# University of Waterloo
# Midterm Examination
# Term: Fall Year: 2013

## Solution

———————begin solution———————

```
Grade breakdown: Fall 2013

Out of  10.0   8.0   8.0  10.0  13.0   9.0  12.0  10.0  80.0
Average  5.8   6.9   6.6   6.0  10.5   4.9   9.9   8.2  58.8
Max     10.0   8.0   8.0  10.0  13.0   9.0  12.0  10.0  79.0
Percent 58.3  86.6  83.0  60.2  80.7  54.2  82.2  81.6  73.5

90-100 23
80-89  71
70-79  71
60-69  34
50-59  16
40-49   8
30-39   5
20-29   4
10-19   0
00-09   0
```

———————end solution———————

| Problem | Topic | Marks | Score | Marker's Initials |
|---|---|---|---|---|
| 1 | Miscellaneous | 10 | | |
| 2 | Threads / Thread Fork | 8 | | |
| 3 | Forking Processes | 8 | | |
| 4 | System calls, Interrupts and Stacks | 10 | | |
| 5 | Synchronization (Semaphores) | 13 | | |
| 6 | Synchronization (Spinlocks) | 9 | | |
| 7 | Synchronization (Reader/Writer Locks) | 12 | | |
| 8 | Virtual Memory (Address Translation) | 10 | | |
| Total | | 80 | | |

**Problem 1 (10 marks)**

a. **(2 mark(s))** Explain how Mesa-style condition variables differ from Hoare-style condition variables.

——————begin solution——————

In Mesa-style condition variables the thread that calls cv_signal or cv_broadcast continues execution. In Hoare-style condition variables the thread that calls cv_signal or broadcast gets blocked, gives up the lock and the thread that was waiting continues executing.

——————end solution——————

b. **(2 mark(s))** How does a `syscall` differ from a normal function call? Identify two distinct differences.

——————begin solution——————

Choose any from:

- syscall transfers control to a fixed location, function call transfers to a caller-specified location
- syscall invokes kernel code, function call invokes application code
- syscall changes processor to privileged mode, function call does not

——————end solution——————

c. **(2 mark(s))** What is the difference between an *exception* and an *interrupt*?

——————begin solution——————

An exception results from the execution of an instruction. An interrupt is a signal received from a device or another processor.

——————end solution——————

d. **(2 mark(s))** What does it mean to provide a "fair" implementation of a synchronization mechanism?

——————begin solution——————

Accept either one of:
Starvation is not possible
or (a stronger version)
Threads get access to the critical section in a strictly FIFO order.

——————end solution——————

e. **(2 mark(s))** In a system that implements paging, the processor uses 37-bit virtual addresses, 44-bit physical addresses and a page size of 16 kilobytes ($2^{14}$ bytes). For the physical address, how many bits are needed to represent the offset, and how many bits are neeed to represent the frame number. **Explain your answer.**

——————begin solution——————

14 bits for the offset because the frame size must equal the page size.
So 44 - 14 = 30 bits must be used for the physical frame.

——————end solution——————

**Problem 2 (8 marks)**
Consider the program below, and suppose that a single initial thread starts executing the `main()` function. As the initial thread runs, additional threads are created as a result of calls to `thread_fork()`. Answer the questions below about the output of this concurrent program.

```
main() {
   helper(NULL,0);
}

void
helper(void *p, unsigned long i) {  /* parameter p is not used */
  if (i < 3) {
     kprintf("%ld",i); /* print the value of i */
     thread_fork("helper1",NULL,helper,NULL,i+1); /* fork thread to run helper(NULL,i+1) */
     thread_fork("helper2",NULL,helper,NULL,i+1); /* fork thread to run helper(NULL,i+1) */
  }
  /* was i=0, as announced this should be i==0 */
  if (i==0) {
     kprintf("%ld",i);
  }
  thread_exit();
}
```

Which of the following outputs could possibly be generated by the concurrent program shown above? Write **YES** after each output that could possibly be generated, and write **NO** after each output that could not possibly be generated.

Note: to avoid rewarding random guessing, the marking scheme for this question awards points only for 5 or more correct answers.

