TCSS 422: OPERATING SYSTEMS

**Thread API, Locks,
Lock Based Data Structures**

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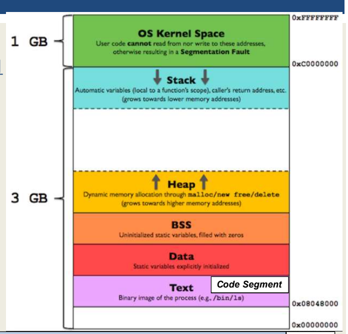
OBJECTIVES

- Homework 0 Review
- Tutorial 1 Questions
- Homework 1 Questions
- Feedback from 1/24
- Ch. 27
  - Thread API
- Ch. 28
  - Locks
- Ch. 29
  - Lock Based Data Structures

SELECTED FEEDBACK FROM 1/24

- **C memory layout clarification: global and constant variables are stored in the data segment**
- Three Easy Pieces – memory diagrams do not show data segment



FEEDBACK - 2

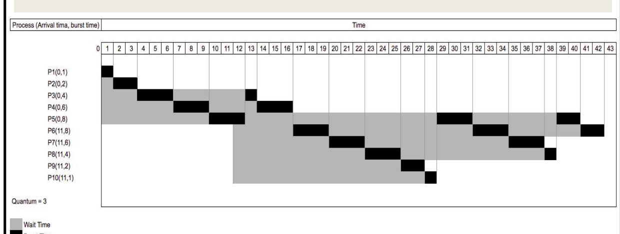
- **When should a thread be used vs. a process?**
- Consider the tradeoffs of Processes vs Threads. . .
- **How does the priority level for a job change?** (*with respect to the MLFQ example*)
- A job uses its entire time slice (e.g. 10ms). When this occurs the job is placed in a lower priority queue with a longer time slice
- Example Time slices: Q0 – 1ms
  Q1 – 2ms
  Q2 – 4ms

FEEDBACK - 3

- **Could you explain the term: "Scheduling Quantum"?**
  - Time slice and scheduling quantum is same
  - Time duration a job runs in the CPU before a timer interrupt forces and a CPU context switch to another job

WHAT IS THE TIME QUANTUM FOR THIS ROUND ROBIN SCHEDULING EXAMPLE?

- Round-robin example:



NICE VALUES AND PROCESS PRIORITIES

- **Nice values** (*user space suggestions for process priority*) :
  - -20 HIGH, 0 NORMAL, 19 LOW
- **Process priorities** (*actual kernel space value*):
  - 0 LOW (user), 39 HIGH (user), >40 to 139 (MAX) Realtime
- To check priorities:
  - `ps ax –o pid,ni,pri,cmd,%cpu`
  - `top (PR NI columns)`

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FEEDBACK - 6

- **What is an example of a program that benefits from multi-threading?**
  - Parts of the computation must be separable to run at same time (parallel)
  - Embarrassingly parallel: Separate parts of computation can run independently without communication
- **Is multithreading overhead offset by the performance gained from parallel processing?**
  - It is entirely dependent in what the program is doing…

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FEEDBACK – 7

- **Is there better ways then locking code to make it run slightly faster if assembly code is known?**
  - Question refers to the fact that incrementing a variable in C requires three non-atomic lines of assembly code
  - Coming soon
- **Blue comment bars in downloadable slides are obscuring content**
  - Actually no, slides are duplicated with and without messages…

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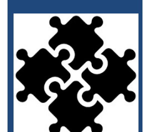
CHAPTER 27 - LINUX THREAD API



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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*)

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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);
        …
}
```

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PASSING A SINGLE VALUE

**Using this approach on your CentOS 7 VM
How large (in bytes) can the primitive data type be?**

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

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


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 ??***


```
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_create(&p1, NULL, worker, &args);
  pthread_join(p1, (void *)&ret_args);
  printf("returned %d %d\n", ret_args->a, ret_args->b);
  return 0;
}
```


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 (pointing to `struct myarg output;`)

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

How can this code be fixed?

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
```


