CSE 410
Computer Systems

Hal Perkins

Spring 2010

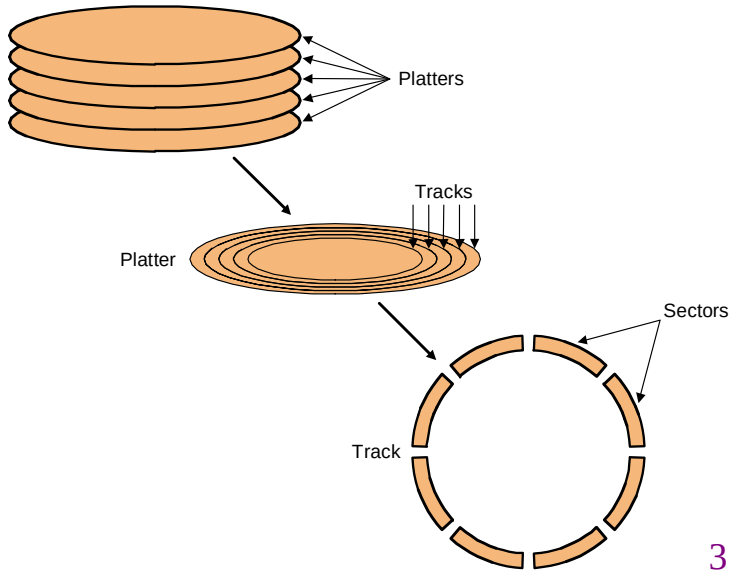
Lecture 22 – Disks & File Systems

Readings and References

- Reading
  - Sec. 6.3 (disk characteristics), *Computer Organization & Design*, Patterson & Hennessy
  - Sec. 10.1-10.3, 10.6, *Operating System Concepts*, Silberschatz, Galvin, and Gagne. The rest of chs. 10-12 have much useful information if you have time to read them.

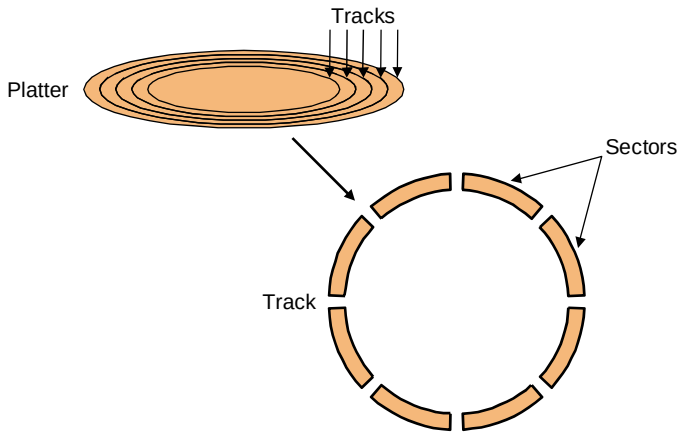
Hard drives

- The ugly guts of a hard disk.
  - Data is stored on double-sided magnetic disks called platters.
  - Each platter is arranged like a record, with many concentric tracks.
  - Tracks are further divided into individual sectors, which are the basic unit of data transfer.
  - Each surface has a read/write head like the arm on a record player, but all the heads are connected and move together.
- A 1TB Hitachi Deskstar has:
  - 2 platters (4 surfaces)
  - 4 heads
  - 512 bytes/sector
  - Logical layout (mapped automatically):
    - 16 heads
    - 63 sectors/track
    - 16,383 cylinders (tracks)



Accessing data on a hard disk

- Accessing a sector on a track on a hard disk takes a lot of time!
  - Seek time measures the delay for the disk head to reach the track.
  - A rotational delay accounts for the time to get to the right sector.
  - The transfer time is how long the actual data read or write takes.
  - There may be additional overhead for the operating system or the controller hardware on the hard disk drive.
- Rotational speed, measured in revolutions per minute or RPM, partially determines the rotational delay and transfer time.



