Concurrency: Lock-based Data Structures

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Lock-based Concurrent Data structure

- **Race Conditions happen around shared state**
- **Good programming practice generally encompasses state in a data structure or object**
- **Common Goal: Add locks to a data structure to makes the structure thread safe.**
- **Considerations**
  - Correctness: Does the data structure still do what we want?
  - Scalability: More threads shouldn't slow down operations
  - These two goals are often in conflict.

Example: Concurrent Counters without Locks

- **Simple, but not correct with multiple updaters**

```
typedef struct __counter_t {
        int value;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
}

void increment(counter_t *c) {
        c->value++;
}

void decrement(counter_t *c) {
        c->value--;
}

int get(counter_t *c) {
        return c->value;
}
```

Example: Concurrent Counters with Locks

- **Add a single lock acquired when calling a routine that manipulates the data structure.**
- **Reminder: Pthread_XXX is a wrapper around pthread_XXX with an error check**

```
typedef struct __counter_t {
        int value;
        pthread_lock_t lock;
} counter_t;

void init(counter_t *c) {
        c->value = 0;
        Pthread_mutex_init(&c->lock, NULL);
}

void increment(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value++;
        Pthread_mutex_unlock(&c->lock);
}

```

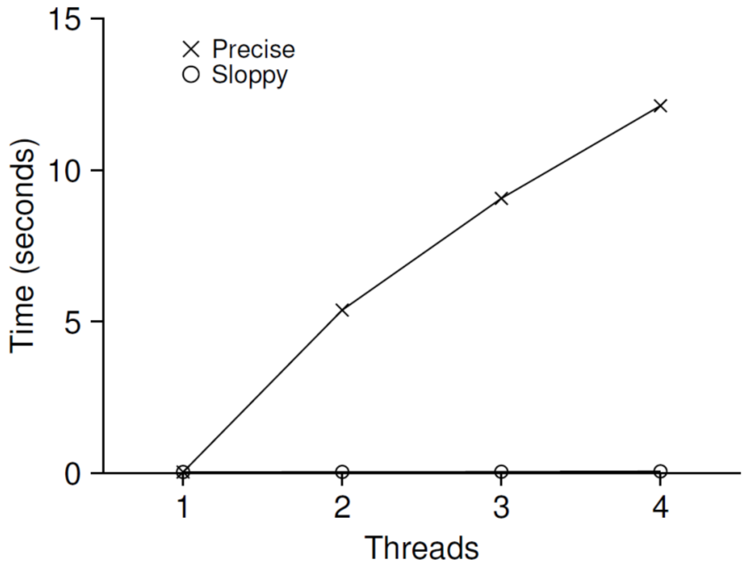
Example: Concurrent Counters with Locks (Cont.)

```
(Cont.)
void decrement(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        c->value--;
        Pthread_mutex_unlock(&c->lock);
}

int get(counter_t *c) {
        Pthread_mutex_lock(&c->lock);
        int rc = c->value;
        Pthread_mutex_unlock(&c->lock);
        return rc;
}
```

The performance costs of the simple approach

- **Each thread updates a single shared counter.**
  - Each thread updates the counter one million times.
  - iMac with four Intel 2.7GHz i5 CPUs.



Synchronized counter scales poorly.

Goal: Perfect Scaling

- **Even though more work is done, it is done in parallel.**
- **The time taken to complete the task is *not increased.***
- **For the counters example:**
  - Perfect scaling with N threads is N times the updates in the same time
  - Our example went from less than 0.1 seconds with 1 thread to about 12 seconds with 4 threads
- **Contending on locks and data structures is very expensive due to architectural reasons**
  - Cross-CPU communication (e.g. for locking)
  - Cross-CPU cache interferences (the counter moves between CPU caches, so things that hit with 1 CPU miss all of the time with 2)

Sloppy counter

- **A common approach: redefine the problem by relaxing consistency**
  - We often don't need perfect count at any given time
  - We just don't want to lose any counts (we eventually see all increments)
- **The sloppy counter works by representing …**
  - A single **logical counter** via numerous local physical counters, one per CPU core
  - A single **global counter**
  - There are **locks**:
    - One for each local counter and one for the global counter
- **Example: on a machine with four CPUs**
  - Four local counters
  - One global counter

The basic idea of sloppy counting

- **When a thread running on a core wishes to increment the counter.**
  - It increments its local counter.
  - Each CPU has its own local counter:
    - Threads across CPUs can update local counters *without contention*.
    - Thus counter updates are scalable.
  - The local values are periodically transferred to the global counter.
    - Acquire the global lock
    - Increment it by the local counter’s value
    - The local counter is then reset to zero.

