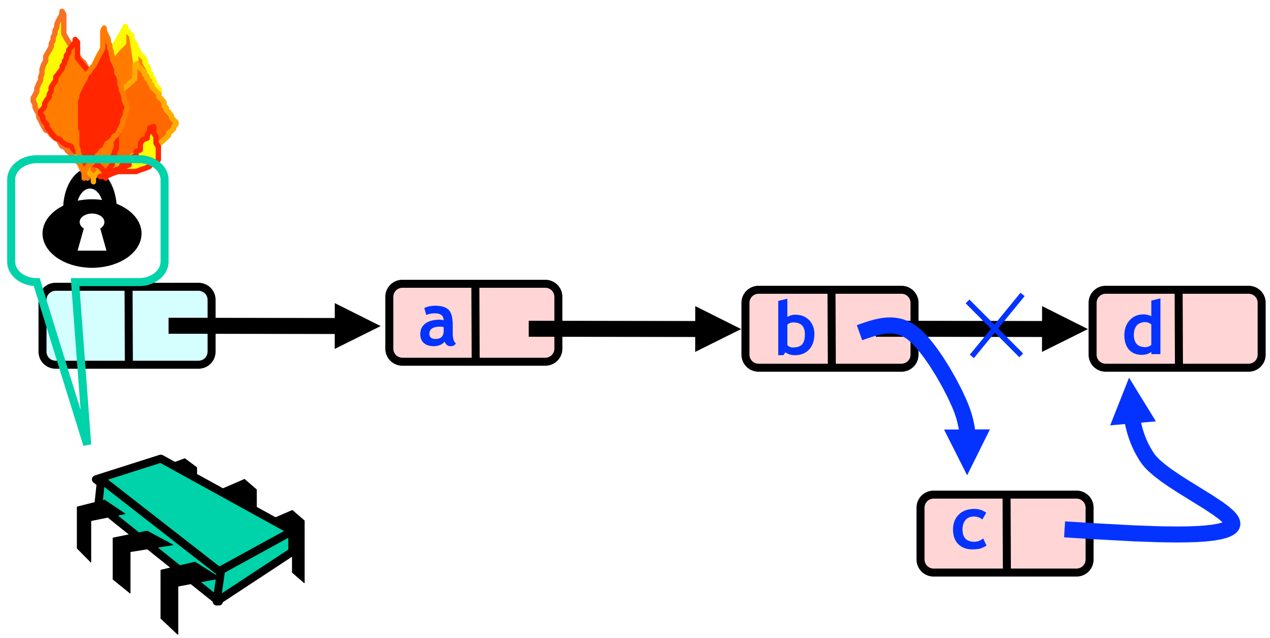
Linked List Lecture

- Five approaches to concurrent data structure design:
  - Coarse-grained locking
  - Fine-grained locking
  - Optimistic synchronization
  - Lazy synchronization
  - Lock-free synchronization

List-based Set

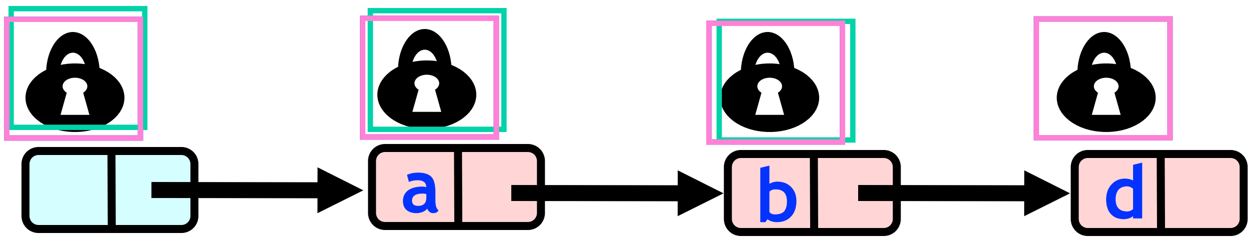
- We used an ordered list to implement a Set:
  - An unordered collection of objects
  - No duplicates
  - Methods:
    - add() a new object
    - remove() an object
    - Test if set contains() object

Course Grained Locking



Simple but hotspot + bottleneck

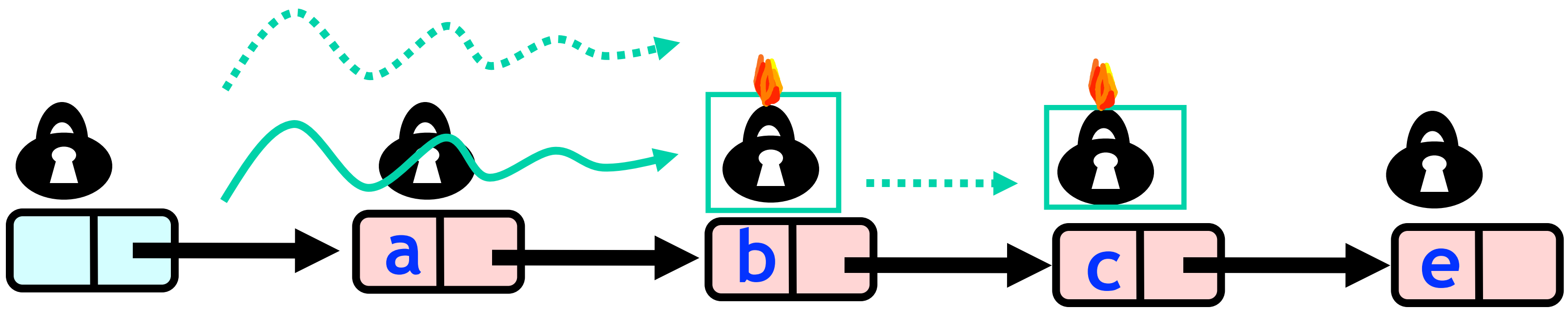
Fine Grained Locking



- Allows concurrency but everyone always delayed by front guy = bottleneck

- Lock acquisition overhead

Optimistic List

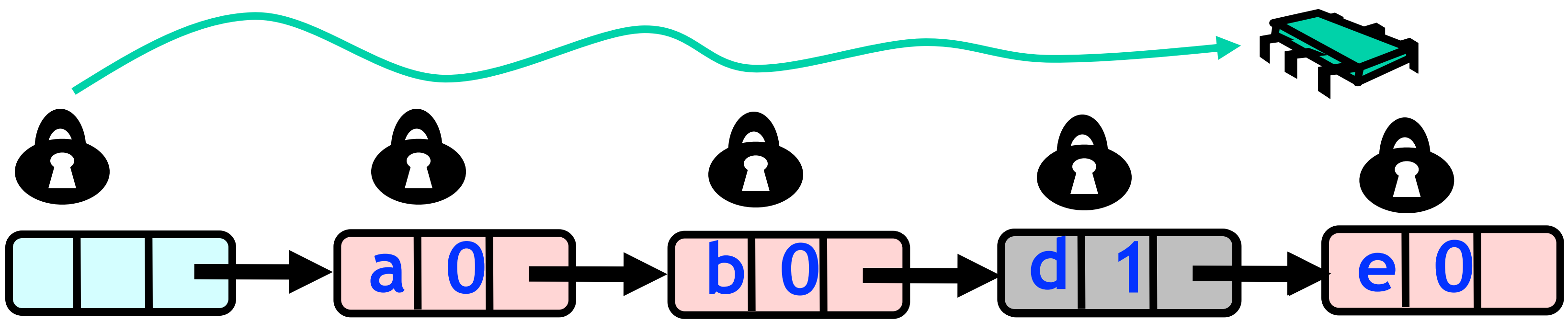


- Limited Hotspots (Only at locked Add(), Remove(), Contains() destination locations, not traversals)

- But two traversals

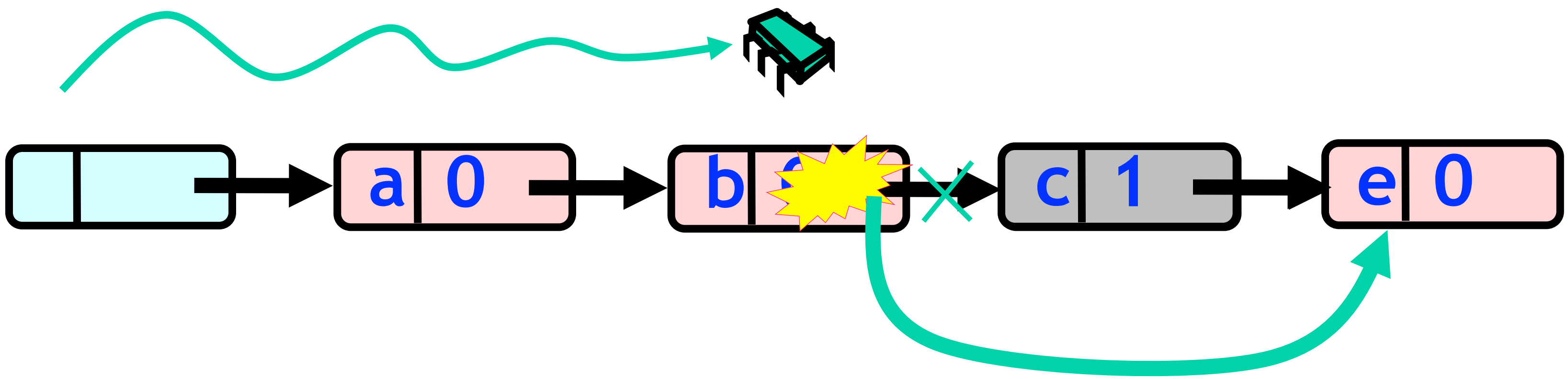
- Yet traversals are wait-free!

Lazy List



Lazy Add() and Remove() + Wait-free Contains()

Lock-free List

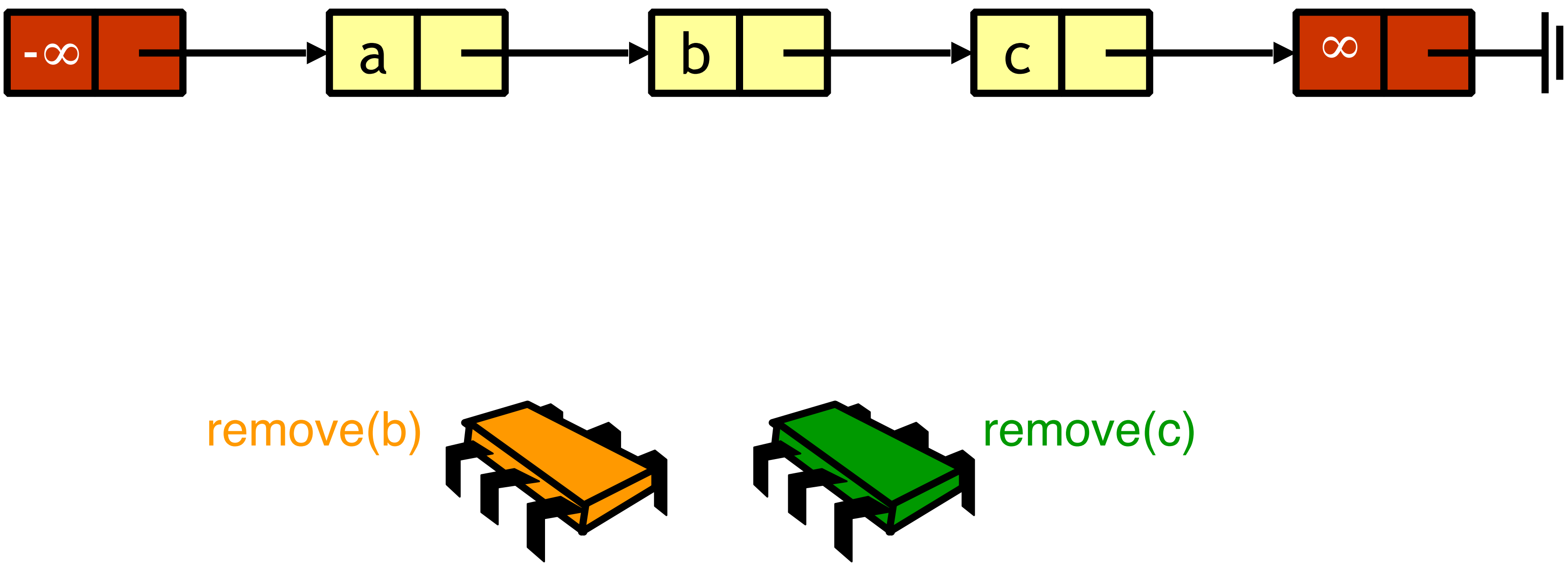


- Add() and Remove() physically remove marked nodes
- Wait-free contains() traverses both marked and removed nodes

3. Optimistic Synchronization

- Find nodes without locking
- Lock nodes
- Check that everything is OK

What Could Go Wrong?



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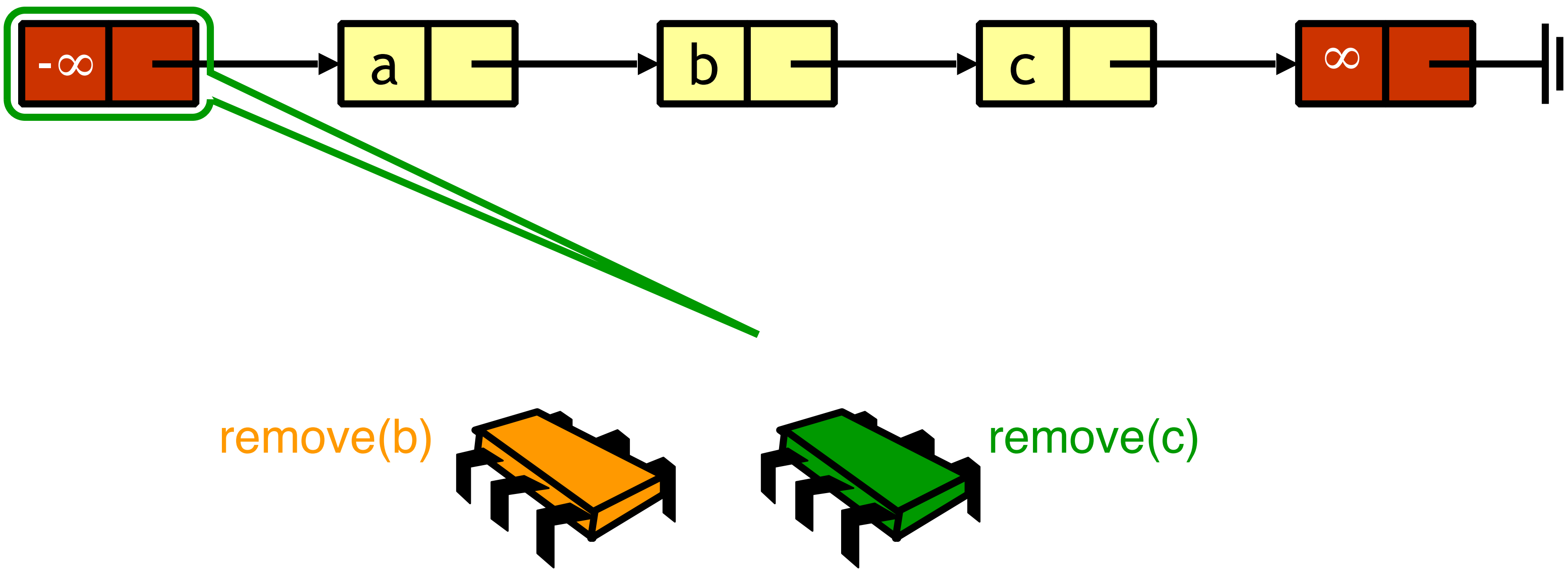

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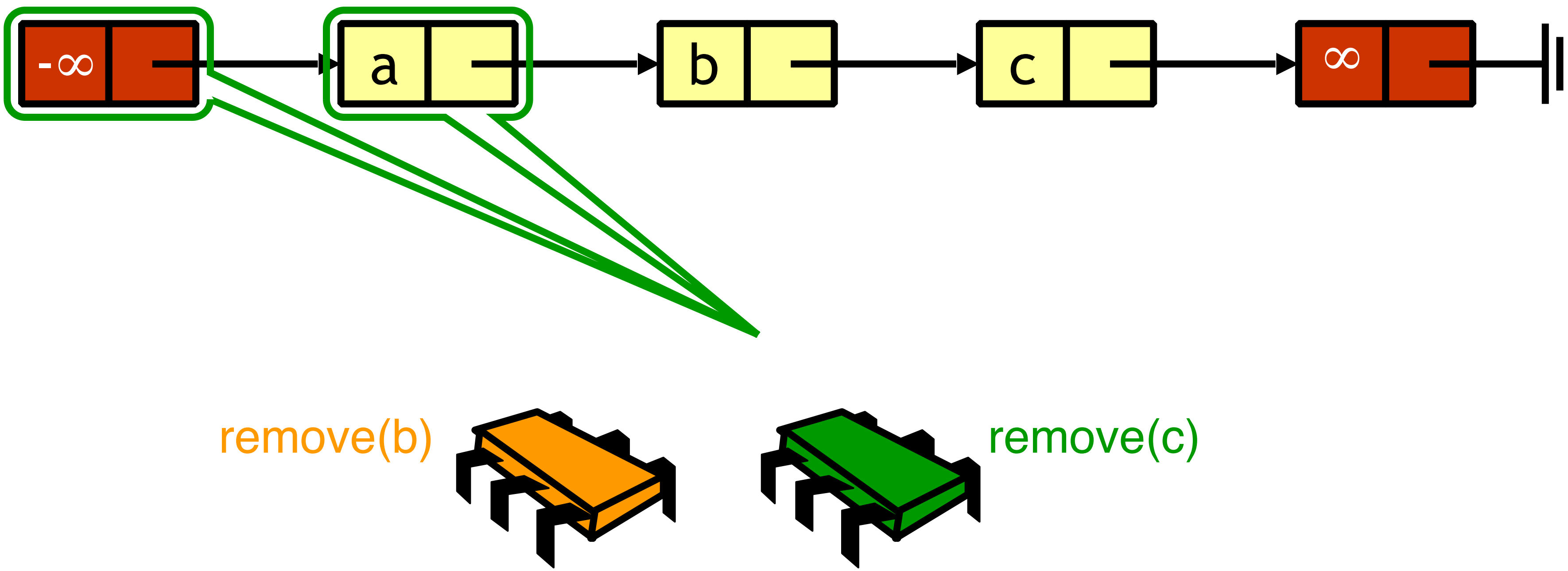

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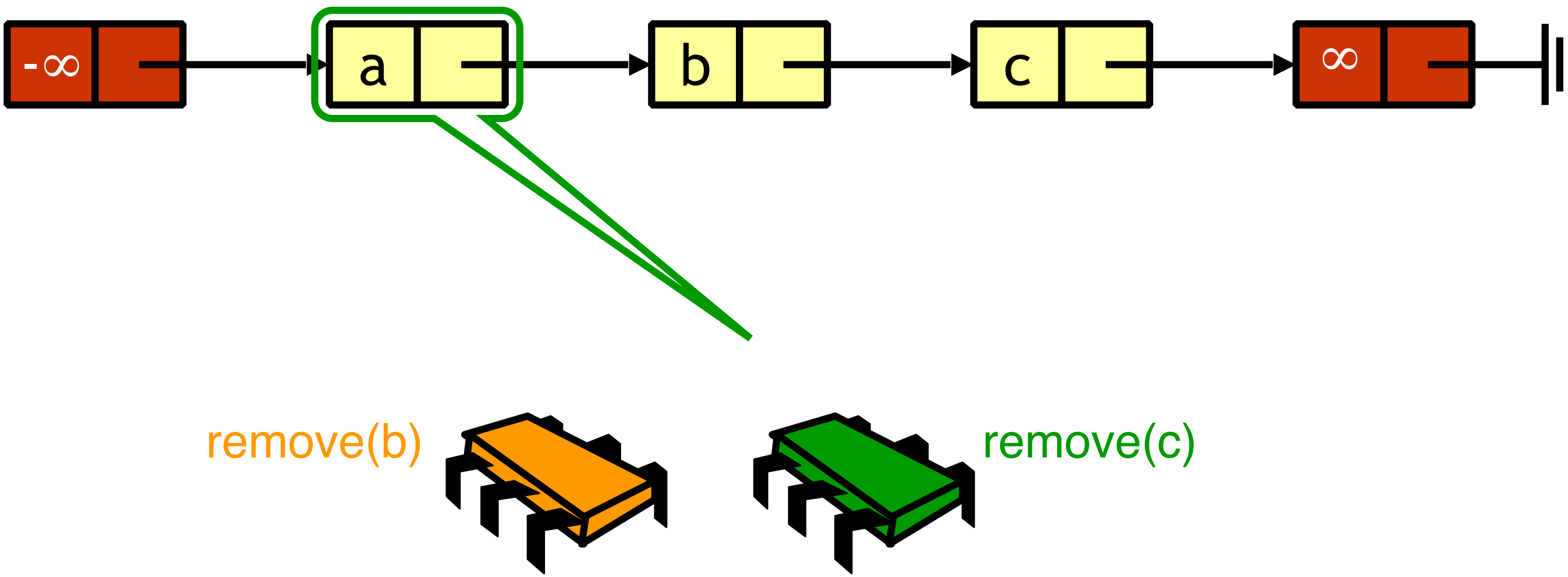

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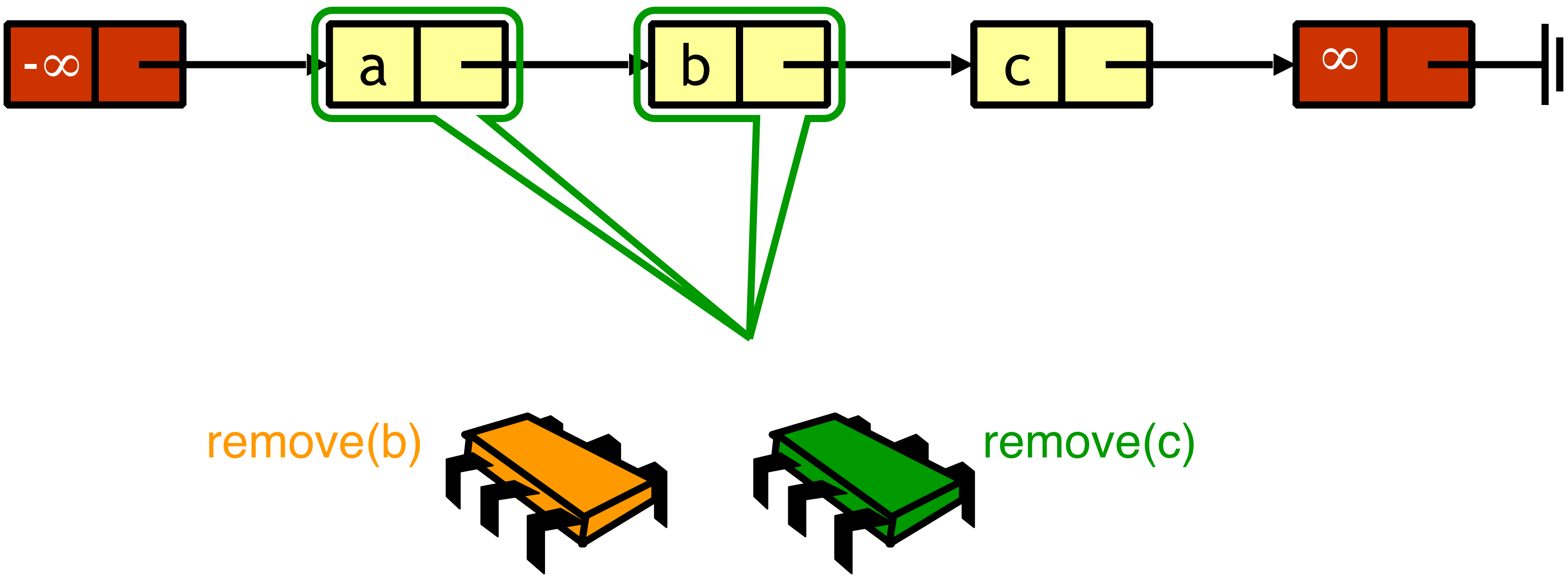

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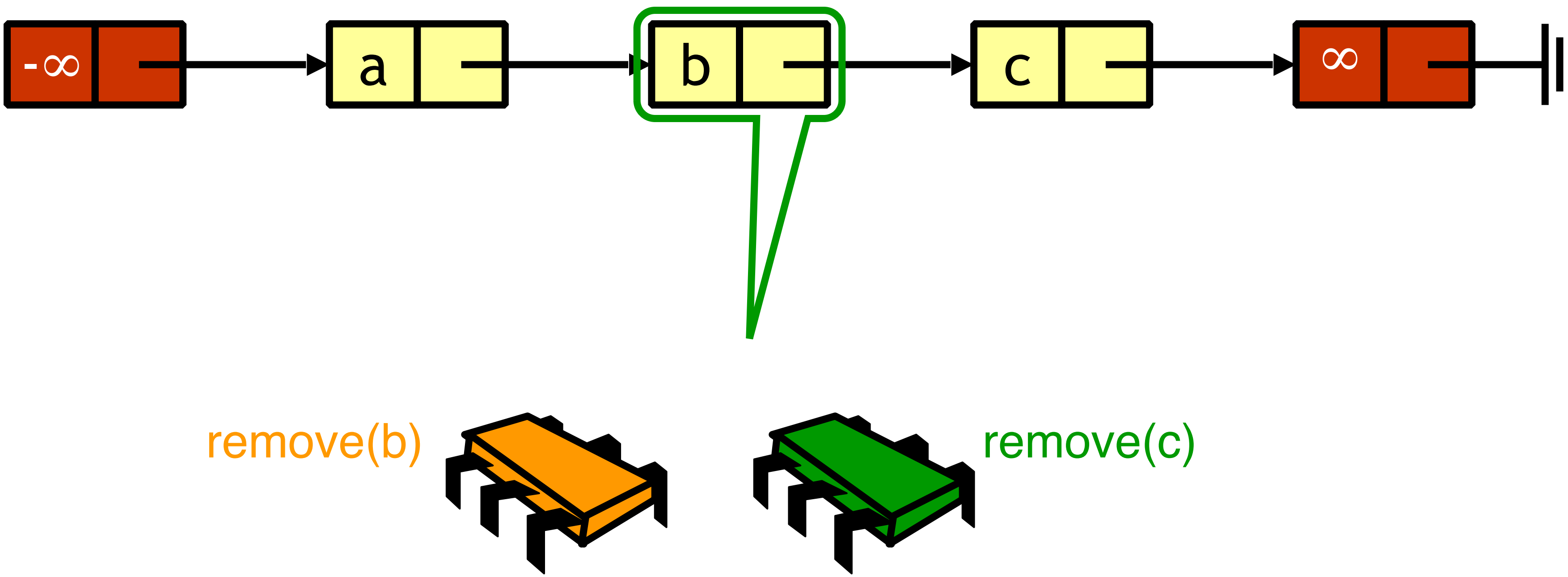

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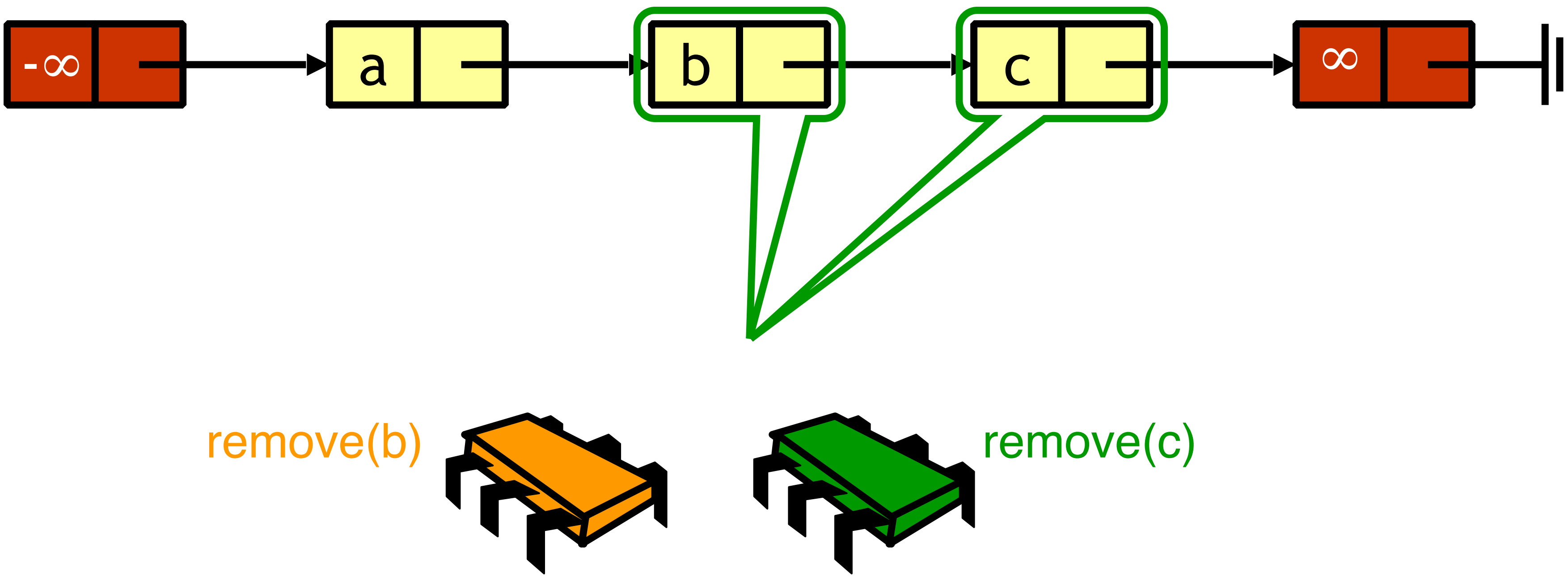

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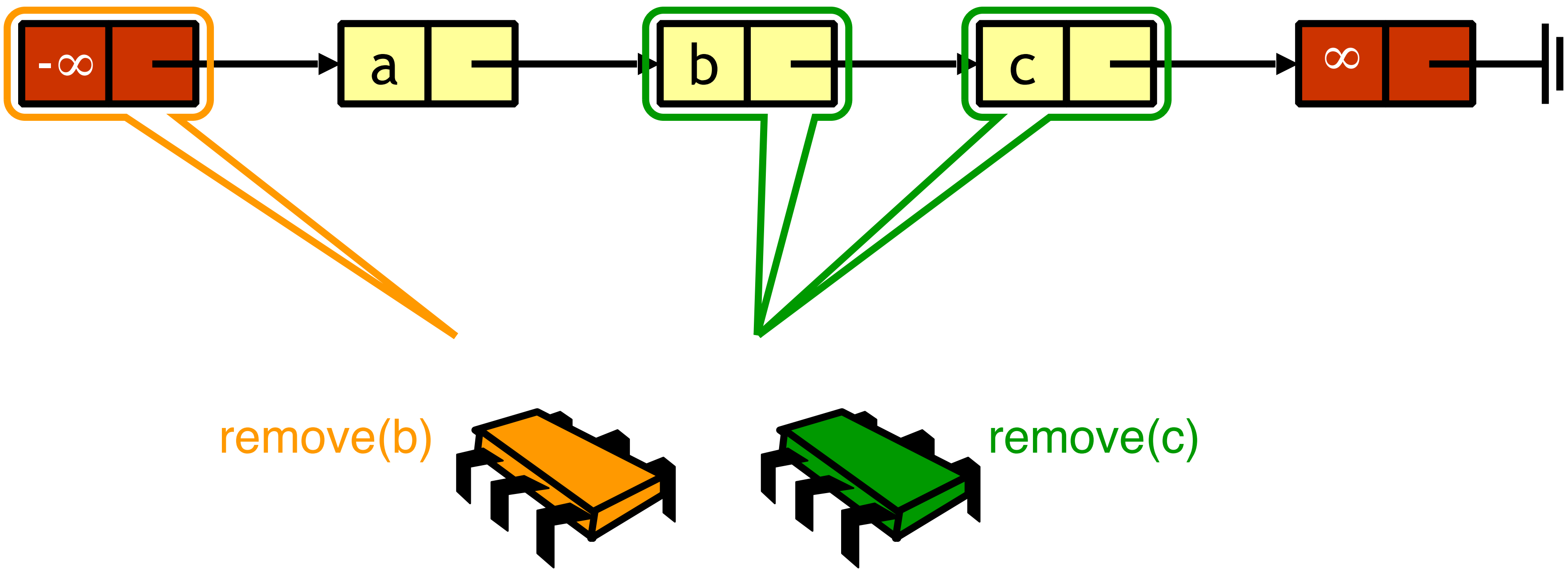

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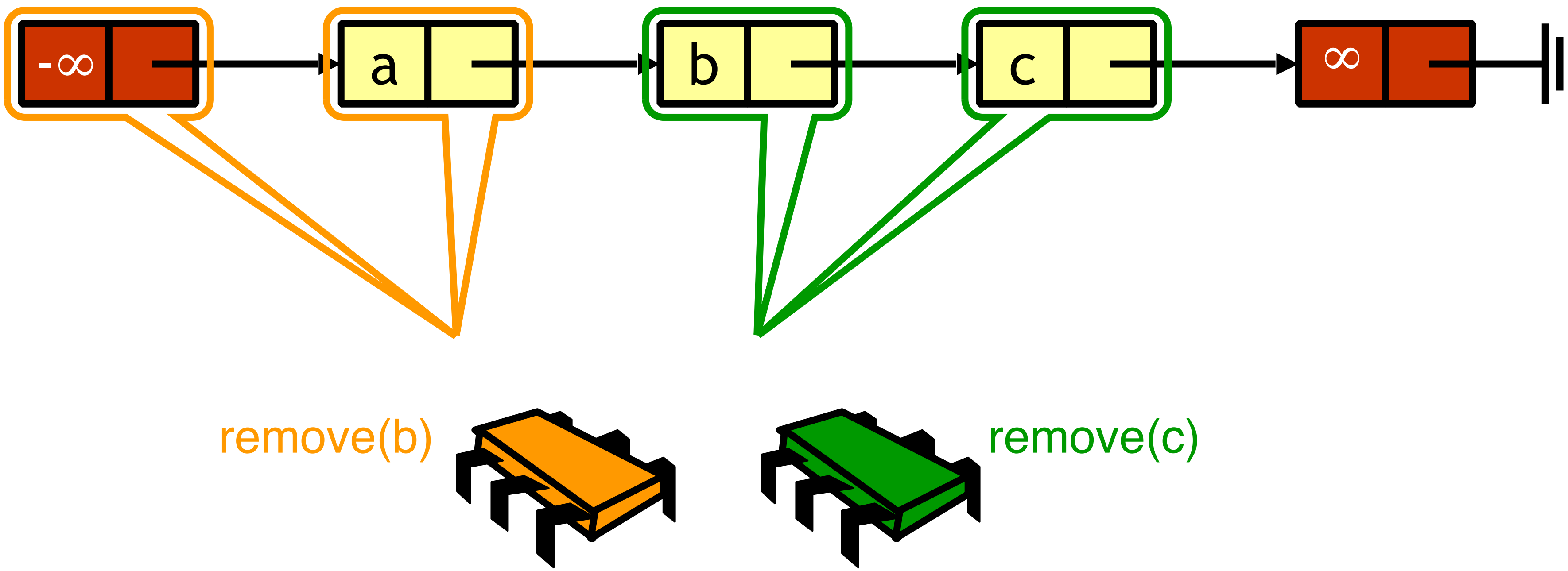

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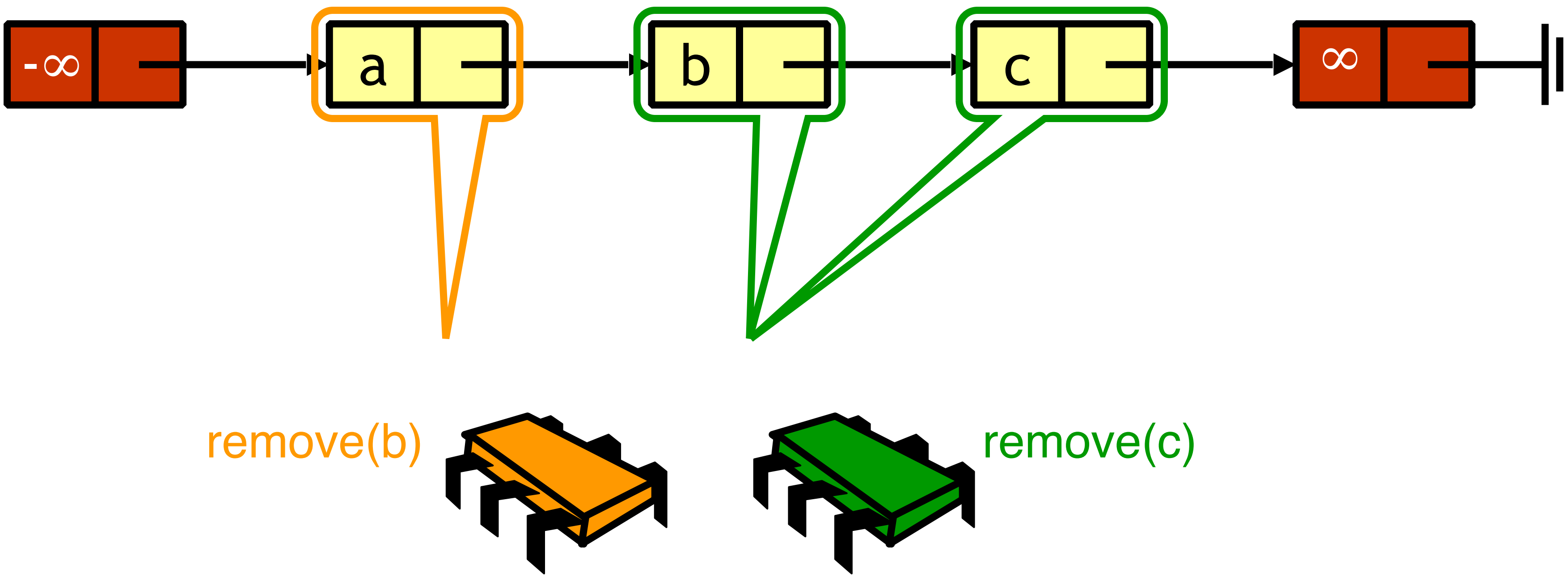

