Overview

- Introduction
- Spin Locks
  - Test-and-Set & Test-and-Test-and-Set
  - Backoff lock
- Queue locks
Introduction: From Single-Core to Multi-Core Computers

Desktop Computer: Single core

Server Architecture: The Shared Memory Multiprocessor (SMP)

All cores on the same chip

Sequential Computation
Concurrent Computation

- **shared memory**
- **object**
- **multiple threads (processes)**

Fault Tolerance & Asynchrony

- **threads**

- **Why fault tolerance?**
  - Even if processes do not die, there are “near-death experiences”

- **Sudden unpredictable delays:**
  - Cache misses (short)
  - Page faults (long)
  - Scheduling quantum used up (really long)
Example: Parallel Primality Testing

- **Challenge**
  - Print all primes from 1 to $10^{10}$
- **Given**
  - Ten-core multiprocessor
  - One thread per processor
- **Goal**
  - Get ten-fold speedup (or close)

- **Naïve Approach**
  - Split the work evenly
  - Each thread tests range of $10^9$

  ![Diagram of range splitting](image)

  Problems with this approach?

- **Issues**
  - Higher ranges have fewer primes
  - Yet larger numbers are harder to test
  - Thread workloads
    - Uneven
    - Hard to predict
  - Need **dynamic** load balancing

- **Better approach**
  - Shared counter!
  - Each thread takes a number

  ![Diagram of shared counter](image)
Counter Implementation

```java
class Counter {
    private long value = 1;

    public long getAndIncrement() {
        return value++;
    }
}
```

What's the problem with this implementation?
Problem

Counter Implementation

```java
class Counter {
    private long value = 1;

    public long getAndIncrement() {
        long temp = value;
        value = temp + 1;
        return temp;
    }
}
```

These steps must be atomic!

We have to guarantee mutual exclusion!

We could use Read-Modify-Write (RMW) instructions.
Common RMW Instructions

```java
int value;

synchronized int testAndSet() {
    int prior = value;
    value = 1;
    return prior;
}

synchronized int getAndIncrement() {
    int prior = value;
    value = value + 1;
    return prior;
}

synchronized int compareAndSwap(int old, int new) {
    int prior = value;
    if (value == old)
        value = new;
    return prior;
}
```

Model

- The Architecture of Multiprocessor Systems
  - Theory vs. Practice

- In Theory
  - Multiple instruction multiple data (MIMD) architecture
  - Each thread/process has its own code and local variables
  - Shared memory feels the same for all threads/processes

- In Practice
  - There is a shared memory that all threads can access
  - Typically, communication runs over a shared bus (alternatively, there may be several channels)
  - Communication contention
  - Communication latency
  - Each thread has a local cache
Model: Where Things Reside

Mutual Exclusion

- We need mutual exclusion for our counter
- We are now going to study mutual exclusion from a different angle
  - Focus on performance, not just correctness and progress
- We will begin to understand how performance depends on our software properly utilizing the multiprocessor machine’s hardware, and get to know a collection of locking algorithms!

- What should you do if you can’t get a lock?
  - Keep trying
    - “spin” or “busy-wait”
    - Good if delays are short
  - Give up the processor
    - Good if delays are long
    - Always good on uniprocessor

E.g., the shared counter is here
Basic Spin-Lock

- Lock introduces sequential bottleneck → No parallelism!
- Lock suffers from contention
- Huh?
- Spin lock
- Critical section
- Resets lock upon exit

Test&Set

- Boolean value
- Test-and-set (TAS)
  - Swap true with current value
  - Return value tells if prior value was true or false
- Can reset just by writing false
- Also known as “getAndSet”
Test&Set in Java

```java
class AtomicBoolean {
    private boolean value;

    public synchronized boolean getAndSet() {
        boolean prior = this.value;
        this.value = true;
        return prior;
    }

    ...
}
```

Test&Set Locks

- Locking
  - Lock is **free**: value is false
  - Lock is **taken**: value is true
- Acquire lock by calling TAS
  - If result is false, you **win**
  - If result is true, you **lose**
- Release lock by writing false
Test&Set Lock

```java
class TASLock implements Lock {
    AtomicBoolean state = new AtomicBoolean(false);

    public void lock() {
        while (!state.getAndSet(true)) {} // Keep trying until lock acquired
    }

    public void unlock() {
        state.set(false); // Release lock by resetting state to false
    }
}
```

Performance

- **Experiment**
  - \( n \) threads
  - Increment shared counter 1 million times (without computing primes)

- How long should it take?
- How long does it take?
Test&Test&Set Locks

- How can we improve TAS?
- A crazy idea: Test before you test and set!