Estimating disk latencies (seek time)

- Manufacturers often report *average* seek times of 8-10 ms.
  - These times average the time to seek from any track to any other track.
- In practice, seek times are often much better.
  - For example, if the head is already on or near the desired track, then seek time is much smaller. In other words, locality is important!
  - Actual average seek times are often just 2-3 ms.

Estimating Disk Latencies (rotational latency)

- Once the head is in place, we need to wait until the right sector is underneath the head.
  - This may require as little as no time (reading consecutive sectors) or as much as a full rotation (just missed it).
  - On average, for random reads/writes, we can assume that the disk spins halfway.

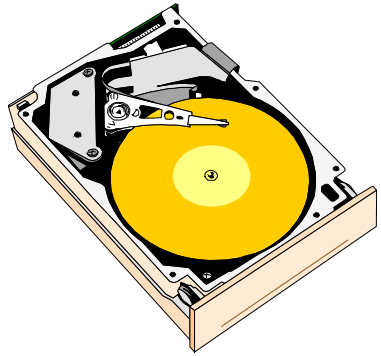
- Rotational delay depends partly on how fast the disk platters spin.

  Average rotational delay = 0.5 x rotations x rotational speed

  - For example, a 5400 RPM disk has an average rotational delay of:

    0.5 rotations / (5400 rotations/minute) = 5.55 ms

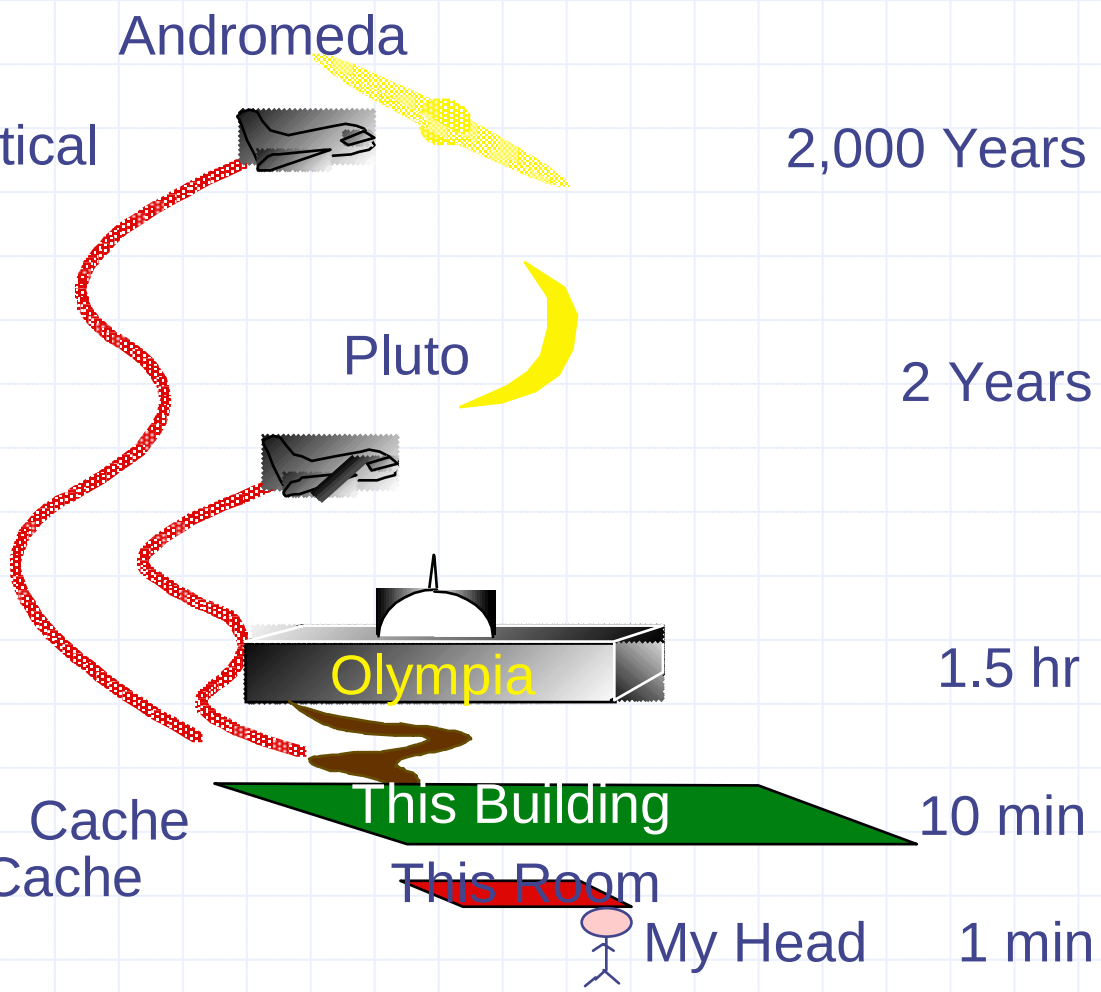
Estimating disk times



- The overall response time is the sum of the seek time, rotational delay, transfer time, and overhead.
- Assume a disk has the following specifications.
  - An average seek time of 9ms
  - A 5400 RPM rotational speed
  - A 10MB/s average transfer rate
  - 2ms of overheads
- How long does it take to read a random 1,024 byte sector?
  - The average rotational delay is 5.55ms.
  - The transfer time will be about (1024 bytes / 10 MB/s) = 0.1ms.
  - The response time is then 9ms + 5.55ms + 0.1ms + 2ms = 16.7ms. That's 16,700,000 cycles for a 1GHz processor!
- One possible measure of throughput would be the number of random sectors that can be read in one second.

(1 sector / 16.7ms) x (1000ms / 1s) = 60 sectors/second.

Storage Latency: How Far Away is the Data?



10^9	Tape /Optical Robot	2,000 Years
10^6	Disk	2 Years
100	Memory	1.5 hr
10	On Board Cache	10 min
2	On Chip Cache	