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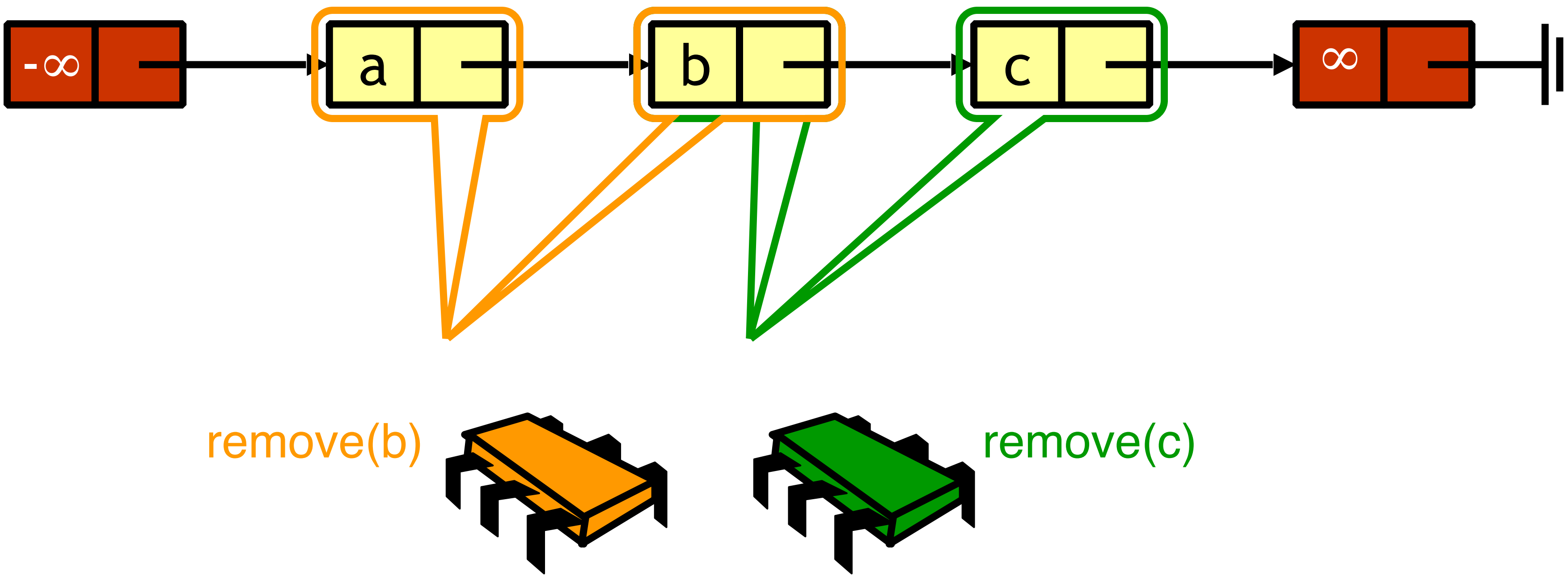

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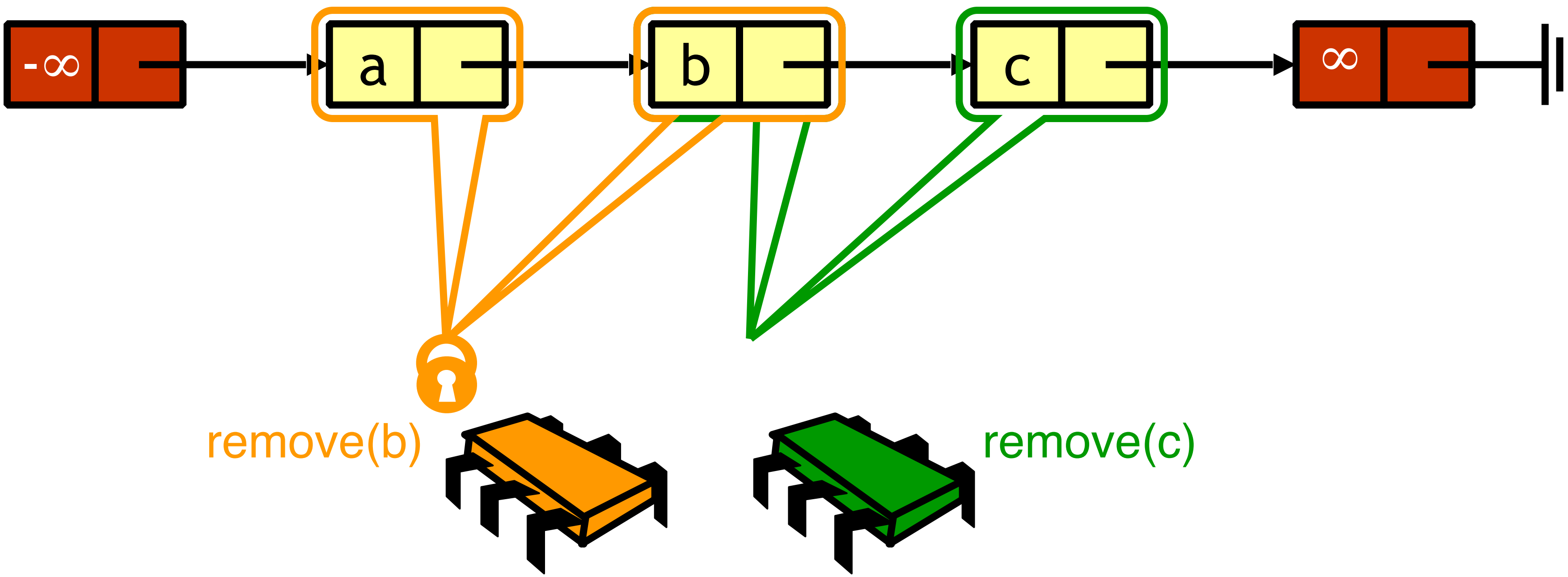

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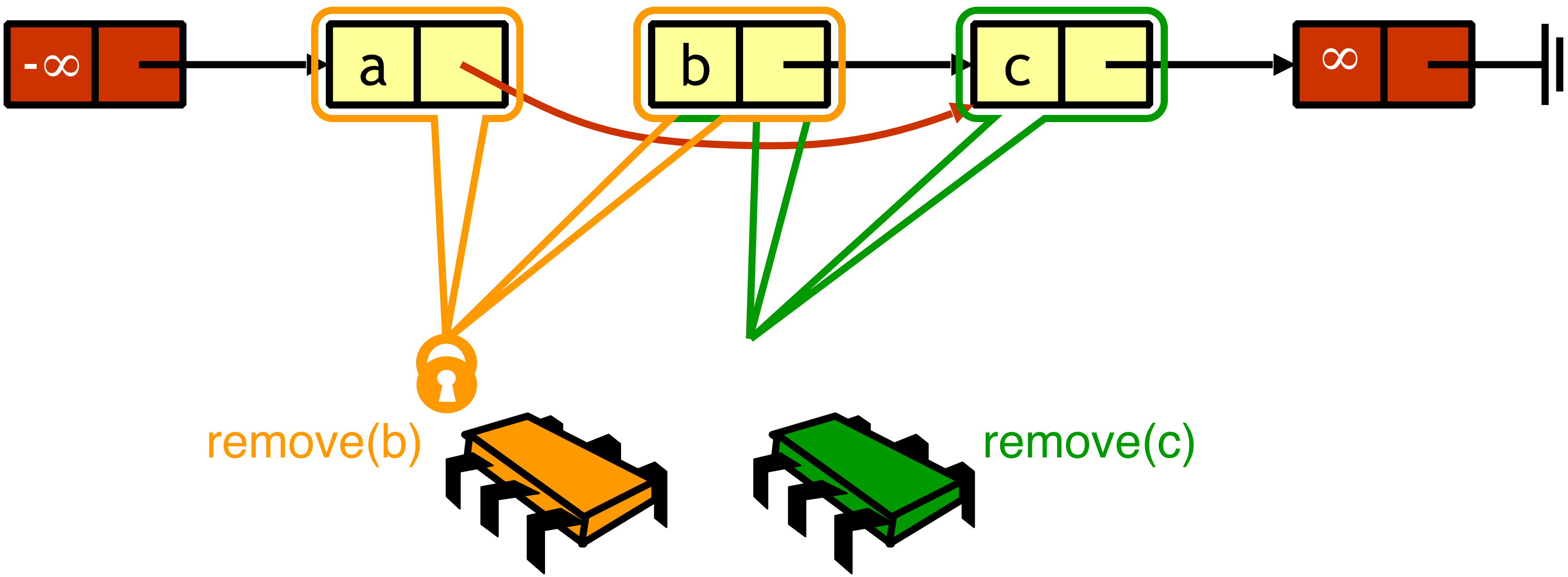

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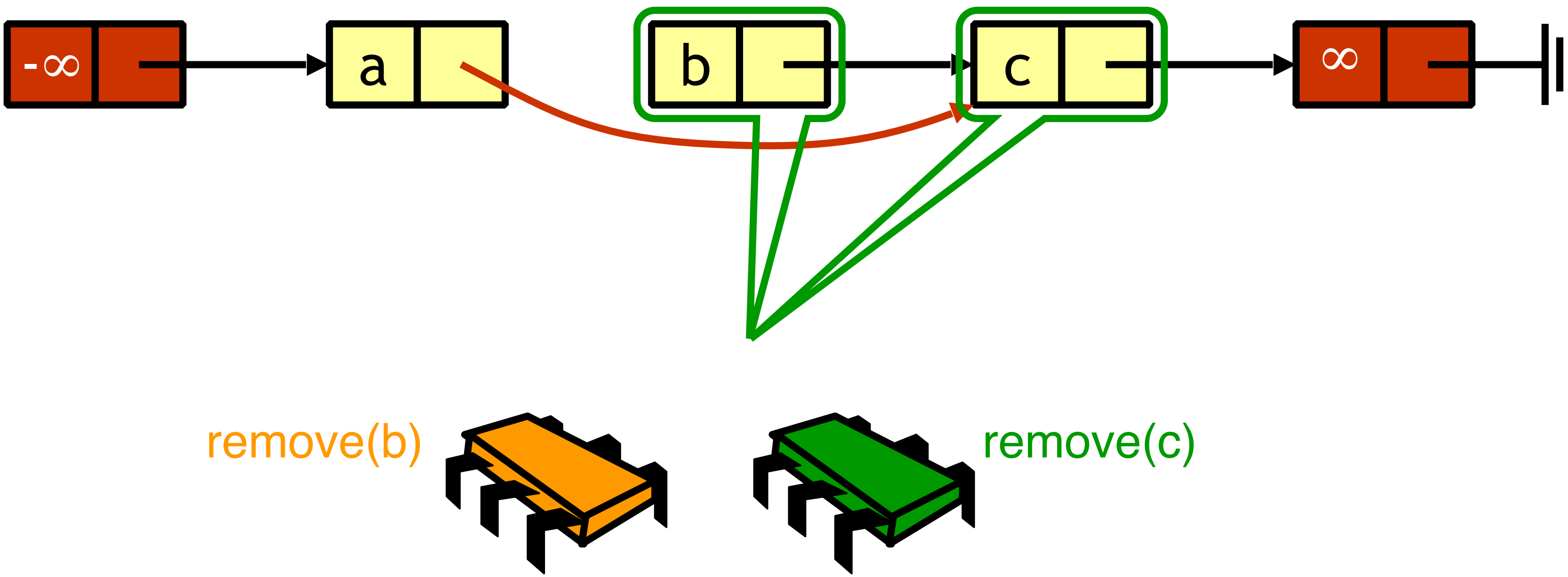

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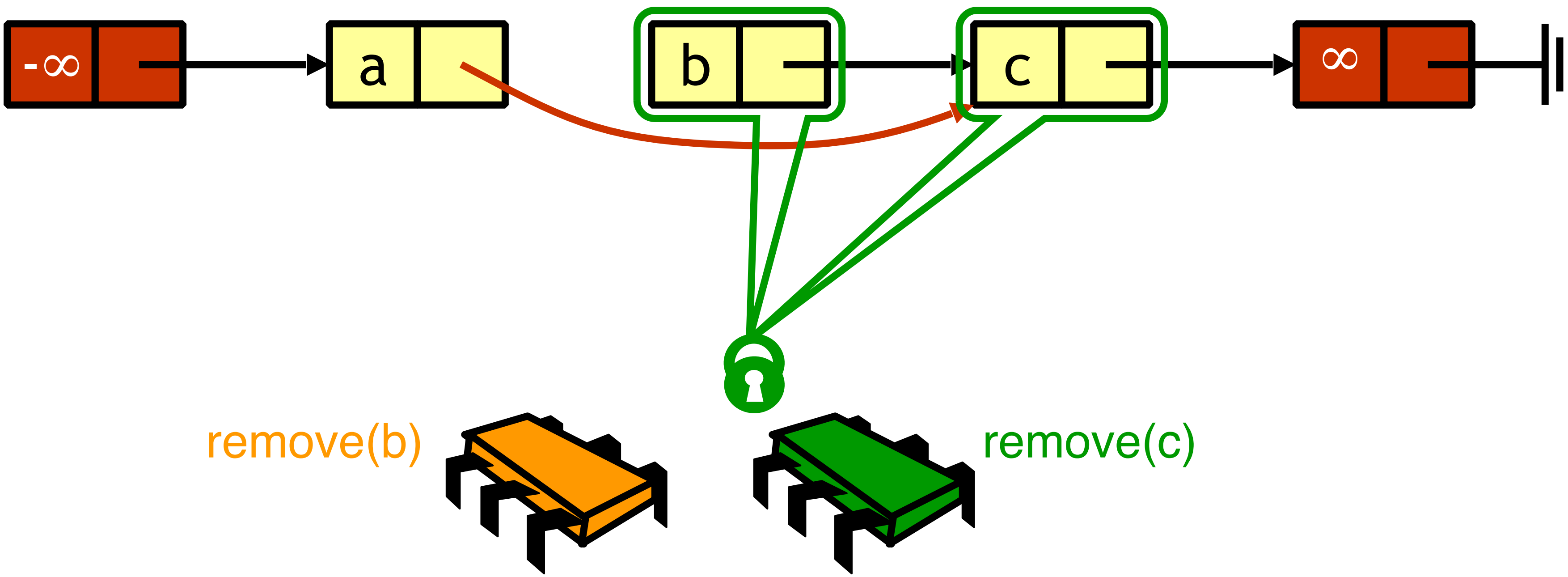

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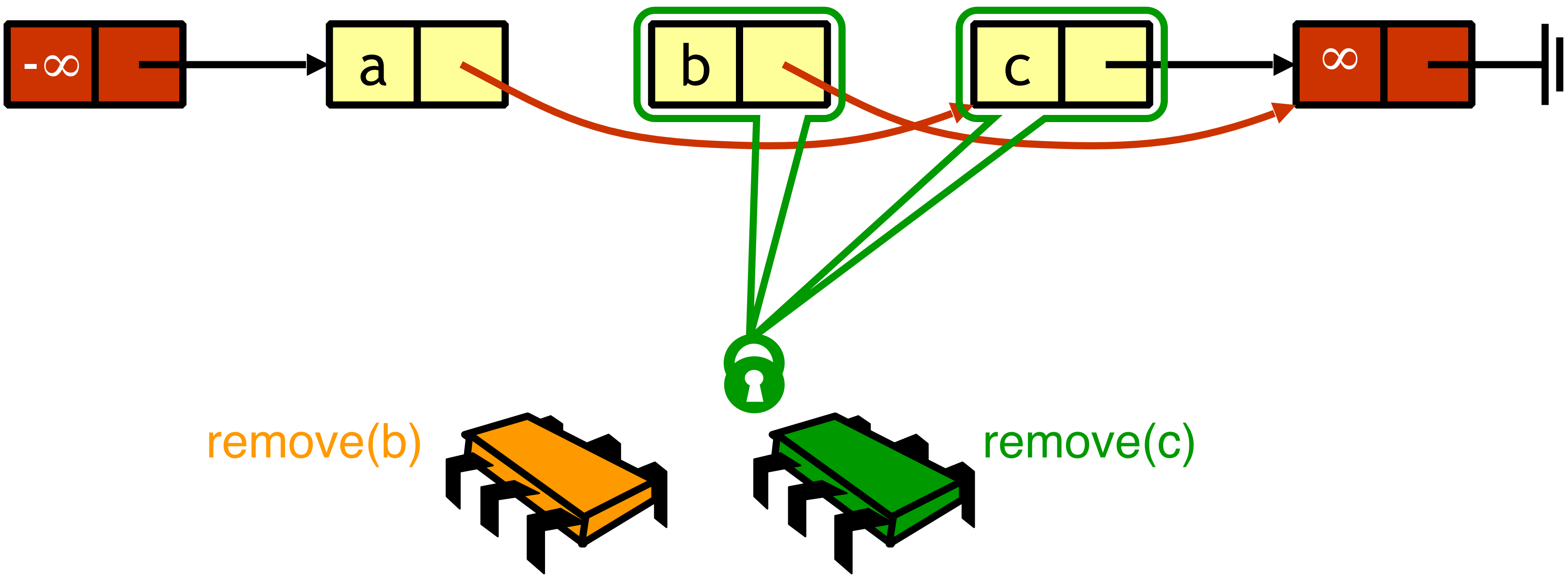

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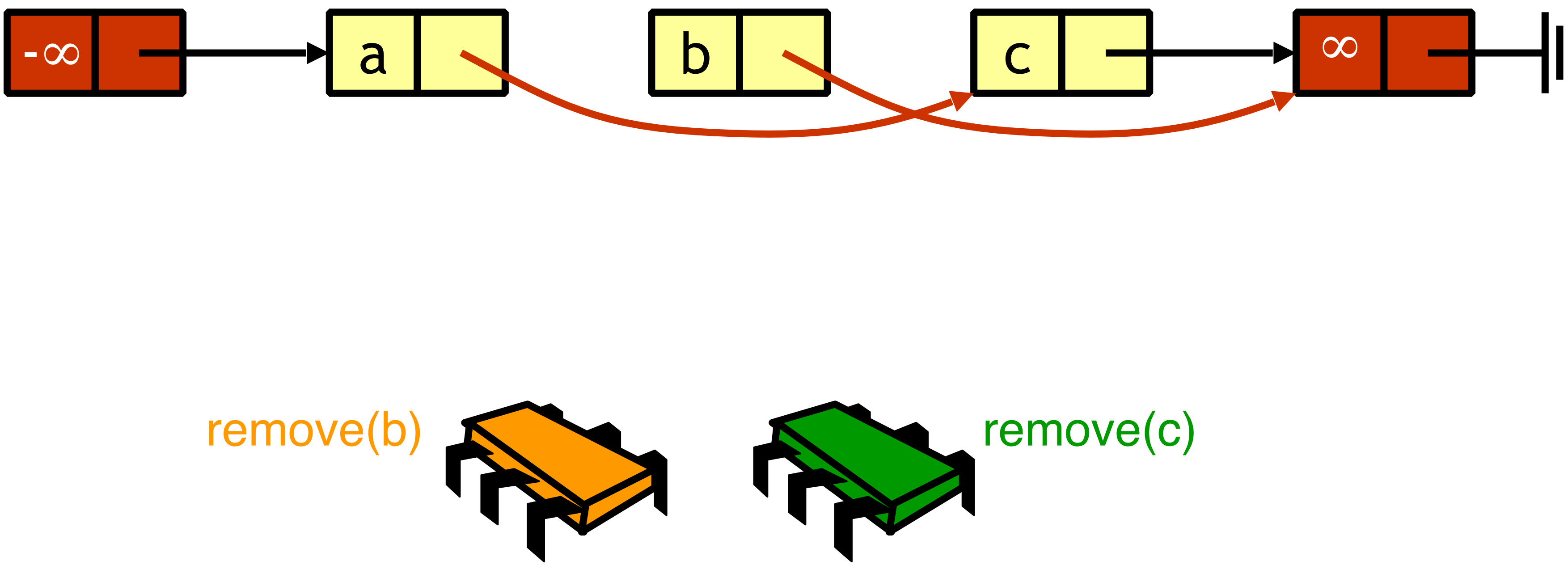

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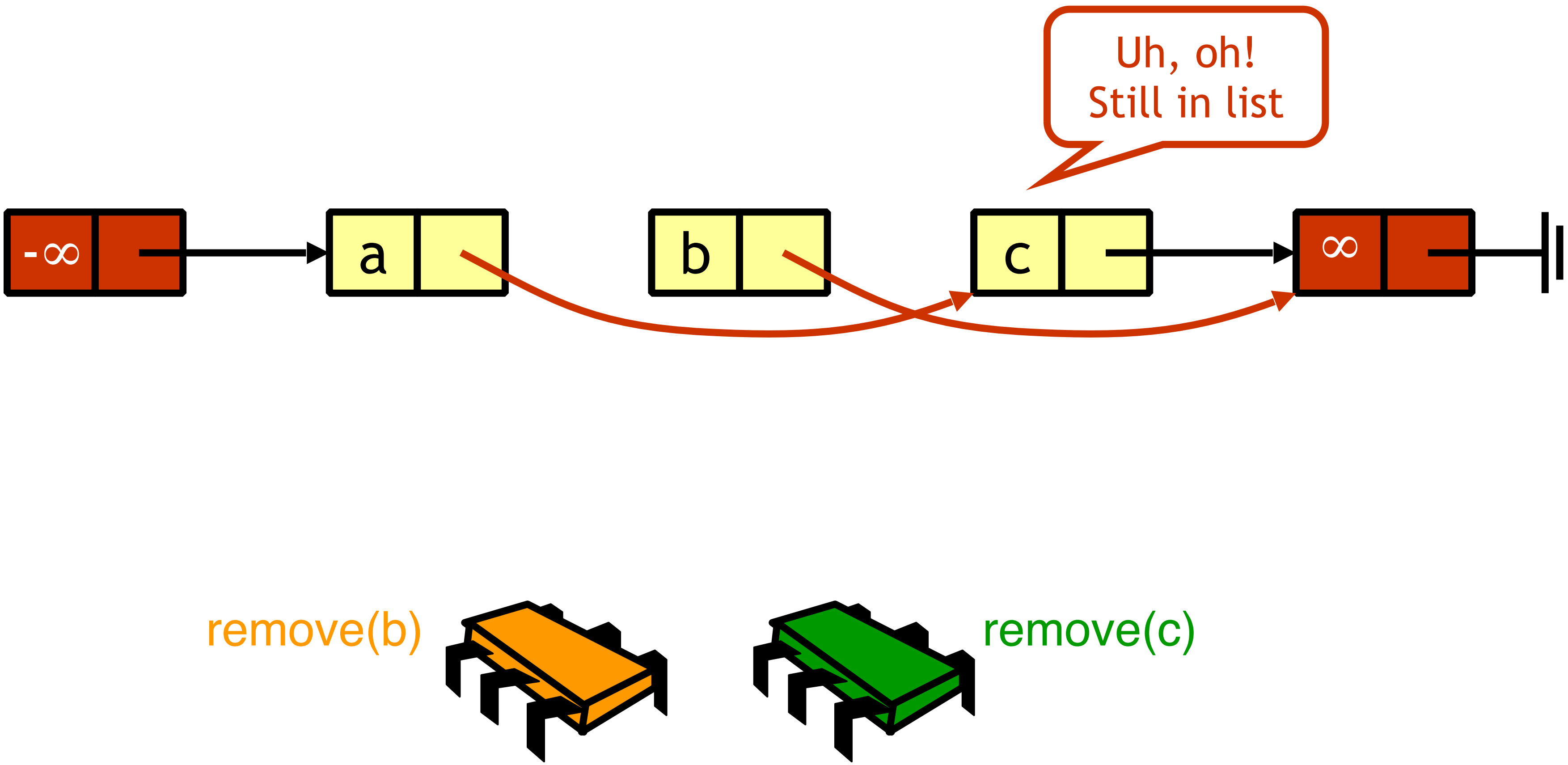

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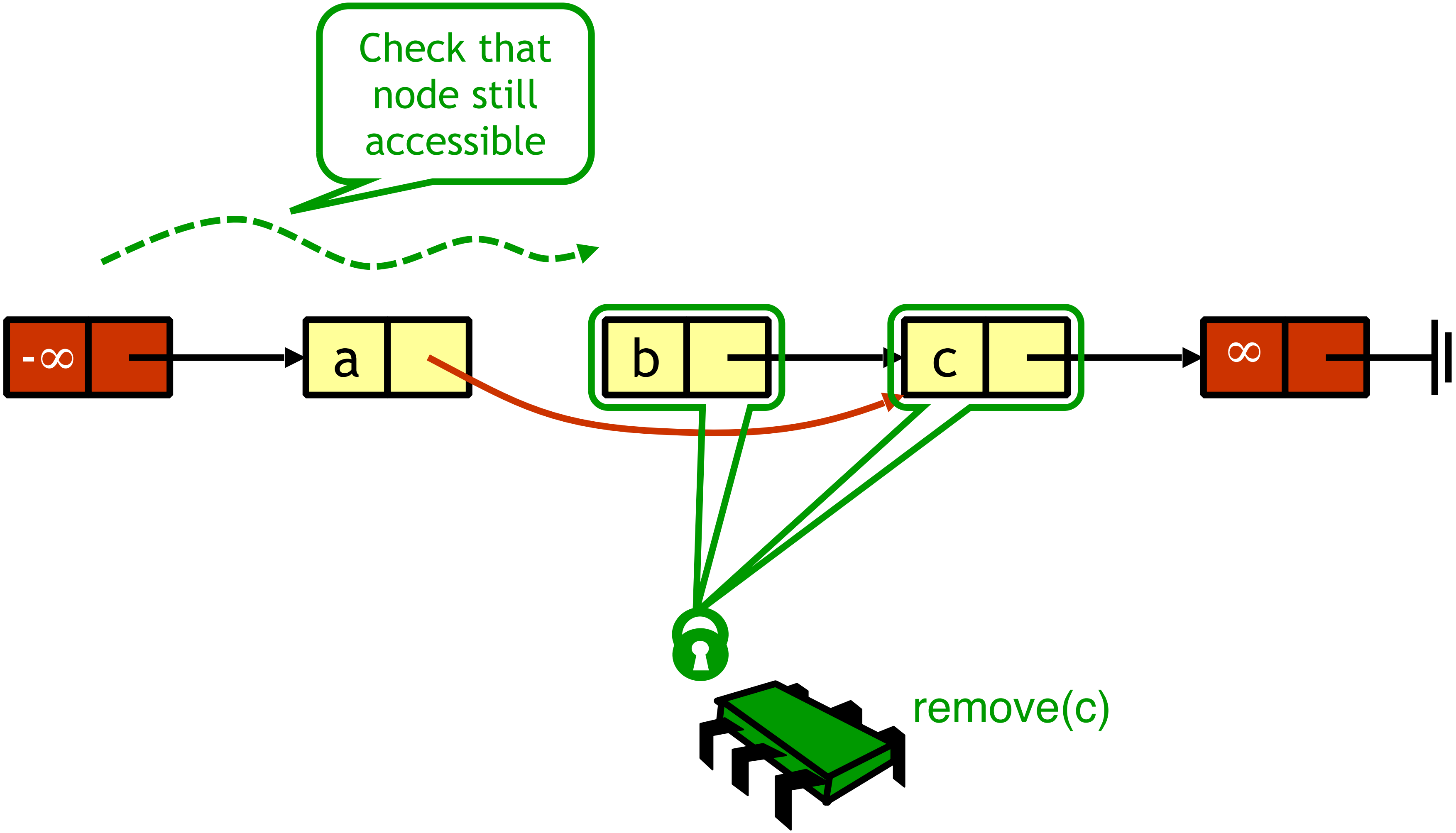

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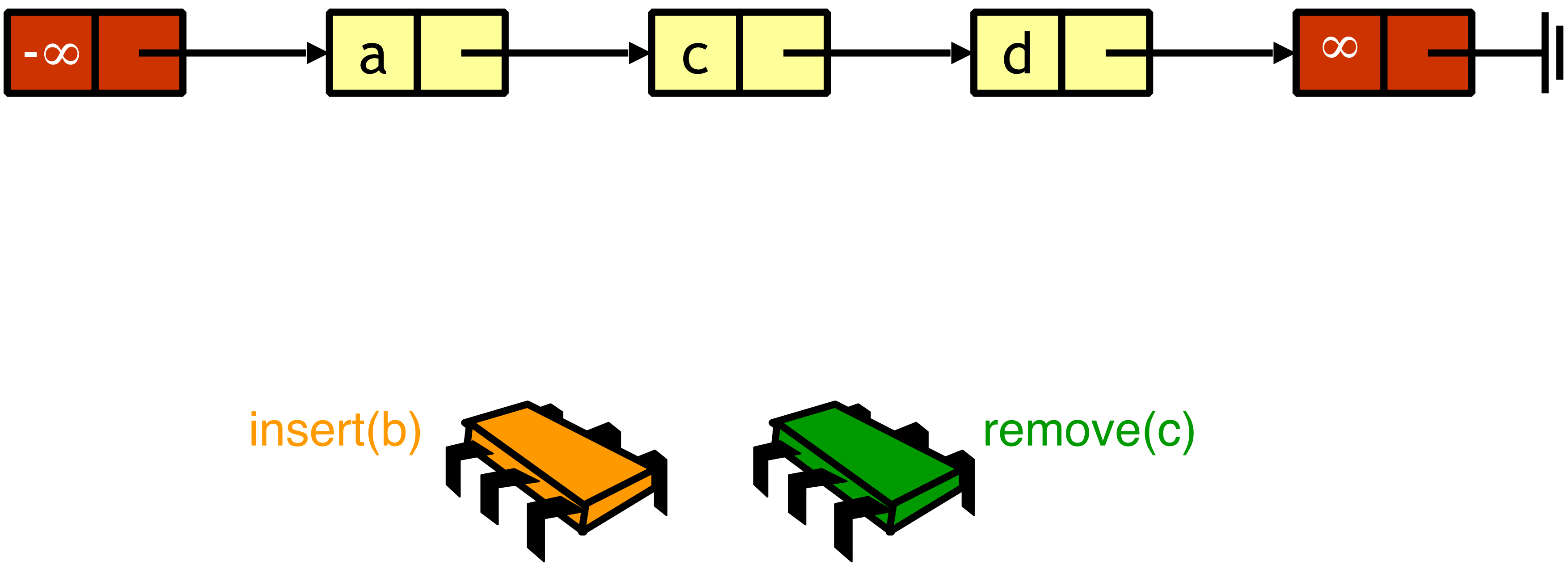

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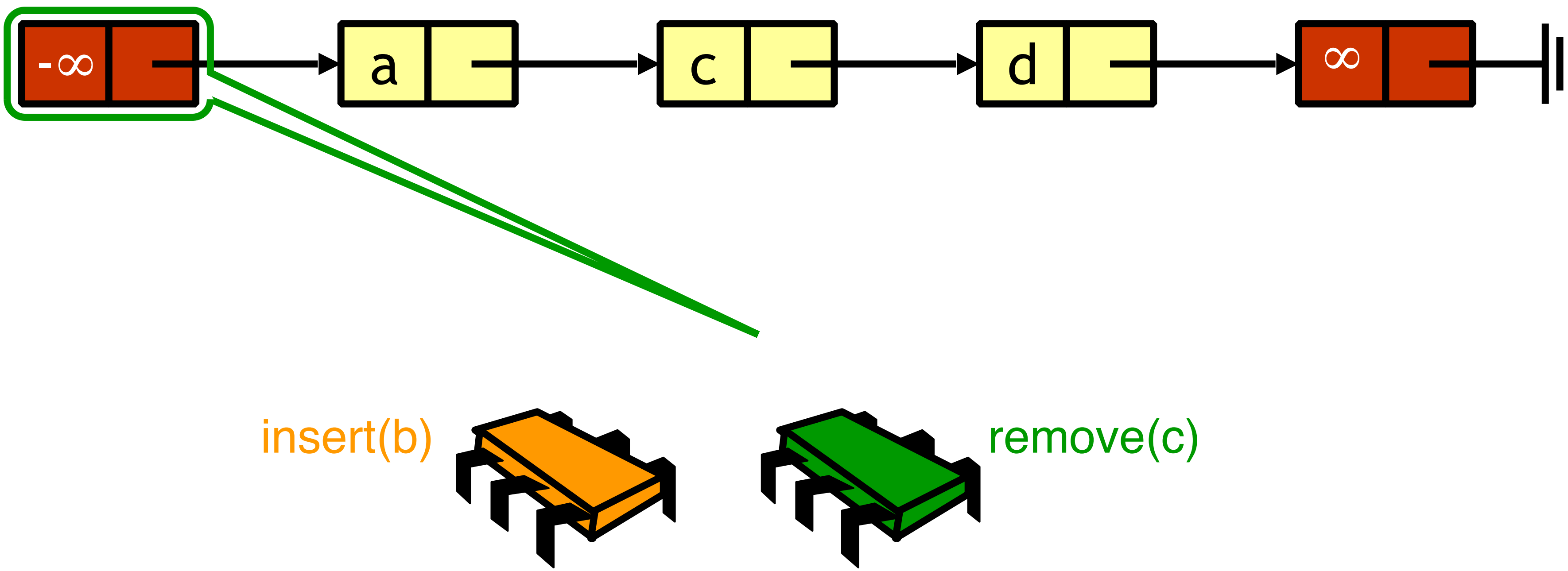

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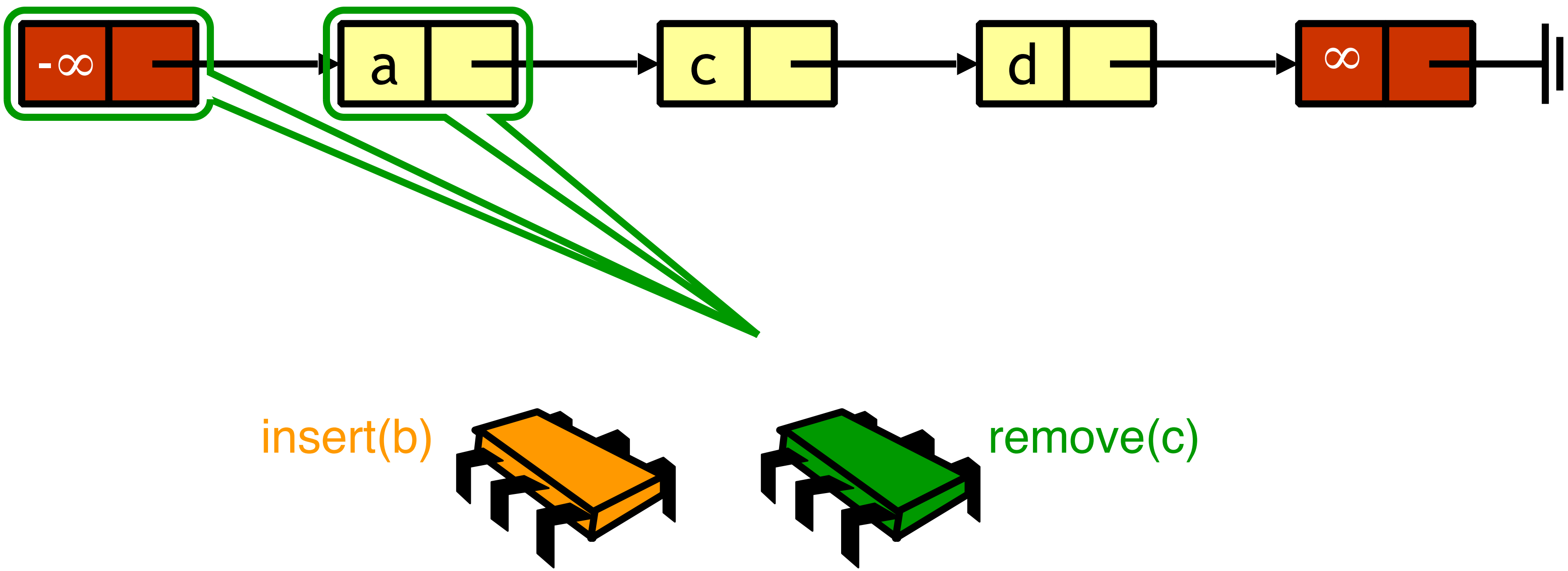

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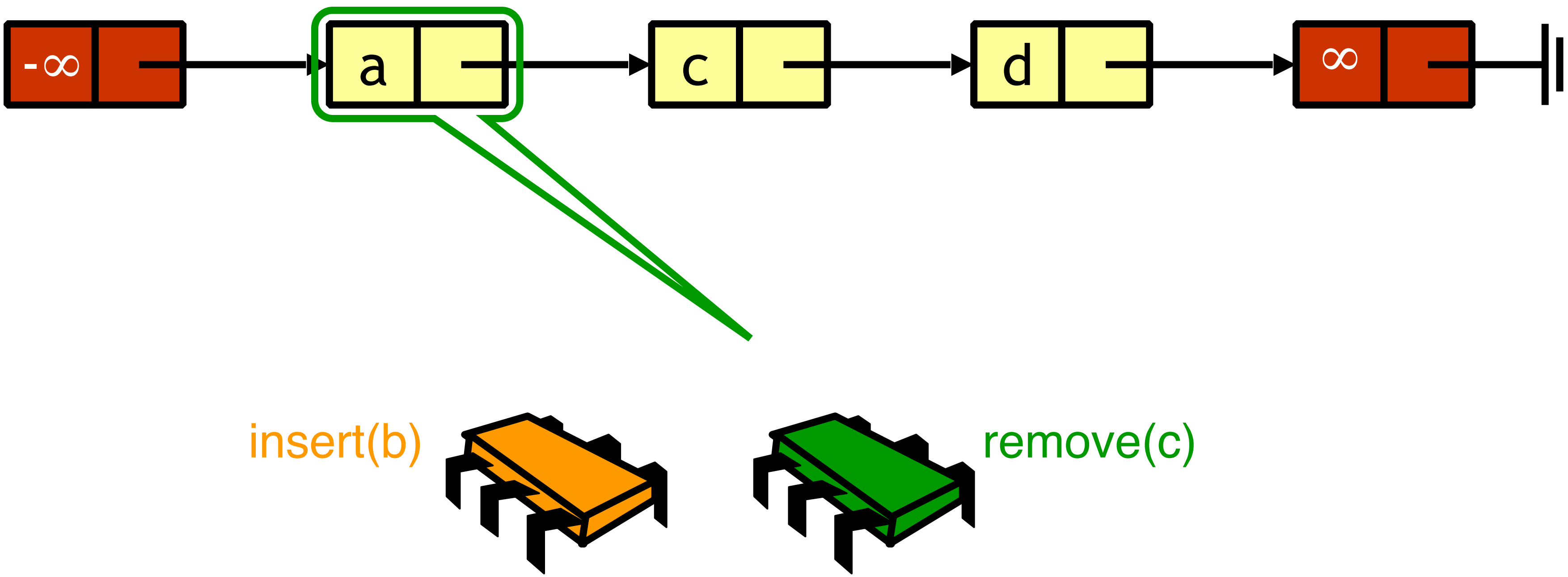

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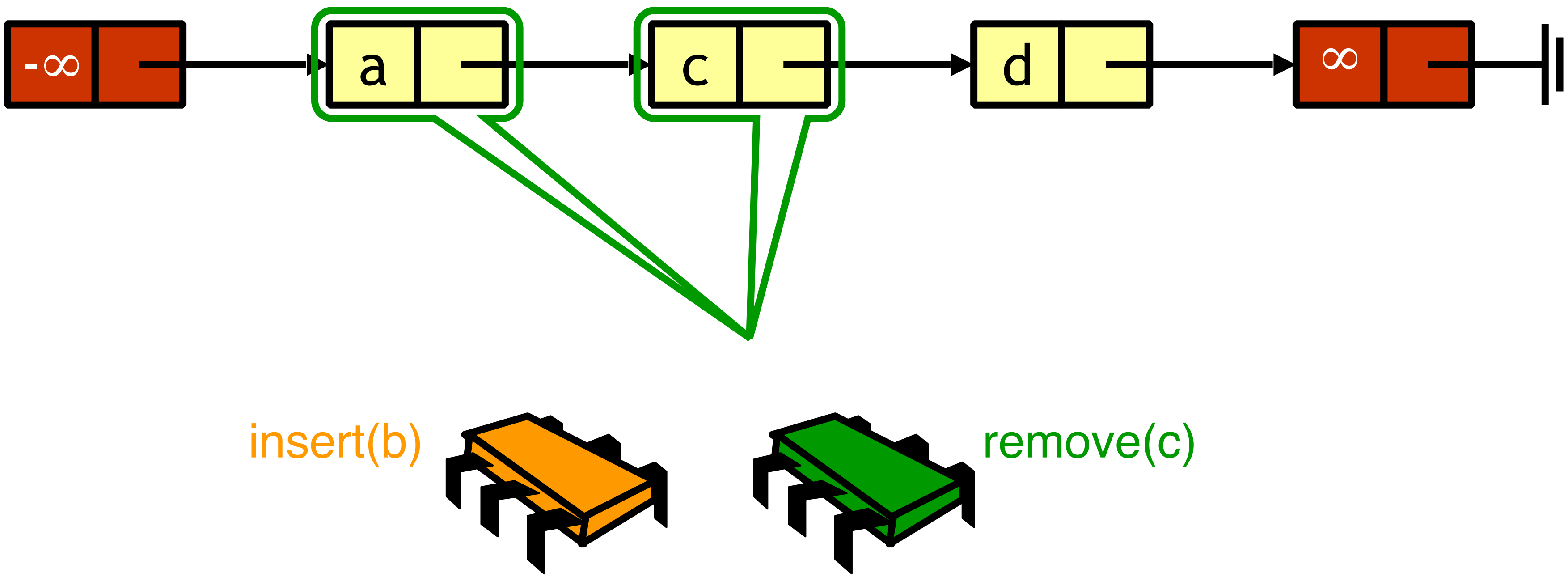

