Advanced Multiprocessor Programming: Locks

Jesper Larsson Träff, Martin Wimmer

TU Wien

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Locks we have seen so far

- Peterson Lock
- Filter Lock
- Bakery Lock

These locks …

… use atomic registers

… have time and space complexity $O(n)$

… spin (busy waiting)

n: Number of threads

Problems with locks, recap

- Not compositional: Error prone, can lead to deadlocks if different locking conventions are used
- Priority inversion: In interaction with OS scheduler, a low priority thread holding a lock can block a high priority thread indefinitely by not being allowed to run because of a medium priority thread being scheduled
- Lock convoying: In interaction with OS scheduler, a descheduled thread holding a lock can cause other threads to queue up waiting for the lock; context switches between queued threads can be expensive

A typical lock interface

```
#include <pthread.h>

pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;

int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *mutexattr);

int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_timedlock(pthread_mutex_t *mutex,
                            const struct timespec *abs_timeout);

int pthread_mutex_unlock(pthread_mutex_t *mutex);

int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

To spin or not

Two types of lock implementations:

- Spin lock: Thread actively keeps trying (test some condition) to acquire lock (Peterson lock, Bakery lock, etc. are spin locks)
- Blocking lock: Thread suspends, scheduler (OS) reawakens thread when lock becomes free

Performance considerations:

- Spin lock: Good if critical section short (fast), low overhead; but keeps processor busy ("burns cycles")
- Blocking lock: Good for long critical sections, high (OS) overhead, processor/core can do something else

For coarse grained locking (pthreads), combinations often used: Spin for some time, then back off, then block

Additional pthread locks

```
#include <pthread.h>

int pthread_spin_lock(pthread_spinlock_t *lock);
int pthread_spin_trylock(pthread_spinlock_t *lock);

int pthread_spin_unlock(pthread_spinlock_t *lock);
```

(Strange) Design decision: Programmer needs to rewrite code to use spin locks
Alternative (why not?): Use attribute at initialization to fix pragmatics

Higher consensus operations

- Consensus number 1
  - Atomic registers
- Consensus number 2
  - (flag) test-and-set
  - get-and-set (aka: exchange, swap)
  - fetch-and-add (also: fetch-and-inc, fetch-and-X)
  - wait-free FIFO queues (also: stack, list, ...)
- Consensus number n
  - swap (aka: exchange)
- Consensus number ∞
  - compare-and-swap (cas, aka: compare-exchange)
  - load-linked - store-conditional (ll/sc)

C11 atomics

```
#include <stdatomic.h>

typedef /* unspecified */ atomic_flag;
_Bool atomic_flag_test_and_set( volatile atomic_flag* obj );
_Bool atomic_flag_test_and_set_explicit( volatile atomic_flag* obj, memory_order
     order );

C atomic_exchange( volatile A* obj, C desired );
C atomic_exchange_explicit( volatile A* obj, C desired, memory_order order );


_Bool atomic_compare_exchange_strong( volatile A* obj,
                                      C* expected, C desired );
_Bool atomic_compare_exchange_weak( volatile A *obj,
                                    C* expected, C desired );
_Bool atomic_compare_exchange_strong_explicit( volatile A* obj,
                                               C* expected, C desired,
                                               memory_order succ,
                                               memory_order fail );
_Bool atomic_compare_exchange_weak_explicit( volatile A *obj,
                                             C* expected, C desired,
                                             memory_order succ,
                                             memory_order fail );
C atomic_fetch_add( volatile A* obj, M arg );
C atomic_fetch_add_explicit( volatile A* obj, M arg, memory_order order );
C atomic_fetch_sub( volatile A* obj, M arg );
C atomic_fetch_sub_explicit( volatile A* obj, M arg, memory_order order );
// also: or, xor, and

void atomic_thread_fence( memory_order order );
```

Weak and strong and explicit compare-exchange

C/C++ beware: A failed compare-exchange is not a no-op, but loads the contents of the object into the location given for the expected value!

A strong compare-exchange must succeed if expected and memory values are indeed equal. A weak compare-exchange is allowed to not succeed and return false, even in case expected and memory values are equal ("spuriously"), but not indefinitely.

Rationale: Some hardware sacrifices strong compare-and-swap for sometimes better performance.

Compare-exchange operations are often used in loops, in some cases weak compare-exchange is correct and can give better performance. But not always.

Explicit atomics explicitly specify conditions on the memory model behavior (later lecture).

Header <atomic>

```
template< class T > struct atomic;
template<> struct atomic<Integral>;
template< class T > struct atomic<T*>;

// Member functions
(constructor) // constructs an atomic object
operator= // stores a value into an atomic object
is_lock_free // checks if the atomic object is lock-free
store // atomically replaces the value of the atomic object with a non-atomic
      argument
load //atomically obtains the value of the atomic object
operator T // loads a value from an atomic object
exchange // atomically replaces the value of the atomic object and obtains the
      value held previously
compare_exchange_weak // atomically compares the value of the atomic object with
      non-atomic argument and performs atomic exchange if equal or atomic load if
      not
compare_exchange_strong
```

Header <atomic>

