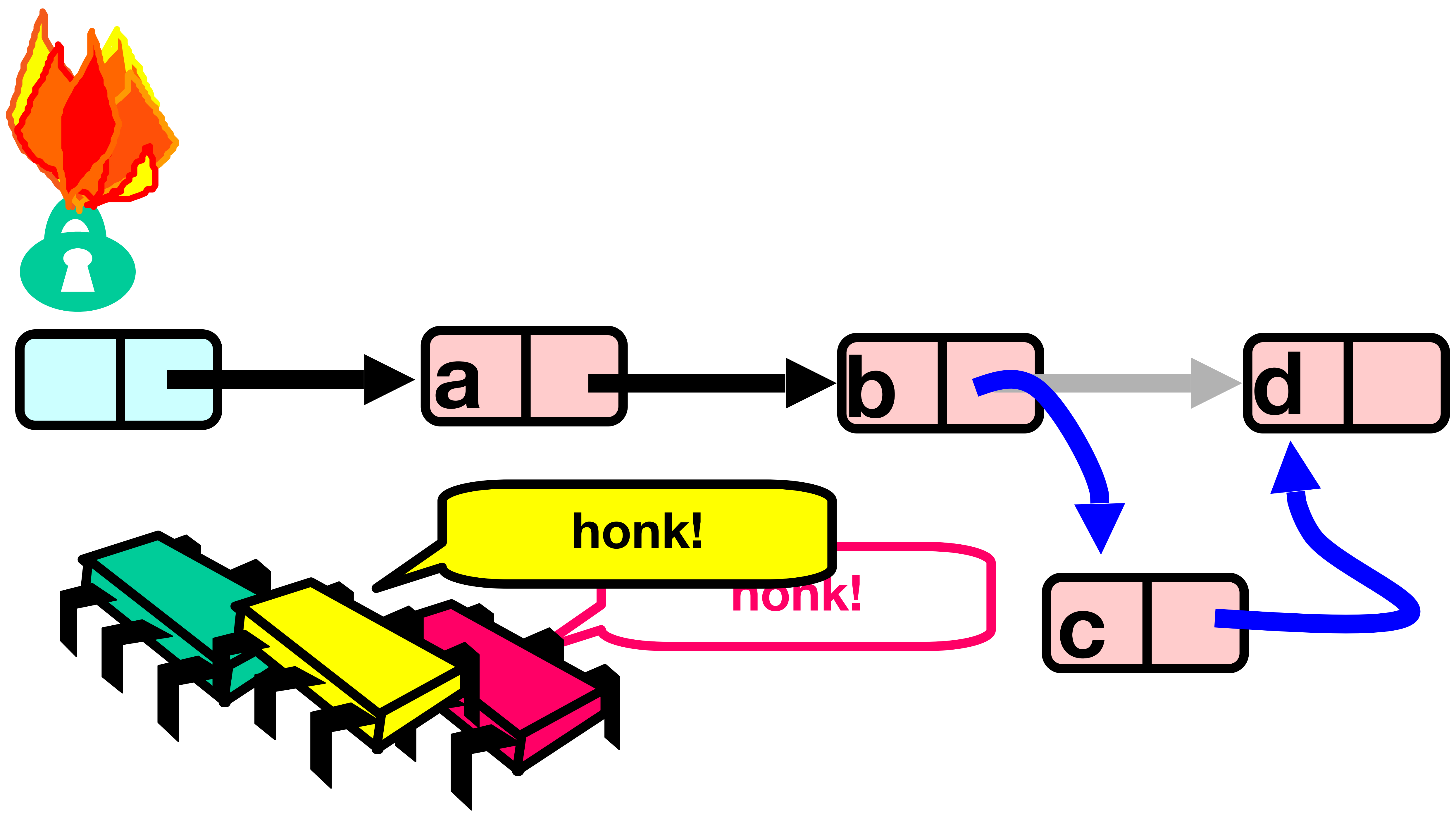
Locking - Optimistic and Lazy

CS 475, Spring 2019
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Course Grained Locking



Simple but hotspot + bottleneck

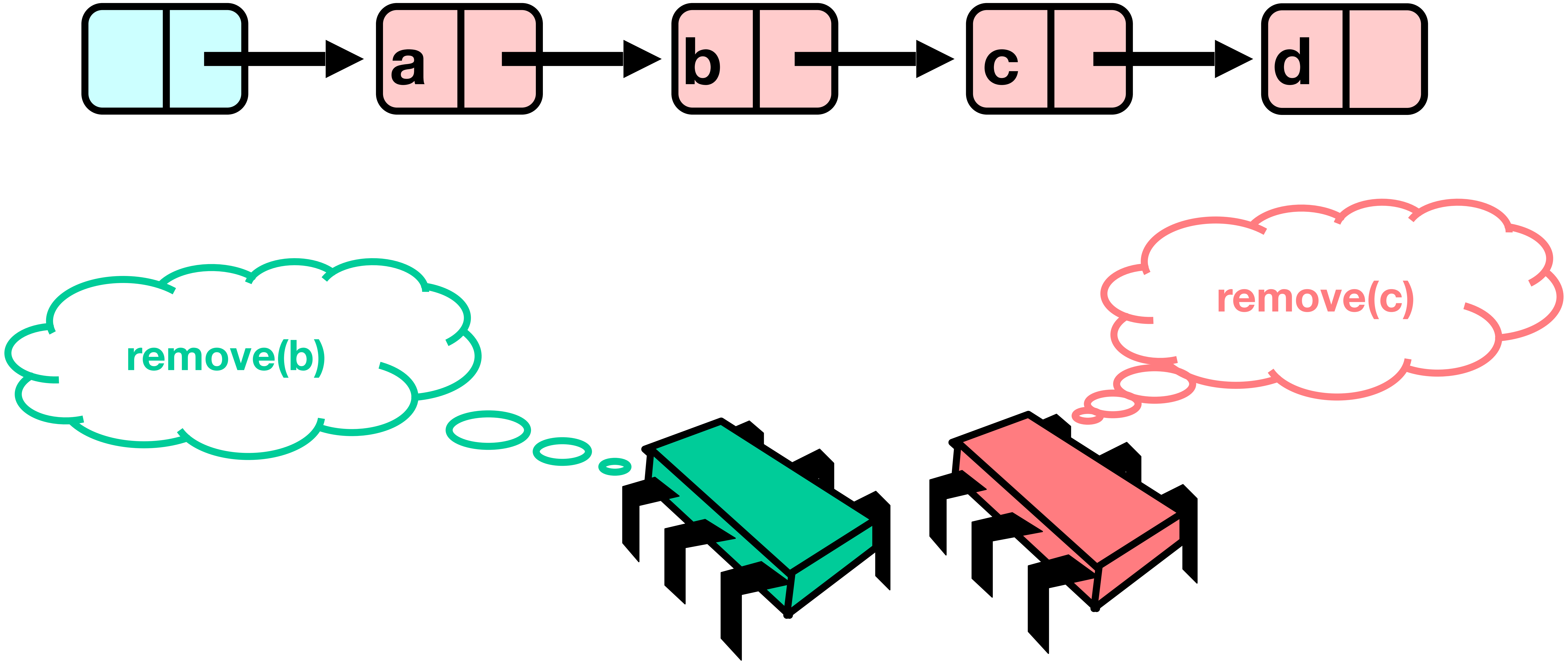
Coarse-Grained Locking

- 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

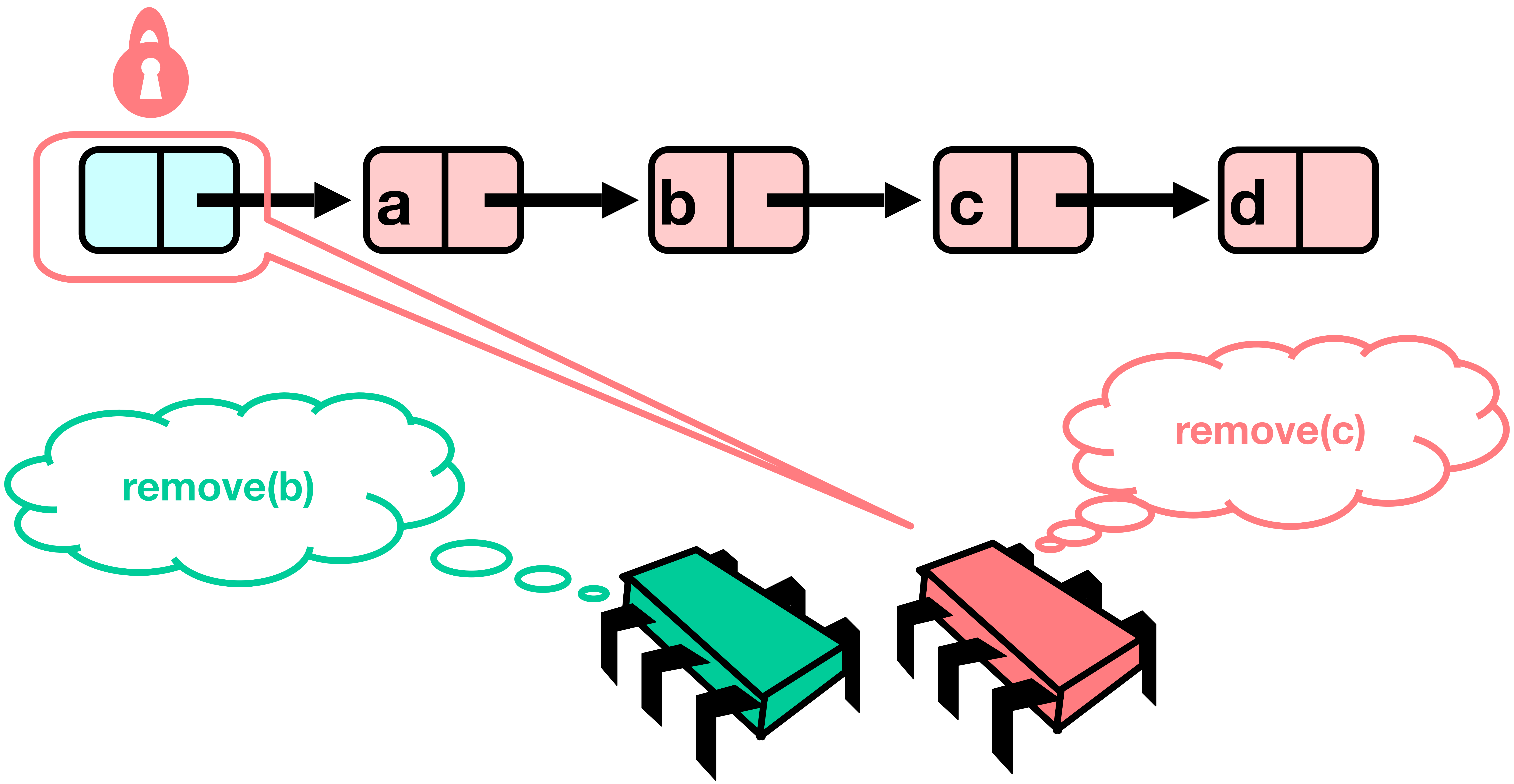
Fine-grained Locking

- 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

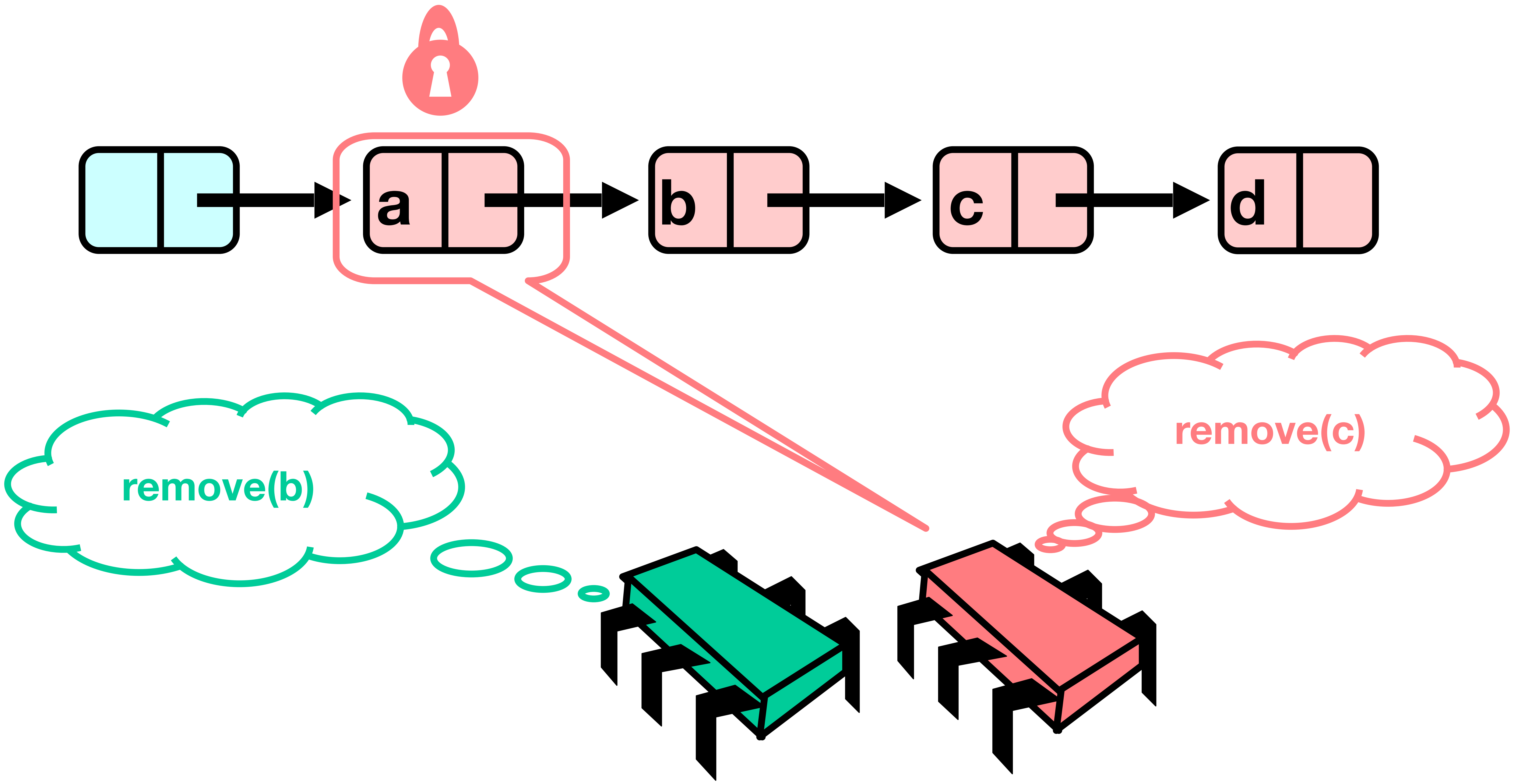
Simple Fine-Grained Locking: Remove



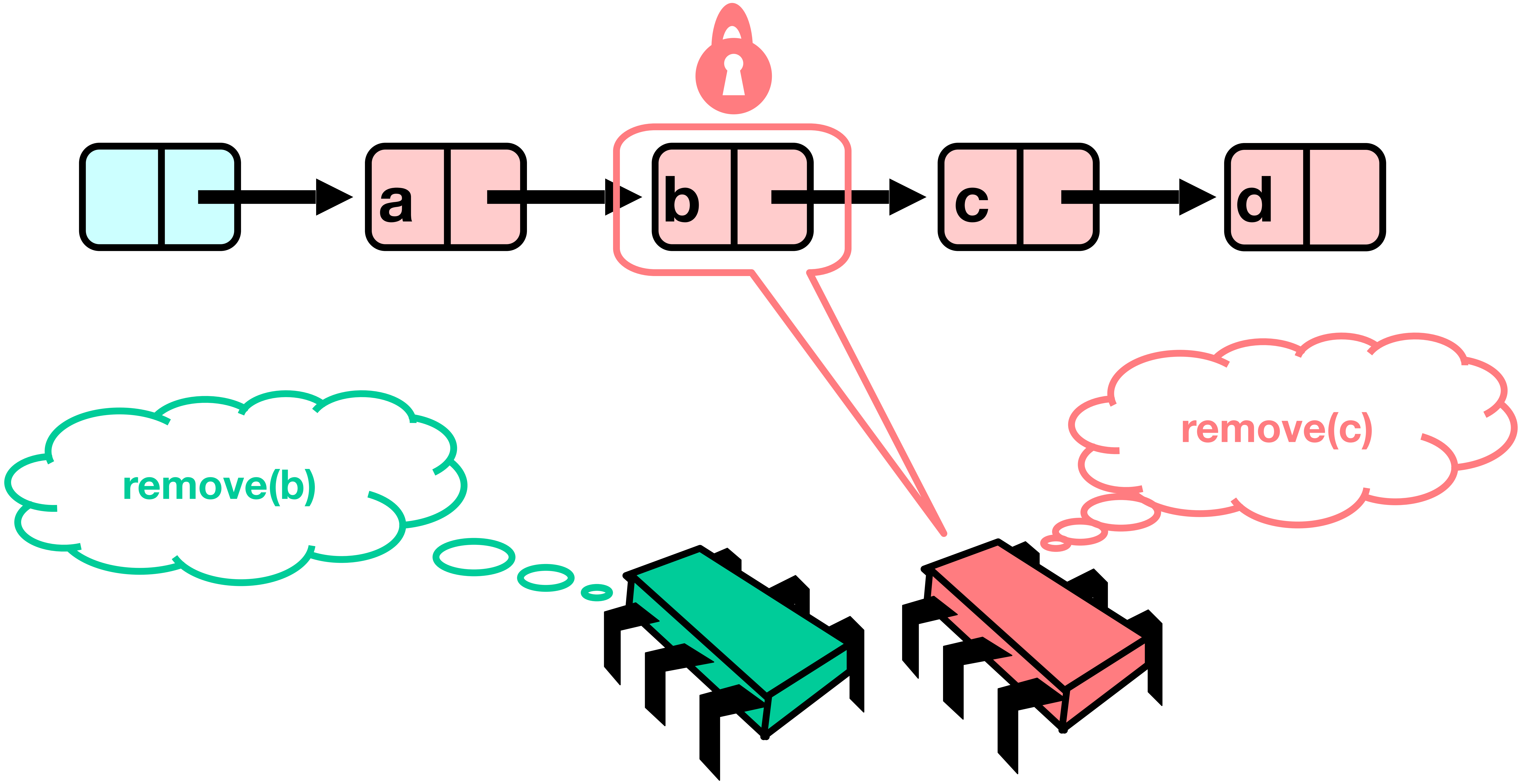
Simple Fine-Grained Locking: Remove



Simple Fine-Grained Locking: Remove



Simple Fine-Grained Locking: Remove



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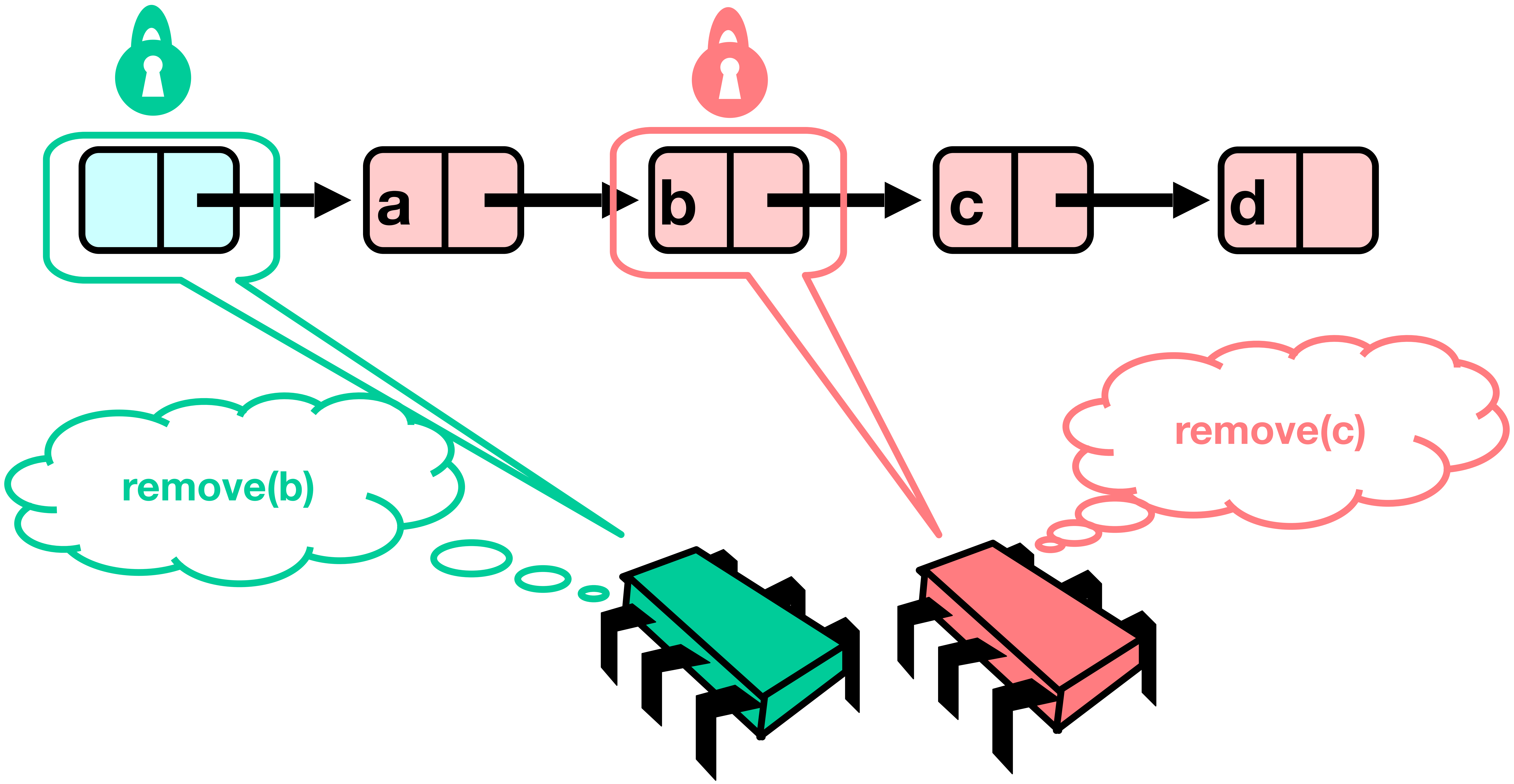

