Overview of the day

- Introduction to storage systems
  - storage devices and their workloads
  - request scheduling
- Disk arrays
  - high-reliability redundant storage:
    making sure it’s there when you need it
  - new kinds of disk arrays
- Storage area networks
  - connecting storage to its clients
  - CMU’s NASD
- Storage management
  - keeping it all together

Acknowledgements

- SSP: Guillermo Alvarez, Eric Anderson, Ralph Becker-Szendy, Martha Escobar, Susie Go, Michael Hobbs, Kim Keeton, Arif Merchant, Erik Riedel, Cristina Solorzano, Mustafa Uysal, Alistair Veitch
- ex-SSP: Richard Golding, David Jacobson, Chris Ruemmler, Mirjana Spasojevic
- Others:
  - Ed Grochowski (IBM Almaden)
  - David Nagle & Garth Gibson (CMU)
- St Andrews University

- **To learn more:**

  http://www.hpl.hp.com/SSP/

Introduction to storage systems [1:15]

Introduction to storage systems

- **An overview of current storage devices**
  - storage hierarchies
  - the storage business
- **How disk drives work**
  - mechanisms
  - technology trends
  - controllers
- **Request scheduling**
- **Workloads**
  - Workload characterization
  - How file systems and databases use storage

Introduction: what are we talking about?

- **Storage systems**
  - **the place where persistent data is kept**
  - the center of the universe!

- **Why?**
  - **information (and hence storage) is key to most endeavours**
  - **storage is big business (tens of US$b/year)**
  - **sheer quantities (hundreds of petabytes/year)**

  - ***“Storage will dominate our business in a few years”***
    - *Compaq VP, 1998*
  - ***“In 3 to 5 years, we will start seeing servers as peripherals to storage”***
    - *SUN Chief Technology Officer, 1998*

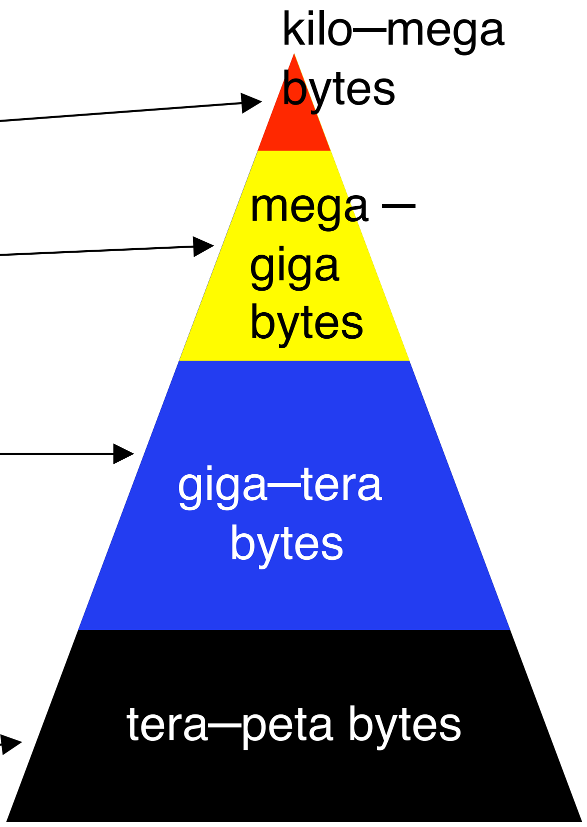
Introduction: what are we talking about?

- Hardware components
  - Storage devices
    - mechanisms, controllers, packaging
  - Storage connectivity
    - bus/interconnect fabric, host adapters

- Software components
  - Critical-path software
    - OS device driver
    - OS logical volume manager
    - File system/database system
  - Storage management software

Introduction: storage hierarchy

- Primary storage: CPU
  - **registers** (1 cycle, a few ns)
  - **cache** (10-200+ cycles, 0.02–0.5us)
  - **local main memory** (0.2–4us)
  - **NUMA memory** (2–10x local memory)
- **Secondary storage ("online storage")**
  - **magnetic disks** (2–20ms)
  - **solid state disks** (0.05–0.5ms)
  - **cache in storage controllers** (0.05–0.5ms)
- Tertiary storage
  - **removable media: tape cartridges, floppies, CD, …** (ms to minutes)
  - **tape libraries, optical jukeboxes "nearline"** (few s to few minutes)
  - **tape vaults** (few minutes to days)



Secondary storage devices

- **Sealed-mechanism magnetic disks** (“Winchesters”)
  - **dominate the industry**
  - **1-50+ GB capacity**

- **Other**
  - **Solid-state disks**
    - **DRAM package with a battery to look and feel like a disk**
  - **Promising(?) “new” technologies**
    - **holographic storage**
    - **ARS/MEMS (micro-actuators)**
    - **MRAM (the return of core memory!)**

Tertiary storage devices

- **Flash-RAM cards** (1-100 MB)
- **Floppy disks, Iomega zip, removable disk,** (1-200 MB)

- **CD-ROM, CD-RW** (600 MB; replacing floppies in many uses)
- **Magneto-optical (MO) disks** (0.6-4 GB/platter)
- **DVD** (up to 4.5 GB; writable DVD “is on its way”)

