CHALMERS

UNIVERSITY OF GOTHENBURG

Parallel linked lists

Lecture 10 of TDA384/DIT391
Principles of Concurrent Programming

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Based on course slides by Carlo A. Furia and Sandro Stucki

Today’s menu

- The burden of locking
- Linked set implementations
  - Nodes, lists, and sets
  - Sequential access
- Parallel linked sets
  - Coarse-grained locking
  - Fine-grained locking
  - Optimistic locking
  - Lazy node removal
  - Lock-free access

The burden of locking

Synchronization costs

A number of factors challenge designing correct and efficient parallelizations:

- sequential dependencies
- synchronization costs
- spawning costs
- error proneness and composability

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In this class, we focus on reducing the synchronization costs associated with locking.

The trouble with locks

Standard techniques for concurrent programming are ultimately based on locks. Programming with locks has several drawbacks:

- performance overhead
- lock granularity is hard to choose:
  - not enough locking: race conditions
  - too much locking: not enough parallelism
- risk of deadlock and starvation
- lock-based implementations do not compose
- lock-based programs are hard to maintain and modify

Message-passing programming is higher-level, but it also inevitably incurs synchronization costs – of magnitude comparable to those associated with locks.

Breaking free of locks

Lock-free programming takes a fresh look at the problems of concurrency and tries to dispense with using locks altogether.

- Lock-based programming is pessimistic: be prepared for the worst possible conditions:

  if things can go wrong, they will.

- Lock-free programming is optimistic: do what you have to do without worrying about race conditions:

  if things go wrong, just try again.

Lock-free programming

Lock-free programming relies on:

- using stronger primitives for atomic access,
- building optimistic algorithms using those primitives.

Compare-and-set operations are an example of stronger primitives:

```
public class AtomicInteger {
  // atomically set to ‘update’ if current value is ‘expect’
  // otherwise do not change value and return false
  boolean compareAndSet(int expect, int update)
}
```

To update an AtomicInteger variable `k`:

```
  do {  // keep trying until no one changes k in between
    int oldValue = k.get();
    int newValue = compute(oldValue);
  } while (!k.compareAndSet(oldValue, newValue));
```

Compare-and-set is not free

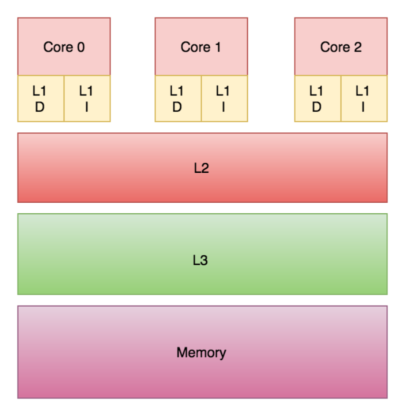

Diagram by Avadlam3, Wikipedia (2016).

CAS operations are not free: they involve memory barrier operations to synchronize caches (∼100-1000 cycles).

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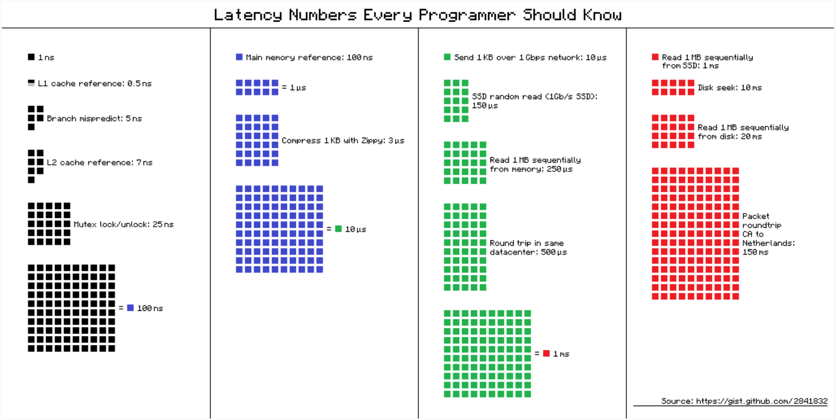

Chart by ayshen, based on Peter Norvig's "Teach Yourself Programming in Ten Years".

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Lock-free vs. wait-free

Two classes of lock-free algorithms, collectively called non-blocking:

lock-free: guarantee system-wide progress: infinitely often, some process makes progress,

wait-free: guarantee per-process progress: every process eventually makes progress.

Which one is stronger?

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Which one is stronger?

Wait-free is stronger than lock-free:

- Lock-free algorithms are free from deadlock.
- Wait-free algorithms are free from deadlock and starvation.

Thread-safe data structures

Programming correctly without using locks is challenging.

Instead of trying to develop general techniques, we focus on implementing reusable data structures that make minimal usage of locking. The effort involved in developing correct implementations pays off since very many applications can then use such thread-safe data structure implementations to synchronize safely and implicitly by accessing the structures through their APIs.

A data structure is thread safe if its operations are free from race conditions when executed by multi-threaded clients.

Our lock-free and wait-free algorithms are some of those used in the implementations of thread safe structures in `java.util.concurrent` (non-blocking data structures atomically accessible in parallel).

Linked set implementations

Parallel linked lists

In the rest of this class, we go through several implementations of linked lists that support parallel access; the implementations differ in how much locking they use to guarantee correctness and, correspondingly, in how much parallelism they allow.

We will use pseudo-code that is very close to regular Java syntax but occasionally takes some liberties to simplify the notation. On the course website you can download fully working implementations of some of the classes.

Linked set implementations

Nodes, lists, and sets

The interface of a set

We use linked lists to implement a set data structure with interface:

```
public interface Set<T>
{
   // add ‘item’ to set; return false if ‘item’ is already in the set
   boolean add(T item);

   // remove ‘item’ from set; return false if ‘item’ not in the set
   boolean remove(T item);

   // is ‘item’ in set?
   boolean has(T item);
}
```

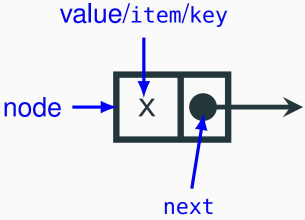
Nodes

The underlying implementations of sets use singly-linked lists, which are made of chains of nodes. Every node:

- stores an `item` – its value
- has a unique `key` – the value's hash code
- points to the `next` node in the chain

In the graphical representations of nodes, we do not distinguish between items and their keys – and represent both by characters:

```
interface Node<T>
{
  // value of node
  T item();
  // hash code of value
  int key();
  // next node in chain
  Node<T> next();
}
```



Lists as chains of nodes

A list with special head and tail nodes implements a set:

- the elements of the set are items in different nodes
- to facilitate searching, the nodes are maintained sorted in ascending keys
- to facilitate searching, the head has the smallest possible key, the tail has the largest possible key, and all elements have finitely many keys that are in between

For example, the set $\{\mathtt{b}, \mathtt{e}, \mathtt{a}, \mathtt{f}, \mathtt{g}\}$ is implemented by:

Relaxing these assumptions is possible at the cost of complicating the implementations a bit.

Linked set implementations

Sequential access

Sequential set: basic linked implementation

We start with a standard linked-list-based implementation of sets, which only works for sequential access.

```
class SequentialSet<T> implements Set<T>
{
  // nodes at beginning and end
  protected Node<T> head, tail;

  // empty set
  public SequentialSet() {
    head = new SequentialNode<>(Integer.MIN_VALUE);  // smallest key
    tail = new SequentialNode<>(Integer.MAX_VALUE);  // largest key
    head.setNext(tail);
  }
```

Empty set: head  tail

Nodes in a sequential set

A node's implementation uses private attributes with getters and setters; this is a bit tedious now (we could just let the set implementations access the attributes directly), but it will lead to nicer designs in the several variants of set implementations we'll describe.

```java
class SequentialNode<T> implements Node<T> {
   private T item;         // value stored in node
   private int key;        // hash code of item
   private Node<T> next;   // next node in chain
     // getters
   T item()       { return item; }
   int key()      { return key; }
   Node<T> next() { return next; }
     // setters
   void setItem(T item)       { this.item = item; }
   void setKey(int key)       { this.key = key; }
   void setNext(Node<T> next) { this.next = next; }
}
```

Finding a position inside a list

Since we maintain nodes in order of key, and every item has a unique key, we can search for the position of any given key by going through the list from head to tail.

The method `find` implements this frequently used operation of finding the position of a key inside a list. The position of `key` is a pair `(pred, curr)` of adjacent nodes, such that `pred.key() < key <= curr.key()`.

For example, the position of `c` in the following list is:

Thanks to the boundary keys chosen for head and tail, searching for any value key returns a valid position in the list.

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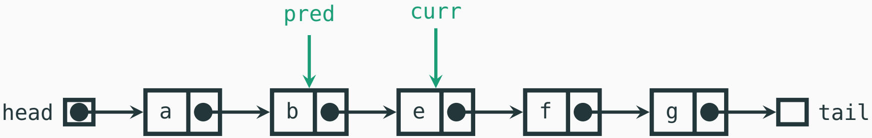

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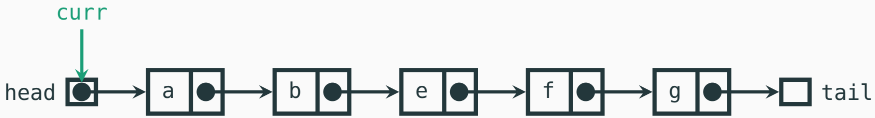


```
// first position from 'start' whose key is no smaller than 'key'
protected Node<T>, Node<T> find(Node<T> start, int key) {
  Node<T> pred, curr; // predecessor and current node in iteration
  curr = start;       // from start node
  do {
    pred = curr; curr = curr.next();    // move to next node
  } while (curr.key() < key);         // until curr.key >= key
  return (pred, curr);                  // return position
}
```

pseudo-code for: `new Position<T>(pred, curr)`

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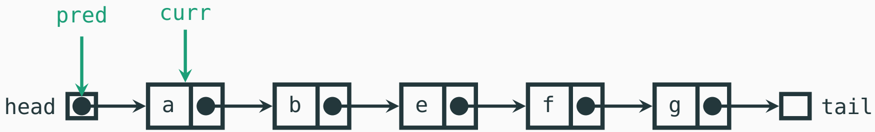


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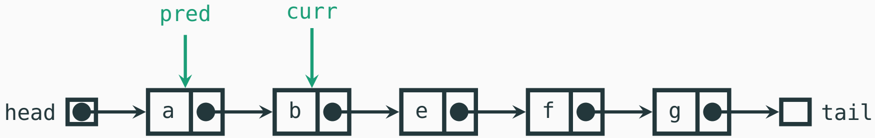


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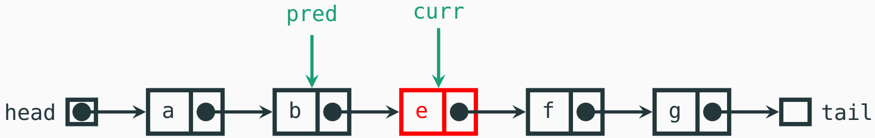


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Sequential set: method `has`

