45

Data Integrity and Protection

Beyond the basic advances found in the file systems we have studied thus far, a number of features are worth studying. In this chapter, we focus on reliability once again (having previously studied storage system reliability in the RAID chapter). Specifically, how should a file system or storage system ensure that data is safe, given the unreliable nature of modern storage devices?

This general area is referred to as **data integrity** or **data protection**. Thus, we will now investigate techniques used to ensure that the data you put into your storage system is the same when the storage system returns it to you.

CRUX: HOW TO ENSURE DATA INTEGRITY

How should systems ensure that the data written to storage is protected? What techniques are required? How can such techniques be made efficient, with both low space and time overheads?

45.1 Disk Failure Modes

As you learned in the chapter about RAID, disks are not perfect, and can fail (on occasion). In early RAID systems, the model of failure was quite simple: either the entire disk is working, or it fails completely, and the detection of such a failure is straightforward. This **fail-stop** model of disk failure makes building RAID relatively simple [S90].

What you didn't learn is about all of the other types of failure modes modern disks exhibit. Specifically, as Bairavasundaram et al. studied in great detail [B+07, B+08], modern disks will occasionally seem to be mostly working but have trouble successfully accessing one or more blocks. Specifically, two types of single-block failures are common and worthy of consideration: **latent-sector errors** (**LSEs**) and **block corruption**. We'll now discuss each in more detail.

	Cheap	Costly
LSEs	9.40%	1.40%
Corruption	0.50%	0.05%

Figure 45.1: **Frequency Of LSEs And Block Corruption**

LSEs arise when a disk sector (or group of sectors) has been damaged in some way. For example, if the disk head touches the surface for some reason (a **head crash**, something which shouldn't happen during normal operation), it may damage the surface, making the bits unreadable. Cosmic rays can also flip bits, leading to incorrect contents. Fortunately, in-disk **error correcting codes** (**ECC**) are used by the drive to determine whether the on-disk bits in a block are good, and in some cases, to fix them; if they are not good, and the drive does not have enough information to fix the error, the disk will return an error when a request is issued to read them.

There are also cases where a disk block becomes **corrupt** in a way not detectable by the disk itself. For example, buggy disk firmware may write a block to the wrong location; in such a case, the disk ECC indicates the block contents are fine, but from the client's perspective the wrong block is returned when subsequently accessed. Similarly, a block may get corrupted when it is transferred from the host to the disk across a faulty bus; the resulting corrupt data is stored by the disk, but it is not what the client desires. These types of faults are particularly insidious because they are **silent faults**; the disk gives no indication of the problem when returning the faulty data.

Prabhakaran et al. describes this more modern view of disk failure as the **fail-partial** disk failure model [P+05]. In this view, disks can still fail in their entirety (as was the case in the traditional fail-stop model); however, disks can also seemingly be working and have one or more blocks become inaccessible (i.e., LSEs) or hold the wrong contents (i.e., corruption). Thus, when accessing a seemingly-working disk, once in a while it may either return an error when trying to read or write a given block (a non-silent partial fault), and once in a while it may simply return the wrong data (a silent partial fault).

Both of these types of faults are somewhat rare, but just how rare? Figure 45.1 summarizes some of the findings from the two Bairavasundaram studies [B+07,B+08].

The figure shows the percent of drives that exhibited at least one LSE or block corruption over the course of the study (about 3 years, over 1.5 million disk drives). The figure further sub-divides the results into "cheap" drives (usually SATA drives) and "costly" drives (usually SCSI or Fibre Channel). As you can see, while buying better drives reduces the frequency of both types of problem (by about an order of magnitude), they still happen often enough that you need to think carefully about how to handle them in your storage system.