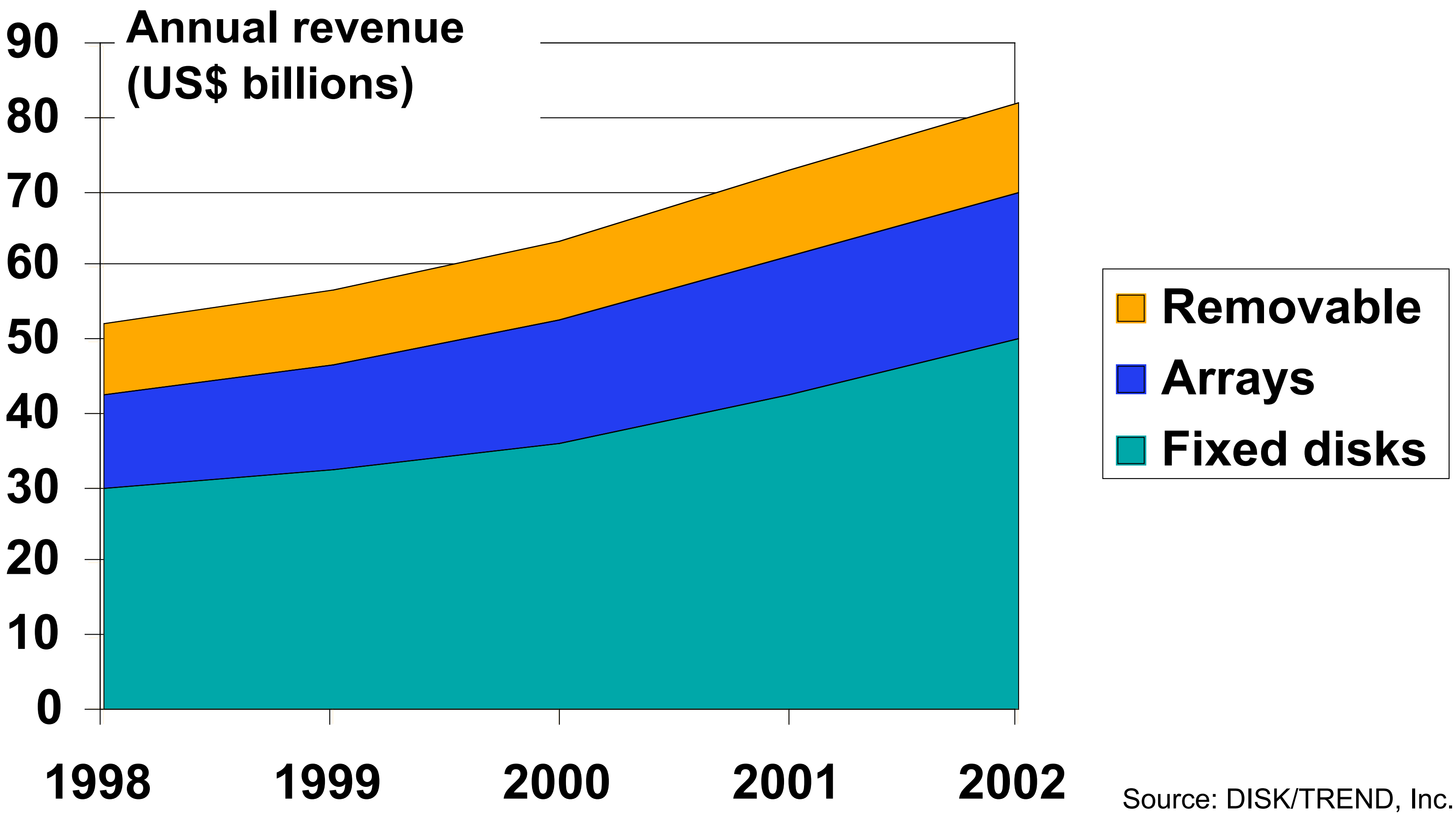
- **Magnetic tapes** (1-100 GB/tape)
  - **linear format: 1/2” open reel (largely vanished); cartridge tapes**
  - **helical-scan: DDS (aka “DAT”)**
  - **serpentine: DLT, Linear Tape Open (LTO)**

- **Libraries (and vaults)**
  - **10-1000+ tapes, CD-ROM, or MO disks**
  - **pick & load times of few seconds to a couple of minutes**

Uses for tertiary storage

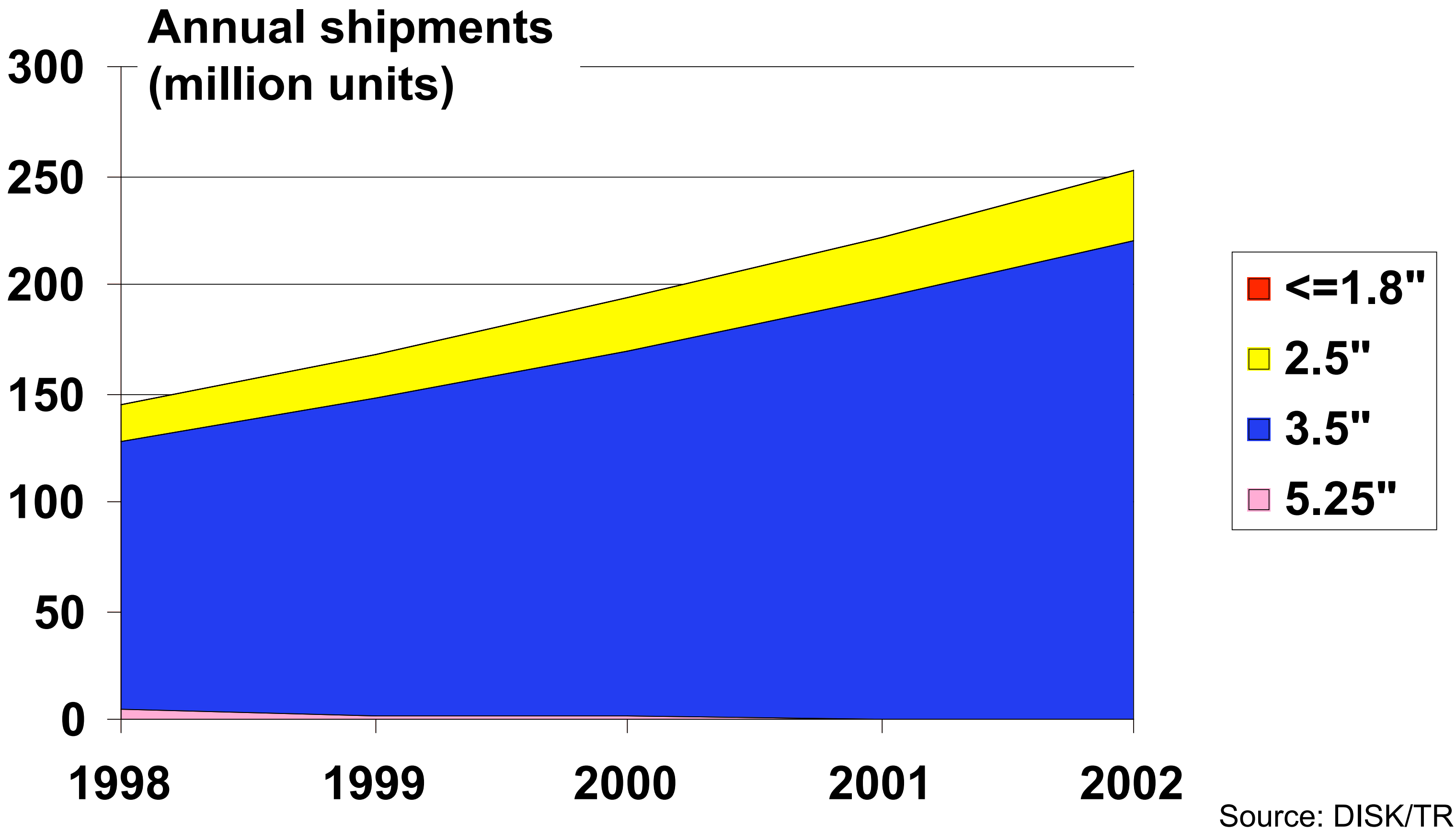
- Portable, personal data
  - data interchange
  - software distribution
- Backups against failures
  - media/site failure
  - user error: `rm * .o; ... "File .o not found"`
- Archiving for later use
  - ordered, indexed, coherent data
  - banks, credit card companies, insurance
  - life-critical engineering industry (e.g., aircraft engines)
- Really big quantities of data
  - NASA satellite data, NSA, ...