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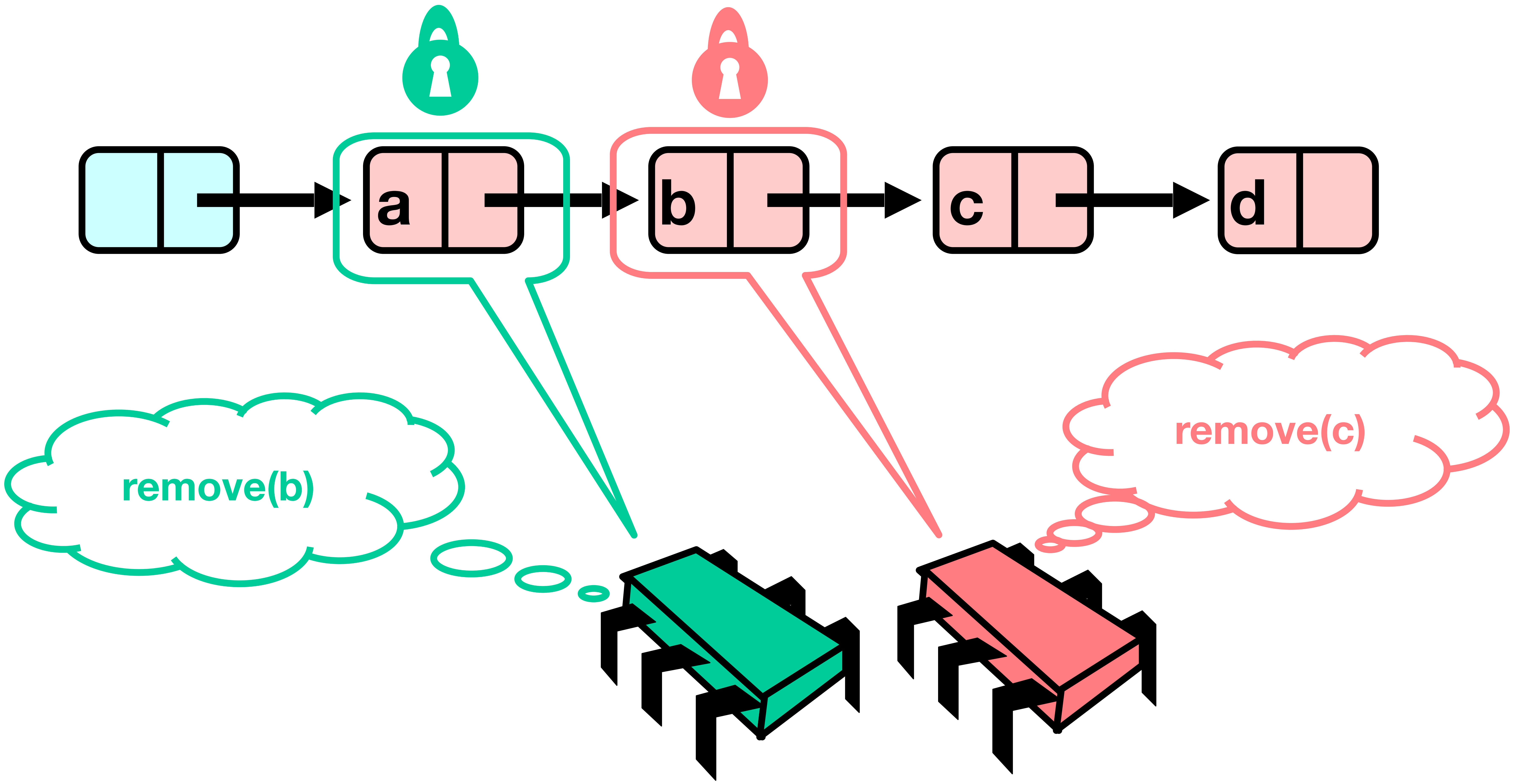
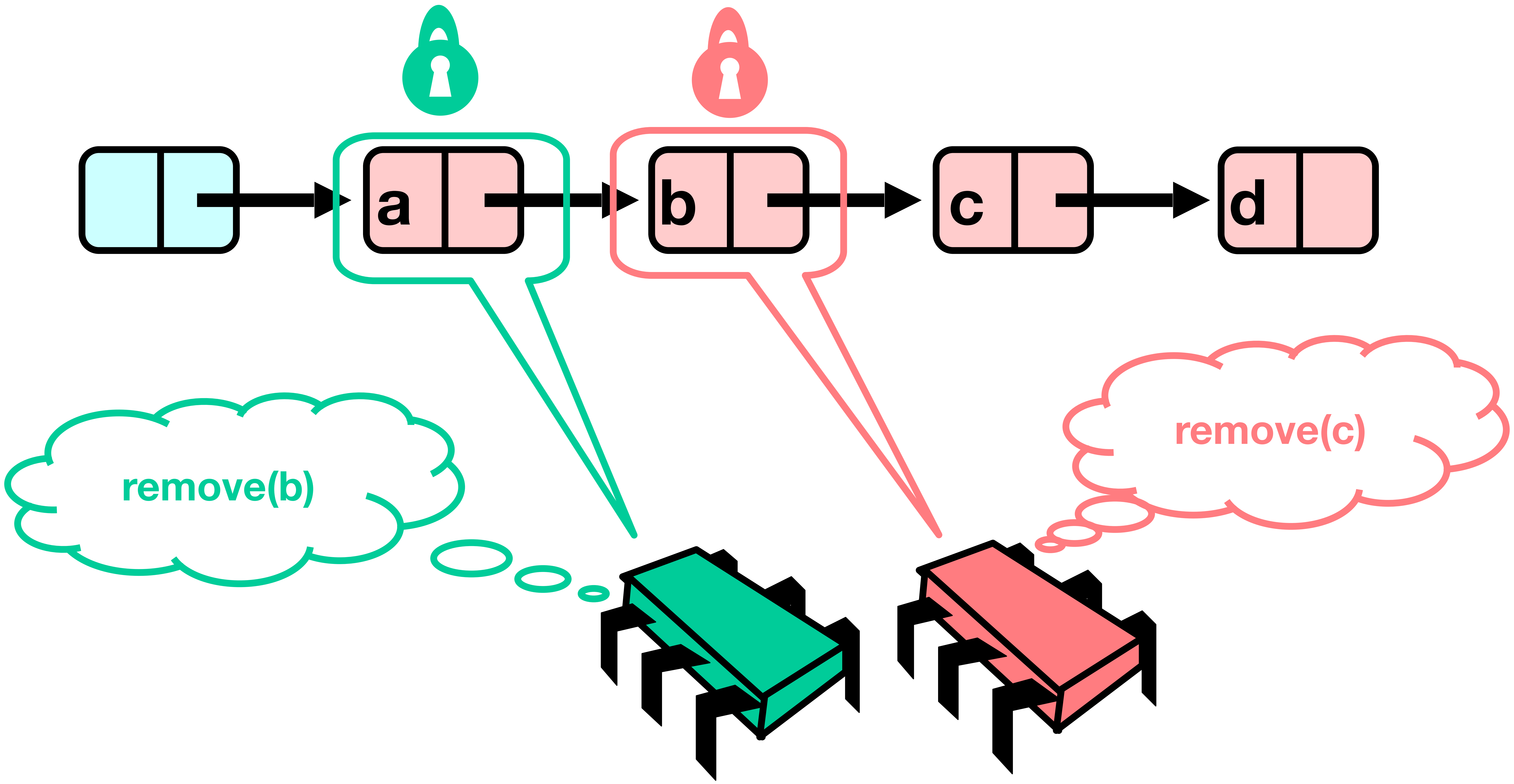
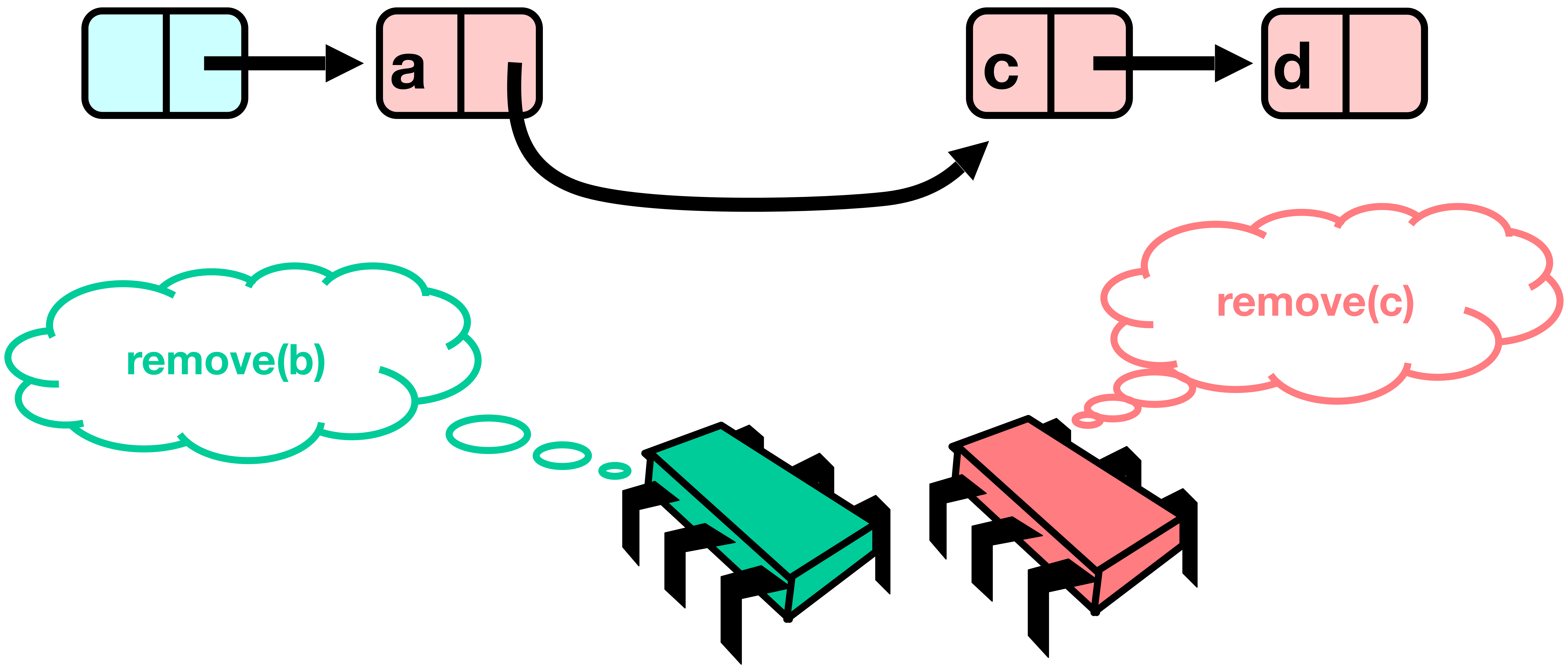


Simple Fine-Grained Locking: Remove



Uh, Oh



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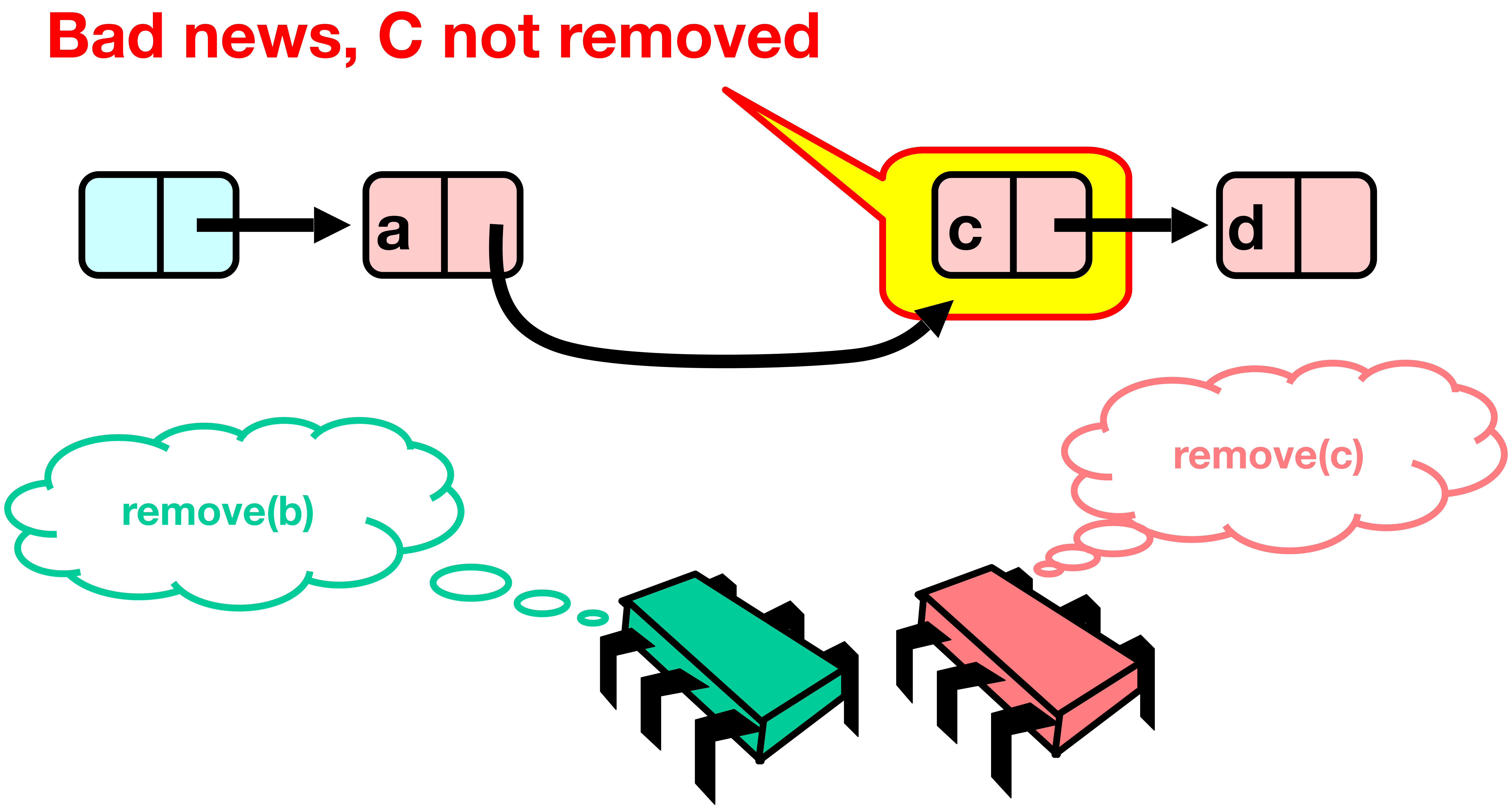
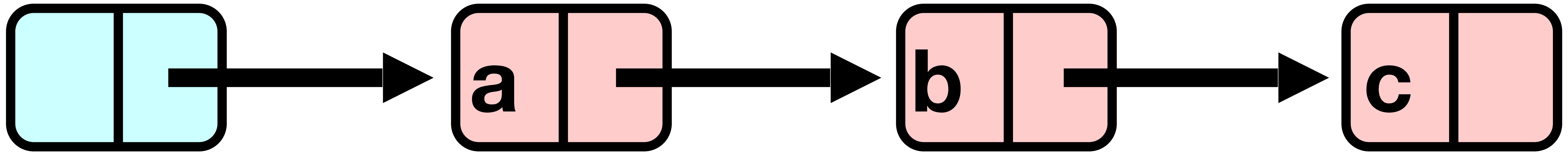
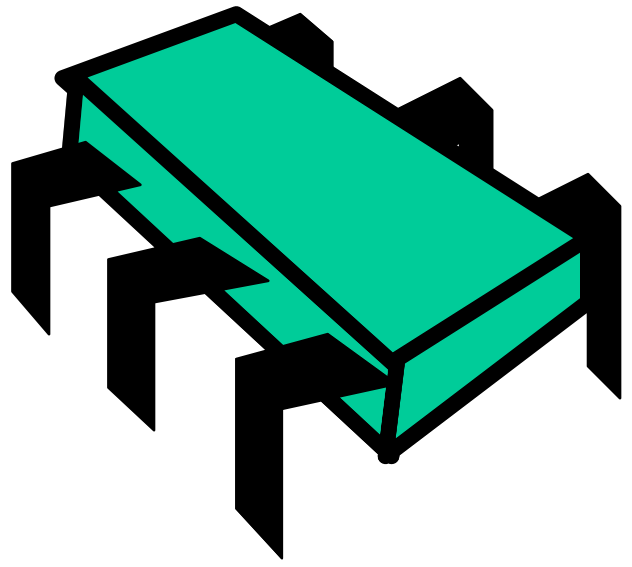
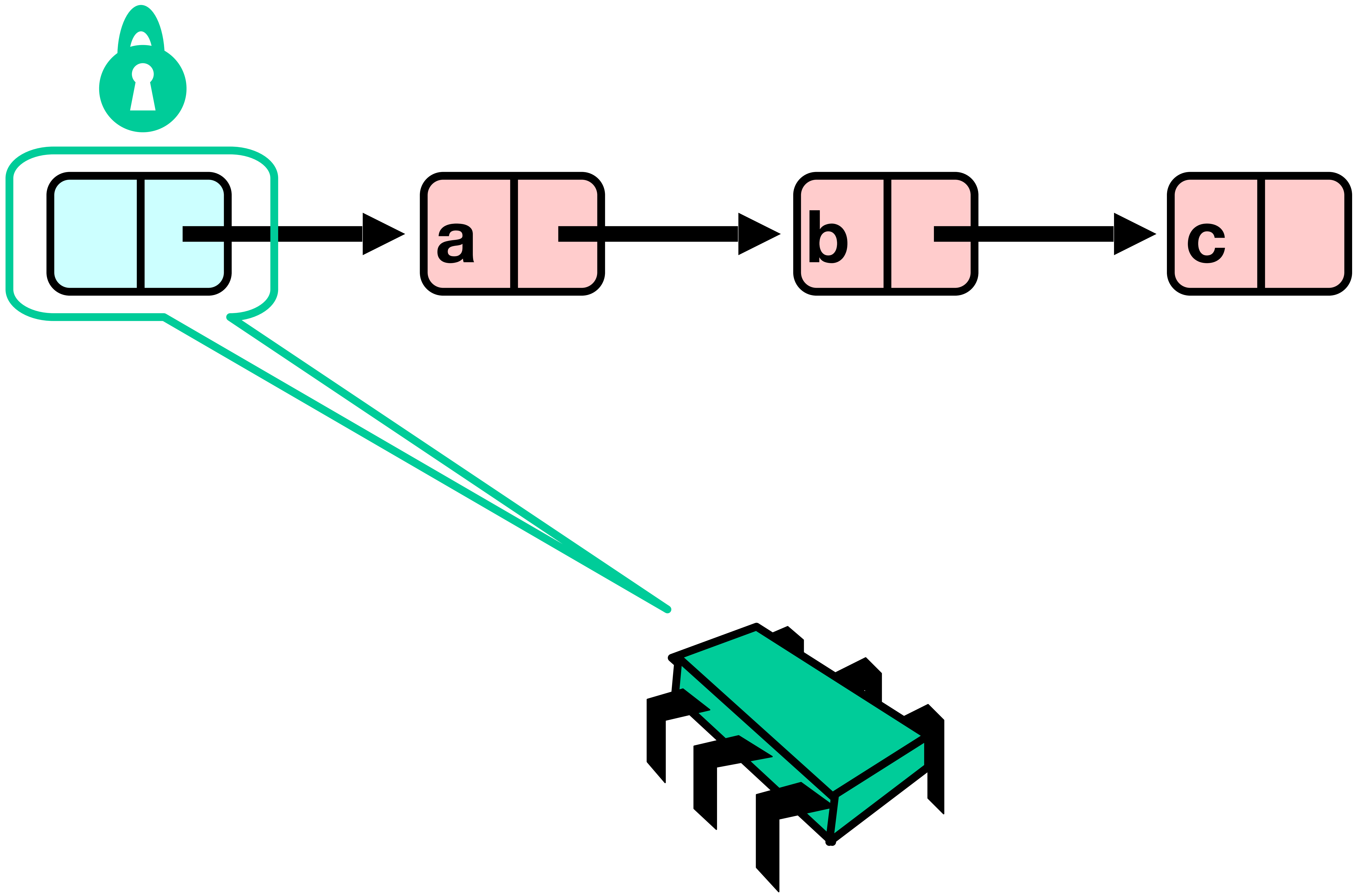


Hand-over-Hand locking

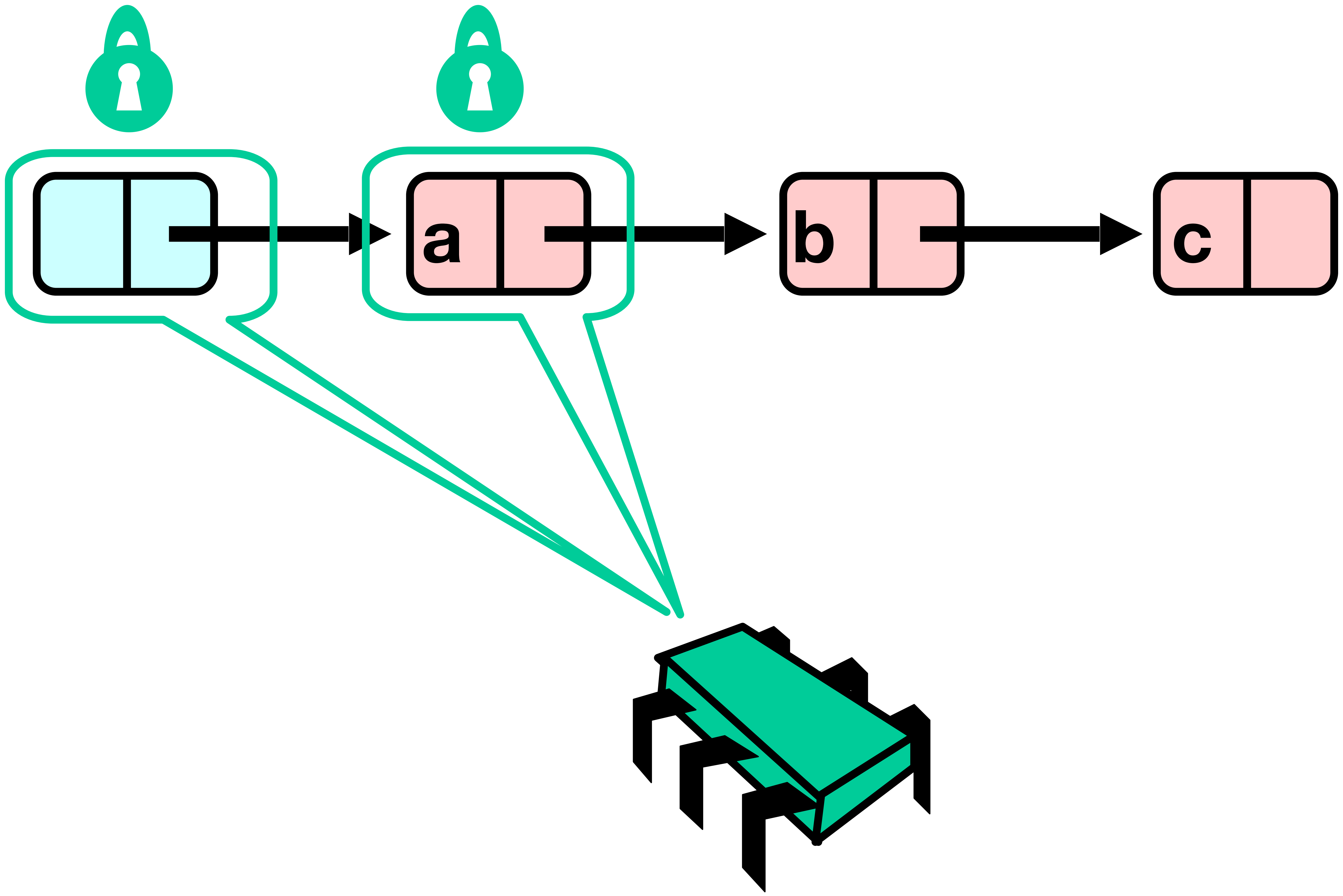




Hand-over-Hand locking



Hand-over-Hand locking



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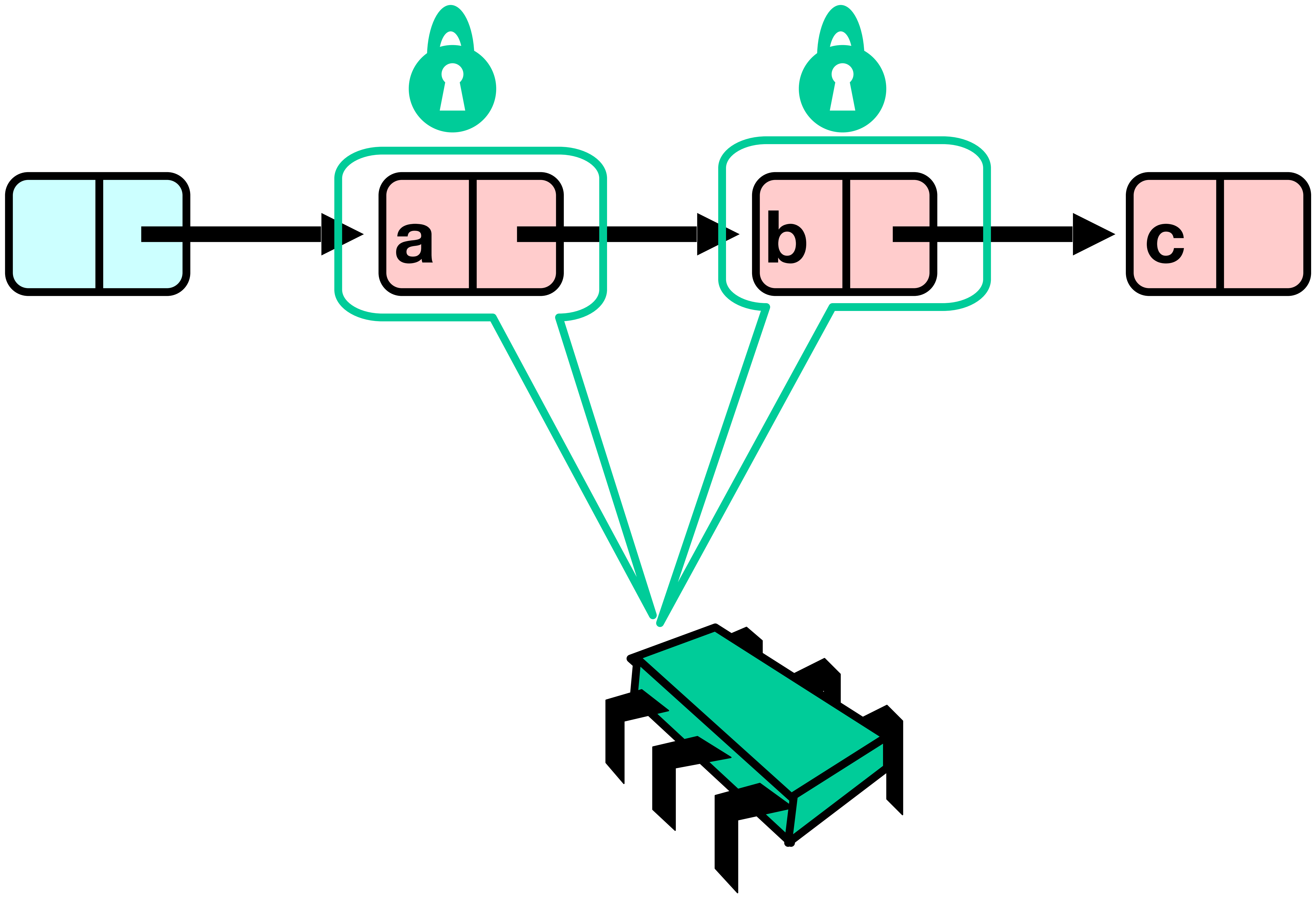
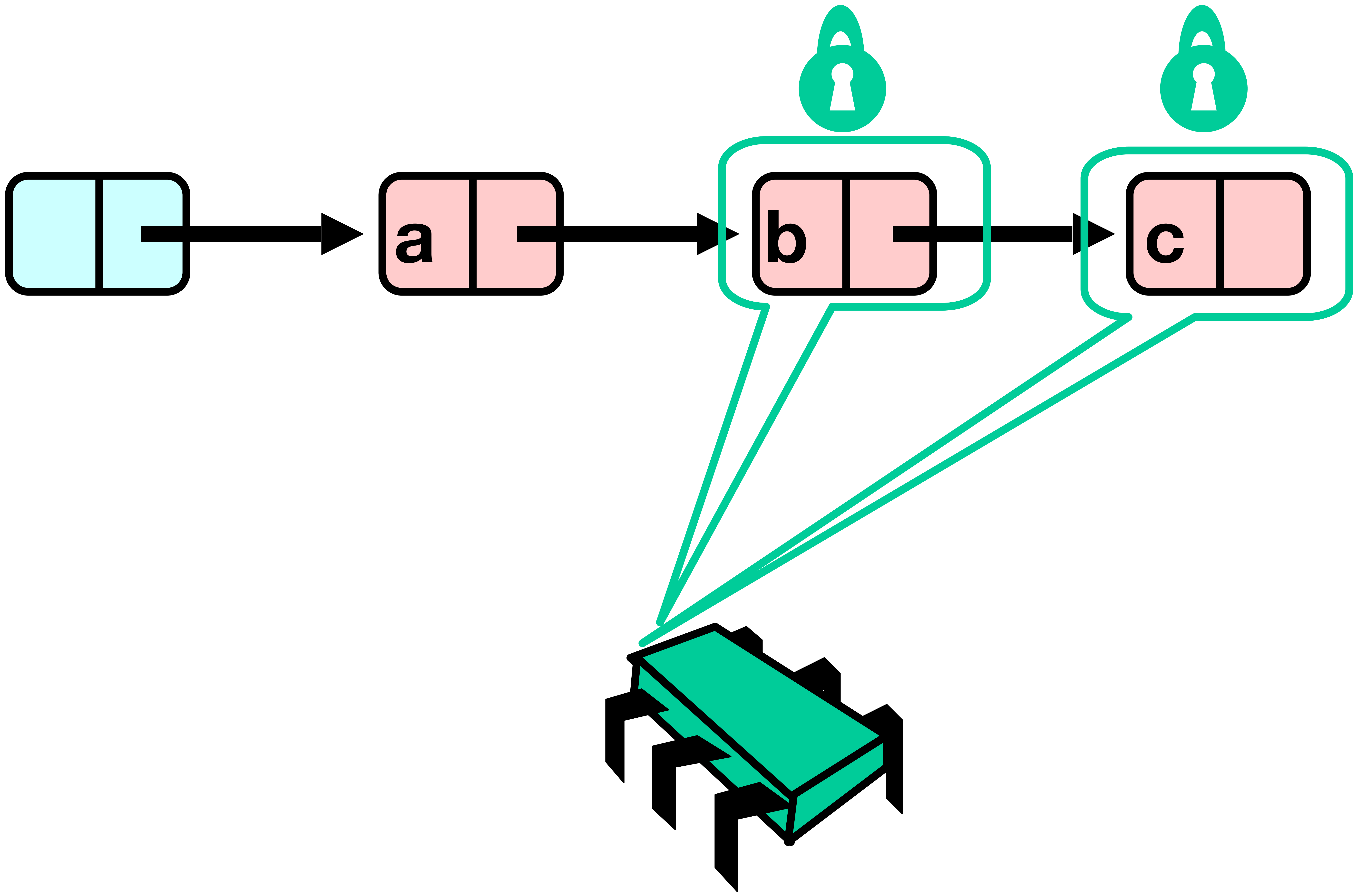
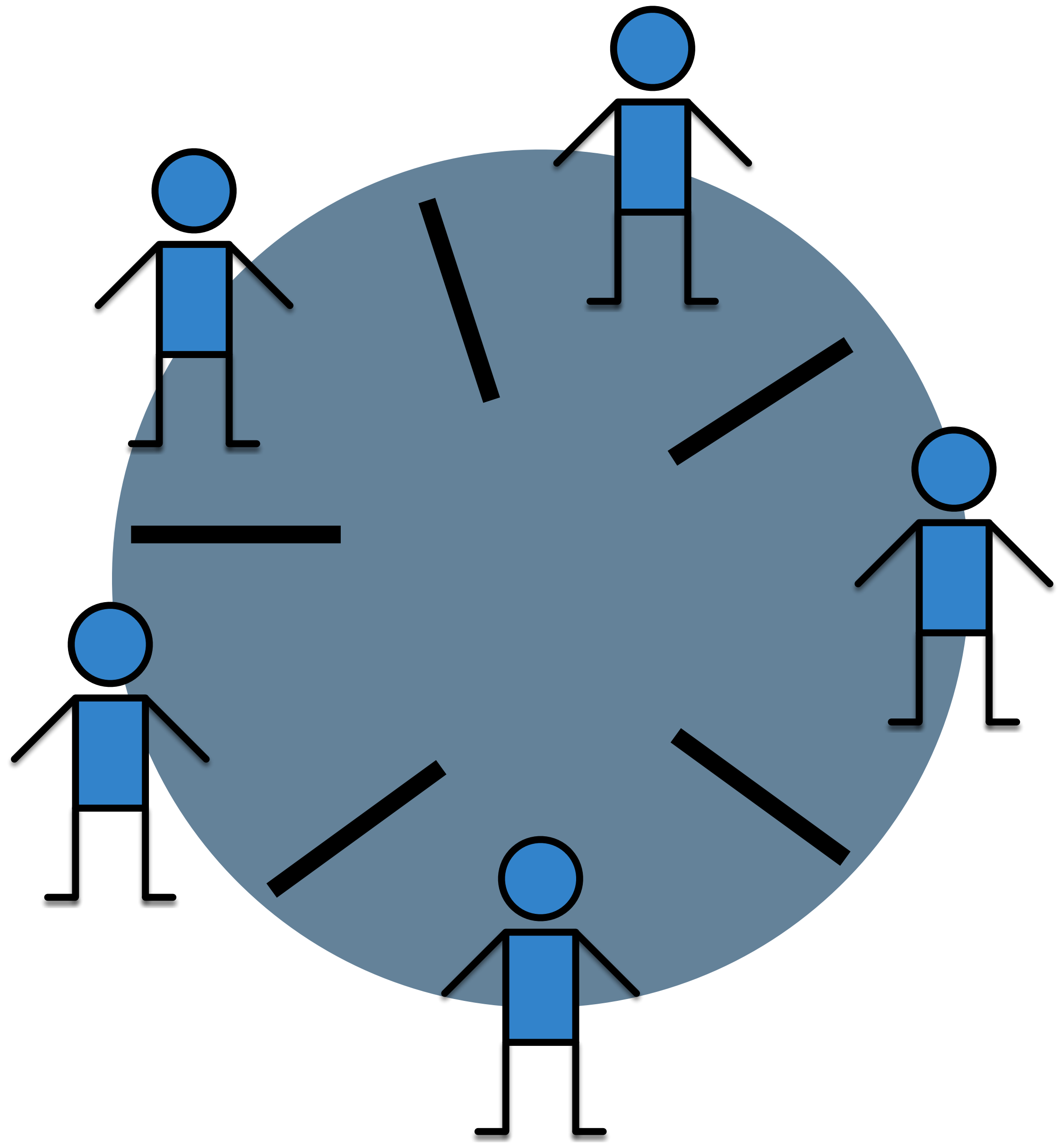