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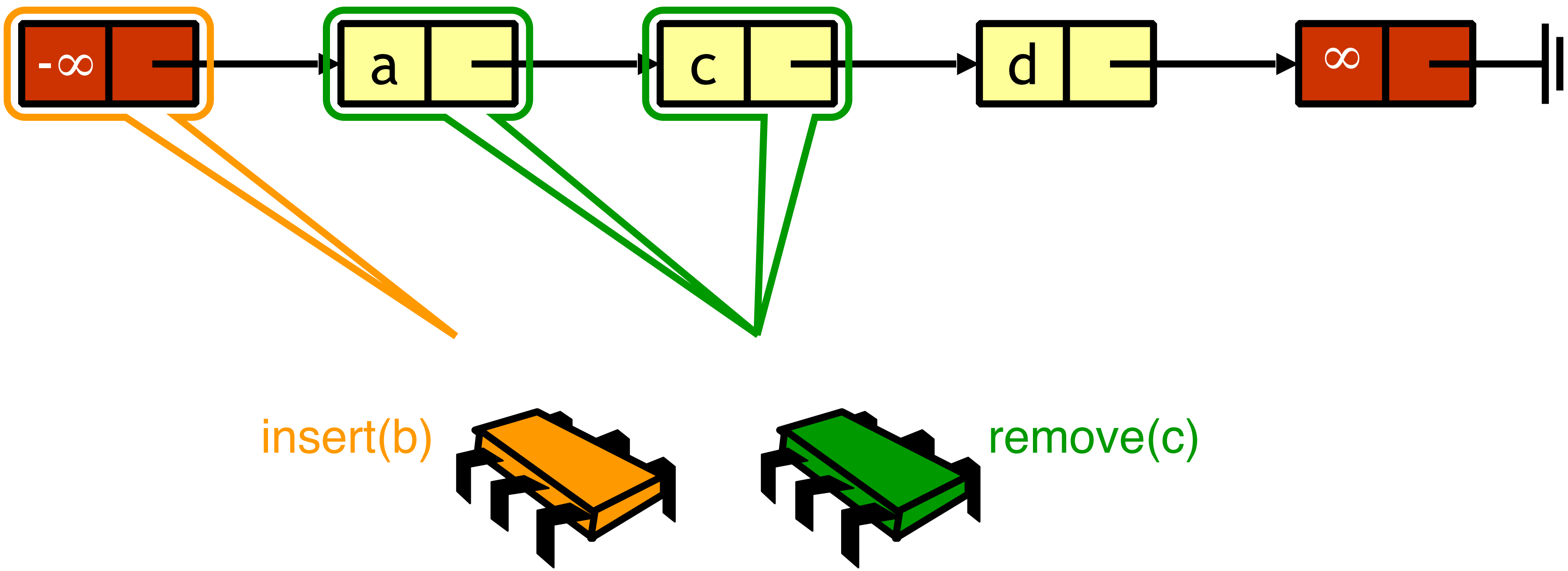

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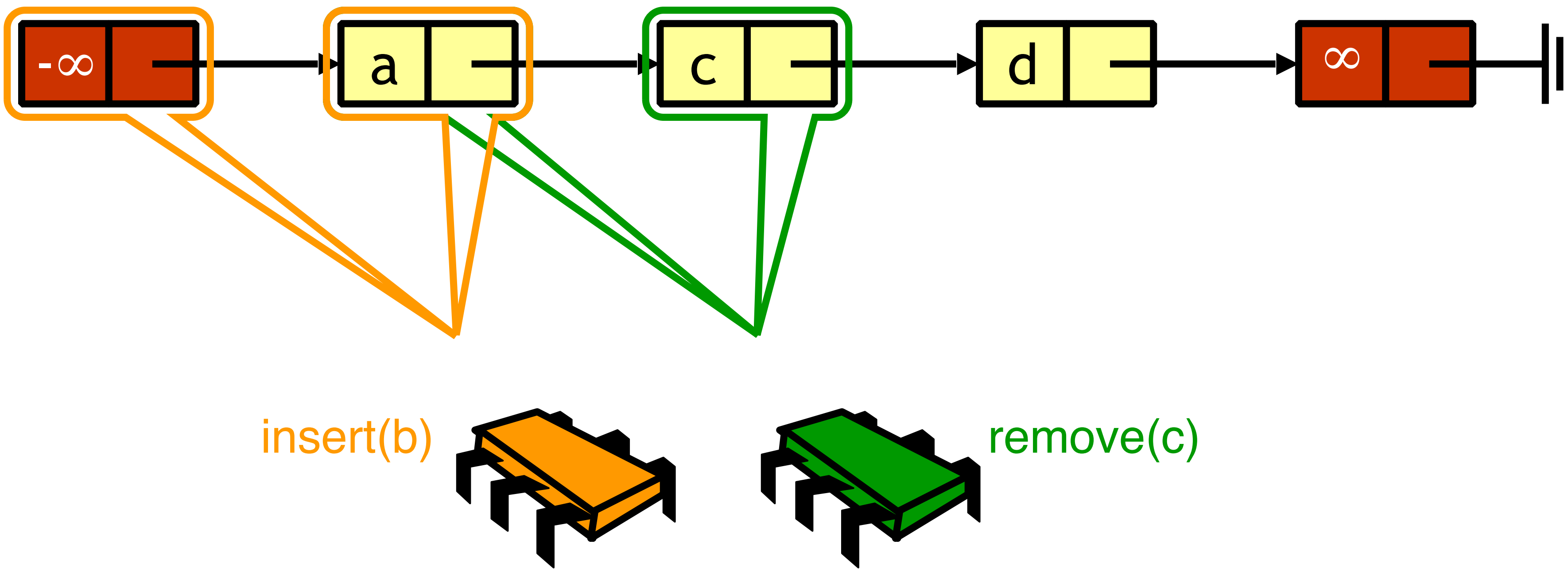

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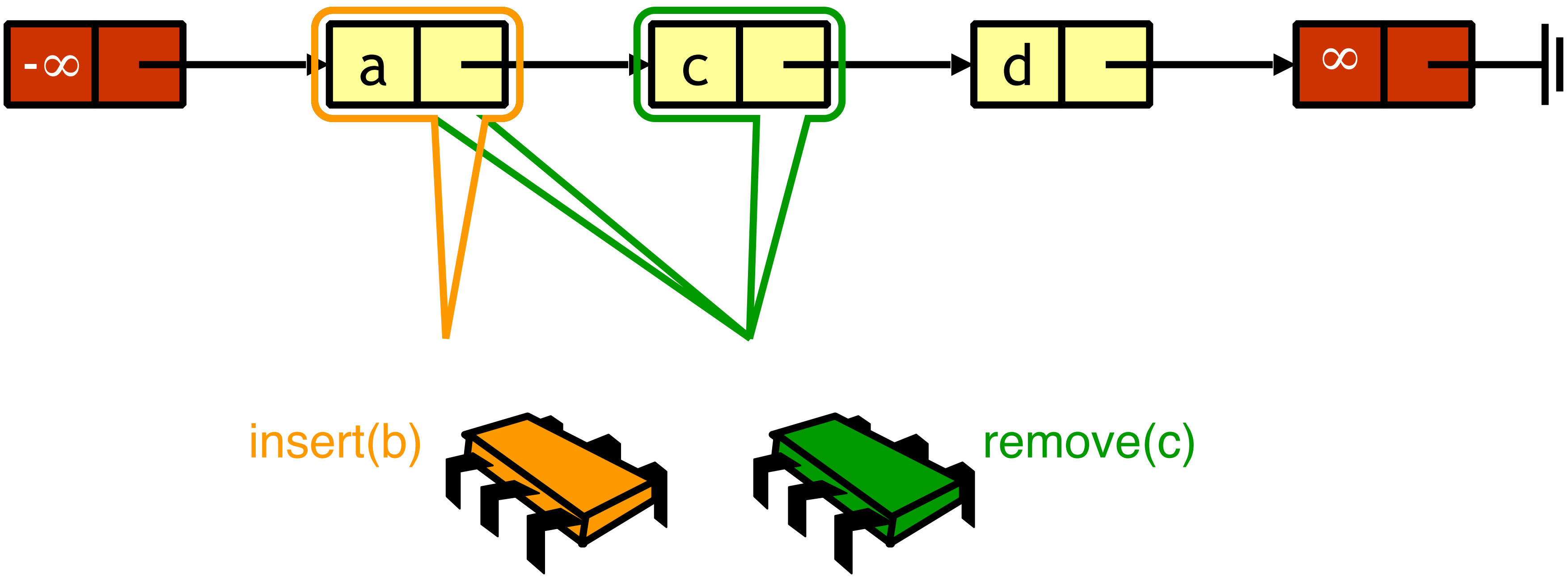

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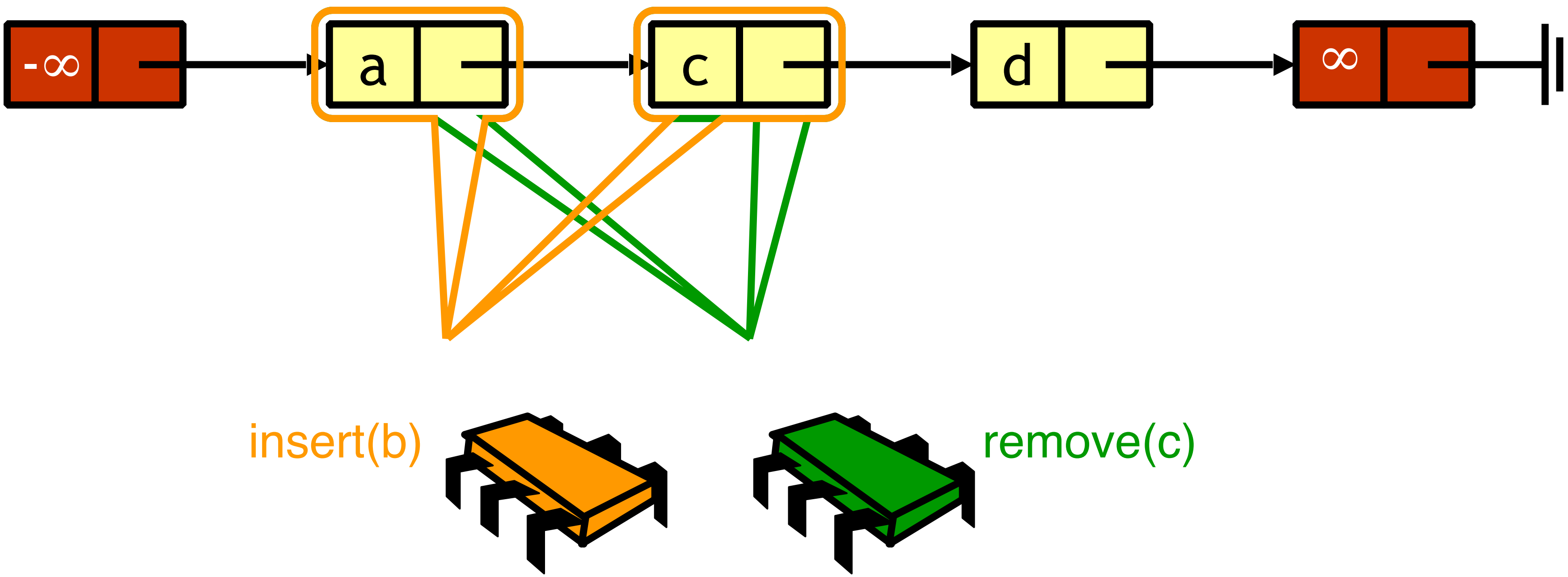

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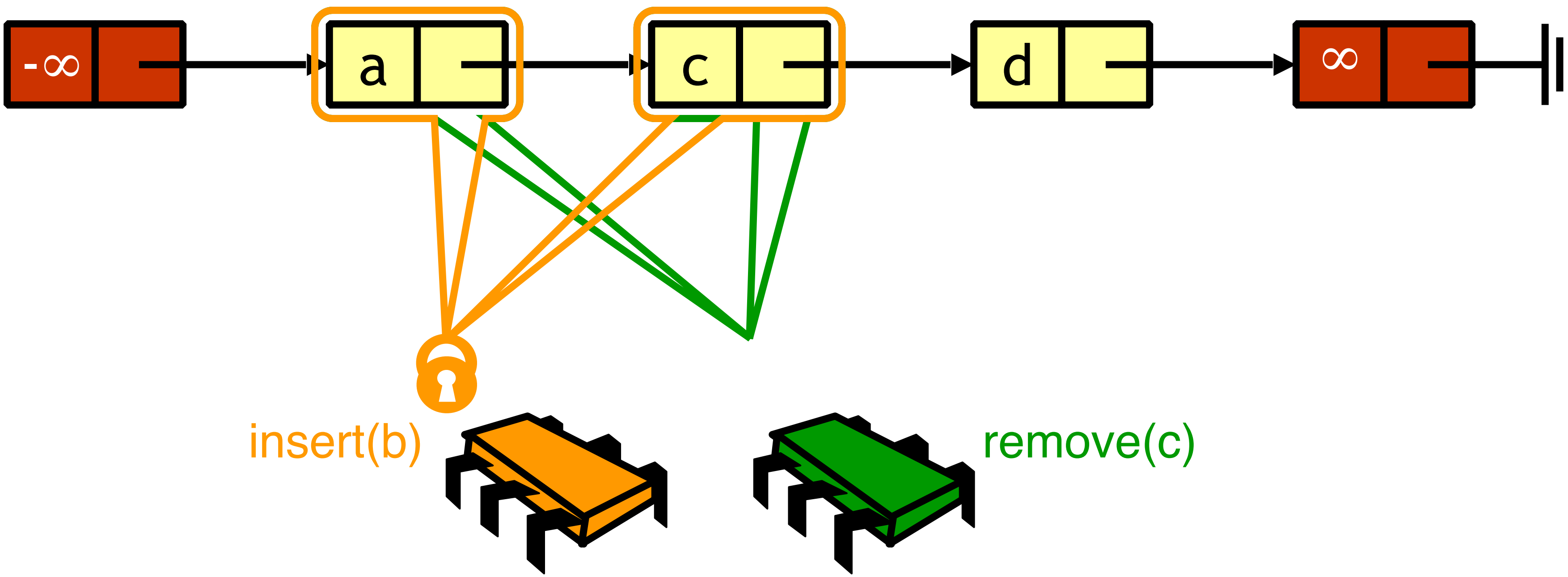

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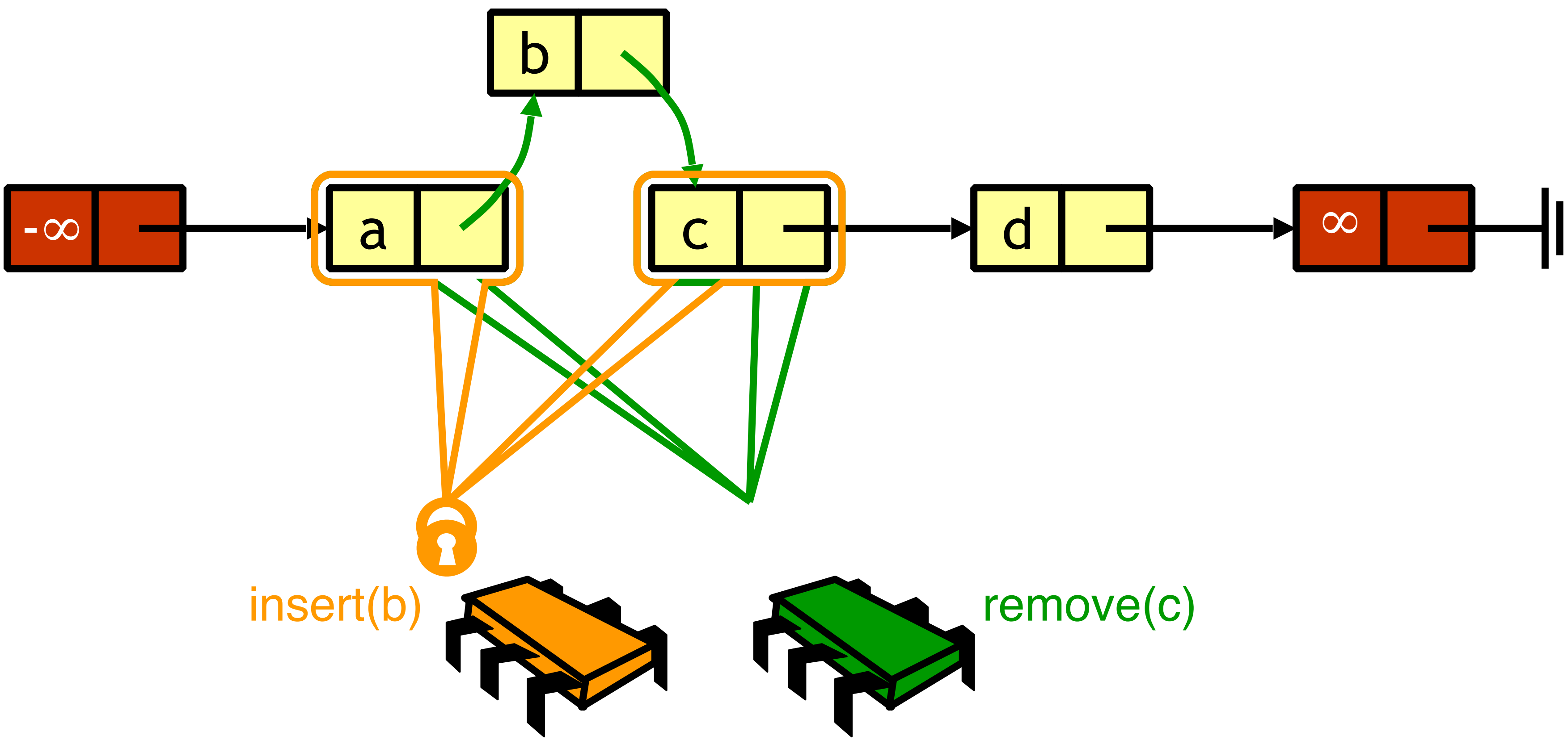

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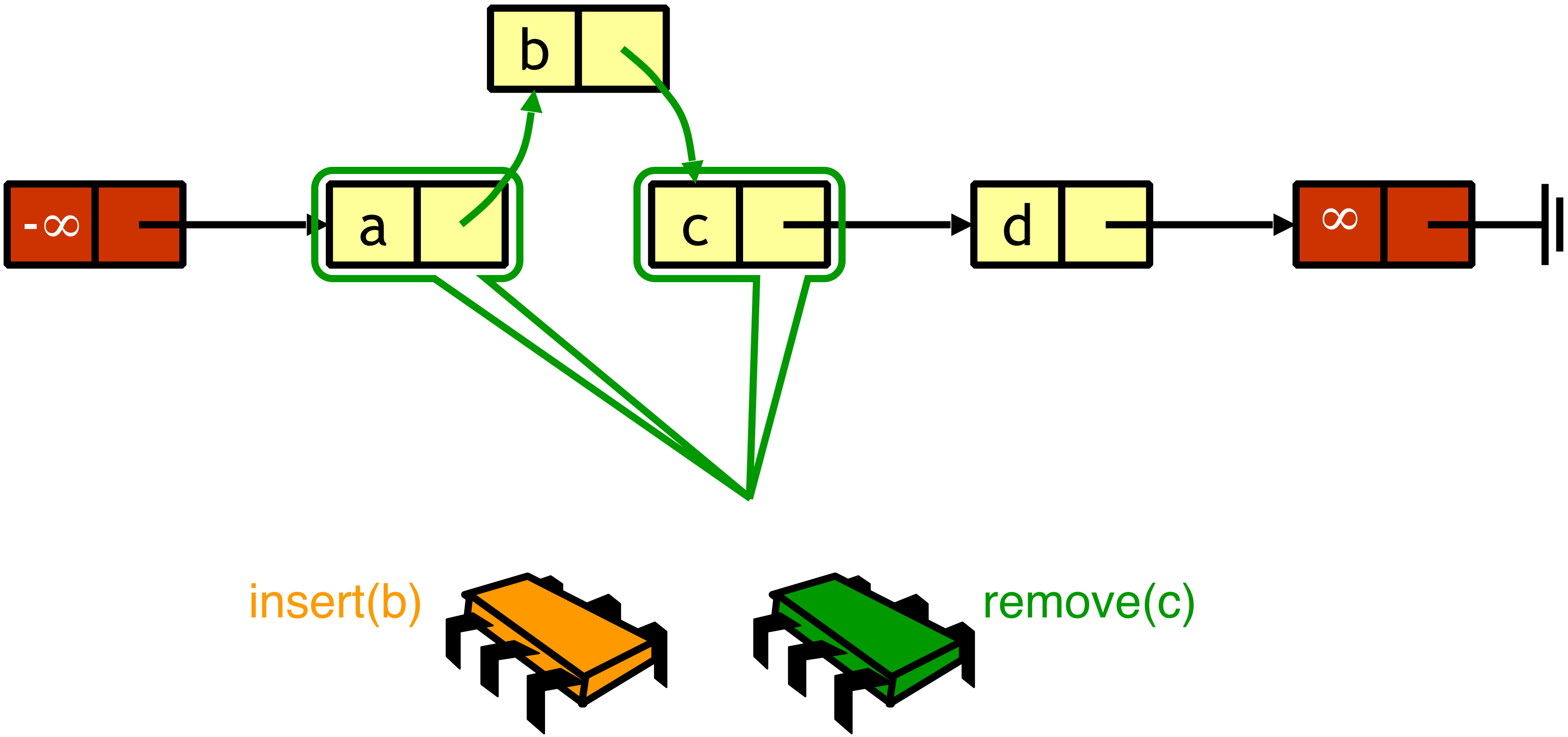

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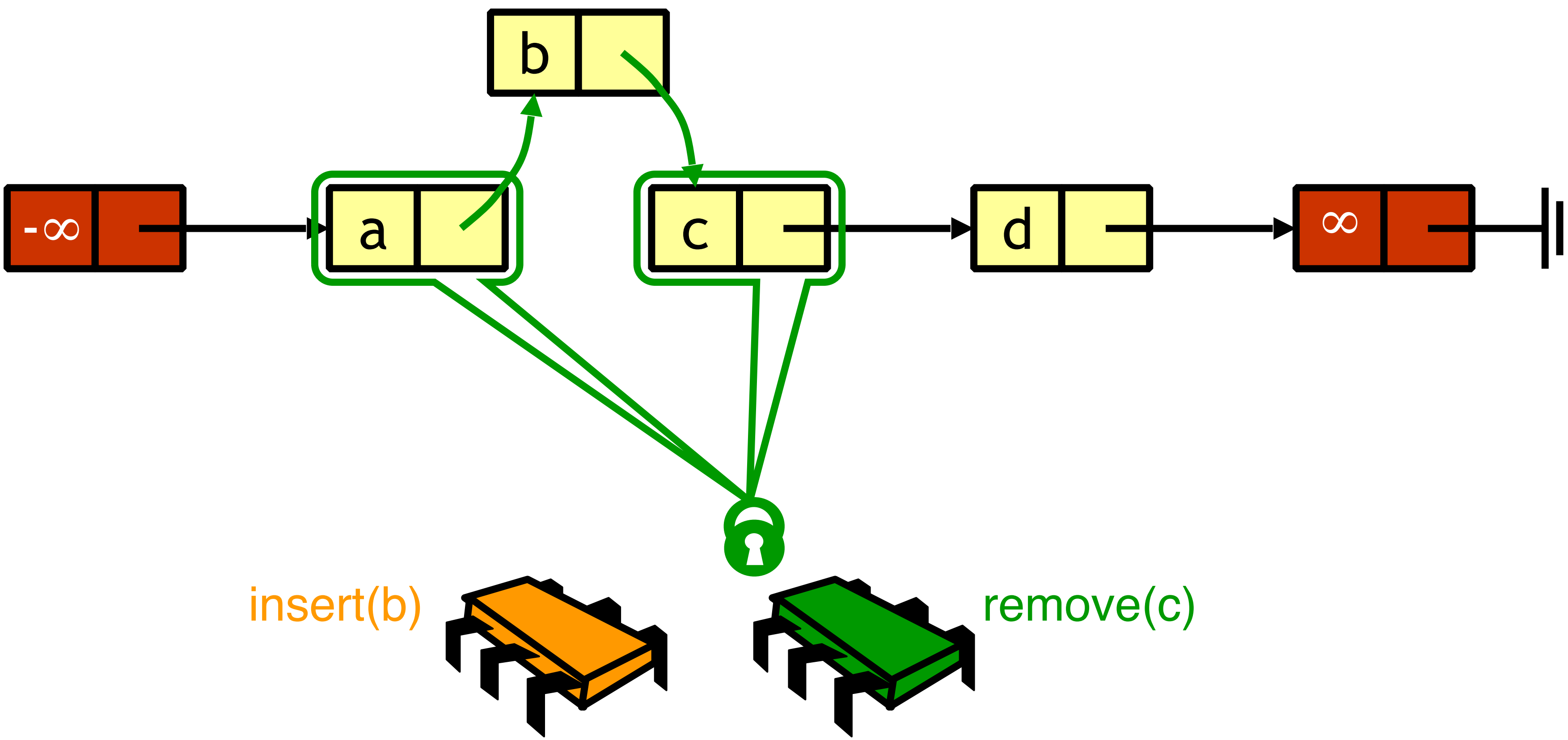

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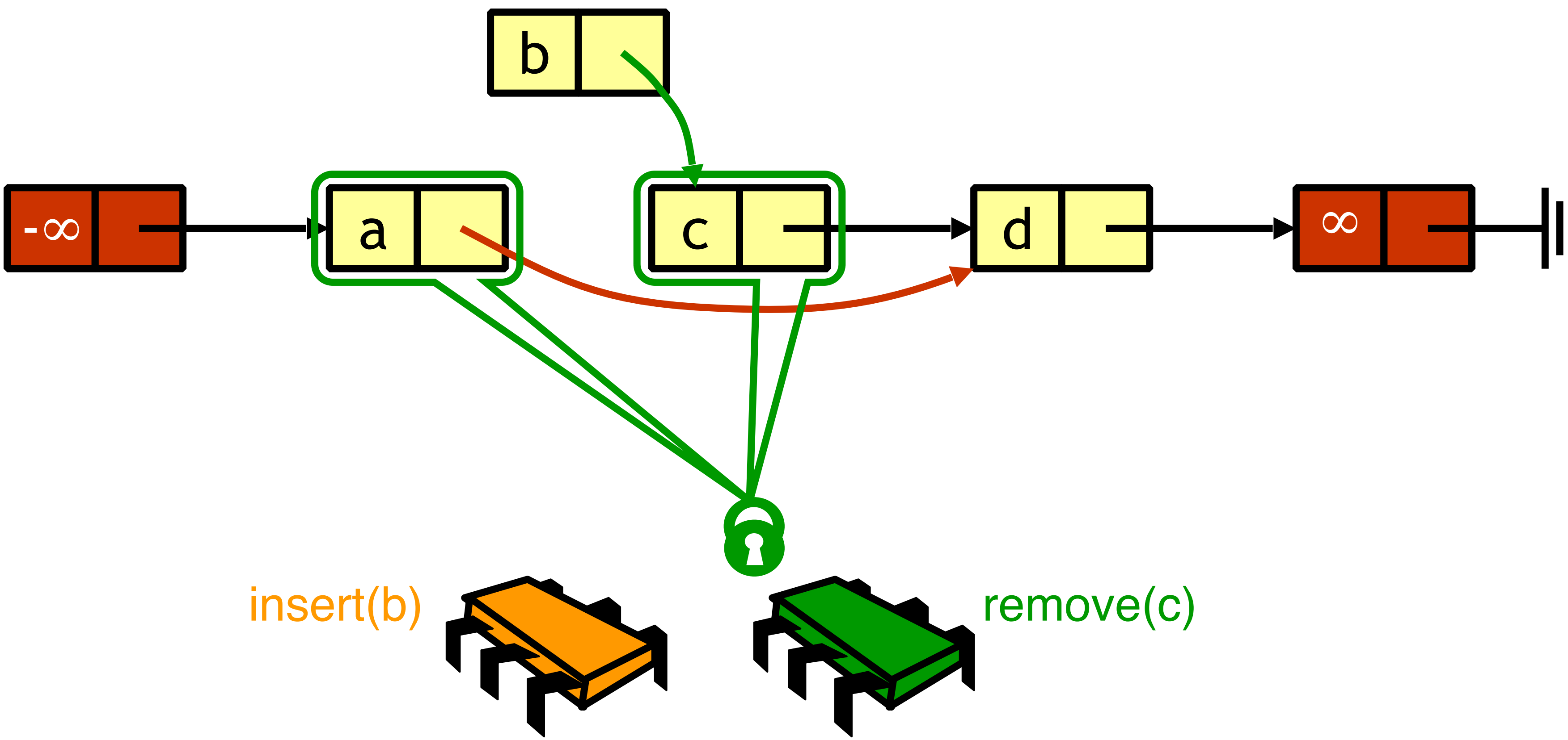

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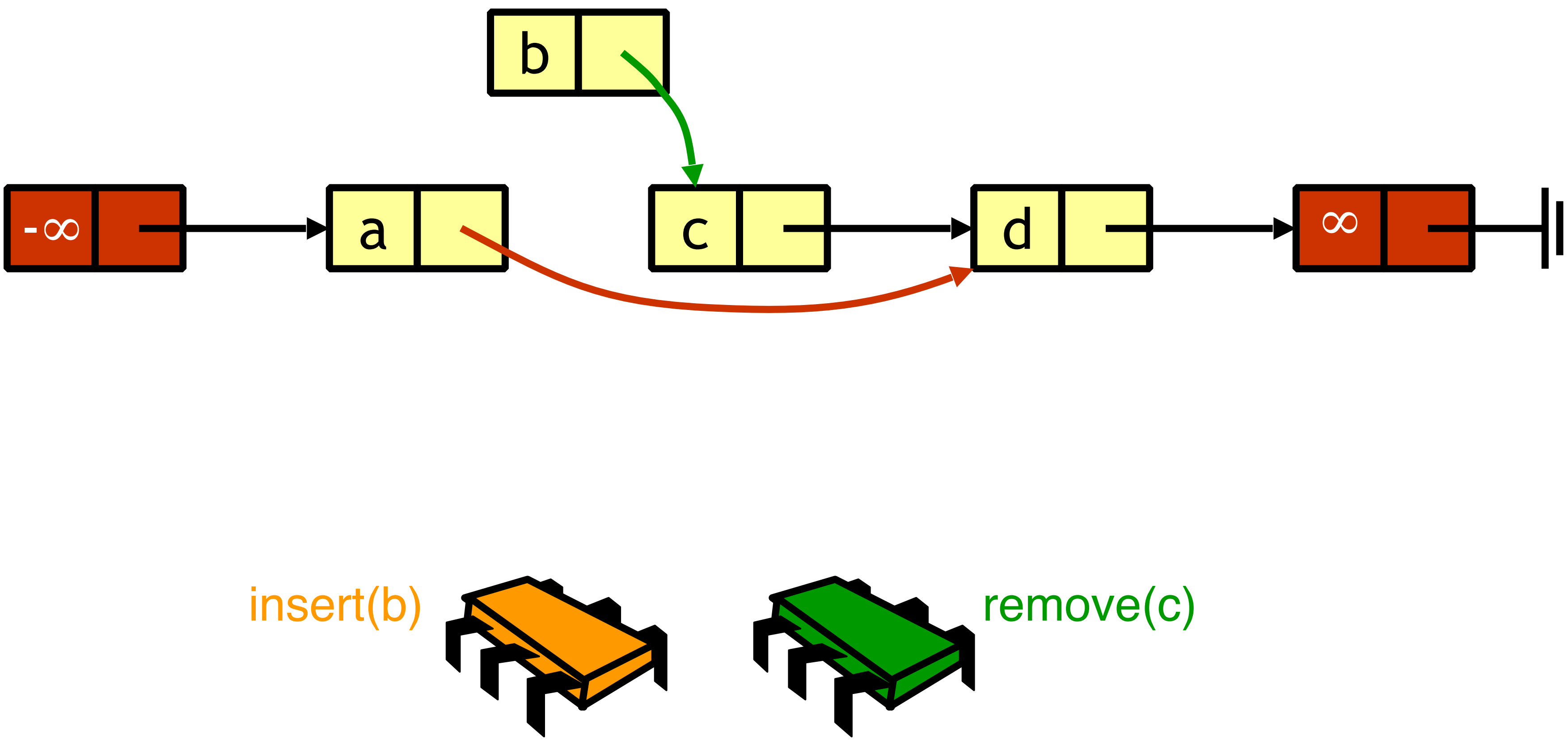

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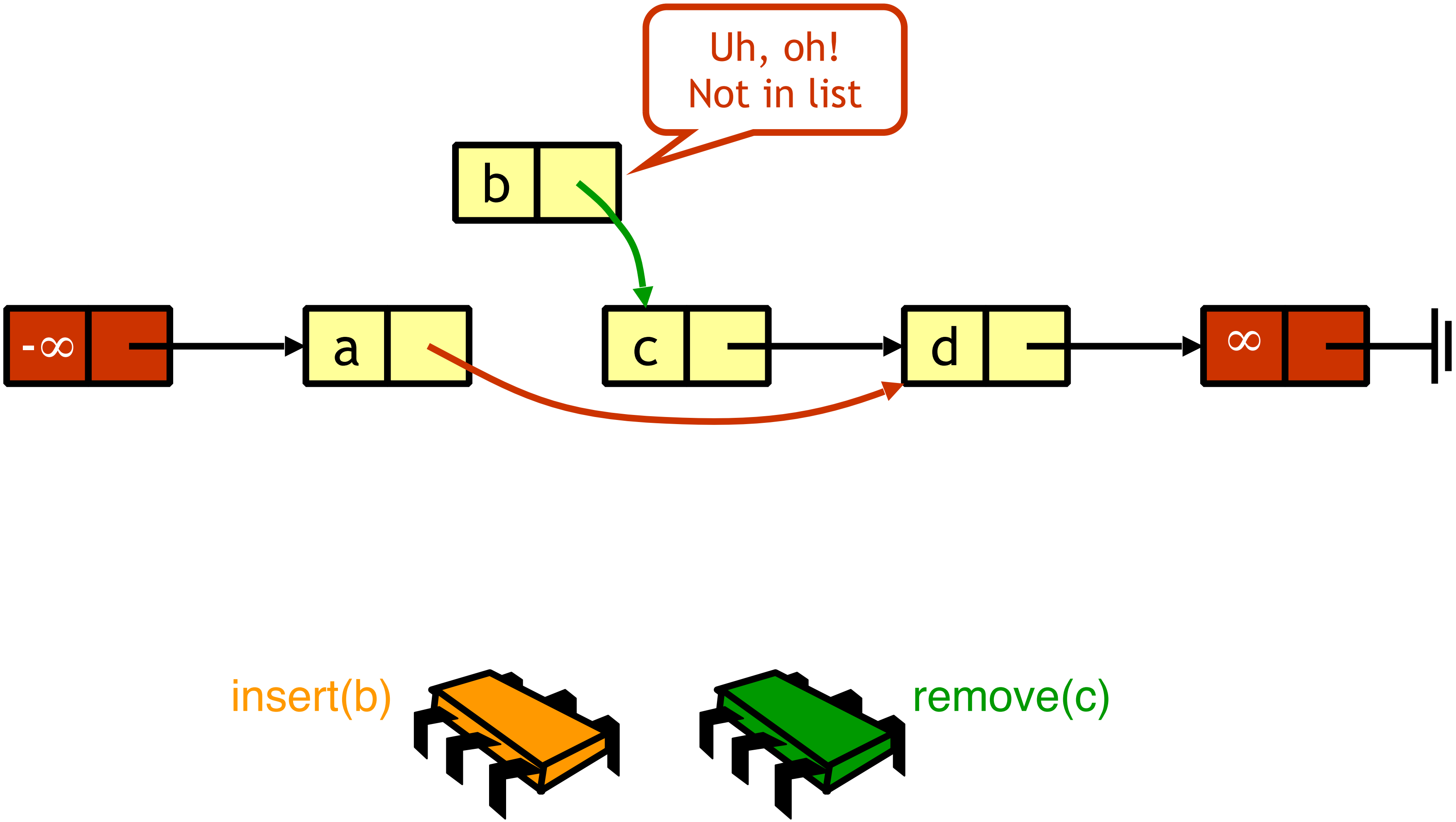