```
// Specialized member functions
fetch_add // atomically adds the argument to the value stored in the atomic object
      and obtains the value held previously
fetch_sub // atomically subtracts the argument from the value stored in the atomic
      object and obtains the value held previously
fetch_and // atomically performs bitwise AND between the argument and the value of
      the atomic object and obtains the value held previously
fetch_or // atomically performs bitwise OR between the argument and the value of
      the atomic object and obtains the value held previously
fetch_xor // atomically performs bitwise XOR between the argument and the value of
      the atomic object and obtains the value held previously

operator++
operator-- // increments or decrements the atomic value by one
operator+=
operator-=
operator&=
operator|=
operator^= // adds, subtracts, or performs bitwise AND, OR, XOR with the atomic
      value
```

C11/C++11 threads

Native thread-model (somewhat like pthreads) with locks (mutexes) since C++11/C11. Use this (or pthreads)

```
#include <thread>

void myfunction()
{
  // make sure all threads start more or less at the same time
  // use mutex-condition variable, or (experimental) barrier construct

}
int main()
{
  // create and start threads (tree like, for larger number of threads
  std::thread t1(myfunction), t2(myfunction), t3(myfunction), t4(myfunction);

  // threads running, join back at end
    t1.join();
    t2.join();
    t3.join();
    t4.join();
}
```

Threads with OpenMP for C/C++

OpenMP: Fork-join thread-model programming language extension. Can be used to easily start and synchronize threads.

```
#include <omp.h>

void benchmark() // called by master thread
{
  double threadtime[omp_get_max_threads()];

#pragma omp parallel // further clauses to control number of threads etc.
  {
    // threads active, per thread scope
    int p = omp_get_num_threads();
    int t = omp_get_thread_num();
    double start, stop;

#pragma omp barrier
    start = omp_get_wtime();

    // code to be benchmarked

    stop = omp_get_wtime();
    threadtime[t] = stop-start; // and other statistics
  }
  // only master thread active
}
```

Threads with OpenMP for C/C++

OpenMP: Fork-join thread-model programming language extension. Can be used to easily start and synchronize threads.

For a concrete example, see the code for

> Jesper Larsson Träff, Manuel Pöter: A more pragmatic implementation of the lock-free, ordered, linked list. PPoPP 2021: 457-459

which is available via
`https://github.com/parlab-tuwien/lockfree-linked-list`

Cost of atomic operations

- All O(1), constant time, and wait-free instructions, imlemented efficiently in hardware (CA: How?)
- But how large are the constants? And same O(1) under all circumstances?
- Reasonable for `exhange` and `fetch_add`?
  - These must always succeed, high contention could cause delays

For a paper attempting to assess costs of atomic operations, see
Hermann Schweizer, Maciej Besta, Torsten Hoefler: Evaluating the Cost of Atomic Operations on Modern Architectures. PACT 2015: 445-456

Higher consensus operations in action:

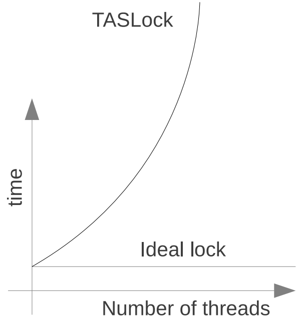
- Test-And-Set Lock
  - Single flag field per lock
  - Acquire lock by changing flag from false to true $\rightarrow$ locked on success
  - Reset flag to unlock

```
bool locked = false; // atomic register

void lock() {
  while (test_and_set(&locked));
}

void unlock() {
  locked = false;
}
```

- Performance (surprisingly?) bad (why?)
  - Each test-and-set call invalidates cached copies for all threads
  - High contention on memory interconnect



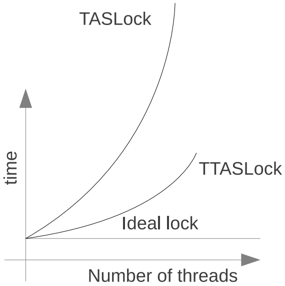
Test-And-Test-And-Set lock

- Test-and-set only if there is a chance of success
- Cache invalidated less often
- Still contention with more threads
- Relies on cache-coherence protocol implementation
- Beware of compiler optimizations (`volatile`)!

