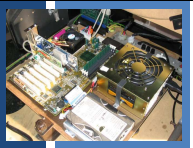
TCSS 422: OPERATING SYSTEMS



Locks, Lock Based Data Structures

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OBJECTIVES

- Tutorial 1 Questions
- Homework 1 Questions
- Feedback from 1/29
- Ch. 28
  - Locks
- Ch. 29
  - Lock Based Data Structures

SELECTED FEEDBACK FROM 1/29

- **What happens when a thread reaches a lock that another thread is holding?**
- **Does it wait on that line of code? (lock line)**
- **Does it continually poll for the lock availability?**
  - pthread_block.c example
  - Check for PID: `ps u`
  - Trace PID: `top -d .1 -H -p <pid>`
- The thread will block (stop executing) until the lock is available

FEEDBACK - 2

- **Please give a real example of when to use:** `pthread_mutex_trylock()` and `pthread_mutex_timelock()`
- Both functions return integer 0 if lock is successfully acquired
- Both return integer error code (non-zero) otherwise
- Consider if 3 threads append text to the same file
- Only one thread is allowed to open the file for writing ***at the same time***
- Locks can be used to synchronize access to append to the file
- If a thread can not acquire the file lock, it accumulates changes in a buffer, but continues to perform useful work

FEEDBACK - 3

- **What are good habits to do when using locks to avoid bugs?**
- This is upcoming in chapter 32
- **What are good habits for fine-grained locking?**
- Want ***more*** opportunities for parallelism in code
- Method-level locking (coarse-grained) **does not** provide them
- Optimal number of locks is between 1 and n locks, where n is the number of variables being changed
- Finding optimal solution requires identifying how often variables will be modified, and in what combinations by multiple threads
- This is non-trivial → thread behavior @ runtime can be random

FEEDBACK - 4

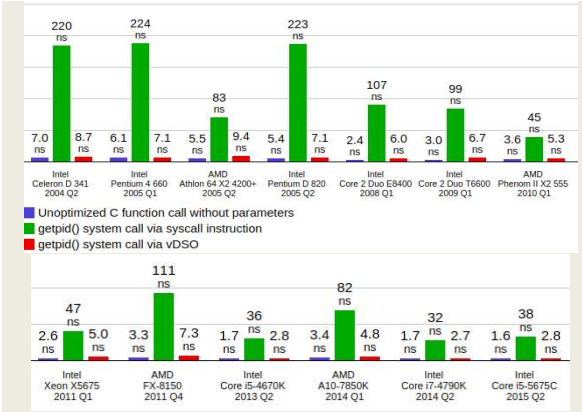
- **How much overhead does lock checking, waiting, and signaling have?**
- All of these are kernel calls
- Making just a few system calls shouldn't introduce too much overhead
- The blog, "Measurements of system call performance and overhead" provides insight:
- http://arkanis.de/weblog/2017-01-05-measurements-of-system-call-performance-and-overhead

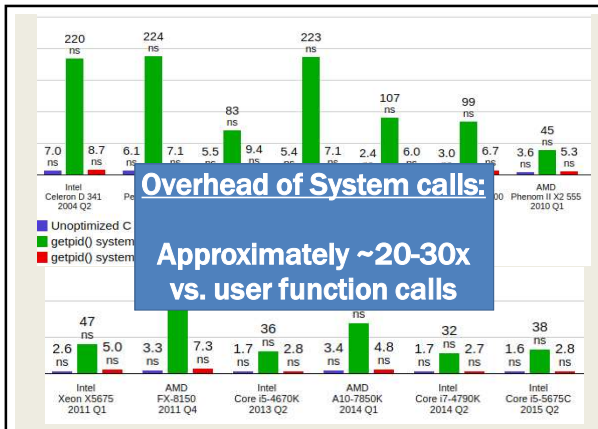
OVERHEAD OF A LINUX C SYSTEM CALL

- What is the performance overhead difference between a user function call, and a kernel system call?
- Ordinary function calls require passing data to/from the stack
- x86 64-bit systems perform kernel calls using **syscall** instruction
- Arguments placed into registers and syscall instruction transitions from ***user mode*** to ***kernel mode*** to call kernel function

OVERHEAD - 2

- Additional overhead is from CPU switching to different (protected) address space, CPU memory caches (TLB) may require updating
- Linux kernel provides optimized kernel calls via the vDSO: **V**irtually **d**ynamically linked **s**hared **o**bject (see https://en.wikipedia.org/wiki/VDSO)
- vDSO provides optimized "virtual" system calls where a selected set of ***common*** kernel space routines are exported to user space applications for faster execution
- Linux (glibc) uses virtual system calls automatically when available