Hand-over-Hand locking



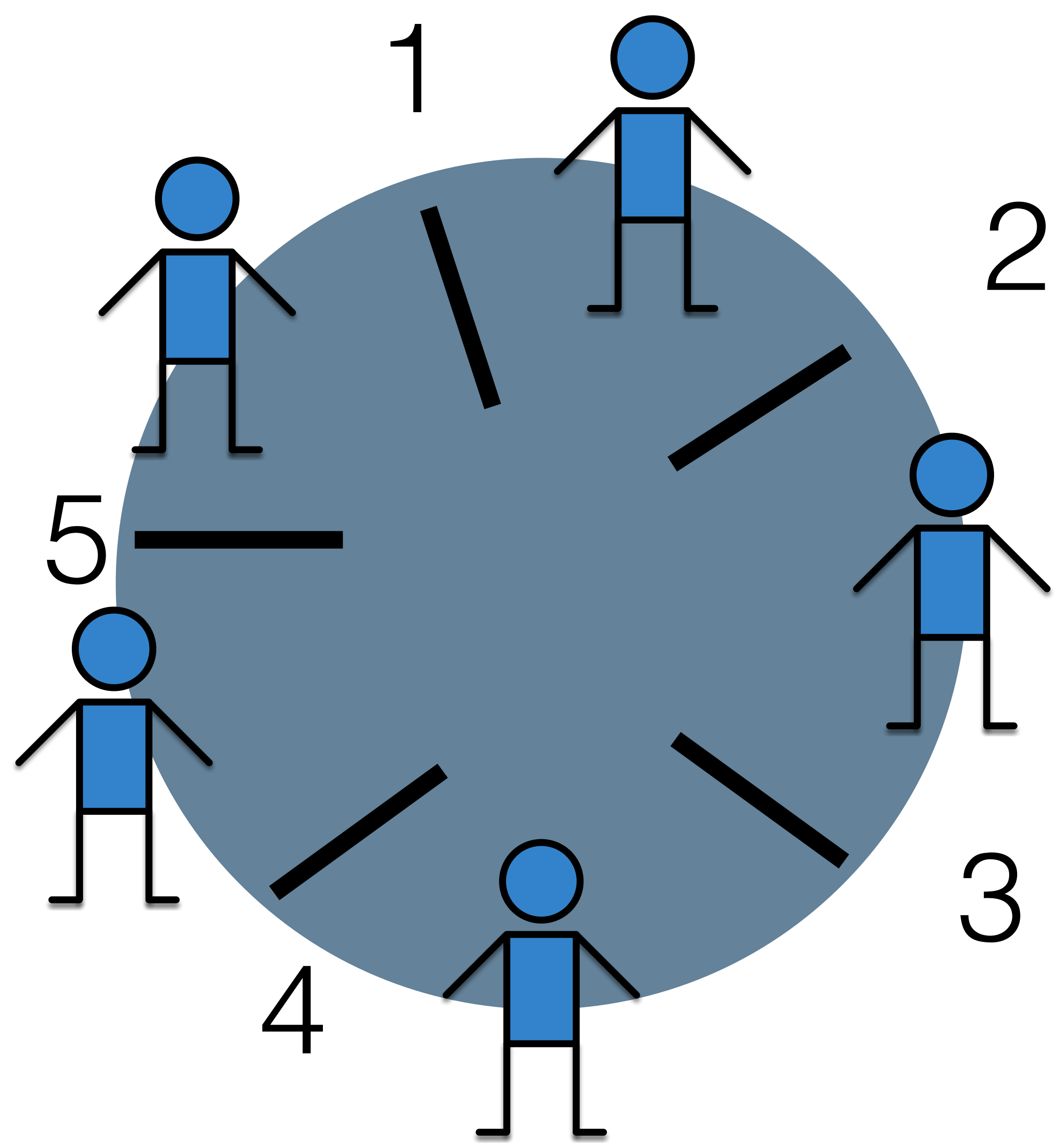
Dining Philosophers

- 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?

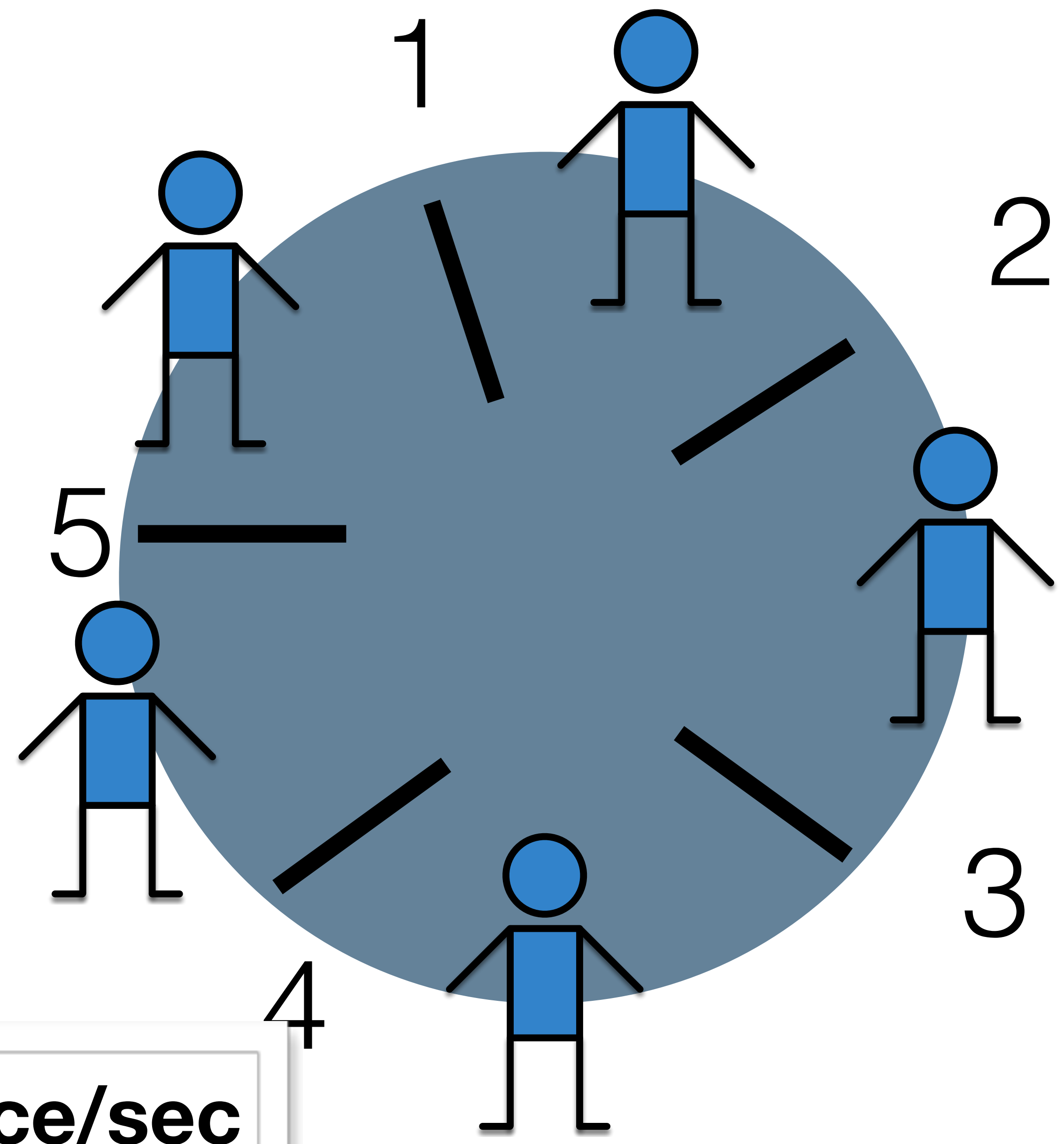


Dining Philosophers

- 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
- 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

1,450 grains of rice/sec

  - Only allow 4 philosophers to pick up chopsticks at once

5,431,616 grains of rice/sec

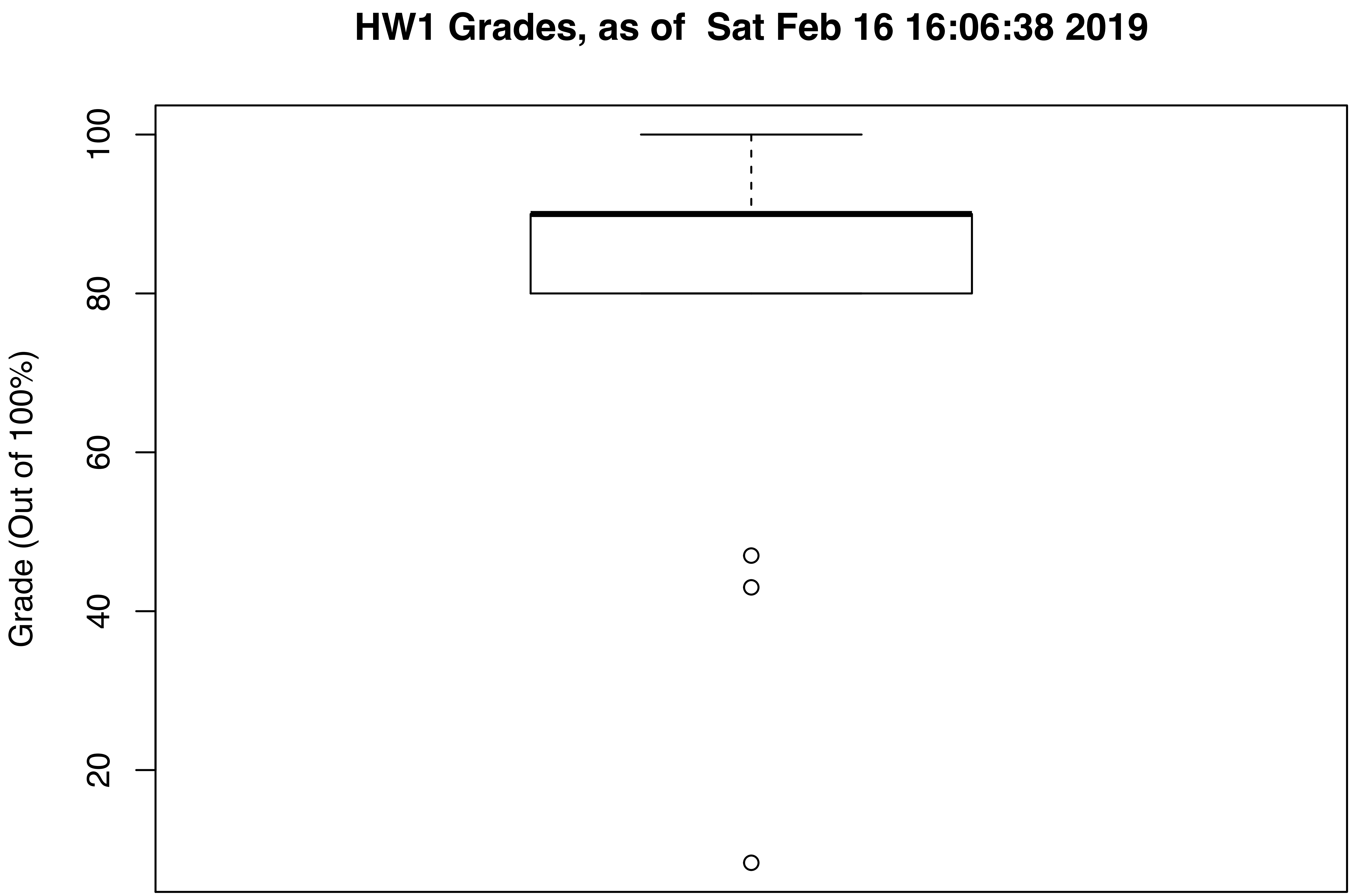
  - Even # seats pick up right chopstick, odd # seats pick up left

12,450,856 grains of rice/sec

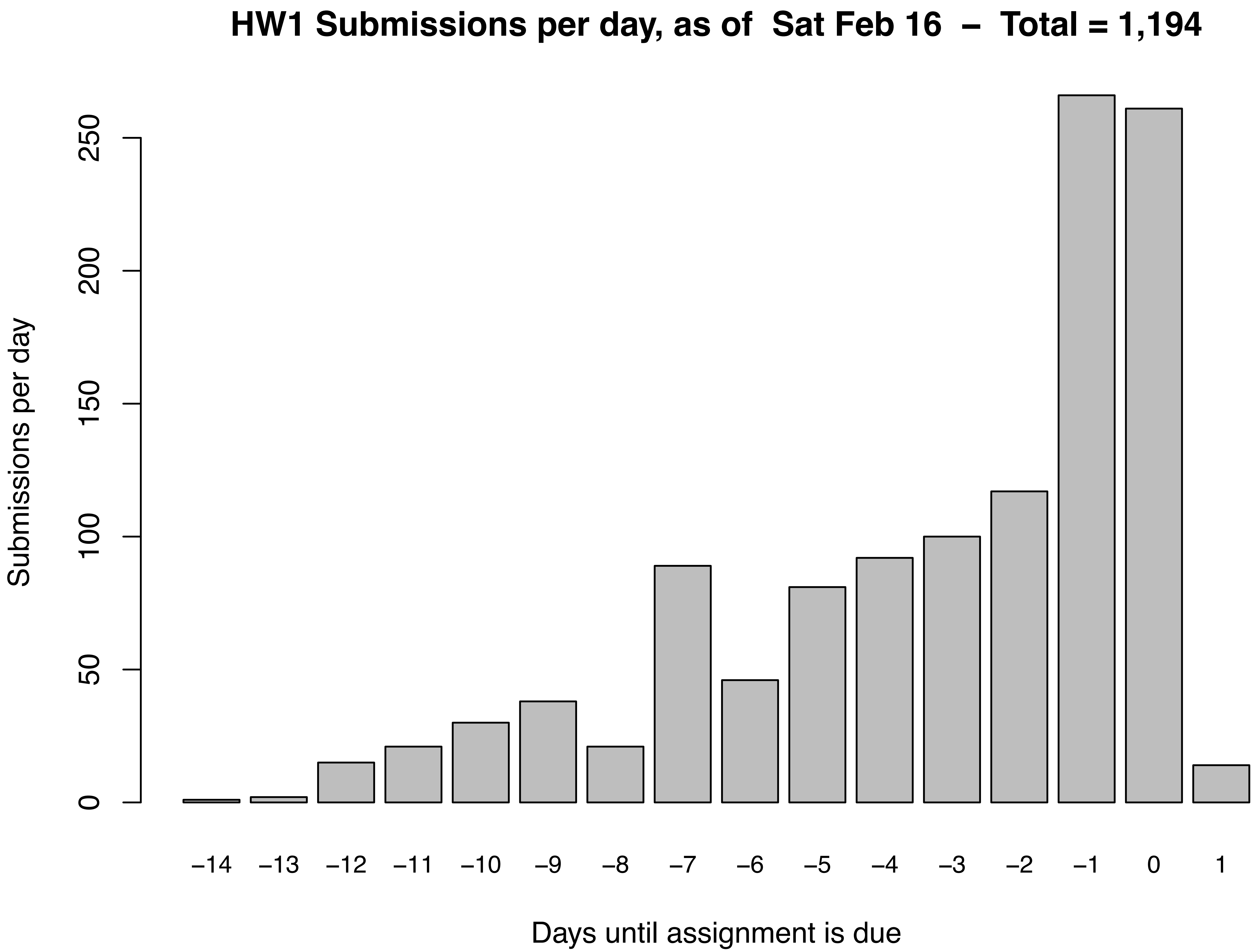
Today

- Adding threads should not lower throughput
  - Contention effects
- Should increase throughput
  - Not possible if inherently sequential
  - How do we structure locks for faster performance?
- Reading: H&S 9.6-9.9

HW1 Discussion



HW1 Discussion



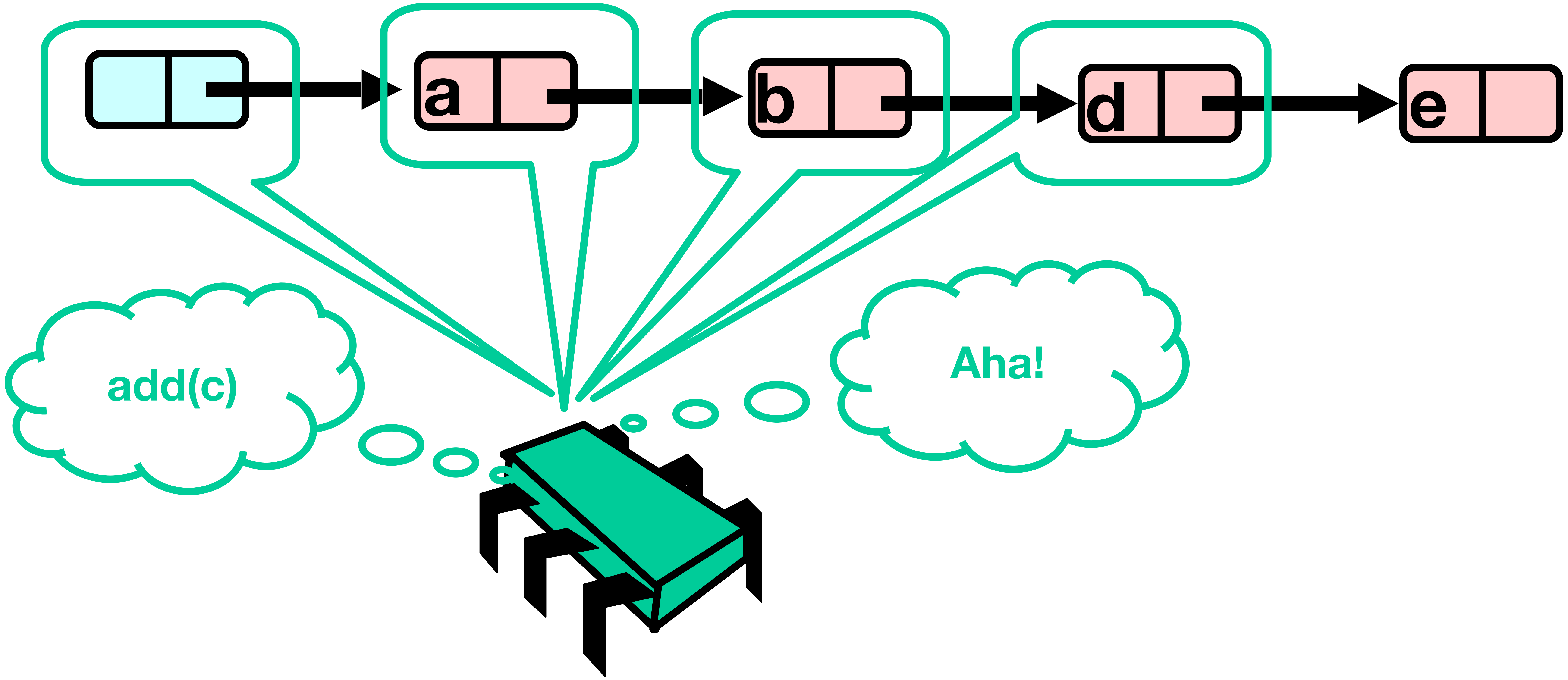
Drawbacks of Fine Grained Locking for List

- Better than coarse-grained lock
  - Threads can traverse in parallel
- Still not ideal
  - Long chain of acquire/release
  - Inefficient (still can have blocking; two threads traversing list at once are sequential)

