Moore’s Law and Data Storage

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Moore’s Law

From “Cramming more components onto integrated circuits, by Gordon E. Moore, Electronics, Volume 38, Number 8, April 19, 1965
Moore’s Law for IC’s

The Number of Transistors Per Chip Double Every 18 Months

Source: Intel
Moore’s Law updated to Pentium 4

MOORE’S LAW

Source: Intel
### Moore’s Law for Intel Processors

<table>
<thead>
<tr>
<th>Silicon Process Technology</th>
<th>1.5μ</th>
<th>1.0μ</th>
<th>0.8μ</th>
<th>0.6μ</th>
<th>0.35μ</th>
<th>0.25μ</th>
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</thead>
<tbody>
<tr>
<td>Intel386™ DX Processor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intel486™ DX Processor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pentium® Processor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pentium® Pro &amp; Pentium® II Processors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Intel
Moore’s Law for Storage Devices

• Capacity increase
  • Hard disks: 100% per annum during the last three years (Doubling every 18 months since 1994)
  • Tapes: Doubling every 18 months
• Transfer rate: slower growth. Does not follow Moore’s law
  disks: single disks, from 2 to 8 MB/s (1990-2000)
  tapes: from 3 MB/s to 12 MB/s (1990-2000)
  RAID: upto 200 MB/s
2001 INSIC Tape Roadmap

• 10 year roadmap
• Consensus of over 40 researchers
  – Representing virtually every large drive manufacturer, tape media and substrate supplier, many of the leading research universities
• Primarily focused on linear tape (helical section by Sony)
• Goal to remain competitive with disk ($/MB) and be technically feasible
• Keep the ratio of the capacities of a tape cartridge to a single 3 1/2 inch disk platter constant. (Ratio = 3.3 at time of roadmap)
• Assume
  – Disk capacity growth will be 60% /year
  – Disk data rate growth will be 26%/year

(From Robert Raymond, STK, THIC June 2002)
Magnetic Recording

• 1898, Valdemar Poulsen in Denmark (wire)

• Picked up in the 50’s: Ampex (audio and video), IBM (data storage)

• Magnetic Disk since 1957 (IBM RAMAC)

• Inductive write, inductive read till mid-90’s

• Magneto-resistive (MR) read -> Giant MR (GMR) -> Colossal MR -> Ballistic MR (BMR)

• MR read heads have proved to be a significant enabler in the pursuit of higher areal densities
Pigments

- Gamma Ferric Oxide
- Co-doped Gamma Ferric Oxide
- CrO$_2$
- Metal Particle (MP)

Coating Technology

- Traditional methods
- Plating
- Sputtering
- Dual coating
## From Round reel to square

<table>
<thead>
<tr>
<th>Year</th>
<th>Product</th>
<th>bpi*</th>
<th>KB/s</th>
<th>capacity (MB)</th>
<th>tpi</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952</td>
<td>IBM726</td>
<td>100</td>
<td>7.5</td>
<td>1.4</td>
<td>14</td>
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<tr>
<td>1953</td>
<td>IBM727</td>
<td>200</td>
<td>15</td>
<td>5.8</td>
<td>14</td>
</tr>
<tr>
<td>1957</td>
<td>IBM729</td>
<td>800</td>
<td>90</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>1965</td>
<td>IBM2401</td>
<td>1600</td>
<td>180</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>1968</td>
<td>IBM2420</td>
<td>1600</td>
<td>320</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>1973</td>
<td>IBM3420</td>
<td>6250</td>
<td>1250</td>
<td>180</td>
<td>18</td>
</tr>
<tr>
<td>1984</td>
<td>IBM3480</td>
<td>38000</td>
<td>3000</td>
<td>200</td>
<td>36</td>
</tr>
<tr>
<td>1991</td>
<td>IBM3490E</td>
<td>76000</td>
<td>3000</td>
<td>800</td>
<td>72</td>
</tr>
<tr>
<td>1995</td>
<td>IBM3590</td>
<td>92000</td>
<td>9000</td>
<td>10000</td>
<td>256</td>
</tr>
</tbody>
</table>

*This is the user bit density in each track; channel code, ECC and other overhead will be reflected in the number of flux transitions per inch, which is not considered here.*

Special thanks to Dr Steve Vogel, IBM Storage Systems Division, Tucson AZ for checking this table, and supplying information to complete it.

