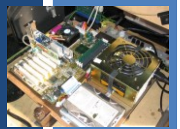
TCSS 422: OPERATING SYSTEMS



**Linux Thread API,
Lock Implementations,
Lock-based data structures,**

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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OBJECTIVES – 4/25

- Questions from 4/23
- C Tutorial - Pointers, Strings, Exec in C - Due Fri Apr 26
- Assignment 1 - Due Tue May 7
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  - pthread_cond_wait/_signal/_broadcast
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  - Introduction, Lock Granularity
  - Spin Locks, Test and Set, Compare and Swap
- Chapter 29: Lock Based Data Structures
  - Approximate Counter (Sloppy Counter)
  - Concurrent Structures: Linked List, Queue, Hash Table

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ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p

TCSS 422 A > Assignments

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Upcoming Assignments
TCSS 422 - Online Daily Feedback Survey - 4/1
Available until Apr 5 at 11:59pm | Due Apr 5 at 10pm | -/1 pts
Quiz 0 - C background survey

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TCSS 422 - Online Daily Feedback Survey - 4/1

Quiz Instructions

Question 1 — 0.5 pts

On a scale of 1 to 10, please classify your perspective on material covered in today's class:

1 2 3 4 5 6 7 8 9 10
Mostly Review To Me — Equal New and Review — Mostly New to Me

Question 2 — 0.5 pts

Please rate the pace of today's class:

1 2 3 4 5 6 7 8 9 10
Slow — Just Right — Fast

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (31 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.45 (↓ - previous 6.58)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.06 (↓ - previous 5.10)**

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FEEDBACK FROM 4/23

- ***Why does pthread_mutex_lock() function call return an integer which is assigned to variable rc?***

```
int rc = pthread_mutex_init(&lock, NULL);
assert(rc == 0); // always check success!
```

  - We capture the function's return code into int rc

- ***Why does rc have to be asserted that it is equal to 0 right after the initialization?***
  - The assert function throws an error (and stops the program) when rc is non-zero
  - Receiving a non-zero return indicates a critical error, and the program should likely not continue to run
  - Calling assert() is optional and not required

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QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Thursday April 25th at 11:59pm
- Link:
- https://faculty.washington.edu/wlloyd/courses/tcss422/quiz/TCSS422_s2024_quiz_1.pdf

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QUIZ 2

- Canvas Quiz – Practice CPU Scheduling Problems
- Posted in Canvas
- Unlimited attempts permitted
- Provides CPU scheduling practice problems
  - FIFO, SJF, STCF, RR, MLFQ (Ch. 7 & 8)
- Multiple choice and fill-in the blank
- Quiz automatically scored by Canvas
  - Please report any grading problems
- Due Tuesday April 30th at 11:59pm
- Link:
- https://canvas.uw.edu/courses/1728244/quizzes/2030525

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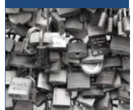
CHAPTER 28 – LOCKS



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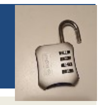
LOCKS



- Ensure critical section(s) are executed atomically-*as a unit*
  - Only one thread is allowed to execute a critical section at any given time
  - Ensures the code snippets are "mutually exclusive"
- Protect a global counter:

```
balance = balance + 1;
```

- A "critical section":

```
lock_t mutex; // some globally-allocated lock 'mutex'
…
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```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LOCKS - 2

- Lock variables are called "MUTEX"
  - Short for mutual exclusion (that's what they guarantee)
- Lock variables store the state of the lock
- States
  - **Locked** (acquired or held)
  - **Unlocked** (available or free)
- Only 1 thread can hold a lock

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LOCKS - 3

- `pthread_mutex_lock(&lock)`
  - Try to acquire lock
  - If lock is free, calling thread will acquire the lock
  - Thread with lock enters critical section
    - Thread "owns" the lock
- No other thread can acquire the lock before the owner releases it.

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LOCKS - 4

- Program can have many mutex (lock) variables to "serialize" many critical sections
- Locks are also used to protect data structures
  - Prevent multiple threads from changing the same data simultaneously
  - Programmer can make sections of code "granular"
    - ***Fine grained*** – means just one grain of sand at a time through an hour glass
  - Similar to relational database transactions
    - DB transactions prevent multiple users from modifying a table, row, field

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FINE GRAINED?

- ***Is this code a good example of "fine grained parallelism"?***