A set has `item` if and only if `item` is (equal to) the first element in the set whose key is greater than or equal to `item`'s.


```
// is 'item' in set?
public boolean has(T item) {
  int key = item.key();            // item's key
    // find position of key from head
  Node<T> pred, curr = find(head, key);
    // curr.key() >= key
  return curr.key() == key;        // item can only appear here!
}
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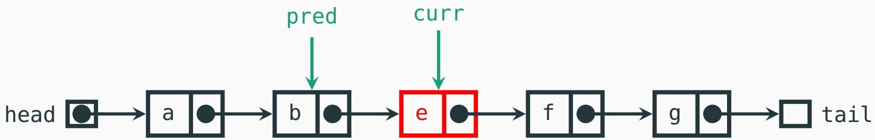


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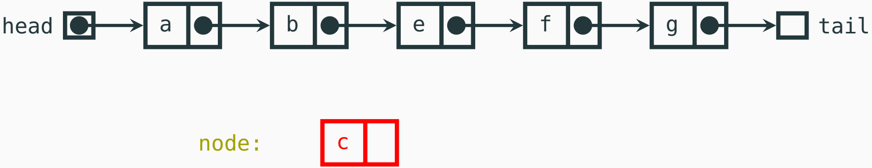
A new `item` must be added between `pred` and `curr`, where `(pred, curr)` is `item`'s position in the list.

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public boolean add(T item) {
  Node<T> node = new Node<>(item);              // new node
  Node<T> pred, curr = find(head, item.key()); // curr.key >= item.key()
  if (curr.key() == item.key()) return false;  // item already in set
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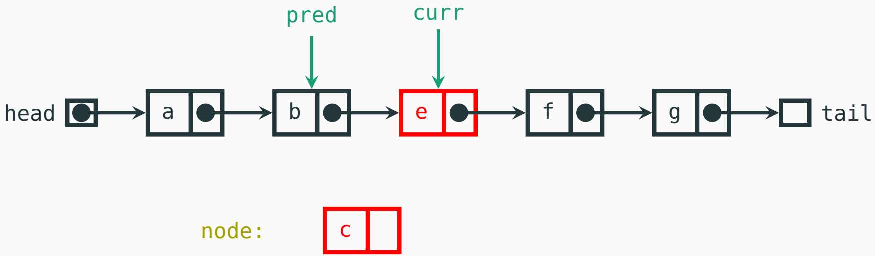


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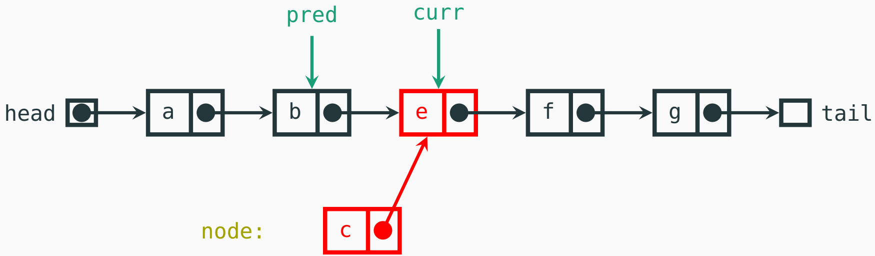


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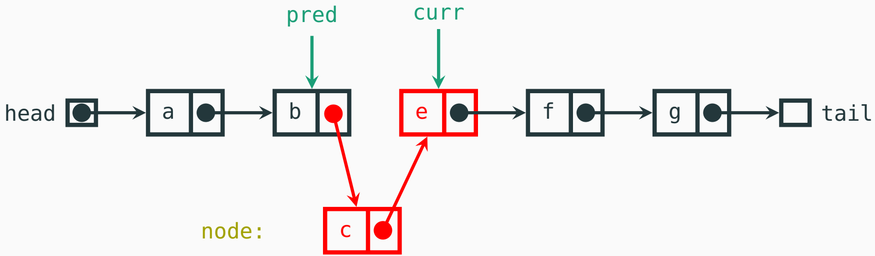


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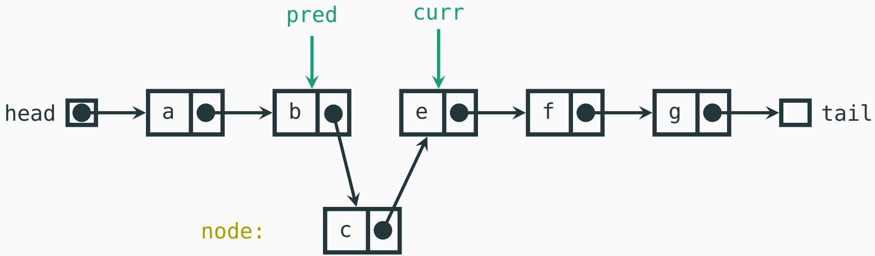


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An element `item` is removed from a set by redirecting `pred.next` to skip over `curr`, where `(pred, curr)` is `item`'s position in the list.


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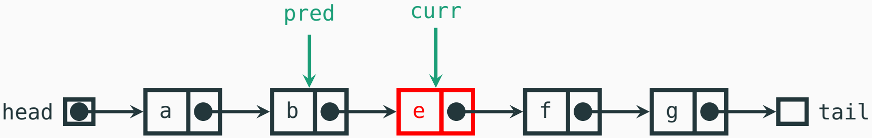


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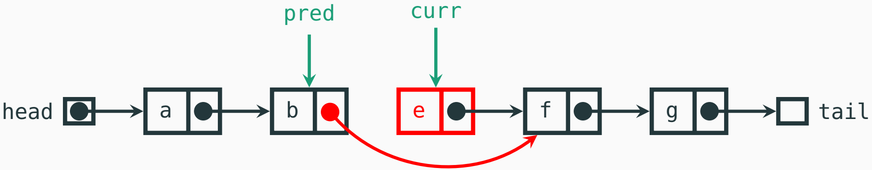


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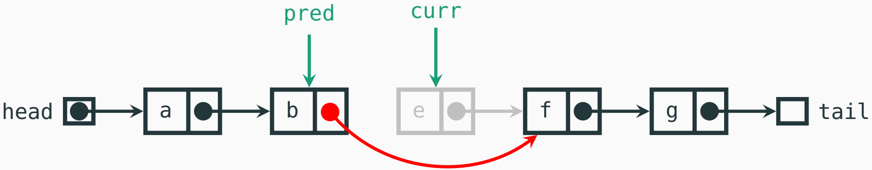


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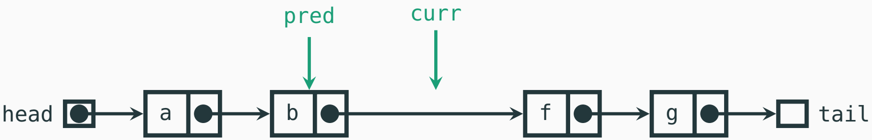


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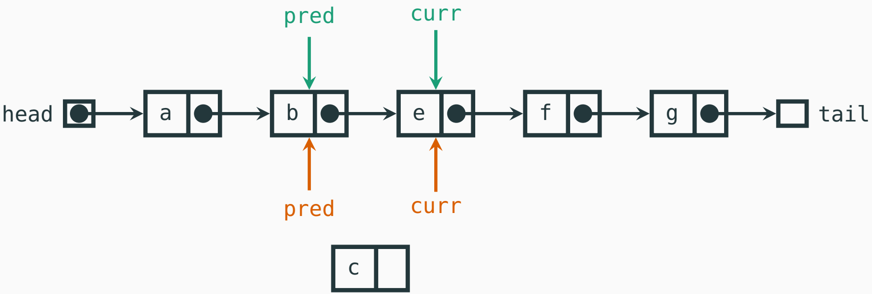

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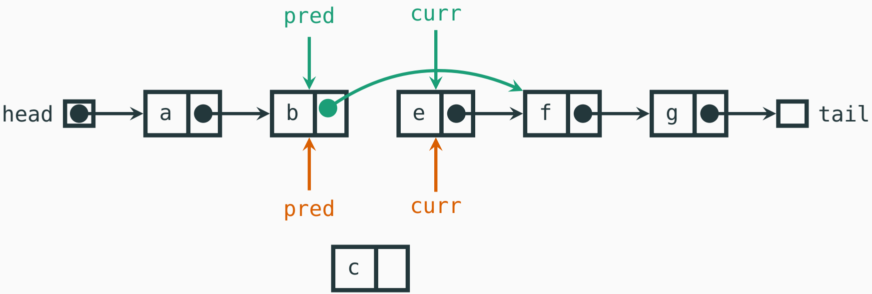

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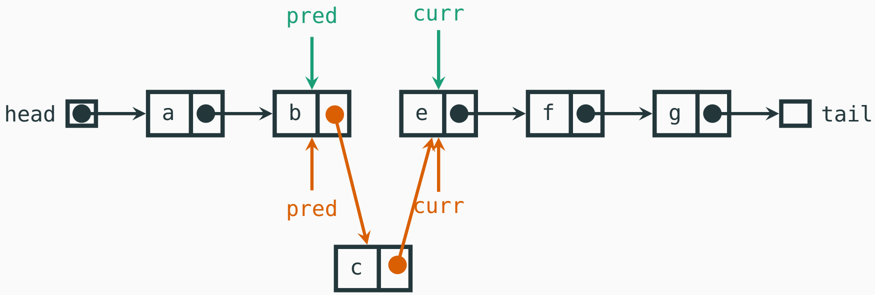

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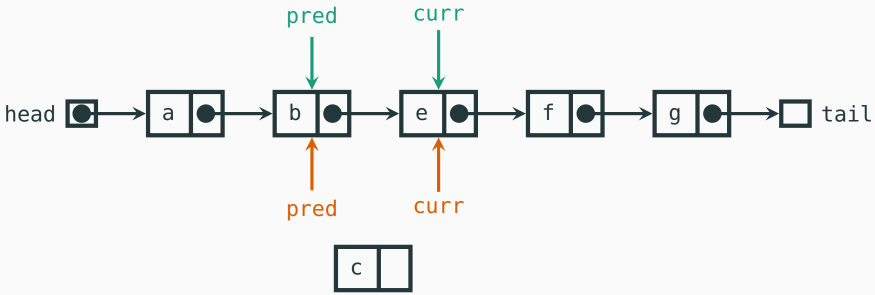

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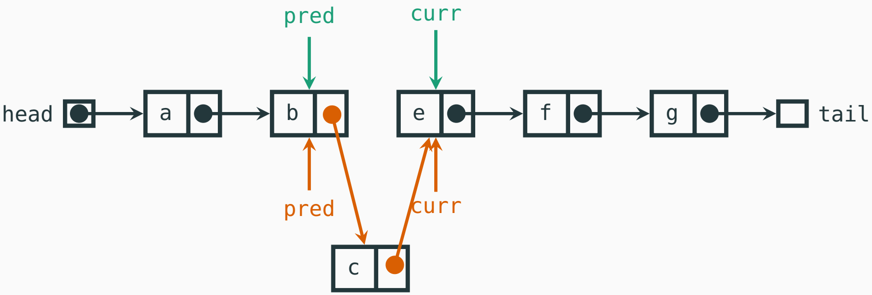

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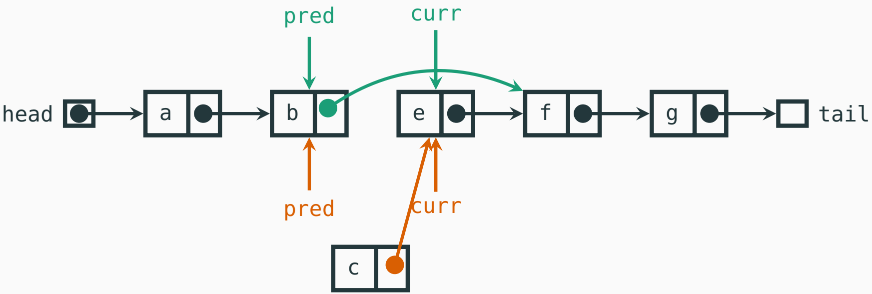
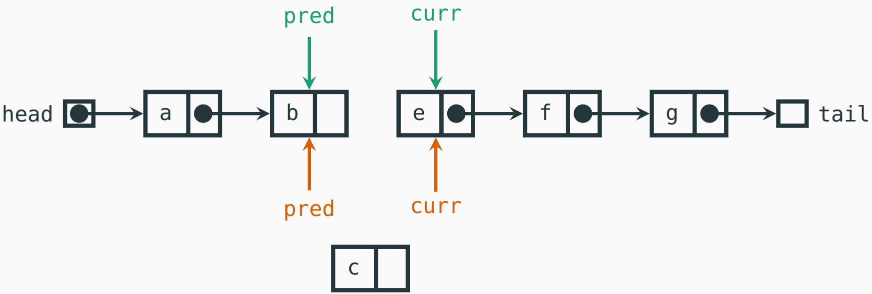


Sequential set does not work under concurrency

If multiple threads are active on the same instance of `SequentialSet`, they can easily interfere with each other's operations – and possibly leave the set in an inconsistent state.

For example, if thread t runs `remove(e)` while thread u runs `add(c)`: in some interleavings, `add` is reverted:



If `find` goes through the list while another thread is modifying it, even more subtle errors may occur.

Parallel linked sets

Parallel linked sets

Coarse-grained locking

Concurrent set with coarse-grained locking

A straightforward way to make `SequentialSet` work correctly under concurrency is using a lock to ensure that at most one thread at a time is operating on the structure.

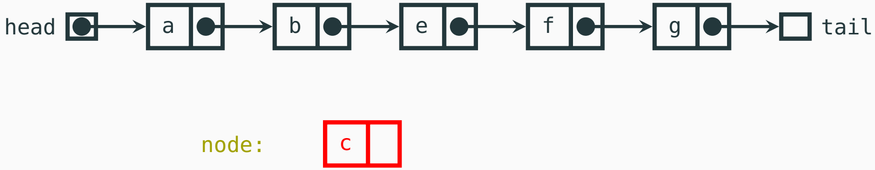
```
class CoarseSet<T> extends SequentialSet<T>
{
  // lock controlling access to the whole set
  private Lock lock = new ReentrantLock();

  // overriding of add, remove, and has
```

Every method `add`, `remove`, and `has` simply works as follows:

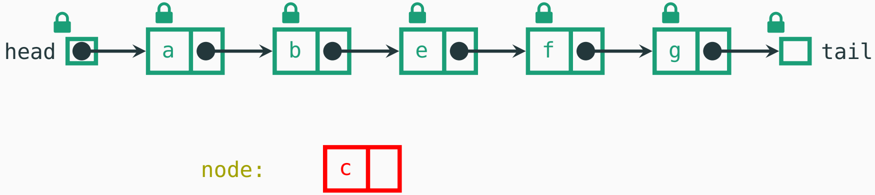
1. acquires the lock on the set
2. performs the operation as in `SequentialSet`
3. releases the lock on the set

Coarse-locking set: method add




```java
public boolean add(T item) {
  lock.lock();                  // lock whole set
  try {
    return super.add(item);  // execute ‘add’ while locking
  } finally {
    lock.unlock();              // done: release lock
  }
}
```

Coarse-locking set: method add

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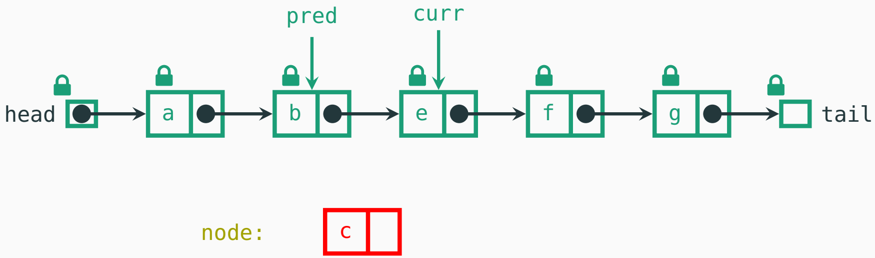


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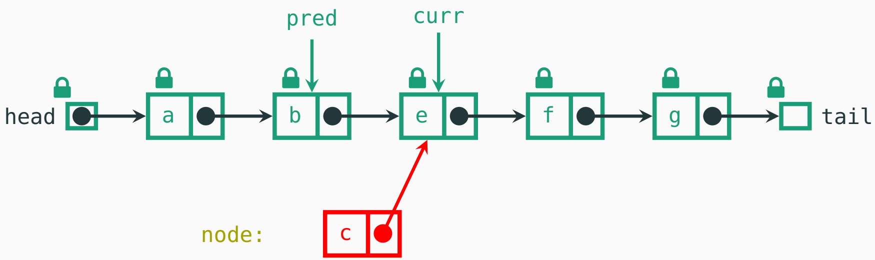


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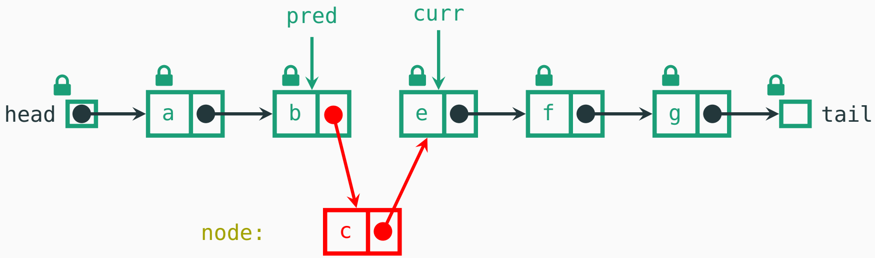


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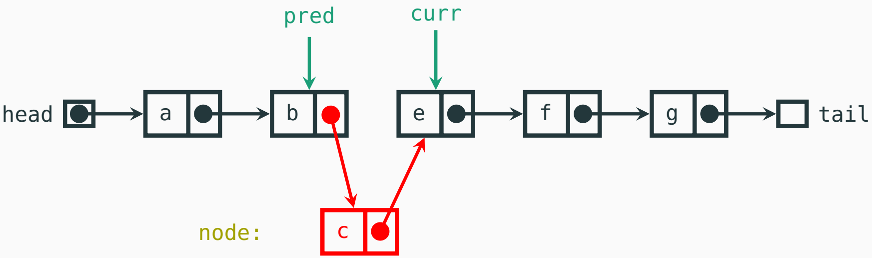


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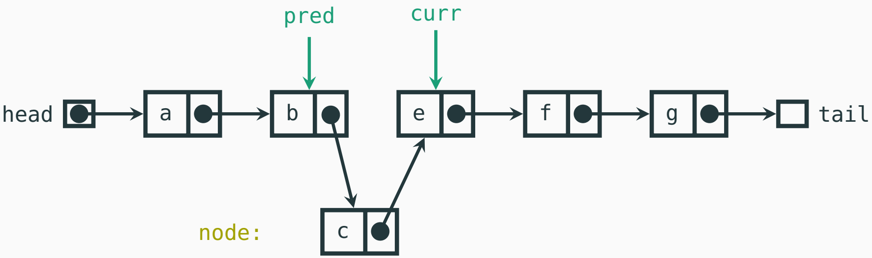


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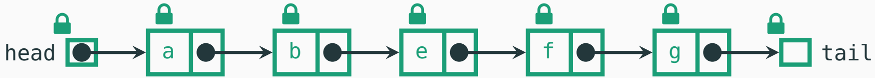
Coarse-locking set: method `remove`


