Mirrored and Hybrid Disk Arrays: Organization, Scheduling, Reliability, and Performance

Alexander Thomasian *

Abstract

Basic mirroring (BM) classified as RAID level 1 replicates data on two disks, thus doubling disk access bandwidth for read requests. RAID1/0 is an array of BM pairs with balanced loads due to striping. When a disk fails the read load on its pair is doubled, which results in halving the maximum attainable bandwidth. We review RAID1 organizations which attain a balanced load upon disk failure, but as shown by reliability analysis tend to be less reliable than RAID1/0. Hybrid disk arrays which store XORed instead of replicated data tend to have a higher reliability than mirroring disks, but incur a higher overhead in updating data. Read request response time can be improved by processing them at a higher priority than writes, since they have a direct effect on application response time. Shortest seek distance and affinity based routing both shorten seek time. Anticipatory arm placement places arms optimally to minimize the seek distance. The analysis of RAID1 in normal, degraded, and rebuild mode is provided to quantify RAID1/0 performance. We compare the reliability of mirrored disk organizations against each other and hybrid disks and erasure coded disk arrays. RAID reliabilities can be compared with a shortcut reliability analysis method.

Categories and Subject Descriptors: B8.1 [Performance and Reliability]: Fault-tolerance-replication. C.4 [Performance of Systems]: Reliability. D4.2 [Operating Systems]: Storage Management - Secondary Storage.

General terms. RAID, mirrored disks, disk scheduling, data layout.

Additional Key Words and Phrases: Reliability models, queuing theory.

1 Introduction

The original Redundant Arrays of Inexpensive/Independent Disks (RAID) paradigm was based on replacing expensive 3390 large-form factor, high capacity disks used by IBM mainframes with inexpensive small form factor, small capacity, commodity Hard Disk Drives - HDDs used by personal computers [65]. Hard Disk Drives - HDDs are reviewed in Appendix I. The Disk Array Controller - DAC emulates Extended Count Key Data - ECKD with variable block sizes on disks with fixed sized 512 byte sectors. Since large for factor disks are not manufactured anymore, the term Inexpensive was replaced with Independent in the RAID abbreviation [15].

Fault-tolerance in the form of replication and erasure coding was introduced to deal with the lowered reliability resulting from the large number of less reliable disks required to replace a large disk. RAID5 is the simplest form of erasure coding with the capacity of a single disk out of $N$ dedicated to parity, while RAID6 utilizes the capacity of two disks for this purpose [15]. Erasure coding in RAID is discussed in [104, 110] and reviewed in Appendix II.

This review paper is mainly concerned with replication based on mirroring or shadowing and its variations. Mirroring classified as RAID1 was used in early high performance systems, such as Tandem’s NonStop SQL [78] and Teradata DBC/1012 computer [79]. Tandem used Basic Mirroring - BM: two disks

*Thomasian & Associates, 17 Meadowbrook Road, Pleasantville, NY 10570, USA, alexthomasian@gmail.com
cross-connected to two processors to tolerate disk as well as processor failures. Scalability was attained by two levels of high bandwidth busses. The Teradata DBC/1012 database computer used Interleaved Declustering (ID), so that the data on each disk is replicated on the remaining disks in the cluster resulting in a lower increase in disk loads than BM if a disk fails [79]. EMC’s Symmetrix was an early successful RAID product based on mirroring. ¹

Another feature of RAID is striping to balance disk loads by partitioning large files into fixed size stripe units or strips, which are placed round-robin across disk rows or stripes. Striping is the main feature of RAID0 which has no redundancy, but is implemented in almost all RAID arrays.

While erasure coding is much more efficient from the viewpoint of space efficiency, Hadoop Distributed File System - HDFS uses three-way replication, which provides reliability and parallel access provided by HDD storage [20]. HDFS places one replica on the local node, another replica on a different node at the local rack, and the last replica on different node at a different rack. This policy improves write performance while not impacting data reliability or read performance.

Solid State Disks (SSDs) in the form of Flash memory provide short access time, consumes less power than magnetic HDDs, are less costly than Dynamic Random Access Memory (DRAM) per byte and are non-volatile. Flash memories can sustain a finite number of program/erase cycles, i.e., there is wearout due to repeated writing to the same location and writing is only possible to areas which have been pre-erased. Specialized erasure codes have been developed to deal with localized errors in SSDs [111].

HDDs remain the current workhorse for data storage and are considered in our discussion of mirroring for three reasons: (1) most work on mirroring has been done in the context of HDDs. (2) mirroring is too expensive to implement with flash memories. (3) 380K PetaBytes (PB) \(10^{15}\) bytes of HDDs were shipped versus 28K PB of NAND Flash in 2012 [25].

We survey research on mirrored and hybrid disk arrays, which instead of storing replicated blocks store XORed blocks. We review the more influential papers, scattered over a large number of publications since 1990. Video-on-demand and multimedia server data layouts are beyond the scope of this survey. Most papers covered in this survey precede the USENIX conference on File and Storage Technologies - FAST since 2002, and ACM Transactions on Storage - TOS since 2005, which publishes independent papers and selected papers from FAST and the Symposium on Mass Storage System Technologies - MSST since 1974.

The paper is organized as follows: Appendix I provides a description of magnetic HDDs and their organization, disk scheduling, and data placement [44]. Section 2 describes several mirrored and hybrid RAID organizations, where the latter maintain a 50% redundancy level, while storing XORs of multiple data blocks. Performance improvement by judicious routing of disk requests is discussed in Section 3. Section 4 discusses efficient processing of disk writes in RAID1. Non-Volatile RAM/Storage - NVRAM/NVS allows the caching of dirty blocks, so that the their destaging can be deferred and while one disk is being written, the other disk is being read. Studies of multi-arm disks and disks with more than one Read/Write (R/W) head on a single arm, to achieve lower seek distances are discussed in Section 5. Section 6 discusses analytic models to estimate seek distances and also cylinder remapping to reorganize data in mirrored disks to reduce seek distances. Performance of mirrored and hybrid arrays in normal, degraded, and rebuild mode is discussed in Section 7. In Section 8 we compare the reliability of mirrored disks against each other and hybrid arrays, but also against erasure coded RAID arrays reviewed in Appendix II. In Section 9 we discuss arrays which combine multiple RAID levels. We conclude with Section 10 Commonly used abbreviations are given preceding Appendix I.

¹https://en.wikipedia.org/wiki/EMC_Symmetrix.
2 Mirrored and Hybrid Disk Organizations

There have been numerous proposals for RAID1 organizations, which provide a more balanced disk load when a disk fails, but a more important consideration is RAID1 reliability as discussed in Section 8. *Hybrid Disk Arrays* - HDA*s store redundant data in the form of *eXclusive-ORed* - XORed* data blocks. HDAs are more reliable than RAID1, but incur more disk accesses for updating data.

2.1 Basic Mirroring (BM)

*Basic Mirroring (BM)* is the original form of disk mirroring, which replicates data on two identical disks, but data can also be replicated on a storage medium with equal capacity. Similarly to other RAID1 organizations BM has the advantage of doubling disk access bandwidth for read requests, but if a disk fails the read load of the surviving disk is doubled. This is especially a problem if the data is not striped and the mirrored pair is heavily loaded. Most performance studies of RAID1 have been conducted in the context of the BM organization.

For higher volumes of data there are $M$ pairs of mirrored disks with BM organization, so that the total number of disks is $N = 2M$. RAID1/0 is a hierarchal RAID organization with mirrored pairs at the lower level, which may be considered a single virtual disk with higher reliability, and RAID0 at the higher level. Up to $M$ disk disk failures can be tolerated, as long as there are no pairs, so that the probability of data loss due to a second disk failure is $1/M$.

RAID0/1 mirrors two RAID0 arrays, each with $M$ disks as shown in Figure 1. Each RAID0 arrays is considered a superdisk, which is considered failed when a single disk fails, so that up to $M$ disk failures can be tolerated as long as they are all on one side. The probability of data loss due to a second disk failure is: $M/(2M − 1) > 0.5$, which is much higher than the same probability for RAID1/0.

RAID1/0 and RAID0/1 are examples of nested RAID levels, $^2$ whose reliability was analyzed in [99] and in Section 8. *Hierarchic RAID* - *HRAID* uses RAID5 erasure coding as both levels [108].

2.2 Group Rotate Declustering - GRD

GRD is a RAID0/1 array with mirroring at the higher level with $M$ primary disks on one side, while the $M$ secondary data at the other side are rotated from row to row as shown in Figure 2. GRD has the advantage that upon the failure of a disk on either side its read accesses are evenly distributed over the $M$ disks at the other side. GRD can tolerate up to $M$ disk failures on one side, but fails if a second disk fails at the other side, so that the probability of data loss similarly to RAID0/1 is $M/(2M − 1) > 0.5$, The fraction of GRD requests routed can be adjusted to balance disk loads as discussed in Section 7.

Two variants of data placements for GRD are shown in Figure 3 in [16]. Disk space may be split by allocating primary data on outer cylinders and secondary data on inner cylinders. Disk capacity is split into halves by allocating half of outer (resp. inner) cylinders to primary (resp. secondary) data. In zoned disks tracks on outer cylinders hold more sectors than inner tracks in zoned disks [44], so that primary data will occupy fewer disk cylinders than secondary data, which implies shorter seeks in accessing randomly placed primary blocks. Primary (resp. secondary) data can be allocated at upper (resp. lower) tracks of a disk cylinder, but this is restricted to disks with an even number of tracks per cylinder.

RAID-X proposed in [39] has a similarity to GRD as shown in Figure 3. Data strips on primary disks are placed diagonally in secondary areas.

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$^2$https://en.wikipedia.org/wiki/Nested_RAID_levels.
Figure 1: RAID0/1 with $N = 8$ disks. Rotated primed blocks replicate unprimed blocks.

Figure 2: Group Rotate Declustering with $N = 8$ disks.

Figure 3: RAID-x architecture with $M = 4$ disks in one cluster.

Figure 4: Interleaved Declustering with $N = 8$ disks, $c = 2$ clusters, and $n = 4$ disks per cluster. Capital letters denote primary data and small letters subsets of secondary data.

Figure 5: Chained declustering with $N = 8$ disks. Primary blocks are in caps and secondaries in small letter.
2.3 Interleaved Declustering (ID)

ID organizes $N$ disks into $c$ clusters with $n = N/c$ disks per cluster, e.g., $N = 8$, $c = 2$, and $n = 4$ as shown in Figure 4. Disk data placement may follow GRD, with half of disk capacity dedicated to primary data and the other half to secondary data. The primary data on each disk is partitioned into $n-1$ equal size areas storing secondary data.

The maximum number of disk failures that can be tolerated by ID is $I = c$, while $I = M$ for BM, GRD, and CD organizations. The advantage of ID over BM is that the read load of primary data on a failed disk is distributed over $n-1$ disks.

The Striped Mirroring Disk Array (SMDA) described in [46] has a layout similar to ID.

2.4 Chained Declustering (CD)

The CD organization was proposed in conjunction with the Gamma database machine project [36], which was inspired by the Teradata DBC/1012 database computer [79]. Disk space is shared equally between primary and secondary areas, so that primary data on disk $D_i$ is replicated as secondary data on disk $D_{i+1 \mod (N)}$ as shown in Figure 5. CD can tolerate up to $M$ disk failures, as long as there are no consecutive disks.

Data can be accessed from its primary or secondary areas, similarly to ID and GRD organizations. Unlike ID, CD does spread secondary data over multiple disks, but CD can be extended by allowing the primary data to be distributed over the next $n-1$ disks. While such a CD array results in a more balanced load, it is less reliable, since data loss will occur if the two failed disks are within $n$ of each other.

A shown in Figure 6 in the case of disk failures fractional routing of read requests can attain a balanced read load [36, 103]. With two disk failures the routing probabilities should be adjusted, as shown by the last two rows of Figure 6.

The Petal disk array utilizes striping (RAID0), but also the CD organization as shown in Figure 5 in [81], which shows that alternate rows are dedicated to primary and secondary data.

2.5 Dual or Hybrid Striping

Dual striping combines large and small stripes to improve performance [57]. Database queries requiring table scans and OLTP workloads accessing small data blocks, access data from the large and small stripes, respectively. Having data distributed over small stripes reduces data access skew for OLTP applications, while fewer seeks are required when table scans are processed over large stripes. Note that the ID organization implicitly utilizes two strip sizes, where secondary strips are $n-1$ times smaller than primary strips.

Disks are modeled as $M/G/1$ queues [48], which are briefly described in Section 7.1. Disks process accesses to short blocks with Poisson arrivals, but also one large disk access one at a time according to the Permanent Customer Model (PCM) [11], which is discussed in more detail in Section 7.4. The
performance study showed that dual striping outperforms uniform striping in both normal and degraded modes (with one disk failure) for the disk workload under consideration. Table scans may result in unacceptable delay in the processing of accesses to short blocks by OLTP transactions. A solution is to temporarily pause lengthy table scans to allow short disk accesses to proceed, as discussed in [78]. This requires an extension of [11] to allow the preemptive policy for permanent customers.

2.6 LSI Logic RAID

LSI Logic RAID combines mirroring and parity by placing Parity disks (Pdisks) between pairs of Data disks (Ddisks) [128]. The Data out-Degree (DoutD) is the number of parities associated with each data element and the Parity in-Degree (PinD) is the number of data elements XORed to compute a parity, so that DoutD=PinD=2 in this case. With \( N = 2M = 8 \) disks there are four Ddisks and four Pdisks denoted by D and P, respectively, so that \( P_{i,j+1(\text{mod} M)} = D_i \oplus D_{i+1(\text{mod} M)}, \) 1 \( \leq i \leq 4 \), as shown below:

\[
(D_1, P_{1,2}, D_2, P_{2,3}, D_3, P_{3,4}, D_4, P_{4,1}).
\]

LSI RAID can tolerate two disk failures and three consecutive disk failures in one half of cases, when the middle disk is a Pdisk, but not otherwise. If the three disks \( (D_1, P_{1,2}, D_2) \) fail then recovery can proceed as follows: \( D_1 = D_4 \oplus P_{4,1}, D_2 = D_3 \oplus P_{2,3}, \) and \( P_{1,2} = D_1 \oplus D_2 \).

An OLTP workload with read and write accesses to small data blocks will result in an unbalanced disk load if all updates, which are uniform over data blocks are carried out as Read-Modify-Wrote (RMW) accesses. This load is balanced in [107] by using a combination of RMW and ReConstruct Write (RCW) accesses [94]. Disk loads can also be balanced as shown below by shifting the strips right from row-to-row, where \( d_s \) and \( p_s \) represent strips in the first row, and \( d \) and \( p \) represent the shifted strips in the second row. The disadvantage of this layout is that it does not tolerate consecutive three disk failures.

\[
(d_1, p_{1,2}, d_2, p_{2,3}, d_3, p_{3,4}, d_4, p_{4,1}).
\]

\[
(p_{4,1}, d_1, p_{1,2}, d_2, p_{2,3}, d_3, p_{3,4}, d_4).
\]

2.7 SSPiRAL (Survivable Storage using Parity in Redundant Array Layout)

Several mirrored and hybrid disk arrays (HDAs) are investigated in [3]. There are \( N = 2M \) disks where \( M \) disks are Ddisks and the other \( M \) are Pdisks. LSI Logic RAID is SSPiRAL(4+4,2) with four Ddisks and four Pdisks and DoutD=PinD=2, as shown in Figure 7.

| D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-----|-----|-----|-----|-----|-----|-----|-----|
| d_1 | p_{1,2} | d_2 | p_{2,3} | d_3 | p_{3,4} | d_4 | p_{4,1} |

Figure 7: SSPiRAL(4+4,2) with four Ddisks and four Pdisks with PinD=DoutD=2.

