# *Lock-free Programming*

Nathaniel Wesley Filardo

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# *Outline*

# *Introduction*

- Suppose some madman says "We shouldn't use locks!"
- You know that this results (eventually!) in inconsistent data structures.
  - Loss of invariants within the data structure
  - Live pointers to dead memory
  - Live pointers to undead memory (Hey, my type changed! Stop poking there!)

# *Introduction*
## *Locks Might Take A While*

- Consider `XCHG` style locks which use `while( xchg( &locked, LOCKED ) == LOCKED )` as their core operation.
- We could spend an unbounded amount of time here waiting...
- This implies we'll have very high latency *on contention*...
- Locks *by definition* reduce parallelism.

# *Introduction*
# *Locks Might Take A While*

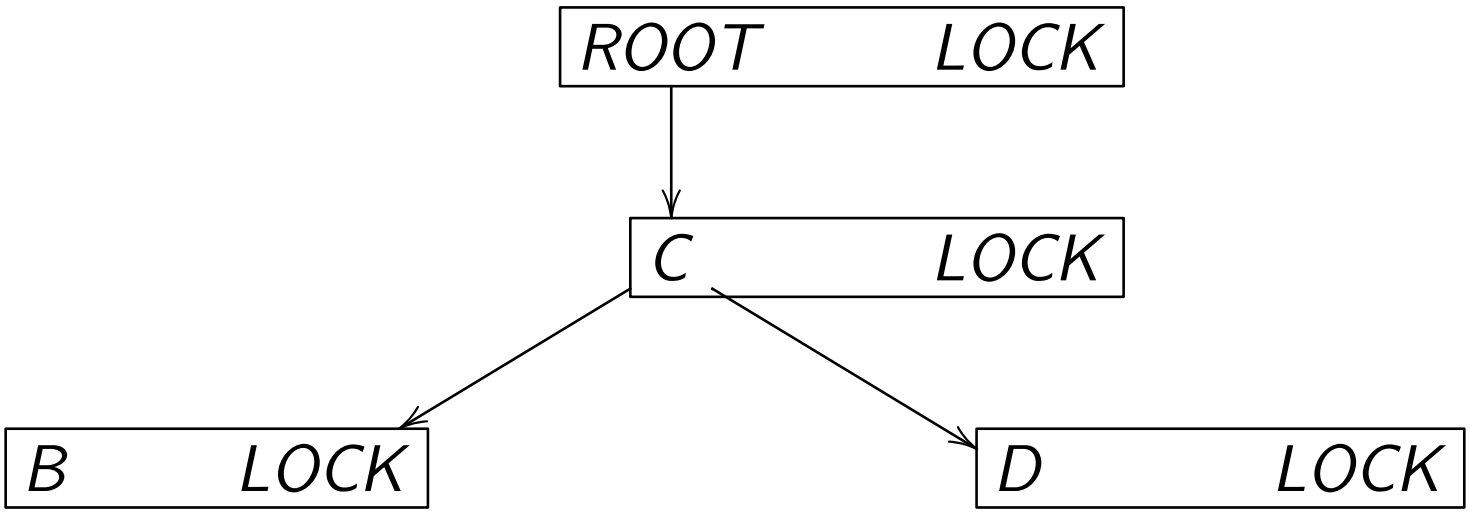
- That is, if $N$ people are contending for a lock, $N - 1$ of them are just wasting time.
- It would be nice if they could all work at once . . .
- . . . being careful not to step on each other when there was actually a problem.

# *Introduction*
# *Locks Might Take A While*

- For a large data structure, we would *like* multiple *local* (independent) operations to be allowed concurrently.
  - *e.g.* "lookup" and "insert" in parallel threads
- Can somewhat get this with a data structure full of locks
- . . . but order requirements mean that threads can still pile up while trying to get to their local site.

## *Introduction*
## *Locks Can Be... Not So Bad?*

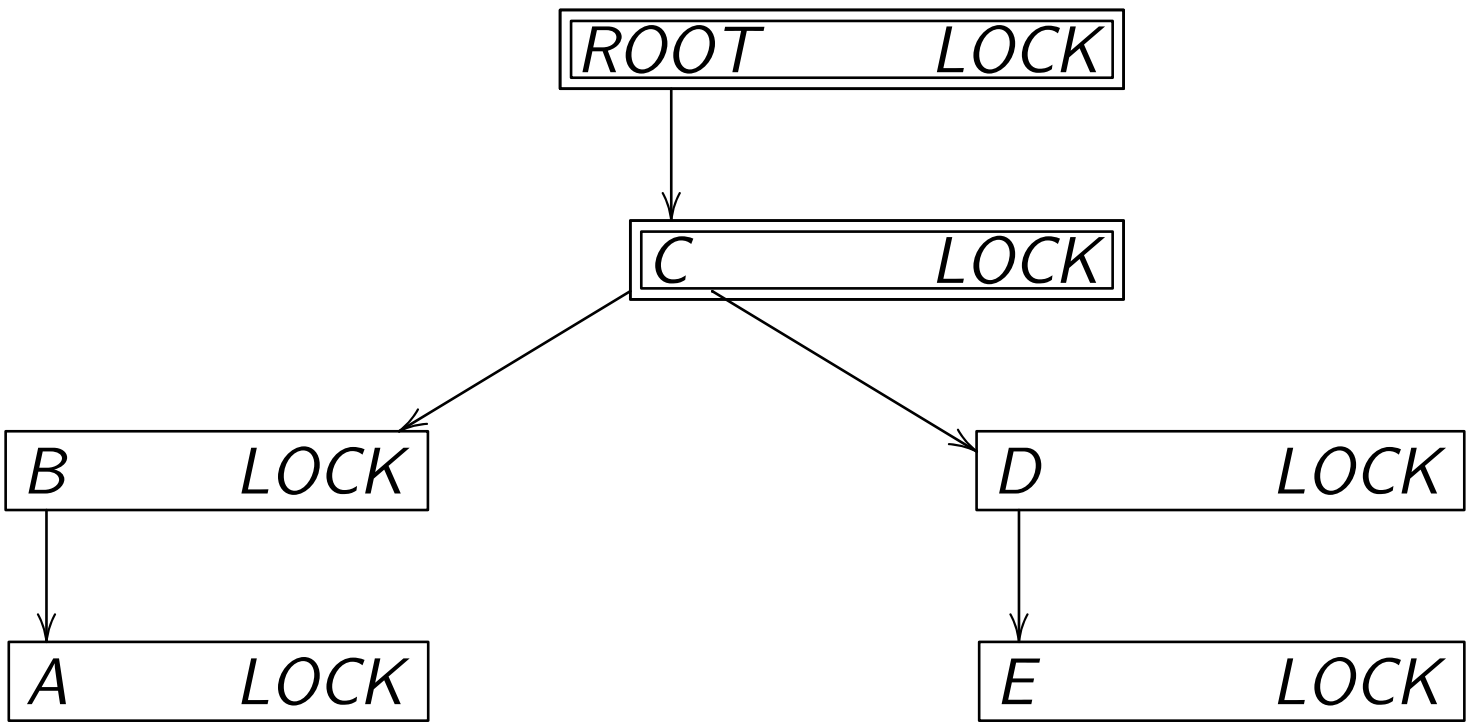
- Instead of a lock around a tree, we could have a tree with locks:




- The protocol is lock the root, then (lock child & unlock parent) as you go down.
  - This kind of *lock handoff* is a very common design.
- Here every time a thread decides to go down one branch, it gets out of roughly half of the others' ways.

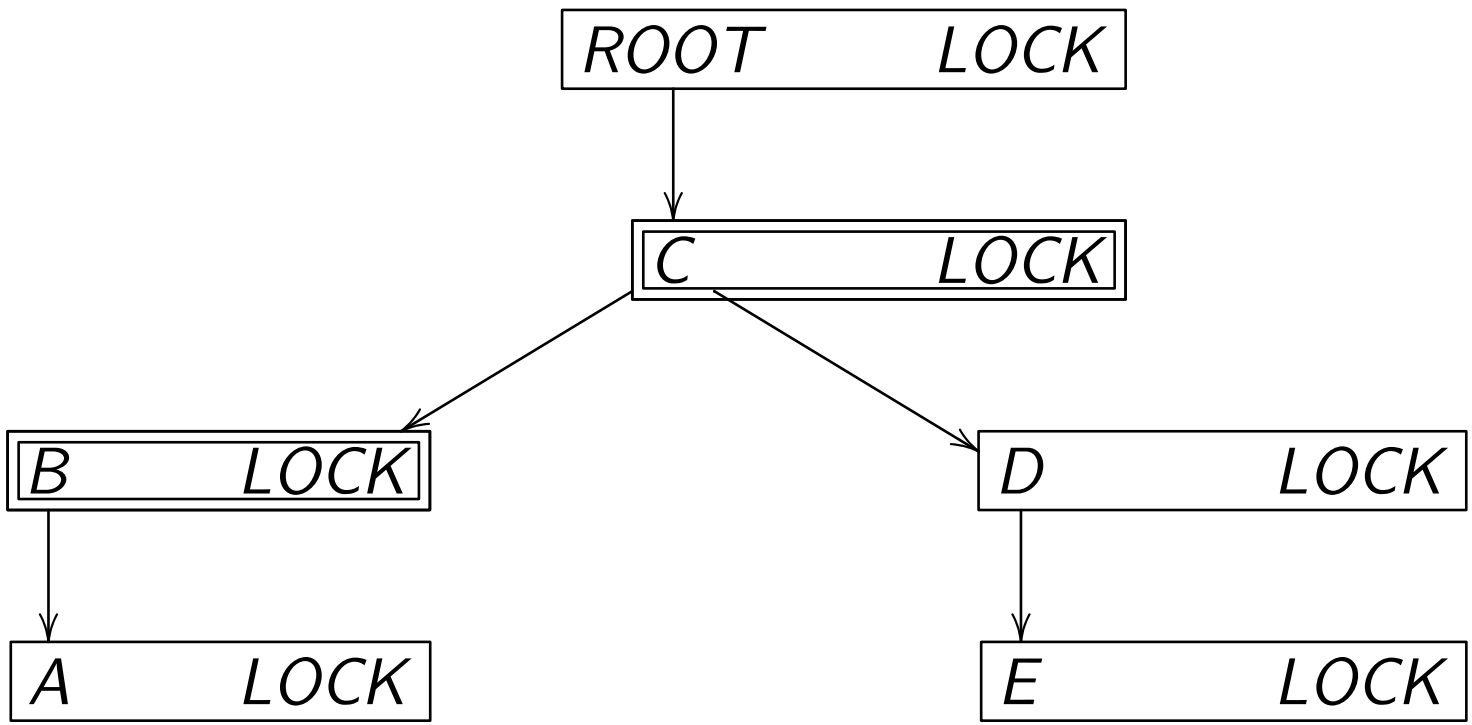
## *Introduction*
## *Locks Can Be. . . Not So Bad?*

- Trying to find node A.
- Step 1: lock root pointer and top node



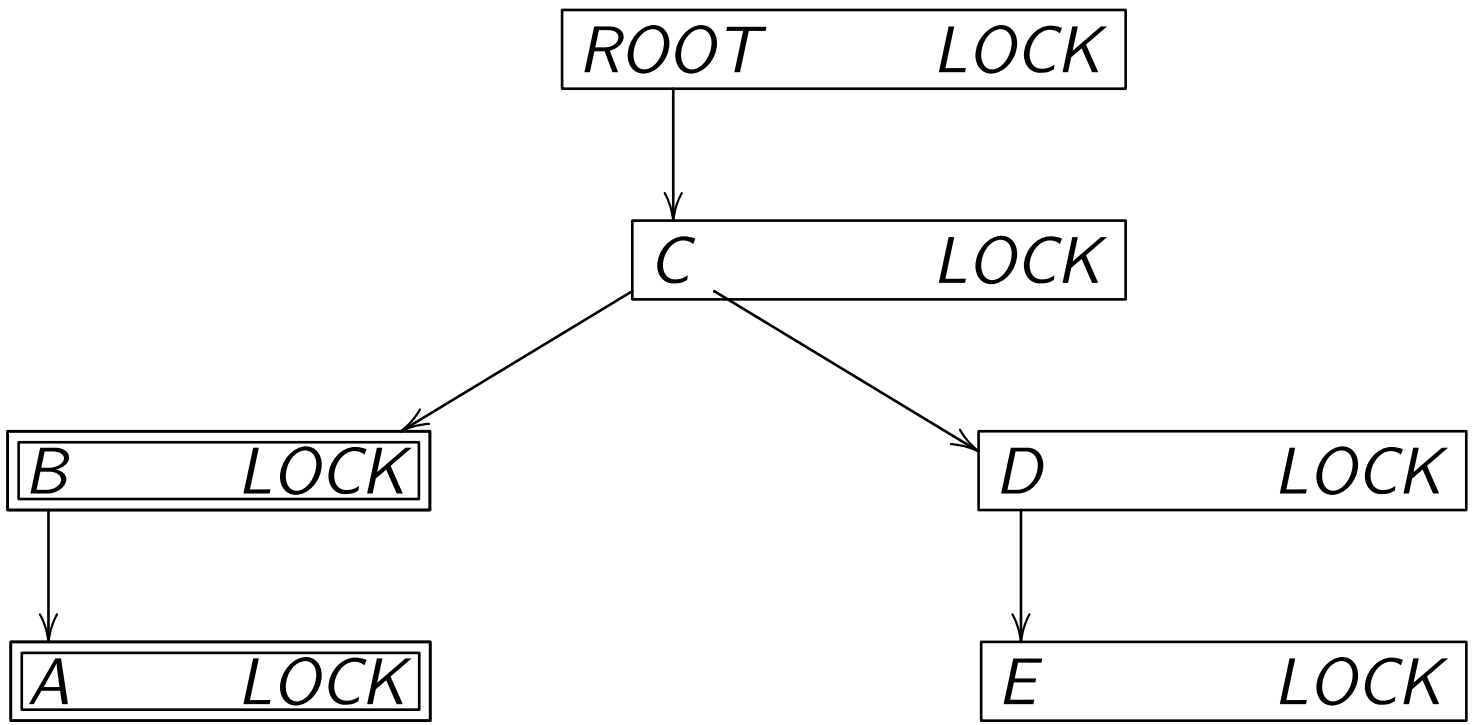
## *Introduction*
## *Locks Can Be... Not So Bad?*

- Trying to find node A.
- Step 2: lock left child and unlock parent.