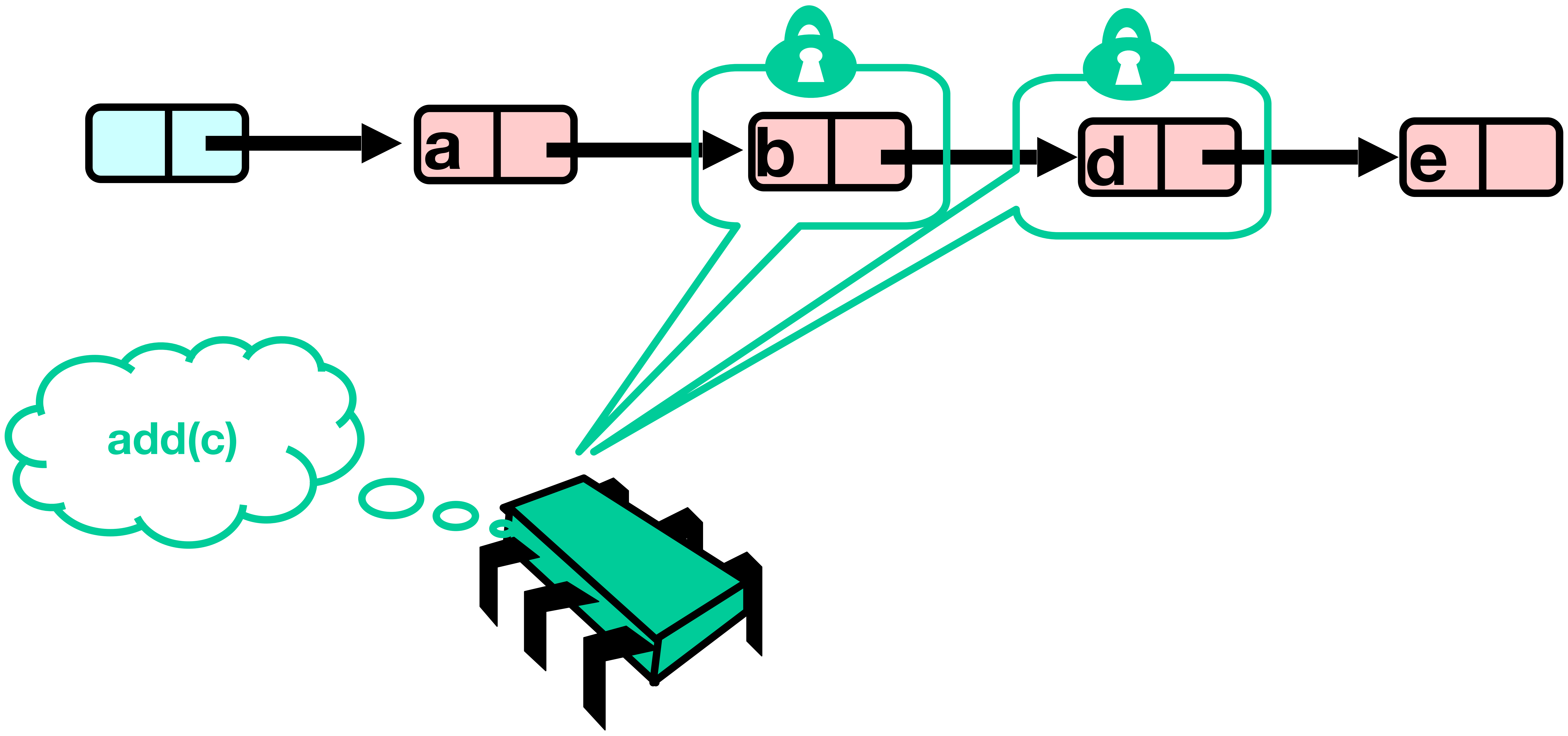
Optimistic Synchronization

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

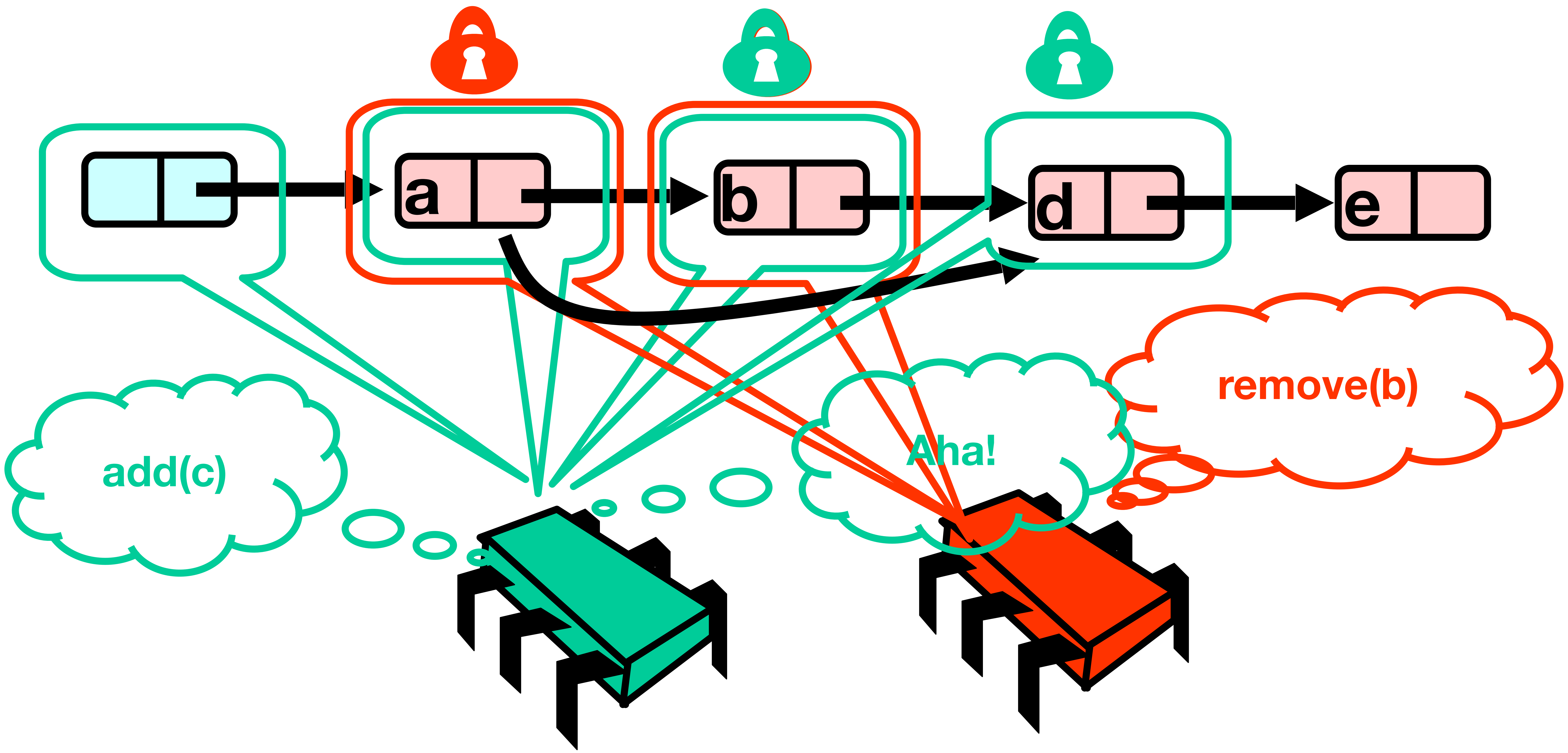
Optimistic: Traverse without Locking



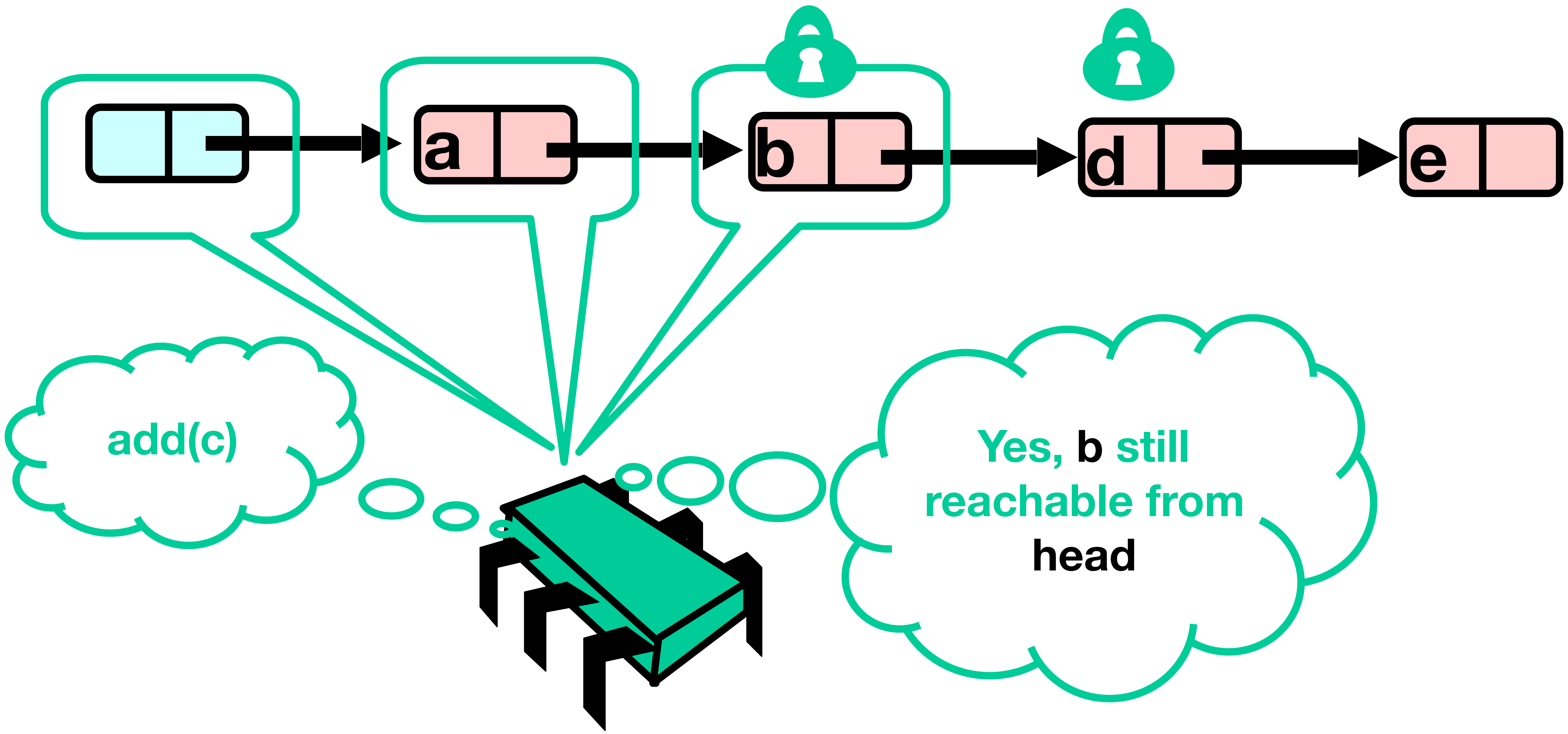
Optimistic: Lock and Load



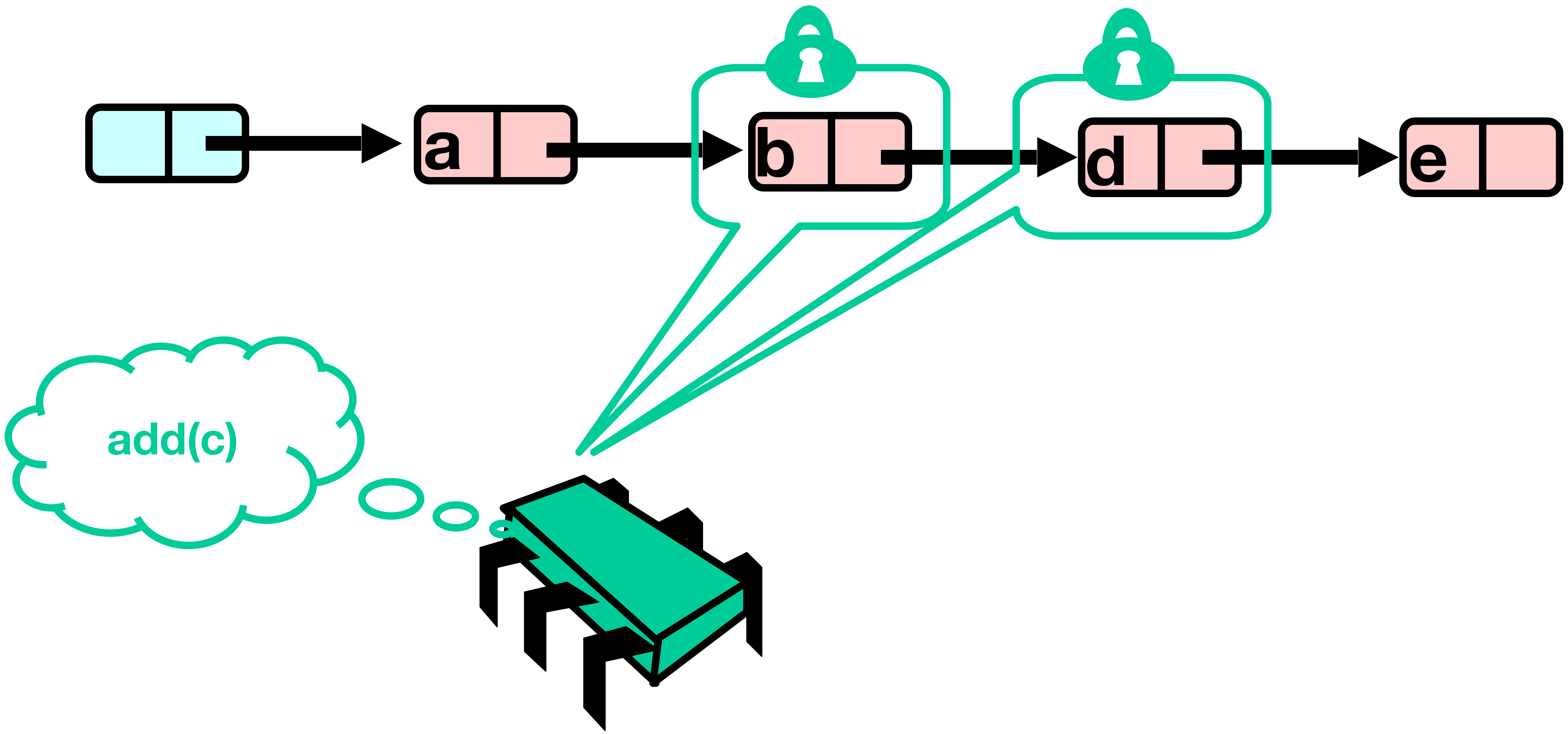
What could go wrong?



Validate – Part 1
(while holding locks)



What Else Can Go Wrong?



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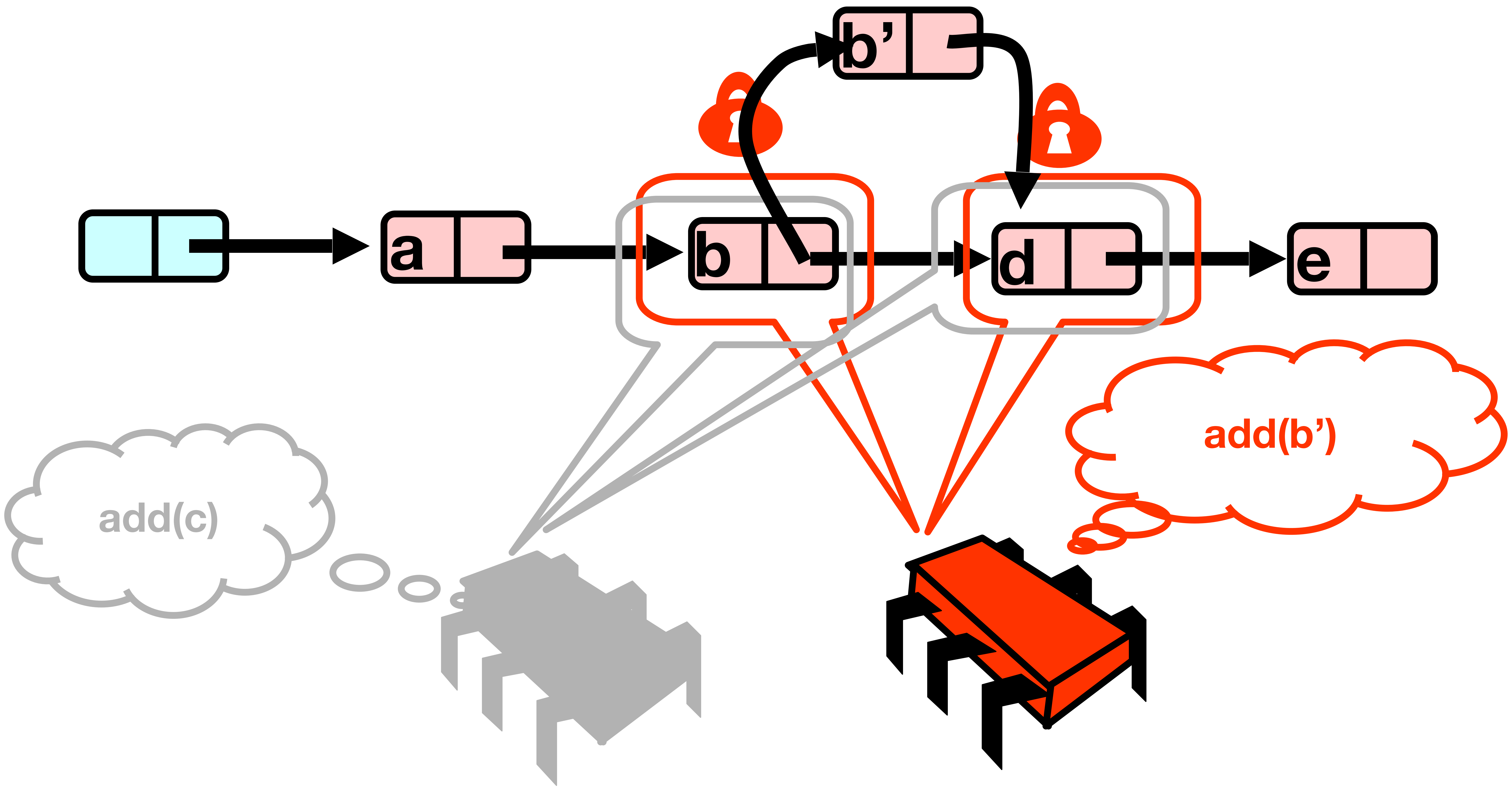

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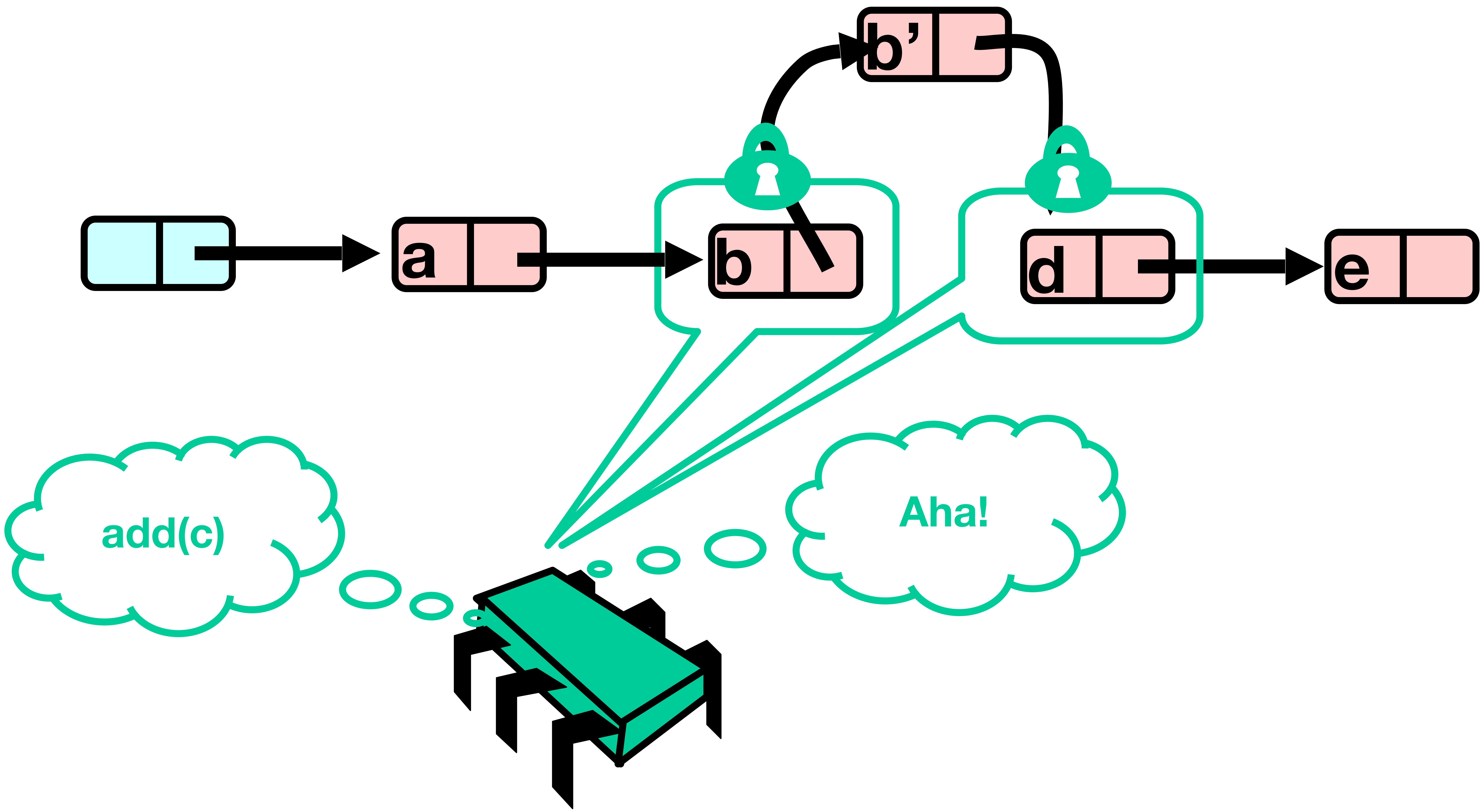
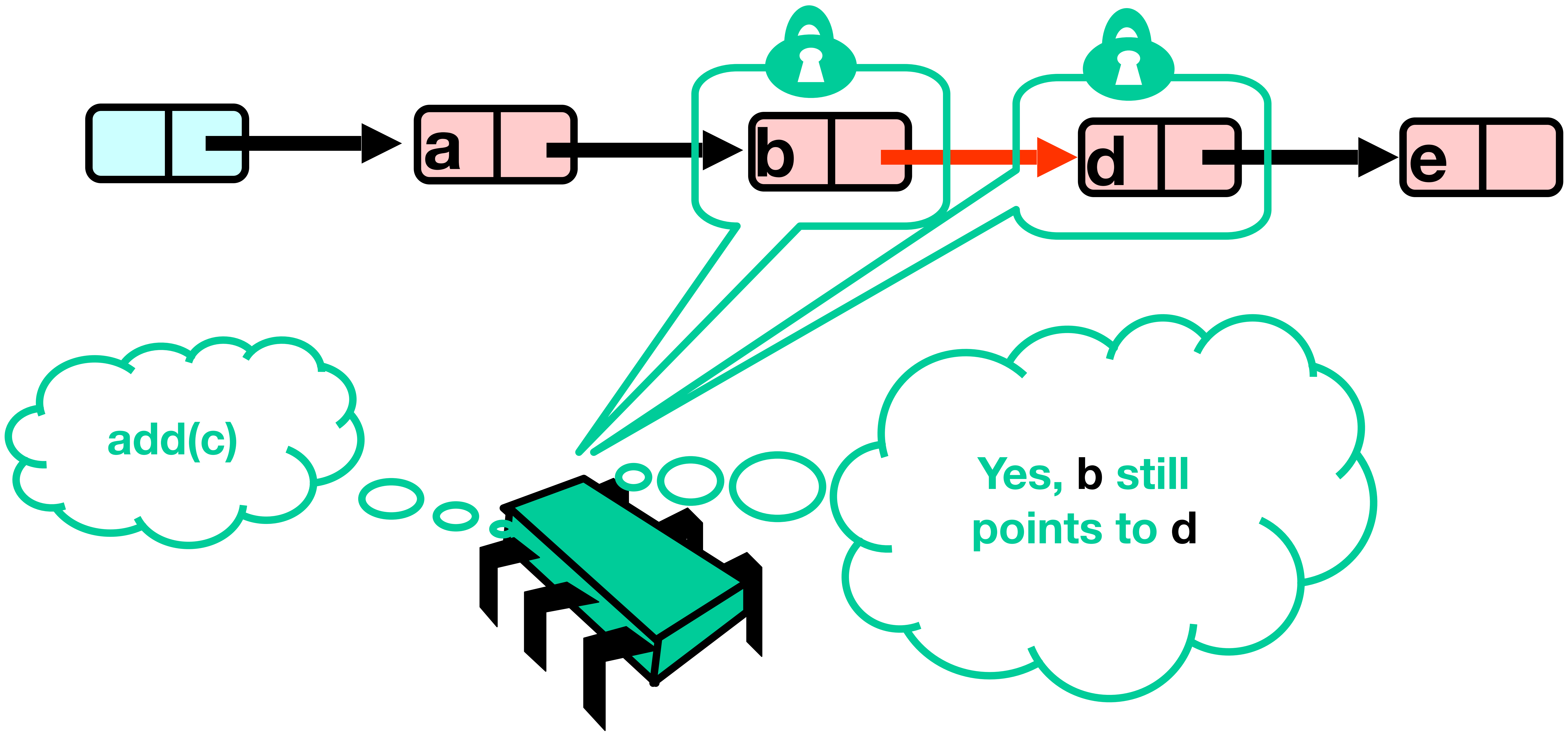
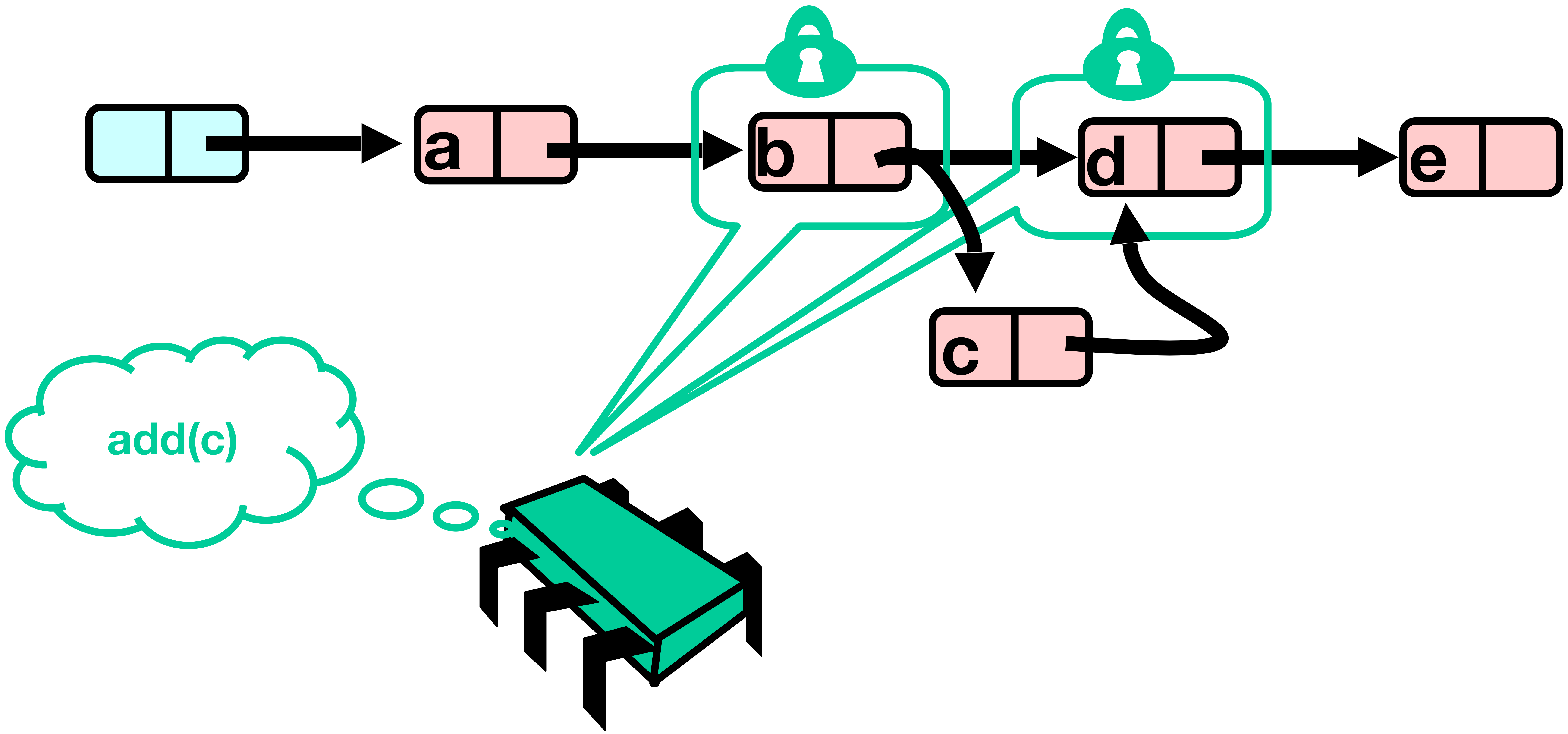


Validate Part 2
(while holding locks)



