Why disk arrays?

- **CPUs improving faster than disks**
  - disks will increasingly be bottleneck
- **New applications (audio/video) require big files (motivation for XFS)**
- **Disk arrays - make one logical disk out of many physical disks**
- **More disks results in two benefits**
  - Higher data transfer rates on large data accesses
  - Higher I/O rates on small data accesses

Reliability implications of arrays

- **JBOD array with 100 disks is 100 times more likely to fail!**
  - Each disk 200,000 hours MTBF → array 2,000 hours (3 months)
    [approximately – double counts two disks failing]
- **Use redundancy to improve reliability**
  - But makes writes slower, since redundant info must be updated
  - Raises issues of consistency in the face of power failures

Disk array basics

- **Data striping - balances load across disks**
- **Redundancy - improve reliability**
- **Many different schemes, depending on**
  - granularity of data interleaving
    - fine grained $\rightarrow$ high transfer rates for all requests
    - course grained $\rightarrow$ allow parallel small requests to different disks
  - method in which redundant information computed & distributed

RAID 0

- **Nonredundant storage (JBOD - just a bunch of disks)**
  - E.g., Stripe sequential 128K logical regions to different disk
- **Offers best possible write performance (only one write per write)**
- **Offers best possible storage efficiency (no redundancy)**
- **Offers good read performance**
- **Use if speed more important that reliability (scientific computing)**

RAID 1

- **Mirrored storage – Each block stored on two disks**
- **Writing slower (twice as many operations)**
- **Storage efficiency 1/2 optimal**
- **Small reads better than other scheme**
  - can read on disk with shortest seek

RAID 2

- **Use Hamming codes, like ECC memory**
  - Multiply data by generator matrix $G = (\, I \quad A \,)$

$$
\begin{aligned}
G &= \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 \end{pmatrix} \\
D &= (\, d_1 \quad d_2 \quad d_3 \quad d_4 \,) \\
E &= G \times D = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_1 + d_3 + d_4 \\ d_1 + d_2 + d_4 \\ d_1 + d_2 + d_3 \end{pmatrix}
\end{aligned}
$$

hamming codes (continued)

- **Decode by multiplying by** $H = (\, A^T \quad I \,)$

$$
\begin{aligned}
H &= \begin{pmatrix} 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{pmatrix} \\
H \times E &= (\, d_1 \quad d_2 \quad d_3 \quad d_4 \quad 0 \quad 0 \quad 0 \,)
\end{aligned}
$$

- **Can recover any two missing bits**
- **Can even recover from one incorrect bit!**
  - If one extra bit is 1, it is wrong
  - If two extra bits are 1, d_2, d_3, or d_4 is wrong
  - If all 3 extra bits are 1, d_1 is wrong

Properties of RAID 2

- **Small reads about like RAID 0**
  - Though more contention for data disks
- **Writes must update multiple parity disks**
- **Storage more efficient than RAID 1 (uses more than half of disks)**
- **Recovers from errors (RAID 1 assumes fail-stop)**
  - Is this overkill?
  - Most disks are fail-stop

RAID 3

- **Bit interleaved parity**
- **Assume fail stop disks, add one parity disk**

$$\begin{aligned} D &= (d_1\ d_2\ d_3\ d_4) \\ E &= (d_1\ d_2\ d_3\ d_4\ d_1 + d_2 + d_3 + d_4) \end{aligned}$$

- **Any read touches all data disks**
- **Any write touches all data disks plus parity disk**

RAID 4

- **Block-interleaved parity**
- **Interleave data in blocks instead of bits**
- **Reads smaller than striping unit can access only one disk**
- **Writes must update data and compute and update parity block**
  - Small writes require **two reads** plus **two writes**
  - Heavy contention for parity disk (all writes touch it)

RAID 5

- **Block-interleaved *distributed* parity**
  - Distribute parity uniformly over all the disks
  - Want to access disks sequentially when sequentially accessing logical blocks:

0	1	2	3	p_0
5	6	7	p_1	4
10	11	p_2	8	9
15	p_3	12	13	14
p_4	16	17	18	19

- **Better load balancing than RAID 4**
- **Small writes still require read-modify-write**

RAID 6

- **P+Q Redundancy (rarely implemented)**
  - Have two parity blocks instead of one
  - With Reed-Solomon codes, can lose any two blocks
- **Now must read-modify-write two parity blocks plus data**

RAID Summary

RAID level	SmRd	SmWr	BigRd	BigWr	Space
0	1	1	1	1	1
1	1	1/2	1	1/2	1/2
3	1/G	1/G	(G-1)/G	(G-1)/G	(G-1)/G
5	1	max(1/G, 1/4)	1	(G-1)/G	(G-1)/G
6	1	max(1/G, 1/6)	1	(G-2)/G	(G-2)/G

- **RAID 4 is strictly inferior to RAID 5**
- **RAID 2 inferior to RAID 5 for fail-stop disks**
- **RAID 1 is just RAID 5 with parity group size G=2**
- **RAID 3 is just like RAID 5 with a very small stripe unit**

When/how do disks fail?

- **Disks can fail very early in their lifetimes (manufacturing errors)**
- **Also tend to fail late in their lifetimes (when disk wears out)**
- **Systematic manufacturing defect can make entire batch of disks fail early**
  - Beware disks with consecutive serial numbers!
- **Environmental factors can kill a bunch of disks (air conditioning failure)**
- **Disks can fail when a bad block is read Bad block may exist for a while before being detected**

Dealing with failures

- **Basic idea:**
  - Add new disk
  - Reconstruct failed disk's state on new disk
- **Must store metadata information during recovery**
  - Which disks are failed?
  - How much of failed disk has been reconstructed?
- **System crashes become very serious in conjunction with disk failure**
  - Parity may be inconsistent (particularly bad for P+Q)
  - You could lose a block other than the one you were writing
  - MUST log in NVRAM enough info to recover parity
  - Makes software-only implementation of RAID risky

Maximizing availability

- **Want to keep operating after failure**
- **Demand reconstruction**
  - Assumes spare disk immediately (or already) installed
  - Reconstruct blocks as accessed
  - Background thread reconstructs all blocks
- **Parity sparing**
  - Replaces parity block with reconstructed data block
  - Need extra metadata to keep track of this

Unrecoverable RAID failures

- **Double disk failures (or tripple, if P+Q redundancy)**
- **System crash followed by disk failure**
- **Disk failure, then read and discover bad block during reconstruction**

RAID improvements

- **Parity logging**
  - Log difference of old and new parity blocks
  - Delay updating actual parity
  - Further writes may save you from a read
- **Declustered parity**
  - Many parity groups, spread over many disks
- **Parity sparing**
  - Use spare disks to improve performance by spreading load

Tuning RAID

- **What is optimal size of data stripe in RAID 0 disk array?**
  $\sqrt{(PX(L-1)Z)/N}$
  - **P** - average positioning time
  - **X** - disk transfer rate
  - **L** - concurrency of workload
  - **Z** - request size
  - **N** - size of array in disks
- **What about in RAID 5?**
  - Reads - similar to RAID 0
  - Writes - optimal is a factor of 4 smaller than for reads (for 16 disks)
  - Seems to vary WITH #disks, while reads vary inversely!
- **Conclusion: Very workload dependent!**