## *Introduction*
## *Locks Can Be... Not So Bad?*

- Trying to find node A.
- Step 3: lock left child and unlock parent



# *Introduction*

But let's see what we can do without any locks at all.

# *Lock-Free Linked List Insertion*

Lock-Free Linked List Node
Insertion into a Linked List Without Locks
Review of Atomic Primitives
Insertion into a Lock-free Linked List

## *Lock-Free Linked List Node*

- Node definition is simple:

| `label_t label` |
|---|
| `void* next` |

- When drawing, we'll use a shorthand:

| `label_t label = A` |
|---|
| `void* next = &B` |

$\Leftrightarrow$

| $A$ | $\&B$ |
|---|---|

## *Insertion into a Linked List Without Locks*
## *Insertion Code*

```
insertAfter(after, newlabel) {
   //lockList();
   new = newNode(newlabel);
   prev = findLabel(after);
   new->next = prev->next;
   prev->next = new;
   //unlockList();
}
```

*Insertion into a Linked List Without Locks*
*"Good trace" in 410 notation*

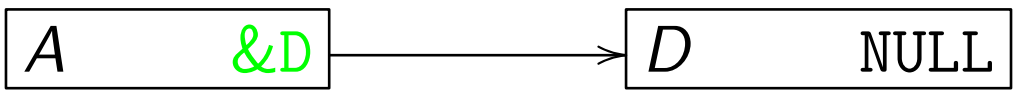
| `insertAfter(A,B)` | `insertAfter(A,C)` |
|---|---|
| prev = &A | |
| `B.next=A.next` | |
| `A.next=B` | |
| | `prev = &A` |
| | `C.next=A.next` |
| | `A.next=C` |

*Insertion into a Linked List Without Locks*
*Race trace in 410 notation*

| `insertAfter(A,B)` | `insertAfter(A,C)` |
|---|---|
| `prev = &A` | |
| `B.next = A.next` | |
| | `prev = &A` |
| | `C.next = A.next` |
| `A.next = B` | `A.next = C` |

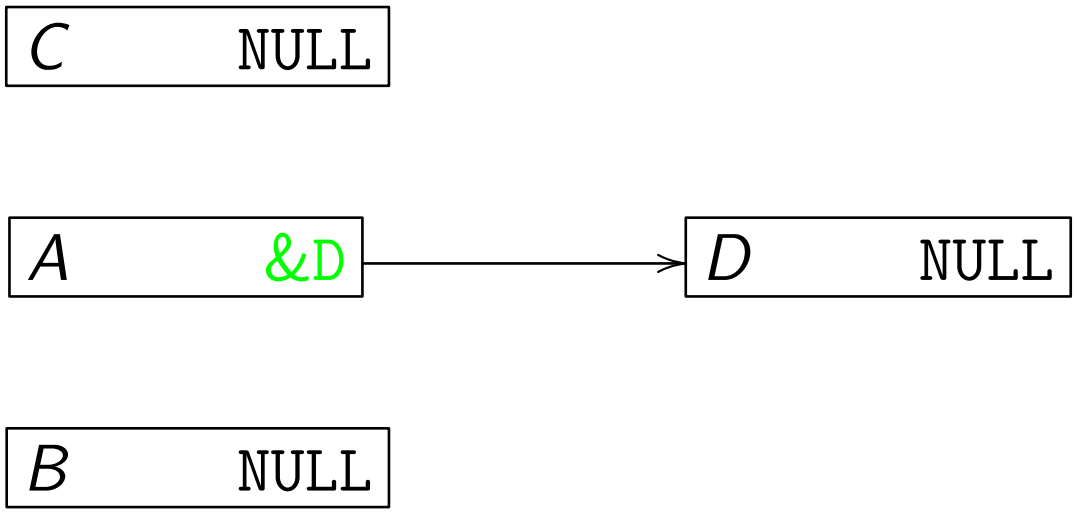
- Either of these assignments makes sense in isolation, but one of them will override the other!

# *Insertion into a Linked List Without Locks Precondition*




- One list, two items on it: *A* and *D*.

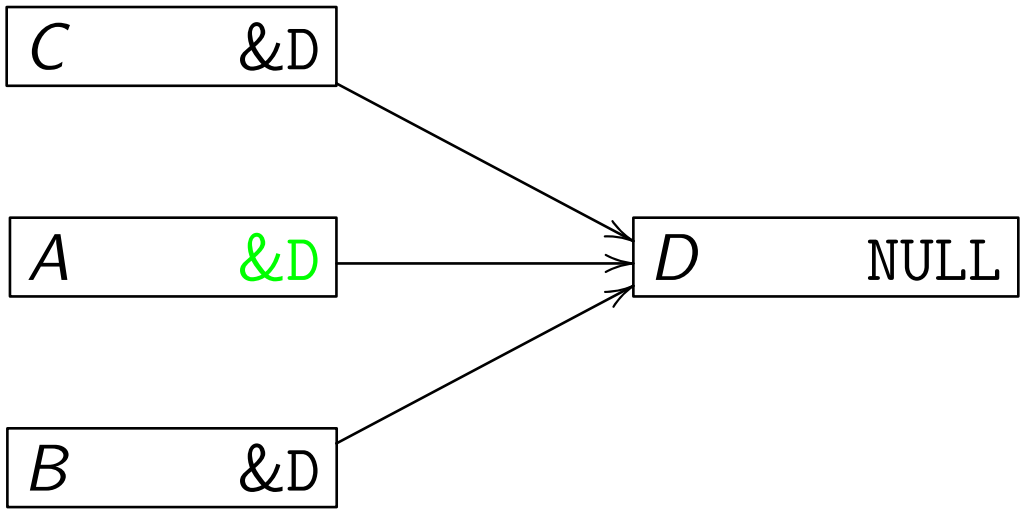
## *Insertion into a Linked List Without Locks*
## *First step*




- Two threads get two nodes, $B$ and $C$, and want to insert.

| new = newNode(B); | new = newNode(C); |
|---|---|
| prev = &A | prev = &A |

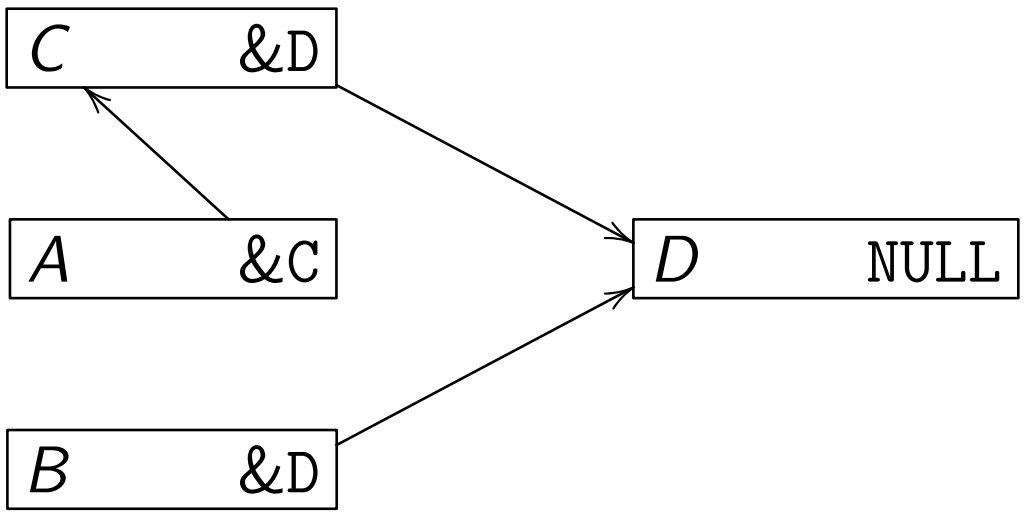
## *Insertion into a Linked List Without Locks*
## *Second step*




- Two threads point their respective nodes $C$ and $B$ into list at $D$

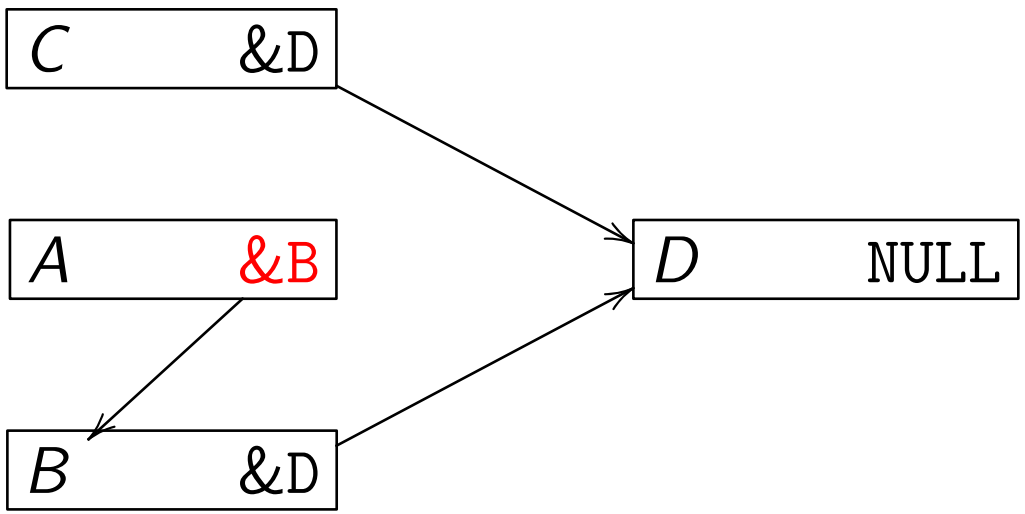
| B.next=&D | C.next=&D |
|---|---|

*Insertion into a Linked List Without Locks*
*One thread goes*

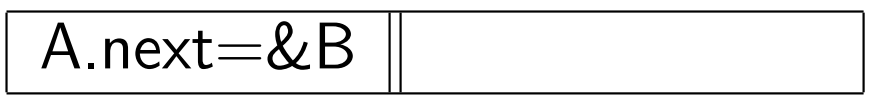



- Suppose the thread owning $C$ completes its assignment first.

*Insertion into a Linked List Without Locks*
*And the other...*




- And the other (owning $B$) completes second, overwriting




- Node $C$ is unreachable!

## *Insertion into a Linked List Without Locks*

- What went wrong?
  1. Thread `B` observed that `&A->next == D`
  2. Thread `C` observed that `&A->next == D`
  3. Thread `C` changed `&A->next` "from `D` to `C`"
  4. Thread `B` changed `&A->next` "from `D` to `B`"
     - But it was `C` not `D`!
- How to fix that?
  - Give `B` and `C` critical sections and serialize them
    - Then there is no gap between observation and changing
    - But that requries locking, which we are avoiding...
  - Take two: assume mistaken beliefs about memory's contents are rare, clean up afterward!

