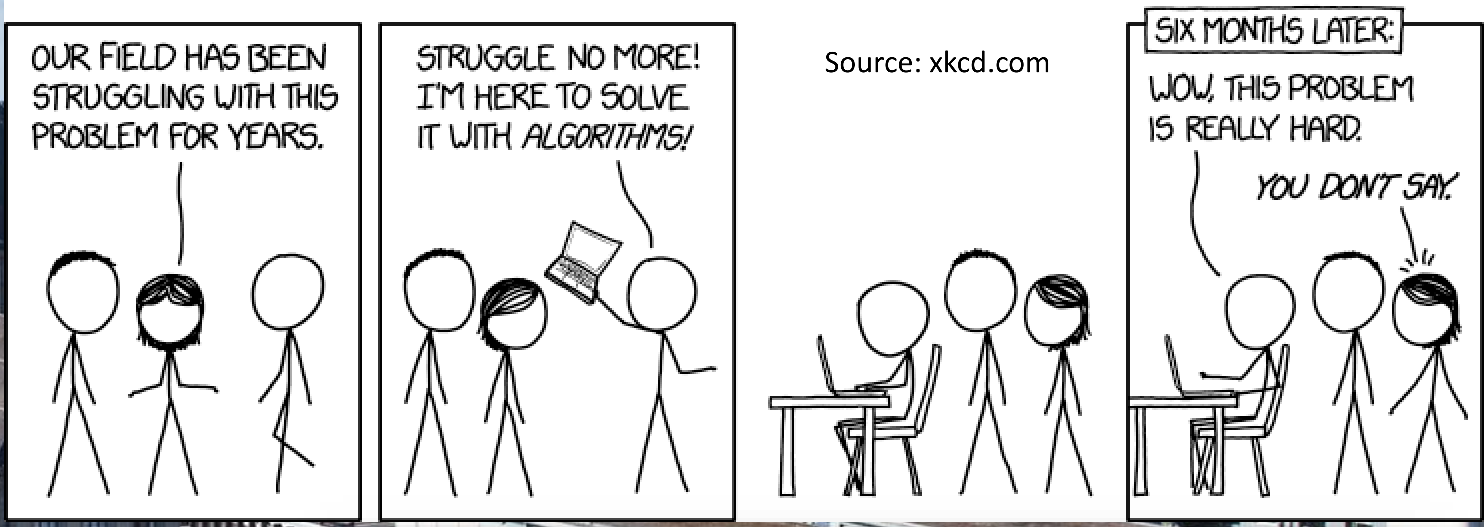
TORSTEN HOEFLER

Parallel Programming
Readers/Writers Lock, Lock Granularity: Coarse Grained, Fine Grained, Optimal, and Lazy Synchronization



Source: xkcd.com

18 Apr 2019 | 19:49 GMT

How the Boeing 737 Max Disaster Looks to a Software Developer

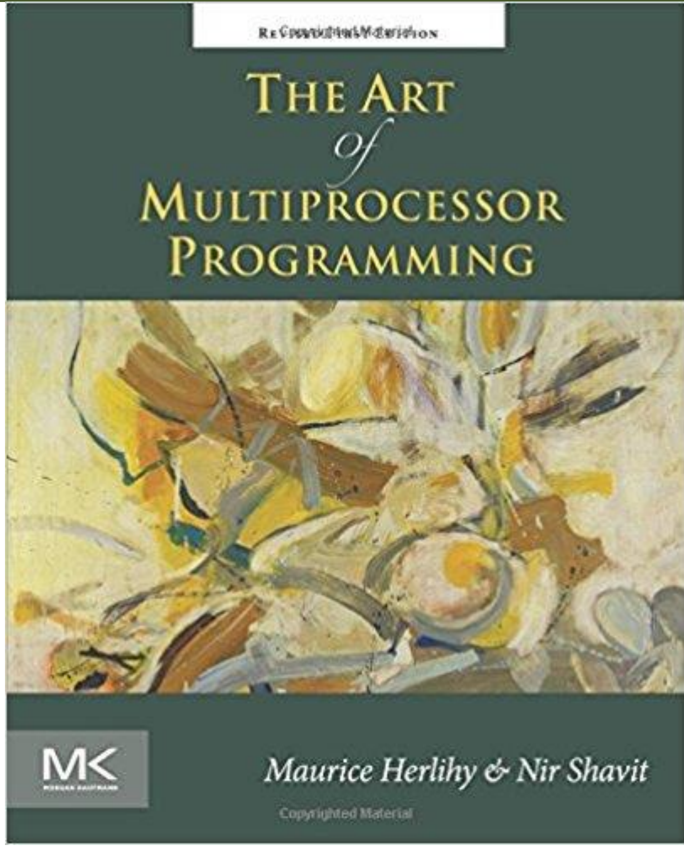
Design shortcuts meant to make a new plane seem like an old, familiar one are to blame

By **Gregory Travis**

SPCL

Administrivia

- **Book for (the second part of) the lecture series:**
  - Herlihy & Shavit: The Art of Multiprocessor Programming
    Contains more concepts (e.g., linearizability) than we use here!



- **Locking objects – terminology clarification**
  - When we say "we lock an object" then I mean "we acquire the lock associated with the object" – data cannot be locked directly in Java (cf. advisory filesystem locks)

- **Starvation-freedom:**
  - *every* thread that tries to make progress, makes progress *eventually*

Last ~~week~~ time

- **Deadlock**
  - Cause (cyclic dependencies)
  - Avoidance (acquire resources in global order)
- **Semaphores**
  - Generalization of locks, can count (enables producer/consumer)
- **Barriers**
  - Multi-process synchronization, important in parallel programming
  - More examples for complexity of parallel programming (trial and error impossible)
- **Producer/Consumer in detail**
  - Queues, implementation
- **Monitors**
  - Condition variables, wait, signal, etc. (continued today)

Learning goals today

- **Finish condition variables and interface locks**
  - Producer-consumer examples

- **More on locks (essentially a bag of tricks)**
  - Reader/writer
  - Coarse-grained vs. fine-grained
  - Optimistic synchronization
  - Lazy synchronization

- **Conflict-minimizing structures**
  - Example: skip lists

Producer / Consumer queues

```
public synchronized void enqueue(long item) {
      while (isFull())
         ; // wait
      doEnqueue(item);
}
```

```
public void doEnqueue(long item) {
  buffer[in] = item;
  in = next(in);
}
public boolean isFull() {
  return (in+1) % size == out;
}
```

```
public synchronized long dequeue() {
      while (isEmpty())
         ; // wait
      return doDequeue();
}
```

```
public long doDequeue() {
  long item = buffer[out];
  out = next(out);
  return item;
}
public boolean isEmpty() {
  return in == out;
}
```

Do you see the problem?

→ **Blocks forever**

infinite loops with a lock held …

Producer / Consumer queues using sleep()

```
public void enqueue(long item) throws InterruptedException {
  while (true) {
    synchronized(this) {
      if (!isFull()) {
        doEnqueue(item);
        return;
      }
    }
    Thread.sleep(timeout); // sleep without lock!
  }
}
```

What is the proper value for the timeout?
Ideally we would like to be notified when the change happens!
When is that?

Producer / Consumer queues with semaphores

```
import java.util.concurrent.Semaphore;

class Queue {
    int in, out, size;
    long buf[];
    Semaphore nonEmpty, nonFull, manipulation;

    Queue(int s) {
        size = s;
        buf = new long[size];
        in = out = 0;
        nonEmpty = new Semaphore(0); // use the counting feature of semaphores!
        nonFull = new Semaphore(size); // use the counting feature of semaphores!
        manipulation = new Semaphore(1); // binary semaphore
    }
}
```

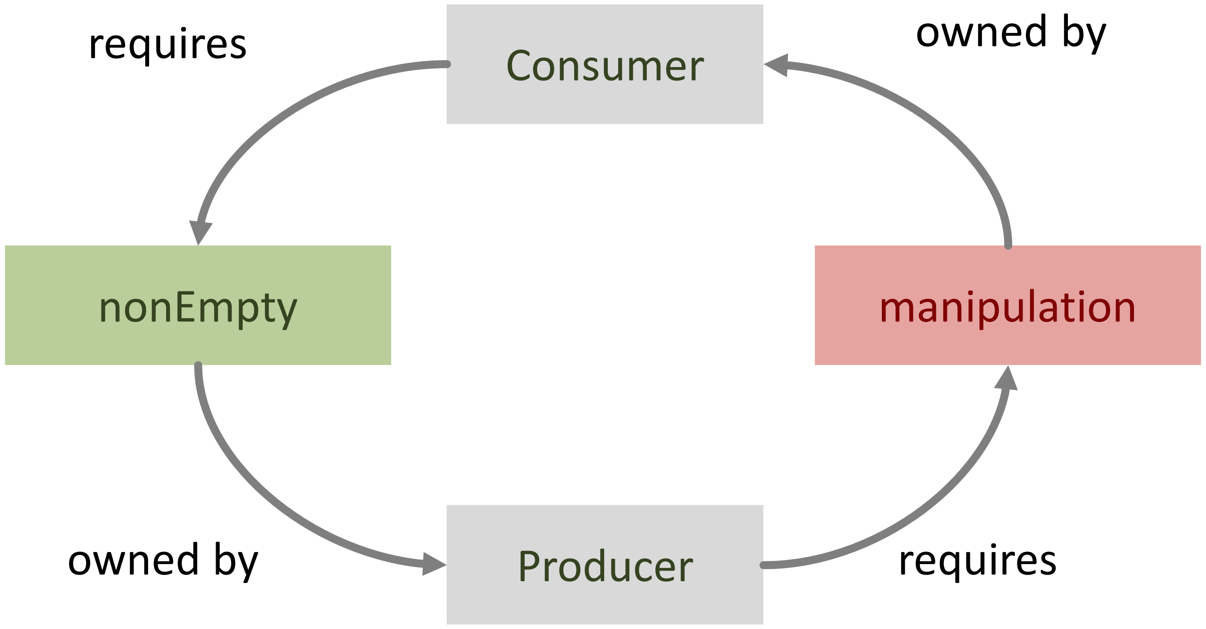
Producer / Consumer queues with semaphores, correct?

Do you see the problem?

```
void enqueue(long x) {

    try {
        manipulation.acquire();
        nonFull.acquire();
        buf[in] = x;
        in = (in+1) % size;
    }
    catch (InterruptedException ex) {}
    finally {
        manipulation.release();
        nonEmpty.release();
    }
}
```

```
long dequeue() {
    long x=0;
    try {
        manipulation.acquire();
        nonEmpty.acquire();
        x = buf[out];
        out = (out+1) % size;
    }
    catch (InterruptedException ex) {}
    finally {
        manipulation.release();
        nonFull.release();
    }
    return x;
}
```

Deadlock (nearly the same as before, actually)!



Producer / Consumer queues with semaphores

```
void enqueue(long x) {

    try {
        nonFull.acquire();
        manipulation.acquire();
        buf[in] = x;
        in = next(in);
    }
    catch (InterruptedException ex) {}
    finally {
        manipulation.release();
        nonEmpty.release();
    }
}
```

```
long dequeue() {
    long x=0;
    try {
        nonEmpty.acquire();
        manipulation.acquire();
        x = buf[out];
        out = next(out);
    }
    catch (InterruptedException ex) {}
    finally {
        manipulation.release();
        nonFull.release();
    }
    return x;
}
```

Why are semaphores (and locks) problematic?

Semaphores are unstructured. Correct use requires high level of discipline.

Easy to introduce deadlocks with semaphores.

We need: a lock that we can temporarily escape from when waiting on a condition.

