Protecting Locks Against Unbalanced Unlock()

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भारतीय प्रौद्योगिकी संस्थान धारवाड

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Locks

- Provide mutual exclusion for shared data
- Most popular mutual-exclusion primitive
- Common usage:

```
m.Lock()
```

Critical Section (CS)

```
m.Unlock()
```

Many Locking Algorithms

- Tens of lock algorithms over the past couple of decades

Test and Set (TAS)
TAS-BO
Ticket
Anderson's Array-based
Reader-Writer
Graunke and Thakker
MCS
TATAS
HBO
CLH
MCS-K42
Cohort
HCLH
HMCS
Hemlock
BRAVO
CNA
Flat-combining
Fissile
Delegation
Malthusian
FLOCK
TWA

All focus on performance

Our Focus: Lock Misuse

```
if cond {
    m.Lock()
}


m.Unlock()
```

Problem: Unbalanced Unlock

- Accidental call to `unlock()` without `lock()`
- Impact
  - Mutex violation?
  - Starvation?
  - Corruption of lock internals?
  - Program corruption?
  - Benign?
- Can we
  - detect unbalanced-unlock?
  - devise/alter lock algorithms to avoid problematic situations?

Analysis of and remedy to popular spinlocks

Contributions

- Show unbalanced-unlock is a common problem
- Analyze popular locks in unbalanced-unlock situations
- Remedy popular locks to be resilient to unbalanced-unlock
- Show remedied lock designs remain performant

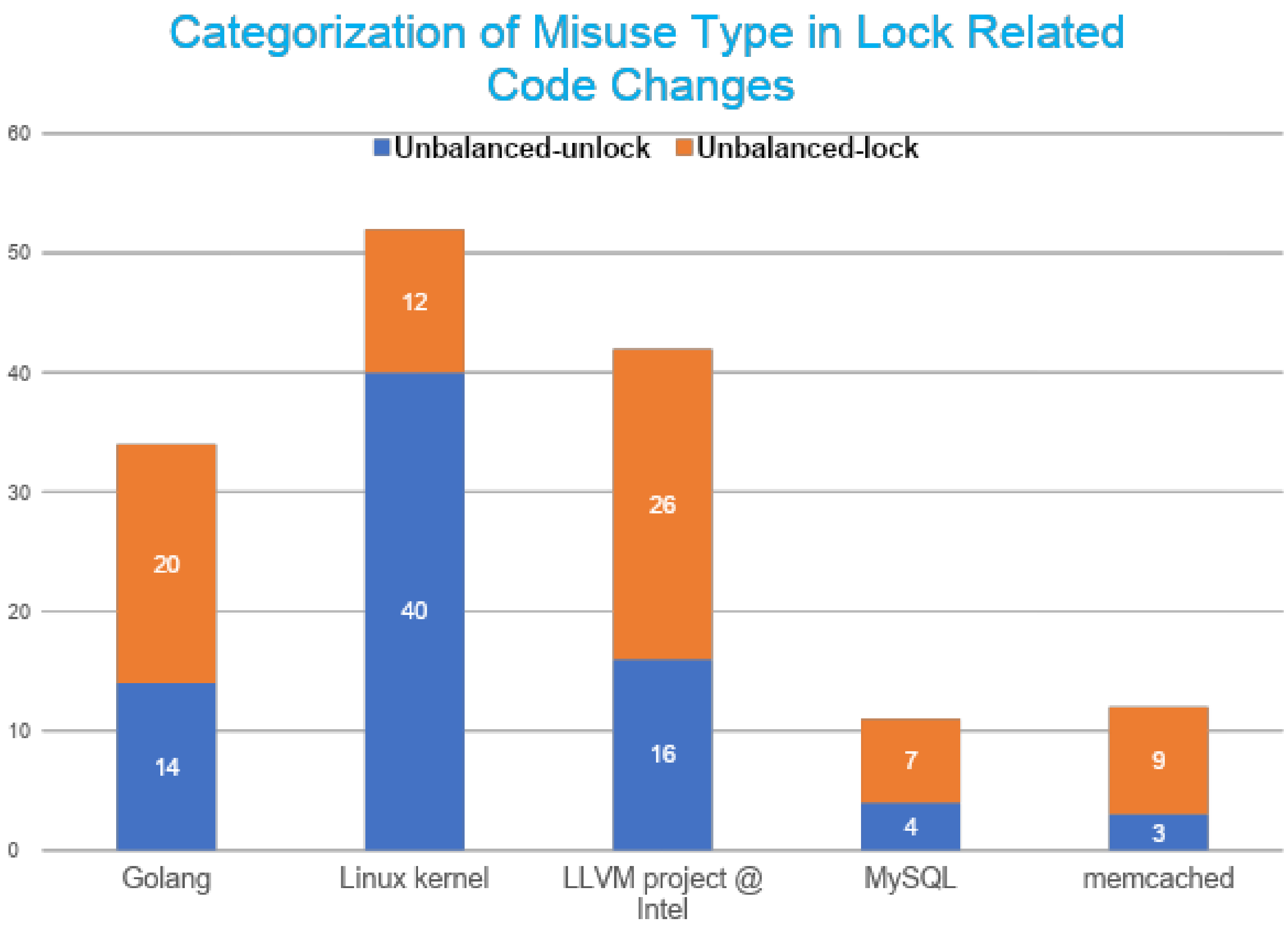
Unbalanced-unlock in the Linux Kernel

```
if (wilc->quit){
        goto out;
    }
    mutex_lock(...);
    tqe = …;
    if (!tqe){
        goto out;
    }
...
out:
    mutex_unlock(...);

    return ret;
```

