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

Spring 2026 John Kubiatowicz

Midterm III

April 30th, 2026

CS162: Operating Systems and Systems Programming

Your Name:	
SID:	
CS162 Login:	
TA Name/Section Time	
Person to Left, Right, Front, and Back of you:	

This is a **closed book** exam. You are allowed 3 pages of notes (both sides). You have 170 minutes 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	18	
2	16	
3	22	
4	26	
5	18	
Total	100	

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3.14159265358979323846264338327950288419716939937510582097494459230781640628620899

Problem 1: True/False [18 pts]

Please *EXPLAIN* your answer in TWO SENTENCES OR LESS (Answers longer than this may not get credit!). Write only in the box. Also, answers without an explanation *GET NO CREDIT*.

Problem 1a[2pts]: The coordinator in two-phase commit (2PC) sends GLOBAL-COMMIT if at least a majority of participants vote VOTE-COMMIT.

☐ True ☐ False

Explain:

Problem 1b[2pts]: An empty Amazon Kindle gains weight when you add electronic books to it.

☐ True ☐ False

Explain:

Problem 1c[2pts]: The FAT file system is faster than the Berkeley Fast File System when performing random accesses to a file.

☐ True ☐ False

Explain:

Problem 1d[2pts]: Because RAID 5 is an erasure code, it requires individual disks to be able to identify when they have failed using some other mechanism (such as ECC codes on each disk).

☐ True ☐ False

Explain:

Problem 1e[2pts]: Assume that we have a filesystem using a buffer cache. If a file is created and then immediately deleted, the filesystem must write to the underlying disk multiple times (once on creation and once on deletion) to keep the buffer cache consistent with the disk.

☐ True ☐ False

Explain:

Problem 1f[2pts]: In Pintos the maximum number of user locks that a user thread can hold at one time is 65536 (i.e. 2^{16}).

☐ True ☐ False

Explain:

Problem 1g[2pts]: Suppose that you and your friend adopted a new IP-layer protocol where every packet has a checksum, and any packet whose contents are changed in transit is detected perfectly. You use this protocol to send a file to a friend, and they reconstruct the file only from packets that pass this checksum. If no additional end-to-end mechanism is used at the sender or receiver, then the friend is guaranteed to receive the file correctly.

☐ True ☐ False

Explain:

Problem 1h[2pts]: When using RPC to communicate over the network, a client and host/server could share arguments and return values even if the communicating entities have processors with different "endianness" (i.e. x86 vs MIPS).

☐ True ☐ False

Explain:

Problem 1i[2pts]: In systems using the network file system (NFS), caches on clients can become temporarily inconsistent with each other (making it appear to different clients that different data is present in a given file).

☐ True ☐ False

Explain:

Problem 2: Multiple Choice [16pts]

Problem 2a[2pts]: Which of the following are *true* about the clock algorithm ***(Choose all that apply):***

A: ☐ The clock algorithm can be considered to be an approximation to LRU.

B: ☐ The clock algorithm will find and replace the least recently used physical page.

C: ☐ The Clock Algorithm arranges *physical* pages into two groups – an active group that is mapped as "valid" and managed in a FIFO list and an inactive group that is mapped as "invalid" and managed as an LRU list.

D: ☐ The clock algorithm sets the *accessed* bit to 0 in software, and lets the hardware set this bit back to 1.

E: ☐ None of the above.

Problem 2b[2pts]: Which of the following is *true* about Pintos' file system? **(*Choose one):***

A: ◯ Directory data (i.e., directory entries) are stored on the directory's inode on disk.

B: ◯ Two threads can always write to the same file concurrently.

C: ◯ The seek syscall should never require blocks in the file to be allocated or freed.

D: ◯ The directory path "/../../" is invalid.

E: ◯ None of the above.

Problem 2c[2pts]: Which of the following are *true* about distributed decision making protocols ***(Choose all that apply):***

A: ☐ The PAXOS protocol will block when one of the participants fail.

B: ☐ Byzantine Agreement protocols are able to come to shared decisions among distributed nodes, even if some of them are malicious (compromised and intentionally trying to corrupt the protocol).

