TCSS 422: OPERATING SYSTEMS

Linux Thread API, Locks, Lock-based data structures

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

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OBJECTIVES – 10/28

- Questions from 10/26
- C Tutorial - Pointers, Strings, Exec in C - Due Fri Oct 29
- Assignment 1 - Due Fri Nov 12
- Quiz 1 (Due Tue Nov 2) – Quiz 2 (Due Thur Nov 4)
- Chapter 26: Concurrency: An Introduction
  - Race condition
  - Critical section
- Chapter 27: Linux Thread API
  - pthread_create/_join
  - pthread_mutex_lock/_unlock/_trylock/_timelock
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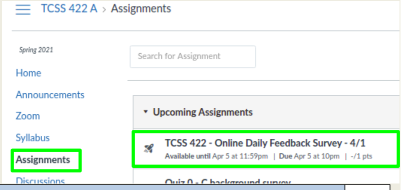
  - Introduction, Lock Granularity
  - Spin Locks, Test and Set, Compare and Swap
- Chapter 29: Lock Based Data Structures
  - Sloppy Counter
  - Concurrent Structures: Linked List, Queue, Hash Table

2

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

Spring 2021

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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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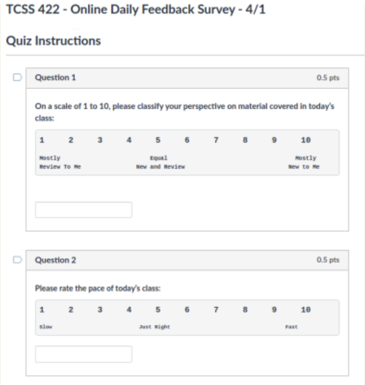

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Quiz Instructions

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                Equal                       Mostly
Review To Me          New and Review              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
```

4

MATERIAL / PACE

- Please classify your perspective on material covered in today's class (25 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.66 (↑ - previous 6.23)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.58 (↑ - previous 5.48)**

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FEEDBACK

- ..

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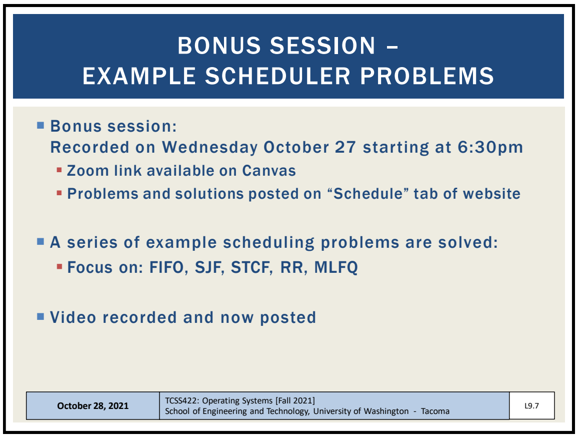
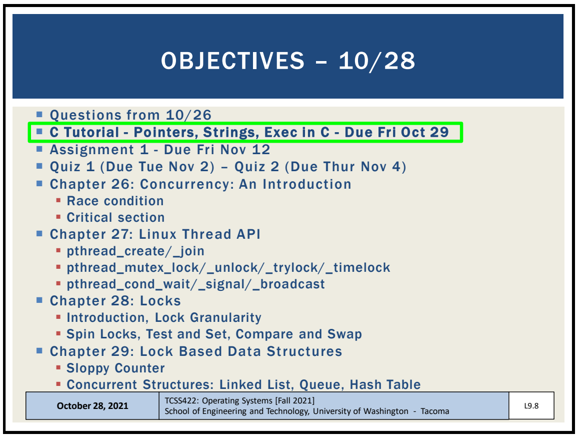


BONUS SESSION – EXAMPLE SCHEDULER PROBLEMS

- Bonus session:
  Recorded on Wednesday October 27 starting at 6:30pm
  - Zoom link available on Canvas
  - Problems and solutions posted on "Schedule" tab of website
- A series of example scheduling problems are solved:
  - Focus on: FIFO, SJF, STCF, RR, MLFQ
- Video recorded and now posted



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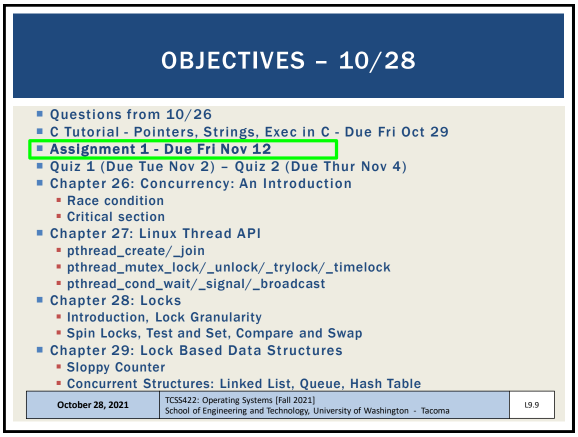

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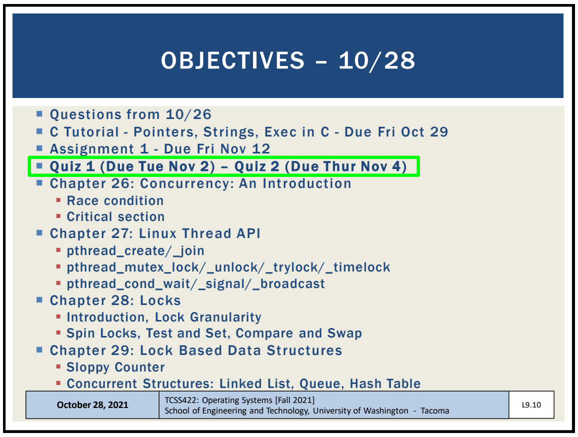

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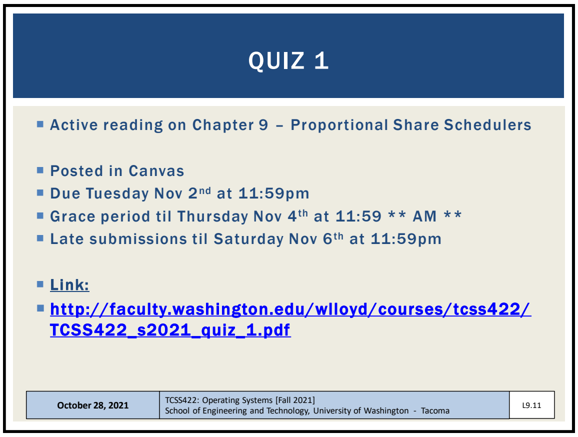
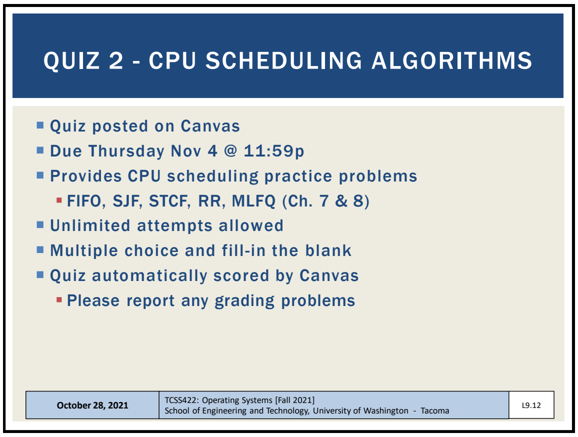


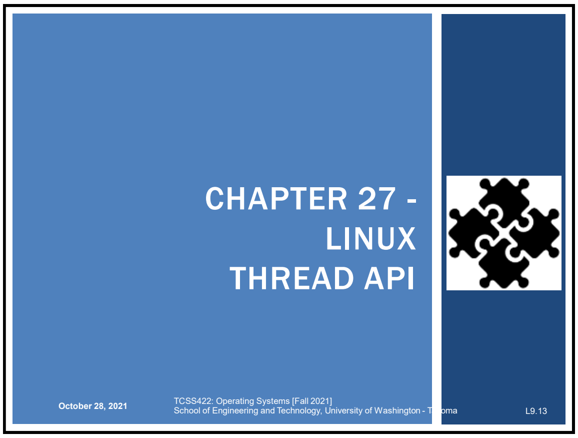
QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Tuesday Nov 2nd at 11:59pm
- Grace period til Thursday Nov 4th at 11:59 ** AM **
- Late submissions til Saturday Nov 6th at 11:59pm
- Link:
- http://faculty.washington.edu/wlloyd/courses/tcss422/TCSS422_s2021_quiz_1.pdf



QUIZ 2 - CPU SCHEDULING ALGORITHMS

- Quiz posted on Canvas
- Due Thursday Nov 4 @ 11:59p
- Provides CPU scheduling practice problems
  - FIFO, SJF, STCF, RR, MLFQ (Ch. 7 & 8)
- Unlimited attempts allowed
- Multiple choice and fill-in the blank
- Quiz automatically scored by Canvas
  - Please report any grading problems



CHAPTER 27 - LINUX THREAD API

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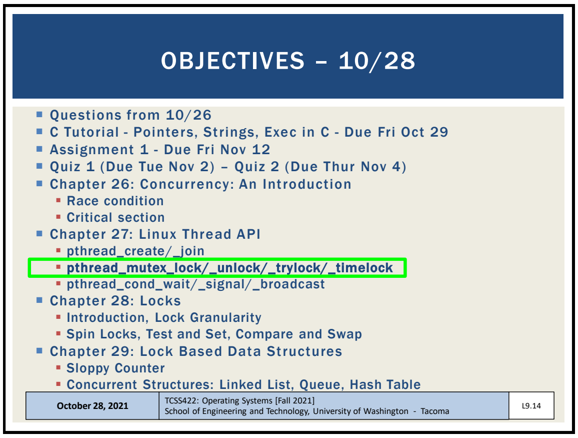

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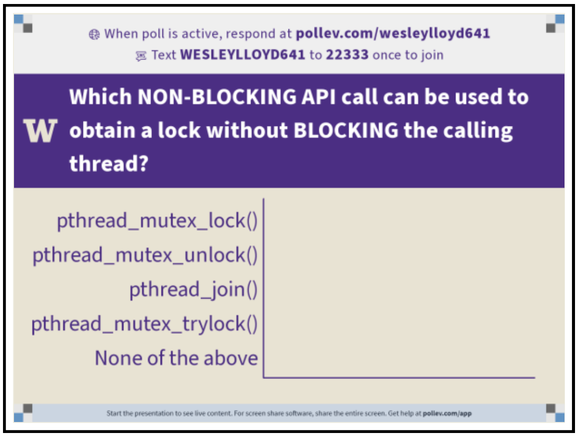

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Which NON-BLOCKING API call can be used to obtain a lock without BLOCKING the calling thread?

pthread_mutex_lock()
pthread_mutex_unlock()
pthread_join()
pthread_mutex_trylock()
None of the above

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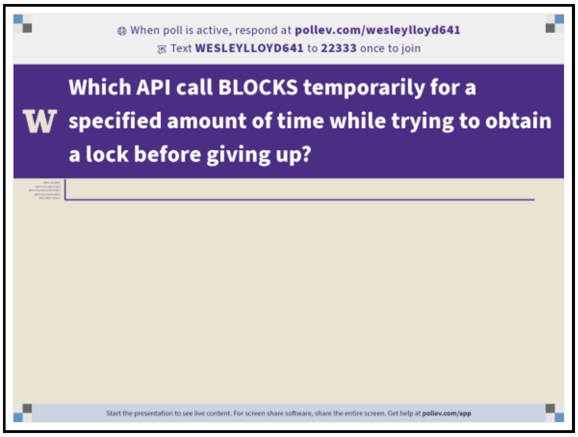

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Which API call BLOCKS temporarily for a specified amount of time while trying to obtain a lock before giving up?

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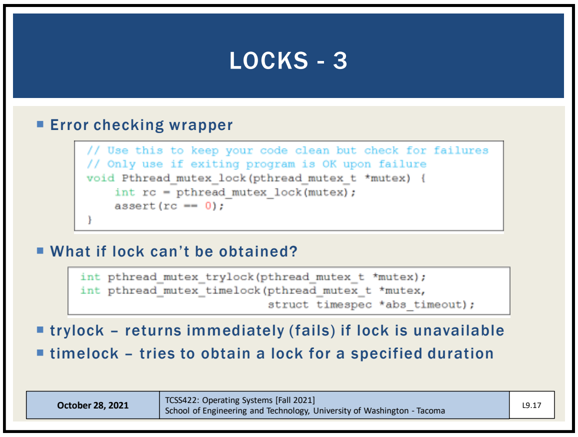

LOCKS - 3

- Error checking wrapper

