# Using the Appropriate Wear Leveling to Extend Product Lifespan

Presented by: Bill Roman
Datalight Software Architect

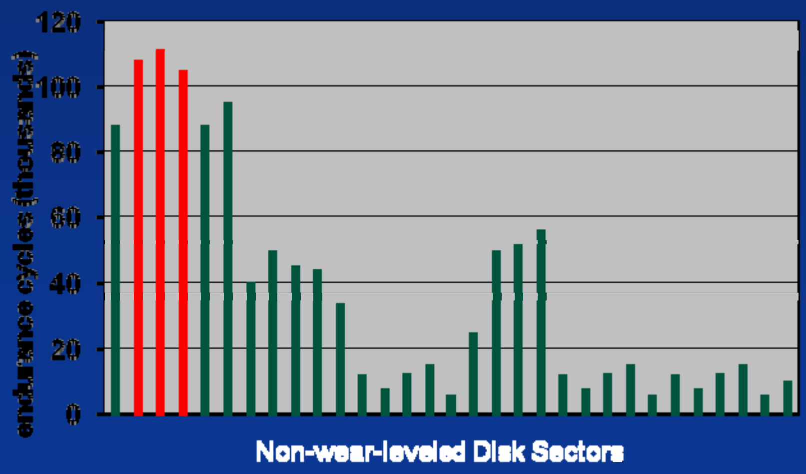
Santa Clara, CA USA
August 2009

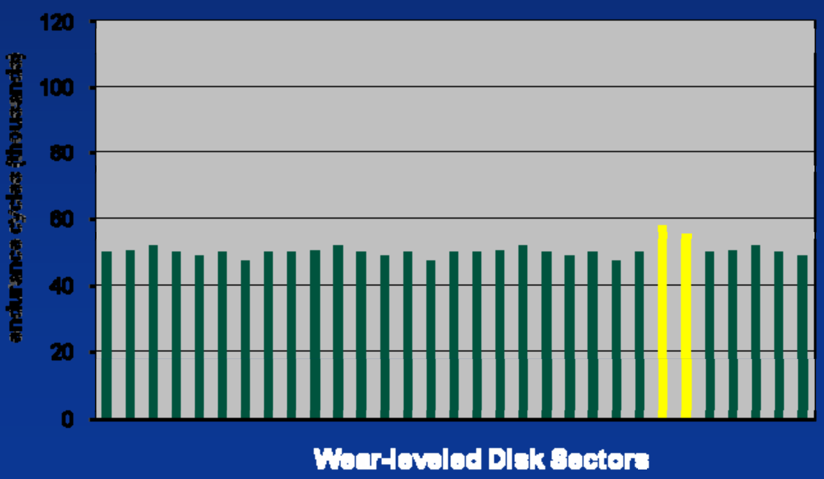
# Overview

- Basics of wear leveling
- Dynamic vs. Static Wear Leveling
- Other Considerations
- Conclusions