Linux Kernel code: drivers/staging/wilc1000/wlan.c (commit id: bd4217c)

Unbalanced-unlock in the Open-Source



Unbalanced-lock: forgetting to call unlock

```
if cond {
    m.Lock()
    ...
  return;
}
m.unlock()
```

Well-known problem

Lock Protocol Analysis - Summary

How do different locks fare in the presence of unbalanced-unlock?

Notation: Tm denotes thread that misbehaves and Tx denotes all other threads

Lock	Violates Mutex	Starves Tm	Starves Others
TAS	✓	✗	NA
Ticket	✓	✗	✓
Anderson ABQL	✓	✗	✗
Graunke-Thakker	✗	✗	✓
MCS	✓	✓	✗
CLH	✓	✗	✓
MCS-K42	✓	✓	✓
Hemlock	✗	✓	✗
HMCS	✓	✓	✗
HCLH	✗	✗	✗
C-RW-NP/RP/WP	✓	✗	✓
Peterson's lock	✗	✗	✗
Fisher's lock	✓	✗	✗
Lamport's lock	✓	✗	✓

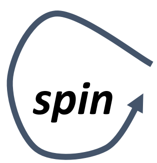
Test and Set (TAS) Lock

lock object L, shared-variable / Global

lock L: UNLOCKED

T1: lock()

Tx: lock()



T1 and Tx are both in CS.
Violation of mutual exclusion!

T1: unlock()

Tm: unlock()

Unbalanced-Unlock

Test and Set Lock Analysis

Lock	Violates Mutex	Starves Tm	Starves Others
TAS	✓	✗	NA

- Mutual exclusion is violated
  - every instance of unbalanced-unlock releases *at most one* waiting thread into CS
- No starvation
  - thread involved in unbalanced-unlock (Tm) returns from the call to `unlock()`
  - By design, TAS lock does not ensure starvation freedom

Test and Set Lock - Remedy

- Intuition: store the PID (unique thread identifier) of the current lock holder instead of the flag (LOCKED/UNLOCKED) in the lock

lock L: ULONG_MAX

T1: lock()

Caller PID is m, stored PID (in L) is 1.
There is a mismatch.

T1: unlock()

tid = m

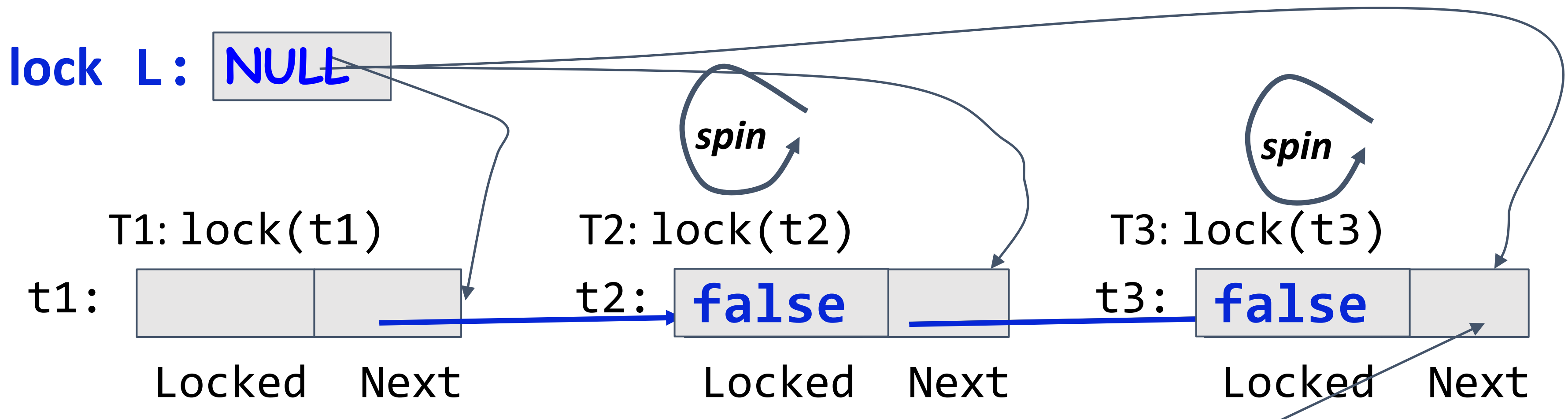
Tm: unlock()

