CS3331 Concurrent Computing Solution 1
Fall 2015

1. **Basic Concepts**

   (a) **[10 points]** Explain *interrupts* and *traps*, and provide a detailed account of the procedure that an operating system handles an interrupt.

   Answer: An *interrupt* is an event that requires the attention of the operating system. These events include the completion of an I/O, a key press, the alarm clock going off, division by zero, accessing a memory area that does not belong to the running program, and so on. Interrupts may be generated by hardware or software. A *trap* is an interrupt generated by software (*e.g.*, division by 0 and system call).

   When an interrupt occurs, the following steps will take place to handle the interrupt:

   - The executing program is suspended and control is transferred to the operating system. Mode switch may be needed.
   - A general routine in the operating system examines the received interrupt and calls the interrupt-specific handler.
   - After the interrupt is processed, a context switch transfers control back to a suspended process. Of course, mode switch may be needed.

   See pp. 6–7 `02-Hardware-OS.pdf`. ∎

   (b) **[10 points]** What is an atomic instruction? What would happen if multiple CPUs/cores execute their atomic instructions?

   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 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]** 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:

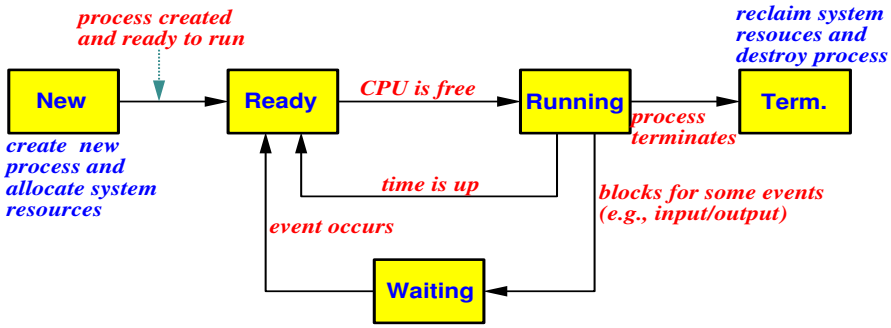
   - The operating system suspends *A*'s execution. A CPU mode switch may be needed.
   - Transfer the control to the CPU scheduler.
   - Save *A*'s context to its PCB and other tables.
   - Load *B*'s context to register, etc. from *B*'s PCB.

- Resume *B*'s execution of the instruction at *B*'s program counter. A CPU mode switch may be needed.

See page 10 and page 11 of `03-Process.pdf`. ∎

(b) **[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 page 5 and page 6 of `03-Process.pdf`. ∎

3. **Threads**

(a) **[10 points]** Enumerate the major differences between kernel-supported threads and user-level threads.

Answer: Kernel-supported threads are threads directly handled by the kernel. The kernel does thread creation, termination, joining, memory allocation, and scheduling in kernel space. User threads are supported at the user level and are not recognized by the kernel, and thread creation, termination, joining, memory allocation, and scheduling are done in the user space. Usually, a library running in user space provides all support. Due to the kernel involvement, the overhead of managing kernel-supported threads is higher than that of user threads.

Since there is no kernel intervention, user threads are more efficient than kernel threads. On the other hand, in a multiprocessor environment, the kernel may schedule kernel-supported threads to run on multiple processors, which is impossible for user threads because the kernel does not schedule user threads. Additionally, since the kernel does not recognize and schedule user threads, if the containing process or its associated kernel-supported thread is blocked, all user threads of that process (or kernel thread) are also blocked. However, blocking a kernel-supported thread will not cause all threads of the containing process to be blocked.

See pp. 5–6 and pp. 9–12 `04-Thread.pdf`. ∎

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 access 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++`" produces different results and hence a race condition is at least **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. 5–10 of `05-Sync-Basics.pdf`. ∎

(b) **[10 points]** Explain the progress and bounded waiting conditions and enumerate their differences. **Note that there are two questions.**

Answer:

- **Progress:** If no process is executing in its critical section and some processes wish to enter their corresponding critical sections, then
  - Only those processes that are waiting to enter can participate in the competition (to enter their critical sections).
  - No other processes can influence this decision.
  - This decision cannot be postponed indefinitely (*i.e.*, making a decision in finite time).
- **Bounded Waiting:** After a process made a request to enter its critical section and before it is granted the permission to enter, there exists a bound on the number of times that other processes are allowed to enter. Hence, even though a process may be blocked by other waiting processes, it will only wait a bounded number of turns before it can enter.

The progress condition only guarantees the decision of selecting a process to enter a critical section will not be postponed indefinitely. It does not mean a waiting process will enter its critical section eventually. In fact, a process may wait forever because it may never be selected, even though every decision is made in finite time.

On the other hand, the bounded waiting condition guarantees that a process will enter the critical section after a bounded number of turns. Bounded waiting does not guarantee that progress will be satisfied because if the decision process takes an infinite amount of time to make none of the waiting processes can enter even though there is a bound. See pp. 16–18 of `05-Sync-Basics.pdf`. ∎

5. **Problem Solving:**

(a) **[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 load and store of `x` is atomic, `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. Use a step-by-step execution sequence of the above processes to show all possible results. **You must provide a clear step-by-step execution of the above algorithm 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
```

The `LOAD` retrieves the value of `x`, and the `SAVE` may change the current value of `x`. Therefore, 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 := x + 1`		1	Process 1 adds 1 to x
`x := x + 1`		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 := x + 1`		1	Process 1 adds 1 to x
	`SAVE x`	0	Process 2 saves 0 to x
`x := x + 1`		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. ∎

(b) **[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

```
START:
     x = 1;
     if (y != 0) {
          repeat until (y == 0);
          goto START;
     }
     y = 1;
     if (x != 1) {
          y = 0;
          repeat until (x == 0);
          goto START;
     }
// critical section
     x = y = 0;
```

Process 2

```
START:                              // All start from here
     x = 2;                         // set my ID to x
     if (y != 0) {                  // if y is non-zero
          repeat until (y == 0);    //    wait until y = 0
          goto START;               //    then try again
     }                              // second section
     y = 1;                         // set y to 1
     if (x != 2) {                  // if x is not my ID
          y = 0;                    //    set y to 0
          repeat until (x == 0);    //    wait until x = 0
          goto START;               //    then try again
     }
// critical section
     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 passed the first `if` statement, set `y` to `1`, and seen `x != 1` being false (*i.e.*, `x = 1` being true). 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. ∎