CS 111 Midterm Examination
Spring Quarter, 2023
Solutions

You have 90 minutes for this examination; the number of points for each question indicates roughly how many minutes you should spend on that question. Make sure you print your name and sign the Honor Code statement below. During this exam you are allowed to consult two double-sided pages of notes that you have prepared ahead of time; other than that, you may not consult books, notes, your laptop or cell phone, or any other materials. If there is a trivial detail that you need for one of your answers but cannot recall, you may ask the course staff for help.

Note: be sure to write only on the front sides of pages. We'll be using Gradescope to grade the exams and may not see information written on the back sides. There are extra pages at the end of the exam, if you need more space for an answer.

I acknowledge and accept the Stanford University Honor Code. I have neither given nor received aid in answering the questions on this examination, and I have not consulted any external information other than two double-sided pages of prepared notes.

____
(Signature)

____
(Print your name, legibly!)

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(SUNet email id)

Problem	#1	#2	#3	#4	#5	Total
Score						
Max	10	6	12	10	40	78

Problem 1 (10 points)

Indicate whether each of the following statements is true or false, and explain your answer briefly.

(a) A lock can be owned by at most one thread at a time.

Answer: true. Locks are intended for implementing critical sections so it must not be possible for more than one thread to have ownership at once.

(b) All of the threads within a process must execute on the same core.

Answer: false. One of the main reasons for having multiple threads within a process is to improve performance by running concurrent operations on different cores.

(c) There are situations where busy-waiting is a good idea.

Answer: true. In most situations it is better to put a thread to sleep when it blocks, rather than busy-waiting. However, there are some situations where blocking is not possible, such as in the implementation of locks. In addition, "spin locks" are sometimes used in concurrent programs where it is known that a lock will be held for a very short period of time. In situations like this busy-waiting may actually be more efficient (by the time the thread has blocked, the lock has already become available again).

(d) With base-and-bound relocation, it is possible to move the code for a process to a different location in physical memory while leaving its data and stack(s) where they were.

Answer: false. It is possible to move the code, but stack and data will have to move with it. This is because base-and-bound relocation requires the entire virtual address space of a process to occupy a single contiguous region of physical memory.

(e) Making a backup of your computer before updating the operating system is an example of trust by substitution.

Answer: true. This is a form of trust by substitution because it ensures that even if the OS update is untrustworthy we can avoid serious consequences.

Problem 2 (6 points)

No existing approach to memory allocation and freeing is perfect. Briefly describe one disadvantage of each of the following techniques:

(a) Slab-based storage allocation

The biggest problem is that free space can get "stranded" in slabs for one object size, while slabs for other object sizes run out of space and require additional slabs to be allocated. This can happen, for example, if the application allocates a large number of objects of a particular size and then frees almost all of them, leaving one live object in each slab. There's no way to move objects between slabs, so most of the memory of the slabs ends up unused.

Another problem is internal fragmentation. This can happen because slabs only exist for certain sizes (e.g. multiples of 16 bytes); object sizes get rounded up his next available slab size, which can leave unused space inside objects.

(b) Reference counting for storage reclamation

The biggest problem is circularities: if there is a circular chain of references among objects, each reference count in the chain will remain positive, even though there are no references from the rest of the system to any of the objects in the chain. Thus the circular chain never gets reclaimed.

(c) Garbage collection for storage reclamation

Garbage collection is expensive both in time and space. It is expensive in time because a full mark-and-copy garbage collection has to read and write all of the memory of the applciation. It is expensive in space because garbage collection typically doesn't run until most of the memory space is free (in order to reduce the amount of memory that must be copied during garbage collection). If most of memory space is free, it means that memory space is being wasted.

Problem 3 (12 points)

(a) In the code below, do all of the references to x refer to the same variable? If so, explain why; if not, explain how many different variables there are, and why.

```
int x = 100;

void func1(...)
{
    ...
    x += 100;
    ...
}

void func2(...)
{
    x--;
    std::thread t([](){x = 300;});
    t.join();
    std::cout << “x = “ << x << std::endl;
    ...
}
```

Answer: yes. x is a global variable, which means it will be shared among all methods and threads in the process.