Unbalanced-Unlock

```
unlock(unsigned long tid) {
if L is tid
   set L to ULONG_MAX; return true
return false
}
```

MCS Lock: Analysis and Remedy

MCS Lock - Analysis



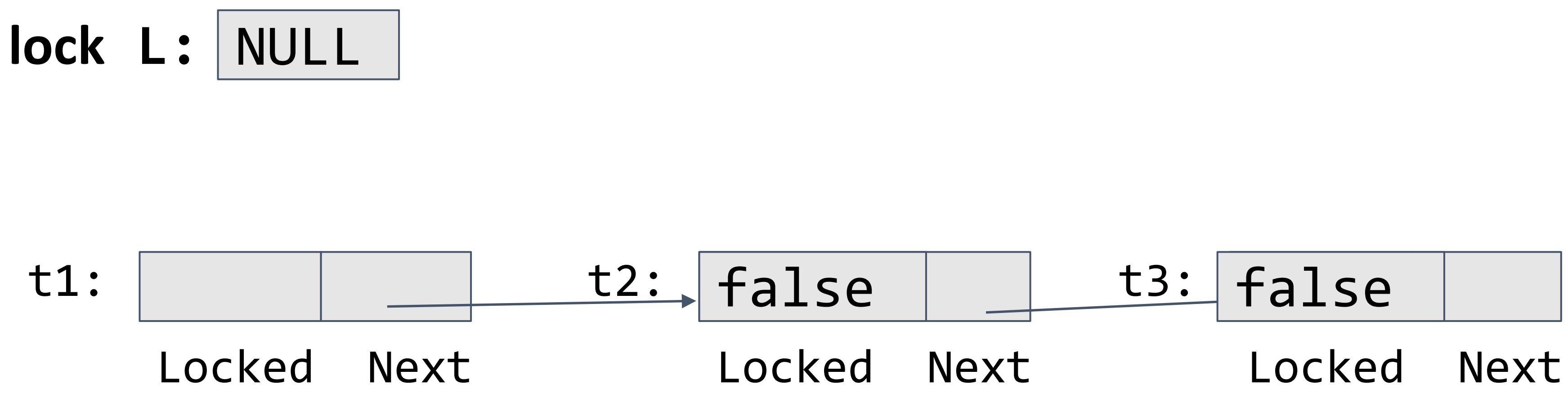
T1: unlock(t1) T2: unlock(t2) T3: unlock(t3)

swaps the lock with itself, gets the predecessor, and attaches itself to predecessor

- No successors / waiters for the lock. Reset L to NULL.

  - **Caution:** before resetting,
    Check if L still points to t3 (no successor has appeared in the meanwhile). If not:
    - wait till the successor appears in t3->next
    - set the successor's locked to false and return