SSPiRAL extends LSI RAID to DoutD=PinD=3, so that each Ddisk is protected by three Pdisks and vice-versa. SSPiRAL(4+4,3) with \( N = 8 \) disks, four Ddisks and four Pdisks is shown in Figure 8.

| D_1 | D_2 | D_3 | D_4 | D_5 | D_6 | D_7 | D_8 |
|-----|-----|-----|-----|-----|-----|-----|-----|
| d_1 | d_2 | d_3 | d_4 | d_1 \oplus d_2 \oplus d_3 | d_2 \oplus d_3 \oplus d_4 | d_3 \oplus d_4 \oplus d_1 | d_1 \oplus d_2 \oplus d_3 |

Figure 8: SSPiRAL(4+4,3) with PinD=DoutD=3.

For SSPiRAL(4+4,3) all disk failures up to three can be tolerated \( A(N,i) = \binom{N}{i}, 0 \leq i \leq 3 \). There are \( \binom{8}{3} = 70 \) possibilities for four disk failures and data loss occurs in 14 cases [3], as follows: (1) A Ddisk and the 3 Pdisks in which it participates (4 cases). (2) Two out of four Ddisks and the two Pdisks in which they both participate (6 cases). (3) Three out of four Ddisks and the Pdisk in which all three
but B-codes like Weaver codes, discussed below, store data on the same device [30]. In the case of 2DFT arrays with horizontal parities, where the former is not MDS and the latter is MDS [104], for B-code and its dual parities associated with data are stored in each column [132]. RM2 and X-code are a special category of interest in this study. Table 1 in [30] is a partial listing of Parity Defining Sets (PDSs) for WEAVER(n,t,t) codes, where the PDS is $\kappa(j) = \kappa_1(j) + s\text{mod}(n)$, e.g., the second row for $t = 3$ in the table: $\kappa_1(0) = (1,2,4)$ and $s = 2$, so that the parities corresponding to $d_j$ are at $(j + 3, j + 4, j + 6)\text{mod}(n)$. LSI Logic RAID is WEAVER(n,2,2) and SSPiRAL is WEAVER(n,3,3), but unlike WEAVER codes they place parities on separate devices.

Properties of B-codes and their duals are listed in [132]. This code is MDS since by placing the 6 data elements have out-degree $t$, so that the parities corresponding to $d_j$ are at $(j + 3, j + 4, j + 6)\text{mod}(n)$. LSI Logic RAID is WEAVER(n,2,2) and SSPiRAL is WEAVER(n,3,3), but unlike WEAVER codes they place parities on separate devices.

Weaver(4,2,2) can tolerate two disk failures, e.g., if disks $D_1$ and $D_2$ fail then $d_1 = d_4 \oplus \{d_4 \oplus d_1\}$, $d_2 = d_1 \oplus \{d_1 \oplus d_2\}$, but unlike LSI Logic RAID three disk failure cannot be tolerated.

Weaver(8,3,3) with $N = 8$ disks with $P_{outD} = P_{inD} = 3$ as shown in Figure 8.

Since a data block and associated parities for Weaver(8,3,3) appear at four different disks all three disk failures can be tolerated. Consider the failure of $D_1, D_4, D_5$, so that $d_1$’s parity is only available at

| $D_1$ | $D_2$ | $D_3$ | $D_4$ |
|-------|-------|-------|-------|
| $d_1$ | $d_2$ | $d_3$ | $d_4$ |
| $d_2 \oplus d_3$ | $d_3 \oplus d_4$ | $d_4 \oplus d_1$ | $d_1 \oplus d_2$ |

Figure 9: Data layout for a Weaver-like (4,2,2) with $N = 4$ disks.

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ | $D_7$ | $D_8$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ | $d_8$ |
| $d_3 \oplus d_4 \oplus d_6$ | $d_4 \oplus d_5 \oplus d_7$ | $d_5 \oplus d_6 \oplus d_8$ | $d_6 \oplus D_7 \oplus d_1$ | $d_7 \oplus d_8 \oplus d_2$ | $d_8 \oplus d_1 \oplus d_3$ | $d_1 \oplus d_2 \oplus d_4$ | $d_2 \oplus d_3 \oplus d_5$ |

Figure 10: Weaver(8,3,3) data layout with $N = 8$ disks and $t = 3$.
To recover \( d_1 \) we need to recover \( d_4 \), since \( d_2 \) is available. We have the following steps \((d_4 \oplus d_5 \oplus d_7) \oplus d_5 \oplus d_7 \rightarrow d_4\) and \((d_7 \oplus d_8 \oplus d_2) \oplus d_7 \oplus d_8 \rightarrow d_2\). Finally, \( d_2 \oplus d_4 \oplus (d_1 \oplus d_2 \oplus d_4) \rightarrow d_1\).

Weaver(8,3,3) can tolerate four disk failures, as long as they do not involve a data strip and its parities. Recovery is possible when the first four disks in Figure 10 fail, as follows: \( d_7 \oplus d_8 \oplus (d_7, d_8, d_2) \rightarrow d_2\), \( d_2 \oplus d_5 \oplus (d_2, d_3, d_5) \rightarrow d_3\), \( d_9 \oplus d_3 \oplus (d_9, d_1, d_3) \rightarrow d_1\), \( d_4 \oplus d_2 \oplus (d_1 \oplus d_2 \oplus d_4) \rightarrow d_4\). For \( N = 8 \) disks and four disk failures there are \( \binom{8}{4} = 70 \) possibilities and out of these \( N = 8 \) rotations of a data strip and its PDS cannot be tolerated.

### 2.10 Robust, Efficient, Scalable, Autonomous, Reliable (RESAR)

The RESAR exabyte scale storage places disklets into two different parity groups with one parity disklet in each stripe [73]. In fact RESAR is RAID5/1, i.e., a mirrored systems where each side is a RAID5 with \( M \) disks. When a disk fails its mirror is accessed first and if this fails data is reconstructed using the RAID5 paradigm. "A RESAR-based layout with 16 data disklets per stripe has about 50 times lower probability of suffering data loss in the presence of a fixed number of failures than a corresponding RAID 6 organization". The simulation to estimate this probability for 100,000 disks required 10,000 hours.

### 2.11 Multiway Placement

Three-way versions of chained, group rotate, and standard mirroring are specified [72]. The **Shifted Declustering (SD)** provides optimal parallelism, since the data replicas are distributed evenly. The similarity of SD to layouts proposed in [2] requires further investigation.

### 3 Routing Read Requests in Mirrored Disks

We summarize routing strategies in mirrored disks in first following [114] and then [98].

1. **Single Queue (SQ)**: Update requests can be processed only when both disks are idle, while read requests can be processed on both disks or only the primary disk (see 1.1).

   1.1 **Primary/Secondary (PSSQ)**: Disks are designated as primary and secondary. (i) **Serial PSSQ (S-PSSQ)** allows only one request to be processed at a time. (ii) **Concurrent PSSQ (C-PSSQ)** allows concurrency between read and update requests. A read request can start service at the primary disk.

   1.2 **Equitable SQ (ESQ)**: Disks are treated equally.

   **Concurrent Read ESQ (CR-ESQ)**: Allows reads to be processed concurrently. Only one update is allowed to be processed at any one time.

   **Concurrent Read Update ESQ (CRU-ESQ)**: Allow concurrency between reads and updates. An update is still required to wait until both disks are available, but a read request may proceed as soon as a disk becomes available.

   **Minimum Read ESQ (MR-ESQ)**: Similarly to S-PSSQ each request waits until the previous request is completed. Read requests are processed at both disks, but when the first read request completes, abort the other request. It should be noted that disk accesses cannot be preempted at all stages, especially during seeks.

2. **Multiple Queue Policies**:

   **Distributed MQ (DMQ)**: Maintain a separate queue for each disk. An update request generates write requests for each queue. Read requests are routed randomly to balance disk loads.

   **Shortest Queue - DMQ (SQ-DMQ)**: Route read requests to the shortest queue. Reads can also spawn requests at both queues. There are two variations Minimum Read - MR with and without preemption. Abort is initiated when a read request begins service or is completed.

   **Common MQ (CMQ)**: The request at the head of the queue starts processing as soon as either disk is free. Update requests are spawned at both disks and are enqueue at the busy disk.
RAID1 performance is compared with RAID5 in [16]. Three RAID1 configurations are considered BM, CD, and GRD, where GRD is shown to provide the best performance for small and large I/O environments. Three routing policies are considered for RAID1: Random Join (RJ), Shortest Queue (SQ), and Minimum Seek (MS). Local disk scheduling policies can additionally be applied at each disk.

Routing policies described in [114] are analyzed in [115] using the Matrix Geometric Method (MGM) [59]. The processing of read and write requests in mirrored disks have similarities to their scheduling in replicated databases, which is reviewed in [112].

Routing of disk accesses in RAID1 is classified according to queue organizations in [98]:

**Private Queue (PQ) with Immediately Routing:** Based on a routing criterion read requests are sent to one of the disks, while write requests are sent to both disks.

**Shared Queue (SQ) with Deferred Routing:** Read requests held at SQ are routed to the first disk that becomes available, while immediate routing may result in idle disk, while the disk has a queue. Dynamic routing based on disk state can be pursued more efficiently than PQ.

**Hybrid Queue (HQ):** Read requests held in SQ are routed to PQs after some delay to ensure the disk queue is not empty.

Two examples of static routing are: uniform with equal probabilities and round-robin routing. It is shown in [98] and Section 7 that with Poisson arrivals and exponential service times round-robin routing improves mean response time with respect to uniform routing.

**Affinity Based Routing (ABR)** divides disks to inner and outer disk blocks, which are delineated by a pivot point, which is *Logical Block Address - LBA* on disk [97]. Numbering LBAs from the outermost disk track, requests with an LBA lower than the pivot point are sent to the disk serving reads on outer tracks and vice-versa. With 2s sectors it seems that the pivot point should be at sector s, but in zoned disks this would entail outer data occupying fewer cylinders than inner data blocks and hence shorter seek times and access times [44], but also see Appendix I. Several criteria to determine the pivot point in zoned disks are considered in [97].

Numerical results show that pivot point selected based on balanced disk utilizations achieve about the same performance as the one based on minimum mean response time, which is justified by Eq. 1. The "transposed mirrored organization", which switches the data on inner and outer tracks achieves the best performance for heavily loaded disks. We also discuss an adaptive approach to implement ABR, so that the pivot point is determined by the router based on the history of routed requests. Sequential reading of large files via successive block accesses benefits from ABR since it eliminates seeks for such accesses. In a situation where multiple large files are being read, the pivot point can be assigned dynamically to split disk space logically to minimize seek times while balancing disk loads. The onboard disk buffer will further improve performance if sequential prefetching is in effect.

The dynamic *Join the Shortest Queue (JSQ)* policy is optimal when the service rates are fixed or non-decreasing [126]. JSQ may not be effective for disk scheduling, since the disk queue length is not a good indicator of the remaining processing time with FCFS scheduling, e.g., consider accesses to neighboring blocks on a track, which can be accessed via a single I/O, an instance of proximal I/O [69]. Instead of estimating the response time of the request to be routed with SATF scheduling, it might be better to reduce the mean response time over all requests [98].

The router may use the LBA to send a request to the disk processing a request with the closest LBA, e.g., the last request in the queue with FCFS scheduling. This is an approximation to the Shortest Job First - SJF, which is the best nonpreemptive policy for single servers [49]. Given the LBA accurate timing emulators can be used to estimate disk service time.
For random disk accesses performance is mainly determined by the local disk scheduling policy and not the PQ (private queue) routing policy. SATF scheduling with SQ (shared queue) applied over all replicated disks provides more opportunities than PQ to improve performance, since twice as many requests are available for SATF scheduling [98]. There are no controllers for mirrored disks which could serve requests from a shared queue.

The Distributed Shortest-Positioning Time First (D-SPTF) protocol dynamically distribute requests in decentralized storage servers, selecting from servers which hold a replica [84]. For 10-200 microsecond network latencies D-SPTF performs as well as a centralized system. D-SPTF achieves up to 65% higher throughput than popular decentralized approaches and adapts more cleanly to heterogeneous server capabilities.

4 Efficient Processing of Writing to Disk in Mirrored Disks

Disk-resident data is cached in computer systems at the main memory buffer, at the cache at the DAC (disk array controller), and onboard disk cache. Large cache capacities have resulted in a reduced miss rate for read requests, so that it has been argued that most disk accesses are writes and it is important to reduce the disk load due to writes.

Write anywhere policy on either or both mirrored disks has been used to minimize disk arm movement to reduce the susceptibility to data loss in systems without an NVRAM cache [74, 75]. A directory keeps track of blocks written anywhere and to allow efficient sequential accesses data is updated later on the primary disk.

The two-phase method for mirrored disks processes read requests at one disk, while the other disk is destaging dirty blocks in a batch mode using a CSCAN scheduling, i.e., SCAN in one direction [66]. It is unlikely that equal durations for the two phases will result in a perfect overlap in read and write processing. Refinements of this method are addressed in [95]: (1) Eliminate forced idleness by processing write requests individually. This can be carried out opportunistically with "freeblock scheduling", which accomplishes useful work during disk rotation time [83]. (2) Given the considerable rotational latency, instead of CSCAN use SATF or destage according to a permutation of outstanding requests to minimize destage time, (3) destaging of dirty blocks is deferred if the number of enqueued read requests exceeds a threshold, whose value is determined by monitoring the system. This provides for more opportunities for dirty blocks to be overwritten.

Part of the DAC cache is an NVRAM, Dynamic Random Access Memory - DRAM [44] protected by Uninterruptible Power Supply (UPS). A duplexed NVRAM is as reliable as a magnetic disks [54], which allows a fast write capability. The destaging/writing of modified data blocks to disk can be deferred, allowing reads to be processed at a higher priority than writes, which improves transaction response time in OLTP. Overwriting of dirty blocks in NVRAM obviates unnecessary destages to disk and deferred writing in batches in LBA order reduces positioning time. The results of trace analysis such as [116] was used to quantify the number overwritten dirty blocks and the proximity of destaged requests (number on the same track) [93]. Destage is initiated when the buffer becomes full or when it is filling rapidly.

An NVRAM is not required for deferred destaging of dirty blocks in OLTP systems with Write Ahead Logging (WAL) [86], but this would entail a costly recovery process if the system crashes. Before and after images of modified data are logged. The before images are used in undoing the updates of aborted transactions, while after images are required to allow the NoForce policy, i.e., a transaction may commits without forcing dirty pages to disk and such dirty pages can be overwritten.

5 Disks with Multiple Arms and Multiple R/W Heads per Arm

Disks with two Read/Write (R/W) heads on one disk arm, which are at a fixed distance from each other are considered in [12, 51]. The Nearer-Server (NS) rule of such a system is analyzed in two cases in [12]:
(1) both heads have to be kept on the surface of the disk. (2) this restriction is relaxed. It was shown that an optimization with respect to $d$ yields an expected seek distance, which is slightly less than that of a system with two independent arms and a single controller which allows the movement of one arm at a time.

It is shown in [51] that for a disk with $C$ cylinders the optimal distance is $d = C/2 - 1$ between the heads and the seek distance is reduced from $C/3$ to $C/6$. A disk with a two heads at a fixed distance $d$ is studied by simulation of an actual system in [63].

Scheduling of a disk with two arms with a single R/W head is studied in [34]. The closest head is used to serve an incoming request, while the other head is moved to a better position in anticipation of the next request. If the accessed cylinder is $a < C/2$ then the head moves somewhere between $a$ and $C$ and if $a > C/2$ the head is positioned between the first cylinder and $a$. More specifically it is shown in [53] that in the first case the head should be positioned at $a + \lfloor (2(C - a)/3 \rfloor$ and otherwise at $\lfloor a/3 \rfloor$. The analysis yields a seek distance $5C/36$, which was given without proof in [34].

There is a Conner patent for multiple actuator Chinook disk [76]. A dual actuator logging disk architecture with one head dedicated to reading and the other arm to logging in regions with free disk sectors is proposed in [14].

The optimal placement for two-headed disk systems is the camel arrangement, which is two consecutive organ-pipe arrangements [52]. There are $2^{N/2 + 1}$ optimal camel arrangements for a disk with $N = 2(2n + 1)$ cylinders.