## *Insertion into a Linked List Without Locks*
## *The Lock Free Approach*

```
while(not done)
    Prepare for update (e.g. set next pointer)
    Determine preconditions for the update
    ATOMICALLY
      if(preconditions hold)
        make update;
        done = true;
```

- Unlike critical sections, this is not (really) bounded
  - Could "encounter trouble" unboundedly.
- But as long as threads "almost always" don't do spatially overlapping updates...
  - Then we gain in parallelism by having not locked.

## *Insertion into a Linked List Without Locks*

- Our assignments were really supposed to be

| `insertAfter(A,B)` | `insertAfter(A,C)` |
|---|---|
| `while(!done)` | `while(!done)` |
| `  setup` | `  setup` |
| `  ATOMICALLY` | `  ATOMICALLY` |
| `  if (A->next == D)` | `  if (A->next == D)` |
| `  A->next = B` | `  A->next = C` |
| `  done = 1` | `  done = 1` |

- If we do that, one critical section will *safely* fail out and tell us to try again.
- How do we do this *ATOMICALLY* without locking?

## *Review of Atomic Primitives*

- Remember our old friend `XCHG`?
- `XCHG (ptr, val)`

```
ATOMICALLY  // lock bus
    old_val = *ptr;
    *ptr = val;
    // unlock bus
    return old_val;
```

- Summary: one fetch and one store under the same (mini) lock.

## *Review of Atomic Primitives*

| XCHG(ptr,new) | CAS(ptr, expect, new) |
|---|---|
| *ATOMICALLY* | *ATOMICALLY* |
| old = *ptr; | old = *ptr; |
| | if(old == expect) |
| *ptr = new; | *ptr = new; |
| return old; | return old; |

Note that CAS is no harder:

- Still one read, one write under same lock.
- (logic time $\ll$ memory time)

## *Insertion into a Lock-free Linked List*

- Our assignments were really supposed to be

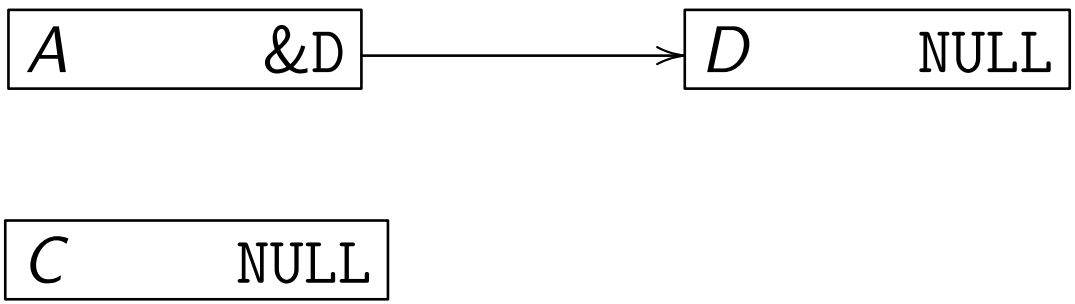
| `insertAfter(A,B)` | `insertAfter(A,C)` |
|---|---|
| `while(!done)` | `while(!done)` |
| `setup` | `setup` |
| *`ATOMICALLY`*<br>`if (A->next == D)`<br>`A->next = B`<br>`done = 1` | *`ATOMICALLY`*<br>`if (A->next == D)`<br>`A->next = C`<br>`done = 1` |

- This translates into

```
while(!done)
   prev = B->next = A->next;
   done = (CAS(&A->next,prev,B) == prev)
```

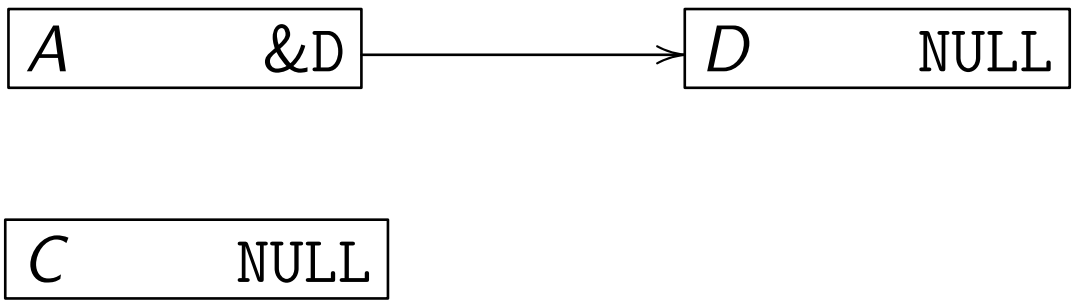
- CAS will assign if match, or bail otherwise.

## *Insertion into a Lock-free Linked List*
## *Simple case, setup*

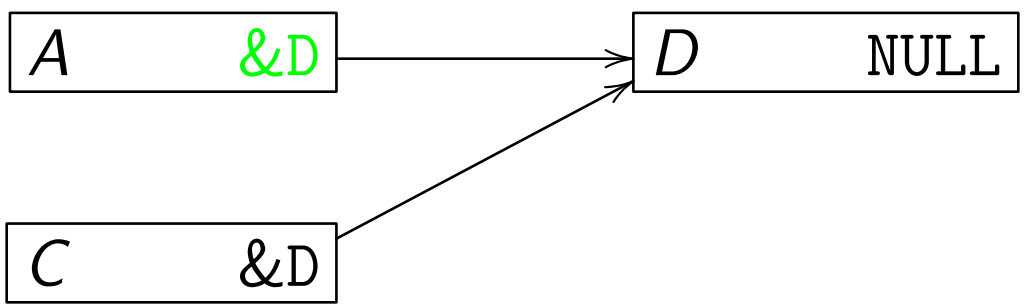



- Some thread constructs the bottom node $C$; wishes to place it between the two above, $A$ and $D$.
- `new = newNode(C);`
- `prev = findLabel(A); /* == &A */`

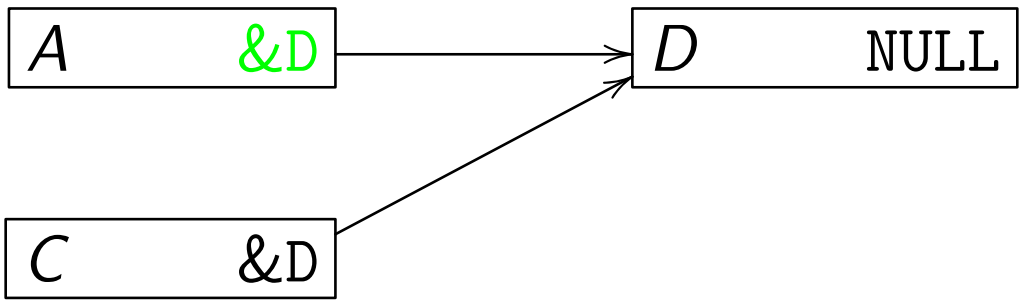
## *Insertion into a Lock-free Linked List*
## *Simple case, first step*



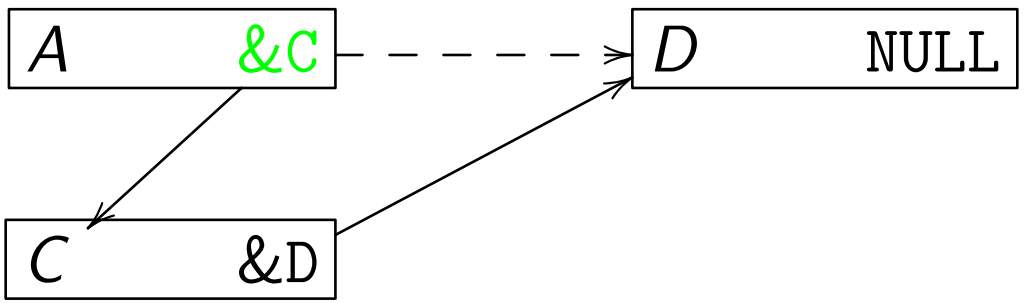

- Thread points *C* node's next into list at *D*.
- `C.next = A.next;`



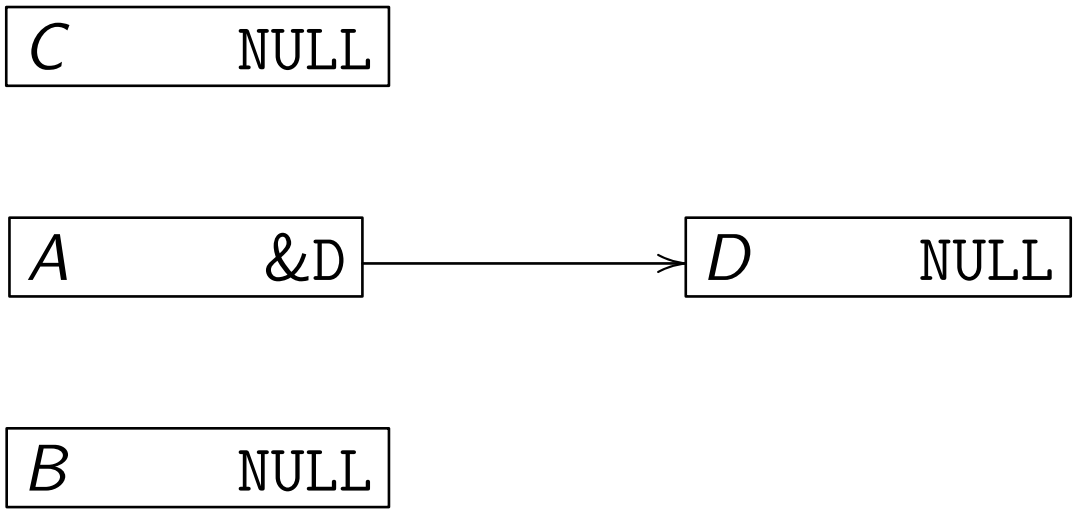
# *Insertion into a Lock-free Linked List*
## *Simple case, second step*




- `CAS(&A.next, &D, &C);`



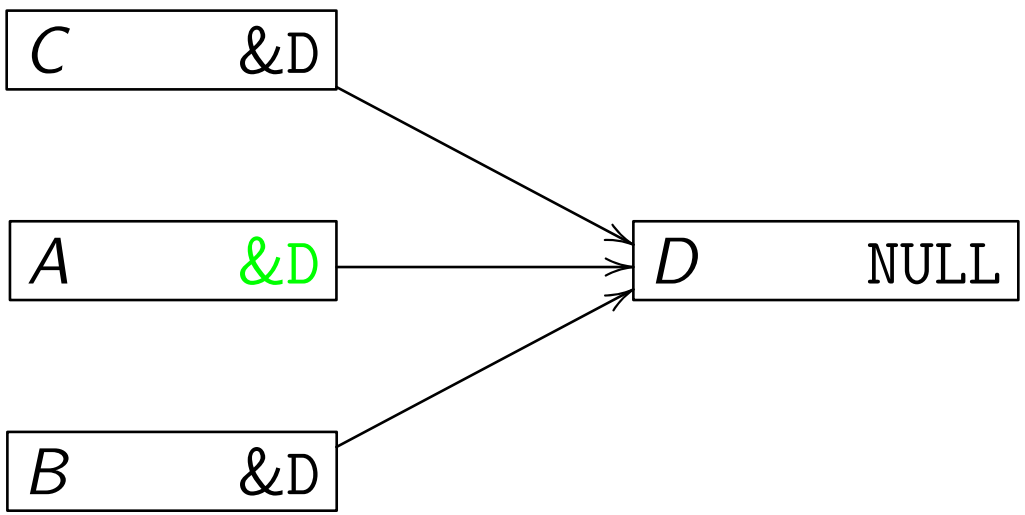
*Insertion into a Lock-free Linked List*
*Race case, setup*




- Two threads get their respective nodes $B$ and $C$.

| new = newNode(B); | new = newNode(C); |
|---|---|
| prev = &A | prev = &A |

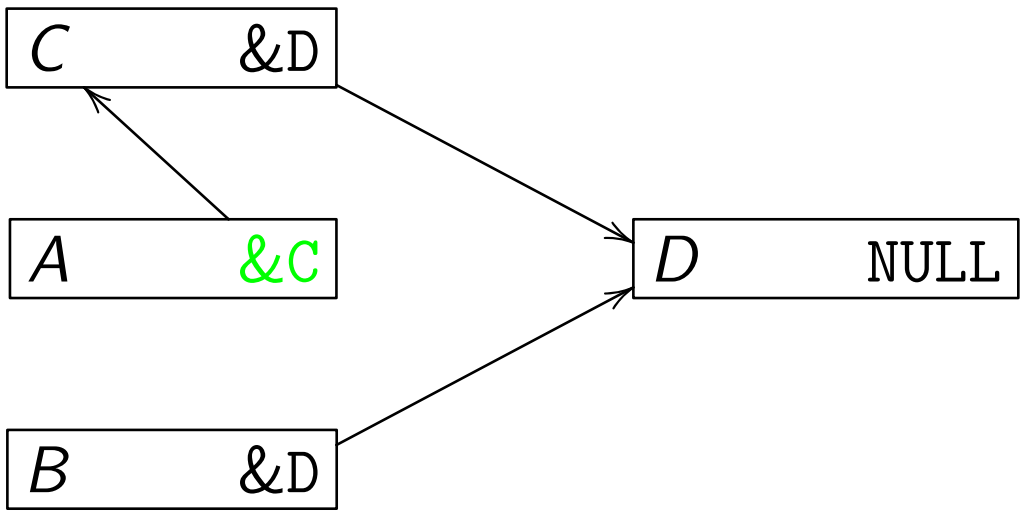
*Insertion into a Lock-free Linked List*
*Race case, first step*




- Both set their new node's next pointer.