C: ☐ Distributed decision making protocols *cannot* be utilized to produce replicated state machines on nodes distributed over the network.

D: ☐ Two-phase commit can block waiting for a failed coordinator to reboot.

E: ☐ None of the above.

Problem 2d[2pts]: Little's Theorem has the following properties ***(Mark all that apply):***

A: ☐ It cannot handle systems with service times that have C > 1.

B: ☐ It can be used to compute the average time spent in a queue, given the average length of the queue and average arrival rate.

C: ☐ It shows why the average length of time spent in a queue grows without bound as the system utilization approaches 100%.

D: ☐ It applies only to systems in equilibrium.

E: ☐ None of the above.

Problem 2e[2pts]: The Meltdown security flaw (made public in 2018) was able to gain access to protected information in the kernel because ***(Choose one)*:**

A: ◯ Some processors with out-of-order instruction execution allowed user-code to *begin* an illegal access to kernel memory in a way which affected cache state – even though the illegal access was not allowed to complete.

B: ◯ A POSIX-compatible system call implemented by multiple operating systems neglected to properly check arguments and could thus be fooled into returning the contents of protected memory to users.

C: ◯ There was a wide-spread bug in the x86 architecture that caused certain loads to ignore kernel/user distinctions in the page table under the right circumstances.

D: ◯ User code could observe the time it took to complete certain system calls and therefore infer the contents of kernel memory.

E: ◯ None of the above.

Problem 2f[2pts]: Which of the following are true about memory-mapped I/O? ***(Choose all that apply):***

A: ☐ Devices which use memory-mapped I/O can be directly controlled from user-mode processes if the kernel maps the I/O address ranges to the process' address space.

B: ☐ Memory-mapped I/O is a software protocol that constructs a coherent distributed shared memory between multiple physical nodes, allowing communication between nodes to occur as reads and writes to the shared memory (address) space.

C: ☐ Memory-mapped I/O is incompatible with DMA.

D: ☐ Memory-mapped I/O is a hardware mechanism that assigns physical memory addresses to I/O devices such that processor read and write operations to these addresses become commands to devices.

E: ☐ None of the above.

Problem 2g[2pts]: Which of the following statements about the buffer cache are true? **(*Mark all that apply)*:**

A: ☐ Prefetching subsequent disk blocks into the buffer cache can reduce the overall access time for disk operations

B: ☐ The buffer cache can hold *dirty data*, i.e. data that is more up-to-date than the data on disk.

C: ☐ The buffer cache uses a write-through caching policy.

D: ☐ Because the buffer cache is positioned *between* the system-call interface and the disk, it is possible for different processes to see different contents for shared files.

E: ☐ None of the above.

Problem 2h[2pts]: Which of the following statements about the Virtual File System (VFS) are true? **(*Mark all that apply)*:**

A: ☐ VFS is a file system for virtual machines that can be mounted on a host machine.

B: ☐ VFS abstracts away details about the underlying mounted filesystem (such as inode structure, directory format, etc) from the rest of the kernel.

C: ☐ VFS allows you to transparently access a remote file system through the network.

D: ☐ VFS exposes a unique syscall interface for every mounted file system type (e.g. POSIX read vs NFS readAt).

E: ☐ None of the above.

Problem 3: Short Answer Potpourri [22 pts]

For the following questions, please provide as short an answer as you can that actually answers the question. In most cases, this means one or two sentences. *We reserve the right to take off points for answers that are not concise.*

Problem 3a[2pts]: Explain why a pure LRU replacement policy is impractical for demand paging (in virtual memory). Why does the clock algorithm not suffer from this issue?

Problem 3b[3pts]: Explain what DMA is (don't just say what it stands for) and explain how it helps to improve the performance of a file system. How does the processor find out that the DMA has completed?

Problem 3c[4pts]: For the following problem, assume a hypothetical machine with 4 pages of physical memory and 7 pages of virtual memory. Given the access pattern:

A B C D E A A E C F F G A C G D C F

Indicate in the following table which pages are mapped to which physical pages for each of the following policies. Assume that a blank box matches the element to the left. We have given the FIFO policy as an example. You may break ties in any order you wish.