SPIN LOCK IMPLEMENTATION

- Operate without atomic-*as a unit* assembly instructions
- "Do-it-yourself" Locks
- Is this lock implementation: Correct? Fair? Performant?

```
1   typedef struct __lock_t { int flag; } lock_t;
2
3   void init(lock_t *mutex) {
4       // 0 → lock is available, 1 → held
5       mutex->flag = 0;
6   }
7
8   void lock(lock_t *mutex) {
9       while (mutex->flag == 1)  // TEST the flag
10          ;  // spin-wait (do nothing)
11      mutex->flag = 1;  // now SET it !
12  }
13
14  void unlock(lock_t *mutex) {
15      mutex->flag = 0;
16  }
```


DIY: TEST-AND-SET - 2

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

```
1   typedef struct __lock_t {
2       int flag;
3   } lock_t;
4
5   void init(lock_t *lock) {
6       // 0 indicates that lock is available,
7       // 1 that it is held
8       lock->flag = 0;
9   }
10
11  void lock(lock_t *lock) {
12      while (TestAndSet(&lock->flag, 1) == 1)
13          ;          // spin-wait
14  }
15
16  void unlock(lock_t *lock) {
17      lock->flag = 0;
18  }
```

COMPARE AND SWAP

- Compare and Swap

```
1   int CompareAndSwap(int *ptr, int expected, int new) {
2       int actual = *ptr;
3       if (actual == expected)
4               *ptr = new;
5       return actual;
6   }
```

- Spin lock usage

```
1   void lock(lock_t *lock) {
2       while (CompareAndSwap(&lock->flag, 0, 1) == 1)
3               ; // spin
4   }
```

- X86 provides "`cmpxchgl`" compare-and-exchange instruction
  - `cmpxchg8b`
  - `cmpxchg16b`

COMPARE AND SWAP

- Compare and Swap

```
1   int CompareAndSwap(int *ptr, int expected, int new) {
2       int actual = *ptr;
3       if (actual == expected)
4               *ptr = new;
5       return actual;
```

1-core VM:
Count is correct, no deadlock

- Spin loc

```
3               ; // spin
4   }
```

- X86 provides "`cmpxchgl`" compare-and-exchange instruction
  - `cmpxchg8b`
  - `cmpxchg16b`

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

LL/SC LOCK

```
1   int LoadLinked(int *ptr) {
2       return *ptr;
3   }
4
5   int StoreConditional(int *ptr, int value) {
6       if (no one has updated *ptr since the LoadLinked to this address) {
7               *ptr = value;
8               return 1; // success!
9       } else {
10              return 0; // failed to update
11      }
12  }
```

- 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

LL/SC LOCK - 2

```
1   void lock(lock_t *lock) {
2       while (1) {
3               while (LoadLinked(&lock->flag) == 1)
4                       ; // spin until it's zero
5               if (StoreConditional(&lock->flag, 1) == 1)
6                       return; // if set-it-to-1 was a success: all done
7                               otherwise: try it all over again
8       }
9   }
10
11  void unlock(lock_t *lock) {
12      lock->flag = 0;
13  }
```

- Two instruction lock

FETCH-AND-ADD

- HW CPU Instruction
- Increment counter atomically-*as a unit* in one instruction

```
1   int FetchAndAdd(int *ptr) {
2       int old = *ptr;
3       *ptr = old + 1;
4       return old;
5   }
```

  - Fetch and return value
  - Increment by 1

TICKET LOCK

- Can build Ticket Lock using Fetch-and-Add
- Ensures progress of all threads (fairness)

```
1   typedef struct __lock_t {
2       int ticket;
3       int turn;
4   } lock_t;
5
6   void lock_init(lock_t *lock) {
7       lock->ticket = 0;
8       lock->turn = 0;
9   }
10
11  void lock(lock_t *lock) {
12      int myturn = FetchAndAdd(&lock->ticket);
13      while (lock->turn != myturn)
14              ; // spin
15  }
16  void unlock(lock_t *lock) {
17      FetchAndAdd(&lock->turn);
18  }
```


TICKET LOCK - 2

```
1   typedef struct __lock_t {
2       int ticket;
3       int turn;
4   } lock_t;
5
6   void lock_init(lock_t *lock) {
7       lock->ticket = 0;
8       lock->turn = 0;
9   }
10
11  void lock(lock_t *lock) {
12      int myturn = FetchAndAdd(&lock->ticket);
13      while (lock->turn != myturn)
14              ; // spin
15  }
16  void unlock(lock_t *lock) {
17      FetchAndAdd(&lock->turn);
18  }
```

