CS 241 Honors
Concurrent Data Structures

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What to go over

- Terminology
- What is lock free
- Example of Lock Free
- Transactions and Linearizability
- The ABA problem
- Drawbacks
- Use Cases

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- Then, you make sure that there is no other algorithm that can just reduce the number of mutex locks outright.
- Then, you have to choose the right lock free data structure. Most of them work best under circumstances with high contention and where the structure is full of elements.
- Then, you have to measure. If you don't measure, then you don't know if you improved.

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- Atomic Compare and Swap

Atomic Compare and Swap?

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```c
int atomic_cas(int *addr, int *expected,
     int value){
        if(*addr == *expected){
            *addr = value;
            return 1; //swap success
        }else{
            *expected = *addr;
            return 0; //swap failed
        }
    }
```

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But this all happens atomically!

Types of Data Structures

- Blocking Data Structures
- Lock-Free Data Structures
- Bounded-Wait Data Structures
- Wait-Free Data Structures

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Advantages:

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- Well defined critical sections
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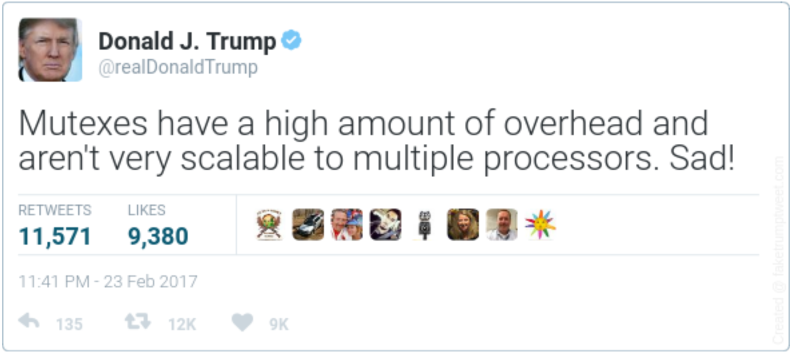
Disadvantages

- Slower under high contention; Mutexes are not scalable across cores
- Lower priority processes often get locks
- Deadlock! Convoy Effect!
- Preemption/Signal Handler Safety

Blocking Structures

Blocking Structures



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Disadvantages

- Critical Section a little harder to define
- Harder to debug
- Can get really complicated

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- Faster than lock free. The CPU is always doing something.
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Disadvantages

- Not always possible
- Hard to guarantee
- Can get *really* complicated.

Building a lock free Data Structure

Alright, let's make a queue. What do we have to think about? Well there are two types of threads. Those pushing things on to the queue, and those popping off the queue.

Starting out - No Code but Ownership

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A fundamental way to solve race conditions is to ask yourself the question "who owns this piece of memory". If you make sure that one thread has access to the piece of memory at once, you will never get deadlock. For the sake of not sitting here for days about lock free structures, we will assume that we have a fast, lock free malloc.

Ownership?

1. We want to introduce the idea that a thread owns a piece of memory. This is to avoid race conditions.
2. There is going to be a shared part of memory and a part only visible to the thread. We are going to do all of our initialization in our memory part and then with one atomic instructions that are carefully placed
3. After that the data structure will be initialized

Lock Free initialization

```
typedef struct node;
typedef struct queue;
new_queue()
destory_queue()
```

Lock Free Enqueue

```c
void enqueue(queue *fifo, void *val){
    node *pkg = malloc(sizeof(*pkg)), *ptr;
    *pkg = {val, NULL};
    int succeeded = 0;
    while(!succeeded){
        node *none = NULL;
        ptr = fifo->tail;
        succeeded = cas(&ptr->next, none, pkg)
    }
    // This is actually a critical section
    cas(&fifo->tail, &ptr, package);
}
```

Lock Free Dequeue

```
node* dequeue(queue *fifo){
    if (!fifo->head) { return NULL; }
    node *start = &fifo->head;
    while(!atomic_cas(&fifo->head, start,
             &fifo->head->next)){
        start = atomic_load(&fifo->head);
        if(start == NULL){
            return NULL;
        }
        // May do sleeping here
    }
    //You now have exclusive access
    return start;
}
```

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2. This is important because this provides high concurrency. Each thread has its own place to do its work, and undergoes contention all at once.
3. You can see this in the previous example.

Lock Free Enqueue

```
node *package = malloc(sizeof(*package));
package->data = val;
package->next = NULL;
node *ptr;
...
```

Lock Free Enqueue

```
ctx *tex = begin_transaction(queue);
queue_pop(tex);
queue_push(tex, 1);
queue_push(tex, 2);
queue_push(tex, 3);
end_transaction(tex);
// Results pushed (only 2 atomics computed)
```

Alterations

```
pop (tex) {
    // Push the pop on the context
}
push (tex) {
    /* Allocate memory and push the
         value on the stack. if there
         is another pop instruction,
         squish the two nodes */
}
```

Alterations