Access→		**A**	B	C	D	E	A	A	E	C	F	F	G	A	C	G	D	C	F
FIFO	1	A				E									C				
	2		B				A										D		
	3			C							F								
	4				D								G						
MIN	1																		
	2																		
	3																		
	4																		
LRU	1																		
	2																		
	3																		
	4																		

Problem 3d[2pts]: What is the guarantee provided by two-phase commit? Why doesn't it violate the General's Paradox?

Problem 3e[2pts]: Give one reason why the performance of write operations on a FLASH device such as an SSD might be both *slower* and *more variable* than reads. Note that answers we are looking for are specifically about what happens in the SSD, not in the OS (filesystem, etc).

Problem 3f[3pts]: Journaling file systems require data to be written twice (once in the journal, then again in the primary file system). How can the file system optimize for good response time? How about good throughput? Explain.

Problem 3g[2pts]: How could the `mmap()` system call be used to set up shared memory between two processes so that they could share a linked list between them (here sharing means that the two of them could add items to the list and traverse the list assuming that suitable synchronization was employed to avoid inconsistencies). Be explicit about the location in the virtual memory space of each process.

Problem 3h[2pts]: Consider two queueing systems handling incoming requests with the same memoryless arrival rate λ. If System A has a deterministic (constant) service time and System B has a highly variable service time (many short jobs and a few long ones). Assume that System A and B have the same mean service time. Which system would you expect to have a larger mean queueing delay? Explain why.

Problem 3i[2pts]: Name and describe two optimizations introduced in BSD 4.2 by the Berkeley Fast File System (FFS)? Make sure to explain the advantage of each of your optimizations.

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Problem 4 starts on the flip side!
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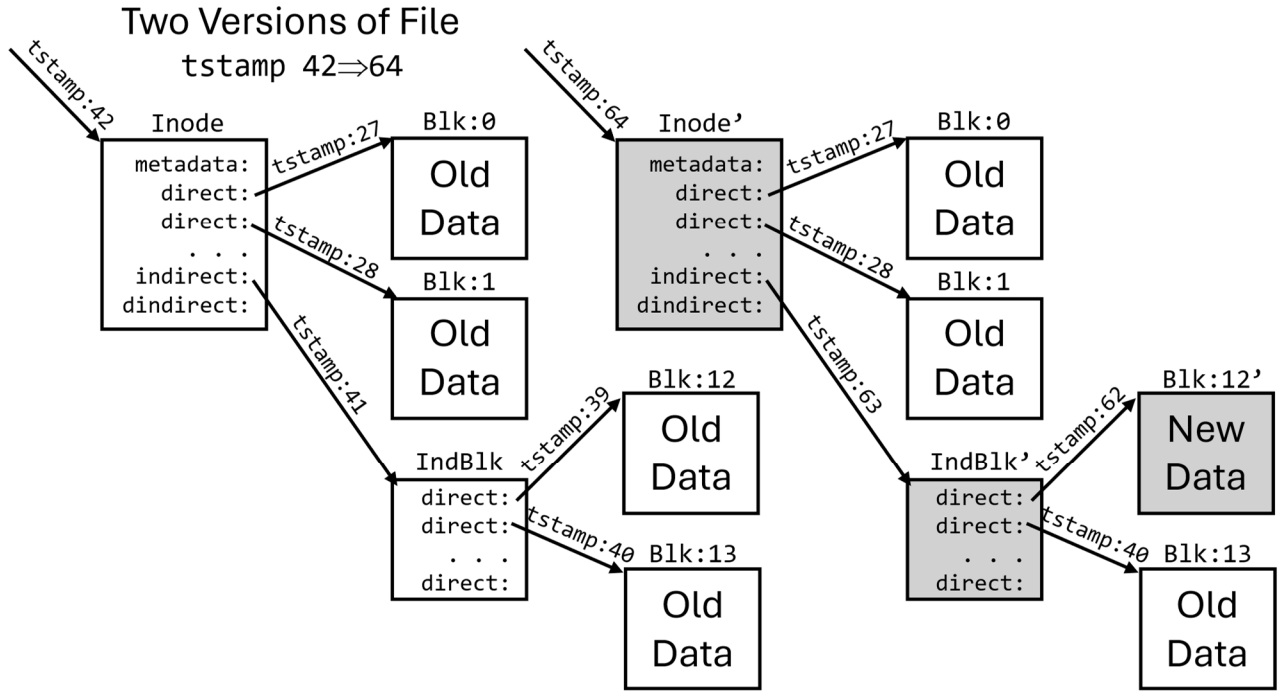
Problem 4: ZFS-Lite for Pintos [26pts]

