Concurrent List-Based Sets

fine-grained, optimistic and lazy synchronization

SLR206, P1, 2020-2021

Implementing a scalable concurrent data structure?

- What *is* a concurrent data structure?
  - ✓Sequential type
  - ✓Wait-free
  - ✓Linearizable
- What is scalable?
  - ✓Throughput: the number of complete operations per time unit
  - ✓Workload: concurrent operations applied
  - ✓Throughput scales with the growing workload (ideally)
- Typically, better concurrency translates to better performance
  - ✓The “number” of accepted concurrent schedules

Example: set type

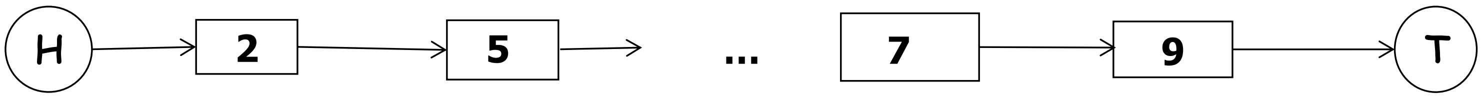
A set abstraction stores a set of integers (no duplicates) and exports operations:

- insert(x) – adds x to the set and returns true if and only if x is not in the set
- remove(x) – removes x from the set and returns true if and only if x is in the set
- contains(x) – returns true if and only if x is in the set