```java
public boolean remove(T item) {
  lock.lock();                    // lock whole set
  try {
    return super.remove(item);  // execute ‘remove’ while locking
  } finally {
    lock.unlock();              // done: release lock
  }
}
```

Coarse-locking set: method `remove`

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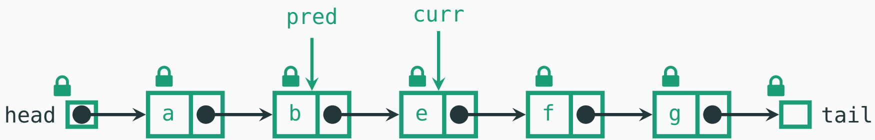


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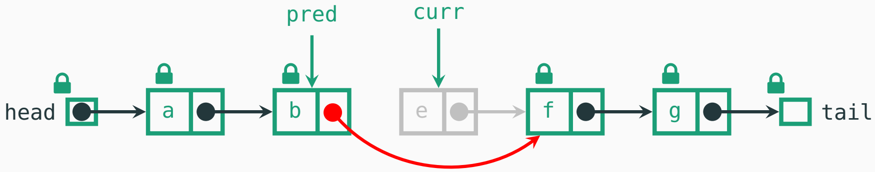


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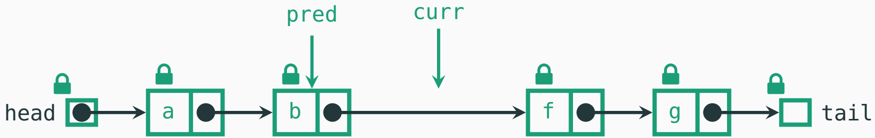


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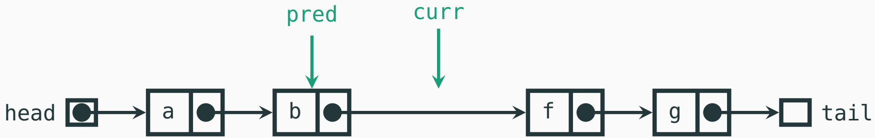


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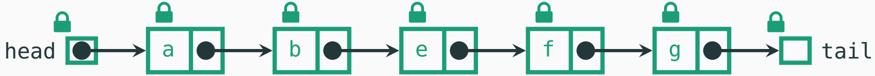
}
```

Coarse-locking set: method has


```java
public boolean has(T item) {
  lock.lock();                 //lock whole set
  try {
    return super.has(item); // execute ‘has’ while locking
  } finally {
    lock.unlock();             // done: release lock
  }
}
```

Coarse-locking set: method `has`

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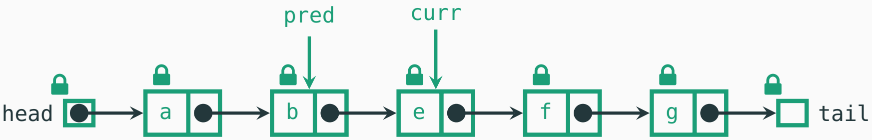


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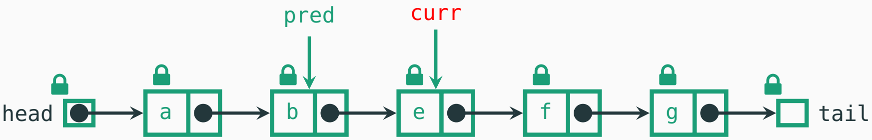


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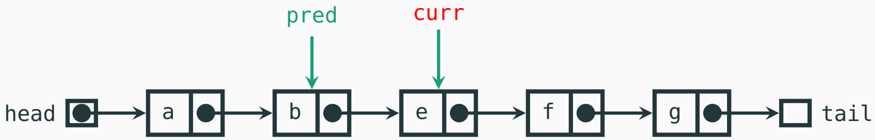


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}
```

Coarse-locking set: pros and cons

Pros:

- obviously correct – it avoids race conditions and deadlocks
- if the lock is fair, so is access to the set
- if contention is low (not many threads accessing the set concurrently), `CoarseSet` is quite efficient

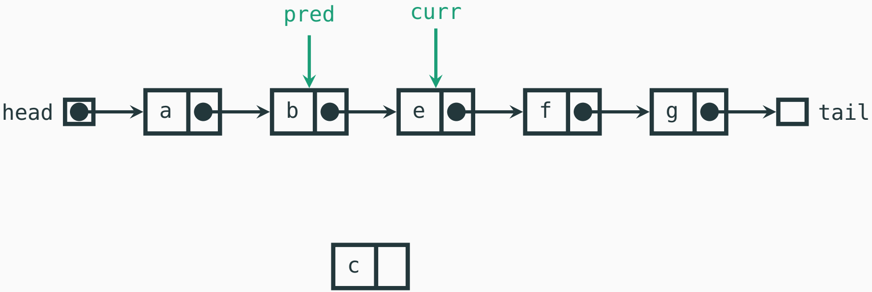
Cons:

- access to the set is essentially sequential – missing opportunities for parallelization
- if contention is high (many threads accessing the set concurrently), `CoarseSet` is quite slow

Locking after finding?

Can we reduce the size of the critical sections by executing `find` without locking, and then acquiring the lock only before modifying the list? No, because the list may be modified between when a thread performs `find` and when it acquires the lock.

For example, suppose thread *t* runs `remove(e)` while thread *u* runs `add(c)`, and *t* acquires the lock first:



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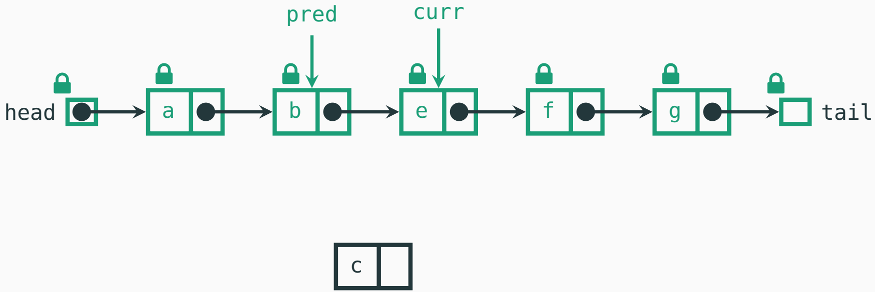

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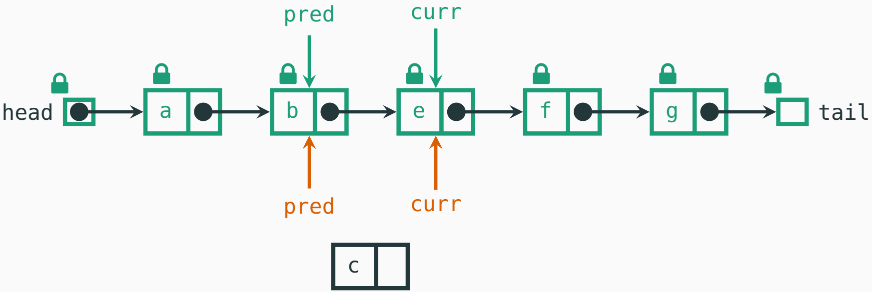

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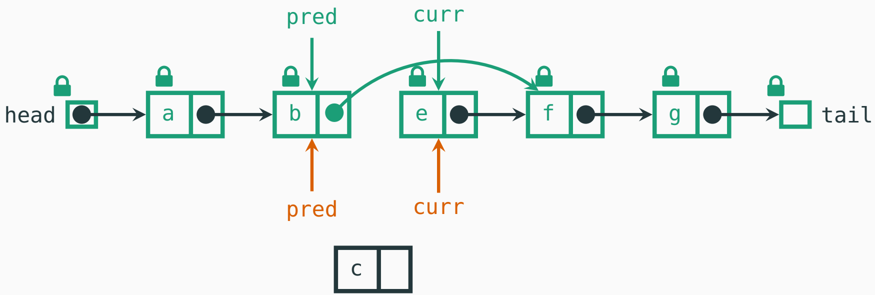

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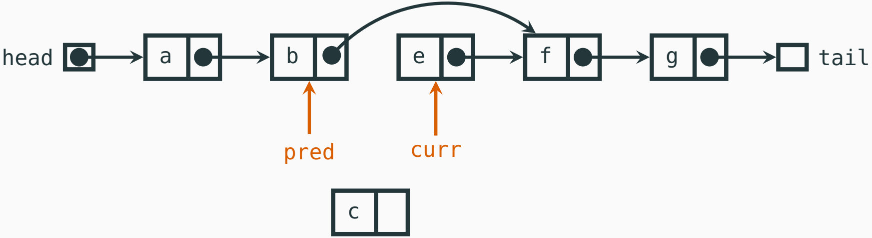

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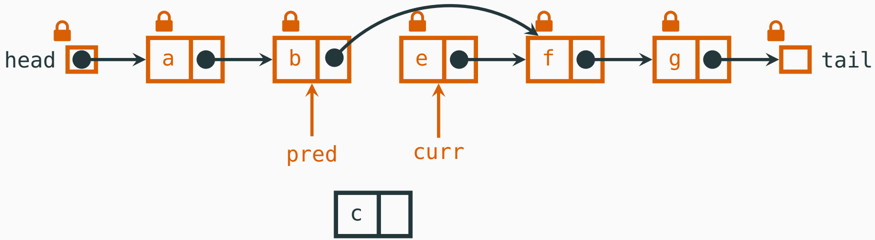

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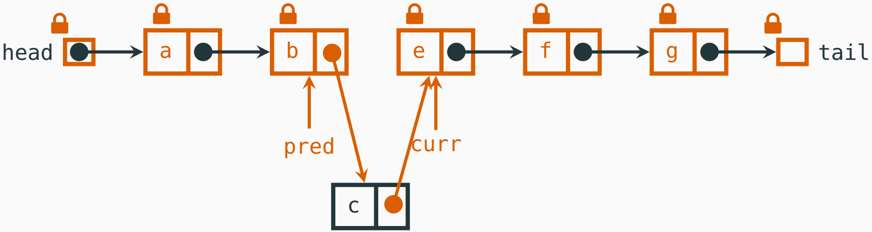

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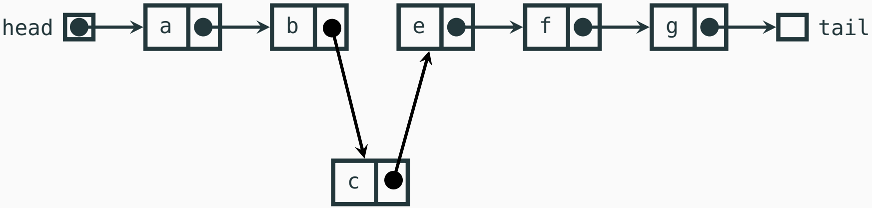

Parallel linked sets

Fine-grained locking

Concurrent set with fine-grained locking

Rather than locking the whole linked list at once, we add a lock to each node. Then, threads only lock the individual nodes on which they are operating.

```
public class FineSet<T> extends SequentialSet<T>
{
  // empty set
  public FineSet() {
    head = new LockableNode<>(Integer.MIN_VALUE);  // smallest key
    tail = new LockableNode<>(Integer.MAX_VALUE);  // largest key
    head.setNext(tail);
  }

  // overriding of find, add, remove, and has
```

Nodes in a fine-locking set

Each node includes a lock object, and `lock` and `unlock` methods that access the lock.

```
class LockableNode<T> extends SequentialNode<T>
{
   private Lock lock = new ReentrantLock();

   void lock()   { lock.lock(); }   // lock node
   void unlock() { lock.unlock(); } // unlock node
}
```

How many nodes do we have to lock?

We have seen (in `CoarseSet`) that we have to lock as soon as we start executing `find`. Thus, we start locking the head node and pass the lock along the chain of nodes.

How many nodes do we have to hold locked at once? Even though `pred`'s node is the only node that is actually modified, only locking `pred` is not enough.

For example, if thread *t* runs `remove(e)` while thread *u* runs `remove(b)`, it may happen that only `b`'s removal takes place:

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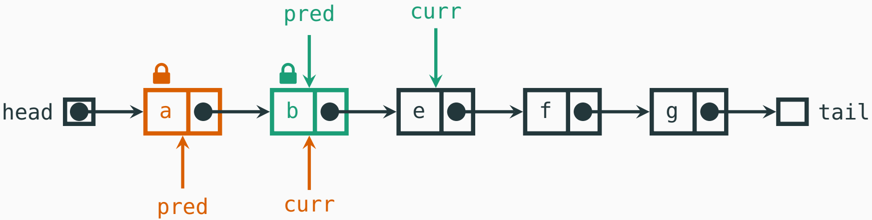

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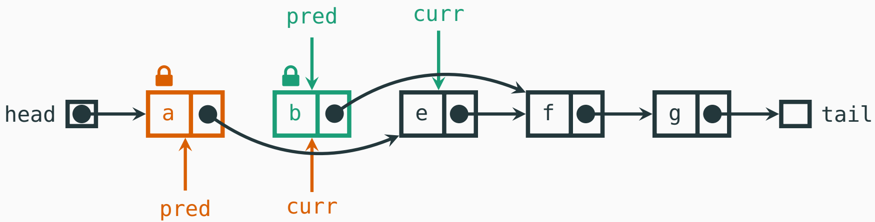


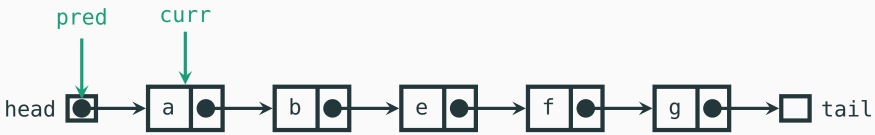
Thus, we lock both `pred` and `curr` at once.

Fine-locking set: method `find`


```
// find while locking pred and curr, return locked position
protected Node<T>, Node<T> find(Node<T> start, int key) {
  Node<T> pred, curr; // predecessor and current node in iteration
  pred = start; curr = start.next(); // from start node
  pred.lock(); curr.lock();           // lock pred and curr nodes
  while (curr.key < key) {
    pred.unlock();                    // unlock pred node
    pred = curr; curr = curr.next(); // move to next node
    curr.lock();                      // lock next node
  } // until curr.key >= key
  return (pred, curr);  // return position
}
```

pseudo-code for: `new Position<T>(pred, curr)`

Fine-locking set: method `find`

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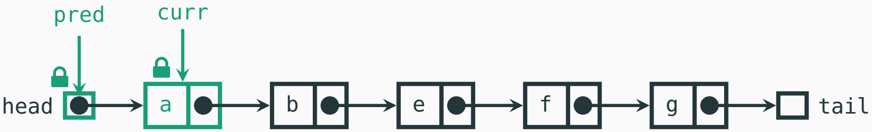


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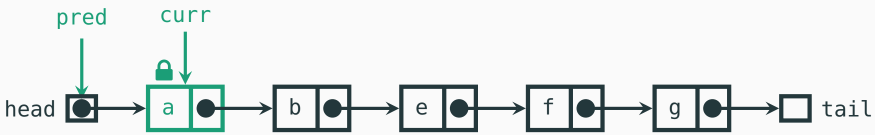
Fine-locking set: method `find`

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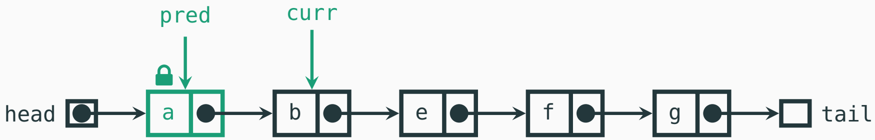
pseudo-code for: **new** `Position<T>(pred, curr)`

Fine-locking set: method find

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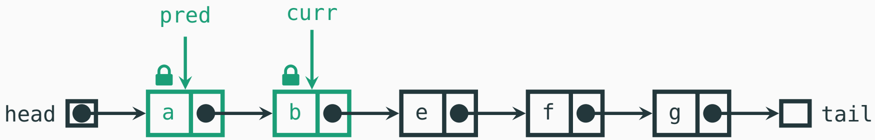
Fine-locking set: method `find`

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```
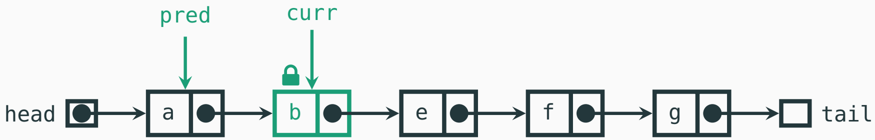

pseudo-code for: `new Position<T>(pred, curr)`

Fine-locking set: method `find`