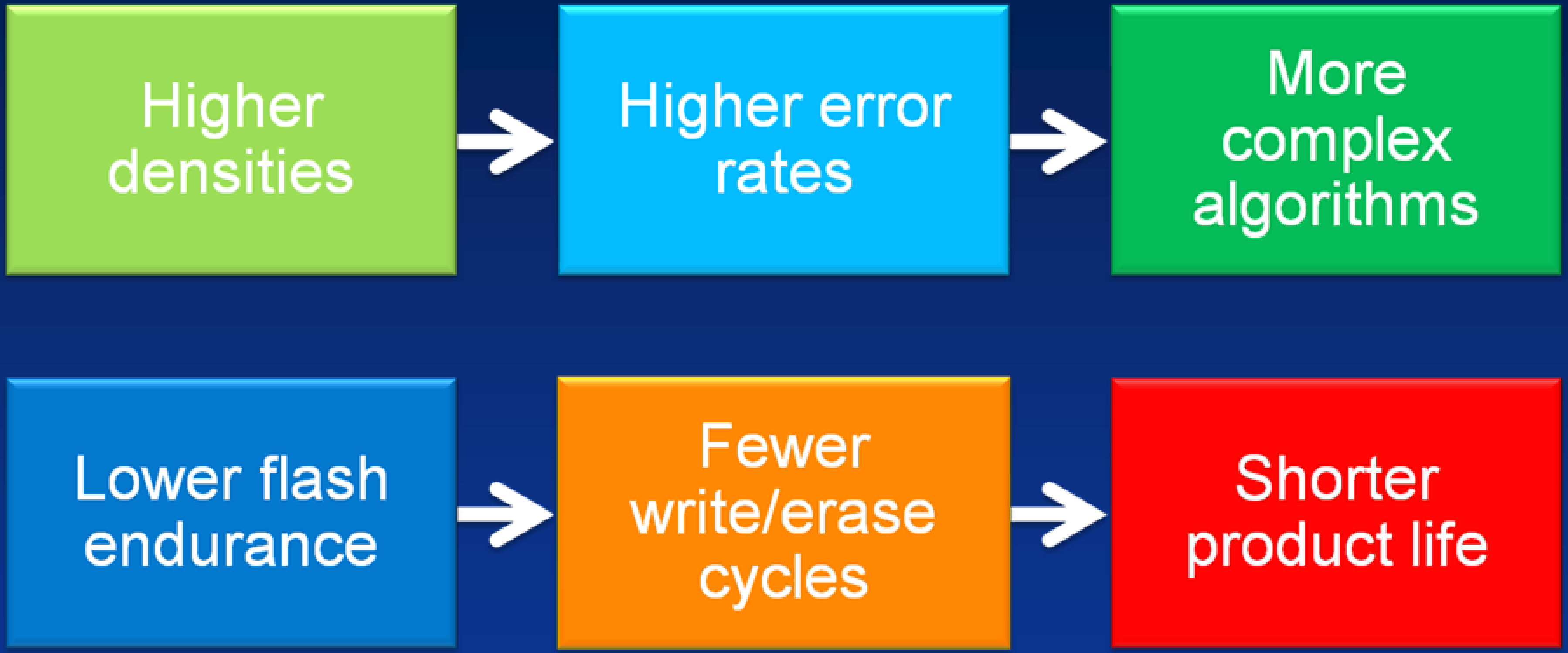
# What is Wear Leveling?

**Wear leveling:** a set of algorithms that attempt to maximize the lifetime of flash memory by evening out the use of individual cells.



# Growing Impact on Product Life

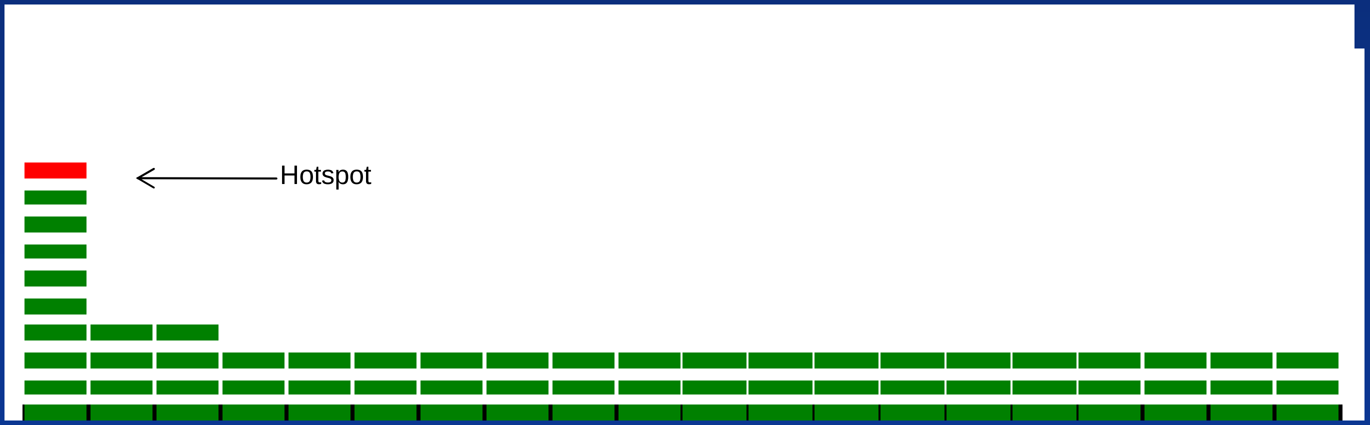


# Ignorance is Costly

- Controller using read-modify-write operations
- If there is no wear leveling, an area of the flash can become unusable in just a few months
- Wear Leveling cannot be ignored, but does not need to be a ‘big deal’