The basic idea of sloppy counting (Cont.)

- **<u>How often</u> the local-to-global transfer occurs is determined by a threshold, S (sloppiness).**
  - The smaller S:
    - The more the counter behaves like the *non-scalable counter*.
  - The bigger S:
    - The more scalable the counter.
    - The further off the global value might be from the *actual count*.
- **Note it's not a counter per thread, it's a counter per CPU**
  - Which is why we have a lock per local counter – multiple threads could update the counter on a single CPU
  - A counter per thread would eliminate this, but result in a lot of state if you have a lot of threads

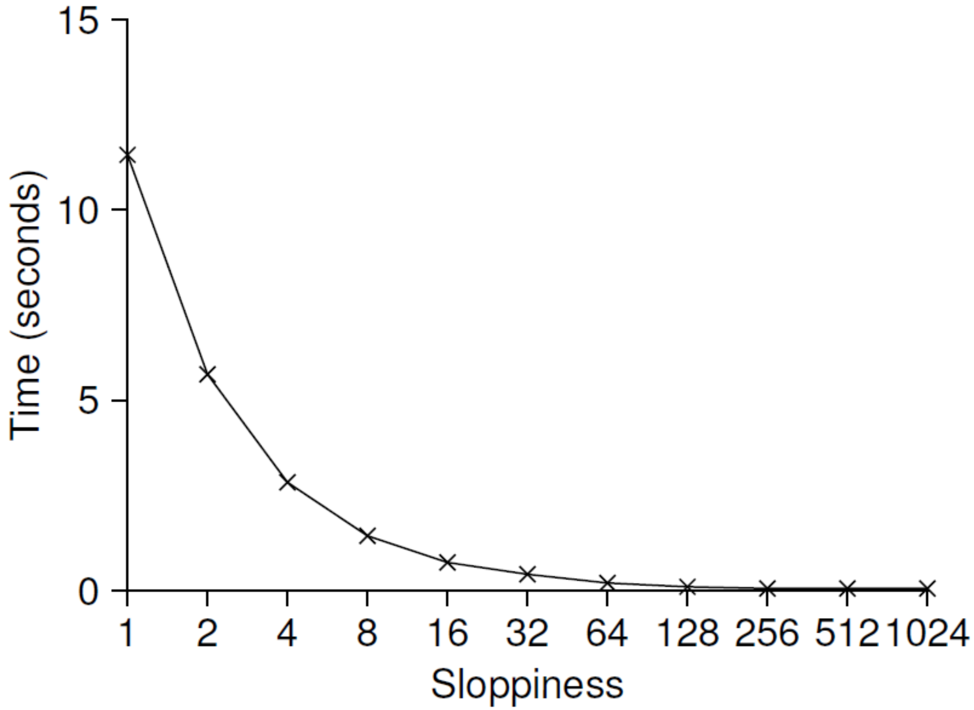
Sloppy counter example

- **Tracing the Sloppy Counters**
  - The threshold S is set to 5.
  - There are threads on each of four CPUs
  - Each thread updates their local counters $L_1 \ldots L_4$.

Time	L_1	L_2	L_3	L_4	G
0	0	0	0	0	0
1	0	0	1	1	0
2	1	0	2	1	0
3	2	0	3	1	0
4	3	0	3	2	0
5	4	1	3	3	0
6	5 → 0	1	3	4	5 (from L_1)
7	0	2	4	5 → 0	10 (from L_4)

Importance of the threshold value *S*

- **Each four threads increments a counter 1 million times on four CPUs.**
  - Low S → Performance is **poor**, The global count is always quire **accurate**.
  - High S → ... **gs**.