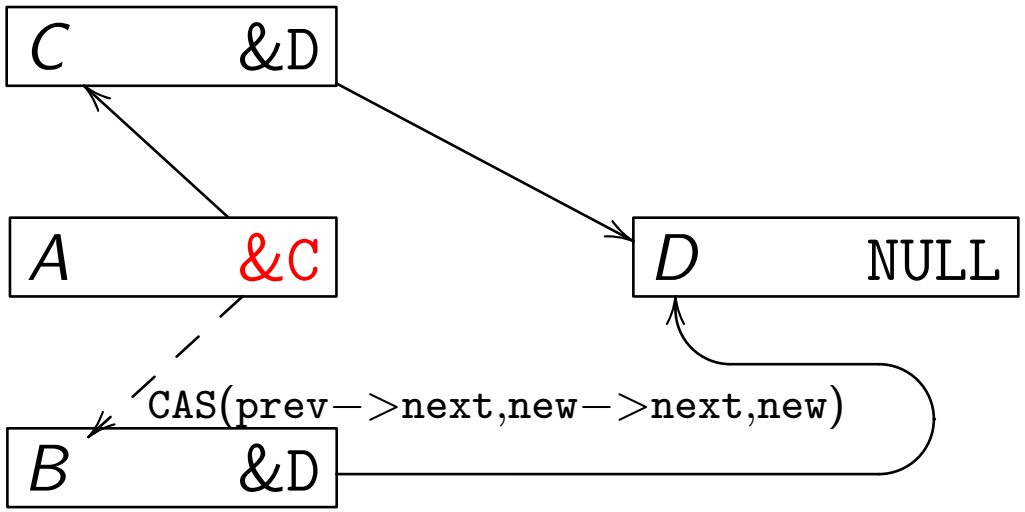
| B.next=&D | C.next=&D |
|---|---|

*Insertion into a Lock-free Linked List*
*Race case, first thread*




- Thread *C* goes first . . .

## *Insertion into a Lock-free Linked List*
## *Race case, second thread*




- And the other (owning $B$)...

```
CAS(&A->next, D, B)
```

- ...fails since `A->next == C`, not `D`.
- So this thread tries again.

## *Insertion into a Lock-free Linked List*

- Rewrite the insertion code to be

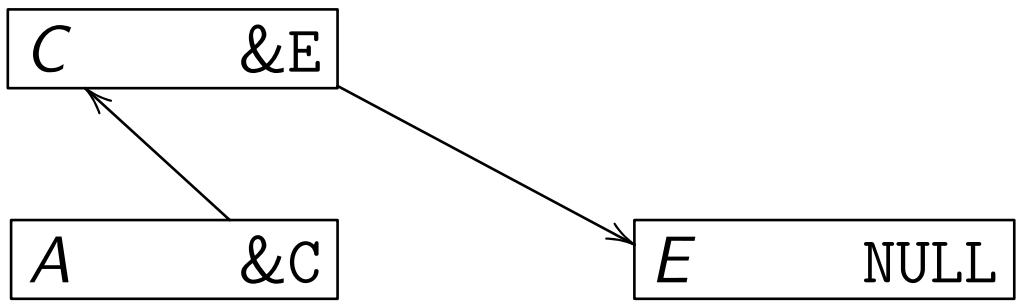
```
insertAfter(after, newlabel) {
   new = newNode(newlabel);
   do {
     prev = findLabel(after);
     expected = new->next = prev->next;
   } while
     ( CAS(&prev->next, expected, new)
                != expected);
}
```

*That's great!*

- It works!
  - No locks!
  - Threads can simultaneously scan and scan the list...
  - Threads can simultaneously scan and *grow* the list!
  - Threads can simultaneously *grow* and grow the list!
- All those while loops... (retrying over and over?)
  - Remember, mutexes had while loops too...
    - maybe even around `CAS()`!
  - Here, whenever we retry we *know* somebody else got work done!
- Are we done?
  - Have we implemented all the standard operations?

# *Deletion is easy?*

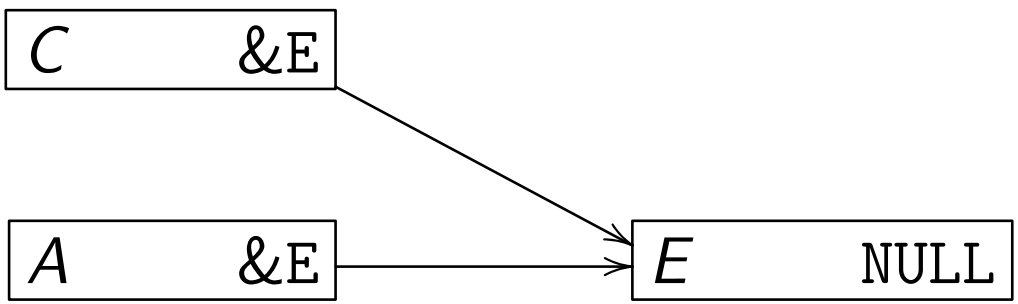
- Suppose we have




- And want to get rid of $C$.
- So `CAS(&A.next, &C, &E)`

# *Deletion is easy?*

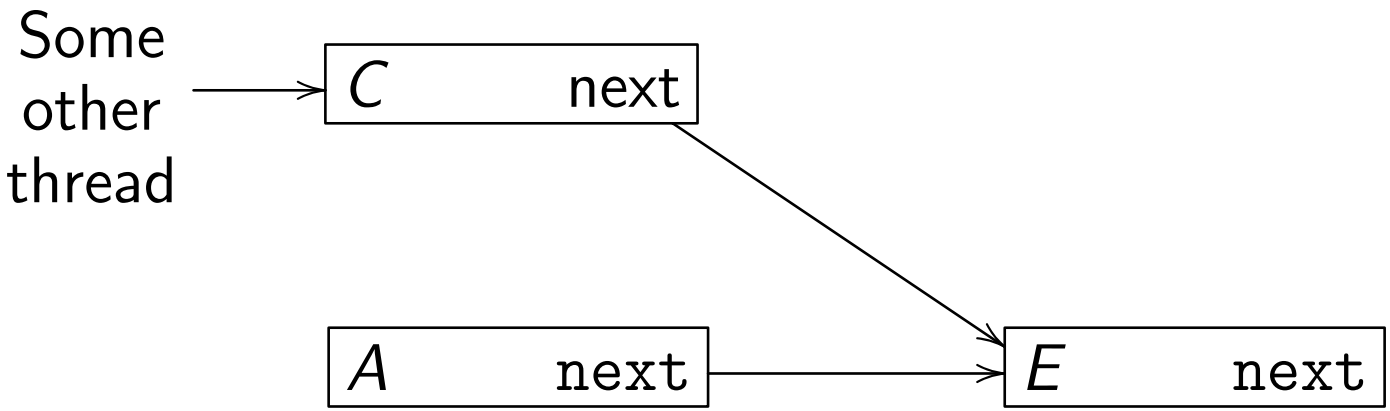
- Now we have




- Great, looks like deletion to me!
  - It's off the data-structure (*logically deleted*) $\cdots$
- But not *freed* ( *"actually" deleted / reclaimed*).

## *Deletion is easy? Continued*

- But imagine there was another thread accessing $C$ (say, scanning the list).




- We don't know when that thread is done with $C$!
- So we can never `free(C);`

*Deletion is easy?*
*What's to be done?*

- We need *some* way to reclaim that memory for reuse..
- Some implementations cheat and assume a stop-the-world garbage collector.
  - (That's like a giant lock!)
- Doing deletion honestly is remarkably tricky!
  - We're not going to really have time to cover it.

*Deletion is easy?*
*What's to be done?*

- Assume: once some memory is committed to being a LF list node that it's OK if it's *always* a LF list node.
- So we can have two lists: the "real" list and a "free" list.
  - This is not real `free()` but is hard enough.
- In particular, we run into the "ABA problem".

# *ABA Problem: Introduction*

- A problem of confused identity

| | |
|---|---|
| global = malloc(sizeof(Foo)) | |
| $local_1$ = global | $local_2$ = global |
| global = NULL | |
| free($local_1$) | |
| global = malloc(sizeof(Foo)) | |
| | /* Validity check */<br>if ( global == $local_2$ )<br>global->foo_baz = ... |

# *ABA Problem: Introduction*

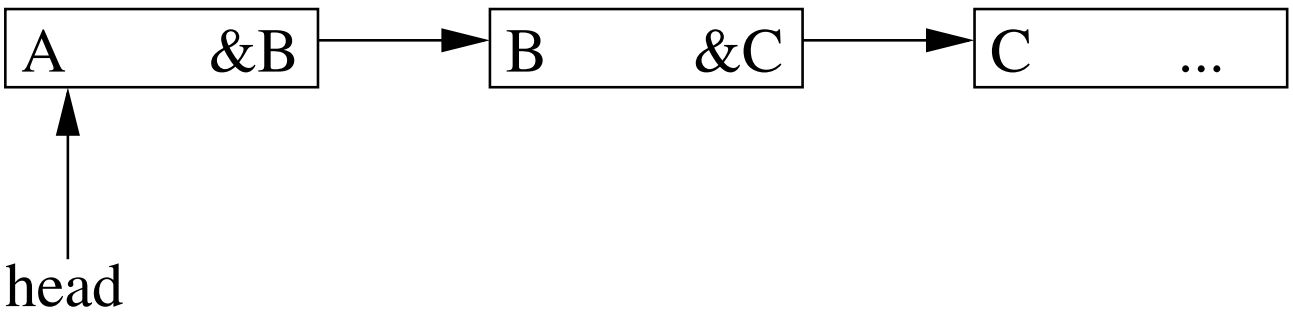
- A problem of confused identity

| | | |
|---|---|---|
| global = malloc(sizeof(Foo)) | | //0x1337 |
| $local_1$ = global | $local_2$ = global | |
| global = NULL | | |
| free($local_1$) | | //0x1337 |
| global = malloc(sizeof(Foo)) | | //0x1337 |
| | /* Validity check */<br>if ( global == $local_2$ )<br>global->foo_baz = ... | |

- Even though $local_2$ and global might point to the same address, they don't *really* mean the same thing.

# *ABA Problem: Introduction*
## *Preliminaries*

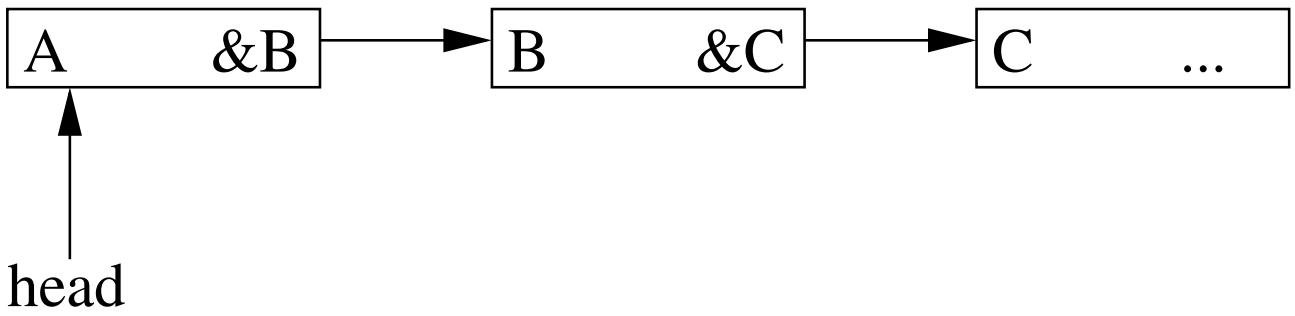
- We begin with an innocent linked list:




- Where `head` is a a global pointer to the list.
- We're just going to do operations at the head – treating the list like a stack.

