TCSS 422: OPERATING SYSTEMS

Intro to Concurrency, Linux Thread API, Locks, Lock-based data structures

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1

TCSS 422 – OFFICE HRS – SPRING 2025

- Office Hours plan for Spring (by Zoom):
- Monday 11:30am - 12:30p GTA Xinghan
- Tuesday 11:30am - 12:30p GTA Xinghan
- Wednesday 11:00am - 12:00p Instructor Wes
- Friday 12:00pm - 1:00p Instructor Wes or GTA Xinghan
  - THIS FRIDAY: Wes
- Instructor is available after class at 6pm in CP 229 each day

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2

OBJECTIVES – 4/29

- Questions from 4/24
- C Tutorial - Pointers, Strings, Exec in C - Due Wed Apr 30 AOE
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  - Race condition
  - Critical section
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  - pthread_create/_join
  - pthread_mutex_lock/_unlock/_trylock/_timelock
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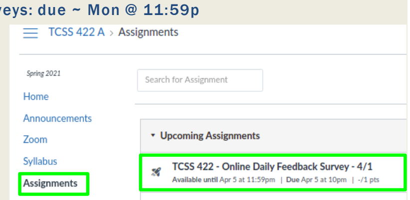
3

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



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4

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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5

MATERIAL / PACE

- Please classify your perspective on material covered in today's class (45 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- Average – 6.33 (↓ - previous 6.55)
- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- Average – 5.11 (↓ - previous 5.19)

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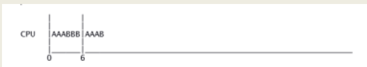
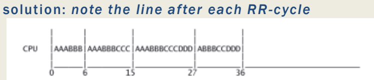
6

FEEDBACK FROM 4/24

- ***Two questions were received on Question 2 from the Quiz.***
- The starter graph should have been drawn as:



- For this RR queue, when jobs arrive, they are added at the back of the runqueue. This RR does not context switch when a new job arrives, but continues to run each job for the 3-sec time slice.
- Graph solution: *note the line after each RR-cycle*



- *All students received credit "CR" for attempting Q2 & Q3*

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8

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9

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10

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11

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12

QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Thursday May 1st AOE
- **Link:**
- **https://faculty.washington.edu/wlloyd/courses/tcss422/quiz/TCSS422_s2025_quiz_1.pdf**

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13

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 May 6th AOE
- Link:
- https://canvas.uw.edu/courses/1809484/assignments/10329061

14

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15

CATCH UP FROM LECTURE 8

- Switch to Lecture 8 Slides
- Slides L8.27 to L8.38 (through Critical Section)

16

LOCKS

- To demonstrate how critical section(s) can be executed "atomically-*as a unit*" Chapter 27 & beyond introduce **LOCKS**

```
lock_t mutex;
. . .
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```

Critical section

- (DEMO) Counter example revisited

17

COUNTER EXAMPLE

- With locks
  - 2 threads count to 16 million
  - ~1.4 seconds
  - COUNT IS CORRECT – no data loss
- Without locks
  - 2 threads count to 16 million
  - ~0.03 seconds
  - COUNT IS INCORRECT - DATA IS LOST
- Correct version is 46.6 x slower
  - Cost is ~16 million Lock & Unlock API calls

18

CHAPTER 27 - LINUX THREAD API

19

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20

THREAD CREATION

- pthread_create

```
#include <pthread.h>

int
pthread_create(       pthread_t*        thread,
                const pthread_attr_t*  attr,
                      void*             (*start_routine)(void*),
                      void*             arg);
```

- thread: thread struct
- attr: stack size, scheduling priority… (*optional*)
- start_routine: function pointer to thread routine
- arg: argument to pass to thread routine (*optional*)

21

PTHREAD_CREATE – PASS ANY DATA

```
#include <pthread.h>

typedef struct __myarg_t {
        int a;
        int b;
} myarg_t;

void *mythread(void *arg) {
        myarg_t *m = (myarg_t *) arg;
        printf("%d %d\n", m->a, m->b);
        return NULL;
}

int main(int argc, char *argv[]) {
        pthread_t p;
        int rc;

        myarg_t args;
        args.a = 10;
        args.b = 20;
        rc = pthread_create(&p, NULL, mythread, &args);
        …
}
```


22

PASSING A SINGLE VALUE

**Using this approach on your Ubuntu VM,
How large (in bytes) can the primitive data type be?**

```
        printf("%d\n", m);
```

How large (in bytes) can the primitive data type be on a 32-bit operating system?