1999 DISK/TREND report: revenue projections



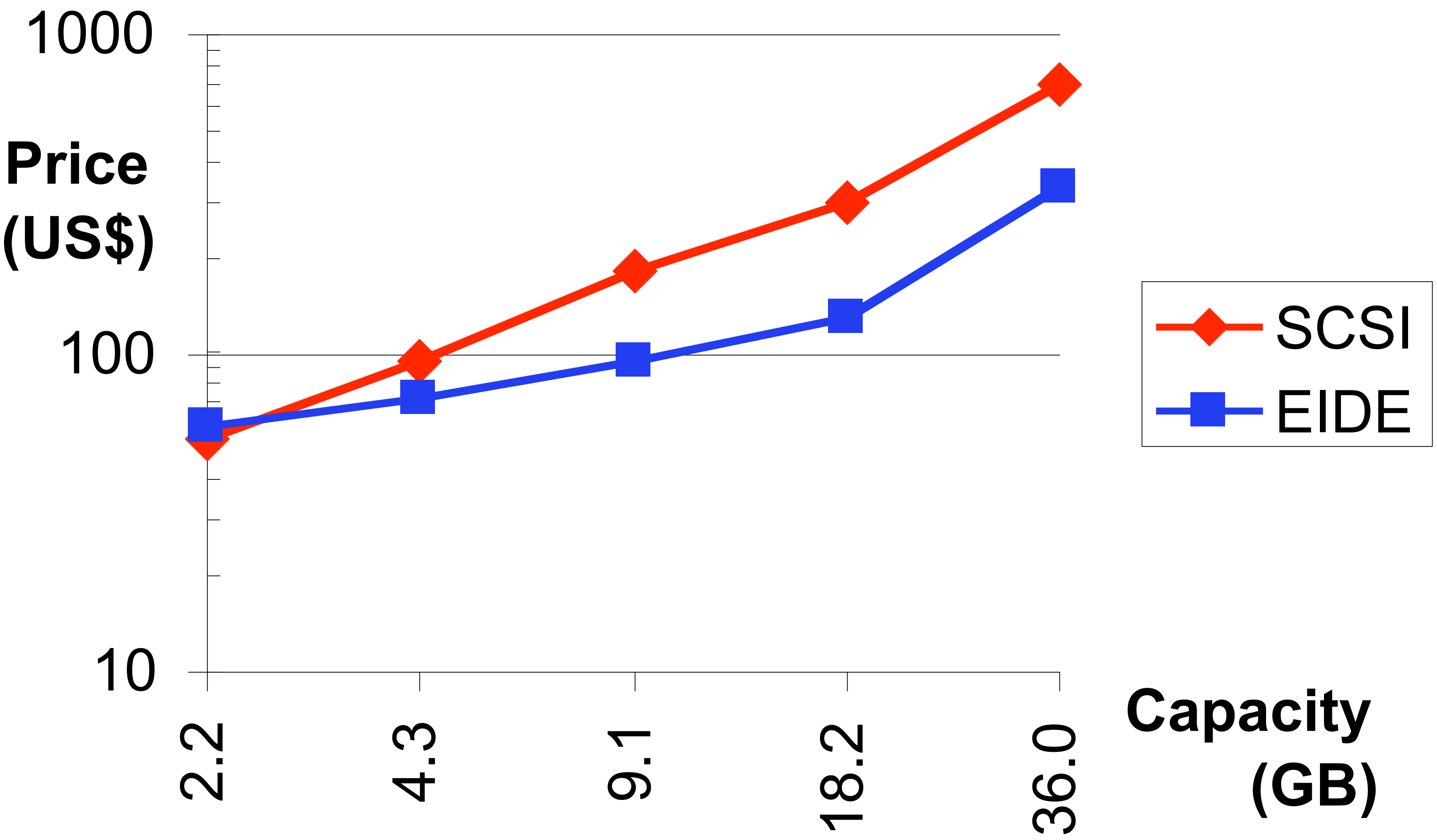
Source: DISK/TREND, Inc.
http://www.disktrend.com
June 1999

1999 DISK/TREND report: unit projections



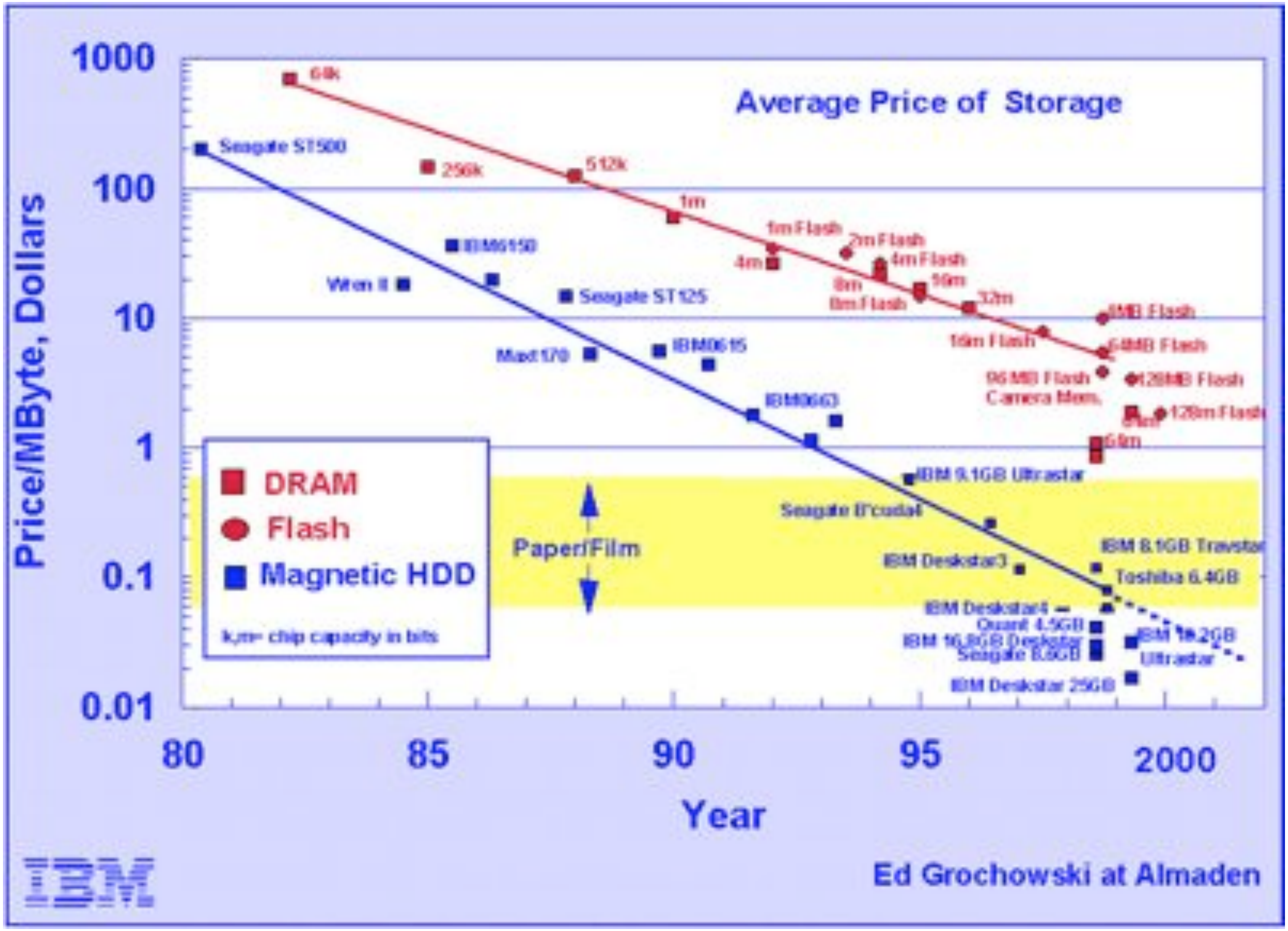
Source: DISK/TREND, Inc.
http://www.disktrend.com
June 1999