Improving disk performance via latency reduction in the context of variable block disks with Rotational Position Sensing (RPS) is addressed in [61]. Three methods are proposed to improve latency, which are also applicable to non-RPS disks: (1) Moving the disk arm seeking to the same cylinder on both disks. Synchronized the two disks to be half a rotation away from each other results in a reduction of latency from $T_{rot}/3$ to $T_{rot}/4$. (2) Two copies of the data are placed 180 degrees out of phase from each other. This can be done by doing so on alternating tracks (even and odd) or using half of the capacity of each track. (3) Dual actuators placed opposite each other.

Given a fixed capacity disk array analytical models are developed in [133] to find the combination of striping, mirroring, and rotational data replication, which yields the best performance, i.e., with reduced seek times and rotational delays, for given workload and disk characteristics. The effectiveness of the configuration models are tried on a prototype.

A taxonomy of disk parallelism is provided in [68]. In DASH, Disk stack is the number of disk platters constituting a cylinder, Arm assembly is the number of arms. Surface is the number of surfaces, e.g., two if data recorded on both sides of platters, and Head (number of R/W heads per arm). A conventional disk is then D1 A1 S1 H1. Air turbulence affects the vibration of platters and heads, which makes it impossible to transfer data simultaneously from multiple tracks. A cost benefit analysis of intradisk parallelism is reported in this paper, which also saves disk power consumption, a topic beyond the scope of this paper.

## 6 Seek Distances with Mirrored Disks

The analysis for the seek distance for reads with $k$-way replication is given in [9]. The analysis is based on the fact that for a disk with $C$ cylinders or tracks the probability mass function - pmf for uniform accesses to disk cylinders is $P[X = i] = 2(C - i)/C^2$, $1 \leq i \leq C - 1$, $P[X \geq i] \approx (1 - i/C)^2$, and $P[X = 0] = 1/C$.

With a degree of replication $k$ the mean seek distance using the Reimann integral is as follows:

$$E[X_k] \approx \frac{1}{C^{2k}} \sum_{i=1}^{C-1} (1 - \frac{i}{C})^{2k} \approx \int_0^1 (1-x)^{2k}dx = \frac{1}{2k+1}.$$  

---

3https://en.wikipedia.org/wiki/Conner_Peripherals#Performance_issues_and_the_Chinook_dualactuator_drive.
e.g., for $k = 2$ the seek distance is $1/5$.

An extension of the analysis in [9] for writes using the maximum function yields

$$E[X_W] \approx C(1 - I_k), \text{ where } I_k = \frac{2k - 2}{2k + 1} \frac{2}{2k - 1} \cdots \frac{2}{3}.$$ 

For $k = 2$ the seek distance is $0.46n$.

The cumulative distribution and density function for the minimum and maximum seek distances for disk systems with two independent arms are compared with one-arm systems in [18].

This analysis in [9] does not take into account the effect of R/W heads being positioned on the same track after a write [82], so that there is no improvement with shortest seek distance routing, i.e., the read seek distance is underestimated and the write seek distance is overestimated.

The more detailed analysis in [119] which takes into account disk scheduling and the number of disk cylinders, shows that previous analyses are accurate for a large number of cylinders and small number of disks. The same team compares seek distances in mirrored disks without and with cylinder replication (multiple copies of a cylinder on a disk), under various placement policies with uniform and normally distributed requests [120]. It is concluded that cylinder replication yields a significant improvement.

The study of seek optimization in RAID1 configurations distinguishes between online and offline algorithms [8]. Online algorithms know the current position of the disk arm, while offline algorithms "choose for each copy $0 \leq i \leq d1$ of each file $0 \leq j \leq 1$ a probability $p_{i,j}$ that a read request from file $j$ will be serviced by the $i$th copy of the file". Mirrored disks such as ID, GRD, and CD are referred to as semistructured and shown to outperform BM as far as seek distances are concerned. A list of studies for seek optimization is listed on [8], including previously mentioned $C/5$ based on [9], which is incorrect in comparison with [13] discussed below.

Two servers move along $C$ positions on a straight line and in a circle. Requests for service from one of the $C$ positions with uniform distribution are served from a FCFS queue one at time. The Nearer-Server (NS) rule is optimal for a circle, with an expected normalized server motion $5/36 \approx 0.13889$. The average distance over an interval (straight line) is $0.1625$, while the optimal policy is shown to be $0.1598$, so that NS is within $0.1625/0.1598 = 1.69\%$ of the optimal policy. It is better than $C/6 = 0.1666C$ for the partition rule which dedicates servers one server dedicated to $(1,C/2)$ and another to $(C/2 + 1, C)$.

The Anticipatory Arm Placement (AAP) in single and mirrored non-zoned disks is presented in [47]. With the seek distance in the range $(0,1)$, the arm should be placed at the middle disk cylinder, reducing the seek distance from $1/3$ to $1/4$. In mirrored disks the two arms should be placed at $1/4$ and $3/4$ so that the seek distance is $1/8$.

AAP in the context of nonzoned and zoned disks with uniform disk accesses over all cylinders as well as a provision for hot spots is considered in [101]. To simplify the analysis in zoned disks, rather than dealing with discrete values for the number of sectors per zone, the cylinder/track capacities are set to be proportional to their radius. Denoting the radius of the innermost and outermost cylinder with $R_i$ and $R_o$, then $R_i + \sqrt{(R_o^2 + R_i^2)/2}$ divides the disk into two parts with equal capacities, so that the two arms should be placed at $R_i + \sqrt{(4R_o^2 + R_i^2)/3}$ and $R_i + \sqrt{(2R_o^2 + 2R_i^2)/3}$. AAP is detrimental for higher disk utilizations, since positioning of the disk arm may delay external requests. Simulation results show that there is a crossover point, so that beyond a certain arrival rate AAP results in degraded performance.

Rearranging data on disk can be used to reduce seek distances, as discussed for single disks in the Appendix I. A study that applies cylinder remapping to both single and mirrored disks is [27]. Trace analysis of cylinder request streams exhibits strong Markovian dependence which are used in expressing the mean seek distance for both the single and mirrored disks. Simulated annealing optimization is used to find permutations reducing seek distance. The computational costs with a disk with 1760 cylinders is reduced by carrying out the optimization on clusters of 40 disk cylinders. The optimal permutations for the two disks is non-identical.
Mirrored Disk Performance in Various Operating Modes

We start with a brief introduction to queueing theory applicable to the analysis of RAID performance. We analyze RAID performance in normal, degraded, and rebuild modes.

7.1 Queueing Theory for Performance Analysis of Mirrored Disks

Disk delay due to disk accesses is a major contributor to mean response transaction time (R), which is the major performance metric for OnLine Transaction Processing (OLTP) workloads with a stringent performance requirement, e.g., the maximum throughput in Transactions per Second - TPS for an OLTP benchmark is determined at $R = 2$ seconds. Ordinarily $R$ is an increasing function of TPS.

I/O trace analysis of an OLTP workload (an airline reservation system) showed that most accesses are to small randomly placed disk blocks [85], we hence consider this workload in our discussions. Access time to large blocks of data is simply determined by disk transfer rate.

Disk accesses can be alleviated by caching, e.g., caching the highest levels of a B+-tree alleviates disk accesses. Caching methods to improve the performance are discussed briefly in Section 4. Disk access times can be reduced by appropriate disk scheduling which is discussed briefly in Appendix I.

Our goal is to determine the relative performance of disk array configurations, rather than estimating accurate performance measures. Trace-driven simulation using DiskSim 4 used in [129] are expected to yield accurate results for disks whose parameters have been extracted using the DIXtrac tool to extract disk parameters 5 6

We adopt the M/G/1 queueing model [48], because it has been applied in several analytic studies of RAID [17, 91, 57, 93, 102]. Disk accesses arrive according to a Poisson process (denoted by M) with rate $\lambda$, with exponentially distributed interarrival times with mean $\bar{t} = 1/\lambda$. Disk service times are General (G) with $t^{th}$ moment $\bar{x}^t$. The variance of service time is $\sigma_X^2 = \bar{x}^2 - (\bar{x})^2$ and its coefficient of variation squared $c_X^2 = \sigma_X^2/(\bar{x})^2$. The mean residual service time (following a random arrival) is $\bar{x}^t = \bar{x}^t/(2\bar{x})$ [48]. The disk utilization factor is $\rho = \lambda\bar{x}$, should be less than one to ensure that the queue-length remains finite. According to Little’s result the mean queue-length is $N_q = \lambda W$, where $W$ is the mean waiting time [48]. The mean response time is $R = W + \bar{x}$. With FCFS scheduling the waiting time is independent of service time, so that the variance of response time is given as follows: $\sigma_R^2 = \sigma_W^2 + \sigma_X^2$ [117]. This equation does not hold for other disk scheduling policies such as SATF.

Given that Poisson Arrivals See Time Averages - PASTA, the mean waiting time for arrivals with FCFS scheduling is given as follows:

$$W = N_q\bar{x} + \rho \bar{x}^2 = \rho W + \frac{\lambda \bar{x}^2}{2\bar{x}}$$

$$W = \frac{\lambda \bar{x}^2}{2(1-\rho)} = \frac{\rho \bar{x}(1 + c_X^2)}{2(1-\rho)}.$$  \hspace{1cm} (1)

For a given $\lambda$ and $\bar{x}$, $W$ increases with $c_X^2$. For an M/M/1 queueing system with exponential service times: $c_X^2 = 1$, $W_E = \rho \bar{x}/(1-\rho)$ and $R_E = \bar{x}/(1-\rho)$ and the response time is exponentially distributed: $F_R(t) = 1 - e^{-t/R}$. For fixed disk service time $W_F = (\rho \bar{x}/2)/(1-\rho)$. For disk service times with $0 \leq c_X^2 < 1$ in [91, 93] $W_F \leq W \leq W_E$.

Plotting the mean response time $R$ versus $0 \leq \rho < 1$ by varying $\lambda$. $R \approx \bar{x}$ for small values of $\lambda$ and $R \to \infty$ as $\lambda \to 1/\bar{x}$.

For $\rho < 1$ an M/G/1 queue alternates between idle and busy periods with means $\bar{g}$ and $\bar{t} = 1/\lambda$. Noting that $\rho$ is the fraction of server busy time is: $\rho = \bar{g}/(\bar{g} + \bar{t})$, it follows $\bar{g} = \bar{x}/(1-\rho)$.  

\hspace{1cm} 5http://www.pdl.cmu.edu/DiskSim/
\hspace{1cm} 6http://www.pdl.cmu.edu/DiskSim/diskspecs.shtml
The arrival rate with to a RAID0/1 disk array with \( N = 2M \) disks is \( \Lambda \). Assuming that disk loads are balanced due to striping, the load at each BM pair is \( \lambda = \Lambda / M \). The fraction of read (resp. write) requests is \( f_r \) (resp. \( f_w = 1 - f_r \)). The \( i \)th moment of read and write accesses is \( \bar{x}_r^i \) and \( \bar{x}_w^i \). Read and write accesses to disk have three components: seek time, latency and transfer time (see Appendix I). Assuming read disk utilization is:

\[
\rho_r = \lambda (f_r/2) \bar{x}_r \quad \text{and} \quad \rho_w = \lambda f_w \bar{x}_w.
\]

The maximum arrival rate per disk is \( \lambda_{\text{normal}}^{\text{max}} = [f_r/2 \bar{x}_r + f_w \bar{x}_w]^{-1} \).

The fraction of read and write accesses to disks is \( f'_r = (f_r/2)/(f_r/2 + f_w) \) and \( f'_w = 1 - f'_r \), so the \( i \)th moment of disk access time is \( \bar{x}_d^i = f'_r \bar{x}_r^i + f'_w \bar{x}_w^i \) with a mean \( \bar{x}_d = f'_r \bar{x}_r + f'_w \bar{x}_w \) and the mean disk utilization is:

\[
\rho = \lambda_d \bar{x}_d = \lambda (f_r/2 \bar{x}_r + f_w \bar{x}_w) = \rho_r + \rho_w,
\]

as before.

If read and write requests are processed in FCFS order the mean waiting time is:

\[
W_r = \frac{\lambda_d \bar{x}_d^2}{2(1 - \rho_r)}.
\]

The response time of read requests can be reduced by processing them at a higher priority than writes. Given the mean residual service times for reads and writes:

\[
\bar{x}_r = \bar{x}_r^2/(2 \bar{x}_r) \quad \text{and} \quad \bar{x}_w = \bar{x}_w^2/(2 \bar{x}_w)
\]

and disk utilizations \( \rho_r \) and \( \rho_w \) for reads and writes, the mean waiting time for read requests is obtained by applying PASTA again:

\[
W_r = \frac{\lambda d \bar{x}_d^2}{2(1 - \rho_r)}.
\]

where we have applied Little’s result \( \bar{N}_d = \lambda W_r \). The improvement due to prioritizing read requests is:

\[
W_r/W = (1 - \rho)/(1 - \rho_r),
\]

e.g., 3-fold decrease for \( \rho = 0.8 \) and \( \rho_r = 0.4 \).

In addition to increasing throughput, mirroring improves the response time for read requests, since they can be processed in parallel. We quantify this effect by assuming that all disk requests are reads \((f_r = 1)\), the arrival rate to a mirrored pair is \( 2\lambda \), and disk access time is exponentially distributed with mean \( \bar{\tau} = 1/\mu \). With uniform routing with equal probabilities, each disk is subjected to Poisson arrivals with rate \( \lambda \) [48, 117] and the per disk utilization is \( \rho = \lambda \bar{\tau} \). The mean response time in normal mode is \( R_{\text{norm}} = \bar{\tau}/(1 - \rho) \) and in degraded mode with one failed disk \( R_{\text{degraded}} = \bar{\tau}/(1 - 2\rho) \). For \( \rho = 0.4 \), \( R_{\text{degraded}} = 5\bar{\tau} \) versus \( R_{\text{norm}} = 1.67\bar{\tau} \).

Round-robin routing - RR of read requests results in balanced disk loads with \( \rho = \lambda / \mu \) per disk, but the interarrival times is the Erlang-2 distribution, which is the sum of two exponentials with parameter \( \lambda \) and coefficient of variation \( c^2_a = 1/2 \) [48]. Everything else being equal a smaller \( c^2_a \) is expected to result in a smaller \( W \), but this is not generally true and a counterexample is given in [110]. The mean waiting time for GI/M/1 is:

\[
W_{E-2} = \sigma \bar{\tau}/(1 - \sigma),
\]

which is smaller than \( W_{M/M/1} = \rho \bar{\tau}/(1 - \rho) \) since \( \sigma < \rho \) for \( \rho < 1 \). \( \sigma \) is the solution to \( \sigma = \Lambda^+ (\mu - \mu \sigma) \) where \( \Lambda^+ (s) \) is the Laplace Stieltjes Transform - LST. In the case of the Erlang-2 distribution: \( \Lambda^+ (s) = [2\lambda/(s + 2\lambda)]^2 \) [48]. Setting \( s = \mu (1 - \sigma) \), factoring out \( 1 - \sigma \), we obtain a quadratic equation, whose negative less than one root is meaningful:

\[
\sigma^2 - (1 + 4\rho)\sigma + 4\rho^2 = 0, \quad \sigma = \frac{1}{2}(1 + 4\rho - \sqrt{1 + 8\rho})
\]

Applying simple algebra it can be shown easily that \( \sigma < \rho \).

Mirrored disks with a shared queue processing read requests can be modeled as an M/M/m queueing system, with \( m = 2 \) servers with disk utilizations \( \rho = 2\lambda \bar{\tau}/2 = \lambda \bar{\tau} \) and mean response time \( R_2 = \bar{\tau}/(1 - \rho^2) \) [48]. Setting \( \rho = 0.9 \), \( R_2 \approx 5\bar{\tau} \), while \( R_1 = 10\bar{\tau} \) for a single disk.