```
volatile bool locked = false;

void lock() {
  do {
    while (locked);
    if (!test_and_set(&locked)) return;
  } while (true);
}

void unlock() {
  locked = false;
}
```



Exponential Backoff

- On failure to acquire lock:
  → Backoff with random duration
- Increase time to wait exponentially
  - Reduces contention
  - Try less often on high contention
  - Randomization ensures that threads wake up at different times
- Threads might wait longer than necessary!
- C++ note: Don't use rand()
  → Not thread-safe: Uses locks inside!

  (Here: Thread-safe pseudo-function `rnd()`)

```
class Backoff {
  int limit = MIN_DELAY;

  void backoff() {
    int delay = rnd() % limit;
    limit =
      min(MAX_DELAY, limit*2);
    sleep(delay); // suspend for
          some time
  }
}
```

```
volatile bool locked = false;

void lock() {
  Backoff bo;
  do {
    while (locked);
    if (!test_and_set(&locked))
      return;
    bo.backoff();
  } while (true);
}

void unlock() {
  locked = false;
}
```

Test-And-Set-Locks: Summary

- Space complexity O(1) for ∞ threads
  - Possible by test-and-set (consensus number 2)
- Unlock wait-free O(1)

- Problem with memory contention
  - All threads spin on a single memory location
    (cache coherence traffic)
- Threads might wait longer than necessary due to backoff
- Unfair, and not starvation free
- "Fault-tolerant": Stalled (crashed) thread not having lock will not prevent other threads from using lock

Thread programming needs thread safety

All functions called by a thread must be thread-safe: Can be called concurrently, outcomes depend only on thread-local state:

- Pure functions: No side-effects, no (global) state
- All functions called must likewise be thread-safe

Fair locks: Ticket Lock

- Atomic ticket counter
- Non-atomic served counter
- Lock: Take ticket and wait for served
- Unlock: Serve next

```
int ticket = 0; // atomic
volatile int served = 0;

void lock() {
  int next = fetch_add(&ticket,1)
  while (served<next) {};
}

void unlock() {
  served++;
}
```

Ticket Lock: Properties

- First-come, first-served, linearization by fetch-and-add
- Space efficient: O(1) per lock!
- Unlock wait-free O(1)
- Ticket grows unboundedly
- Each thread spins on a local copy of a variable (in cache)
- False sharing might occur (if both served and ticket variables on same cache-line)
- Slow (stalled, crashed) thread will stall later threads. Not "fault-tolerant"

Too strong fairness; the following locks will have the same problem.
Problem: all threads before calling thread must be served.

Fair locks: Array Lock

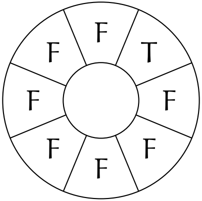
- Circular array of atomic memory locations
- Lock: Spin on next free slot
- Unlock: Release slot

```
bool flags[n] =
  {true, false, false, false, ...}
int tail = 0; // atomic
thread_local int mySlot;

void lock() {
  mySlot = fetch_add(&tail,1) % n;
  while(!flags[mySlot]) {};
}

void unlock() {
  flags[mySlot] = false;
  flags[(mySlot + 1) % n] = true;
}
```

$\mathsf{tail} = \boxed{0}$



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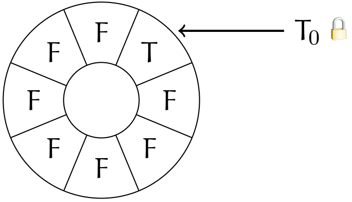
int tail = 0; // atomic
thread_local int mySlot;

void lock() {
  mySlot = fetch_add(&tail,1) % n;
  while(!flags[mySlot]) {};
}

void unlock() {
  flags[mySlot] = false;
  flags[(mySlot + 1) % n] = true;
}
```

$\mathsf{tail} = \boxed{1}$



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  while(!flags[mySlot]) {};
}

void unlock() {
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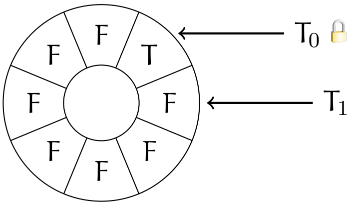
  flags[(mySlot + 1) % n] = true;
}
```

tail = $\boxed{2}$



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  while(!flags[mySlot]) {};
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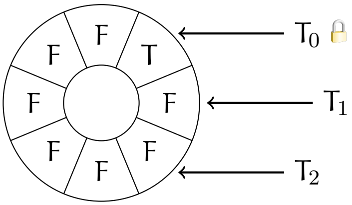
  flags[mySlot] = false;
  flags[(mySlot + 1) % n] = true;
}
```