1	Registers	1 min

File systems

- The concept of a file system is simple
  - the implementation of the abstraction for secondary storage
    - abstraction = files
  - logical organization of files into directories
    - the directory hierarchy
  - sharing of data between processes, people and machines
    - access control, consistency, …

Files

- A file is a collection of data with some properties
  - contents, size, owner, last read/write time, protection …
- Files may also have types
  - understood by file system
    - device, directory, symbolic link
  - understood by other parts of OS or by runtime libraries
    - executable, dll, source code, object code, text file, …
- Type can be encoded in the file's name or contents
  - windows encodes type in name
    - .com, .exe, .bat, .dll, .jpg, .mov, .mp3, …
  - old Mac OS stored the name of the creating program along with the file
  - unix has a smattering of both
    - in content via magic numbers or initial characters (e.g., #!)

Basic operations

Unix

- create(name)
- open(name, mode)
- read(fd, buf, len)
- write(fd, buf, len)
- sync(fd)
- seek(fd, pos)
- close(fd)
- unlink(name)
- rename(old, new)

NT

- CreateFile(name, CREATE)
- CreateFile(name, OPEN)
- ReadFile(handle, …)
- WriteFile(handle, …)
- FlushFileBuffers(handle, …)
- SetFilePointer(handle, …)
- CloseHandle(handle, …)
- DeleteFile(name)
- CopyFile(name)
- MoveFile(name)

File access methods

- Some file systems provide different access methods that specify ways the application will access data
  - sequential access
    - read bytes one at a time, in order
  - direct access
    - random access given a block/byte #
  - record access
    - file is array of fixed- or variable-sized records
  - indexed access
    - FS contains an index to a particular field of each record in a file
    - apps can find a file based on value in that record (similar to DB)
- Why do we care about distinguishing sequential from direct access?
  - what might the FS do differently in these cases?

