CS3331 Concurrent Computing Exam 1 Solutions
Spring 2018

1. **Basic Concepts**

(a) **[10 points]** Explain what are CPU modes. Explain their uses. How does the CPU know what mode it is in? **There are three questions.**

Answer: The following has the answers.

- CPU modes are operating modes of the CPU. Modern CPUs have two execution modes: the user mode and the supervisor (or system, kernel, privileged) mode, controlled by a mode bit.
- The OS runs in the supervisor mode and all user programs run in the user mode. Some instructions that may do harm to the OS (*e.g.*, I/O and CPU mode change) are privileged instructions. Privileged instructions, for most cases, can only be used in the supervisor model. When execution switches to the OS (*resp.*, a user program), execution mode is changed to the supervisor (*resp.*, user) mode.
- A mode bit can be set by the operating system, indicating the current CPU mode.

See page 5 of `02-Hardware-OS.pdf`. ■

(b) **[10 points]** What is an atomic instruction? What would happen if multiple CPUs/cores execute their atomic instructions? **Make sure you will explain atomic instructions fully. Otherwise, you may receive a lower or very low score.**

Answer: An atomic instruction is a machine instruction that executes as one *uninterruptible* unit without interleaving and cannot be split by other instructions. When an atomic instruction is recognized by the CPU, we have the following:

- All other instructions being executed in various stages by the CPUs are suspended (and perhaps re-issued later) until this atomic instruction finishes.
- No interrupts can occur.

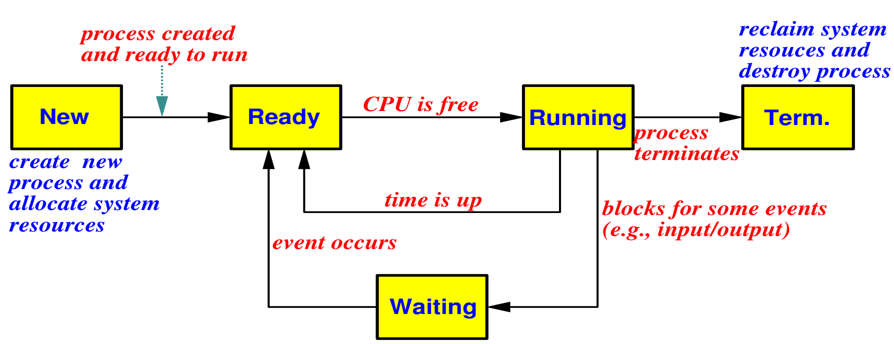
If two such instructions are issued at the same time on different CPUs/cores, they will be executed sequentially in an arbitrary order determined by the hardware.

See pp. 12–13 of `02-Hardware-OS.pdf`. ■

2. **Processes**

(a) **[10 points]** Draw the state diagram of a process from its creation to termination, including all transitions. Make sure you will elaborate **every state** and **every transition** in the diagram.

Answer: The following state diagram is taken from my class note.



There are five states: **new**, **ready**, **running**, **waiting**, and **terminated**.

- **New**: The process is being created.
- **Ready**: The process has everything but the CPU, and is waiting to be assigned to a processor.
- **Running**: The process is executing on a CPU.
- **Waiting**: The process is waiting for some event to occur (*e.g.*, I/O completion or some resource).
- **Terminated**: The process has finished execution.

The transitions between states are as follows:

- **New→Ready**: The process has been created and is ready to run.
- **Ready→Running**: The process is selected by the CPU scheduler and runs on a CPU/core.
- **Running→Ready**: An interrupt has occurred forcing the process to wait for the CPU.
- **Running→Waiting**: The process must wait for an event (*e.g.*, I/O completion or a resource).
- **Waiting→Ready**: The event the process is waiting has occurred, and the process is now ready for execution.
- **Running→Terminated**: The process exits.

See pp. 5–6 of `03-Process.pdf`. ■

(b) **[10 points]** What is a *context*? Provide a detail description of *all* activities of a *context switch*.