# Conventional File System on Flash

- Inefficient
- Hot spots
- Not interruption-safe
- Usable for read-only

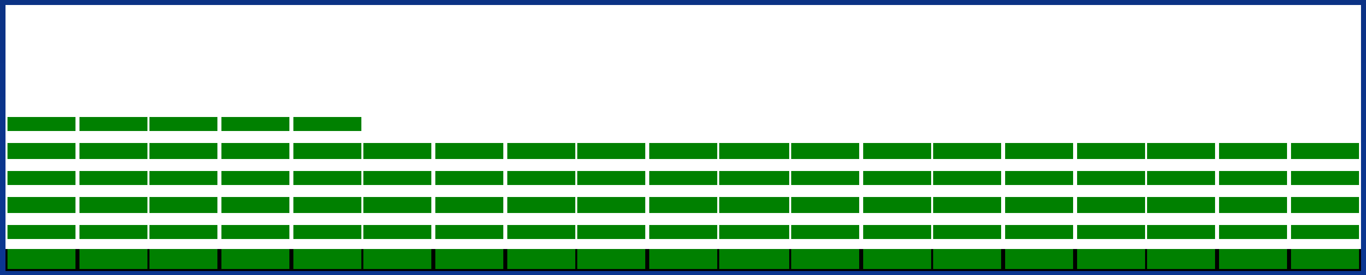


# Dynamic is Usually Standard

- Largely inherent in any flash management system
  - Overwrites in flash are generally not allowed
  - Writes to NAND must be sequential
  - Requires data to be moved to efficiently use NAND