Some additional findings about LSEs are:

- Costly drives with more than one LSE are as likely to develop additional errors as cheaper drives
- For most drives, annual error rate increases in year two
- The number of LSEs increase with disk size
- Most disks with LSEs have less than 50
- Disks with LSEs are more likely to develop additional LSEs
- There exists a significant amount of spatial and temporal locality
- Disk scrubbing is useful (most LSEs were found this way)

Some findings about corruption:

- Chance of corruption varies greatly across different drive models within the same drive class
- Age effects are different across models
- Workload and disk size have little impact on corruption
- Most disks with corruption only have a few corruptions
- Corruption is not independent within a disk or across disks in RAID
- There exists spatial locality, and some temporal locality
- There is a weak correlation with LSEs

To learn more about these failures, you should likely read the original papers [B+07,B+08]. But hopefully the main point should be clear: if you really wish to build a reliable storage system, you must include machinery to detect and recover from both LSEs and block corruption.

45.2 Handling Latent Sector Errors

Given these two new modes of partial disk failure, we should now try to see what we can do about them. Let's first tackle the easier of the two, namely latent sector errors.

CRUX: HOW TO HANDLE LATENT SECTOR ERRORS
How should a storage system handle latent sector errors? How much extra machinery is needed to handle this form of partial failure?

As it turns out, latent sector errors are rather straightforward to handle, as they are (by definition) easily detected. When a storage system tries to access a block, and the disk returns an error, the storage system should simply use whatever redundancy mechanism it has to return the correct data. In a mirrored RAID, for example, the system should access the alternate copy; in a RAID-4 or RAID-5 system based on parity, the system should reconstruct the block from the other blocks in the parity group. Thus, easily detected problems such as LSEs are readily recovered through standard redundancy mechanisms.

The growing prevalence of LSEs has influenced RAID designs over the years. One particularly interesting problem arises in RAID-4/5 systems when both full-disk faults and LSEs occur in tandem. Specifically, when an entire disk fails, the RAID tries to **reconstruct** the disk (say, onto a hot spare) by reading through all of the other disks in the parity group and recomputing the missing values. If, during reconstruction, an LSE is encountered on any one of the other disks, we have a problem: the reconstruction cannot successfully complete.

To combat this issue, some systems add an extra degree of redundancy. For example, NetApp's **RAID-DP** has the equivalent of two parity disks instead of one [C+04]. When an LSE is discovered during reconstruction, the extra parity helps to reconstruct the missing block. As always, there is a cost, in that maintaining two parity blocks for each stripe is more costly; however, the log-structured nature of the NetApp **WAFL** file system mitigates that cost in many cases [HLM94]. The remaining cost is space, in the form of an extra disk for the second parity block.

45.3 Detecting Corruption: The Checksum

Let's now tackle the more challenging problem, that of silent failures via data corruption. How can we prevent users from getting bad data when corruption arises, and thus leads to disks returning bad data?

CRUX: HOW TO PRESERVE DATA INTEGRITY DESPITE CORRUPTION
Given the silent nature of such failures, what can a storage system do to detect when corruption arises? What techniques are needed? How can one implement them efficiently?

Unlike latent sector errors, *detection* of corruption is a key problem. How can a client tell that a block has gone bad? Once it is known that a particular block is bad, *recovery* is the same as before: you need to have some other copy of the block around (and hopefully, one that is not corrupt!). Thus, we focus here on detection techniques.

The primary mechanism used by modern storage systems to preserve data integrity is called the **checksum**. A checksum is simply the result of a function that takes a chunk of data (say a 4KB block) as input and computes a function over said data, producing a small summary of the contents of the data (say 4 or 8 bytes). This summary is referred to as the checksum. The goal of such a computation is to enable a system to detect if data has somehow been corrupted or altered by storing the checksum with the data and then confirming upon later access that the data's current checksum matches the original storage value.

