162 Dis 5 Notes

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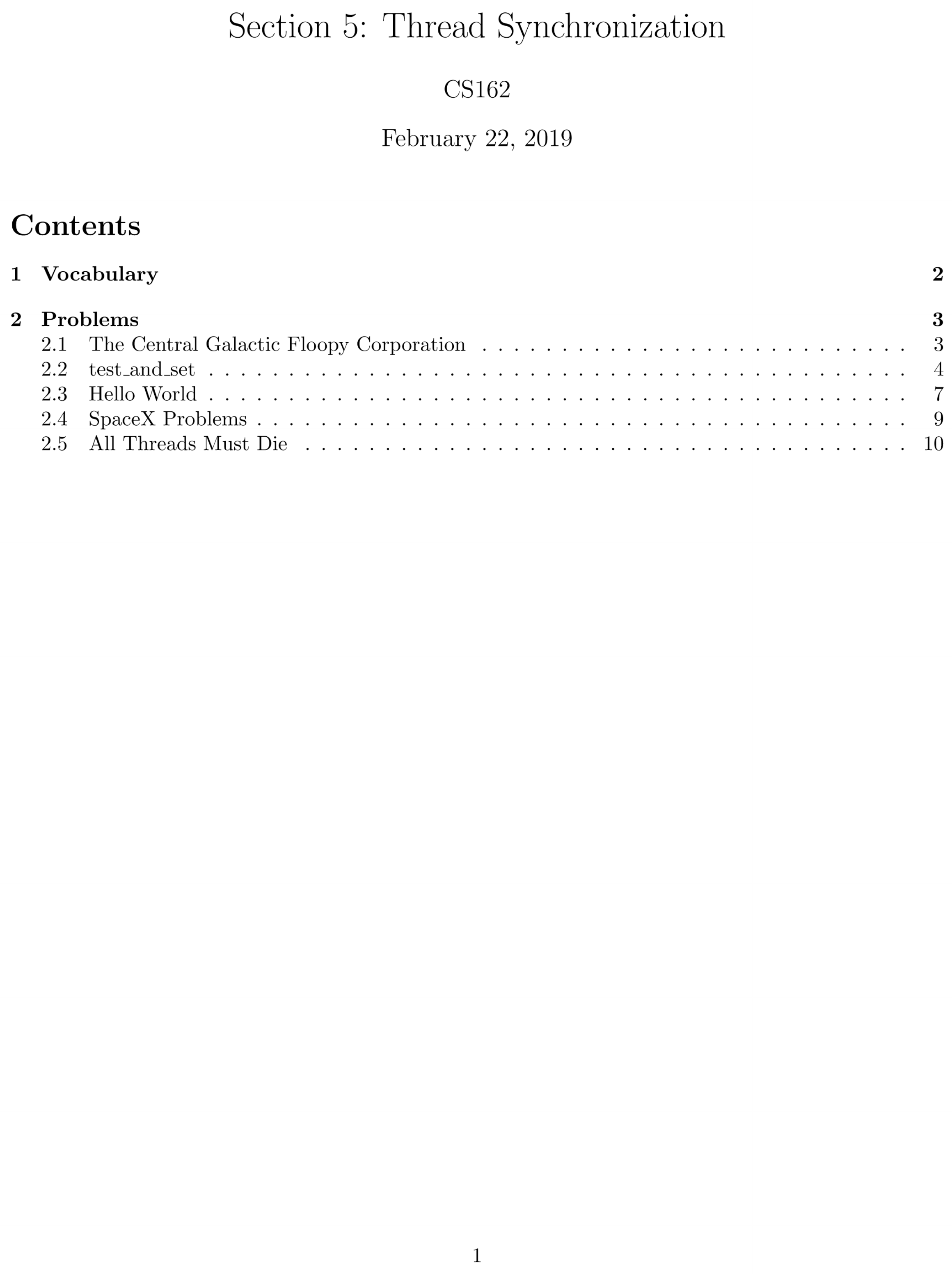