To attain lower response times, it is meaningful at times to issue a read request to both disks and accept the first completed request. Disks modeled as M/M/1 queues have exponential response times as noted earlier, so that \( R_{\text{min}} = R/2 \) [117].
The completion time of writes on both mirrored disks represented as M/M/1 queues is: $R_{2\textit{f}/\textit{i}}^F = R_{1}(1.5 - \rho/8)$ [110], which is smaller than the maximum of two response times $R_{2\textit{max}}^R = H_{2}R$, where $H_{k} = \sum_{i=1}^{k} 1/i$ is the Harmonic sum [117]. This mean response time holds if all requests are writes, but simulation results have shown that with interfering read requests the write response time is higher and closer to $R_{2\textit{max}}^R$, when the overall $\rho$ remains the same.

Performance analyses of RAID1 in normal and degraded mode are given in [16, 103]. The performance of LSI RAID with RMW versus Reconstruct Write (RCW) method [94] is given in [107].

### 7.3 Operation in Degraded Mode

When one of two mirrored disks fails in BM the read load on the surviving disk is doubled. The mean disk service time is $\lambda_{d}^{\textit{deg}} = f_{r}\bar{x}_{r} + f_{w}\bar{x}_{w}$ and $\lambda_{\textit{max}}^{\textit{deg}} = 1/\lambda_{d}^{\textit{deg}}$. The maximum requests per second drops 2-fold for $f_{r} = 1$, but this drop is less significant for a large $f_{w}$. RAID1/0 tolerates $k \leq M$ disks failures and assuming balanced disk loads due to striping: $R_{\textit{overall}} = (k/M)R_{r}^{\textit{deg}} + (1 - k/M)R_{r}^{\textit{norm}}$.

In the case of ID with $n$ disks we assume the read load is evenly distributed between primary and secondary data blocks, so that the normalized load at each disk is normal mode is one, since: $\frac{1}{2} + \frac{1}{2(n-1)} = 1$. When a disk fails the load on remaining disks increases by $1/(n-1)$, so that: $1 + \frac{1}{n-1} = \frac{n}{n-1}$, so that for ID $n = 4$ the load increase is 33.3%, versus 50% for BM.

Denoting the load in normal mode on primary and secondary disks in GRD by one, the load of secondary disks increases by $k/M$ when $k$ primary disks fail. We reduce the load on primary disks with $k$ disk failures a fraction $1 - \alpha_{k}$ of read requests, so that a fraction $\alpha_{k}$ is routed to secondary disks. To balance disk loads on both sides we set $1 - \alpha_{k} = \alpha_{k} + k/M$, hence $\alpha_{k} = (M - k)/2M$, so that with $k = M$ failures the load on primary disks is zero and secondary disks receive twice the load.

Static routing of requests can be used to balance disk loads due to reads in CD as illustrated in Figure 6 [36] in Sectionsec:org. Since CD can tolerate multiple disk failures the routing probabilities should be adjusted, as shown by the last two rows of the figure.

As a simple example we consider balanced disk loads in normal mode with $f_{r} = 1$. $D_{3}$ load will be doubled while the loads on remaining disks will increase to $6/5$. In case $D_{7}$ fails the loads of $D_{5}$-$D_{6}$ and $D_{8}$-$D_{1}$ will increase to $3/2$ of normal load. This is an instance when given a single spare disk the rebuilding $D_{2}$ or $D_{4}$ should be prioritized with respect to $D_{7}$.

### 7.4 Rebuild Processing in RAID1

Both RAID1 and RAID5 are one disk failure tolerant (1DFTs) and are susceptible to data loss if a second disk fails, so a spare disk should be provided to start rebuild immediately if a spare disk is available. Disk failures prediction by predictive failure analysis reduces rebuild overhead by copying the contents of a failing disk onto a spare disk. Rebuild time can be minimized if the processing of external disk requests is quiesced, but this step is unacceptable because the cost of downtime is quite high for most lines of business as shown in Figure 1.3 in [32], so rebuild processing is carried out while the disk array operates in degraded mode.

Rebuild processing in RAID5 XORs consecutive Rebuild Units - RUs, which may be tracks to reconstruct the contents of the failed disk on a spare disk. Repair with rebuild processing affects the mean response of disk accesses as quantified in Section sec:rebui'dana. A subset of disks in HDAs need to be XORed to reconstruct data, but this step is not required for RAID1, which simply copies the contents of the surviving disk onto a spare.
The time to read the contents of an idle disk: $T_{copy}(0) = N_{track} \times T_{rot}$, where $N_{track}$ is the number of disk tracks and $T_{rot}$ is the disk rotation time. We ignore minor delays such as track and cylinder skew [44]. Given that the disk utilization due to user requests in normal mode was $\rho$, the disk utilization in degraded mode with all read requests is $\rho_{deg} = 2\rho$. and the fraction of time that the surviving disk is idle and available rebuild processing is $1 - 2\rho$.

The Vacationing Server Model (VSM) [77] utilized in [91] extends the analysis in [55] to analyze RAID5 performance in normal, degraded, and rebuild modes with an M/G/1 rather than M/M/1 queueing model with general rather than exponential disk service times utilized in [55]. The analysis quantifies the effect of rebuild processing on the mean response time of external disk requests and also determines the rebuild time, which can be approximated by the time to read a surviving disk, since disk loads are balanced.

Rebuild requests are processed at a lower priority than external requests when the queue of external requests is emptied, at which time the server starts taking vacations, which correspond to reading successive RUs/tracks from the surviving disk. There are two types of vacation: type one vacations ($V_1$) require a seek to access the next track to be rebuild and a disk rotation to read the track. Successive type 2 vacations ($V_2$) read consecutive tracks without incurring seek.

While the analysis in [91] takes into account two vacation types, we simplify the discussion by ignoring the seeks required for $V_1$ vacations and consider only $V_2$ rebuild requests, whose residual vacation time is $\overline{V}_r = \overline{V}/(2\overline{V}) = T_{rot}/2$, i.e., half of disk rotation time.

We ignore the difference between the access time of read and write requests to randomly placed disk blocks: $\overline{x}_r \approx \overline{x}_w = \overline{x}$. Given that the processing of first request is delayed by $\overline{V}$, then the first disk request has duration $\overline{y} = \overline{x} + \overline{V}_r$ and the modified busy period, which is called a delay cycle $\overline{d} = \overline{y}/(1 - \rho)$.

We use an argument similar to the one used in obtaining $\overline{d}$ to obtain the delay busy period $d$.

$$\rho = \frac{\overline{d} - \overline{V}_r}{d + 1/\lambda} \implies \overline{d} = \frac{\overline{x} + \overline{V}_r}{1 - \rho}. \quad (3)$$

The mean time to the arrival of the first request after the completion of a busy period is $1/\lambda$ so that we define a cycle as $T_{cycle} = \overline{d} + 1/\lambda$. The probability that a request arrives during rebuild is $p = \lambda T_{rot}$ [48], so that the distribution of the number rebuilds per idle period is $P_n = (1 - p)p^{n-1}$ with a mean $\overline{n} = 1/p$. Given a disk with $N_{track}$ tracks, rebuild time is $T_{rebuild} = N_{track} \times T_{cycle}/\overline{n}$.

With read redirection in effect reconstructed data blocks are read directly from the spare disk rather than reconstructing them on demand [58]. This results in a reduction in disk loads in degraded mode processing and an acceleration of rebuild processing. In the case of RAID1 the read load on the surviving disk is reduced as read requests to reconstructed blocks are directed to the spare disk. As rebuild progresses in addition to redirected reads data blocks reconstructed on the spare disk should be updated. The fraction of read requests to be redirected to accelerate rebuild rate is determined in [58]. Rebuild analysis should be carried out in stages to take into account the variation in rebuild load [91, 93]

To estimate the mean waiting while is in progress we apply the PASTA principle again: $W_{VSM} = \overline{N}_q \overline{x} + \rho \overline{x}^2 + (1 - \rho)\overline{V}$ and simplifying:

$$W_{VSM} = \frac{\lambda \overline{x}^2}{2(1 - \rho)} + \frac{\overline{V}^2}{2\overline{y}} = W_{M/G/1} + \frac{\overline{V}^2}{2\overline{y}}. \quad (4)$$

This corresponds to Eq. (2.14a) in Chapter 2 in [77]. Eq. (11) for $W_{VSM}$ in [7] uses Eq. (2.40a) in Chapter 2 in [77], which is for the case when the first request has an exceptional service time. This is not the case here.

Queues with the Permanent Customer Model (PCM) process two types of requests: (i) ordinary requests to randomly placed disk blocks with Poisson arrivals which are served in FCFS order, (ii) permanent requests which rejoin the tail of the queue of ordinary requests upon completing service and are
also served in FCFS order [11]. PCM was adopted to analyze rebuild in mirrored disks in [56]. where permanent requests represent the reading of a track, while ordinary requests are accesses to read and update randomly placed disk blocks. PCM and VSM rebuild in ordered and greedy order in mirrored disks are compared in [7]. Greedy rebuild is intended to reduce rebuild time by out-of-order processing of track reads, i.e., by reading the closest unread track to the read-write head after the last ordinary request is processed. Note that greedy rebuild is not applicable to RAID5, because of excessive buffer space requirements.

VSM incurs fewer seeks than PCM in reading successive tracks, since the probability that there are interim arrivals and the R/W head moves after reading the current track is lower for VSM than PCM: $P_{VSM} = 1 - e^{-\lambda T_{rot}}$ and $P_{PCM} = 1 - e^{\lambda(T_{rot}+N_q)}$, where $T_{rot}$ is track rotation time. As shown in Figures 3(a) and 3(b) rebuild time with VSM is lower than PCM, and except for the highest arrival rates $R_{PCM} > R_{VSM}$. The greedy policy shows very little improvement for $R_{VSM}$, which significantly outperforms $R_{PCM}$, this is because VSM processes rebuild requests at a lower priority than external requests, while PCM processes them at the same priority.

Rebuild processing can be parallelized with the CD, ID, and GRD RAID1 organizations. The rebuilding of a failed disk $D_i$ for the CD organization can be parallelized by copying from $D_{i-1}$ and $D_{i+1}$ into $D_i$. $n-1$-fold parallelism is possible with the ID organization for rebuilding primary data. In the case of GRD with $N = 2M$ disks, $M$ disks can participate in rebuild processing. At low disk utilization the spare disk will constitute a bottleneck and the reading rate from source disks should be throttled.

8 Reliability Analysis

We first provide reliability expressions for RAID1 organizations with no repair and obtain their MTTDL 8.1. In Section 8.3 we discuss approximate reliability analysis, which is suited for the comparing of the relative reliabilities of RAID1 configurations against each other and RAID$(4+k)$ arrays. Data loss may occur due to disk controller failures and an analysis using Continuous Time Markov Chains - CTMCs is discussed in Section 8.5. The MTTDL of RAID1 with repair is obtained in Section 8.4. Storage reliability modeling research at IBM Research at Zurich, which is relevant to this study is reviewed in Section 8.6. In response to articles that MTTDL is no longer a good measure of reliability, especially for RAID6, we refer the reader to [43], which gives a solid response this criticism and continue using the MTTDL. We conclude with simulation techniques reliability modeling in Section 8.7.

Disk failure rates are reported in [28] and [70], which is a followup study that takes into account other storage components. The frequency of Latent Sector Errors - LSEs is reported in [71], which also investigates the effectiveness of disk scrubbing and IntraDisk Redundancy (IDR) in dealing with LSEs. The weaknesses of [71] are addressed in [40].

8.1 Reliability Expressions for Mirrored and Hybrid Disk Arrays

The reliability function of a system is the complement of the probability distribution of time to failure: $R(t) = 1 - F(t)$ [117]. In our discussion we will be mainly concerned with disk reliabilities rather than DACs, interconnects, power supplies, cooling fans, etc, since we are interested in the relative reliability of various RAID configurations, rather than assessing the overall reliability.

The Weibull distribution [117] is a good fit for the time to disk failure according to [28, 70], but most mathematical analyses of RAID reliability use the exponential distribution $R(t) = e^{-\delta t}$ as an approximation to the Weibull distribution because of its mathematical tractability [28, 117]. The Mean Time to Failure (MTTF) of a disk is $MTTF_{disk} = \int_0^\infty R(t)dt = 1/\delta$. One consequence of the exponential distribution is that the reliability of $n$ disks is: $R_{n-disks}(t) = R^n(t) = e^{-n\delta}$ and $MTTF_{n-disk} = MTTF_{disk}/n$. This is a justification for introducing redundancy in large disk arrays.
CTMC models are applicable to modeling the failure and repair process in disk arrays [117]. While repair time is not exponential, analytical models of repair have assumed an exponential distribution for tractability. The Proteous simulator described in [50] showed little difference between values obtained assuming deterministic versus exponential repair time, which is required by CTMC models. This simulator was used to predict the risk of data loss for RESAR disk array [73] described in Section 2. We start the discussion with the no repair case, which can be modeled as a pure death-process.

Let $S_i$ denote the state with $0 \leq i \leq I$ failed disks, where $I$ is the maximum number of disk failures that can be tolerated without data loss. Let $A(N, i)$ denote the number of possibilities that $i$ disk failures do not lead to data loss. The probability that $i^{th}$ disk failures does not lead to data loss is then:

$$p_i = A(N, i)/\binom{N}{i}, 1 \leq i \leq I.$$  

The rates of transitions not leading to data loss for failed disk are: $S_{i-1}$ to $S_i$: $(N - i + 1)p_i\delta$. The rates of transitions leading to the failed state $(S_F)$ are $(N - i + 1)q_i\delta$, $2 \leq i \leq N$, where $q_i = 1 - p_i$.

For RAID1 with $N = 2M$ disks, $I = M$ for BM and most RAID1 organizations, and $I = c$ for the ID organization, since only one disk failure per cluster is allowed. Generally, $A(N, i) = \binom{N}{i}, i = 0, 1$ and $A(N, i) = 0$ for $i > I$. The expressions for RAID reliability with the setting $r = R(i)$ can be expressed as:

$$R_{RAID}(N) = \sum_{i=0}^{I} A(N, i) r^{N-i}(1-r)^{i}. \quad (5)$$

In the case of RAID1/0 with $N = 2M$ disks (RAID1 at lower level and RAID0 at higher level), which is a RAID0 array with $M$ virtual disks each one of which is a BM, as few as two disk failure may lead to data loss, but up to $M$ disk failures can be tolerated, as long as failed disks are not pairs.

$$A(N, i) = \binom{M}{i} 2^i, \quad 0 \leq i \leq M. \quad (6)$$

For $n$-way replication with $M = N/n$ groups of $n$-way replicated disks: $A(N, i) = \binom{M}{i} n^i, \quad 0 \leq i \leq M$.

In the case of GRD and RAID0/1 up to $M$ disks on either side can fail as long as they are all on one side:

$$A(N, i) = 2\binom{M}{i}, \quad 0 \leq i \leq M. \quad (7)$$

ID with $c$ clusters and $n = N/c$ disks per cluster, can have only one disk failure per cluster and any one of the $n$ disks in a cluster can fail.

$$A(N, i) = \binom{c}{i} n^i, \quad 0 \leq i \leq c. \quad (8)$$

The expression for $A(N, i)$ for CD is derived in [100] and also in the Appendix in [26]:

$$A(N, i) = \binom{N - i - 1}{i - 1} + \binom{N - i}{i}, \quad 1 \leq i \leq M. \quad (9)$$

Let $v_i$ denote the number of visits to state $S_i$. When repair returning the system to its initial state is not allowed $v_i$:

$$v_i = v_{i-1}p_i, \quad v_i = \prod_{j=0}^{i} p_j, \quad 1 \leq i \leq I. \quad (10)$$

A closed form expression for $A(N, i)$ for LSI Logic RAID is not available, but can be obtained using enumeration [107]. $A(8, i) = \binom{8}{i}, 0 \leq i \leq 2, A(8, 3) = \binom{8}{3} - 4 = 52$ since there are four cases where the Ddisk is in the middle, so that $q_3 = 4/56 = 1/14$.
There are $\binom{8}{4}$ configurations of four disk failures, but according to the enumeration given in Table 2 only 25 cases lead to data loss, so that $q_4 = 25/70 = 5/14$, which differs from $q_4 = 16/65$ given in Section 3.1.2 in [3].

