University of California, Berkeley
College of Engineering
Computer Science Division: EECS

Summer 2019 Jack Kolb

Midterm I SOLUTIONS

July 18th, 2019
CS162: Operating Systems and Systems Programming

Your Name:	
SID AND 162 Login (e.g. s042):	
TA Name:	
Discussion Section Time:	

General Information:
This is a **closed book** exam. You are allowed 1 page of handwritten notes (both sides). You have two (2) hours to complete as much of the exam as possible. Make sure to read all of the questions first, as some of the questions are substantially more time consuming.

Write all of your answers directly on this paper. *Make your answers as concise as possible.* On programming questions, we will be looking for performance as well as correctness, so think through your answers carefully. If there is something about the questions that you believe is open to interpretation, please ask us about it!

Problem	**Possible**	**Score**
1	22	
2	12	
3	16	
4	16	
5	16	
Total	82	

Problem 1: True/False [22 pts]

Please **explain** your answer in **two sentences or fewer** (Answers longer than this may not get credit!). Also, answers without an explanation ***get no credit***.

Problem 1a[2pts]: The number of allocated kernel stacks is always equal to the number of allocated userspace stacks.

☐ True x False

Explain:

If a process is running a user-level threading library, then there can be more stacks in userspace (one per user-level thread) than in the kernel (just on kernel thread for the process). Additionally, there are kernel threads that perform tasks entirely within the operating system and do not require a userspace stack.

Problem 1b[2pts]: When using a simple "Base and Bound" scheme to enforce memory protection, the CPU only sees virtual memory addresses.

☐ True x False

Explain:

This depends on how the Base and Bound scheme is implemented. If memory addresses are translated at run time (adding the Base value to each address referenced before it is passed on to the memory controller), then the CPU *does* only see virtual memory addresses. However, if instead a program's instructions are relocated at load time, then the CPU still uses physical addresses directly.

Problem 1c[2pts]: When fork returns a negative integer, an error has occurred that must be dealt with in both the parent and child process.

☐ True x False

Explain:

When fork returns a negative integer, an error has occurred, but no child process is actually created.

Problem 1d[2pts]: Switching between two threads within the same process is generally more efficient than switching between two threads belonging to different processes.

x True ☐ False

Explain:

Switching between two threads always requires changing the execution context (registers, stack pointer, program counter, etc.). For two threads belonging to different processes, the OS must also change the current address space, which incurs an additional cost.

Problem 1e[2pts]: The Linux Completely Fair Scheduler always gives a shorter time slice to lower priority threads.

☐ True x False

Explain:

Imagine we have three threads t1, t2, and t3 with weights 17, 2, and 1, with a latency target of 10ms and a minimum granularity of 1ms.

1. t1 gets a time slice of 17/(17+ 2 + 1) * 10 = 8.5 ms.
2. t2 gets a time slice of 2/(17 + 2 + 1) * 10 = 1 ms.
3. t3 gets a time slice of 1/(17 + 2 + 1) * 10 = 0.5ms ***except*** now the minimum granularity takes effect, and t3's time slice becomes 1ms.

Problem 1f[2pts]: When using an atomic operation like `test&set` to implement a lock, we must apply the `test&set` operation to check the lock's state (either `BUSY` or `FREE`) within a "spin loop."

☐ True x False

Explain:

This implementation would force the waiting thread to spin wait while the lock owner is in the critical section. Instead, we can use a `guard` variable in the lock's implementation, as demonstrated in lecture. We use `test&set` within a loop to check the value of `guard` rather than the lock's state. This means one thread will spin wait while any other thread is in the middle of `acquire` or `release`, but sleep on a queue while the lock's owner is inside the critical section.

Problem 1g[2pts]: Locks can prevent a thread from being preempted.

☐ True x False

Explain:

Locks do not prevent a thread from being preempted. Threads can be interrupted during a critical section. Locks only guarantee that the critical section is only entered by one thread at a time.

Problem 1h[2pts]: If the Banker's algorithm blocks a request for a resource, then granting that request would have caused the system to deadlock.

