Parity 1-4 = (Strip 1) XOR (Strip2) XOR (Strip3) XOR (Strip4)

**Figure 7.30** RAID-4, Block Interleave Data Striping with One Parity Disk

+ now can read independent disks, supporting multiple transactions

Read data from a missing disk can be reconstructed on the fly until we get a replacement disk but we need to read all other disks (including parity) in order to determine missing data.

Data can even be “written” to a missing disk:
  a) read data from all other data disks
  b) compute new parity using new data and data from other disks
  c) write new parity

A missing disk will interfere with independent transactions so the RAID system will be slower until a replacement disk is inserted and reconstructed.
Eg: Raid 4 - When writing new data to a non failed drive, there is no need to read all other drives

Drive #1: ???????? (Data)
Drive #2: ???????? (Data)
Drive #3: 11110111 (Data)
    01111111 new data
    ↑    ↑
Drive #4: ???????? (Data)
Drive #5: _________ (Hot Spare)
Drive #6: 11100110 (Parity)
    01101110 new Parity
Eg: Raid 4 - When writing new data to a non failed drive, there is no need to read all other drives

Drive #1: ???????? (Data)
Drive #2: ???????? (Data)
Drive #3: 11110111 (Data)
              01111111 new data
              10001000 D3 ⊕ nD3

Drive #4: ???????? (Data)
Drive #5: _________ (Hot Spare)
Drive #6: 11100110 (Parity)      nP = P ⊕ D3 ⊕ nD3
              01101110 new Parity
Parity 1-4 = (Strip 1) XOR (Strip2) XOR (Strip3) XOR (Strip4)

**Figure 7.30** RAID-4, Block Interleave Data Striping with One Parity Disk

- can not support simultaneous independent writes
Figure 7.31  RAID-5, Block Interleave Data Striping with Distributed Parity

+ can support several independent simultaneous writes
**Figure 7.32** RAID-6, Block Interleave Data Striping with Dual Error Protection

+ Can support up to 2 failed drives
  – needs 2 extra drives
  – more complex processing for Reed-Solomon than for parity

\[ P = \text{Parity} \]
\[ Q = \text{Reed-Solomon} \]
The recovery of A2 is provided by the overlap of equations AP1 and BP2.
Figure 7.34  Restoring Two Crashed Spindles using RAID DP

a. A catastrophic crash occurs. Two drives are affected. Both drives are replaced.
**Figure 7.34** Restoring Two Crashed Spindles using RAID DP

b. Platter A2 is restored using the equation: $A2 = B3 \oplus C4 \oplus DP1 \oplus BP2$
Figure 7.34  Restoring Two Crashed Spindles using RAID DP

c. Platter A1 is restored using the equation:  \( A1 = A2 \oplus A3 \oplus A4 \oplus AP1 \)
Figure 7.34  Restoring Two Crashed Spindles using RAID DP

d. Platter B2 is restored using the equation: $B_2 = A_1 \oplus C_3 \oplus D_4 \oplus \text{AP2}$
Figure 7.34  Restoring Two Crashed Spindles using RAID DP

AP\textsubscript{1} = A\textsubscript{1} \oplus A\textsubscript{2} \oplus A\textsubscript{3} \oplus A\textsubscript{4} \\
BP\textsubscript{1} = B\textsubscript{1} \oplus B\textsubscript{2} \oplus B\textsubscript{3} \oplus B\textsubscript{4} \\
CP\textsubscript{1} = C\textsubscript{1} \oplus C\textsubscript{2} \oplus C\textsubscript{3} \oplus C\textsubscript{4} \\
DP\textsubscript{1} = D\textsubscript{1} \oplus D\textsubscript{2} \oplus D\textsubscript{3} \oplus D\textsubscript{4} \\

AP\textsubscript{2} = A\textsubscript{1} \oplus B\textsubscript{2} \oplus C\textsubscript{3} \oplus D\textsubscript{4} \\
BP\textsubscript{2} = A\textsubscript{2} \oplus B\textsubscript{3} \oplus C\textsubscript{4} \oplus DP\textsubscript{1} \\
CP\textsubscript{2} = A\textsubscript{3} \oplus B\textsubscript{4} \oplus CP\textsubscript{1} \oplus D\textsubscript{1} \\
DP\textsubscript{2} = A\textsubscript{4} \oplus BP\textsubscript{1} \oplus C\textsubscript{1} \oplus D\textsubscript{2} \\
e. Platter B\textsubscript{1} is restored using the equation: B\textsubscript{1} = B\textsubscript{2} \oplus B\textsubscript{3} \oplus B\textsubscript{4} \oplus BP\textsubscript{1}
Figure 7.35  Hybrid RAID Levels

a) RAID 10, Stripe of Mirrors
b) RAID 01, Mirror of Stripes
Figure 7.36  RAID 50, Striping and Parity
<table>
<thead>
<tr>
<th>RAID Level</th>
<th>Description</th>
<th>Reliability</th>
<th>Throughput</th>
<th>Pro and con</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Block interleave data striping</td>
<td>Worse than single disk</td>
<td>Very good</td>
<td>Least cost, no protection</td>
</tr>
<tr>
<td>1</td>
<td>Data mirrored on second identical set</td>
<td>Excellent</td>
<td>Access better than single disk on reads, worse on writes</td>
<td>Excellent protection, high cost</td>
</tr>
<tr>
<td>2</td>
<td>Bit interleave data striping with Hamming code</td>
<td>Good</td>
<td>Very good</td>
<td>Good performance, high cost, not used in practice</td>
</tr>
<tr>
<td>3</td>
<td>Bit interleave data striping with parity disk</td>
<td>Good</td>
<td>Very good</td>
<td>Good performance, reasonable cost</td>
</tr>
<tr>
<td>4</td>
<td>Block interleave data striping with one parity disk</td>
<td>Very good</td>
<td>(Much) worse on writes than single disk, very good on reads</td>
<td>Reasonable cost, poor performance, not used in practice</td>
</tr>
<tr>
<td>5</td>
<td>Block interleave data striping with distributed parity</td>
<td>Very good</td>
<td>On writes not as good as single disk, very good on reads</td>
<td>Good performance, reasonable cost</td>
</tr>
<tr>
<td>6</td>
<td>Block interleave data striping with dual error protection</td>
<td>Excellent</td>
<td>On writes much worse than single disk, very good on reads</td>
<td>Good performance, reasonable cost, complex to implement</td>
</tr>
<tr>
<td>10</td>
<td>Mirrored disk striping</td>
<td>Excellent</td>
<td>Better than single disk on reads, not as good as single disk on writes</td>
<td>Good performance, high cost, excellent protection</td>
</tr>
<tr>
<td>50</td>
<td>Parity with striping</td>
<td>Excellent</td>
<td>Excellent read performance. Better than RAID 5; not as good as RAID 5; not as good as RAID 10.</td>
<td>Good performance, high cost, good protection</td>
</tr>
<tr>
<td>DP</td>
<td>Block interleave data striping with dual parity disks</td>
<td>Excellent</td>
<td>Better than single disk on reads, not as good as single disk on writes</td>
<td>Good performance, reasonable cost, excellent protection</td>
</tr>
</tbody>
</table>

**Table 7.1** Summary of RAID Capabilities