Directories

- Directories provide:
  - a way for users to organize their files
  - a convenient file name space for both users and FS's
- Most file systems support multi-level directories
  - naming hierarchies (/, /usr, /usr/local, /usr/local/bin, …)
- Most file systems support the notion of current directory
  - absolute names: fully-qualified starting from root of FS

    ```
    bash$ cd /usr/local/bin
    ```

  - relative names: specified with respect to current directory

    ```
    bash$ cd /usr/local   (absolute)
    bash$ cd bin          (relative, equivalent to cd /usr/local/bin)
    ```

Directory internals

- A directory is typically just a file that happens to contain special metadata
  - directory = list of (name of file, file attributes)
  - attributes include such things as:
    - size, protection, location on disk, creation time, access time, …
  - the directory list is usually unordered (effectively random)
    - when you type “ls”, the “ls” command sorts the results for you
  - Key difference from ordinary files: system will not allow user process to write a directory with ordinary I/O calls, even if the user created/owns it. Why?

Path name translation

- Let's say you want to open "/one/two/three"

```
fd = open("/one/two/three", O_RDWR);
```

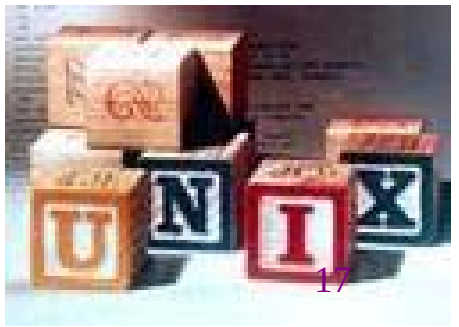
- What goes on inside the file system?
  - open directory "/" (well known, can always find)
  - search the directory for "one", get location of "one"
  - open directory "one", search for "two", get location of "two"
  - open directory "two", search for "three", get loc. of "three"
  - open file "three"
  - (of course, permissions are checked at each step)
- FS spends lots of time walking down directory paths
  - this is why open is separate from read/write (session state)
  - OS will cache prefix lookups to enhance performance
    - /a/b, /a/bb, /a/bbb all share the "/a" prefix

Protection systems

- FS must implement some kind of protection system
  - to control who can access a file (user)
  - to control how they can access it (e.g., read, write, or exec)
- More generally:
  - generalize files to objects (the “what”)
  - generalize users to principals (the “who”, user or program)
  - generalize read/write to actions (the “how”, or operations)
- A protection system dictates whether a given action performed by a given principal on a given object should be allowed
  - e.g., you can read or write your files, but others cannot
  - e.g., your can read `/etc/motd` but you cannot write to it

The original Unix file system

- Dennis Ritchie and Ken Thompson, Bell Labs, 1969
- “UNIX rose from the ashes of a multi-organizational effort in the early 1960s to develop a dependable timesharing operating system” -- Multics
- Designed for a “workgroup” sharing a single system
- Did its job exceedingly well
  - Although it has been stretched in many directions and made ugly in the process
- A wonderful study in engineering tradeoffs



All Unix disks are divided into five parts

- Boot block
  - can boot the system by loading from this block
- Superblock
  - specifies boundaries of next 3 areas, and contains head of freelists of inodes and file blocks
- i-node area
  - contains descriptors (i-nodes) for each file on the disk; all i-nodes are the same size; head of freelist is in the superblock
- File contents area
  - fixed-size blocks; head of freelist is in the superblock
- Swap area
  - holds processes that have been swapped out of memory

So …

- You can attach a disk to a dead system …
- Boot it up …
- Find, create, and modify files …
  - because the superblock is at a fixed place, and it tells you where the i-node area and file contents area are
  - by convention, the second i-node is the root directory of the volume

i-node format

- User number
- Group number
- Protection bits
- Times (file last read, file last written, inode last written)
- File code: specifies if the i-node represents a directory, an ordinary user file, or a “special file” (typically an I/O device)
- Size: length of file in bytes
- Block list: locates contents of file (in the file contents area)
  - more on this soon!
- Link count: number of directories referencing this i-node