Optimistic: Linearization Point



Same Abstraction Map

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

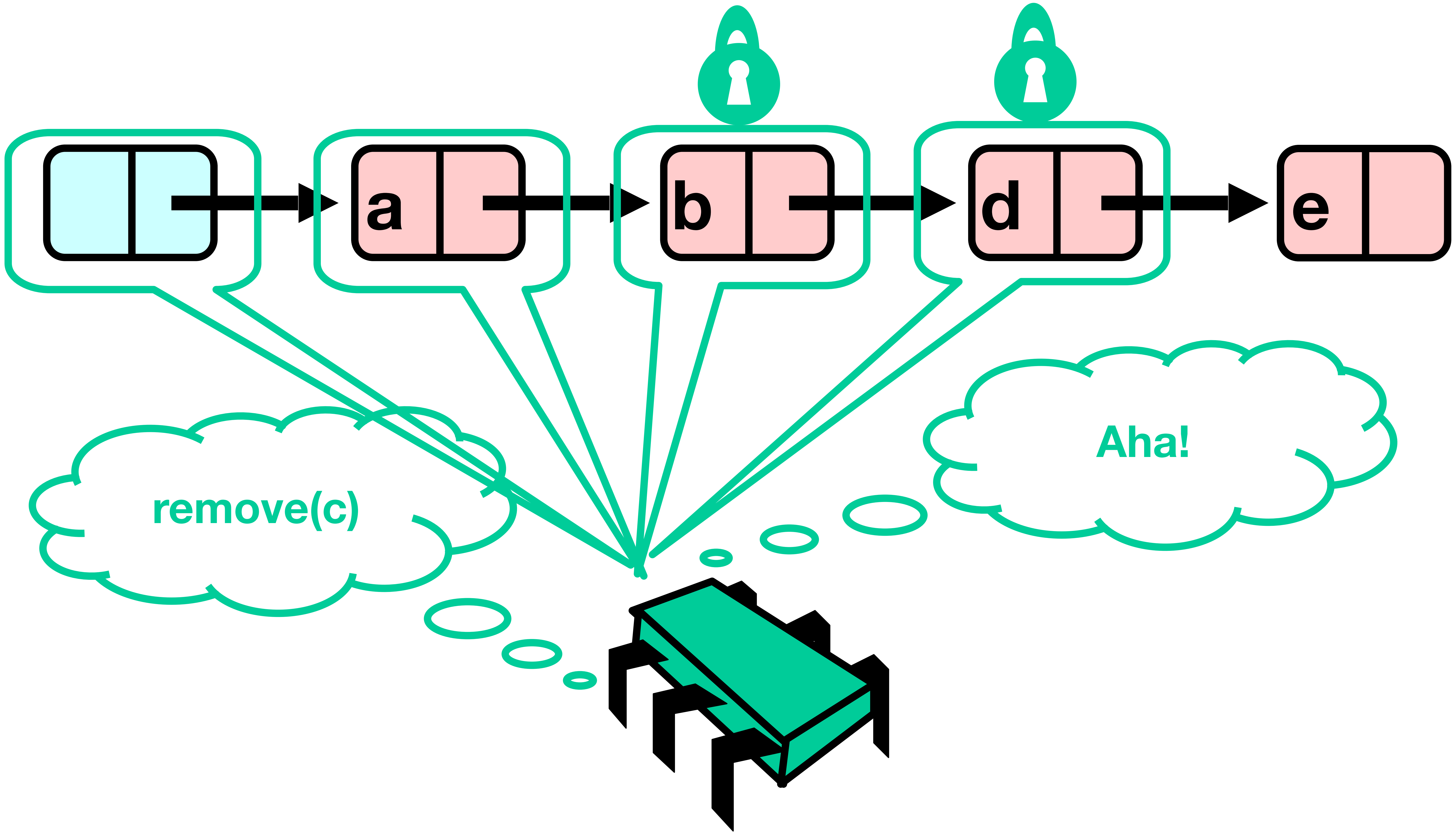
Invariants

- Careful: we may traverse deleted nodes
- But we establish properties by
  - Validation
  - After we lock target nodes

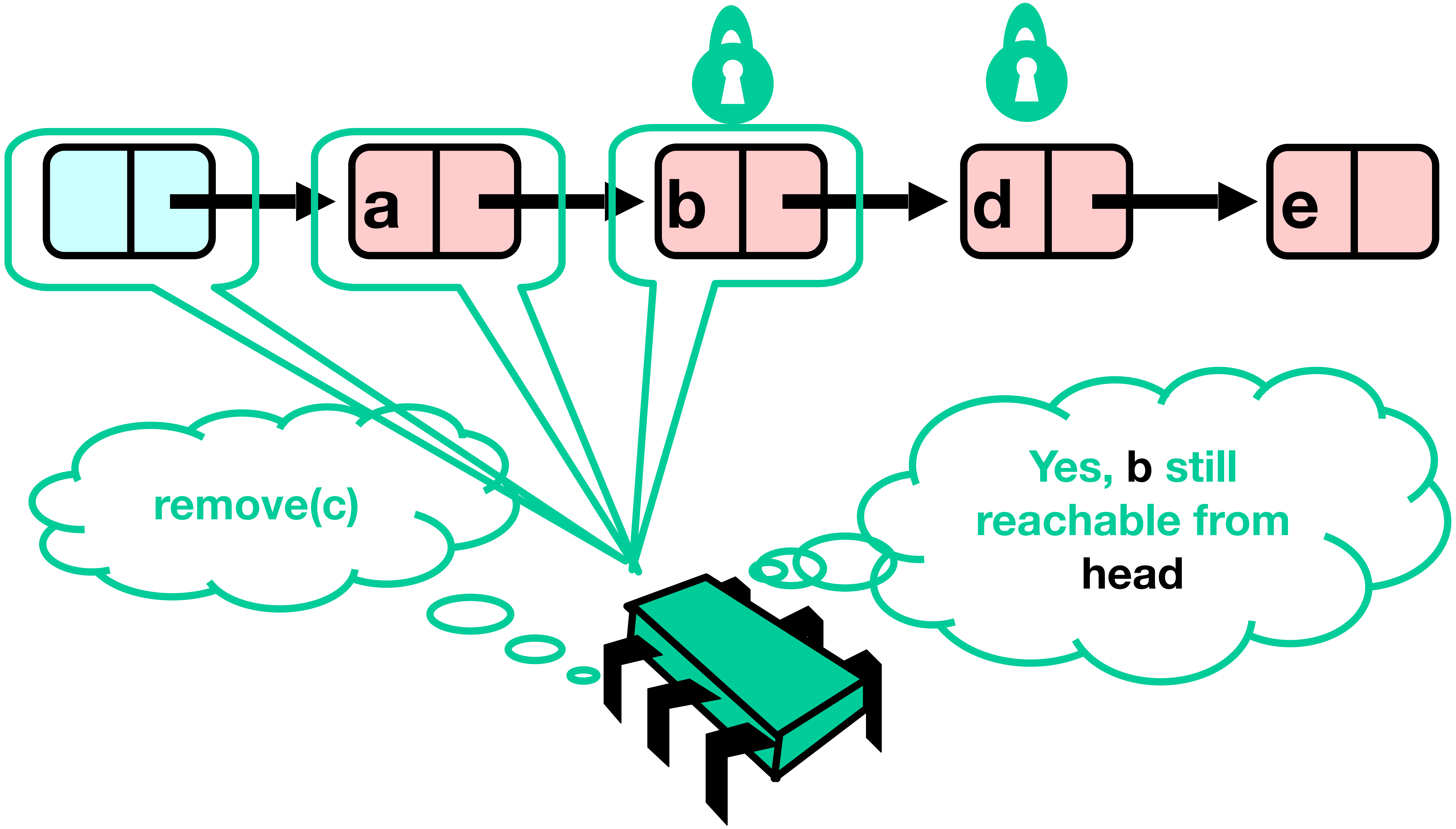
Correctness

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

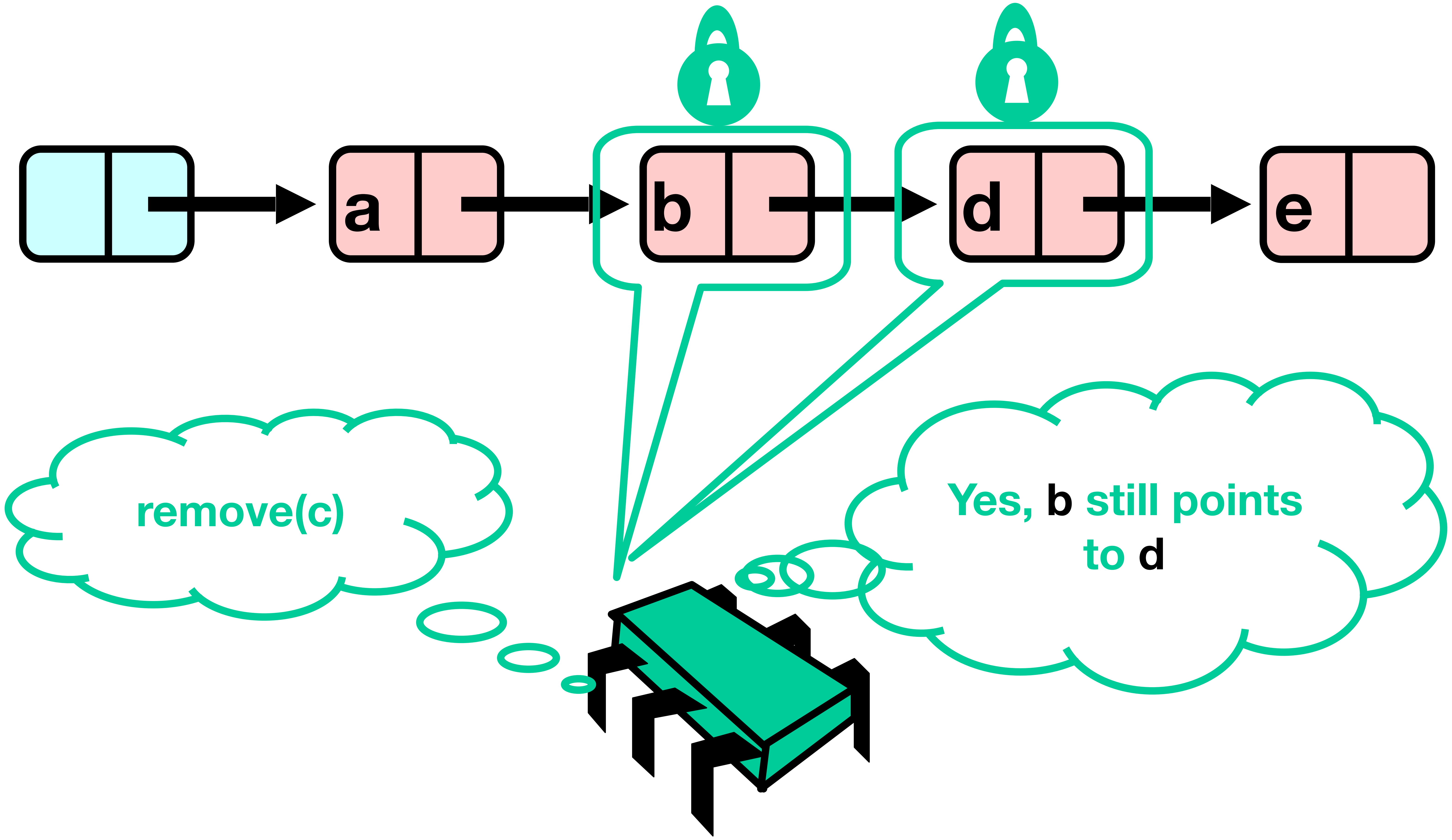
Unsuccessful Remove



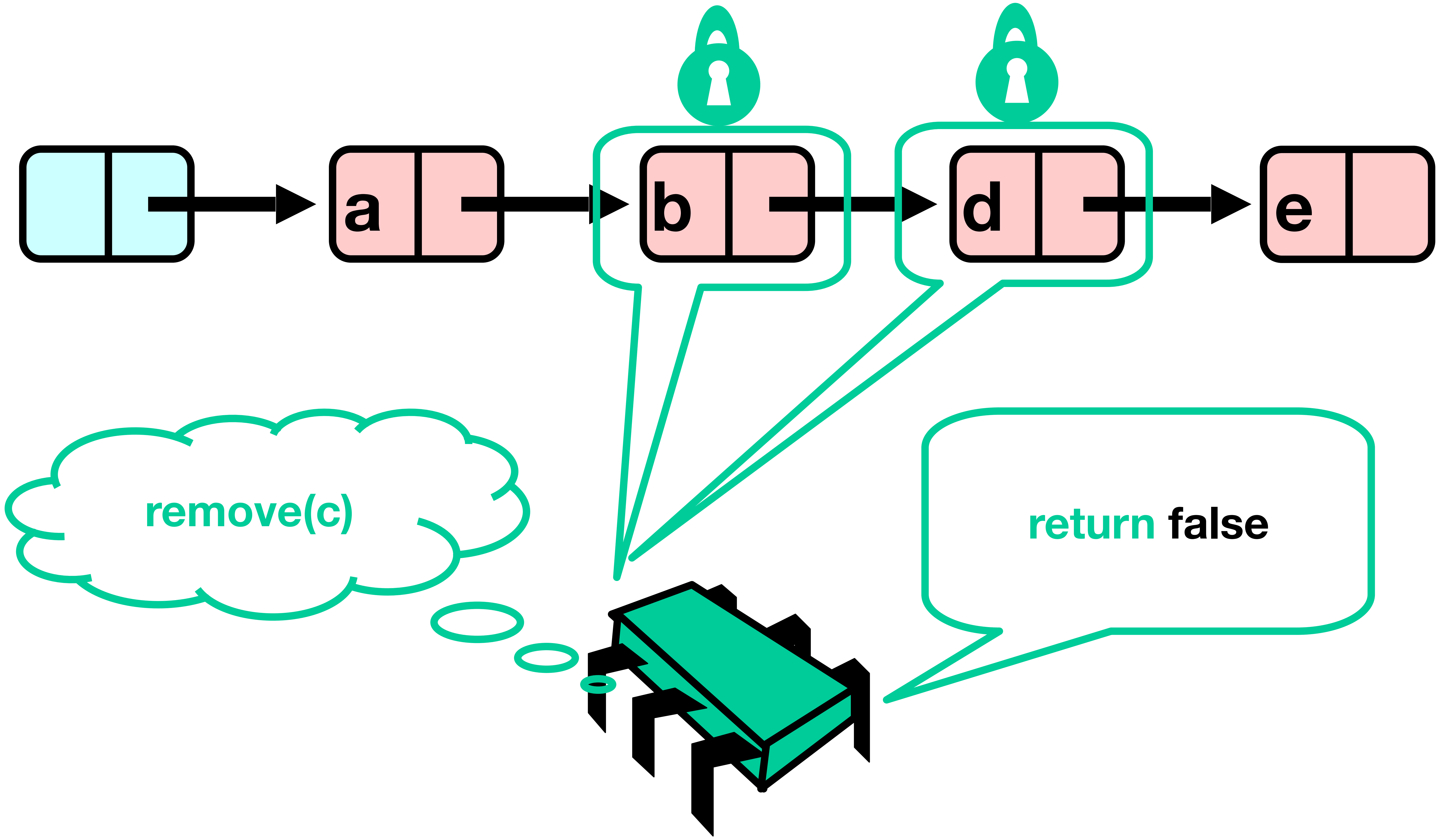
Validate (1)



Validate (2)



OK Computer



Correctness

- If
  - Nodes b and d both locked
  - Node b still accessible
  - Node d still successor to b
- Then
  - Neither will be deleted
  - No thread can add c after b
  - OK to return false

Validation

```
private boolean
 validate(Node pred,
          Node curry) {
 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,
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 Node node = head;
 while (node.key <= pred.key) {
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}
```
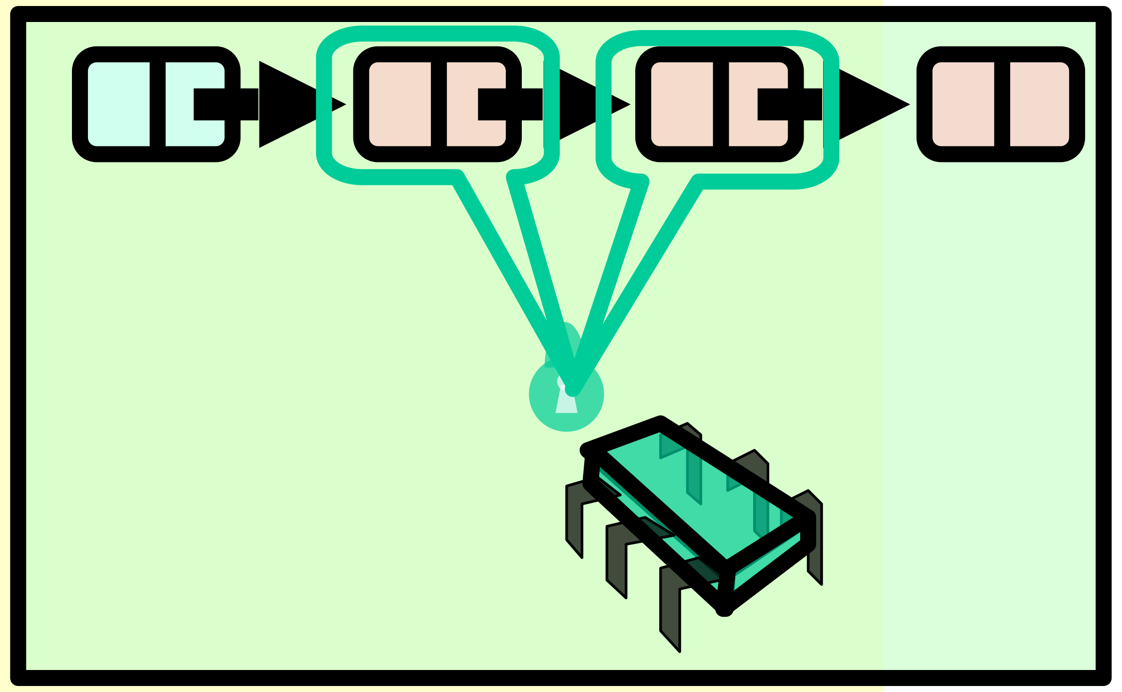
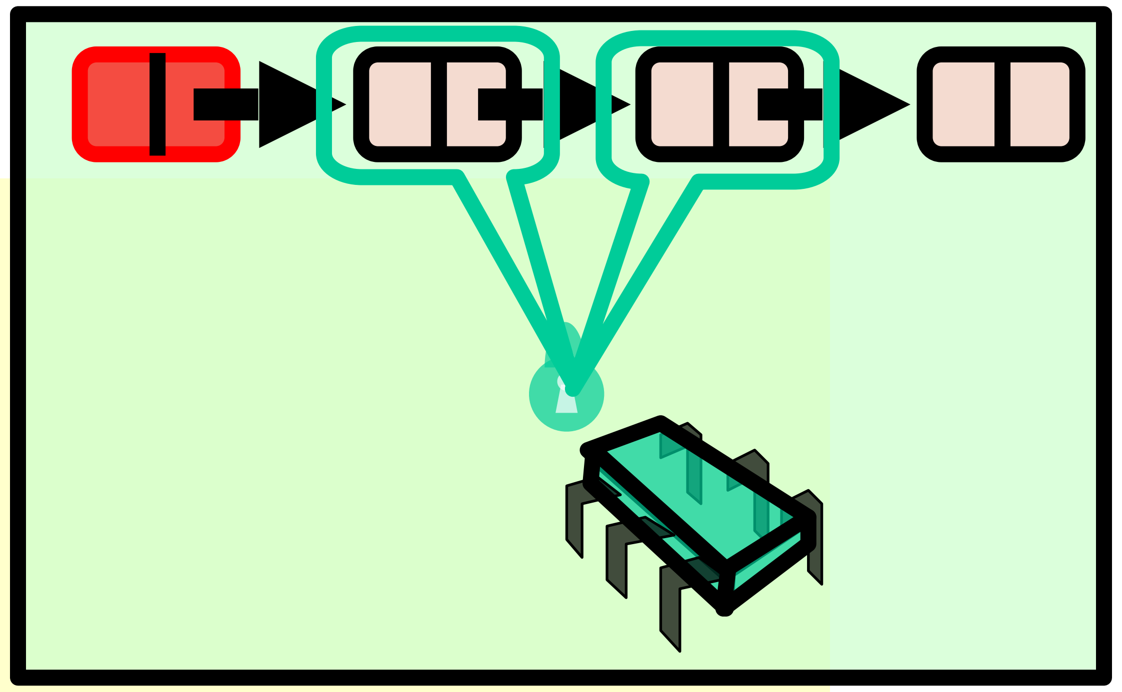

Predecessor & current nodes



Validation



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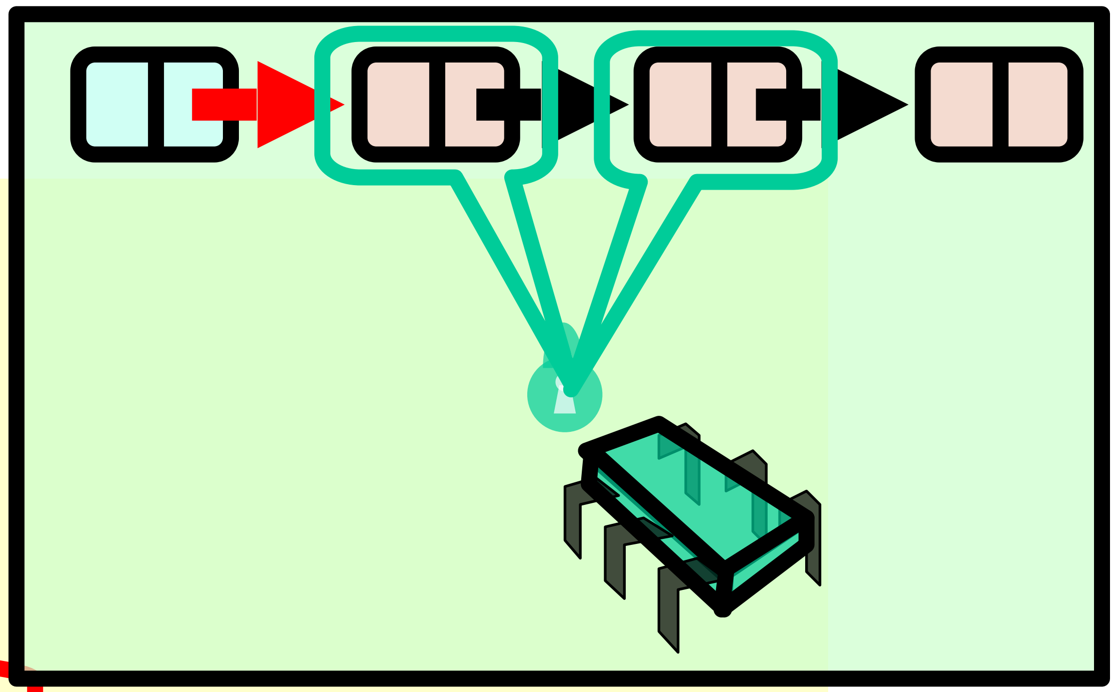
  node = node.next;
 }
 return false;
}
```

Begin at the beginning

Validation



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 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```
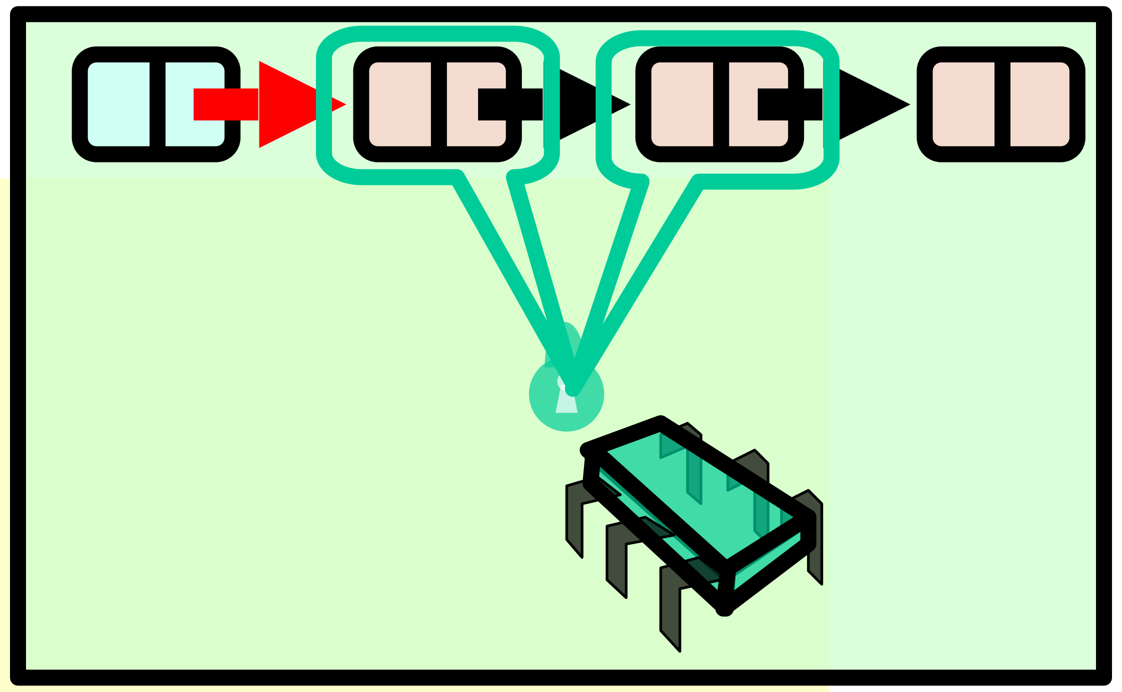

Search range of keys

Validation



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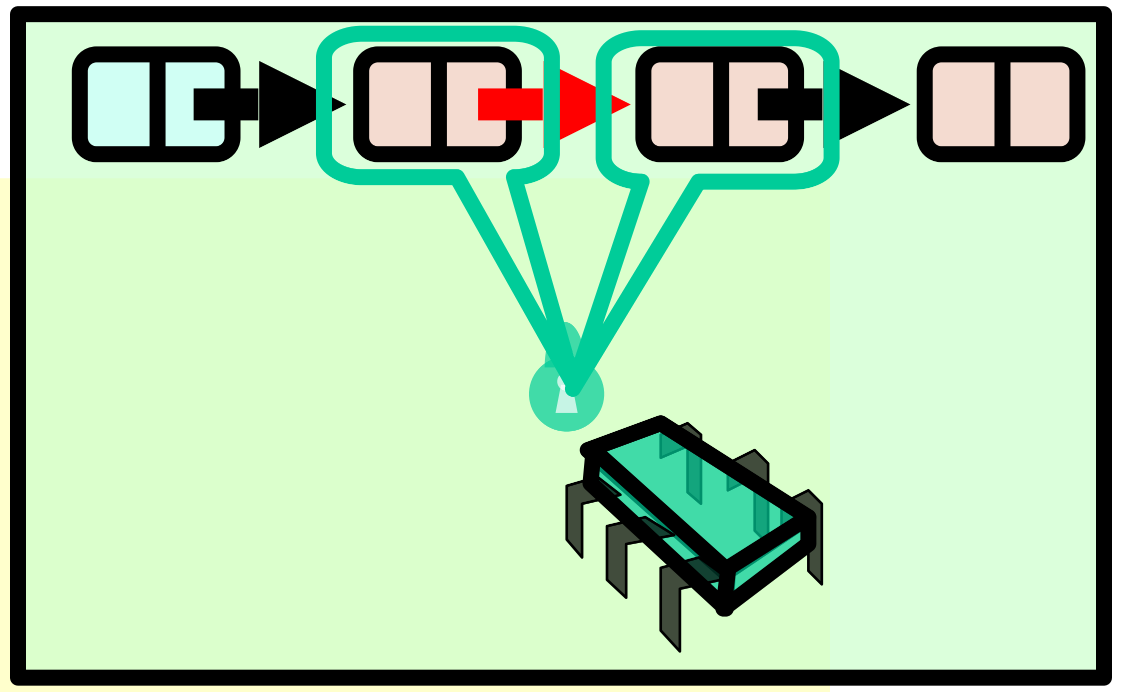
  node = node.next;
 }
 return false;
}
```