☐ True x False

Explain:

When the Banker's algorithm blocks a request, the system would have entered an *unsafe state* in which deadlock is possible, but not certain.

Problem 1i[2pts]: Synchronization primitives in base Pintos are implemented with `test&set`.

☐ True x False

Explain:

The synchronization primitives in `synch.c` are implemented by disabling interrupts.

Problem 1j[2pts]: According to the End-to-End Principle, reliable transport should be implemented by the two communications endpoints, not the network infrastructure.

x True ☐ False

Explain:

The End-to-End Principle states that many features should be implemented by end hosts on a computer network, rather than built in to the network infrastructure itself. Reliable transport is a good example of such a feature, and we saw how TCP achieves this in lecture.

Problem 1k[2pts]: After a call to `fork`, `stdin`, `stdout`, and `stderr` are reset to their default states in the child process.

☐ True x False

Explain:

A newly-forked child process inherits the file descriptors of its parents, including the descriptors for `stdin`, `stdout`, and `stderr`.

Problem 2: Short Answer [12 pts]

Problem 2a[3pts]: What is the Interrupt Vector Table and what role does it play in protecting the kernel?

The Interrupt Vector Table is a mapping from interrupt type (expressed as a number) to the proper handler for that interrupt (typically expressed as an address in memory to jump to). This ensures that we start executing kernel code only at predefined entry points.

Problem 2b[3pts]: Why are device drivers divided into a top half and bottom half? What is each half responsible for?

Device drivers execute on two separate occasions. First, the top half is invoked by the kernel's IO subsystem to issue a request to hardware, say to read or write data on a hard drive. Second, the bottom half is invoked by an interrupt handler, after the hardware has fulfilled the original request. The bottom half does the work required to copy data off of the device and back into kernel memory (this is usually not something we want to do within the interrupt handler itself).

Problem 2c[3pts]: In Pintos, how would we allow a `struct thread` to be an element of two lists at the same time?

We can allow this by adding a second `struct list_elem` member to `struct thread`.

Problem 2d[3pts]: Does First-Come First-Served or Round-Robin scheduling have lower overhead? Explain.

First-come first-served scheduling has lower overhead because it will require fewer context switches between threads. Because FCFS is non-preemptive, a context switch will only occur when one thread terminates and the scheduler needs to pick a new thread to run. Round-Robin scheduling is preemptive and will context switch between threads whenever the running thread's quantum has expired.

Problem 3: Processes and Syscalls [16 pts]

Assume that we have the following two pieces of code (with all header files included):

`write_and_print.c`, compiled to the binary file `write_and_print`

```
/* Takes a file descriptor (int) and a buffer (string) as input and
   writes the buffer into the provided file descriptor. ALSO prints
   out the buffer to stdout. */
```

`main.c`, compiled to the binary file `main`

```
int new_fd = -1;

void signal_handler(int sig) {
    dup2(new_fd, STDOUT_FILENO);
}

int main() {
    int hello_fd = open("greetings.txt", O_WRONLY | O_CREAT | O_TRUNC);
    char *child_buf = "Child hello!";
    char *parent_buf = "Parent howdy!";

    /* Assume char *arguments[] is correctly formed with ./write_and_print
       hello_fd, and child_buf as arguments */

    new_fd = dup(STDOUT_FILENO);
    dup2(hello_fd, STDOUT_FILENO);

    struct sigaction sa;
    sa.sa_flags = 0;
    sa.sa_handler = &signal_handler;
    sigemptyset(&sa.sa_mask);
    sigaction(SIGTERM, &sa, NULL);

    pid_t pid = fork();
    if (pid == 0) {
        execv(arguments[0], arguments);
        kill(getppid(), SIGTERM);
    } else {
        kill(pid, SIGTERM);
        wait(NULL);
        dprintf(hello_fd, "%s: %d\n", parent_buf, pid);
        printf("%s: %d\n", parent_buf, pid);
    }

    return 0;
}
```

List all possible outputs of the `main` program in each row of the table below (where one row corresponds to one run of the program). You may not need all the tables provided. Assume that all system calls succeed EXCEPT that `execv()` may possibly fail and assume that *the child's PID is 162*.