Monitors

Monitors

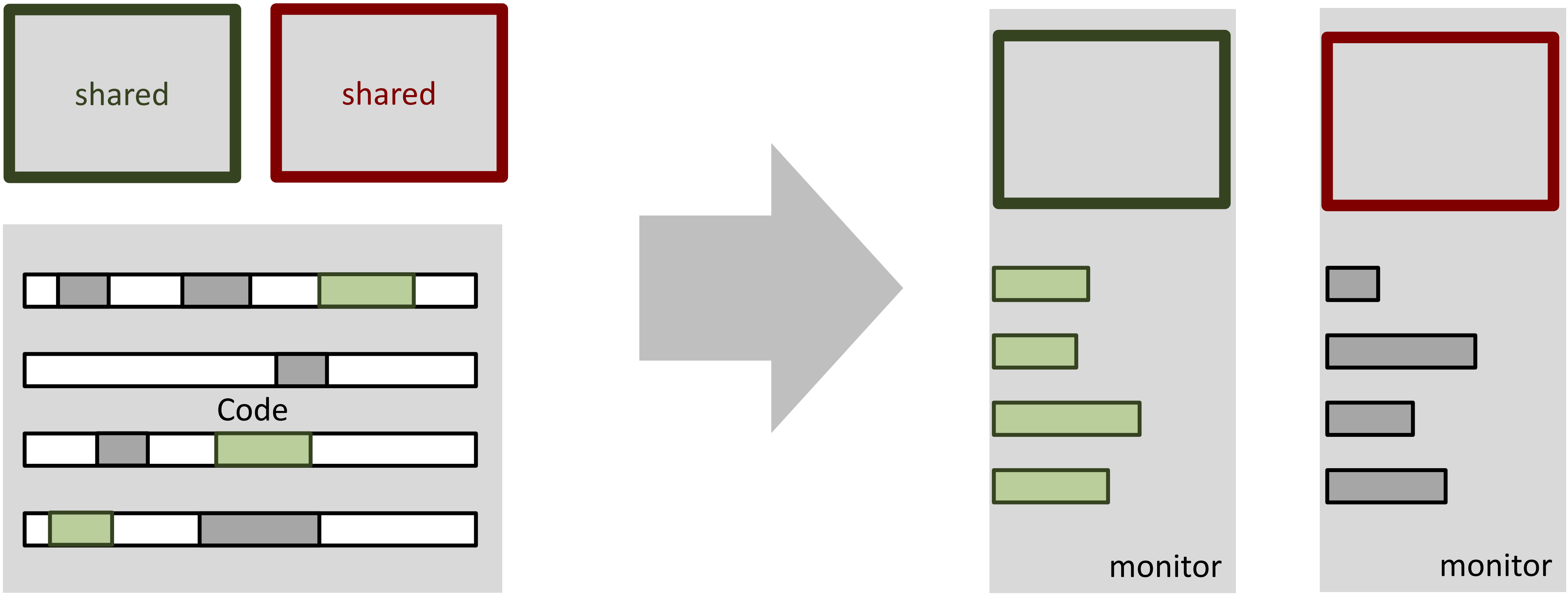
Monitor:
abstract data structure equipped with a set of operations that run in mutual exclusion.

Invented by Tony Hoare and Per Brinch Hansen (cf. Monitors: An Operating System Structuring Concept, Tony Hoare, 1974)

Tony Hoare
(1934-today)

Per Brinch Hansen
(1938-2007)

Monitors vs. Semaphores/Unbound Locks



Producer / Consumer queues

```
public void synchronized enqueue(long item) {
   "while (isFull()) wait"
   doEnqueue(item);
}
```

```
public long synchronized dequeue() {
   "while (isEmpty()) wait"
   return doDequeue();
}
```

The mutual exclusion part is nicely available already.
But: while the buffer is full we need to give up the lock, how?

Monitors

Monitors provide, in addition to mutual exclusion, a mechanism to check conditions with the following semantics:

If a condition does not hold

- Release the monitor lock
- Wait for the condition to become true
- Signaling mechanism to avoid busy-loops (spinning)

Monitors in Java

Uses the intrinsic lock (`synchronized`) of an object

+ `wait / notify / notifyAll`:

`wait()` – the current thread waits until it is signaled (via notify)

`notify()` – wakes up *one* waiting thread (an arbitrary one)

`notifyAll()` – wakes up *all* waiting threads

Producer / Consumer with monitor in Java

```
class Queue {
      int in, out, size;
      long buf[];

      Queue(int s) {
            size = s;
            buf = new long[size];
            in = out = 0;
      }
      ...
}
```

Producer / Consumer with monitor in Java

```
synchronized void enqueue(long x) {

    while (isFull())
        try {
            wait();
        } catch (InterruptedException e) { }
    doEnqueue(x);
    notifyAll();
}
```

```
synchronized long dequeue() {
    long x;
    while (isEmpty())
        try {
            wait();
        } catch (InterruptedException e) { }
    x = doDequeue();
    notifyAll();
    return x;
}
```

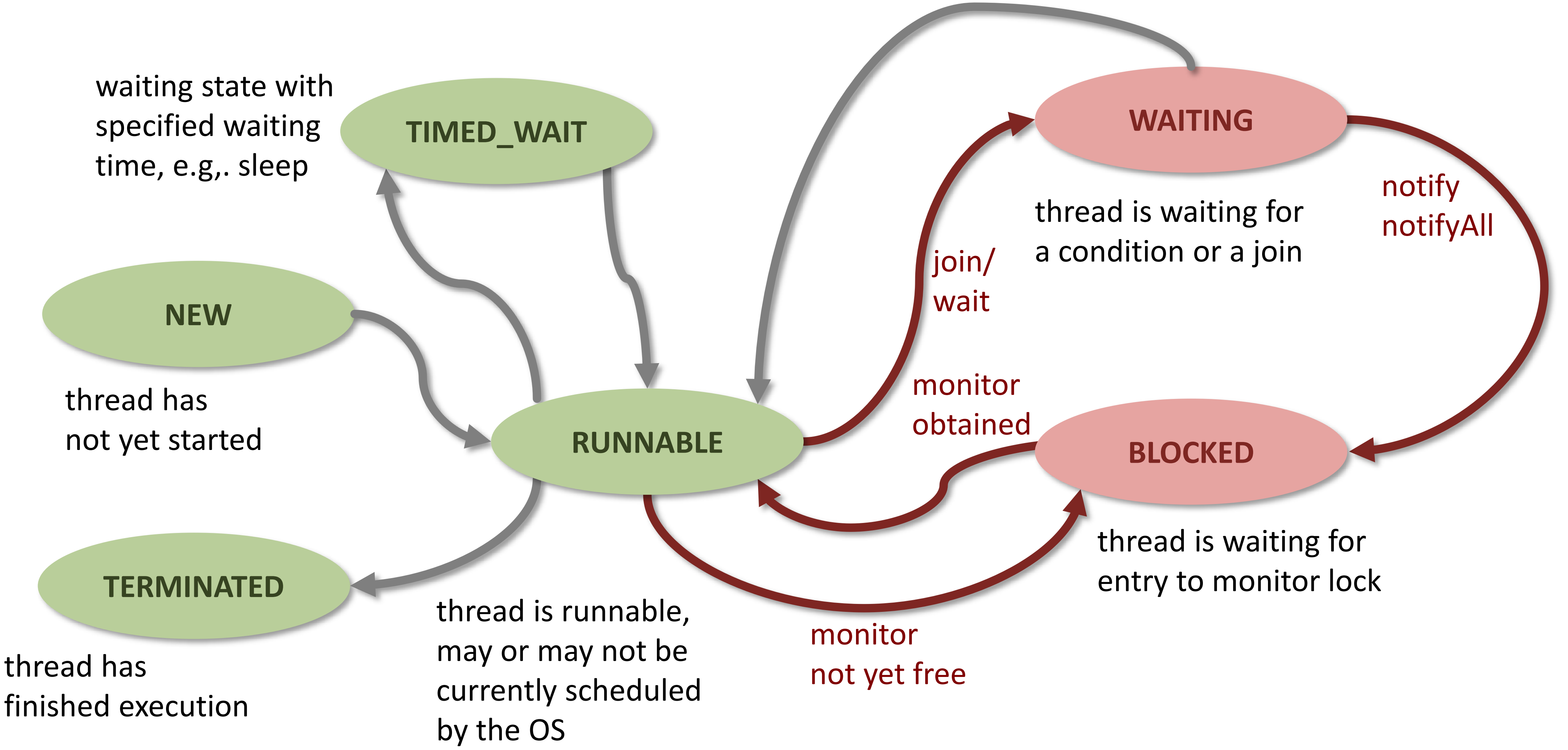
Wouldn't an if be sufficient?

(Why) can't we use notify()?

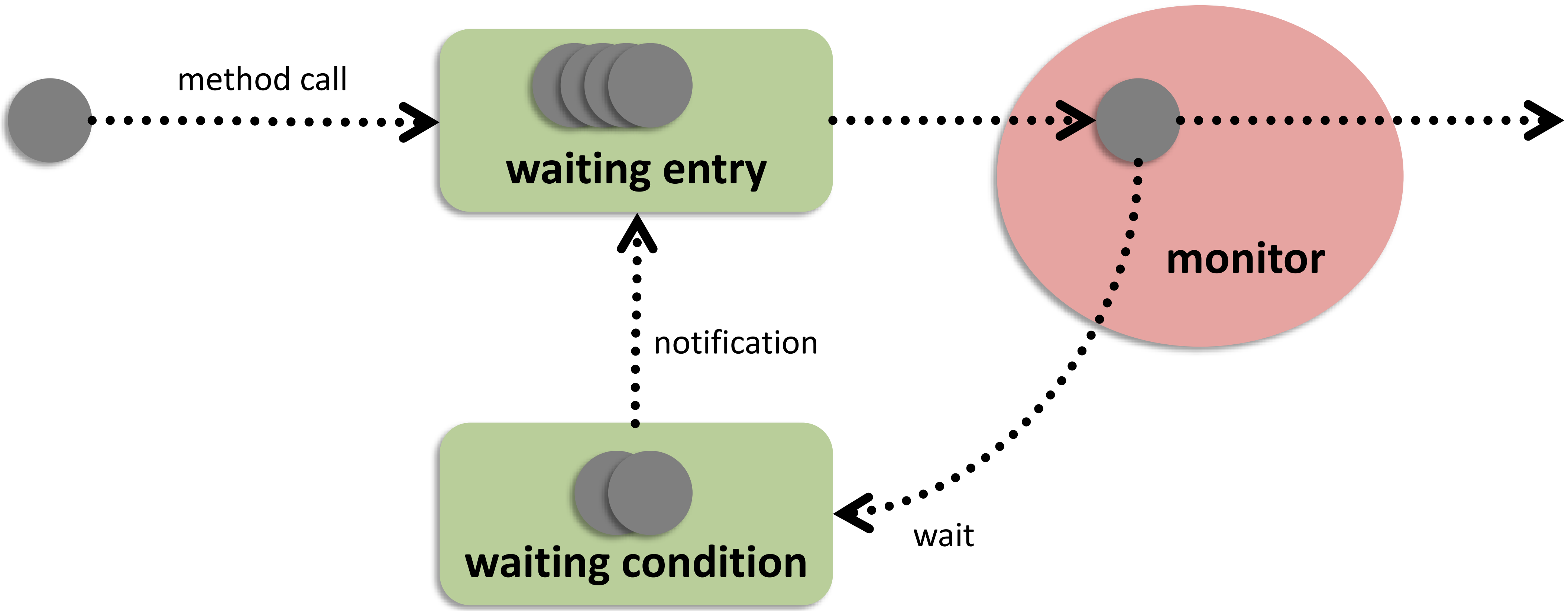
IMPORTANT TO KNOW JAVA MONITOR IMPLEMENTATION DETAILS

Thread States in Java

> ## Spaced repetition
> From Wikipedia, the free encyclopedia
>
> **Spaced repetition** is a learning technique that incorporates increasing intervals of time between subsequent review of previously learned material in order to exploit the psychological spacing effect. Alternative names include *spaced rehearsal*, *expanding rehearsal*, *graduated intervals*, *repetition spacing*, *repetition scheduling*, *spaced retrieval* and *expanded retrieval*.[1]



Monitor Queues



Various (exact) semantics possible

Important to know for the programmer (you): what happens upon notification? Priorities?

signal and wait

- signaling process exits the monitor (goes to waiting entry queue)
- signaling process passes monitor lock to signaled process

signal and continue

- signaling process continues running
- signaling process moves signaled process to waiting entry queue

other semantics: signal and exit, signal and urgent wait …

Why is this important? Let's try this implementing a semaphore:

```
class Semaphore {
   int number = 1; // number of threads allowed in critical section

   synchronized void acquire() {
      if (number <= 0)
         try { wait();   } catch (InterruptedException e) { };
      number--;
   }

   synchronized void release() {
      number++;
      if (number > 0)
         notify();
   }
}
```

Looks good, doesn't it?
But there is a problem.
Do you know which?