```
// Use this to keep your code clean but check for failures
// Only use if exiting program is OK upon failure
void Pthread_mutex_lock(pthread_mutex_t *mutex) {
    int rc = pthread_mutex_lock(mutex);
    assert(rc == 0);
}
```

- What if lock can’t be obtained?

```
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_timelock(pthread_mutex_t *mutex,
                           struct timespec *abs_timeout);
```

- trylock – returns immediately (fails) if lock is unavailable
- timelock – tries to obtain a lock for a specified duration

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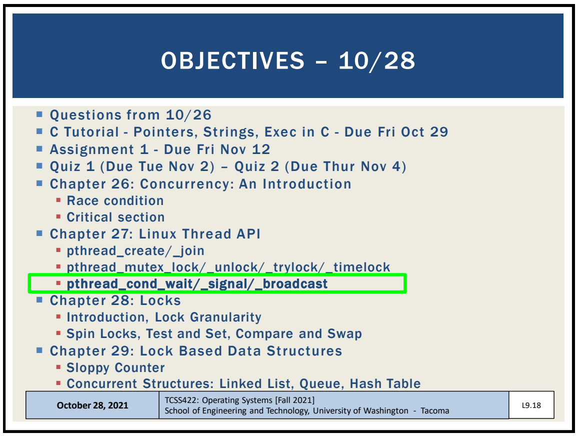

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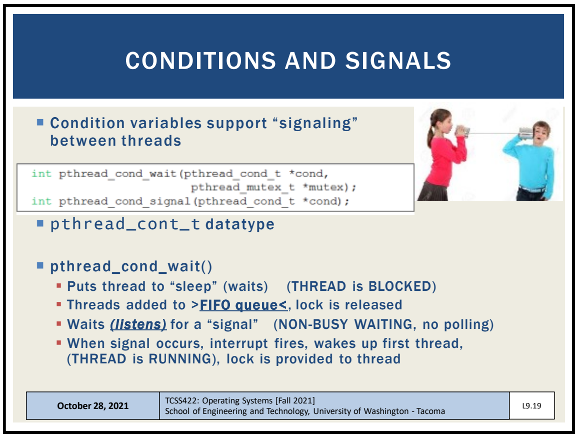

CONDITIONS AND SIGNALS

- Condition variables support “signaling” between threads

```
int pthread_cond_wait(pthread_cond_t *cond,
                      pthread_mutex_t *mutex);
int pthread_cond_signal(pthread_cond_t *cond);
```

- `pthread_cont_t` datatype
- pthread_cond_wait()
  - Puts thread to “sleep” (waits)   (THREAD is BLOCKED)
  - Threads added to >**FIFO queue<**, lock is released
  - Waits ***(listens)*** for a “signal”   (NON-BUSY WAITING, no polling)
  - When signal occurs, interrupt fires, wakes up first thread, (THREAD is RUNNING), lock is provided to thread

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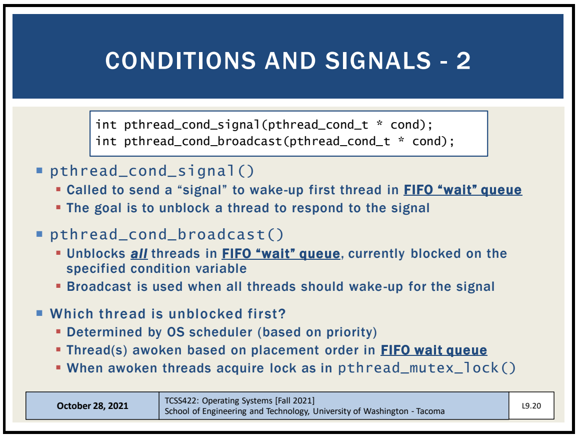

CONDITIONS AND SIGNALS - 2

```
int pthread_cond_signal(pthread_cond_t * cond);
int pthread_cond_broadcast(pthread_cond_t * cond);
```

- `pthread_cond_signal()`
  - Called to send a “signal” to wake-up first thread in **FIFO “wait” queue**
  - The goal is to unblock a thread to respond to the signal
- `pthread_cond_broadcast()`
  - Unblocks ***all*** threads in **FIFO “wait” queue**, currently blocked on the specified condition variable
  - Broadcast is used when all threads should wake-up for the signal
- Which thread is unblocked first?
  - Determined by OS scheduler (based on priority)
  - Thread(s) awoken based on placement order in **FIFO wait queue**
  - When awoken threads acquire lock as in `pthread_mutex_lock()`

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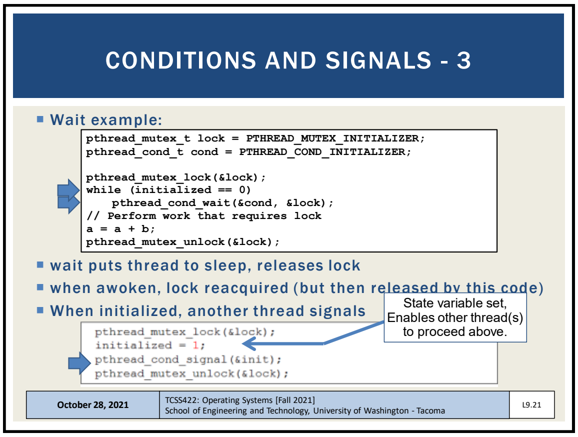

CONDITIONS AND SIGNALS - 3

- Wait example:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
    pthread_cond_wait(&cond, &lock);
// Perform work that requires lock
a = a + b;
pthread_mutex_unlock(&lock);
```

- wait puts thread to sleep, releases lock
- when awoken, lock reacquired (but then released by this code)
- When initialized, another thread signals

```
pthread_mutex_lock(&lock);
initialized = 1;
pthread_cond_signal(&init);
pthread_mutex_unlock(&lock);
```

State variable set, Enables other thread(s) to proceed above.