Standard Output	`greetings.txt`
Parent howdy!: 162	Parent howdy!: 162
Child hello!	Child hello! Parent howdy!: 162 Parent howdy!: 162
	Child hello! Child hello! Parent howdy!: 162 Parent howdy!: 162

Case 1: After the parent process forks, the child process fails to `execv`, prompting the child process to send a `SIGTERM` signal to the parent process. The parent process invokes `signal_handler()` upon returning, restoring file descriptor 1 to `stdout`. The parent process then prints **"`Parent howdy!: 162`"** to both `stdout` and `greetings.txt`.

Case 2: After the parent process forks, it continues execution and sends a `SIGTERM` signal to the child process. The parent process calls `wait`, context switching back to the child process. Upon executing, the child process invokes `signal_handler()` and restores file descriptor 1 to `stdout`. Thus, the child process prints **"`Child hello!`"** to both `stdout` and `greetings.txt`. When the parent process returns from

`wait`, it prints `"Parent howdy!: 162"` to `greetings.txt` twice because its file descriptor 1 never got restored to `stdout`.

Case 3:After the parent process forks, the child process continues execution and writes `"Child hello!"` twice to `greetings.txt`. The child then exits, context switching back to the parent process. The parent process sends a `SIGTERM` signal to zombie child process, which has no effect because the child process is no longer running. The parent process calls `wait`, returning right away. The parent process then prints `"Parent howdy!: 162"` twice to `greetings.txt`.

Common Mistakes:

- Students would often mix the output of `greetings.txt` with the output of `stdout`.
- Some students would print the parent process's greeting before the child process's greeting, but the `wait` call in the parent process prevents it from writing any output before the child process exits.

Problem 4: DeadLockList [16 pts]

Thanos needs to collect all 6 Infinity Locks. He creates a new structure called a `locklist` to manage the locks he has acquired or still needs. Instead of just acquiring one lock, threads now have to acquire a series of locks to 'lock' the `locklist` structure. Think of this as needing a collection of resources before being able to perform your operations. For all questions, assume the `locklist` has already been initialized for you and that we cannot preempt locks.

```
#DEFINE NUM_LOCKS 6
struct locklist {
      lock my_locks[NUM_LOCKS];
      int magic;
};
```

Problem 4a[2pts]: If all locks are released one after another with no other operations between them, does the sequence they are released in matter with respect to deadlock? *(Short Answer)*

No. There is no situation where unlocking locks can lead to deadlock. The thread has ownership over the locks already and is not waiting on a lock it does not own.

Problem 4b[2pts]: Does the lock release order matter with respect to performance? Explain. *(Short Ans.)*

Yes. Context switching is highly inefficient. If we unlock the locks in the same order we acquire them, there is the possibility that a different thread (also trying to lock the locklist structure) starts to acquire some of the locks before all are free. It would then partially acquire the locks in the locklist, but it wouldn't be able to finish. We would have to switch back to unlock the rest, which is very inefficient. If we unlocked it in reverse order of acquisition, no threads will be unblocked before.

Thanos is now trying to decide in what order to lock the Infinity Locks in the `locklist`. Which of the following definitions of `lock_locklist` can cause deadlock? Explain your answer for each selection. If deadlock is possible, please provide an acquisition ordering in your explanation.

Problem 4c[2pts]: Lock acquisition code:

```
void lock_locklist(struct locklist *list) {
      int start = 0;
      for (int i = start; i < NUM_LOCKS; i++) {
            int index = i;
            lock_acquire (list->my_locks + index);
      }
}
```

☐ Can Cause Deadlock x Cannot Cause Deadlock

Explain:

This *cannot* cause deadlock. The preference order for each thread is the same (acquiring lower indices first), so we will never cause deadlock.