(b) In the code below, do all of the references to x refer to the same variable? If so, explain why; if not, explain how many different variables there are, and why.

```
int x = 100;

void func(char **argv)
{
    x += 100;

    int childPid = fork();
    if (childPid == 0) {
        // This code runs in the child process.
        x += 100;
        execvp(argv[0], argv);
        ...
    }

    // This code runs in the parent process.
    waitpid(childPid, NULL, 0);
    std::cout << “x = “ << x << std::endl;
}
```

Answer: no. The fork system call creates a new process whose memory is copied from the parent. Thus there will be 2 x variables after the fork, one in the parent and one in the child..

Problem 3, cont'd

(c) In the code below, do all of the references to x refer to the same variable? If so, explain why; if not, explain how many different variables there are, and why.

```
void func1(int x)
{
    int sum = x;

    for (int i = 0; i < 10; i++) {
        int x = i*i;
        sum += x;
    }
    sum += x;
    std::cout << "x = " << x << std::endl;
}
```

Answer: no. There will be 11 total x variables: one for the parameter and a separate variable created during each iteration of the "for" loop. Note: inside the "for" loop the local variable is used in preference to the parameter.

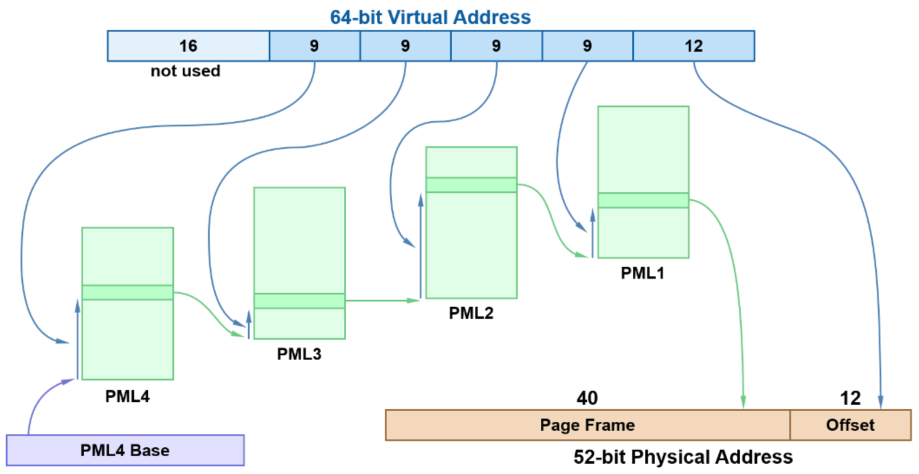
(d) In the code below, do all of the references to x refer to the same variable? If so, explain why; if not, explain how many different variables there are, and why.

```
void func1(void)
{
    int x = 0;

    for (int i = 0; i < 10; i++) {
        x += i*i;
    }
    std::cout << "x = " << x << std::endl;
}

void func2(void)
{
    int x = 0;

    for (int i = 0; i < 10; i++) {
        x += i+20;
    }
    std::cout << "x = " << x << std::endl;
}
```

Answer: no. There will be 2 x variables, one local variable for each method (local variables are allocated on the thread stack, so they are not shared between threads).

Problem 4 (10 points)

The figure below shows the address translation mechanism used for 64-bit mode in Intel x86 processors, which was discussed in lecture. It uses 4 levels of page map to translate 48 bits of virtual address to 52-bit physical addresses.



(a) (5 points) Consider a process that needs only one page each for code, data, and stack (assume it has only one thread), with virtual memory layout as discussed in lecture. How many PML2 page maps will the operating system have to allocate for this process? Explain your answer briefly.

Answer: there will be 2 PML2 tables. One will cover the highest range of virtual addresses (for the stack) and the other will cover the lowest range of virtual addresses (for code and data).