———————begin solution———————

a. 01221220 YES

b. 01120222 YES

c. 01342560 NO (no digits larger than 2)

d. 01222120 NO (not enough 2's after the 2nd 1)

e. 01122220 YES

f. 01234560 NO (no digits larger than 2)

g. 01212220 YES

h. 00112222 YES

———————end solution———————

**Problem 3 (8 marks)**
**(8 mark(s))** For the program shown below, fill in the table at the bottom of the page to show the output that would be printed by both the parent and child processes. Briefly explain how you arrived at your solution. Assume that all function, library and system calls are successful. If you need to make additional assumptions be sure to clearly state them.

```
int x;

main()
{
  int rc;
  x = 0;

  rc = fork();

  if (rc == 0) {
    x = 10;
    printf("A: %d\n", x);
  } else {
    printf("B: %d\n", x);
    x = 100;
  }

  printf("C: %d\n", x);
}
```

——————begin solution——————

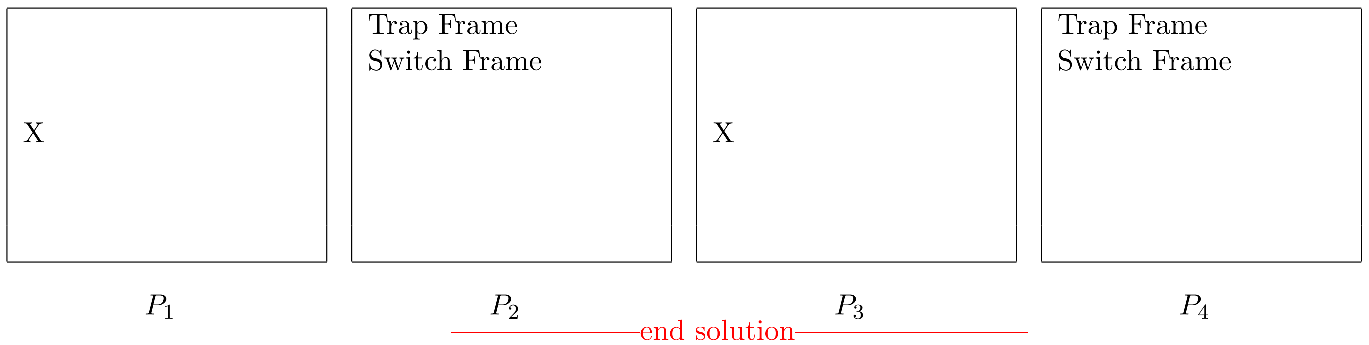
```
Parent:       Child:
B: 0          A: 10
C: 100        C: 10

No other results are possible.
Fork creates a copy of the process so x is not shared.
```

——————end solution——————

**Problem 4 (10 marks)**
Consider an OS/161 system with 2 CPUs ($C_1$ and $C_2$) and 4 processes ($P_1$, $P_2$, $P_3$, and $P_4$). Processes $P_1$ and $P_2$ only ever run on CPU $C_1$. Currently $P_1$ is running and $P_2$ is on the ready-to-run queue for $C_1$. Processes $P_3$ and $P_4$ only ever run on CPU $C_2$. Currently $P_3$ is running and $P_4$ is on the ready-to-run queue for $C_2$. When answering the questions below recall that stacks will grow from high addresses to low addresses. Your diagrams MUST place high addresses at the top of the stack picture.

a. **(4 mark(s))** The boxes in the diagram below represent the kernel stacks of the four processes. Complete the diagram to show what the kernel stacks currently contain. Include only trap frames and switch frames and do not include frames that have been popped. Mark any empty stacks with a large X.