Problem 4d[2pts]: Lock acquisition code:

```
void lock_locklist(struct locklist *list) {
      int start = getpid() % NUM_LOCKS;
      for (int i = start; i < start + NUM_LOCKS; i++) {
            int index = i % NUM_LOCKS;
            lock_acquire (list->my_locks + index);
      }
}
```

x Can Cause Deadlock ☐ Cannot Cause Deadlock

Explain:

Example: thread 1 acquires lock 1, thread 2 acquires lock 2. Thread 1 blocks waiting for lock 2. Thread 2 acquires locks 3-5, but blocks on acquiring lock 1.

This *can* cause deadlock. The preference order for each thread is different, so we acquire locks in different orders and can end up with deadlock.

Problem 4e[2pts]: Lock acquisition code:

```
void lock_locklist(struct locklist *list) {
      int start = NUM_LOCKS - 1;
      for (int i = start; i >= 0; i--) {
            int index = i;
            lock_acquire (list->my_locks + index);
      }
}
```

☐ Can Cause Deadlock x Cannot Cause Deadlock

Explain:

This *cannot* cause deadlock. The preference order for each thread is the same (acquiring higher indices first), so we will never cause deadlock.

Problem 4f[2pts]: Lock acquisition code:

```
void lock_locklist(struct locklist *list) {
      int start = NUM_LOCKS/2;
      for (int i = start; i < start + NUM_LOCKS; i++) {
            int index = i % NUM_LOCKS;
            lock_acquire (list->my_locks + index);
      }
}
```

☐ Can Cause Deadlock x Cannot Cause Deadlock

Explain:

This *cannot* cause deadlock. The preference order for each thread is the same (starting from the middle indices first), so we will never cause deadlock.

Thinking about how much work it will take to lock the `locklist` structure, Thanos doesn't always want to go through the trouble of acquiring all the Infinity Locks. He decides to create the following function to access the structure faster, acquiring just one lock and later releasing it. **Assume all other threads execute the code from problem 4c when using the `locklist`.**

```
void snap(struct locklist *list) {
      lock_acquire (list->my_locks + OFFSET);
}
```

Problem 4g[2pts]: If `OFFSET = 0`, can `snap` cause deadlock to happen? If so, provide an example execution order that leads to deadlock. If not, explain why deadlock is not possible. *(Short Answer)*

Deadlock is not possible. Since `snap` is only acquiring one lock, its order of preference will always be consistent with the other threads. This means having this function will not cause deadlock.

Problem 4h[2pts]: If `OFFSET = NUM_LOCKS - 1`, can `snap` cause deadlock to happen? If so, provide an example execution order that leads to deadlock. If not, explain why deadlock is not possible. *(Short Answer)*

Same as the previous answer.

Problem 5: Just One TCP Connection [16 pts]

Bob is trying to build a system which helps people process jobs. After learning about how sockets work in CS162, he wants to write a server program which listens on port 162 and takes jobs from clients. Each job is represented by the following data structure:

```
struct Job {
   int job_number;
   char job_details[200];
   int result;
};
```

However, Bob thinks that having clients make a new connection for each job they want the server to process seems to be an inefficient design because it consumes resources unnecessarily.

For 5a and 5b, full points are awarded to answers which have demonstrated not only correct conceptual understandings but also clarity in the expression. Students need to both *identify the resource constraints* and then elaborate on *why establishing new connections will consume that scarce resource*.

Problem 5a[2pts]: Briefly explain why establishing new connections consumes additional resources *in userspace.*

Acceptable answers include: More memory needed to manage the connection (e.g., `int` for the file descriptor), more *userspace* buffers to store contents sent to or received from each connection, and potentially more threads to work with connections concurrently, which consumes memory.

Common Mistakes:

1. Not clear about the scarce resource. e.g. Memory, CPU time, bandwidth, disk, ...
2. We do not consider the time taken to process a new user connection as a resource. You have to point out clearly that the CPU time is the scarce resource here
3. When talking about buffer, answers need to highlight that they are referring to *userspace* buffer
4. TCP state management (e.g. ACK, retries, seq number …) is in the kernel space
5. “because we need to establish sockets” is too vague

Problem 5b[2pts]: Briefly explain why establishing new connections consumes additional resources *in the OS kernel.*