$\text{tail} = \boxed{3}$



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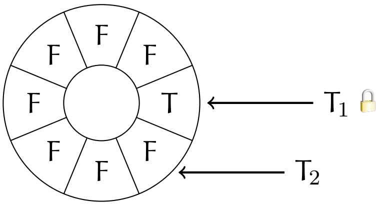
}
```

tail = $\boxed{3}$



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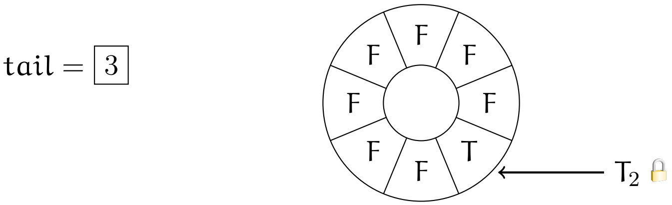

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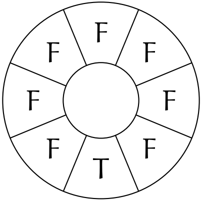


Array Lock: Properties

- First-come, first-served, linearization by fetch-and-add
- Unlock wait-free $O(1)$
- Less contention than simple test-and(-test-and)-set lock
  - Each thread spins on a local copy of a variable
  - False sharing might occur, resolvable by padding
- Not space efficient: $O(n)$ per lock!
- Not fault-tolerant

False sharing: Unrelated addresses on same cache-line still entail remote cache invalidation/updates.

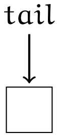
CLH Queue Lock

- Independently by Craig & Landin and Hagersten
- Linked list
- Single Sentinel node
- Spin on locked flag of next node

```
Node* tail = new Node();
tail->locked = false; // unlocked
thread_local Node* node;

void lock() {
  node = new Node();
  node->locked = true;
  node->next = exchange(&tail,node);
  while (node->next->locked) {}
}

void unlock() {
  delete node->next;
  node->locked = false;
}
```



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}

void unlock() {
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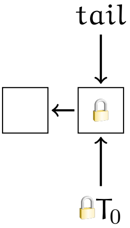
}
```



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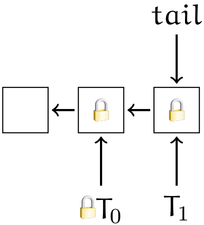

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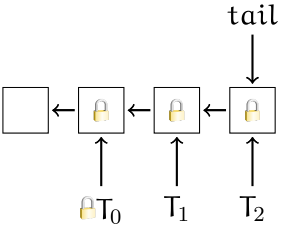

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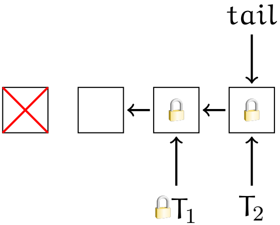

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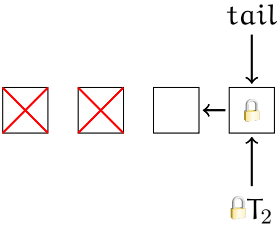

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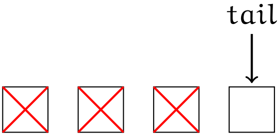


CLH Queue Lock: Implementation notes

- C++ only supports static thread_local variables
  - Either pass on some data on lock and unlock
    (if allowed by interface)
  - Or implement thread-local object storage yourself
    (Or use `boost::thread_specific_ptr`)

- Implementation (and field names) here differs slightly from Herlihy/Shavit
  - Next field stored in node
  - Manual memory management
  - Next can safely be deleted at unlock
    (no other thread accessing it)

CLH Queue Lock: Properties

- First-come, first-served, linearization by `exchange`
- Unlock wait-free $O(1)$
- $O(L)$ space, where L is the number of threads currently accessing the lock
  - More space depending on implementation of thread_local data
  - Herlihy/Shavit implementation requires $O(n)$
- Each thread spins on a separate location
  - Allocated locally by each thread, reduces false sharing
- Potential problem on NUMA architectures:
  - Locked field is in remote location
- Not fault-tolerant

MCS Queue Lock

- Maintain head instead of tail in list
- Spin on field in own node
- To unlock, modify locked field of next node
- If no successor exists, reset head

$$\begin{array}{c} \text{head} \\ \downarrow \\ \perp \end{array}$$

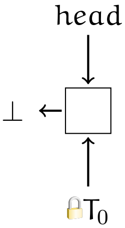
```
Node* head = nullptr;
thread_local Node* node = new Node();
node->next = nullptr;

void lock() {
  Node* n = node;
  Node* pred = exchange(&head,n);
  if (pred != nullptr) {
    n->locked = true;
    pred->next = n;
    while (n->locked);
  }
}

void unlock() {
  Node* n = node;
  if (n->next == nullptr) {
    if (compare_exchange(&head,n,
                         nullptr))
      return;
    // Wait for next thread
    n = node; // Be careful with C/C++
    while (n->next == nullptr);
  }
  n->next->locked = false;
  n->next = nullptr;
}
```

MCS Queue Lock

- Maintain head instead of tail in list
- Spin on field in own node
- To unlock, modify locked field of next node
- If no successor exists, reset head

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    // Wait for next thread
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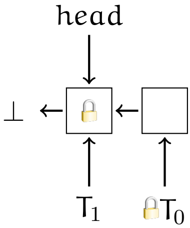