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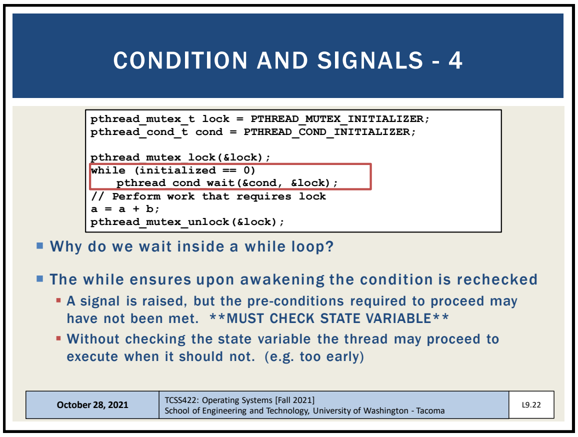

CONDITION AND SIGNALS - 4

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

pthread_mutex_lock(&lock);
while (initialized == 0)
    pthread_cond_wait(&cond, &lock);
// Perform work that requires lock
a = a + b;
pthread_mutex_unlock(&lock);
```

- Why do we wait inside a while loop?
- The while ensures upon awakening the condition is rechecked
  - A signal is raised, but the pre-conditions required to proceed may have not been met. **MUST CHECK STATE VARIABLE**
  - Without checking the state variable the thread may proceed to execute when it should not. (e.g. too early)

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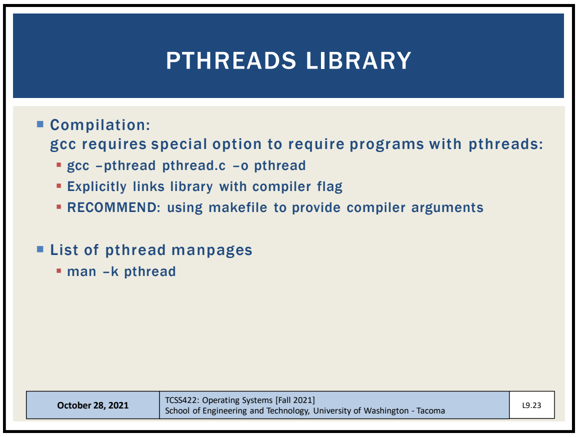

PTHREADS LIBRARY

- Compilation:
  gcc requires special option to require programs with pthreads:
  - gcc –pthread pthread.c –o pthread
  - Explicitly links library with compiler flag
  - RECOMMEND: using makefile to provide compiler arguments
- List of pthread manpages
  - man –k pthread

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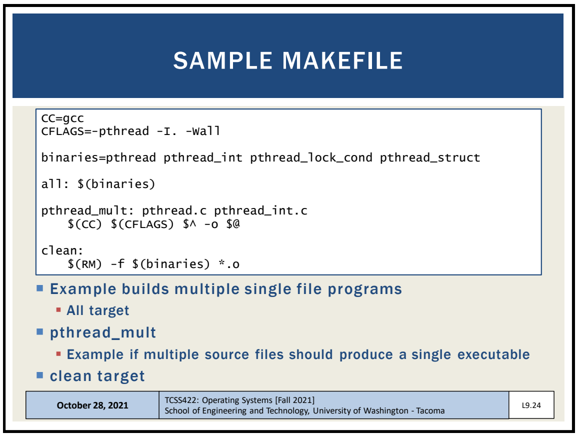

SAMPLE MAKEFILE

```
CC=gcc
CFLAGS=-pthread -I. -Wall

binaries=pthread pthread_int pthread_lock_cond pthread_struct

all: $(binaries)

pthread_mult: pthread.c pthread_int.c
    $(CC) $(CFLAGS) $^ -o $@

clean:
    $(RM) -f $(binaries) *.o
```

- Example builds multiple single file programs
  - All target
- pthread_mult
  - Example if multiple source files should produce a single executable
- clean target

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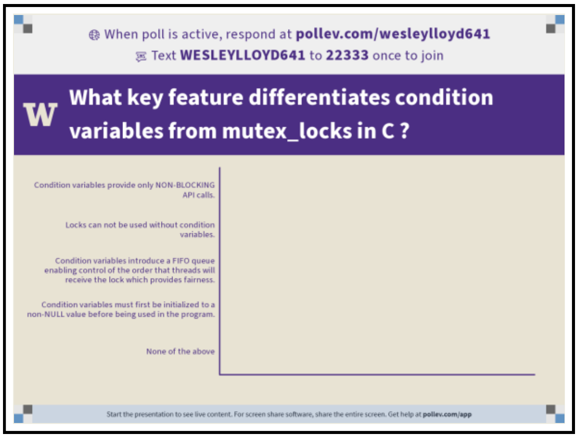

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What key feature differentiates condition variables from mutex_locks in C ?

Condition variables provide only NON-BLOCKING API calls.

Locks can not be used without condition variables.

Condition variables introduce a FIFO queue enabling control of the order that threads will receive the lock which provides fairness.

Condition variables must first be initialized to a non-NULL value before being used in the program.

None of the above

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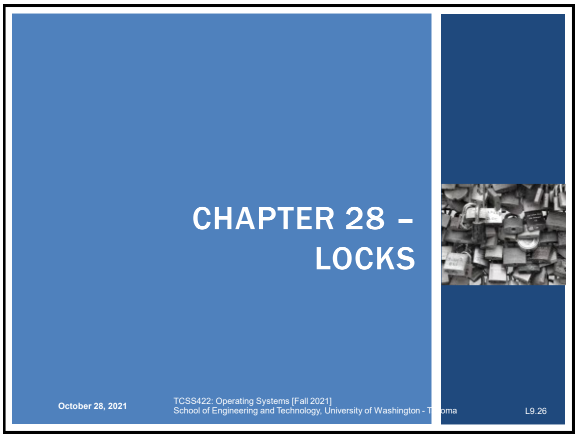

CHAPTER 28 – LOCKS

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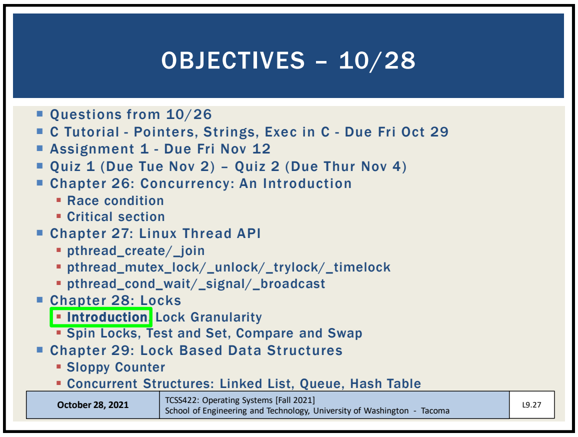

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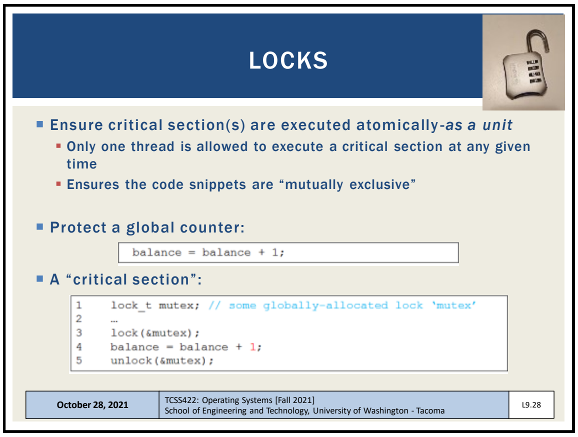

LOCKS

- 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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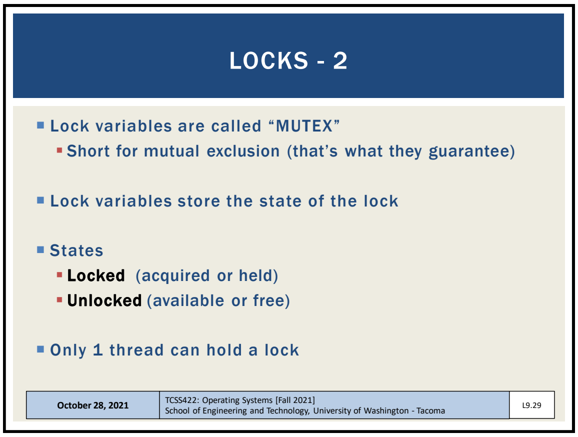

LOCKS - 2

- 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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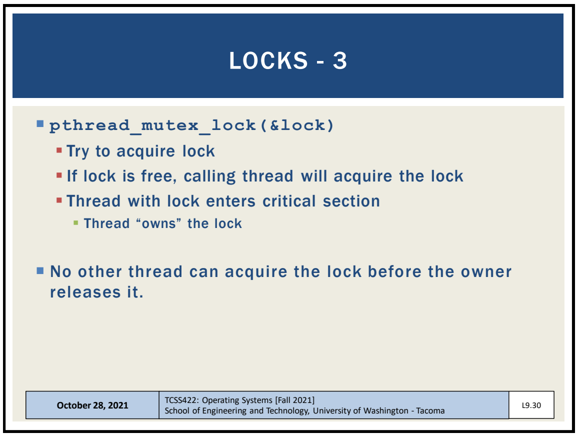

LOCKS - 3

- `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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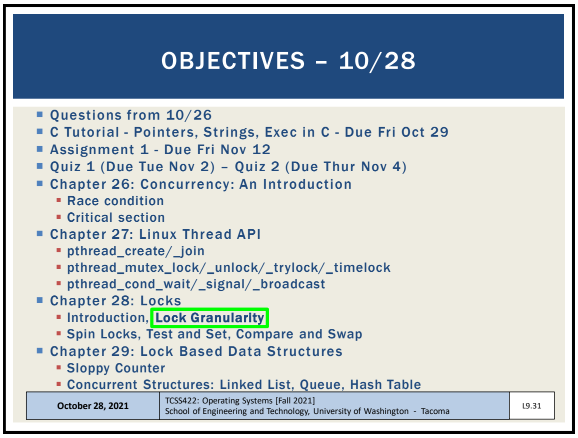

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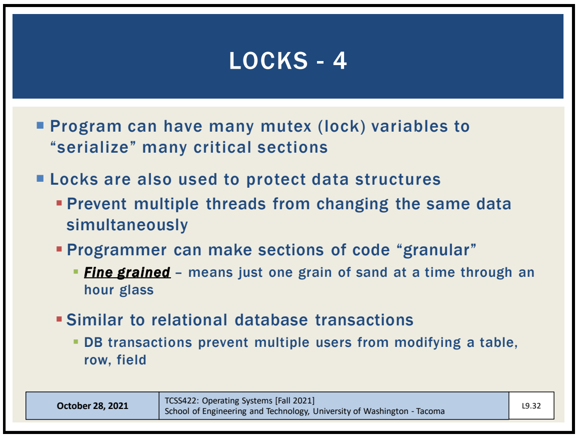

LOCKS - 4

- 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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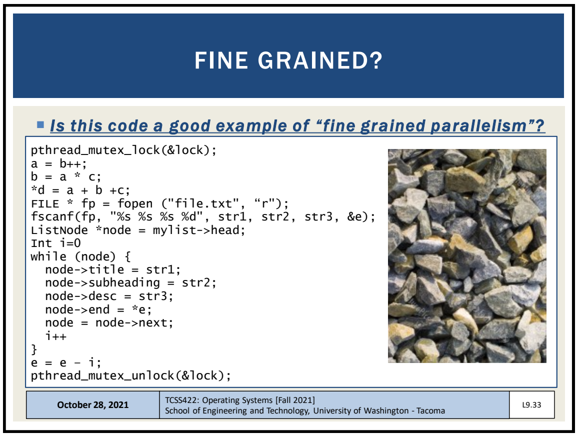

FINE GRAINED?

- ***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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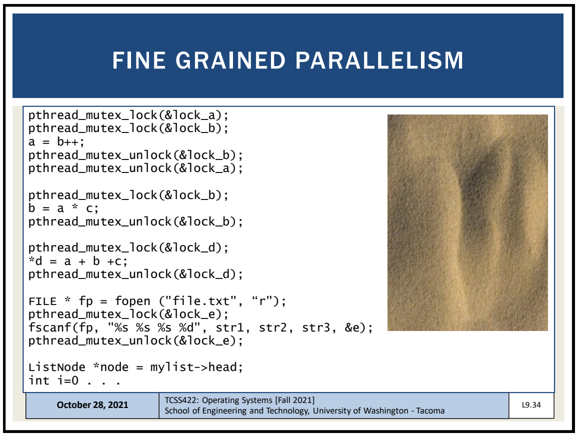

FINE GRAINED PARALLELISM