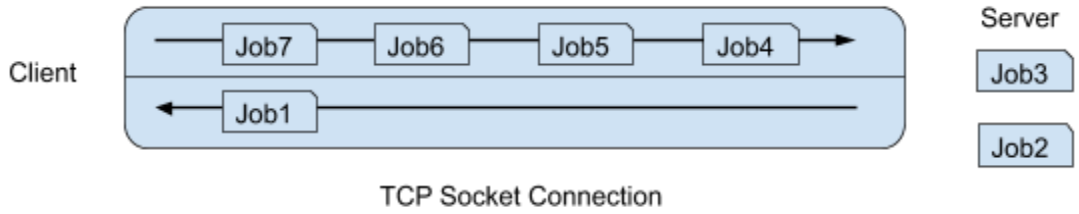
Acceptable answers include: More elements in the process’s file descriptor table, more elements in the OS-wide file description table, and more *kernel* buffers to store data sent to or received from the network interface card.

Common Mistakes:

1. Unclear about the scarce resource. e.g. Memory, CPU time, bandwidth, disk, ...
2. Discussions of an “inode table” are not relevant, as this is a network socket.
3. Statements like “the OS needs to do more work” do not specify a scarce resource
4. Some answers mentioned additional interrupts but did not specify where they would come from

Bob comes up with a scheme where the server just needs to maintain, for each client, a single connection through which multiple jobs can be sent and through which processed jobs can be sent back. More specifically, *each connection is managed by one thread* and *whenever a new job is received, a new thread is created to do the work in parallel and then send back the results via the same connection*.

Graphically, it looks like this:



Problem 5c[2pts]: Bob approaches you for help with implementing his design. He's done most of the coding but left out some critical functions. You are required to fill in the missing lines below. Note that you might not need all the lines provided.

Assumptions:

1. When you call `ssize_t read(int fd, void *buf, size_t count)`, it always reads `count` bytes if there is data available. Otherwise, the call blocks.
2. When you call `ssize_t write(int fd, const void *buf, size_t count)`, it always writes `count` bytes successfully. You do not have to handle the case when `read` fails because of client disconnection.

```
1. struct Job {
2.     int job_number;
3.     char job_details[200];
4.     int result;
5. };
6.
7. struct Arg_struct{
8.    Job *job;
9.    int socket_fd;
10.}
11.
12.void do_work (struct Job *job) {
13.   /* This function does the work and set the result back into job */
14.   /* This function is compute-intensive */
15.}
16.
17.void *new_conn(void *arg) {
18.   /* Handles a new client connection */
19.   struct  Job         *new_job;
20.   struct  Arg_struct  *new_args;
21.   ssize_t bytes_read;
22.
23.   int  con_sockfd = (int) arg;
24.   while (1) {
```

```
25.
26.     new_job = malloc(sizeof(struct Job));
27.
28.     bytes_read = read(con_sockfd, new_job, sizeof(struct Job));
29.
30.     new_args = malloc(sizeof(struct Arg_struct));
31.
32.     new_args->job = new_job;
33.     new_args->socket_fd = con_sockfd;
34.     pthread_create(&thread, NULL, process_job, (void*) new_args);
35.   }
36. }
37. void *process_job(void *arg) {
38.   struct Arg_struct *new_args = (struct Arg_struct*) arg;
39.
40.   /* Do the work by calling do_work() and send back response */
41.
42.   do_work(new_args->job);
43.
44.   write(new_args->socket_fd, new_args->job, sizeof(struct Job));
45.
46.
47.
48.
49.   /* Free resources */
50.
51.   free(new_args->job);
52.
53.   free(new_args);
54.
55. }
56.
57. /* Code Segment in main() */
58. /* Assume bind() and listen() have been called */
59.
60. while (1) {
61.   /* When a new client connects */
62.
63.   con_sockfd = accept(lstn_sockfd, NULL, NULL);
64.   pthread_create(&thread, NULL, new_conn, (void*) con_sockfd);
65. }
66.
67. close(lstn_sockfd);
```

Common Mistakes:

1. For `sizeof`, the argument must be `struct Job`, not just `Job`.
2. Many answers did not `read`/`write` the whole struct. For example, `job_number` is an important field to return to the client as well. Since the client is submitting jobs asynchronously, the client needs to generate a client-side id to keep track of the new jobs sent and completed jobs received. The idea of client-side ids is important in RPC calls.
3. Students should read clearly what each function reads and returns.