# FIFO

- Original JFFS used this strategy
- Strictly linear
- “Perfect” wear-leveling



# FIFO

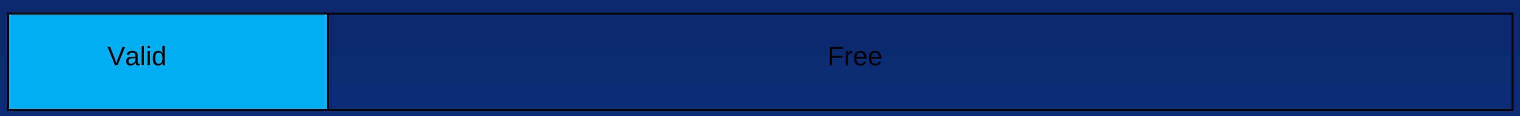
## Immediately after erasing

Free

Erase Block

# FIFO

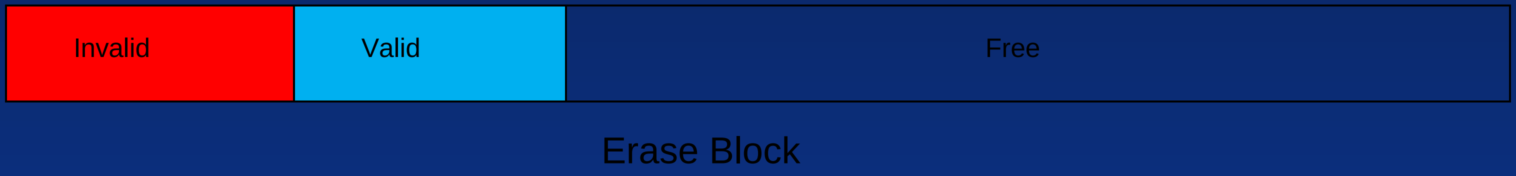
A file is written




Erase Block

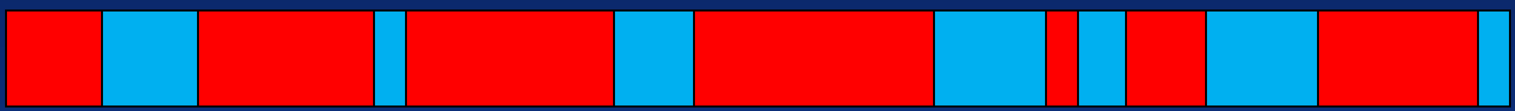
# FIFO

Data in the file is modified



# FIFO

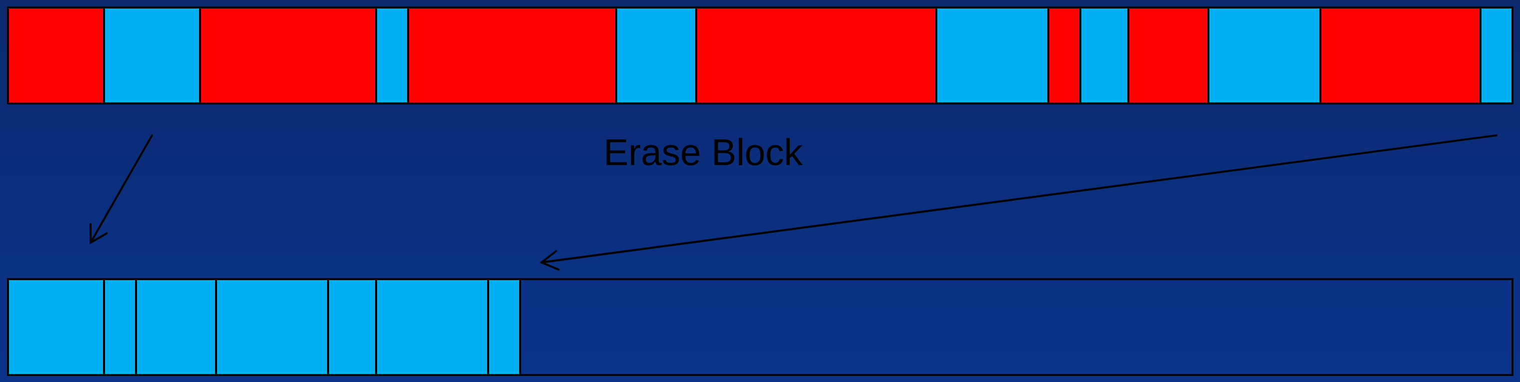
More files are created, modified, deleted



Erase Block

# FIFO

So it's necessary to compact valid data into a free erase block



# FIFO

Becomes

# Simple Cuts Both Ways

- Effectiveness is based on application use case
  - How much data is unchanged?
  - Only works on areas of flash which are frequently updated
  - Static data therefore reduces life of the flash

# Effect of FIFO on Flash Life

- Actual Life = Specified Life * (1- static data size/total flash size)
- Balance “perfect” wear leveling against efficiency by occasionally moving static data

# Dynamic Considerations

- Ignorance is bliss
  - The system can ignore what it does not know
  - If data is never written, it is not considered (remains unmoved)
  - Decisions to move data can be based purely on performance needs

# Static Does the Heavy Lifting

- Static WL is most effective
  - Largely independent of the systems' use case
  - Large (or all) portions of the media are considered
  - Static data does not significantly degrade life of the flash

# Static Complicates Things

- Implementations are more complex
  - The system must track media usage and evaluate otherwise unused media
  - Requires additional erase and copy operations with zero return to performance
  - Impacts to performance can be substantial

# Static and Dynamic Together

- Both approaches should be evaluated for an effective wear leveling solution.
- Dynamic is low effort and high performance
- Static ensures that media life is maximized, but at a cost to performance
- Statistical implementations may not handle certain use cases or break down entirely