```
end_transaction (tex) {
    void *none = NULL;
    cas(&tex->queue->head,
        &tex->queue->head, none);
    // My queue
    for (transaction in tex) {
        if (transaction->type == push)
            queue_push(tex->queue,
                transaction->data)
        //...
    }
}
```

Transactions

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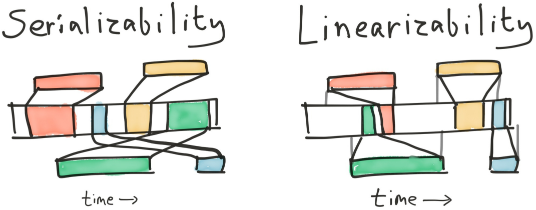
2. You also may have to deal with a transaction failing because the queue may have run out of space.
3. This is mainly a tool for the people using the lock free data structures keep track of their operations.

Linearizability & Serializability



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3. Also good to determine a semi-ordering (Think of a reader writer consistency model).
4. But sometimes we need stronger consistency models.

Serializability

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3. Think of a stock market application that needs to tell which monetary transaction happened first. We need the application to be fast but we need to know who bought and sold first

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2. Meaning that the order of transactions make sense if computed by one thread.
3. Hardest to obtain.

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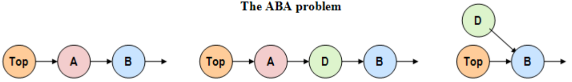
3. This is a problem because over the long term the entire data structure could either break or leak memory.
4. Some cases there are no ways of preventing this problem, especially in a language like C without automagic garbage collection.

ABA Problem

```
void enqueue(queue *fifo, void *val) {
    node *pkg = malloc(sizeof(*pkg)), *ptr;
    *pkg = {val, NULL};
    int succeeded = 0;
    while(!succeeded) {
        node *none = NULL;
        ptr = fifo->tail;
        succeeded = cas(&ptr->next, none, pkg)
        if(!succeeded){
            cas(&fifo->next, &ptr, ptr->next);
        }
    }
    cas(&fifo->tail, &ptr, package);
    void *data = pkg->val;
    free(pkg);
}
```

ABA Problem

The ABA problem



Thread A calls method POP that reads Top (pointer to A) and *Top (pointer to B). Thread A gets preemted before doing CAS(Top,*Top).

Thread B also does POP by doing CAS(Top,*Top), then deletes returned pointer to A. After that Thread B calls PUSH with D by doing CAS(Top, D) and PUSH with new A by doing CAS(Top,A).

Thread A resumes and completes it's CAS(Top,B) leaving D hanging.

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1. Our data structure does not need to worry about that!
2. Our dequeue instead of returning the item returns the entire node.
3. That means the ABA problem has a near zero chance of actually occuring if the user doesn't free the node until after they are done using it.

Drawbacks

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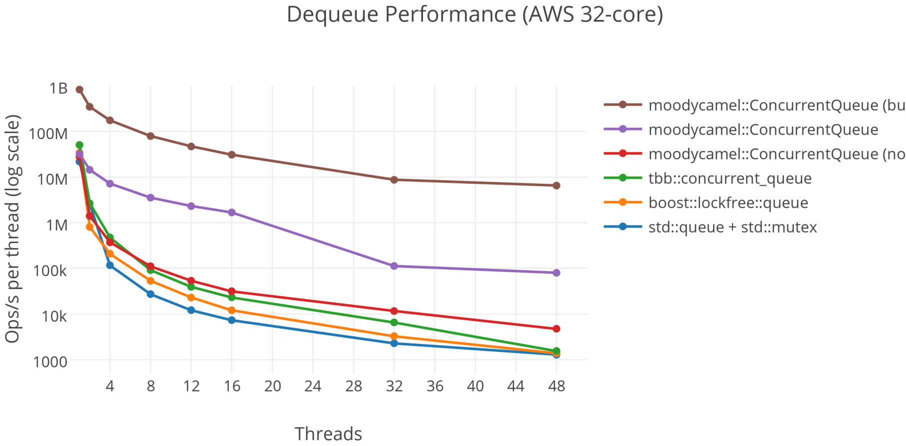
3. Sometimes they can't always work
4. Sometimes they are slower

Drawbacks



Dequeue Performance (AWS 32-core)
Ops/s per thread (log scale)
1B
100M
10M
1M
100k
10k
1000
4
8
12
16
20
24
28
32
36
40
44
48
Threads
moodycamel::ConcurrentQueue (bu
moodycamel::ConcurrentQueue
moodycamel::ConcurrentQueue (no
tbb::concurrent_queue
boost::lockfree::queue
std::queue + std::mutex

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4. Only then move down to other orders

Sequential Consistency

```
-Thread 1-                    -Thread 2-
y = 1                     if (x.load() == 2)
store(x, 2);                  y != 1 && *NULL = 1;
```

Will never segfault

Relaxed Consistency

```
-Thread 1-          -Thread 2-
store(x, 1)         first = load(x)
store(x, 2);        second = load(x)
                    first <= second
```

A new value will never become old

Use Cases

1. RabbitMQ/Apache Kafka is a distributed message queue that uses a queue similar to the one we described to distribute messages to a group of nodes.
2. Apache Spark and Hadoop use this for consensus, finger tables, and communicating and joining results together.
3. Every distributed (and a lot of non-distributed) databases use lock-free data structures to service SQL queries or read/write form disks
4. HPC uses them to manage concurrency (Possible MPI)

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Bonus! Why Spurious Wakeups Happen

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3. Let's take the Windows NT way of implementing a condition variable.
4. The real problem with CVs are broadcast.

Windows NT

```
struct CV {
    linked_list waiters;
}

void wait(cv, mtx) { // mtx must be locked
    enqueue(cv.waiters, self());
    m.Release();
    self().sema.wait();
    m.Acquire();
}
```

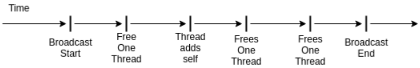
Not Interesting

```
void signal(cv) {
    if (waiters != null) {
        waiters.sema.post();
        cas(waiters, waiters, waiters.next);
    }
}
```

Interesting

```
void broadcast(cv) {
    while (waiters != null) {
        waiters.sema.post();
        cas(waiters, waiters, waiters.next);
    }
}
```

Interesting



Questions?

Thanks for sticking along!