Java Monitors = signal + continue

R
```
synchronized void acquire() {
    if (number <= 0)
        try { wait(); } Q
        catch (InterruptedException e) { };
    number--;
}

synchronized void release() {
P   number++;
    if (number > 0)
        notify();
}
```

Scenario:

1. Process P has previously acquired the semaphore and decreased number to 0.
2. Process Q sees number = 0 and goes to waiting list.
3. P is executing release. In this moment process R wants to enter the monitor via method acquire.
4. P signals Q and thus moves it into wait entry list (signal and continue!). P exits the function/lock.
5. R gets entry to monitor before Q and sees the number = 1
6. Q continues execution with number = 0!

Inconsistency!

The cure – a while loop.

```
synchronized void acquire() {
 while (number <= 0)
  try { wait(); }
   catch (InterruptedException e) { };
 number--;
}
```

```
synchronized void release() {
   number++;
   if (number > 0)
      notify();
}
```

If, additionally, different threads evaluate different conditions, the notification has to be a `notifyAll`. In this example it is not required.

Something different: Java Interface Lock

Intrinsic locks ("synchronized") with objects provide a good abstraction and should be first choice

Limitations

- **one implicit lock per object**
- **are forced to be used in blocks**
- **limited flexibility**

Java offers the Lock interface for more flexibility (e.g., lock can be polled).

```
final Lock lock = new ReentrantLock();
```

Condition interface

Java Locks provide *conditions that can be instantiated*

```
Condition notFull  = lock.newCondition();
```

Java conditions offer

.await() – the current thread waits until condition is signaled

.signal() – wakes up one thread *waiting on this condition*

.signalAll() – wakes up all threads *waiting on this condition*

Condition interface

→ Conditions are always associated with a lock
lock.newCondition()

.await()
- called with the lock held
- **atomically** releases the lock and waits until thread is signaled
- when returns, it is **guaranteed** to hold the lock
- thread **always** needs to check condition

.signal{,All}() – wakes up one (all) waiting thread(s)
- called with the lock held

Producer / Consumer with explicit Lock

```
class Queue {
     int in=0, out=0, size;
     long buf[];
     final Lock lock = new ReentrantLock();
     final Condition notFull  = lock.newCondition();
     final Condition notEmpty = lock.newCondition();

     Queue(int s) {
          size = s;
          buf = new long[size];
     }

...

}
```

Producer / Consumer with Lock

```
void enqueue(long x) {

   lock.lock();
   while (isFull())
      try {
         notFull.await();
      } catch (InterruptedException e){}
   doEnqueue(x);
   notEmpty.signal();
   lock.unlock();
}
```

```
long dequeue() {
   long x;
   lock.lock();
   while (isEmpty())
      try {
         notEmpty.await();
      } catch (InterruptedException e){}
   x = doDequeue();
   notFull.signal();
   lock.unlock();
   return x;
}
```

The Sleeping Barber Variant (E. Dijkstra)

Disadvantage of the solution: notFull and notEmpty signal will be sent in any case, even when no threads are waiting.

Seemingly simple solution (in barber analogy)

1. ***Barber cuts hair, when done, check waiting room, if nobody left, sleep***
2. ***Client arrives, either enqueues or wakes sleeping barber***

What can go wrong (really only in a threaded world)?

Sleeping barber **requires additional counters for checking if processes are waiting:**

$m \leq 0 \Leftrightarrow$ **buffer full &** $-m$ **producers (clients) are waiting**

$n \leq 0 \Leftrightarrow$ **buffer empty &** $-n$ **consumers (barbers) are waiting**

Producer Consumer, Sleeping Barber Variant

```
class Queue {
    int in=0, out=0, size;
    long buf[];
    final Lock lock = new ReentrantLock();
    int n = 0; final Condition notFull  = lock.newCondition();
    int m; final Condition notEmpty = lock.newCondition();

    Queue(int s) {
        size = s; m=size-1;
        buf = new long[size];
    }
...
}
```

Two variables ☹ sic!
(cf. last lecture)

Producer Consumer, Sleeping Barber Variant

```
void enqueue(long x) {

   lock.lock();
   m--; if (m<0)
      while (isFull())
         try { notFull.await(); }
         catch(InterruptedException e){}
   doEnqueue(x);
   n++;
   if (n<=0) notEmpty.signal();
   lock.unlock();

}
```

```
long dequeue() {
   long x;
   lock.lock();
   n--; if (n<0)
      while (isEmpty())
         try { notEmpty.await(); }
         catch(InterruptedException e){}
   x = doDequeue();
   m++;
   if (m<=0) notFull.signal();
   lock.unlock();
   return x;
}
```

Guidelines for using condition waits

- **Always have a condition predicate**
- **Always test the condition predicate:**
  - before calling wait
  - after returning from wait
- **Always call wait in a loop**
- **Ensure state is protected by lock associated with condition**

Check out java.util.concurrent

Java (luckily for us) provides many common synchronization objects:

- Semaphores
- Barriers (CyclicBarrier)
- Producer / Consumer queues
- and many more... (Latches, Futures, ...)

Reader / Writer Locks

Literature: Herlihy – Chapter 8.3

Reading vs. writing

Recall:

- Multiple concurrent reads of same memory: *Not* a problem
- Multiple concurrent writes of same memory: Problem
- Multiple concurrent read & write of same memory: Problem

So far:

- If concurrent write/write or read/write might occur, use synchronization to ensure one-thread-at-a-time

But this is unnecessarily conservative:

- Could still allow multiple simultaneous readers!

Example

Consider a hashtable with one coarse-grained lock

- So only one thread can perform operations at a time

But suppose:

- There are many simultaneous `lookup` operations
- `insert` operations are very rare

Note: Important that `lookup` does not actually mutate shared memory, like a move-to-front list operation would

WIKIPEDIA
The Free Encyclopedia

Number of edits (2007-11/27/2017): 921,644,695
Average views per day: ~200,000,000

→ 0.12% write rate

Another Example

Shared use of text, e.g., in an IDE

writers: editor(s), copy&paste agents, syntax highlighter

readers: compiler, editor(s), text viewers, copy&paste agents, search tools

Reader/writer locks

A new abstract data type for synchronization : The reader/writer lock

This lock's states fall into three categories:

- **"not held"**
- **"held for writing" by one thread**
- **"held for reading" by *one or more* threads**

$0 \leq$ writers ≤ 1
$0 \leq$ readers
writers*readers == 0

Reader/writer locks

`new:`	make a new lock, initially "not held"
`acquire_write:`	block if currently "held for reading" or "held for writing", else make "held for writing"
`release_write:`	make "not held"
`acquire_read:`	block if currently "held for writing", else make/keep "held for reading" and increment *readers count*
`release_read:`	decrement readers count, if 0, make "not held"

Pseudocode example

```
class Hashtable<K,V> {
 …
 // coarse-grained, one lock for table
 RWLock lk = new RWLock();
 …
```

```
 V lookup(K key) {
   int bucket = hashval(key);
   lk.acquire_read();
   … read array[bucket] …
   lk.release_read();
 }
```

```
  void insert(K key, V val) {
    int bucket = hashval(key);
    lk.acquire_write();
    … write V to array[bucket] …
    lk.release_write();
  }
  …
}
```

A Simple Monitor-based Implementation

```
class RWLock {
  int writers = 0;
  int readers = 0;

synchronized void acquire_read() {
  while (writers > 0)
    try { wait(); }
    catch (InterruptedException e) {}
  readers++;
}

synchronized void release_read() {
  readers--;
  notifyAll();
}
```

Is this lock fair?

The simple implementation gives priority to readers:

- when a reader reads, other readers can enter
- no writer can enter during readers reading

```
 synchronized void acquire_write() {
   while (writers > 0 || readers > 0)
     try { wait(); }
     catch (InterruptedException e) {}
   writers++;
 }

 synchronized void release_write() {
   writers--;
   notifyAll();
 }
}
```

Exercise: come up with a better performing version using condition variables!

Strong priority to the writers

```
class RWLock {
  int writers = 0;
  int readers = 0;
  int writersWaiting = 0;

  synchronized void acquire_read() {
    while (writers > 0 || writersWaiting > 0)
      try { wait(); }
      catch (InterruptedException e) {}
    readers++;
  }

  synchronized void release_read() {
    readers--;
    notifyAll();
  }
```

```
  synchronized void acquire_write() {
    writersWaiting++;
    while (writers > 0 || readers > 0)
       try { wait(); }
      catch (InterruptedException e) {}
    writersWaiting--;
    writers++;
  }

  synchronized void release_write() {
   writers--;
   notifyAll();
  }
}
```

Is this lock now fair?
(this was just to see of you're awake)

A fair(er) model

What is fair in this context?

For example

- **When a writer finishes, a number k of currently waiting readers may pass.**
- **When the k readers have passed, the next writer may enter (if any), otherwise further readers may enter until the next writer enters (who has to wait until current readers finish).**

A fair(er) model

writers: # writers in CS
readers: # readers in CS
writersWaiting: # writers trying to enter CS
readersWaiting: # readers trying to enter CS
writersWait: # readers the writers have to wait

```
class RWLock{
  int writers = 0; int readers = 0;
  int writersWaiting = 0; int readersWaiting = 0;
  int writersWait = 0;

  synchronized void acquire_read() {
   readersWaiting++;
   while (writers > 0 ||
         (writersWaiting > 0 && writersWait <= 0))
     try { wait(); }
     catch (InterruptedException e) {}
   readersWaiting--;
   writersWait--;
   readers++;
  }

  synchronized void release_read() {
   readers--;
   notifyAll();
  }
```

Writers are waiting and the readers don't have priority any more.

When a writer finishes, the number of currently waiting readers may pass.

Writers have to wait until the waiting readers have finished.

```
  synchronized void acquire_write() {
   writersWaiting++;
   while (writers > 0 || readers > 0 || writersWait > 0)
       try { wait(); }
      catch (InterruptedException e) {}
   writersWaiting--;
   writers++;
  }

  synchronized void release_write() {
   writers--;
   writersWait = readersWaiting;
   notifyAll();
  }
}
```

Exercise: come up with a better performing version using condition variables! Introduce an upper bound of k readers!

Reader/writer lock details

A reader/writer lock implementation ("not our problem") usually gives *priority* to writers:

- Once a writer blocks, no readers *arriving later* will get the lock before the writer
- Otherwise an **`insert`** could *starve*

Re-entrant?