P C Hariharan
## Areal Density of Magnetic Tape

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3480 (200 MB)</td>
<td>ID-1 (14-96 GB)</td>
<td>DLT-7 (40 GB)</td>
<td>SDLT-320 (160 GB)</td>
</tr>
<tr>
<td>TPI</td>
<td>36</td>
<td>655</td>
<td>336</td>
<td>1058</td>
</tr>
<tr>
<td>Kbits/in</td>
<td>38.0</td>
<td>50.8</td>
<td>123</td>
<td>190</td>
</tr>
<tr>
<td>Mb/in²</td>
<td>1.36</td>
<td>33.3</td>
<td>41.4</td>
<td>201</td>
</tr>
<tr>
<td>μm²/bit</td>
<td>474</td>
<td>19.4</td>
<td>15.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Further Information will be available in talks by Wayne Imaino/Joe Gordon II (IBM), John Woelbern (SONY)
## DLT from Quantum

<table>
<thead>
<tr>
<th>Year</th>
<th>Product</th>
<th>Transfer Rate (MB/s)</th>
<th>Capacity (GB)</th>
<th>Tracks per Inch (tpi)</th>
<th>Bits per inch (bpi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>2000</td>
<td>1.25</td>
<td>15</td>
<td>256</td>
<td>62500</td>
</tr>
<tr>
<td>1994</td>
<td>4000</td>
<td>1.5</td>
<td>20</td>
<td>256</td>
<td>82500</td>
</tr>
<tr>
<td>1996</td>
<td>7000</td>
<td>5.0</td>
<td>35</td>
<td>416</td>
<td>86000</td>
</tr>
<tr>
<td>1999</td>
<td>8000</td>
<td>6.0</td>
<td>40</td>
<td>416</td>
<td>98000</td>
</tr>
<tr>
<td>2001</td>
<td>SuperDLT 220</td>
<td>11.0</td>
<td>110</td>
<td>1058</td>
<td>130000</td>
</tr>
<tr>
<td>2002</td>
<td>SuperDLT 320</td>
<td>16.0</td>
<td>160</td>
<td>1058</td>
<td>190000</td>
</tr>
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</table>
## Areal Density of Hard disk drives

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>3330</td>
<td>3380</td>
<td>Corsair</td>
<td>Micro-drive</td>
<td>Today’s Drive</td>
</tr>
<tr>
<td>TPI</td>
<td>192</td>
<td>801</td>
<td>2,238</td>
<td>19,000</td>
<td>67,300</td>
</tr>
<tr>
<td>Kbits/in</td>
<td>4.04</td>
<td>15.2</td>
<td>58.9</td>
<td>265</td>
<td>522</td>
</tr>
<tr>
<td>Mb/in²</td>
<td>0.776</td>
<td>12.2</td>
<td>131.8</td>
<td>5,035</td>
<td>35,300</td>
</tr>
<tr>
<td>µm²/bit</td>
<td>830</td>
<td>53</td>
<td>4.9</td>
<td>0.128</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Further Information will be available in talks by Dr. Dmitri Litvinov (Seagate Research)
Optical Recording

• WORM
• Rewritable
• CD
• CD-ROM, -R, -RW
• Calimetrics (multi-level, 3x conventional capacity)
• DVD-ROM
• The +/- wars
• Blu-ray and the next generation wars
## Areal Density of Optical Disk

<table>
<thead>
<tr>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CD 650 MB</td>
<td>DVD-RAM 2.6 GB</td>
<td>DVD-RAM 4.7 GB</td>
<td>Next Gen 15~25 GB</td>
</tr>
<tr>
<td>TPI</td>
<td>15,875</td>
<td>34,300</td>
<td>41,300</td>
<td>85,000</td>
</tr>
<tr>
<td>Kbits/in</td>
<td>30.5</td>
<td>62.1</td>
<td>90.7</td>
<td>120</td>
</tr>
<tr>
<td>Mb/in²</td>
<td>484</td>
<td>2,130</td>
<td>3,745</td>
<td>10,000</td>
</tr>
<tr>
<td>µm²/bit</td>
<td>1.3</td>
<td>0.303</td>
<td>0.172</td>
<td>0.065</td>
</tr>
</tbody>
</table>
Fell by the wayside?