The reliability analyses of SSPiRAL(4+4,3) disk array in [3] uses a CTMC, which yields the reliability expression [117], which can be used to determine the probability of data loss at the end of its “economic lifespan”. We have the following transitions $S_i \rightarrow S_{i+1}$, with failure rate $(8-i)\lambda$, $0 \leq i \leq 3$ and $S_{i+1} \rightarrow S_i$, $0 \leq i \leq 3$ with repair rate $\mu_i$, $2 \geq i \geq 0$. Finally, $(1/5)^{th}$ of failures with rate $5\lambda$ from $S_3$ lead to data loss ($S_{DL}$) and $(4/5)^{th}$ to $S_4$. There are two transitions from $S_4$: with rate $4\lambda$ to $S_{DL}$ and $4\mu$ to $S_3$.

The analysis has the following shortcomings: (i) The repair rate is set proportional to the number of failed disks and does not take into account potential hardware bottlenecks. (ii) An infinite supply of spare disks is postulated. (iii) Repair rates are exponentially distributed, and as a new disk fails due to the memoryless property of this distribution it is as if the rebuild process at all disks under repair is restarted. (iv) The analysis does not take into account LSEs, which are the main cause of rebuild failures [40].

SSPiRAL(4+4,3) tolerates up to three failed disks. Eighty percent of four disk failures are tolerated for $N = 8$, so that $v_4 = 4/5$ and $A(8,4) = (4/5)\binom{8}{4} = 56$.

The reliability of RAID$(4+k)$ arrays with $N$ disks, which can tolerate up to $k$ disk failures is:

$$R_{RAID(4+k)}(N) = \sum_{i=0}^{k} \binom{N}{i} r^{N-i} (1-r)^i.$$ 

In Figure 11 we plot the reliabilities for various RAID1 organizations and RAID5/6/7 and LSI RAID for $N = 8$ disks versus time normalized with respect to MTTF. For small values of $t$, RAID7 which tolerates all three disk failures has the highest reliability, while LSI is second since it tolerates half of three disk failures. For smaller values of $t$ RAID6 is more reliable than BM, which is the most reliable of mirrored disk organizations, but there is a crossover point since BM can tolerate more than two disk failures. RAID5 has the lowest reliability since it can only tolerate single disk failures.

Figure 11: Reliability versus time normalized with respect to disk MTTF [107].

The MTTDL in a RAID systems can be obtained by integration or noting that the mean holding time: $H_i = [(N-i)\delta]^{-1}$ is the inverse of the failure rate at $S_i$:

$$MTTDL = \int_0^{\infty} R_{RAID}(N)dt = \sum_{i=0}^{M} v_i H_i = \sum_{i=0}^{M} \frac{v_i}{(N-i)\delta}. \quad (11)$$
8.2 Performability Analysis

The performability measure combines the failure process with performance [117]. In [103] we define performability as the number of I/O requests that are processed by a disk array system from the beginning of its operation to the point that data loss occurs. Using a birth death process the performability is obtained by summing over all intervals with varying number of failed disks \( (i) \) the product of the durations of the interval times and the maximum throughput denoted by \( T_{N-i},0leqi \leq I, \) e.g., \( T_N = N/\bar{x}_d \), where overline \( \bar{x}_d \) is the disk service time:

\[
P = \sum_{i=0}^{I} \frac{v_i T_i}{(N-i)\delta}.
\]

Note similarity to Eq. (11) to compute the MTTDL. The performability of various RAID organizations is compared via barcharts in [103].

8.3 Approximate Reliability Analysis

The reliability analysis in [99] expresses disk reliability as \( r = 1 - \varepsilon \), where \( \varepsilon \ll 1 \). For example, assuming an exponential distribution and an MTTF= 10⁶ hours or 114 years, after three 3 years \( R(3) \approx 1 - 3/114 = 0.975 \) and \( \varepsilon = 0.025 \). The reliability of a system is then expressed as one minus the smallest power of \( \varepsilon \). Note that the exponential distribution is not required for this analysis. For example, for \( n \)-way replication has data loss with \( n \) disk failures and allows at most \( n - 1 \) disk failures: \( R_{n-way}(n) = 1 - (1-r)^n \approx 1 - \varepsilon^n \).

For the BM configuration we utilize the expression for \( A(N, i) \) given by Eq. (6), but only retain the \( \varepsilon^2 \) term, which is sufficient for comparing reliabilities. ⁸

⁸We have corrected the first part of Eq. (7) in [99].
The above discussion is summarized in Table 1. The following conclusions can be drawn for RAID1, RAID2, RAID3, RAID4, RAID5, RAID6, RAID7, RAID8, and LSI RAID:

1. RAID5 is less reliable than the four RAID1 organizations, since RAID1 arrays can tolerate more than two disk failures up to $M = N/2$.

2. RAID6 is less reliable than LSI RAID, since the latter in addition to all two disk failures tolerates half of three disk failures, but RAID7 is more reliable than LSI RAID since it tolerates all three disk failures, while LSI RAID does not.

$$R_{LSI}(N) \approx 1 - \frac{N}{2} \epsilon^4,$$

3. RAID8 is more reliable than SSPiRAL(4+4,3), since the latter cannot tolerate $1/5$th of four disk failures.

$$R_{SSPiRAL}(8) \approx 1 - 14\epsilon^5.$$ 

The above discussion is summarized in Table 1.
8.4 RAID Reliability with Repair

Early analyses of RAID reliability with repair dealt with whole disk failures [28]. These analyses were later extended to include the effect of LSEs, but also intradisk redundancy and disk scrubbing on LSEs [40]. Adjusting the disk failure rate has been used to take account these complications.

The expression for reliability $R(t)$ can be obtained by solving the related linear differential expressions. The analysis in [28] yields the reliability $R(t)$ of RAID5 as the sum of two exponentials [28]. The MTTDL can be obtained by integrating $R(t) = 1 - F(t)$: $\text{MTTDL} = \int_0^\infty R(t)\,dt$. Specialized packages SHARPE Symbolic Hierarchical Automated Reliability and Performance Evaluator - SHARPE [117] were applied in [28] to analyze more complex cases.

A shortcut method to obtain the RAID5 MTTDL with $N$ disks, failure rate $\delta$, and repair rate $\mu$ which provides insight into the rebuild process. Operation of the systems is specified by a 3-state CTMC: $S_N$: no failed disks, $S_{N-1}$: single failed disk, $S_{N-2}$: two failed disks and data loss. The transition rates are $S_N \rightarrow S_{N-1}$: $N\delta$, $S_{N-1} \rightarrow S_{N-2}$: $(N-1)\delta$, $S_{N-1} \rightarrow S_N$: $\mu$. At $S_{N-1}$ there are two competing transitions with exponential rates: rebuild is successful the repair process finishes before another disk fails, otherwise there is data loss. The probability of a successful rebuild is the ratio of transition rates $p = \mu/(\mu + (N-1)\delta)$ [117]. The distribution of successful rebuilds is $P_{\text{succ}} = (1 - p_s)p_s^k$, $k \geq 0$, which has a mean $v_N = p/(1 - p) = \mu/(N\delta) = \text{MTTF}/(1/N \times \text{MTTR})$. The MTTDL is dominated by the time spent at $S_N$, which is exponentially distributed with mean holding time $H_N = \text{MTTF}/N$, while the time spent in $S_{N-1}$ is small, since $\mu \gg (N-1)\lambda$. Multiplication by $v_N$ yields:

$$\text{MTTDL}_{\infty} \approx v_NH_N = \frac{\mu}{N(N-1)\lambda^2} = \frac{\text{MTTF}^2}{N(N-1)\text{MTTR}}. \quad (18)$$

The subscript specifies an unlimited number of spare disks. For $N = 2$ we have the MTTDL for RAID1.

The analysis in [21] yields

$$\text{MTTDL} = \frac{(2N-1)\lambda + \mu}{N\lambda(N-1)\lambda + \mu P_{af}}$$

which extends the analysis of [28] by multiplying $\mu$ with $P_{af}$, which is the probability of an uncorrectable disk failure.

The analysis in [15] provides the MTTDL of RAID6 arrays as

$$\text{MTTDL}_2 = \frac{\text{MTTF}^3}{N(N-1)(N-2)\text{MTTR}^2},$$

which assumes that the repair-rate with two disk failures remains $\mu$. If RAID$(4 + k)$ tolerates $k$ failures a generalization of the above formulas is:

$$\text{MTTDL}_k = \frac{\text{MTTF}^{k+1}(N-k-1)}{N!\text{MTTR}^k}.$$

Unlimited repairman were postulated in [6] and his analysis yields

$$\text{MTTDL} \approx \frac{\text{MTTF}^{k+1}}{(N-k)(N)}\text{MTTR}^k \times \sum_{i=0}^{k} \binom{N}{i} \left(\frac{\text{MTTR}}{\text{MTTF}}\right)^i \approx \frac{\text{MTTF}}{(N-k) \times \binom{N}{k}} \times \left(\frac{\text{MTTF}}{\text{MTTR}}\right)^k.$$

It is easy to see that the MTTDL with the latter formula estimates an MTTDL which is $\approx k!$ times higher than the original MTTDL formula given in [15].

A more realistic MTTDL can be obtained by allowing a few spares. In a RAID5 disk array with $N$ disks, one of which is a spare, we have four states $S_{N-i}, 0 \leq i \leq 3$, where $S_{N-2}$ designates a successful
rebuild on the spare disk and \( S_{N-3} \) is the failed state. Given \( v_N = v_{N-1} = 1 \) and the transition probabilities: \( S_{N-1} \rightarrow S_{N-2} \): \( p_s = \mu / (\mu + (N-1)\delta) \) and we have \( v_{N-2} = p \), so that the MTDDL is: \( \text{MTTDL}_1 = 1/(N\delta) + 1/((N-1)\delta) + p/((N-2)\delta) \approx (2+p)(N\delta) \). The MTDDL with \( k \) spares is:

\[
\text{MTTDL}_k = \frac{1}{N\delta} + \sum_{i=0}^{k} \frac{p^i}{(N-1-i)\delta}.
\]

The contribution to MTDDL decreases with increasing \( k \) since \( p < 1 \). The depletion of spare disks is not a problem if additional spare disks are ordered as the supply is depleted (see Figure 5.22 in [28]).

Given a RAID1/0 array with \( M \) disk pairs an approximate way to estimate MTDDL of a RAID1/0 array is to treat the disk pair as a single unit with an exponential failure rate, so that \( R_{\text{array}} = e^{M/\text{MTTDL}_{\text{pair}}} \), which uses Eq. 18 with \( N = 2 \).

The direct path approximation method developed in [42], which can be used to estimate the MTDDL in some interesting cases, such as RAID5/1:

\[
\text{MTDDL}_{R5/1} \approx \frac{\mu^3}{3M(M-1)\lambda^3} = \frac{\text{MTTF}^4}{3M(M-1)\text{MTTR}^3}.
\]

The method is applicable to Weibull and Gamma distributions and has been extended to multiple shortest paths. Using Eq. 18 a hierarchical reliability modeling approach was used in [131] to get good estimate for RAID5/1 MTDDL.

\[
\text{MTDDL}_{R1} = \frac{\text{MTTDL}_{R5}^2}{2\text{MTTR}}, \quad \text{MTDDL}_{R5} = \frac{\text{MTTF}^2_{\text{disk}}}{M(M-1)\text{MTTR}}, \quad \text{MTDDL}_{R5/1} \approx \frac{\text{MTTF}^4}{4M(M-1)\text{MTTR}^3}.
\]

**Multivel RAID**

The approximate reliability of an RAID5/1 and RAID1/5 array can be determined by substituting the expression for RAID5 into the reliability expression for RAID1, and vice-versa. It follows that RAID5/1 is more reliable than RAID5/1.

\[
R_{R1} = 2R_{R5} - R_{R5}^2, \quad R_{R5} = r^M + Mr^{M-1}(1-r) \quad R_{5/1} \approx 1 - M^3 \epsilon^3.
\]

\[
R_{R5} = R_{R1}^M + MR_{R1}^{M-1}(1-R_{R1}), \quad R_{R1} = 1 - (1-r)^2 \quad R_{1/5} \approx 1 - M(M-1)\epsilon^4.
\]

### 8.5 Taking into Account Controller Failures

Three mirrored disk configurations: \( C_i, 1 \leq i \leq 3 \) are considered in [60]. (a) \( C_1 \) has a single controller for the duplexed disks. (b) \( C_2 \) has one controller per disk and incoming reads are routed to both disks. (c) \( C_3 \) has two controllers crossconnected to disk. The MTDDL is determined by a CTMC with three states: \( S_0 \): no failed disks. \( S_1 \): single failed disk. \( S_2 \): Both disks or the control unit has failed. For example, given that disk and controller failure rates are \( \lambda_c \) and \( \lambda_d \) and the disk and controller repair rates are \( \mu_d \) and \( \mu_c \). The transition rate for \( C_1 \) are: \( S_0 \rightarrow S_1 2\lambda_c, S_1 \rightarrow S_0 \mu_d, S_2 \rightarrow S_2 \lambda_c + \lambda_d, \) and \( S_0 \rightarrow S_2 \lambda_d \). These and similar CTMCs can be solved to estimate the MTDDL and the availability, which is the fraction of time data can be accessed.

The *Crosshatch Disk Array (CDA)* proposed in [62] has \( N \times N \) disks which are doubly connected to horizontal and vertical busses attached to \( 2N \) controllers. Parity groups are defined over diagonal disks, so data loss occurs with (1) Double disk failures, (2) single disk plus double controller failures, (3) quadruple controller failures. Reliability analysis is used to show that the MTDDL attained by CDA exceeds the MTDDL attained with less complex organizations.
8.6 Storage Reliability Research at IBM Research at Zurich

Efficient replica maintenance and placement to attain high availability and data durability has been the topic of research, which lead to implementations such as Carbonite [19]. In this section we briefly review recent research at IBM Research at Zurich.

Replica placement in the context of large-scale data storage systems to attain increased availability is investigated in [121]. There are $n$ nodes and user data blocks are replicated $r$ times. Three data placements are considered: (a) Declustered: $r$ data replicas are placed randomly at the nodes. (b) Clustered: nodes are divided into disjoint sets of $r$ nodes on which data is replicated. (c) $k$-clustered: “the $n$ nodes are divided into disjoint sets of $k$ nodes called clusters. Each of these clusters is an independent storage system with $k$ nodes with a declustered placement scheme. No data block in one cluster is replicated in another cluster nodes partitioned into disjoint sets of $k$ nodes and the declustered placement is followed at these nodes”. Analytic and simulation results show that for a replication factor of two all placements have an MTTDL within a factor of two.

Clustered Placement (CP) and Declustered Placement (DP) is considered in [122]. DP spreads replicas across all nodes, while a minimum number of nodes are used by CP. The average lifetime of a node is set to be of the order of $\delta^{-1} = 10^5$ hours and given $c$ bytes per node and a rebuild bandwidth $b$ it takes $c/b = 10$ hours to rebuild a node, so that $\delta c/b \ll 1$. Given that the probability that the system experiences data loss is $P_{DL}$, then $MTTDL \approx (n\delta P_{DL})^{-1}$. Eq. (4) in the paper leads to $P_{DL}$.

For $r = 2$ $MTTDL_{clus} \approx b/(nc^2\delta^2)$ and $MTTDL_{declus} \approx b/(2nc^2\lambda^2)$, so that the MTTDL is inversely proportional to the number of nodes.

For $r = 3$ $MTTDL_{clus} \approx b^2/(nc^2\delta^3)$ $MTTDL_{declus} \approx (n-1)b^2/(4nc^2\delta^3)$, which is almost independent of the number of nodes.

Reliability of data storage systems under rebuild bandwidth constraints is discussed in [123]. An increased degree of replication increases parallelism for rebuild, but this is so if sufficient bandwidth is available for this purpose.