- Mostly an orthogonal issue
- But some libraries support *upgrading* from reader to writer

In Java

Java's `synchronized` statement does not support readers/writer

Instead, library

`java.util.concurrent.locks.ReentrantReadWriteLock`

Different interface: methods `readLock` and `writeLock` return objects that themselves have `lock` and `unlock` methods

Does *not* have writer priority or reader-to-writer upgrading

- Always read the documentation

LOCK GRANULARITY

Literature: Herlihy – Chapter 9

The Five-Fold Path

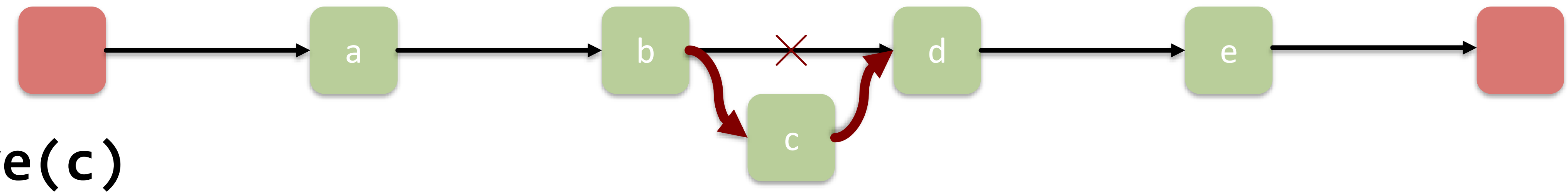
- Coarse-grained locking
- Fine-grained locking
- Optimistic synchronization (locking)
- Lazy synchronization (locking)

- Next lecture: Lock-free synchronization

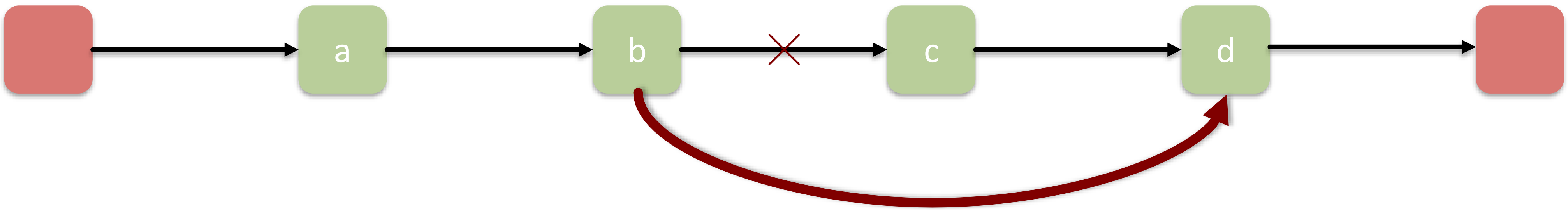
Running Example: Sequential List Based Set

Add, Remove, and Find unique elements in a sorted linked list.

- `add(c)`

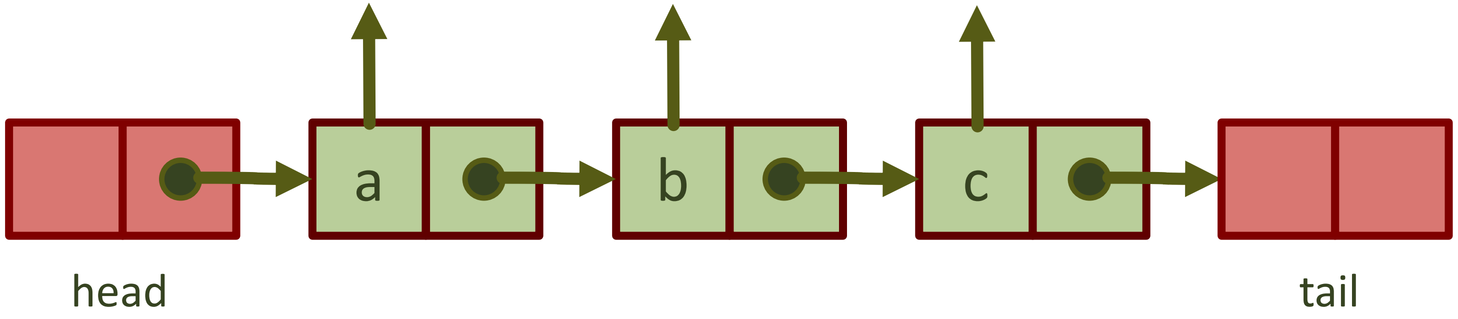


- `remove(c)`



Set and Node

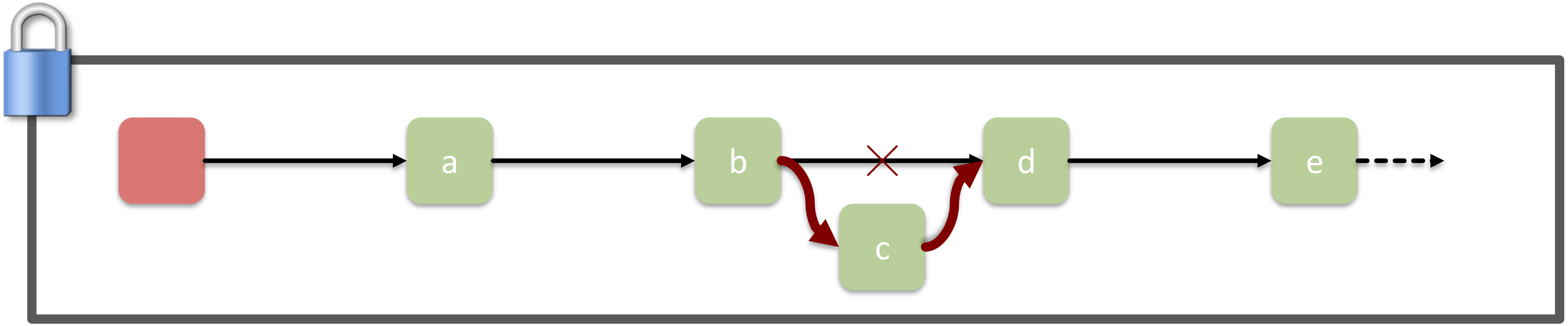
```
public class Set<T> {

   private class Node {
      T item;
      int key;
      Node next;
   }
   private Node head;
   private Node tail;

   public boolean add(T x) {...};
   public boolean remove(T x) {...};
   public boolean contains(T x) {...};
}
```



Note that the list is not "in place" but provides references to its items

Coarse Grained Locking

```
public synchronized boolean add(T x) {...};
public synchronized boolean remove(T x) {...};
public synchronized boolean contains(T x) {...};
```



Simple, but a bottleneck for all threads.

Fine grained Locking

Often more intricate than visible at a first sight

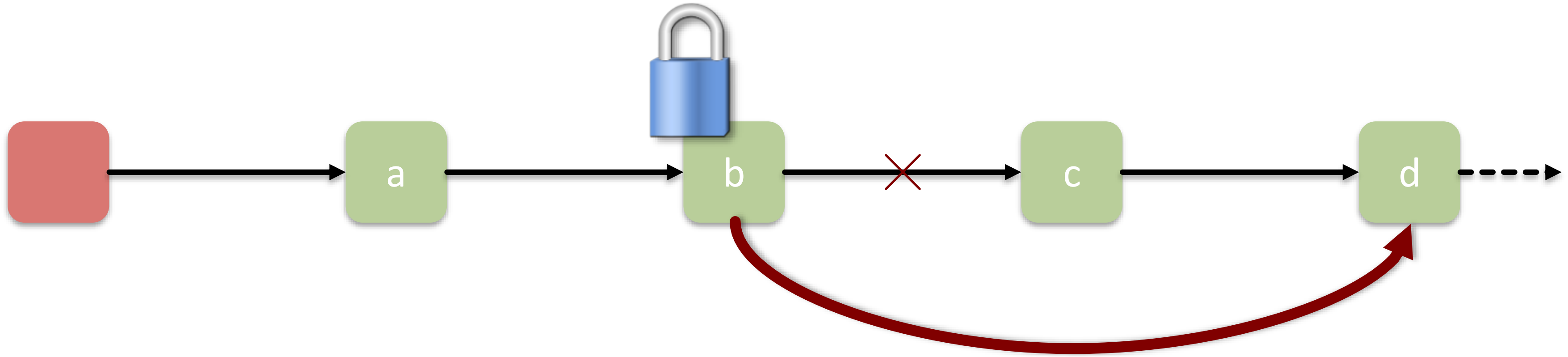
- **requires careful consideration of special cases**

Idea: split object into pieces with separate locks

- **no mutual exclusion for algorithms on disjoint pieces**

Let's try this

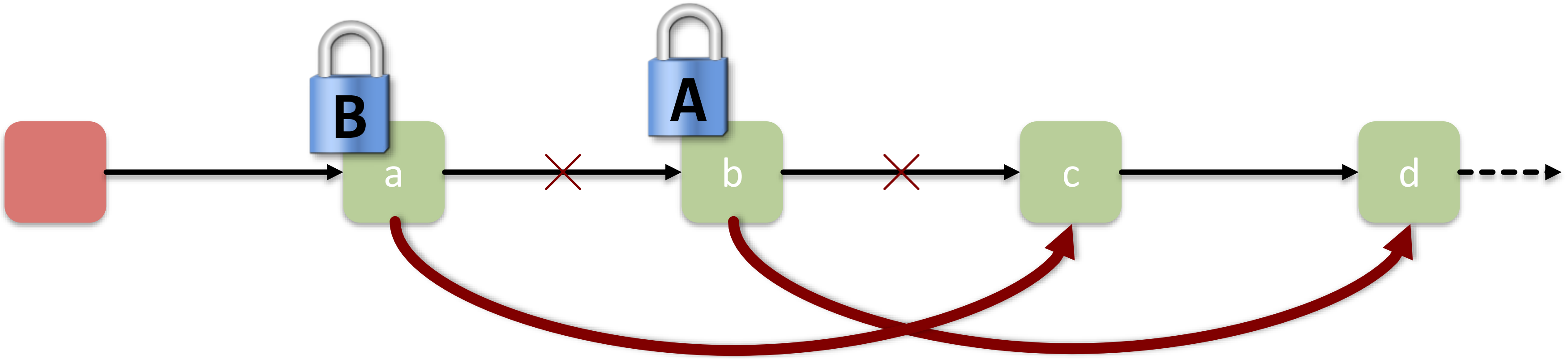
`remove(c)`



`Is this ok?`

Let's try this

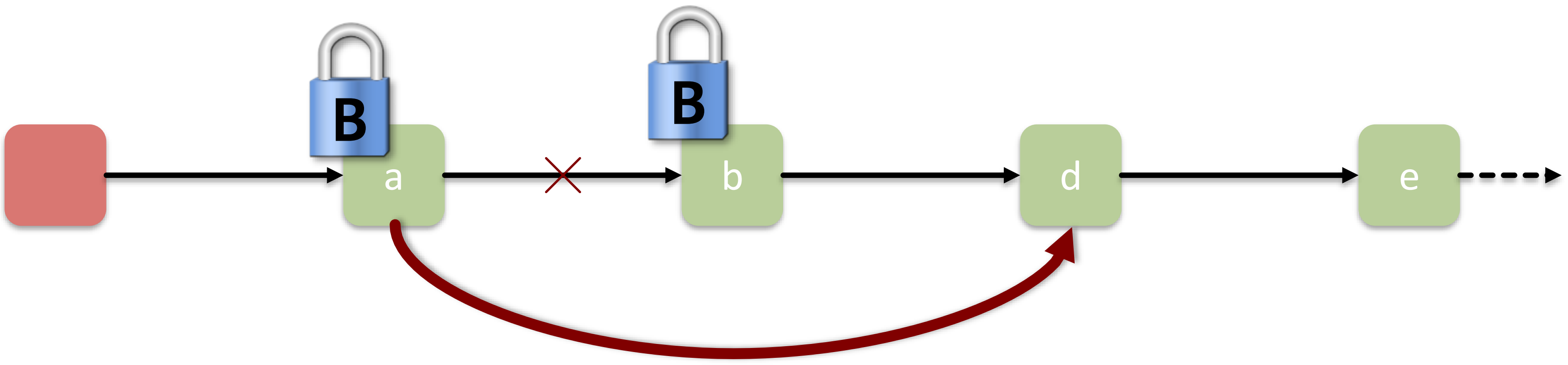
```
Thread A: remove(c)
Thread B: remove(b)
```



c not deleted! ☹

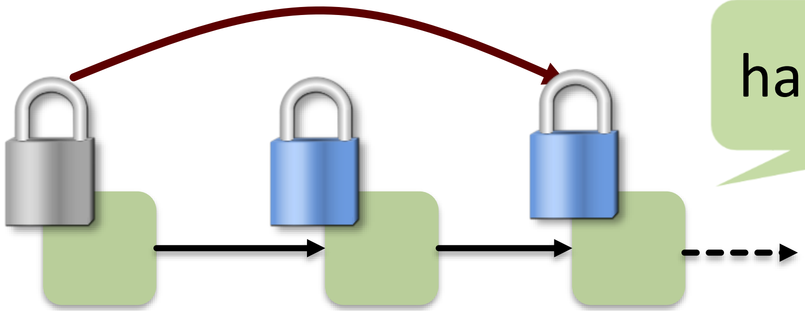
What's the problem?