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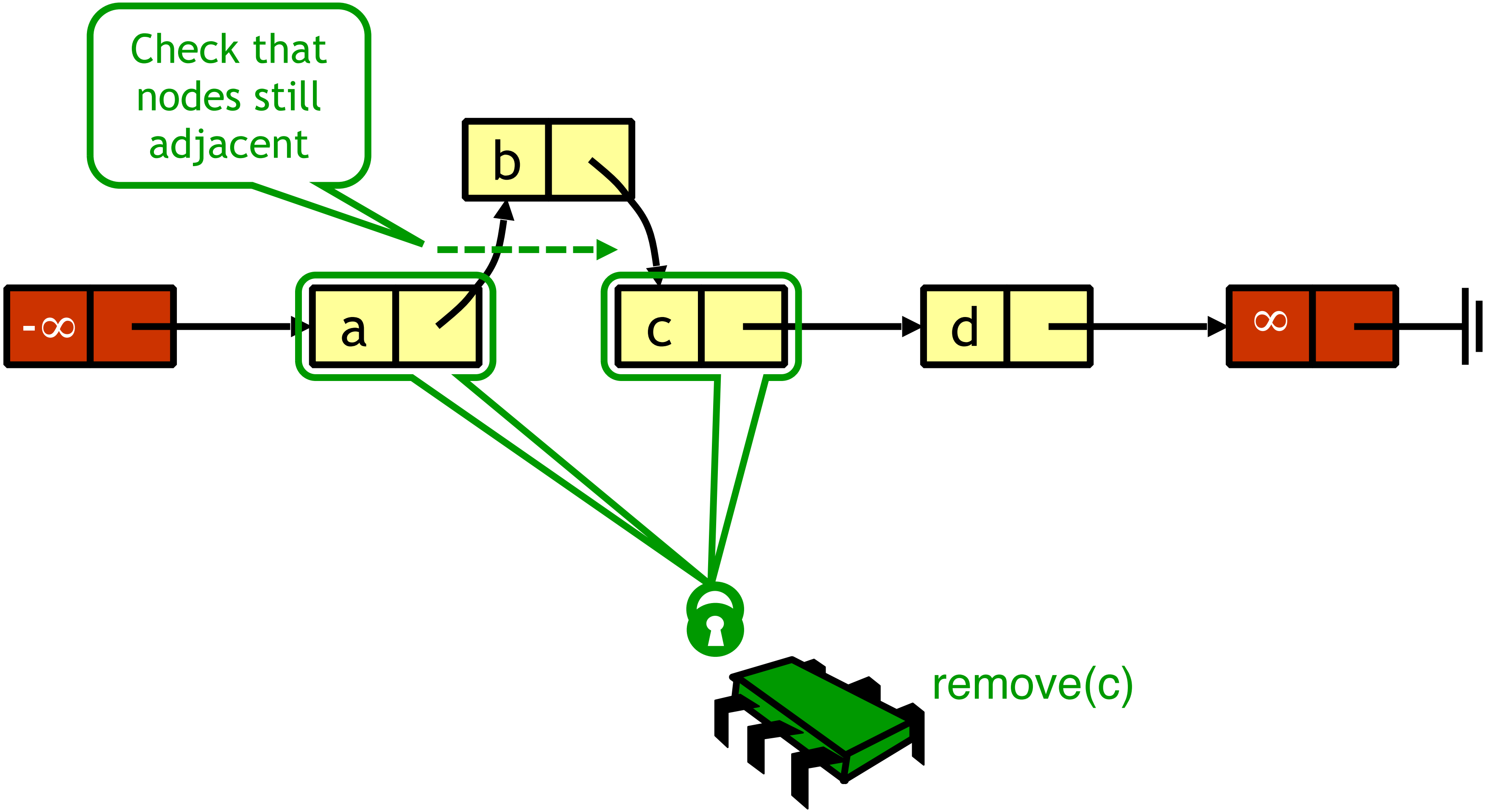
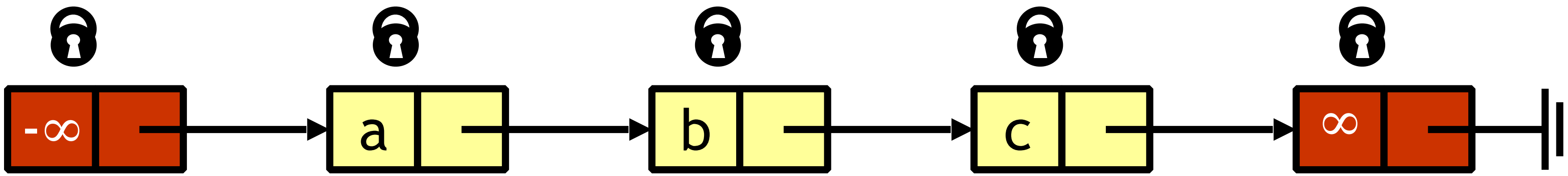
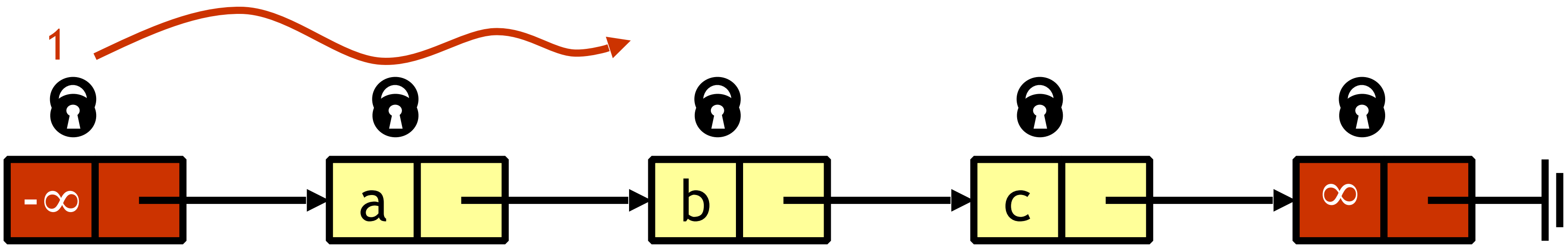


Optimistic Fine Grained



- To remove c
  - Optimistically traverse list to find c
  - Lock c.pred then lock c.curr
  - Re-Traverse list to find c and verify that c.pred precedes c.curr
  - Perform removal and release locks

Optimistic Fine Grained



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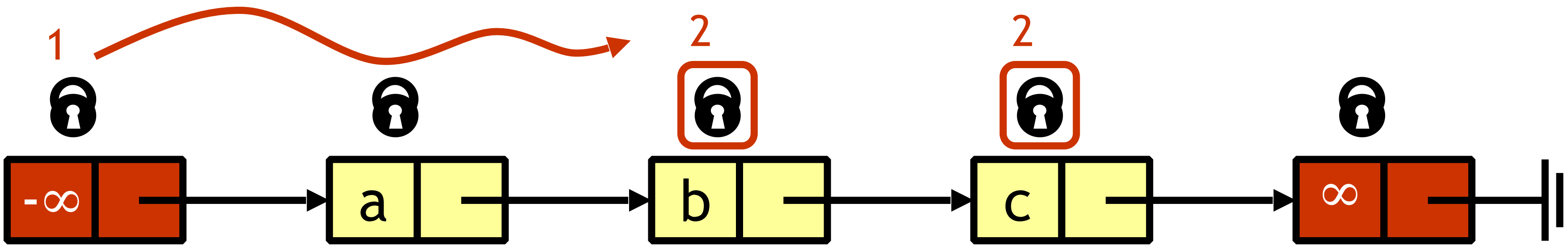

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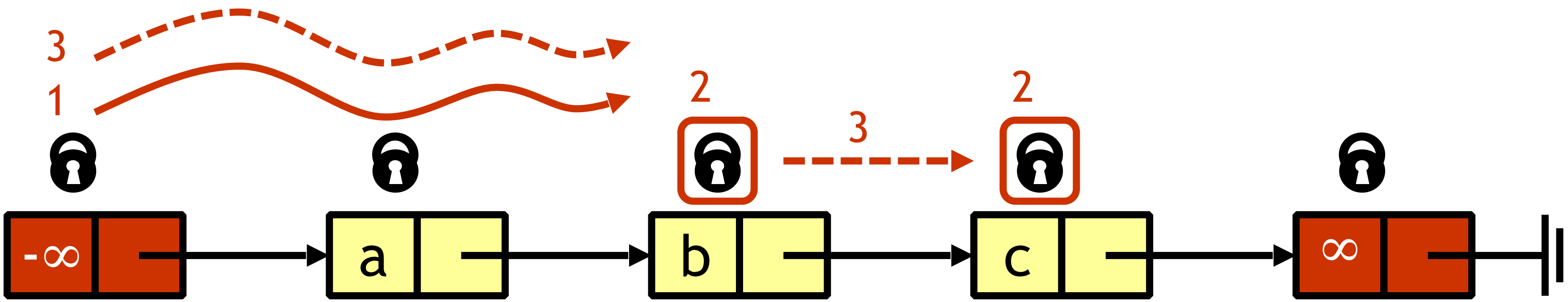

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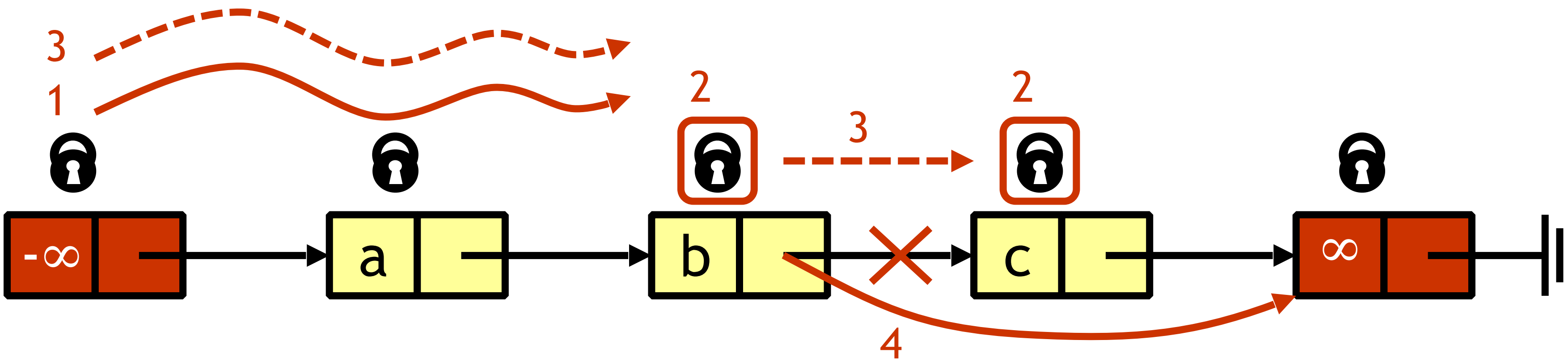
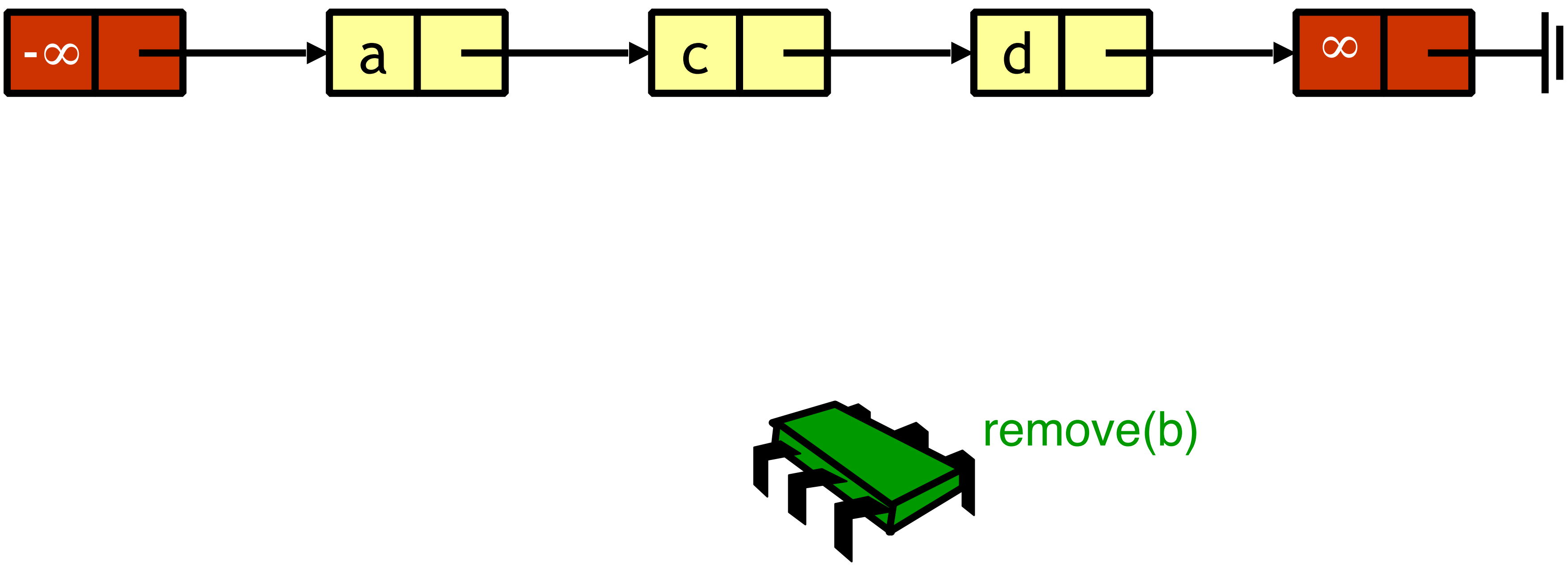


- To remove c
  - Optimistically traverse list to find c
  - Lock c.pred then lock c.curr
  - Re-Traverse list to find c and verify that c.pred precedes c.curr
  - Perform removal and release locks

Correctness

- If
  - Nodes b and c both locked
  - Node b still accessible
  - Node c still successor to b
- Then
  - Neither has been deleted
  - OK to delete c and return true

Removing an Absent Node



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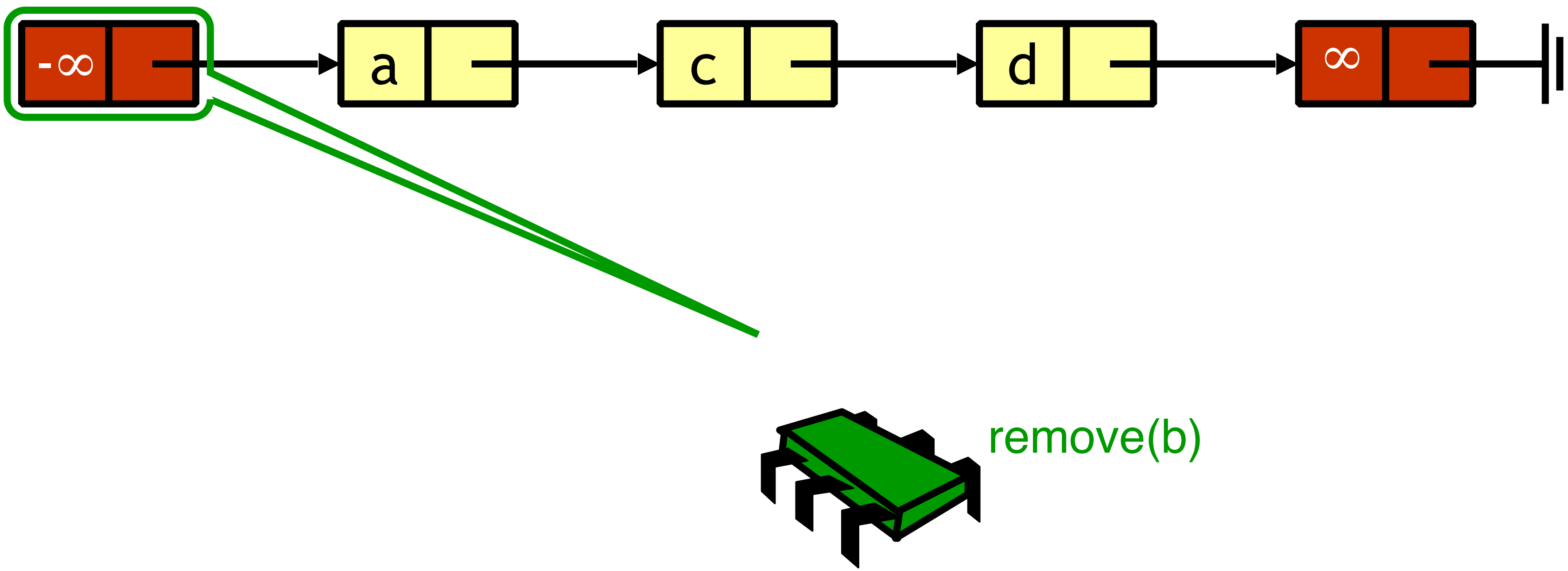

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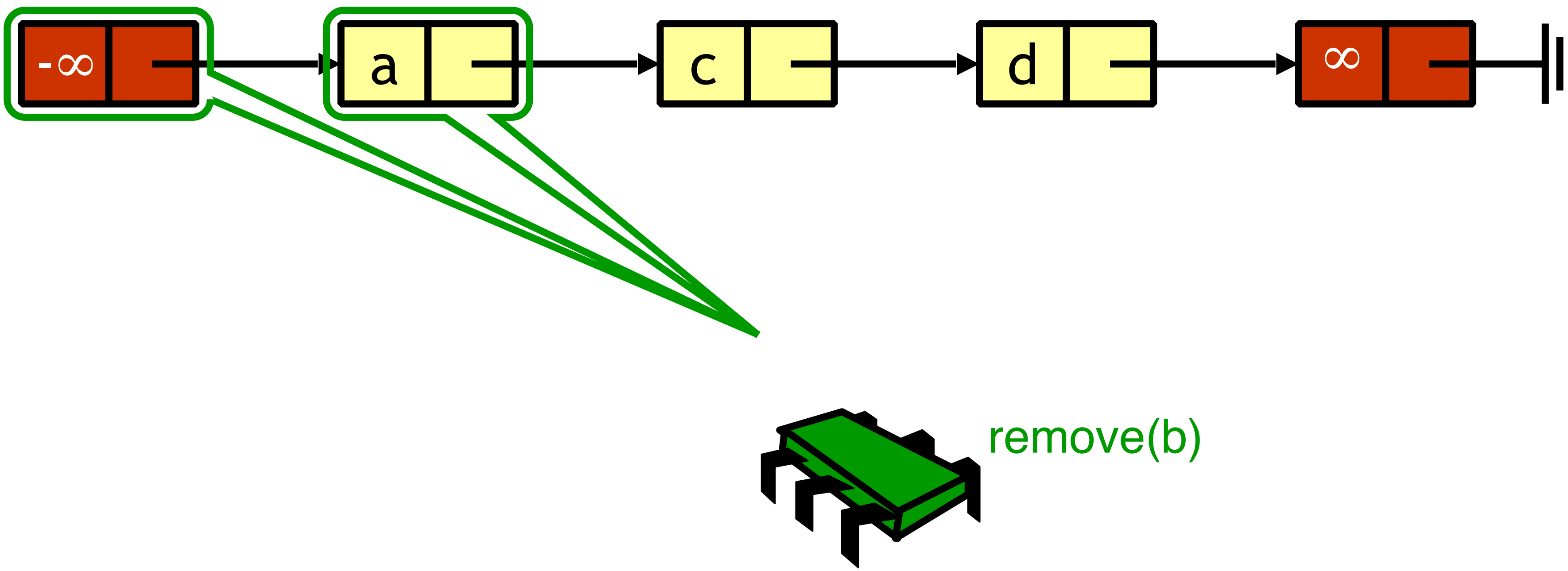

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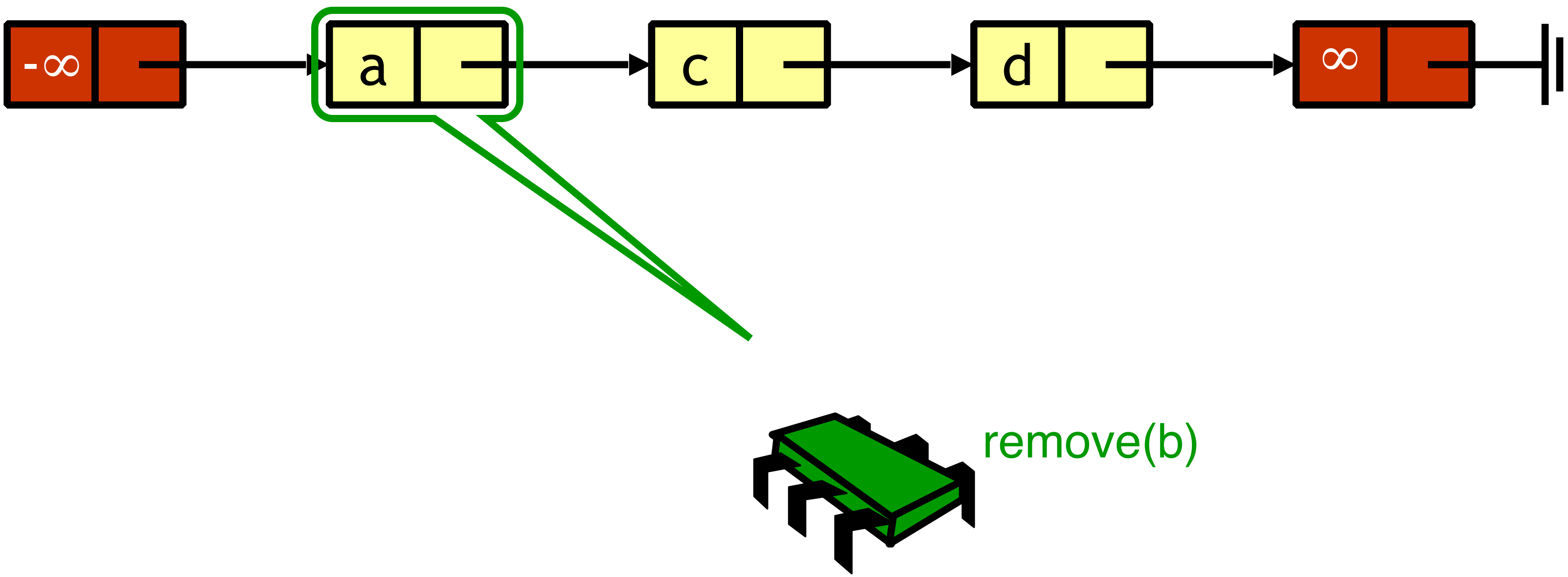

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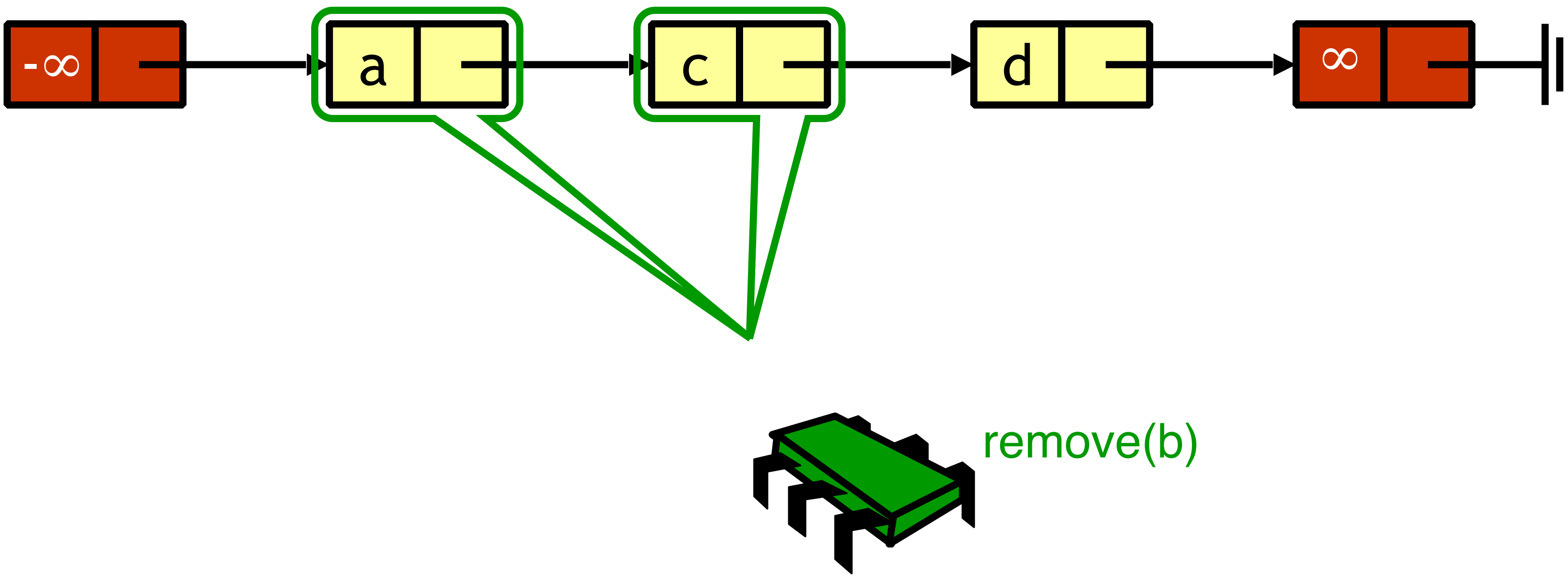

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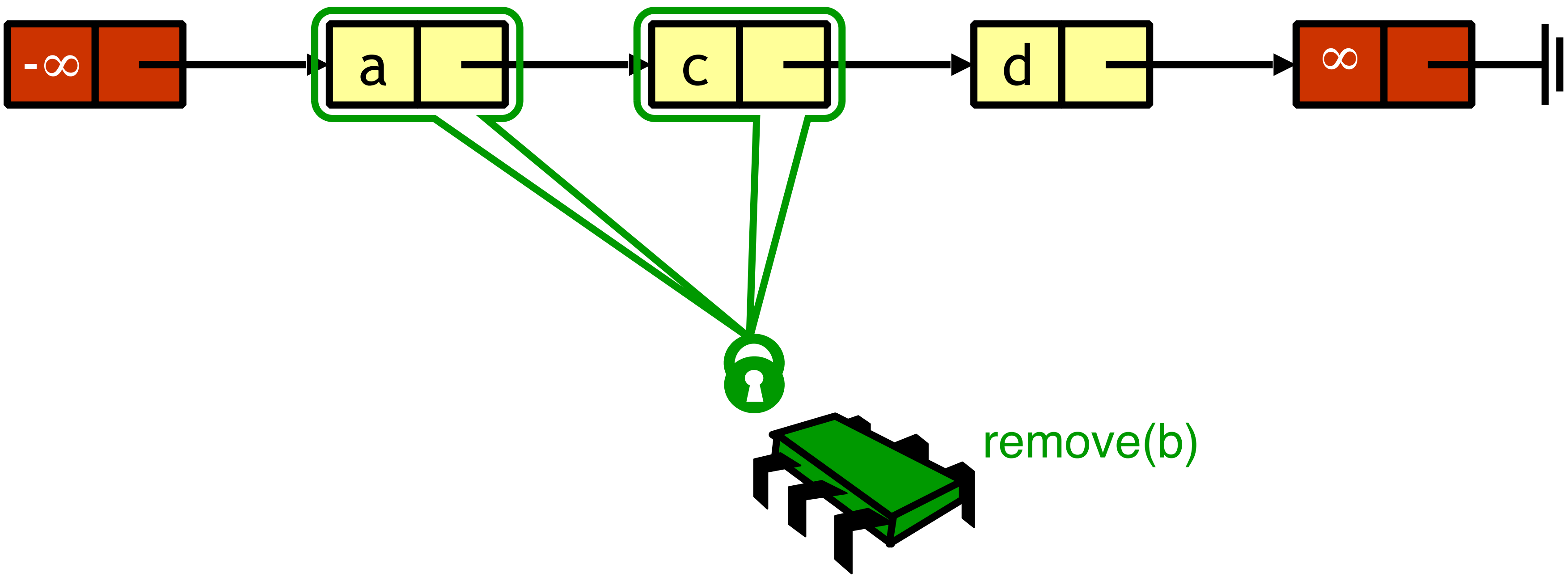

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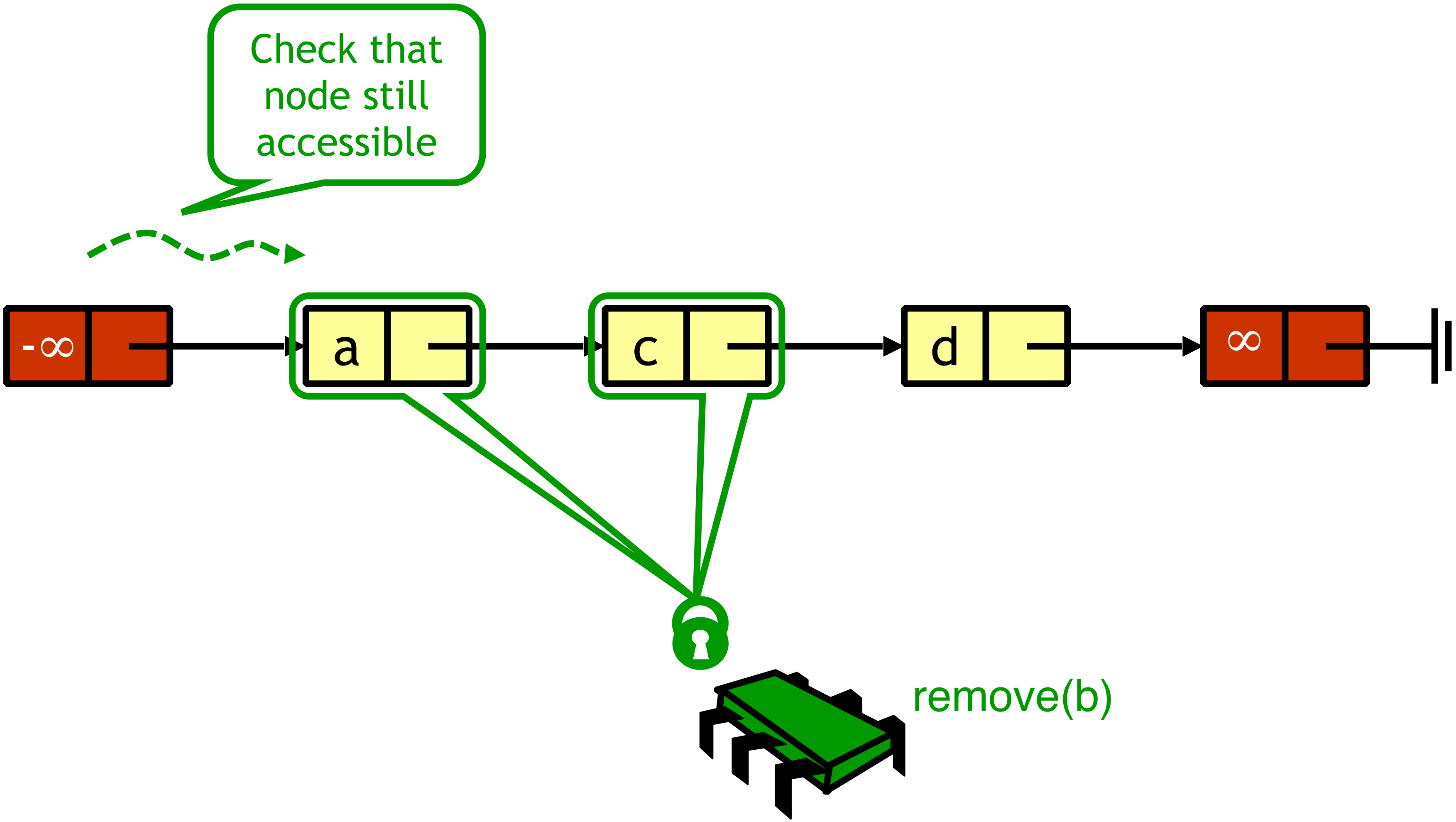

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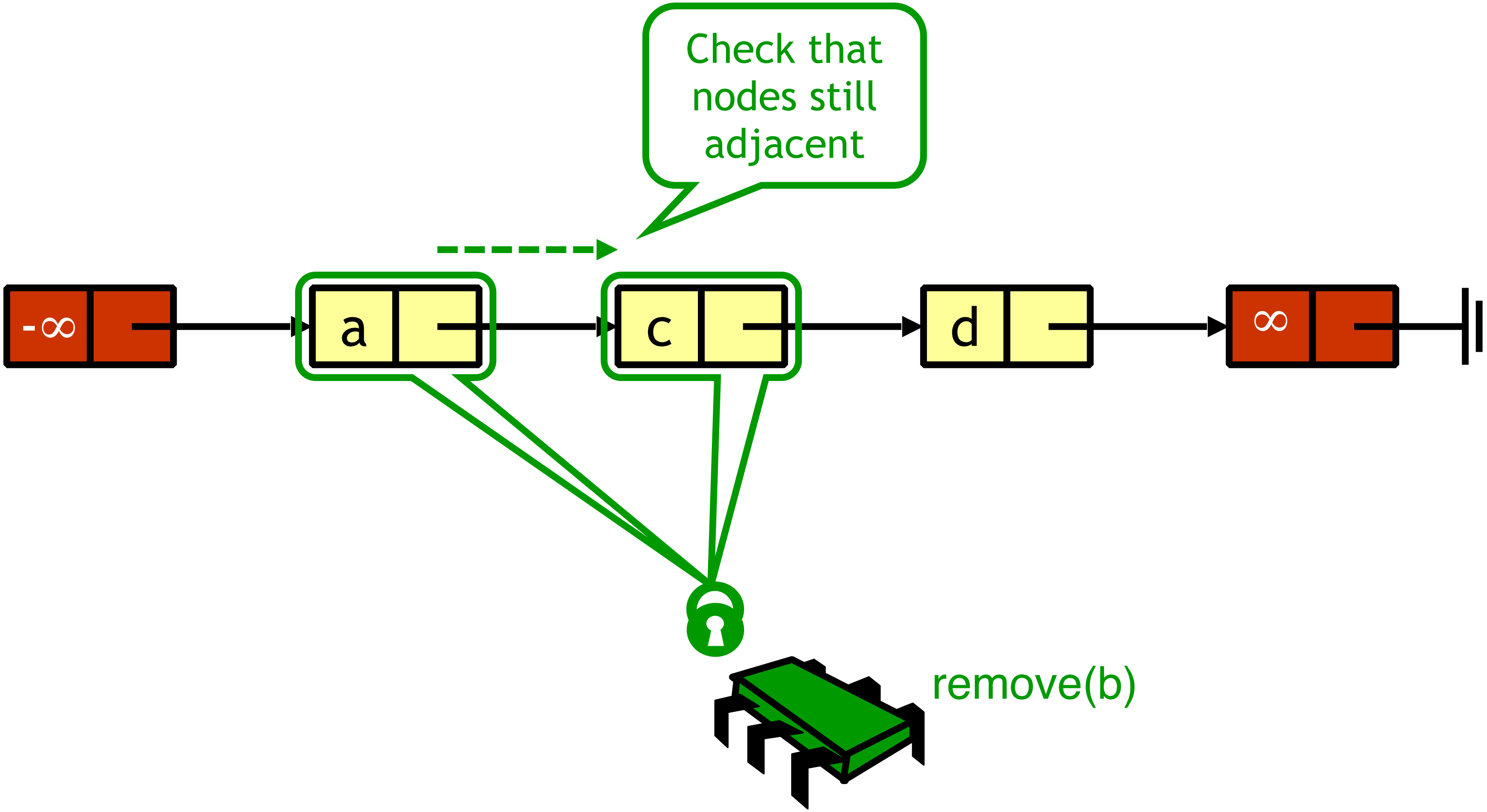
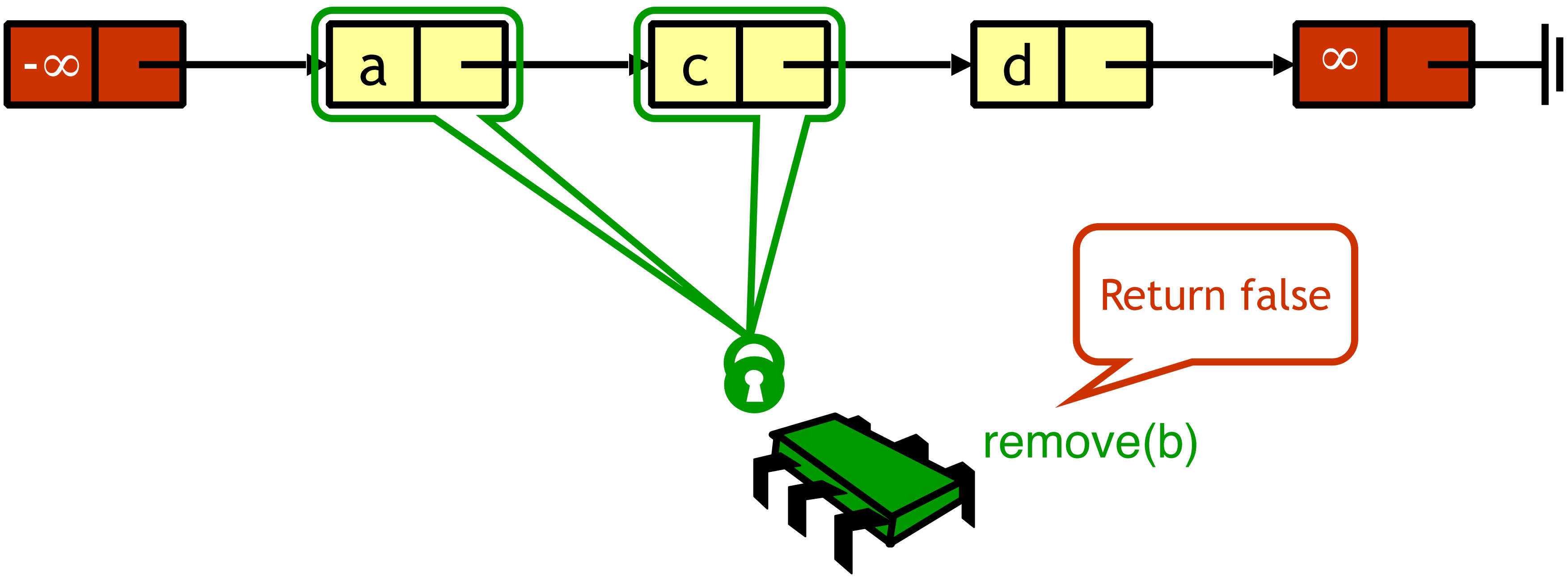


Removing an Absent Node



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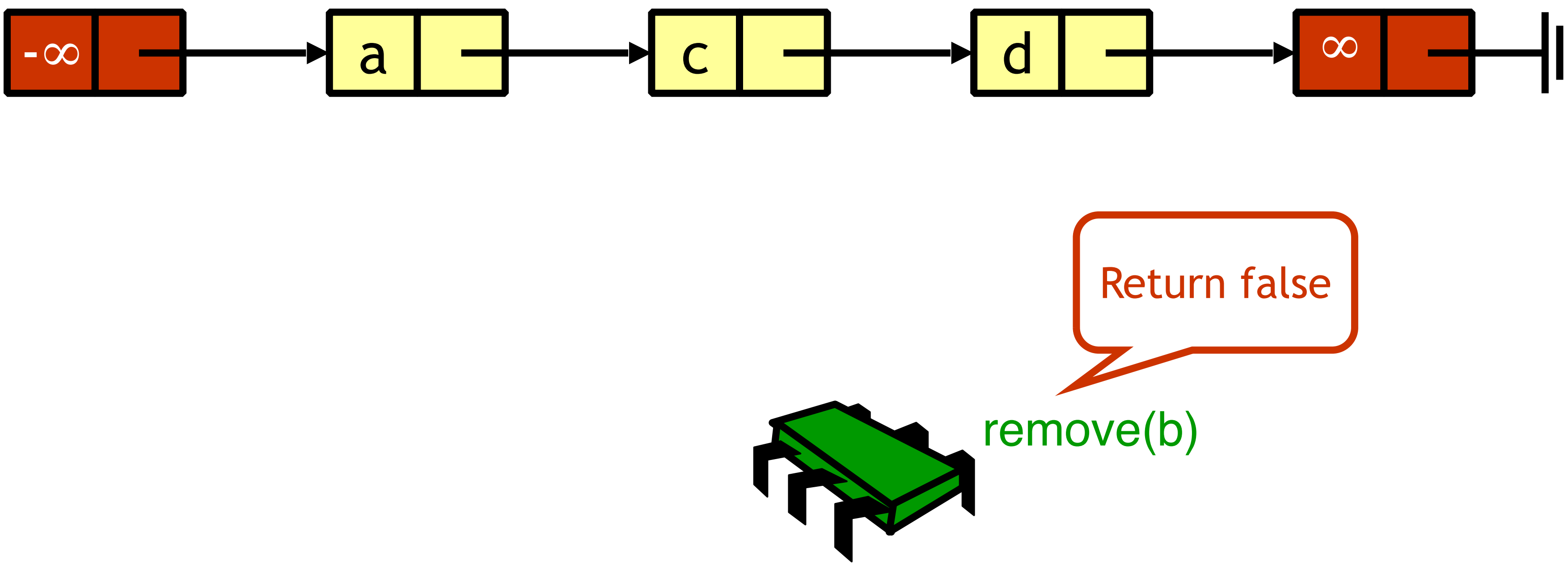


Correctness

- If
  - Nodes a and c both locked
  - Node a still accessible
  - Node c still successor to a
- Then
  - Neither has been deleted
  - No thread can add b after a while a is locked
  - OK to return false

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Predecessor & current nodes

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Start at the beginning

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Search range of keys

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Predecessor reachable?