```
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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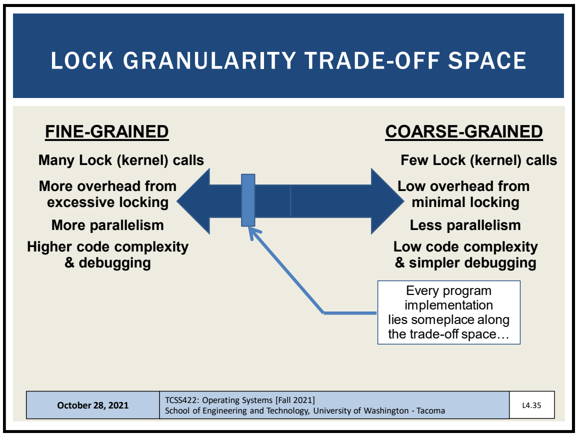

LOCK GRANULARITY TRADE-OFF SPACE

FINE-GRAINED	**COARSE-GRAINED**
Many Lock (kernel) calls	Few Lock (kernel) calls
More overhead from excessive locking	Low overhead from minimal locking
More parallelism	Less parallelism
Higher code complexity & debugging	Low code complexity & simpler debugging

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

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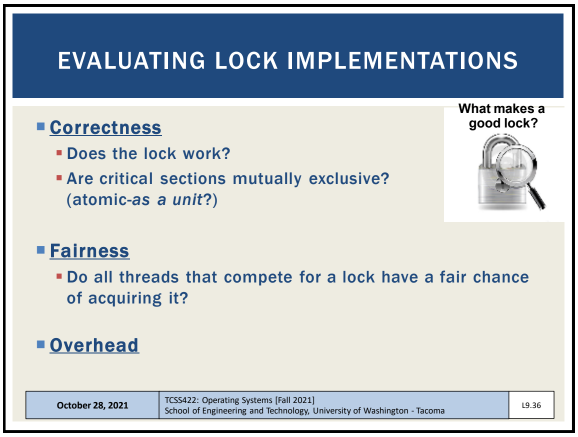

EVALUATING LOCK IMPLEMENTATIONS

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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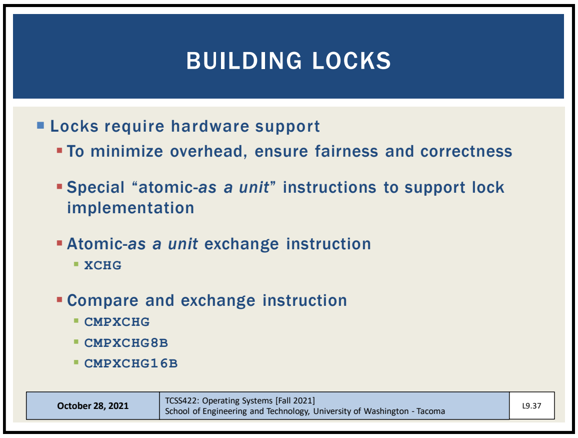

BUILDING LOCKS

- 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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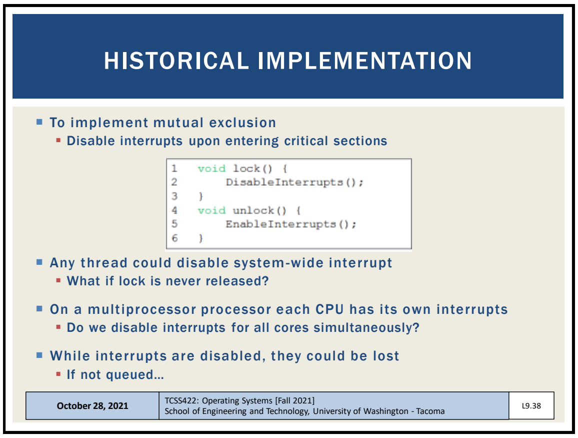

HISTORICAL IMPLEMENTATION

- 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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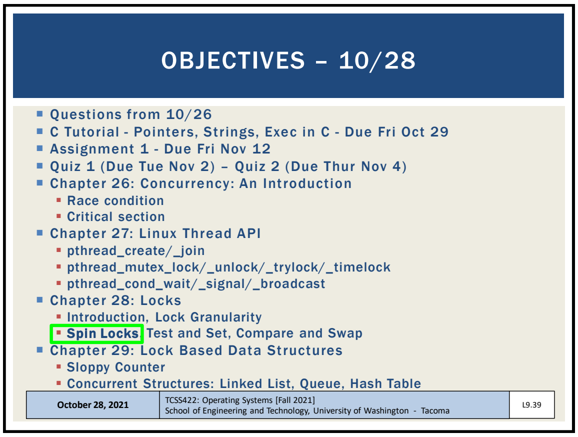

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  - Concurrent Structures: Linked List, Queue, Hash Table

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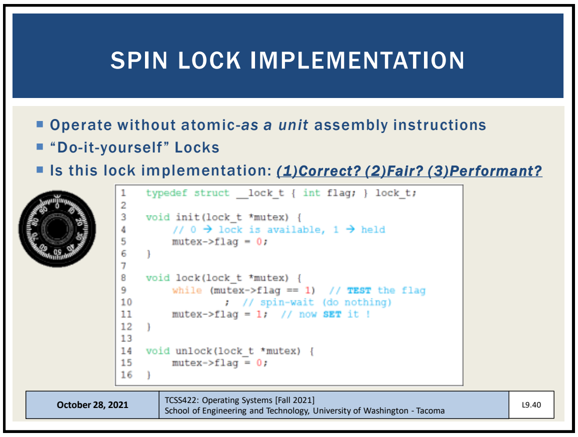

SPIN LOCK IMPLEMENTATION

- Operate without atomic-*as a unit* assembly instructions
- "Do-it-yourself" Locks
- 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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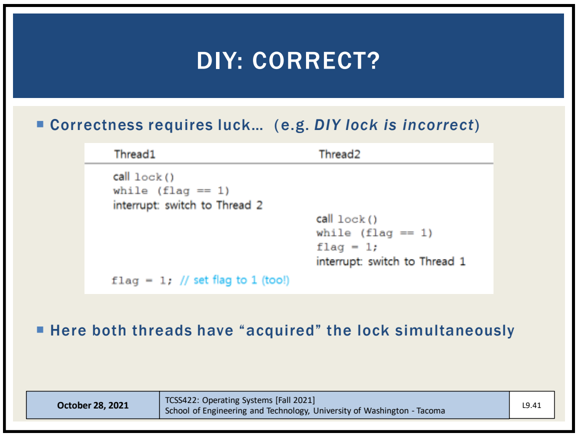

DIY: CORRECT?