# Dynamic vs. Static

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 66 | 5504 | 17 | 1 | 103 | 1 | 57 | 1 | 75 | 1 | 60 | 5440 | 1 | 1 | 74 | 1 |
| 5488 | 1 | 5472 | 1 | 5235 | 5339 | 1 | 1 | 5389 | 1 | 23 | 5455 | 1 | 5353 | 1 | 39 |
| 27 | 1 | 52 | 1 | 161 | 47 | 1 | 95 | 1 | 27 | 81 | 65 | 1 | 62 | 1 | 5496 |
| 5463 | 1 | 5413 | 1 | 166 | 5362 | 1 | 5583 | 1 | 5387 | 69 | 1 | 5403 | 1 | 253 | 1 |
| 5534 | 1 | 5410 | 1 | 1 | 184 | 64 | 1 | 5404 | 1 | 72 | 3 | 63 | 5429 | 1 | 77 |
| 13 | 1 | 1 | 46 | 5469 | 1 | 1 | 43 | 1 | 66 | 1 | 5375 | 1 | 16 | 5481 | 1 |
| 1 | 136 | 1 | 23 | 1 | 169 | 1 | 5436 | 1 | 5420 | 5291 | 1 | 7 | 1 | 5205 | 5338 |
| 1 | 2 | 92 | 172 | 5431 | 121 | 5480 | 139 | 305 | 1 | 41 | 242 | 1 | 32 | 172 | 39 |
| 5412 | 5186 | 1 | 38 | 91 | 5407 | 88 | 32 | 126 | 112 | 5313 | 32 | 47 | 2 | 23 | 1 |
| 1 | 1 | 1 | 837 | 1 | 1 | 1 | 1 | 87 | 5355 | 5359 | 1 | 1 | 4 | 1 | 1 |
| 1 | 155 | 5352 | 1 | 1 | 1 | 1 | 40 | 1 | 1 | 1 | 1 | 99 | 1 | 1 | 1 |
| 2 | 39 | 1 | 86 | 5265 | 1 | 111 | 1 | 26 | 5401 | 1 | 1 | 35 | 1 | 38 | 1 |
| 22 | 51 | 1 | 5291 | 1 | 32 | 5490 | 1 | 55 | 1 | 40 | 1 | 100 | 1 | 52 | 1 |
| 70 | 5404 | 1 | 554 | 1 | 5264 | 5374 | 1 | 121 | 1 | 5321 | 5348 | 1 | 84 | 1 | 115 |
| 5457 | 1 | 1 | 147 | 1 | 5347 | 1 | 312 | 1 | 5369 | 230 | 1 | 1 | 42 | 1 | 104 |
| 1 | 5332 | 1 | 5399 | 140 | 1 | 5418 | 1 | 5619 | 1 | 1 | 177 | 4 | 1 | 5424 | 1 |
| 246 | 1 | 288 | 1 | 1 | 5466 | 82 | 1 | 2 | 1 | 5339 | 29 | 1 | 5451 | 1 | 144 |
| 5377 | 1 | 5318 | 1 | 154 | 5097 | 1 | 10 | 1 | 5314 | 5371 | 1 | 1 | 5462 | 1 | 243 |
| 169 | 1 | 116 | 1 | 5364 | 20 | 1 | 3 | 1 | 14 | 364 | 238 | 1 | 5330 | 64 | 1 |
| 5328 | 1 | 5384 | 5410 | 1 | 1 | 5350 | 1 | 5371 | 1 | 191 | 1 | 5318 | 5535 | 1 | 1 |
| 61 | 1 | 61 | 1 | 5348 | 5321 | 1 | 143 | 1 | 128 | 1 | 5339 | 1 | 1 | 5391 | 323 |
| 1 | 5396 | 1 | 61 | 1 | 5371 | 5342 | 5486 | 5428 | 1 | 5495 | 1 | 114 | 5305 | 1 | 5310 |
| 1 | 5491 | 42 | 1 | 60 | 1 | 89 | 44 | 1 | 5438 | 1 | 1 | 5357 | 2 | 1 | 67 |
| 1 | 5328 | 5383 | 1 | 5431 | 1 | 48 | 37 | 1 | 5460 | 1 | 5336 | 1378 | 1 | 8 | 1 |
| 65 | 1 | 5427 | 1 | 2 | 1 | 1 | 5366 | 105 | 1 | 15 | 1 | 9 | 17 | 79 | 192 |
| 1 | 78 | 77 | 1 | 5339 | 1 | 178 | 1 | 5387 | 1 | 3 | 5347 | 1 | 1 | 133 | 1 |
| 26 | 1 | 5455 | 65 | 33 | 5401 | 1 | 5446 | 1 | 69 | 1 | 331 | 57 | 1 | 40 | 1 |
| 10 | 35 | 1 | 5324 | 1 | 60 | 5319 | 1 | 70 | 1 | 32 | 72 | 214 | 1 | 5511 | 1 |
| 55 | 5379 | 117 | 73 | 53 | 2 | 5436 | 1 | 737 | 1 | 5488 | 135 | 1 | 5405 | 1 | 1 |
| 183 | 85 | 1 | 167 | 1 | 103 | 1 | 57 | 1 | 1 | 61 | 123 | 1 | 5 | 5396 | 5399 |
| 62 | 5564 | 73 | 114 | 1 | 18 | 5257 | 74 | 93 | 80 | 1 | 90 | 99 | 5386 | 5404 | 5402 |