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Current node next?

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  Node node = head;
  while (node.key <= pred.key) {
    if (node == pred)
      return pred.next == curr;
    node = node.next;
  }
  return false;
}
```

Otherwise move on

Validation

```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
   if (node == pred)
     return pred.next == curr;
   node = node.next;
 }
 return false;
}
```

Predecessor not reachable

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Search key

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Retry on synchronization conflict

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Examine predecessor and current nodes

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Search by key

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Stop if we find object

Remove: Searching

```
public boolean remove(Object object) {
  int key = object.hashCode();
  while (true) {
    Node pred = this.head;
    Node curr = pred.next;
    while (curr.key <= key) {
      if (object == curr.object)
        break;
      pred = curr;
      curr = curr.next;
    }
    …
```

Move along

On Exit from Loop

- If object is present
  - curr holds object
  - pred just before curr
- If object is absent
  - curr has first higher key
  - pred just before curr
- Assuming no synchronization problems

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr)) {
    if (curr.object == object) {
      pred.next = curr.next;
      return true;
    } else
      return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr)) {
    if (curr.object == object) {
      pred.next = curr.next;
      return true;
    } else
      return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Always unlock

Remove

```
try {
 pred.lock(); curr.lock();
 if (validate(pred, curr)) {
   if (curr.object == object) {
     pred.next = curr.next;
     return true;
   } else
     return false;
 }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Lock both nodes

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr)) {
    if (curr.object == object) {
      pred.next = curr.next;
      return true;
    } else
      return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Check for synchronization conflicts

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr)) {
    if (curr.object == object) {
      pred.next = curr.next;
      return true;
    } else
      return false;
  }
} finally {
     pred.unlock(); curr.unlock();
} …
```

Object found,
remove node

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr)) {
    if (curr.object == object) {
      pred.next = curr.next;
      return true;
    } else
      return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Object not found

Summary: Optimistic List

- Wait-free traversal
  - May traverse removed nodes
  - Must have non-interference (natural in languages with GC like Java)
- Limited hotspots
  - Only at locked add(), remove(), contains() destination locations, not traversals
- But two traversals
  - Yet traversals are wait-free

So Far, So Good

- Much less lock acquisition/release
  - Performance
  - Concurrency
- Problems
  - Need to traverse list twice
  - contains() acquires locks
    - Most common method call (90% in many applications)
- Optimistic works if
  - Cost of scanning twice without locks <
    cost of scanning once with locks

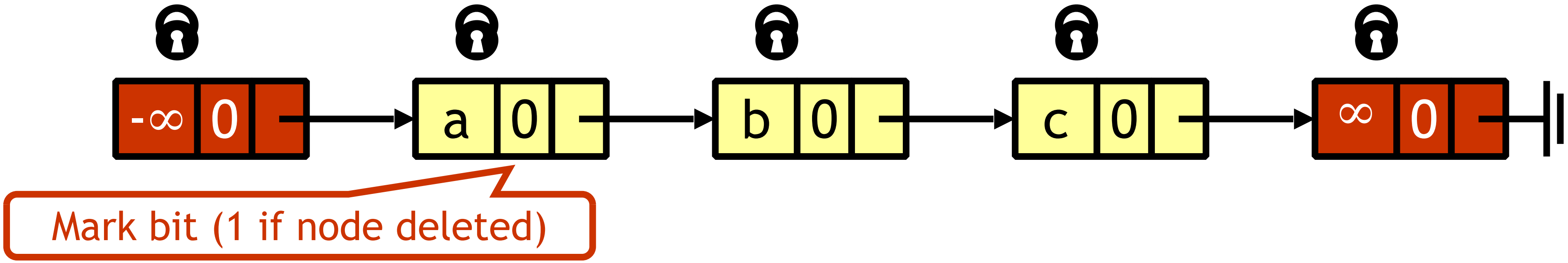
Lazy List

- Like optimistic, except
  - Scan once
  - contains() never locks
- Key insight
  - Removing nodes causes trouble
  - Do it “lazily”

Lazy List

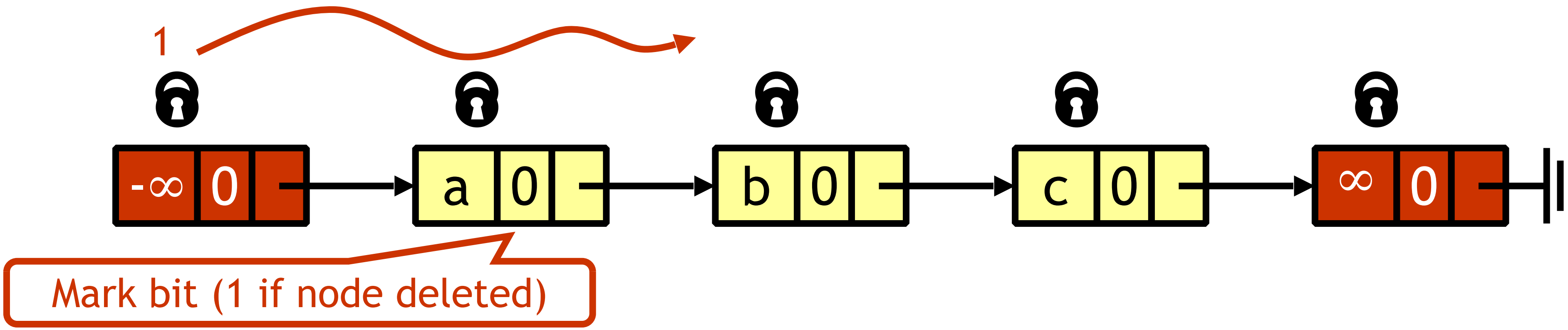
- Remove Method
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
  - Use additional mark bit in node
- Physical delete
  - Redirects predecessor's next (as before)

Lazy Removal



- To remove c
  - Optimistically traverse list to find c
  - Lock c.pred then lock c.curr
  - Verify marks and that c.pred precedes c.curr
  - Set mark bit (logical removal)
  - Perform physical removal and release locks

Lazy Removal



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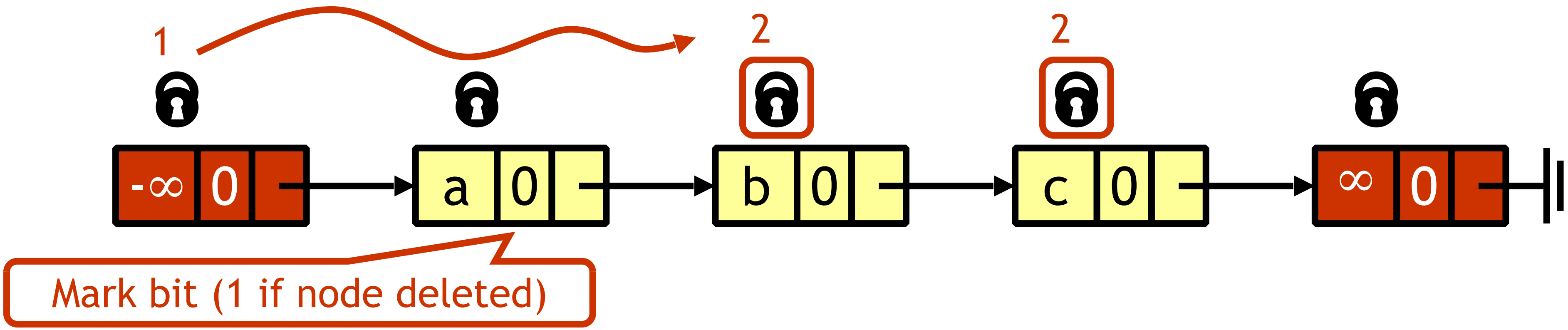

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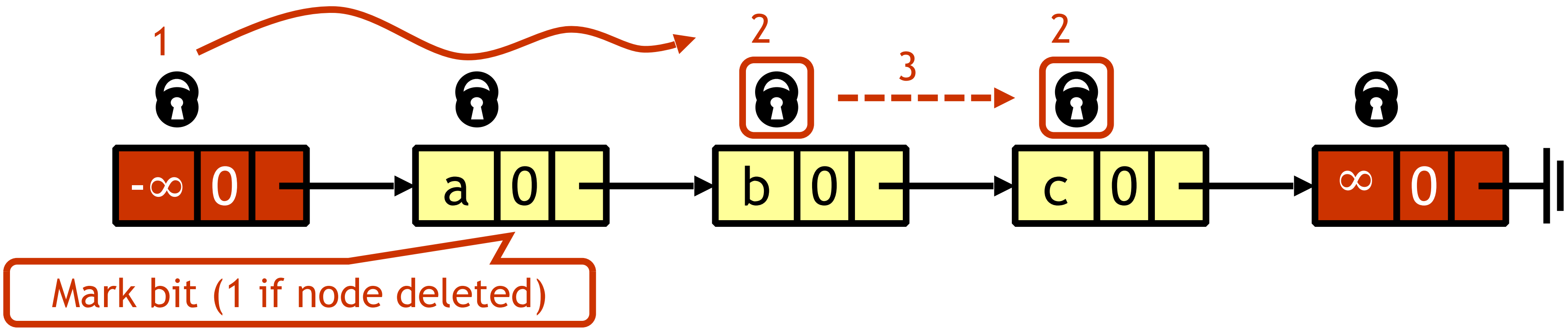

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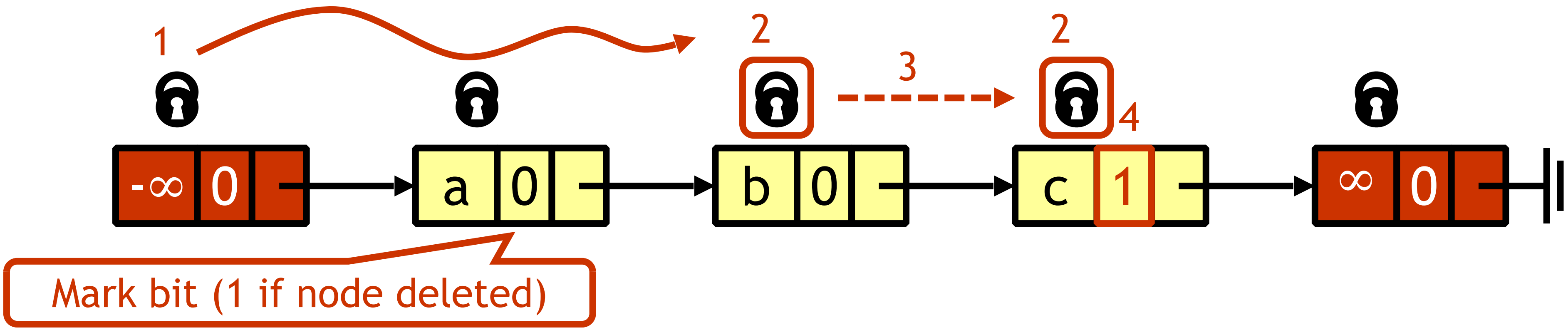

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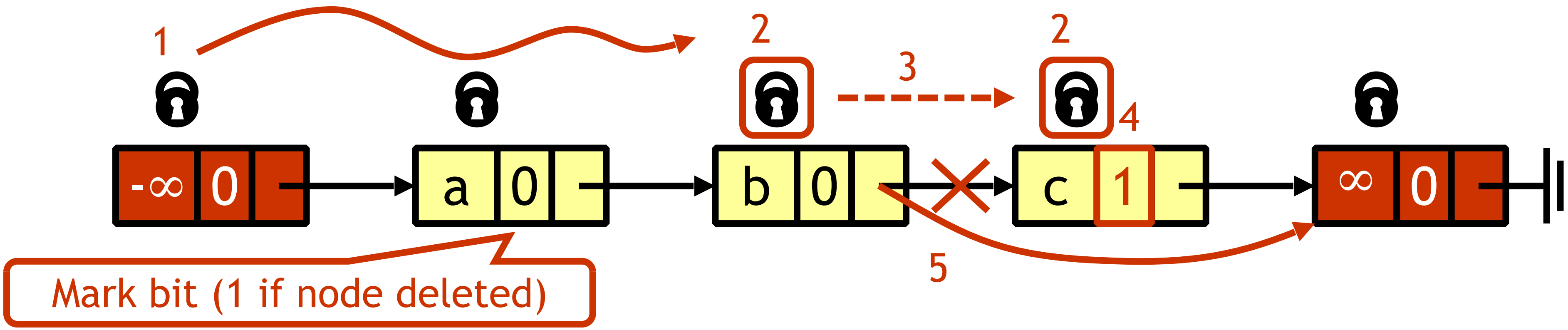

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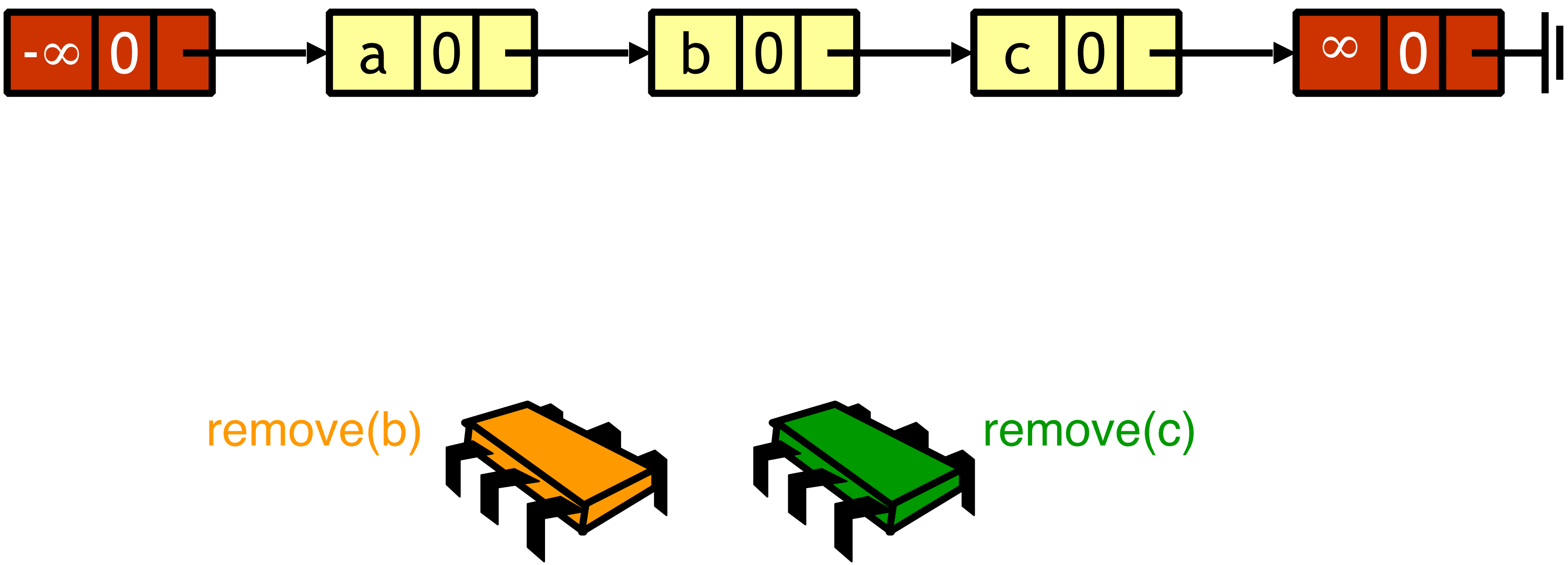
  - Set mark bit (logical removal)
  - Perform physical removal and release locks

Lazy List

- All Methods
  - Scan through locked and marked nodes
  - Removing a node does not slow down other method calls…
  - Must still lock pred and curr nodes
- Validation
  - No need to rescan list!
  - Check that pred is not marked
  - Check that curr is not marked
  - Check that pred points to curr

What Could Go Wrong?



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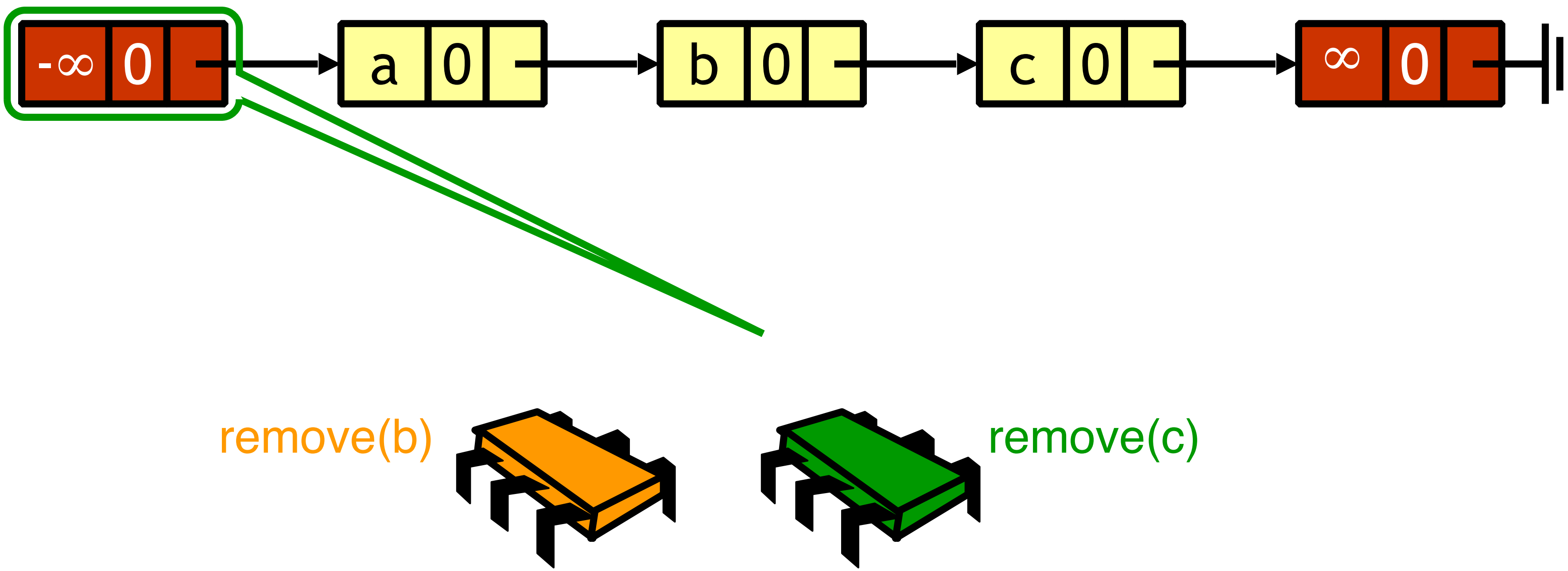

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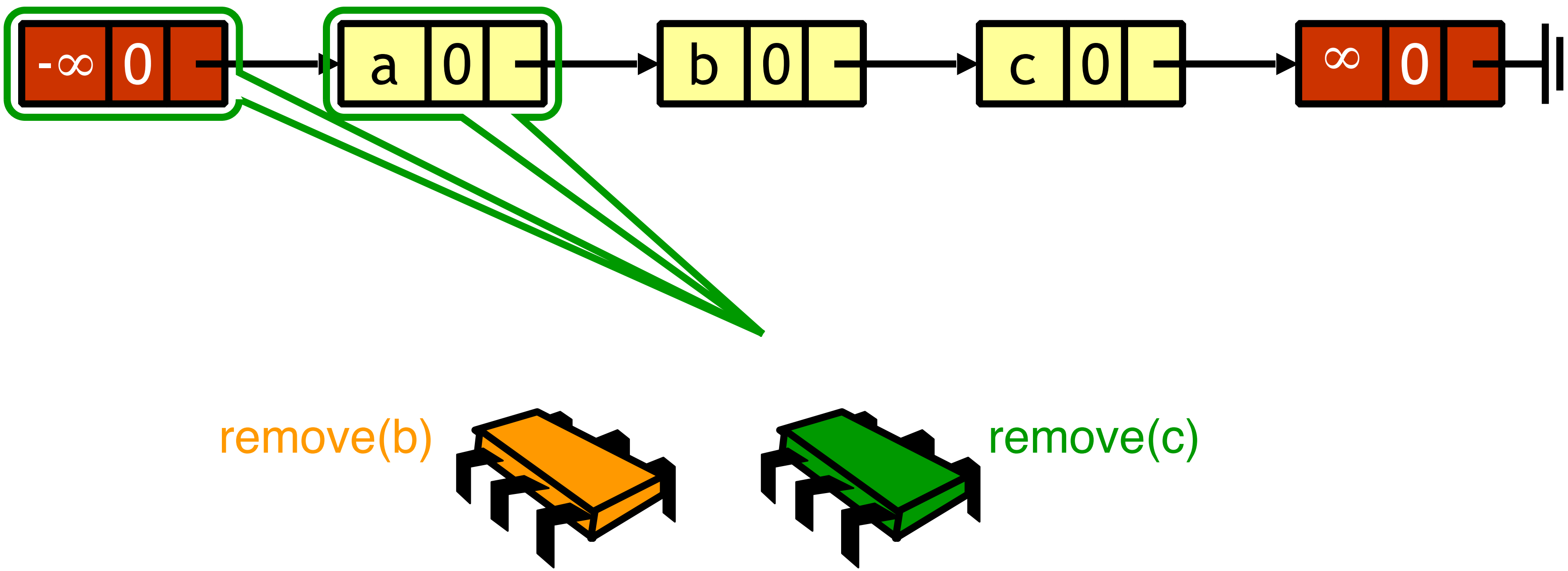

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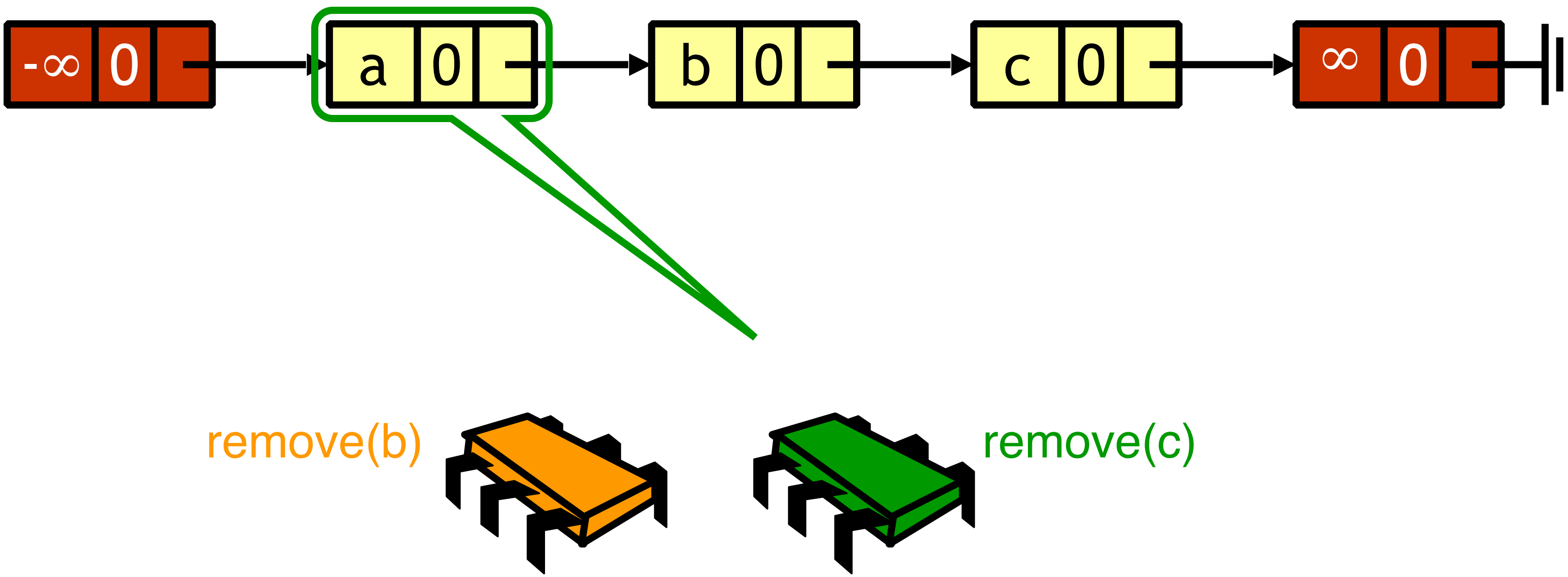

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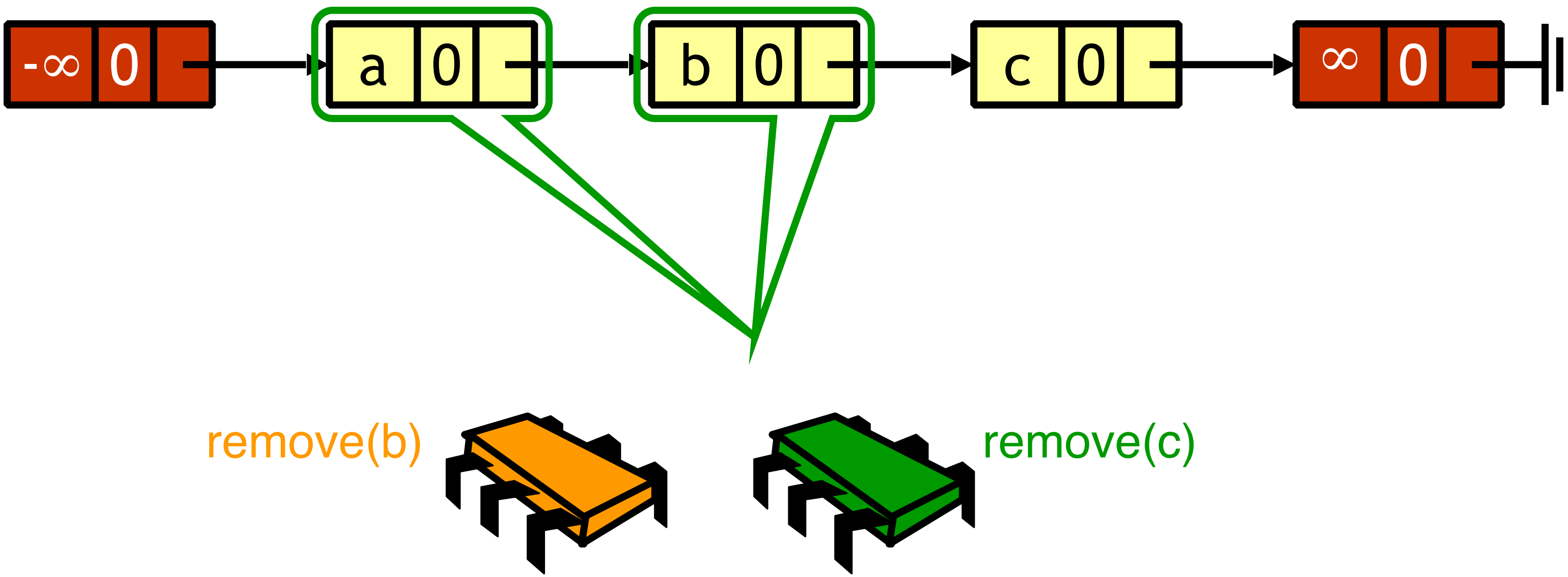

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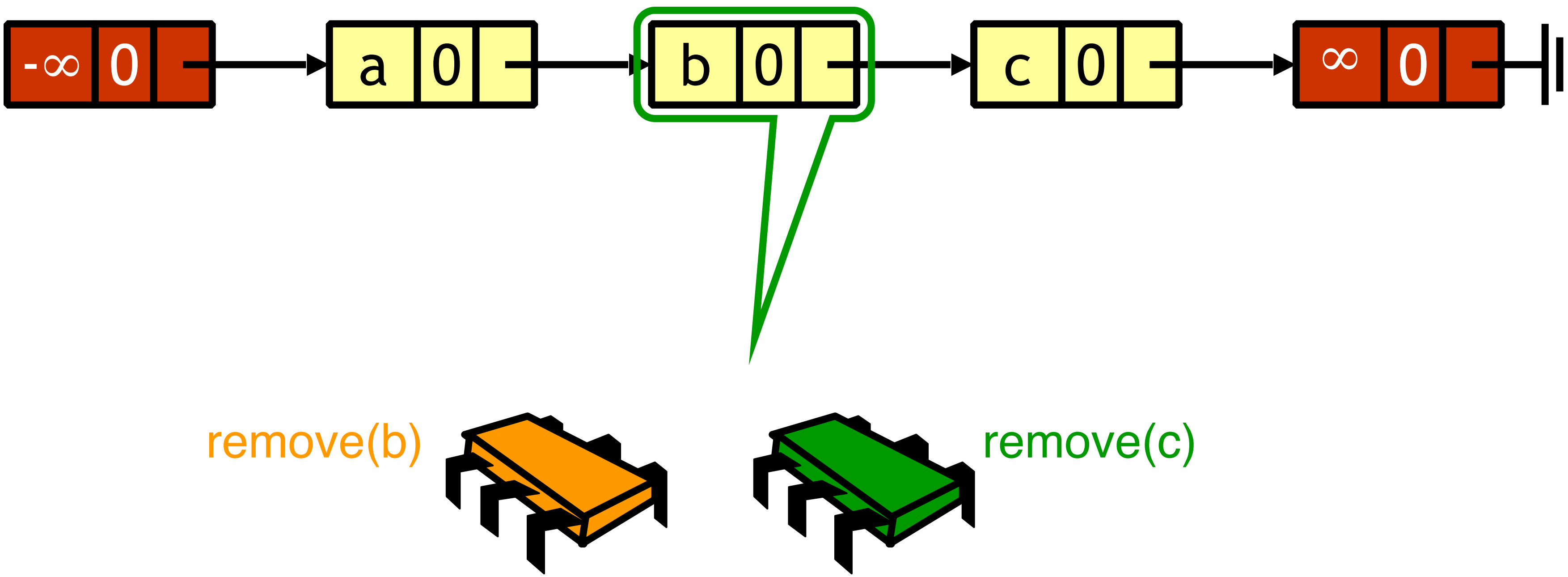

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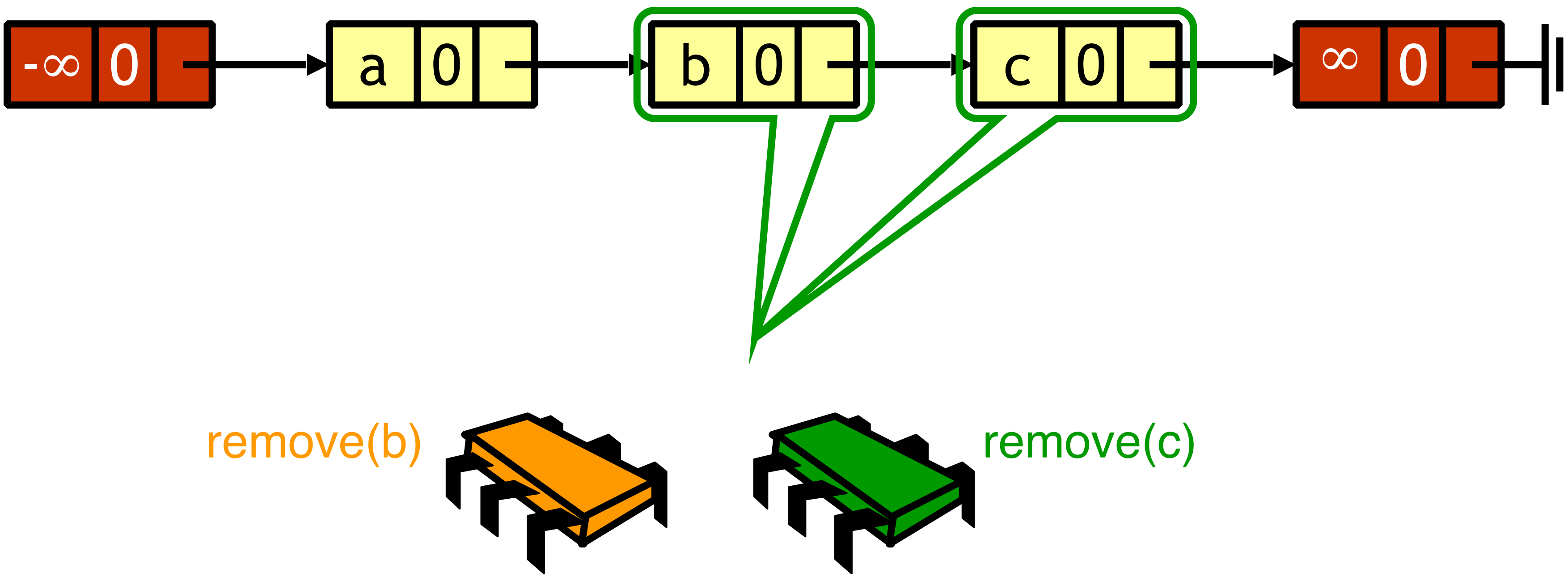

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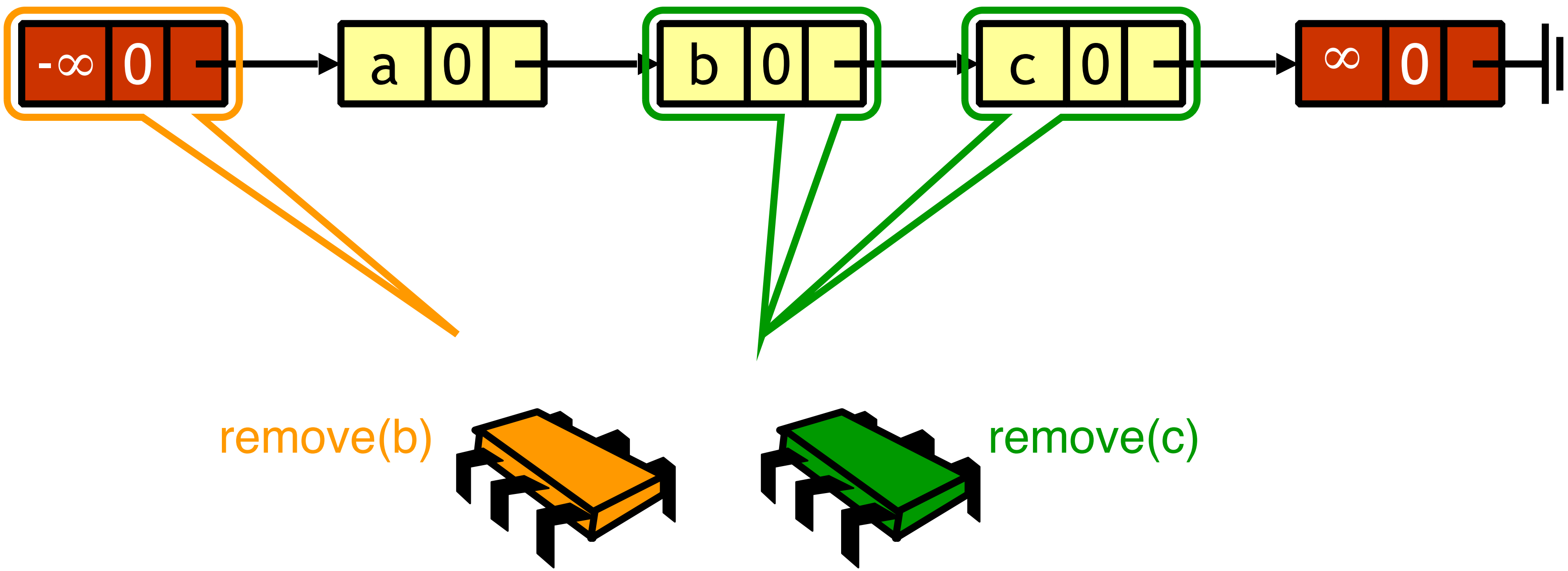

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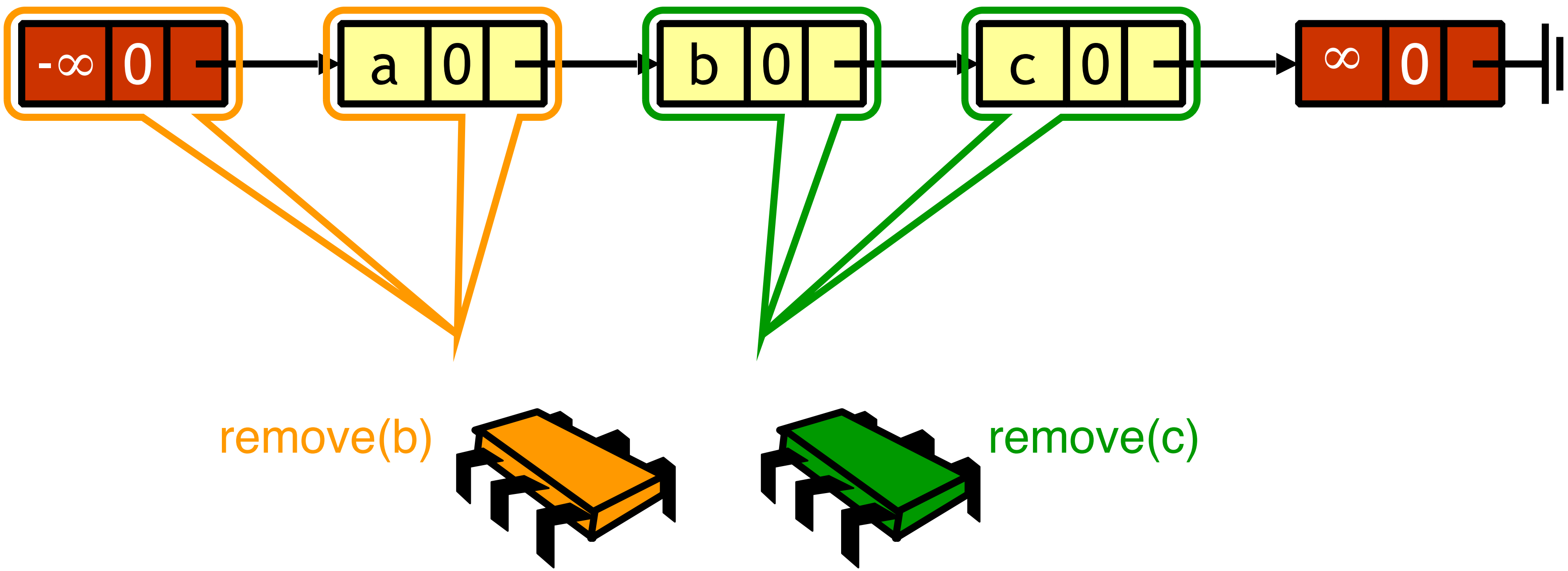
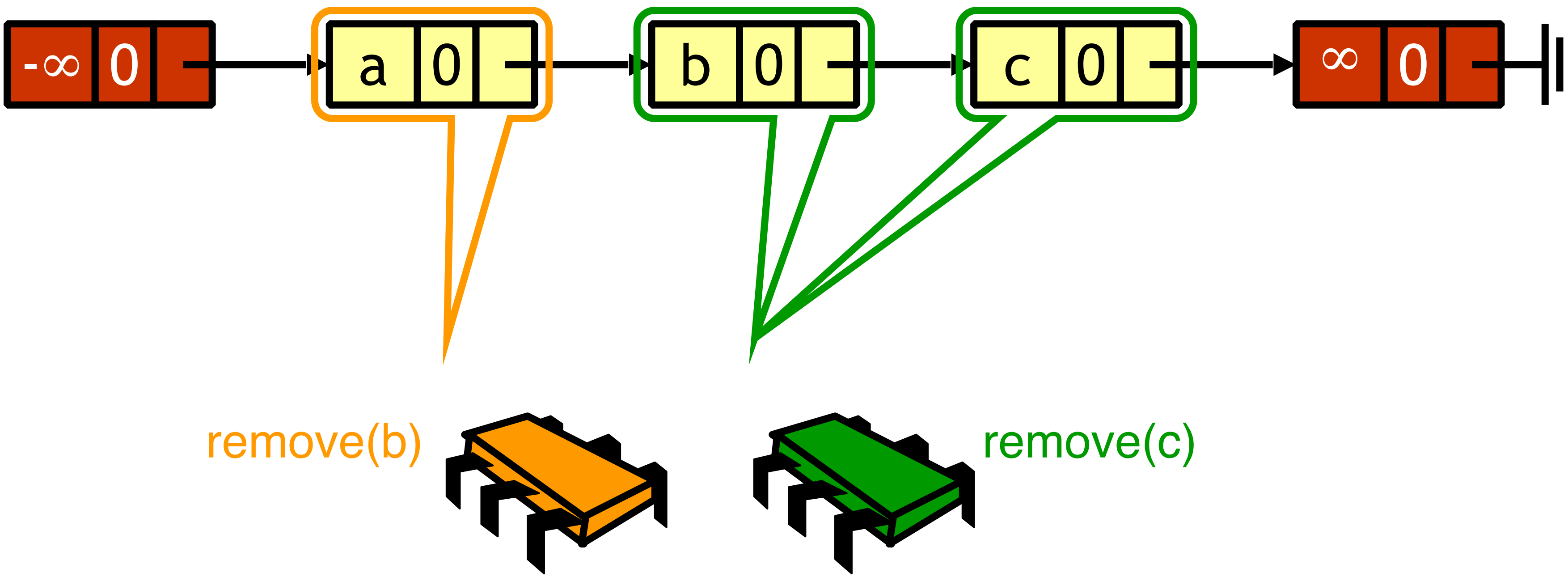
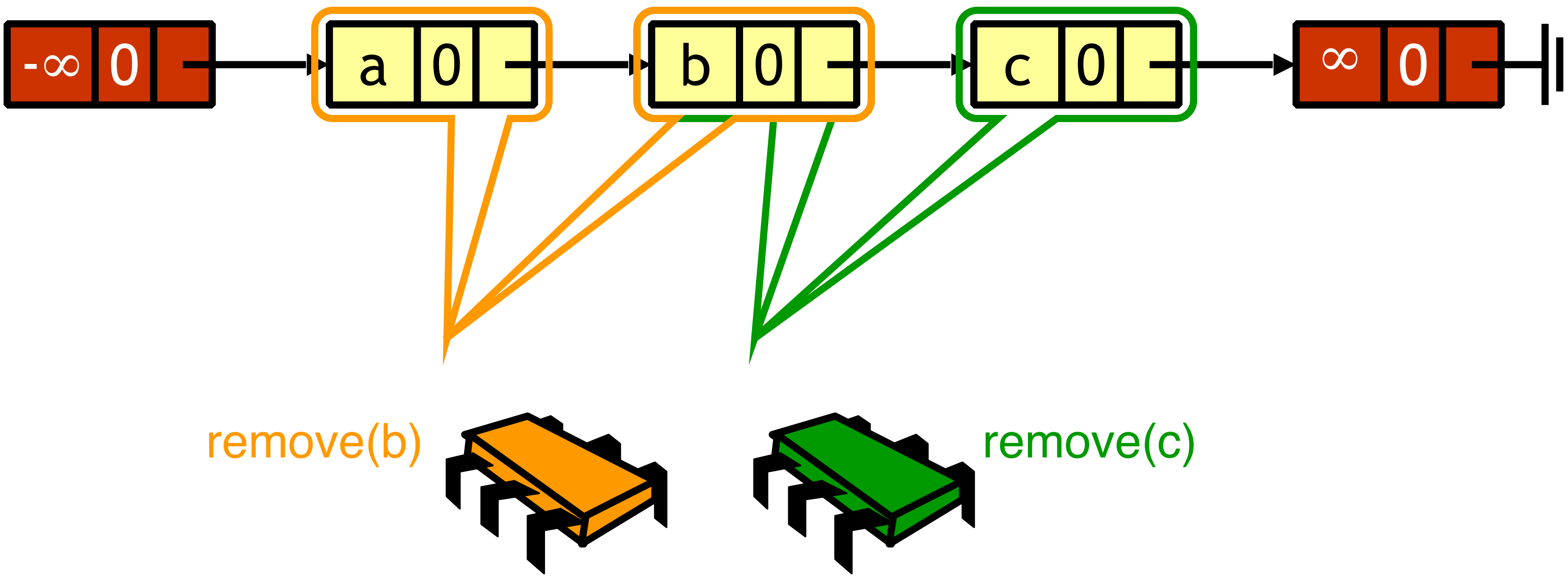


What Could Go Wrong?



What Could Go Wrong?



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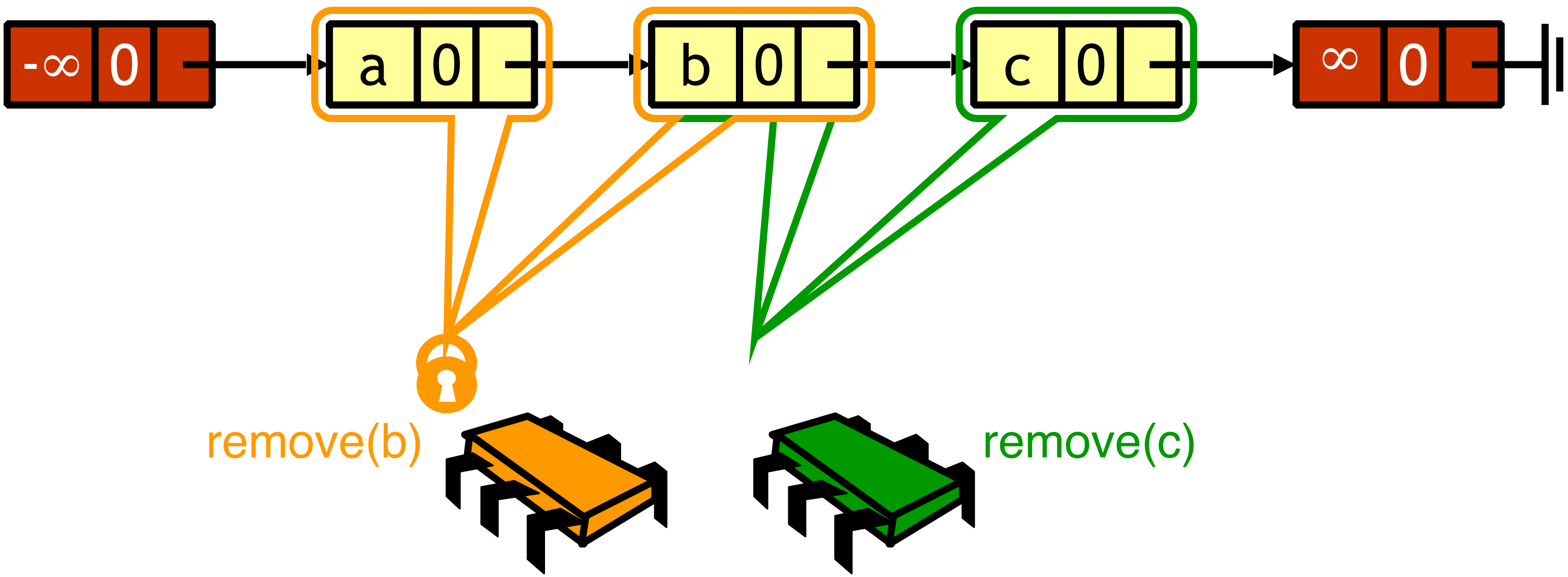
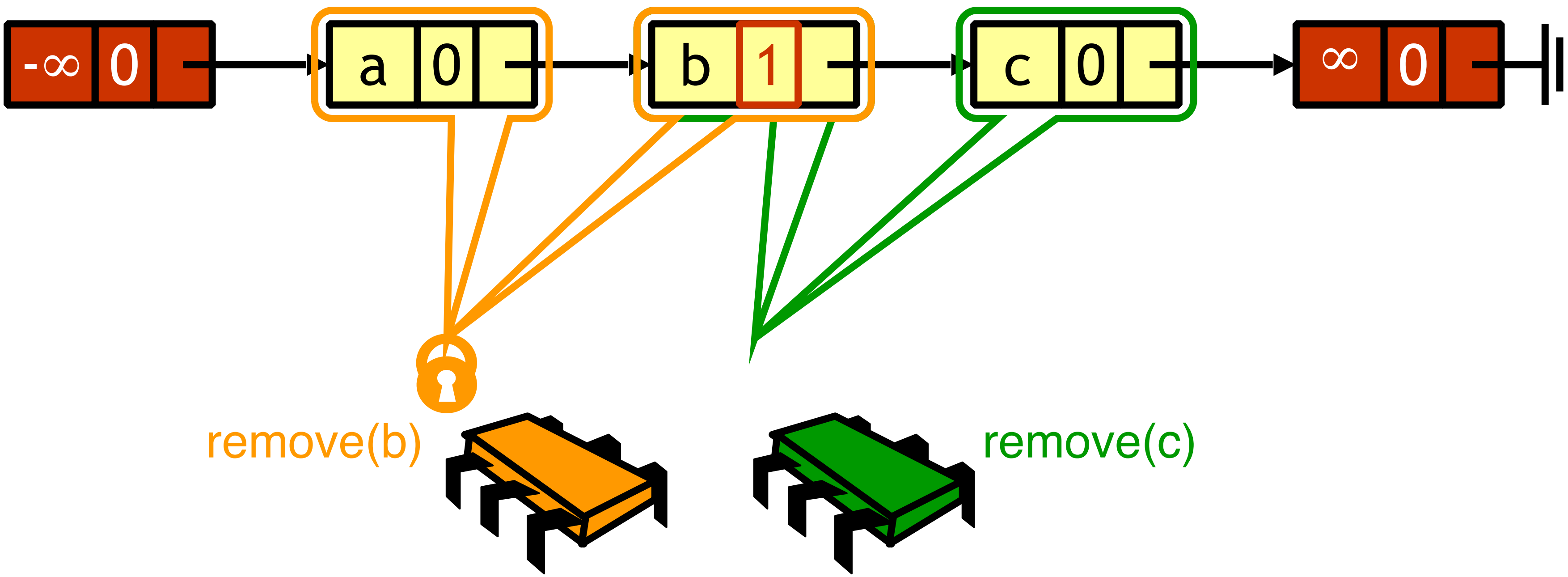
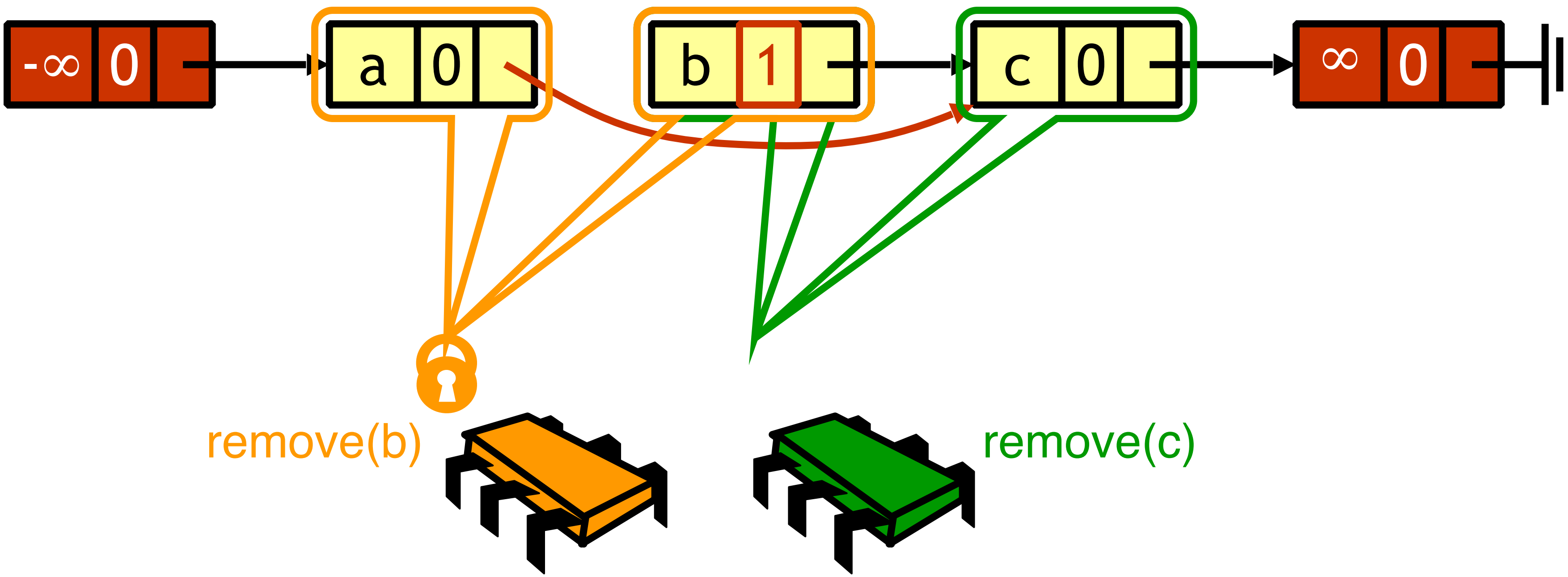


What Could Go Wrong?



What Could Go Wrong?



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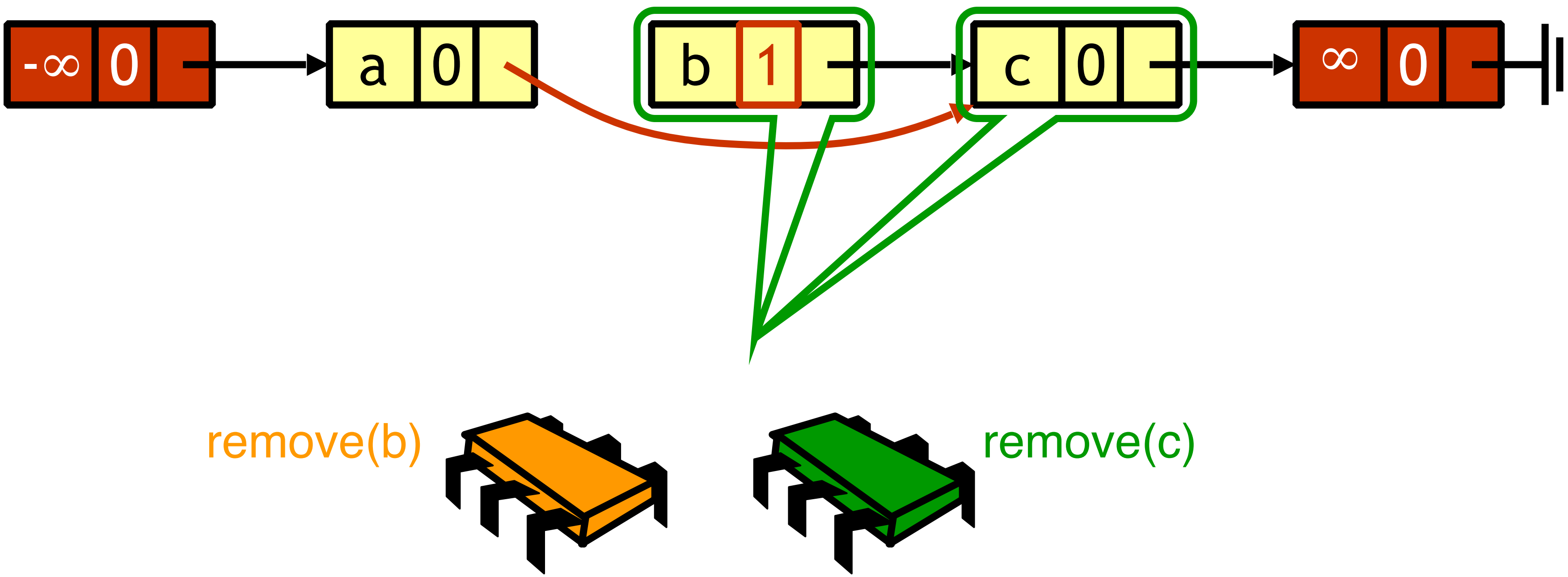
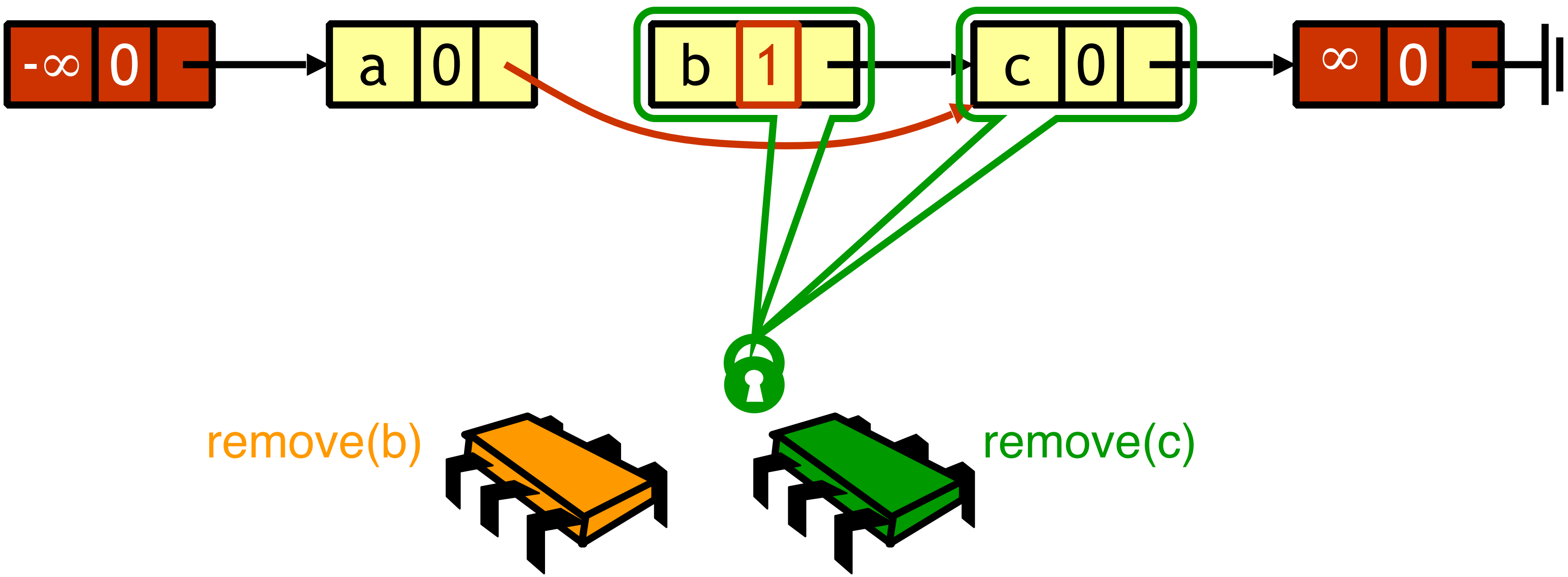


What Could Go Wrong?



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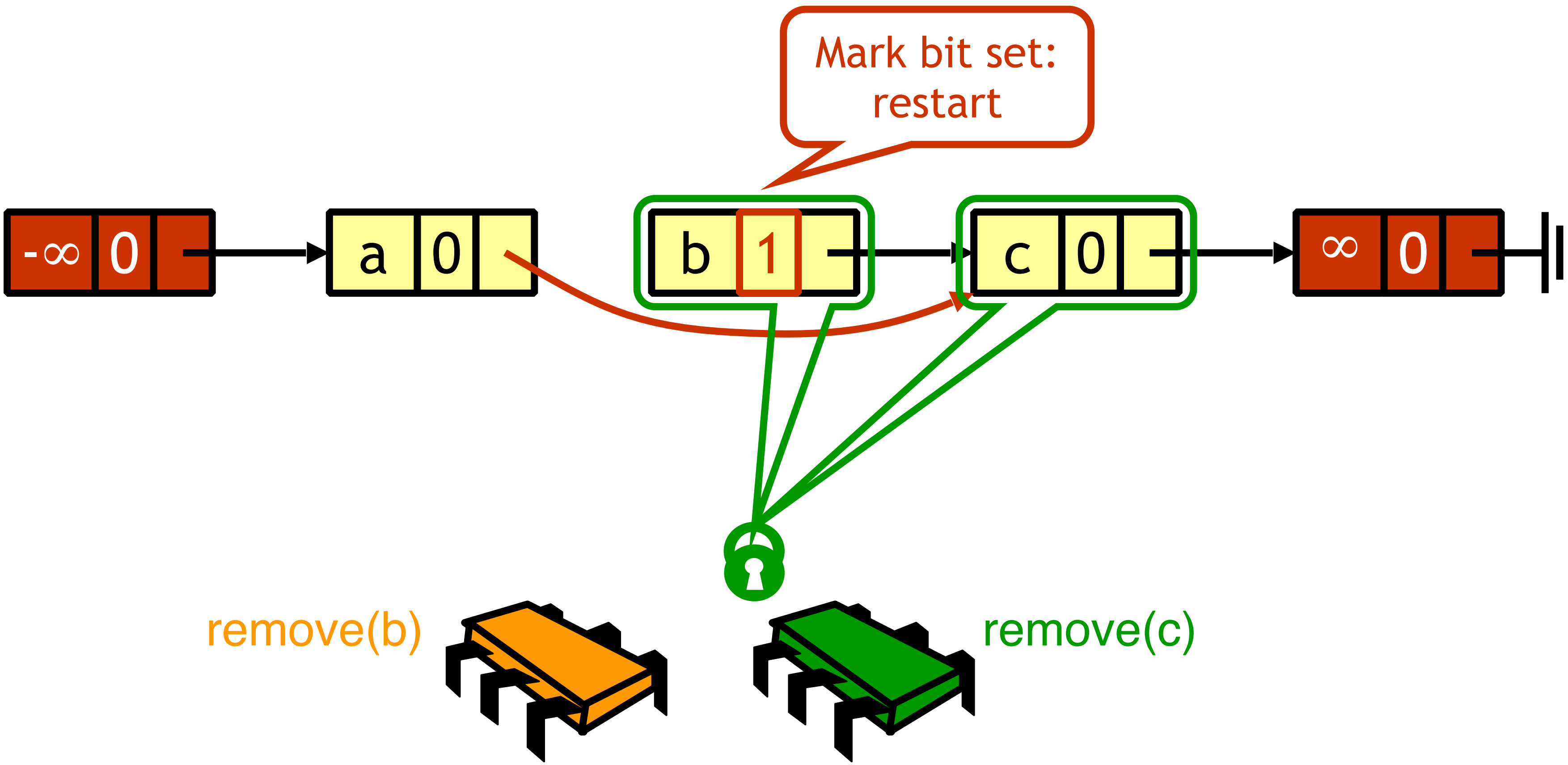


Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  return
    !pred.marked &&
    !curr.marked &&
    pred.next == curr;
}
```