```
// find while locking pred and curr, return locked position
protected Node<T>, Node<T> find(Node<T> start, int key) {
  Node<T> pred, curr; // predecessor and current node in iteration
  pred = start; curr = start.next(); // from start node
  pred.lock(); curr.lock();          // lock pred and curr nodes
  while (curr.key < key) {
    pred.unlock();                   // unlock pred node
    pred = curr; curr = curr.next(); // move to next node
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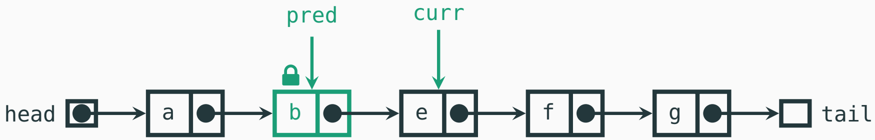


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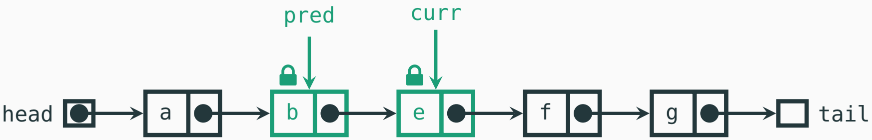


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```
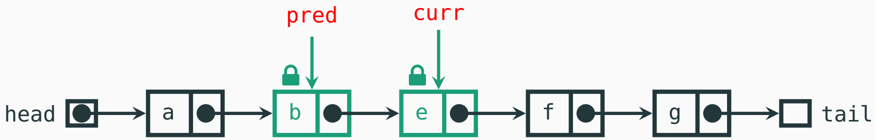

pseudo-code for: `new Position<T>(pred, curr)`

Fine-locking set: method `find`

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  while (curr.key < key) {
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Hand-over-hand locking

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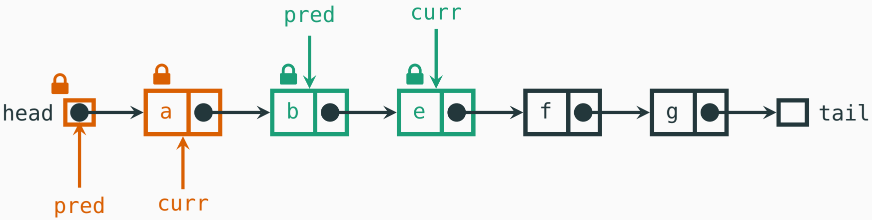

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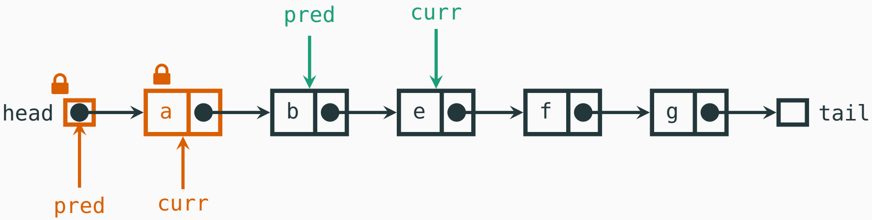

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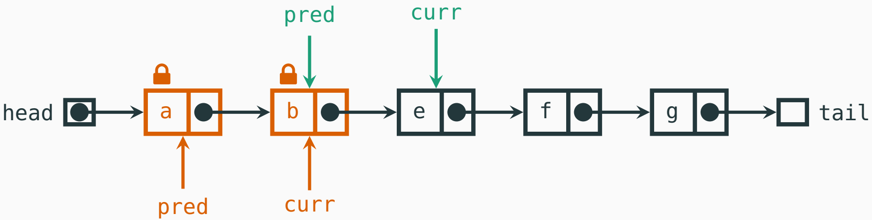

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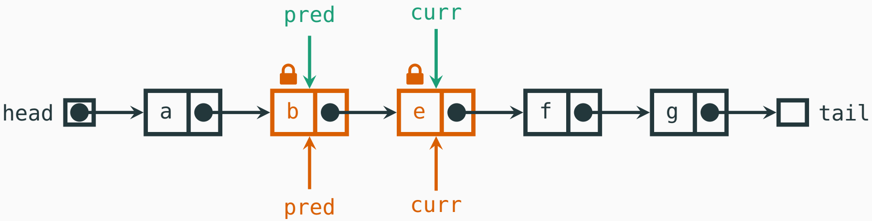

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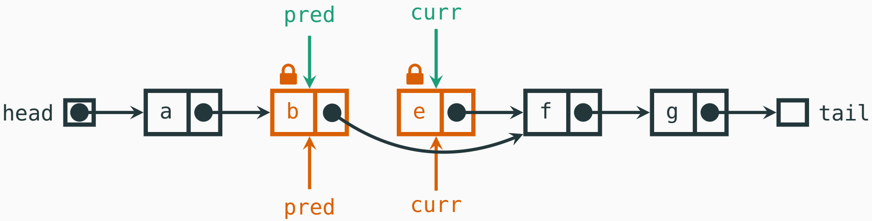

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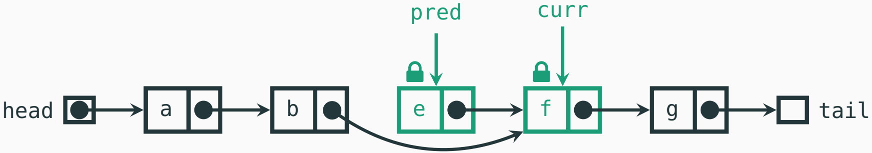

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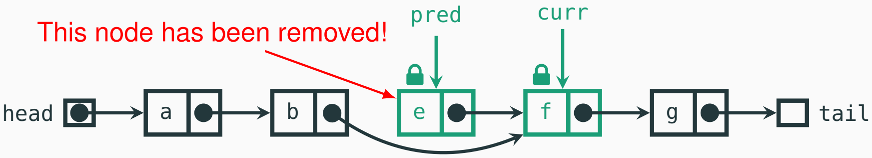

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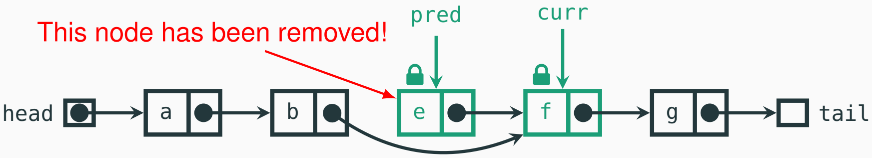
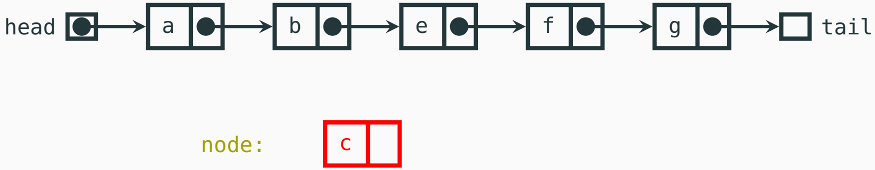


- Locking two nodes at once is sufficient to prevent problems with conflicting operations: threads proceed along the linked list in order, without one thread "overtaking" another thread that is further out
- The protocol ensures that locks are acquired by all threads in the same order, thus avoiding deadlocks

Fine-locking set: method `add`

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public boolean add(T item) {
  Node<T> node = new LockableNode<>(item);  // new node
  try { // find with hand-over-hand locking
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    Node<T> pred, curr = find(head, item.key()); // locking
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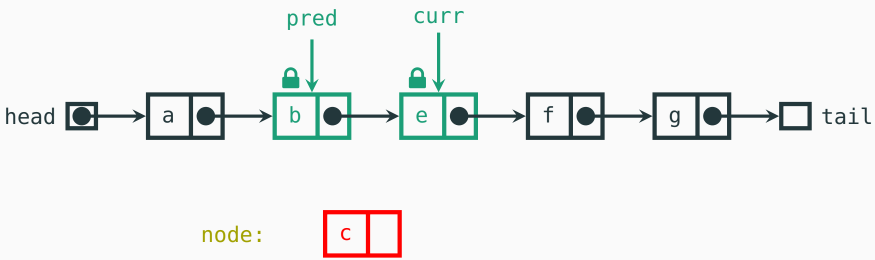


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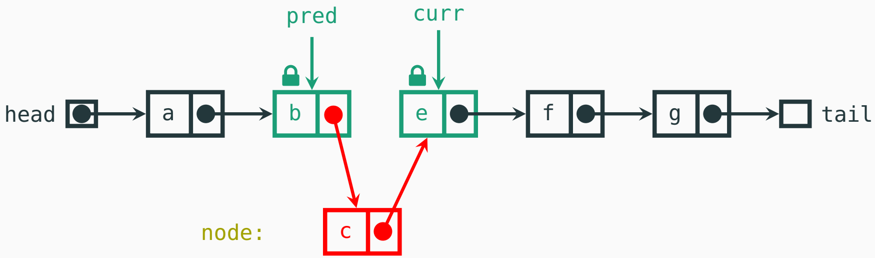


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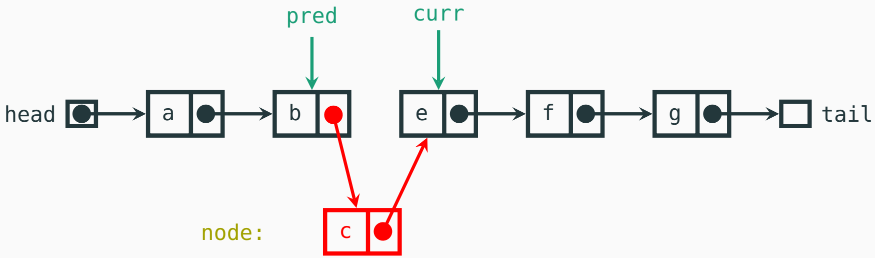


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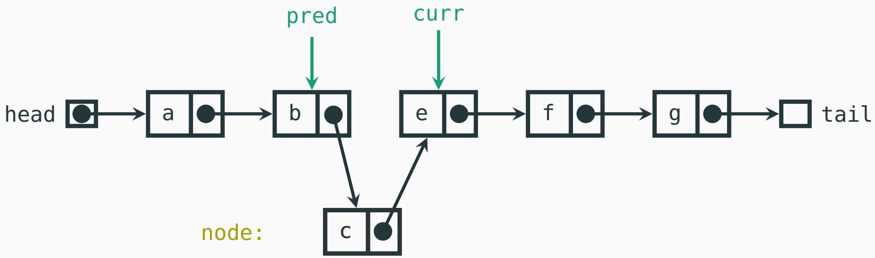


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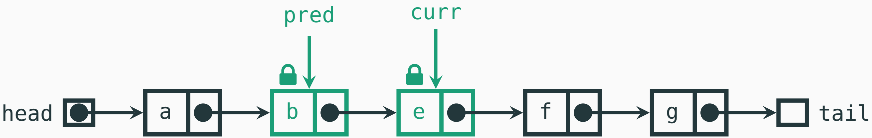
}
```

Fine-locking set: method `remove`


```
public boolean remove(T item) {
  try { // find with hand-over-hand locking
        // the first position such that curr.key >= item.key
    Node<T> pred, curr = find(head, item.key()); // locking
    ... // remove node as in SequentialSet, while locking
  } finally { pred.unlock(); curr.unlock(); } // done: unlocking
}
```

Fine-locking set: method `remove`

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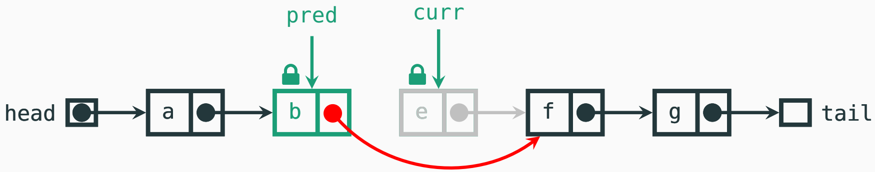


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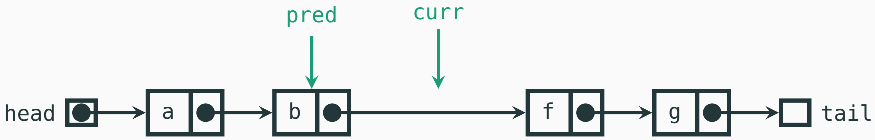


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  } finally { pred.unlock(); curr.unlock(); } // done: unlocking
}
```

Fine-locking set: method has


```
public boolean has(T item) {
  try { // find with hand-over-hand locking
        // the first position such that curr.key() >= item.key()
    Node<T> pred, curr = find(head, item.key()); // locking
    ... // check node as in SequentialSet, while locking
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```
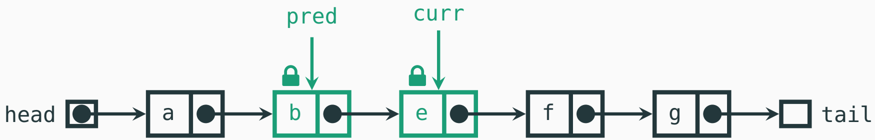

Fine-locking set: method `has`

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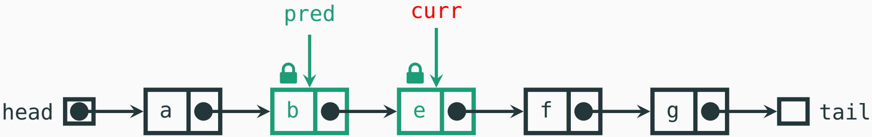


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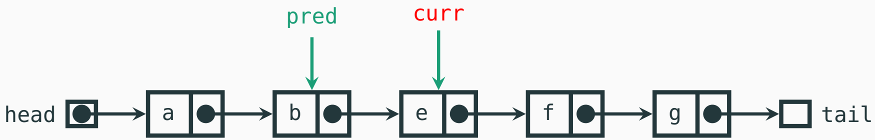


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Fine-locking set: pros and cons

Pros:

- if locks are fair, so is access to the set, because threads proceed along the list one after the other without changing order
- threads operating on disjoint portions of the list may be able to operate in parallel

Cons:

- it is still possible that one thread prevents another thread from operating in parallel on a disjoint portion of the list – for example, if one thread wants to access the end of the list but another thread blocks it while locking the beginning of the list
- the hand-over-hand locking protocol may be quite slow, as it involves a significant number of lock operations

Parallel linked sets

Optimistic locking

Concurrent set with optimistic locking

Let us revisit the idea of performing `find` without locking. We have seen that problems may occur if the list is modified between when a threads finds a position and when it acquires locks on that position. Thus, we validate a position after finding it and while the nodes are locked, to verify that no interference took place.

