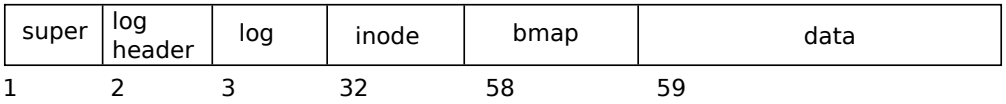
Principles of Operating Systems **Name (Print):** _____
Winter 2017
Final
03/22/2017
Time Limit: 8:00am - 10:00am

- **Don't forget to write your name on this exam.**
- **This is an open book, open notes exam. But no online or in-class chatting.**
- **Ask me if something is not clear in the questions.**
- **Organize your work**, in a reasonably neat and coherent way, in the space provided. Work scattered all over the page without a clear ordering will receive very little credit.
- **Mysterious or unsupported answers will not receive full credit**. A correct answer, unsupported by explanation will receive no credit; an incorrect answer supported by substantially correct explanations might still receive partial credit.
- If you need more space, use the back of the pages; clearly indicate when you have done this.

Problem	Points	Score
1	20	
2	10	
3	20	
4	20	
5	15	
6	5	
Total:	90	

1. File system

   Xv6 lays out the file system on disk as follows:



   Block 1 contains the super block. Blocks 2 through 31 contain the log header and the log. Blocks 32 through 57 contain inodes. Block 58 contains the bitmap of free blocks. Blocks 59 through the end of the disk contain data blocks.

   Ben modifies the function bwrite in bio.c to print the block number of each block written.

   Ben boots xv6 with a fresh fs.img and types in the command ln cat cat2. This command creates a symbolic link cat2 to file cat. This command produces the following trace:

```
$ ln cat cat2
write 3
write 4
write 2
write 32
write 59
write 2
$
```

   (a) (5 points) Why is block 2 written twice?

   Block 2 is written first time to record the fact that two blocks are in the log, i.e. the inmemory log header is written to disk. After the entire log is installed, the header is updated the second time to indicate the fact that transaction is fully commited, and no recovery is needed in case of a system crash.

   (b) (5 points) Briefly explain what block 32 contains in the above trace. Why is it written?

   Block 32 contains the inode for the cat file. Since we're creating a simbolic link, the inode reference count is incremented to 2 (the same inode is referenced by both "/cat" and "/cat2", and is written back to disk.

(c) (5 points) What does block 3 contain?
Block 3 contains the copy of block 32, i.e., the inode that contains "/cat" and "/cat2"

(d) (5 points) If writes to 32 and 59 are reordered like below, will it violate correctness of the file system, explain why?

```
$ ln cat cat2
write 3
write 4
write 2
write 59
write 32
write 2
$
```

No, since we install all the writes atomically, i.e., all or none, the write order doesn't matter.

2. Memory management.

   (a) (5 points) Explain organization of the xv6 memory allocator.

   The xv6 memory allocator is implemented as a linked list of pages. On allocation, an element of the list that is pointed by the head pointer is removed from the list. The virtual address of the list element is used as the allocated address and is returned to the caller.

   (b) (5 points) Why do you think xv6 does not have buddy or slab allocators? Under what conditions you would have to add these allocators to the xv6 kernel?

   Xv6 doesn't implement buddy and slab allocators, since it doesn't really allocate any memory for kernel data structures. I.e., all data structures used by the kernel are statically preallocated as arrays with max number of elemements, e.g.,

   ```
   struct proc proc[NPROC];
   ```

   Xv6 allocates only pages of memory for user-level processes, kernel stacks, and page tables. If xv6 allocated kernel data structures dynamically, it would require a hierarchy of allocators, malloc on top of slab, on top of buddy to serve allocations of variable size.

3. Synchronization

   (a) (10 points) The code below is the xv6's sleep() function. Remember the whole idea of passing a lock inside sleep() is to make sure it is released before the process goes to sleep (otherwise it will never be woken up). However, it looks like that if the lock passed inside sleep is ptable.lock (i.e., lk == &ptable.lock) the lock remains acquired and is never released. But xv6 does call sleep with ptable.lock as an argument and it works, can you explain why?

```
2806 // Atomically release lock and sleep on chan.
2807 // Reacquires lock when awakened.
2808 void
2809 sleep(void *chan, struct spinlock *lk)
2810 {
2811   if(proc == 0)
2812     panic("sleep");
2813
2814   if(lk == 0)
2815     panic("sleep without lk");
2816
2817   // Must acquire ptable.lock in order to 2818   // change p>state and
2818   // change p>state and then call sched.
2819   // Once we hold ptable.lock, we can be
2820   // guaranteed that we wont miss any wakeup
2821   // (wakeup runs with ptable.lock locked),
2822   // so its okay to release lk.
2823   if(lk != &ptable.lock){
2824     acquire(&ptable.lock);
2825     release(lk);
2826   }
2827
2828   // Go to sleep.  2829   proc>chan = chan; 2830   proc>state =
2829   proc>chan = chan;
2830   proc>state = SLEEPING;
2831   sched();
2832
2833   // Tidy up.
2834   proc>chan = 0;
2835
2836   // Reacquire original lock.
2837   if(lk != &ptable.lock){
2838     release(&ptable.lock);
2839     acquire(lk);
2840   }
2841 }
```

