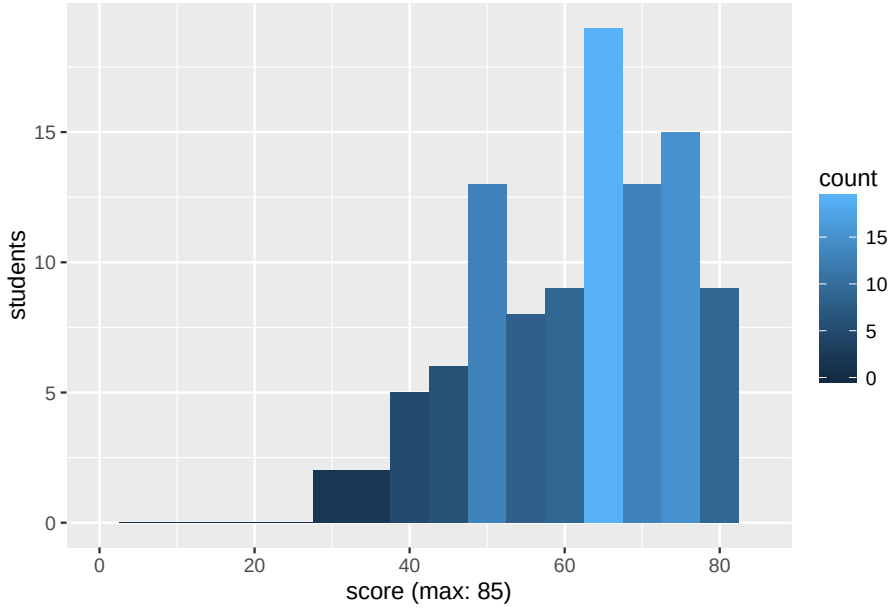
Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

6.828 Fall 2016

Quiz II Solutions

Mean 61.5 Median 63.0 Standard deviation 12.6 Kurtosis -0.69



I Logging

```
1  inMemoryLog = {}
2
3  def log_flush():
4      i = 0
5      for (a, v) in inMemoryLog.iteritems():
6          if i >= LOGSIZE: return None
7          disk_write(LOGSTART + i, v)
8          logHeader.sector[i] = a
9          i = i + 1
10     logHeader.len = len(inMemoryLog)
11     return logHeader
12
13 def log_apply():
14     for (a, v) in inMemoryLog.iteritems():
15         disk_write(a, v)
16
17 def log_commit():
18     logHeader = log_flush()
19     if logHeader is None: return False
20     disk_sync()
21     disk_write(COMMITBLOCK, logHeader)
22     disk_sync()
23     log_apply()
24     disk_sync()
25     logHeader.len = 0
26     disk_write(COMMITBLOCK, logHeader)
27     disk_sync()
28     inMemoryLog = {}
29     return True
30
31 def log_recover():
32     logHeader = disk_read(COMMITBLOCK)
33     for i in range(0, logHeader.len):
34         v = disk_read(LOGSTART + i)
35         disk_write(logHeader.sector[i], v)
36     disk_sync()
37     logHeader.len = 0
38     disk_write(COMMITBLOCK, logHeader)
39     disk_sync()
```

The pseudo-code above replicates the key functions of the logging system from Figure 14 in the paper *Using Crash Hoare Logic for Certifying the FSCQ File System*. The logging system guarantees that if a transaction successfully commits, then all the blocks modified by the transaction will be installed or none.

The intended use is that every system call is wrapped in a transaction, starting with a call to `log_begin` and ending with a call to `log_commit`. `disk_write` writes a block to the disk's non-persistent buffer. `disk_sync` tells the disk to flush its internal buffer to the persistent storage medium; when `disk_sync` returns, the disk has finished writing its internal buffer to persistent storage.

1. [5 points]: The Linux ext3 file system as described in the paper *Journaling the Linux ext2fs Filesystem* also wraps system calls inside a transaction, but provides different persistence guarantees. Briefly explain the difference between the persistence guarantees of the pseudo-code above and ext3. You should assume ext3 journals both file contents and meta-data.