Answer: A process needs some system resources (*e.g.*, memory and files) to run properly. These system resources and other information of a process include process ID, process state, registers, memory areas (for instructions, local and global variables, stack and so on), various tables (*e.g.*,, PCB), a program counter to indicate the next instruction to be executed, etc. They form the *environment* or *context* of a process. The steps of switching process *A* to process *B* are as follows:

- The operating system suspends *A*'s execution. A CPU mode switch may be needed.
- Transfer the control to the CPU scheduler.
- Save *A*'s context to its PCB and other tables.
- Load *B*'s context to register, etc. from *B*'s PCB.
- Resume *B*'s execution of the instruction at *B*'s program counter. A CPU mode switch may be needed.

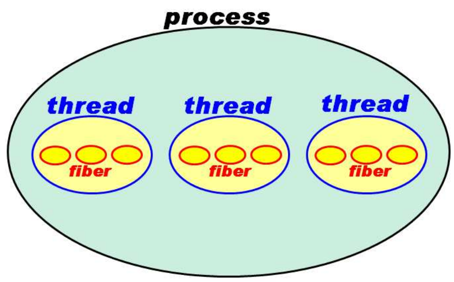
See pp. 10–11 of `03-Process.pdf`. ■

3. **Threads**

(a) **[10 points]** Do your best to define and compare the concepts of *process*, *thread* and *fiber*. In particular, how are they scheduled? **You have to define each first, followed by a comparison of these three. You are expected to explain the way of scheduling each. Without doing so, you will receive no credit for this problem.**

Answer: A *process* is the execution of a program; a *thread* (*i.e.*, *lightweight process*), is a unit of CPU execution that is created by a process; and a *fiber* is a lightweight thread, created by a thread, just like a thread being a lightweight process. A comparison can be based on hierarchy, resource usage and scheduling as follows:

- **Hierarchy:** Processes create threads, and threads create fibers. Thus, a process contains the threads it creates, and a thread contains the fibers it creates. This hierarchy is shown below:



- **Resource Sharing:** A *process* must acquire all resources for that process to run properly. These resources include files, memory, registers, etc.
  A *thread* is a lightweight process. All peer threads created within a process share with each other files opened by the containing process, memory allocated to the containing process, etc. Thus, a thread has a program counter, a register set, and a stack, and shares the resources acquired by the containing process with other peer threads.
  A *fiber* also has a program counter, a subset of the registers, and a stack. A fiber shares all resources acquired by the containing threads with other peer fibers.
- **Scheduling:** *processes* are scheduled by the CPU scheduling in the kernel. *Threads* can be user-level threads that are scheduled by a thread scheduler built into a thread library in a user address space, or can be kernel-supported threads that are scheduled by the thread scheduler in the kernel. *Fibers*, on the other hand, are scheduled by a co-operative policy. In other words, a fiber gives up the CPU in a voluntary way, usually through the execution of the `YIELD` statement.

■

4. **Synchronization**

(a) **[10 points]** Define the meaning of a *race condition*? Answer the question first and use execution sequences with a clear and convincing argument to illustrate your answer. **You must explain step-by-step why your example causes a race condition.**

Answer: A *race condition* is a situation in which *more than one* processes or threads manipulate a shared resource *concurrently*, and the result depends on *the order of execution*.

The following is a simple counter updating example discussed in class. The value of `count` may be 9, 10 or 11, depending on the order of execution of the **machine instructions** of `count++` and `count--`.

```
int          count = 10;   // shared variable

Process 1                  Process 2

count++;                   count--;
```

The following execution sequence shows a race condition. Two processes run concurrently (condition 1). Both processes access the shared variable `count` concurrently (condition 2) because `count` is accessed in an interleaved way. Finally, the computation result depends on the order of execution of the `SAVE` instructions (condition 3). The execution sequence below shows the result being 9; however, switching the two `SAVE` instructions yields 11. Since all conditions are met, we have a race condition. **Note that you have to provide TWO execution sequences, one for each possible result, to justify the existence of a race condition.**

Thread_1	Thread_2	*Comment*
do somthing	do somthing	`count = 10` initially
`LOAD count`		`Thread_1` executes `count++`
`ADD #1`		
	`LOAD count`	`Thread_2` executes `count--`
	`SUB #1`	
`SAVE count`		`count` is 11 in memory
	`SAVE count`	Now, `count` is 9 in memory

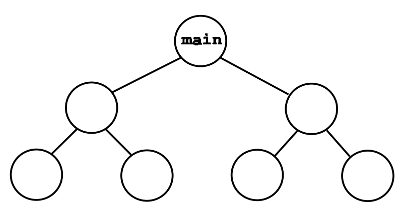
Stating that "`count++` followed by `count--`" or "`count--` followed by `count++`", even using machine instructions, produces different results and hence a race condition is **incomplete**, because the two processes do not access the shared variable `count` concurrently. Note that the use of higher-level language statement interleaved execution may not reveal the key concept of "sharing" as discussed in class. Therefore, use instruction level interleaved instead.