Section 5: Thread Synchronization

CS162

February 22, 2019

Contents

1 Vocabulary

- **Thread** - a thread of execution is the smallest unit of sequential instructions that can be scheduled for execution by the operating system. Multiple threads can share the same address space, but each thread independently operates using its own program counter.
- **Atomic operation** - An operation that appears to be indivisible to observers. Atomic operations must execute to completion or not at all.
- **Critical section** - A section of code that accesses a shared resource and must not be concurrently run by more than a single thread.
- **Race condition** - A situation whose outcome is dependent on the sequence of execution of multiple threads running simultaneously.
- **test_and_set** - An atomic operation implemented in hardware. Often used to implement locks and other synchronization primitives. In this handout, assume the following implementation.

  like amoswap from 61C (ish)

  ```
  int test_and_set(int *value) {
      int result = *value;
      *value = 1;
      return result;
  }
  ```

  ← if it returns 0 ⇒ we own lock
  else, we would try again

  This is more expensive than most other instructions, and it is not preferable to repeatedly execute this instruction.

also called mutex →

- **Lock** - Synchronization variables that provide mutual exclusion. Threads may acquire or release a lock. Only one thread may hold a lock at a time. If a thread attempts to acquire a lock that is held by some other thread, it will block at that line of code until the lock is released and it successfully acquires it. Implementations can vary.
- **Scheduler** - Routine in the kernel that picks which thread to run next given a vacant CPU and a ready queue of unblocked threads. See next_thread_to_run() in Pintos.
- **Priority Inversion** - If a higher priority thread is blocking on a resource (a lock, as far as you're concerned but it could be the Disk or other I/O device in practice) that a lower priority thread holds exclusive access to, the priorities are said to be inverted. The higher priority thread cannot continue until the lower priority thread releases the resource. This can be amended by implementing priority donation.
- **Priority Donation** - If a thread attempts to acquire a resource (lock) that is currently being held, it donates its effective priority to the holder of that resource. This must be done recursively until a thread holding no locks is found, even if the current thread has a lower priority than the current resource holder. (Think about what would happen if you didn't do this and a third thread with higher priority than either of the two current ones donates to the original donor.) Each thread's effective priority becomes the max of all donated priorities and its original priority.
- **Condition Variable** - A synchronization variable that provides serialization (ensuring that events occur in a certain order). A condition variable is associated with:
  - a lock (a condition variable + its lock are known together as a **monitor**)
  - some boolean condition (e.g. `hello < 1`)
  - a queue of threads waiting for the condition to be true

In order to access any CV functions **OR** to change the truthfulness of the condition, a thread must/should hold the lock. Condition variables offer the following methods:

- **cv_wait(cv, lock)** - Atomically unlocks the lock, adds the current thread to **cv**'s thread queue, and puts this thread to sleep.
- **cv_notify(cv)** - Removes one thread from **cv**'s queue, and puts it in the ready state.
- **cv_broadcast(cv)** - Removes all threads from **cv**'s queue, and puts them all in the ready state.

When a **wait()**ing thread is notified and put back in the ready state, it also re-acquires the lock before the **wait()** function returns.
When a thread runs code that may potentially make the condition true, it should acquire the lock, modify the condition however it needs to, call notify() or broadcast() on the condition's CV, so waiting threads can be notified, and finally release the lock.
Why do we need a lock anyway? Well, consider a race condition where thread 1 evaluates the condition C as false, then thread 2 makes condition C true and calls **cv.notify**, then 1 calls **cv.wait** and goes to sleep. Thread 1 might never wake up, since it went to sleep too late.

- **Hoare Semantics** - (In terms of condition variable) Wake a blocked thread when the condition is true and transfer control of the CPU and ownership of the lock to that thread immediately. This is difficult to implement in practice and generally not used despite being conceptually easier to deal with.

- **Mesa Semantics** - (In terms of condition variable) Wake a blocked thread when the condition is true, with no guarantee that the thread will execute immediately. The newly woken thread simply gets put on the ready queue and is subject to the same scheduling mechanisms as any other thread. The implication of this is that **you must check the condition with a while loop instead of an if statement because it is possible for the condition to change to false between the time the thread was unblocked and the time it takes over the CPU**.

2 Problems

2.1 The Central Galactic Floopy Corporation

It's the year 3162. Floopies are the widely recognized galactic currency. Floopies are represented in digital form only, at the Central Galactic Floopy Corporation (CGFC).