Answer: For the pseudo-code given, if a system call returns, then its changes are guaranteed to be persisted on disk, and to be present after a reboot. In contrast, Linux ext3 defers persisting the effects of a system call until later (i.e., after a `(f)sync`).

Ben Bitdiddle observes that `disk_sync` takes a long time, so he deletes the `disk_sync` at line 27. He reasons that erasing the commit record on disk isn't really necessary after the transaction has already completed.

2. [5 points]: Give an example scenario that demonstrates that Ben's change will break the correctness of the logging system. (Briefly explain your answer)

Answer: A transaction writes some entries to the log, and commits. A second transaction writes some of its blocks to the on-disk log but the computer crashes before writing the commit record (i.e., on line 20). On recovery, the code will read the old commit record, and install blocks from the log (which contains the second transaction's writes), because it reads the length from `logHeader` of the previous transaction. This violates correctness, because that transaction didn't commit.

II Scalable locks

After reading the paper *Non-scalable locks are dangerous*, Ben is excited by scalable locks. But studying the lecture notes and 6.828 quizzes from previous years, he is intimidated by the complexity of MCS locks. He considers a simpler scalable lock design:

```
1  struct lock {
2    struct alock {
3      int x;
4    } __attribute__ ((aligned (CACHELINE)));
5    struct alock has_lock[NCORE];
6    unsigned int next_slot;
7  }
8
9  void init(lock *l) {
10   for (int i = 0; i < NCORE; i++)
11     l->has_lock[i].x = 0;
12   l->has_lock[0].x = 1;
13   next_slot = 0;
14 }
15
16 int acquire(lock *l)
17 {
18   int me = fetch_and_add(&l->next_slot, 1);
19   me = me % NCORE;
20   while(l->has_lock[me].x == 0)
21     ;
22   l->has_lock[me].x = 0;
23   return me;
24 }
25
26 void release(lock *l, int me)
27 {
28   l->has_lock[(me + 1) % NCORE].x = 1;
29 }
```

Ben's implementation assumes there is one thread per core. Each lock has as many `alock` structures as there are cores. Each `alock` is on a separate cache line. `fetch_and_add` is an atomic instruction that atomically increments `next_slot` and returns the previous value.

A core is supposed to use the lock as follows:

```
1    struct lock l;
2    int me;
3
4    init(&l);  // call once for a lock
5
6    me = acquire(&l);
7    // critical section
8    release(&l, me);
```

You should assume that the compiler and the processor do not eliminate or re-order memory references. You can also assume that `next_slot` is on a separate cache line.

3. [5 points]: Ben runs a sequence of experiments with increasing numbers of cores that all continuously acquire and release the same lock. Ben observes that his lock doesn't experience a performance collapse. Instead, the lock is scalable: the number of acquires (and releases) completed per second stays roughly constant regardless of the number of cores. Explain why, focusing on cache line transfers.

Answer: Each core spins on a separate cache line in `acquire`. `release` results in constant number of cache line transfers, independent of the number of cores waiting for the lock.

4. [5 points]: What is a downside of Ben's lock compared to a single spinlock? Explain your answer.

Answer: Space overhead

III Refcache

Figure 2 in the *RadixVM: Scalable address spaces for multithreaded applications* paper describes the refcache algorithm to implement scalable reference counters. Ben Bittdiddle finds it difficult to understand this code and implements a different plan. The following code gives his scalable implementation for a distributed reference counter for a single object.

```
1   struct obj *p;
2   int counter[NCORE];
3
4   void allocref() {
5     p = malloc(sizeof(*p));
6     counter[mycore()] = 1;
7     return p;
8   }
9
10  struct obj *getref() {
11    counter[mycore()]++;
12    return p;
13  }
14
15  void releaseref() {
16    counter[mycore()]--;
17    if (counter[mycore()] == 0 && isZero()) {
18      free(p);
19    }
20  }
21
22  bool isZero() {
23    int sum = 0;
24
25    for (int i = 0; i < NCORE; i++) {
26      sum += counter[i];
27    }
28    return sum == 0;
29  }
```

You can assume that there is exactly one thread per core. Each core maintains a local counter for the object referenced by `p` in the array `counter`. A single core calls `allocref` to initialize the counter. Before another core uses `p`, it calls `getref`, increasing its local counter. If a core is done with the object, it calls `releaseref`, decreasing its local counter. If the local counter is 0, `releaseref` checks if the object can be freed using `isZero`, which sums up all the per-core counters and checks if the sum is 0.