- **When deleting, the next field of next is read, i.e., next also has to be protected.**
- **A thread needs to lock both, predecessor and the node to be deleted (hand-over-hand locking).**



Remove method

```
public boolean remove(T item) {
   Node pred = null, curr = null;
   int key = item.hashCode();
   head.lock();
   try {
    pred = head;
    curr = pred.next;
    curr.lock();
    try {
       // find and remove
    } finally { curr.unlock(); }
   } finally { pred.unlock(); }
}
```



hand over hand

```
while (curr.key < key) {
    pred.unlock();
    pred = curr; // pred still locked
    curr = curr.next;
    curr.lock(); // lock hand over hand
}
if (curr.key == key) {
    pred.next = curr.next; // delete
    return true;
}
return false;
```

remark: sentinel at front and end of list prevents an exception here

Disadvantages?

- **Potentially long sequence of acquire / release before the intended action can take place**
- **One (slow) thread locking "early nodes" can block another thread wanting to acquire "late nodes"**

OPTIMISTIC SYNCHRONIZATION

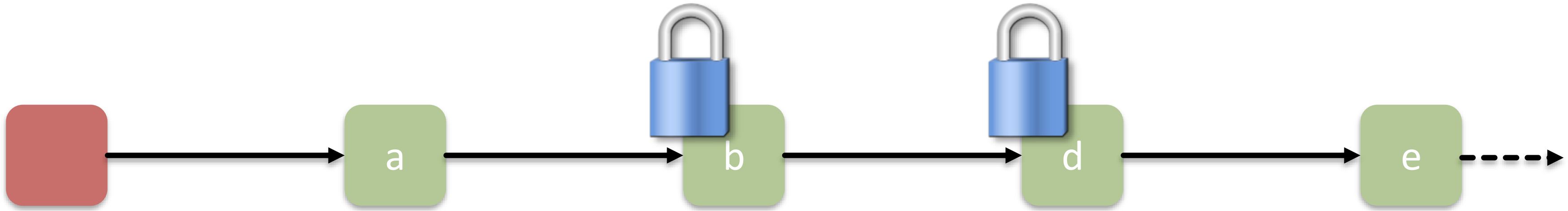
Idea

Find nodes without locking,

- **then lock nodes and**
- **check that everything is ok (validation)**

What do we need to "validate"?

e.g., add(c)



Validation: what could go wrong?

Thread A: add(c)

A: find insertion point

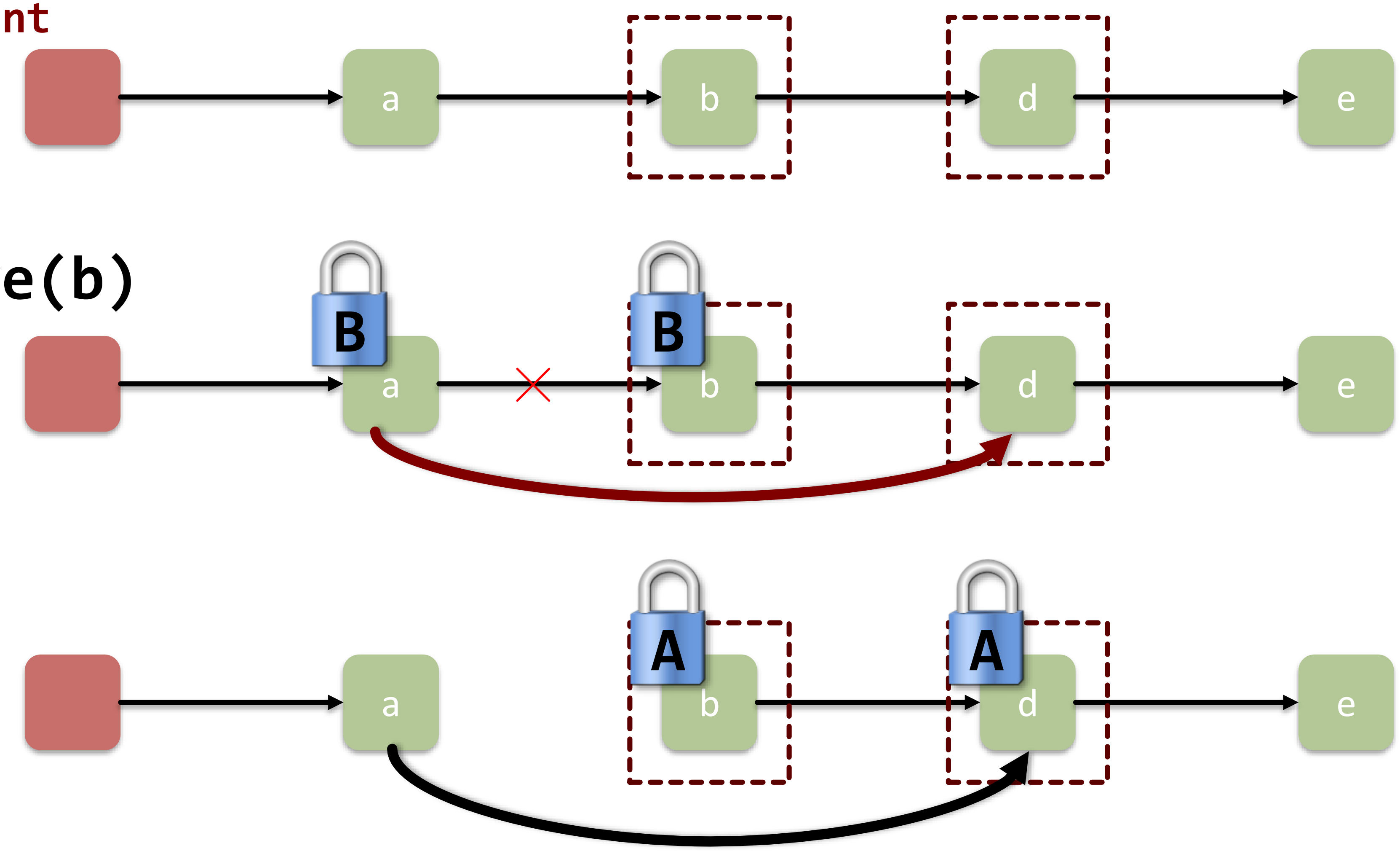
Thread B: remove(b)

A: lock

A: validate: rescan

A: b not reachable

→return false

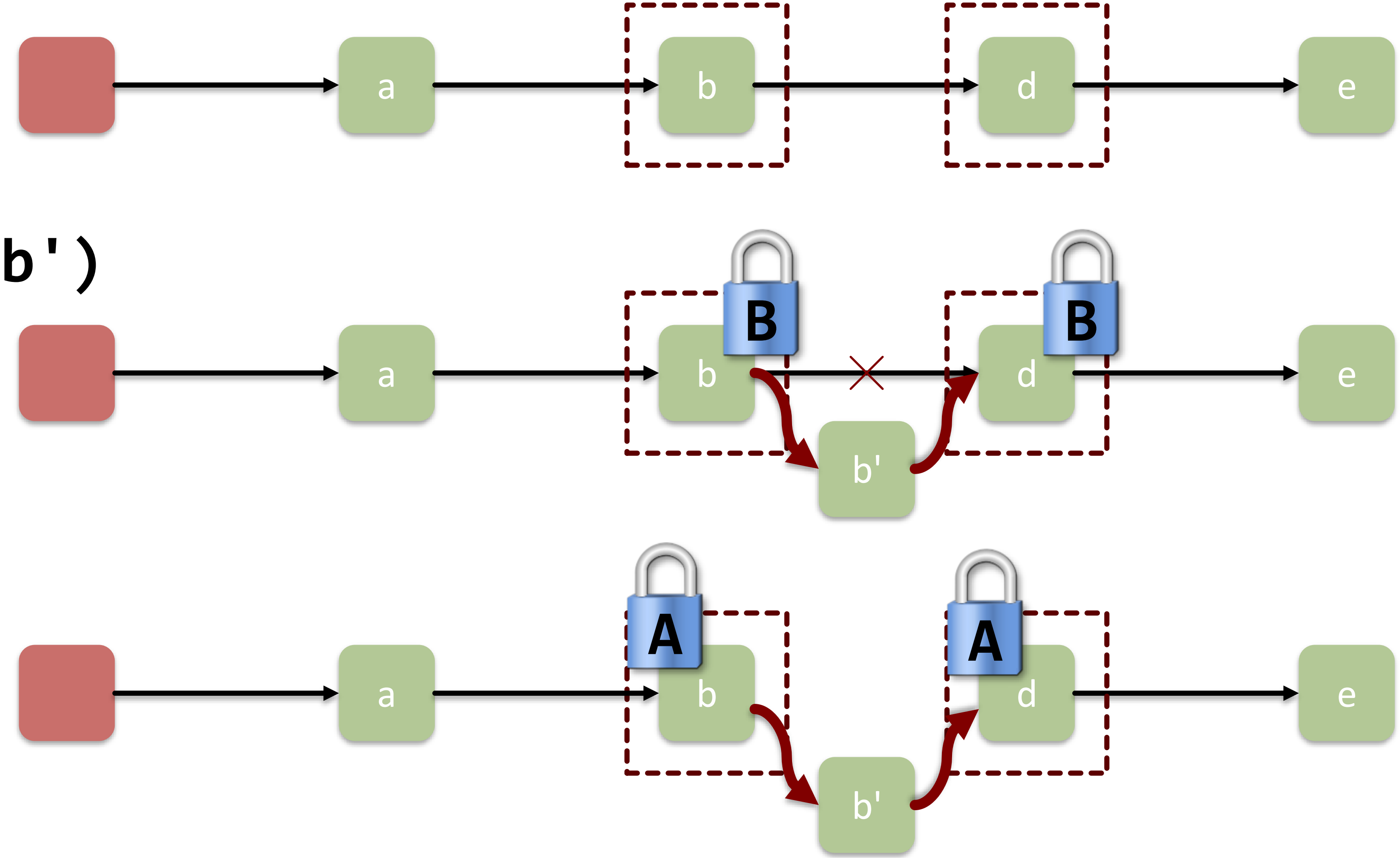


Validation: what could go wrong?

`Thread A: add(c)`

`A: find insertion point`

`Thread B: insert(b')`



`A: lock`

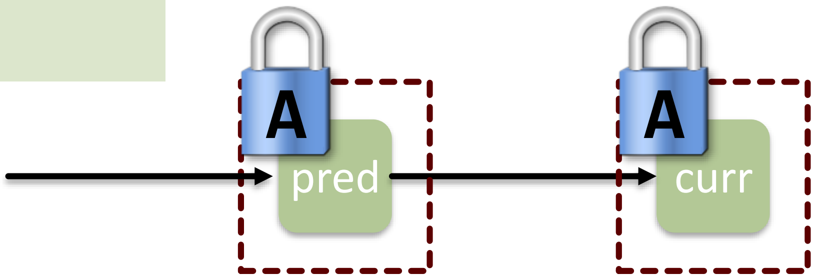
`A: validate: rescan`

`A: d != succ(b)`

`→return false`

Validate

```
private Boolean validate(Node pred, Node curr) {
  Node node = head;
  while (node.key <= pred.key) { // reachable?
      if (node == pred)
            return pred.next == curr; // correct?
      node = node.next;
  }
  return false;
}
```



Correctness (remove c)

If

- **nodes b and c both locked**
- **node b still reachable from head**
- **node c still successor to b**

then

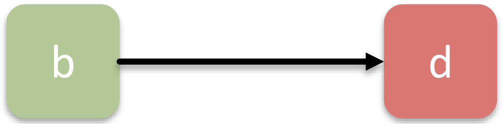
- **neither is in the process of being deleted**

➔ ok to delete and return true

Correctness (remove c)

If

- nodes b and d both locked
- node b still reachable from head
- node d still successor to b



then

- neither is in the process of being deleted,
  therefore a new element c must appear between b and d
- no thread can add between b and d:
  c cannot have appeared after our locking

➔ ok to return false

Optimistic List

Good:

- No contention on traversals.
- Traversals are wait-free.
- Less lock acquisitions.