Hard-disk prices



Source: http://www.pricewatch.com/
16 Feb 2000

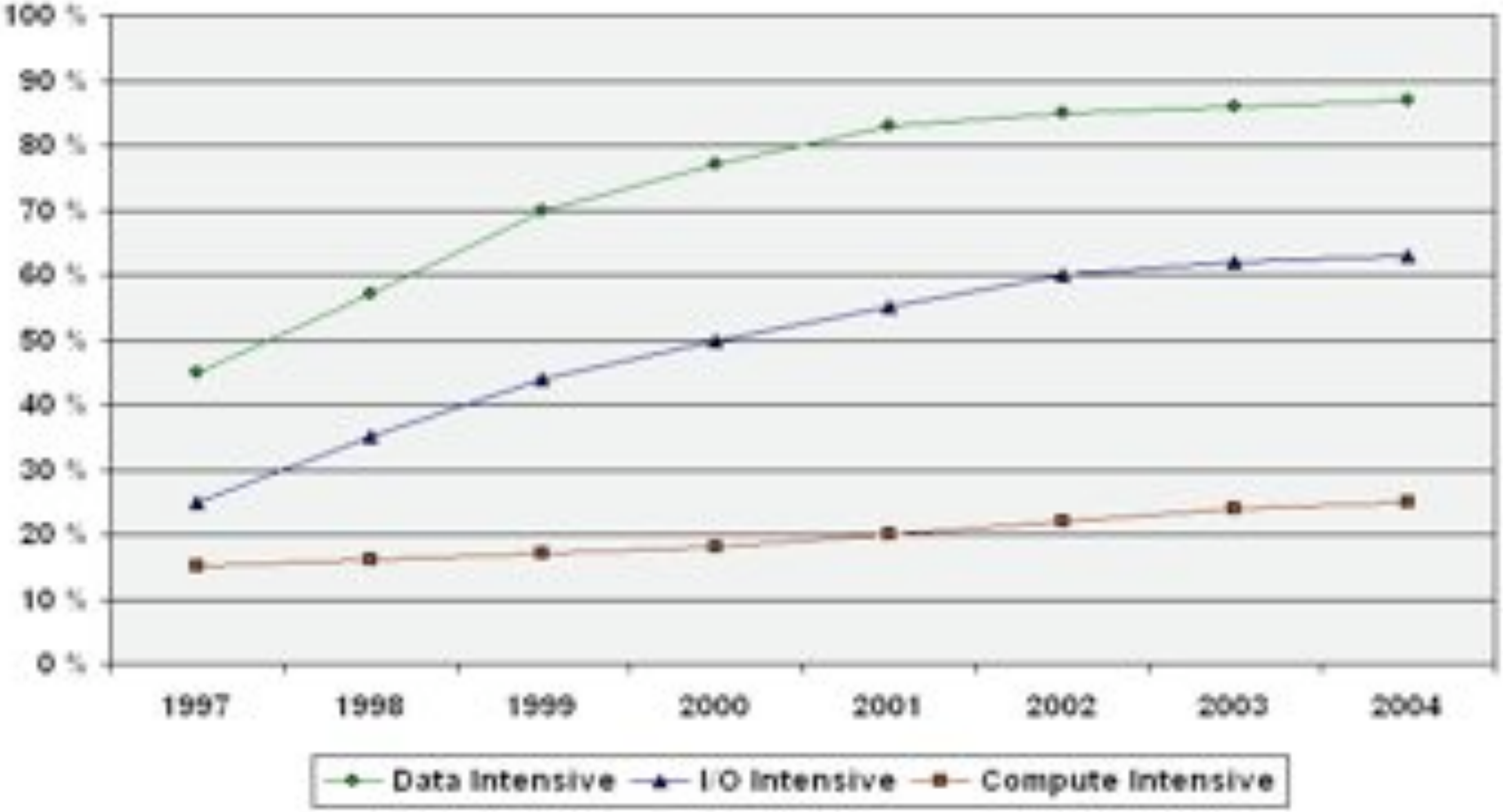
HEWLETT
PACKARD



Average Price of Storage

Ed Grochowski at Almaden