Dynamic Only

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2252 | 2163 | 1573 | 1508 | 1944 | 2167 | 1869 | 1590 | 2261 | 2188 | 2233 | 1922 | 2182 | 1768 | 1601 | 1598 |
| 2171 | 1610 | 1912 | 2058 | 1598 | 1643 | 1753 | 2211 | 2042 | 2151 | 1597 | 1554 | 1624 | 2139 | 1541 | 1756 |
| 2302 | 1648 | 1542 | 1586 | 1683 | 2294 | 1589 | 1722 | 1673 | 2167 | 1991 | 1579 | 2333 | 2208 | 1573 | 2055 |
| 1702 | 1763 | 1524 | 1944 | 2197 | 1656 | 1922 | 1544 | 1664 | 1551 | 1541 | 2174 | 2191 | 1889 | 2193 | 2168 |
| 1812 | 2230 | 2184 | 2206 | 1707 | 2124 | 2163 | 1531 | 2184 | 2164 | 1988 | 1658 | 1591 | 1613 | 2225 | 2225 |
| 2167 | 1549 | 1548 | 1669 | 1593 | 2000 | 2234 | 2242 | 1616 | 2149 | 2213 | 2228 | 2224 | 1592 | 1539 | 1719 |
| 1530 | 1542 | 2217 | 1673 | 1572 | 1717 | 1542 | 1536 | 2190 | 1614 | 1634 | 1631 | 2221 | 1512 | 1578 | 1509 |
| 2161 | 1673 | 2259 | 1563 | 1703 | 2038 | 2245 | 2255 | 1722 | 2248 | 1575 | 1524 | 2249 | 2207 | 1666 | 2181 |
| 2194 | 1601 | 2240 | 1822 | 2163 | 1526 | 2204 | 2163 | 1687 | 2256 | 1593 | 2146 | 1627 | 1950 | 2139 | 2181 |
| 1884 | 1536 | 2185 | 2289 | 2117 | 2240 | 1851 | 1510 | 2292 | 1937 | 1568 | 1623 | 2308 | 2178 | 1568 | 2154 |
| 1638 | 2176 | 1703 | 1625 | 1608 | 1520 | 2142 | 2200 | 2161 | 2185 | 2214 | 1774 | 1590 | 2086 | 1529 | 2159 |
| 2164 | 2130 | 1521 | 2162 | 1651 | 2246 | 1620 | 1823 | 1871 | 1511 | 2329 | 1639 | 1522 | 1566 | 2175 | 1675 |
| 1540 | 1736 | 1696 | 1513 | 2249 | 2366 | 1909 | 1517 | 2194 | 1608 | 2165 | 1628 | 2216 | 1920 | 1905 | 2154 |
| 1652 | 2198 | 1591 | 1543 | 1843 | 2205 | 1549 | 1533 | 2150 | 1553 | 1580 | 2165 | 1522 | 1568 | 1850 | 1648 |
| 1776 | 1872 | 2026 | 2253 | 1532 | 2216 | 2156 | 1540 | 1505 | 1607 | 2260 | 2306 | 1612 | 1544 | 1771 | 1629 |