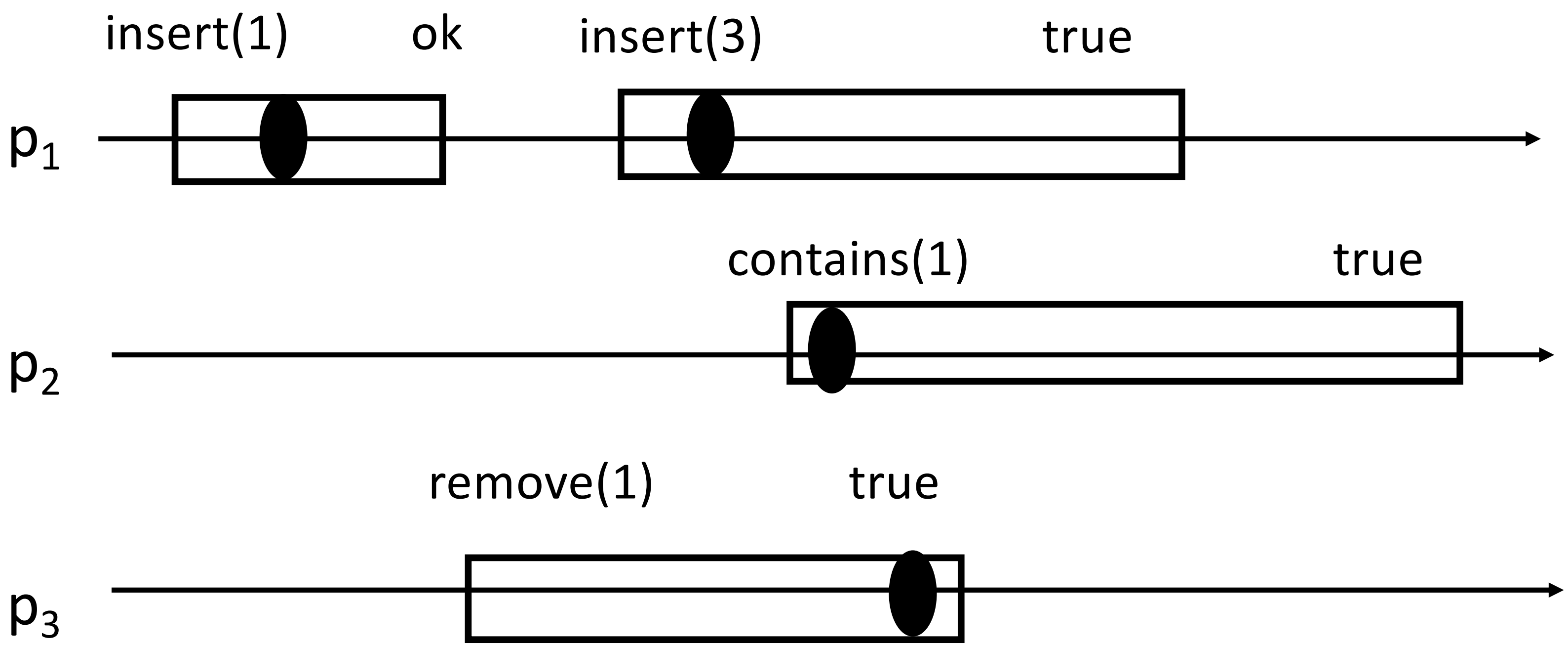
Sequential list-based set

Implementing a set using a sorted linked list:

- To locate x, search starting from the head *curr* points to the first node storing x’≥x, *prev* points to its predecessor
- To remove x (if x’=x), point *prev.next* to *curr.next*
- To insert x (if x’>x), set *prev.next* to the new node storing x and pointing to *curr*



Linearizable histories



The history is equivalent to a legal sequential history on a set (real-time order preserved)

Linked-list for Set: sequential implementation

```
/* The node of an integer list. At creation, default pointer
   is null */
public class Node{
    Node(int item){key=item;next=null;}
    public int key;
    public Node next;}


public class SetList{

    private Node head;

    public SetList(){
          head = new Node(Integer.MIN_VALUE);
          head.next = new Node(Integer.MAX_VALUE);
    }
```

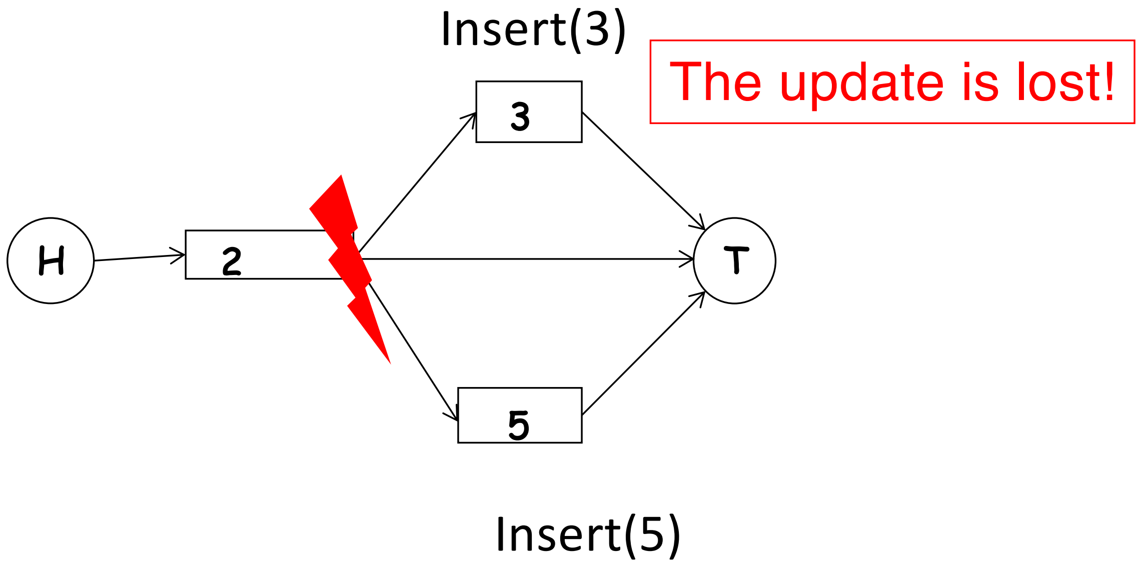
Linked-list for Set: sequential implementation

```
public boolean insert(int item){
       Node pred=head;
       Node curr=head.next;
       while (curr.key < item){
           pred = curr;
           curr = pred.next;}
       if (curr.key==item)
           {return false;}
       else{
           Node node = new
           Node(item);
           node.next=curr;
           pred.next=node;
               return true;
       } }
```