TB while (1 != 1) **acquire lock**

TB myturn=1 ticket=2 turn=0

TA myturn=0 ticket=1 turn=0

TA while (0 != 0) **acquire lock**

TB while (0 != 1) **spin**

TA-unlock myturn=0 ticket=2 turn=1

YIELD() – SYSTEM CALL

```
1   void init() {
2       flag = 0;
3   }
4
5   void lock() {
6       while (TestAndSet(&flag, 1) == 1)
7           yield(); // give up the CPU
8   }
9
10  void unlock() {
11      flag = 0;
12  }
```

- Give up the CPU – instead of busy waiting…
  - running →ready
- Ready relinquishes the CPU for another thread (ctxt. switch)
- How does the thread get the CPU back?
  - OS must opportunistically reschedule it: ready → running

HARDWARE SPIN LOCKS - SUMMARY

- Simple, correct
- Slow
- With long locks, waiting threads spin for entire timeslice
  - Repeat comparison continuously
  - Busy waiting

How To Avoid *Spinning*?
Need both HW & OS Support !

THREAD QUEUES

- Don't allow the OS to control your program
  - Use internal **Thread Queues**
- Allows programmer to maintain control
  - Ensure fairness, prevent starvation
  - Better for synchronizing large #'s of threads
- Require OS support to add/remove threads to/from queue(s)
- Solaris API:
  - park(): puts thread to sleep
  - unpark(threadID): wakes specified thread
- Linux API: futex()

THREAD QUEUES - 2

```
1   typedef struct __lock_t { int flag; int guard; queue_t *q; } lock_t;
2
3   void lock_init(lock_t *m) {
4       m->flag = 0;
5       m->guard = 0;
6       queue_init(m->q);
7   }
8
9   void lock(lock_t *m) {
10      while (TestAndSet(&m->guard, 1) == 1)
11          ; // acquire guard lock by spinning
12      if (m->flag == 0) {
13          m->flag = 1; // lock is acquired
14          m->guard = 0;
15      } else {
16          queue_add(m->q, gettid());
17          m->guard = 0;
18          park();
19      }
20  }
21  …
```

Guard uses a spin-lock to protect the critical sections in lock() and unlock()

Obtain guard lock

try to obtain actual lock

lock unavailable; add thread to queue

potential wakeup/waiting race

THREAD QUEUES - 3

- Unlock

```
22  void unlock(lock_t *m) {
23      while (TestAndSet(&m->guard, 1) == 1)
24          ; // acquire guard lock by spinning
25      if (queue_empty(m->q))
26          m->flag = 0; // let go of lock; no one wants it
27      else
28          unpark(queue_remove(m->q)); // hold lock (for next thread!)
29      m->guard = 0;
30  }
```

Obtain guard lock (spin)

wake up thread from queue

release guard lock

- Note: no change to m->flag if unparking a thread
- Lock is passed to the unparked thread "directly"

WAKEUP/WAITING RACE

- Thread B: context switch occurs immediately before call to park()
- Thread A: releases lock, calls unpark, queue is empty
- Thread B: regains context, proceeds to lock itself forever

- Need new system call
  - **setpark()**- informs OS about soon to be parked thread
  - Subsequent calls to unpark() are aware that ThreadB is about to park
  - ThreadB's call to park() immediately returns

FUTEX

- Fast Userspace MuTEX
- Linux futex system calls similar to park() and unpark()
- Linux uses an in-kernel queue
- Provides a futex() system call

- Provides atomic-*as a unit* compare-and-block operation

- **Futex is a lower-level construct**
- Used as building blocks for:
  mutex, condition variables, semaphores

- Objective: reduce the number of system calls

FUTEX: WRITE YOUR OWN MUTEX LOCK

- futex_wait(addr, expected)
  - Put calling thread to sleep
  - If value @ addr != expected → return immediately
- futex_wake(addr)
  - Wake one thread that is waiting on the queue

- These are not exposed as C library calls directly
  - Call futex() with FUTEX_WAIT or FUTEX_WAKE

- Use a 32-bit integer
  - The leftmost bit (the +/- sign) tracks the lock state
    - 0 – free
    - 1 – locked
  - Remaining 31 bits: identifies thread

FUTEX: MUTEX_LOCK PSUEDO CODE

```
void mutex_lock(int *mutex) {
    int v;
    /* Bit 31 was clear, we got the mutex (this is a fast lock!) */
    if (atomic_bit_test_set (mutex, 31) == 0)
        return;
    // "adds" mutex to queue
    atomic_increment (mutex);
    while (1)  {
        // is lock available?
        if (atomic_bit_test_set (mutex, 31) ==0 {
            // remove mutex from queue – it has the lock now
            atomic_decrement (mutex);
            return;
        }
        // Have to wait. Make sure futex value is locked (negative)
        v = *mutex;
        iv (v >= 0)
          continue;
        // wait to be woken up when lock is available
        // this is not a spin lock… (signal)
        futex_wait (mutex, v);
    }
}
```


