Concurrency: Locked Data Structures

CS 537: Introduction to Operating Systems

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Administrivia

- Code Reviews going on this week
- Project 4 Coming out today
- Exam Grades will not be posted until at least next week

Review: Locks

- A correctly implemented lock is a way to ensure **mutual exclusion**, should not cause **deadlock** or **starvation**. Locks are judged on correctness, fairness, and performance.
- Locks typically require hardware support:
  - Disable Interrupts
  - `int TestAndSet(int *old_ptr, int new)` or `xchg()`
  - `int CompareAndSwap(int *addr, int expected, int new)`
  - `int LoadLinked(int *ptr)` and `int StoreConditional(int *ptr, int value)`
- Different types of locks: Spin-locks, Ticket-locks, and 2-phase blocking locks
  - Utilize `yield()` and `park()` and `unpark()`

Quiz: Locks

https://tinyurl.com/cs537-fa24-q10/

Lock-based Concurrent Data Structures

Creating **thread-safe** (and fast) data structures:

- Counters
- Linked Lists
- Queues
- Hash Tables

Counter Without Locks

```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) ...
int get(counter_t *c) ...
```

Counter With Locks

```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) ...
int get(counter_t *c) ...
```

Locked version works correctly, but **doesn't scale**

Approximate Counter

```c
typedef struct __counter_t {
  int             global;
  pthread_mutex_t glock;
  int             local[NUMCPUS];
  pthread_mutex_t llock[NUMCPUS];
  int             threshold;
} counter_t;

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);
  }
}
```

Approximate Counter (cont.)

```c
void update(counter_t *c, int threadID, int amt){
  int cpu = threadID % NUMCPUS;
  pthread_mutex_lock(&c->llock[cpu]);
  c->local[cpu] += amt;
  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]);
}

int get(counter_t *c) {
  pthread_mutex_lock(&c->glock);
  int val = c->global;
  pthread_mutex_unlock(&c->glock);
  return val;
}
```

Approximate Counter Trace with Threshold $= 5$

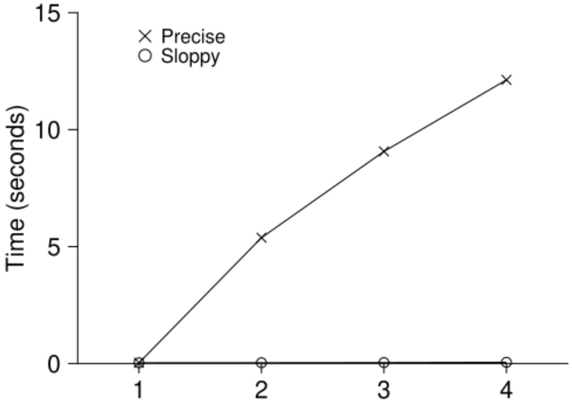
Time	L_1	L_2	L_3	L_4	G
0	0	0	0	0	0
1	0	0	1	1	0
2	1	0	2	1	0
3	2	0	3	1	0
4	3	0	3	2	0
5	4	1	3	3	0
6	$5 \rightarrow 0$	1	3	4	5 (from L_1)
7	0	2	4	$5 \rightarrow 0$	10 (from L_4)

Figure 29.3: **Tracing the Approximate Counters**

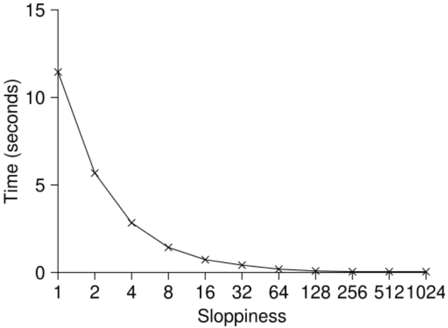
Comparing Exact vs Approx. Counter

4 threads each incrementing counter 1 million times on 4 CPUs

`threshold` set at 1024



Approximate Counter Scaling



Changing Threshold:

- Low – global count accurate
- High – improved performance

Concurrent Linked Lists

```
typedef struct __node_t {
  int                 key;
  struct __node_t   *next;
} node;

typedef struct __list_t {
  node               *head;
  pthread_mutex_t   lock;
} list;

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

Concurrent Linked Lists (cont.)

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