- Correctness requires luck… (e.g. *DIY 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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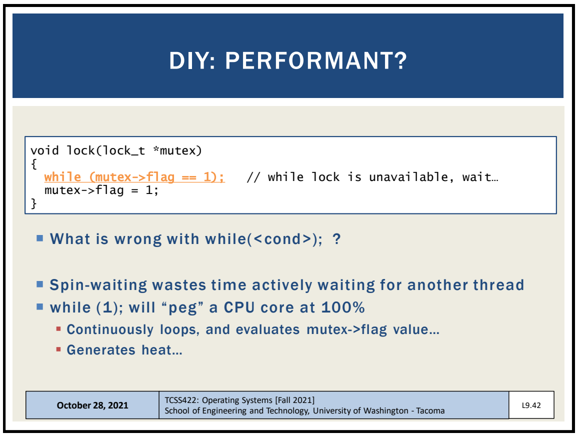

DIY: PERFORMANT?

```
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…
  - Generates heat…

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WE WILL RETURN AT 2:57PM

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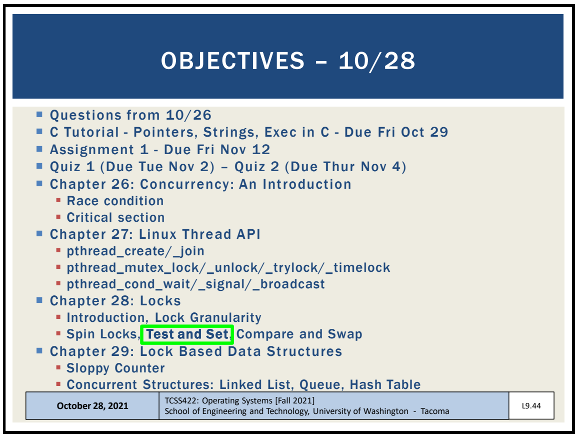

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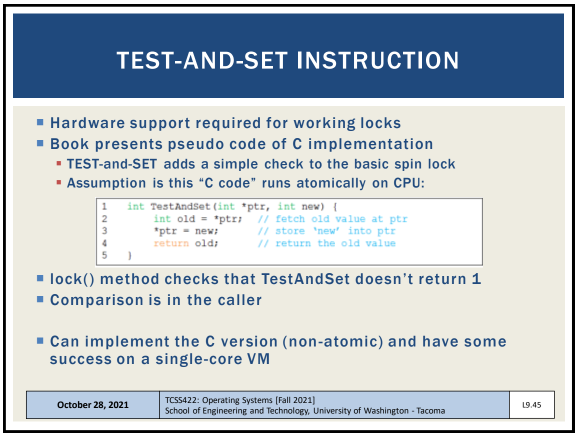

TEST-AND-SET INSTRUCTION

- Hardware support required for working locks
- Book presents pseudo code of C implementation
  - TEST-and-SET adds a simple check to the basic spin lock
  - Assumption is this "C code" runs atomically on CPU:

```
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
}
```

- lock() method checks that TestAndSet doesn't return 1
- Comparison is in the caller
- Can implement the C version (non-atomic) and have some success on a single-core VM

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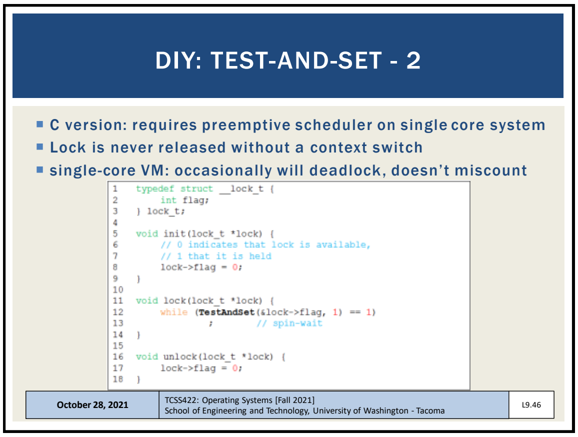

DIY: TEST-AND-SET - 2

- C version: requires preemptive scheduler on single core system
- Lock is never released without a context switch
- single-core VM: occasionally will deadlock, doesn't miscount

```
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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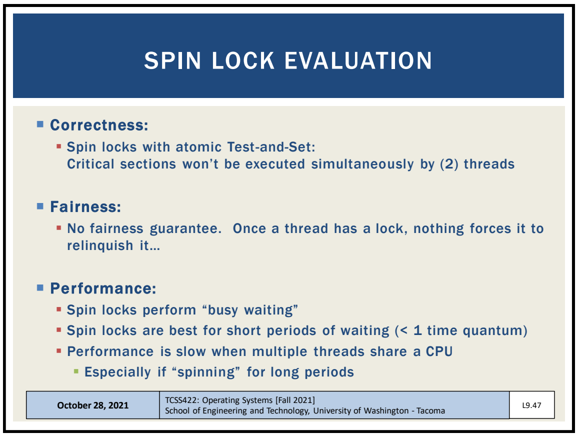

SPIN LOCK EVALUATION

- **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…
- **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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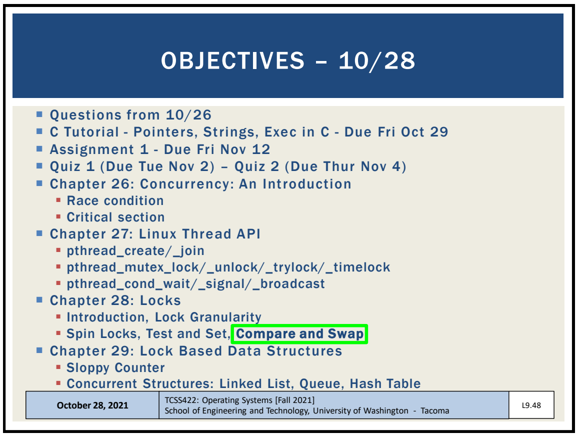

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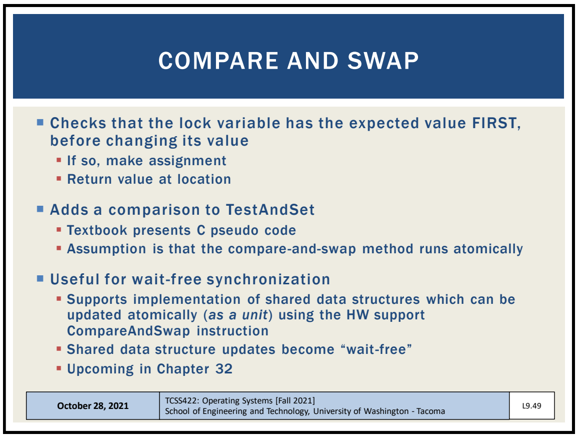

COMPARE AND SWAP

- 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
  - 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 the HW support CompareAndSwap instruction
  - Shared data structure updates become “wait-free”
  - Upcoming in Chapter 32

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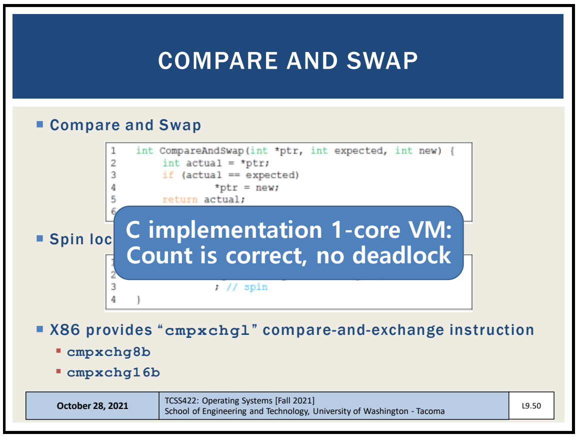

COMPARE AND SWAP

- Compare and Swap

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

- Spin loc

```
            ; // spin
}
```

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

- X86 provides “`cmpxchgl`” compare-and-exchange instruction
  - `cmpxchg8b`
  - `cmpxchg16b`

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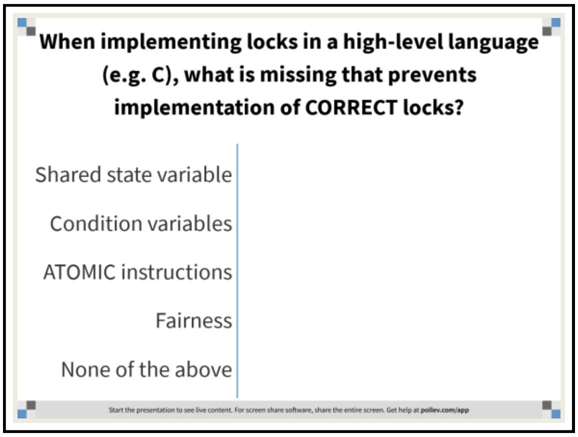

When implementing locks in a high-level language (e.g. C), what is missing that prevents implementation of CORRECT locks?

Shared state variable

Condition variables

ATOMIC instructions

Fairness

None of the above

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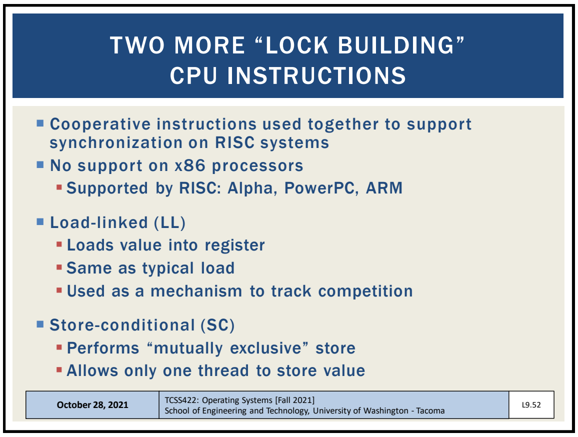

TWO MORE “LOCK BUILDING” CPU INSTRUCTIONS

- 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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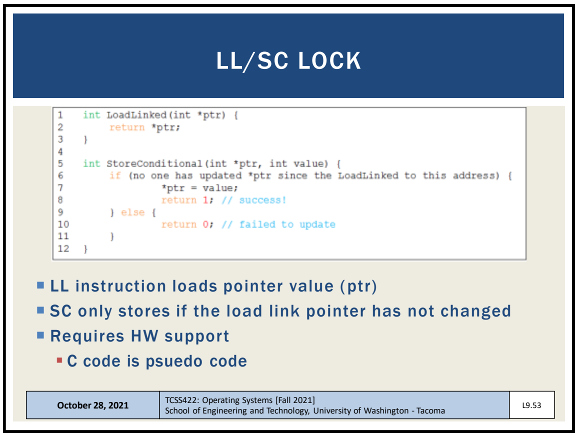