In this problem we design a Pintos file system in the spirit of ZFS, where every update generates a new version of the file using copy-on-write (COW). To make this problem tractable, we produce a file system with only one file in it, but you should be able to see how the ideas generalize. Our filesystem (ZFS-Lite) uses a Linux-style `inode` structure with up to two levels of indirection: each file has NDIRECT (defined as 12) direct block pointers, one single-indirect block pointer, and one double-indirect block pointer.

ZFS-Lite has two properties that we want to highlight here. First, we never overwrite data blocks in place. Instead, we create a new block for the data and then update the `inode` and any indirect blocks with *copy-on-write* (COW) by first copying their contents into new blocks before modifying them. When completed, we have a new `inode` for the updated file which can replace the previous `inode` with a single atomic write to disk. This scheme provides clean update semantics (a type of transaction) without a journal. In a full ZFS filesystem, `inodes` are actually called `dnodes` and placed into arrays which are updated via COW with every update and for which updates proceed up to a top block called an "überblock" (`superblock`). For this problem, we have only one `inode`, a pointer to which gets written into the `superblock` when the file is updated. We place the `superblock` in a well defined place on disk so that we can always read our file after reboot.

Second, ZFS-Lite associates a monotonically increasing "birth time" with every new block. These birth times are kept with *pointers* to blocks within metadata, as shown by the figure below. The following figure shows an original version of the file constructed at `tstamp=42`. At `tstamp=62`, a write of block 12 is requested, which completes at `tstamp=64`. *In grey are the new blocks generated during this write.* Note that datablocks that are unchanged (i.e. blocks 0-11 and 13) are still in use with the new version of the file and retain their original timestamps. Note further that metadata blocks must have timestamps that are later than the blocks that they point to (this really just states that metadata blocks must be newer than the blocks they point to).



Problem 4a[2pts]: Writing new data to a file involves updating multiple blocks. Explain why performing a final atomic write of the `inode` *pointer* to the `superblock` can be viewed as providing transactional semantics to the file update. Explain any conditions that must be satisfied to view this `superblock` write as a transaction commit.

Problem 4b[2pts]: A *snapshot* is a read-only version of a file from the past that persists until the snapshot is deleted. You can only create a snapshot of the file at the current time. Explain why we could view the `inode` with `tstamp=42` in the above figure as a *snapshot* of the file, assuming that we keep this pointer in a separate location of the `superblock` so that it does not get overwritten every time that the file is updated. What rule must we follow about garbage collecting old data blocks to make sure that a snapshot remains just that – a valid read-only copy of the file?

Problem 4c[2pts]: Assume that a file has *N* blocks in it. What is the algorithmic complexity of creating a snapshot of this file with respect to *N?* Use Big-O notation. Explain.

Problem 4d[2pts]: Consider the `inode` with `tstamp=42` in the above figure as the most recent snapshot and the `inode'` with `tstamp=64` as the most recent version of the file. If we update this most recent version of the file (leaving the snapshot alone), we will displace some data or metadata blocks of this file. How will we know whether or not to free these displaced blocks? Explain.
Hint: The time-complexity of deciding whether or not to free a block is independent of the number of blocks in the file or size and number of snapshots.