The flat (i-node) file system

- Each file is known by a number, which is the number of the i-node
  - seriously – 1, 2, 3, etc.!
  - why is it called “flat”?
- Files are created empty, and grow when extended through writes

The tree (directory, hierarchical) file system

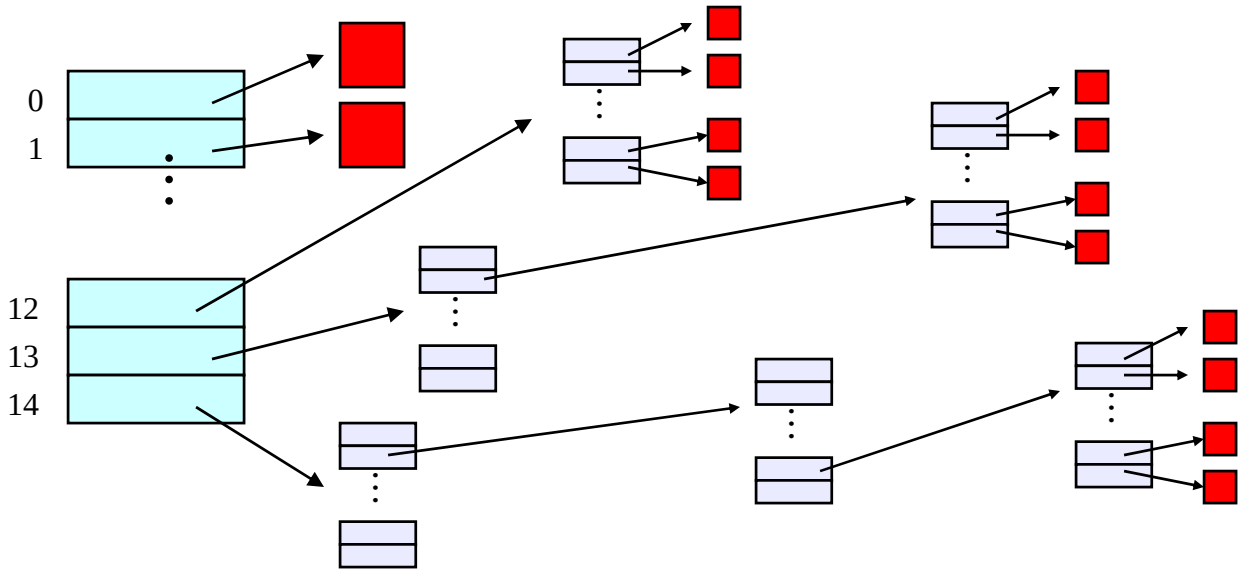
- A directory is a flat file of fixed-size entries
- Each entry consists of an i-node number and a file name

i-node number	File name
152	.
18	..
216	my_file
4	another_file
93	oh_my_god
144	a_directory

- It's as simple as that!

The “block list” portion of the i-node

- Clearly it points to blocks in the file contents area
- Must be able to represent very small and very large files. How?
- Each inode contains 15 block pointers
  - first 12 are direct blocks (i.e., 4KB blocks of file data)
  - then, single, double, and triple indirect indexes



So …

- Only occupies 15 x 4B in the i-node
- Can get to 12 x 4KB = a 48KB file directly
  - (12 direct pointers, blocks in the file contents area are 4KB)
- Can get to 1024 x 4KB = an additional 4MB with a single indirect reference
  - (the 13th pointer in the i-node gets you to a 4KB block in the file contents area that contains 1K 4B pointers to blocks holding file data)
- Can get to 1024 x 1024 x 4KB = an additional 4GB with a double indirect reference
  - (the 14th pointer in the i-node gets you to a 4KB block in the file contents area that contains 1K 4B pointers to 4KB blocks in the file contents area that contain 1K 4B pointers to blocks holding file data)
- Maximum file size is 4TB