- Lurking stage
  - Wait until lock “looks” free
  - Spin while read returns true (i.e., the lock is taken)

- Pouncing state
  - As soon as lock “looks” available
  - Read returns false (i.e., the lock is free)
  - Call TAS to acquire the lock
  - If TAS loses, go back to lurking

Test&Test&Set Lock

class TTASLock implements Lock {
    AtomicBoolean state = new AtomicBoolean(false);

    public void lock() {
        while (true) {
            while (state.get()) {}  // Wait until lock looks free
            if (!state.getAndSet()) // Then try to acquire it
                return;
        }
    }

    public void unlock() {
        state.set(false);
    }
}
Performance

- Both TAS and TTAS do the same thing (semantically)
- So, we would expect basically the same results

![Graph showing comparison between TAS lock and TTAS lock time vs. threads]

- Why is TTAS so much better than TAS? Why are both far from ideal?

Opinion

- TAS & TTAS locks
  - are provably the same (in theory)
  - except they aren’t (in reality)
- Obviously, it must have something to do with the model...
- Let’s take a closer look at our new model and try to find a reasonable explanation!
Bus-Based Architectures

Per-processor caches
- Small
- Fast: 1 or 2 cycles
- Address and state information

Shared bus
- Broadcast medium
- One broadcaster at a time
- Processors (and memory) “snoop”

Jargon Watch

- Load request
  - When a thread wants to access data, it issues a load request
- Cache hit
  - The thread found the data in its own cache
- Cache miss
  - The data is not found in the cache
  - The thread has to get the data from memory
Load Request

- Thread issues load request and memory responds

![Diagram showing memory access]

Another Load Request

- Another thread wants to access the same data. Get a copy from the cache!
Modify Cached Data

- Both threads now have the data in their cache
- What happens if the red thread now modifies the data...?

Cache Coherence

- We have lots of copies of data
  - Original copy in memory
  - Cached copies at processors
- Some processor modifies its own copy
  - What do we do with the others?
  - How to avoid confusion?
Write-Back Caches

- Accumulate changes in cache
- Write back when needed
  - Need the cache for something else
  - Another processor wants it
- On first modification
  - Invalidate other entries
  - Requires non-trivial protocol ...

- Cache entry has three states:
  - Invalid: contains raw bits
  - Valid: I can read but I can’t write
  - Dirty: Data has been modified
    - Intercept other load requests
    - Write back to memory before reusing cache

Invalidate

- Let’s rewind back to the moment when the red processor updates its cached data
- It broadcasts an invalidation message → Other processor invalidates its cache!
Invalidation

- Memory provides data only if not present in any cache, so there is no need to change it now (this is an expensive operation!)
- Reading is not a problem → The threads get the data from the red process

Mutual Exclusion

- What do we want to optimize?
  1. Minimize the bus bandwidth that the spinning threads use
  2. Minimize the lock acquire/release latency
  3. Minimize the latency to acquire the lock if the lock is idle
TAS vs. TTAS

- TAS invalidates cache lines
- Spinners
  - Always go to bus
- Thread wants to release lock
  - delayed behind spinners!!!

- TTAS waits until lock “looks” free
  - Spin on local cache
  - No bus use while lock busy
- Problem: when lock is released
  - Invalidation storm ...

This is why TAS performs so poorly...

Local Spinning while Lock is Busy

- While the lock is held, all contenders spin in their caches, rereading cached data without causing any bus traffic
On Release

- The lock is released. All spinners take a cache miss and call Test&Set!

Time to Quiescence

- Every process experiences a cache miss
  - All state.get() satisfied sequentially
- Every process does TAS
  - Caches of other processes are invalidated
- Eventual quiescence ("silence") after acquiring the lock
- The time to quiescence increases \textit{linearly} with the number of processors for a bus architecture!
Mystery Explained

- Now we understand why the TTAS lock performs much better than the TAS lock, but still much worse than an ideal lock!

```

```

- How can we do better?