After you are done writing the program, you realize that it doesn't work. Clients are receiving gibberish when they try to read each struct that is sent back. You show it to master systems programmer Jeff Dean, who sees two problems in the code that cause the program to fail.

Firstly, the assumptions that `read` and `write` will always return `count` bytes do not hold. In fact, these sys calls often read/write fewer than `count` bytes before returning.

Problem 5d[2pts]: Provide a reason why a `write` system call might write fewer than count bytes.
The `write` system call may be interrupted while in progress by a signal, in which case some of the requested bytes will not be written.
Common Mistakes:

1. `\x00` does not stop the write call from continuing.
2. If the user buffer passed in as the argument for `write` is shorter than `count`, this could lead to access of an invalid portion of memory and cause the program to crash.

Problem 5e[2pts]: To solve this problem, Bob proposes writing a new function with the signature:

```
write_bob(int fd, const void* buf, size_t count)
```

`write_bob` makes use of `write` syscall in its implementation and makes sure that it always writes `count` bytes before returns. Provide an implementation for `write_bob`:
Hint: If `write` returns 3, then 3 bytes are already written. You don't have to write them again.

```
void write_bob(int fd, const void *buf, size_t count) {
  char *buffer = (char*) buf;
  /* Your code below */
  while (bytes_written < count){
    bytes_written += write(fd, buffer + bytes_written, count - bytes_written)
  }
```

Common Mistakes:

1. Arithmetic on a `void` pointer is invalid. Therefore, `buffer`, instead of `buf`, should be used. To make things simpler, we cast the pointer for you on the first line as a hint.
2. Making the `write` call twice doesn't guarantee successful writing of the full buffer. Even repeating `write` ten times may not work.
3. Do not `write` again whatever is already written.
4. This function returns `void`, so there is no need to return an integer.
5. `fflush` and `fsync` are not relevant in this context.

Your temporary variable should use `ssize_t` instead of `int`. Otherwise there could be a buffer overflow vulnerability. However, we did not deduct points for this.

Problem 5f[3pts]: Jeff Dean points out a new problem with the code, because the threads share the same connection socket. Bob proposes solving this problem with a mutex lock. List between which of the lines above you need to add `lock_acquire()` and `lock_release()` with a global mutex to solve Jeff's problem. For instance, if you needed a `lock_acquire()` between lines 1 and 2, you would write (1, 2) under `lock_acquire()` below. *You may not need all six spaces.*

`lock_acquire()`

(_____43_____, _____44_____) (_____, _____) (_____, _____)

`lock_release()`

(_____44_____, _____45_____) (_____, _____) (_____, _____)

You must acquire a lock before the call to `write` and release it after the `write`.

We took away one point if any unnecessary locks were added. Locking around `read` is unnecessary since only a single thread is reading from that connection. This, however, is not true for `write`.

Problem 5g[3pts]: Bob successfully builds the server above, but his computer is slow, and can only handle up to 5 jobs being processed concurrently per connection. Jeff proposes a solution where a semaphore would block new jobs from being processed if 5 other jobs are already being processed, and only allow new jobs to start once an existing job is finished. Assume each thread has a semaphore initialized to 5 and that the line numbers are as originally (ignore the lock operations above). List between which lines you need to add `sema_up()` and `sema_down()` to allow only up to 5 jobs to be concurrently processed per connection.

`sema_down()`

(_____41_____, ____42_____) (_____, _____) (_____, _____)

`sema_up()`

(_____42_____, _____43_____) (_____, _____) (_____, _____)

Call `sema_up` before `do_work` and call `sema_down` after `do_work`.

We took away one point if any unnecessary semaphores were added. If the unnecessary semaphores have the potential to cause deadlock, the answer was not given any points.

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[Scratch Page: Do not put answers here!]