Linked Lists: The Role of Locking

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Why Data Structures?

- Concurrent Data Structures are building blocks
  - Used as libraries
  - Construction principles apply broadly
This Lecture

• Designing the first concurrent data structure: the linked-list
  – How do we use locks?
  – How do we achieve progress guarantees
Proper Credit

Several drawings are taken from the book, or from its accompanying slides.
Locking vs. Progress Guarantees
Counter Example

T1
local := counter
local++
counter := local

T2
local := counter
local++
counter := local

concurrent execution is not safe!
Use a Lock

Lock (L)
local := counter
local++
counter := local
Unlock(L)

Synchronization:
Only one thread can acquire a lock L
Compare and Swap (CAS)

- CAS (addr, expected, new)

  **Atomically:**
  
  ```
  if (MEM[addr] == expected) {
    MEM[addr] = new
    return (TRUE)
  } else return (FALSE)
  ```
Use a Lock or a CAS

Lock (L)
local := counter
local++
counter := local
Unlock(L)

START:
old := counter
new := old ++
if ( !CAS(&counter,old,new) )
goto START

Synchronization:
Only one thread can acquire a lock L

Synchronization:
Only one thread changes from old in a concurrent CAS.
Use a Lock or a CAS

Lock (L)
local := counter
local++
counter := local
Unlock(L)

START:
old := counter
new := old ++
if ( !CAS(&counter,old,new) )
goto START

Issues:
Efficiency, scalability, Fairness, progress guarantee, design complexity.
What Does “Lock-Free” Mean?

- First try: “never using a lock”.
- Well, is this using a lock? (word is initially zero.)

```c
while (!CAS(&word,0,1)) {}  
local := counter  
local++;  
counter := local  
word := 0
```

- It is not easy to say if something is a “lock”.
What Does “Lock-Free” Mean?

- **Better**: “No matter which interleaving is scheduled, my program will make progress.”.
- A.k.a. non-blocking.
- Our second example is lock-free.

```plaintext
START:
old := counter
new := old ++
if (!CAS(&counter,old,new))
goto START
```
Lock-Freedom

If you schedule enough steps across all threads, one of them will make progress.

- **Realistic (though difficult):** Various lock-free data structures exist in the literature (stack, queue, hashing, skiplist, trees, etc.).

- **Advantages:** Worst-case responsiveness, scalability, no deadlocks, no livelocks, added robustness to threads fail-stop.
Linked List: Our First Example

Fine-grained locking and lock-freedom
The Linked List

Support: insert, delete, contains.
Implements a set: no duplicates, order maintained.
Sequential Implementation

• Delete 6:

• Insert 7:
But don’t try this concurrently!

- Delete 6 || Insert 7:

- A similar problem with concurrent deletes.
Solutions

- **Coarse-grained locking.**
  - Sequential with overhead...
- **Fine-grained locking**
  - hand-over-hand, optimistic, lazy synchronization.
- **Lock-free** (or wait-free) implementation.
scalability / performance
Fine-Grained Locking

#1:

Hand-Over-Hand
Hand-over-Hand locking
[Bayer-Schkolnik 1977]
Operation 1: Remove a Node

remove(b)
Removing a Node

remove(b)
Removing a Node

remove(b)
Removing a Node

remove(b)
Removing a Node

remove(b)
Removing a Node

Why do we need to always hold 2 locks?
Concurrent Removes

remove(b)
remove(c)
Concurrent Removes

remove(b)

remove(c)
Concurrent Removes

```plaintext
remove(b)
remove(c)
```
Concurrent Removes

\[ \text{remove}(b) \quad \text{remove}(c) \]
Concurrent Removes

- remove(b)
- remove(c)
Concurrent Removes

remove(b)

remove(c)
Uh, Oh

remove(b)

remove(c)
Uh, Oh

Bad news, C not removed

remove(b)

remove(c)
With Two Locks

remove(b)

remove(c)
Removing a Node

remove(b)

remove(c)
Removing a Node

- remove(b)
- remove(c)
Removing a Node

remove(b)

remove(c)
Removing a Node

remove(b)

remove(c)
Removing a Node

remove(b)

remove(c)
Removing a Node

remove(b)

remove(c)
Removing a Node

Must acquire Lock of b

remove(c)
Removing a Node

Cannot acquire lock of b

remove(c)
Removing a Node

Wait!