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  return
   !pred.marked &&
   !curr.marked &&
   pred.next == curr;
}
```

Predecessor not logically removed

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  return
   !pred.marked &&
   !curr.marked &&
   pred.next == curr;
}
```

Current not logically removed

Validation

```
private boolean
  validate(Node pred,
           Node curr) {
  return
    !pred.marked &&
    !curr.marked &&
    pred.next == curr;
}
```

Predecessor still points to current

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr) {
    if (curr.object == object) {
      curr.marked = true;
      pred.next = curr.next;
      return true;
    } else return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr) {
    if (curr.object == object) {
      curr.marked = true;
      pred.next = curr.next;
      return true;
    } else return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Validate as before

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr) {
    if (curr.object == object) {
      curr.marked = true;
      pred.next = curr.next;
      return true;
    } else return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Object found

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr) {
    if (curr.object == object) {
      curr.marked = true;
      pred.next = curr.next;
      return true;
    } else return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Logical removal

Remove

```
try {
  pred.lock(); curr.lock();
  if (validate(pred, curr) {
    if (curr.object == object) {
      curr.marked = true;
      pred.next = curr.next;
      return true;
    } else return false;
  }
} finally {
    pred.unlock(); curr.unlock();
} …
```

Physical removal

Contains

```
public boolean contains(Object object) {
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  return object == curr.object && !curr.marked;
}
```

Contains

```
public boolean contains(Object object) {
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  return object == curr.object && !curr.marked;
}
```

Start at the head

Contains

```
public boolean contains(Object object) {
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  return object == curr.object && !curr.marked;
}
```

Traverse without locking
(nodes may have been removed)

Contains

```
public boolean contains(Object object) {
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  return object == curr.object && !curr.marked;
}
```

Present and undeleted?

Summary: Lazy List

- Wait-free traversal uses mark bit + fact that list is ordered
  - Not marked ⇒ in the set
  - Marked or missing ⇒ not in the set
- Lazy add()
- Lazy remove()
- Wait-free contains()

Evaluation

- Good
  - contains() does not need to lock
    - In fact, it is wait-free!
    - Good because it is typically called often
  - Uncontended calls do not re-traverse
- Bad
  - Contended calls do re-traverse
  - Traffic jam if one thread delays

Traffic Jam

- Any concurrent data structure based on mutual exclusion has a weakness
- If one thread
  - Enters critical section
  - And "eats the big muffin" (stops running)
    - Cache miss, page fault, de-scheduled…
  - Everyone else using that lock is stuck!

Wait/Lock/Obstruction Freedom

Wait freedom

"All thread always makes progress"

Guarantees per-thread progress

vs.

Lock freedom

"Some thread always makes progress"

Guarantees system-wide progress

vs.

Obstruction freedom

"Any thread that runs by itself for long enough makes progress"

Lock-Free Data Structures

- No matter what…
  - Some thread will complete method call
  - Even if others halt at malicious times
  - Weaker than wait-free, yet
- Implies that
  - You cannot use locks
  - Um, that is why they call it lock-free

RMW Atomic Operations

- Read-modify-write operation combines…
  - Read from memory
  - Modify value
  - Write to memory
- … atomically
- Supported by modern processors
  - Atomic increment/decrement, test-and-set, compare-and-set, etc.
- In Java: `java.util.concurrent.atomic`

Atomic-Inc/Dec

```
public class AtomicInteger {
  int value;

  public synchronized int
  incrementAndGet() {
    value = value + 1;
    return value;
  }
  public synchronized int
  decrementAndGet() {
    return --value;
  }
}
```

Atomic-Inc/Dec

```
public class AtomicInteger {
  int value;

  public synchronized int
  incrementAndGet() {
    value = value + 1;
    return value;
  }
  public synchronized int
  decrementAndGet() {
    return --value;
  }
}
```

Package
java.util.concurrent.atomic

Atomic-Inc/Dec

```
public class AtomicInteger {
  int value;

  public synchronized int
  incrementAndGet() {
    value = value + 1;
    return value;
  }
  public synchronized int
  decrementAndGet() {
    return --value;
  }
}
```

Increment value

Atomic-Inc/Dec

```
public class AtomicInteger {
  int value;

  public synchronized int
  incrementAndGet() {
    value = value + 1;
    return value;
  }
  public synchronized int
  decrementAndGet() {
    return --value;
  }
}
```

Decrement value (pre-decrement operator is not atomic!)

Atomic-Inc/Dec

```
public class AtomicInteger {
  int value;

  public synchronized int
  incrementAndGet() {
    value = value + 1;
    return value;
  }
  public synchronized int
  decrementAndGet() {
    return --value;
  }
}
```

```
; x86
LOCK INC …
LOCK DEC …
LOCK XADD …
```

Decrement value (pre-decrement operator is not atomic!)

Get-and-Set

```
public class AtomicBoolean {
  boolean value;

  public synchronized boolean
  getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
  }
}
```

Get-and-Set

```
public class AtomicBoolean {
  boolean value;

  public synchronized boolean
  getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
  }
}
```

Set new value and return old value

Get-and-Set

```
public class AtomicBoolean {
  boolean value;

  public synchronized boolean
  getAndSet(boolean newValue) {
    boolean prior = value;
    value = newValue;
    return prior;
  }
}
```

Set new value and return old value

```
; x86
LOCK XCHG …
```

Compare-and-Set

```
public class AtomicInteger {
  int value;

  public synchronized boolean
  compareAndSet(int expValue,
              int newValue) {
    if (value == expValue) {
      value = newValue;
      return true;
    }
    return false;
  }
}
```

Compare-and-Set

```
public class AtomicInteger {
  int value;

  public synchronized boolean
  compareAndSet(int expValue,
              int newValue) {
    if (value == expValue) {
      value = newValue;
      return true;
    }
    return false;
  }
}
```

Set new value and return true if old value matches expected value, return false otherwise

Compare-and-Set

```
public class AtomicInteger {
  int value;

  public synchronized boolean
  compareAndSet(int expValue,
                int newValue) {
    if (value == expValue) {
      value = newValue;
      return true;
    }
    return false;
  }
}
```

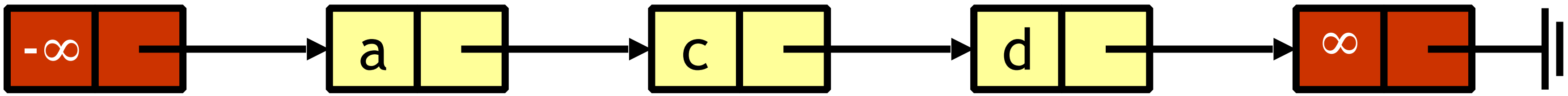
Set new value and return true if old value matches expected value, return false otherwise

```
; x86
LOCK CMPXCHG …
```

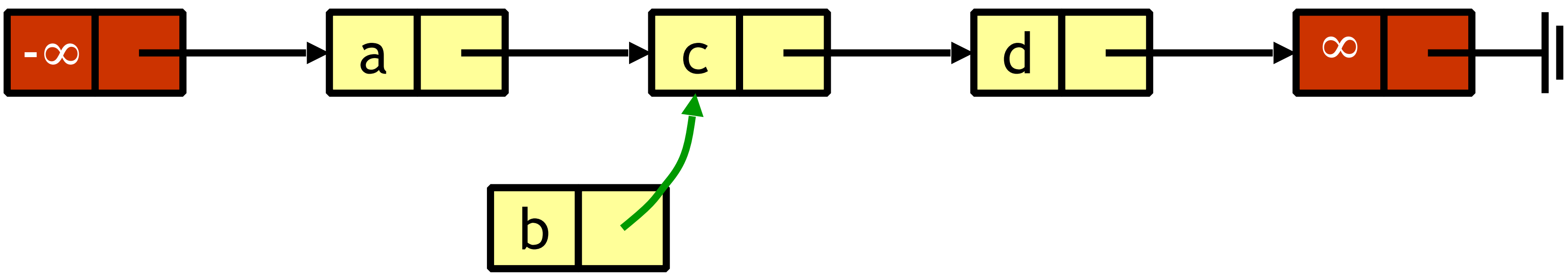
Lock-Free Lists

- Next logical step
- Eliminate locking entirely
- contains() wait-free and add() and remove() lock-free
- Use only compareAndSet() to atomically update links

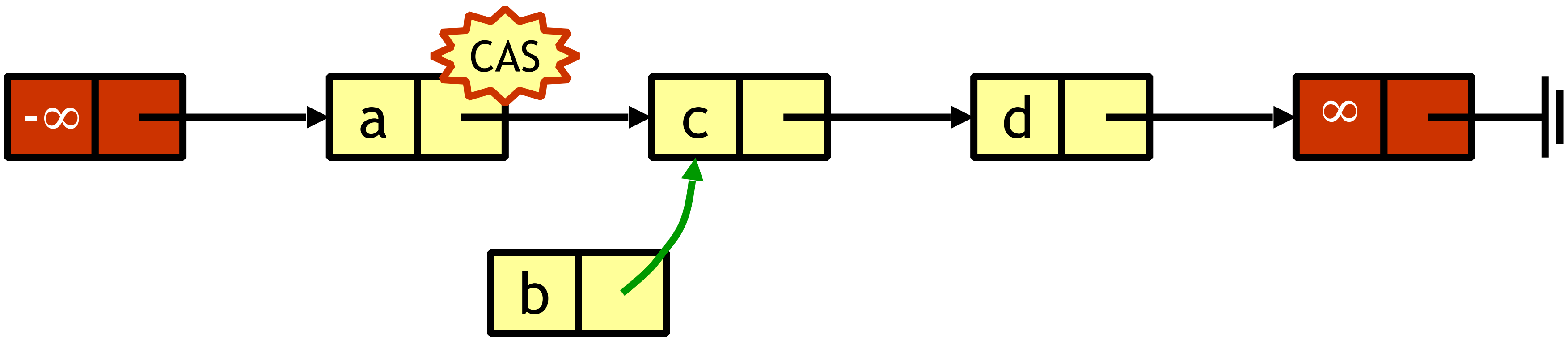
Adding a Node



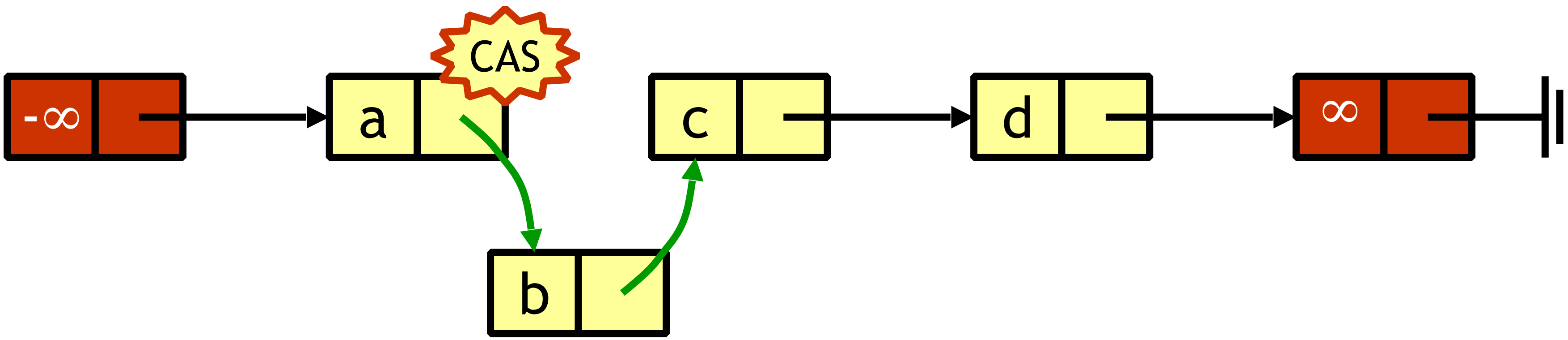
Adding a Node



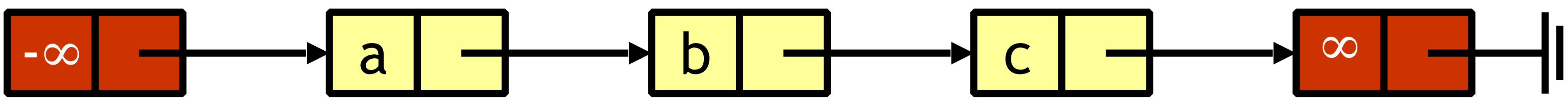
Adding a Node



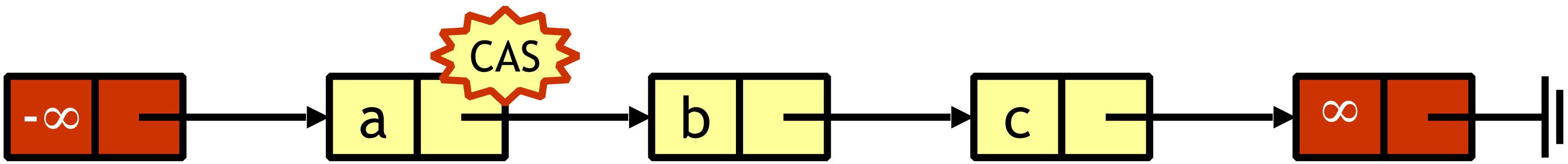
Adding a Node



Removing a Node



Removing a Node



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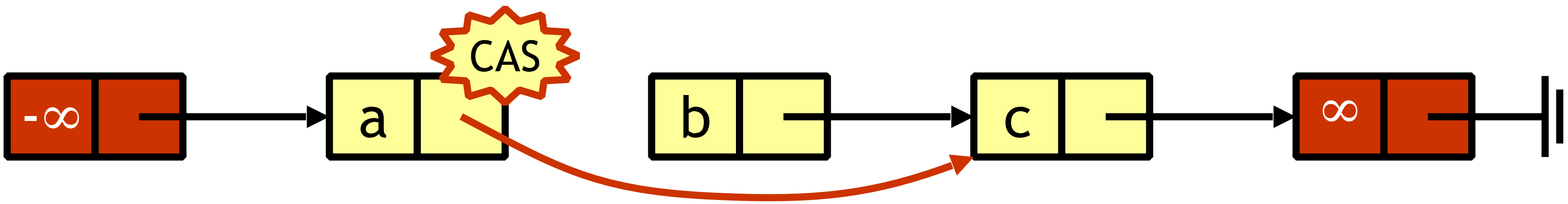

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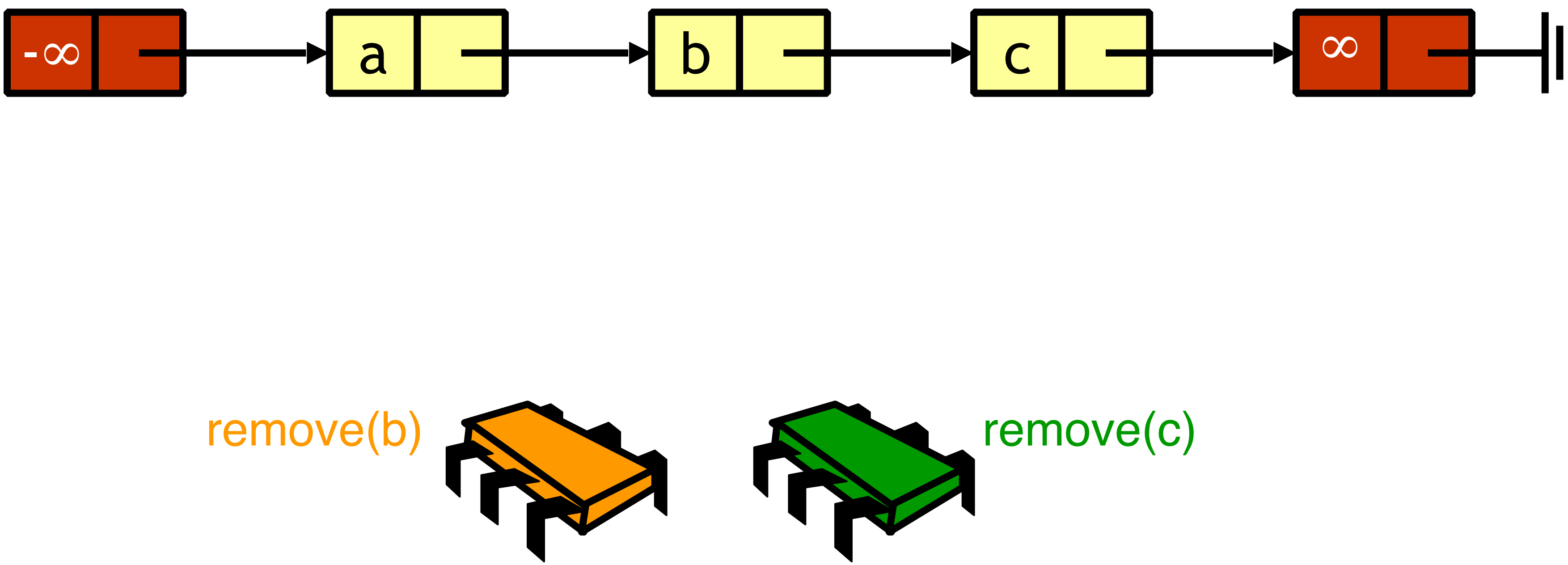