Predecessor reachable

Validation



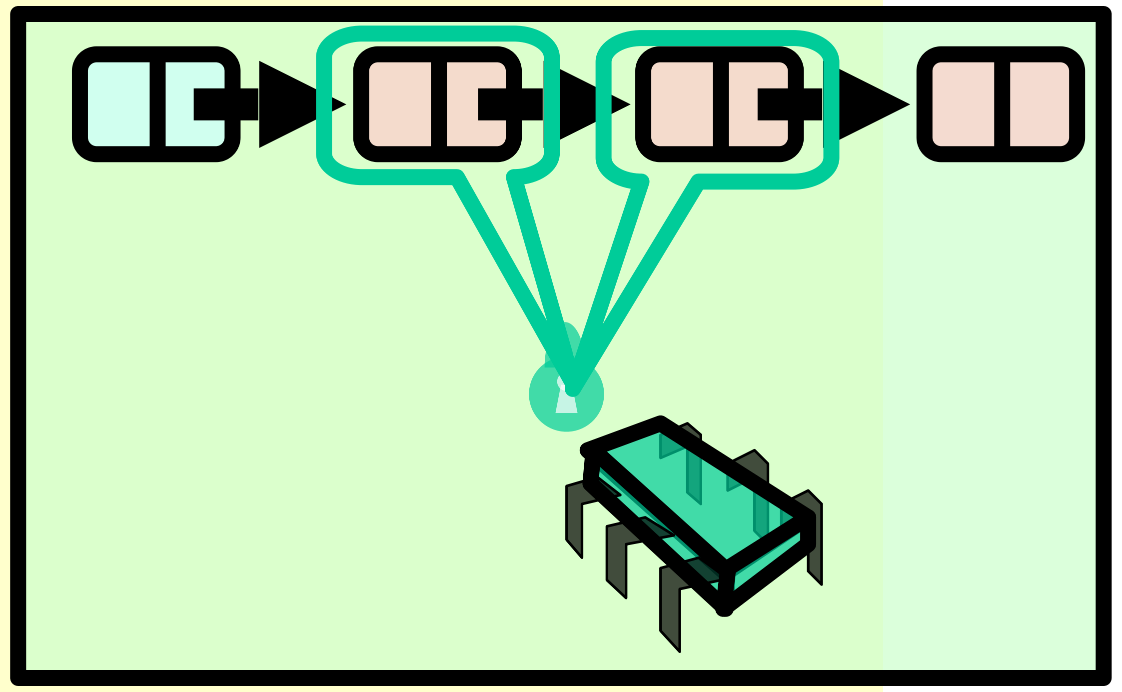
```
private boolean
 validate(Node pred,
          Node curry) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```

Is current node next?

Validation

Otherwise move on

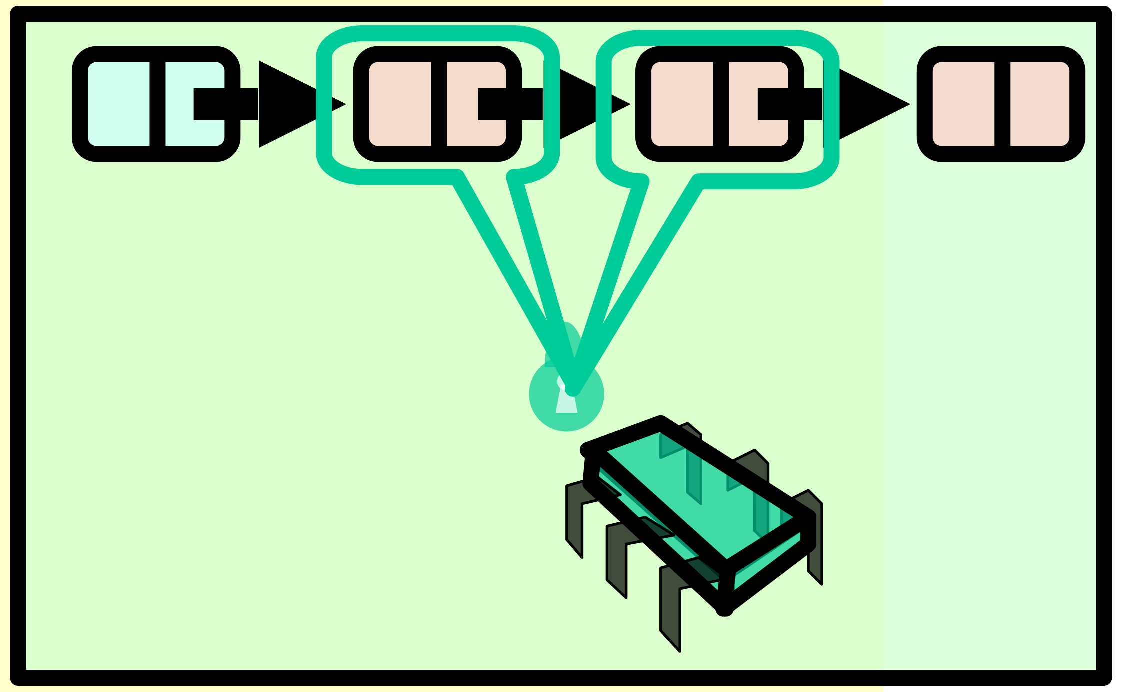
```
private boolean
 validate(Node pred,
          Node curr) {
 Node node = head;
 while (node.key <= pred.key) {
  if (node == pred)
   return pred.next == curr;
  node = node.next;
 }
 return false;
}
```



Validation

Predecessor not reachable

```
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;
}
```



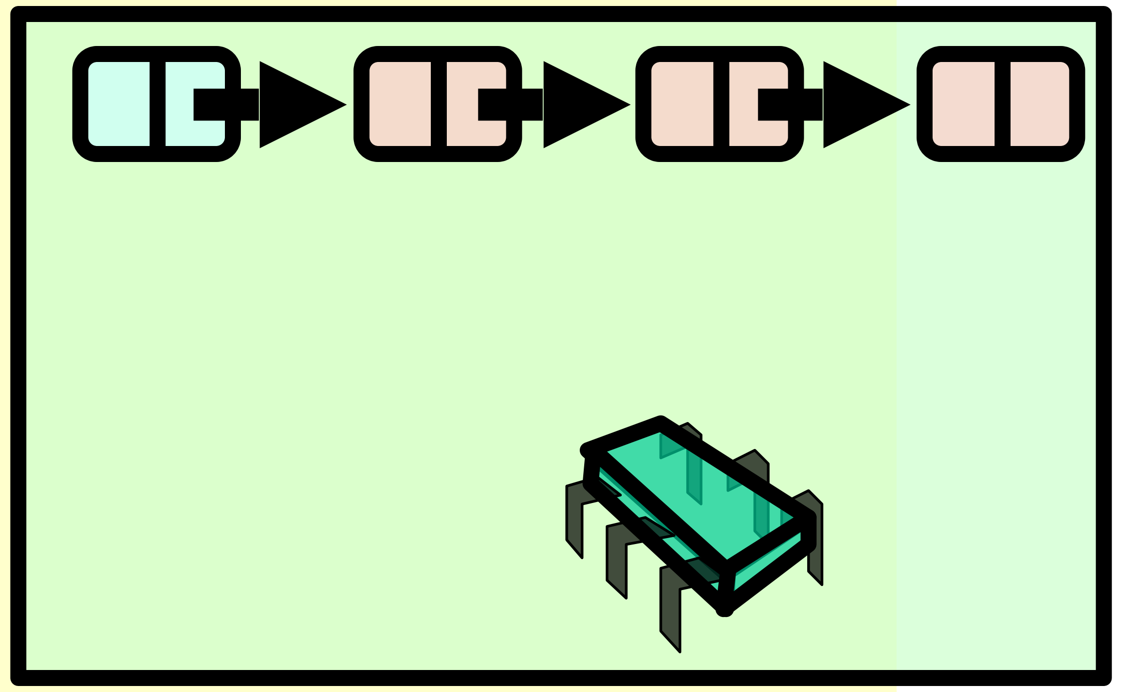
Remove: searching

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

Remove: searching

```
public boolean remove(Item item) {
 int key = item.hashCode();
 retry: while (true) {
   Node pred = this.head;
   Node curr = pred.next;
   while (curr.key <= key) {
    if (item == curr.item)
     break;
    pred = curr;
    curr = curr.next;
   } ...
```

Search key



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   Node curr = pred.next;
   while (curr.key <= key) {
    if (item == curr.item)
     break;
    pred = curr;
    curr = curr.next;
   } …
```
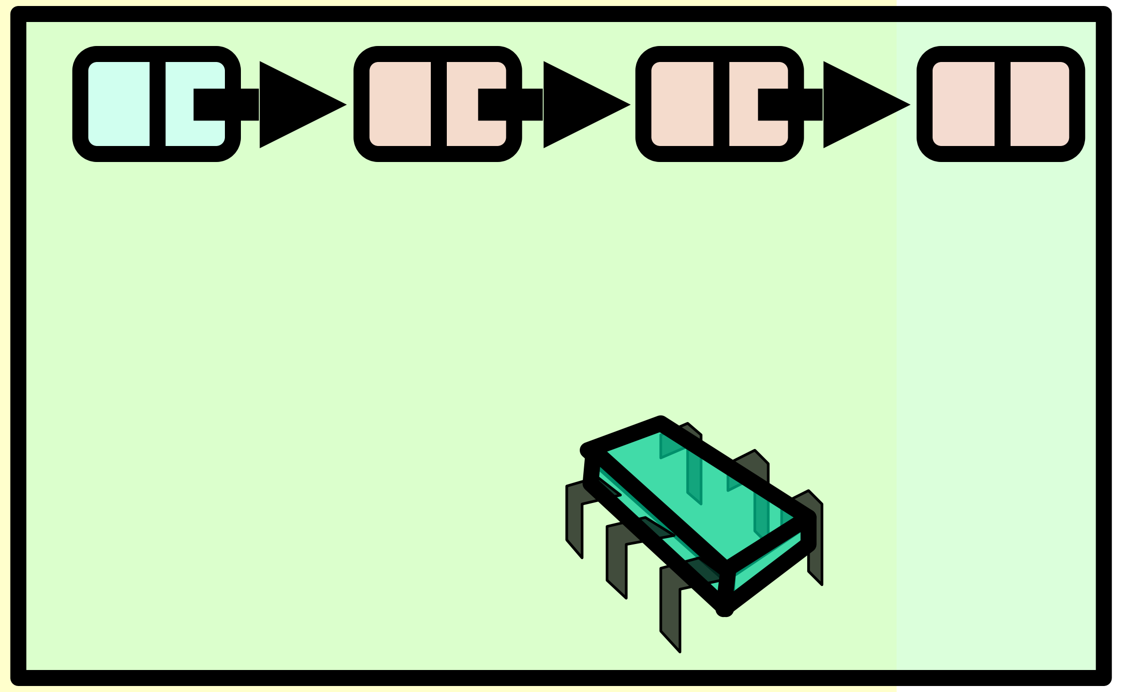
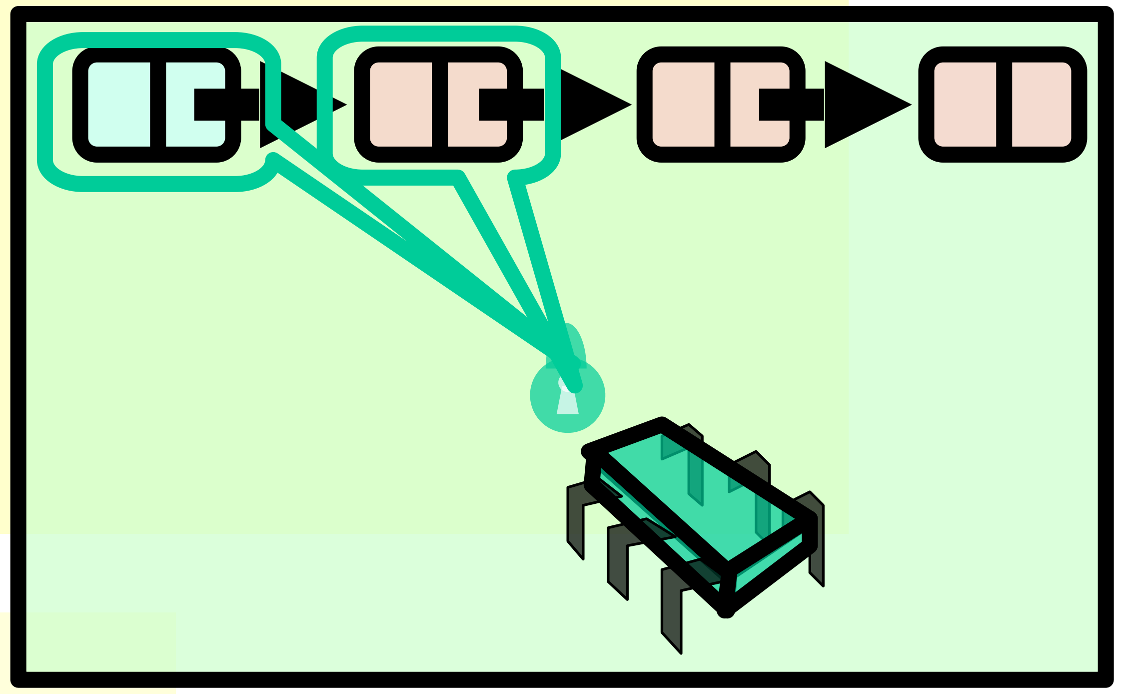



Retry on synchronization conflict

Remove: searching

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

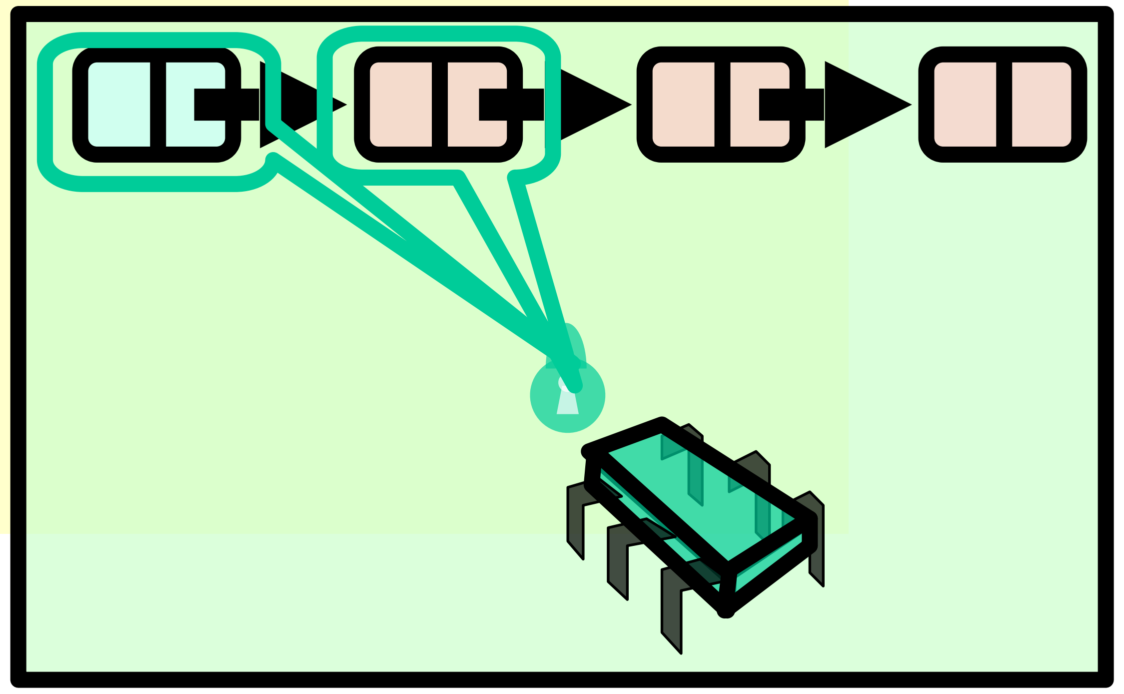
Examine predecessor and current nodes



Remove: searching

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

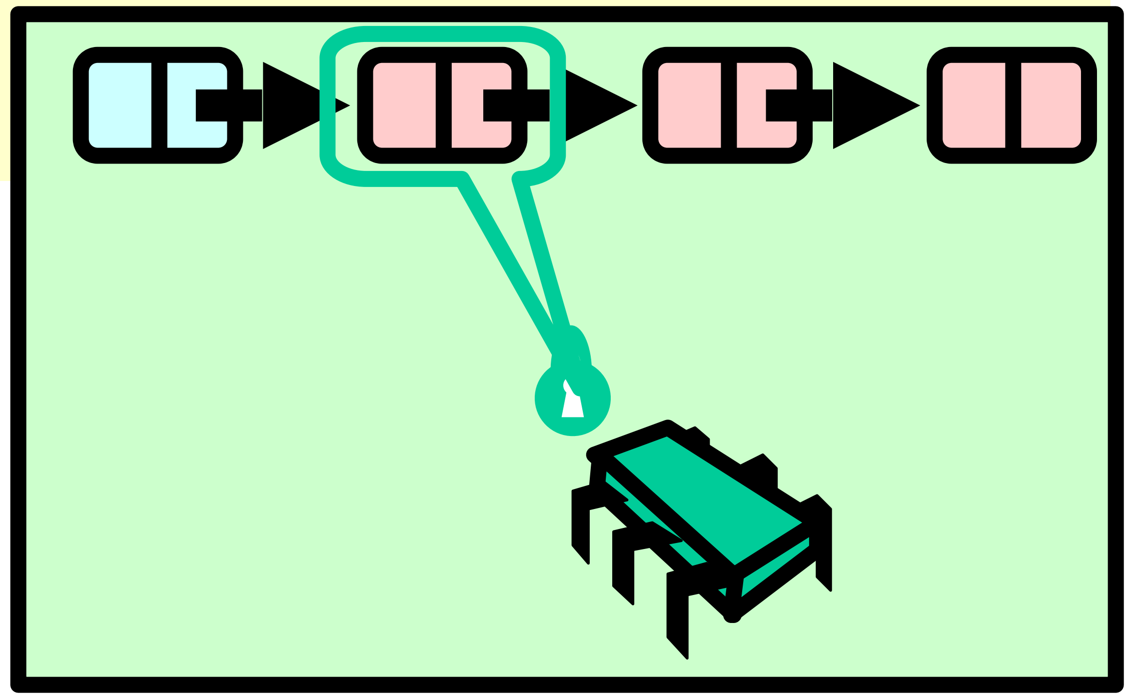
Search by key



Remove: searching

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

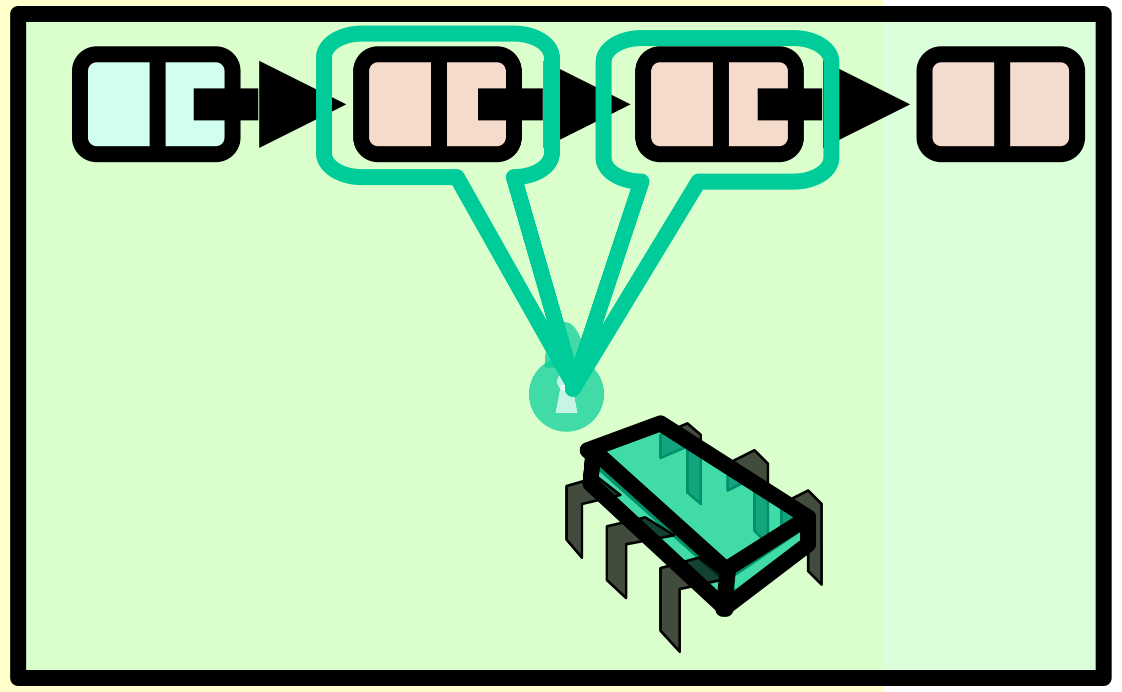
Stop if we find item



Remove: searching

Move along

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



On Exit from Loop

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

Remove Method

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

Remove Method

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

Always unlock

Remove Method

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

Lock both nodes

Remove Method

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

Check for synchronization conflicts

Remove Method

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

target found, remove node

Remove Method

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

target not found

Optimistic List

- Limited hot-spots
  - All methods follow same scheme: traverse (no locks), then lock and validate
  - Targets of add(), remove(), contains()
  - No contention on traversals
- Moreover
  - Traversals are wait-free
  - Food for thought …

So Far, So Good

- Much less lock acquisition/release
  - Performance
  - Concurrency
- Problems
  - Need to traverse list twice
  - contains() method acquires locks

Evaluation

- Optimistic is effective if
  - cost of scanning twice without locks

  is less than
  - cost of scanning once with locks
- Drawback
  - contains() acquires locks
  - 90% of calls in many apps

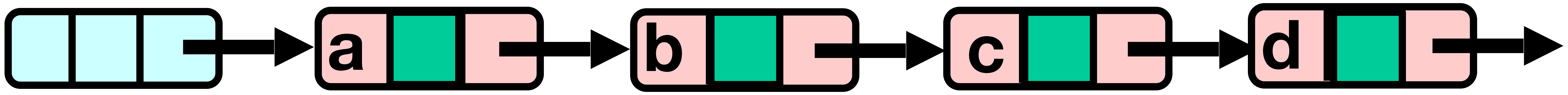
Lazy List

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

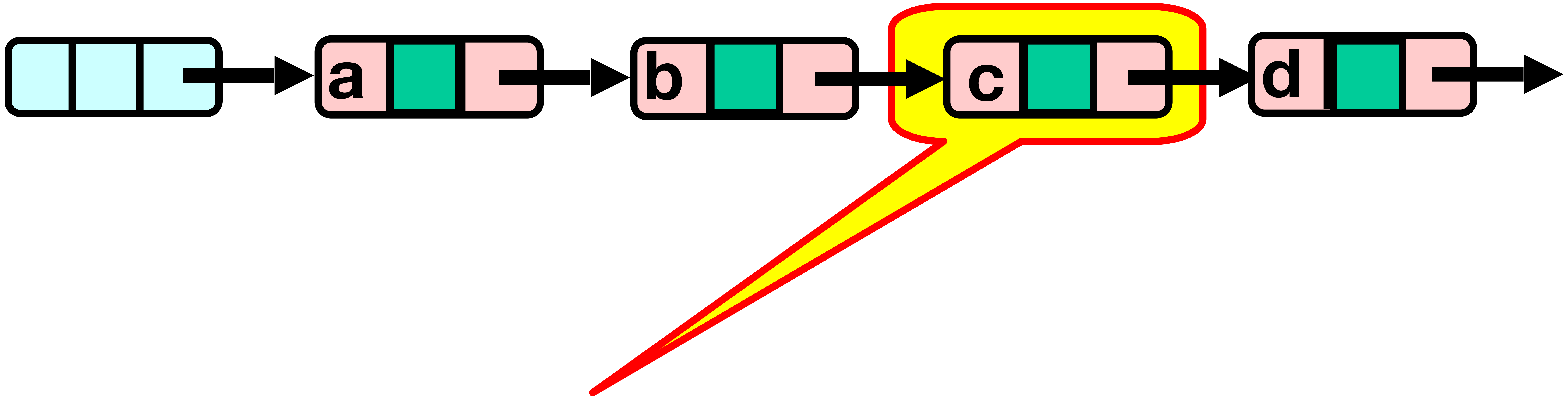
Lazy List

- `remove()`
  - Scans list (as before)
  - Locks predecessor & current (as before)
- Logical delete
  - Marks current node as removed (new!)
- Physical delete
  - Redirects predecessor’s next (as before)

