Self-Adjusting Two-Failure Tolerant Disk Arrays

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Self-Adjusting Two-Failure Tolerant Disk Arrays

- Disk arrays suffer from disk failures:
  - Reliability in large scale “real” storage facilities is surprisingly high
    - 1.7% - 8.6% Annual Failure Rate (AFR) observed by Pinheiro et al.
    - 0.5% - 13.5% AFR observed by Schroeder and Gibson
- Many disks develop latent sector failures:
  - Data is lost on a single or a few sectors
    - 3.45% over 32 months according to Bairavasundaram et al. 2008
- Disks are not the only failure mechanism:
  - Disk Failure (20%-55% in study by Jiang et al, 2008)
  - Physical Interconnect Failure (27%–68% in the same study)
  - Protocol Failure and performance failure are also important

References:
- B. Schroeder and G. Gibson, “Disk failures in the real world: What does an MTTF of 1,000,000 hours mean to you?”, FAST, 2007
- L. Bairavasundaram, A. Arpaci-Dusseau, R. Arpaci-Dusseau, G. Goodson, and B. Schroeder: “An analysis of data corruption in the storage stack” ACM Transactions on Storage (TOS), 2008
- W. Jiang, C. Hu, Y. Zhou, and A. Kanevsky: Are disks the dominant contributor for storage failures? A comprehensive study of storage subsystem failure characteristics, ACM Transactions on Storage (TOS), 2008
Self-Adjusting Two-Failure Tolerant Disk Arrays

- As we know, to protect user data, it has to be stored redundantly
  - Mirroring / Replication
    - Same data is stored twice / several times
    - Good performance, good reliability, high storage overhead
  - Parity / Erasure coding
    - Bad to reasonable performance
      - Can be alleviated by caching, large writes, ...
    - Good reliability
    - Low storage overhead
Self-Adjusting Two-Failure Tolerant Disk Arrays

- 2d-layout (Hellerstein, et al)
  - Places each data disk in two parity blocks
  - Uses a square layout

- General layout:
  - Data is stored in disklets (of fixed size)
  - A number of disklets is stored at a single disk
    - Allows use of different types of disks
  - Layout: Each data disklet is in exactly two parity stripes
    - Higher failure tolerance is usually not needed
    - Higher failure tolerance costs in storage and performance

Coding techniques for handling failures in large disk arrays
2-d layout with 16 data and 8 parity disks
Self-Adjusting Two-Failure Tolerant Disk Arrays

- Criteria for good layout:
  - Each reliability stripe consists of $n$ data disklets and one parity disklet
  - Each disk contains the same number of parity disklets
    - To equalize write load
  - Each disk contains the same number of data disklets
    - To equalize write and read load
  - Each disklet contains the same number of unassigned disklets
    - Spare space to be used in case of disk failure
    - To equalize write and read load
  - If one disk fails, then the reconstruction load is equally distributed
    - Reads to a failed disk are satisfied by reading from all other disks in a reliability stripe containing the failed disk
    - Piggy-backing on read load, we reconstruct loss data and write it to other disks
Self-Adjusting Two-Failure Tolerant Disk Arrays

- Key Observations:
  - Large scale storage organizations are dynamic
    - Disks enter system in batches
    - Disk capacity changes over the lifetime of the system
    - Leave it through failure and decommissioning
  - Optimal layouts only for some parameters
  - Optimal layouts do not adjust well to changes

- Conclusion:
  - By applying maxim: “The better is the enemy of the good”

- **Layouts that are close to satisfying these conditions usually suffice and can be easily adapted to changing number of disks.**
Self-Adjusting Two-Failure Tolerant Disk Arrays

- We store data in disklets – virtual disks of fixed size
  - Disklets are large-sized contiguous sections of disks (~10GB – 200GB ≈ 200 – 10 disklets per disk)
  - Each data disklet is placed in two reliability stripes with one parity disklet each.
- We can move disklets transparently to other disks
  - E.g. to reorganize the disk array after failures or when adding disks to the array
Graph Representation

- Each disklet is in two reliability stripes
- Mathematical design theory knows this as a configuration:
  - Elements (data disklets) and blocks (reliability stripe)
  - Each element is in exactly two blocks
  - Each block has $n$ elements
  - Two different elements share at most one block