```c
int List_Lookup(list *L, int key) {
  pthread_mutex_lock(&L->lock);
  node *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
}
```

- One Big Lock – Does Not Scale Well – how else could we lock?
- Exceptional Control Flow – Remember to release lock!

Improved Exceptional Control Flow

```c
void List_Insert(list *L, int key) {
  node_t *n = malloc(sizeof(node));
  if (n == NULL) {
    perror("malloc");
    return;
  }
  n->key = key;
  pthread_mutex_lock(&L->lock);
  n->next = L->head;
  L->head = n;
  pthread_mutex_unlock(&L->lock);
  return;
}
```

```c
int List_Lookup(list *L, int key) {
  int rv = -1;
  pthread_mutex_lock(&L->lock);
  node *curr = L->head;
  while(curr) {
    if (curr->key == key) {
     rv = 0;
     break;
    }
    curr = curr->next;
  }
  pthread_mutex_unlock(&L->lock);
  return rv;
}
```

- **Hand-over-hand** locking, having one lock per node. When traversing the list, acquire lock of next node then release lock of current node. In practice, so much locking/unlocking, difficult to make faster than one lock
- Perhaps hybrid approach, one lock for blocks of nodes

Concurrent Queues

- One standard approach – add a big lock around the entire data structure
  - Accurate but not very efficient
- Improved approach – add a lock around the head and another around the tail
  - Allows concurrent enqueue and dequeue operations
- Add a dummy node to separate the head from the tail
- More fully developed bounded queue discussed with condition variables

Concurrent Queue Implementation

```c
typedef struct __node_t {
  int                 value;
  struct __node_t   *next;
} node;

typedef struct __queue_t {
  node               *head;
  node               *tail
  pthread_mutex_t   hLock;
  pthread_mutex_t   tLock;
} queue;

void Queue_Init(queue *q) {
  node *tmp = malloc(sizeof(node));
  tmp->next = NULL;
  q->head = q->tail = tmp;
  pthread_mutex_init(&q->hLock,NULL);
  pthread_mutex_init(&q->tLock,NULL);
}
```

Concurrent Queue Implementation (cont.)

```c
void Enqueue(queue *q, int value) {
  node *tmp = malloc(sizeof(node));
  assert(tmp !=NULL);
  tmp->value = value;
  tmp->next = NULL;
  pthread_mutex_lock(&q->tLock);
  q->tail->next=tmp;
  q->tail = tmp;
  pthread_mutex_unlock(&q->tLock);
}
```

```c
int Dequeue(queue *q, int *value) {
  pthread_mutex_lock(&q->hLock);
  node *tmp = q->head;
  node *newHead = tmp->next;
  if (newHead == NULL) {
   pthread_mutex_unlock(&q->hLock);
   return -1; //empty queue
  }
  *value = newHead->value;
  q->head = newHead;
  pthread_mutex_unlock(&q->hLock);
  free(tmp);
  return 0;
}
```

Concurrent Hash Table

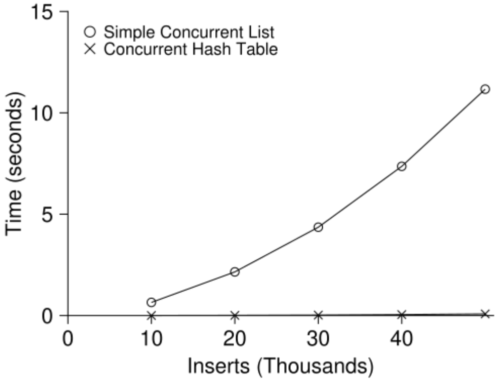
- Utilizes a concurrent list for each hash bucket
- Rather than having a single lock, each bucket is locked independently
  - Allows many concurrent operations

Concurrent Hash Table Implementation

```c
#define BUCKETS (101)
typedef struct __hash_t {
  list    lists[BUCKET];
} hash_t;

void Hash_Init(hash_t *H) {
  int i=0;
  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);
}
```

Hashtable Performance

- Single List doesn't scale, but hashtable does
- 10,000 to 50,000 concurrent updates from 4 threads



Summary

- Be carefull with acquisition and release of locks
- Enabling more concurrency does not necessarily increase performance
- Performance problems should only be remedied once they exist
  - **Start with single big lock (likely correct)**
  - Only if it doesn't meet needs, refine it

Premature Optimization is the root of all evil. – Donald Knuth