NON-BLOCKING DATA STRUCTURES
AND TRANSACTIONAL MEMORY

Tim Harris, 11 Oct 2019
Lecture 1/3

- Introduction
- Basic spin-locks
- Queue-based locks
- Hierarchical locks
- Reader-writer locks
- Reading without locking
- Flat combining
Overview

- Building shared memory data structures
  - Lists, queues, hashtables, ...

- Why?
  - Used directly by applications (e.g., in C/C++, Java, C#, ...)
  - Used in the language runtime system (e.g., management of work, implementations of message passing, ...)
  - Used in traditional operating systems (e.g., synchronization between top/bottom-half code)

- Why not?
  - Don’t think of “threads + shared data structures” as a default/good/complete/desirable programming model
  - It’s better to have shared memory and not need it...
Different techniques for different problems

- Ease to write
- Correctness
- When can it be used?
- How fast is it?
- How well does it scale?
Suggested reading

- “The art of multiprocessor programming”, Herlihy & Shavit – excellent coverage of shared memory data structures, from both practical and theoretical perspectives
Suggested reading

- “The art of multiprocessor programming”, Herlihy & Shavit – excellent coverage of shared memory data structures, from both practical and theoretical perspectives
Suggested reading

- “The art of multiprocessor programming“, Herlihy & Shavit – excellent coverage of shared memory data structures, from both practical and theoretical perspectives
- Recent research papers on in-memory databases built from concurrent data structures – search for SILO, and work from Haibo Chen and colleagues
Suggested reading

- “The art of multiprocessor programming”, Herlihy & Shavit – excellent coverage of shared memory data structures, from both practical and theoretical perspectives
- Recent research papers on in-memory databases built from concurrent data structures – search for SILO, and work from Haibo Chen and colleagues
- “Transactional memory, 2\textsuperscript{nd} edition”, Harris, Larus, Rajwar – survey of transactional memory work, with 350+ references
- “NOrec: streamlining STM by abolishing ownership records”, Dalessandro, Spear, Scott, PPoPP 2010
Basic spin-locks
bool testAndSet(bool *b) {
    bool result;
    atomic {
        result = *b;
        *b = TRUE;
    }
    return result;
}
Test and set

• Suppose two threads use it at once

Thread 1:

\[\text{testAndSet}(b) \rightarrow \text{true}\]

Thread 2:

\[\text{testAndSet}(b) \rightarrow \text{false}\]
Test and set lock

void acquireLock(bool *lock) {
  while (testAndSet(lock)) {
    /* Nothing */
  }
}

void releaseLock(bool *lock) {
  *lock = FALSE;
}

FALSE => lock available
TRUE => lock held

Each call tries to acquire the lock, returning TRUE if it is already held

NB: all this is pseudo-code, assuming SC memory
Test and set lock

lock: TRUE

void acquireLock(bool *lock) {
    while (testAndSet(lock)) {
        /* Nothing */
    }
}

void releaseLock(bool *lock) {
    *lock = FALSE;
}

Thread 1

Thread 2

Non-blocking data structures and transactional memory
What are the problems here?

testAndSet implementation causes contention
Contention from testAndSet

- Single-threaded core
  - L1 cache
  - L2 cache
- Single-threaded core
  - L1 cache
  - L2 cache

Main memory

Non-blocking data structures and transactional memory
Multi-core h/w – separate L2

- Single-threaded core
- Single-threaded core
- L1 cache
- L1 cache
- L2 cache
- L2 cache
- Main memory

- testAndSet(k)
Multi-core h/w – separate L2

- Single-threaded core
  - L1 cache
  - L2 cache
  - Main memory
- Single-threaded core
  - L1 cache
  - L2 cache
  - Main memory

Non-blocking data structures and transactional memory

`testAndSet(k)`
Does this still happen in practice? Do modern CPUs avoid fetching the line in exclusive mode on failing TAS?
What are the problems here?