Wait-Free:
Every call finishes in a finite number of steps (NEVER waits for other threads).

Bad:

- Need to traverse list twice
- The contains() method needs to acquire locks
- Not starvation-free

Is the optimistic list starvation-free? Why/why not?

LAZY SYNCHRONISATION

Laziness

The quality that makes you go to great effort to reduce overall energy expenditure [...] **the first great virtue of a programmer.**

Larry Wall, Programming Perl
(emphasis mine)

Lazy List

Like optimistic list but

- Scan only once
- Contains() never locks

How?

- Removing nodes causes trouble
- Use deleted-markers → invariant: every unmarked node is reachable!
- Remove nodes «lazily» after marking

Lazy List: Remove

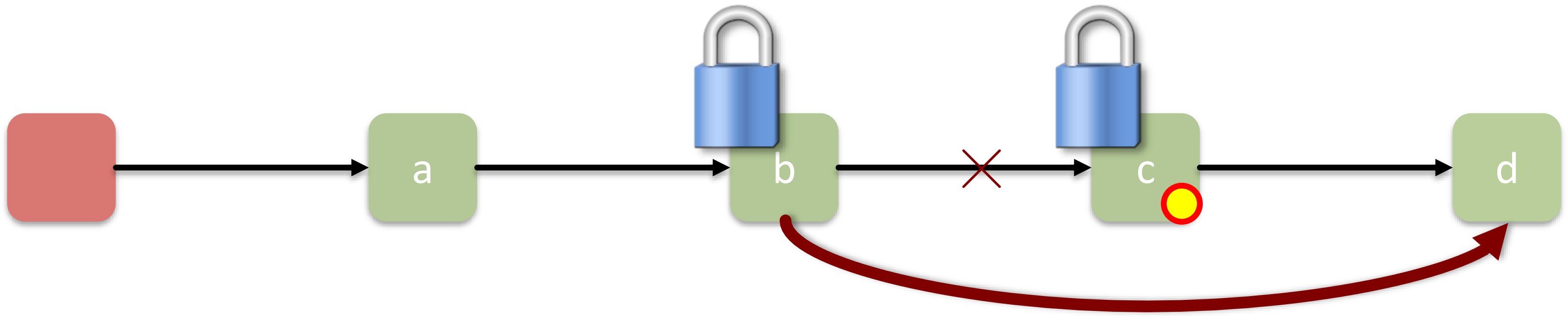
Scan list (as before)

Lock predecessor and current (as before)

Logical delete: mark current node as removed

Physical delete: redirect predecessor's next

e.g., remove(c)



Invariant

If a node is not marked then

- It is reachable from head
- And reachable from its predecessor

A: remove(c)

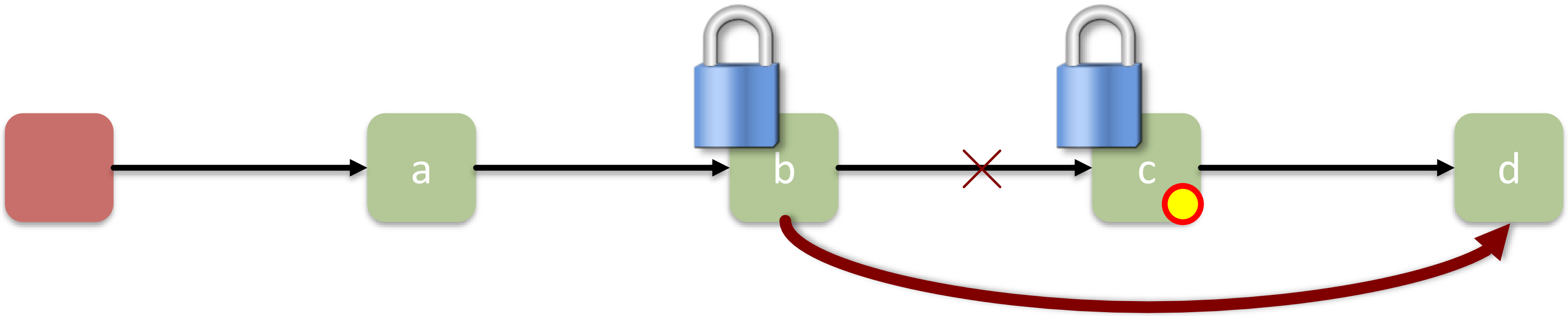
lock

check if b or c are marked

not marked? ok to delete:

mark c

delete c



Remove method

```
public boolean remove(T item) {
  int key = item.hashCode();
  while (true) { // optmistic, retry
    Node pred = this.head;
    Node curr = head.next;
    while (curr.key < key) {
      pred = curr;
      curr = curr.next;
    }
    pred.lock();
    try {
      curr.lock();
      try {
        // remove or not
      } finally { curr.unlock(); }
    } finally { pred.unlock(); }
  }
}
```

```
if (!pred.marked && !curr.marked &&
      pred.next == curr) {
   if (curr.key != key)
      return false;
   else {
      curr.marked = true;    // logically remove
      pred.next = curr.next; // physically remove
      return true;
   }
}
```

Wait-Free Contains

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

This set data structure is again for demonstration only. Do not use this to implement a list! Now on to something more practical.

Bill Pugh received a Ph.D. in Computer Science (with a minor in Acting) from Cornell University. He was a professor at the University of Maryland for 23.5 years, and in January 2012 became professor emeritus to start new adventure somewhere at the crossroads of software development and entrepreneurship.

Bill Pugh is a Packard Fellow, and invented Skip Lists, a randomized data structure that is widely taught in undergraduate data structure courses. He has also made research contributions in in techniques for analyzing and transforming scientific codes for execution on supercomputers, and in a number of issues related to the Java programming language, including the development of JSR 133 - Java Memory Model and Thread Specification Revision. Prof. Pugh's current research focus is on developing tools to improve software productivity, reliability and education. Current research projects include FindBugs, a static analysis tool for Java, and Marmoset, an innovative framework for improving the learning and feedback cycle for student programming projects.

Prof. Pugh has spoken at numerous developer conferences, including JavaOne, Goto/Jaoo in Aarhus, the Devoxx conference in Antwerp, and CodeMash. At JavaOne, he received six JavaOne RockStar awards, given to the speakers that receive the highest evaluations from attendees.

Professor Pugh spent the 2008-2009 school year on sabbatical at Google, where, among other activities, he learned how to eat fire.

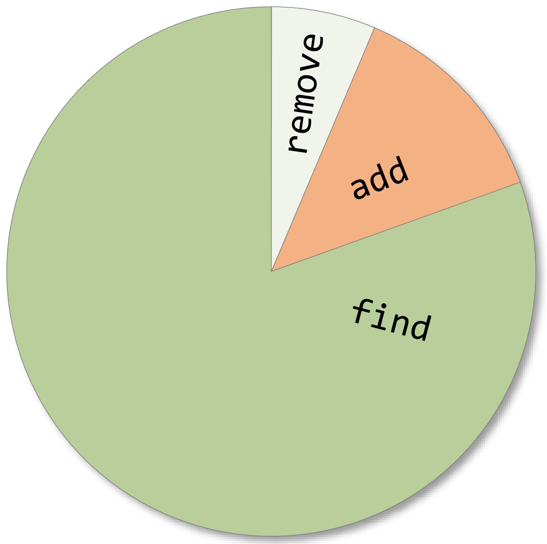
More practical:
Lazy Skiplists

Bill Pugh

Skiplist

- **Collection of elements (without duplicates)**
- **Interface:**
  - `add` // add an element
  - `remove` // remove an element
  - `find` // search an element

- **Assumption:**
  - Many calls to find()
  - Fewer calls to add() and much fewer calls to remove()



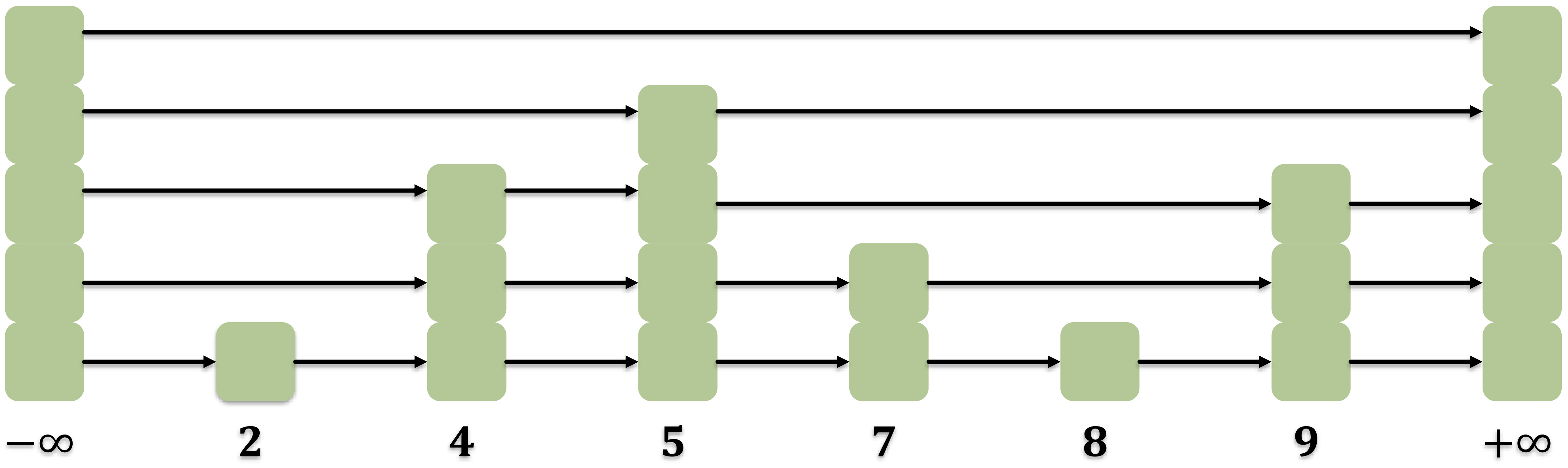
How about balanced trees?

- **AVL trees, red-black trees, treaps, ...**
  - rebalancing after `add` and `remove` expensive
  - rebalancing is a *global* operation (potentially changing the whole tree)
  - particularly hard to implement in a lock-free way.