```
public class OptimisticSet<T> extends SequentialSet<T>
{
  public FineSet()
  { head = new ReadWriteNode<>(Integer.MIN_VALUE);  // smallest key
    tail = new ReadWriteNode<>(Integer.MAX_VALUE);  // largest key
    head.setNext(tail); }

  // is (pred, curr) a valid position?
  protected boolean valid(Node<T> pred, Node<T> curr) // ...

  // overriding of find, add, remove, and has
```

Nodes in an optimistic-locking set

Since we need to be able to follow the chain of `next` references without locking, attribute `next` must be declared **`volatile`** in Java – so that modifications to it (which occur while the node is locked) are propagated to all threads (even if they have not locked a node). Other than for this detail, a `ReadWriteNode` is the same as a `LockableNode`.

With a little abuse of notation, we can pretend that `ReadWriteNode` inherits from `LockableNode` and overrides its `next` attribute. Overriding of attributes is however not possible in Java (shadowing takes place instead); the actual implementation that we make available does not reuse `LockableNode`'s code through inheritance.

```java
class ReadWriteNode<T> extends LockableNode<T>
{
   private volatile Node<T> next;   // next node in chain
}
```

Delayed locking as optimistic locking

In `OptimisticSet`, operations work as follows:

1. find the item's position inside the list without locking – as in `SequentialSet`
2. lock the position's nodes `pred` and `curr`
3. validate the position while the nodes are locked:
    3.1 if the position is valid, perform the operation while the nodes are locked, then release locks
    3.2 if the position is invalid, release locks and repeat the operation from scratch

This approach is optimistic because it works well when validation is often successful (so we don't have to repeat operations).

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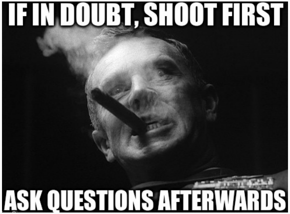
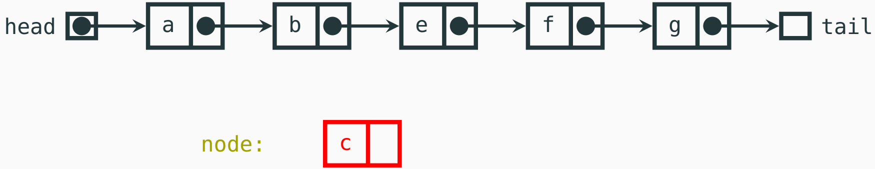


Optimistic set: method add

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public boolean add(T item) {
  Node<T> node = new ReadWriteNode<>(item);         // new node
  do { Node<T> pred, curr = find(head, item.key()); // no locking
       pred.lock(); curr.lock();                    // now lock position
       try { // if position still valid, while locked:
         if (valid(pred, curr)) { ... }    // physically add node
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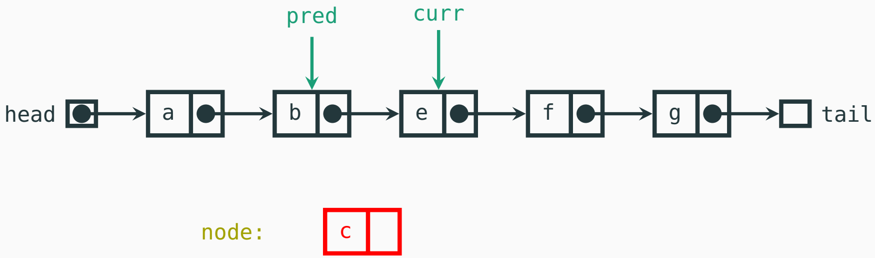


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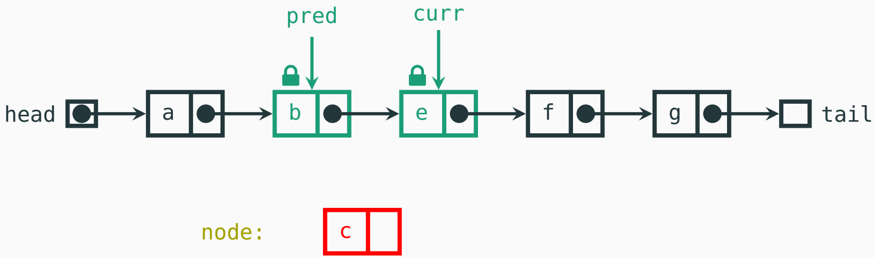


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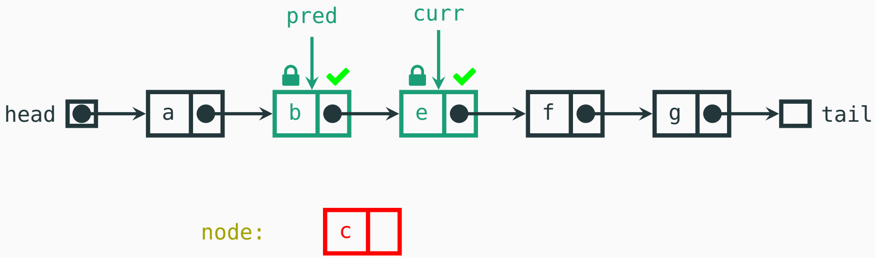


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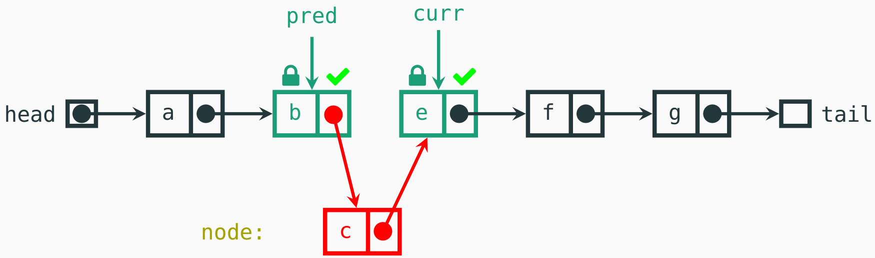


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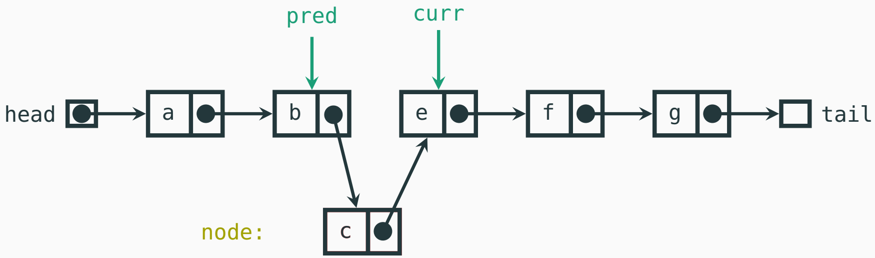


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  } while (true);                      // if not valid: try again!
}
```

Optimistic set: method `remove`


```
public boolean remove(T item) {
  do { Node<T> pred, curr = find(head, item.key()); // no locking
       pred.lock(); curr.lock();                 // now lock position
       try { // if position still valid, while locked:
         if (valid(pred, curr)) { ... } // physically remove node
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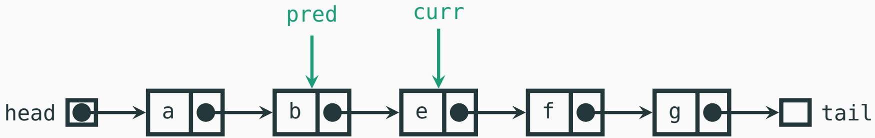


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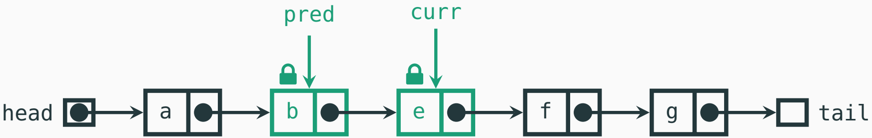


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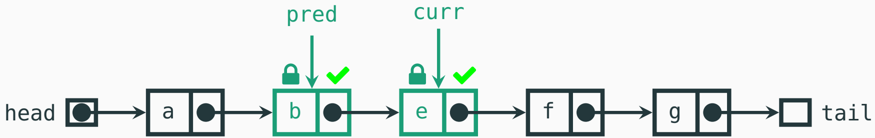


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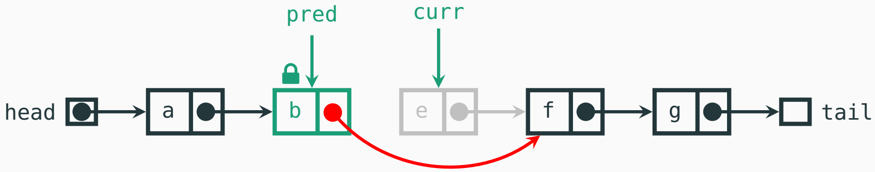


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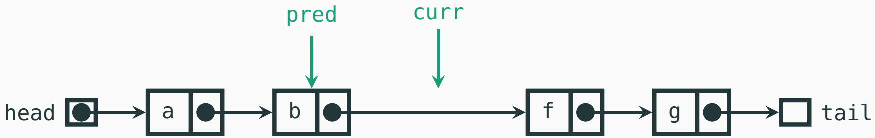


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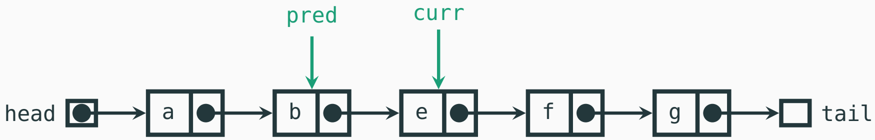


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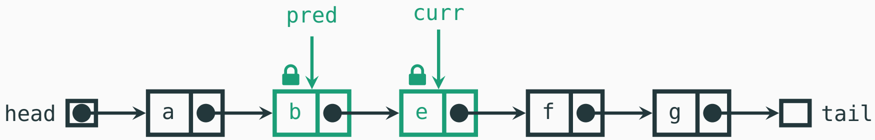


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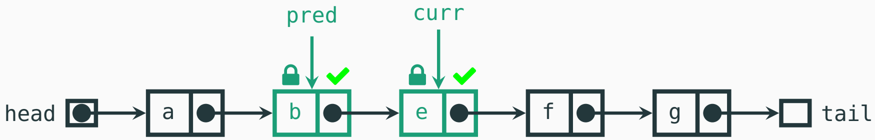


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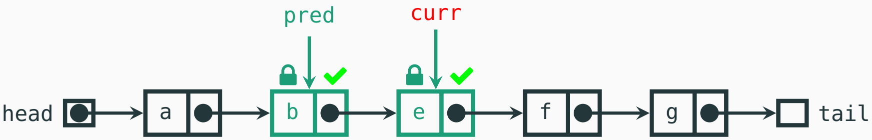


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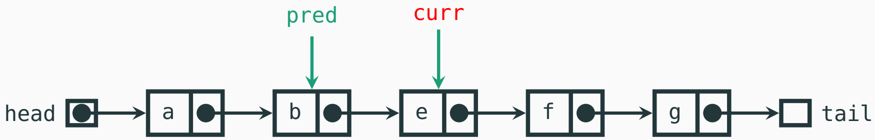


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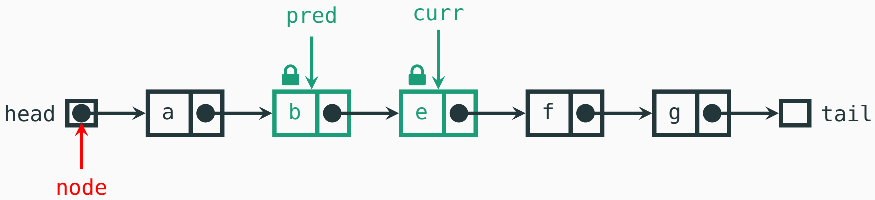
Optimistic set: validating a position

Validation goes through the nodes until it reaches the given position.

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  Node<T> node = head;  // start from head
  while (node.key() <= pred.key()) { // does pred point to curr?
    if (node == pred) return pred.next() == curr;
    node = node.next(); // continue to the next node
  } // until node.pred > pred.key
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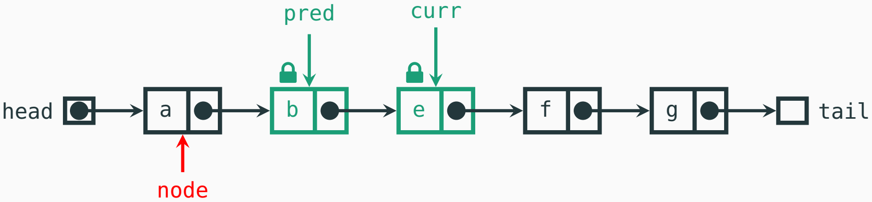


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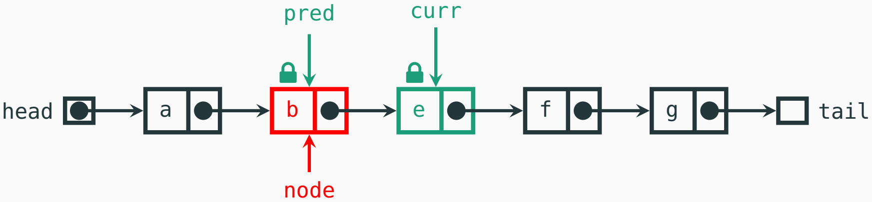


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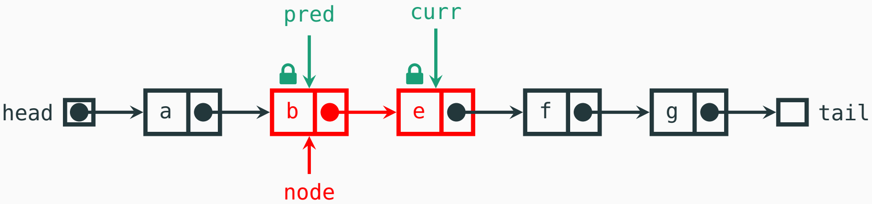


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```

How validation works

What can happen between the time when a thread finds a position `(pred, curr)` and when it locks nodes `pred` and `curr`?

- Node `pred` is removed: validation fails because `pred` is not reachable
- Node `curr` is removed: validation fails because `pred` does not point to `curr`
- A node is added between `pred` and `curr`: validation fails because `pred` does not point to `curr`
- Any other modification of the set: validation succeeds because operations leave the set in a consistent state

Is validation safe?

What happens if the set is being modified while a thread is validating a locked position `(pred, curr)`?

- If a node following `curr` is modified: validation is not affected because it only goes up until `curr`
- If a node `n` before `pred` is removed: validation succeeds even if it goes through `n`, since `n` still leads back to `pred`
- If a node `n` is added before `pred`: validation succeeds even if it skips over `n`

Optimistic-locking set: pros and cons

Pros:

- threads operating on disjoint portions of the list can operate in parallel
- when validation often succeeds, there is much less locking involved than in `FineSet`

Cons:

- `OptimisticSet` is not starvation free: a thread *t* may fail validation forever if other threads keep removing and adding `pred`/`curr` between when *t* performs `find` and when it locks `pred` and `curr`
- if traversing the list twice without locking is not significantly faster than traversing it once with locking, `OptimisticSet` does not have a clear advantage over `FineSet`

Parallel linked sets

Lazy node removal

Testing membership without locking

In many applications, the operation `has` is executed many more times than `add` and `remove`. Can `has` work correctly without locking?

Problems may occur if another thread removes `curr` between `find` and `has`'s check: since `remove` is not atomic without locking, if `has` does not acquire locks it may not notice that `curr` is being removed.

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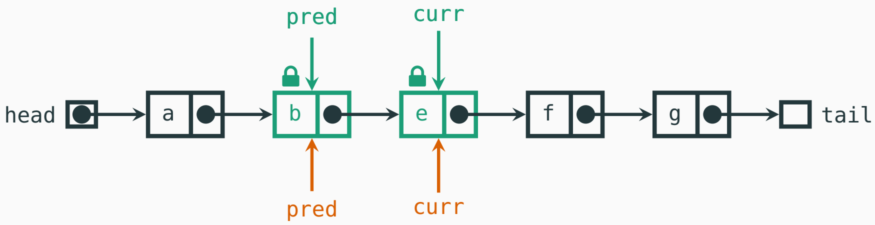
For example, if thread t runs `remove(e)` while thread u runs `has(e)` without locking, u may incorrectly think that `e` is in the list even if t is about to remove it – that is thread t is in its critical section:



Nodes in a lazy-removal set

We need a way to atomically share the information that a node is being removed, but without locking.

To this end, each node includes a flag `valid` with setters and getters:

- `valid() == true`: the node is part of the set
- `valid() == false`: the node is being (or has been) removed