TIP: THERE'S NO FREE LUNCH

There's No Such Thing As A Free Lunch, or TNSTAAFL for short, is an old American idiom that implies that when you are seemingly getting something for free, in actuality you are likely paying some cost for it. It comes from the old days when diners would advertise a free lunch for customers, hoping to draw them in; only when you went in, did you realize that to acquire the "free" lunch, you had to purchase one or more alcoholic beverages. Of course, this may not actually be a problem, particularly if you are an aspiring alcoholic (or typical undergraduate student).

Common Checksum Functions

A number of different functions are used to compute checksums, and vary in strength (i.e., how good they are at protecting data integrity) and speed (i.e., how quickly can they be computed). A trade-off that is common in systems arises here: usually, the more protection you get, the costlier it is. There is no such thing as a free lunch.

One simple checksum function that some use is based on exclusive or (XOR). With XOR-based checksums, the checksum is computed by XOR'ing each chunk of the data block being checksummed, thus producing a single value that represents the XOR of the entire block.

To make this more concrete, imagine we are computing a 4-byte checksum over a block of 16 bytes (this block is of course too small to really be a disk sector or block, but it will serve for the example). The 16 data bytes, in hex, look like this:

```
365e c4cd ba14 8a92 ecef 2c3a 40be f666
```

If we view them in binary, we get the following:

```
0011 0110 0101 1110    1100 0100 1100 1101
1011 1010 0001 0100    1000 1010 1001 0010
1110 1100 1110 1111    0010 1100 0011 1010
0100 0000 1011 1110    1111 0110 0110 0110
```

Because we've lined up the data in groups of 4 bytes per row, it is easy to see what the resulting checksum will be: perform an XOR over each column to get the final checksum value:

```
0010 0000 0001 1011    1001 0100 0000 0011
```

The result, in hex, is 0x201b9403.

XOR is a reasonable checksum but has its limitations. If, for example, two bits in the same position within each checksummed unit change, the checksum will not detect the corruption. For this reason, people have investigated other checksum functions.

Another basic checksum function is addition. This approach has the advantage of being fast; computing it just requires performing 2's-complement addition over each chunk of the data, ignoring overflow. It can detect many changes in data, but is not good if the data, for example, is shifted.

A slightly more complex algorithm is known as the **Fletcher checksum**, named (as you might guess) for the inventor, John G. Fletcher [F82]. It is quite simple to compute and involves the computation of two check bytes, $s1$ and $s2$. Specifically, assume a block D consists of bytes $d1$ ... dn; $s1$ is defined as follows: $s1 = (s1 + d_i) \ mod \ 255$ (computed over all d_i); $s2$ in turn is: $s2 = (s2 + s1) \ mod \ 255$ (again over all d_i) [F04]. The Fletcher checksum is almost as strong as the CRC (see below), detecting all single-bit, double-bit errors, and many burst errors [F04].

One final commonly-used checksum is known as a **cyclic redundancy check** (**CRC**). Assume you wish to compute the checksum over a data block D. All you do is treat D as if it is a large binary number (it is just a string of bits after all) and divide it by an agreed upon value (k). The remainder of this division is the value of the CRC. As it turns out, one can implement this binary modulo operation rather efficiently, and hence the popularity of the CRC in networking as well. See elsewhere for more details [M13].

Whatever the method used, it should be obvious that there is no perfect checksum: it is possible two data blocks with non-identical contents will have identical checksums, something referred to as a **collision**. This fact should be intuitive: after all, computing a checksum is taking something large (e.g., 4KB) and producing a summary that is much smaller (e.g., 4 or 8 bytes). In choosing a good checksum function, we are thus trying to find one that minimizes the chance of collisions while remaining easy to compute.

Checksum Layout

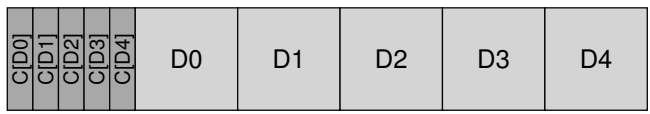
Now that you understand a bit about how to compute a checksum, let's next analyze how to use checksums in a storage system. The first question we must address is the layout of the checksum, i.e., how should checksums be stored on disk?