Consider the following definitions for our implementation of ZFS-Lite. You should interpret these in light of your Project 3 knowledge from Pintos. First, we have our new "timestamped pointers", which combine a sector reference (on disk) with a timestamp. The type is "ts_block_ptr_t":

```
#define BLOCKSIZE    512              // Sector(==block) size in bytes
typedef uint32_t block_sector_t;      // Pointer to physical sector
typedef uint32_t tstamp_t             // Timestamp

// A pointer to a disk block, stamped with the logical time of creation
typedef struct ts_block_ptr {
    block_sector_t sector;
    tstamp_t       birth;
} ts_block_ptr_t;
```

Here we have modified versions of the inode structures you are used to (using timestamped pointers to sectors instead of just pointers to sectors):

```
// Inode definitions (note that an inode takes up a full BLOCK)
#define NDIRECT    12
#define NINDIRECT  (BLOCKSIZE / sizeof(ts_block_ptr_t)

typedef struct inode_disk {   // inodes look like this
  off_t length;
  ts_block_ptr_t direct[NDIRECT];
  ts_block_ptr_t indirect;
  ts_block_ptr_t double_indirect_t;
  /* padding */
} inode_disk_t;

typedef struct indirect_block {  // indirect blocks look like this
   ts_block_ptr_t next_ptrs[NINDIRECT];
} indirect_block_t;

typedef struct inode {        // File version or snapshot
  ts_block_ptr_t sector;
  inode_disk_t data;
} inode_t;
```

Problem 4e[2pts]: Compute the maximum file size for ZFS-Lite, keeping in mind that BLOCKSIZE=512. Please simplify your answer to a number. Show your work.

Problem 4f[4pts]: Consider *a time-ordered* sequence of snapshots, SN_t, SN_{t+1}, SA, SB, SC,…, SN_{t+k-1}, with SN_{t+k-1} being the latest. Can you *briefly* describe an algorithm for removing an arbitrary snapshot, say snapshot SB from the middle of the set of snapshots? It should delete any sectors which are no longer needed. SA and SC here are on either side of the snapshot we are deleting. What is the time complexity of your solution?

Time Complexity: _____

Description of your algorithm:

Consider the following device-level/device driver definitions. We want to define a `write_block()` function that will write a block at a given byte offset of our file. Definitions of interest are as follows. *Assume that device operations (read, write, allocate, release) always succeed.*

```
tstamp_t fs_time;                // Current filesystem time (for timestamps)
extern struct block *fs_device;  // Our device

/*
 * Here is our superblock.  Contains latest inode pointer and snapshots that
 * we have chosen to write out to disk.  It may or may not be written to
 * disk with every update to the file.
 * Note: superblock.current_inode is the ts_block_ptr_t to latest inode
 *       superblock.snapshots[0] is the ts_block_ptr_t to latest snapshot
 */
#define SUPERBLOCK_SECTOR 2      // Some well-defined spot on disk
typedef struct superblk {
  ts_block_ptr_t current_inode;
  ts_block_ptr_t snapshots[NINDIRECT-1]; // Rev order, snapshots[0] latest
} superblk_t;
superblk_t superblock;

// Atomic read/write of one sector
void block_read(struct block *, block_sector_t sector, void *buf);
void block_write(struct block *, block_sector_t sector, const void *buf);

// Assume that allocation and release functions always succeed
void free_map_allocate (size_t cnt, block_sector_t *sector_out);
void free_map_release  (block_sector_t sector, size_t cnt);
```

Problem 4g[2pts]: Complete the following implementation of cow_alloc_write() which takes a pointer to a buffer full of data, writes this data to a freshly allocated sector on disk, and returns a time-stamped `ts_block_ptr_t` to this sector:

```
static ts_block_ptr_t cow_alloc_write (const void *buf) {
  ts_block_ptr_t p;

  ____________________________________________________________________;

  ____________________________________________________________________;

  ____________________________________________________________________;
  return p;
}
```