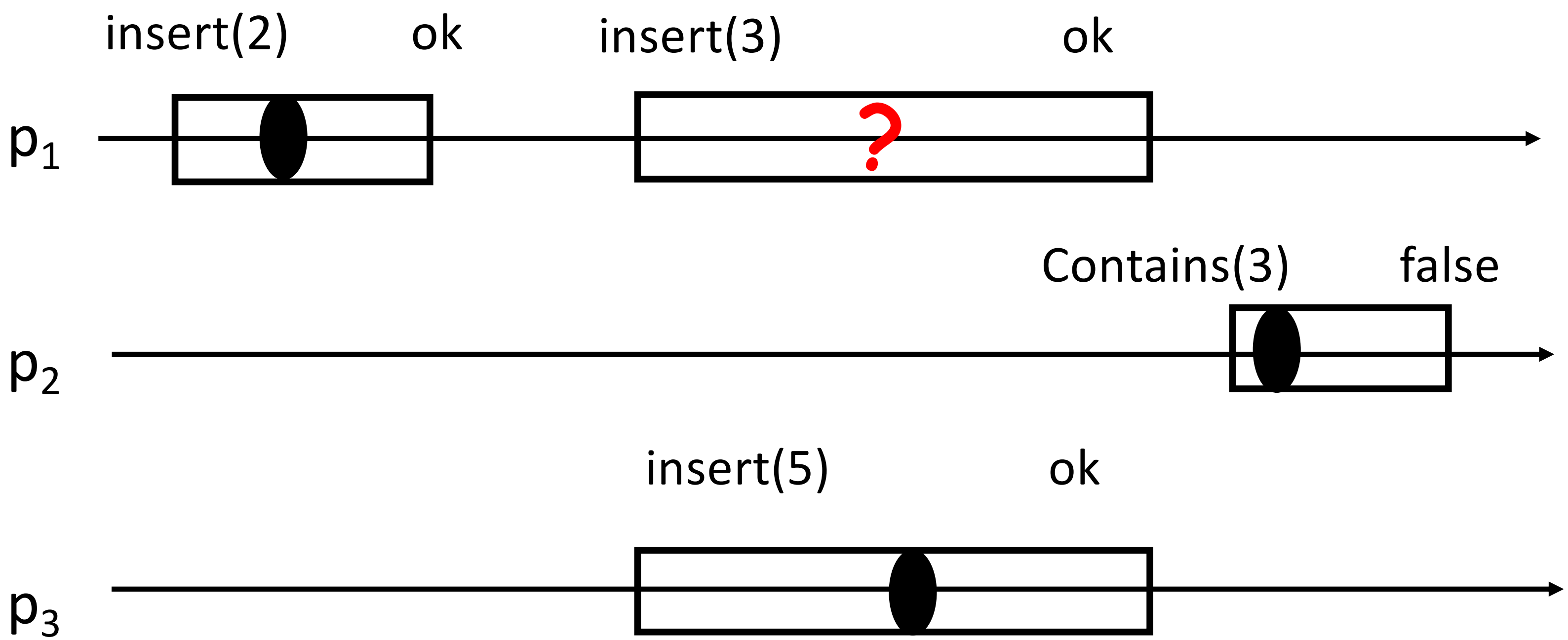
```
public boolean contains(int item){
       Node pred=head;
       Node curr=head.next;
       while (curr.key < item){
         pred = curr;
         curr = pred.next;}
         if (curr.key==item)
            {return true;}
         else {return false;}}
```

```
public boolean remove(int item){
     Node pred=head;
     Node curr=head.next;
     while (curr.key < item){
        pred = curr;
        curr = pred.next;}
        if (curr.key==item)
         {pred.next=curr.next;
              return true;}
         else {return false;}}
```

As is?