<table>
<thead>
<tr>
<th>Design Theory</th>
<th>Disk Array Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks are</td>
<td>Stripes are</td>
</tr>
<tr>
<td>A = {1,2,3}</td>
<td>1,2,3,A</td>
</tr>
<tr>
<td>B = {1,4,5}</td>
<td>1,4,5,B</td>
</tr>
<tr>
<td>C = {2,4,6}</td>
<td>2,4,6,C</td>
</tr>
<tr>
<td>D = {3,5,6}</td>
<td>3,5,6,D</td>
</tr>
<tr>
<td></td>
<td>With A, B, C, D parity disklets</td>
</tr>
</tbody>
</table>
Graph Representation

Disk Array Layout
Stripes are
1,2,3,A
1,4,5,B
2,4,6,C
3,5,6,D
With A, B, C, D parity disklets
Graph Representation

- Dual in design theory: Blocks become elements, elements become blocks
- Dual of dual is the original design
- Dual of configuration is a regular graph.

<table>
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<th>Blocks are</th>
<th>Stripes are</th>
<th>Dual:</th>
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<tr>
<td>B = {1,4,5}</td>
<td>1,4,5,B</td>
<td>2: (A,C)</td>
</tr>
<tr>
<td>C = {2,4,6}</td>
<td>2,4,6,C</td>
<td>3: (A,D)</td>
</tr>
<tr>
<td>D = {3,5,6}</td>
<td>3,5,6,D</td>
<td>4: (B,C)</td>
</tr>
<tr>
<td></td>
<td>With A, B, C, D parity disklets</td>
<td>5: (B,D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6: (C,D)</td>
</tr>
</tbody>
</table>
Graph Representation

- Dual is a graph
  - Vertices correspond to parity
  - Edges to data

Dual:
1: (A,B)
2: (A,C)
3: (A,D)
4: (B,C)
5: (B,D)
6: (C,D)

Stripes are
1,2,3,A
1,4,5,B
2,4,6,C
3,5,6,D
With A, B, C, D parity disklets
Graph Representation

- Data disklets are the edges of the graph
- Parity disklets are the vertices of the graph
- Reliability stripe is composed of a vertex (parity disklet) and all edges adjacent to vertex (data disklets)
Two-dimensional RAID
Graph Representation
Graph Representation

• **Any** graph corresponds to a disklet layout
  - Vertices correspond to parity disklets and reliability stripes
  - Edges correspond to data disklets
  - Adjacency corresponds to reliability stripe membership

Reliability Stripe: 1, 8, 12, 22, 36, 98 + parity a
Representing Failures

- Mark failed disklets red:
  - Failed parity a, b, c
  - Failed data 1, 2, 3, 4
Representing Failures

- Data 1 can be recovered using parity disklet r or s
- Place on new disklet
Representing Failures

- Parity disklet a can be recovered
- All data disklets in the stripe are there
Representing Failures

- Data disklet 2 can be recovered using stripe with parity $t$
Representing Failures

- Data disklet 3 can now be recovered, too.
Representing Failures

- Data disklet 3 can now be recovered, too.
Representing Failures

- But now we are stuck:
  - This represents data loss
Representing Failure

- Disk(s) or rack failure mark(s) many disklets red
  - This is a failure pattern
- Many disklets can be recovered
  - Their data is reconstructed and placed on new disklets
- Parity disklet (vertex) can be recovered if all edges are not marked failed
- Data disklet (edge) can be recovered if one of its adjacent vertices and all other edges at this vertex are not marked failed
Representing Failure

- Irreducible failure pattern:
  - Cannot reconstruct (un-mark) any marked edge or vertex
- Minimal irreducible failure pattern
  - An irreducible failure pattern that is not contained in another irreducible failure pattern
Theorem: Minimal Irreducible Failure Patterns are:

- Chains
- Cycles

Representing Failure

- Not all layouts (graphs) are equal:
  - Cannot avoid the barbell
    - Edges need to be between two vertices
  
- But can avoid a triangle
Representing Failure

- We use graphs based on $n$-dimensional grids
- Guaranteed to be triangle free
- Have vertex degree $= 2n$
Assigning disklets to disks