- **→ SkipList**

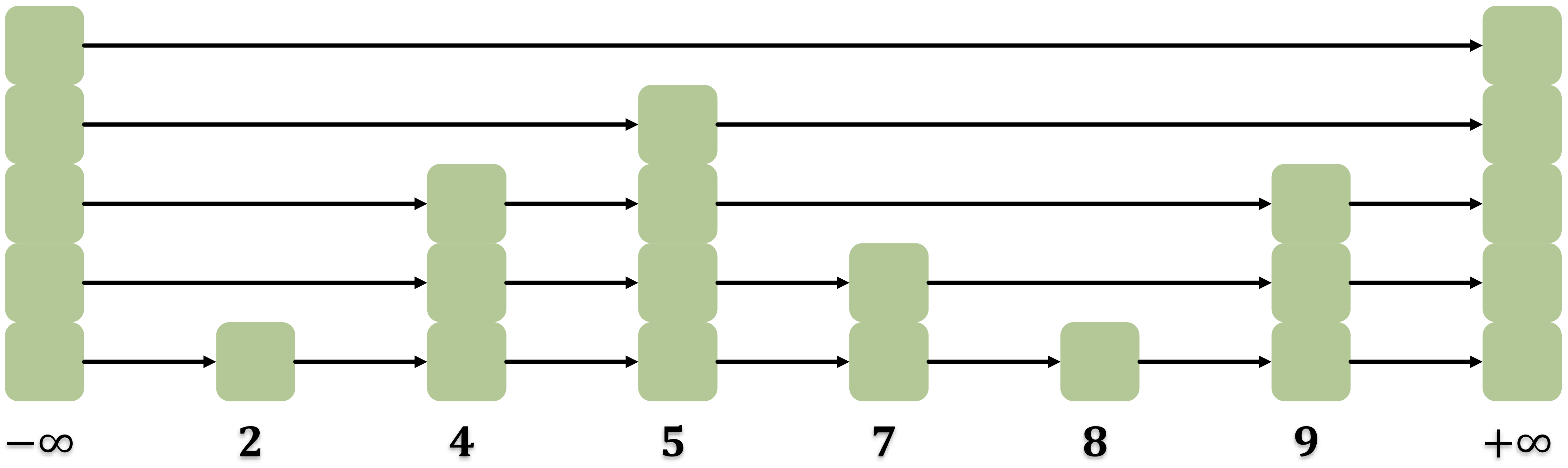
Skip Lists

- **Sorted multi-level list**
- **Node height probabilistic, e.g.,** $\mathbb{P}(height = n) = 0.5^n$, **no rebalancing**



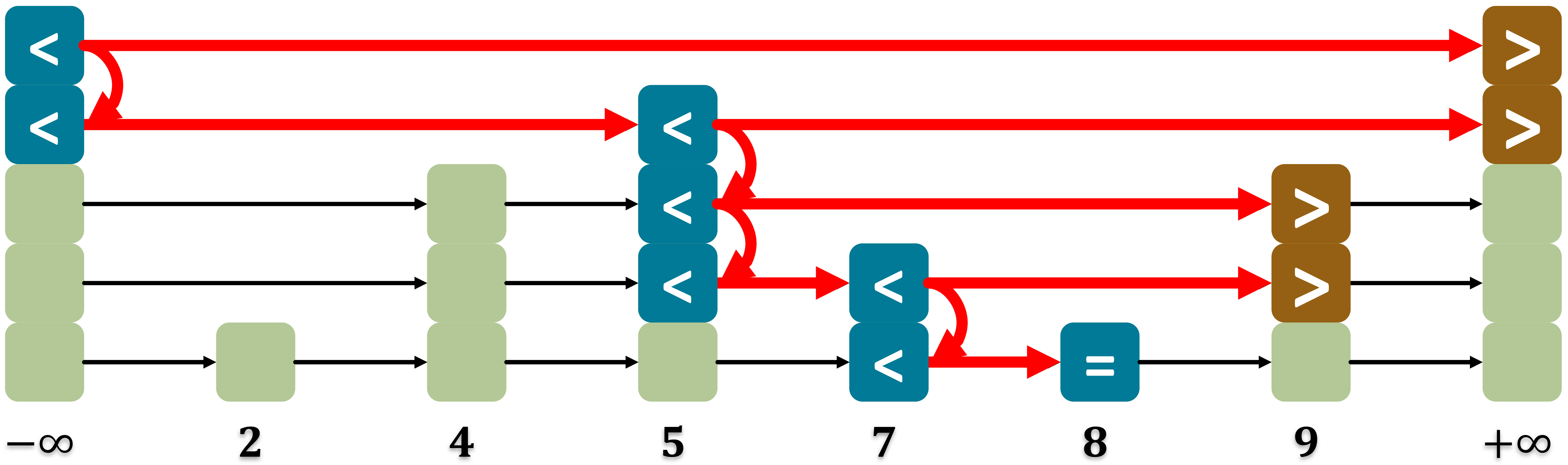
Skip List Property

- **Sublist relationship between levels: higher level lists are always contained in lower-level lists. Lowest level is entire list.**



Searching

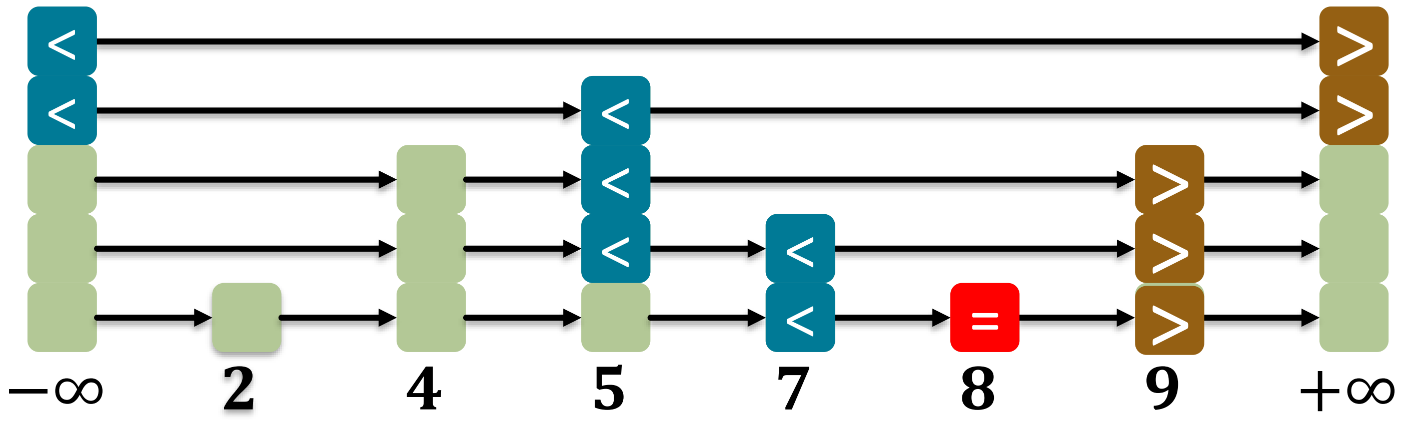
- **Logarithmic Search (with high probability)**
- **Example: Search for 8**



Sequential Find

- `// find node with value x`
- `// return -1 if not found, node level otherwise`
- `// pre = array of predecessor node for all levels`
- `// succ = array of successor node for all levels`
- `int find(T x, Node<T>[] pre, Node<T>[] succ)`

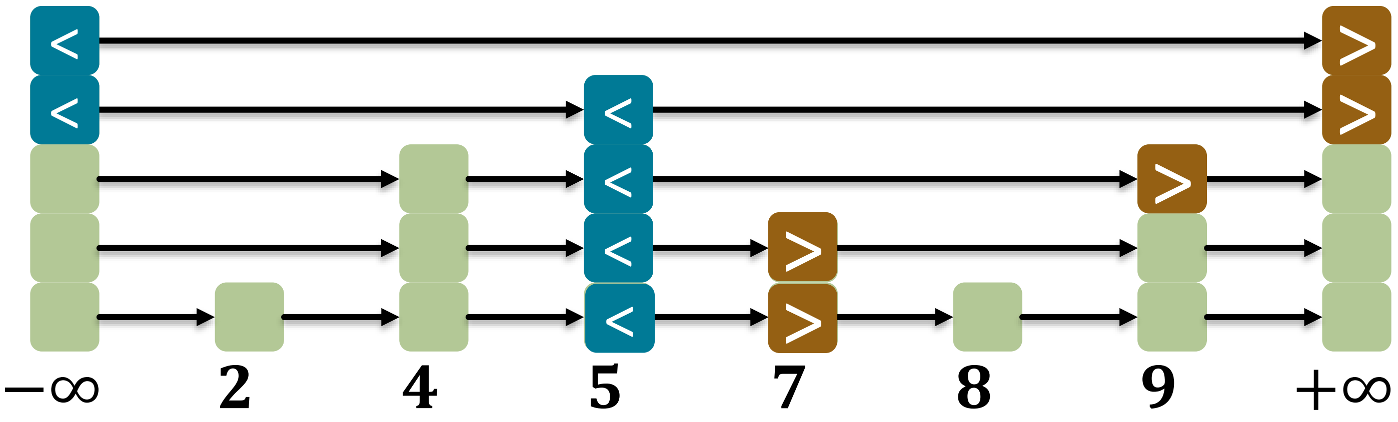
- `e.g., x = 8`
- `returns 0`



Sequential Find

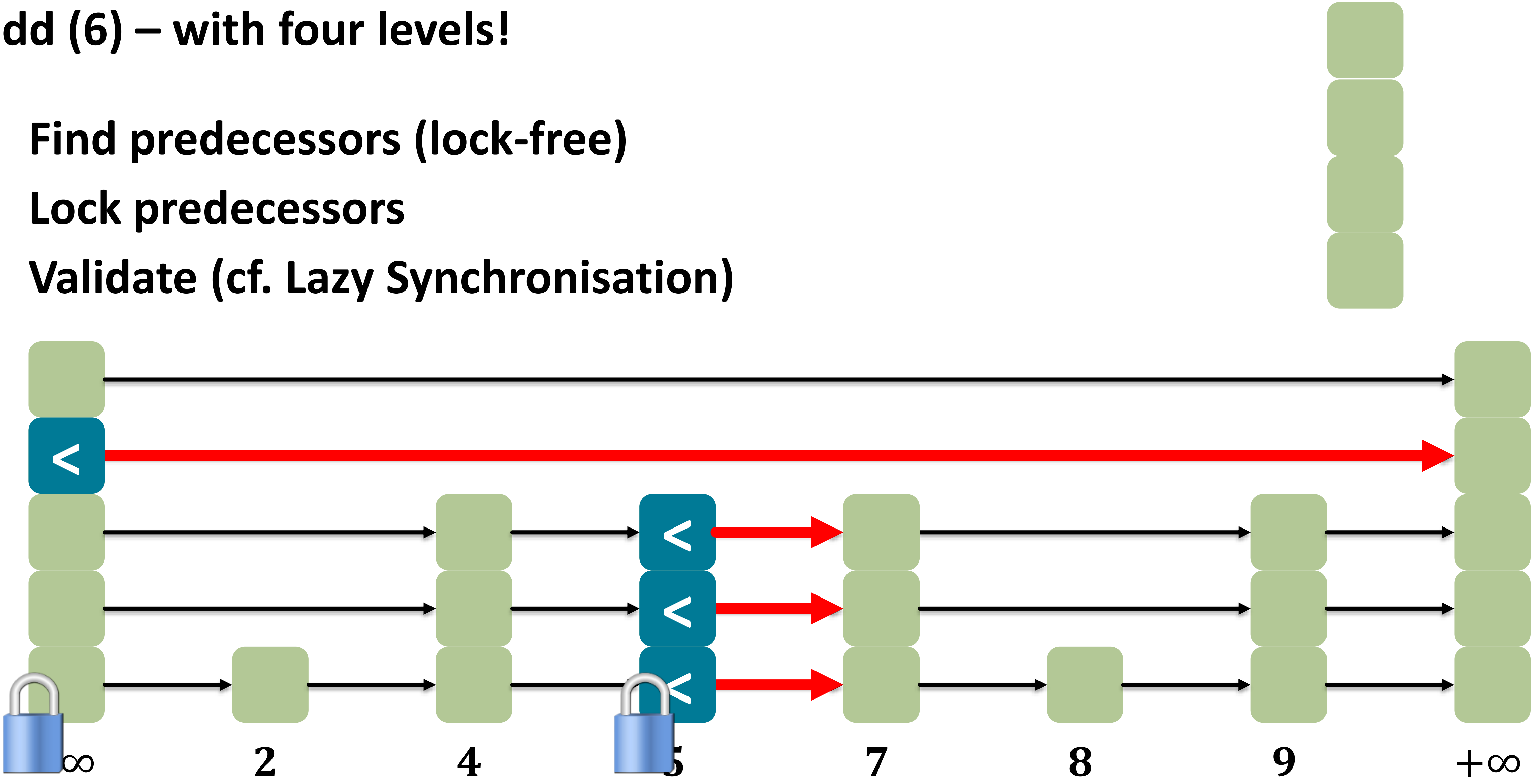
```
// find node with value x
// return -1 if not found, node level otherwise
// pre = array of predecessor node for all levels
// succ = array of successor node for all levels
int find(T x, Node<T>[] pre, Node<T>[] succ)
```