The extension with contains(3) is not linearizable!



Need to protect the list elements:

locks, transactional memory…

Concurrent reasoning?

- How to show that an implementation is correct (linearizable)?
- Invariants: *true* initially, no transition can render it *false*
  - ✓E.g., the object representation "makes sense"
- (Sorted) list-based sets:
  - ✓ *head* and *tail* are sentinels
  - ✓ nodes are sorted and keys are unique
  - ✓(the structure can be produced sequentially)

Progress guarantees?

- Locks are used to protect list elements (assuming cooperation):
  - ✓Deadlock-freedom: at least one process makes progress (completes all its operations)
  - ✓Starvation-freedom: every process makes progress
- Nonblocking approaches:
  - ✓Wait-free: every operation completes in a finite number of steps
  - ✓Lock-free: some operation completes in a finite number of steps

Coarse grained solution

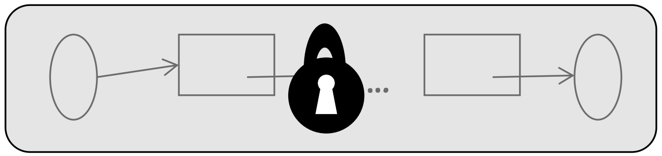
```
public class CoarseList{

    private Node head;
    private Lock lock = new ReentrantLock();


    public boolean insert(int item){
      lock.lock();
      Node pred=head;
      try {
        Node curr=head.next;
        while (curr.key < item){
            pred = curr;
            curr = pred.next;
        }
        if (curr.key==item){return false;}
        Node node = new Node(item);
        node.next=curr;
        pred.next=node;
        return true;
      } finally{
      lock.unlock();
       }
    }
```

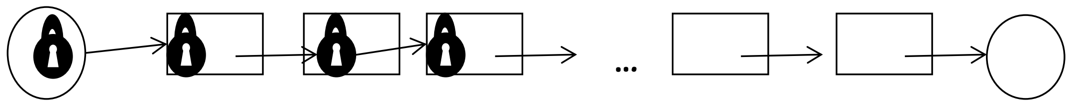
- Same progress guarantees as lock
  - ✓ ReentrantLock – starvation-free
- Good for low contention
- Sub-optimal for moderate to high contention: operations run sequentially

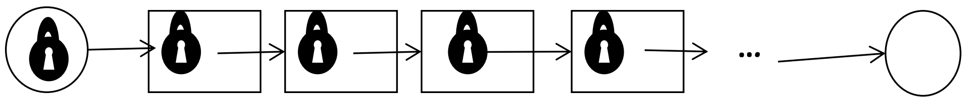
Locking schemes for a linked-list



Coarse-grained locking

2-phase locking





Hand-over-hand locking

Fine-grained solution: hand-over-hand

```
public boolean insert(int item){
        head.lock();
        Node pred=head;
        try {
          Node curr=head.next;
          curr.lock();
          try {
             while (curr.key < item){
                    pred.unlock();
                    pred = curr;
                    curr = pred.next;
                    curr.lock()
                }
              if (curr.key==item){
                        return false;}
              Node node = new Node(item);
               node.next=curr;
              pred.next=node;
              return true;
         } finally{
                  curr.unlock();
          }
    finally{
       pred.unlock();
    }
}
```

```
public boolean remove(int item){
        head.lock();
        try {
          Node pred=head;
          Node curr=pred.next;
           curr.lock();
          try {
             while (curr.key < item){
                    pred.unlock();
                    pred = curr;
                    curr = pred.next;
                    curr.lock()
                }
              if (curr.key==item){
                      pred.next=curr.next;
                      return true;}
             return false;
         } finally{
                  curr.unlock();
          }
    finally{
       pred.unlock();
    }
}
```