```
class ValidatedNode<T> extends ReadWriteNode<T>
{
   private volatile boolean valid;

   boolean valid()    { return valid; }  // is node valid?
   void setValid()    { valid = true; }  // mark valid
   void setInvalid() { valid = false; } // mark invalid
}
```

Nodes of type `ValidatedNode` can also be locked, since `ValidatedNode` inherits from `ReadWriteNode`.

Concurrent set with lazy node removal

In a lazy set:

- Validation only needs to check the mark `valid`
- Operation `remove` marks a node invalid before removing it
- Operation `has` is lock free
- Operation `add` works as in `OptimisticSet`

```
public class LazySet<T> extends OptimisticSet<T>
{
  public LazySet() {
    head = new ValidatedNode<>(Integer.MIN_VALUE);  // smallest key
    tail = new ValidatedNode<>(Integer.MAX_VALUE);  // largest key
    head.setNext(tail);
  }

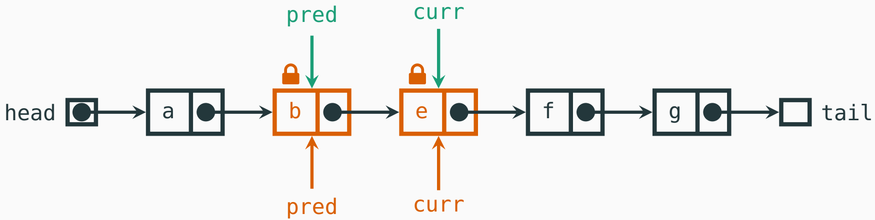
  // overriding of valid, remove, and has
```

Lazy set: validating a position

Validation becomes a constant-time operation:

- Node `pred` is reachable from the head iff it has not been removed iff it is marked valid
- Node `curr` follows `pred` in the list iff `pred.next() == curr` and `curr` is marked valid

Scenario: *t*'s validation of `curr` succeeds:

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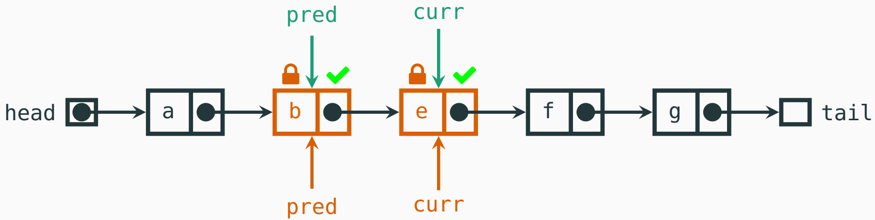


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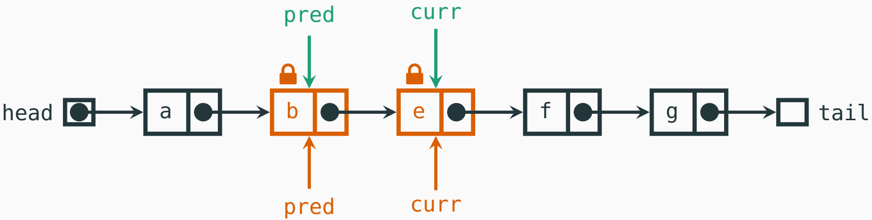


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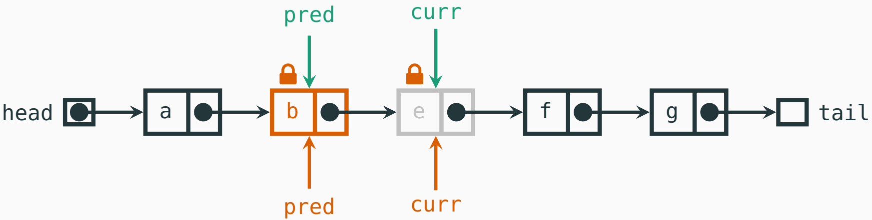


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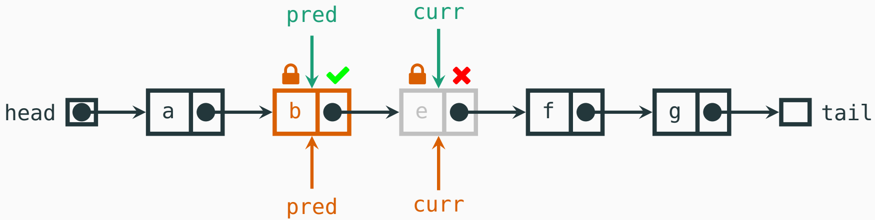


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Method `has` runs without locking: it finds the position `(pred, curr)`, validates `curr`, and checks whether `curr`'s key is equal to `item`'s.


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Method find may traverse invalid nodes; this does not prevent it from eventually reaching all valid nodes in the list.

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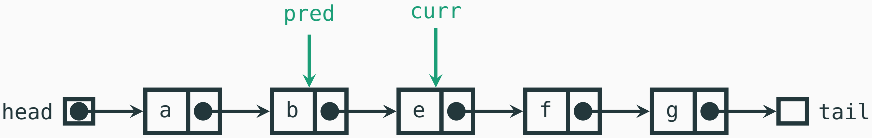


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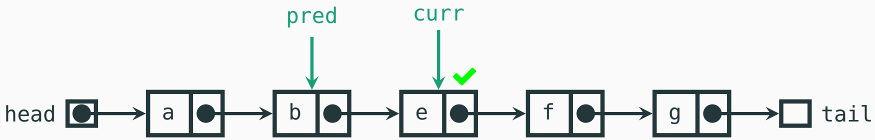


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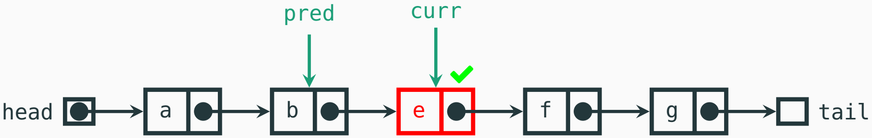


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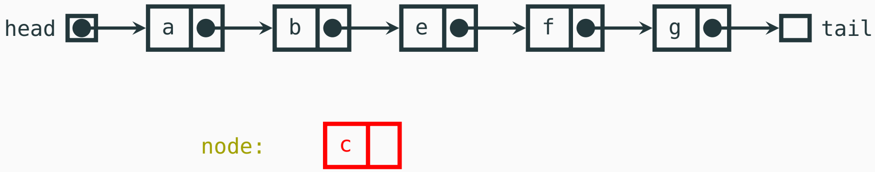

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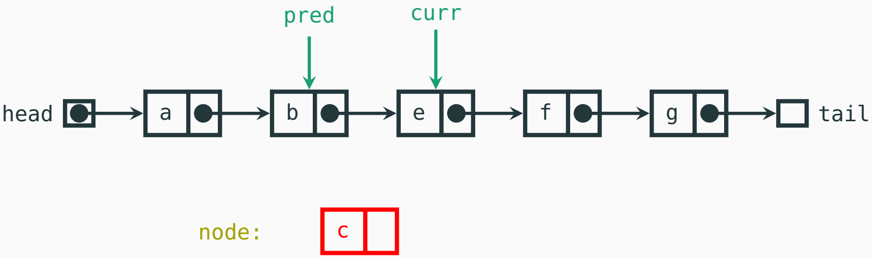

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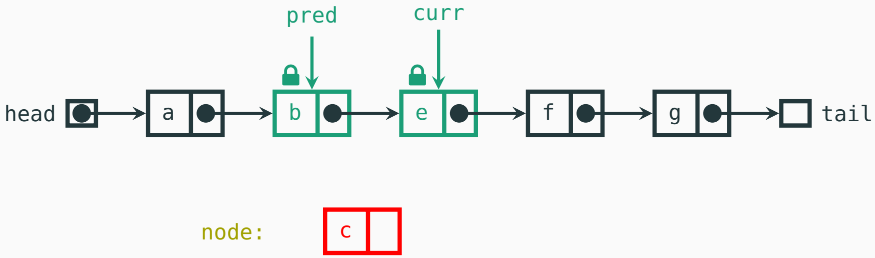

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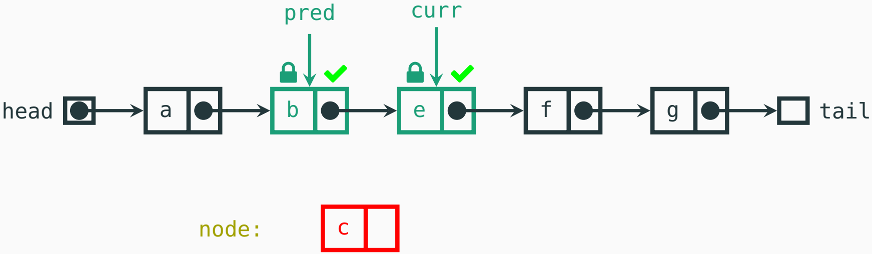

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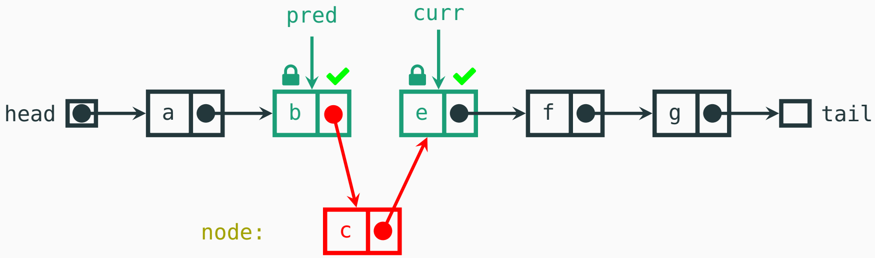

Lazy set: method `add`

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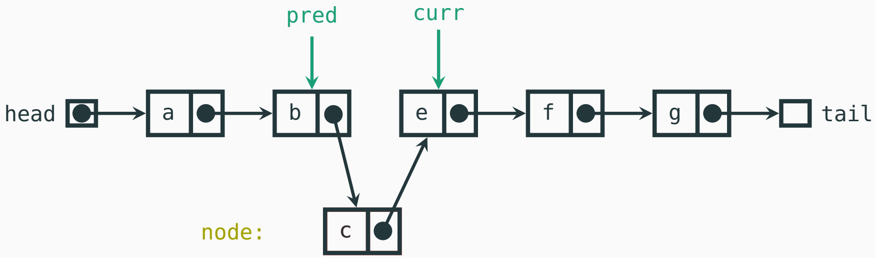

Lazy set: method `remove`

After finding the position of a node to be removed, the actual removal consists of two steps:

1. logical removal: mark the node to be removed as invalid
2. physical removal: skip over the node by redirecting its predecessor's `next`

This removal is lazy because logical and physical removal may be done at different times: after a node has been logically removed, every thread is aware that it should not be considered part of the list.

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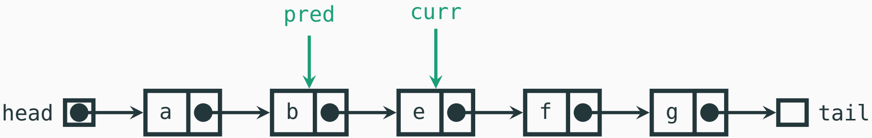

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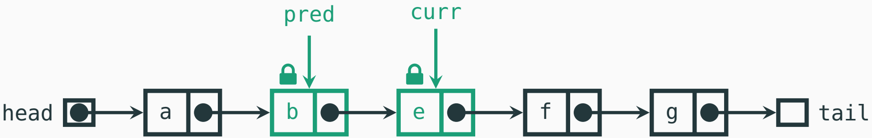

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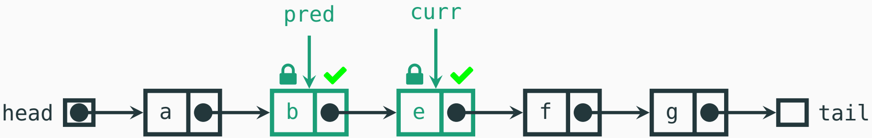

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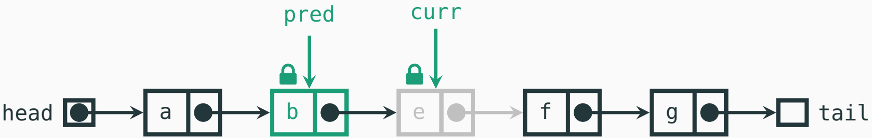

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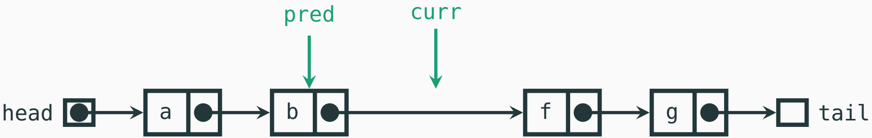

This removal is lazy because logical and physical removal may be done at different times: after a node has been logically removed, every thread is aware that it should not be considered part of the list.

Lazy set: method `remove`

```java
public boolean remove(T item) {
  do { Node<T> pred, curr = find(head, item.key()); // no locking
       pred.lock(); curr.lock();                  // now lock position
       try { // if position still valid, while locking:
         if (valid(pred, curr)) {
           if (curr.key() != item.key())
             return false;      // item not in the set
           else { // item in the set at curr: remove it
             curr.setInvalid();        // logical removal
             pred.setNext(curr.next()); // physical removal
             return true;
           }
         }
       } finally { pred.unlock(); curr.unlock(); }// done: unlock
  } while (true);                        // if not valid: try again!
}
```

Lazy-removal set: pros and cons

Pros:

- validation is constant time
- membership checking does not require any locking – it's even wait free (it traverses the list once without locking)
- physical removal of logically removed nodes could be batched and performed when convenient – thus reducing the number of times the physical chain of nodes is changed, in turn reducing the expensive propagation of information between threads

Cons:

- operations `add` and `remove` still require locking (as in `OptimisticSet`), which may reduce the amount of parallelism

Parallel linked sets

Lock-free access

Atomic references

To implement a set that is correct under concurrent access without using any locks we need to rely on synchronization primitives more powerful than just reading and writing shared variables.

We are going to use a variant of the compare-and-set operation.

