Lock-based Concurrent Data Structures
Lock-based Concurrent Data structures

• Adding threads is a good way to parallelize your program
• Must be done correctly however
  • 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
  • Adding threads may actually slow down your code
Example: Concurrent Counters without Locks

• Single threaded

```c
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

```c
typedef struct __counter_t {
  int value;
  pthread_mutex_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);
}

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
• Ideally threads complete just as quickly on multiple processors as a single thread does on one
  • Even though more work is done, it is done in parallel
  • The time taken to complete the task on each core is not increased
• For our example:
  • Single thread on one core: about 0.03 seconds
  • Two threads running concurrently: little over 5 seconds

Synchronized counter scales poorly
Approximate counter

- The approximate counter works by representing:
  - A single logical counter, via numerous local physical counters, one per CPU core
  - A single global counter
  - There are multiple 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
Basic idea of approximate 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*
    - Therefore, 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
Approximation Threshold

• How often the local-to-global transfer occurs is determined by threshold $S$
  • 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*
      • Worst case: $S \times \text{NUMCPUS}$
Approximate counter example

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

<table>
<thead>
<tr>
<th>Time</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$L_3$</th>
<th>$L_4$</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>5 $\rightarrow$ 0</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5 (from $L_1$)</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>5 $\rightarrow$ 0</td>
<td>10 (from $L_4$)</td>
</tr>
</tbody>
</table>
# Approximate Counter Implementation

```c
typedef struct __counter_t {
    int global; // global count
    pthread_mutex_t glock; // global lock
    int local[NUMCPUS]; // local count (per cpu)
} counter_t;
```

```c
void init(counter_t *c, int threshold) {
    c->threshold = 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);
    }
}
```

```c
void update(counter_t *c, int threadID, int amt) {
    int cpu = threadID % NUMCPUS;
    pthread_mutex_lock(&c->llock[cpu]);
    c->local[cpu] += amt; // assumes amt > 0
    pthread_mutex_unlock(&c->llock[cpu]);
    if (c->local[cpu] >= c->threshold) {
        pthread_mutex_lock(&c->glock);
        c->global += c->local[cpu];
        pthread_mutex_unlock(&c->glock);
        c->local[cpu] = 0;
    }
    pthread_mutex_unlock(&c->llock[cpu]);
}
```

```c
int get(counter_t *c) {
    pthread_mutex_lock(&c->glock);
    int val = c->global;
    pthread_mutex_unlock(&c->glock);
    return val; // only approximate!
}
```
Importance of the threshold value $S$

- Each four threads increments a counter 1 million times on four CPUs
  - Low $S \rightarrow$ Performance is poor, the global count is always quire accurate
  - High $S \rightarrow$ Performance is excellent, the global count lags

![Scaling of Approximate Counters](image-url)
Concurrent Linked Lists

```c
typedef struct __node_t {
    int key;
    struct __node_t *next;
} node_t;

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);
}

int List_Insert(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
}

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
}
```

3/23/2023
CMPU 334 -- Operating Systems
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
malloc is thread safe

man malloc
...

ATTRIBUTES

For an explanation of the terms used in this section, see attributes(7).

<table>
<thead>
<tr>
<th>Interface</th>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>malloc(), free(),</td>
<td>Thread safety</td>
<td>MT-Safe</td>
</tr>
<tr>
<td>calloc(), realloc()</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

man 7 attributes
...

MT-Safe

MT-Safe or Thread-Safe functions are safe to call in the presence of other threads. MT, in MT-Safe, stands for Multi Thread.

Being MT-Safe does not imply a function is atomic, nor that it uses any of the memory synchronization mechanisms POSIX exposes to users. It is even possible that calling MT-Safe functions in sequence does not yield an MT-Safe combination. For example, having a thread call two MT-Safe functions one right after the other does not guarantee behavior equivalent to atomic execution of a combination of both functions, since concurrent calls in other threads may interfere in a destructive way.

Whole-program optimizations that could inline functions across library interfaces may expose unsafe reordering, and so performing inlining across the GNU C Library interface is not recommended. The documented MT-Safety status is not guaranteed under whole-program optimization. However, functions defined in user-visible headers are designed to be safe for inlining.

3/23/2023
CMPU 334 -- Operating Systems

14
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);
}

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

Not this guy
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);
}

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);
}

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

- Simple 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**

```c
#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);
}
```
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

![Graph showing performance comparison between Simple Concurrent List and Concurrent Hash Table](chart.png)

- The simple concurrent hash table scales very well
Summary

• We looked at a few of the concurrent data structures out there
  • Counters
  • Lists
  • Queues
  • Hash Tables

• Tips
  • Be careful with acquiring and releasing locks around control flow changes
  • Enabling more concurrency does not necessarily increase performance
  • Premature optimization is the root of all evil! (Knuth’s Law)