The effect of CP and DP with two reliability metrics: Expected Annual Fraction of Data Loss (EAFDL) and MTTDL is investigated in [41]. There are $n$ storage devices and $r = 2, 3$ is the replication factor. CP (resp. DP) replicates data at the other $r1$ (resp. $n-1$ devices). Rebuild time is obtained taking into account disk capacities ($c$), the amount of user data $U = nc/r$. The reserved bandwidth per device is $b$ so that time to read a disk is $c/b$. Given that mean time to disk failure is $1/\delta$ for $r = 2$:

$$MTTDL_{CP} = b/(nc^2\delta^2) \text{ and } MTTDL_{DP} = b/(2nc^2\delta^2).$$

$$EAFDL_{CP} = \delta^2 c/b \text{ and } EAFDL = 2\delta^2 c(n-1)b.$$

A study comparing erasure coding with replication, in the context of peer-to-peer systems built to provide storage durability by taking advantage of network bandwidth, storage capacity, and computational resources is [125]. It is shown that erasure coding provides an MTTF many orders of magnitude higher than replicated systems, while utilizing an order of magnitude less bandwidth and storage.

8.7 Simulation for Reliability Modeling

We have discussed the reliability analysis of small disk arrays, but more complex methods, possibly based on hierarchical reliability modeling, might be required to analyze large storage systems. When the system is represented by a CTMC, numerical methods can be applied to solve it, but there is an exponential increase in the state-space, which limits the applicability of numerical methods.

Fast simulation with importance sampling is a powerful tool applicable in this case. ⁹ can be applied to reliability analysis of systems with a large number of components,

⁹https://en.wikipedia.org/wiki/Importance_sampling.
Survey of approaches for high availability solutions yielded the following statistics [23]: Experimentation 28, Simulation 3, Quantitative 1, Modeling 0. There are few publications modeling large-scale systems such as storage clouds and interestingly simulation has played a small role.

Hierarchical RAID (HRAID) extends the RAID paradigm to two levels [108]. There are \( N \) Storage Nodes (SNs) with their own DAC and RAID\((4+\ell)\) array with \( M \) disk. There are \( k \) check codes for internode redundancy, so that the overall redundancy level is \( (k+\ell)/M \). The pseudo-code for the simulator to obtain the HRAID\(k/\ell\) MTTDL is given in [108]. The code is simplified by postulating the exponential distribution for disks and DACs, but can be extended to other failure distributions. Modeling rebuild requires specifying repair time, which requires a detailed specification of the internode communication network, at least the bandwidth available for large data transfers.

*Cloud Quality of Service Simulator for Reliability - CQSIM-R* is a Monte-Carlo simulator for large scale storage systems, which takes into account the placement of data [31]. A more recent study along these lines is [134].

## 9 Heterogeneous Disk Arrays

RAID1 has been used in combination with other RAID levels, which provide higher storage efficiency via lower redundancy levels. Three examples of data stored in replicated form, later converted to erasure coding are as follows.

The Self-Adaptive Disk Array (SADA) starts as a RAID0/1 array and reconfigures itself onto an HDA with parity coding to prevent data loss and then RAID5 and RAID0 arrays [64]. The RAID0/1 array has four disk pairs \( A_1, A_2, B_1, B_2, C_1, C_2, D_1, D_2 \), which hold copies of datasets \( A, B, C, \) and \( D \). If \( B_1 \) fails extra protection is provided for \( B \) by setting \( A_1 = A \oplus B \). If \( D_1 \) fails the system sets \( C_2 = C \oplus D \). If \( D_2 \) fails the system sets \( A_1 = (A \oplus B) \oplus (C \oplus D) \) and \( C_2 = D \). In effect this is a RAID5 array with one parity disk. Finally, if \( B_2 \) fails the system XORs \( A \) from \( A_2, C \) from \( C_1, \) and \( D \) from \( C_2 \) with \( A_1 \) so that \( A_1 = B \) and we have an unprotected array. Restriping is a generalization, which has a similarity to distributed sparing [93]. When applied to RAID\((4+k)\)\(,k \geq 1\) it overwrites check strips. In the case of RAID7 with \( P, Q, R \) check strips, overwriting starts with \( R \) strips and we have the transitions RAID7 \( \rightarrow \) RAID6 \( \rightarrow \) RAID5 \( \rightarrow \) RAID0 [108]

HP’s AutoRAID combines RAID1 and RAID5 arrays by initially storing data in RAID1 format, which is converted to RAID5 format as RAID1 storage capacity is getting exhausted [127]. Hot mirroring in [80] partitions storage space to areas dedicated to RAID1 and RAID5. The main criterion to invoke migration from RAID1 to RAID5 is the number of free blocks for RAID1. Mirrored data is placed in separate parity groups to ensure that they are not both affected by a disk failure in the same parity group.

DiskReduce [130] initially writes three copies of data to accommodate the *Hadoop Data File Systems (HDFS)*, but then converts triplicated data to RAID5 or RAID6 formats.

*Heterogeneous Disk Arrays (HDAs)* combine RAID1 and RAIDand generally parity and erasure coding in one disk array [113], whereas [96] takes into account heterogeneous disks as well. Data is allocated at the level of Virtual Arrays (VAs), which are either RAID1 or RAID5. Based on the volume of data and access rate a VA is allocated as multiple Virtual Disks (VDs) on different disks. The VA RAID level is determined by its size and data access intensity, e.g., VAs with high access rates to read and write small data blocks are assigned as RAID1, while VAs with RAID5 can process large reads and writes more efficiently [106].

An advantage of HDA is that rebuild can be carried out at the level of VAs, which is especially advantageous if they reside on disjoint drives. Priority should be given to more critical VAs. This is important because the time to read multiterabyte (TB) disks makes them vulnerable to a second disk failure, e.g., according to [38] an 8D+1P RAID5 with 7200 RPM disks takes 40 hours for 4 TB disks. The Huawei OceanStor RAID2.0 [38] similarly to HDA speeds up rebuild processing by bypassing empty disk space and XORs chunks in the same parity group to reconstruct data (see figure on page 11).
A RAID1 array combining HDD and MEMS storage is described in [118]. Even though MEMS storage costs ten times more than magnetic disks, hybrid MEMS/disk arrays substantially improve the performance and cost/performance over conventional mirrored disks.

10 Conclusions

RAID1 arrays have a 50% redundancy in disk capacity, which is higher than the $100k/N\%$ for RAID$(4+k)$ array with $N$ disks. But this redundancy is acceptable in view of increased disk capacities. RAID1 has two advantages over RAID$(4+k)$ arrays: (1) Updating small data blocks requires writing the modified block to two disks. While updates in RAID$(4+k)$ involve the SWP, where each writes requires $2(k+1)$ reads and writes to update data and check blocks. (2) RAID1 doubles disk access bandwidth to small data blocks. On the negative side RAID$(4+k)$ allows parallel reading of strips when accessing large chunks of data and efficient full stripe writes.

Distributed storage systems utilize replication to ensure data availability and durability. It is difficult to tell the difference between transient network failures and disk failures in wide-area bandwidth-limited systems. To ensure an acceptable degree of replication copying is invoked to return the system to a desirable degree of replication [19]. A limited form of replication is remote backup database systems, which track a primary system and take over its operation when it fails.

Commonly Used Abbreviations: CD - Chained Declustering. DAC - Disk Array Controller. GRD - Group Rotate Declustering. HDD - Hard Disk Drive. ID - Interleaved Declustering. LBA - Logical Block Address. LSE - Latent Sector Error. kDFT - $k$ Disk Failure Tolerant. MDS - Maximum Distance Separable. MTTDL - Mean Time To Data Loss. MTTF - Mean Time to Failure. NVRAM - NonVolatile Random Access Memory. OLTP - OnLine Transaction Processing. PCM - Permanent Customer Model. RAID - Redundant Array of Independent Disks. RMW - Read-Modify-Write. SSD - Solid State Disk. SWP - Small Write Penalty. VSM - Vacationing Server Model.

Appendix I: Magnetic Hard Disk Drives

HDDs consist of circular disk platters coated with ferromagnetic material rotated at high speed, referred to as "spinning rust". Data is recorded on concentric tracks formatted as 512 byte sectors, where each sector has a header and a 40 byte long ECC (Error Correcting Code) [44]. Longer 4096 byte sectors, known as Advanced Format, provide 5-13% higher capacity and improved error correction capability. 10

Disk capacity is increased by recording on both sides of a platter and stacking platters, which are served by a single disk arm with one R/W head per surface. Tracks with the same diameter constitute a cylinder. Disk data is modeled as a one dimensional array whose sectors are specified as Logical Block Addresses - LBAs, which are translated by the disk controller to determine LBA’s location: cylinder, surface, sector number, which is accessed by mechanically moving the disk arm to an appropriate track, while the disk rotation places appropriate sectors under the R/W head. Media failures are handled by relocating bad sectors to a good area on disk: slipping moves a faulty sector to the next physical sector as data is being written, while sparing assigns empty sectors.

Zoned bit recording stores a higher number of sectors on its outer tracks to take advantage of increased circumference. In the case of the IBM 18ES disk drives, for example, the number of sectors on the outermost track is approximately 60% higher than the innermost track. 11 With a linear increase in disk sectors there would be a 30% increase in disk capacity with respect to a non-zoned disk with the same number of sectors at all disks.

10https://en.wikipedia.org/wiki/Disk_sector.
11http://www.pdl.cmu.edu/DiskSim/diskspecs.shtml.
Disk recording density has been increasing at variable rates: 29%, 60%, 100%, 30% per year till 1988, 1988-1996, 1997-2003, and since then respectively [32]. The increased linear recording density combined with higher disk RPMs has resulted in an increased disk transfer rate (50% in the year 2000 [29]). Shingled Magnetic Recording (SMR), which allows in higher areal recording densities in HDDs by writing overlapping sectors [24].

Disk access time has three components [44]: (1) Seek time to move the R/W head to the appropriate track, (2) Rotational latency is the time for the appropriate disk block to rotate underneath the R/W head to be read or written (3) Transfer time is the time for the disk block to rotate past the R/W head.

Given the seek time characteristic of a disk $t_{\text{seek}}(d), 1 \leq d \leq C - 1$, where $C$ is the number of disk cylinders, the seek time is determined by the number of disk tracks traversed ($d$) by the R/W head. For an HDD considered a recent study: $t_{\text{seek}} = \text{constant}$, for $d \leq 100$, followed by a discontinuity, $t_{\text{seek}}(d) \propto \sqrt{d}$ for $100 \leq d \leq (C - 1)/3$, after which it is linear. Seek time decreases with increased radial density, but there is an increase in head settling time for writes [44]. Transfer time for small disk blocks is negligible, so that disk access time is determined by positioning time, which was improving at a rate of 8% annually at the turn of the century [29].

The rotational latency for small randomly placed disk blocks is one half of disk rotation time and improves with the RPM. For 7200 RPM disks $T_{\text{rot}} = 8.33 \text{ ms}$. so that the mean latency is $T_{\text{rot}}/2$. Disk transfer time is negligibly short, e.g., for a 7200 RPM disk with 400 sectors the transfer time for a 4 KB is: $(8/400) \times 8.33 < 0.166 \text{ ms}$.

In view of rapidly increasing disk capacities, disk access bandwidth to randomly placed disk blocks may be a limiting factor. Increasing cache sizes at different levels of memory hierarchy lower the miss rate per Gigabyte (GB), so that the disk access rate does not increase in proportion with disk capacity.

Rather than serving disk requests in FCFS order, disk arm scheduling is used to reduce disks access time, so that the disk can process more request per second. The Shortest Seek Time First (SSTF) and SCAN are two early methods to reduce the seek distance [109], but since rotational latency is significant with respect to seek time, the Shortest Access/Positioning Time First (SATF/SPTF) policy, which is implemented locally at the disk controller minimizes the sum of seek time and rotational latency. SATF outperforms the SSTF and SCAN methods at heavier loads [129, 99].

Proximal I/O described in [69] is a technique to improving random disk I/O performance by aggregating random updates in a flash cache whose size is 1% of disk space and this allows 5.3 user writes to be destaged per revolution. Compared to update-in-place or write-anywhere file systems, proximal I/O provides a nearly seven-fold improvement in random I/O performance, while maintaining near sequential data layout. Despite the higher cost of flash memory, the overall system cost is one third of that of a system achieving an equivalent number of random I/O operations.

Disk performance can be improved by reducing seek distances by rearranging its data blocks in the middle disk cylinders resulting in the organ-pipe organization [44]. The design and implementation of a disk subsystem that adaptively reorganizes data is described and the resulting performance improvement verified via experiments in [124]. In a followup study frequently accessed data is shuffled and placed at the center of the disk surface [89]. It is noted Shuffling can backfire by placing the data of a split file at opposite ends of the organ-pipe. There is the issue of frequency of data shuffling and the unit to be shuffled.

A technique to reducing disk seek times is estimate frequencies by monitoring referenced blocks and moving frequently accessed blocks from their original locations to reserved space near the middle of the disk [1]. The scheme was implemented by modifying a UNIX device driver and trace-driven simulations showed that seek times can be cut substantially by copying a small number of blocks.

The Automatic Locality Improving Storage (ALIS) scheme automatically reorganizes disk blocks accessed together to place them so they can be accessed efficiently via a sequential access [37, 44].

A multimegabyte track buffer is usually provided with modern disks, which is mainly used for
prefetching blocks associated with sequential data transfers [44].

HDDs have been classified into Enterprise Storage - ES and Personal Storage - PS [5]. ES drives used by high performance servers utilize more advanced technology in the form of faster seek times and higher RPMs (rotations per minute). Disk power consumption which increases with the cube of RPM requires smaller diameter disks: 2.5”, 3.3”, and 3.7” for 15,000, 10,000, and 7200 RPM drives. PS drives are used several hours a day, while ES drives are powered up all the time, but disks may be powered down in archival storage. HDDs are also classified by their interface: ES drives use Small Computer System Interface - SCSI or Fibre Channel - FC and PS drives use Advanced Technology Attachment - ATA [5]. Serial ATA - SATA HDDs start wearing out after three years.

Appendix II: Erasure Coded RAID Arrays

RAID5 dedicates a single strip per stripe to parity, which is the eXclusive-OR - XOR of the data strips in that stripe. The updating of small data blocks incurs the Small Write Penalty - SWP: two reads to access old data ($d_{old}$) and parity ($p_{old}$) blocks, if they are not cached, to compute $p_{new} = d_{old} \oplus d_{new} \oplus d_{old}$ and two writes for $d_{new}$ and $p_{new}$. Updating small data blocks in RAID1 requires both copies of the data to be updated.

To balance disk loads for updating parity strips in RAID5 they are placed in right-to-left repeating diagonals, called the left-symmetric organization [15]. In an all-stripe write when all data strips are updated the check strips can be computed on the fly. When a majority of strips in a stripe are updated the ReConstruct Write (RCW) method can be used by reading the remaining strips in a stripe to compute the parity without incurring RMWs [94]. These concepts are applicable to HDAs discussed in Section 2.

Requested blocks on a failed disk are reconstructed on demand by XORing corresponding blocks from surviving disks. This results in the doubling of disk load due to read requests, but this load can be reduced by adopting the Clustered RAID (CRAID) paradigm, which uses a smaller parity group size ($G$) than the number of disks: $G < N$, in which case the load increase is $\alpha = (G - 1)/(N - 1) < 1$ [58]. Implementations of CRAID are discussed in [104]. CRAID with $G = 2$ has the same level of redundancy as RAID1.

RAID5 with a single failed disks is susceptible to data loss if a second disk fails. If a spare disk is available the rebuild process should be initiated as soon as possible to reconstruct the data on the failed disk on the spare to return the system to its normal mode [58]. RAID5 rebuild is accomplished by reading successive Rebuild Units (RUs) to be XORed for reconstruction [91]. CRAID accelerates the rebuild process, but the writing of rebuilt blocks on the spare disk may constitute a bottleneck. RAID5 rebuild may fail due to Latent Sector Errors (LSEs) and this has led to RAID6 and generally RAID($4 + k$) $k \geq 1$ arrays, which are $k$-Disk-Failure-Tolerant (kDFT) [104].