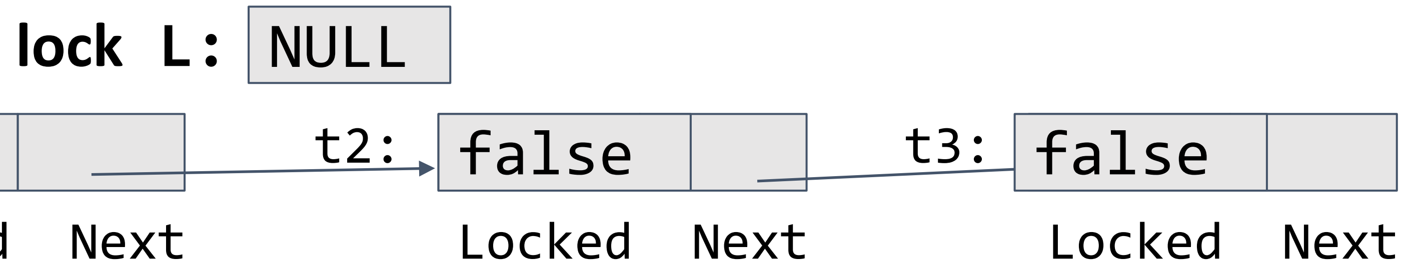
MCS Lock - Analysis



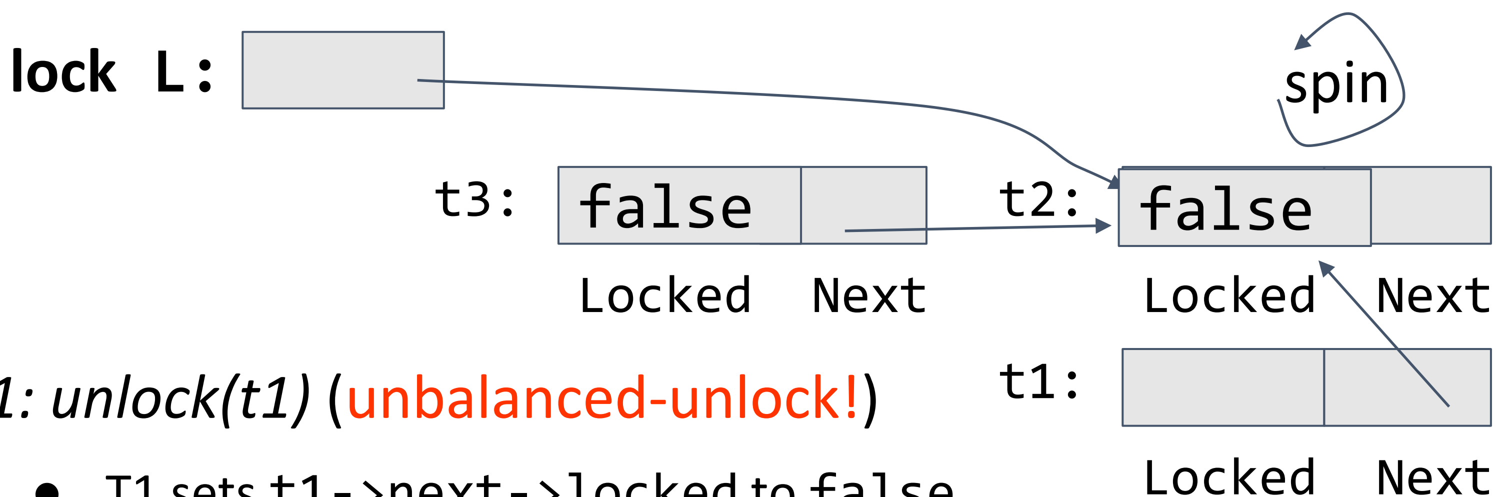
node objects still exist and the fields are not reset. Links may exist.

MCS Lock - Analysis (Scenario 1)

- *Earlier -*



- *Now: suppose T3 is holding the lock and T2 is spinning:*

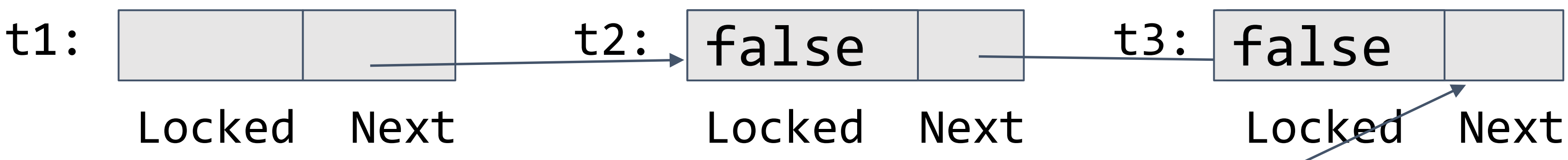


- *Next: T1: unlock(t1)* (unbalanced-unlock!)
  - T1 sets `t1->next->locked` to `false`.

T3 and T2 are both in CS. Violation of mutual exclusion.