Business trend: storage as % of system cost

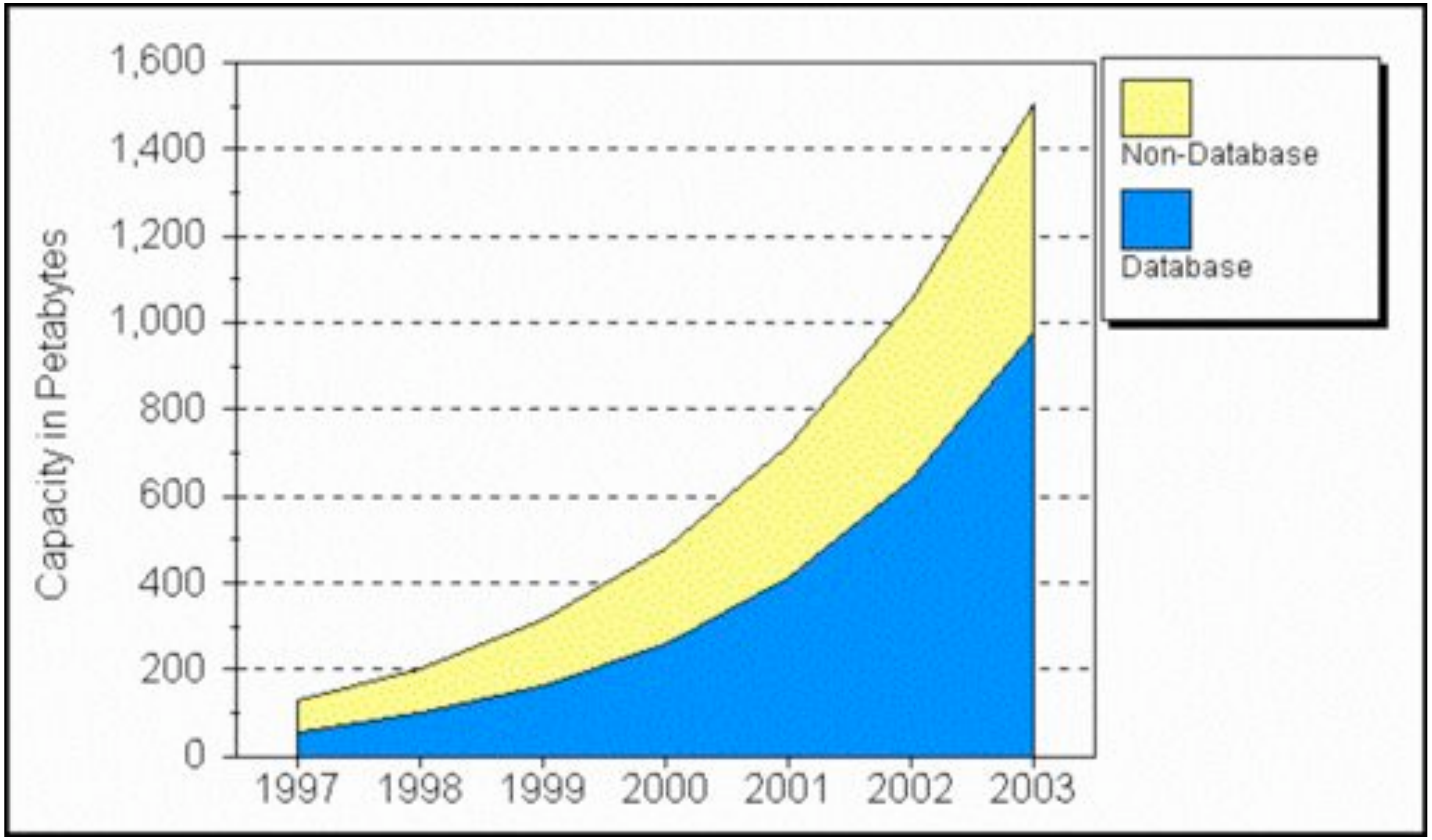


Source: Gartner group

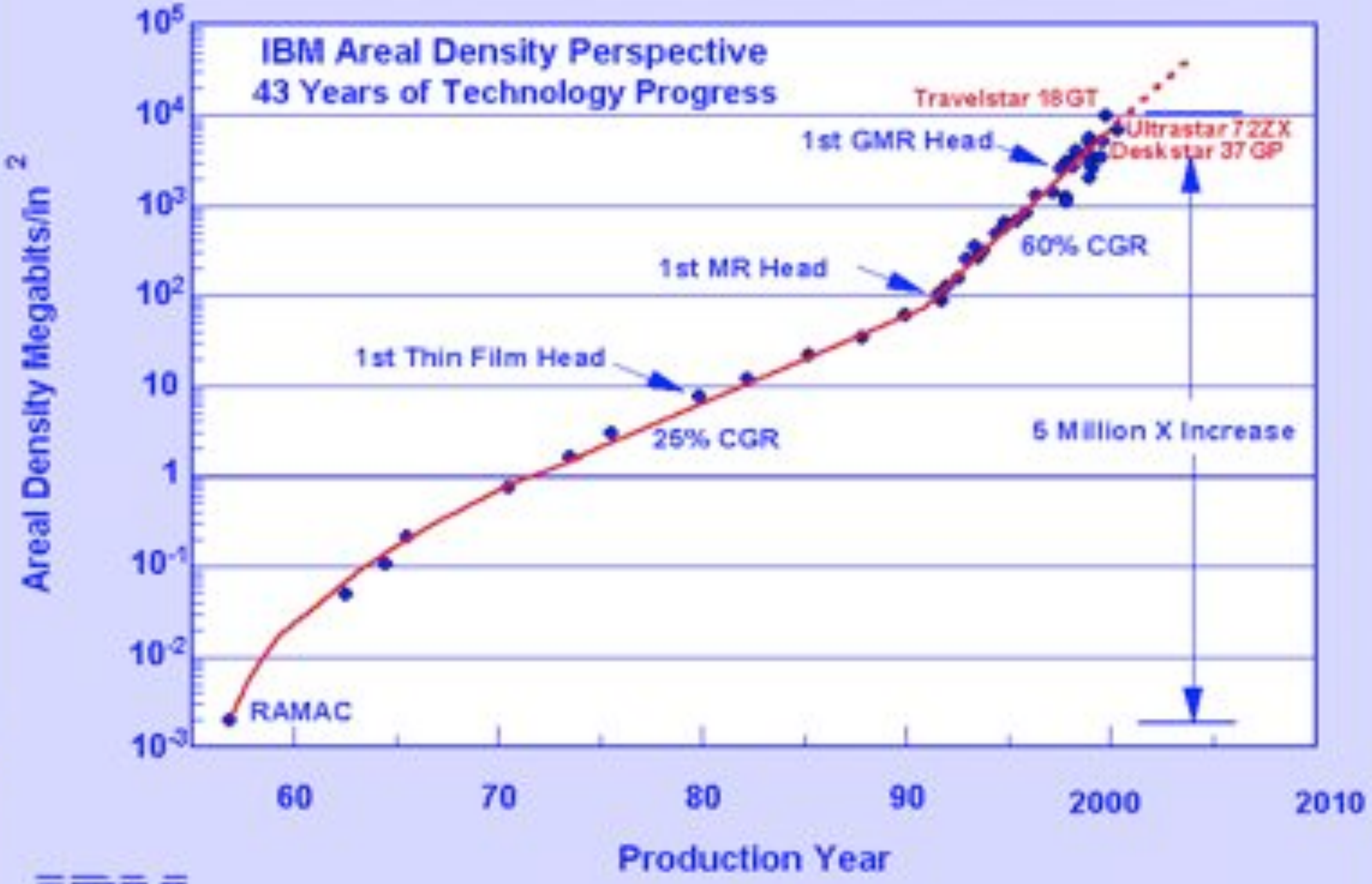
Business trend: data is moving into databases

WHO OWNS THE DATA?