Scaling Sloppy Counters

Sloppy Counter Implementation

```c
typedef struct __counter_t {
    int global;                  // global count
    pthread_mutex_t glock;       // global lock
    int local[NUMCPUS];          // local count (per cpu)
    pthread_mutex_t llock[NUMCPUS]; // ... and locks
    int threshold;               // update frequency
} counter_t;

// init: record threshold, init locks, init values
//       of all local counts and global count
void init(counter_t *c, int threshold) {
    c->thres hold = threshold;

    c->global = 0;
    pthread_mutex_init(&c->glock, NULL);

    int i;
    for (i = 0; i < NUMCPUS; i++) {
        c->local[i] = 0;
        pthread_mutex_init(&c->llock[i], NULL);
    }
}
```

Sloppy Counter Implementation (Cont.)

```
(Cont.)
// update: usually, just grab local lock and update local amount
//         once local count has risen by 'threshold', grab global
//         lock and transfer local values to it
void update(counter_t *c, int threadID, int amt) {
    pthread_mutex_lock(&c->llock[threadID]);
    c->local[threadID] += amt;      // assumes amt > 0
    if (c->local[threadID] >= c->threshold) { // transfer to global
        pthread_mutex_lock(&c->glock);
        c->global += c->local[threadID];
        pthread_mutex_unlock(&c->glock);
        c->local[threadID] = 0;
    }
    pthread_mutex_unlock(&c->llock[threadID]);
}

// get: just return global amount (which may not be perfect)
int get(counter_t *c) {
    pthread_mutex_lock(&c->glock);
    int val = c->global;
    pthread_mutex_unlock(&c->glock);
    return val;    // only approximate!
}
```

Concurrent Linked Lists

- **Simple list with a single lock**

```
// basic node structure
typedef struct __node_t {
        int key;
        struct __node_t *next;
} node_t;

// basic list structure (one used per list)
typedef struct __list_t {
        node_t *head;
        pthread_mutex_t lock;
} list_t;

void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

```

(Cont.)

Concurrent Linked Lists

- **Hold the lock to insert or remove from the list**

```
(Cont.)
    int List_Insert(list_t *L, int key) {
        pthread_mutex_lock(&L->lock);
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
            perror("malloc");
            pthread_mutex_unlock(&L->lock);
            return -1; // fail
        }
        new->key = key;
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
        return 0; // success
    }
(Cont.)
```

Concurrent Linked Lists (Cont.)

```
(Cont.)

    int List_Lookup(list_t *L, int key) {
            pthread_mutex_lock(&L->lock);
            node_t *curr = L->head;
            while (curr) {
                    if (curr->key == key) {
                            pthread_mutex_unlock(&L->lock);
                            return 0; // success
                    }
                    curr = curr->next;
            }
            pthread_mutex_unlock(&L->lock);
            return -1; // failure
    }
```

Concurrent Linked Lists (Cont.)

- **The code acquires a lock in the insert routine upon entry.**
- **The code releases the lock upon exit.**
  - If `malloc()` happens to *fail*, the code must also release the lock before failing the insert.
  - This kind of exceptional control flow has been shown to be quite error prone.
    - You have to release a single lock in multiple places
    - Changes to how you lock/unlock have to propagate to multiple places in the code (and its easy to miss one).
  - **Solution**: The lock and release *only surround* the actual critical section in the insert code

Concurrent Linked List Insert: Rewritten

```
void List_Init(list_t *L) {
        L->head = NULL;
        pthread_mutex_init(&L->lock, NULL);
}

void List_Insert(list_t *L, int key) {
        // synchronization not needed
        node_t *new = malloc(sizeof(node_t));
        if (new == NULL) {
                perror("malloc");
                return;
        }
        new->key = key;

        // just lock critical section
        pthread_mutex_lock(&L->lock);
        new->next = L->head;
        L->head = new;
        pthread_mutex_unlock(&L->lock);
}

```

Scaling Linked List

- **Current linked list has poor scalability – lock the entire list while you walk it.**
- **Hand-over-hand locking (lock coupling)**
  - Add **a lock per node** of the list instead of having a single lock for the entire list.
  - When traversing the list,
    - First grabs the next node's lock.
    - And then releases the current node's lock.
  - Enable a high degree of concurrency in list operations.
    - However, in practice, the overheads of acquiring and releasing locks for each node of a list traversal is *prohibitive*.
- **Scaling arbitrary linked lists is difficult because the sheer amount of state to be protected**

Michael and Scott Concurrent Queues

- **What if all we want is a queue?**
- **There are two locks.**
  - One for the **head** of the queue.
  - One for the **tail**.
  - The goal of these two locks is to enable concurrency of *enqueue* and *dequeue* operations.