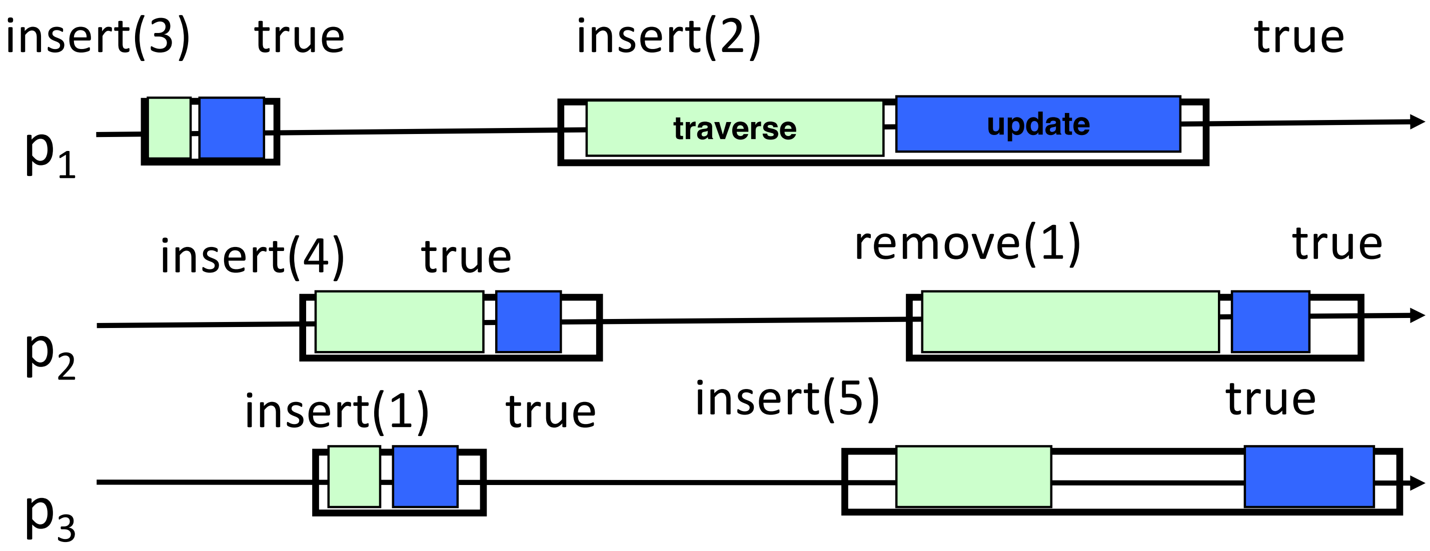
Hand-over-hand: concurrency limitations

```
public boolean contains(int item){
     head.lock();
      Node pred=head;
      try {
      Node curr=head.next;
      curr.lock();
      try {
      while (curr.key < item){
            pred.unlock();
            pred = curr;
            curr = pred.next;
            curr.lock()
       }
            return (curr.key==item);
       } finally{
            curr.unlock();
       }
   finally{
     pred.unlock();
   }
}
```

- More concurrency:
  - ✓ An operation working on a "high" node does not obstruct ones working on "low" nodes

Hand-over-hand: linearization

- Every complete operation is linearized within the critical section (between locks and unlocks)
- No update concerning pred or any subsequent node concurrently occurs: pred remains reachable as long as it is locked



Hand-over-hand: progress

- Starvation-freedom (assuming starvation-free locks)
  - ✓Operations acquire locks in the order of growing items: no deadlock possible
  - ✓Every lock acquisition eventually completes
  - ✓Traverse for item eventually reaches a node with item'≥ item
  - ✓Why?

- But! Operations concerning disjoint nodes may obstruct each other
  - ✓E.g. insert(2) obstructs insert(5), when applied to {3,4}
- Optimistic algorithm?
  - ✓No locks on the traverse path

Quiz 2.1: hand-over-hand

- Check if contains requires locking
  - ✓What if contains traversed the list without lock acquisition?
- What if traverse (in remove, insert) checks the value in curr before locking it (only holds lock on pred when traverse terminates)?
- Can we just use one lock at a time?
- Prove starvation-freedom (assuming starvation-free locks)
  - ✓Can an operation be blocked (delayed forever) by infinitely many concurrent inserts?