| 2250 | 1506 | 1579 | 1578 | 2037 | 2143 | 1668 | 1512 | 2250 | 2201 | 1801 | 1648 | 2197 | 1568 | 2158 | 1859 |
| 1654 | 1676 | 2248 | 2261 | 1666 | 1596 | 1981 | 2034 | 1545 | 2268 | 2308 | 2249 | 2292 | 1526 | 1530 | 2160 |
| 1607 | 1880 | 1537 | 1904 | 2236 | 1522 | 2216 | 2220 | 2162 | 2213 | 2174 | 2190 | 2193 | 2195 | 2222 | 1509 |
| 2258 | 2194 | 2134 | 1523 | 1720 | 2254 | 2257 | 1525 | 1613 | 2194 | 1970 | 1530 | 2102 | 2219 | 1944 | 1939 |
| 2061 | 2131 | 1855 | 2202 | 2303 | 2242 | 1912 | 2184 | 2289 | 1844 | 1533 | 2188 | 2232 | 1697 | 2044 | 2213 |
| 2406 | 2072 | 1558 | 1519 | 2181 | 1505 | 1716 | 1983 | 1558 | 2233 | 1606 | 1596 | 1509 | 1657 | 2232 | 2255 |
| 2208 | 2267 | 2229 | 2259 | 2248 | 2191 | 2005 | 2154 | 1539 | 2199 | 2249 | 2307 | 2197 | 1797 | 2375 | 1967 |
| 2173 | 2219 | 2192 | 1693 | 2109 | 1596 | 2147 | 1550 | 1639 | 2094 | 2177 | 2285 | 1549 | 2395 | 1948 | 1886 |
| 1555 | 2206 | 2206 | 2213 | 2350 | 2064 | 2053 | 2152 | 2286 | 2131 | 1621 | 1528 | 1778 | 1912 | 1513 | 2257 |
| 2190 | 2222 | 2245 | 1513 | 1548 | 1833 | 1622 | 1592 | 2252 | 1780 | 1572 | 2180 | 1696 | 2216 | 1602 | 2248 |
| 1871 | 2189 | 2185 | 1636 | 1821 | 2138 | 1611 | 1542 | 2197 | 2338 | 1625 | 2129 | 2184 | 2211 | 2217 | 1572 |
| 2146 | 1531 | 1559 | 1546 | 1683 | 1607 | 1519 | 1568 | 1975 | 1951 | 1602 | 2189 | 1550 | 1524 | 1562 | 2165 |
| 2060 | 1581 | 1657 | 2170 | 1622 | 2162 | 2284 | 1626 | 1544 | 1506 | 1639 | 1606 | 2143 | 2286 | 1614 | 2185 |
| 1721 | 1936 | 2312 | 1867 | 2147 | 2254 | 1774 | 2306 | 2175 | 1669 | 2177 | 1548 | 1579 | 2209 | 1926 | 1630 |
| 1756 | 2083 | 1863 | 1587 | 1520 | 1530 | 1821 | 1572 | 2225 | 2256 | 1923 | 1913 | 1676 | 2235 | 1534 | 1540 |
| 1548 | 2168 | 1594 | 2218 | 1534 | 1589 | 2176 | 1605 | 2216 | 1506 | 1530 | 1516 | 2200 | 1518 | 2212 | 1728 |