- **Add a dummy node**
  - Allocated in the queue initialization code
  - Enable the separation of head and tail operations

Concurrent Queues (Cont.)

```
typedef struct __node_t {
        int value;
        struct __node_t *next;
} node_t;

typedef struct __queue_t {
        node_t *head;
        node_t *tail;
        pthread_mutex_t headLock;
        pthread_mutex_t tailLock;
} queue_t;

void Queue_Init(queue_t *q) {
        node_t *tmp = malloc(sizeof(node_t));
        tmp->next = NULL;
        q->head = q->tail = tmp;
        pthread_mutex_init(&q->headLock, NULL);
        pthread_mutex_init(&q->tailLock, NULL);
}

(Cont.)
```

Concurrent Queues (Cont.)

```
(Cont.)
void Queue_Enqueue(queue_t *q, int value) {
        node_t *tmp = malloc(sizeof(node_t));
        assert(tmp != NULL);

        tmp->value = value;
        tmp->next = NULL;

        pthread_mutex_lock(&q->tailLock);
        q->tail->next = tmp;
        q->tail = tmp;
        pthread_mutex_unlock(&q->tailLock);
}
(Cont.)
```

Concurrent Queues (Cont.)

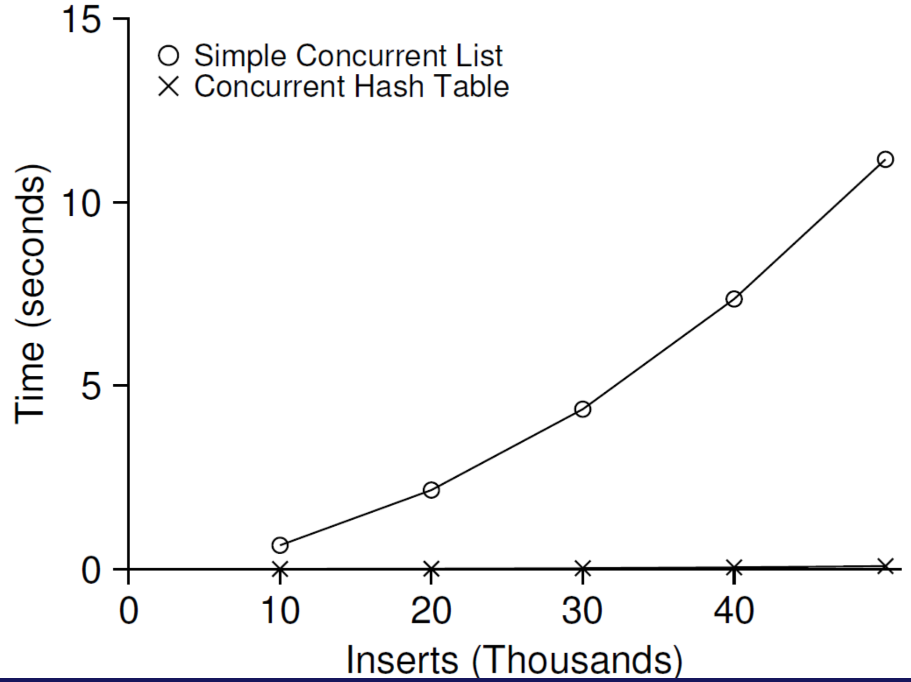
```
(Cont.)
int Queue_Dequeue(queue_t *q, int *value) {
        pthread_mutex_lock(&q->headLock);
        node_t *tmp = q->head;
        node_t *newHead = tmp->next;
        if (newHead == NULL) {
                pthread_mutex_unlock(&q->headLock);
                return -1; // queue was empty
        }
        *value = newHead->value;
        q->head = newHead;
        pthread_mutex_unlock(&q->headLock);
        free(tmp);
        return 0;
}
```

Concurrent Hash Table

- **Focus on a simple hash table**
  - The hash table does not resize.
  - Built using the concurrent lists
  - It uses a lock per hash bucket each of which is represented by *a list*.

Performance of Concurrent Hash Table

- **From 10,000 to 50,000 concurrent updates from each of four threads.**
  - iMac with four Intel 2.7GHz i5 CPUs.



- **The simple concurrent hash table scales magnificently.**
- **With few threads << buckets, threads are generally on independent lists!**

Concurrent Hash Table

```
#define BUCKETS (101)

typedef struct __hash_t {
        list_t lists[BUCKETS];
} hash_t;

void Hash_Init(hash_t *H) {
        int i;
        for (i = 0; i < BUCKETS; i++) {
                List_Init(&H->lists[i]);
        }
}

int Hash_Insert(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Insert(&H->lists[bucket], key);
}

int Hash_Lookup(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Lookup(&H->lists[bucket], key);
}
```