CIS 371
Computer Organization and Design

Unit 11: Reliability

Reliability of Logic and Memory

- As transistors get smaller, they are less reliable
  - Wasn't a problem a few years ago, becoming a big problem
  - Small transistors means fewer electrons represent 1 or 0
- **Transient faults**
  - A bit "flips" randomly, **temporarily**
  - Cosmic rays and such (more common at higher altitudes!)
  - Memory cells (especially memory) vulnerable today, logic soon
- **Permanent (hard) faults**
  - A gate or memory cell wears out, **breaks and stays broken**
  - Temperature & electromigration gradually deform components
- Solution for both: use **redundancy** to detect and tolerate

DRAM Error Detection

- Idea: add extra state to DRAM to detect a bit flip
- **Parity**: simplest scheme
  - One extra bit, detects any single bit flip
  - Parity bit = XOR($data_{N-1}$, …, $data_1$, $data_0$)
- Example:
  - 010101 0^1^0^1^0^1 = "1" so parity is "odd" (versus "even")
  - So, store "010101 **1**" in memory
  - When you read the data, and re-calculate the parity, say
    - 01**1**101 **1**, if the parity bit doesn't match, error detected
- Multiple bit errors? more redundancy can detect more

DRAM Error Detection

- What to do on a parity error?
- **Crash**
  - **Dead programs tell no lies**
  - Fail-stop is better than silent data corruption
  - Avoiding writing that "$1m check"
- For user-level data, OS can kill just the program
  - Not the whole system, unless it was OS data
- Alternative: correct the error

SEC Error Correction Code (ECC)

- **SEC**: single-error correct (a hamming code)

- Example: Four data bits, three "code" bits
  - $d_1\ d_2\ d_3\ d_4\ \mathbf{c_1\ c_2\ c_3} \rightarrow \mathbf{c_1\ c_2}\ d_1\ \mathbf{c_3}\ d_2\ d_3\ d_4$
  - $c_1 = d_1 \wedge d_2 \wedge d_4$, $c_2 = d_1 \wedge d_3 \wedge d_4$, $c_3 = d_2 \wedge d_3 \wedge d_4$
  - Syndrome: $c_i \wedge c'_i = 0$? no error
    - Otherwise, then $c_3'\ c_2',\ c_1'$ points to flipped-bit

- Working example
  - Original data = 0110 $\rightarrow c_1 = 1,\ c_2 = 1,\ c_3 = 0$
  - Flip d_2 = 0010 $\rightarrow c'_1 = 0,\ c'_2 = 1,\ c'_3 = 1$
    - Syndrome = 101 (binary 5) $\rightarrow$ 5th bit? D_2
  - Flip $c_2 \rightarrow c'_1 = 1,\ c'_2 = 0,\ c'_3 = 0$
    - Syndrome = 010 (binary 2) $\rightarrow$ 2nd bit? c_2

SECDED Error Correction Code (ECC)

- **SECDED**: single error correct, double error detect

- Example: D = 4 $\rightarrow$ C = 4
  - $d_1\ d_2\ d_3\ d_4\ \mathbf{c_1\ c_2\ c_3} \rightarrow \mathbf{c_1\ c_2}\ d_1\ \mathbf{c_3}\ d_2\ d_3\ d_4\ \mathbf{c_4}$
  - $c_4 = c_1 \wedge c_2 \wedge d_1 \wedge c_3 \wedge d_2 \wedge d_3 \wedge d_4$
  - Syndrome == 0 and $c'_4 == c_4 \rightarrow$ no error
  - Syndrome != 0 and $c'_4 != c_4 \rightarrow$ 1-bit error
  - Syndrome != 0 and $c'_4 == c_4 \rightarrow$ 2-bit error
  - Syndrome == 0 and $c'_4 != c_4 \rightarrow c_4$ error
  - **In general: $C = \log_2 D + 2$**
- Many machines today use 64-bit SECDED code
  - C = 8 (64bits + 8bits = 72bits, 12% overhead)
  - ChipKill - correct any aligned 4-bit error
    - If an entire DRAM chips dies, the system still works!