You receive some inside intel from the CGFC that they have a Galaxynet server running on some old OS called x86 Ubuntu 14.04 LTS. Anyone can send requests to it. Upon receiving a request, the server forks a POSIX thread to handle the request. In particular, you are told that sending a transfer request will create a thread that will run the following function immediately, for speedy service.

```
void transfer(account_t *donor, account_t *recipient, float amount) {
  assert (donor != recipient); // Thanks CS161

  if (donor->balance < amount) {
    printf("Insufficient funds.\n");
    return;
  }
  donor->balance -= amount;
  recipient->balance += amount;
}
```

1 line but multiple ops ↳

read d→b
subtract
write d→b

donor→balance = d→balance − amount

recipient → balance = r→balance + amount

read
add
write

Assume that there is some struct with a member balance that is typedef-ed as account_t. Describe how a malicious user might exploit some unintended behavior.

Free money from bank →

alice ~~5~~ ~~0~~ 5 bob ~~5~~ ~~0~~ 10

1) a→b , a-=5, b+=5 ; read, add a=0 b=5

2) b→a, b-=5, a+=5 a=5, b=0 (rey=10)

3) a→b op completes b+=5 write

Since you're a good person who wouldn't steal floopies from a galactic corporation, what changes would you suggest to the CGFC to defend against this exploit?

lock the structures , or disable interrupts (for single processor). Be careful of deadlock if we have one lock per account

Or alice ~~5~~ ~~0~~ -5 bob ~~0~~ ~~5~~ 10

1) a→b , a- =5, check a=5 b=0

2) a→b, a-=5, check a=5 b=0

3) a→b completes a=0, b=5

4) a→b completes, a=-5, b=10

not transferred yet, but both approved

Lock
- single lock for all transactions
→ slow !!

Deadlock
- 2 acc, locks A, B
transfer A→B
B→A ⇒

T1	T2
acquire(A)	
	acquire(B)
acquire(B)	
	acquire(A)

BAD X

how to solve deadlock?

acquire locks in same preference order

→ acquire highest ace #'s lock first.

2.2 test_and_set

In the following code, we use test_and_set to emulate locks.

```
int value = 0;
int hello = 0;

void print_hello() {
    while (test_and_set(&value));
    hello += 1;
    printf("Child thread: %d\n", hello);
    value = 0;
    pthread_exit(0);
}

void main() {
    pthread_t thread1;
    pthread_t thread2;
    pthread_create(&thread1, NULL, (void *) &print_hello, NULL);
    pthread_create(&thread2, NULL, (void *) &print_hello, NULL);
    while (test_and_set(&value));
    printf("Parent thread: %d\n", hello);
    value = 0;
}
```

← T1 gets stuck here

← M gets stuck here

value hello

0 ~~0~~ ~~1~~

0

M T1 T2

Assume the following sequence of events:

1. Main starts running and creates both threads and is then context switched right after
2. Thread2 is scheduled and run until after it increments hello and is context switched
3. Thread1 runs until it is context switched
4. The thread running main resumes and runs until it get context switched
5. Thread2 runs to completion
6. The thread running main runs to completion (but doesn't exit yet) runs, sets to 1 then 0, exit
7. Thread1 runs to completion runs, sets to 1 then 0, exit

Is this sequence of events possible? Why or why not?

yes M and T1 block until T2

At each step where `test_and_set(&value)` is called, what value(s) does it return?

1) N/A 4) same as 3

2) 0 5) 0

3) 1 6) 0 ← "lock" free

3 (runs test + set until we switch it)

Given this sequence of events, what will C print?

Child thread 1
Parent thread 1
Child thread 2

deterministic?
no, we made assumptions about run order

Is this implementation better than using locks? Explain your rationale.

busy waits (step 3+4) bad

2.3 Hello World

This code compiles (given a sprinkling of #includes etc.) but doesn't work properly. Why?

```
pthread_mutex_t lock;
pthread_cond_t cv;
int hello = 0;

void* print_hello(void* arg) {  ← lock acquire (&lock)
    hello += 1;
    printf("First line (hello=%d)\n", hello);
    pthread_cond_signal(&cv);  ← release
    pthread_exit(0);                                   ← mapage for official
}                                                              syntax

int main() {                    ← init(&lock, 0)
    pthread_t thread;             init(&cv, 0)
    pthread_create(&thread, NULL, print_hello, NULL);
lock acquire →
    while (hello < 1) {
      pthread_cond_wait(&cv, &lock);
    }
release →
    printf("Second line (hello=%d)\n", hello);
    return 0;
}
```

Add in the necessary code to the above problem to make it work correctly.