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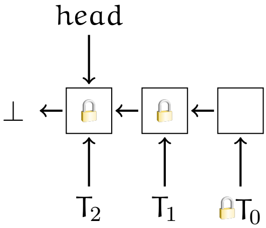


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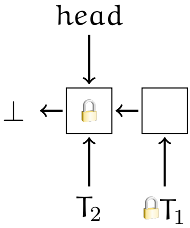


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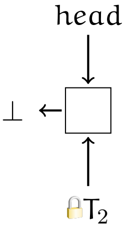


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MCS Queue Lock: Properties

- First-come, first-served
- $O(n)$ space total
  - More space depending on implementation of thread_local data
- Each thread spins on its own memory location
  - Updated by other thread
- No additional memory management

- Requires compare-and-swap
  (consensus number ∞)
- Unlock not wait-free any more!
  (Waiting for next lock owner to set `next` pointer)
- Not fault-tolerant

Space Requirements in Array and Queue Locks

- These locks are starvation free (first-come, first-served fair)
- Array and queue locks all need $\Omega(n)$ space (thread local nodes, slot in array); shown by Hendler/Fich/Shavit
- In this sense, higher consensus operations do not improve on the simple register locks

Queue Locks with timeouts (trylock)

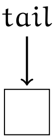
- Abandoning is easy for Test-And-Set lock
  - Just stop trying to acquire lock
  - Timing out is wait-free
- More difficult for queue locks
  - If we just exit, the following thread will starve
  - Can't just unlink the node

    (other thread might be accessing it)

- Lazy approach
  - Mark node as abandoned
  - Successor is responsible for cleanup

Queue Locks with timeouts (here: CLH Queue Lock)

- Add flag `abandoned` to nodes
- To abandon, set flag to `true`
- Next node is responsible for clean-up

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Node* tail = new Node();
thread_local Node* node;

bool try_lock(int timeout) {
  node = new Node();
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  node->abandoned = false;
  node->next = exchange(&tail,node);
  int start = time();
  while (node->next->locked) {
    if (node->next->abandoned) {
      Node* pp = node->next->next;
      delete node->next;
      node->next = pp;
    }
    if (start + timeout <= time() {
      node->abandoned = true;
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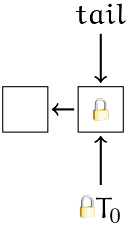


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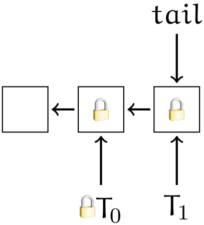


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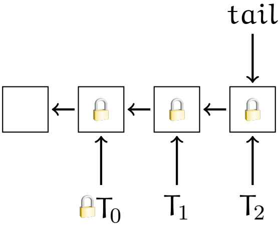


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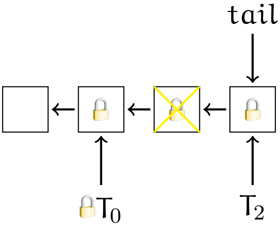


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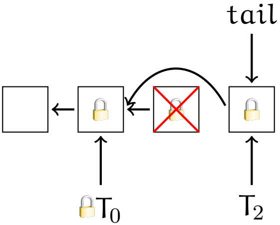


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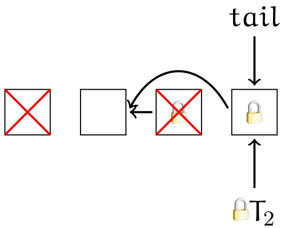


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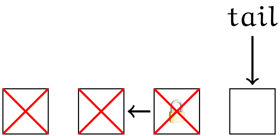


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- Combines Backoff lock and Queue lock
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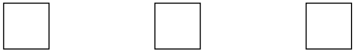

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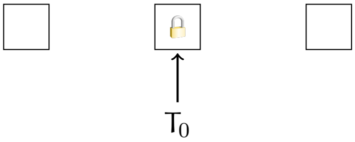

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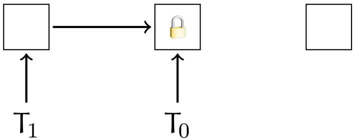

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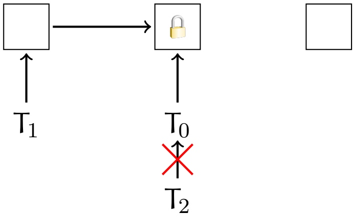

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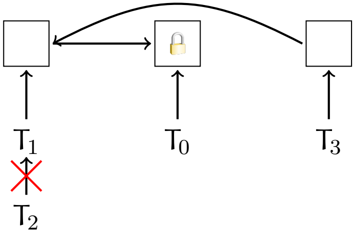