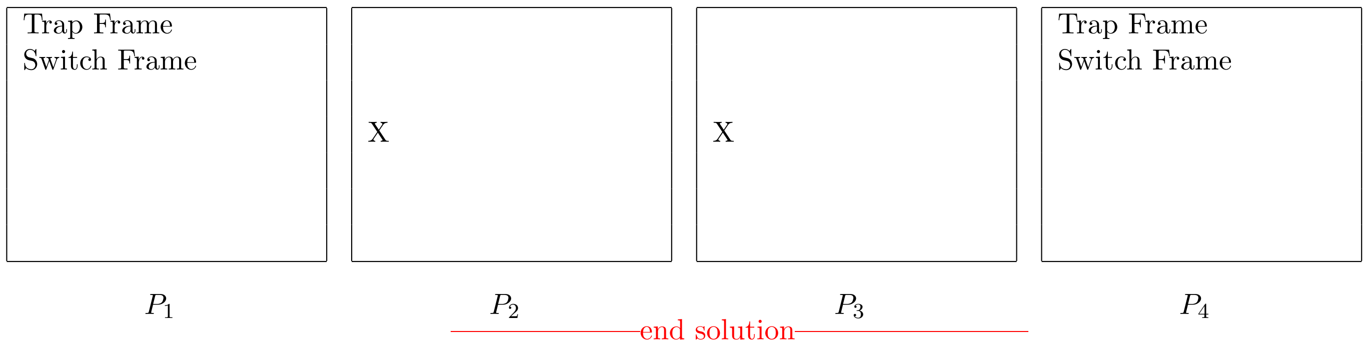
begin solution



end solution

b. **(3 mark(s))** Next, assume that a **blocking** system call is executed by $P_1$, and $P_2$ runs on CPU $C_1$ after the system call. Fill in the diagrams below to show the contents of the kernel stacks for each of the 4 processes after execution of $P_2$ resumes. Include only trap frames and switch frames and do not include any that have been popped. Mark any empty stacks with a large X.

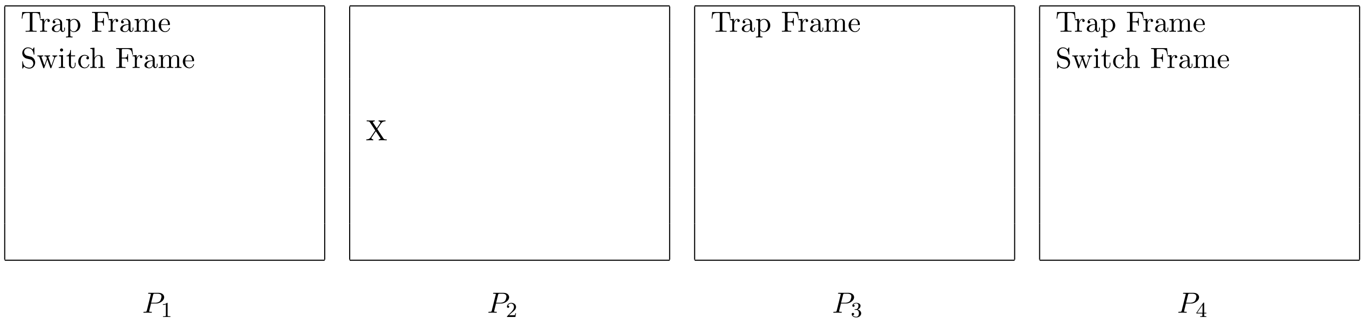
begin solution



end solution

c. **(3 mark(s))** Next, assume that a timer interrupt occurs on CPU $C_2$. While handling the interrupt, OS/161 decides that $P_3$'s scheduling quantum has expired, and that $P_4$ should start running next on $C_2$. Fill in the diagrams below to show the contents of the kernel stacks for each of the 4 processes at the point in the OS/161 kernel just before `thread_switch` is called to switch from $P_3$ to $P_4$. Include only trap frames and switch frames and do not include any that have been popped. Mark any empty stacks with a large X.

end solution
begin solution



**Problem 5 (13 marks)**
Suppose that a system initially has only a single thread (T1), which is running the function `f1()`. `f1()` calls `thread_fork()` to create a new thread, T2, to run function `f2()` concurrently with T1. These two threads and the functions they execute are illustrated in the two columns of the figure below.

As illustrated in the figure, thread T1 calls function `fb()`, and thread T2 calls functions `fa()` and `fc()`. Your task is to synchronize the calls to `fa()`, `fb()`, and `fc()` so that the following synchronization rules are enforced:

- function `fa()` finishes before function `fb()` is called, and
- function `fb()` finishes before function `fc()` is called.

Show how to use semaphore(s) to enforce these sychronization rules by adding `P()` and `V()` calls in suitable places in functions `f1()` and `f2()` in the diagram below. You must also declare (at the top of the diagram) global variables to point to any semphores you use in your solution. Finally, you must include **sem_create** calls in suitable places in `f1()` and/or `f2()` to create and initialize the semaphores you need. Be sure that your `sem_create()` calls show the intial semaphore value for each newly created semaphore.
Do not use any synchronization primitives or techniques other than sempahores. Keep your solution as simple as possible - unnecessarily complex solutions may be penalized.