Reed-Solomon (RS) codes can be used to protect against more than one disk failure [104]. RS codes are Maximum Distance Separable (MDS) with minimal redundancy, i.e., it takes the capacity of $k$ disks to tolerate $k$ disk failures. Because of the high computational cost of RS codes, parity based coding methods, such as EVENODD have been developed to tolerate two or more disk failures [10, 104].

References

[1] Sedat Akyurek and Kenneth Salem. 1995. Adaptive Block Rearrangement. ACM Trans. on Computer Systems (TOCS) 13, 2 (1995), 89-121.

[2] Guillermo A. Alvarez, Walter A. Burkhard, Larry J. Stockmeyer, and Flaviu Cristian. 1998. Declustered Disk Array Architectures With Optimal and Near-Optimal Parallelism. In Proc. 25th Ann’l Int’l Symp. on Computer Architecture (ISCA 1998). Barcelona, Spain, June 1998, 109-120.
Ahmed Amer, Darell D. E. Long, Jehan Francois Paris, and Thomas S.E. Schwarz. 2008. Increased Reliability with SSPiRAL Data Layouts. In Proc. 16th Int’l Symp. on Modeling, Analysis, and Simulation of Computer and Telecomm. Systems (MASCOTS’08). Baltimore, MD, September 2008, 189-198.

Tehmina Amjad, Muhammad Sher, and Ali Daud 2012. A Survey Of Dynamic Replication Strategies for Improving Data Availability In Data Grids. Future Generation Computer Systems 28, (2012), 337349.

Dave Anderson, Jim Dykes, and Erik Riedel. 2003. More Than an Interface - SCSI Vs. ATA. In Proc. 2nd USENIX Conf. on File and Storage Technologies (FAST’03). San Francisco, CA, March-April 2003.

J. E. Angus. 1998. On Computing MTBF For A k-out-of-n:G Repairable Systems. IEEE Trans. on Reliability 37, 2 (August 1998), 312-313.

Eitan Bachmat and Jiri Schindler. 2002. Analysis of Methods for Scheduling Low Priority Disk Drive Tasks. In Proc. ACM SIGMETRICS Conf. on Measurement and Modeling of Computer Systems. Marina del Rey, CA, June 2002. 55-65.

Eitan Bachmat and T. K. Lam. 2005. On The Effect of a Configuration Choice on the Performance of a Mirrored Storage System. J. Parallel and Distributed Computing (JPDC) 65, 3 (2005), 382-395.

Dina Bitton and Jim Gray. 1988. Disk Shadowing. In Proc. 24th Int’l Conf. on Very Large Data Bases (VLDB). Brisbane, Australia, August 1988, 331-338.

Mario Blaum, James Brady, Jehoshua Bruck, Jai Menon, and Alex Vardy. 2001. The EVENODD Code and Its Generalization. In High Performance Mass Storage and Parallel I/O: Technologies and Applications, H. Jin, T. Cortes, R. Buyya, eds, IEEE & Wiley Press 2001, Chapter 14, 187-208.

Onno J. Boxma and Jacob W. Cohen. 1991. The M/G/1 Queue with Permanent Customers. IEEE J. Selected Topics in Communications 9, 2 (1991), 179-184.

A. Robert Calderbank, Edward G. Coffman Jr., and Leopold Flatto. 1984. Optimum Head Separation in a Disk System with Two Read/Write Heads. Journal of the ACM 31, 4 (1984), 826-838.

A. Robert Calderbank, Edward G. Coffman Jr., and Leopold Flatto. 1985. Sequencing Problems in Two-Server Systems. Mathematics of Operations Research 10, 4 (1985), 585-598.

John A. Chandy. 2003. A Dual Actuator Logging Disk Architecture. In Proc. IASTED Int’l Conf. on Computer Science and Technology. Cancun, Mexico, May 2003.

Peter M. Chen, Edward K. Lee, Garth A. Gibson, Randy H. Katz, and David A. Patterson. 1994. RAID: High-Performance, Reliable Secondary Storage. ACM Computing Surveys 26, 2 (June 1994), 145-185.

Shen-Zee Chen and Donald F. Towsley. 1996. A Performance Evaluation of RAID architectures. IEEE Trans. on Computers 45, 10 (October 1996), 1116-1130.

Shenze Chen and Donald F. Towsley. 1993. The Design and Evaluation of RAID 5 and Parity Stripping Disk Array Architecture. J. Parallel Distributed Computing (JPDC) 17, 1-2 (January/February 1993), 58-74.
[18] Chiahon Chien. 1993. Seek Distances in Disks with Dual Arms and Mirrored Disks. Performance Evaluation 18, 3 (1993), 175-188.

[19] Byung-Gon Chun, Frank Dabek, Andreas Haeberlen, Emil Sit, Hakim Weatherspoon, M. Frans Kaashoek, John Kubiatowicz, and Robert Morris. 2006. Efficient Replica Maintenance for Distributed Storage Systems. Proc. 3rd Symp. Networked Systems Design and Implementation (NSDI 2006), San Jose, CA, May 2006.

[20] Asaf Cidon, Stephen M. Rumble, Ryan Stutsman, Sachin Katti, John K. Ousterhout, and Mendel Rosenblum. 2013. Copysets: Reducing the Frequency of Data Loss in Cloud Storage. Proc. 2013 USENIX Annual Technical Conf. (ATC), San Jose, CA, June 2013, 37-48.

[21] Ajay Dholakia, Evangelos Eleftheriou, Xiao-Yu Hu, Ilias Iliadis, Jai Menon, Krishnakumar Rao. 2008. A New Intra-Disk Redundancy Scheme for High-Reliability RAID Storage Systems in the Presence of Unrecoverable Errors. ACM Trans. on Storage 4, 1 (2009), 1.1-1.42.

[22] Jon G. Elerath and Jiri Schindler. 2014. Beyond MTTDL: A Closed-Form RAID 6 Reliability Equation. ACM Trans. on Storage (TOS) 10, 2 (March 2014), 7.1-7.21.

[23] Patricia T. Endo, Moiss Rodrigues, Glaucio E. Gonalves, Judith Kelner, Djamel H. Sadok, and Calin Curescu. 2016. High Availability in Clouds: Systematic Review and Research Challenges. J. Cloud Computing: Advances, Systems and Applications 5, (2016), 16 pages.

[24] Tim Feldman and Garth Gibson. 2013. Shingled Magnetic Recording: Areal Density Increase Requires New Data Management. USENIX ;login: 38(3) June 2013.

[25] Robert Fontana (Bio), Gary Decad, and Steven Hetzler. 2013. The Impact of Areal Density and Millions of Square Inches (MSI) of Produced Memory on Petabyte Shipments of Tape, NAND Flash, and HDD Storage Class Memories (Presentation). Proc 29th IEEE Conf. on Massive Data Storage (MSST’13), Queen Mary, Long Beach, CA, May 2013.

[26] Jamel Gafsi and Ernst Biersack. 2000. Modeling and Performance Comparison of Reliability Strategies for Distributed Video Servers. IEEE Trans. Parallel Distributed Systems 11, 4 (2000), 412-430.

[27] Robert Geist, Robert G. Reynolds, and Darrell Suggs. 1994. Minimizing Mean Seek Distance in Mirrored Disk Systems by Cylinder Remapping. Performance Evaluation 20, 1-3 (1994), 97-114.

[28] Garth A. Gibson. 1992. Redundant Disk Arrays: Reliable, Parallel Secondary Storage. MIT Press 1992.

[29] Jim Gray and Prashant J. Shenoy. 2000. Rules of thumb in data engineering. Proc. 16th IEEE Int’l Conf. on Data Engineering (ICDE’2000). San Diego, CA, February-March 2000, 3-10.

[30] James L. Hafner. 2005. WEAVER codes: Highly Fault Tolerant Erasure Codes for Storage Systems. Proc. 4th USENIX Conf. on File and Storage Technologies (FAST’05). San Francisco, CA, December 2005, 211-224.

[31] Robert J. Hall. 2016. Tools for Predicting the Reliability of Large Scale Storage Systems. ACM Trans. on Storage (TOS) 12, 4, (July 2016), 24.1-24.30.

[32] John Hennessy and David Patterson. 2007. Computer Architecture: A Quantitative Approach, 5th Edition. Morgan Kaufman Publishers 2007.
[33] Steven R. Hetzler. 2011. System Design Impacts of Storage Technology Trends. Proc. 9th USENIX Conf. on File and Storage Technologies (FAST’11), San Jose, CA, February 2011.

[34] Micha Hofri. 1983. Should the Two-Headed Disk Be Greedy? - Yes, It Should. Information Processing Letters (IPL) 16 2 (1983), 83-85.

[35] Mark Holland, Garth A. Gibson, and Daniel P. Siewiorek. 1994. Architectures and Algorithms for On-Line Failure Recovery in Redundant Disk Arrays. J. Distributed and Parallel Databases 2, 3 (1994), 295-335.

[36] Hui-I. Hsiao and David J. DeWitt. 1990. Chained Declustering: A New Availability Strategy for Multiprocessor Database Machines. Proc. 6th IEEE Int’l Conf. on Data Engineering (ICDE’90), Los Angeles, CA, February 1990, 456-465.

[37] Windsor W. Hsu, Alan Jay Smith, and Honesty C. Young. 2005. The Automatic Improvement of Locality in Storage Systems. ACM Trans. on Computing Systems 23, 4 (2005), 424-473.

[38] Huawei Technologies. 2014. Huawei OceanStor Enterprise Unified Storage System, RAID2.0+ Technical White Paper 2014. Shenzhen, China. http://support.huawei.com/huaweiconnect/enterprise/thread-298411.html

[39] Kai Hwang, Hai Jin, and Roy S. C. Ho. 2002. Orthogonal Striping and Mirroring in Distributed RAID for I/O-Centric Cluster Computing. IEEE Trans. Parallel and Distributed Systems 13, 1 (January 2002), 26-44.

[40] Ilias Iliadis, Robert Haas, Xiao-Yu Hu, and Evangelos Eleftheriou. 2011. Disk Scrubbing versus Intradisk Redundancy for RAID Storage Systems. ACM Trans. on Storage (TOS) 7 2 (July 2011), 5.1-5.42.

[41] Ilias Iliadis and Vinodh Venkatesan. 2014. Expected Annual Fraction of Data Loss as a Metric for Data Storage Reliability. Proc. 22nd Int’l Symp. Modelling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS’14), Paris, France, September 2014, 375-384

[42] Ilias Iliadis and Vinodh Venkatesan. 2015. An Efficient Method for Reliability Evaluation of Data Storage Systems. Proc. 8th Int’l Conf. on Communication Theory, Reliability, and Quality of Service (CTRQ’15). Barcelona, Spain, April 2015.

[43] Ilias Iliadis and Vinodh Venkatesan. 2015. Rebuttal to ”Beyond MTTDL: A Closed-Form RAID-6 Reliability Equation. ACM Trans. on Storage (TOS) 11, 2 (2015), 9:1-9:10.

[44] Bruce L. Jacob, Spencer W. Ng, and David T. Wang. 2008. Memory Systems: Cache, DRAM, Disk. Morgan Kaufmann Publishers 2008.

[45] David M. Jacobson and John Wilkes. 1991. Disk Scheduling Algorithms Based on Rotational Position. Technical Report HPL-CSP-91-7rev1, HP Laboratories, Palo Alto, CA, February 1991, revised March 1991.

[46] Hai Jin and Kai Hwang 2000. Striped Mirroring RAID Architecture. J. Systems Architecture 46, 6 (2000), 543-550.

[47] Richard P. King. 1990. Disk Arm Movement in Anticipation of Future Requests. ACM Trans. Computer Systems 8, 3 (1990), 214-229.
[48] Leonard Kleinrock. 1975. *Queueing Systems, Volume I: Theory* Wiley-Interscience 1975.

[49] Leonard Kleinrock. 1976. *Queueing Systems, Volume II: Computer System Applications* Wiley-Interscience 1976.

[50] Hsu-Wan Kao, Jehan-François Paris, Darrell D. E. Long, and Thomas Schwarz. 2013. A Flexible Simulation Tool for Estimating Data Loss Risks in Storage Arrays, *Proc. 29th IEEE Symp. on Massive Storage Systems and Technologies*, Long Beach, CA, May 2013.

[51] Yannis Manolopoulos and John G. Kollias. 1989. Performance of a Two-Headed Disk System when Serving Database Queries Under the Scan Policy. *ACM Trans. Database Systems* 14 3 (1989), 425-442.

[52] Yannis Manolopoulos and John G. Kollias. 1990. Optimal Data Placement in Two-headed Disk Systems. *BIT* 30 (1990), 216-219.

[53] Yannis Manolopoulos and Athena Vakali. 1991. Seek Distances in Disks with Two Independent Heads per Surface. *Information Processing Letters (IPL)* 37, 1 (1991), 37-42.

[54] Jai Menon and Jim Cortney. 1993. The Architecture of a Fault-Tolerant Cached RAID Controller. *Proc 20th Ann’l Int’l Symp. on Computer Architecture (ISCA)*, San Diego, CA, May 1993, 76-86

[55] Jai Menon. 1994. Performance of RAID5 Disk Arrays with Read and Write Caching. *Distributed and Parallel Databases* 2 3, (1994), 261-293.

[56] Arif Merchant and Philip S. Yu. 1994. An Analytical Model of Reconstruction Time in Mirrored Disks. *Performance Evaluation* 20 1-3, (1994), 115-129.

[57] Arif Merchant and Philip S. Yu. 1995. Analytic Modeling and Comparisons of Striping Strategies for Replicated Disk Arrays. *IEEE Trans. on Computers* 44 3, (March 1995), 419-433.

[58] Richard R. Muntz and John C. S. Lui. 1990. Performance Analysis of Disk Arrays under Failure. *Proc. 6th Int’l Conf. on Very Large Data Bases (VLDB’90)*, Brisbane, Queensland, Australia, August 1990, 162-173.

[59] Marcel F. Neuts. 1995. *Matrix Geometric Solutions in Stochastic Model - An Algorithmic Approach, revised edition*. John Hopkins University Press 1981, Dover Publications 1995.

[60] Spencer W. Ng. 1987. Reliability, Availability, and Performance Analysis of Duplex Disk Systems. In *Reliability and Quality Control*, M. H. Hamza (editor). Acta Press 1987: 5-9.

[61] Spencer W. Ng. 1991. Improving Disk Performance via Latency Reduction. *IEEE Trans. on Computers* 40 1 (January 19910, 22-30.

[62] Spencer W. Ng. 1994. Crosshatch Disk Array for Improved Reliability and Performance. *Proc. 21st Ann’l Int’l Symp. on Computer Architecture (ISCA)*, Chicago, IL, April 1994, 255-264.

[63] Ivor P. Page and R. T. Wood. 1981. Empirical Analysis of a Moving Head Disc Model with Two Heads Separated by a Fixed Number of Tracks. *The Computer Journal* 24, 4 (1981), 339-342.

[64] Jehan F. Paris, Thomas J. E. Schwarz, and Darrell D. E. Long. 2006. Self-adaptive Disk Arrays. In *Proc. 8th Int’l Symp. on Stabilization, Safety, and Security of Distributed Systems (SSS 2006)*, Dallas, TX, November 2006, 469-483.
[65] David A. Patterson, Garth A. Gibson, and Randy H. Katz. 1988. A Case for Redundant Arrays of Inexpensive Disks (RAID). In *Proc. ACM SIGMOD Int’l Conf. on Management of Data*, Chicago IL, June 1988, 109-116

[66] Christos Polyzois, Anupam Bhide, and Daniel M. Dias. 1993. Disk mirroring with alternating deferred updates. In *Proc. 19th Int’l Conf. on Very Large Data Bases (VLDB)*, Dublin, Ireland, August 1993, 604-617.

[67] William H. Press, Saul A. Teukolsky, William T. Vetterling, and Brian P. Flannery. 2007. "Section 10.12. Simulated Annealing Methods". In *Numerical Recipes: The Art of Scientific Computing (3rd ed.)* Cambridge University Press 2007.

