Data Integrity

CS333

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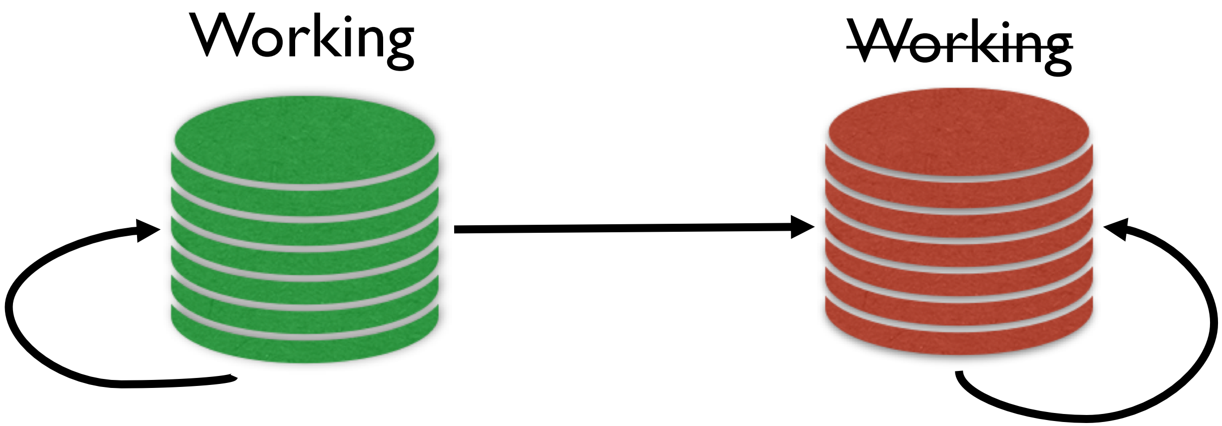
This Video

- Media Errors
  - Types of failures
  - Causes/effects
- Techniques for Identifying Errors
  - Error correcting codes
  - Checksums

Revisiting Failure Modes

- In RAID, we assumed errors were fail-stop



- In reality, other types of errors not only exist, but are unfortunately more common than we'd like

Additional Types of HDD Errors

- Latent-sector errors (LSEs)
  - A sector or group of sectors becomes damaged
    - For example, if a disk head scrapes against the platter, damaging the surface
- Sector corruption
  - A disk block's contents store incorrect data
    - For example, if the bus that transfers data from the host to the drive has an error: the disk may write what it was told to write but that data is not correct
    - For example, if the firmware has a bug and writes to the wrong sector: the data is valid, but the location is wrong
- LSEs are detectable by the disk
- Sector corruptions go unnoticed

What Should We Do?

Two main challenges:

1. Detection
   - We want to know when a failure happens so that we don't propagate the problem
2. Correction
   - Ideally we wouldn't just learn that we have an error, we would fix it

The Anatomy of a Sector

- In addition to the data, an HDD sector actually stores some additional information
  - Header: information used by the drive controller (firmware), possibly including:
    - Address (so the R/W head can identify its position)
    - Flags (e.g., to note that the sector is broken)
    - Alternate address (e.g., to use if the sector failed)
  - Data:
    - User's bytes
    - Error correcting codes (ECC)

Note about ECCs

- Error Correcting/Correction Codes contain redundant information that can both identify *and fix* a subset of possible errors
  - Commonly used in modern HDDs and SSDs
  - Handled entirely within the device's firmware
    - Low-overhead and transparent to users

- We won't discuss specific ECCs; we'll focus on software strategies built on top of disks.

Detecting Errors

- Although ECCs can fix some errors, we still want to detect LSEs and block corruptions
  - Once we identify an error, we can utilize other techniques, like RAID or replication, to recover
- Challenge: want a low-overhead mechanism to detect what our data should be, so we can compare it to what our data actually is
  - CPU cost
  - Storage cost
  - Memory cost