Introduce Delay

- If the lock looks free, but I fail to get it, there must be lots of contention
- It’s better to back off than to collide again!

- Example: Exponential Backoff
- Each subsequent failure doubles expected waiting time
Exponential Backoff Lock

```java
class Backoff implements Lock {
    AtomicBoolean state = new AtomicBoolean(false);

    public void lock() {
        int delay = MIN_DELAY;
        while (true) {
            while (state.get()) {}
            if (!state.getAndSet())
                return;
            "sleep"(random() % delay);
            if (delay < MAX_DELAY)
                delay = 2 * delay;
        }
    }

    // unlock() remains the same
}
```

Backoff Lock: Performance

- The backoff lock outperforms the TTAS lock!
- But it is still not ideal...
Backoff Lock: Evaluation

- **Good**
  - Easy to implement
  - Beats TTAS lock
- **Bad**
  - Must choose parameters carefully
  - Not portable across platforms

- How can we do better?
- Avoid useless invalidations
  - By keeping a queue of threads
- Each thread
  - Notifies next in line
  - Without bothering the others

ALock: Initially

- The Anderson queue lock (ALock) is an array-based queue lock
- Threads share an atomic tail field (called next)
ALock: Acquiring the Lock

- To acquire the lock, each thread atomically increments the tail field
- If the flag is true, the lock is acquired
- Otherwise, spin until the flag is true

\\begin{center}
\begin{tikzpicture}
  \node[draw, rectangle, minimum width=2cm, minimum height=1cm] (acquired) at (0,0) {acquired};
  \node[draw, rectangle, minimum width=2cm, minimum height=1cm] (next) at (-2,0) {next};
  \node[draw, rectangle, minimum height=1cm] (flags) at (-4,-2) {flags};
  \draw[->, red] (flags) -| (acquired);
  \draw[->, red] (flags) -| (next);
  \node[draw, circle, fill=purple, text=white, inner sep=0.5cm] at (acquired) {The lock is mine!};
\end{tikzpicture}
\\end{center}

ALock: Contention

- If another thread wants to acquire the lock, it applies get\&increment
- The thread spins because the flag is false

\\begin{center}
\begin{tikzpicture}
  \node[draw, rectangle, minimum width=2cm, minimum height=1cm] (acquired) at (0,0) {acquired};
  \node[draw, rectangle, minimum width=2cm, minimum height=1cm] (next) at (-2,0) {next};
  \node[draw, rectangle, minimum height=1cm] (flags) at (-4,-2) {flags};
  \draw[->, red] (flags) -| (acquired);
  \draw[->, red] (flags) -| (next);
  \node[draw, circle, fill=red, text=white, inner sep=0.5cm] at (acquired) {acquiring};
\end{tikzpicture}
\\end{center}
ALock: Releasing the Lock

- The first thread releases the lock by setting the next slot to true
- The second thread notices the change and gets the lock

```
class Alock implements Lock {
    boolean[] flags = {true, false, ..., false};
    AtomicInteger next = new AtomicInteger(0);
    ThreadLocal<Integer> mySlot;

    public void lock() {
        mySlot = next.getAndIncrement();
        while (!flags[mySlot % n]) {}
        flags[mySlot % n] = false;
    }

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

- Shorter handover than backoff
- Curve is practically flat
- Scalable performance
- FIFO fairness

![Graph showing performance comparison of TAS lock, TTAS lock, ALock, and ideal time against threads]

ALock: Evaluation

- Good
  - First truly scalable lock
  - Simple, easy to implement
- Bad
  - One bit per thread
  - Unknown number of threads?
ALock: Alternative Technique

- The threads could update own flag and spin on their predecessor’s flag

  ![Diagram](image)

  - This is basically what the CLH lock does, but using a linked list instead of an array
  - Is this a good idea?

NUMA Architectures

- **Non-Uniform Memory Architecture**
  - **Illusion**
    - Flat shared memory
  - **Truth**
    - No caches (sometimes)
    - Some memory regions faster than others

  Spinning on local memory is fast:  Spinning on remote memory is slow:
MCS Lock

- Idea
  - Use a linked list instead of an array → small, constant-sized space
  - Spin on own flag, just like the Anderson queue lock

- The space usage
  - $L =$ number of locks
  - $N =$ number of threads
- of the Anderson lock is $O(LN)$
- of the MCS lock is $O(L+N)$

MCS Lock: Initially

- The lock is represented as a linked list of QNodes, one per thread
- The tail of the queue is shared among all threads
MCS Lock: Acquiring the Lock

- To acquire the lock, the thread places its QNode at the tail of the list by swapping the tail to its QNode
- If there is no predecessor, the thread acquires the lock

MCS Lock: Contention

- If another thread wants to acquire the lock, it again applies swap
- The thread spins on its own QNode because there is a predecessor
MCS Lock: Releasing the Lock

- The first thread releases the lock by setting its successor’s QNode to false.