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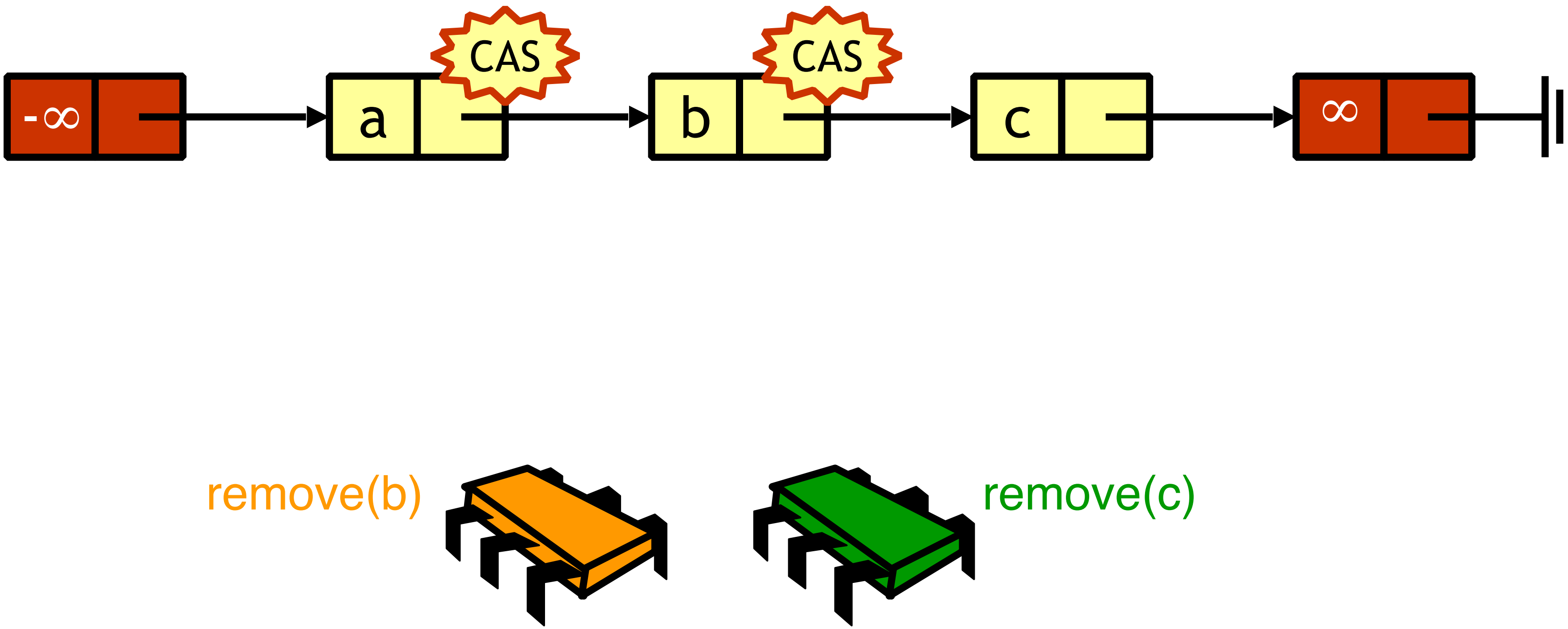

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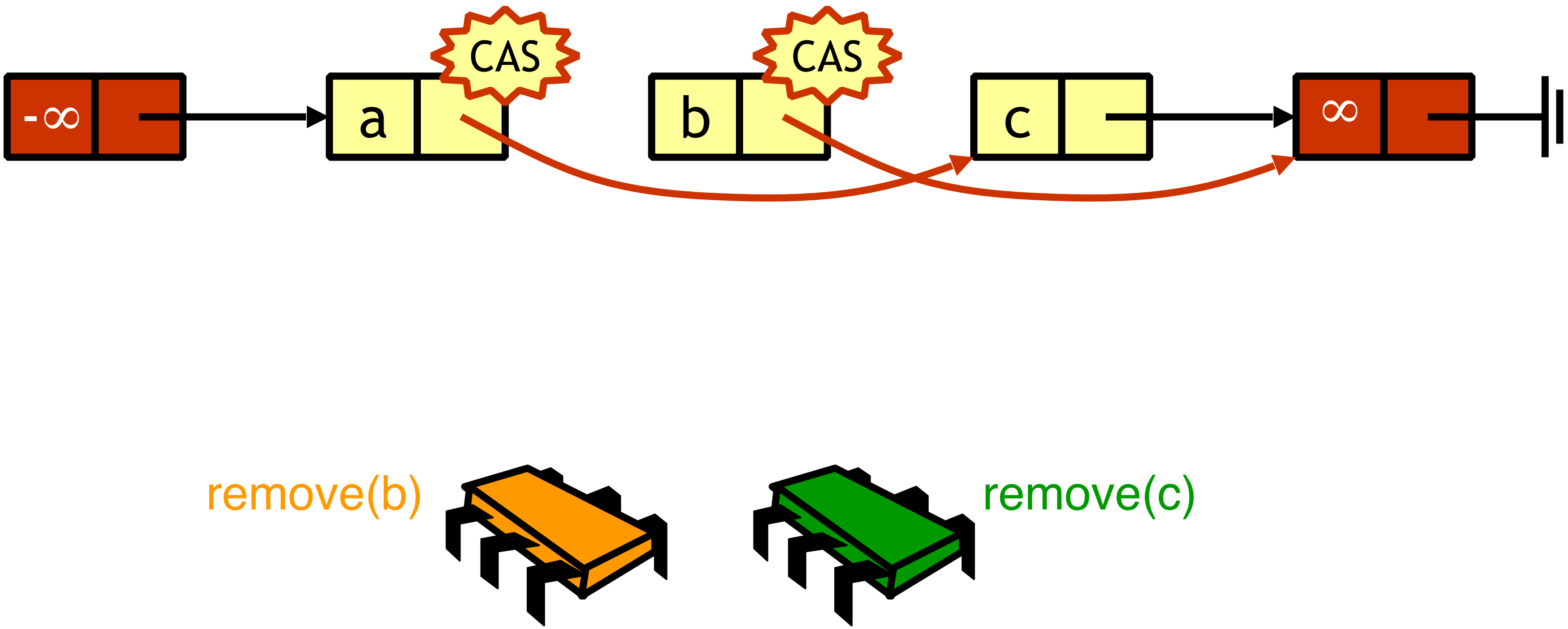

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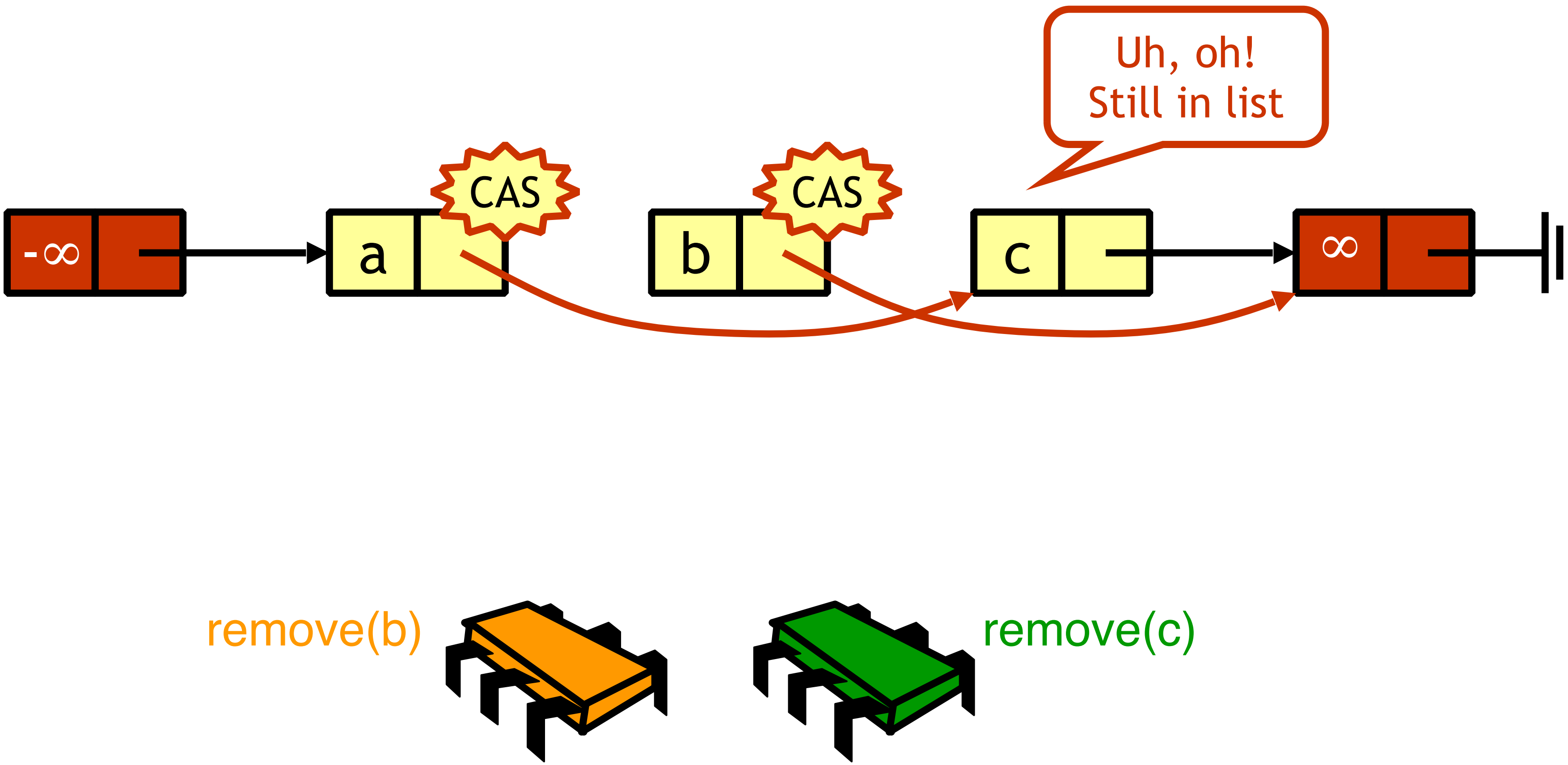

What Could Go Wrong?

- Problem
  - Method updates node's next field after node has been removed
- Solution
  - Use AtomicMarkableReference
  - Atomically
    - Swing reference and update flag
  - Remove in two steps
    - Set mark bit in next field
    - Redirect predecessor's pointer

Marking a Node

- AtomicMarkableReference class
  - In package java.util.concurrent.atomic
  - Holds a reference and a mark bit

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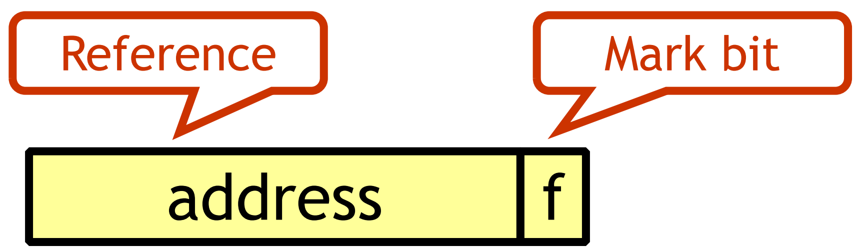

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

AtomicMarkableReference

Data type

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
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  public boolean attemptMark(
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  …
}
```

AtomicMarkableReference

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    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

Extract reference and mark (at index 0)

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

If this is the current reference…

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

If this is the current reference…

…and this is the current mark…

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

…then change to this new reference…

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```

…then change to this new reference…

…and this new mark

AtomicMarkableReference

```
public class AtomicMarkableReference <T> {
  public T get(boolean[] marked);
  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
    boolean expectedMark,
    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
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  …
}
```

If this is the current reference…

AtomicMarkableReference

```
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  public boolean compareAndSet(
    T expectedRef,
    T updateRef,
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    boolean updateMark);
  public boolean attemptMark(
    T expectedRef,
    boolean updateMark);
  …
}
```
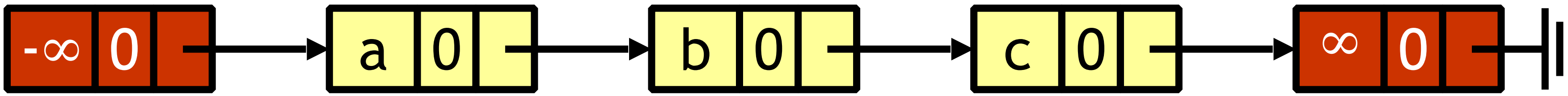

…then change to this new mark

Removing a Node



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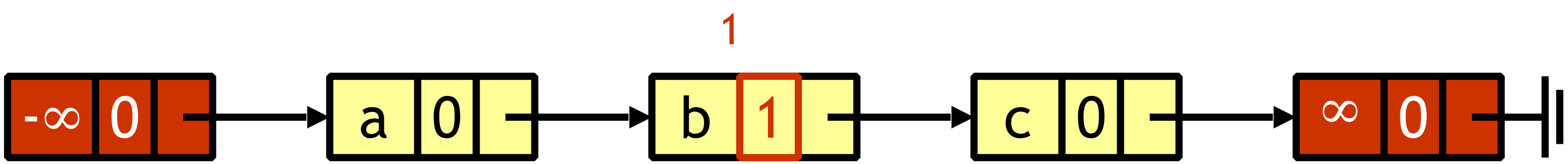

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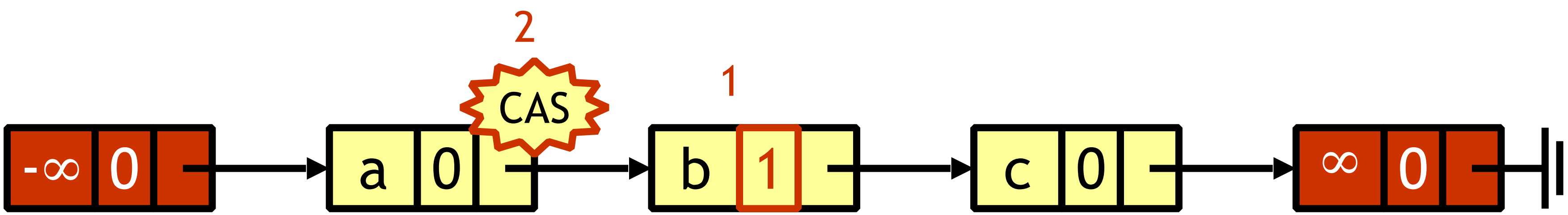

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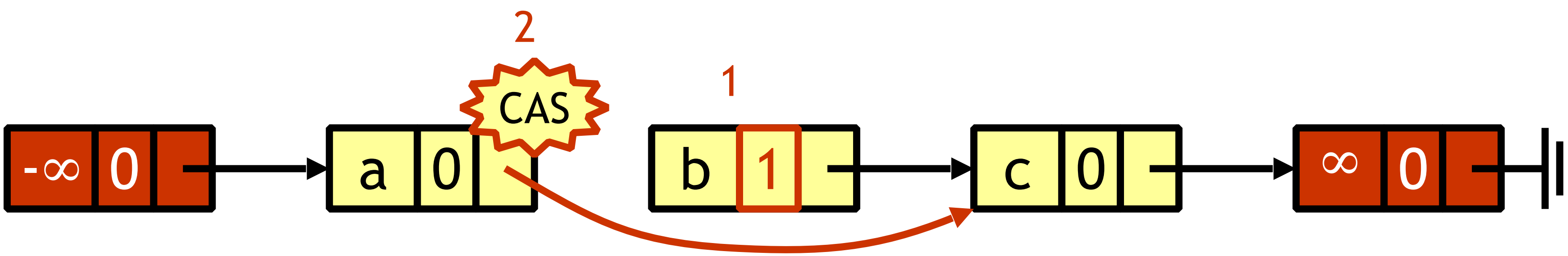

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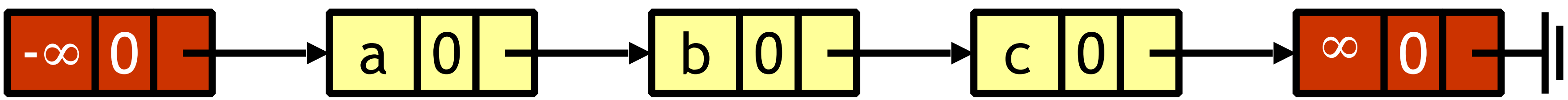

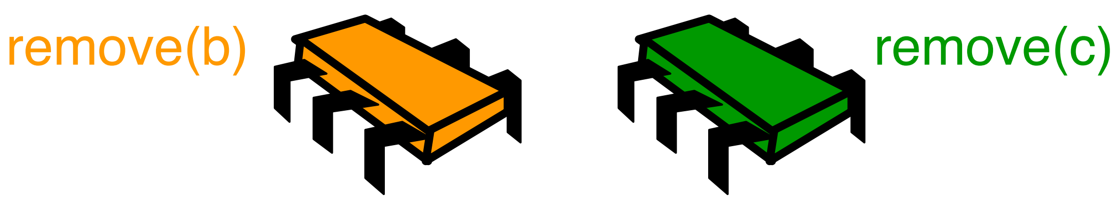

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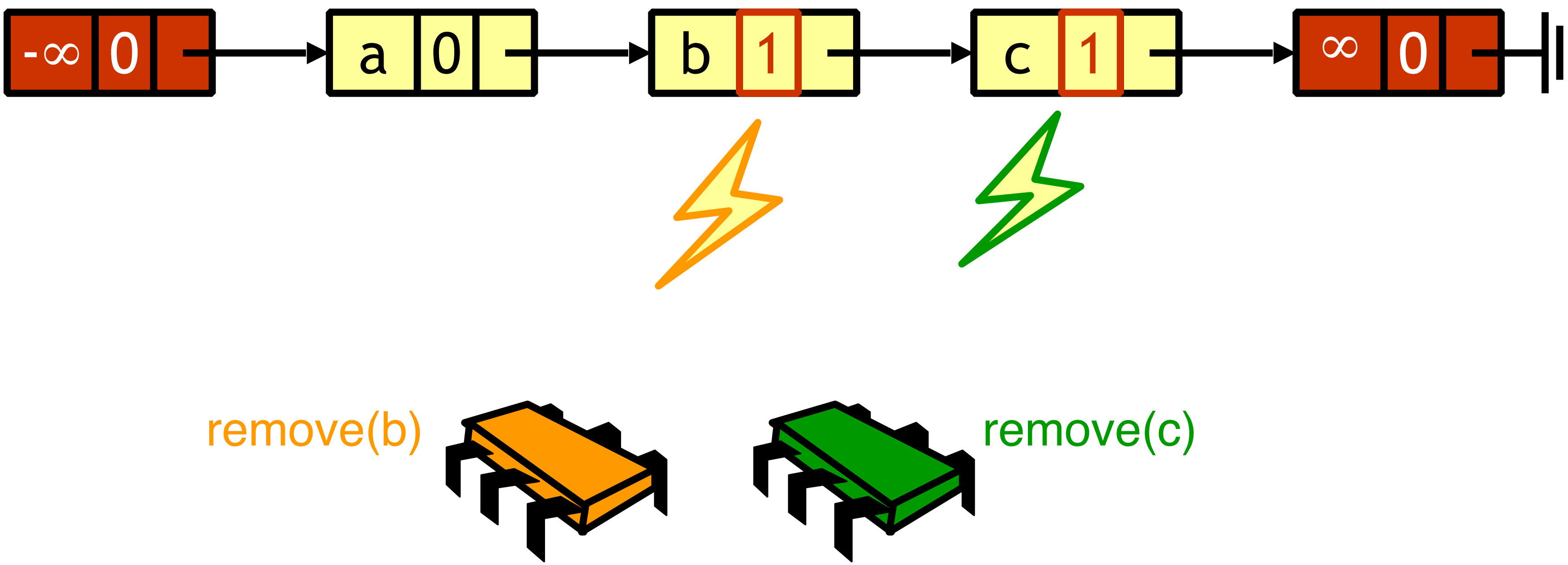

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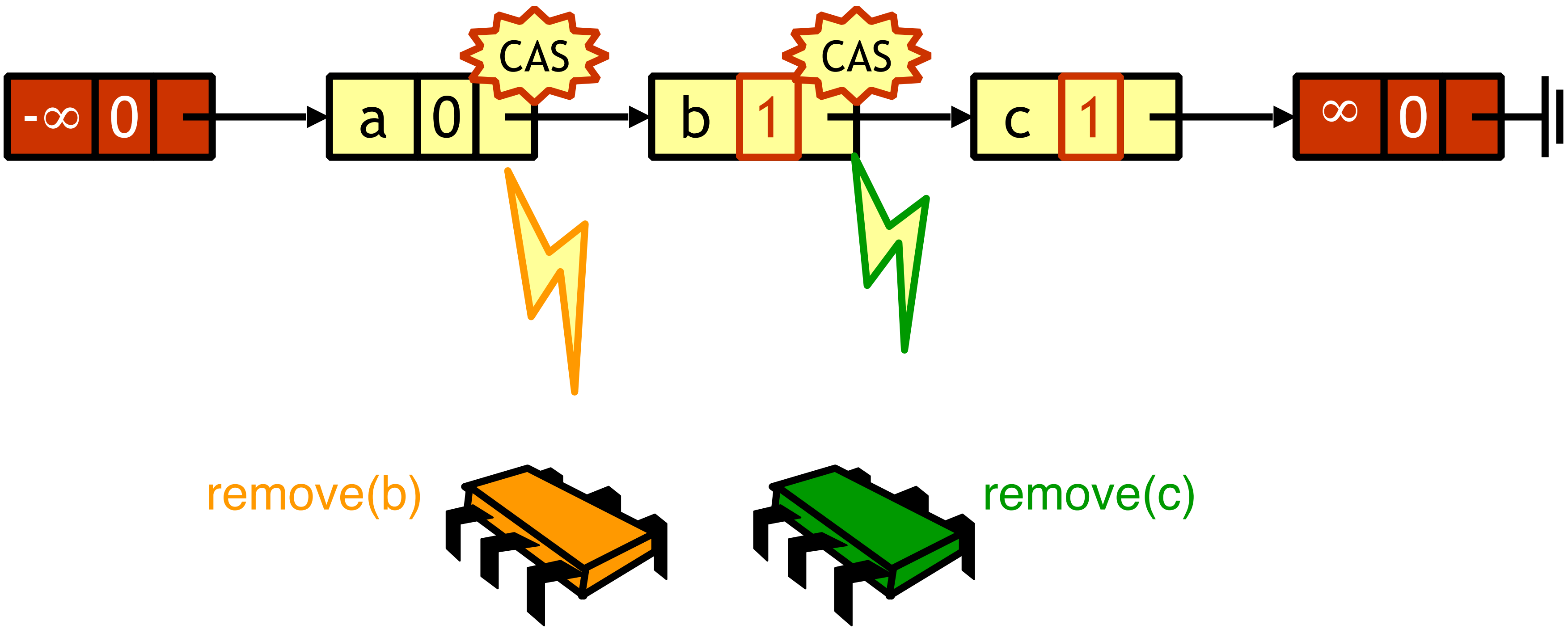

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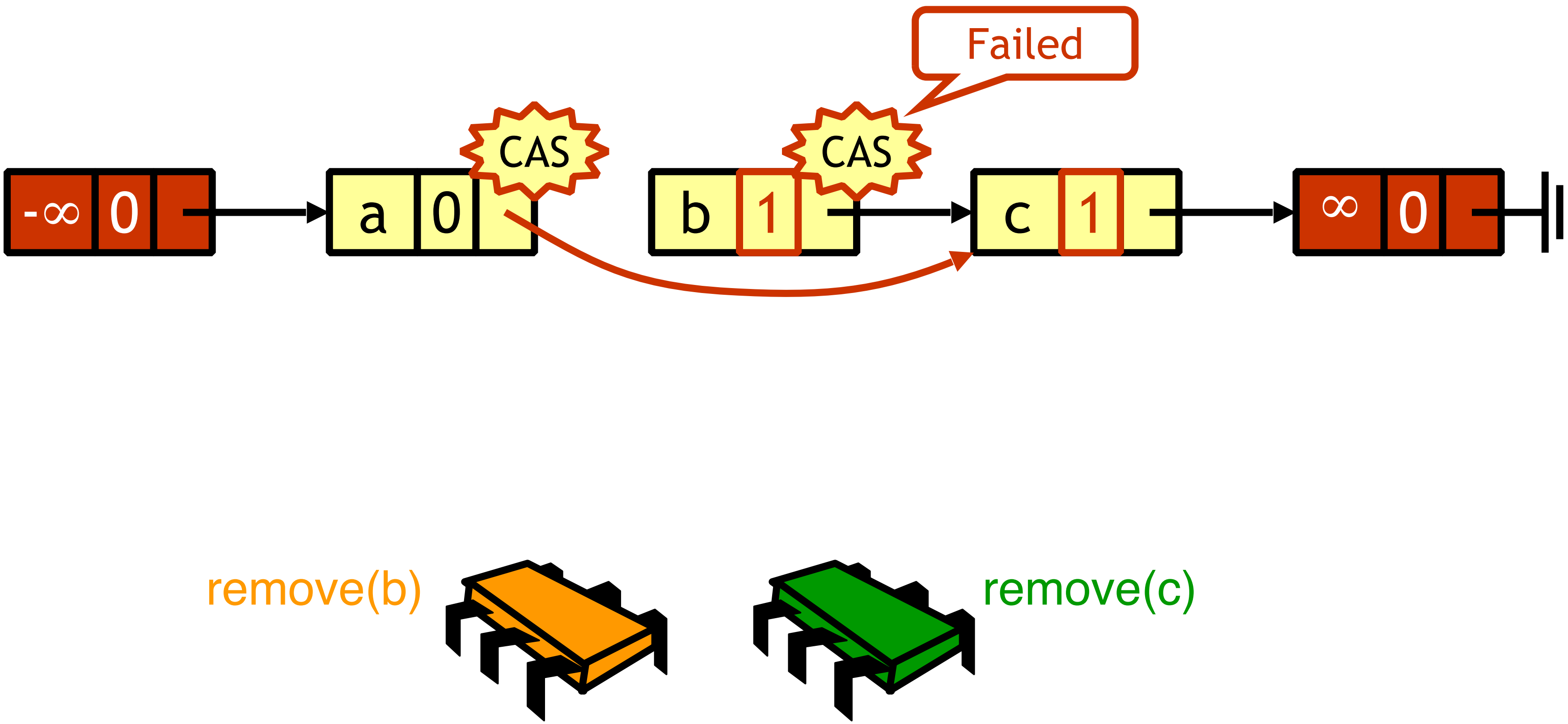

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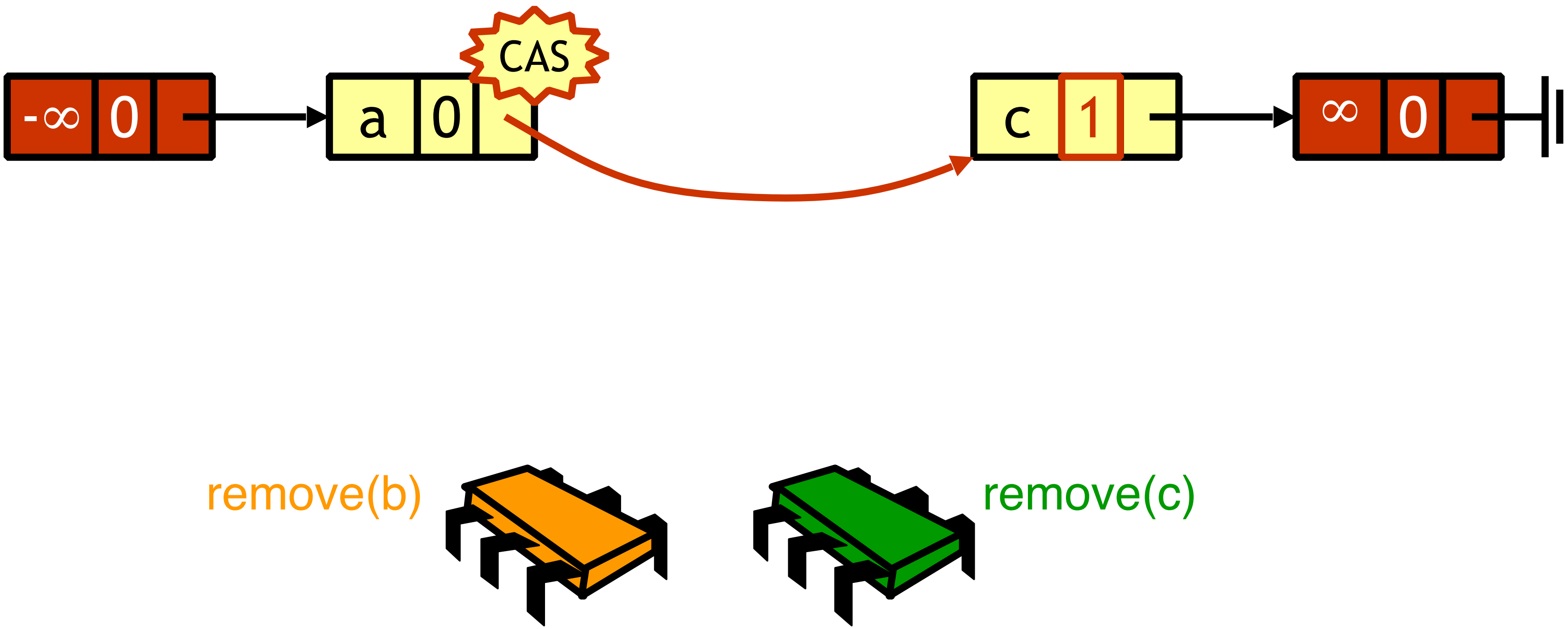

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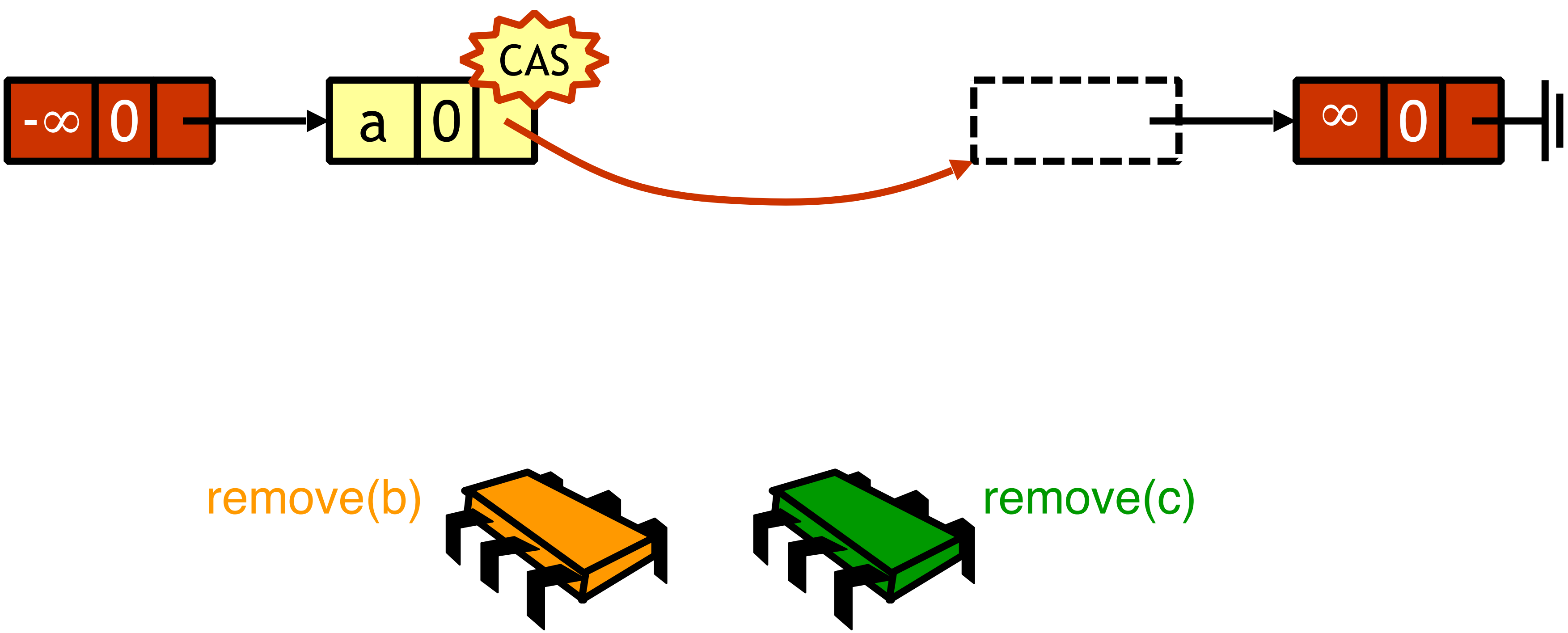
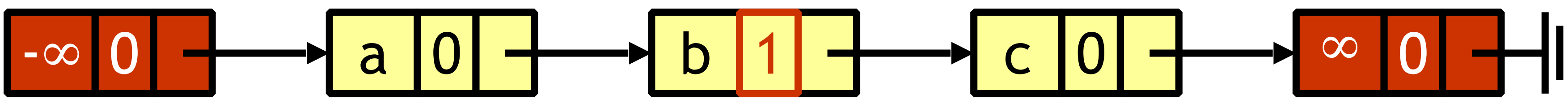
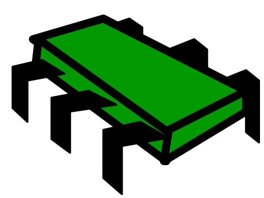


Traversing the List

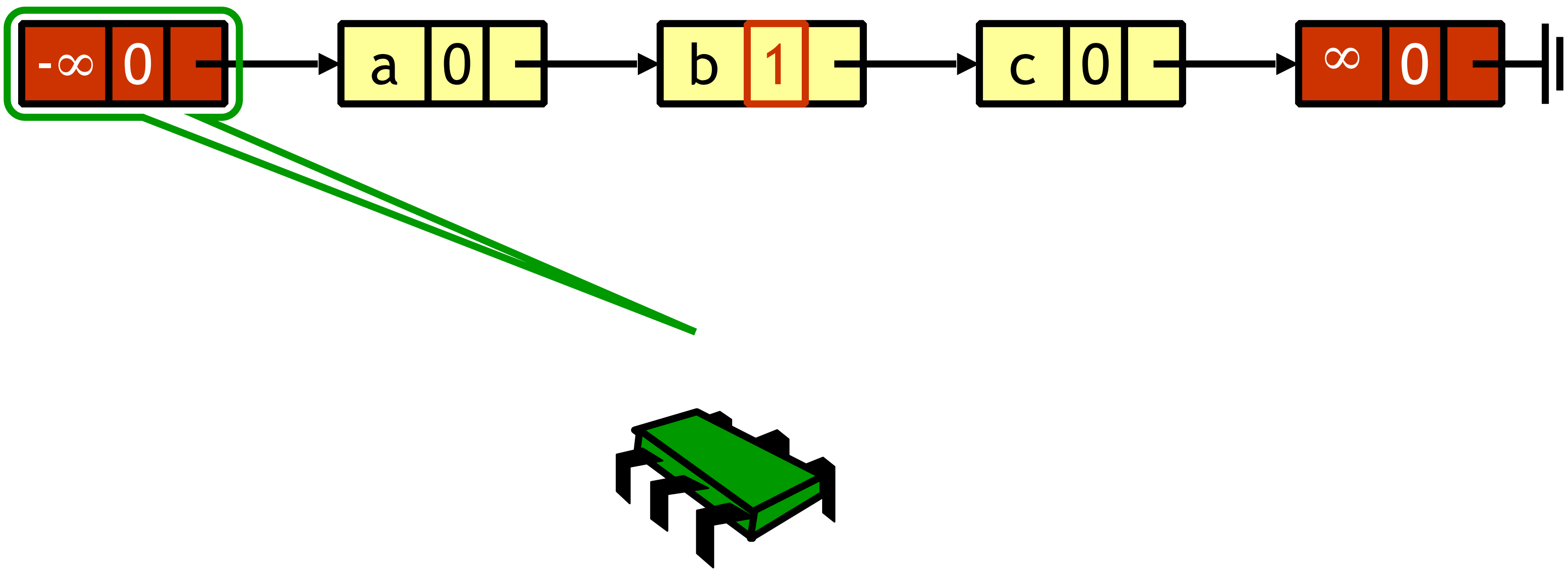
- What do you do when you find a “logically” deleted node in your path?
- Finish the job
  - CAS the predecessor’s next field
  - Proceed (repeat as needed)

Lock-Free Traversal

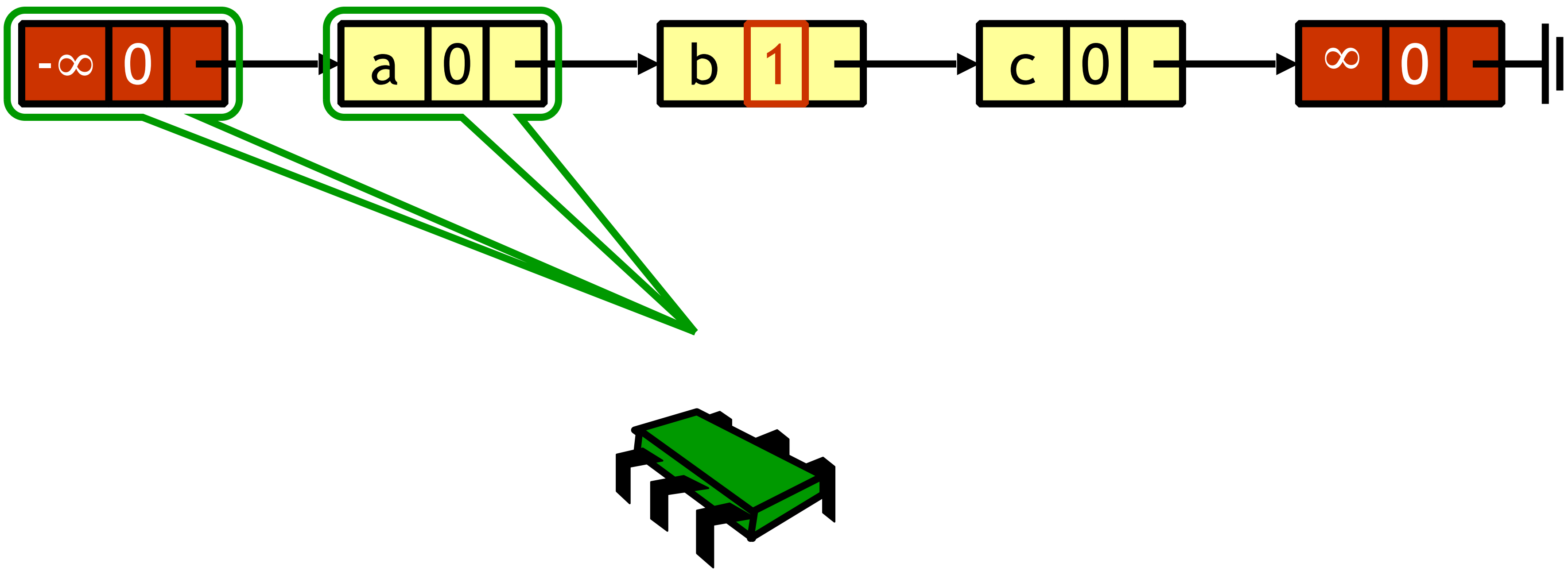




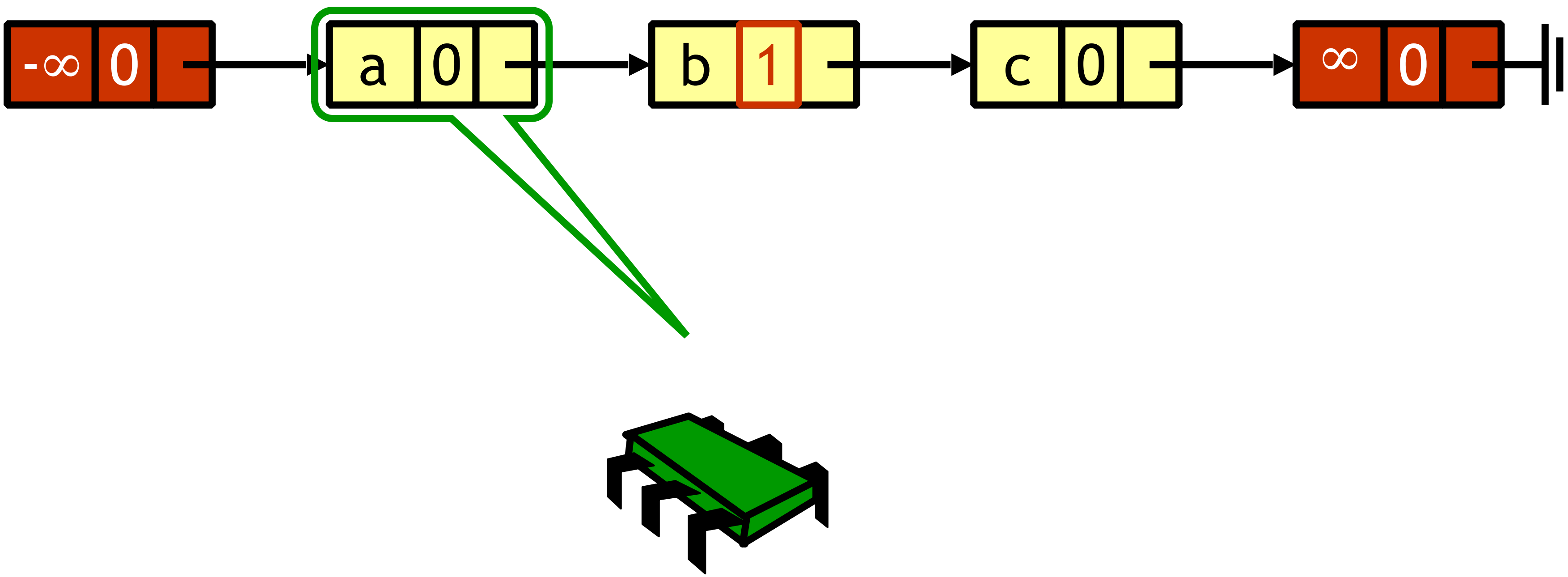
Lock-Free Traversal



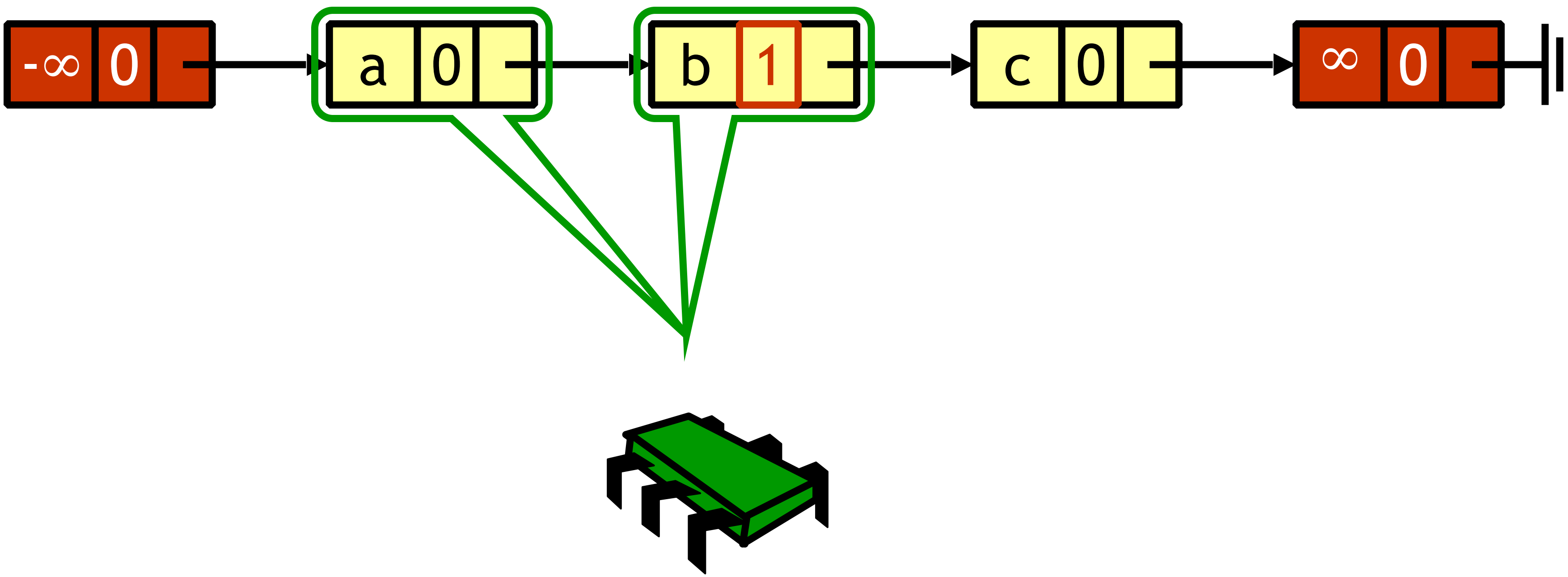
Lock-Free Traversal



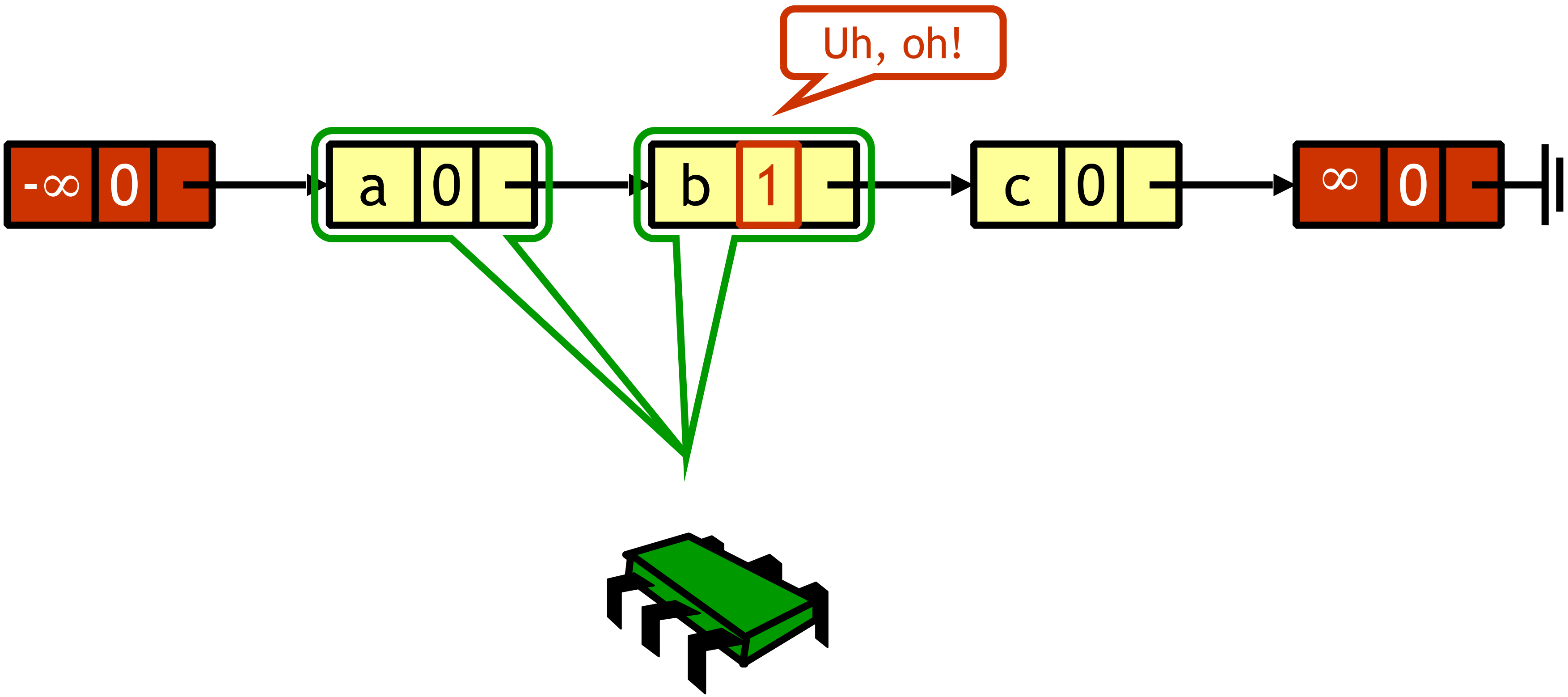
Lock-Free Traversal



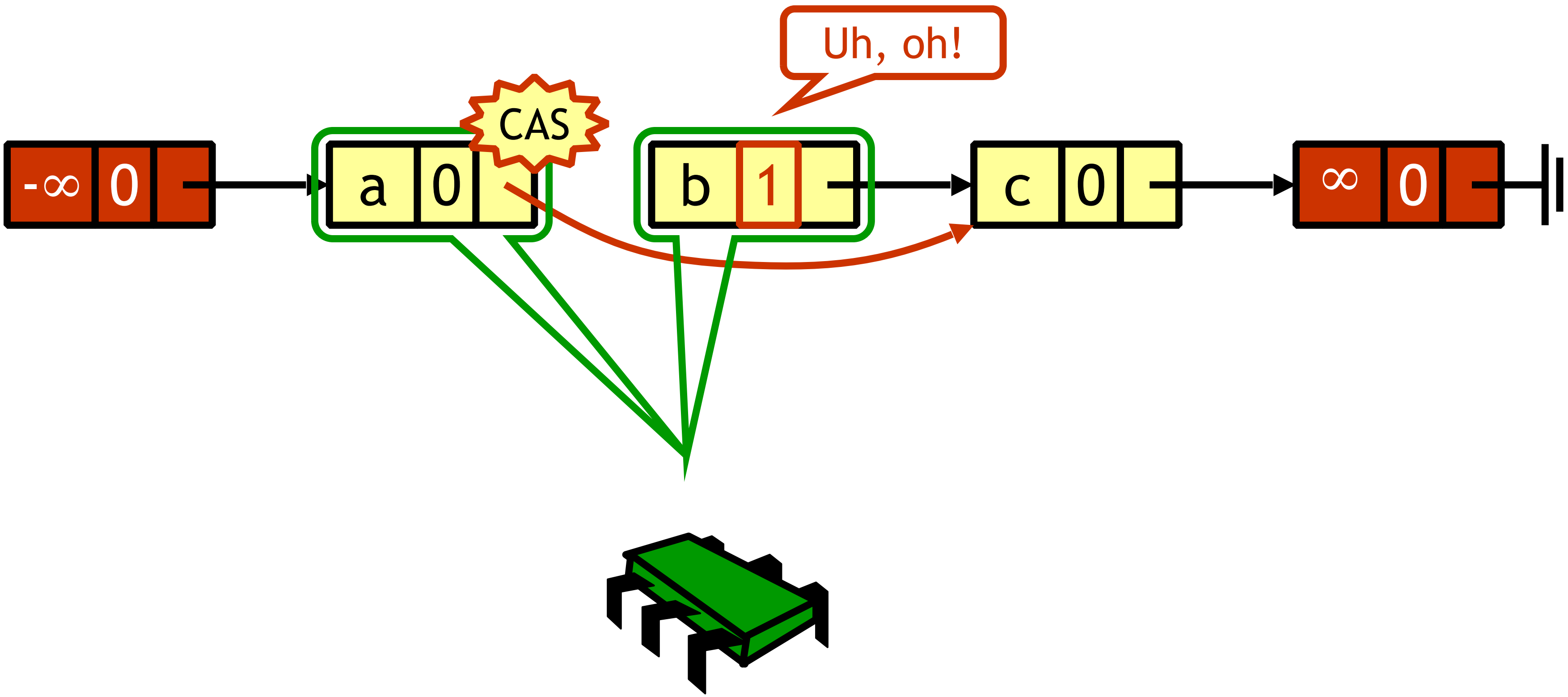
Lock-Free Traversal



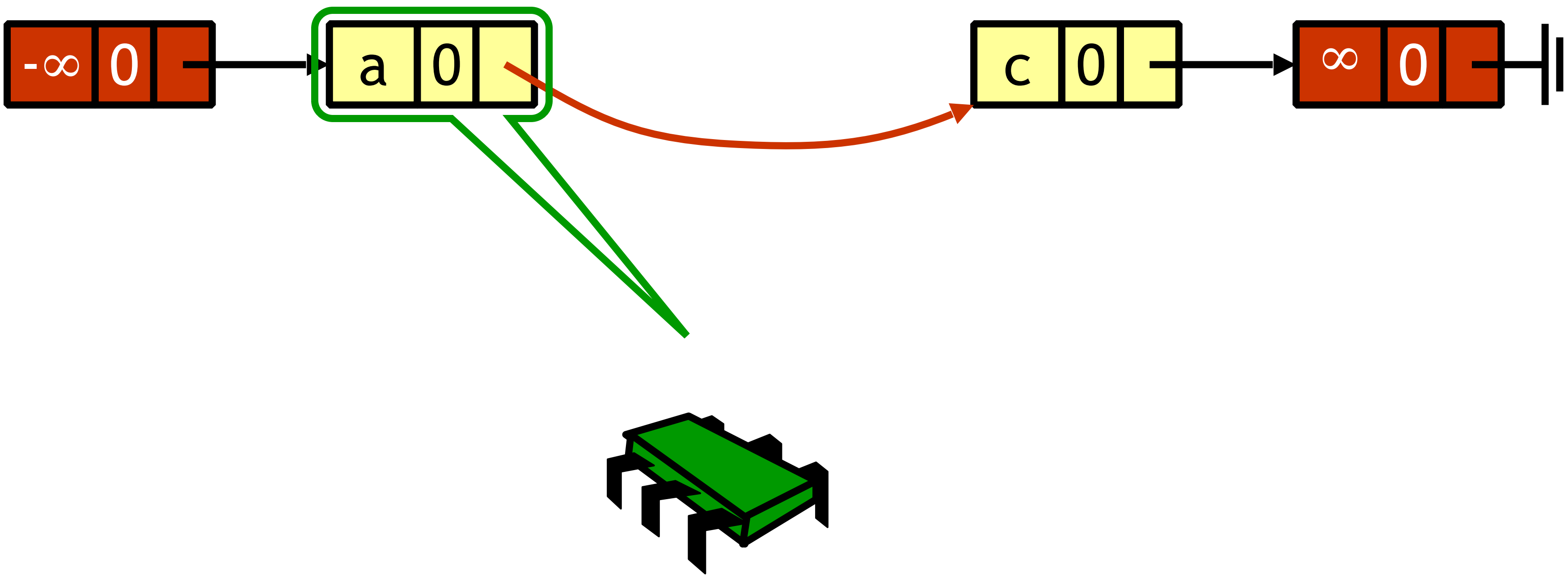
Lock-Free Traversal



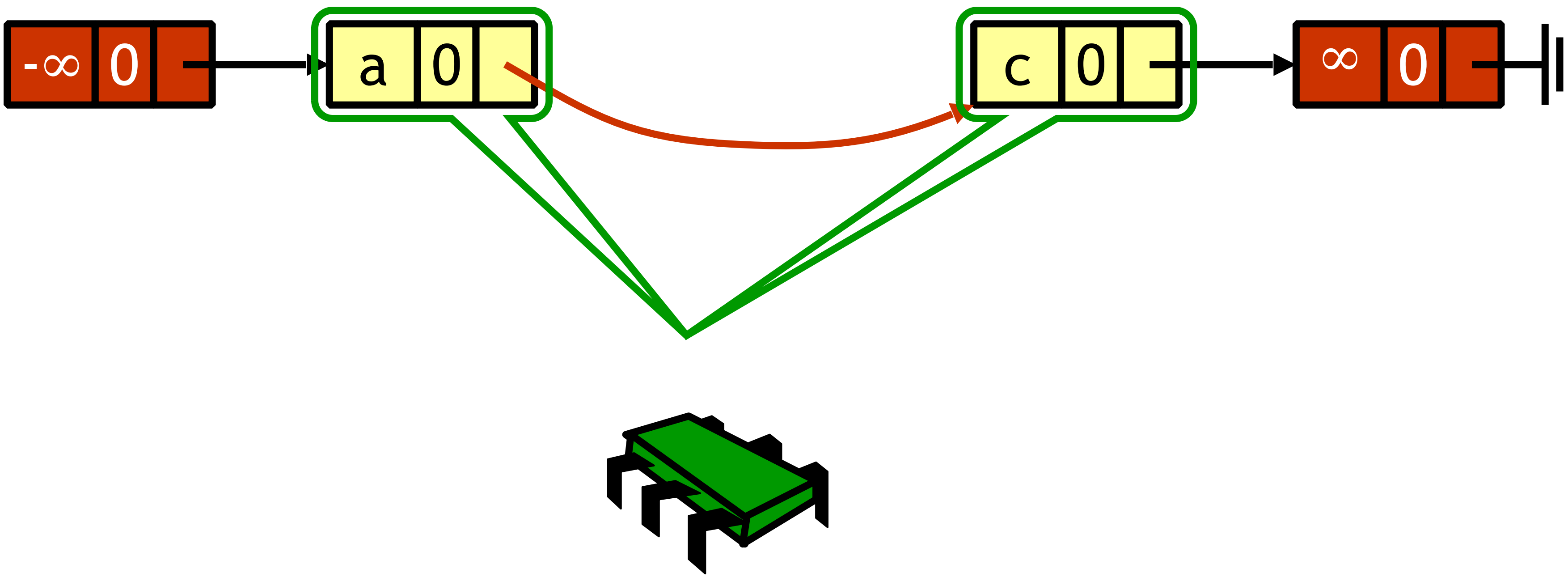
Lock-Free Traversal



Lock-Free Traversal



Lock-Free Traversal



The Window Class