Data Resident on Open Systems Servers



Source: Systems Research, 1998



Ed Grochowski at Almaden

Introduction to storage systems

- An overview of current storage devices
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  - **mechanisms**
  - **technology trends**
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  - Workload characterization
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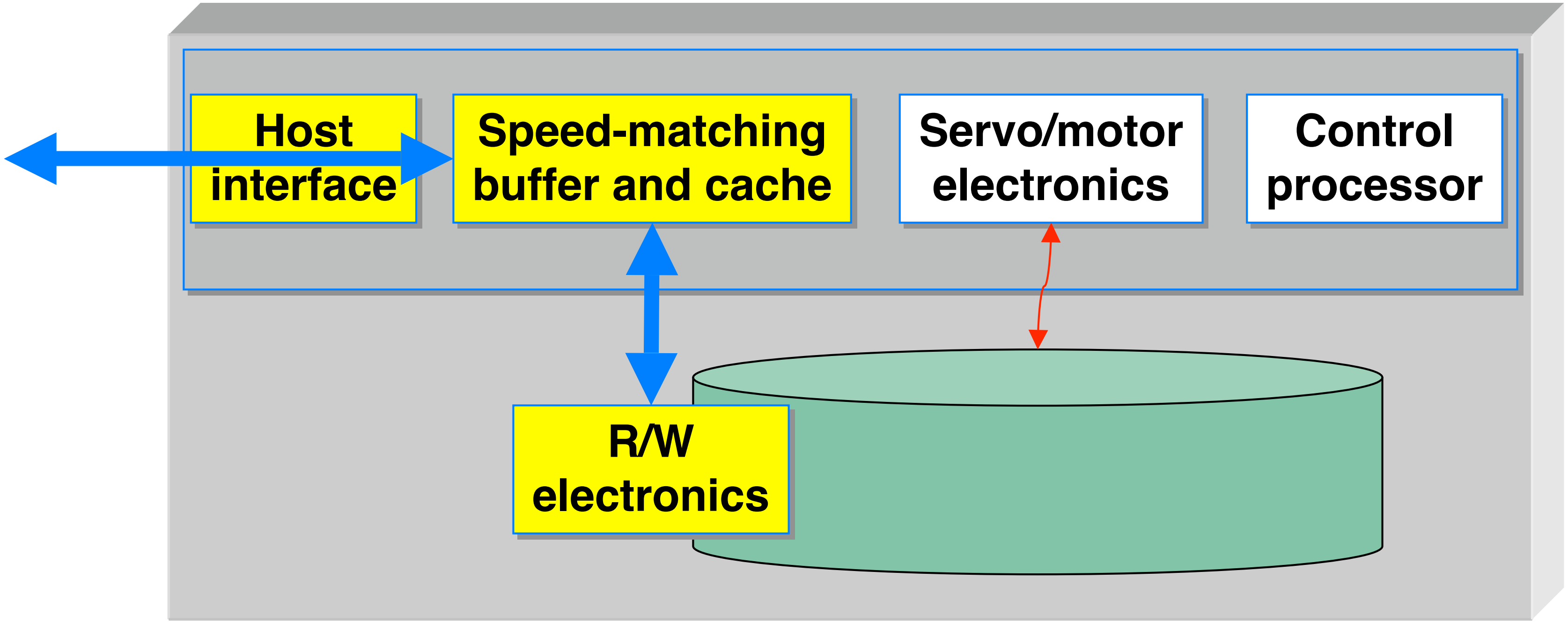
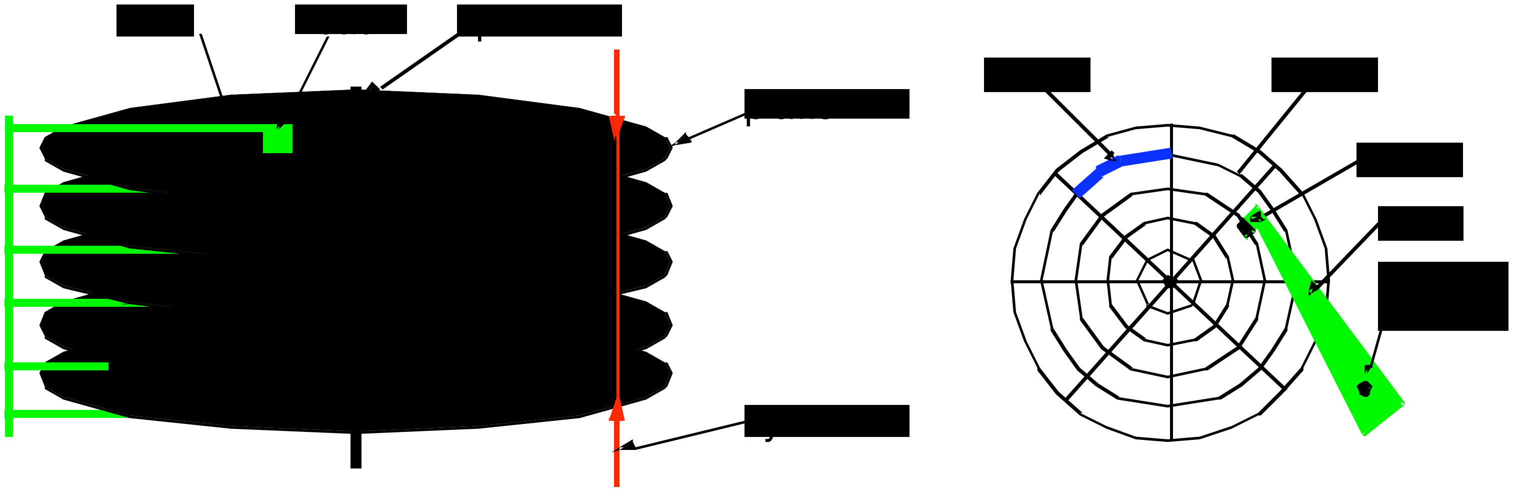
Magnetic disk drives: what is inside them?