# *ABA Problem: Introduction*
## *Pop*

- We begin with a linked list:



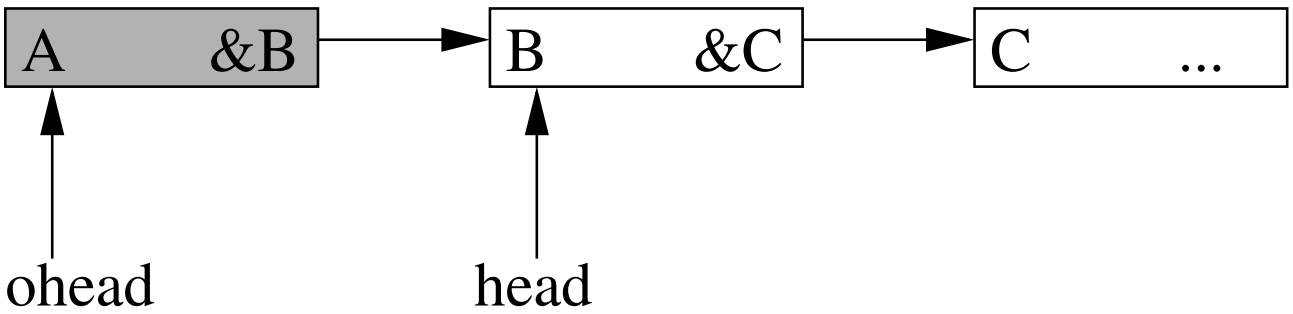

- Removing the head looks like

| | |
|---|---|
| `ohead = head` | `/* == &A */` |
| `onext = ohead->next` | `/* == &B */` |
| `CAS(head, ohead, onext);` | |

- If not, retry.

# *ABA Problem: Introduction*
## *Pop*

- If successful,



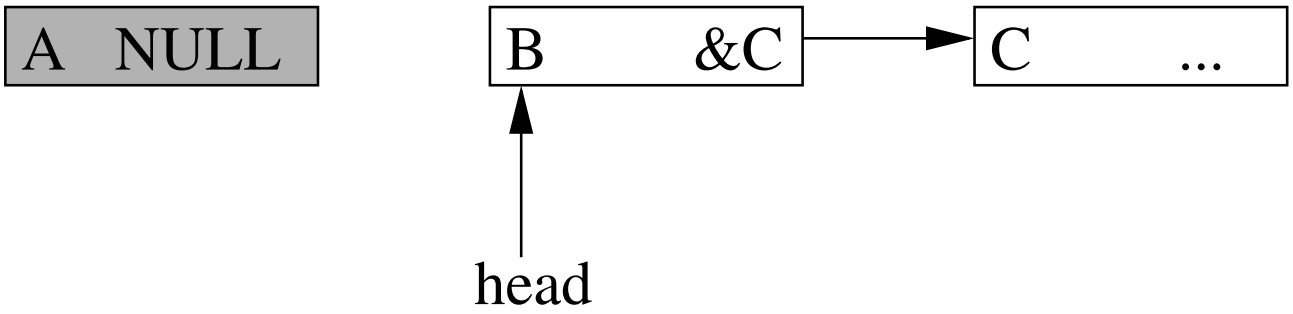

- is the result of

| | |
|---|---|
| `ohead = head` | `/* == &A */` |
| `onext = ohead->next` | `/* == &B */` |
| `CAS(head, ohead, onext);` | |

- If not, retry.

# *ABA Problem: Introduction*
## *Push*

- We begin with a linked list and private item



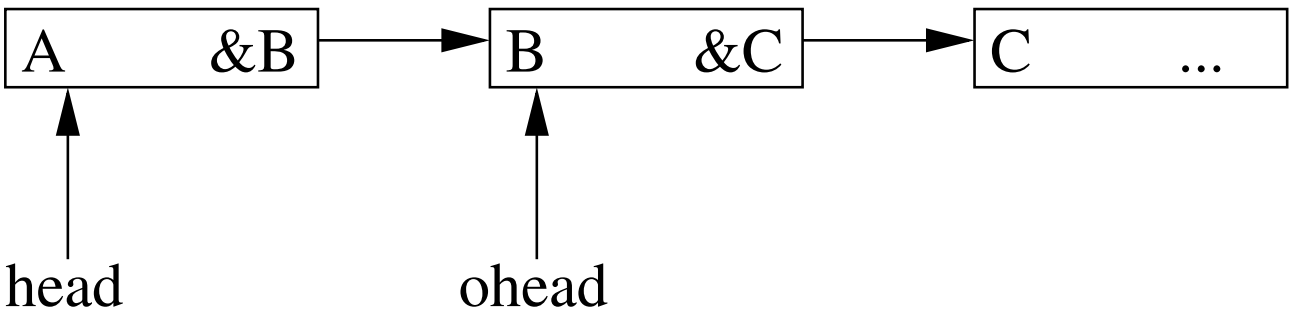

- Inserting at the head looks like

| | |
|---|---|
| `ohead = head` | `/* == &B */` |
| `A.next = ohead` | `/* A points at B */` |
| `CAS(head, ohead, &A);` | |

- If not, retry.

# *ABA Problem: Introduction*
## *Push*

- If that works, we get




- from

| | |
|---|---|
| `ohead = head` | `/* == &B */` |
| `A.next = ohead` | `/* A points at B */` |
| `CAS(head, ohead, &A);` | |

- If not, retry.

## *ABA Problem: Things go south*

Three threads:

*Thread 1* Pop an item.

*Thread 2* Pop an item, then push it right back.

*Thread 3* Pop an item.

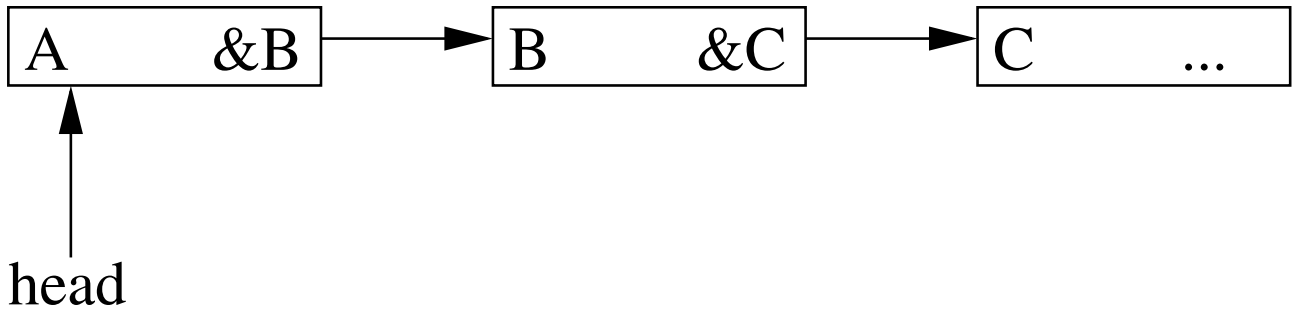
## *ABA Problem: Things go south*
## *And now it breaks!*

Here's a 30,000-foot look at how this is going to break.

| **Thread 1** | **Thread 2** | **Thread 3** |
|---|---|---|
| Pop | Pop | |
| | | Pop |
| | Push | |
| BANG! | | |

- In words: An extremely slow pop is racing against
  - A thread which pops and then immediately pushes.
  - A third which thread executes a pop.

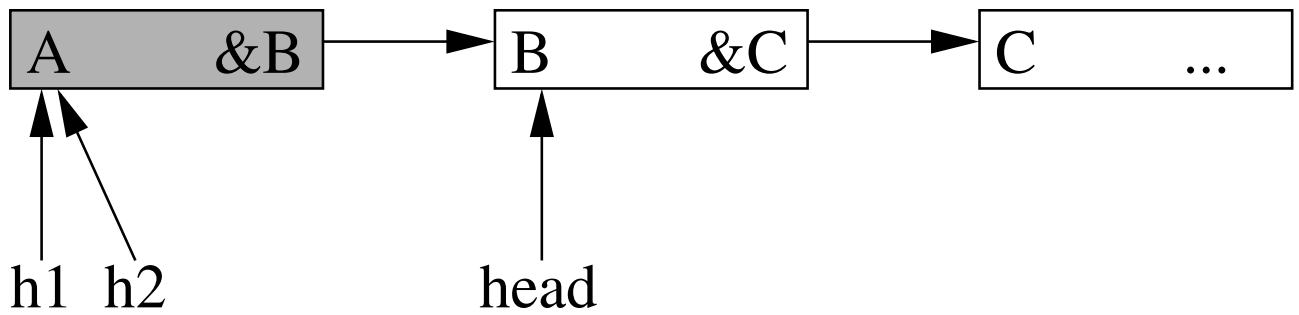
## *ABA Problem: Things go south*




- The first thread gets one instruction into its pop, while
- The second thread completes its pop operation:

| | | |
|---|---|---|
| `h1 = head` | `h2 = head` | `== &A` |
| | `n2 = h2->next` | `== &B` |
| | `CAS(head, h2, n2)` | Success! |

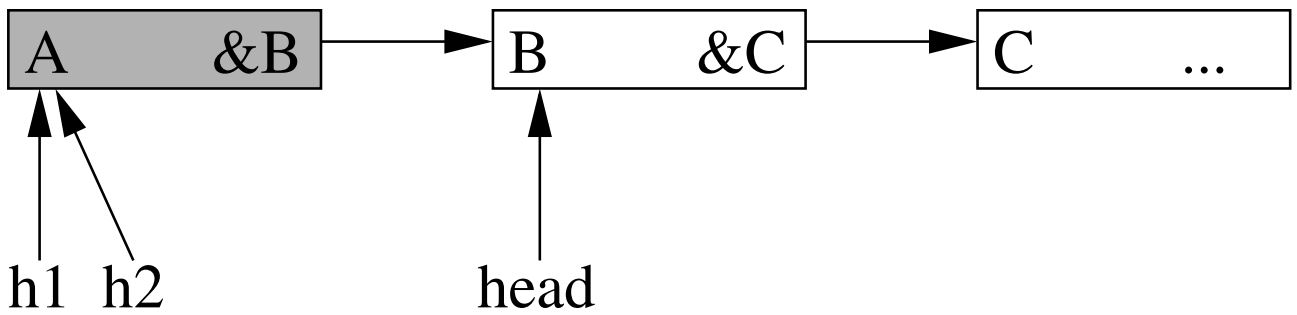
## *ABA Problem: Things go south*




- The first thread got one instruction into its pop, while
- The second thread completed its pop operation.

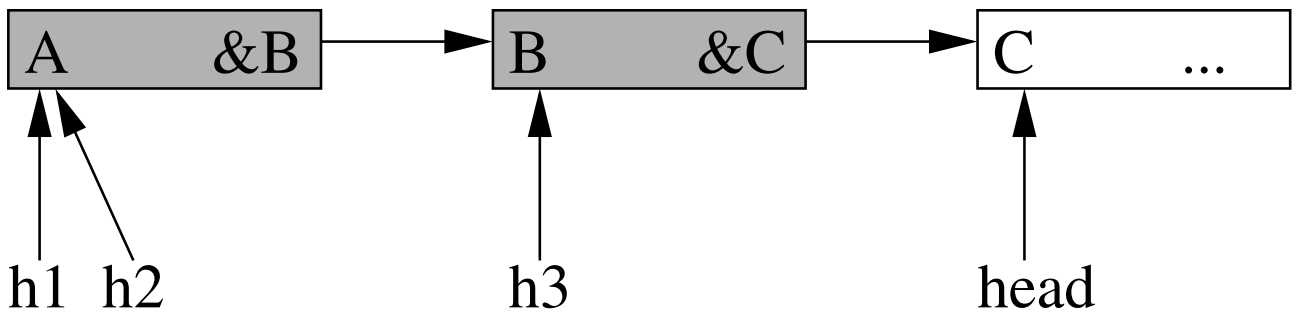
| | | |
|---|---|---|
| `h1 = head` | `h2 = head` | `== &A` |
| | `n2 = h2->next` | `== &B` |
| | `CAS(head, h2, n2)` | Success! |

## *ABA Problem: Things go south*



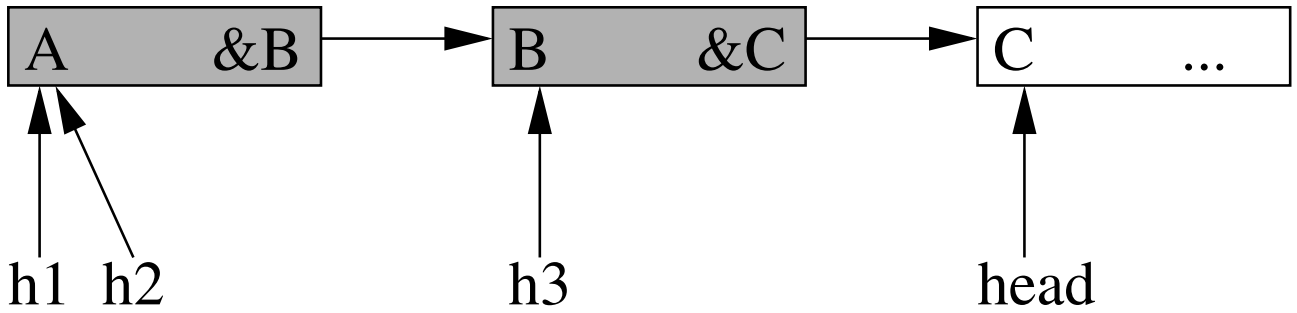

- The third thread executes a pop operation.