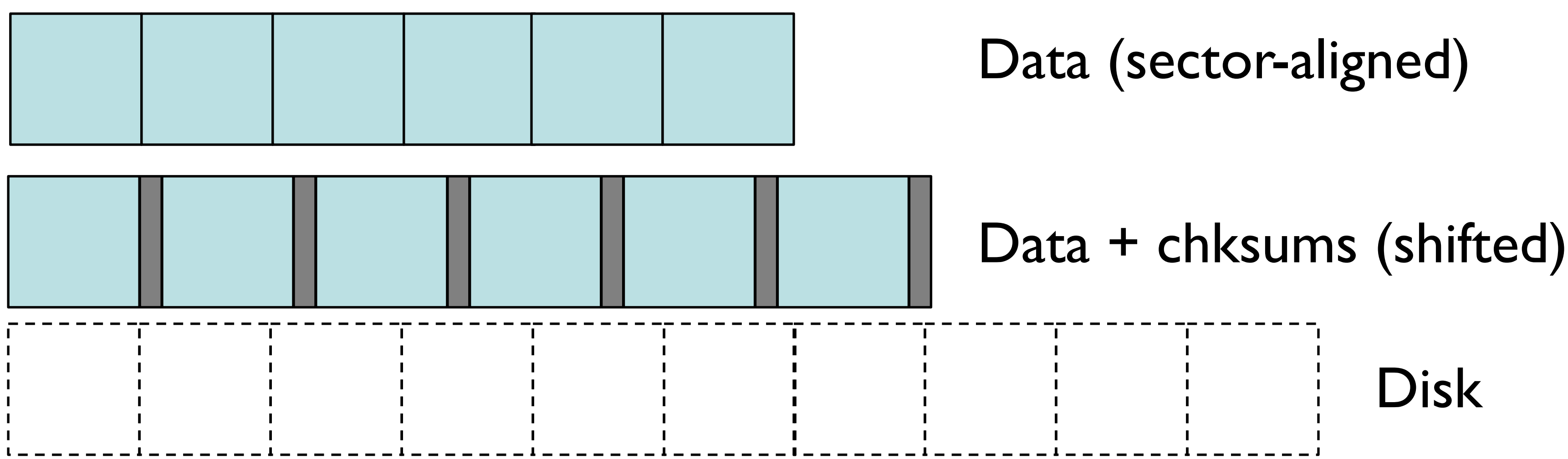
Detecting Errors

- Checksums are a relatively cheap and effective approach to identify data discrepancies
  - Store output of a deterministic function over our data
    - XOR
    - CRC
    - Fletcher checksum
- If we recompute the checksum function on our data, we should get the same result
  - Store a checksum *somewhere* after each write I/O
  - On each read, ERROR if:

    stored checksum != recomputed checksum

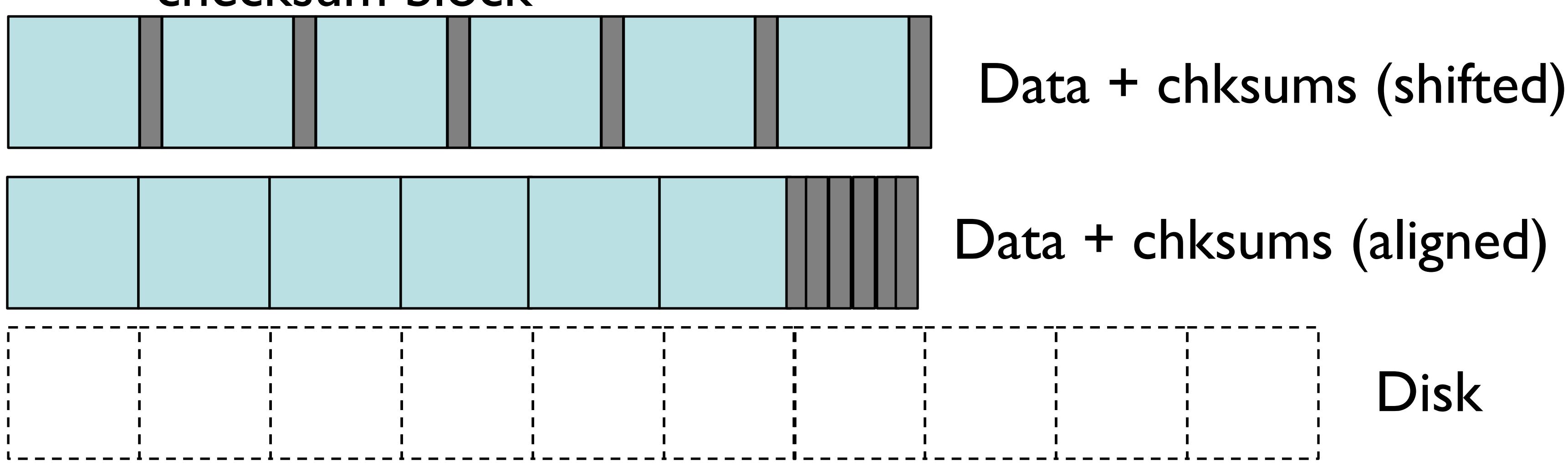
Storing Checksums

- Disk sector is our fixed-size transfer unit
  - If the drive internally uses checksums (as was the case before ECC), can be stored alongside data
  - Otherwise, we need a place that is separate from our sector data. But where?



Storing Checksums

- Idea: store checksums as data in a dedicated checksum block, separate (but near) data
  - But now we need two write I/Os + one read I/O to update a data block
    - Read checksum block, update checksum, write updated checksum block



Detecting Errors

- Can compute & compare checksums *reactively*
  - When we read a block, we recompute its checksum and compare
  - Lazy/on-demand approach
- Can compute & compare checksums *actively*
  - Disk scrubbing: intentionally traversing on-disk data and looking for checksum mismatches
    - Pros: detect errors sooner, hopefully fix before needed
    - Cons: expensive, scales with size of disk

Limitations/Issues

- Block checksums let us answer the question:
  - Does a physical data block match a physical value?
- They do not answer:
  - Was a data block written to the logically correct location? (misdirected write)
  - Was a data block written at all? (lost write)
  - Are my data structures logically consistent?

Checksums (or similar ideas) **CAN** be used as tools to answer these questions. We just need careful design: which layer do we perform the checksumming? What objects are we verifying? Do we need additional information beyond a checksum well?

Brief Case Study

- Consider the following (simplified) inode:

```
struct inode {
  size_t size;
  int blocks;
  lba_t block_ptrs[10];
}
```

If a block pointer refers to logically incorrect data, (misdirected or lost write) the block checksum might still match.

- Compare it to:

```
struct inode {
  size_t size;
  int blocks;
  lba_t block_ptrs[10];
  long block_checksums[10];
}
```

By adding a checksum *inside* the inode, we can verify that the data refers to the correct *logical* value, not just that the physical sector's contents match the most recent write.

Summary

- Checksums give some confidence that a value has not changed or been corrupted
  - Only detect certain classes of changes/errors
  - Only detect *physical* changes/errors
- Checksums can be a useful building block for safeguarding our systems
  - After identify errors, can be fixed by other means
- Checksums can be deployed at different layers with different advantages/costs
  - Disk, block layer, FS layer, application layer, …