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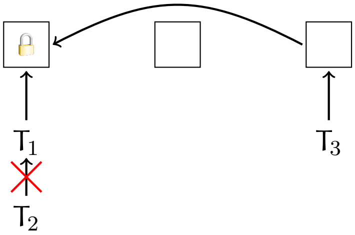

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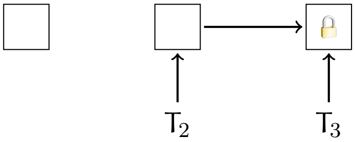

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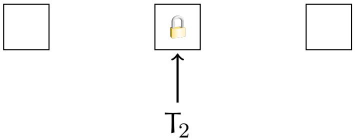

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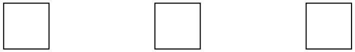
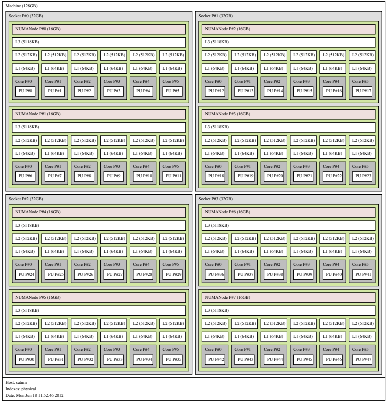


- Most modern architectures are NUMA architectures
- Some processors are near to each other
  - → Smaller memory access times
- Hierarchical locks minimize lock migration[1]

- Look at the architecture of your own machine
  - `lstopo` tool (part of hwloc)
  - Try it on mars/saturn and ceres



[1] A lock L migrates if two threads running on a different NUMA clusters (nodes) acquire L one after the other - from Dice et al., PPoPP 2012

Hierarchical Backoff Lock

- Original idea by Zoran Radovic and Erik Hagersten
- Based on Backoff Lock
- Length of backoff dependent on distance to lock owner

  (2-level hierarchy common)
- Local threads are more likely to acquire lock
- May starve remote threads!

```
int noowner = 1;
int owner = noowner;

void lock() {
  int current_owner;
  do {
    current_owner = noowner;
    if (compare_exchange(
          &owner,&current_owner,
               thread_id()))
    break;

    /* C11 convention:
       Failed compare_exchange loads
       old value of owner into
       current_owner
    */

    int distance =
      memory_distance(current_owner,
                      thread_id());
    backoff(distance);
  } while (1);
}
```

Hierarchical CLH Lock

- By Victor Luchangco, Dan Nussbaum and Nir Shavit

- Multiple clusters of processors
- 1 global queue
- 1 local queue per cluster

- Add node to local queue
- First node in local queue is the cluster master and splices local queue into global queue
- Others wait until they have the lock or become cluster master

```
thread_local Node* pred, node;
// cluster local queues
cluster_local Node* lq;
Node* gq; // global queue

void lock()
{
  // Splice into local queue
  pred = exchange(&lq,node);

  if (pred != nullptr) {
    bool lock =
      wait_lock_or_master(pred);
    if (lock) // Lock acquired
      return;
  }

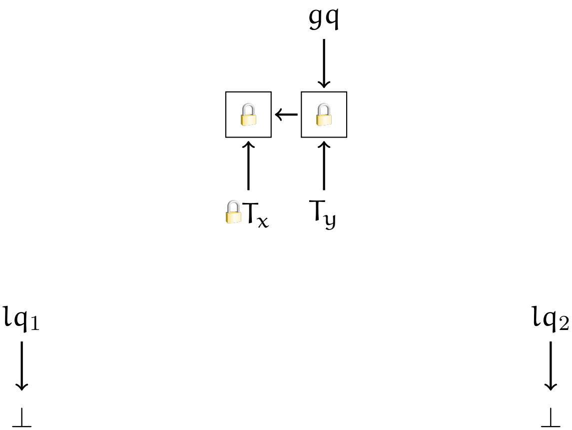
  // Thread is now cluster master

  // Splice local into global queue
  tail = *lq;
  pred = exchange(&gq,tail);
  node->pred = pred;

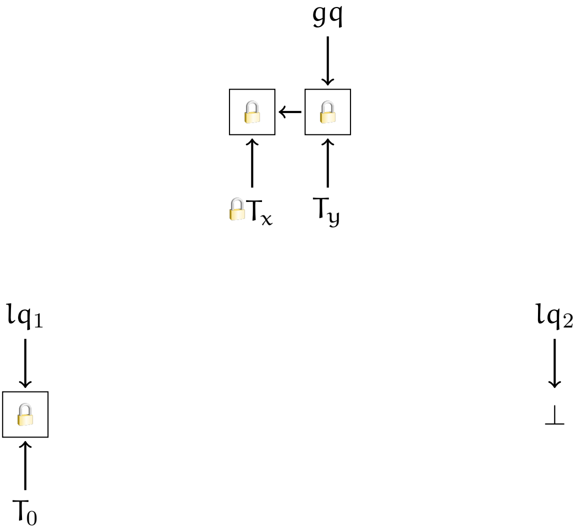
  // Successor is new cluster master
  tail->newmaster = true;

  // Wait for lock
  while (pred->locked);
}
```