remove(c)
Removing a Node

Proceed to remove(b)
Removing a Node

```
remove(b)
```
Removing a Node

```
remove(b)
```
Removing a Node

\[ \text{remove(b)} \]
Removing a Node

![Diagram showing the removal of a node from a linked list. The node labeled 'a' is being removed, and the connection to the node labeled 'd' is maintained.](image)
Adding Nodes

• To add node e
  – Go hand-over-hand
  – Lock predecessor
  – Lock successor
• Neither can be deleted
• Actually it is enough to lock predecessor (for an insert).
  – But must go hand-over-hand.
No Deadlock

- In general, no deadlock if locks are always acquired in the same order.
Why Is It Correct

• The idea: snapshot.
• Each thread sees all operations executed “earlier”, and no operation that started “afterwards”.
• Start time: take head’s lock.
• Implications:
  • sequentialization of operations
  • Good only for “hierarchical” data structures.
Properties

• Scalability better than coarse-grained locking.
• But long chains of threads waiting for the first thread to advance.
  – Limited parallelism.
• Excessive locking harms performance.

• Can we obtain more parallelism and better performance?
Second List: Optimistic

(First was hand-over-hand.)
Optimistic Synchronization
[Herlihy-Shavit 2008]

• Find nodes without locking
• Lock nodes
• Check that everything is OK
Optimistic: Traverse without Locking

add(c)

Aha!
Optimistic: Lock and Load

add(c)
What could go wrong?

Aha!

add(c)

remove(b)
First node must be in the list!

- While holding the lock, check that first node is reachable from the head.
- While we hold the lock this node cannot be removed.
Validate – Part 1
(while holding locks)

Yes, b still reachable from head (after locks acquired!)
What Else Can Go Wrong?

add(c)
What Else Can Go Wrong?

add(c)

add(b')
What Else Can Go Wrong?

add(c)

Aha!
First node must still point to second!

- Validation 1: first node still reachable.
  - While we hold the lock the node cannot be removed.
- Validation 2: first node pointing to second.
  - While we hold the lock the pointer from the first node cannot be modified (no adding and no removing).
Validate Part 2 (while holding locks)

Yes, b still points to d (after locks were acquired!)
Validation Failure?

• Upon failure to validate start from scratch.
• Assumed to happen infrequently.
Insert (After Validation)
Optimistic Synchronization

• More parallelism, better scalability.
  – Only lock nodes where actually modifying.
  – Scalability depends on the actual workload.

• Excessive work on validation (double traversal).
  – Less efficient.

• There is another fine-grained locking methodology.
  – But let’s jump to lock-freedom
Third List: Lock-Free

We did hand-over-hand and optimistic
Lock-Freedom

• Don’t use locks.
• And more important: guarantee progress!
  – Complete robustness against worst-case scheduling
  – No swapping problems
  – Even when a thread dies, the other threads will continue to make progress.

• Design by [Harris 2001], improvement by [Michael 2002].
Lock-Free Linked Lists
[Harris-Michael 2001-2]

• First attempt: insert/delete using CAS instead of a regular read/write operation.
First Attempt: Use CASes Instead of Locks

• Delete 6:

• Insert 7:
The original problem still exists

- Outcome for deleting 6 and inserting 7 in parallel:
We Keep the Simple Insert

- A single CAS to insert 7, after locally allocating and initializing it.

  ![Diagram](image)

- But *delete* will be more complicated.
Recall the Problem

- Outcome for deleting 6 and inserting 7 in parallel:
The Crux of the Problem

- When deleting 6, we want to block changes both on the pointer that points at 6, as well as the pointer that points out of 6.
The Crux of the Problem

• When deleting 6, we want to block changes both on the pointer that points at 6, as well as the pointer that points out of 6.

• Harris’s idea:
  1. “mark” the pointer out of 6, and then
  2. “modify” the pointer out of 4.
Solution: Mark & Delete

- Logically delete 6 by marking the outgoing pointer of 6.

- Physically delete 6 by unlinking it from the list.
Implementing a “Red Pointer”

• Use least bit.
• Essentially unused with pointers as words are composed of 4 or 8 bytes.