## *ABA Problem: Things go south*




- The third thread executed a pop operation.

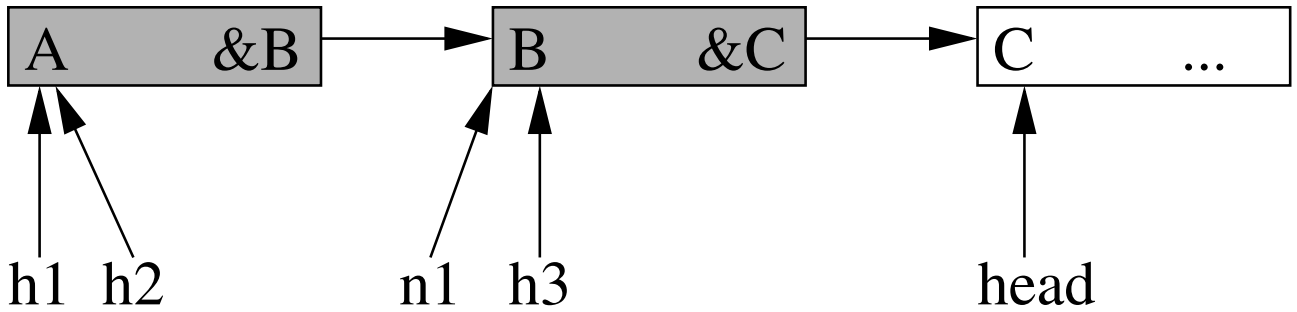
## *ABA Problem: Things go south*




And the slower thread gets a few more instructions:

| `n1 = h1->next;` | | `== &B` |
|---|---|---|

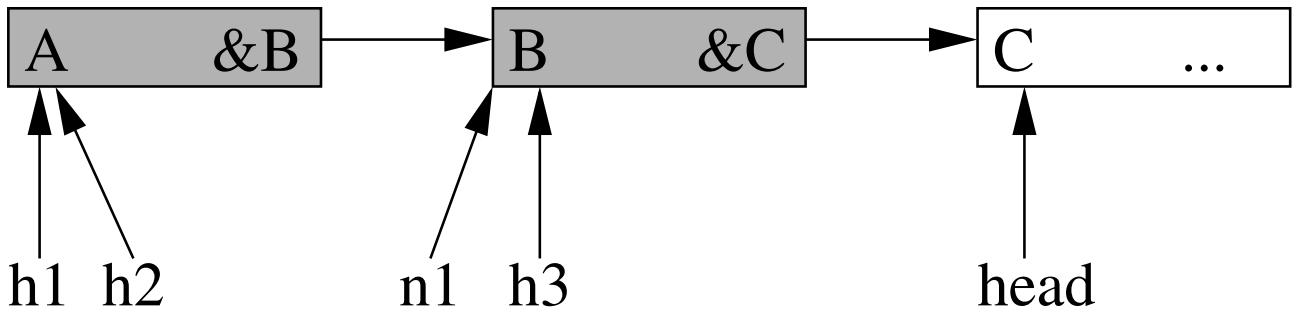
## *ABA Problem: Things go south*




And the slower thread got a few more instructions:

| | | |
|---|---|---|
| `n1 = h1->next;` | | `== &B` |

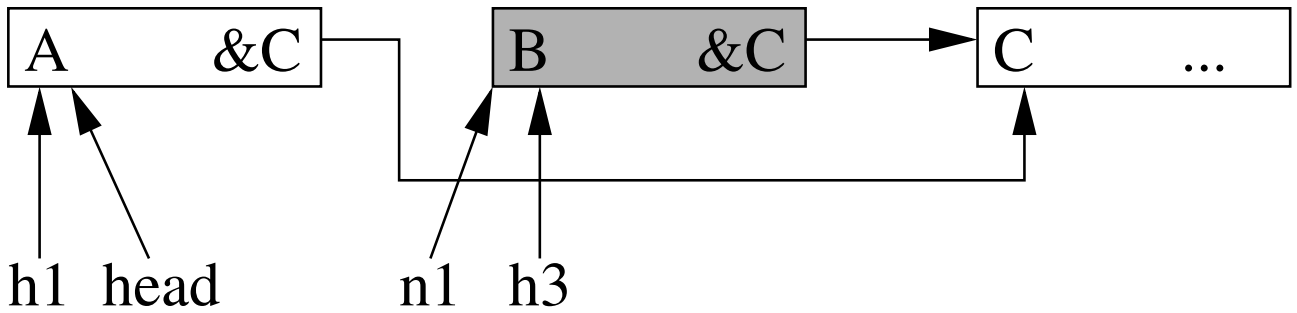
## *ABA Problem: Things go south*




Now the second thread does its push operation...

| | | |
|---|---|---|
| | `h2 = head;` | `== &C` |
| | `h2->next = h2;` | `A.next` $\leftarrow$ `&C` |
| | `CAS(head, h2, &A)` | Success! |

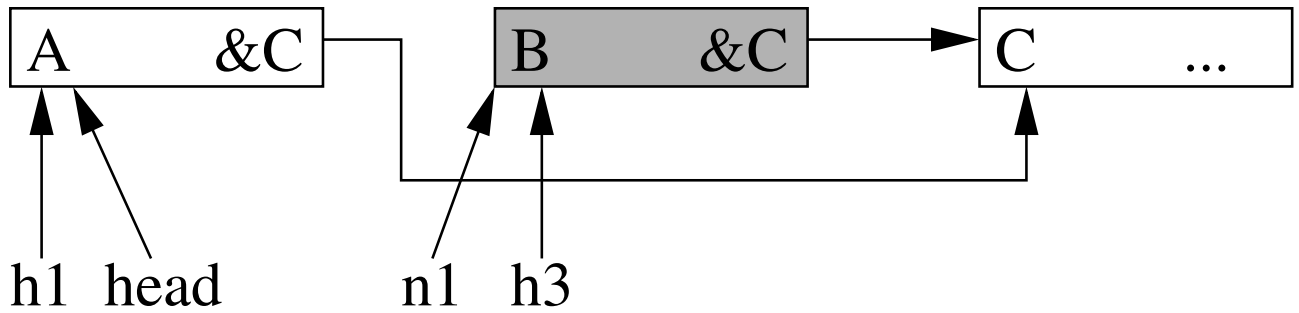
## *ABA Problem: Things go south*




Now the second thread did its push operation...

| | | |
|---|---|---|
| | `h2 = head;` | `== &C` |
| | `h2->next = h2;` | `A.next` $\leftarrow$ `&C` |
| | `CAS(head, h2, &A)` | Success! |

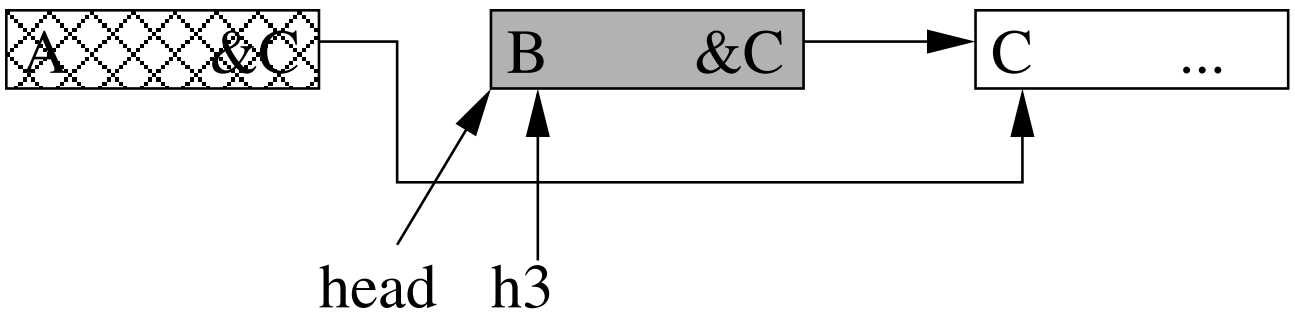
## *ABA Problem: Things go south*




And the slower thread finally completes its pop operation...

| `CAS(head, h1, n1)` | | Suc... hm! |
|---|---|---|

## *ABA Problem: Things go south*




And the slower thread finally completed its pop operation...

| `CAS(head, h1, n1)` | | Suc... hm! |
|---|---|---|

## *ABA Problem: Things go south*

- *B*, which was well and quite off the list, and not owned by Thread 1, is now at the head!
- Thread 1 missed its chance to be notifed of having stale data.
  - All that matters is that *A* ended up back on the list head when Thread 1 was CAS-ing.
- There's relatively little that *thread 1* can do about this!
- For fun, try designing a different failure case.
  - Try getting a circular list.

## *Fixing ABA*

- Generation counters are a simple way to solve ABA
  - Let's replace all pointers with

```
struct versioned_ptr {
   void * p; /* Pointer */
   unsigned int v; /* Version */
};
```

- This will allow a "reasonably large" number of pointer updates before we have to worry.

## *Fixing ABA*

- Suppose we had a primitive which let us write things like *ATOMICALLY*

```
if ((head.p == &C) && (head.v == 4))
  head.p = &D
  head.v = 5
```

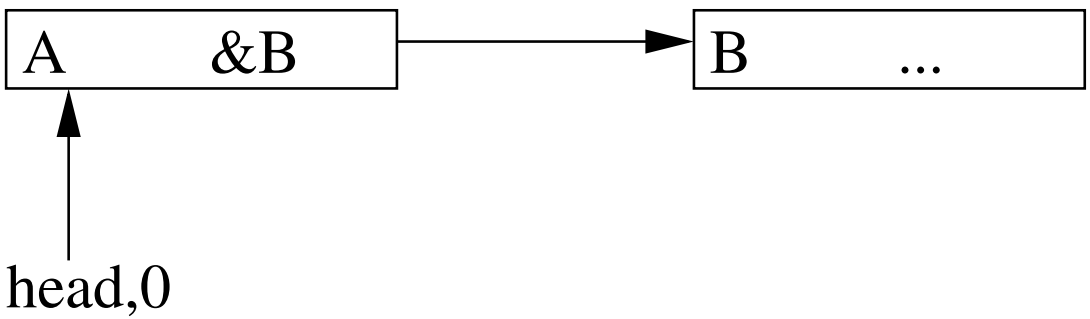
# *Fixing ABA*

- Like `CAS`, we want a `CAS2`, which operates on two (adjacent) words at once:
  `CAS2(*curs, *expects, *news)` atomically:

```
olds[0] = curs[0]; olds[1] = curs[1];
if (curs[0]==expects[0] && curs[1]==expects[1])
   curs[0] = news[0]; curs[1]= news[1];
return { olds[0], olds[1] };
```

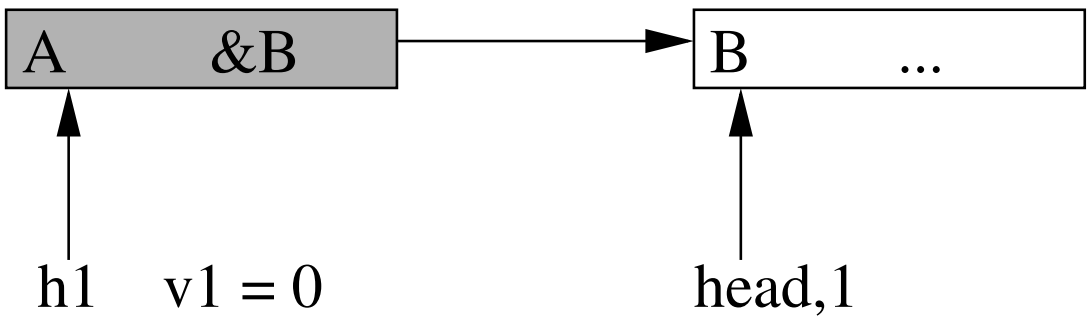
- `CAS2` looks more expensive than `CAS`?
  - Two reads, two writes.
  - With luck, it's one cache line; without, it could be two.
  - May be $(1 + \epsilon)$ times as hard as `CAS`...
  - May be $\infty$ times as hard as `CAS`...

