Answer all questions. This is a long exam, so try to be concise.

**Problem 1:** (12 pts; 8 minutes)

Briefly explain 3 of the following terms

- Working Set
- Pre-cleaning
- Thrashing
- Cyclic restart

**Problem 2:** (15 points; 12 minutes) Give concise explanations for 3 of the following potentially wrong statements:

1. A TLB is only necessary for virtual memory
2. The clock algorithm replaces pages based on how old they are
3. Deadlock detection can be carried out using the Banker’s algorithm
4. A system can either be deadlocked or safe

**Problem 3:** (20 points; 20 minutes)

(a) (10 points) What is Belady’s anomaly? Prove that optimal replacement policy does not suffer from it.
(b) (10 points) What are the implications of dynamic memory allocation (memory requested at run time; for example, using C’s malloc() or C++’ new) on a system that uses (1) dynamic partitioning; (2) fixed partitioning.

**Problem 4:** (5 points; 5 minutes)

Consider a computer where the page tables are kept in memory. The cost of accessing memory is 500nsec. A TLB is used to optimize translation; the cost of accessing the TLB is 50nsec. What should the TLB hit rate be to make the average translation time 75nsec?

**Problem 5:** (10 points; 10 minutes)

In an electronics fund transfer system, there are hundreds of identical processes that work as follows. Each process reads an input line specifying an amount of money, the account to be credited, and the account to be debited. Then it locks both accounts and transfers the money, releasing locks after it is done. With many processes running concurrently, there is a danger of deadlock occurring.

(a) (3 points) Explain how deadlock would occur.
(b) (7 points) Devise two protocols that prevent deadlock from happening.

**Problem 6:** (38 points; 30 minutes)

Consider a system where logical memory is $2^{38}$ bytes, and physical memory is $2^{20}$ bytes. The memory system is paged. There is a total of $2^{16}$ frames in the physical memory. The system is multiprogrammed (more than one process).

(a) (5 points) What is the page size?
(b) (15 points) You are trying to decide whether to use an inverted page table or a two level page table for this system. Assume a page table entry is 8 bytes, while an inverted page table entry is 16 bytes. Assume that in a two level page table scheme, every process needs the directory as well as 4 pages of the page table in memory all the time. Typically, you will have 16 processes active in the system. Which page table organization do you pick to minimize the amount of memory taken up by the page tables? Show your work
(c) (12 points) The system has a TLB and a cache that is indexed on physical addresses and uses a two level page table. Show in painful detail the process of a memory access showing the alternatives at every step. Also, discuss what is implemented in hardware and what is implemented in software.
(d) (6 points) What needs to be done when a context switch occurs in terms of memory management in the system described in part (c)?