————————begin solution————————

```
/* declare any global semaphore variables you need here, like this:  */
/* struct semaphore *s1 */
struct sempahore *sa; /* NEW */
struct sempahore *sb; /* NEW */
```

Thread T1

```
void f1() {
  /* NEW create with initial value 0 */
  sa = sem_create{"sa",0}; /* NEW */
  sb = sem_create{"sb",0}; /* NEW */

  /* create thread T2 to run f2() */
  thread_fork(...)

  /* NEW wait for fa() to finish */
  P(sa);  /* NEW */
  /* call function fb() */
  fb();

  /* NEW signal fb() is finished */
  V(sb);  /* NEW */

  thread_exit();
}
```

Thread T2

```
void f2() {

   /* call function fa() */
   fa();

   /* NEW signal fa() is finished */
   V(sa);  /* NEW */

   /* NEW wait for fb() to finish */
   P(sb); /* NEW */

   /* call function fc() */
   fc();
   thread_exit();
}
```

———————end solution———————

**Problem 6 (9 marks)**
Suppose that there are only two threads, $T_a$ and $T_b$, running in a system. Each of the threads attempts to execute a shared critical section that is protected by a shared spinlock, by executing code like this:

```
spinlock_acquire(&lock)
  /* execute critical section */
spinlock_release(&lock)
```

Each thread needs to acquire the spinlock and execute the critical section only one time, and there are no other threads running in the system.

The threads are preemptively scheduled, using a scheduling quantum of $q$ time units. Once a thread has acquired the spinlock, it will spend $c$ time units executing the critical section before releasing the spinlock. Assume that $c << q$.

For all of the following questions, assume that thread $T_a$ acquires the spinlock and executes the critical section before $T_b$ does.

**a. (3 mark(s))** Suppose that the spinlock implementation is as in OS/161, which means in particular that interrupts are disabled when a thread acquires the spinlock and enabled again when the spinlock is released. Suppose that $T_a$ and $T_b$ are timesharing the processor in a system with only one processor. In the *worst case*, what is the maximum amount of time that $T_b$ will have to spin in **spinlock_acquire()**? Express your answer in terms of $c$ and $q$, and briefly justify your answer by identifying a situation in which $T_b$ would have to spin that long.

——————begin solution——————

Since $T_a$ cannot be interrupted once it has acquired the spinlock, $T_b$ will not be able request the spinlock until after $T_b$ has released it. Thus, $T_b$ will not spin at all. Answer: 0.

——————end solution——————

**b. (3 mark(s))** Repeat part (a), but this time under the assumption that the system has two processors, and that $T_a$ and $T_b$ are running on different processors.

——————begin solution——————

In the worst case, $T_b$ tries to acquire the spinlock right after $T_a$ has acquired it. In that case, $T_b$ will spin until $T_a$ releases the spinlock. Answer: $c$ time units.

——————end solution——————

**c. (3 mark(s))** Suppose that the spinlock implementation is similar to the one in OS/161, except that interrupts are *not* disabled while a thread holds the spinlock. Suppose that $T_a$ and $T_b$ are timesharing the processor in a system with only one processor. In the *worst case*, what is the maximum amount of time that $T_b$ will have to spin when it calls **spinlock_acquire()**? Express your answer in terms of $c$ and $q$, and briefly your answer by identifying a situation in which $T_b$ would have to spin that long.

——————begin solution——————

The worst case is that $T_a$ gets pre-empted while it holds the spinlock, which can occur because interrupts are not disabled. If $T_b$ then runs and tries to acquire the spinlock, it will spin for its entire quantum, $q$. Once $T_b$ is preempted, $T_a$ will run and release the spinlock before its quantum expires again, since $c < q$. When $T_a$ is eventually pre-empted again, $T_b$ will run and will acquire the spinlock without any further spinning. Answer: $q$ time units.

——————end solution——————

**Problem 7 (12 marks)**

a. **(8 mark(s))** Assume that each of the functions below (`FuncA`, `FuncB`, and `FuncC`) are being executed by different threads using the OS/161 kernel thread library. Assume that reader/writer locks have been implemented as described in the course notes and in class. Add calls to `rwlock_acquire(rwlock *lk, READ_MODE)` or `rwlock_acquire(rwlock *lk, WRITE_MODE)`, and `rwlock_release(rwlock *lk)` and only those calls to ensure that `FuncA`, `FuncB`, and `FuncC` are atomic. The locks have already been declared and initialized and `xlock`, `ylock`, and `zlock` must be used to protect the variables `x`, `y`, and `z`, respectively. Additionally, your locks **must not use `WRITE_MODE` unneccessarily, AND you must ensure that that deadlock can not occur**.