1) initialize lock + CV

2) should have acquired lock before waiting on condition

2.4 SpaceX Problems

Consider this program.

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

int n = 3;

void* counter(void* arg) {
  pthread_mutex_lock(&lock);
  for (n = 3; n > 0; n--)
    printf("%d\n", n);
  pthread_cond_signal(&cv);
  pthread_mutex_unlock(&lock);
}

void* announcer(void* arg) {
  while (n != 0) {
    pthread_mutex_lock(&lock);
    pthread_cond_wait(&cv, &lock);
    pthread_mutex_unlock(&lock);
  }
  printf("FALCON HEAVY TOUCH DOWN!\n");
}

int main() {
  pthread_t t1, t2;
  pthread_create(&t1, NULL, counter, NULL);
  pthread_create(&t2, NULL, announcer, NULL);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  return 0;
}
```

moral of the story?
read n without any synchro

lock outside

What is wrong with this code?

1) announcer enters while loop since n!=0, but does NOT acquire lock
2) counter finishes (can acquire lock)
3) announcer waits, never to wake again

2.5 All Threads Must Die

You have three Pintos threads with the associated priorities shown below. They each run the functions with their respective names.

Tyrion : 4
Ned: 5
Gandalf: 11

Assume upon execution that all threads are unblocked and begin at the top of their code blocks. The operating system runs with a preemptive priority scheduler. You may assume that set_priority commands are atomic. (Note: The following uses references to Pintos locks and data structures.)

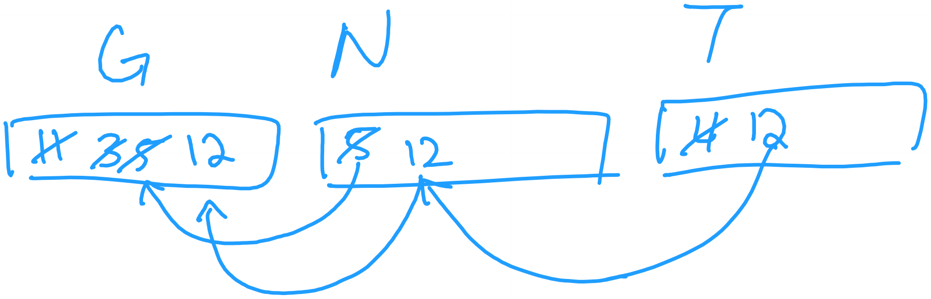
```
struct list brace_yourself;   // pintos list. Assume it's already initialized and populated.
struct lock midterm;          // pintos lock. Already initialized.
struct lock is_coming;

void tyrion(){
8 5     thread_set_priority(12);
9 6     lock_acquire(&midterm);
        lock_release(&midterm);
        thread_exit();
}

void ned(){
3 3     lock_acquire(&midterm);
4 4     lock_acquire(&is_coming);
11 →    list_remove(list_head(brace_yourself));
        lock_release(&midterm);
        lock_release(&is_coming);
        thread_exit();
}

void gandalf(){
1 1     lock_acquire(&is_coming);
2 2     thread_set_priority(3);
5 7     while (thread_get_priority() < 11) {
6  [       printf("YOU .. SHALL NOT .. PAAASS!!!!!!);
7  [       timer_sleep(20);
        }
        lock_release(&is_coming);
10      thread_exit();
}
```

never stops ↙



Kernel panic

↑ ASSERT (is_interior (elem))

↑
head fails this.

What is the output of this program when there is no priority donation? Trace the program execution and number the lines in the order in which they are executed.

What is the output and order of line execution if priority donation was implemented? Draw a diagram of the three threads and two locks that shows how you would use data structures and struct members (variables and pointers, etc) to implement priority donation for this example.