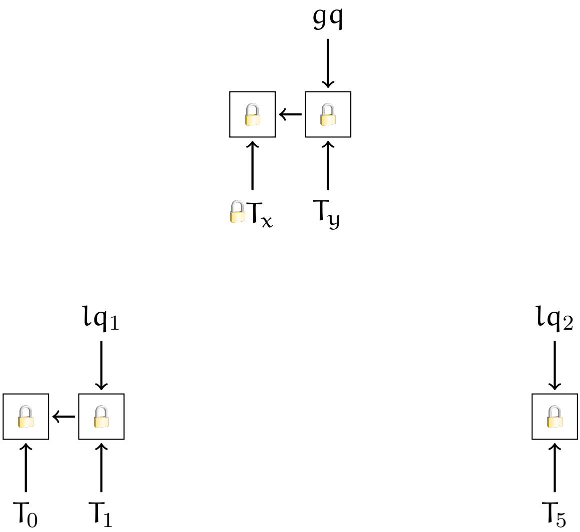
Hierarchical CLH Lock



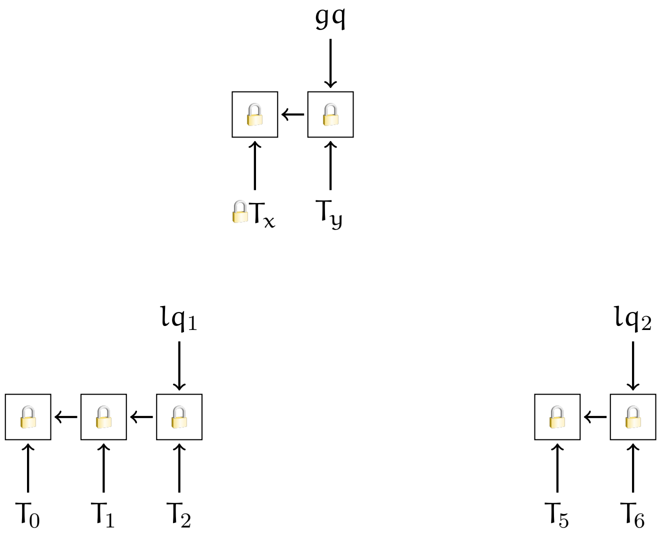
Hierarchical CLH Lock



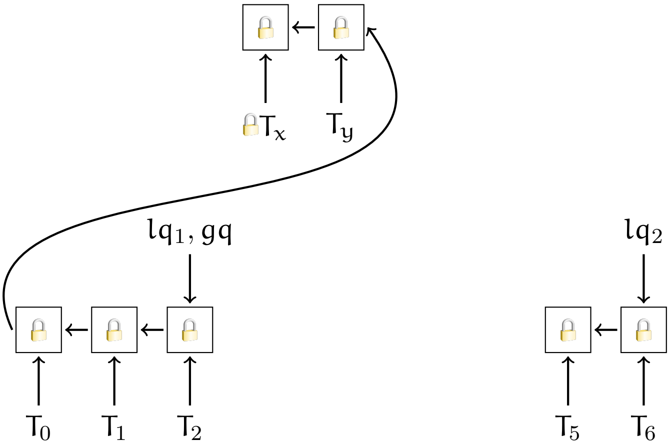
Hierarchical CLH Lock



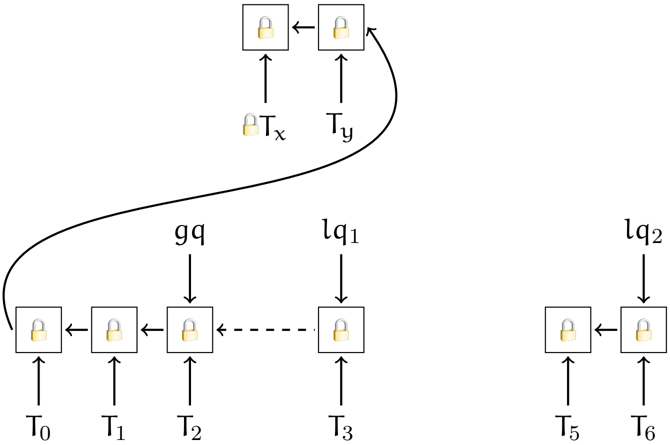
Hierarchical CLH Lock



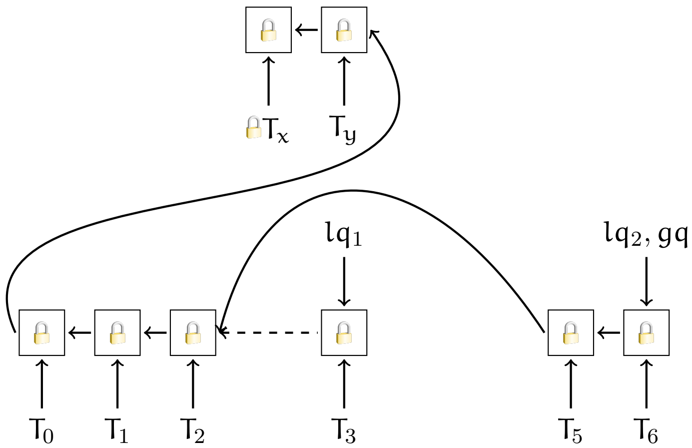
Hierarchical CLH Lock



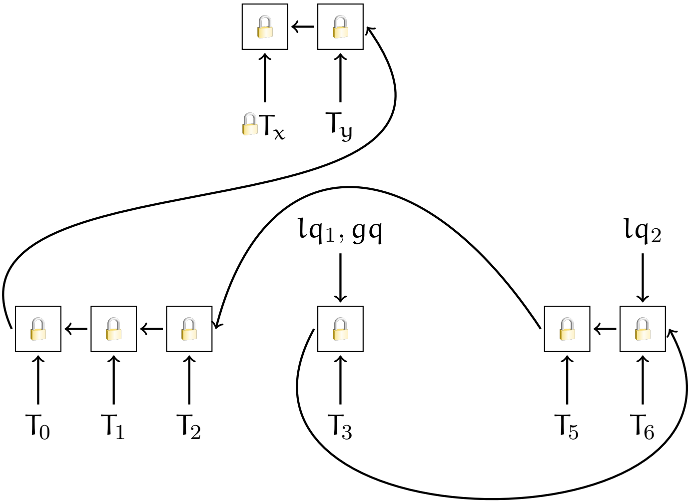
Hierarchical CLH Lock



Hierarchical CLH Lock



Hierarchical CLH Lock



Lock Cohorting

- Introduced in 2012 by David Dice, Virendra J. Marathe and Nir Shavit

- General technique to construct NUMA-aware locks from normal locks
- 1 global lock (not NUMA aware)
- 1 local lock per cluster
  - Requires cohort detection ability

    (Other threads from same cluster wait for global lock)
- Threads must acquire both locks
  - Global lock can be passed around inside NUMA cluster
  - Release global lock at some point for fairness
- Supports abortable locks

Final remarks

- There is no one lock for every application
- Choice depends on congestion in application
- NUMA-awareness improves performance on modern systems

- Reader-Writer Locks not discussed in this lecture
  - See Herlihy-Shavit book
  - A recent result: NUMA-aware reader-writer locks by Calciu et al., PPoPP 2013

Pthreads readers-writers locks

Many readers, at most one writer in critical section.

```c
#include <pthread.h>

int pthread_rwlock_init(pthread_rwlock_t *restrict rwlock,
                        const pthread_rwlockattr_t *restrict attr);

int pthread_rwlock_rdlock(pthread_rwlock_t *rwlock);
int pthread_rwlock_tryrdlock(pthread_rwlock_t *rwlock);