## *Fixing ABA*
## *$2^{nd}$ thread pops...*



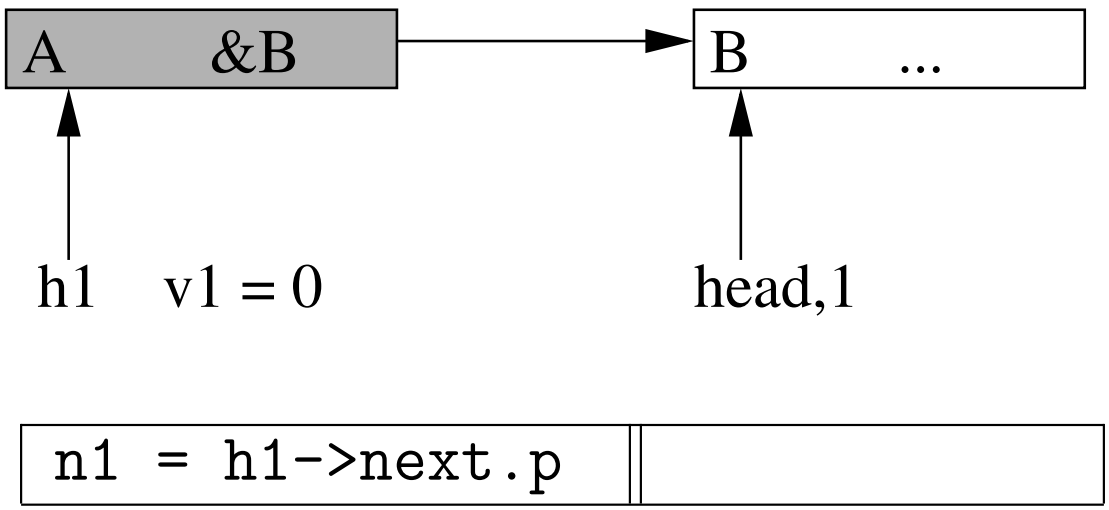

| | | |
|---|---|---|
| `h1 = head.p`<br>`v1 = head.v` | `h2 = head.p` | `== &A` |
| | `n2 = h2->next.p`<br>`v2 = head.v` | `== &B`<br>`== 0` |
| | `CAS2(head,{h2,v2},{n2,v2+1})` | Success! |

## *Fixing ABA*
## *$2^{nd}$ thread popped...*



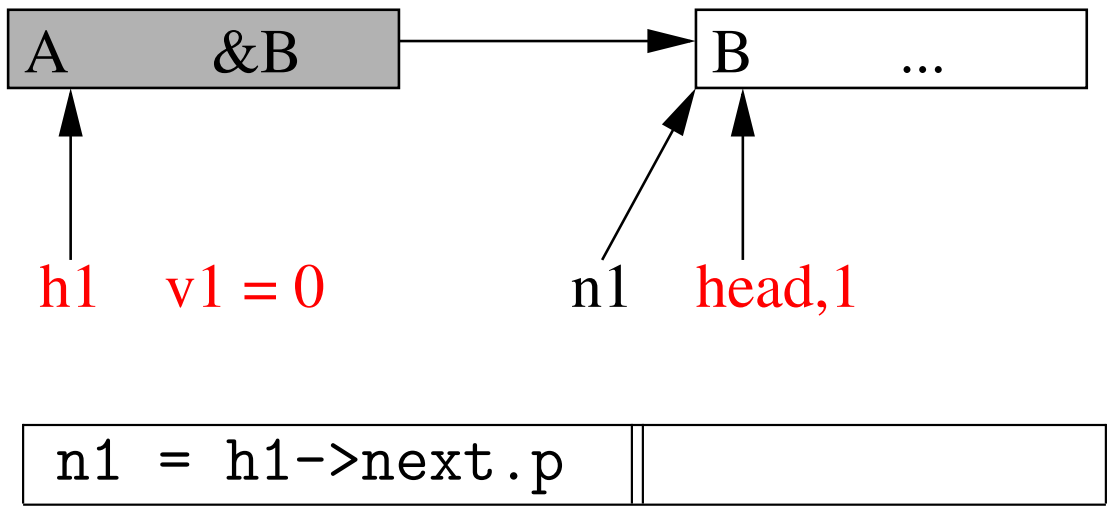

| h1 = head.p | h2 = head.p | == &A |
|---|---|---|
| | n2 = h2->next.p | == &B |
| | v2 = head.v | == 0 |
| | CAS2(head,{h2,v2},{n2,v2+1}) | Success! |

## *Fixing ABA*
## *1st thread reads* `n1`



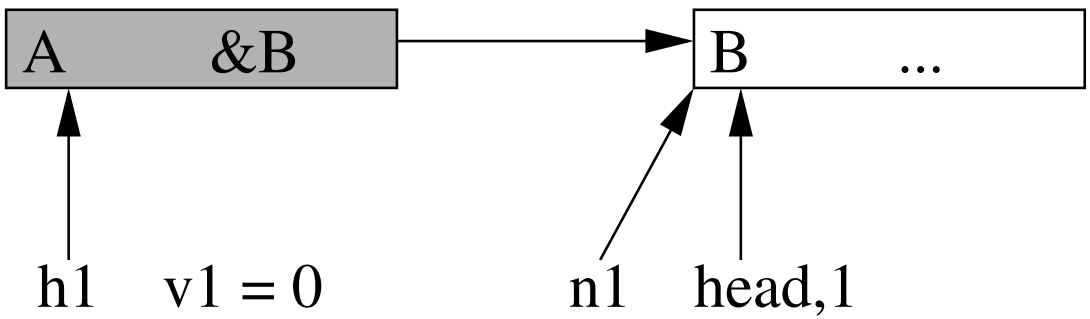

- `n1` and `v1` are just local variables in preparation for...
  `CAS2(head,{h1,v1},{n1,v1+1})`

# *Fixing ABA*
## *1st thread read* `n1`




- `n1` and `v1` are just local variables in preparation for... `CAS2(head,{h1,v1},{n1,v1+1})`
- So if that were to happen right now...

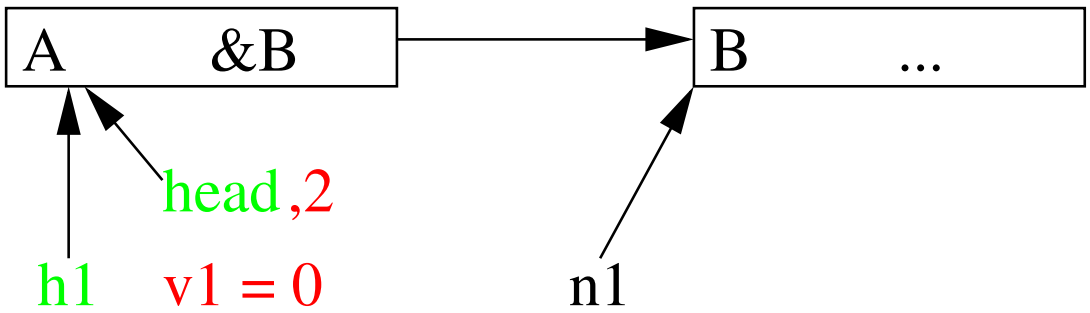
# *Fixing ABA*
## *$2^{nd}$ thread pushes...*




| | |
|---|---|
| | `h2 = head.p;`<br>`v2 = head.v;` |
| | `A.next = h2;` |
| | `CAS2(head,{h2,v2},{&A,v2+1})` |

# *Fixing ABA*

## *$2^{nd}$ thread pushed; here's where it broke before*




| | |
|---|---|
| | `h2 = head.p;`<br>`v2 = head.v;` |
| | `A.next.p = h2;` |
| | `CAS2(head,{h2,v2},{&A,v2+1})` |

- `CAS2(head,{h1,v1},{n1,v1+1})`
- `head == h1` but `v1 == 0` $\neq$ 2. Hooray!

## *Fixing ABA For Real*

- Generation counters kinda stink to actually use.
- It turns out that we need to be slightly more clever.
  - Summary: wait until the coast is clear.
  - Look at [FR04] or [Mic02a] (or others) for more details.
- Or use different hardware ("make the EEs do it"):
  - "Load-Linked/Store-Conditional/Validate" atomic primitives instead.
  - These assure you of no ABA because the $A \rightarrow B$ transition nullifies your ability to successfully store, even if $B$ turns back into $A$.
  - To the EEs in the room: no missed edges!

## *Some real algorithms?*

[Mic02a] specifies a CAS-based lock-free list-based sets and hash tables using a technique called SMR to solve ABA and allow reuse of memory.

- SMR actually solves ABA as a side effect of safely reclaiming memory. Instead of blocking the writer until everybody leaves a critical section, it can efficiently scan to see if threads are interested in a particular chunk of memory.
- Their performance figures are worth looking at. Summary: fine-grained locks (lock per node) show linear-time increase with # threads, their algorithm shows essentially constant time.

# *Read-Copy-Update Mutual Exclusion Preliminaries*

- The ABA problems would all be solved if we could wait for everyone who might have read what is now a stale pointer to complete.
- Phrased slightly differently, we need to separate the *memory update* (*atomic delete*) phase from the *private use* (`free()`) phase.
- And ensure that no readers hold a critical section that might see the update *and* private phases.
    - Seeing one or the other is OK!

# *Read-Copy-Update Mutual Exclusion Preliminaries*

- Read-Copy-Update (RCU, [Wikc, McK03]; earlier papers) uses techniques from lock-free programming.
- Is used in several OSes, including Linux.
- It's a bit more complicated than the examples given here and not truly lock-free, but certainly interesting.

# *Read-Copy-Update Mutual Exclusion Preliminaries*

- Looks like a reader-writer lock from 30,000 ft.
- Key assumptions:
  - Many more readers than writers.
  - Reader critical sections are *short*:
    - No `yield()`, `malloc()`, page faults, ...
  - Readers want to see a consistent data structure.
  - The ABA problems would all be solved if we could force everybody who might have read what is now a stale pointer to complete.

## *Read-Copy-Update Mutual Exclusion Preliminaries*

- Many more readers than writers.
  - So we should make sure that the readers don't have to do much.
  - Kind of like a rwlock.
- Readers frequently can complete critical sections in bounded time (no `yield()` etc.).
  - Required property of RCU readers.
  - We'll see why this is important in a bit.
- Readers want to see a consistent data structure.
  - Not all consistency guarantees need to be kept, but, for example, we want to avoid use-after-free and the possibility of faulting.
  - But it might be the case that we let `node->next->prev != node` as readers only use these pointers to traverse.

# *Read-Copy-Update Mutual Exclusion Preliminaries*

- Disclaimer: function names have been changed from, *e.g.*, the Linux implementation, to make the meanings more clear.
- Disclaimer 2: RCU comes in many flavors - the one here is a small toy model but works on real hardware (like Pebbles).

# *Read-Copy-Update Mutual Exclusion API*

- Reader critical section functions.
  - `void rcu_read_lock(void);`
  - `void rcu_read_unlock(void);`
  - Note the absence of parameters (how odd!).
- Accessor functions:
  - `void * rcu_fetch(void *);` is used to fetch a pointer from an RCU protected data structure.
  - `void * rcu_assign(void *, void *);` is used to assign a new value to an RCU protected pointer.
- Synchronization points:
  - `void rcu_synchronize(void);` is used once a writer is finished to signal that updates are complete.
    - Moves from "update" to "private" phase.