```java
class QNode {
    boolean locked = false;
    QNode next = null;
}
```
MCS Queue Lock

```java
class MCSLock implements Lock {
    AtomicReference tail;
    
    public void lock() {
        QNode qnode = new QNode();
        QNode pred = tail.getAndSet(qnode);
        if (pred != null) {
            qnode.locked = true;
            pred.next = qnode;
            while (qnode.locked) {} 
        }
    }
}
```

MCS Lock: Unlocking

- If there is a successor, unlock it. But, be cautious!
- Even though a QNode does not have a successor, the purple thread knows that another thread is active because tail does not point to its QNode!
MCS Lock: Unlocking Explained

- As soon as the pointer to the successor is set, the purple thread can release the lock.

  Set my successor’s QNode to false!

  The lock is mine!

  tail

  false

  false

MCS Queue Lock

```java
public void unlock() {
    if (qnode.next == null) {
        if (tail.CAS(qnode, null)) {
            while (qnode.next == null) {}
            qnode.next.locked = false;
            return;
        }
    }
}
```

Missing successor?
- If really no successor, tail = null

Otherwise, wait for successor to catch up
- Pass lock to successor
Abortable Locks

- What if you want to give up waiting for a lock?
- For example
  - Time-out
  - Database transaction aborted by user

- Back-off Lock
  - Aborting is trivial: Just return from lock() call!
  - Extra benefit: No cleaning up, wait-free, immediate return

- Queue Locks
  - Can’t just quit: Thread in line behind will starve
  - Need a graceful way out...

Problem with Queue Locks
Abortable MCS Lock

- A mechanism is required to recognize and remove aborted threads
  - A thread can set a flag indicating that it aborted
  - The predecessor can test if the flag is set
  - If the flag is set, its new successor is the successor’s successor
  - How can we handle concurrent aborts? This is not discussed in this lecture

Composite Locks

- Queue locks have many advantages
  - FIFO fairness, fast lock release, low contention
    but require non-trivial protocols to handle aborts (and recycling of nodes)
- Backoff locks support trivial time-out protocols
  but are not scalable and may have slow lock release times

- A composite lock combines the best of both approaches!
  - Short fixed-sized array of lock nodes
  - Threads randomly pick a node and try to acquire it
  - Use backoff mechanism to acquire a node
  - Nodes build a queue
  - Use a queue lock mechanism to acquire the lock
One Lock To Rule Them All?

- TTAS+Backoff, MCS, Abortable MCS...
- Each better than others in some way
- There is not a single best solution
- Lock we pick really depends on
  - the application
  - the hardware
  - which properties are important

Handling Multiple Threads

- Adding threads should not lower the throughput
  - Contention effects can mostly be fixed by Queue locks

- Adding threads should increase throughput
  - Not possible if the code is inherently sequential
  - Surprising things are parallelizable!

- How can we guarantee consistency if there are many threads?
Coarse-Grained Synchronization

- Each method locks the object
  - Avoid contention using queue locks
  - Mostly easy to reason about
  - This is the standard Java model (synchronized blocks and methods)

- Problem: Sequential bottleneck
  - Threads “stand in line”
  - Adding more threads does not improve throughput
  - We even struggle to keep it from getting worse...

- So why do we even use a multiprocessor?
  - Well, some applications are inherently parallel...
  - We focus on exploiting non-trivial parallelism

Credits

- The TTAS lock is due to Kruskal, Rudolph, and Snir, 1988.
- Tom Anderson invented the ALock, 1990.
- The MCS lock is due to Mellor-Crummey and Scott, 1991.
That’s all!
Questions & Comments?

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