MCS Lock - Analysis (Scenario 2)

- *Earlier -* **lock L:** NULL



- *Now - T3: unlock(t3)* (unbalanced-unlock!)
  - No successors / waiters for the lock. Reset L to NULL.
    - before resetting,

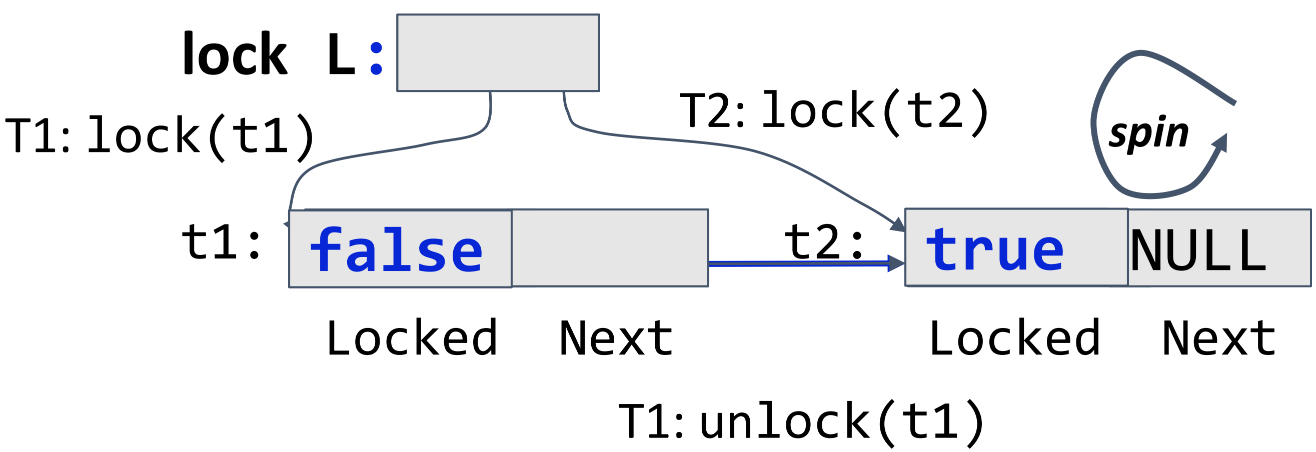
      Check if L still points to t3 (no successor has appeared in the meanwhile). If not:
      - wait till the successor appears in t3->next

This is never going to happen! T3 starves.

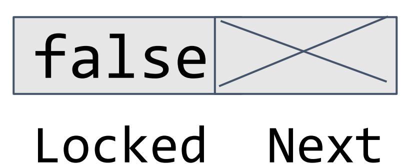
MCS Lock - Remedy

- Intuition: maintain an invariant that a flag (Locked) should be true whenever the releaser wants to release the lock.

Initialize, reset and check `Locked`

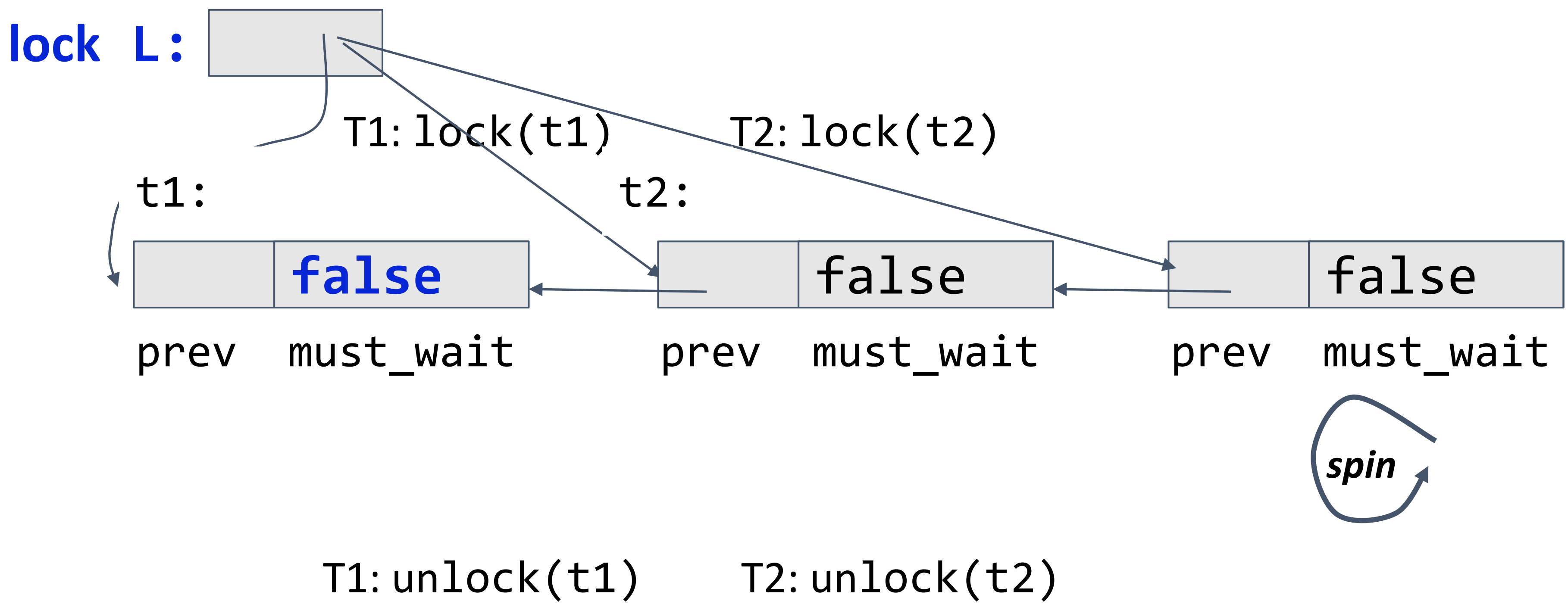



```
Tm: unlock(tm) {
    if (locked == false)
            return false
...
```