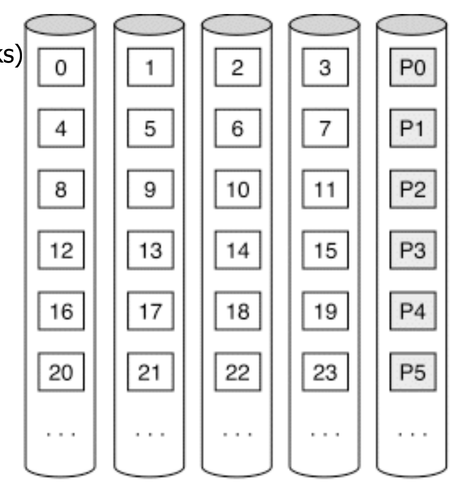
Disk Reliability: RAID

- **Error correction**: more important for disk than for memory
  - Error correction/detection per block (handled by disk hardware)
  - Mechanical disk failures (entire disk lost) most common failure mode
    - Many disks means high failure rates
    - Entire file system can be lost
- **RAID (redundant array of inexpensive disks)**
  - Add redundancy
  - Similar to DRAM error correction, but…
  - Major difference: which disk failed is known
    - Even parity can be used to recover from single failures
    - Parity disk can be used to reconstruct data faulty disk
  - RAID design balances bandwidth and fault-tolerance
  - Implemented in hardware (faster, more expensive) or software

Simple RAIDs

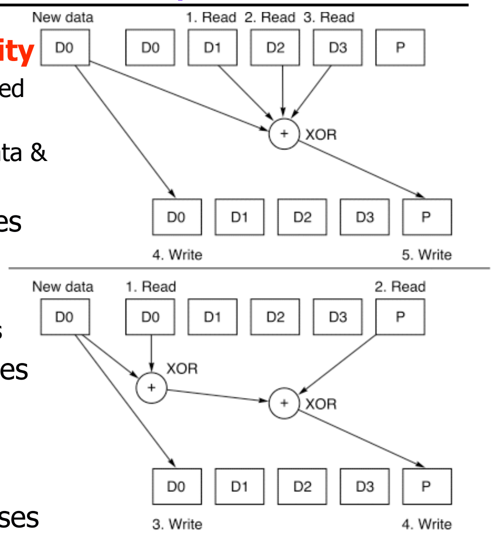
- **Simplest: mirroring**
  - N disks (for example, 2 disks)
  - Write all disks
  - Read any one disk

- **Bit-level parity**
  - dedicated parity disk
  - N+1 disks, calculate parity (**write all, read all**)
  - Good sequential read/write bandwidth, poor random accesses
  - If N=8, only 13% overhead



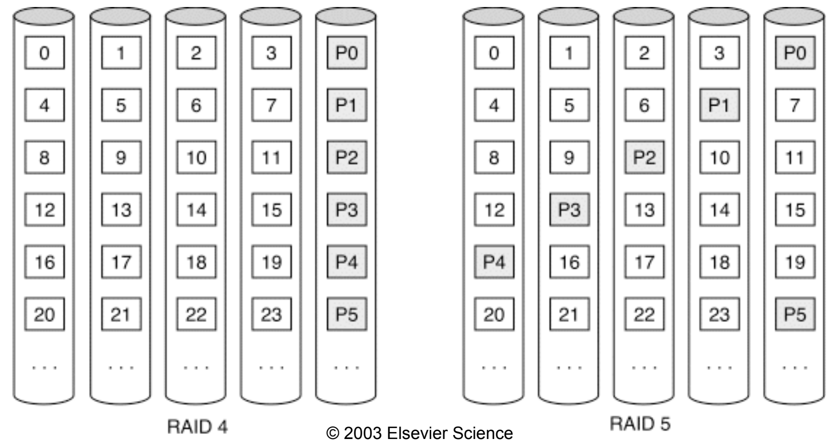
RAID with Block-level Parity

- **RAID with block parity**
  - Reads: only data you need
  - Writes: require reads, calculate parity, write data & parity
- Naïve approach to writes
  1. Read all disks
  2. Calculate parity
  3. Write data & parity disks
- Better approach to writes
  - Read *old* data & parity
  - Calculate parity
  - Write new data & parity
- Writes are 4 disk accesses



RAID with Block-level Parity

- Rotates the parity disk, avoid single-disk bottleneck



Aside: Storage Backup

- **Data is more valuable than hardware!**
  - Almost always true
- **Protecting data - three aspects**
  - **User error** - accidental deletion
    - Aside: ".snapshot" on enaic-l/halfdome filesystem
  - **Disk failure** - mechanical, wears out over time
    - Disk arrays (RAID) works well
  - **Disaster recovery** - An entire site is disabled
- **Two approaches:**
  - Frequent tape backups, taken off site (most common today)
  - Handle each problem distinctly
    - File system, redundant disks, network-based remote backup