```
class AtomicReference<V> {

  V get();                        // current reference
  void set(V newRef);             // set reference to newRef

  // if reference == expectRef, set to newRef and return true
  // otherwise, do not change reference and return false
  boolean compareAndSet(V expectRef, V newRef);
}
```

Atomic lock-free access: first naive attempt

As a first attempt, we make attribute `next` of type `AtomicReference<Node<T>>`, and use `compareAndSet` to update it: if one thread changes `next` when another thread is also trying to change it, we repeat the operation.

An implementation of `remove()` following this idea:

```
public boolean remove(T item) {
  boolean done;
  do {
    Node<T> pred, curr = find(head, item.key());
    if (curr.key() >= item.key()) return false;  // item not in set
    else
      // try to remove curr by setting pred.next using compareAndSet
      done = pred.next().compareAndSet(pred.next(), curr.next());
  } while (!done); return true;
}
```

`pred.next` may have changed when `compareAndSet()` executes

Atomic lock-free access: first naive attempt

Unfortunately, the first attempt does not work: for example, if thread *t* runs `remove(e)` while thread *u* runs `remove(b)`, it may happen that only `b`'s removal takes place.

We have seen a similar problem before: modifications of the list need to have control of both `pred` and `curr` – even if it is only the former node that is actually modified.

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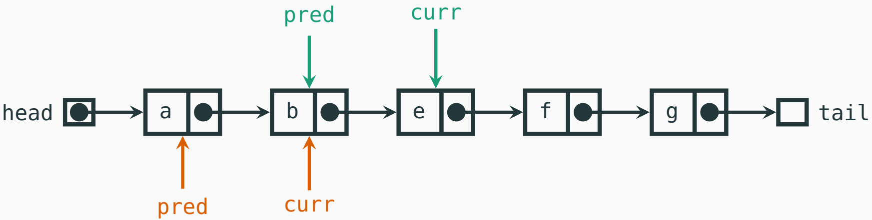

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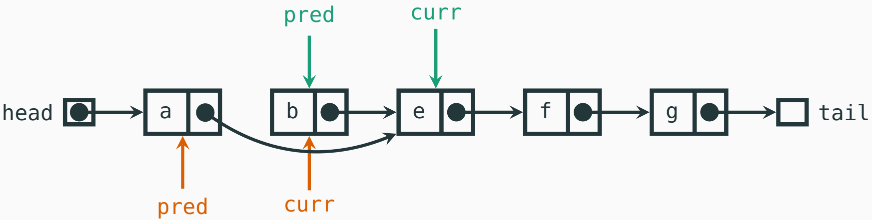

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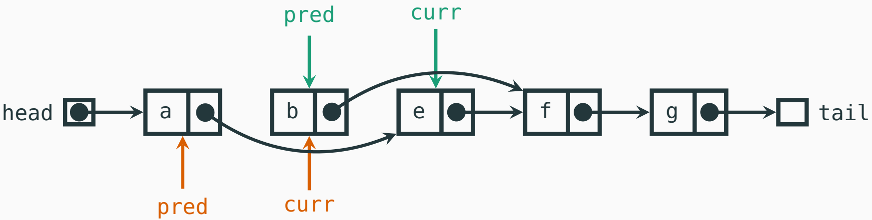

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Atomic markable references

As in `LazySet`, nodes can be marked valid or invalid; an invalid node is logically removed. In addition, we need to access the information of both attributes `valid` and `next` atomically; to this end, every node includes an attribute `nextValid` of type `AtomicMarkableReference<Node<T>>`, which provides methods to both update a reference and a mark it, atomically.

```
class AtomicMarkableReference<V> {
  V, boolean get();           // current reference and mark
   // if reference == expectRef set mark to newMark and return true
   // otherwise do not change anything and return false
  boolean attemptMark(V expectRef, boolean newMark);
   // if reference == expectRef and mark == expectMark,
   // set reference to newRef, mark to newMark and return true;
   // otherwise, do not change anything and return false
  boolean compareAndSet(V expectRef, V newRef,
                        boolean expectMark, boolean newMark);
}
```

Nodes in a lock-free set

Every node includes an attribute `nextValid` of type `AtomicMarkableReference<Node<T>>`. The node interface provides methods to retrieve and conditionally update the current value of `nextValid`, which includes a reference (corresponding to `next`) and a mark (corresponding to `valid`).

```
class LockFreeNode<T> extends SequentialNode<T> {

  // reference to next node and validity mark of current node
  private AtomicMarkableReference<Node<T>> nextValid;

  // return next and valid as a pair
  Node<T>, boolean nextValid() { return nextValid.get(); }

  Node<T> next()
   { Node<T> next, boolean valid = nextValid(); return next; }
  boolean valid()
   { Node<T> next, boolean valid = nextValid(); return valid; }
```

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```
class LockFreeNode<T> extends SequentialNode<T> {

  // try to set invalid; return true if successful
 boolean setInvalid()
  { Node<T> next = next();
    return nextValid.compareAndSet(next, next, true, false); }

  // try to update to newNext if valid; return true if successful
 boolean setNextIfValid(Node<T> expectNext, Node<T> newNext)
  { return nextValid.compareAndSet(expectNext, newNext, true, true); }
```

update `next` only if the node is valid

Concurrent set with lock-free access

In a lock-free set:

- Operation `remove` marks a node invalid before removing it
- Operations that modify nodes complete successfully only if the nodes are valid and not concurrently modified by another thread
- Failed operations are repeated until success (no interference)

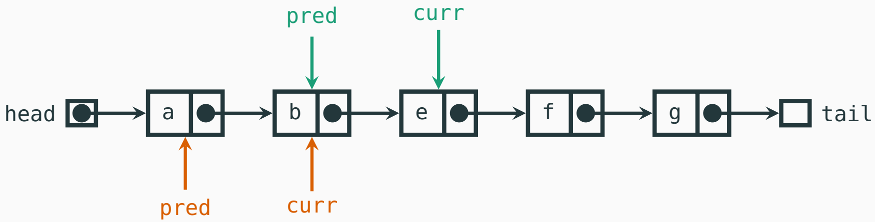
```
public class LockFreeSet<T> extends SequentialSet<T>
{
  public LockFreeSet() {
    head = new LockFreeNode<>(Integer.MIN_VALUE);  // smallest key
    tail = new LockFreeNode<>(Integer.MAX_VALUE);  // largest key
    head.setNext(tail);  // unconditionally set next
                         // only in new nodes
  }

  // overriding of all methods
```

Lock-free set: method `remove`


```java
public boolean remove(T item) {
  do { Node<T> pred, curr = find(head, item.key()); // not in set
       if (curr.key() != item.key() || !curr.valid()) return false;
        // try to invalidate; try again if node is being modified
       if (!curr.setInvalid()) continue;
        // try once to physically remove curr
       pred.setNextIfValid(curr, curr.next());
       return true;
  } while (true);  // changed during logical removal: try again!
}
```

Lock-free set: method `remove`

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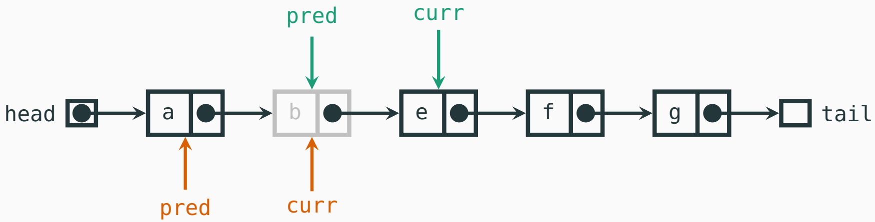


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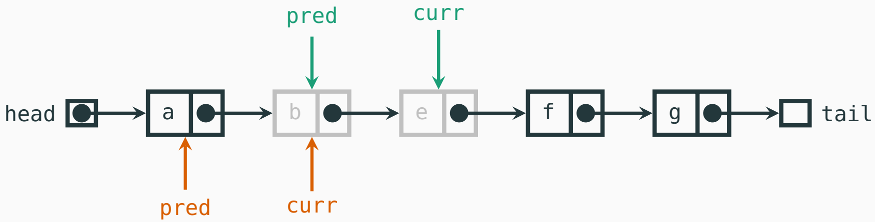


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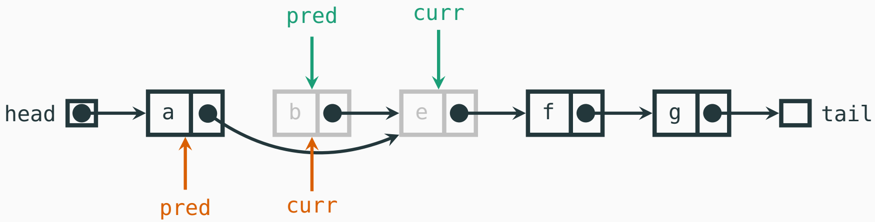


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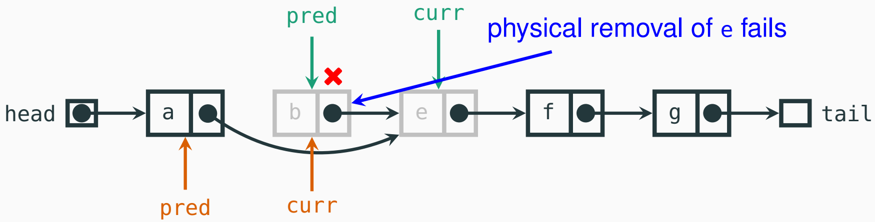


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physical removal of e fails: never mind!

Lock-free set: method `remove`


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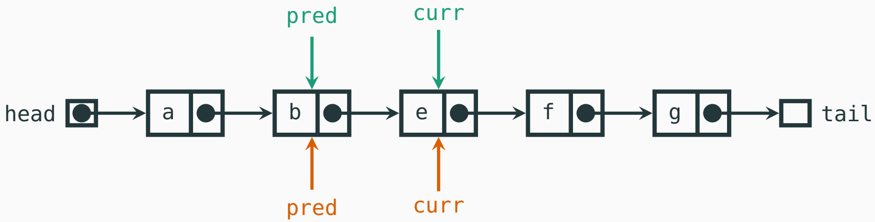


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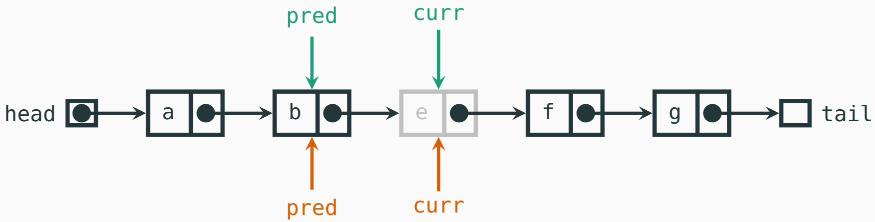


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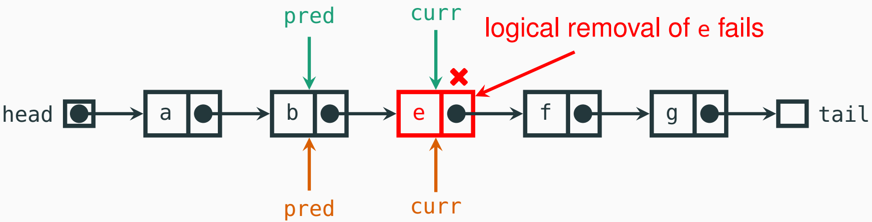


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        // try once to physically remove curr
       pred.setNextIfValid(curr, curr.next());
       return true;
  } while (true);  // changed during logical removal: try again!
}
```

logical removal of e fails: retry!

Lock-free set: method `remove`


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public boolean remove(T item) {
  do { Node<T> pred, curr = find(head, item.key()); // not in set
       if (curr.key() != item.key() || !curr.valid()) return false;
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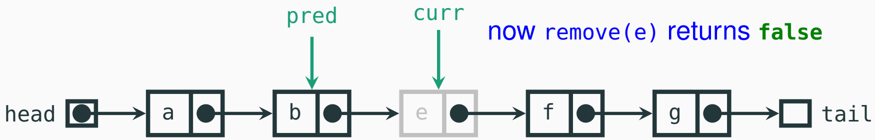

now `remove(e)` returns **`false`**

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Logical removal: only one thread succeeds

If two threads both try to mark a node invalid, only one can succeed – so it is guaranteed that no other thread is touching the node.

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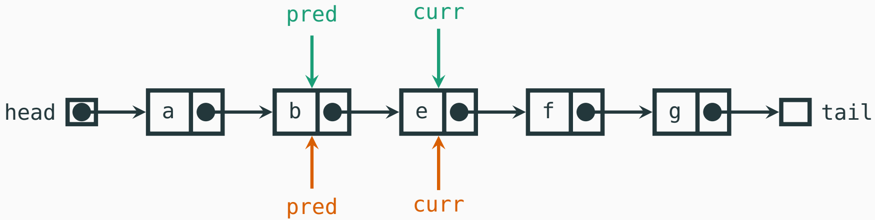

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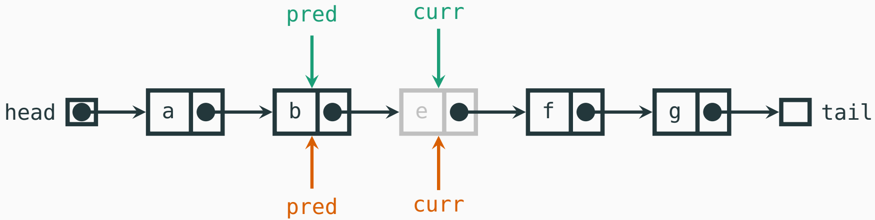

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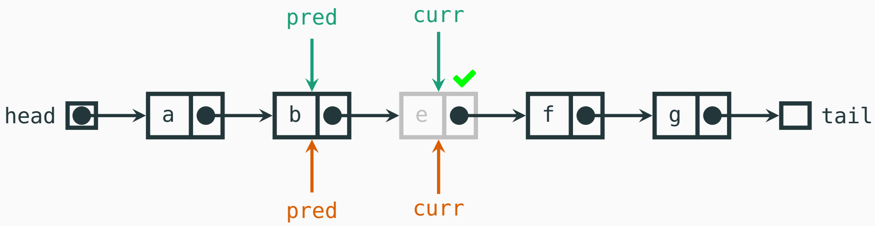

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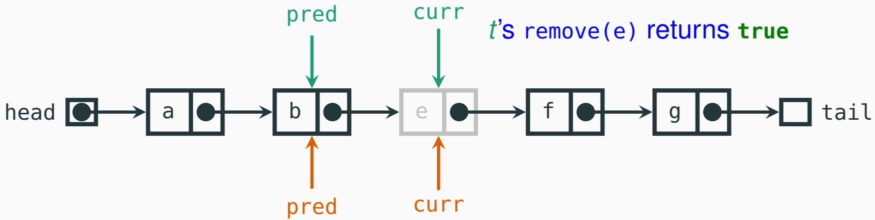

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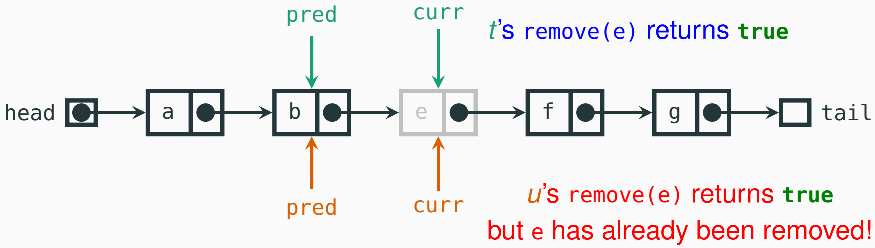
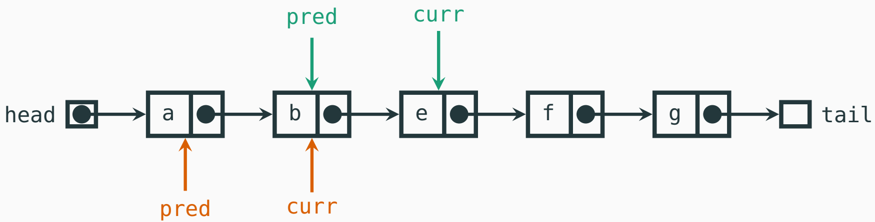


Lock-free set: method add


