Concurrent Data Structures

Lock-based Concurrent Data Structures

- Adding locks to a data structure makes the structure thread safe
  - How locks are added determine both the correctness and performance of the data structure

Example: Concurrent Counters without Locks

- Incorrect version

```
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**
  - The lock is acquired when calling a routine that manipulates the data structure

```
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);
}

```

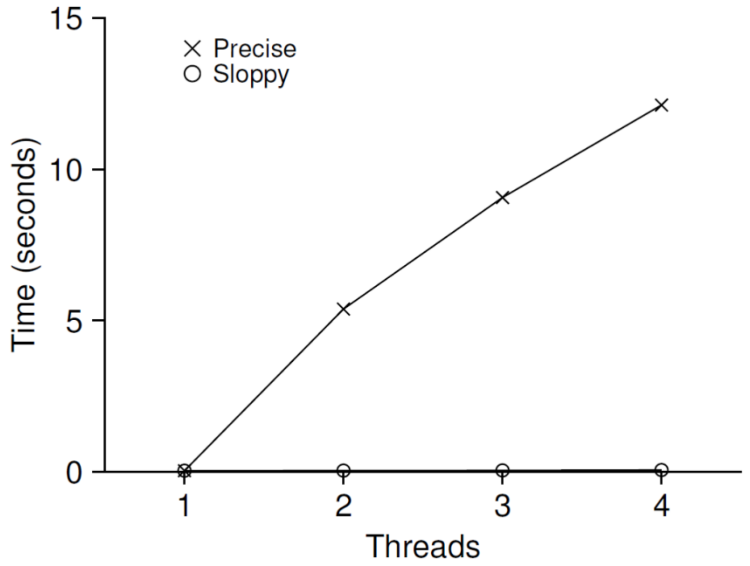
Example: Concurrent Counters with Locks

```
(Cont.)
    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;
    }
```

Overhead of 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



Performance of
Traditional vs. Sloppy Counters
(Threshold of Sloppy, S, is set to 1024)

Synchronized counter scales poorly

Perfect Scaling

- Even though more work is done, it is **done in parallel**
- The time taken to complete the task is *not increased*

Sloppy counter

- The sloppy counter works by representing …
  - A single **logical counter** via numerous local physical counters, on per CPU core
  - A single **global counter**
  - There is only one lock for the global counter

- Example: on a machine with four CPUs
  - Four local counters
  - One global counter

Basic Ideas of Sloppy Counting

- When a thread running on a core wishes to increment the counter
  - It increment 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
    - Local counter is then reset to zero

The basic idea of sloppy counting

- How often 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*

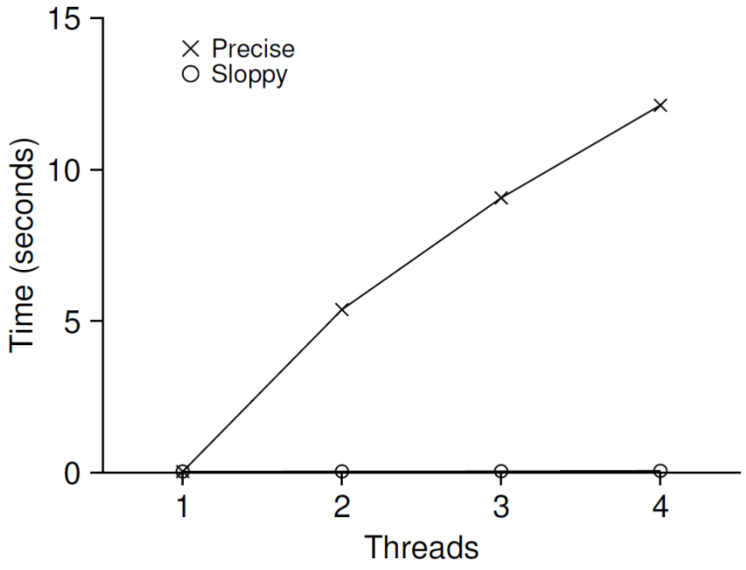
Sloppy Counter Example

- 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)

Sloppy Counter Performance

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

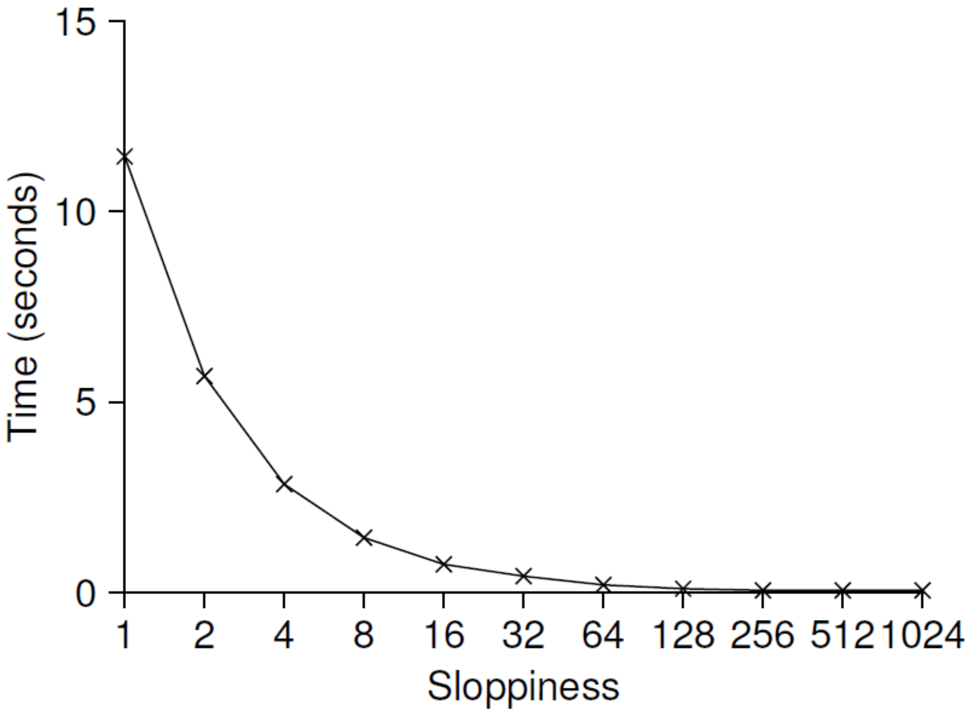


Performance of
Traditional vs. Sloppy Counters
(Threshold of Sloppy, S, is set to 1024)

Sloppy counter scales well

Importance of Threshold Value *S*

- Each four threads increments counter 1 million times, respectively
  - Low S → **poor** performance, accurate global counter
  - High S → Performance is **excellent**, The global count **lags**.



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.)
// 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