See pp. 5–12 of `05-Sync-Basics.pdf`. ∎

5. **Problem Solving:**

(a) **[10 points]** Design a C program segment so that the `main()` creates two child processes with `fork()`, each of these two child processes creates two child processes, etc. such that the parent-child relationship is a perfectly balanced binary tree of depth `n` with `main()` at the root. The depth `n` have already been stored a valid positive integer. The `main()` prints its PID, and each child process prints its PID and its parent's PID.

The following diagram shows a tree of processes of depth 3 (*i.e.*, `n` = 3). Your program segment must be correct for any valid value of `n` > 0. Only providing a program segment for `n` = 3 will receive **zero** point. To save your time, you do not have to perform error checking. However, proper wait and exit are expected.



Answer: The parent forks two child processes and waits for them. Each child process prints the needed information, and loops back to fork its own child processes. However, if a child process is a leaf node, it just prints and exits. This idea is illustrated in the code segment below.

```
#include <stdio.h>

#define  PRINT { printf("My PID = %ld   My PPID = %ld\n", getpid(), getppid()); }

int main(int argc, char **argv)
{
   int i, n;

   printf("main()'s PID = %ld\n\n", getpid());
   n = atoi(argv[1])-1;
   for (i = 1; i <= n; i++)    // for each level
      if (fork() > 0)          // parent forks the 1st child
         if (fork() > 0) {     // parent forks the 2nd child
            wait(NULL);        // parent waits them to complete
            wait(NULL);
            exit(0);           // and exit
         }
         else {                // the 2nd child process
            PRINT              // print the needed info
            if (i == n)        // if it is a leaf node
               exit(0);        // exit w/o coming back to fork
         }
      else {                   // the 1st child process
            PRINT              // print the needed info
            if (i == n)        // if it is a leaf node
               exit(0);        // exit w/o coming back to fork
      }
}
```

You may also do the same using recursion as binary tree creation is basically recursive. Note that a process prints only if the level number is larger than 1. If the level number is 1, printing `getpid()` and `getppid()` will print the PID of the `main()` and the PID of the shell.

```
#include <stdio.h>

#define PRINT   { printf("My PID = %ld   My PPID = %ld\n", getpid(), getppid()); }

void pCreate(int i, int n)
{
   if (i < n) {               // still have level to go
      if (fork() > 0) {       // fork the 1st child
         if (fork() > 0) {    // fork the 2nd child
            if (i > 1)        // if this is higher than level 1
               PRINT          //    print
            wait(NULL);       // wait for both child processes
            wait(NULL);
            exit(0);          // exit
         }
         else                 // the 2nd child goes for level i+1
            pCreate(i+1, n);
      }
      else                    // the 1st child goes for level i+1
         pCreate(i+1, n);
   }
   else {                     // leaf node
      PRINT                   // print info only w/o forking
      exit(0);
   }
}


int main(int argc, char **argv)
{
   int i, n;

   printf("main()'s PID = %ld\n\n", getpid());
   n = atoi(argv[1]);
   pCreate(1, n);
   wait(NULL);
}
```

There are two commonly seen problems in your solutions. **First**, no `wait()` statements were included. If you do not include `wait()` statements, some child processes can become orphans whose parent is the `init` process with PID being 1, and, as a result, the parent-child relationship is incorrect. **Second**, even though you are allowed to use `printf()`, separating the parent PID and the child PID into two `printf()` calls is an incorrect approach. It is because the two `printf()` calls may prints their output lines scattered all over in the output report. As a result, the parent-child relationship is, again, not shown properly. ■

(b) **[15 points]** Consider the following two processes, *A* and *B*, to be run concurrently using a shared memory for the `int` variable `x`.

```
Process A                     Process B
---------                     ---------
for (i = 1; i <= 2; i++)      x = 2*x;
   x++;
```

Assume that `x` is initialized to 0, and `x` must be loaded into a register before further computations can take place. What are **all possible** values of `x` after both processes have terminated. **You must use clear step-by-step execution sequences of the above processes with a convincing**

argument. Any vague and unconvincing argument receives no points.