Lazy Removal

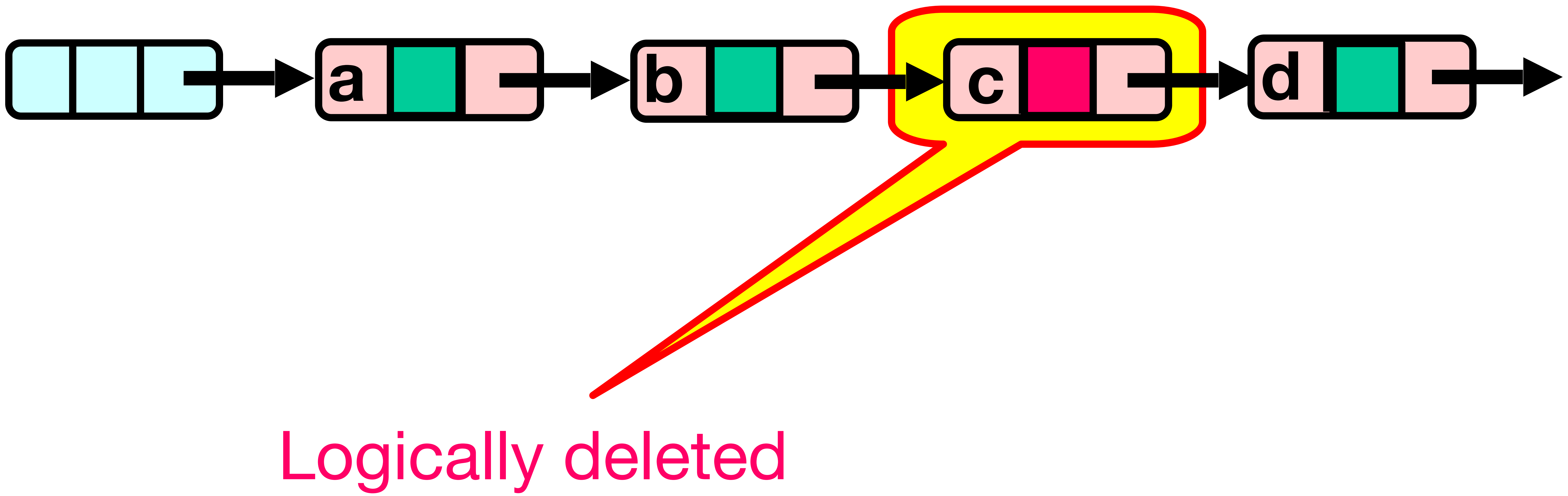


Lazy Removal

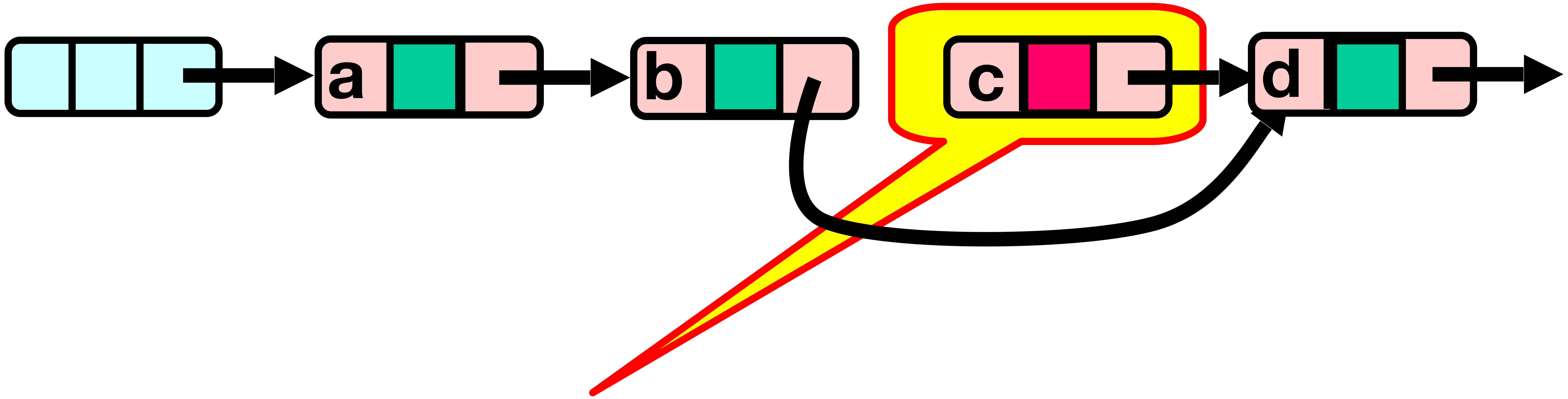


Present in list

Lazy Removal

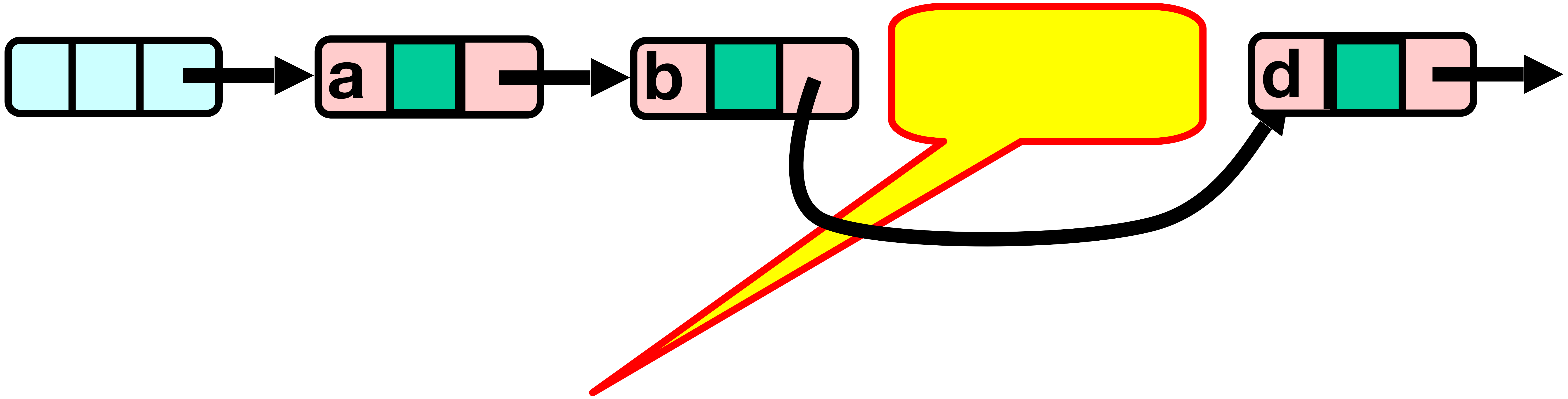


Lazy Removal



Physically deleted

Lazy Removal



Physically deleted

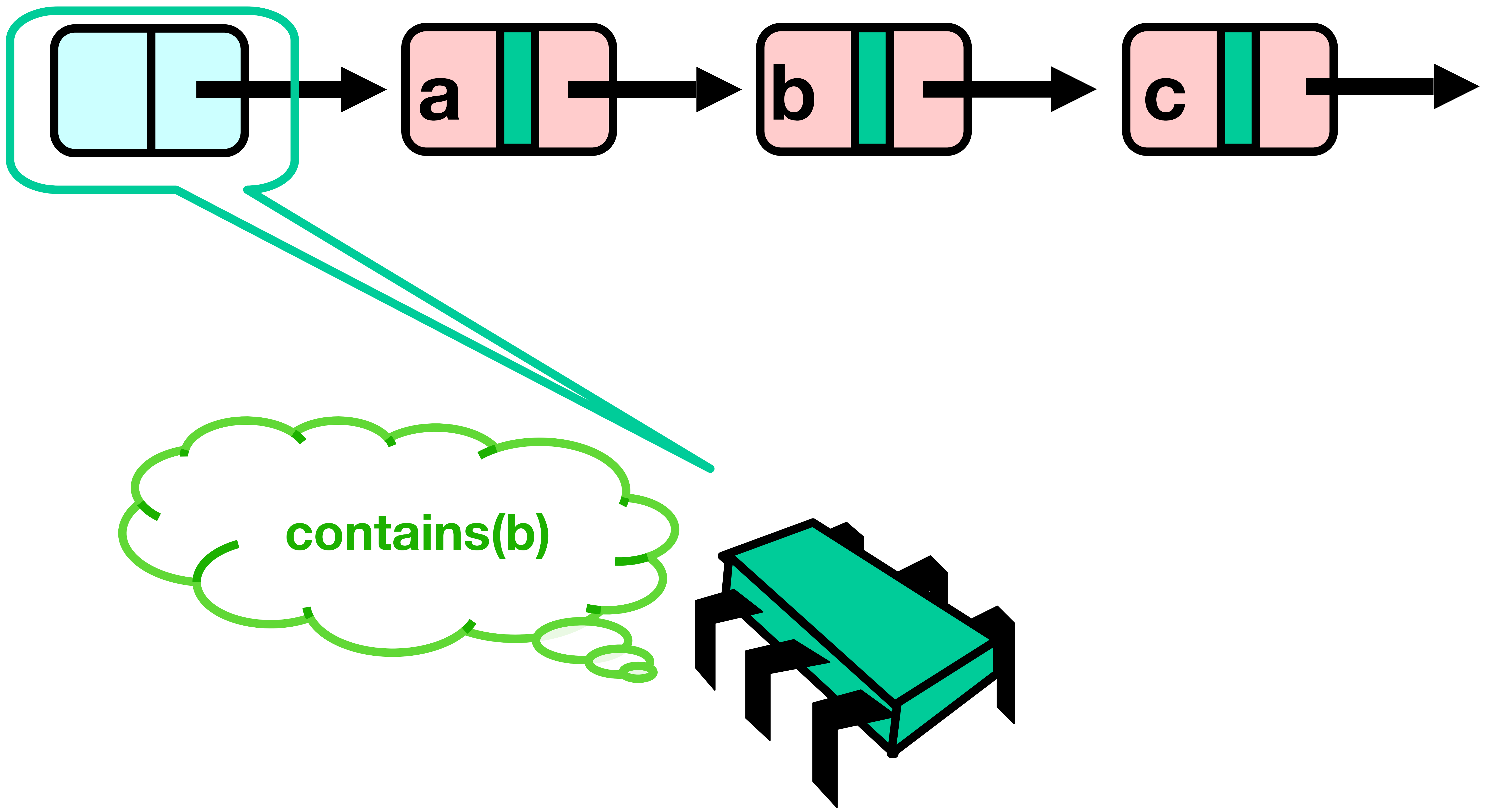
Lazy List

- All Methods
  - Scan through locked and marked nodes
  - Removing a node doesn’t slow down other method calls …
- Must still lock pred and curr nodes.

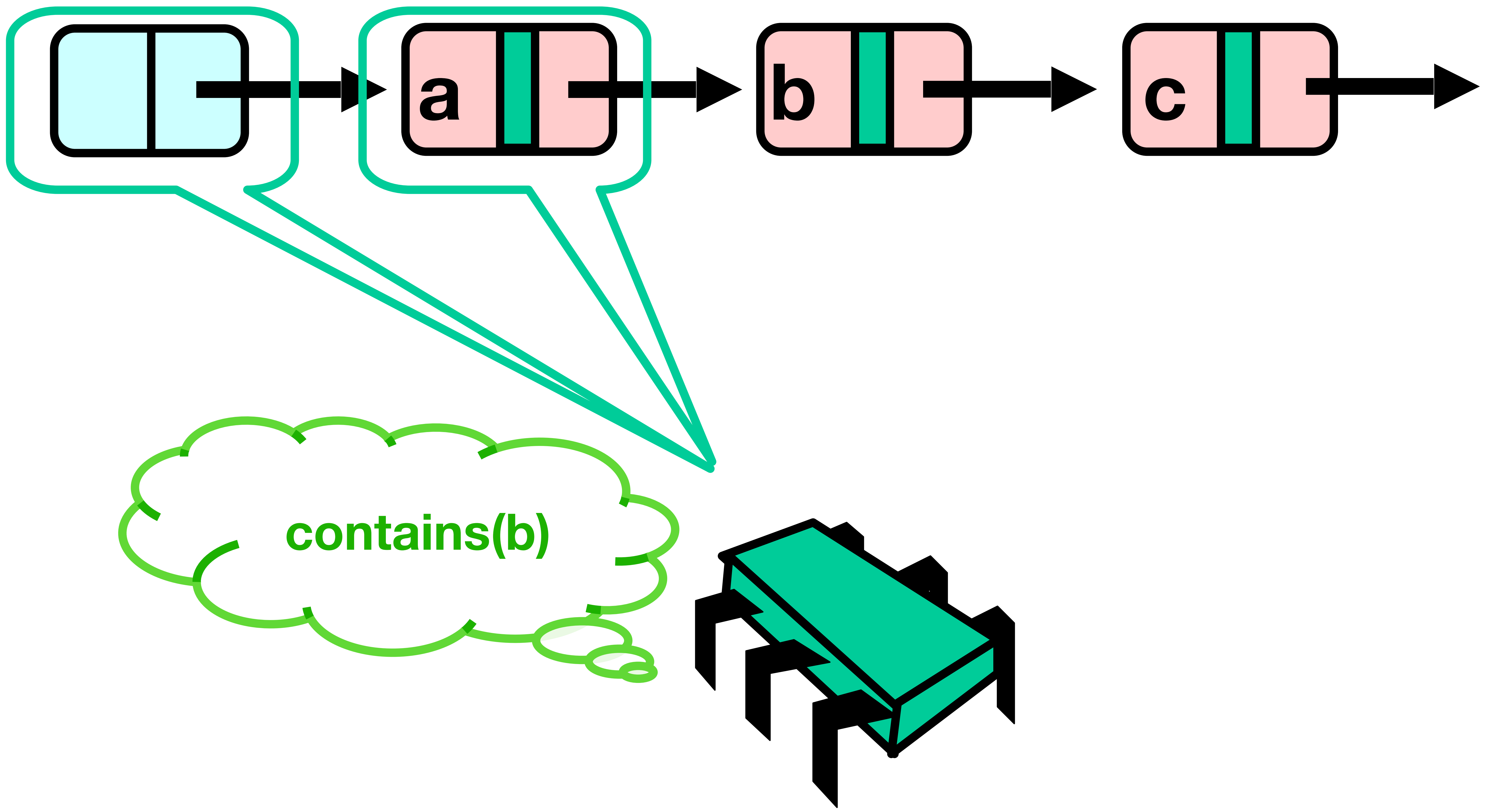
Validation

- No need to rescan list!
- Check that pred is not marked
- Check that curr is not marked
- Check that pred points to curr