```
class Window {
  Node pred;
  Node curr;
  Window(Node pred, Node curr) {
    this.pred = pred;
    this.curr = curr;
  }
}
```

The Window Class

```
class Window {
  Node pred;
  Node curr;
  Window(Node pred, Node curr) {
    this.pred = pred;
    this.curr = curr;
  }
}
```

A container for predecessor and current nodes

Using the Find Method

```
…
Window window = find(head, object);
Node pred = window.pred;
Node curr = window.curr;
…
```

Using the Find Method

```
…
Window window = find(head, object);
Node pred = window.pred;
Node curr = window.curr;
…
```

Find window

Using the Find Method

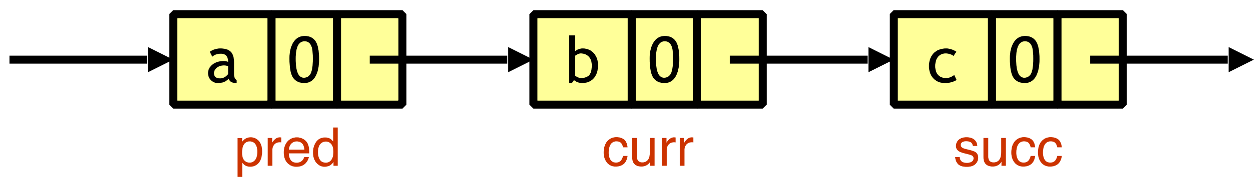
```
…
Window window = find(head, object);
Node pred = window.pred;
Node curr = window.curr;
…
```

Extract pred and curr

The Find Method

```
Window window = find(head, b);
Node pred = window.pred;
Node curr = window.curr;
```

Object in list:



Object not in list:

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {                Keep trying
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Find neighbors

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Not there

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Try to mark node as deleted

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

If it fails, retry, otherwise job done

Remove

```
public boolean remove(T object) {
  boolean b;
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object != object)
      return false;
    Node succ = curr.next.getReference();
    b = curr.next.compareAndSet(succ, succ, false, true);
    if (!b) continue;
    pred.next.compareAndSet(curr, succ, false, false);
    return true;
  }
}
```

Try to advance reference
(if it fails, someone else did or will advance it)

Add

```
public boolean add(T object) {
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object == object)
      return false;
    Node n = new Node(object);
    n.next = new AtomicMarkableReference(curr, false);
    if (pred.next.compareAndSet(curr, n, false, false))
      return true;
  }
}
```

Add

```
public boolean add(T object) {
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object == object)
      return false;
    Node n = new Node(object);
    n.next = new AtomicMarkableReference(curr, false);
    if (pred.next.compareAndSet(curr, n, false, false))
      return true;
  }
}
```

Already there

Add

```
public boolean add(T object) {
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object == object)
      return false;
    Node n = new Node(object);
    n.next = new AtomicMarkableReference(curr, false);
    if (pred.next.compareAndSet(curr, n, false, false))
      return true;
  }
}
```

Create new node

Add

```
public boolean add(T object) {
  while (true) {
    Window window = find(head, object);
    Node pred = window.pred, curr = window.curr;
    if (curr.object == object)
      return false;
    Node n = new Node(object);
    n.next = new AtomicMarkableReference(curr, false);
    if (pred.next.compareAndSet(curr, n, false, false))
      return true;
  }
}
```

Install new node, else retry loop

Wait-Free Contains

```
public boolean contains(T object) {
  boolean marked[] = new boolean[1];
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  curr.next.get(marked);
  return (object == curr.object && !marked[0]);
}
```

Wait-Free Contains

```
public boolean contains(T object) {
  boolean marked[] = new boolean[1];
  int key = object.hashCode();
  Node curr = this.head;
  while (curr.key <= key) {
    if (object == curr.object)
      break;
    curr = curr.next;
  }
  curr.next.get(marked);
  return (object == curr.object && !marked[0]);
}
```

Only difference from lazy list is that we get and check mark

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

Restart if list changes while traversed

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

Start from head

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {                                   Move down the list
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

Lock-Free Find

```
public Window find(Node head, T object) {
 Node pred, curr, succ; int key = object.hashCode();
 boolean[] marked = { false }; boolean b;
 retry: while (true) {
  pred = head; curr = pred.next.getReference();
  while (true) {
   succ = curr.next.get(marked);
   while (marked[0]) { … }
   if ((curr.key == key && curr.object == object)
       || curr.key > key)
    return new Window(pred, curr);
   pred = curr; curr = succ;
  }
 }
}
```

Get successor and mark

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

Try to remove deleted nodes

Lock-Free Find

```
public Window find(Node head, T object) {
  Node pred, curr, succ; int key = object.hashCode();
  boolean[] marked = { false }; boolean b;
  retry: while (true) {
    pred = head; curr = pred.next.getReference();
    while (true) {
      succ = curr.next.get(marked);
      while (marked[0]) { … }
      if ((curr.key == key && curr.object == object)
          || curr.key > key)
        return new Window(pred, curr);
      pred = curr; curr = succ;
    }
  }
}
```

If found object or greater key, return pred and curr

Lock-Free Find

```
public Window find(Node head, T object) {
 Node pred, curr, succ; int key = object.hashCode();
 boolean[] marked = { false }; boolean b;
 retry: while (true) {
  pred = head; curr = pred.next.getReference();
  while (true) {
   succ = curr.next.get(marked);
   while (marked[0]) { … }
   if ((curr.key == key && curr.object == object)
       || curr.key > key)
    return new Window(pred, curr);
   pred = curr; curr = succ;
  }
 }
}
```

Otherwise advance window and loop again

Lock-Free Find

```
…
while (marked[0]) {
  b = pred.next.compareAndSet(curr, succ, false, false);
  if (!b) continue retry;
  curr = succ;
  succ = curr.next.get(marked);
}
…
```

Lock-Free Find

Try to snip out node

```
…
while (marked[0]) {
  b = pred.next.compareAndSet(curr, succ, false, false);
  if (!b) continue retry;
  curr = succ;
  succ = curr.next.get(marked);
}
…
```

Lock-Free Find

```
…
while (marked[0]) {
  b = pred.next.compareAndSet(curr, succ, false, false);
  if (!b) continue retry;
  curr = succ;
  succ = curr.next.get(marked);
}
…
```

If predecessor's next field changed must retry whole traversal

Lock-Free Find

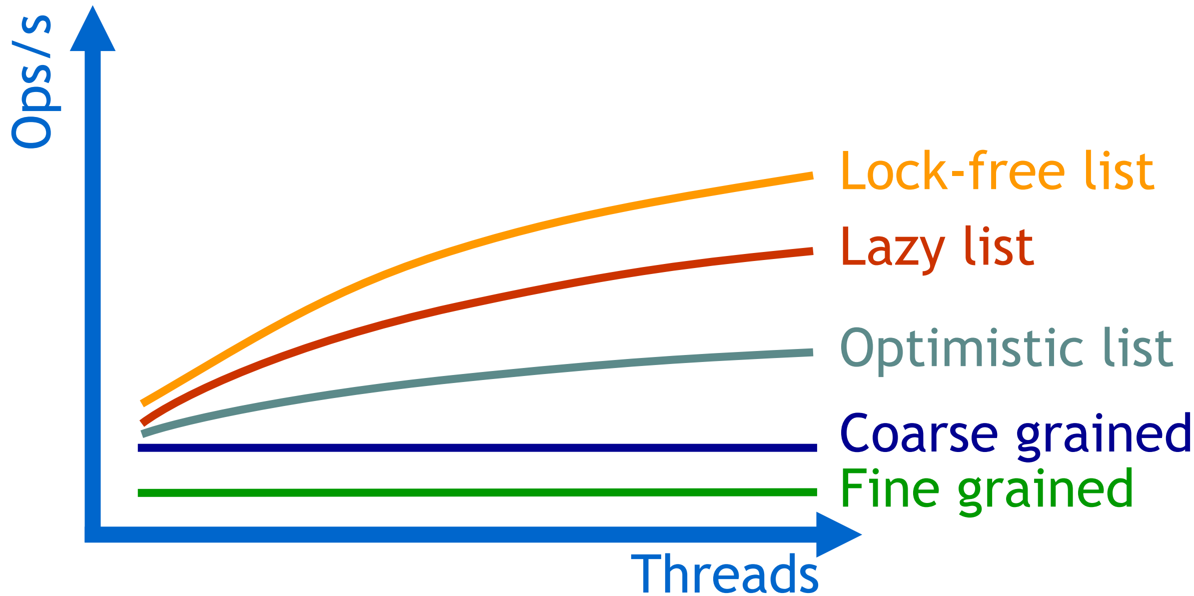
```
…
while (marked[0]) {
  b = pred.next.compareAndSet(curr, succ, false, false);
  if (!b) continue retry;
  curr = succ;
  succ = curr.next.get(marked);
}
…
```

Otherwise move on to check if next node deleted

Summary: Lock-Free List

- AtomicMarkableReference atomically updates mark and reference
    - Prevents manipulation of logically-removed next pointer
- Lock-free add() and remove()
    - Remove performs logical removal, may leave node
- Lock-free find() traverses both marked and removed nodes
    - Physically clean up (remove) marked nodes

Performance



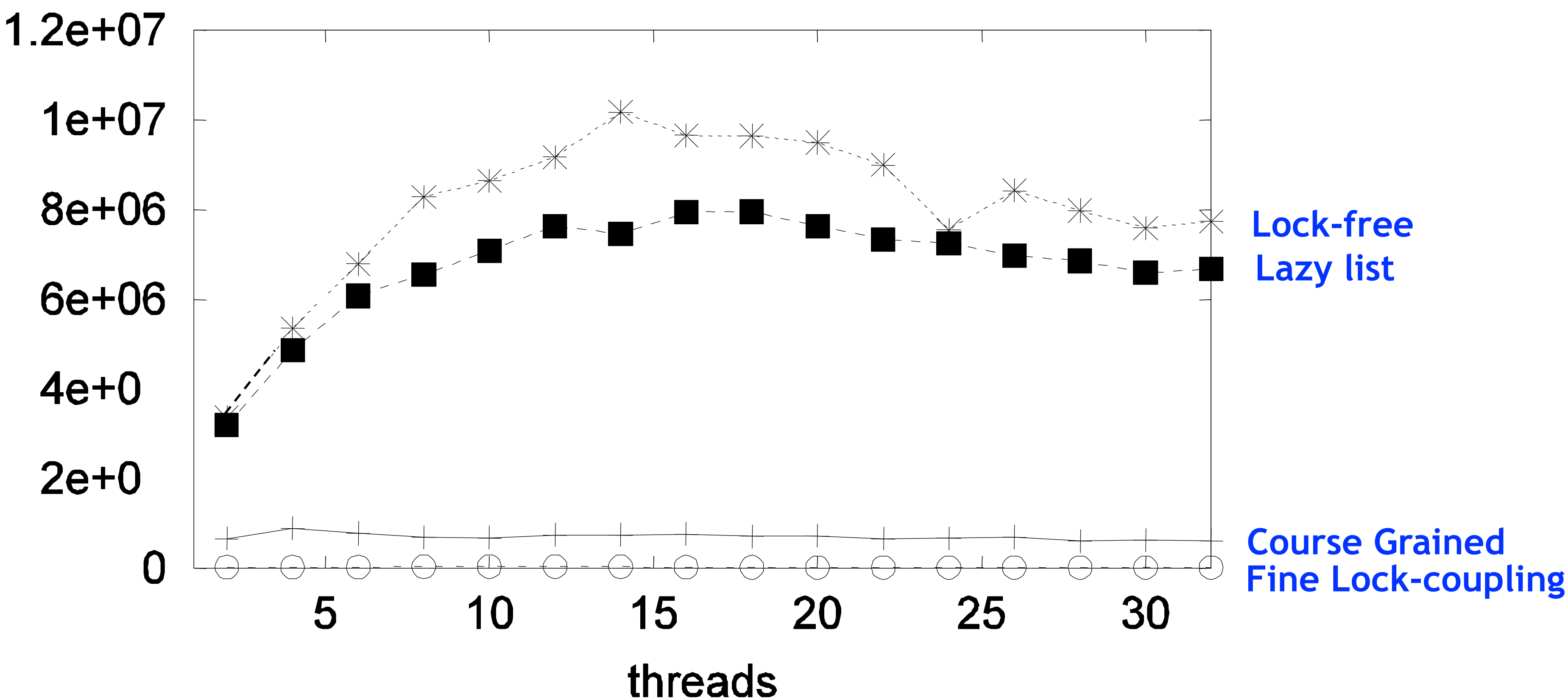
Performance

On 16 node shared memory machine

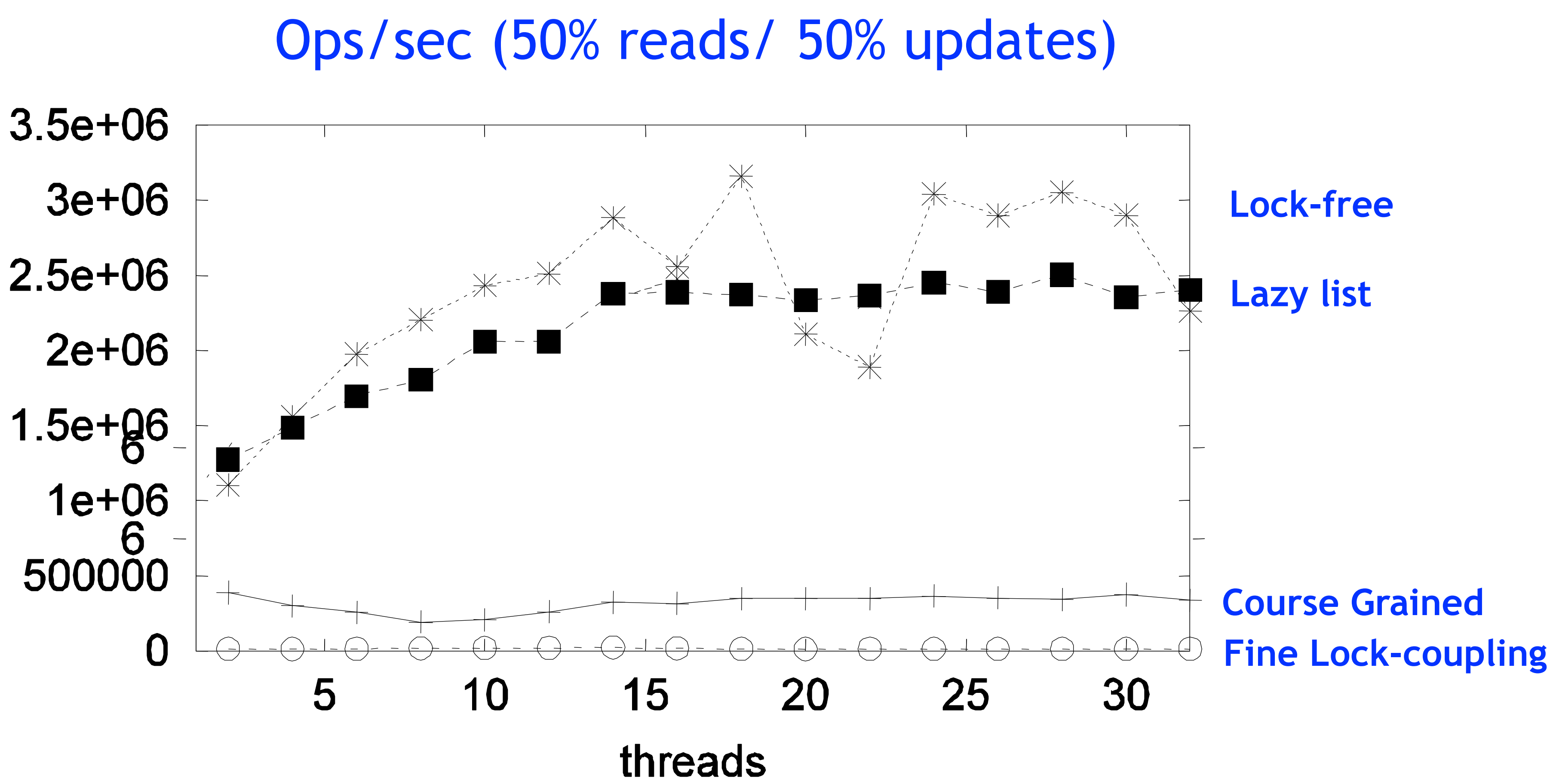
Benchmark throughput of Java List-based Set algs. Vary % of Contains() method Calls.

High Contains Ratio

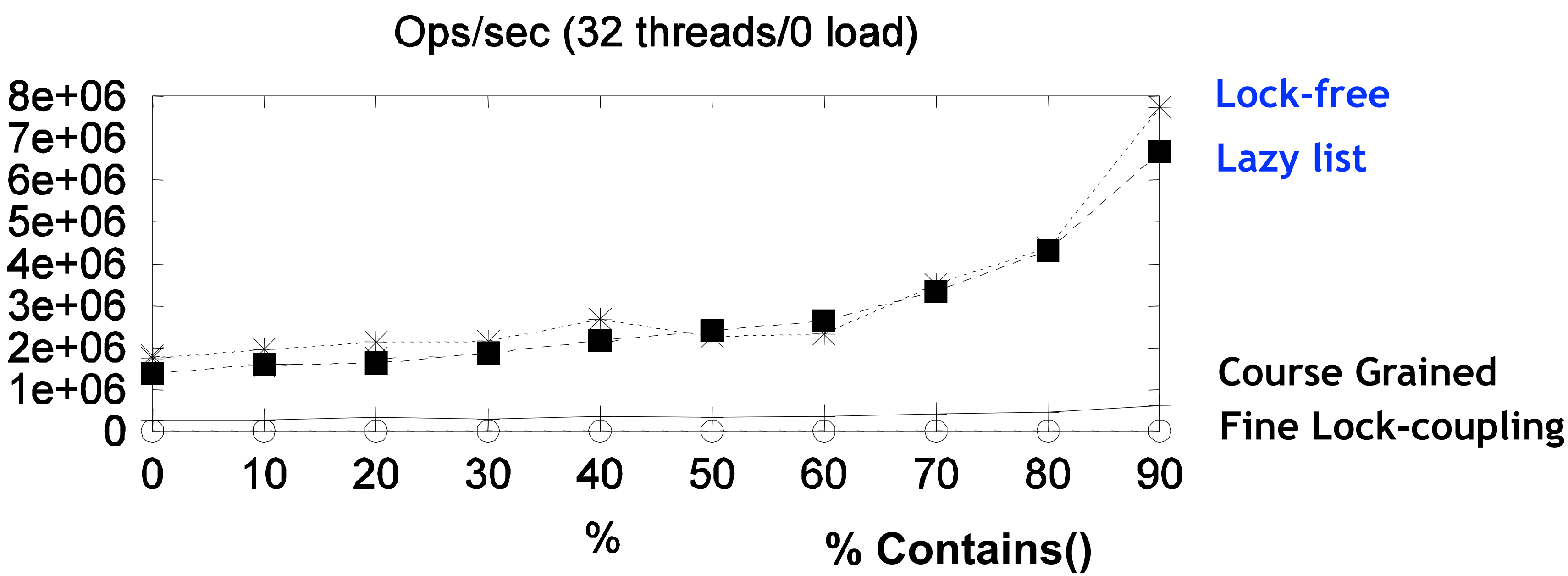
Ops/sec (90% reads/ 10% updates)



Low Contains Ratio



As Contains Ratio Increases



Summary

- Four “generic” approaches to concurrent data structure design
  - Fine-grained locking
  - Optimistic synchronization
  - Lazy synchronization
  - Lock-free synchronization

"To Lock or Not to Lock"

- Locking vs. non-blocking
  - Extremist views on both sides
- Nobler to compromise, combine locking and non-blocking
  - Example: Lazy list combines blocking add() and remove() and a wait-free contains()
  - Blocking/non-blocking is a property of a method