- e.g., x = 6
- returns -1



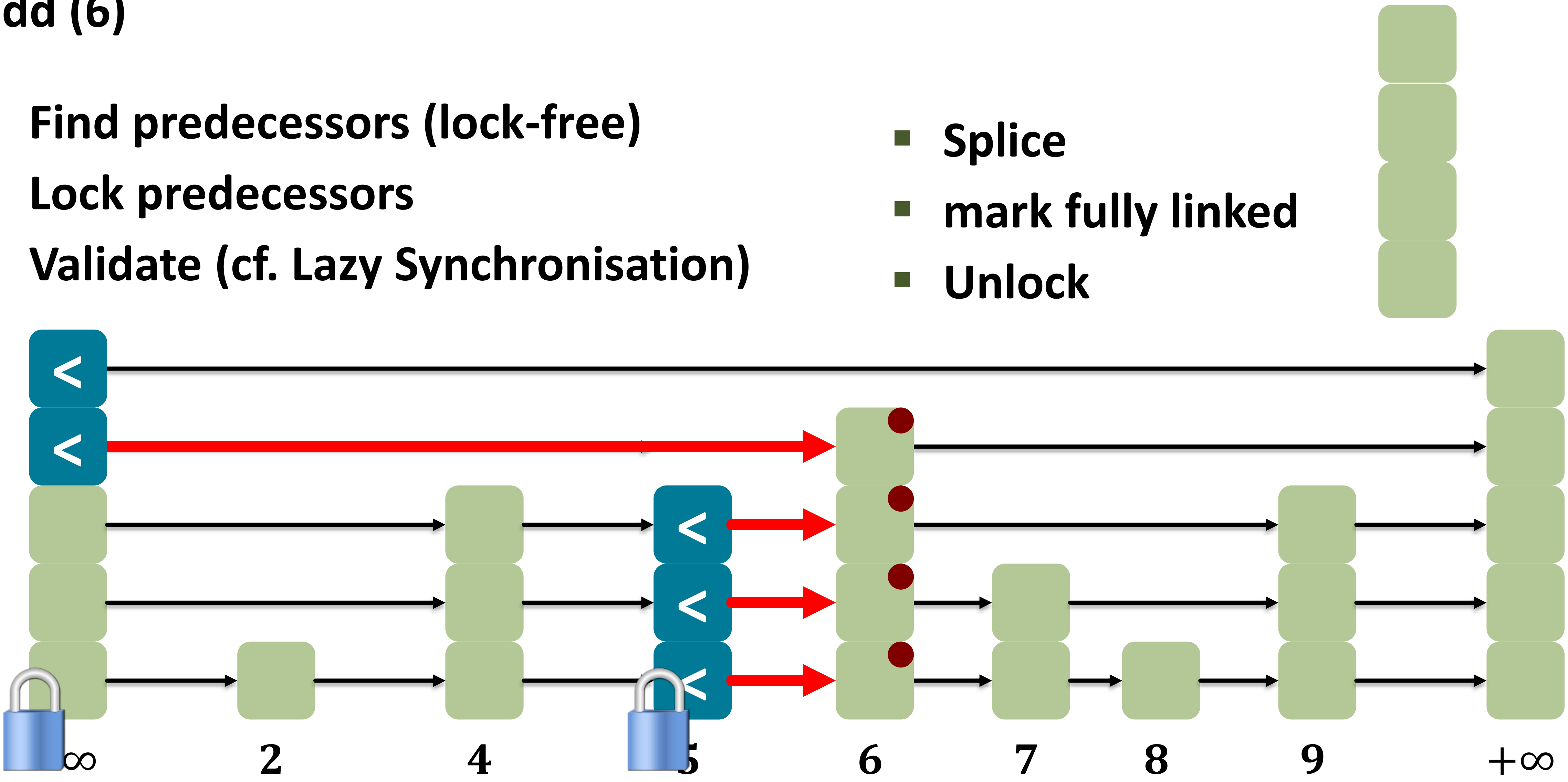
add (6) – with four levels!

- Find predecessors (lock-free)
- Lock predecessors
- Validate (cf. Lazy Synchronisation)



add (6)

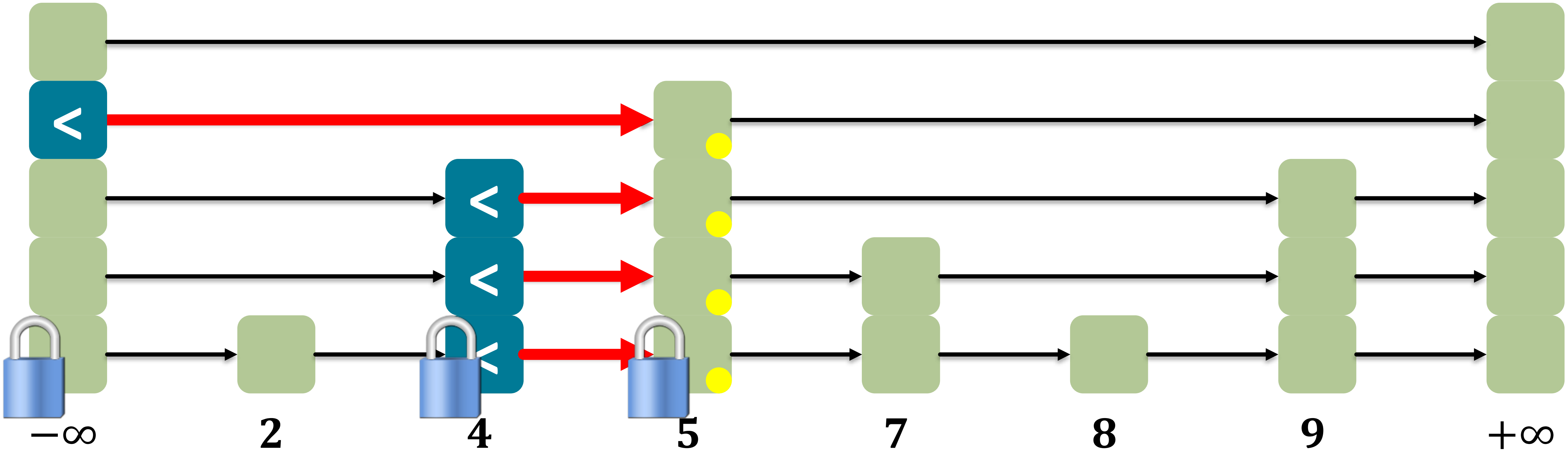
- Find predecessors (lock-free)
- Lock predecessors
- Validate (cf. Lazy Synchronisation)
- Splice
- mark fully linked
- Unlock



remove(5)

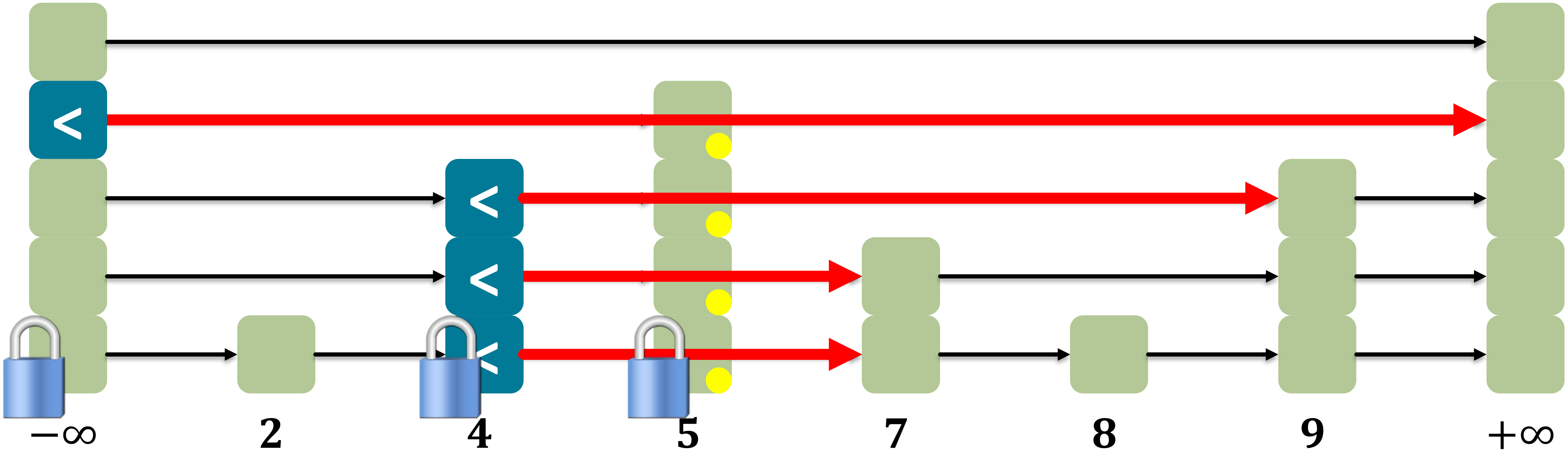
- find predecessors
- lock victim
- logically remove victim (mark)

- Lock predecessors and validate



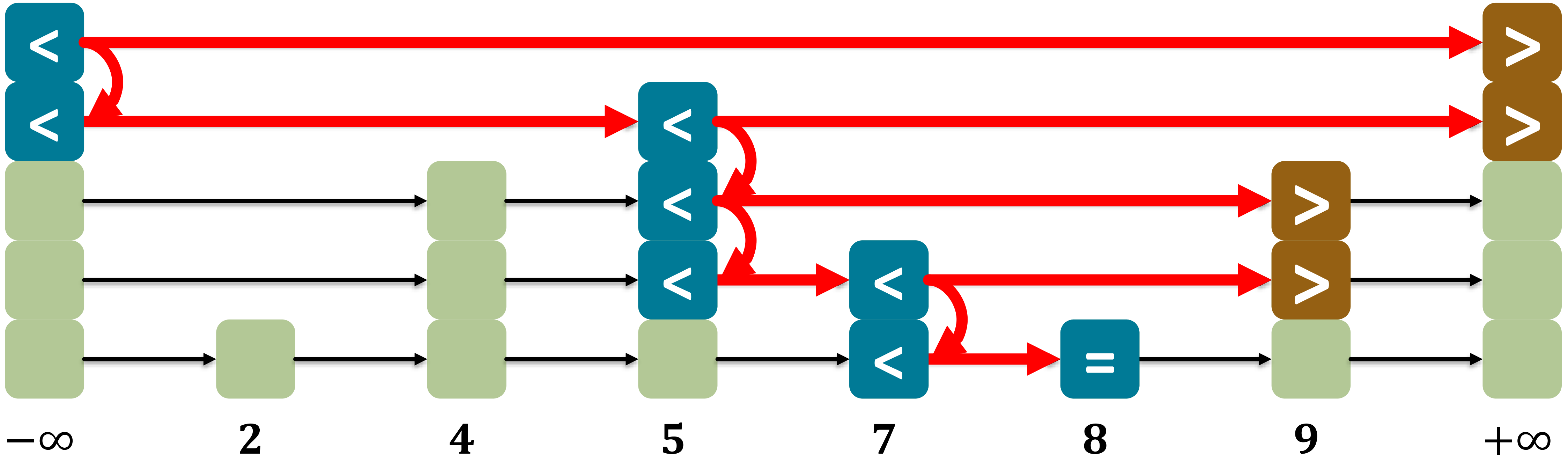
remove(5)

- find predecessors
- lock victim
- logically remove victim (mark)
- Lock predecessors and validate
- physically remove
- unlock



contains(8)

- sequential find() & not logically removed & fully linked
- even if other nodes are removed, it stays reachable
- contains is wait-free (while add and remove are not)



Skiplist

- **Practical parallel datastructure**
- **Code in book (latest revision!) – 139 lines**
  - Too much to discuss in detail here
- **Review and implement as exercise**