```
pthread_mutex_lock(&lock);
a = b++;
b = a * c;
*d = a + b +c;
FILE * fp = fopen ("file.txt", "r");
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
ListNode *node = mylist->head;
Int i=0
while (node) {
  node->title = str1;
  node->subheading = str2;
  node->desc = str3;
  node->end = *e;
  node = node->next;
  i++
}
e = e - i;
pthread_mutex_unlock(&lock);
```

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FINE GRAINED PARALLELISM

```
pthread_mutex_lock(&lock_a);
pthread_mutex_lock(&lock_b);
a = b++;
pthread_mutex_unlock(&lock_b);
pthread_mutex_unlock(&lock_a);

pthread_mutex_lock(&lock_b);
b = a * c;
pthread_mutex_unlock(&lock_b);

pthread_mutex_lock(&lock_d);
*d = a + b +c;
pthread_mutex_unlock(&lock_d);

FILE * fp = fopen ("file.txt", "r");
pthread_mutex_lock(&lock_e);
fscanf(fp, "%s %s %s %d", str1, str2, str3, &e);
pthread_mutex_unlock(&lock_e);

ListNode *node = mylist->head;
int i=0 . . .
```

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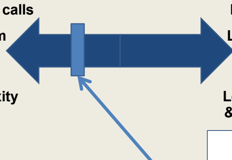
LOCK GRANULARITY TRADE-OFF SPACE

FINE-GRAINED

Many Lock (kernel) calls
More overhead from excessive locking
More parallelism
Higher code complexity & debugging

COARSE-GRAINED

Few Lock (kernel) calls
Low overhead from minimal locking
Less parallelism
Low code complexity & simpler debugging



Every program implementation lies someplace along the trade-off space…

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EVALUATING LOCK IMPLEMENTATIONS

What makes a good lock?

- **Correctness**
  - Does the lock work?
  - Are critical sections mutually exclusive? (atomic-*as a unit*?)
- **Fairness**
  - Do all threads that compete for a lock have a fair chance of acquiring it?
- **Overhead**

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BUILDING LOCKS

- Locks require hardware support
  - To minimize overhead, ensure fairness and correctness
  - Special "atomic-*as a unit*" instructions to support lock implementation
  - Atomic-*as a unit* exchange instruction
    - XCHG
  - Compare and exchange instruction
    - CMPXCHG
    - CMPXCHG8B
    - CMPXCHG16B

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HISTORICAL IMPLEMENTATION

- To implement mutual exclusion
  - Disable interrupts upon entering critical sections

```
void lock() {
    DisableInterrupts();
}
void unlock() {
    EnableInterrupts();
}
```

- Any thread could disable system-wide interrupt
  - What if lock is never released?
- On a multiprocessor processor each CPU has its own interrupts
  - Do we disable interrupts for all cores simultaneously?
- While interrupts are disabled, they could be lost
  - If not queued…

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BASIC SPIN LOCK IMPLEMENTATION

- Demonstration of lock implementation using C code
- C code is compiled to assembly, instructions are not atomic
- Idea is to imagine “what if” the lock code were atomic

- Is this lock implementation:
  (1)Correct?
  (2)Fair?
  (3)Performant?

```
typedef struct __lock_t { int flag; } lock_t;

void init(lock_t *mutex) {
    // 0 → lock is available, 1 → held
    mutex->flag = 0;
}

void lock(lock_t *mutex) {
    while (mutex->flag == 1)  // TEST the flag
        ;  // spin-wait (do nothing)
    mutex->flag = 1;  // now SET it !
}

void unlock(lock_t *mutex) {
    mutex->flag = 0;
}
```


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BASIC SPIN LOCK: CORRECT?

- If both threads can run at the same time, then correctness requires luck… (e.g. *basic spin lock is incorrect*)

Thread1	Thread2
call `lock()`	
`while (flag == 1)`	
interrupt: switch to Thread 2	
	call `lock()`
	`while (flag == 1)`
	`flag = 1;`
	interrupt: switch to Thread 1
`flag = 1;` // set flag to 1 (too!)	

- Here both threads have “acquired” the lock simultaneously

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BASIC SPIN LOCK: PERFORMANCE ?