Static + Dynamic

# Do I really need to care about Wear Leveling?

- Use case description
  - System is a 40GB SSD in a notebook running Windows XP
  - OS and applications account for 18GB and 12GB respectively
  - Use is primarily communication, presentations, etc.
  - The flash used consists of MLC parts with 2.5K cycle rating

# A Use Case

- Average daily writes by the OS… about 1.8GB… Surprised?
- User application writes are dwarfed by comparison
- A single cycle of the entire media requires nearly a month (22 days)

# Use Case Static Wear Leveling

- And assuming reasonably effective static wear leveling (60%), entire media is available for wear leveling
- 2,500 cycles x 22 days = 1,855 months x .60 = 211 years

# Use Case Dynamic Wear Leveling

- Assuming we have a lackluster dynamic algorithm (90%) reduce available size by 30GB (application and OS)
- 2,500 cycles x 6 days = 750 months x 0.6 = 37 years

# What Wear Leveling Does for Reads

- Dynamic wear leveling will not move areas that are only read
- High differences in erase counts result in higher BER
- Uncorrectable error rates are increased by 2-3 orders of magnitude

# Wear Leveling for Reads

- Reads ~ Writes, but startup and hibernate cost additional 7GB of reads
- NAND manufacturers recommend cycling after 100,000 reads
- In use case, upwards of 2000 reads from the same areas daily
- With no caching and no wear leveling, cycle limits reached in 2.5 months

# Balancing Wear Leveling with Performance

- Wear level operations should be bounded
  - Impacts to performance must be low
  - Take advantage of idle time if possible
- Features such as trim, pre-erase, discards will mitigate negative performance impacts of wear leveling

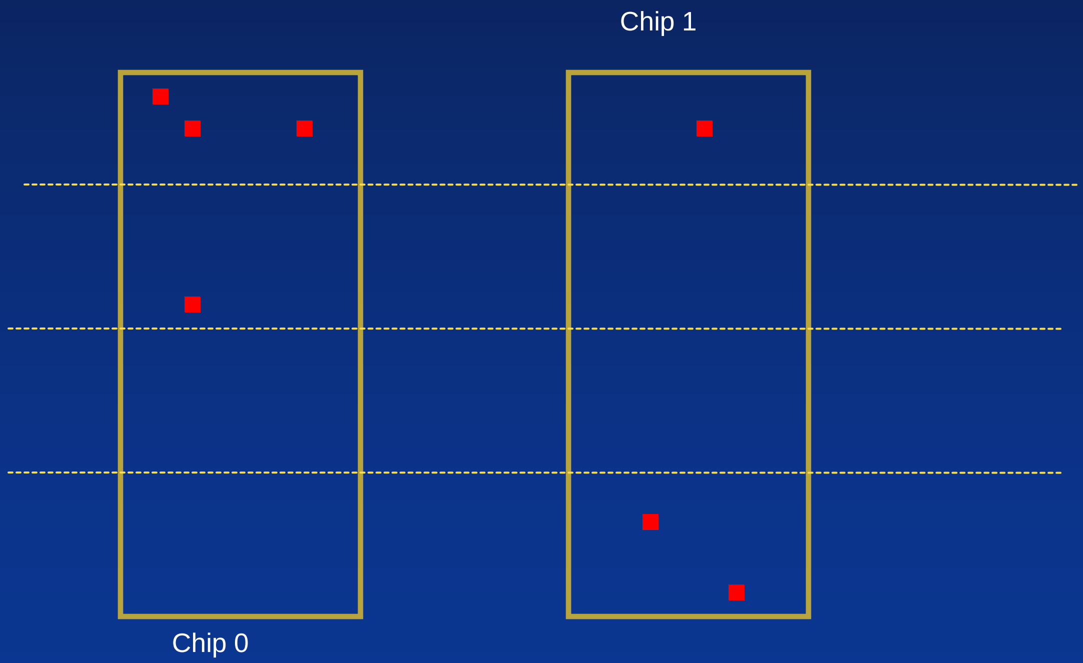
# Balancing Wear Leveling with Performance

- Interleaving = speed
  - We interleave multiple plans on single devices for concurrency
  - Then two or more devices for a wider data path (more concurrency)
  - And then we do it again with multiple NAND channels or banks
  - And then once again in the field (RAID)

# Definition of Interleaving

- To arrange data in a non-contiguous way to improve performance – Webopedia.com

# Interleaving




Interleaving can cause unacceptable error counts

# Interleaving = More Errors

- Interleaving two NAND devices can double the number of bad blocks
- Requiring more complex systems, more overhead, and/or stronger EDC

# Conclusions

- Wear leveling requirements are *substantially* dependent upon use case
- Impacts to performance will increase with more static data in the disk
- Embedded systems will have more stringent requirements
- Understand your target customers' use case

# References


- http://ieeexplore.ieee.org/Xplore/login.jsp?url=http://ieeexplore.ieee.org/iel5/4550747/4558854/04558857.pdf&authDecision=-203
- http://www.stanford.edu/class/ee380/Abstracts/081112-Fazio-slides.pdf
- http://download.micron.com/pdf/presentations/events/WinHEC_Cooke.pdf