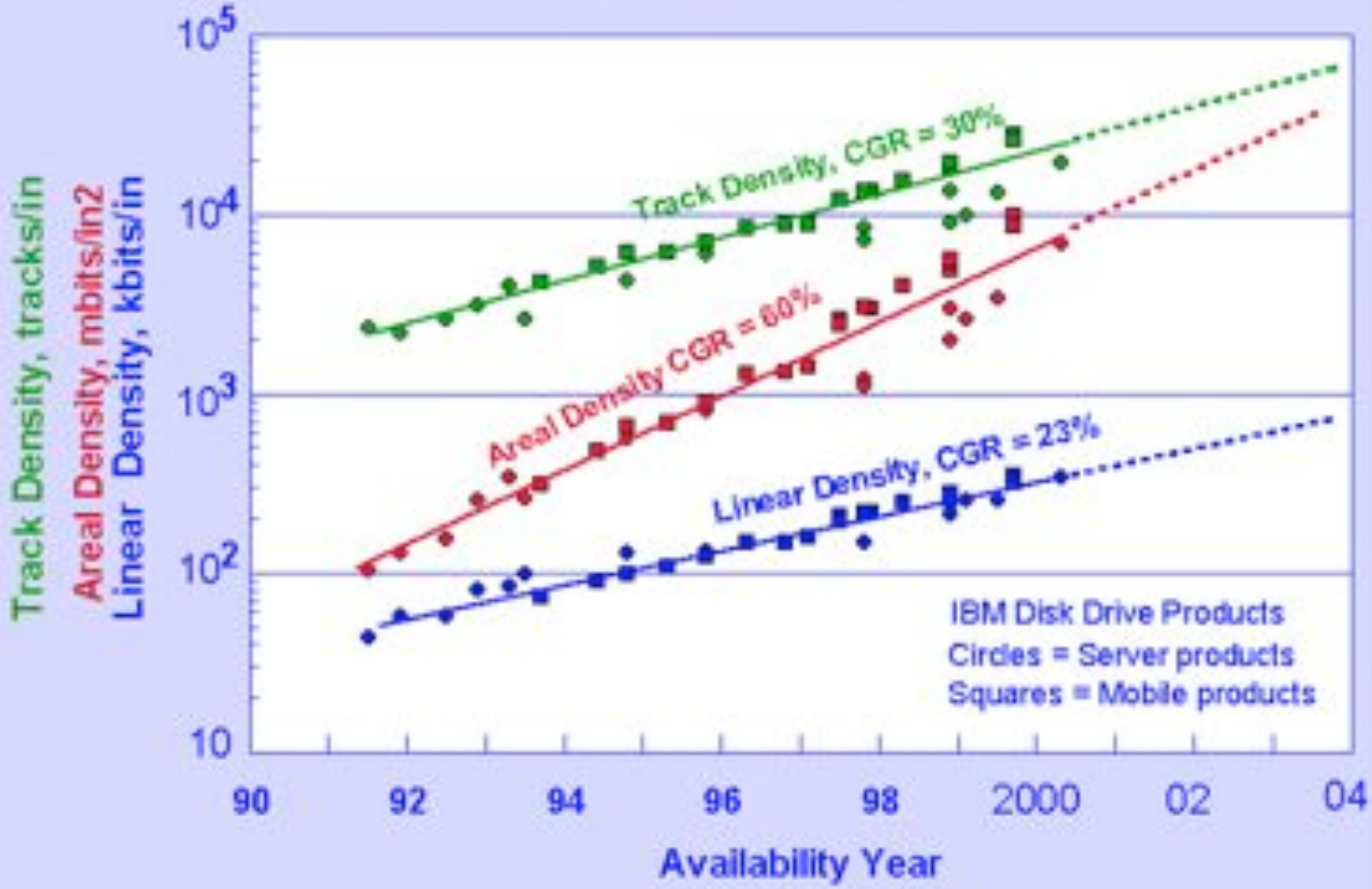
Magnetic disk drive: mechanical innards



Areal density = linear density * track density

- **a disk drive has 1 to 12 platters, 2 heads per platter**
- **a platter has ~2,000-40,000 tracks**
- **1 track contains ~50-200KB**
- **1 sector is ~512 B** (may be growing to 1-2KB)