Optimistic:
wait-free traversal plus validation

```
public boolean remove(int item)
   while (true){
      Node pred=head;
      Node curr=pred.next;
      while (curr.key<item){
         pred=curr;
         curr=curr.next;
      }
      pred.lock(); curr.lock();
      try {
         if
   (validate(pred,curr)){
           if (curr.key==item) {

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

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

Validation necessary for updates?

Optimistic:
wait-free traversal plus validation

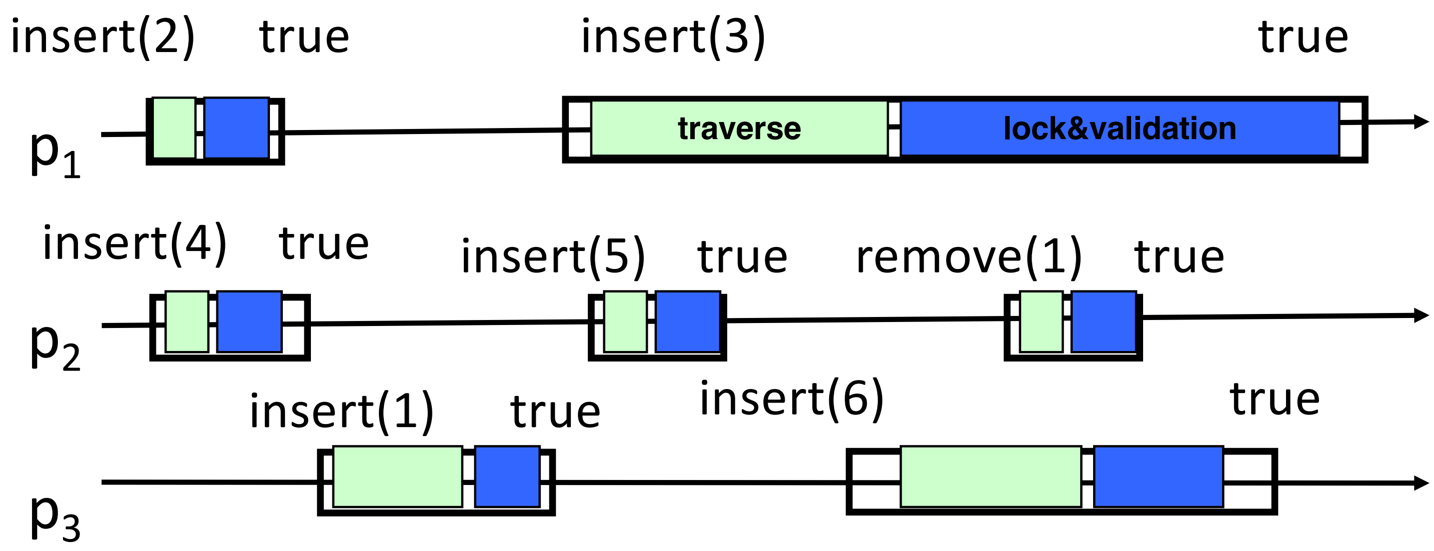
```
public boolean insert(int item){
   while (true){
      Node pred=head;
      Node curr=pred.next;
      while (curr.key<item){
         pred=curr;
         curr=curr.next;
      }
      pred.lock(); curr.lock();
      try {
         if (validate(pred,curr)){
           if (curr.key==item) {
               return false;
            }
           Node node = new Node(item);
           node.next=curr;
           pred.next=node;
           return true; }
      } finally{
         pred.unlock();
         curr.unlock();}
   }
}
```