——————begin solution——————

```
/* NOTE: IF ONE ASSUMES THAT NO
 * OTHER CODE MODIFIES THESE
 * VARIABLES, z DOES NOT REQUIRE LOCKING */
volatile int x = 10;
volatile int y = 20;
volatile int z = 0;
struct rwlock *xlock; /* protect x */
struct rwlock *ylock; /* protect y */
struct rwlock *zlock; /* protect z */

void init()
{
  xlock = rwlock_create("xlock");
  ylock = rwlock_create("ylock");
  zlock = rwlock_create("zlock");
}

void FuncB(int i)
{

  rwlock_acquire(xlock, WRITE_MODE); /* NEW */
  rwlock_acquire(zlock, READ_MODE);  /* NEW */

  if ((i == z) || (i == x)) {
     x = z + x;
  }

  rwlock_release(zlock); /* NEW */
  rwlock_release(xlock); /* NEW */
}
```

```
void FuncA()
{
  rwlock_acquire(ylock, WRITE_MODE); /* NEW */
  rwlock_acquire(zlock, READ_MODE);  /* NEW */

  if (y == 10) {
    y = y + z;
  }

  rwlock_release(zlock); /* NEW */
  rwlock_release(ylock); /* NEW */

}


void FuncC()
{
  rwlock_acquire(xlock, WRITE_MODE); /* NEW */
  rwlock_acquire(ylock, WRITE_MODE); /* NEW */
  rwlock_acquire(zlock, READ_MODE);  /* NEW */

  x = y + x + z;
  y = z + x;

  rwlock_release(zlock); /* NEW */
  rwlock_release(ylock); /* NEW */
  rwlock_release(xlock); /* NEW */
}
```

———————end solution———————

b. **(2 mark(s))** Briefly explain why deadlock can not occur with your solution.

———————begin solution———————

Deadlock can not occur because locks are always acquired in the same order (x, y, z)

———————end solution———————

c. **(2 mark(s))** In your solution, which if any of the functions can be executing in their critical sections concurrently. Briefly explain your answer.

———————begin solution———————

FuncA and FuncB can be executed concurrently because the only shared variable between them is z and it is not modified, it is only read.

———————end solution———————

**Problem 8 (10 marks)**

Suppose that a system uses a single CPU with an MMU that uses a relocation register and a max address (or address limit) register to perform dynamic relocation. Several processes are running in this system. Each process has a simple virtual address space with virtual address ranging from 0 to the maximum address (or limit address) for that process. The kernel maintains a list of processes, their maximum virtual address (limit address) and where in physical memory each process is located (the relocation address), as shown below. All of the addresses used in this problem are decimal (base 10) numbers.

| PID | Max Addr | Relocation Addr |
|---|---|---|
| 100 | 1000 | 8000 |
| 123 | 2000 | 12 |
| 159 | 3000 | 2200 |
| 230 | 3000 | 10000 |
| 393 | 1000 | 6000 |
| 516 | 2000 | 20000 |

Where possible perform each of the address translations described below. Assume the kernel takes the necessary steps to set up the MMU before running each process. When the address translation is not possible explain why. In all cases be sure to describe how you arrived at your answer. Assume all addresses are in decimal.

a. **(2 mark(s))** When PID 516 is running, what is the resulting physical address for virtual address 1999?

———begin solution———

21999. Phys = Virtual (1999) + Relocation Reg (20000) = 21999.

———end solution———

b. **(2 mark(s))** When PID 516 is running, what is the resulting physical address for virtual address 2000?

———begin solution———

22000. Phys = Virtual (2000) + Relocation Reg (20000) = 22000.
This wasn't meant to be a trick question or so easy. The PID was supposed to be 393.

———end solution———

c. **(2 mark(s))** Which virtual address, in which process, corresponds to physical address 2800? Indicate both a virtual address and a PID, or answer "NONE" if no virtual address maps to the given physical address.

———begin solution———

3600 by PID 159. Base addr = 2200 and 2800 was accessed so 600 is the difference. So add 600 to the base virtual address (0) = 600.

———end solution———

d. **(2 mark(s))** Which virtual address, in which process, corresponds to physical address 7100. Indicate both a virtual address and a PID, or answer "NONE" if no virtual address maps to the given physical address.

———begin solution———

"NONE"

———end solution———

e. **(2 mark(s))** If process 100 is running and a context switch occurs to process 230, briefly descibe the steps the kernel takes to set up the MMU.

———begin solution———

It needs to copy 3000 into the max addr / limit register and 10000 into the relocation reg.

———end solution———