The caller of sleep always holds the ptable.lock. Moreover, all callers of sched() also hold the ptable.lock. Hence, there is no need to reaquire it again (it would result in a deadlock anyway), but no matter where we context switch to with sched() the ptable.lock will be released.

(b) (10 points) Alyssa runs xv6 on a machine with 8 processors and 8 processes. Each process calls uptime() (3738) system call continuously, reading the number of ticks passed since boot. Alyssa measures the number of uptime() system calls per second and notices that 8 processes achieve the same total throughput as 1 process, even though each process runs on a different processor. Why is the throughput of 8 processes the same as that of 1 process?

Uptime() acquires the tickslock lock. Hence, all 8 processes are serialized, i.e., one is reading the ticks variable, and 7 others are waiting for the lock. Of course, reading ticks counter takes only 1 cycle, and Alyssa will see some speed up, but not a lot. The process that wins the lock, reads the counter, exits to user-space and returns back to the kernel (around 400 cycles) to wait on the lock again (on average waiting for 7*time-to-acquire-and-release-the-lock cycles, which depending on the architecture can take 240-620 cycles).

4. Scheduling

   (a) (10 points) You would like to extend xv6 with priority based scheduler, i.e., each process has a priority, and processes with a higher priority are scheduled first. Write the code for your implementation below (which xv6 functions need to be changed?)

   Implement the Linux O(1) scheduler.

```
struct proc* sched_next() {
  int i;

  do {
    // Loop through the priority array starting from the
    // highest priority
    for (i = MAX_PRIORITY - 1; i--; i >= 0) {
      if(current->prio[i]->head ! = 0) {
        p = current->prio->[i]->head;
        current[i]->head = current->prio[i]->head->next;
        break;
      }
    }

    if(p != 0)
      return p;

    // No processes in the current queue
    // flip current and expried queues
    tmp = current;
    current = expired;
    expired = tmp;

    // we believe there is always one non-sleeping process
    // now we'll definitely find something
  } while (1);

  return 0;
}

// Put the process in expired queue
void sched_put(struct proc *p) {
  p->next = expired->prio[p->prio]->head;
  expired->prio[p->prio]->head = p;
  return;
}

scheduler(void)
{
  struct proc *p;
  for(;;) {
    sti();
```

```
    acquire(&ptable.lock);
    // get the next process to run
    p = sched_next();
    proc = p;
    switchuvm(p);
    p->state = RUNNING;
    swtch(&cpu->scheduler, p->context);
    switchkvm();
    proc = 0;
    // put the process back
    sched_put(p);
    release(&ptable.lock);
  }
}
```

(b) (10 points) Now you would like to extend your priority scheduler with support for interactive tasks, e.g., a task that spends a lot of time waiting, should run first (i.e., receive priority boost). Provide code that handles waiting tasks and implements priority boost (again, just change related xv6 functions).

```
// Put the process in expired queue but now with a boost
void sched_put(struct proc *p) {
  p->next = expired->prio[p->prio + p->boost]->head;
  expired->prio[p->prio + p->boost]->head = p;
  return;
}

// Naive boost function
int boost(int wait_time){

   if (wait_time > 10)
      return 5;

   return 0;
}

wakeup1(void *chan)
{
  struct proc *p;

  for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
    if(p->state == SLEEPING && p->chan == chan) {
      p->state = RUNNABLE;
      // compute the boost based on how long the process was waiting
      p->boost = boost(sys_uptime() - p->start_wait_ticks);
      sched_put(p);
    }
}

// Modify sleep to account for wait time
void
sleep(void *chan, struct spinlock *lk) {
  ...
  proc->state = SLEEPING;
  proc->start_wait_ticks = sys_uptime();
  sched();
  ...
}
```