```
public boolean add(T item) {
  do { Node<T> pred, curr = find(head, item.key()); // already in set
       if (curr.key() == item.key() && curr.valid()) return false;
       // new node, pointing to curr
       Node<T> node = new LockFreeNode<>(item).setNext(curr);
       // if pred valid and points to curr, make it point to node
       if (pred.setNextIfValid(curr, node)) return true;
  } while (true);  // pred changed during add: try again!
}
```

Lock-free set: method add

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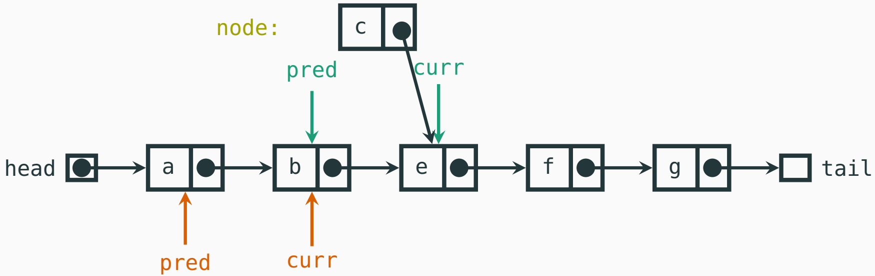


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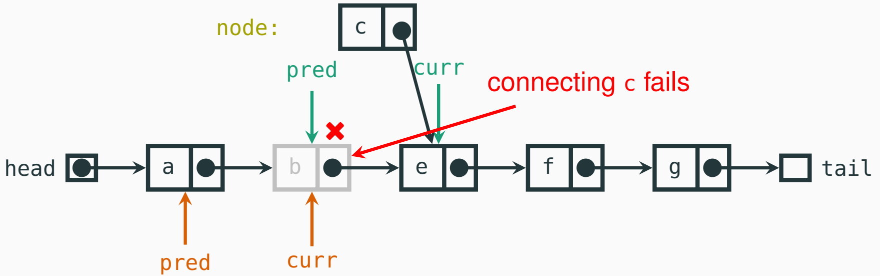
Lock-free set: method add

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      if (curr.key() == item.key() && curr.valid()) return false;
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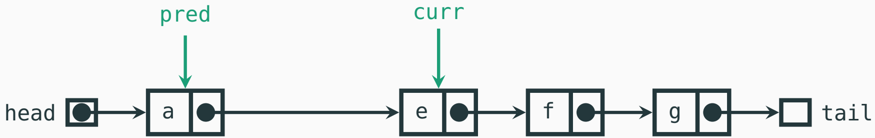


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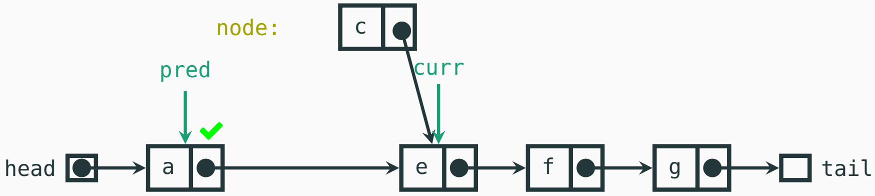


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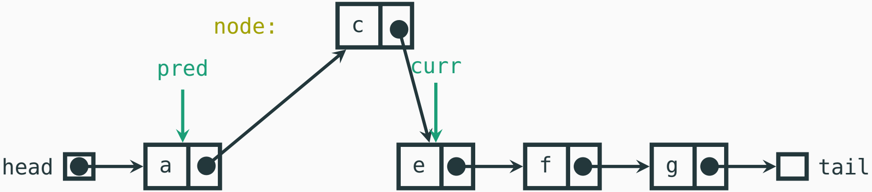


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Lock-free set: method `has`

Method `has` works as in `LazySet`: it finds the position `(pred, curr)`, validates `curr`, and checks whether `curr`'s key is equal to `item`'s. Unlike `add` and `remove` (which use a new version of `find`), `has` traverses both valid and invalid nodes, and makes no attempt at removing the latter.


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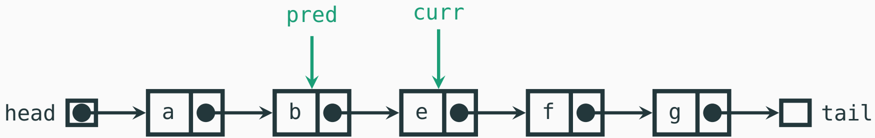


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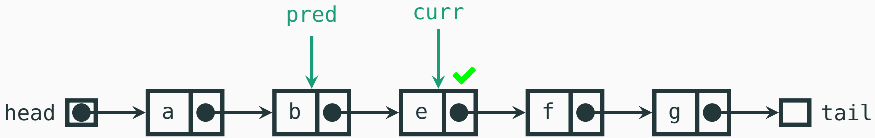


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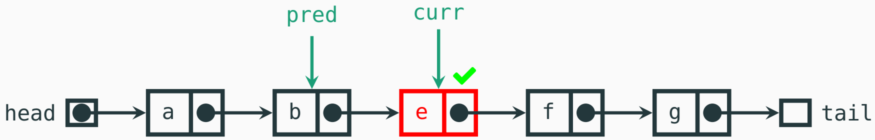


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When to physically remove nodes?

Method `has` does not modify the set, so it can safely traverse valid and invalid nodes without changing the node structure.

In contrast, methods `add` and `remove` physically remove all logically removed nodes encountered by `find`. This is a convenient time to perform physical removal, because it avoids the buildup of long chains of invalid nodes.

For example, the logical removal of nodes `f` and `g` requires thread *t* to physically remove `f` before it can physically remove `g`:

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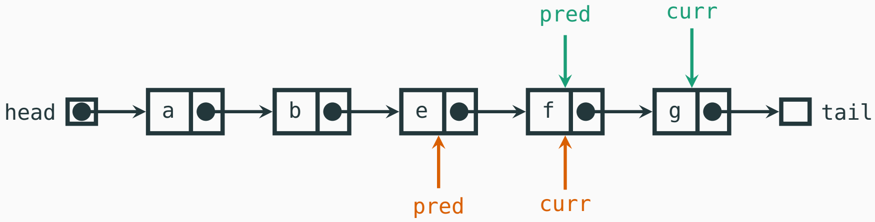

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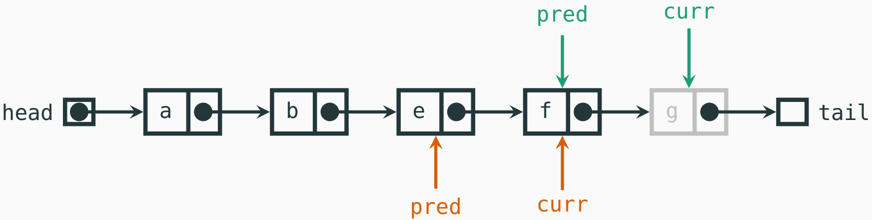

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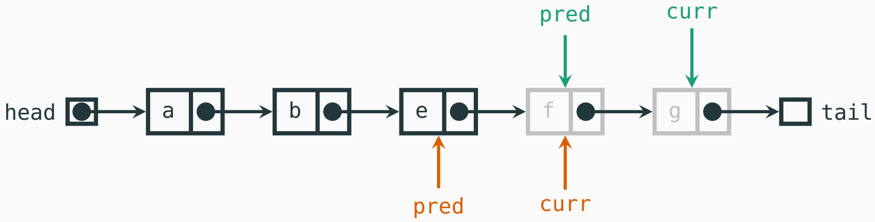

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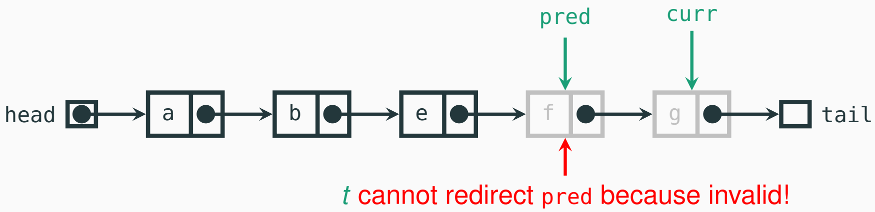

Lock-free set: how `find` works

A run of `find(k)` that also physically removes three invalid nodes.

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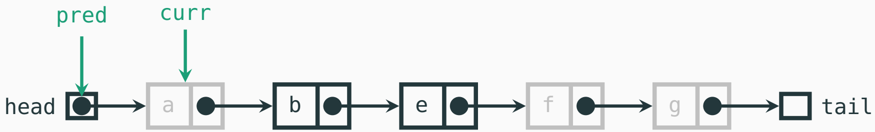

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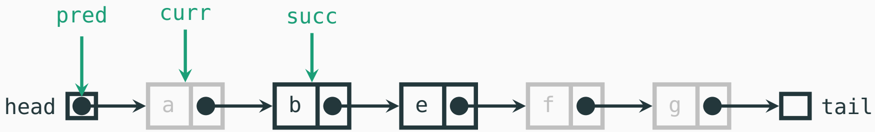

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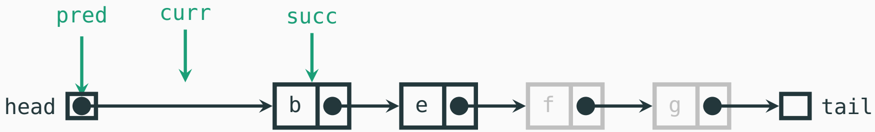

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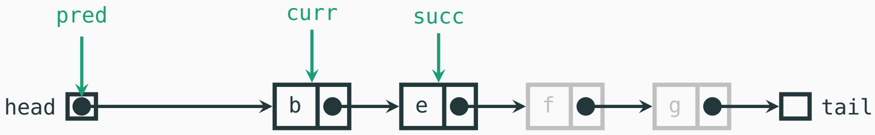

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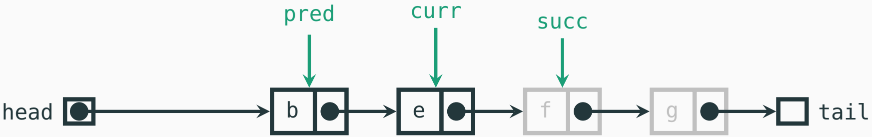

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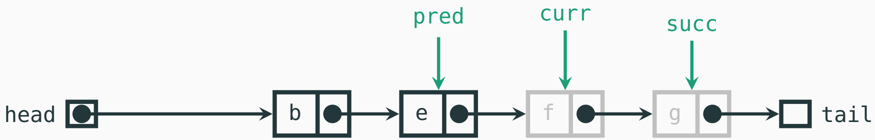

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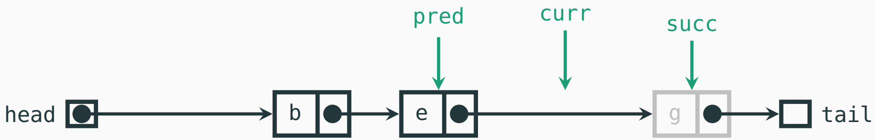

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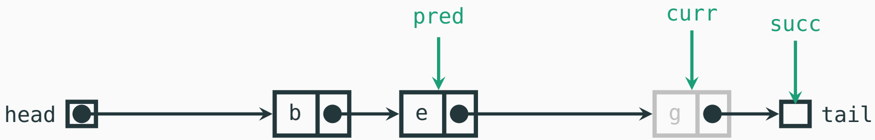

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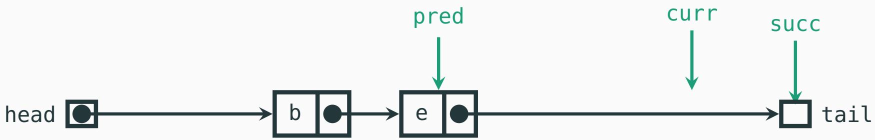

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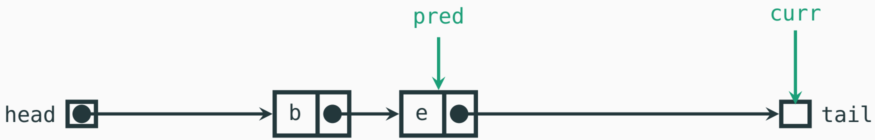

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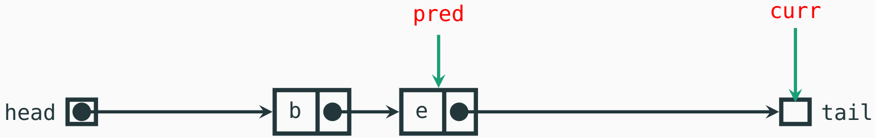

Lock-free set: how `find` works

A run of `find(k)` that also physically removes three invalid nodes.

Threads may interfere with `find`, requiring to restart it; in the worst case, starvation may occur with a thread continuously restarting `find` while others make progress modifying the list.

Lock-free set: method `find`

```
protected Node<T>, Node<T> find(Node<T> start, int key) {
  boolean valid;              // is curr valid?
  Node<T> pred, curr, succ;   // consecutive nodes in iteration
  retry: do {
    pred = start; curr = start.next();  // from start node
    do {  // succ is curr's successor; valid is curr's validity
      succ, valid = curr.nextValid();
      while (!valid) { // while curr is not valid, try to remove it
          // if pred is modified while trying to redirect it, retry
        if (!pred.setNextIfValid(curr, succ)) continue retry;
          // curr has been physically removed: move to next node
        curr = succ; succ, valid = curr.nextValid();
      } // now curr is valid (and so is pred)
      if (curr.key() >= key) return (pred, curr);
      pred = curr; curr = succ;   // continue search
    } while (true);
  } while (true);
```

Lock-free set: pros and cons

Pros:

- no operations require locking: maximum potential for parallelism
- membership checking does not require any locking – it's even wait free (it traverses the list once without locking)

Cons:

- the implementation needs test-and-set-like synchronization primitives, which have to be supported and come with their own performance costs
- operations `add` and `remove` are lock free but not wait free: they may have to repeat operations, and they may be delayed while they physically remove invalid nodes, with the risk of introducing contention on nodes that have been already previously logically deleted

To lock or not to lock?

Each of the different implementations of concurrent set is the best choice for certain applications and not for others:

- `CoarseSet` works well with low contention
- `FineSet` works well when threads tend to access the list orderly
- `OptimisticSet` works well to let threads operate on disjoint portions of the list
- `LazySet` works well when batching invalid node removal is convenient
- `LockFreeSet` works well when locking is quite expensive

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