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Problem 4h is on the flip side!
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Problem 4h[8pts]: Complete the definition for `write_block()`, below. Note that last step will be to write new version of inode to disk (see figure again):

```
static void write_block(inode_t *inode, size_t pos, const void *data) {
  size_t lbn = pos / BLOCKSIZE;
  inode_disk_t *id = &inode->data;
  ts_block_ptr_t old_data  = {0, 0};  // Init to null, since might not use
  ts_block_ptr_t old_ind   = {0, 0};  // Init to null, since might not use
  ts_block_ptr_t old_inner = {0, 0};  // Init to null, since might not use
  ts_block_ptr_t old_outer = {0, 0};  // Init to null, since might not use

  // Allocate new sector and fill with data
  ts_block_ptr_t new_data = cow_alloc_write(data);
  if (lbn < NDIRECT) {
    // Write is to a direct block.  Save old pointer to possibly free.

    old_data = ____________________________________________________________;

    id->direct[lbn] = ____________________________________________________________;
  } else if (lbn < NDIRECT + NINDIRECT) {
    // Write is to indirect block.
    ts_block_ptr_t ind[NINDIRECT] = {}; // Zeroed if no existing block
    if (id->indirect.sector != 0) { // Block exists, so read
      block_read (fs_device, id->indirect.sector, ind);
    }
    // Before replacing, save old pointer to possibly free.

    old_data = ____________________________________________________________;

    ____________________________________________________________;

    old_ind = ____________________________________________________________;

    ____________________________________________________________;
  } else {
    // Write is to double-indirect block
    ts_block_ptr_t outer[NINDIRECT]={}; //Zeroed if no double-indirect block
    ts_block_ptr_t inner[NINDIRECT]={}; //Zeroed if no single-indirect block

    // Compute index of lbn in double (outer) and single-indirect (inner)

    size_t off = ____________________________________________________________;

    size_t outer_idx = ____________________________________________________________;

    size_t inner_idx = ____________________________________________________________;

    if (id->double_indirect.sector != 0) { // Block exists, so read
      block_read(fs_device, id->double_indirect.sector, outer);
    }
    if (outer[outer_idx].sector != 0) { // Block exists, so read
      block_read(fs_device, outer[outer_idx].sector, inner);
    }
```

```
    old_data = ____________________________________________________;

    ____________________________________________________;

    old_inner = ____________________________________________________;

    ____________________________________________________;

    old_outer = ____________________________________________________;

    ____________________________________________________;
  }

  // Finally, allocate new sector for inode and write to disk
  ts_block_ptr_t old_inode = inode->sector;

  inode->sector = ____________________________________________________;

  // put into superblock and save superblock before releasing old inode
  superblock->current_inode = inode->sector;
  block_write(fs_device, SUPERBLOCK_SECTOR, superblock);
  cow_free(old_inode);  // Release old inode

  // Free any non-zero blocks not in use by any snapshots
  cow_free(old_data);
  cow_free(old_ind);
  cow_free(old_inner);
  cow_free(old_outer);
}
```

Problem 4i[2pts]: Considering your answer from (4d), fill in the missing blanks for the cow_free() function which will conditionally free (i.e. release) a disk sector displaced when updating the contents of a file. *Hint: Your answer requires a time that is independent of the size or number of snapshots. Possibly helpful: time of most recent snapshot:* `superblock.snapshots[0].birth`

```
static void cow_free(block_ptr_t p) {
  if (p.sector == 0)
    return;

  ____________________________________________________________________

  ____________________________________________________________________

  ____________________________________________________________________

}
```

Problem 4j[3pts Ex Credit]: Explain how you would generalize the above implementation of ZFS-Lite to include a full file system (with directories) and for which snapshots are across the whole file system, not just for a single file.

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Problem 5 starts on the flip side!
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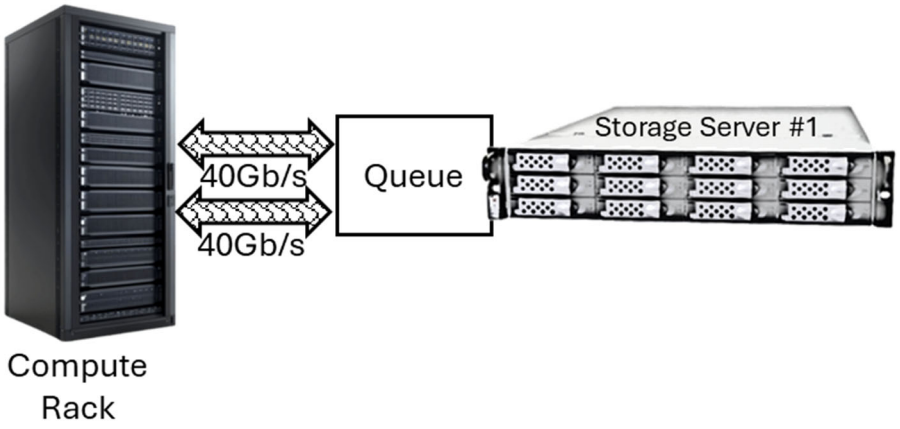
Problem 5: RAID6 File System Performance [18pts]