5. [5 points]: Can Ben's reference counter code cause the object to be freed even though there are still references to it? Explain your answer.

Answer: Yes. Suppose, before `isZero()`, `count[0]` is zero, `count[1]` is 1, and `count[2]` is 1. Core 2 calls `releaseref()` and then `isZero()`. `isZero()` sees `count[0] == 0`. Then, core 0 calls `getref()` and core 1 calls `releaseref()`. Then `isZero()` proceeds and sees `count[1] == 0` and `count[2] == 0`. `sum` will be zero, and `releaseref()` will free the object even though core 1 has a reference!

IV Dune

Suppose an application running as a Dune process has virtual address v_1 mapped to a page of memory allocated from the kernel.

6. [5 points]: What does the application have to do to create a second virtual address v_2 that refers to the same memory?

Answer: The Dune process has an x86 page table which it can modify directly. It only needs to update the PTE for v_2 to refer to v_1's "guest-physical" address, obtained from the kernel when it was allocated. No interaction with the Dune kernel (i.e., the VM host) is necessary.

V Singularity

Ben is implementing a file server as a SIP in Singularity. It will talk to client SIPs on the same machine through Singularity channels. Ben would like his file server to maintain a cache of file blocks. Because some files need to be read by many applications, Ben would like each cached block to be useable by multiple clients without having to copy it.

7. [5 points]: Explain why this is difficult to achieve in Singularity.

Answer: Singularity only allows SIPs to share memory via the exchange heap. But there can be only one reference to any given object in the exchange heap. Ben's file server can store cached blocks in the exchange heap, and give a cached block to the first client that asks for it without copying, but the file server is not allowed to retain a reference to that block, so as to be able to give it to a second client. Ben's file server could keep the cached block in its private memory, and make a new copy in the exchange heap for each client that asks for it, but that would not achieve Ben's goals of no copying.

Consider the bar marked "Add Ring 3" in Figure 5 of the Singularity paper. This bar reflects the run-time of the benchmark with the client SIP running at CPL=3. The run-time is noticeably longer than if the client SIP runs at CPL=0 (the "Add Separate Domain" bar).

8. [5 points]: Explain why the system is slower when the client SIP runs with CPL=3 rather than CPL=0.

Answer: At `CPL=3`, each system call involves an `INT` instruction and a stack switch, which take time. At `CPL=0` each system call is an ordinary function call, with no stack switch.

VI IX

Consider the paper *IX: A Protected Dataplane Operating System for High Throughput and Low Latency*, by Belay *et al.*

In the experiment in the paper's Section 5.2 (Figure 2), for a message size of 20 kilobytes, the client sends 20 kilobytes, and then the server sends a 20-kilobyte reply. The experiments use 1500-byte packets, so a 20-kilobyte message consists of roughly 14 packets.

9. [5 points]: How many transitions between IX and the application (ring 0 and ring 3 in Figure 1) does the server make in receiving and replying to one 20-kilobyte message? Briefly explain your answer.

Answer: It depends on the batch size, and on how many packets arrive before the server's polling notices them. The minimum possible is two: one for run_io() to give all 14 received packets to ring 3, and one for the next run_io() to pass a 14-packet reply to IX at ring 0.

10. [5 points]: IX requires use of a NIC that supports multiple independendent hardware DMA queues (called Receive Side Scaling (RSS)). Explain how IX benefits from these multiple queues. **Answer:**

IX uses the multiple queues to help avoid lock and cache-line contention between cores in the IX network stack, to allow different applications to each have direct access to the NIC without interfering with each other, and to deliver packets direct to each application while ensuring that each application only sees its own packets.