LL/SC LOCK

```
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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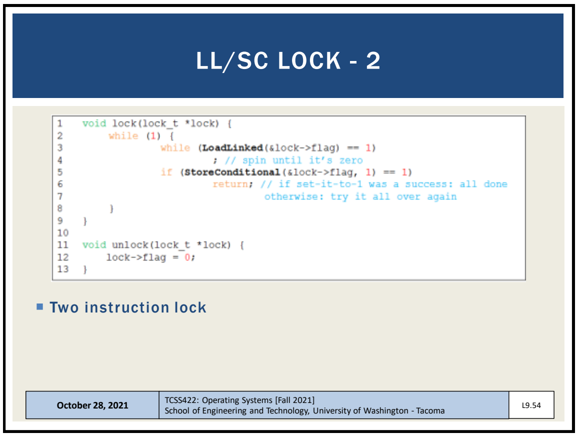

LL/SC LOCK - 2

```
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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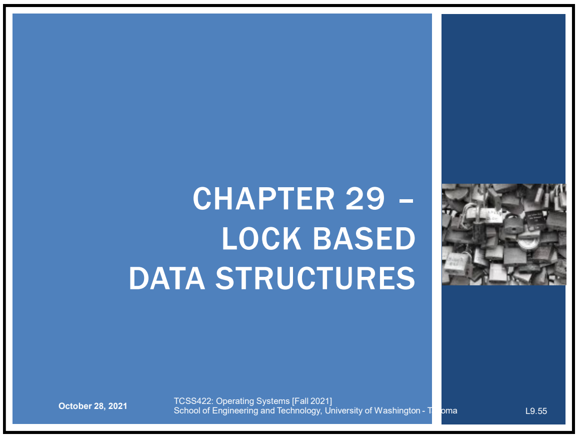

CHAPTER 29 – LOCK BASED DATA STRUCTURES

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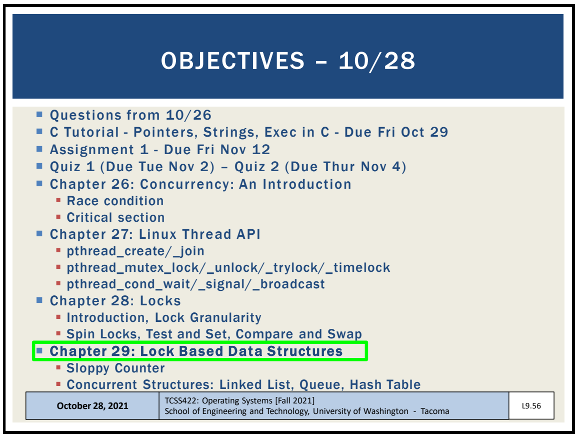

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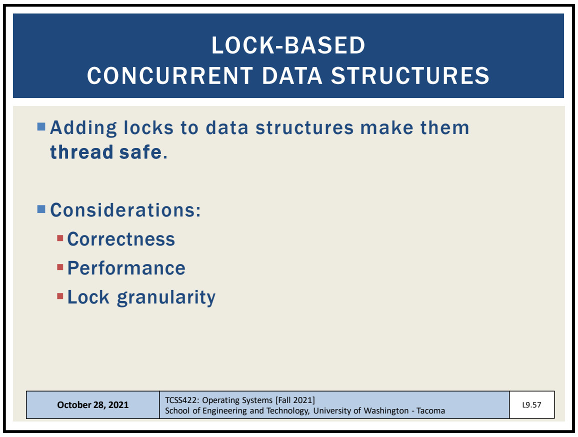

LOCK-BASED CONCURRENT DATA STRUCTURES

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

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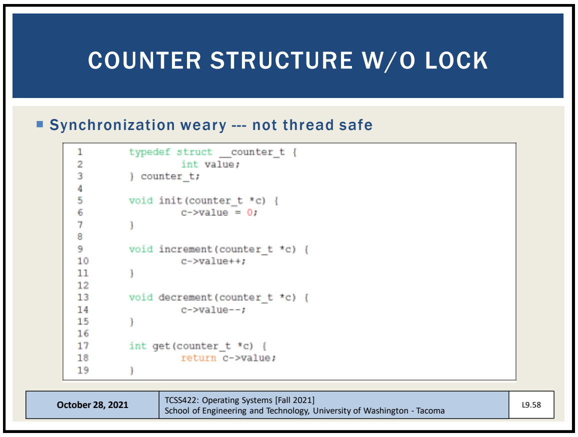

COUNTER STRUCTURE W/O LOCK

- 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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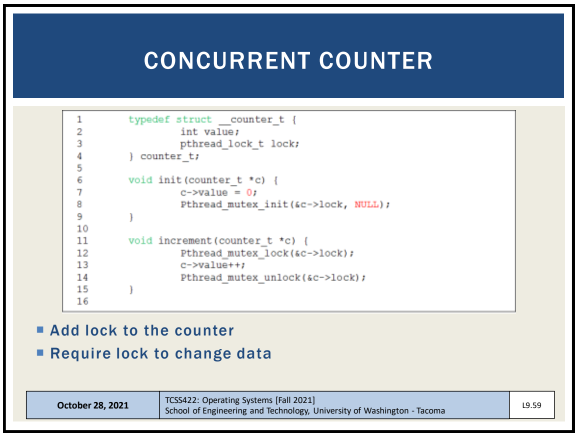