NOTE: IN THE FOLLOWING PROBLEM, ALL OF THE NUMBERS HAVE BEEN CHOSEN SO THAT ANSWERS CAN BE COMPUTED WITHOUT A CALCULATOR



In this problem, we will consider a network-based storage system consisting of a storage server connected to a high-performance compute system via high-bandwidth optical links.

The Storage server is characterized as follows:

- Contains two links connecting it to a high bandwidth network switch. Each link handles 40Gb/s of network traffic and is routed through a queue to handle bursts of traffic.
- Contains 12 disks, each of which is 50TiB in size
- Uses disks that rotate at 15,000RPM, have a data transfer rate of 131072 KB/s (for each disk), have a 2.4ms average seek time, and a 4096 Byte sector size. *Note 131072/4096 = 32*.
- Each disk has a SCSI interface with a 100µs controller command time. Assume that a group of consecutive sectors can be fetched with a single request.
- Disks are combined into RAID6 partitions of 6 disks each, which means that each partition has 4 data disks and 2 parity disks. It also means that there are 2 independent partitions/server.
- All RAID processing is done via internal buses in the storage server.

Because the disks are configured in RAID6 partitions, the system will spread consecutive sectors of a file across multiple disks when writing a large file, and read them back in a similar fashion. Specifically, the first sector worth of data in the file will be read from disk zero (0). The second sector will be read from disk one (1). Eventually it will wrap around to disk 0, after reading *one sector from each data disk*. Consequently, to read sector *X* from the file, the system will contact disk (*X* mod *N*), where *N* is the number of data disks in the strip.

Possibly helpful numbers include:

4096×16 = 65536,	*1/8 = 0.125*
4096×32 = 131072,	*1/16 = 0.0625*
4096×64 = 262144,	*1/32 = 0.03125*
4096×128 = 524288	*1/64 = 0.015625*
,	*,*

Each of the following answers should be simplified to a single number without rounding. However, to get full credit you must show your work.

Problem 5a[4pts]: What is the average *service time* to retrieve one sector from a single disk starting at a random location on disk? *Hint: there are four terms in this service time.*

Problem 5b[2pts]: Write an equation for the average *service time* to read a contiguous set of *X* sectors from one of the RAID6 partitions as a single request. Assume that disks are independent of one another so that accesses for independent disks can be initiated in parallel. Your equation will be a 2-term latency function as discussed in class with a constant *overhead* (intercept) and a linear term that depends on X (although this term will involve a "ceiling" function).

Problem 5c[2pts]: Suppose that we frequently access very large files in chunks of 64 sectors at a time from a partition. What is the average *service time* for such a request (assume that you start reading in a random part of the file)? *Hint: Use your equation from* ***(5b).***

Problem 5d[2pts]: *Ignoring queueing effects*, what is the maximum number of these large (64 sector) I/O requests that can be made per second (IOPS) from any one server partition? Does this exceed our network bandwidth to the switch?

Problem 5e[3pts]: Consider a series of 64-sector requests to a single partition. Treat the entire system as a M/G/1 queue, with a coefficient of variance of C=1.5. Also assume that we do not want to have our total response time (time spent in queue + service time), to be more than 50% larger than the raw service time. What is the *utilization* of the RAID6 server at this point? What is the maximum rate of requests that we can sustain? Show your work. You can simplify your answers to rational numbers (i.e. a fractions).

Problem 5f[3pts]: What is the service time for *modifying a single sector* in a file at a random place in one of our RAID6 servers? Explain why this number is different from your answer to **(5a)** and how you might avoid the extra overhead when you are appending to a large file one block at a time (the way that files normally grow in Unix-like OSes).

Problem 5g[2pts]: If one of the disks in a partition fails, explain what happens when we try to read data that was on that failed disk. Ignoring queuing effects, what might get in the way of achieving the same maximum read IOPS that we computed in **(5d)**?

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