```
void lock(lock_t *mutex)
{
  while (mutex->flag == 1);   // while lock is unavailable, wait…
  mutex->flag = 1;
}
```

- What is wrong with while(<cond>); ?
- Spin-waiting wastes time actively waiting for another thread
- while (1); will “peg” a CPU core at 100%
  - Continuously loops, and evaluates mutex->flag value…
  - If multiple threads wait for the CPU, more CPU capacity is wasted
  - Generates heat…

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TEST-AND-SET INSTRUCTION

- Hardware support required for working locks
- Book presents pseudo code of C implementation for <u>TEST-AND-SET</u> instruction that needs to be atomic
  - TEST-and-SET checks old value improving on basic spin lock
  - TEST-and-SET returns the old value so it can be checked
  - Comparison is made in the caller
  - Assumption is the TEST-AND-SET routine runs atomically on the CPU
  - Here is the C-pseudo code:

```
int TestAndSet(int *ptr, int new) {
    int old = *ptr;   // fetch old value at ptr
    *ptr = new;       // store 'new' into ptr
    return old;       // return the old value
}
```


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TEST-AND-SET - 2

- lock() method checks that TestAndSet doesn't return 1
- If TestAndSet returns 1:
  - This indicates someone else has the lock

```
typedef struct __lock_t {
    int flag;
} lock_t;

void init(lock_t *lock) {
    // 0 indicates that lock is available,
    // 1 that it is held
    lock->flag = 0;
}

void lock(lock_t *lock) {
    while (TestAndSet(&lock->flag, 1) == 1)
        ;        // spin-wait
}

void unlock(lock_t *lock) {
    lock->flag = 0;
}
```


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SPIN LOCK EVALUATION

- **Correctness:**
  - Spin locks with atomic Test-and-Set: Critical sections won't be executed simultaneously by (2) threads
- **Fairness:**
  - No fairness guarantee. Once a thread has a lock, nothing forces it to relinquish it… lock distribution is random
- **Performance:**
  - Spin locks perform "busy waiting"
  - Spin locks are best for short periods of waiting (< 1 time quantum)
  - Performance is slow when multiple threads share a CPU
    - Especially if "spinning" for long periods

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COMPARE AND SWAP

- Checks that the lock variable has the expected value FIRST, before changing its value
  - If so, make assignment
  - Return value at location
- Adds a comparison to TestAndSet method
  - Textbook presents C pseudo code
  - Assumption is that the compare-and-swap method runs **atomically**
- Useful for wait-free synchronization
  - Supports implementation of shared data structures which can be updated atomically (*as a unit*) using Hardware support: x86 CompareAndSwap instructions
  - Shared data structure updates become "wait-free"
  - Upcoming in Chapter 32

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COMPARE AND SWAP

- Compare and Swap

```
int CompareAndSwap(int *ptr, int expected, int new) {
    int actual = *ptr;
    if (actual == expected)
            *ptr = new;
    return actual;
```

- Spin l

C implementation on 1-core VM: Count is correct, no deadlock

```
            ; // spin
}
```

- x86 CPU provides "cmpxchgl" compare-and-exchange instructions
  - cmpxchg8b
  - cmpxchg16b

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When implementing locks in a high-level language (e.g. C), what is missing that prevents implementation of CORRECT locks?

- Shared state variable
- Condition variables
- ATOMIC instructions
- Fairness
- None of the above

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"LOCK BUILDING" CPU INSTRUCTIONS ON ARM PROCESSORS

- Cooperative instructions used together to support synchronization on RISC systems
- No support on x86 processors
  - Supported by RISC: Alpha, PowerPC, ARM
- Load-linked (LL)
  - Loads value into register
  - Same as typical load
  - Used as a mechanism to track competition
- Store-conditional (SC)
  - Performs "mutually exclusive" store
  - Allows only one thread to store value

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LL/SC LOCK