CONCURRENT COUNTER

```
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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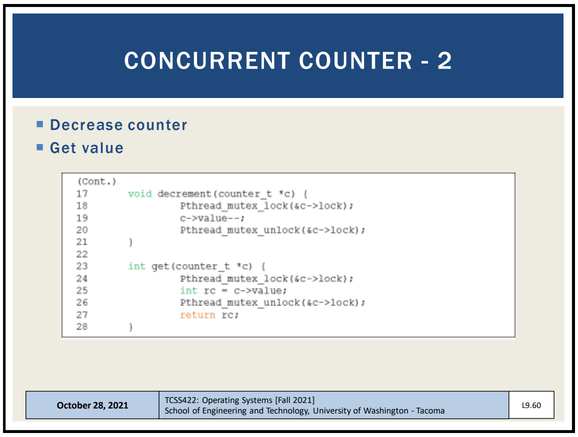

CONCURRENT COUNTER - 2

- 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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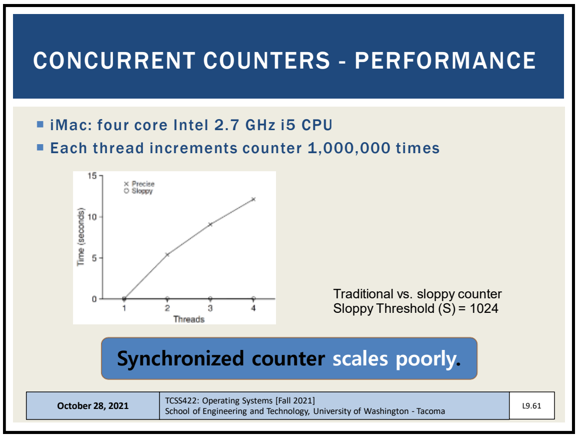
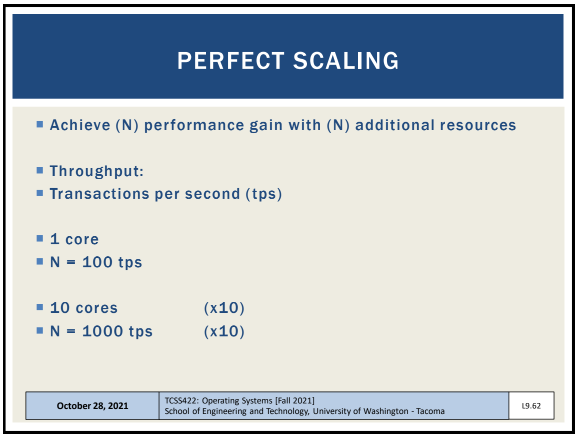


CONCURRENT COUNTERS - PERFORMANCE

- iMac: four core Intel 2.7 GHz i5 CPU
- Each thread increments counter 1,000,000 times

Traditional vs. sloppy counter
Sloppy Threshold (S) = 1024

Synchronized counter scales poorly.



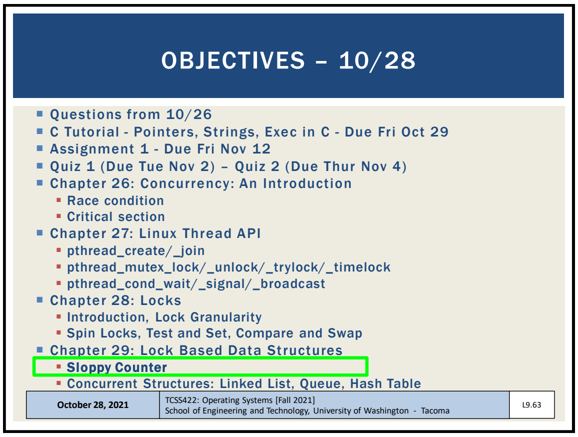
PERFECT SCALING

- 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)



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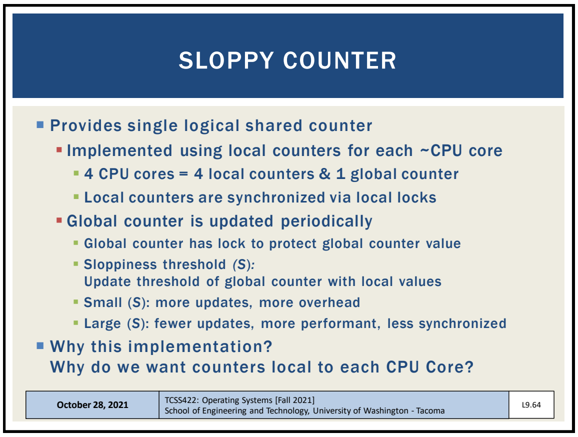
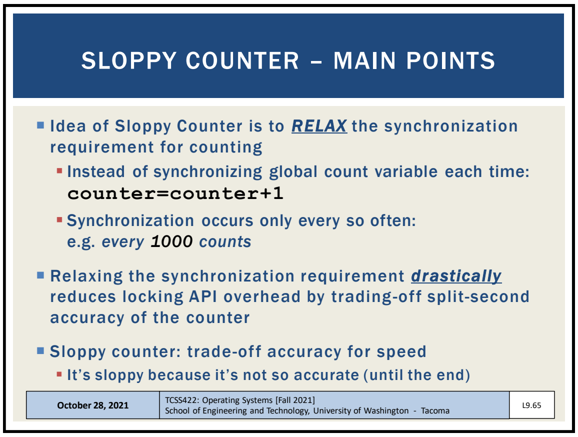


SLOPPY COUNTER

- 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
    - Sloppiness threshold (S):
      Update threshold of global counter with local values
    - 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?

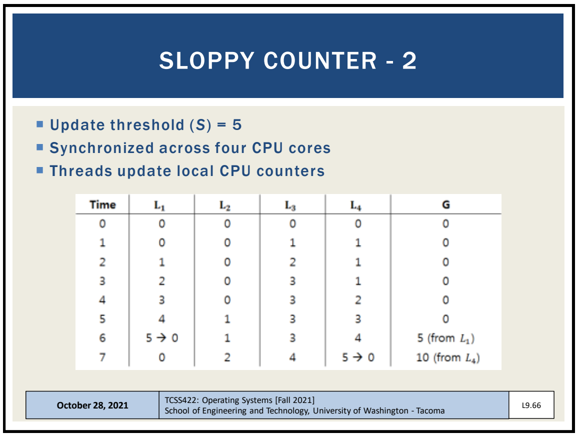


SLOPPY COUNTER – MAIN POINTS

- Idea of Sloppy 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

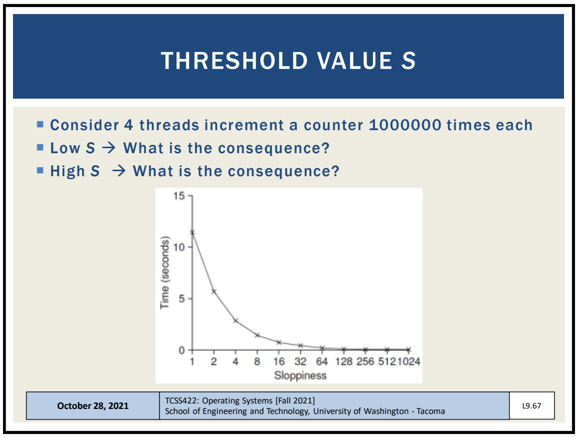
- Sloppy counter: trade-off accuracy for speed
  - It's sloppy because it's not so accurate (until the end)



SLOPPY 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)



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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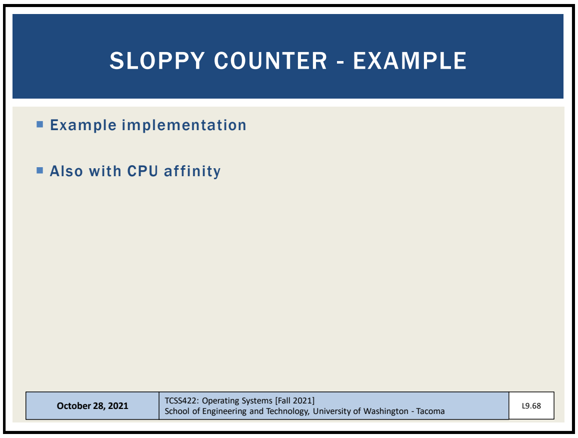

SLOPPY COUNTER - EXAMPLE

- Example implementation
- Also with CPU affinity

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OBJECTIVES – 10/28

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  - **Concurrent Structures: Linked List,** Queue, Hash Table

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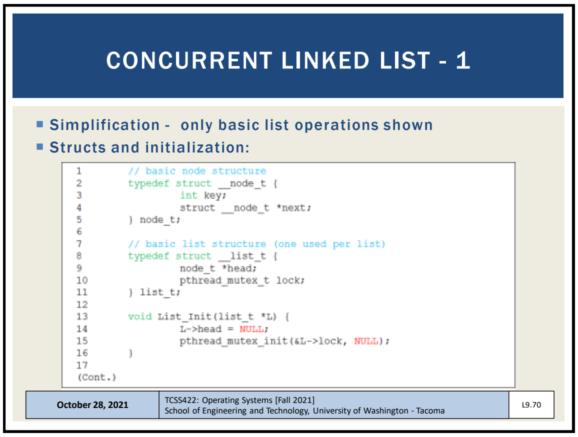

CONCURRENT LINKED LIST - 1

- 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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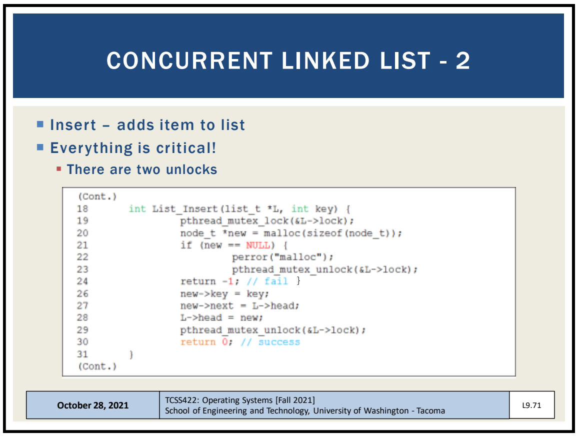

CONCURRENT LINKED LIST - 2

- 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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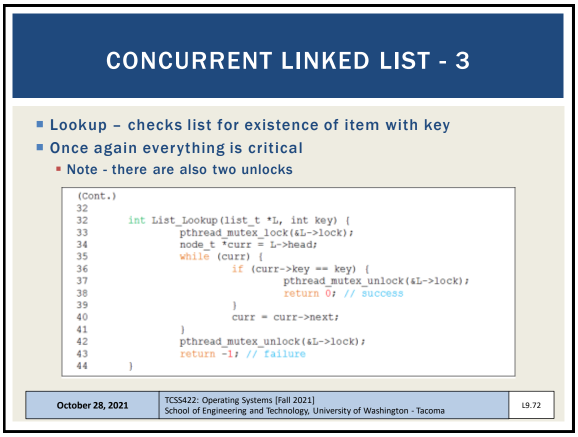

CONCURRENT LINKED LIST - 3

- 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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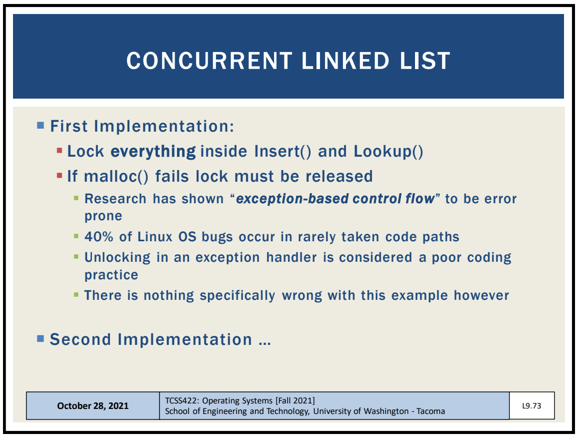

CONCURRENT LINKED LIST

- 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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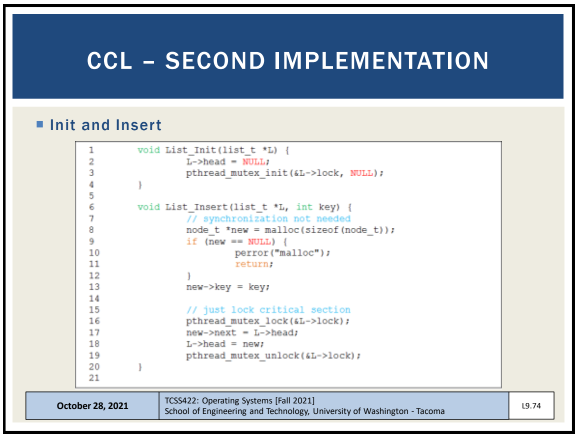

CCL – SECOND IMPLEMENTATION

- 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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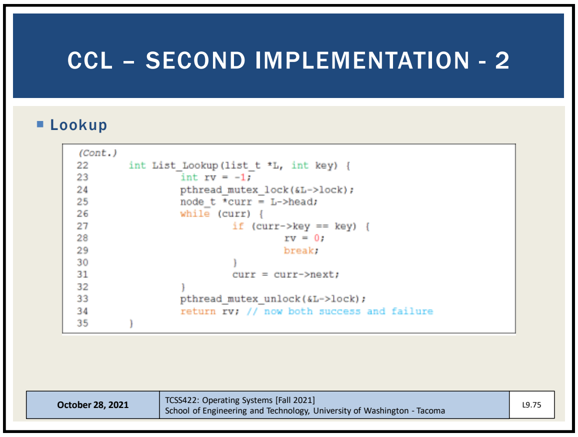

CCL – SECOND IMPLEMENTATION - 2

- 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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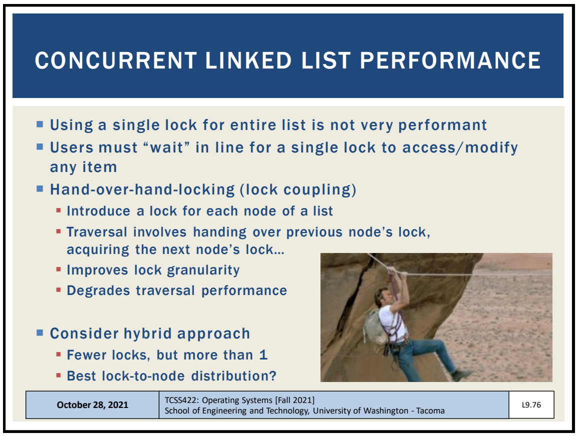

CONCURRENT LINKED LIST PERFORMANCE

- 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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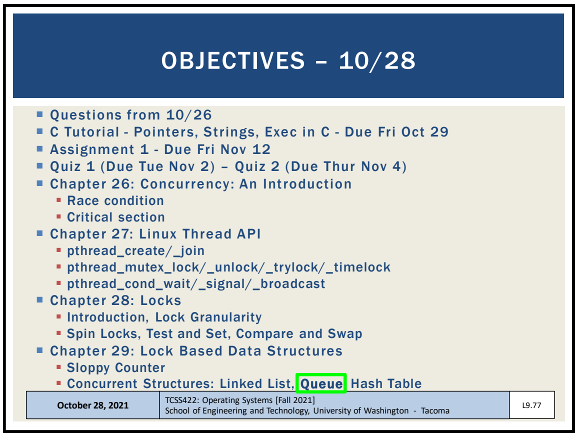

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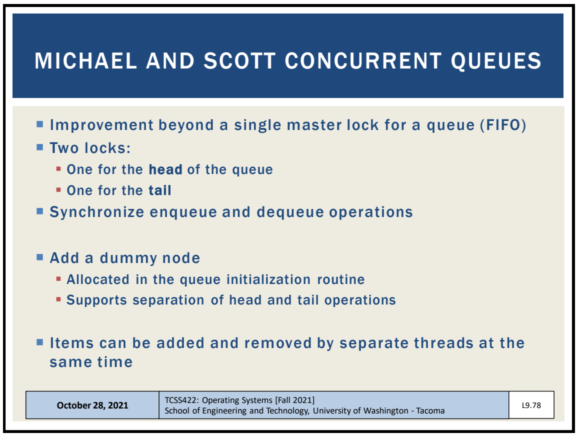

MICHAEL AND SCOTT CONCURRENT QUEUES

- 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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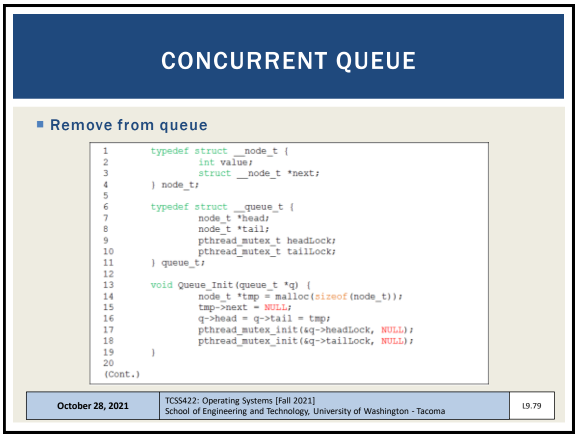


CONCURRENT QUEUE

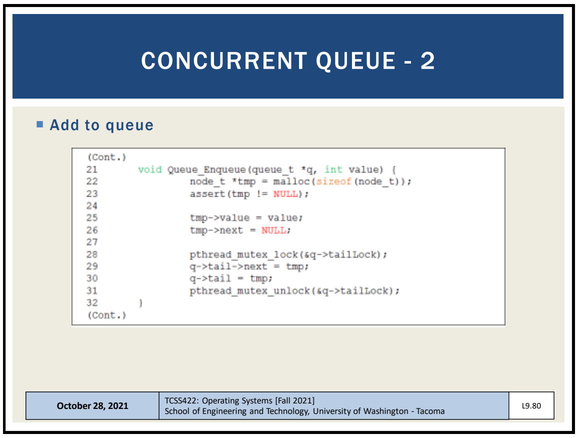
- Remove from queue