```
        int rc, m;
        pthread_create(&p, NULL, mythread, (void *) 100);
        pthread_join(p, (void **) &m);
        printf("returned %d\n", m);
        return 0;
}
```


23

WAITING FOR THREADS TO FINISH

```
int pthread_join(pthread_t thread, void **value_ptr);
```

- thread: which thread?
- value_ptr: pointer to return value
  type is dynamic / agnostic
- Returned values *must* be on the heap
- Thread stacks destroyed upon thread termination (join)
- Pointers to thread stack memory addresses are invalid
  - May appear as gibberish or lead to crash (seg fault)
- Not all threads join – ***What would be Examples ??***

24

What will this code do?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  struct myarg output;
  output.a = 1;
  output.b = 2;
  return (void *) &output;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_
  pthread_
  printf("
  return 0
}
```

Data on thread stack

```
$ ./pthread_struct
a=10 b=20
Segmentation fault (core dumped)
```

How can this code be fixed?

25

How about this code?

```
struct myarg {
  int a;
  int b;
};

void *worker(void *arg)
{
  struct myarg *input = (struct myarg *) arg;
  printf("a=%d b=%d\n",input->a, input->b);
  input->a = 1;
  input->b = 2;
  return (void *) &input;
}

int main (int argc, char * argv[])
{
  pthread_t p1;
  struct myarg args;
  struct myarg *ret_args;
  args.a = 10;
  args.b = 20;
  pthread_create(&p1, NULL, worker, &args);
  pthread_join(p1, (void *)&ret_args);
  printf("returned %d %d\n", ret_args->a, ret_args->b);
  return 0;
}
```

```
$ ./pthread_struct
a=10 b=20
returned 1 2
```


26

ADDING CASTS

- Casting
- Suppresses compiler warnings when passing "typed" data where (void) or (void *) is called for
- Example: uncasted capture in pthread_join

```
pthread_int.c: In function 'main':
pthread_int.c:34:20: warning: passing argument 2 of 'pthread_join'
from incompatible pointer type [-Wincompatible-pointer-types]
   pthread_join(p1, &p1val);
```

- Example: uncasted return

```
In file included from pthread_int.c:3:0:
/usr/include/pthread.h:250:12: note: expected 'void **' but argument
is of type 'int **'
 extern int pthread_join (pthread_t __th, void **__thread_return);
```


27

ADDING CASTS - 2

- pthread_join

```
int * p1val;
int * p2val;
pthread_join(p1, (void *)&p1val);
pthread_join(p2, (void *)&p2val);
```

- return from thread function

```
int * counterval = malloc(sizeof(int));
*counterval = counter;
return (void *) counterval;
```


28

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29

LOCKS

- pthread_mutex_t data type
- /usr/include/bits/pthread_types.h

```
// Global Address Space
static volatile int counter = 0;
pthread_mutex_t lock;

void *worker(void *arg)
{
  int i;
  for (i=0;i<10000000;i++)  {
    int rc = pthread_mutex_lock(&lock);
    assert(rc==0);
    counter = counter + 1;
    pthread_mutex_unlock(&lock);
  }
  return NULL;
}
```


30

LOCKS - 2

- Ensure critical sections are executed atomically-*as a unit*
  - Provides implementation of "***Mutual Exclusion***"
- API

```
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- Example w/o initialization & error checking

```
pthread_mutex_t lock;
pthread_mutex_lock(&lock);
x = x + 1; // or whatever your critical section is
pthread_mutex_unlock(&lock);
```

  - Blocks forever until lock can be obtained
  - Enters critical section once lock is obtained
  - Releases lock

31

LOCK INITIALIZATION

- Assigning the constant

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
```

- API call:

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

- Initializes mutex with attributes specified by 2nd argument
- If NULL, then default attributes are used
- Upon initialization, the mutex is initialized and unlocked

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32

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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33

When poll is active, respond at pollev.com/wesleylloyd641
Text WESLEYLLOYD641 to 22333 once to join

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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34

POLL EV

- Which NON-BLOCKING API call can be used to obtain a lock without BLOCKING the calling thread ?
- (A) pthread_mutex_lock()
- (B) pthread_mutex_unlock()
- (C) pthread_join()
- (D) pthread_mutex_trylock()
- (E) None of the above

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35

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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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36

POLL EV

- Whichi API call BLOCKS temporarily for a specified amount of time while trying to obtain a lock before giving up ?
- (A) pthread_join()
- (B) pthread_cond_wait()
- (C) pthread_mutex_timelock()
- (D) pthread_mutex_lock()
- (E) None of the above

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37

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38

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_cond_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

39

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()

40

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

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

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


41

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)

42

WE WILL RETURN AT 5:00PM

43

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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44

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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45

What key feature differentiates condition variables from mutex_locks in C ?