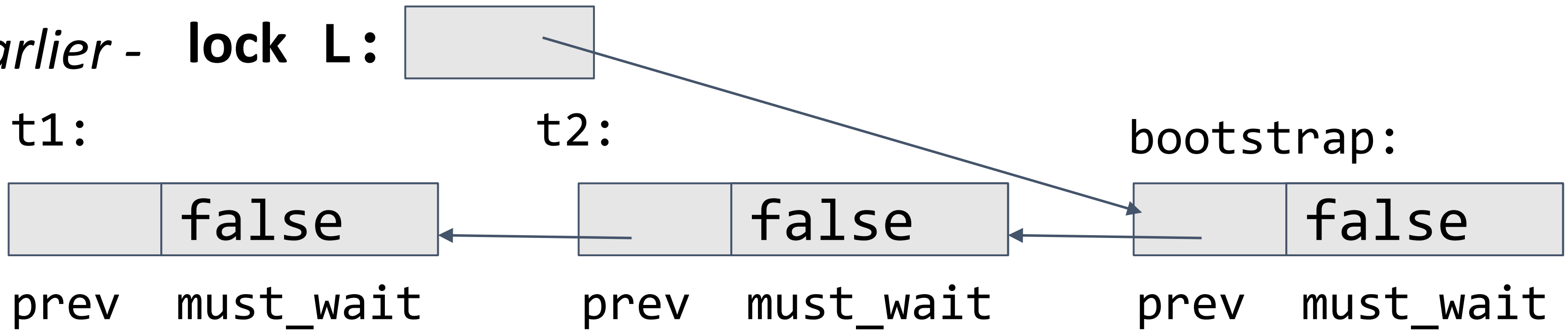
CLH Lock: Analysis and Remedy

CLH Lock - Analysis

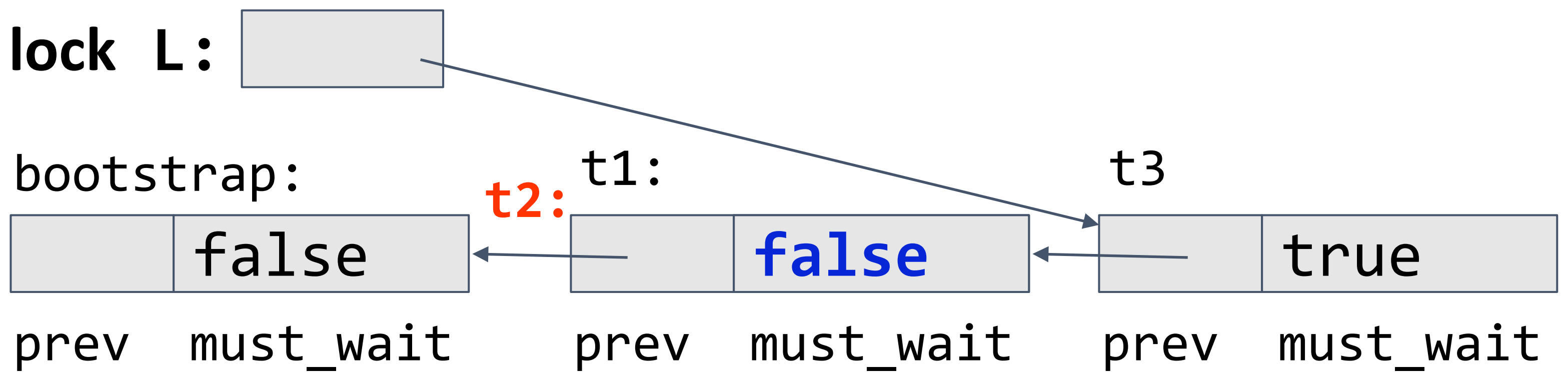


CLH Lock - Analysis (Scenario 1)

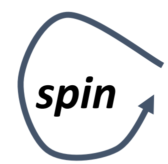
- *Earlier -*



- *Now: suppose T1 is holding the lock and T3 is spinning:*