(b) (5 points) Now suppose that the process' thread makes deeply nested recursive method calls, which cause the stack to grow, and that the operating system allocates additional pages for the stack as needed. How many pages must the stack consume before the operating system will have to allocate another PML2 page map? You can express your answer as a power of 2 if that is more convenient. Explain your answer briefly.

2^{18} + 1 pages.

The original PML2 has pointers to 2^9 PML1 maps, each of which has pointers to 2^9 stack pages. Once the stack grows to $2^9 * 2^9 = 2^{18}$ pages the PML2 will be full, so the next page allocation will require a new PML2 map.

Problem 5 (40 points)

In this problem you must implement an airplane boarding process similar to that of Southwest Airlines: each boarding pass contains an integer boarding position (no groups A, B, and C) and passengers board in order of their positions (lowest boarding position first). Specifically, you must define a C++ class `Flight` with a constructor, destructor, and two methods:

```
Flight(size_t max_passengers);
~Flight();
void wait_to_board(size_t position);
bool board_next();
```

The `max_passengers` argument to the constructor indicates the maximum number of passengers that will board the flight. When a passenger arrives at the gate, it invokes `wait_to_board`; the `position` argument indicates the position from the passenger's boarding pass: you can assume that it is unique for this `Flight` and lies between `0` and `max_passengers-1`, inclusive. The `wait_to_board` method must not return until it is this passenger's turn to board.

The gate agent will call `board_next` to allow the first waiting passenger to begin boarding; once that passenger has passed the boarding pass scanner, the gate agent will invoke `board_next` to board the next passenger, and so on until `board_next` returns false. The `board_next` method should return false if there are no available passengers; otherwise it should wake up the passenger with the lowest remaining boarding position and return true. If a passenger is not present when their boarding position is reached, they will be skipped and the next higher position will board; if such a passenger eventually arrives, then they must board before other passengers with higher positions.

You do not need to worry about what passengers do after `wait_to_board` returns or how the gate agent determines that it should make each call to `board_next`.

Additional information:

- You must write your solution in C++ using `std::mutex` and `std::condition_variable`.
- Use the monitor style for your code, as discussed in class and required for Assignment 2.
- Your solution must not use busy-waiting.
- For full credit, you must not use `notify_all`, and each call to `board_next` should invoke `notify_one` at most once.
- Try to make your solution simple and obvious; we will reduce your score by up to 20% if your solution is overly complicated.
- If you can't remember exact names and syntax for C++ library methods you can either ask the staff or just make your best guess. As long as your intent is clear and precise we aren't going to quibble about syntax.

Use the next page(s) for your answer.

Implement the Flight class here:

```
class Flight {
public:
    Flight(size_t max_passengers);
    ~Flight();
    void wait_to_board(size_t position);
    bool board_next();
class Flight {
public:
    Flight(size_t max_passengers);
    void wait_to_board(size_t position);
    bool board_next();

private:
    std::mutex mutex;

    // The key for each entry in the map is a position from a
    // boarding pass; the value points to a condition variable
    // to notify when it is that position’s turn to board. An
    // entry exists in the map only as long as the passenger
    // is executing in wait_to_board().
    std::map<size_t, std::condition_variable*> ready_passengers;
};

Flight::Flight(size_t maxPassengers)
        : mutex(), ready_passengers()
{
}

Flight::~Flight() {}

void Flight::wait_to_board(size_t position)
{
    std::unique_lock<std::mutex> lock(mutex);
    std::condition_variable my_turn;

    ready_passengers.emplace(position, &my_turn);
    my_turn.wait(lock);
}

bool Flight::board_next()
{
    std::unique_lock<std::mutex> lock(mutex);
    if (ready_passengers.empty()) {
        return false;
    }
    ready_passengers.begin()->second->notify_one();
    ready_passengers.erase(ready_passengers.begin());
    return true;
}
```

Additional working space for any problem, if needed

Additional working space for any problem, if needed