5. Page tables.

   Xv6 uses 4MB page table during boot. It is defined as:

```
1406 // The boot page table used in entry.S and entryother.S.
1407 // Page directories (and page tables) must start on page boundaries,
1408 // hence the __aligned__ attribute.
1409 // PTE_PS in a page directory entry enables 4Mbyte pages.
1410
1411 __attribute__((__aligned__(PGSIZE)))
1412 pde_t entrypgdir[NPDENTRIES] = {
1413   // Map VAs [0, 4MB) to PAs [0, 4MB)
1414   [0] = (0) | PTE_P | PTE_W | PTE_PS,
1415   // Map VAs [KERNBASE, KERNBASE+4MB) to PAs [0, 4MB)
1416   [KERNBASE>>PDXSHIFT] = (0) | PTE_P | PTE_W | PTE_PS,
1417 };
```

   (a) (5 points) What virtual addresses (and to what physical addresses) does this page table map?

   The page table maps virtual addresses 0 to 4MB to physical 0 to 4MB, and virtual 2GB to 2GB + 4MB to physical 0 to 4MB.

   (b) (10 points) Imagine now that 4MB pages are not available, and you have to use regular 4KB pages. How do you need to change the definition of entrypgdir for xv6 to work correctly (provide code and short explanation).

```
#define NPDENTRIES 1024

__attribute__((__aligned__(PGSIZE)))
pde_t entrypgdir[NPDENTRIES] = {
// Map VA's [0, 4MB) to PA's [0, 4MB)
[0]
= ((uint)entry_pgtable - KERNBASE) + PTE_P + PTE_W,
// Map VA's [KERNBASE, KERNBASE+4MB) to PA's [0, 4MB)
[KERNBASE>>PDXSHIFT]
             = ((uint)entry_pgtable - KERNBASE) + PTE_P + PTE_W,
};

// Entry 0 of the page table maps to physical page 0, entry 1 to
// physical page 1, etc.
__attribute__((__aligned__(PGSIZE)))
pte_t entry_pgtable[NPTENTRIES] = {
0x000000 | PTE_P | PTE_W,
0x001000 | PTE_P | PTE_W,
0x002000 | PTE_P | PTE_W,
0x003000 | PTE_P | PTE_W,
0x004000 | PTE_P | PTE_W,
0x005000 | PTE_P | PTE_W,
0x006000 | PTE_P | PTE_W,
0x007000 | PTE_P | PTE_W,
....
0x3fc000 | PTE_P | PTE_W,
0x3fd000 | PTE_P | PTE_W,
0x3fe000 | PTE_P | PTE_W,
0x3ff000 | PTE_P | PTE_W,
};
```

6. ics143A. I would like to hear your opinions about 6.828, so please answer the following questions. (Any answer, except no answer, will receive full credit.)

   (a) (1 point) Grade ics143A on a scale of 0 (worst) to 10 (best)?
   1, 2, 5, 5, 6, 7, 7, 7, 7, 7, 7, 7, 7, 7, 8, 8, 9

   (b) (2 points) Any suggestions for how to improve ics143A?
   More practice problems for the midterm and finals (x2). More homework for better understanding (x3). Maybe group work. Mandatory discussion. Longer lectures and discussions. Move notes on the slides. Small class. Draw more diagrams. Assign readings before lecture. Students come from different backgrounds, explain concepts slower. More clear slides and drawings (x2). More organized lectures. Don't get off topic. Instead of covering features xv6 chose not to implement, concentrate on what is there. Plan schedule better in advance. No descriptions of diagrams. Mix of easy and challenging questions on the exam. More specific homework directions (x2). Check knowledge more frequently. Have newer ways to explain material. Explain better in lectures. Take home exams. In discussion sections talk about advanced features, e.g., virtualization or making changes to xv6. Wasn't clear whether to attend discussion sections.

   (c) (1 point) What is the best aspect of ics143A?
   Help on the message board. Detailed, in-depth view of the system (x3). Lecture slides. Real OS (x6). Read and understand xv6 code. Xv6 had a lot of documentation. Learning the basics. Breadth of material and topics (x3). Lecture notes online. Enthusiasm of the instructor (x2).

   (d) (1 point) What is the worst aspect of ics143A?
   The material is hard, especially for 10 weeks (x7). Too much material (x3). Homeworks (3x). Homeworks worth too much. Homeworks don't match lectures. Xv6. Sidetracks in class make lectures slow. Difficult to keep up, but the book helps a lot. Hard to work with low-level systems. Xv6 book is impossible to understand without prior OS knowledge.