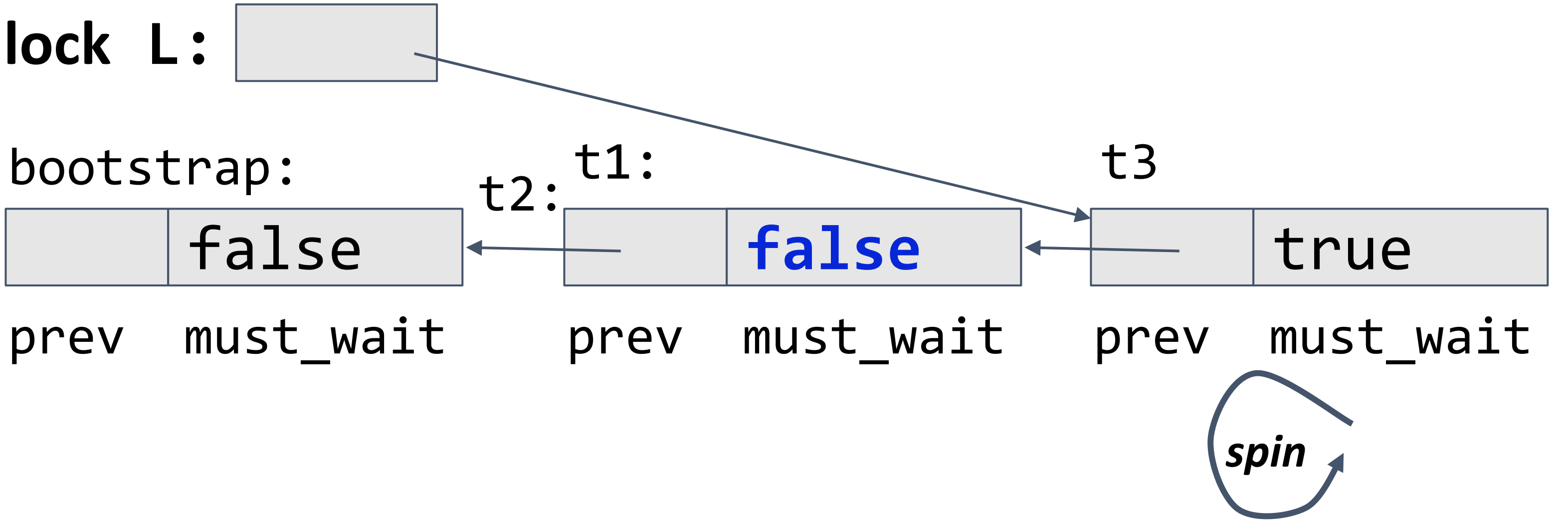
- *Next: T2: unlock(t2)* (unbalanced-unlock!)
  - T2 sets `t2->must_wait = false`
  - Takes ownership of `t1`! (predecessor of `t2`)



T2: unlock(t2) now releases T3 from spinning : T3 and T1 are both in CS. Violation of mutual exclusion.