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);
```

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;
```


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;
}
```


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

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

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

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()
  - Waits (sleeps)
  - Listens for a "signal"
  - Releases the lock until signaled

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 all listeners → to wake them up
  - The goal is to unblock (at least one) to respond to the signal
- pthread_cond_broadcast()
  - Unblocks all threads currently blocked on the specified condition
  - Used when all threads should respond to the signal
- Which thread is unblocked first?
  - Determined by OS scheduler (based on priority)
  - Thread(s) gain the lock individually (based on priority) as if they called pthread_mutex_lock()

CONDITIONS AND SIGNALS - 3

- Wait example

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

pthread_mutex_lock(&lock);
while (initialized == 0)
        pthread_cond_wait(&init, &lock); ...
pthread_mutex_unlock(&lock);
```

- wait puts thread to sleep, releases lock
- when awoken, lock reacquired (and released by this code)
- Another thread signals the thread

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

Code performs required work before other thread(s) can continue

CONDITION AND SIGNALS - 4

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

pthread_mutex_lock(&lock);
while (initialized == 0)
        pthread_cond_wait(&init, &lock);
pthread_mutex_unlock(&lock);
```

- Why do we wait inside a while loop?
- The while ensures upon awakening the condition is rechecked
  - A signal may have been raised, but the condition to proceed has not been satisfied.
  - Without checking the condition the thread may proceed to execute when it should not.

PTHREADS LIBRARY

- Compilation
  - gcc –pthread pthread.c –o pthread
  - Requires explicitly linking the library with compiler flag
- List of pthread manpages
  - man –k pthread

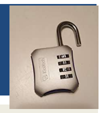
SAMPLE MAKEFILE

```
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

CHAPTER 28 – LOCKS

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);
```


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

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.

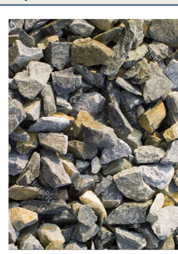
LOCKS - 4

- Programs 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

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);
```



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 . . .
```

EVALUATING LOCK IMPLEMENTATIONS

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

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

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…

SPIN LOCK IMPLEMENTATION

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


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

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…

TEST-AND-SET INSTRUCTION

- C implementation: not atomic
  - Adds a simple check to basic spin lock
  - One a single core CPU system with preemptive scheduler:
  - Try this…

```
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
- Single core systems are becoming scarce
- Try on a one-core VM

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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

```
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 guarantee: 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
  - Performance is slow when multiple threads share a CPU
    - Especially for long periods

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COMPARE AND SWAP

- Checks that the lock variable has the expected value FIRST, before changing its value
  - If so, make assignment
  - Return value at location
- Adds a comparison to TestAndSet
- 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 lock usage

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

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

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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

1-core VM:
Count is correct, no deadlock

```
        ; // spin
}
```

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

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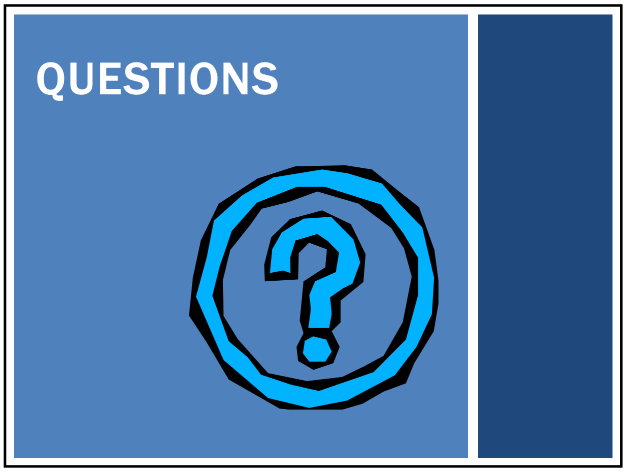
QUESTIONS