The most basic approach simply stores a checksum with each disk sector (or block). Given a data block D, let us call the checksum over that data $C(D)$. Thus, without checksums, the disk layout looks like this:

With checksums, the layout adds a single checksum for every block:

Because checksums are usually small (e.g., 8 bytes), and disks only can write in sector-sized chunks (512 bytes) or multiples thereof, one problem that arises is how to achieve the above layout. One solution employed by drive manufacturers is to format the drive with 520-byte sectors; an extra 8 bytes per sector can be used to store the checksum.

In disks that don't have such functionality, the file system must figure out a way to store the checksums packed into 512-byte blocks. One such possibility is as follows:



In this scheme, the n checksums are stored together in a sector, followed by n data blocks, followed by another checksum sector for the next n blocks, and so forth. This approach has the benefit of working on all disks, but can be less efficient; if the file system, for example, wants to overwrite block $D1$, it has to read in the checksum sector containing $C(D1)$, update $C(D1)$ in it, and then write out the checksum sector and new data block $D1$ (thus, one read and two writes). The earlier approach (of one checksum per sector) just performs a single write.

45.4 Using Checksums

With a checksum layout decided upon, we can now proceed to actually understand how to *use* the checksums. When reading a block D, the client (i.e., file system or storage controller) also reads its checksum from disk $C_s(D)$, which we call the **stored checksum** (hence the subscript C_s). The client then *computes* the checksum over the retrieved block D, which we call the **computed checksum** $C_c(D)$. At this point, the client compares the stored and computed checksums; if they are equal (i.e., $C_s(D)$ == $C_c(D)$, the data has likely not been corrupted, and thus can be safely returned to the user. If they do *not* match (i.e., $C_s(D)$!= $C_c(D)$), this implies the data has changed since the time it was stored (since the stored checksum reflects the value of the data at that time). In this case, we have a corruption, which our checksum has helped us to detect.

Given a corruption, the natural question is what should we do about it? If the storage system has a redundant copy, the answer is easy: try to use it instead. If the storage system has no such copy, the likely answer is

to return an error. In either case, realize that corruption detection is not a magic bullet; if there is no other way to get the non-corrupted data, you are simply out of luck.

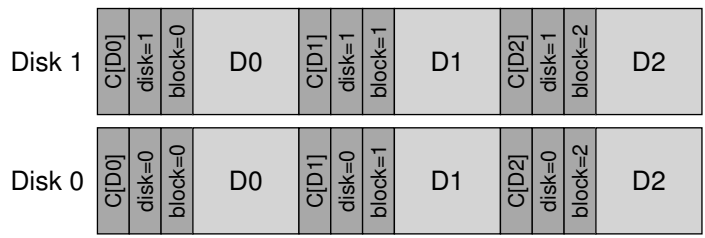
45.5 A New Problem: Misdirected Writes

The basic scheme described above works well in the general case of corrupted blocks. However, modern disks have a couple of unusual failure modes that require different solutions.

The first failure mode of interest is called a **misdirected write**. This arises in disk and RAID controllers which write the data to disk correctly, except in the *wrong* location. In a single-disk system, this means that the disk wrote block D_x not to address x (as desired) but rather to address y (thus "corrupting" D_y); in addition, within a multi-disk system, the controller may also write $D_{i,x}$ not to address x of disk i but rather to some other disk j. Thus our question:

CRUX: HOW TO HANDLE MISDIRECTED WRITES
How should a storage system or disk controller detect misdirected writes? What additional features are required from the checksum?

