LAB #4 – mdadm Linear Device (Caching) CMPSC311 - Introduction to Systems Programming Spring 2022 - Prof. Sencun Zhu and Prof. Suman Saha

**Due date: April 1, 2022 (11:59 PM) EST**

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You just completed implementing mdadm and it is working. The software engineers who plan to build secure crypto wallet on top of your storage system have been torturing your storage system by throwing at it all sorts of I/O patterns, and they have been unable to find any inconsistency in your implementation. This is great, because now you have a working system, even though it may not be performant. As professor John Ousterhout of Stanford says, “the best performance improvement is the transition from nonworking state to working state”. The software engineers are happy that your storage system is working correctly, but now they want you to make it fast as well. To this end, you are going to implement a block cache in mdadm. Caching is one of the oldest tricks in the book for reducing request latency by saving often used data in a faster (and smaller) storage medium than your main storage medium. Since we covered caching extensively in the class, we are skipping its details in this document. You must watch the lecture to understand what caching is, and how the least-recently

used (LRU) algorithm that you are going to implement in this assignment works.

# Overview

In general, caches store *key* and *value* pairs in a fast storage medium. For example, in a CPU cache, the key is the memory address, and the value is the data that lives at that address. When the CPU wants to access data at some memory address, it first checks to see if that address appears as a key in the cache; if it does, the CPU reads the corresponding data from the cache directly, without going to memory because reading data from memory is slow.

In a browser cache, the key is the URL of an image, and the value is the image file. When you visit a web site, the browser fetches the HTML file from the web server, parses the HTML file and finds the URLs for the images appearing on the web page. Before making another trip to retrieve the images from the web server, it first checks its cache to see if the URL appears as a key in the cache, and if it does, the browser reads the image from local disk, which is much faster than reading it over the network from a web server.

In this assignment you will implement a block cache for mdadm. In the case of mdadm, the key will be the tuple consisting of disk number and block number that identifies a specific block in JBOD, and the value will be the contents of the block. When the users of mdadm system issue mdadm\_read call, your implementation of mdadm\_read will first look if the block corresponding to the address specified by the user is in the cache, and if it is, then the block will be copied from the cache without issuing a slow JBOD\_READ\_BLOCK call to JBOD. If the block is not in the cache, then you will read it from JBOD and insert it to the cache, so that if a user asks for the block again, you can serve it faster from the cache.

# Cache Implementation

Typically, a cache is an integral part of a storage system and it is not accessible to the users of the storage system. However, to make the testing easy, in this assignment we are going to implement cache as a separate module, and then integrate it to mdadm\_read and mdadm\_write calls.

Please take a look at cache.h file. Each entry in your cache is the following struct.

typedef struct { bool valid; int disk\_num; int block\_num;

uint8\_t block[JBOD\_BLOCK\_SIZE]; int access\_time;

} cache\_entry\_t;

The valid field indicates whether the cache entry is valid. The disk\_num and block\_num fields identify the block that this cache entry is holding and the block field holds the data for the corresponding block. The access\_time field stores when the cache element was last accessed—either written or read.

The file cache.c contains the following predefined variables.

static cache\_entry\_t \*cache = NULL; static int cache\_size = 0;

static int clock = 0; static int num\_queries = 0; static int num\_hits = 0;

Now let’s go over the functions declared in cache.h that you will implement and describe how the above variables relate to these functions. You must look at cache.h for more information about each function.