```
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.)
```



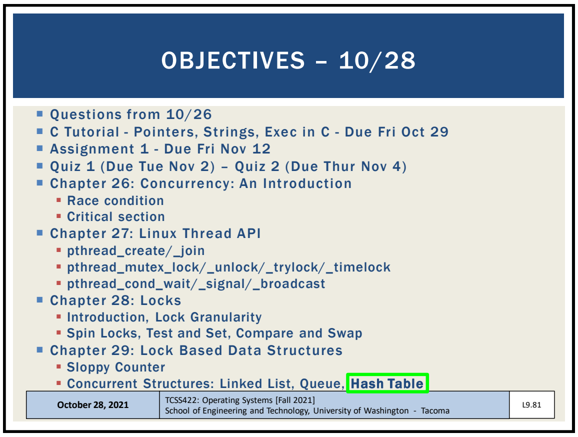
CONCURRENT QUEUE - 2

- 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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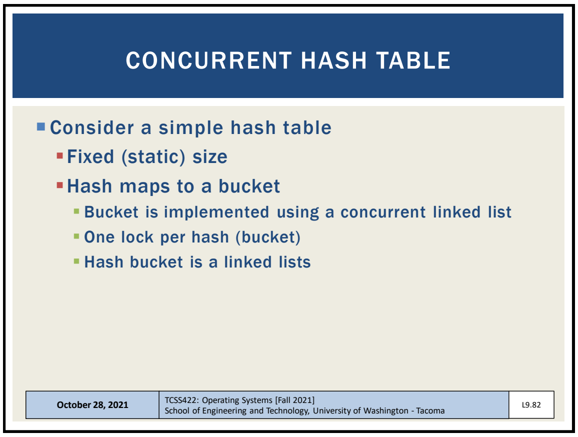
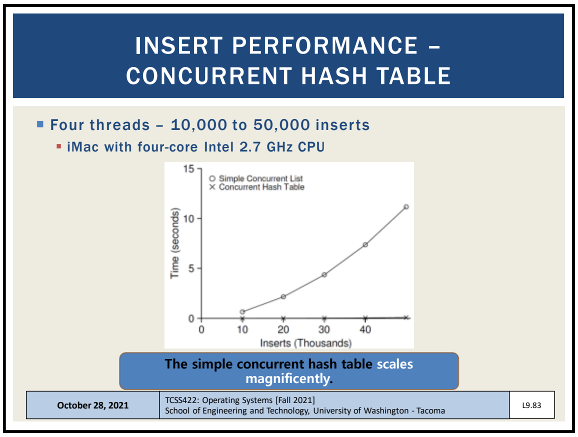


CONCURRENT HASH TABLE

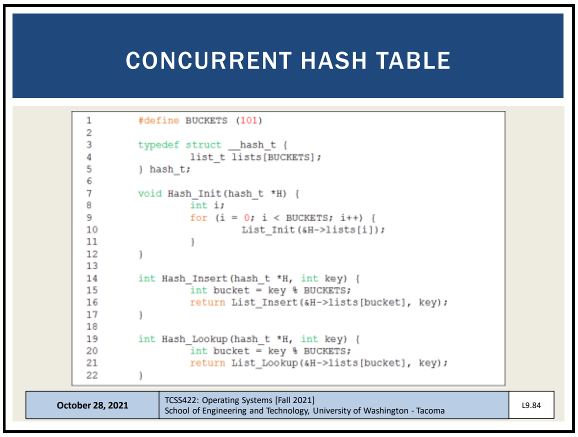
- Consider a simple hash table
  - Fixed (static) size
  - Hash maps to a bucket
    - Bucket is implemented using a concurrent linked list
    - One lock per hash (bucket)
    - Hash bucket is a linked lists



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.



CONCURRENT HASH TABLE

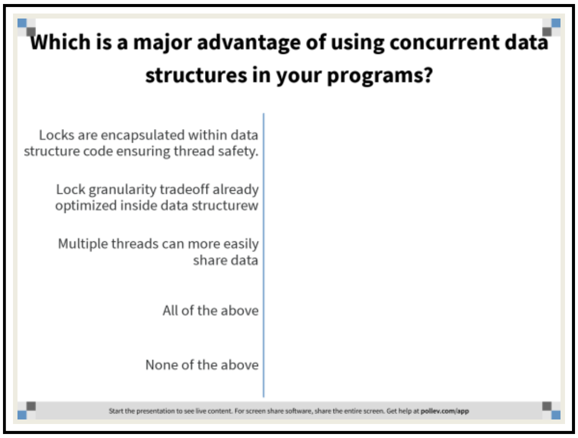
```
#define BUCKETS (101)

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);
}
```



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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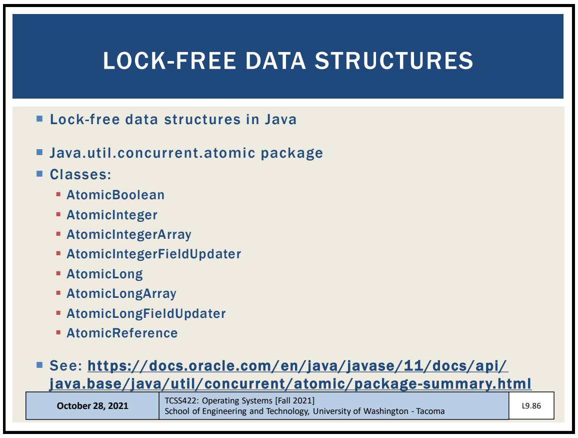

LOCK-FREE DATA STRUCTURES

- 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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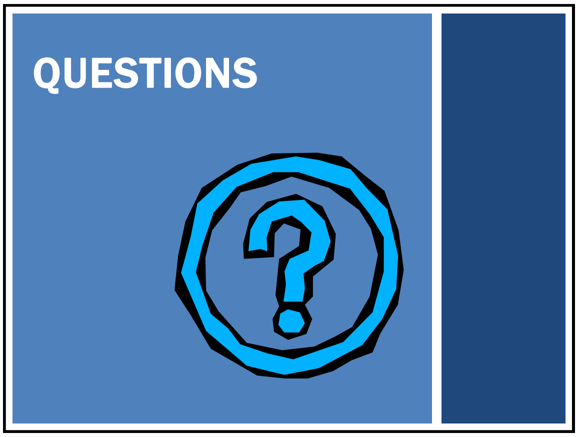

QUESTIONS

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