Answer: Obviously, the answer must be in the range of 0 and 4. It is non-negative, because the initial value is 0 and no subtraction is used. It cannot be larger than 4, because the two `x++` statements and `x = 2*x` together can at most double the value of `x` twice.

The easiest answers are 2, 3 and 4 if `x = 2*x` executes before, between and after the two `x++` statements, respectively. The following shows the possible execution sequences.

`x = 2*x` **is before both** `x++`		
Process 1	Process 2	`x` in memory
	`x = 2*x`	0
`x++`		1
`x++`		2

`x = 2*x` **is between the two** `x++`		
Process 1	Process 2	`x` in memory
`x++`		1
	`x = 2*x`	2
`x++`		3

`x = 2*x` **is after both** `x++`		
Process 1	Process 2	`x` in memory
`x++`		1
`x++`		2
	`x = 2*x`	4

The situation is a bit more complex with instruction interleaving. Process B's `x = 2*x` may be translated to the following machine instructions:

```
LOAD x
MUL  #2
SAVE x
```

Because the `LOAD` retrieves the value of `x`, and the `SAVE` may change the current value of `x`, the results depend on the positions of `LOAD` and `SAVE`. The following shows the result being 0. In this case, `LOAD` loads 0 *before* both `x++` statements, and the result 0 is saved *after* both `x++` statements.

Process 1	Process 2	`x` in memory	Comments
	`LOAD x`	0	Load $x = 2$ into register
	`MUL #2`	0	Process 2's register is 0
`x++`		1	Process 1 adds 1 to x
`x++`		2	Process 1 adds 1 to x
	`SAVE x`	0	Process 2 saves 0 to x

If the `SAVE` executes between the two `x++` statements, the result is 1.

Process 1	Process 2	`x` in memory	Comments
	`LOAD x`	0	Load $x = 2$ into register
	`MUL #2`	0	Process 2's register is 0
`x++`		1	Process 1 adds 1 to x
	`SAVE x`	0	Process 2 saves 0 to x
`x++`		1	Process 1 adds 1 to x

You may try other instruction interleaving possibilities and the answers should still be in the range of 0 and 4. ■

(c) **[15 points]** Consider the following solution to the mutual exclusion problem for two processes P_1 and P_2. This solution uses two global `int` variables, `x` and `y`. Both `x` and `y` are initialized to `0`.

```
int x = 0, y = 0;
```

Process 1 **Process 2**

```
START:                            START:                           // All start from here
  x = 1;                            x = 2;                         // set my ID to x
  if (y != 0) {                     if (y != 0) {                  // if y is non-zero
    repeat until (y == 0);            repeat until (y == 0);       //    wait until y = 0
    goto START;                       goto START;                  //    then try again
  }                                 }                              // second section
  y = 1;                            y = 1;                         // set y to 1
  if (x != 1) {                     if (x != 2) {                  // if x is not my ID
    y = 0;                            y = 0;                       //    set y to 0
    repeat until (x == 0);            repeat until (x == 0);       //    wait until x = 0
    goto START;                       goto START;                  //    then try again
  }                                 }
    // critical section               // critical section
  x = y = 0;                        x = y = 0;                     // set x and y to 0
```

Prove rigorously that this solution satisfies the mutual exclusion condition. *You will receive* **zero** *point if* **(1)** *you prove by example, or* **(2)** *your proof is vague and/or unconvincing.*

Answer: We shall prove the mutual exclusion property by contradiction. Consider process P_1 first. If P_1 is in its critical section, its execution must have set `x` to `1`; passed the first `if` statement which does not modify the value of `x`; set `y` to `1`; and seen `x != 1` being false. Therefore, if P_1 is in its critical section, `x` and `y` must both be `1`. By the same reason, if P_2 is in its critical section, `x` and `y` must be `2` and `1`, respectively. Now, if P_1 and P_2 are **both** in their critical sections, `x` must be both `1` and `2`. This is impossible because a variable can only hold one value. As a result, the assumption that P_1 and P_2 are both in their critical sections cannot hold, and, the mutual exclusion condition is satisfied. ■