```
public boolean contains(int item) {
   while (true){
      Node pred=head;
      Node curr=pred.next;
      while (curr.key<item){
         pred=curr;
         curr=curr.next;
      }
      pred.lock(); curr.lock();
      try {
         if (validate(pred,curr)){
            return (curr.key==item);
            }
      } finally{
         pred.unlock();
         curr.unlock();}
      }
   }
}
```

- contains grabs locks
- updates re-traverse even if no contention.

Optimistic: linearization

- Every complete operation is linearized within the critical section (between locks and unlocks)
- No update concerning pred and curr can take place concurrently
- And validation in the CS ensures that pred->curr are still reachable (possibly via a new path)



Quiz 2.2: optimistic

- Show that validation is necessary for updates
  - ✓Hint: consider an algorithm without validation and show that an update can get lost because of a series of concurrent removes
- Is validation necessary for contains?
- Show that the algorithm is not starvation-free (even if all locks are)

Lazy synchronization: logical removals and wait-free contains

```
private boolean validate(Node pred, Node
    curr) {

  return !pred.marked && !curr.marked &&
            pred.next==curr;
}
```

- remove first marks the node for deletion and then physically removes it
- contains returns true iff the node is reachable and not marked
- A node is in the set iff it is an unmarked reachable node

```
public boolean remove(int item)
   while (true){
      Node pred=head;
      Node curr=pred.next;
       while (curr.key<item){
         pred=curr;
          curr=curr.next;
       }
      pred.lock();
       try {
          curr.lock();
          try {
           if (validate(pred,curr)){
              if (curr.key!=item){
                  return false;}
              curr.marked=true;
              pred.next=curr.next;
              return true; }
          } finally{
              curr.unlock(); }
      } finally{
         pred.unlock();}
   }
}
```

Lazy synchronization: wait-free contains

```
public boolean insert(int item){
   while (true){
      Node pred=head;
      Node curr=pred.next;
      while (curr.key<item){
         pred=curr;
         curr=curr.next;
      }
      pred.lock();
      try {
         curr.lock();
         try {
          if (validate(pred,curr)){
           if (curr.key==item) {
              return false;
             }
           Node node = new Node(item);
           node.next=curr;
           pred.next=node;
           return true; }
         } finally{
            curr.unlock(); }
      } finally{
         pred.unlock();}
      }
}
```

```
public boolean contains(int item){

   Node curr=head;
   while (curr.key<item){
      curr=curr.next;
   }
   return (curr.key==item)&& !curr.marked ;
}
```

Quiz 2.3: lazy

- Show that both conditions in the validation check are necessary
  Hint: consider concurrent removes on two consecutive nodes, or a remove concurrent to an insert of a preceding node

- Is the check `!curr.marked` necessary in contains?

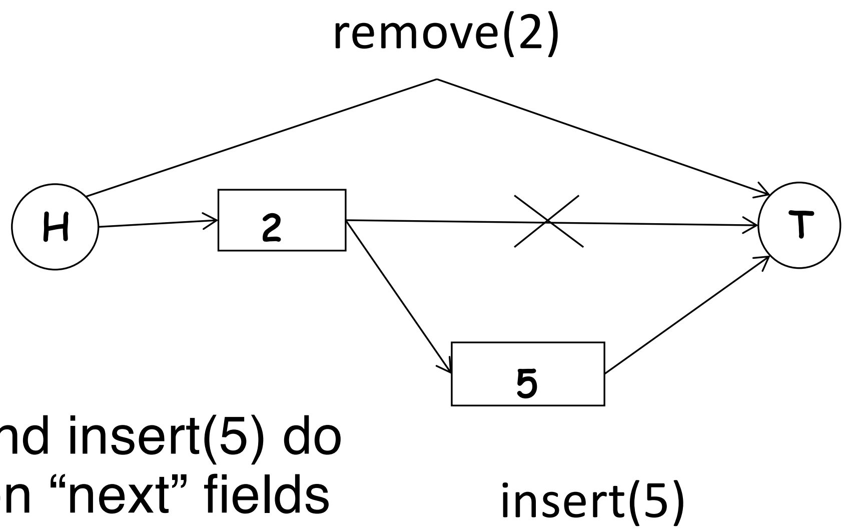
- Determine linearization points for all operations:
  - ✓ insert(successful or not)
  - ✓ remove (successful or not)
  - ✓ contains (successful or not)

  Hint: for an unsuccessful contains(x), linearization point may vary depending on the presence of a concurrent insert(x)

From locks to nonblocking

- Lazy [Heller et al.]: best of the class?
  - ✓contains wait-free
  - ✓add and remove are only deadlock-free
- Can we make updates lock-free?
  - ✓Wait-free for contains
- Replace read and update of curr.next with CAS?
  - ✓Not that easy: may need to atomically update the reference and check the logical deletion mark
  - ✓AtomicMarkableReference in java, bit stealing in C++
  - ✓Maintain reference to the next item and logical deletion mark "together"

Why AMR or bit stealing?



- remove(2) and insert(5) do not conflict on “next” fields
- insert(5) is lost!
- non-coupled logical deletion checks do not prevent “lost updates”

Nonblocking synchronization [Harris 2003]: lock-free updates and wait-free contains