Unmarked: 00010…1010010101110000100
Marked: 00010…10100101011100000101
Logical Deletion

Logical Removal =
Set Mark Bit

Mark-Bit and Pointer are CASed together

Physical Removal CAS

An attempted insert will fail the CAS after logical removal
Concurrent Removal

- remove b
- CAS
- CAS
- failed
- remove c
Removing a Node

- Remove node b
- Remove node c
Removing a Node

- Remove node b
- Remove node c
Traversing the List

• When you find a “logically” deleted node in your path:
  – Finish the job:
    • CAS the predecessor’s next field,
  – Proceed (repeat as needed).
Lock-Free Traversal
(only Add and Remove)
CAS Failures

- Node removal:
  - Logical remove fails: start from scratch.
  - Physical remove fails: ignore.
    - Why?

- Node insert:
  - CAS fails: start from scratch.
Why is it Lock-Free?

• **Node removal:**
  – Logical remove fails:
    either someone else has succeeded to *remove* this node, or
    someone else has *inserted* a node.
  – Logical remove succeeds:
    I succeeded to delete a node (and will finish the operation after
    trying the physical remove once).

• **Node insert:**
  – CAS fails: someone else succeeded to *insert* or *delete* a node.
  – CAS succeeds: I succeeded in inserting a node.
The Main Intuition

• Logical marking locks the next pointer from being modified.
• But this “lock” can be unlocked by anyone (by trimming the node from the list), so no one is stuck.
• Different from “normal” locking that only the owner can unlock.
• This is the methodology in all lock-free algorithms:
  – Make a change in the data structure, leaving it “unstable”.
  – Anyone can stabilize the data structure and continue to work on it.
Progress Guarantees are good for

- Real-time, OS, interactive systems, service level agreements, etc.
- But it’s always good to have.
  - Avoid deadlock, live-lock, convoying, priority inversion, etc.
- Scalability.
Progress Guarantees

**Great guarantee!**
Until recently considered difficult to achieve and inefficient.

**Wait-Freedom**
If you schedule enough steps of *any thread*, it will make progress.

**Lock-Freedom**
If you schedule enough steps across *all threads*, one of them will make progress.
Contains is Wait-Free

- Contains(key);
  - curr = head;
  - while (curr.key < key)
    - curr = removeMark ( curr.next )
    - succ = removeMark ( curr.next )
  - return (curr.key == key && !marked(curr.next) )
Fourth List:

Third (and Best) Fine-Grained Locking:

Lazy List

We discussed hand-over-hand, optimistic, and lock-free.
Lazy Synchronization

[Heller et al. 2005]

• Lock only relevant nodes
• Do not validate reachability
• Instead, leave a mark on deleted nodes, like in lock-free algorithm.

• To remove a node:
  – Logically remove it by marking it “removed”.
  – Physically remove it by unlinking it.
Remove or Add

- Scan through the list
- Lock predecessor and current nodes
- Validate that
  - both are not deleted, and that
  - predecessor points to current.
- Perform the add or the remove.
- Search can simply traverse the list.
Lazy List
Lazy List

Art of Multiprocessor Programming
Lazy List
Lazy List

remove(b)
Lazy List

The diagram illustrates a lazy list, where nodes a, b, and c are connected in a specific order, with node a not being marked as ready for processing.
Lazy List

Diagram showing a lazy list with elements 'a', 'b', and 'c'. The element 'b' is not marked, indicated by a thought bubble saying 'b not marked'.
Lazy List

- The diagram illustrates a lazy list structure where elements a, b, and c are connected.
- Element a still points to element b.

Art of Multiprocessor Programming
Lazy List

Art of Multiprocessor Programming
Lazy List

physical delete
Lazy List
Invariant

• If a node is not marked then its key is in the set
  – and reachable from head
The contains Method

- Simply traverses the list and reports finding.
- Very efficient, progress guaranteed.
  - Wait-free
- Most “popular” method.
Properties of Lazy List

• Good performance
  – no rescanning,
  – a small number of locks,
  – hopefully not too many validation failures

• Good scalability
  – Lock only relevant nodes.

• Still standard locking problems
  – No progress guarantee
  – A thread holding a lock may face a cache-miss, page-fault, swap-out, etc.
  – Worst-case scalability issues, scheduler critical here…
Summary

- Starting data structures
- Locking and Lock-freedom
- Linked list (ordered for sets)
- Parallization problems
- Fine grained locking:
  - Hand-over-hand
  - Optimistic
  - Lazy
- Lock-Free version
Which List Should You Use?

- If little contention: coarse-grained locking.
- To handle contention pretty well: lazy list.
- To handle high contention and provide a progress guarantee: lock-free list.
The End