File system consistency

- Both i-nodes and file blocks are cached in memory
- The “sync” command forces memory-resident disk information to be written to disk
  - system does a sync every few seconds
- A crash or power failure between sync’s can leave an inconsistent disk
- You could reduce the frequency of problems by reducing caching, but performance would suffer big-time

i-check: consistency of the flat file system

- Is each block on exactly one list?
  - create a bit vector with as many entries as there are blocks
  - follow the free list and each i-node block list
  - when a block is encountered, examine its bit
    - If the bit was 0, set it to 1
    - if the bit was already 1
      - if the block is both in a file and on the free list, remove it from the free list and cross your fingers
      - if the block is in two files, call support!
  - if there are any 0's left at the end, put those blocks on the free list

d-check: consistency of the directory file system

- Do the directories form a tree?
- Does the link count of each file equal the number of directories links to it?
  - I will spare you the details
    - uses a zero-initialized vector of counters, one per i-node
    - walk the tree, then visit every i-node

Protection

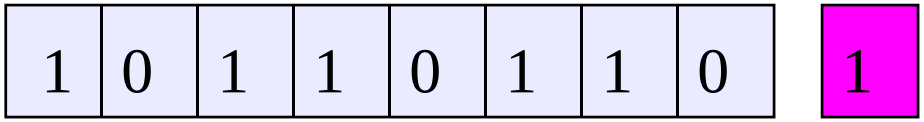
- Objects: individual files
- Principals: owner/group/world
- Actions: read/write/execute

- This is pretty simple and rigid, but it has proven to be about what we can handle!

Performance and Reliability

- Disk transfer rates are improving, but much less fast than CPU performance
- We can use multiple disks to improve performance
  - by *striping* files across multiple disks (placing parts of each file on a different disk), we can use parallel I/O to improve access time
- Striping reduces reliability
  - 100 disks have 1/100th the MTBF (mean time between failures) of one disk
- So, we need striping for performance, but we need something to help with reliability / availability
- To improve reliability, we can add redundant data to the disks, in addition to striping

Refresher: What's parity?



- To each byte, add a bit set so that the total number of 1's is even
- Any single missing bit can be reconstructed

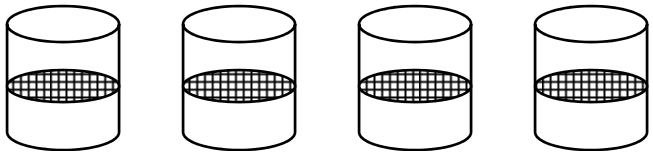
- More complex schemes (e.g., based on Hamming codes) can detect multiple bit errors and correct single bit errors. Called ECC (error correcting code) memory.

RAID

- A RAID is a Redundant Array of Inexpensive Disks
- Disks are small and cheap, so it's easy to put lots of disks (10s to 100s) in one box for increased storage, performance, and availability
- Data plus some redundant information is striped across the disks in some way
- How striping is done is key to performance and reliability

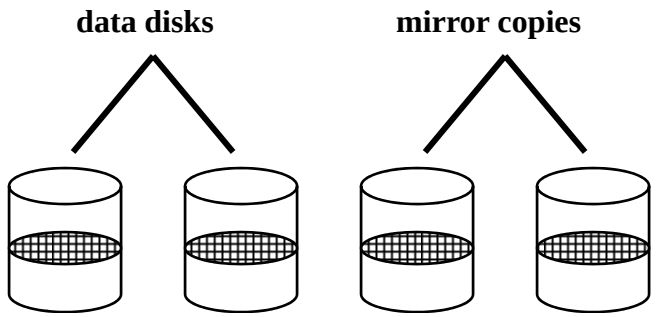
RAID Level 0

- RAID Level 0 is a non-redundant disk array
- Files are striped across disks, no redundant info
- High read throughput
- Best write throughput (no redundant info to write)
- Any disk failure results in data loss