0

Condition variables provide only NON-BLOCKING API calls. 0%

Locks can not be used without condition variables. 0%

Condition variables introduce a FIFO queue enabling control of the order that threads will receive the lock which provides fairness. 0%

Condition variables must first be initialized to a non-NULL value before being used in the program. 0%

None of the above 0%

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POLLEV

- What key feature differentiates condition variables from mutex_locks in C?
- (A) Condition variables provide only NON-BLOCKING API calls
- (B) Locks can not be used without condition variables
- (C) Condition variables introduce a FIFO queue enabling control of the order that threads will receive the lock which provides fairness
- (D) Condition variables must first be initialized to a non-NULL value before being used in the program
- (E) None of the above

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47

CHAPTER 28 – LOCKS

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48

OBJECTIVES – 4/29

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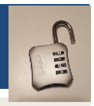
49

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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50

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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51

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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52

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53

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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54

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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55

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 . . .
```

56

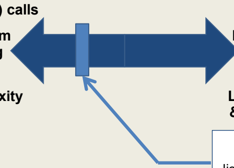
LOCK GRANULARITY TRADE-OFF SPACE

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…

57

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**

58

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

59

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…

60

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61

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;
}
```


62

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

63

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…

64

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65

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

66

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;
}
```


67

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

68

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69

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

70

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`

71

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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72

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

73

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

74

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

75

CHAPTER 29 – LOCK BASED DATA STRUCTURES

76

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77

LOCK-BASED CONCURRENT DATA STRUCTURES

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

78

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;
}
```


79

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

80

CONCURRENT COUNTER - 2

- Decrease counter
- Get value

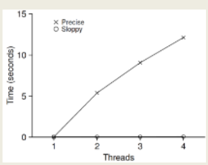
```
(Cont.)
        void decrement(counter_t *c) {
                Pthread_mutex_lock(&c->lock);
                c->value--;
                Pthread_mutex_unlock(&c->lock);
        }

        int get(counter_t *c) {
                Pthread_mutex_lock(&c->lock);
                int rc = c->value;
                Pthread_mutex_unlock(&c->lock);
                return rc;
        }
```


81

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.

82

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)

83

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84

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?

85

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)

86

SLOPPY COUNTER - 2

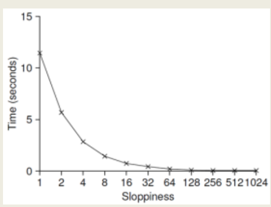
- Update threshold (S) = 5
- Synchronized across four CPU cores
- Threads update local CPU counters

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)

87

THRESHOLD VALUE S

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



88

SLOPPY COUNTER - EXAMPLE

- Example implementation
- Also with CPU affinity

89

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90

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.)
```


91

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.)
```


92

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
    }
```


93

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 …

94

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);
    }

```


95

CCL – SECOND IMPLEMENTATION - 2

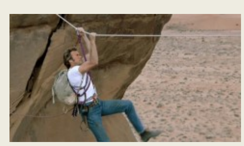
- Lookup

```
(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
    }
```


96

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?



97

OBJECTIVES – 4/29

- Questions from 4/24
- C Tutorial - Pointers, Strings, Exec in C - Due Wed Apr 30 AOE
- Assignment 0 - Closes Tue Apr 29 AOE | Assignment 1
- Quiz 1 (Due Thur May 1 AOE) – Quiz 2 (Due Tue May 6 AOE)
- Chapter 26: Concurrency: An Introduction
  - Race condition
  - Critical section
- Chapter 27: Linux Thread API
  - pthread_create/_join
  - pthread_mutex_lock/_unlock/_trylock/_timelock
  - pthread_cond_wait/_signal/_broadcast
- Chapter 28: Locks
  - 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

98

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

99

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.)
```


100

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.)
```


101

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

102

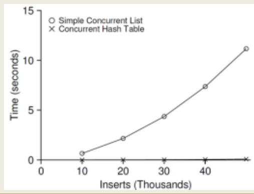
CONCURRENT HASH TABLE

- 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

103

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.

104

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);
}
```


105

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

0

- Locks are encapsulated within data structure code ensuring thread safety. 0%
- Lock granularity tradeoff already optimized inside data structure 0%
- Multiple threads can more easily share data 0%
- All of the above 0%
- None of the above 0%

106

POLL EV

- Which is a major advantage of using concurrent data structures in your programs?
- (A) Locks are encapsulated within data structure code ensuring thread safety
- (B) Lock granularity tradeoff already optimized inside data structure
- (C) Multiple threads can more easily share data
- (D) All of the above
- (E) None of the above

107

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

108

QUESTIONS

109