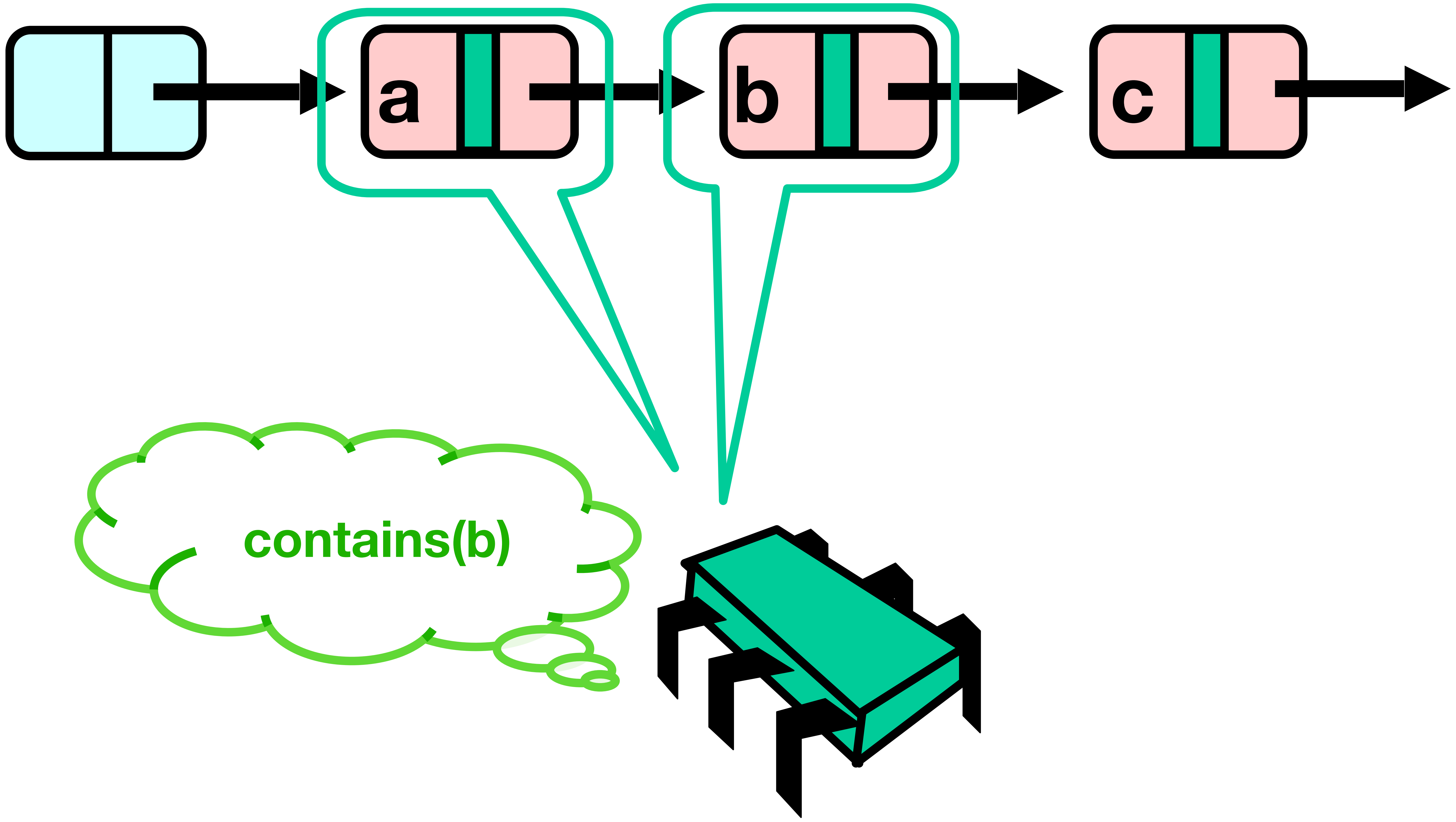
Business as Usual



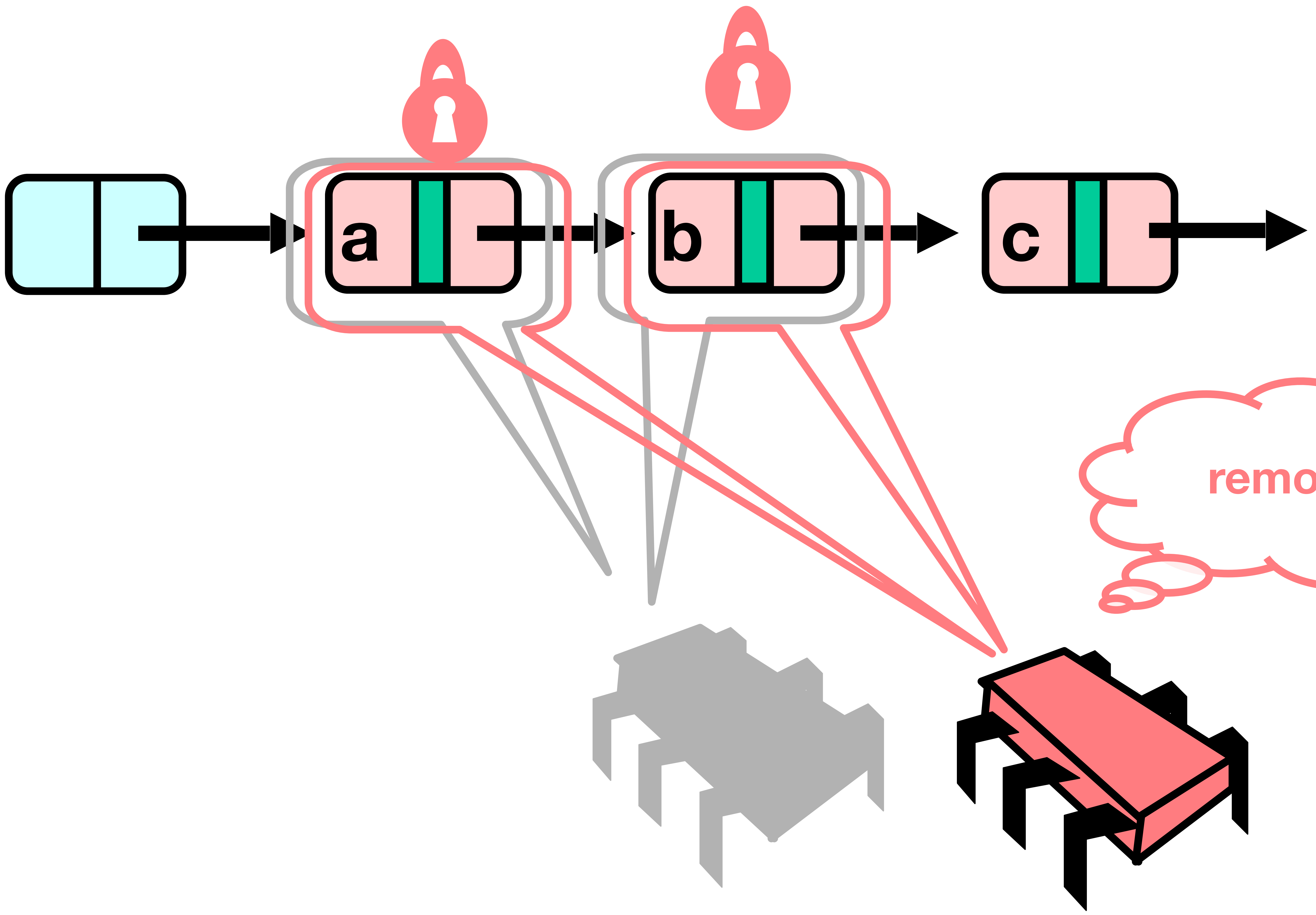
Business as Usual



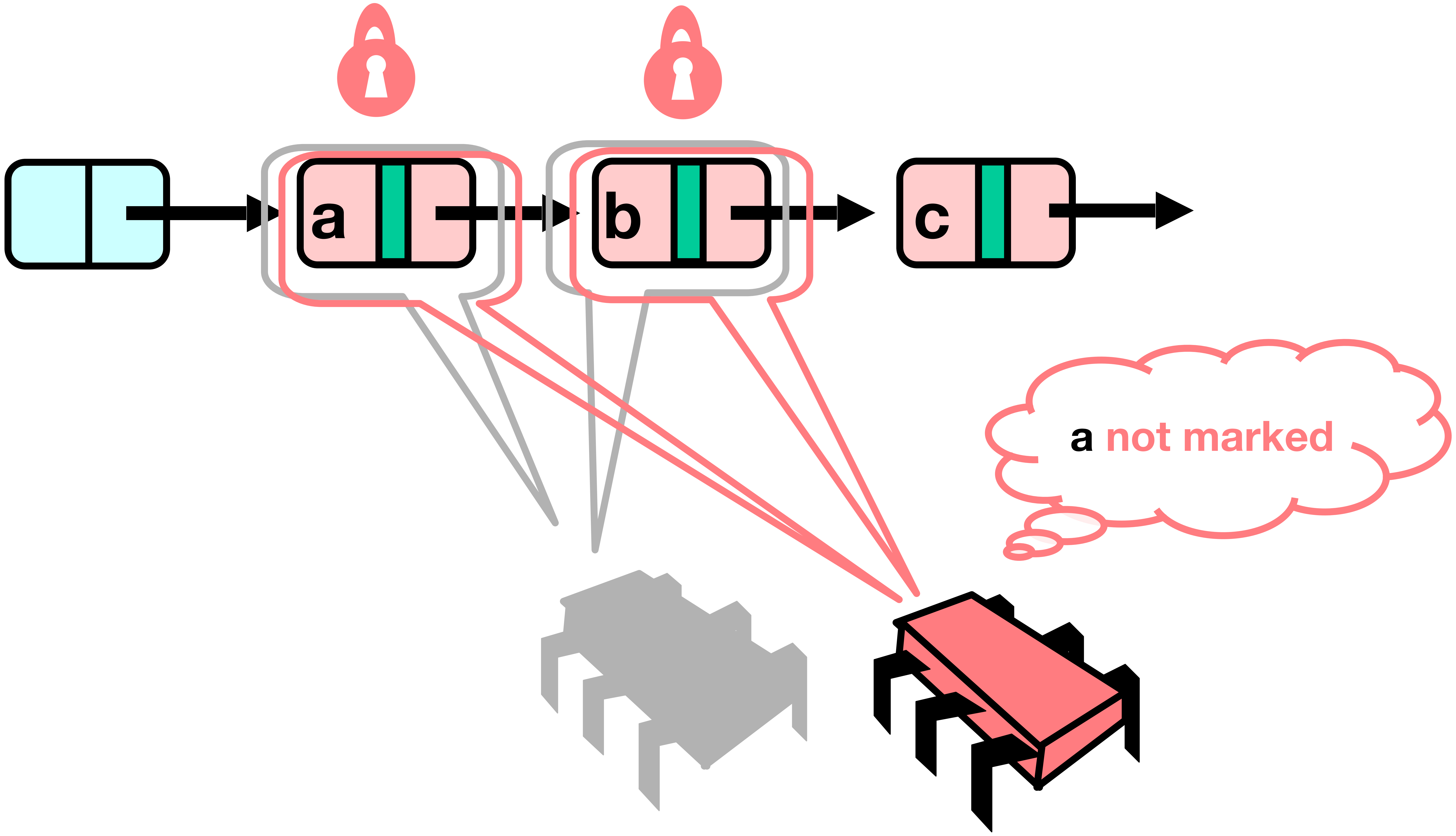
Business as Usual



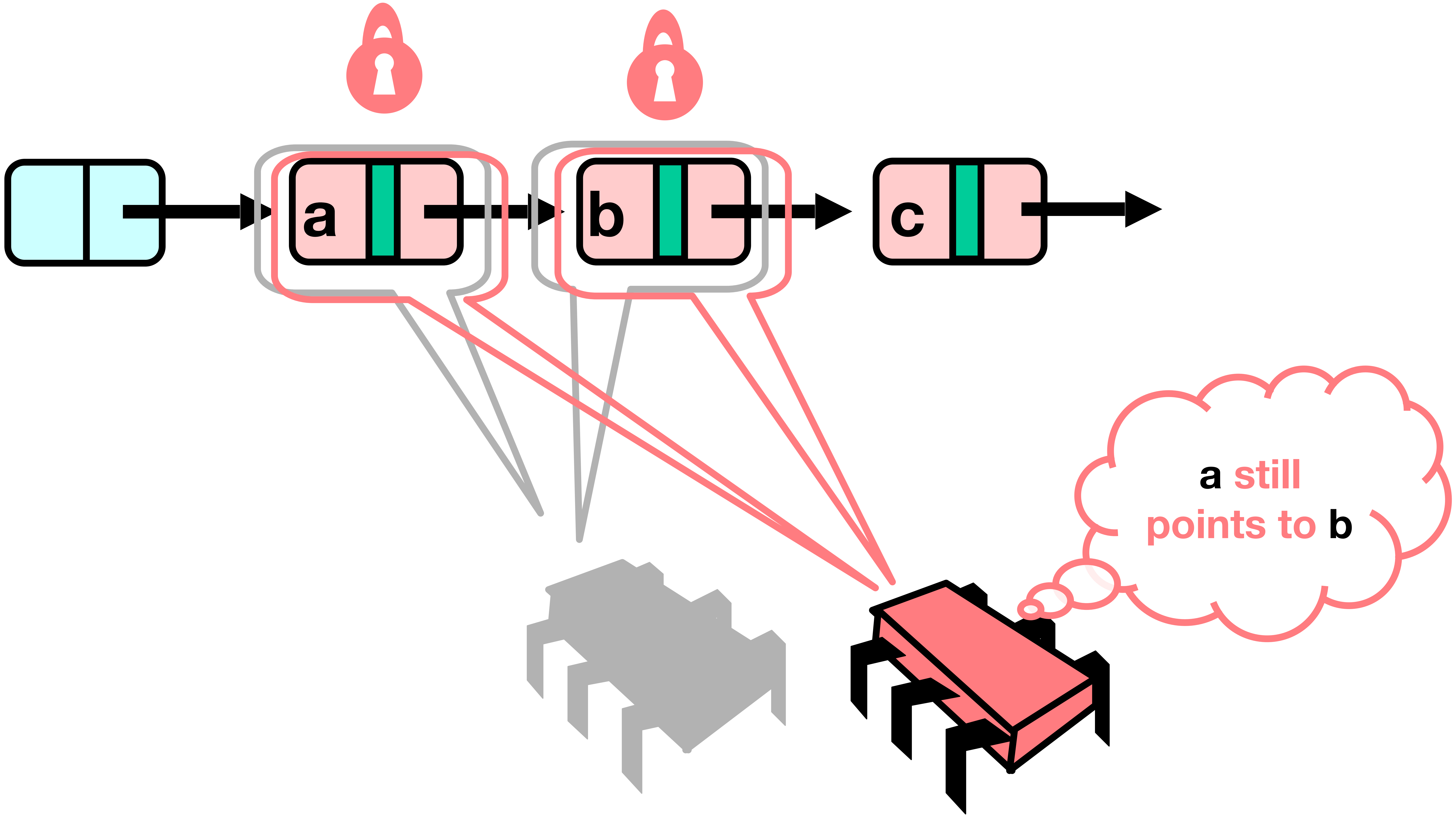
Business as Usual



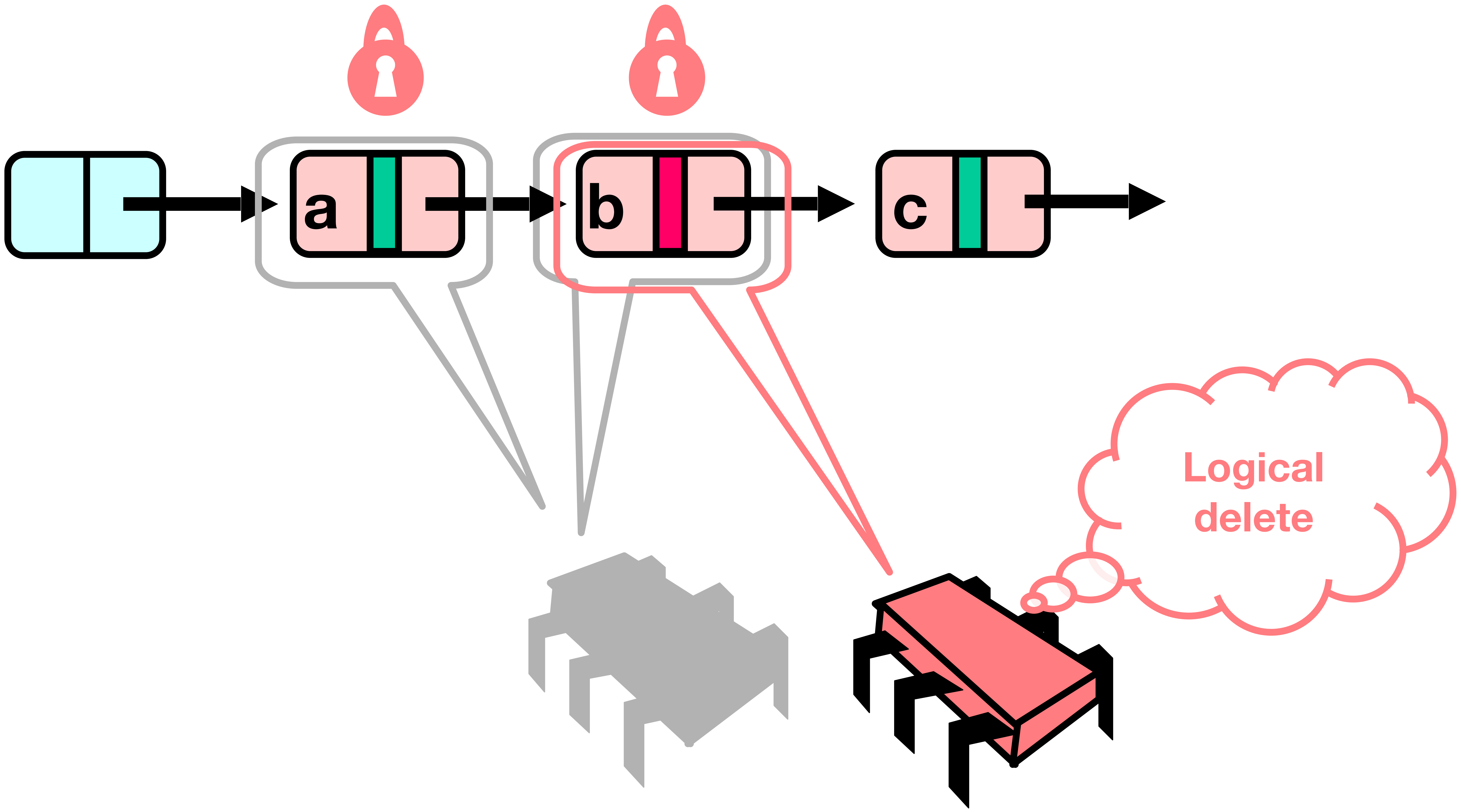
Business as Usual



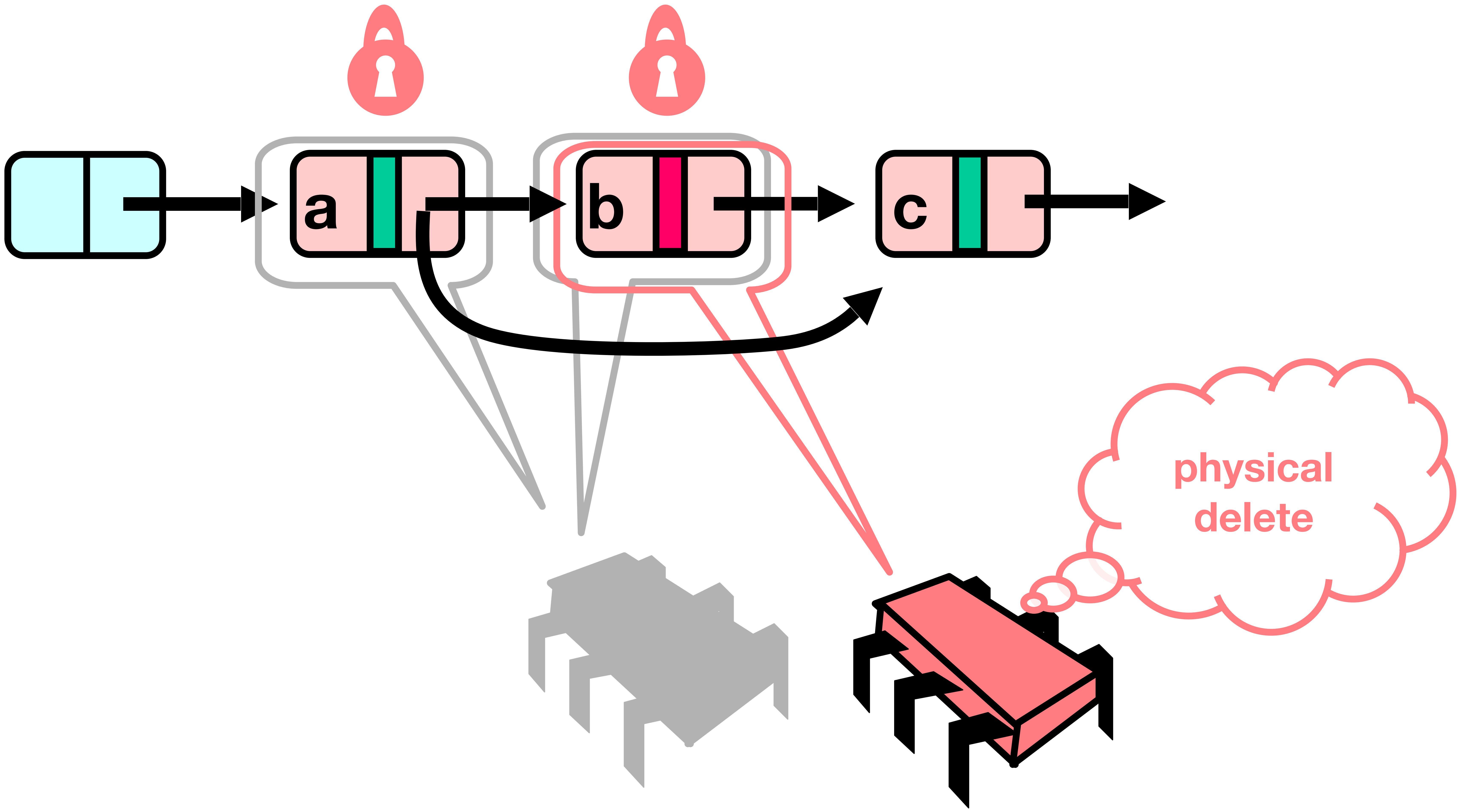
Business as Usual



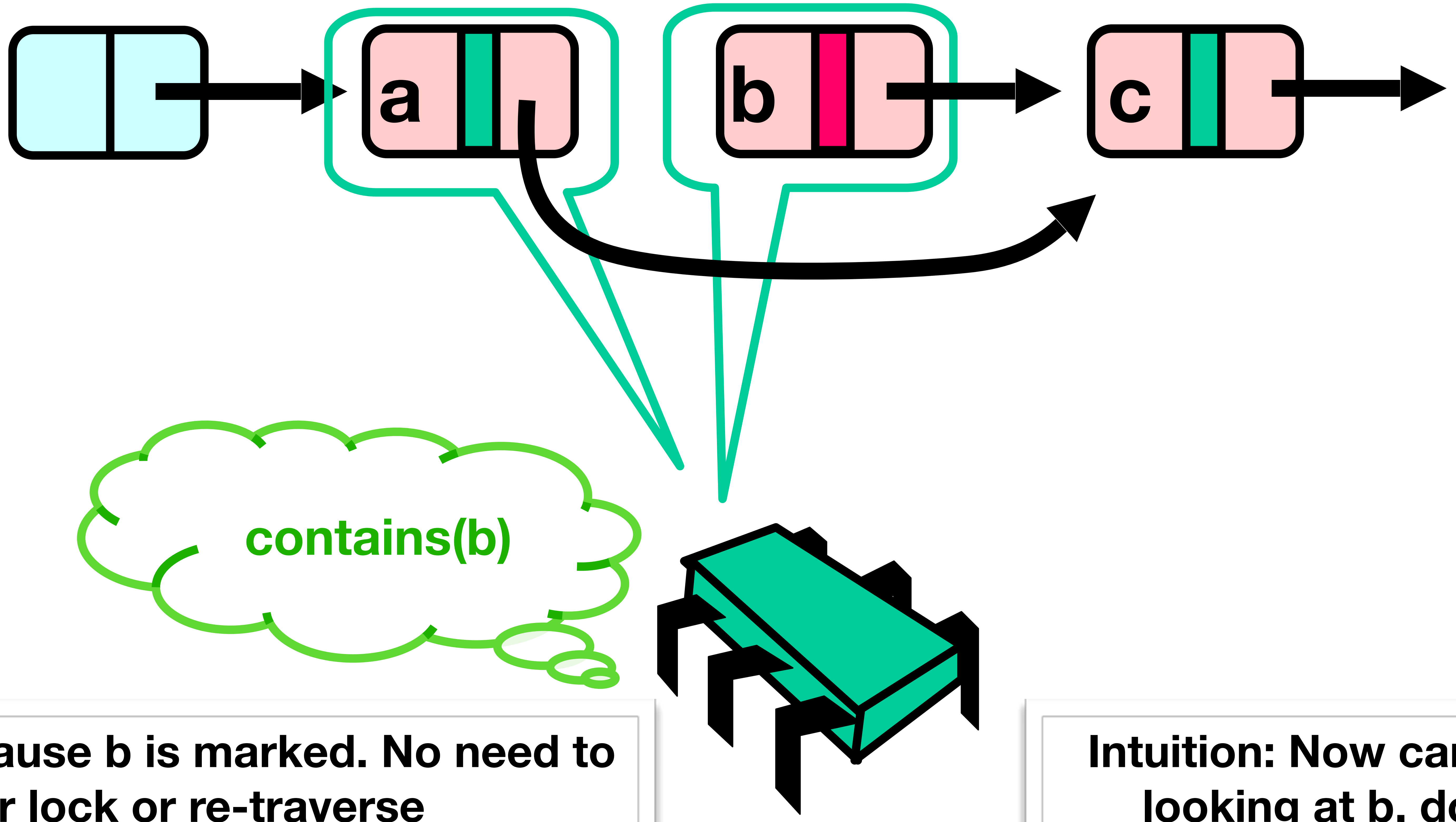
Business as Usual



Business as Usual



Business as Usual



Returns false, because b is marked. No need to validate or lock or re-traverse

Intuition: Now can judge if b is in list ONLY by looking at b, don't also need to look at a

New Abstraction Map

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

Invariant

- If not marked then item in the set
- and reachable from head
- and if not yet traversed it is reachable from pred

Validation

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

List Validate Method

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

Predecessor not
Logically removed

List Validate Method

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

Current not Logically removed

List Validate Method

```
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.key == key) {
    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.key == key) {
   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.key == key) {
    curr.marked = true;
    pred.next = curr.next;
    return true;
   } else {
    return false;
   }}} finally {
          pred.unlock();
          curr.unlock();
   }}}
```

Key found

Remove

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

Logical remove

Remove

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

physical remove

Contains

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

Contains

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

Start at the head

Contains

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

Search key range

Contains

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

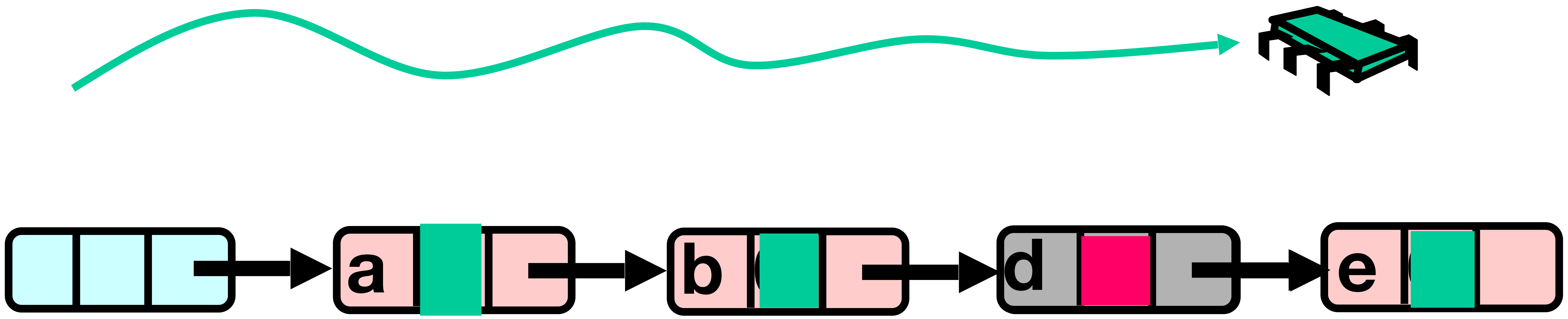
Traverse without locking
(nodes may have been removed)

Contains

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

Present and undeleted?

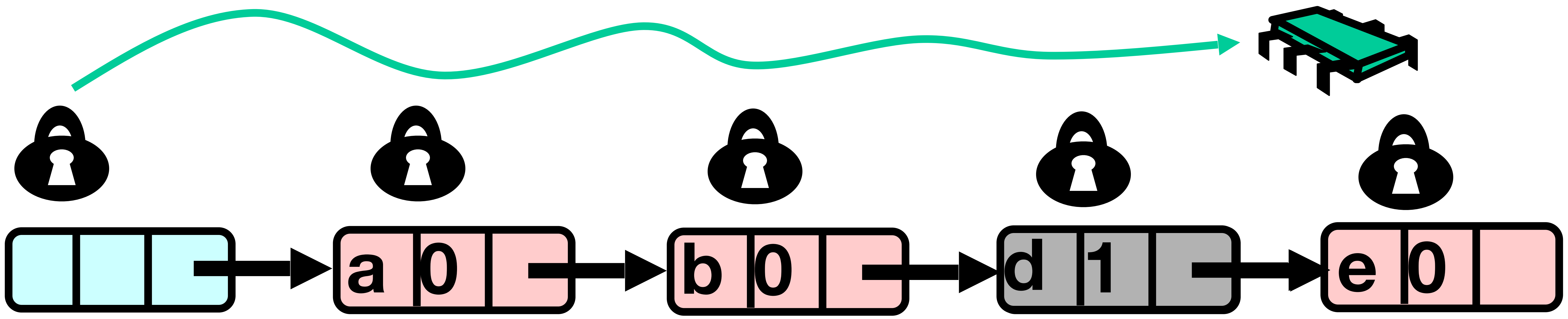
Summary: Wait-free Contains



Use Mark bit + Fact that List is ordered

1. Not marked → in the set
2. Marked or missing → not in the set

Lazy List



Lazy add() and remove() + Wait-free contains()

Evaluation

- Good:
  - contains() doesn't lock
  - In fact, its wait-free!
  - Good because typically high % contains()
  - Uncontended calls don't re-traverse
- Bad
  - Contended add() and remove() 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”
    - Cache miss, page fault, descheduled …
  - Everyone else using that lock is stuck!
  - Need to trust the scheduler….

Reminder: Lock-Free Data Structures

- No matter what …
  - Guarantees minimal progress in any execution
  - i.e. some thread will always complete a method call
  - **Even** if others halt at malicious times
  - Implies that implementation can't use locks

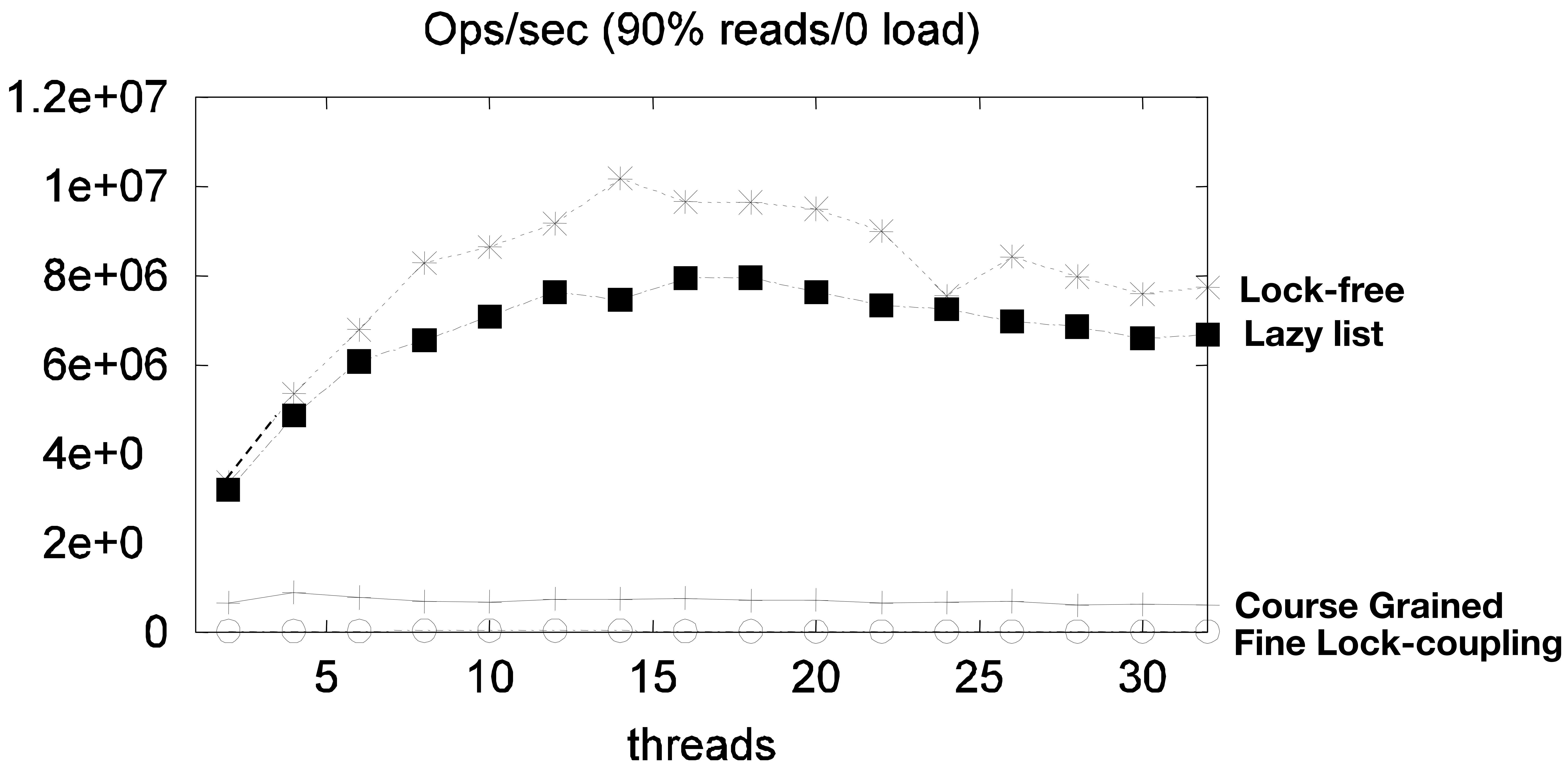
Lock-free Lists

- Next logical step
- Eliminate locking entirely
- contains() wait-free and add() and remove() lock-free
- Use only compareAndSet()
- What could go wrong?
- The textbook works through this

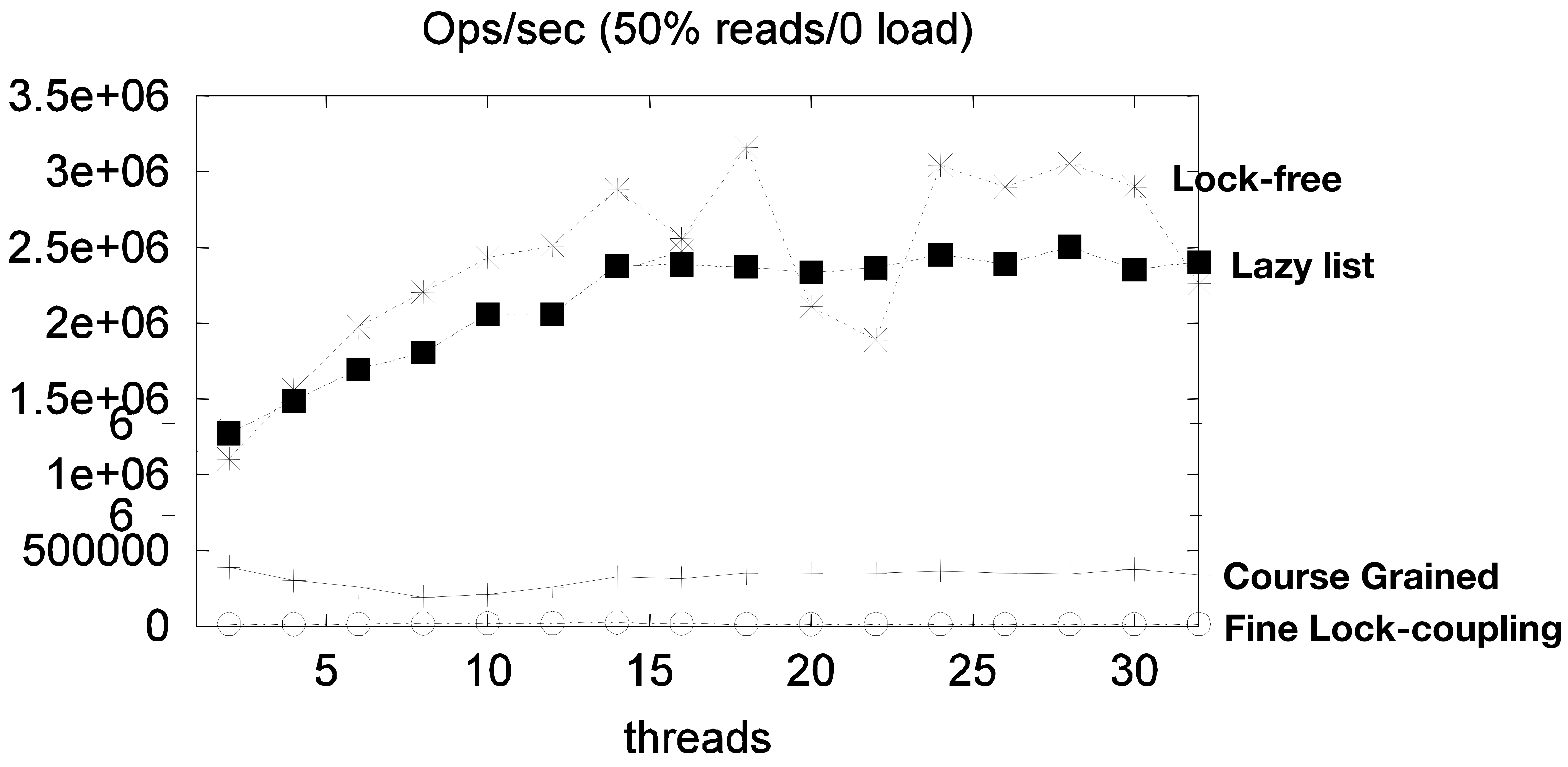
Performance

On 16 node shared memory machine
Benchmark throughput of Java List-based Set algs. Vary % of Contains() method Calls.

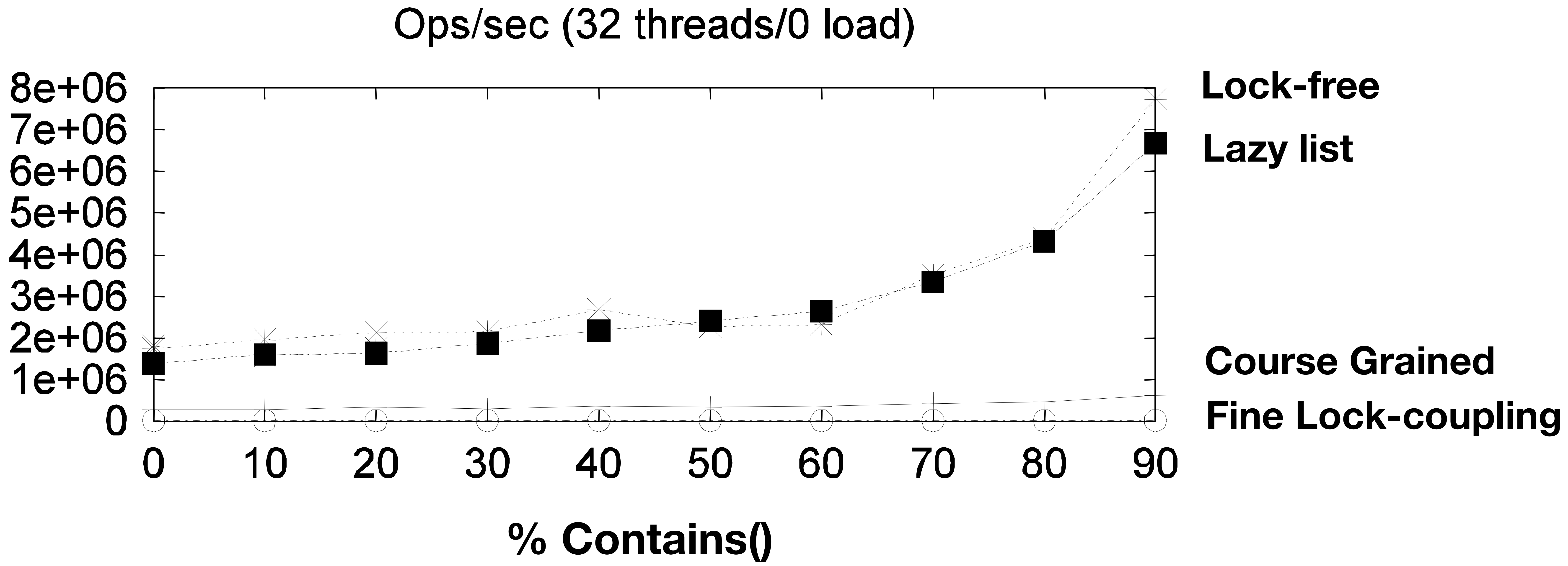
High Contains Ratio



Low Contains Ratio



As Contains Ratio Increases



First:
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

Second:
Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - OK: we are done
  - Oops: start over
- Evaluation
  - Usually cheaper than locking
  - Mistakes are expensive

Third:
Lazy Synchronization

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

Fourth: Lock-Free Synchronization

- Don't use locks at all
  - Use compareAndSet() & relatives …
- Advantages
  - No Scheduler Assumptions/Support
- Disadvantages
  - Complex
  - Sometimes high overhead

“To Lock or Not to Lock”

- Locking vs. Non-blocking: Extremist views on both sides
- The answer: nobler to compromise, combine locking and non-blocking
  - Example: Lazy list combines blocking add() and remove() and a wait-free contains()
  - Remember: Blocking/non-blocking is a property of a method
- Note that compromise makes reasoning even harder…

Plan

- More concurrent data structures in the book if you are interested (Ch 10-15)
- Weds: How to distribute work?
- Mon: Barrier synchronization
- Then we're off to networks and distributed systems land!
- Reminder: HW2 due 3/4 - http://www.jonbell.net/gmu-cs-475-spring-2019/cs475-s2019-homework-2/