The answer, not surprisingly, is simple: add a little more information to each checksum. In this case, adding a **physical identifier** (**physical ID**) is quite helpful. For example, if the stored information now contains the checksum $C(D)$ and both the disk and sector numbers of the block, it is easy for the client to determine whether the correct information resides within a particular locale. Specifically, if the client is reading block 4 on disk 10 ($D_{10,4}$), the stored information should include that disk number and sector offset, as shown below. If the information does not match, a misdirected write has taken place, and a corruption is now detected. Here is an example of what this added information would look like on a two-disk system. Note that this figure, like the others before it, is not to scale, as the checksums are usually small (e.g., 8 bytes) whereas the blocks are much larger (e.g., 4 KB or bigger):



You can see from the on-disk format that there is now a fair amount of redundancy on disk: for each block, the disk number is repeated within each block, and the offset of the block in question is also kept next to the block itself. The presence of redundant information should be no surprise, though; redundancy is the key to error detection (in this case) and recovery (in others). A little extra information, while not strictly needed with perfect disks, can go a long ways in helping detect problematic situations should they arise.

45.6 One Last Problem: Lost Writes

Unfortunately, misdirected writes are not the last problem we will address. Specifically, some modern storage devices also have an issue known as a **lost write**, which occurs when the device informs the upper layer that a write has completed but in fact it never is persisted; thus, what remains is the old contents of the block rather than the updated new contents.

The obvious question here is: do any of our checksumming strategies from above (e.g., basic checksums, or physical identity) help to detect lost writes? Unfortunately, the answer is no: the old block likely has a matching checksum, and the physical ID used above (disk number and block offset) will also be correct. Thus our final problem:

CRUX: HOW TO HANDLE LOST WRITES
How should a storage system or disk controller detect lost writes? What additional features are required from the checksum?

There are a number of possible solutions that can help [K+08]. One classic approach [BS04] is to perform a **write verify** or **read-after-write**; by immediately reading back the data after a write, a system can ensure that the data indeed reached the disk surface. This approach, however, is quite slow, doubling the number of I/Os needed to complete a write.

Some systems add a checksum elsewhere in the system to detect lost writes. For example, Sun's **Zettabyte File System** (**ZFS**) includes a checksum in each file system inode and indirect block for every block included within a file. Thus, even if the write to a data block itself is lost, the checksum within the inode will not match the old data. Only if the writes to both the inode and the data are lost simultaneously will such a scheme fail, an unlikely (but unfortunately, possible!) situation.

45.7 Scrubbing

Given all of this discussion, you might be wondering: when do these checksums actually get checked? Of course, some amount of checking

occurs when data is accessed by applications, but most data is rarely accessed, and thus would remain unchecked. Unchecked data is problematic for a reliable storage system, as bit rot could eventually affect all copies of a particular piece of data.

To remedy this problem, many systems utilize **disk scrubbing** of various forms [K+08]. By periodically reading through *every* block of the system, and checking whether checksums are still valid, the disk system can reduce the chances that all copies of a certain data item become corrupted. Typical systems schedule scans on a nightly or weekly basis.

45.8 Overheads Of Checksumming

Before closing, we now discuss some of the overheads of using checksums for data protection. There are two distinct kinds of overheads, as is common in computer systems: space and time.

Space overheads come in two forms. The first is on the disk (or other storage medium) itself; each stored checksum takes up room on the disk, which can no longer be used for user data. A typical ratio might be an 8-byte checksum per 4 KB data block, for a 0.19% on-disk space overhead.

The second type of space overhead comes in the memory of the system. When accessing data, there must now be room in memory for the checksums as well as the data itself. However, if the system simply checks the checksum and then discards it once done, this overhead is short-lived and not much of a concern. Only if checksums are kept in memory (for an added level of protection against memory corruption [Z+13]) will this small overhead be observable.

While space overheads are small, the time overheads induced by checksumming can be quite noticeable. Minimally, the CPU must compute the checksum over each block, both when the data is stored (to determine the value of the stored checksum) and when it is accessed (to compute the checksum again and compare it against the stored checksum). One approach to reducing CPU overheads, employed by many systems that use checksums (including network stacks), is to combine data copying and checksumming into one streamlined activity; because the copy is needed anyhow (e.g., to copy the data from the kernel page cache into a user buffer), combined copying/checksumming can be quite effective.