1. int cache\_create(int num\_entries); Dynamically allocate space for num\_entries cache entries and should store the address of the created cache in the cache global variable. The num\_- entries argument can be 2 at minimum and 4096 at maximum. It should also set cache\_size to num\_entries, since that describes the size of the cache and will also be used by other functions. cache\_size is fixed once the cache is created. You can view it as the maximum capacity of the cache. As such, for simplicity you’d implement it as an array of size cache\_size instead of a linked list, al- though the latter allows one to dynamically adding or deleting cache entries. Calling this function twice without an intervening cache\_destroy call (see below) should fail.
2. int cache\_destroy(void); Free the dynamically allocated space for cache, and should set cache to NULL, and cache\_size to zero. Calling this function twice without an intervening cache\_- create call should fail.
3. int cache\_lookup(int disk\_num, int block\_num, uint8\_t \*buf); Lookup the block identified by disk\_num and block\_num in the cache. If found, copy the block into buf, which can- not be NULL. This function must increment num\_queries global variable every time it performs a lookup. If the lookup is successful, this function should also increment num\_hits global variable; it should also increment clock variable and assign it to the access\_time field of the corresponding entry, to indicate that the entry was used recently. We are going to use num\_queries and num\_hits variables to compute your cache’s hit ratio.
4. int cache\_insert(int disk\_num, int block\_num, uint8\_t \*buf); Insert the block identified by disk\_num and block\_num into the cache and copy buf—which cannot be NULL—to the corresponding cache entry. Insertion should never fail: if the cache is full, then an entry should be overwritten according to the LRU policy using data from this insert operation. This function should also increment and assign clock variable to the access\_time of the newly inserted entry.
5. void cache\_update(int disk\_num, int block\_num, const uint8\_t \*buf); If the entry exists in cache, updates its block content with the new data in buf. Should also update the access\_time if successful.
6. bool cache\_enabled(void); Returns true if cache is enabled (cache\_size is larger than the minimum 2). This will be useful when integrating the cache to your mdadm\_read and mdadm\_write functions. That is, in your mdadm functions, you should call this function first whenever cache is possibly involved.

# Strategy for Implementation

The tester now includes new tests for your cache implementation. You should first aim to implement functions in cache.c and pass all the tester unit tests. Once you pass the tests, you should incorporate your cache into your mdadm\_read and mdadm\_write functions—you need to implement caching in mdadm\_write as well, because we are going to use write-through caching policy, as described in the class. Once you do that, make sure that you still pass all the tests.

Next, try your implementation on the trace files and see if it improves the performance. To evaluate the performance, we have introduced a new cost is a metric into JBOD for measuring the effectiveness of your cache, which is calculated based on the number of operations executed. Each JBOD operation has a different cost, and by effective caching, you reduce the number of read operations, thereby reducing your cost. Now, the tester also takes a cache size when used with a workload file, and prints the cost and hit rate at the end. The cost is computed internally by JBOD, whereas the hit rate is printed by cache\_print\_hit\_rate function in cache.c. The value it prints is based on num\_queries and num\_hits variables that you should increment.

Here’s how the results look like with the reference implementation. Your implementation may produce

different cost and hit rate values, depending on how you implement it (optimized or not). You are not required to output the same values, but they should be at the same magnitude as what are given. First, we run the tester on random input file:

$ ./tester -w traces/random-input >x Cost: 18948700

Hit rate: -nan%

The is 18948700, and the hit rate is undefined because we have not enabled cache. Next, we rerun the tester and specify a cache size of 1024 entries, using -s option:

$ ./tester -w traces/random-input -s 1024 >x Cost: 17669400

Hit rate: 24.5%

As you can see, the cache is working, given that we have non-zero hit rate, and as a result, the cost is now reduced. Let’s try it one more time with the maximum cache size:

$ ./tester -w traces/random-input -s 4096 >x Cost: 13091800

Hit rate: 87.9%

$ diff x traces/random-expected-output

$

Once again, we significantly reduced the cost using a larger cache. We also make sure that introducing caching does not violate correctness by comparing the outputs. **If introducing a cache violates correctness of your mdadm implementation, you will get a zero grade for the corresponding trace file.**

# Grading

**Grading rubric** The grading would be done according to the following rubric:

* Passing cache test cases (Totally 19 cases, but since most of them are read/write test cases for lab2 and lab3, we only count 2 write cases and 6 cache cases. The perfect score is 10 out of 10) : 70%
* Passing random and linear trace files with cache to reduce the cost: 15%
* Adding meaningful descriptive comments: 5%
* Successful “make” and execution without error and **warnings**: 5%
* Submission of commit id: 5%

**Penalties:** 10% per day for late submission (up to 3 days). The lab assignment will not be graded if it is more than 3 days late.