## *Read-Copy-Update Mutual Exclusion API: Reader's View*

- Suppose we have a global list, called `list`, that we want to read under RCU.
- The code for iteration looks like

```
rcu_read_lock();
list_head_t *llist = rcu_fetch(list);
list_node_t *node = rcu_fetch(llist->head);
while(node != NULL) {
  ... /* Do something reader-like */
  node = rcu_fetch(node->next);
}
rcu_read_unlock();
```

## *Read-Copy-Update Mutual Exclusion API: Writer's View*

- Suppose we want to delete the head of the same global list, `list`.
- We need to give it a writer exclusion mutex, `list_wlock`.

```
void delete_head_of_list() {
   list_node_t *head;
   mutex_lock(&list_wlock); // No other writers
    head = list->head; // No rcu_fetch()
    list_node_t *next = head->next;
    rcu_assign(list, next);
   mutex_unlock(&list_wlock);
   rcu_synchronize();
   free(head); /* Reclaim phase */
}
```

# *Read-Copy-Update Mutual Exclusion API: Summary*

- This is kinda like a rwlock:
  - It allows an arbitrary number of readers to run against each other.
  - It prevents multiple writers from writing at once.
- It is absolutely unlike a rwlock because
  - readers and writers do not exclude each other!

# *Read-Copy-Update Mutual Exclusion API: Wait,* WHAT*?*

Readers can run alongside writers! There's no mechanism in the reader to serialize against the writer! See:

| CPU 1 (reader) | CPU 2 (writer) |
|---|---|
| `rcu_read_lock();` | `mutex_lock(...);` |
| `llist = rcu_fetch(list);` | `...` |
| | `rcu_assign(list, new);` |
| | `rcu_synchronize();` |
| `rcu_fetch(llist->head);` | |

Some Restrictions Apply™: Remember, only one writer, so `rcu_assign` doesn't use CAS.

# *Read-Copy-Update Mutual Exclusion Implementation: Key Ideas*

- "All the magic is inside `rcu_synchronize()`" ...
- The deletion problem, and ABA, was a problem of not knowing when nobody had a stale reference.
- If
  - readers agree to drop *all* references in bounded time
  - AND writers can tell *when* readers have dropped references
- Then we know when it is safe to consider memory private.
- Being safe for *private use* is exactly the same as being safe for *reuse*.

# *Read-Copy-Update Mutual Exclusion Implementation: Approximation*

- Want:
  - readers agree to drop *all* references in bounded time
  - AND writers can tell when readers have dropped references
- You can imagine that there's an array of `reading[i]` values out there, with each thread having its own index...
- Each reader sets `reading[me] = 1`, reads, then sets `reading[me] = 0`.
- The writer then scans the array looking for all flags to be 0.
- When this happens, the writer knows that no readers have stale references, and is now OK to `free` deleted item(s).

# *Read-Copy-Update Mutual Exclusion Implementation*

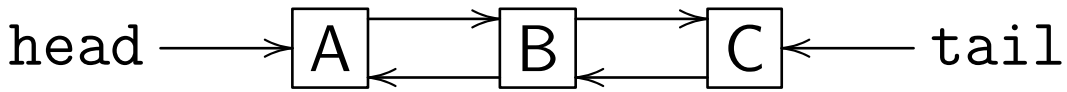
- So how does RCU *actually* do this?
  - "All the magic is inside `rcu_synchronize()`" ...
- `rcu_read_lock()` simply disables the local CPU's preemptive scheduler.
  - So we need readers that won't call `yield()`.
- `rcu_assign()` inserts a write memory barrier ("write fence") to force all writes in the out-of-order buffers to be made visible *before* it does the assignment requested.
- `rcu_fetch(x)` is just `(x)` on most architectures.
  - There are [increasingly rare] exceptions (DEC ALPHA).

# *Read-Copy-Update Mutual Exclusion Implementation*

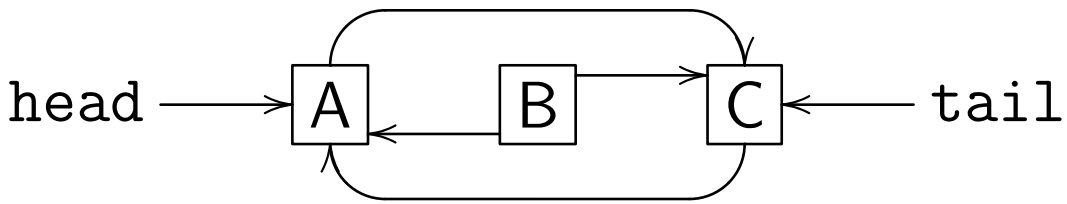
- Given all of this, what does `rcu_synchronize()` do?
- It waits until every CPU undergoes a context switch!
  - Could just have a context switch counter per CPU and wait for each to fire, or...
  - Ensure that the thread calling synchronize gets run on every CPU before the synchronize returns (using something like `move_me_to_cpu(int cpunum);`)
- Because readers are non-preemptible, waiting until all CPUs preempt means that all readers must have dropped their "lock" and so have forgotten any pointers to memory we want to free.

## *Read-Copy-Update Mutual Exclusion Pictures: Writer view*

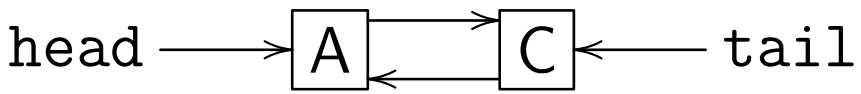
- Let's again take a linked list, this time a doubly linked one.




- Now suppose the writer acquires the write lock and updates to delete *B*:

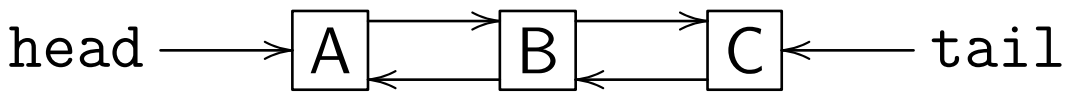



- Now the writer synchronizes, forcing all readers with references to *B* out of the list. Only then can *B* be reclaimed!

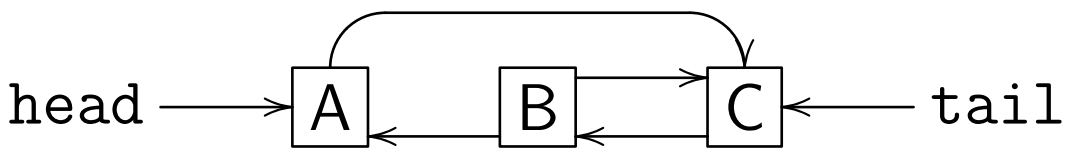


## *Read-Copy-Update Mutual Exclusion Pictures: Reader View*

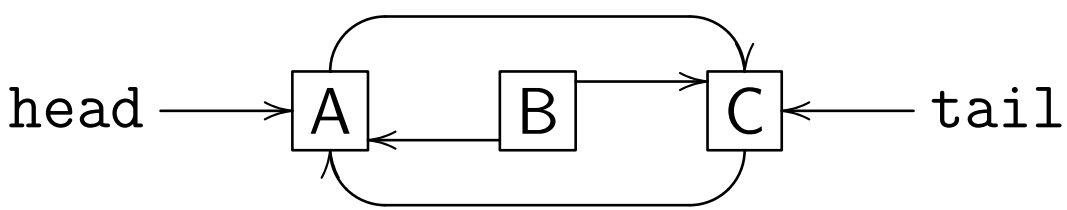
- Looking at that again, from the reader's side now. Originally




- The writer first sets it to




- And then



## *Read-Copy-Update Mutual Exclusion Pictures*

- The writer forced memory consistency (fencing) between each update.
- So each reader's dereference occurred *entirely before* or *entirely after* each write.
- So the reader's traversal in either direction is entirely consistent!
    - (moving back and forth might expose the writer's action.)
- But it's OK, because we'll just see a disconnected node.
- It's not *gone* yet, just disconnected.
- It won't be reclaimed until we drop our critical section.

*Read-Copy-Update Mutual Exclusion*
*Confessions of an Instructor*

Real-world RCU once upon a time worked this way but more recent implementations are much fancier. For the really enthusiastic, see things like Linux's "Sleepable RCU" implementation [McK06].

# *Lessons*
## *What Have We Learned?*

1. We can replace fixed-time lock-based critical sections with "almost-always-fixed-time" compare-and-swap loops...
   - Note that getting the lock was not fixed-time, just the critical section.
   - `CAS` is a kind of critical mini-section in hardware.
   - (For the really enthusiastic, there are also "wait-free" algorithms which ensure not only systemic but per-thread progress.)
2. Because many threads may have references into a data structure, knowing when something has no references is both very *important* and very *difficult*.
   - But all is not lost!
   - Generation counters, LL/SC, RCU, & others

## *Lessons*
## *Write Your Own?*

- It's *extremely hard* to roll your own lockfree algorithm.
- But moreover, it's *almost impossible* to debug one.
- Thus all the papers are long not because the algorithms are hard, . . .
- . . . but because they prove the correctness of the algorithm so they at least don't have to debug that.

## *Lessons*
## *Lockfree vs. Locking.*

- Most lock-free algorithms increase the number of atomic operations, compared to the lockful variants.
- Thus we may starve processors for bus activity on bus-locking systems.
- On systems with cache coherency protocols, we might livelock with no processor able to make progress due to cacheline stealing and high transit times.
    - Nobody can get all the cachelines to execute an instruction before a request comes in and and steals one of the ones they had.

# *Conclusion*

- Lock-free data structures are extremely cool.
  - (IMHO, YMMV)
- A different form of concurrency:
  - Was: "grab lock to *exclude* everybody else"
  - Now: "carefully signal everybody else who's looking"
- Lock-free algorithms proper have their place, but that place may be somewhat small.
  - Generally more complex than standard lockful algorithms.
  - Much harder ("impossible?") to debug.
  - Usually used only when there is no other option.

Thanks. Questions?

- Mikhail Fomitchev and Eric Ruppert, *Lock-free linked lists and skip lists*, PODC (2004), no. 1-58113-802-4/04/0007, 50–60, http://www.research.ibm.com/people/m/michael/podc-2002.pdf.
- Paul McKenney, *Kernel Korner - Using RCU in the Linux 2.5 Kernel*, http://www.linuxjournal.com/article/6993.
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- Maged M. Michael, *High performance dynamic lock-free hash tables and list-based sets*, SPAA (2002),

no. 1-58113-529-7/02/0008, 73–83, http://portal.acm.org/ft_gateway.cfm?id=564881&type=pdf&coll=GUIDE&dl=ACM&CFID=73232202&CFTOKEN=1170757.

 _____, *Safe memory reclamation for dynamic lock-free objects using atomic reads and writes*, PODC (2002), no. 1-58113-485-1/02/0007, 1–10, http://www.research.ibm.com/people/m/michael/podc-2002.pdf.

 _____, *Hazard pointers: Safe memory reclamation for lock-free objects*, IEEECS (2004), no. TPDS-0058-0403, 1–10, http://www.research.ibm.com/people/m/michael/podc-2002.pdf.

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- [ Nobody on this list deserves any of the blame, but merely credit, for this lecture. ]

## *Full fledged deletion & reclaim*

- Even though we might be able to solve ABA, it still doesn't solve memory reclaim!
- Imagine that instead of being reclaimed by the list, the deleted node before had been reclaimed by something else...
  - A different list
  - A tree
  - For use as a thread control block

## *Full fledged deletion & reclaim*

- What if we looked at ABA differently . . .
- It only matters if there is the possibility of confusion.
- In particular, might demonstrate strong interest in things that might confuse me
  - Hazard Pointers ("Safe Memory Reclaimation" or just "SMR") [Mic02b] and [Mic04]
  - Wait-free reference counters [Sun05]
- These are ways of asking "If I, Thread 189236, were to put something here, would anybody be confused?"
- This solves ABA, but really as a side effect: it lets us reclaim address space (and therefore memory) because we know nobody's using it!

## *The SMR Algorithm*

- Every thread comes pre-equipped with a *finite* list of "hazards"
- Memory reclaim involves scanning everybody's hazards to see if there's a collision
- Threads doing reclaim `yield()` (to the objecting thread) until the hazard is clear
- Difficulty
  - Show that hazards can only decrease when deletions are pending
  - Show that deletions eventually succeed (can't deadlock on hazards)
  - Managing the list of threads' hazards is difficult

## *Observation On Object Lifetime*

Instance of a general problem [Mem06]:

> *Things get tricky when the object must go away. [...] Any thread looking up the object – by definition – does not yet have the object and thus cannot hold the object's lock during the lookup operation. [...] Thus, whatever higher-level synchronization is used to coordinate the threads looking up the object must also be used as part of removing the object from visibility.*

## *Miscellany*
## *Locking vs. RCU*

- Interestingly, this kind of RCU tends to decrease the number of (bus) atomic operations.
  - Uses scheduler to get per-CPU atomicity.
- RCU requires the ability to force a thread to run on every CPU or at least observe when every CPU has context switched.
  - Difficult to use RCU in userland!
- RCU, like lockfree, suffers a slowdown from cache line shuffling, but will make progress due to having at most one writer.