Beyond CPU overheads, some checksumming schemes can induce extra I/O overheads, particularly when checksums are stored distinctly from the data (thus requiring extra I/Os to access them), and for any extra I/O needed for background scrubbing. The former can be reduced by design; the latter can be tuned and thus its impact limited, perhaps by controlling when such scrubbing activity takes place. The middle of the night, when most (not all!) productive workers have gone to bed, may be a good time to perform such scrubbing activity and increase the robustness of the storage system.

45.9 Summary

We have discussed data protection in modern storage systems, focusing on checksum implementation and usage. Different checksums protect against different types of faults; as storage devices evolve, new failure modes will undoubtedly arise. Perhaps such change will force the research community and industry to revisit some of these basic approaches, or invent entirely new approaches altogether. Time will tell. Or it won't. Time is funny that way.

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Homework (Simulation)

In this homework, you'll use `checksum.py` to investigate various aspects of checksums.

Questions

1. First just run `checksum.py` with no arguments. Compute the additive, XOR-based, and Fletcher checksums. Use `-c` to check your answers.
2. Now do the same, but vary the seed (`-s`) to different values.
3. Sometimes the additive and XOR-based checksums produce the same checksum (e.g., if the data value is all zeroes). Can you pass in a 4-byte data value (using the `-D` flag, e.g., `-D a,b,c,d`) that does not contain only zeroes and leads the additive and XOR-based checksum having the same value? In general, when does this occur? Check that you are correct with the `-c` flag.
4. Now pass in a 4-byte value that you know will produce a different checksum values for additive and XOR. In general, when does this occur?
5. Use the simulator to compute checksums twice (once each for a different set of numbers). The two number strings should be different (e.g., `-D a1,b1,c1,d1` the first time and `-D a2,b2,c2,d2` the second) but should produce the same additive checksum. In general, when will the additive checksum be the same, even though the data values are different? Check your specific answer with the `-c` flag.
6. Now do the same for the XOR checksum.
7. Now let's look at a specific set of data values. The first is: `-D 1,2,3,4`. What will the different checksums (additive, XOR, Fletcher) be for this data? Now compare it to computing these checksums over `-D 4,3,2,1`. What do you notice about these three checksums? How does Fletcher compare to the other two? How is Fletcher generally "better" than something like the simple additive checksum?
8. No checksum is perfect. Given a particular input of your choosing, can you find other data values that lead to the same Fletcher checksum? When, in general, does this occur? Start with a simple data string (e.g., `-D 0,1,2,3`) and see if you can replace one of those numbers but end up with the same Fletcher checksum. As always, use `-c` to check your answers.

Homework (Code)

In this part of the homework, you'll write some of your own code to implement various checksums.

Questions

1. Write a short C program (called `check-xor.c`) that computes an XOR-based checksum over an input file, and prints the checksum as output. Use a 8-bit unsigned char to store the (one byte) checksum. Make some test files to see if it works as expected.
2. Now write a short C program (called `check-fletcher.c`) that computes the Fletcher checksum over an input file. Once again, test your program to see if it works.
3. Now compare the performance of both: is one faster than the other? How does performance change as the size of the input file changes? Use internal calls to `gettimeofday` to time the programs. Which should you use if you care about performance? About checking ability?
4. Read about the 16-bit CRC and then implement it. Test it on a number of different inputs to ensure that it works. How is its performance as compared to the simple XOR and Fletcher? How about its checking ability?
5. Now build a tool (`create-csum.c`) that computes a single-byte checksum for every 4KB block of a file, and records the results in an output file (specified on the command line). Build a related tool (`check-csum.c`) that reads a file, computes the checksums over each block, and compares the results to the stored checksums stored in another file. If there is a problem, the program should print that the file has been corrupted. Test the program by manually corrupting the file.