- testAndSet implementation causes contention
- No control over locking policy
- Only supports mutual exclusion: not reader-writer locking
- Spinning may waste resources while waiting
General problem

- No logical conflict between two failed lock acquires
- Cache protocol introduces a physical conflict
- For a good algorithm: only introduce physical conflicts if a logical conflict occurs
  - In a lock: successful lock-acquire & failed lock-acquire
  - In a set: successful insert(10) & failed insert(10)
- But not:
  - In a lock: two failed lock acquires
  - In a set: successful insert(10) & successful insert(20)
  - In a non-empty queue: enqueue on the left and remove on the right
Test and test and set lock

```c
void acquireLock(bool *lock) {
    do {
        while (*lock) {
        }
    } while (testAndSet(lock));
}

void releaseLock(bool *lock) {
    *lock = FALSE;
}
```

FALSE => lock available
TRUE => lock held

Spin while the lock is held... only do testAndSet when it is clear
Performance

\[ \text{Time} \]
\[ \# \text{Threads} \]

TAS

TATAS

Ideal

Based on Fig 7.4, Herlihy & Shavit, “The Art of Multiprocessor Programming”
Stampedes

lock: TRUE

```c
void acquireLock(bool *lock) {
    do {
        while (*lock) {}  
    } while (testAndSet(lock));
}

void releaseLock(bool *lock) {
    *lock = FALSE;
}
```
Back-off algorithms

1. Start by spinning, watching the lock for “s” iterations
2. If the lock does not become free, wait locally for “w” (without watching the lock)

What should “s” be?
What should “w” be?
Time spent spinning on the lock “s”

- **Lower values:**
  - Less time to build up a set of threads that will stampede
  - Less contention in the memory system, if remote reads incur a cost
  - Risk of a delay in noticing when the lock becomes free if we are not watching

- **Higher values:**
  - Less likelihood of a delay between a lock being released and a waiting thread noticing
Local waiting time “w”

- **Lower values:**
  - More responsive to the lock becoming available

- **Higher values:**
  - If the lock doesn’t become available then the thread makes fewer accesses to the shared variable
Methodical approach

- For a given workload and performance model:
  - What is the best that could be done (i.e. given an “oracle” with perfect knowledge of when the lock becomes free)?
  - How does a practical algorithm compare with this?
- Look for an algorithm with a bound between its performance and that of the oracle
- “Competitive spinning”
Rule of thumb

- Spin on the lock for a duration that’s comparable with the shortest back-off interval
- Exponentially increase the per-thread back-off interval (resetting it when the lock is acquired)
- Use a maximum back-off interval that is large enough that waiting threads don’t interfere with the other threads’ performance
Systems problems

- The threads need to “wait efficiently”
- Not consuming processing resources (contending with lock holder) & not consuming power
- “monitor” / “mwait” operations – e.g., SPARC M7

Lots of h/w threads multiplexed over a core
Systems problems

- Spinning gets in the way of other s/w threads, even if done efficiently
- For long delays, may need to actually block and unblock
- ...as with back-off, how long to spin for before blocking?
Queue-based locks
Queue-based locks

- Lock holders queue up: immediately provides FCFS behavior
- Each spins *locally* on a flag in their queue entry: no remote memory accesses while waiting
- A lock release wakes the next thread directly: no stampede
MCS locks

Local flag

Lock identifies tail

QNode 1
FALSE

QNode 2
FALSE

QNode 3
FALSE

Head
Tail

Non-blocking data structures and transactional memory
MCS lock acquire

```c
void acquireMCS(mcs *lock, QNode *qn) {
    QNode *prev;
    qn->flag = false;
    qn->next = NULL;
    while (true) {
        prev = lock->tail;
        if (CAS(&lock->tail, prev, qn)) break;
    }
    if (prev != NULL) {
        prev->next = qn;
        while (!qn->flag) { } // Spin
    }
}
```

Find previous tail node

Atomically replace “prev” with “qn” in the lock itself

Add link within the queue
MCS lock release

```c
void releaseMCS(mcs *lock, QNode *qn) {
  if (lock->tail == qn) {
    if (CAS(&lock->tail, qn, NULL)) return;
  }
  while (qn->next == NULL) { }
  qn->next->flag = TRUE;
}
```