[68] Sriram Sankar, Sudhanva Gurumurthi, and Mircea R. Stan. 2008. Intra-Disk Parallelism: An Idea Whose Time Has Come. In *Proc. 35th Int’l Symp. on Computer Architecture (ISCA)*, Beijing, China, June 2008, 303-314.

[69] Jiri Schindler, Sandip Shete, and Keith A. Smith. 2011. Improving Throughput for Small Disk Requests with Proximal I/O. In *Proc. 9th USENIX Conf. on File and Storage Technologies (FAST’11)*, San Jose, CA, February 2011, 133-147.

[70] Bianca Schroeder and Garth A. Gibson. 2007. Understanding Disk Failure Rates: What Does an MTTF of 1,000,000 Hours Mean to You? *ACM Trans. on Storage (TOS)* 3, 3 (September 2007), 8.1-8.31.

[71] Bianca Schroeder, Sotiros Damouras, and Philipa Gill. 2010. Understanding Latent Sector Errors and How to Protect Against Them. *ACM Trans. on Storage (TOS)* 8, 3 (October 2010), 9.1-9.23.

[72] Pengiu Shang, Jun Wang, Huijun Zhu, and Peng Gu. 2011. A New Placement-Ideal Layout for Multiway Replication Storage System. *IEEE Trans. on Computers* 60 8 (August 2011), 1142-1156.

[73] Thomas Schwarz, Ahmed Amer, Thomas Kroeger, Ethan L. Miller, Darrell D. E. Long, and Jehan-Francois Pris. 2016. RESAR: Reliable Storage at Exabyte Scale. In *Proc. 24th Int’l Symp. on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems (MASCOTS 2016)*, London, UK, September 2016, 211-220.

[74] Jon A. Solworth and Cyril U. Orji. 1991. Distorted Mirrors. In *Proc. 1st Int’l Conf. on Parallel and Distributed Information Systems (PDIS’91)*, Miami Beach, Florida, December 1991, 10-17.

[75] Jon A. Solworth and Cyril U. Orji. 1993. Distorted Mapping Techniques to Achieve High Performance in Mirrored Disk Systems,. *Distributed and Parallel Databases I*, 1 (January 1993), 81-102.

[76] John P. Squires, Glade N. Bagnell, Charles M. Sander, and Kurt M. Anderson. 1994. Multiple Actuator Disk Drive. Conner Peripherals, March 1994. US Patent No. 5,293,282, WIPO Patent No. 9209077.

[77] Hideaki Takagi. 1991. *Queueing Analysis, Volume 1: Vacations and Priority Systems*. North Holland 1991.

[78] Tandem Database Group. 1989. NonStop SQL: A Distributed, High-Performance, High-Availability Implementation of SQL. In *Proc. 2nd Int’l Workshop on High Performance Transaction Systems (HPTS’87)*, Dieter Gawlick, Mark N. Haynie, Andreas Reuter (editors): Pacific Grove, CA, September 1987, *Lecture Notes in Computer Science 359*. Springer 1989, 60-104.
[79] Teradata. 1985. DBC/1012 Database Computer System Manual Release 2.0. Document No. C10-0001-02, Teradata Corp., November 1985.

[80] Kazuhiko Mogi, Masaru Kitsuregawa: Hot mirroring: A study to Hide Parity Upgrade Penalty and Degradations During Rebuilds for RAID5. In Proc. ACM SIGMOD Int’l Conf. on Management of Data. Montreal, Quebec, Canada, June 1996, 183-194.

[81] Edward K. Lee and Chandramohan A. Thekkath. 1996. Petal: Distributed Virtual Disks. In Proc. 7th Int’l Conf. on Architectural Support for Programming Languages and Operating Systems (ASPLOS-VII). Cambridge, MA, October 1996, 84-92

[82] Raymond W. Lo and Norman S. Matloff. 1992. Probabilistic Limit on the Virtual Size of Replicated Disc Systems. IEEE Trans. on Knowledge and Data Engineering (TKDE) 4, 1 (January 1992), 99-102.

[83] Chris R. Lumb, Jiri Schindler, and Greg R. Ganger. 2002. Freeblock Scheduling Outside of Disk Firmware. In Proc. 1st USENIX Conf. on File and Storage Technologies (FAST’02), Monterey, CA, January 2002, 275-288.

[84] Christopher R. Lumb and Richard A. Golding. 2004. D-SPTF: Decentralized Request Distribution in Brick-Based Storage Systems. In Proc. 11th Int’l Conf. on Architectural Support for Programming Languages and Operating Systems (ASPLOS). Boston, MA, October 2004, 37-47.

[85] K. K. Ramakrishnan, Prabuddha Biswas, Ramakrishna Karedla. 1992. Analysis of File I/O Traces in Commercial Computing Environments. In Proc. ACM SIGMETRICS Conf. on Measurement and Modeling of Computer Systems. Newport, RI, June 1992, 78-90.

[86] Raghu Ramakrishnan and Johannes Gehrke. 2002. Database Management Systems, 3rd edition. McGraw-Hill 2002.

[87] Jason Resch and Ilya Volvovski. 2013. Reliability Models for Highly Fault-tolerant Storage Systems. https://arxiv.org/abs/1310.4702

[88] Mendel Rosenblum and John K. Ousterhout. 1992. The Design and Implementation of a Log-Structured File System. ACM Trans. Computer Systems (TOCS) 10, 1 (February 1992), 26-52.

[89] Chris Ruemmler and John Wilkes. 1991. Disk shuffling. Technical Report HPL91156, HP Laboratories, Palo Alto, CA, 1991.

[90] Alexander Thomasian and Victor F. Nicola. 1993. Performance Evaluation of a Threshold Policy for Scheduling Readers and Writers. IEEE Trans. Computers 42, 1 (January 1993), 83-98.

[91] Alexander Thomasian and Jai Menon. 1994. Performance Analysis of RAID5 Disk Arrays with a Vacationing Server Model for Rebuild Mode Operation. In Proc. Tenth IEEE Int’l Conf. on Data Engineering (ICDE’94). Houston, TX, February 1994, 111-119.

[92] Alexander Thomasian. 1995. Rebuild Options in RAID5 Disk Arrays. In Proc. 7th IEEE Symp. on Parallel and Distributed Processing (SPDP ’95). San Antonio, TX, October 1995, 511-518.

[93] Alexander Thomasian and Jai Menon. 1997. RAID5 Performance with Distributed Sparing. IEEE Trans. Parallel and Distributed Systems 8, 6 (June 1997), 640-657.

[94] Alexander Thomasian. 2005. Reconstruct versus Read-Modify Writes in RAID. Information Processing Letters (IPL) 93, 4 (February 2005), 163-168.
[95] Alexander Thomasian and Chang Liu. 2005. Performance Comparison of Mirrored Disk Scheduling Methods with a Shared Non-Volatile Cache. Distributed and Parallel Databases 18, 3 (November 2005), 253-281.

[96] Alexander Thomasian, Bogdan A. Branzoi, and Chunqi Han. 2005. Performance Evaluation of a Heterogeneous Disk Array Architecture. In Proc. 13th IEEE Int’l Symp. on Modeling, Analysis and Simulation of Computer and Telecommunications Systems (MASCOTS05). Atlanta, GA, September 2005, 517-520.

[97] Alexander Thomasian and Chunqi Han. 2005. Affinity-Based Routing in Zoned Mirrored Disks. Computer Journal 48, 3 (June 2005), 292-299.

[98] Alexander Thomasian. 2006. Mirrored Disk Routing and Scheduling. Cluster Computing 9, 4 (October 2006), 475-484.

[99] Alexander Thomasian. 2006. Shortcut Method for Reliability Comparisons in RAID5. J. Systems and Software (JSS) 79, 11 (November 2006), 1599-1605.

[100] Alexander Thomasian and Mario Blaum. 2006. Mirrored Disk Organization Reliability Analysis. IEEE Trans. on Computers 55, 12 (December 2006), 1640-1644.

[101] Alexander Thomasian and Gang Fu. 2006. Anticipatory Disk Arm Placement to Reduce Seek Time. Computer Systems: Science and Engineering 21 3 (September 2006), 173-182.

[102] Alexander Thomasian, Gang Fu, and Chunqi Han. 2007. Performance of Two-Disk Failure-Tolerant Disk Arrays. IEEE Trans. on Computers 56 6 (June 2007), 799-814.

[103] Alexander Thomasian and Jun Xu. 2008. Reliability and Performance of Mirrored Disk Organizations. The Computer Journal 51, 6 (November 2008), 615-629.

[104] Alexander Thomasian and Mario Blaum. 2009. Higher Reliability Redundant Disk Arrays: Organization, Operation, and Coding, ACM Trans. on Storage (TOS) 5 3 (November 2009), 7.1-7.59.

[105] Alexander Thomasian. 2011. Survey and Analysis of Disk Scheduling Methods. SIGARCH Computer Architecture News (CAN) 39 2 (May 2011), 8-25.

[106] Alexander Thomasian and Jun Xu. 2011. RAID Level Selection for Heterogeneous Disk Arrays. Cluster Computing 14 2 (June 2011), 115-127.

[107] Alexander Thomasian and Yujie Tang. 2012. Performance, Reliability, and Performability of a Hybrid RAID Array and a Comparison with Traditional RAID1 arrays. Cluster Computing 15, 3 (September 2012), 239-253.

[108] Alexander Thomasian, Yujie Tang, and Yang Hu. 2012. Hierarchical RAID: Design, Performance, Reliability, and Recovery. J. Parallel Distributed Computing 72, 12 (December 2012), 1753-1769.

[109] Alexander Thomasian. 2013. Improved Storage System Performance by Disk Scheduling. Computer Systems: Science and Engineering 28, 2, (2013), 117-133.

[110] Alexander Thomasian. 2014. Performance Evaluation of Computer Systems. In Computing Handbook, Third Edition: Computer Science and Software Engineering, Teofilo F. Gonzalez, Jorge Diaz-Herrera, Allen Tucker, editors, CRC Press 2014: Chapter 56: 1-50.
[111] Alexander Thomasian. 2014. Secondary Storage Systems. In Handbook of Computer Science and Engineering, 3rd Edition, Chapter 19, Teofilso Gonzalez, Jorge Diaz-Herrera, and Allen Tucker, editors, Taylor & Francis/CRC Press 2014, 1-42.

[112] Alexander Thomasian. 2014. Analysis of Fork/Join and Related Queueing Systems. ACM Computing Surveys 47, 2 (August 2014), 17:1-17:71.

[113] Alexander Thomasian and Jun Xu. 2016. Data allocation in a Heterogeneous Disk Array (HDA) with Multiple RAID Levels for Database Applications. Computer Systems: Science & Engineering 31, 5 (September 2016), 345-359.

[114] Donald F. Towsley, Shenze Chen, and Shou-Pin Yu. 1990. Performance Analysis of a Fault-Tolerant Mirrored Disk System. In Proc. 14th IFIP WG 7.3 Int’l Symp. on Computer Performance Modelling, Measurement and Evaluation, Edinburgh, Scotland, September 1990, 239-253.

[115] Donald F. Towsley and Shenze Chen. 1991. Design and Evaluation of Scheduling Policies for Two-Server Fork/Join Queueing Systems. Dept of Computer and Information Science, University of Massachusetts at Amherst, COINS Technical Report 91-39, April 1991.

[116] Kent Treiber and Jai Menon. 1995. Simulation Study of Cached RAID5 Designs. In Proc. 1st IEEE Symp. on High Performance Computer Architecture (HPCA), Raleigh, NC, January 1995, 186-197.

[117] Kishor S. Trivedi. 2001. Probability and Statistics with Reliability, Queueing, and Computer Science Applications, 2nd Edition, John Wiley & Sons, New York, 2001.

[118] Mustafa Uysal, Arif Merchant, and Guillermo A. Alvarez. 2003. Using MEMS-Based Storage in Disk Arrays. In Proc. 2nd USENIX Conf. on File and Storage Technologies (FAST’03), San Francisco, CA, March 2003, 89-101.

[119] Athena Vakali and Yannis Manolopoulos. 1997. An Exact Analysis on Expected Seeks in Shadowed Disks. Information Processing Letters (IPL) 61, 6 (March 1997), 323-329.

[120] Athena Vakali and Yannis Manolopoulos. 2000. Data Placement Schemes in Replicated Mirrored Disk Systems. J. Systems Software 55, 2 (December 2000), 115-128.

[121] Vinodh Venkatesan, Ilias Iliadis, Xiao-Yu Hu, and Christina Fragouli. 2010. Effect of Replica Placement on the Reliability of Large-Scale Data Storage Systems. In Proc. 18th Ann’l Int’l Symp. on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS’10), Miami, FL, August 2010, 79-88

[122] Vinodh Venkatesan, Ilias Iliadis, Xiao-Yu Hu, Robert Haas, and Christina Fragouli. 2011. Reliability of Clustered vs. Declustered Replica Placement in Data Storage Systems. In Proc. 19th Ann’l Int’l Symp. on Modeling, Analysis and Simulation of Computer and Telecomm. Systems (MASCOTS’11), Raffles Hotel, Singapore, August 2011, 307-317.

[123] Vinodh Venkatesan, Ilias Iliadis, and Robert Haas. 2012. Reliability of Data Storage Systems under Network Rebuild Bandwidth Constraints. In Proc. 20th Int’l Symp. Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS 2012). Washington, D.C., August 2012, 189-197.

[124] Paul Vongsathorn and Scott D. Carson. 1990. A System for Adaptive Disk Rearrangement. Software Practice and Experience 20, 3 (1990), 225-242.
[125] Hakim Weatherspoon and John Kubiatowicz. 2002. Erasure Coding vs. Replication: A Quantitative Comparison. In *Proc. First Int’l Workshop on Peer-to-Peer Systems*. Cambridge, MA, March 2002, 328-338.

[126] Ward Whitt. 1986. Deciding Which Queue to Join: Some Counterexamples. *Operations Research* 34, 1 (January 1986), 55-62 (January-February 1986).

[127] John Wilkes, Richard Golding, Carl Staelin, and Tim Sullivan. 1996. The HP AutoRAID Hierarchical Storage System. *ACM Trans. Computer Systems* 14(1): 108-136 (February 1996).

[128] Alden Wilner. 2000. Multiple Drive Failure Tolerant RAID System. US Patent 6,327,672, LSI Logic Corp., 2000.

[129] Bruce L. Worthington, Gregory R. Ganger, and Yale N. Patt. 1994. Scheduling Algorithms for Modern Disk Drives. *Proc. ACM SIGMETRICS Conf. on Measurement and Modeling of Computer Systems*. Nashville, TN, May 1994, 241-252.

[130] Bin Fan, Wittawat Tantisiriroj, Lin Xiao, and Garth Gibson. 2009. DiskReduce: RAID for Data-Intensive Scalable Computing. In *Proc. 4th Petascale Data Storage Workshop*, Portland, OR, November 2009.

[131] Qin Xin, Ethan L. Miller, Thomas Schwarz, Darrell D. Long, Scott A. Brandt, and Witold Litwin. 2003. Reliability Mechanisms for Very Large Storage Systems. In *Proc. 20th IEEE/11th NASA Goddard Conference on Mass Storage Systems and Technologies (MSST)*. San Diego, CA, April 2003.

[132] Lihao Xu, Vasken Bohossian, Jehoshua Bruck, and David G. Wagner. 1999. Low-density MDS codes and factors of complete graphs. *IEEE Trans. on Information Theory* 45, 6, (June 1999), 1817-1836.

[133] Xiang Yu, Benjamin Gum, Yuqun Chen, Randolph Y. Wang, Kai Li, Arvind Krishnamurthy, and Thomas E. Anderson. 2000. Trading Capacity for Performance in a Disk Array. In *Proc. 4th Symp. on Operating System Design and Implementation (OSDI 2000)*. San Diego, CA, October 2000. 243-258.

[134] Mi Zhang, Shujie Han, and Patrick P.C. Lee. 2017. Simulation Analysis of Reliability in Erasure-Coded Data Centers. In *Proc. 2017 IEEE 36th Symp. on Reliable Distributed Systems (SRDS)*, Hong Kong, September 2017.