VII Lab 4

Alyssa P. Hacker is working her way through the Copy-on-Write fork implementation in Lab 4. When she gets to the part on setting up user-level pagefault handling, she feels that it is silly to have two separate stacks—a normal stack and a user exception stack—for every environment. So she decides to have a single stack instead. Her implementation uses this single stack for both application code and exception handling. Her fork implementation maps the page of this single stack COW.

11. [5 points]: Explain what will go wrong with Alyssa's single stack scheme.

Answer: If the fork implementation treats the normal stack page as copy-on-write, and the user-level pagefault handler runs on the same stack, then this can result in endless recursive pagefaults before the kernel eventually kills the environment. This occurs because, at a minimum, the user-level pagefault handler has to invoke system calls to modify page-mappings. However, any function call writes to the stack (by pushing the return address, for instance). Since the stack is marked as copy-on-write, this causes a pagefault, thus transferring control back to the beginning of the user-level pagefault handler, and this repeats indefinitely.

Ben Bitdiddle decides to change the success return value of sys_ipc_recv() from zero to 0x6828. So he modifies his kernel to look like this:

```
static int
sys_ipc_recv(void *dstva)
{
        if ((dstva < (void*)UTOP) && ((uint32_t)dstva % PGSIZE != 0))
                return -E_INVAL;
        curenv->env_ipc_recving = 1;
        curenv->env_ipc_dstva = dstva;
        curenv->env_status = ENV_NOT_RUNNABLE;
        sched_yield();
        return 0x6828; // success!
}
```

12. [5 points]: Explain why this change will **not** cause 0x6828 to be returned from a successful call to sys_ipc_recv().

Answer: The return statement in `sys_ipc_recv()` is never executed. The call to `sched_yield()` in `sys_ipc_recv()` transfers control to the scheduler, which eventually runs the receiving environment by calling `env_run()`. `env_run()` resumes the execution of that environment *in user space* by restoring the CPU's registers with the trap-frame values that were saved when that environment last trapped into the kernel. This includes the `eax` register, whose value is the return value from the system call.

Ben modifies the sys_ipc_try_send() system call implementation to keep trying until the send succeeds, instead of returning an error if the target environment isn't ready. Here's his code:

```
static int
sys_ipc_try_send(envid_t envid, uint32_t value, void *srcva, unsigned perm)
{
  while (do_ipc_try_send(envid, value, srcva, perm) == -E_IPC_NOT_RECV)
    ;

  return 0;
}
```

`do_ipc_try_send` tries to deliver the IPC to the destination environment. When he runs the pingpong program, however, it hangs.

13. [5 points]: Explain why Ben's modification causes the program to hang.

Answer: If the destination of the IPC has not invoked `sys_ipc_recv()` yet, `sys_ipc_send()` retries indefinitely while still executing in the kernel. But since JOS uses a big kernel lock to ensure that only one environment can execute in the kernel at a time, the destination environment will never get to execute the `sys_ipc_recv()` system call. Therefore `sys_ipc_send()` will be stuck forever in the kernel, resulting in the hang.

VIII Lab 5

14. [5 points]: Ben Bitdiddle is working on exercise 7 of lab 5, and is writing up his implementation of the `sys_env_set_trapframe` syscall. He proudly shows his code to Alyssa. Alyssa promptly points out that his code is wildly insecure since he doesn't do any checks on the values set in the user trapframe. Ben is skeptical that this is actually a problem, and stubbornly challenges Alyssa to find a way to use `sys_env_set_trapframe` to give an environment privileges it wouldn't normally have. Describe how Alyssa might construct a malicious trapframe, and what privileges this trapframe would give to an environment.

Answer: She could set the CPL of the code segment selector to 0, which lets the environment read and write kernel memory. She could not enable interrupts in an environment, letting it perform a denial of service attack by going into an infinite loop. She could set the `FL_IOPL` eflag to let an environment directly access and modify the jos boot disk, potentially changing the kernel such that permission checks are removed after a reboot.