```
int LoadLinked(int *ptr) {
    return *ptr;
}

int StoreConditional(int *ptr, int value) {
    if (no one has updated *ptr since the LoadLinked to this address) {
        *ptr = value;
        return 1; // success!
    } else {
        return 0; // failed to update
    }
}
```

- LL instruction loads pointer value (ptr)
- SC only stores if the load link pointer has not changed
- Requires HW support
  - C code is psuedo code

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LL/SC LOCK - 2

```
void lock(lock_t *lock) {
    while (1) {
        while (LoadLinked(&lock->flag) == 1)
            ; // spin until it's zero
        if (StoreConditional(&lock->flag, 1) == 1)
            return; // if set-it-to-1 was a success: all done
                    otherwise: try it all over again
    }
}

void unlock(lock_t *lock) {
    lock->flag = 0;
}
```

- Two instruction lock

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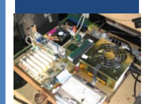
WE WILL RETURN AT 5:10PM



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CHAPTER 29 – LOCK BASED DATA STRUCTURES

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LOCK-BASED CONCURRENT DATA STRUCTURES

- **Adding locks to data structures make them thread safe.**
- Considerations:
  - Correctness
  - Performance
  - Lock granularity

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COUNTER STRUCTURE W/O LOCK

- Synchronization weary --- not thread safe

```
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;
}
```


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CONCURRENT COUNTER

```
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);
}

```

- Add lock to the counter
- Require lock to change data

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CONCURRENT COUNTER - 2

- Decrease counter
- Get value

```
(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;
}
```


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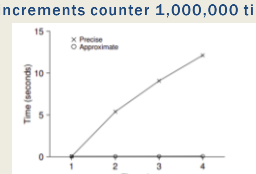
CONCURRENT COUNTERS - PERFORMANCE

- Concurrent counter is considered a "precise counter"
- iMac: four core Intel 2.7 GHz i5 CPU
- Each thread increments counter 1,000,000 times



Precise counter scales poorly.

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PERFECT SCALING

- Achieve (N) performance gain with (N) additional resources
- Throughput:
- Transactions per second (tps)
- 1 core
- N = 100 tps
- 10 cores (x10)
- N = 1000 tps (x10)
- ***Is parallel counting with a shared counter an embarrassingly parallel problem?***

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APPROXIMATE (SLOPPY) COUNTER

- Provides single logical shared counter
  - Implemented using local counters for each ~CPU core
    - 4 CPU cores = 4 local counters & 1 global counter
    - Local counters are synchronized via local locks
  - Global counter is updated periodically
    - Global counter has lock to protect global counter value
    - Update threshold (S) – *referred to as sloppiness threshold:* How often to push local values to global counter
    - Small (S): more updates, more overhead
    - Large (S): fewer updates, more performant, less synchronized
- Why this implementation?
  Why do we want counters local to each CPU Core?

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APPROXIMATE COUNTER – MAIN POINTS

- Idea of the Approximate Counter is to ***RELAX*** the synchronization requirement for counting
  - Instead of synchronizing global count variable each time: `counter=counter+1`
  - Synchronization occurs only every so often: e.g. *every 1000 counts*
- Relaxing the synchronization requirement ***drastically*** reduces locking API overhead by trading-off split-second accuracy of the counter
- Approximate counter: trade-off accuracy for speed
  - It's approximate because it's not so accurate (until the end)

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APPROXIMATE COUNTER - 2

- Update threshold (S) = 5
- Synchronized across four CPU cores
- Threads update local CPU counters

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)

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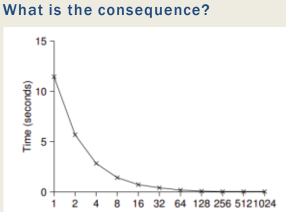
THRESHOLD VALUE S

- Consider 4 threads increment a counter 1000000 times each
- Low S → What is the consequence?
- High S → What is the consequence?



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APPROXIMATE COUNTER - EXAMPLE

- Example implementation – sloppybasic.c
- Also with CPU affinity

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Text **WESLEYLLOYD641** to **22333** once to join

Which of the following is NOT a problem as a result of having a low S-value for the approximate counter (Sloppy Counter) threshold?

- The counter overhead is very high.
- The counter implementation performs a very large number of LOCK/UNLOCK API calls.
- The global counter value is highly accurate.
- The counter performs very few local to global counter updates.
- None of the above

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

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OBJECTIVES – 4/25

- Questions from 4/23
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  - Concurrent Structures: Linked List, Queue, Hash Table

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CONCURRENT LINKED LIST - 1

- Simplification - only basic list operations shown
- Structs and initialization:

```
// 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.)
```


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CONCURRENT LINKED LIST - 2

- Insert – adds item to list
- Everything is critical!
  - There are two unlocks

```
(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.)
```


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CONCURRENT LINKED LIST - 3

- Lookup – checks list for existence of item with key
- Once again everything is critical
  - Note - there are also two unlocks

```
(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
}
```


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CONCURRENT LINKED LIST

- First Implementation:
  - Lock **everything** inside Insert() and Lookup()
  - If malloc() fails lock must be released
    - Research has shown "***exception-based control flow***" to be error prone
    - 40% of Linux OS bugs occur in rarely taken code paths
    - Unlocking in an exception handler is considered a poor coding practice
    - There is nothing specifically wrong with this example however
- Second Implementation …

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CCL – SECOND IMPLEMENTATION

- Init and Insert

```
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);
}
```

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CCL – SECOND IMPLEMENTATION - 2

- Lookup

```
(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
}
```

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CONCURRENT LINKED LIST PERFORMANCE

- Using a single lock for entire list is not very performant
- Users must "wait" in line for a single lock to access/modify any item
- Hand-over-hand-locking (lock coupling)
  - Introduce a lock for each node of a list
  - Traversal involves handing over previous node's lock, acquiring the next node's lock…
  - Improves lock granularity
  - Degrades traversal performance
- Consider hybrid approach
  - Fewer locks, but more than 1
  - Best lock-to-node distribution?

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- Chapter 29: Lock Based Data Structures
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MICHAEL AND SCOTT CONCURRENT QUEUES

- Improvement beyond a single master lock for a queue (FIFO)
- Two locks:
  - One for the **head** of the queue
  - One for the **tail**
- Synchronize enqueue and dequeue operations
- Add a dummy node
  - Allocated in the queue initialization routine
  - Supports separation of head and tail operations
- Items can be added and removed by separate threads at the same time

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CONCURRENT QUEUE

- Remove from queue

```
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.)
```

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CONCURRENT QUEUE - 2

- Add to queue

```
(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.)
```


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CONCURRENT HASH TABLE

- Consider a simple hash table
  - Fixed (static) size
  - Hash maps to a bucket
    - Bucket is implemented using a concurrent linked list
    - One lock per hash (bucket)
    - Hash bucket is a linked lists

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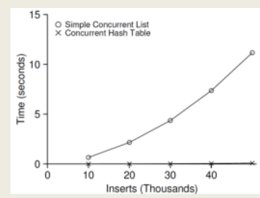
INSERT PERFORMANCE – CONCURRENT HASH TABLE

- Four threads – 10,000 to 50,000 inserts
  - iMac with four-core Intel 2.7 GHz CPU



The simple concurrent hash table scales magnificently.

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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);
}
```


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Which is a major advantage of using concurrent data structures in your programs?

- Locks are encapsulated within data structure code ensuring thread safety.
- Lock granularity tradeoff already optimized inside data structurew
- Multiple threads can more easily share data
- All of the above
- None of the above

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LOCK-FREE DATA STRUCTURES

- Lock-free data structures in Java
- Java.util.concurrent.atomic package
- Classes:
  - AtomicBoolean
  - AtomicInteger
  - AtomicIntegerArray
  - AtomicIntegerFieldUpdater
  - AtomicLong
  - AtomicLongArray
  - AtomicLongFieldUpdater
  - AtomicReference
- See: https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/util/concurrent/atomic/package-summary.html

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QUESTIONS

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