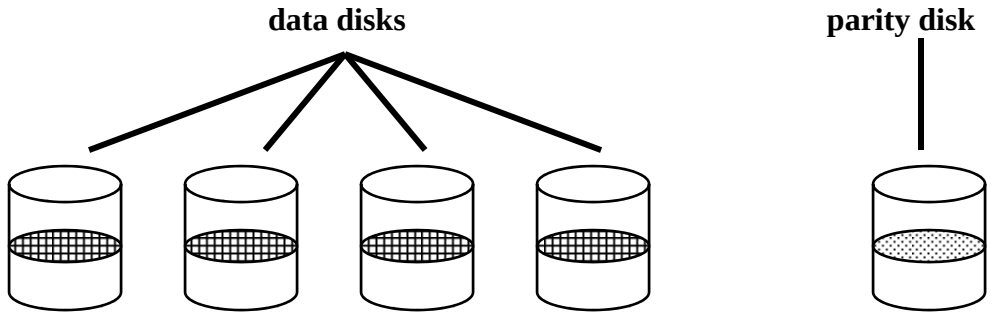
RAID Level 1

- RAID Level 1 is mirrored disks
- Files are striped across half the disks
- Data is written to two places – data disks and mirror disks
- On failure, just use the surviving disk
- 2x space expansion



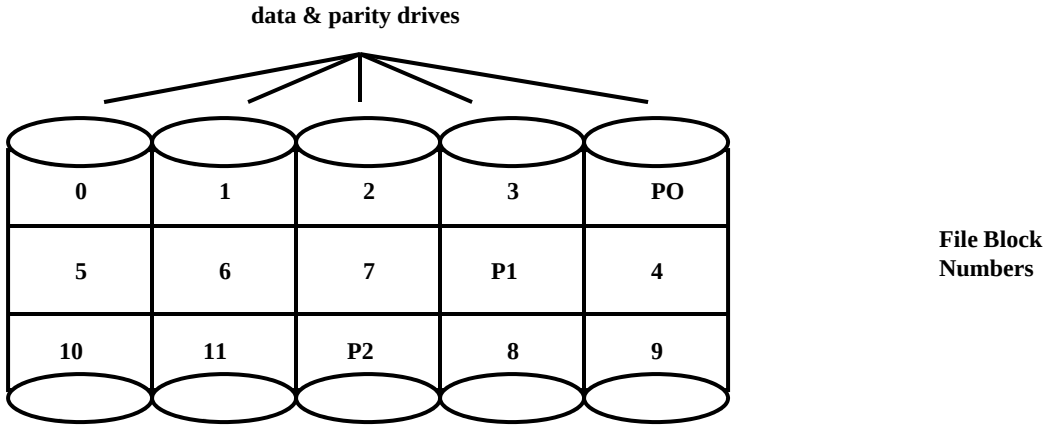
RAID Levels 2, 3, and 4

- RAID levels 2, 3, and 4 use ECC (error correcting code) or parity disks
  - E.g., each byte on the parity disk is a parity function of the corresponding bytes on all the other disks
- A read accesses all the data disks
- A write accesses all the data disks plus the parity disk
- On disk failure, read the remaining disks plus the parity disk to compute the missing data



RAID Level 5

- RAID Level 5 uses block interleaved distributed parity
- Like parity scheme, but distribute the parity info (as well as data) over all disks
  - for each block, one disk holds the parity, and the other disks hold the data
- Significantly better performance
  - parity disk is not a hot spot



RAID Level 6

- Basically like RAID 5 but with replicated parity blocks so that it can survive two disk failures.
- Useful for larger disk arrays where multiple failures are more likely.

- RAID 10 – striping plus mirroring
- RAID 50 – RAID 5 plus mirroring
- RAID xx – something for you to invent ☺