Ben is on exercise 3, and is having issues with his implementation of `alloc_block`. Here is the full code of Ben's implementation:

```
int
alloc_block(void)
{
  uint32_t i, blockno;
  for (i = 0; i < BLKSIZE; i++) {
    if (bitmap[i] != 0) {
      // assume this correctly identifies the first free block
      blockno = 32*i + (32 - __builtin_clzl(bitmap[i])-1);
      break;
    }
  }
  // assume this correctly sets the bit corresponding to blockno
  bitmap[blockno/32] ^= (1<<(blockno%32));
  return blockno;
}
```

15. [5 points]: When he runs the tests, he observes that the disk never seems to fill (i.e., `alloc_block` always returns a block number). Not even for the tests that are designed to write enough to fill the disk. What check is Ben's code missing?

Answer: Ben is not checking that `blockno` is not past the end of the disk, as indicated by `super->s_nblocks`. Note that it is *not* sufficient for Ben to return `-E_NO_DISK` when `i == BLKSIZE` after the loop, because that will likely still be beyond the real size of the disk.

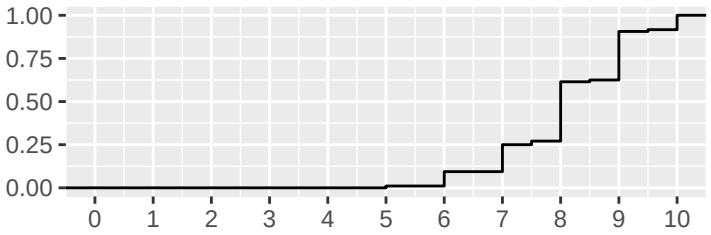
16. [5 points]: When Ben runs the persistence tests with the code above, he observes that after a reboot, certain file system operations corrupt data in entirely unrelated files. In particular, appends to an existing file, or creating and/or writing to a new file, exhibit this behavior, but modifying the blocks of an existing file does not. What is causing this mysterious issue?

Answer: Ben is not flushing the bitmap with `flush_block(bitmap)`, so after a reboot his file system may start to give out occupied blocks as free (since they aren't marked as busy in the on-disk bitmap).

IX 6.828

We'd like to hear your opinions about 6.828, so please answer the following questions. (Any answer, except no answer, will receive full credit.)

17. [1 points]: Grade 6.828 on a scale of 0 (worst) to 10 (best)?



Answer:

18. [2 points]: Any suggestions for how to improve 6.828?

Answer:
Labs: 11x less hand holding, 8x less boilerplate code, 8x better code review/feedback, 5x more test cases, 4x release reference code, 3x list of common mistakes, 2x more focus on design, 2x more final project idea suggestions

Homework: 3x less of it, 2x more feedback, 2x not 10pm deadline

Readings: 4x fewer, but in more depth, 3x more in depth (discussion/recitations), 2x more guidance, 2x make more interesting, 2x connect back to XV6 and JOS

Lectures: 11x clearer lecture notes, 6x lecture videos, 3x shorter, 3x relate to the lab, 2x better JOS lectures, 2x revist the big picture, 2x better TA lectures

Other: 6x have recitations, 3x no exams, 2x grades are unclear

19. [1 points]: What is the best aspect of 6.828?

Answer: 71x labs, 14x building/understanding OS, 11x papers, 5x staff, 3x lectures, 3x freedom of lab 6, 2x office hours, 2x material

20. [1 points]: What is the worst aspect of 6.828?

Answer: 34x debugging (incl. debugging previous labs), 27x quizzes, 9x long papers, 4x time/amount of work, 3x confusing papers, 3x classroom (1-190), 3x pre-class assignments, 3x forgetting about pre-class assignments, 2x fast pace, 2x early question deadlines, 2x long lectures, 2x code reviews, 2x hand-holding in labs, 2x reading manuals, 2x amount of HW

End of Quiz II