If we were at the tail then remove us

Wait for next lock holder to announce themselves; signal them
Hierarchical locks
Hierarchical locks

- Core 1
- Core 2
- Core 3
- Core 4
- Shared L2 cache

- Core 5
- Core 6
- Core 7
- Core 8
- Shared L2 cache

Memory bus

Memory
Hierarchical locks

Non-blocking data structures and transactional memory
Hierarchical locks

Pass lock "nearby" if possible

Call this a "cluster" of cores

Non-blocking data structures and transactional memory
Hierarchical TATAS with backoff

void acquireLock(bool *lock) {
    do {
        holder = *lock;
        if (holder != -1) {
            if (holder == MY_CLUSTER) {
                BackOff(SHORT);
            } else {
                BackOff(LONG);
            }
        }
    } while (!CAS(lock, -1, MY_CLUSTERS));
}
Hierarchical locks: unfairness vs throughput

Avoid this cycle repeating, starving 5 & 7...
Lock cohorting

Lock cohorting

- Lock acquire, uncontended

(1) Acquire local lock

(2) Acquire global lock
Lock cohorting

- Lock acquire, contended

1. Wait for local lock (e.g., MCS)
Lock cohorting

- Lock release, with successor

(1) Pass global lock to successor
Lock cohorting, requirements

- Global: “thread oblivious” (acq one thread, release another)
- Local lock: “cohort detection” (can test for successors)
Reader-writer locks
Reader-writer locks (TATAS-like)

void acquireWrite(int *lock) {
    do {
        if ((*lock == 0) &&
            (CAS(lock, 0, -1))) {
            break;
        } while (1);
    }
}

void acquireRead(int *lock) {
    do {
        int oldVal = *lock;
        if ((oldVal >= 0) &&
            (CAS(lock, oldVal, oldVal+1))) {
            break;
        } } while (1);
}

void releaseWrite(int *lock) {
    *lock = 0;
}

void releaseRead(int *lock) {
    FADD(lock, -1); // Atomic fetch-and-add
}
The problem with readers

```c
int readCount() {
    acquireRead(lock);
    int result = count;
    releaseRead(lock);
    return result;
}
```

```c
void incrementCount() {
    acquireWrite(lock);
    count++;
    releaseWrite(lock);
}
```

- Each acquireRead fetches the cache line holding the lock in exclusive mode
  - Again: acquireRead are not logically conflicting, but this introduces a physical conflict
- The time spent managing the lock is likely to vastly dominate the actual time looking at the counter
- Many workloads are read-mostly...
Keeping readers separate

Acquire write on core i: CAS the owner from 0 to i

...then spin until all of the flags are clear

Acquire read on core i: set own flag to true...

...then check that the owner is 0 (if not then clear own flag and wait)
Keeping readers separate

- With care, readers do not need to synchronize with other readers
  - Extend the flags to be whole cache lines
  - Pack multiple locks flags for the same thread onto the same line
  - Exploit the cache structure in the machine: Dice & Shavit’s TLRW byte-lock on SPARC Niagara

- If "N" threads is very large..
  - Dedicate the flags to specific important threads
  - Replace the flags with ordinary multi-reader locks
  - Replace the flags with per-NUMA-domain multi-reader locks
Other locking techniques

- Affinity
  - Allow one thread fast access to the lock
  - “One thread” – e.g., previous lock holder
  - “Fast access” – e.g., with fewer / no atomic CAS operations
  - Mike Burrows “Implementing unnecessary mutexes”
    (Do the assumptions hold? How slow is an uncontended CAS on a modern machine? Are these techniques still useful?)
Other locking techniques

- Affinity
  - Allow one thread fast access to the lock
  - “One thread” – e.g., previous lock holder
  - “Fast access” – e.g., with fewer / no atomic CAS operations
  - Mike Burrows “Implementing unnecessary mutexes”
    (Do the assumptions hold? How slow is an uncontended CAS on a modern machine? Are these techniques still useful?)