- Tamarack and the Gigastore (1994)
- Surface-enhanced Raman spectroscopy
- Bacteriorhodopsin
- Terastore Near Field Optical Storage (SIL)

Holography

- Has been in the lab for two decades, but components for a system are now beginning to become available (see: Roadmap from InPhase)
- Two-photon storage, truly three-dimensional
<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
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<tbody>
<tr>
<td><strong>Recordable Specs</strong></td>
<td>100 Gb/in²</td>
<td>200 Gb/in²</td>
<td>400 Gb/in²</td>
<td>800 Gb/in²</td>
<td>1600 Gb/in²</td>
</tr>
<tr>
<td></td>
<td>20 MB/s</td>
<td>40 MB/s</td>
<td>80 MB/s</td>
<td>160 MB/s</td>
<td>250 MB/s</td>
</tr>
</tbody>
</table>
| **Drive Configuration** | • Angle Mux ~1000 pages
• Blue Laser | • Custom SLM, Detector
• Grayscale | • 2000 pages by using 2 wavelengths
• 4 λ’s | • Custom laser
• 8λ’s | • Or more angles used |
| **Re-Writable Specs** |               | 200 Gb/in²    | 400 Gb/in²    | 800 Gb/in²    |
|                      |               | 30 MB/s       | 60 MB/s       | 120 MB/s      |
| **Drive Configuration** |               |               | • Custom SLM, Detector
• Grayscale | • 2000 pages by using 2 wavelengths | • Custom laser
• 4λ’s |

*From Presentation by Dr. William Wilson, InPhase, THIC, June 2002, Boulder, CO*
Microelectromechanical Systems (MEMS)

- Only system in conformance with Reed’s First Law (Don’t separate the head from the media)

Microelectromechanical systems (MEMS) come closest to the clay tablet. See recent announcement by IBM Zurich about the Millipede. It is a self-contained read/write system with an areal density of 1 Tb/in².


500,000 rpm (normal auto at highway speed ~ 3000 rpm); the maximum rpm observed was $7 \times 10^9$! An auto engine would accumulate this many revolutions if it was driven to the moon and back 6 times.

High performance disk drives: 10,000 or 15,000 rpm
MEMS (continued)

- Linear dimensions a thousand times larger than those of nanoscale devices
Volumetric Density Trends (bits/in³)

Areal Density (bits/in²)

Layer Density (layers/in)

Optical Tape

Super Paramagnetic Limit

INSIC Magnetic Tape Goal

Optical Wavelength Limit

Magnetic Linear Tapes

Magnetic Helical Scan Tapes

Optical Tape

Holographic Storage

Optical Disk

Magnetic Disk

Gbit/cu in

Tbit/cu in

Pbit/cu in
How far can we go? Nanoscale storage

In 1959, Richard Feynman gave a visionary talk entitled “There’s Plenty of Room at the Bottom”. He asked the question whether it will be possible to shrink devices all the way down to the atomic level.

Allowing $5 \times 5 \times 5 = 125$ atoms to store one bit, he estimated that all printed information accumulated over centuries since the Gutenberg Bible could be stored in a cube of material $1/200" = 0.1$ mm wide.

The University of Wisconsin created a two-dimensional version of Feynman's atomic memory, formed on the surface of silicon by a small amount of gold. Extra silicon atoms (white) sit on top of self-assembled tracks that are formed by the gold. Each track is exactly five atoms wide.

Feynman's 1959 suggestion of spacing the bits 5 atoms apart was right on the mark.

Using Si atoms on a gold surface, density achievable is 250 Tb/in$^2$.

For comparison, DNA storage density is estimated to be 100 Tb/in$^2$.

(32 atoms, on the average, to store a bit)

R. Bennewitz et al., Nanotechnology 13, 499 (2002).
University of Wisconsin Nanoscale Memory

CD-ROM

Works at liquid He temperatures

Au atoms on Si in tracks 5 atoms wide (Feynman, 1957)

X $10^6$ areal density