FUTEX: MUTEX UNLOCK PSUEDO CODE

```
void mutex_unlock(int *mutex) {

    // Adding 0x80000000 to counter results in 0 if and only if
    // there are no other interested threads

    if (atomic_add_zero (mutex, 0x80000000))
        return;

    // There are other threads waiting for this lock (mutex)
    // wake one of them up..
    // (e.g. dequeue it)
    futex_wake (mutex);

}
```

- Interesting note: Futex bug in Redhat Linux
- https://www.infoq.com/news/2015/05/redhat-futex

HYBRID - TWO PHASE LOCKS

- Hybrid between spin-locks and yielding
- Useful if lock is about to be released
- First phase – spin lock
  - Spin for some time waiting for the lock to be released
  - If lock is not acquired after time expires enter phase two.
- Second phase - yield
  - Thread sleeps (yields)
  - Is awoken when the lock becomes free

CHAPTER 29 – LOCK BASED DATA STRUCTTURES

OBJECTIVES

- Concurrent Data Structures
- Performance
- Lock Granularity

LOCK-BASED CONCURRENT DATA STRUCTURES

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

COUNTER STRUCTURE W/O LOCK

- Synchronization weary --- not thread safe

```
1       typedef struct __counter_t {
2               int value;
3       } counter_t;
4
5       void init(counter_t *c) {
6               c->value = 0;
7       }
8
9       void increment(counter_t *c) {
10              c->value++;
11      }
12
13      void decrement(counter_t *c) {
14              c->value--;
15      }
16
17      int get(counter_t *c) {
18              return c->value;
19      }
```


CONCURRENT COUNTER

```
1       typedef struct __counter_t {
2               int value;
3               pthread_lock_t lock;
4       } counter_t;
5
6       void init(counter_t *c) {
7               c->value = 0;
8               Pthread_mutex_init(&c->lock, NULL);
9       }
10
11      void increment(counter_t *c) {
12              Pthread_mutex_lock(&c->lock);
13              c->value++;
14              Pthread_mutex_unlock(&c->lock);
15      }
16
```

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

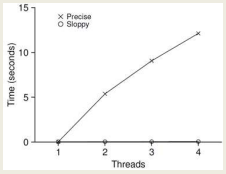
CONCURRENT COUNTER - 2

- Decrease counter
- Get value

```
(Cont.)
17      void decrement(counter_t *c) {
18              Pthread_mutex_lock(&c->lock);
19              c->value--;
20              Pthread_mutex_unlock(&c->lock);
21      }
22
23      int get(counter_t *c) {
24              Pthread_mutex_lock(&c->lock);
25              int rc = c->value;
26              Pthread_mutex_unlock(&c->lock);
27              return rc;
28      }
```


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

- 1 core
- N = 100 tps

- 10 core
- N = 1000 tps

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?

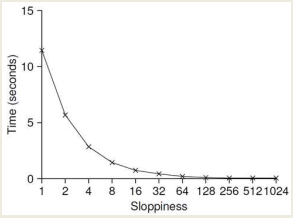
SLOPPY COUNTER - 2

- 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?



SLOPPY COUNTER - EXAMPLE

- Example implementation
- Also with CPU affinity

CONCURRENT LINKED LIST - 1

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

```
1       // basic node structure
2       typedef struct __node_t {
3               int key;
4               struct __node_t *next;
5       } node_t;
6
7       // basic list structure (one used per list)
8       typedef struct __list_t {
9               node_t *head;
10              pthread_mutex_t lock;
11      } list_t;
12
13      void List_Init(list_t *L) {
14              L->head = NULL;
15              pthread_mutex_init(&L->lock, NULL);
16      }
17
(Cont.)
```


CONCURRENT LINKED LIST - 2

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

```
(Cont.)
18      int List_Insert(list_t *L, int key) {
19              pthread_mutex_lock(&L->lock);
20              node_t *new = malloc(sizeof(node_t));
21              if (new == NULL) {
22                      perror("malloc");
23                      pthread_mutex_unlock(&L->lock);
24              return -1; // fail
26              new->key = key;
27              new->next = L->head;
28              L->head = new;
29              pthread_mutex_unlock(&L->lock);
30              return 0; // success
31      }
(Cont.)
```


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.)
32
32      int List_Lookup(list_t *L, int key) {
33              pthread_mutex_lock(&L->lock);
34              node_t *curr = L->head;
35              while (curr) {
36                      if (curr->key == key) {
37                              pthread_mutex_unlock(&L->lock);
38                              return 0; // success
39                      }
40                      curr = curr->next;
41              }
42              pthread_mutex_unlock(&L->lock);
43              return -1; // failure
44      }
```


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 …

QUESTIONS