- Inflation
  - Start out with a simple lock for likely-to-be-uncontended use
  - Replace with a “proper” lock if contended
  - David Bacon (thin locks), Agesen et al (meta-locks)
  - Motivating example: standard libraries in Java
Where are we

- Amdahl’s law: to scale to large numbers of cores, we need critical sections to be rare and/or short
- A lock implementation may involve updating a few memory locations
- Accessing a data structure may involve only a few memory locations too
- If we try to shrink critical sections then the time in the lock implementation becomes proportionately greater
- So:
  - try to make the cost of the operations in the critical section lower, or
  - try to write critical sections correctly without locking
Reading without locking
What if updates are very rare

- Modest number of updates: could use reader-writer locks
- No updates at all: no need for locking
Version numbers

Sequential data structure with write lock

Per-data-structure version number
Version numbers: writers
Version numbers: writers

Writers:
1. Take write lock
2. Increment version number
Version numbers: writers

**Writers:**
1. Take write lock
2. Increment version number
3. Make update
Version numbers: writers

Writers:
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock
Version numbers: readers

Writers:
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock

Readers:
1. Wait for version number to be even
Version numbers: readers

Writers:
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock

Readers:
1. Wait for version number to be even
2. Do operation
Version numbers: readers

**Readers:**
1. Wait for version number to be even
2. Do operation
3. Has the version number changed?
4. Yes? Go to 1

**Writers:**
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock
Why do we need the two steps?

**Writers:**
1. Take write lock
2. Increment version number
3. Make update
4. Increment version number
5. Release write lock

**Readers:**
1. Wait for version number to be even
2. Do operation
3. Has the version number changed?
4. Yes? Go to 1
Read-Copy-Update (RCU)
Read-Copy-Update (RCU)

1. Copy existing structure
Read-Copy-Update (RCU)

1. Copy existing structure
2. Update copy
Read-Copy-Update (RCU)

1. Copy existing structure
2. Update copy
3. Install copy with CAS on root pointer
Read-Copy-Update (RCU)

- Use locking to serialize updates (typically)
  - ...but allow readers to operate concurrently with updates
- Ensure that readers don’t go wrong if they access data mid-update
  - Have data structures reachable via a single root pointer: update the root pointer rather than updating the data structure in-place
  - Ensure that updates don’t affect readers – e.g., initializing nodes before splicing them into a list, and retaining “next” pointers in deleted nodes
  - Exact semantics offered can be subtle (ongoing research direction)
- Memory management problems common with lock-free data structures
When will these techniques be effective?

- Update rate low
  - So the need to serialize updates is OK
- Readers behaviour is OK mid-update
  - E.g., structure small enough to clone, rather than update in place
  - Readers will be OK until a version number check (not enter endless loops / crash / etc.)
- Deallocation or re-use of memory can be controlled
Flat combining
Flat combining

- “Flat Combining and the Synchronization-Parallelism Tradeoff”, Hendler *et al*

Intuition:
- Acquiring and releasing a lock involves numerous cache line transfers on the interconnect
- These may take hundreds of cycles (e.g., between cores in different NUMA nodes)
- The work protected by the lock may involve only a few memory accesses...
- ...and these accesses may be likely to hit in the cache of the previous lock holder (but miss in your own)
- So: if a lock is not available, request that the current lock holder does the work on your behalf
Flat combining

- Lock
- Sequential data structure
  - Request / response table
    - Thread 1
    - Thread 2
    - Thread 3
    ...
Flat combining: uncontended acquire

1. Write proposed op to req/resp table
2. Acquire lock if it is free
3. Process requests
4. Release lock
5. Pick up response
Flat combining: contended acquire

1. Write proposed op to req/resp table
2. See lock is not free
3. Wait for response
4. Pick up response
Lecture 1/3

- Introduction
- Basic spin-locks
- Queue-based locks
- Hierarchical locks
- Reader-writer locks
- Reading without locking
- Flat combining