CLH Lock - Analysis (Scenario 2)

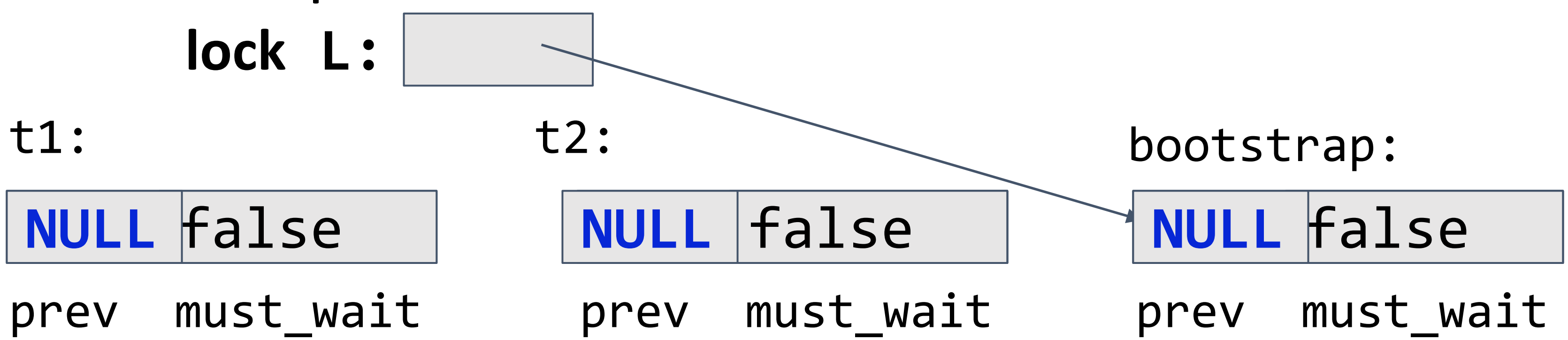
- *Extension of scenario 1 from previous slide*



- T2: `unlock(t2)` and T1: `unlock(t1)` racily update the `must_wait` field
- The updates may be lost preventing waiting threads from getting the lock. Successors starve!

CLH Lock - Remedy

- Intuition: maintain an invariant that `prev` pointer is not null only when a lock is being held
  - Initialize, reset and check `prev`
- After an episode of successful `lock-unlock`:




```
Tm: unlock(tm) {
    ...
      tm->prev = NULL
      return true
```

```
Tm: unlock(tm) {
      if(tm->prev == NULL)
        return false
    ...
```

Detects and prevents unbalanced-unlock

Fischer's Software Lock

```
start:
      while <x != 0>;
             <x := i>;
             <delay>
      if <x != i> goto start;
      critical section;
      if <x != i> goto exit;
      x := 0
exit:
```

lock()

unlock()

More Locks, Analysis and Remedies…

- Hierarchical locks
- Reader-Writer locks
- Reentrant Locks
- Hemlock
- MCS-K42 lock
- Software locks

Experimental Setup

- Configuration
  - dual-socket system
  - 24-core, Intel Xeon Gold 6240C@2.60GHz processor
  - CPU has 64 KB shared data and instruction caches
  - 1 MB unified L2 and 36 MB L3 unified caches
  - 384GB DDR4 memory
  - Rocky Linux 9
- Benchmarks
  - SPLASH-2x [6] and PARSEC 3.0 [5]
  - $barnes$, $dedup$, $ferret$,$fluidanimite$, fmm, $ocean$, $radiosity$, $raytrace$, and $streamcluster$
  - $Native$ input dataset

Results

Takeaway: Overhead of proposed remedy for lock algorithms is negligible (<5%)

Barnes (48)	-0.14	1.04	-0.12	0.54	0.93	1.18
Dedup (48)	-1.59	3.47	-3.32	0.32	4.25	1.62
Ferret (48)	-0.31	0.42	-0.45	-0.05	1.45	-0.97
Fluidanimate (32)	0.19	2.8	-0.78	1.96	NA	1.96
FMM (48)	0	0.64	-0.29	-0.85	0.4	-0.29
Ocean (32)	1.68	4.23	3.79	0.94	3.31	0.55
Radiosity (48)	2.08	19.5	0.87	2.62	1.72	-0.88
Raytrace (48)	16.9	86.7	3.08	-0.89	2.83	2.38
Streamcluster (48)	1.3	61.3	1.72	1.13	NA	-2.17
Synthetic (48)	22	118	-0.15	3.2	3.27	1.64

Numbers indicate overhead percentage at maximum thread count (48)

Conclusions

- **Unbalanced-unlock** is surprisingly common in popular open-source repositories.
- A systematic analysis of popular locks in unbalanced-unlock situation shows:
  - Mutex violation
  - Starvation
  - Corruption of lock internals and program
  - sometimes be side-effect free
- Remedy to eliminate side effects are simple and we apply the remedy to a representative set of lock implementations
- The modified lock implementations did not significantly affect performance

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