- Disklets need to be stored on disks
  - Simultaneous failure of two disks cannot lead to data loss
- We model this by coloring disklets with the color of a disk
  - There are conditions on coloring:
    - To provide two failure tolerance:
      - Every disklet (edge or vertex) needs to be at walking distance > 2 of another disklet colored with the same disk
        - Walking distance = Number of elements on the smallest walk connecting two elements
      - This prevents having an irreducible failure pattern generated by a double disk failure
Assigning disklets to disks

- There are conditions on coloring:
  - To provide two failure tolerance:
    - Every disklet (edge or vertex) needs to be at walking distance \( > 2 \) of another disklet colored with the same disk
  - Every disk should have same proportion of parity and data disklets
- Reconstruction loads should be evenly distributed
  - In fact, given a massive failure pattern, there are many ways to reconstruct all the data that needs to be reconstructed, as each data disklet is in two reliability stripes
    - This should follow from our algorithms, but we do not have any results yet
Assigning disklets to disks

- We use a heuristic / greedy algorithm
  - Line up all disks in a list, then shuffle the list
    - *We call a list of disks a palette*
  - Go systematically through the graph, assigning colors from the list first to vertices, then to edges
    - Check whether walking distance is violated by an assignment, if yes, pick other color, if necessary, backtrack
  - Algorithm guarantees 2 failure tolerance, equal amount of parity
Assigning disklets to disks

- Algorithm works well for racks:
  - Assume that the disk array consists of a reasonably large number of racks, which can fail
  - All disks in a rack are colors in a palette
    - To color an element:
      - First pick a palette (rack) subject to walking distance restriction
      - Then a color (disk) in the palette (rack)
Representing other tasks

• Dealing with massive failure
  • Probably do not have enough spare disklets unassigned in the array
  • Need to **change** graph:
    • Number of data disklets per reliability group needs to be increased so that we need less parity disklets that can then be used to store reconstructed data
  • Changes in the graph correspond to simple operations in the disk array
    • (But these operations move large amount of data from one disk to another)
Representing other tasks

- Moving large amounts of disks into or out of a disk array
  - Corresponds to rather simple graph manipulations
What can we achieve

• Make administration of two-failure resilient, very large disk array \textit{simple}

• Work in progress:
  • Algorithms need to be fast
  • Need to show that disk layouts are good enough:
    • Resilience against larger sets of failures
    • Distribution of recovery workload
Layout Design: Execution Time

- Graph layout is linear on the number of disks
- Execution time is roughly 1.329 ms per disk
- This is very fast

System configuration: 10 disklets per Disk, 8 data disklets per reliability group, each data disklet has 2 reliability groups
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Layout Design: Failure Tolerance

- Alternative: Reliability stripes with two-erasure correcting code (RAID Level 6)

- Two parity disklets per stripe:
  - One normal parity

- Has lower robustness
Comparison in Probability of Data Loss (PDL) for three disk failure with 10 disklets per disk between our scheme, below, and RAID level 6 with same storage overhead
Layout Design: Failure Tolerance

- Why is the double stripe strategy more robust:
  - Double stripe with three disk failure:
    - Assume data disklets on one failed disk suffers data loss
    - Then the parity disklets are on the other two disks
  - RAID Level 6 stripe:
    - Assume data disklet on one failed disk suffers data loss
    - If any two of the other disklets in the stripe are on the other two failed disks, we have data loss
    - For $m = 8$, 36 possible failure arrangements.
Layout Design : Failure Tolerance

- Failure tolerance increases with the # of disks in the system
- The system can sustain multiple simultaneous disk failures without data loss

System configuration: 10 disklets per Disk, 8 data disklets per reliability group, each data disklet has 2 reliability groups
Complete Rack Failure

System configuration: 10 disklets per Disk, 8 data disklets per reliability group, each data disklet has 2 reliability groups
More disklets increase probability of something bad happening at least once
Amount of data lost actually decreases
System configuration: 8 data disklets per reliability group, each data disklet has 2 reliability groups
# of Disklets per Disk > Failure Tolerance

- Although the # of units lost increases with the disklets per disk
- The % of actual data lost decreases with the # of disklets per disk

System configuration: 8 data disklets per reliability group, each data disklet has 2 reliability groups