int pthread_rwlock_trywrlock(pthread_rwlock_t *rwlock);
int pthread_rwlock_wrlock(pthread_rwlock_t *rwlock);

int pthread_rwlock_unlock(pthread_rwlock_t *rwlock);

int pthread_rwlock_destroy(pthread_rwlock_t *rwlock);
```

Lock summary

- Test-And-Set Locks
  - \+ Low overhead
  - \+ Abortable by design
  - \- Unfair
  - \- All threads spin on same memory location
  - \- Threads may wait longer than necessary with backoff
- Queue Locks
  - \+ Fair
  - \+ Threads spin on different locations
  - \- Hard to abort
  - \- Cleanup often difficult without garbage collection
  - \- Need $\Omega(n)$ space
- Composite Lock
  - \+ Tries to take advantages of both TAS locks and Queue locks
  - \+ Good at high congestion
  - \- High overhead on low congestion
  - \- Quite complex
- Hierarchical Locks
  - \+ Higher performance on NUMA systems due to less lock migrations
  - \+ Cohorting allows to use all lock types for NUMA-aware locks
  - \- Added complexity

References

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- Peter S. Magnusson, Anders Landin, and Erik Hagersten. Queue locks on cache coherent multiprocessors. In Proceedings of the 8th International Symposium on Parallel Processing, pages 165–171, 1994.
- David Dice, Virendra J. Marathe, and Nir Shavit. Lock cohorting: a general technique for designing NUMA locks. In Proceedings of the 17th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming (PPOPP), pages 247–256, 2012.
- Faith Ellen, Danny Hendler, Nir Shavit On the Inherent Sequentiality of Concurrent Objects. SIAM J. Comput., 41(3): 519–536, 2012.