```
// 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

```
(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.)

    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

- 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
  - **Solution**: The lock and release *only surround* the actual critical section in the insert code

Concurrent Linked List: Rewritten

```c
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);
}
```

Concurrent Linked List: Rewritten

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

Scaling Linked List

- 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*

Michael and Scott Concurrent Queues

- 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

Me with Prof. Scott in 2024

Concurrent Queues

```
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.)
    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

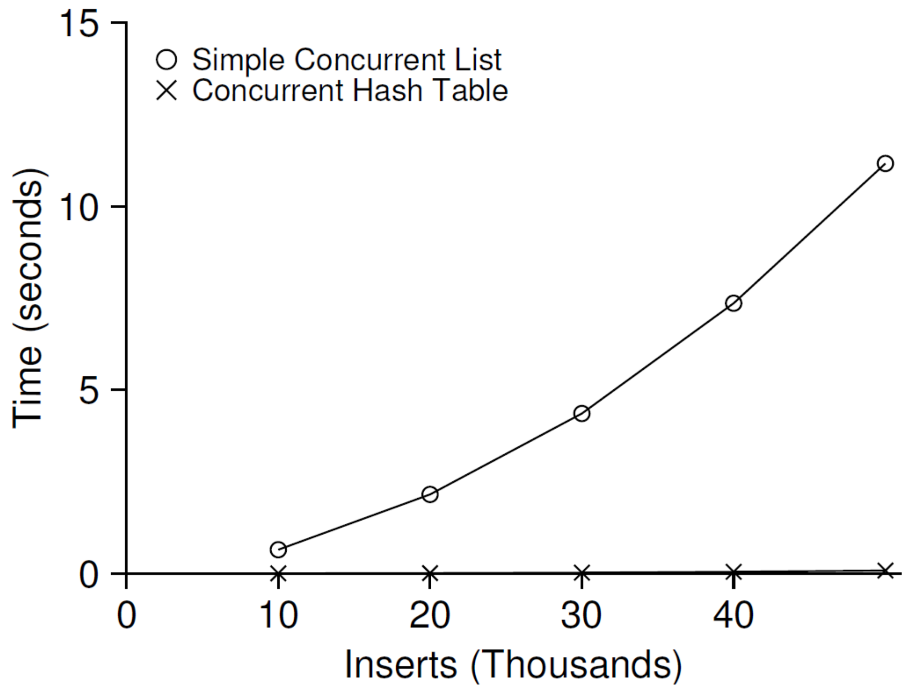
```
(Cont.)
int Queue_Dequeue(queue_t *q, int *value) {
        pthread_mutex_lock(&q->headLock);
        node_t *tmp = q->head;
        node_t *newHead = tmp->next;
        if (newHead == NULL) {
                pthread_mutex_unlock(&q->headLock);
                return -1; // queue was empty
     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

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);
}
```