```
public boolean remove(int item)
   …
while (true){
   \\ traverse with physical
   \\ removal of marked nodes
   \\ determine pred and curr

   if (curr.key!=item)){
            return false;}
   Node succ=curr.next.getReference();
   snip =
   curr.next.compareAndSet(succ,succ,
            false,true);
   if (!snip) continue;
   pred.next.compareAndSet(curr,succ,
            false,false);
\\ just try once
    return true;
   }
}
}
```

- Even lazier: a successful remove does not always unlink the node, but marks it for deletion
- Updates unlink nodes marked for deletion by previous removes
- Remove first tests if curr.next stores the expected reference and, if yes, logically marks curr (restart if no)
- Then it uses CAS on two fields: succeeds only if the reference and mark do not change

Nonblocking synchronization [Harris 2003]: lock-free updates and wait-free contains

```
public boolean insert(int item)
   …
while (true){
   \\ traverse with physical
   \\ removal of marked nodes
   \\ determine pred and curr

   if (curr.key==item)){
           return false;}
   Node node=new Node();
   node.next = new   AtomicMarkableReference(curr, false);
   if (pred.next.compareAndSet(curr, node, false, false))
           {
               return true;
   }
}
}
```

Insert atomically updates the markable reference pred.next with a reference to a new node, making sure sure that pred is not removed meanwhile

- **More details in [Herlihy and Shavit, Chapter 9.8]**

Conventional synchronization

- Locks are hard to use efficiently
- Nonblocking implementations with CAS have inherent (hardware) limitations
- Multiple operations cannot be easily composed

What can we do about it?

Transactions?

```
public class TxnList{

    private Node head;


    public boolean add(int item){
     atomic {
      Node pred=head;
      Node curr=head.next;
      while (curr.key < item){
            pred = curr;
            curr = pred.next;
      }
      if (curr.key==item){return false;}
      Node node = new Node(item);
      node.next=curr;
      pred.next=node;
      return true;
      }
     }
```

Transactional memory

- A transaction atomic {…} commits or aborts
- Committed transactions serialize:
  - ✓ Constitute a sequential execution
- Aborted transactions "never happened"
  - ✓ Can affect other aborted ones?
- A correct sequential program implies a correct concurrent one
- Composition is easy:

```
atomic{
        x=q0.deq();
        q1.enq(x);
}
```

So what is better?

It depends on:

- the data structure (some are more concurrency-friendly than others, cf. queues vs. lists)
- workload (high update-rate vs. read-dominated)
- Programming skills
- TM inherent costs

- Project (in teams): list-based sets in java
  - ✓What is better on what workload?
  - ✓SynchroBench: https://github.com/gramoli/synchrobench
  - ✓Compare Coarse-grained, HOH, Optimistic, Lazy
  - ✓Various update ratios, scales, list sizes
  - ✓Use a multiprocessor!
- Next time (30.09): discussion of exercises