Track, Areal, Linear Density Perspective



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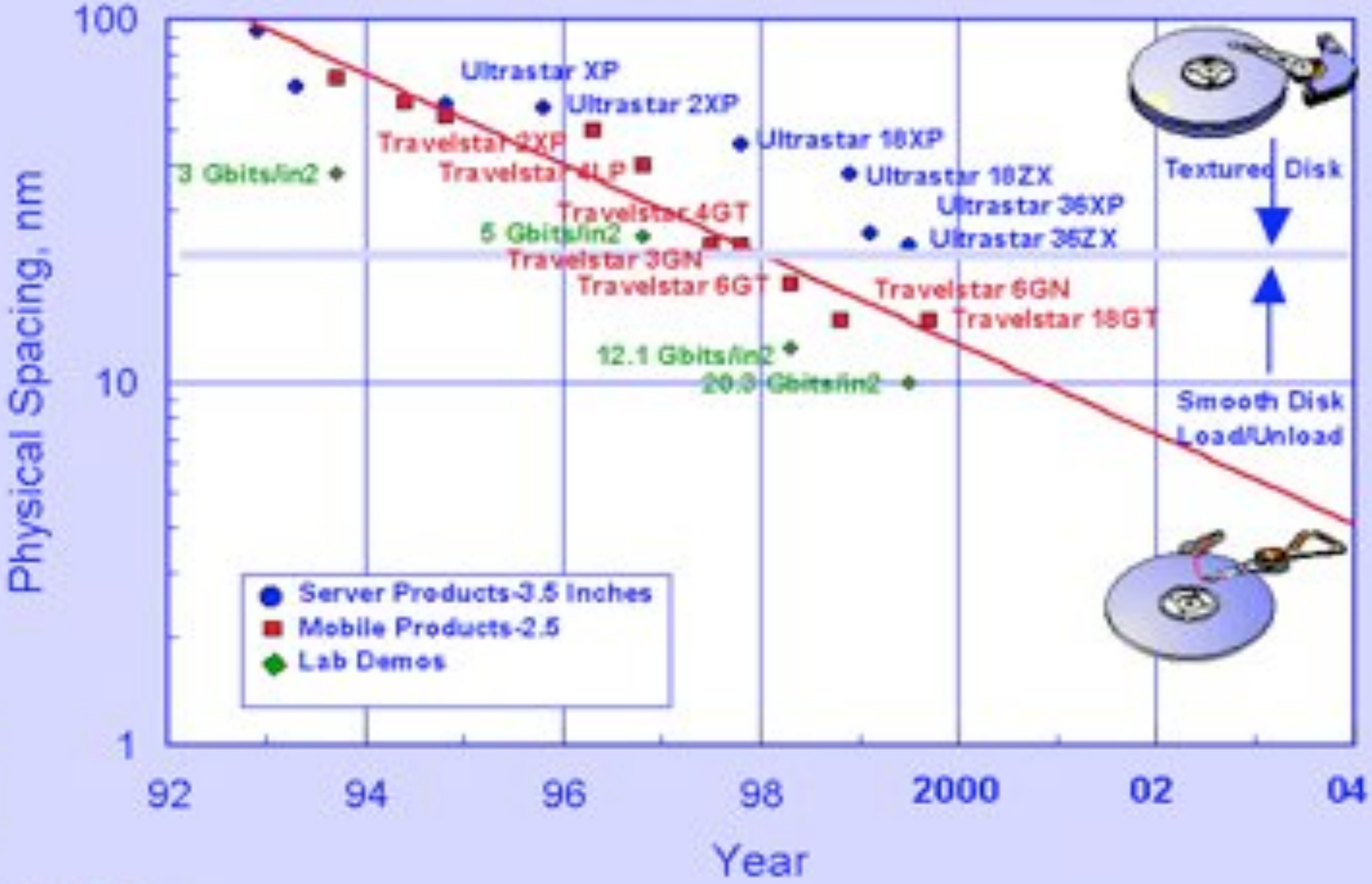
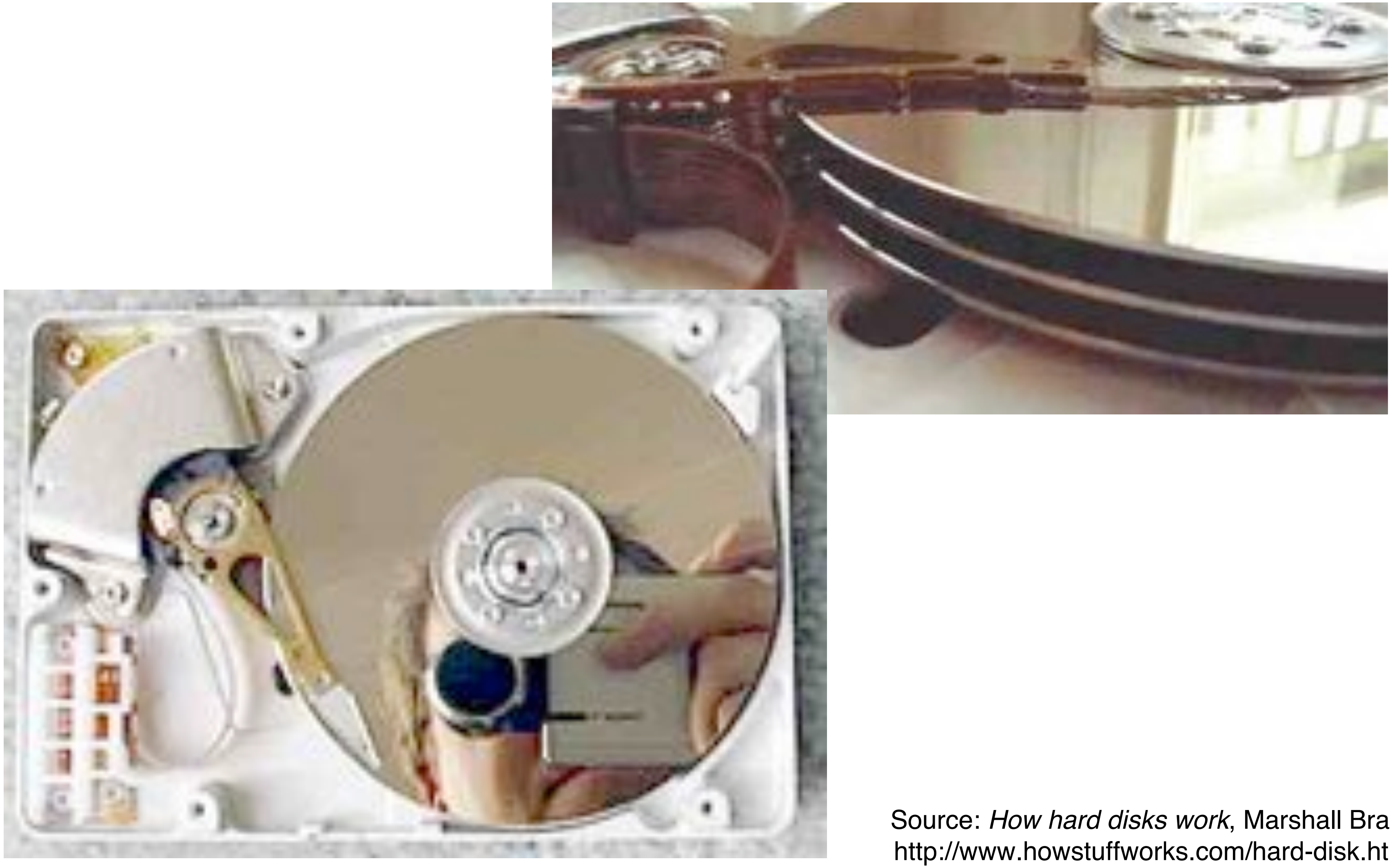
Physical spacing and disk surface evolution



ED GROCHOWSKI at ALMADE

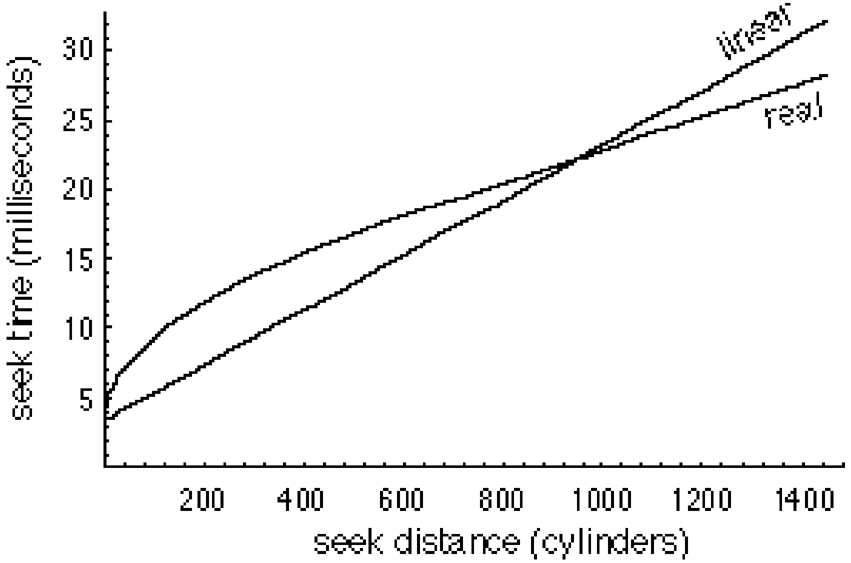
Magnetic disk drive: mechanical innards



Source: *How hard disks work*, Marshall Brain
http://www.howstuffworks.com/hard-disk.htm
1999

Magnetic disk drives: mechanical performance

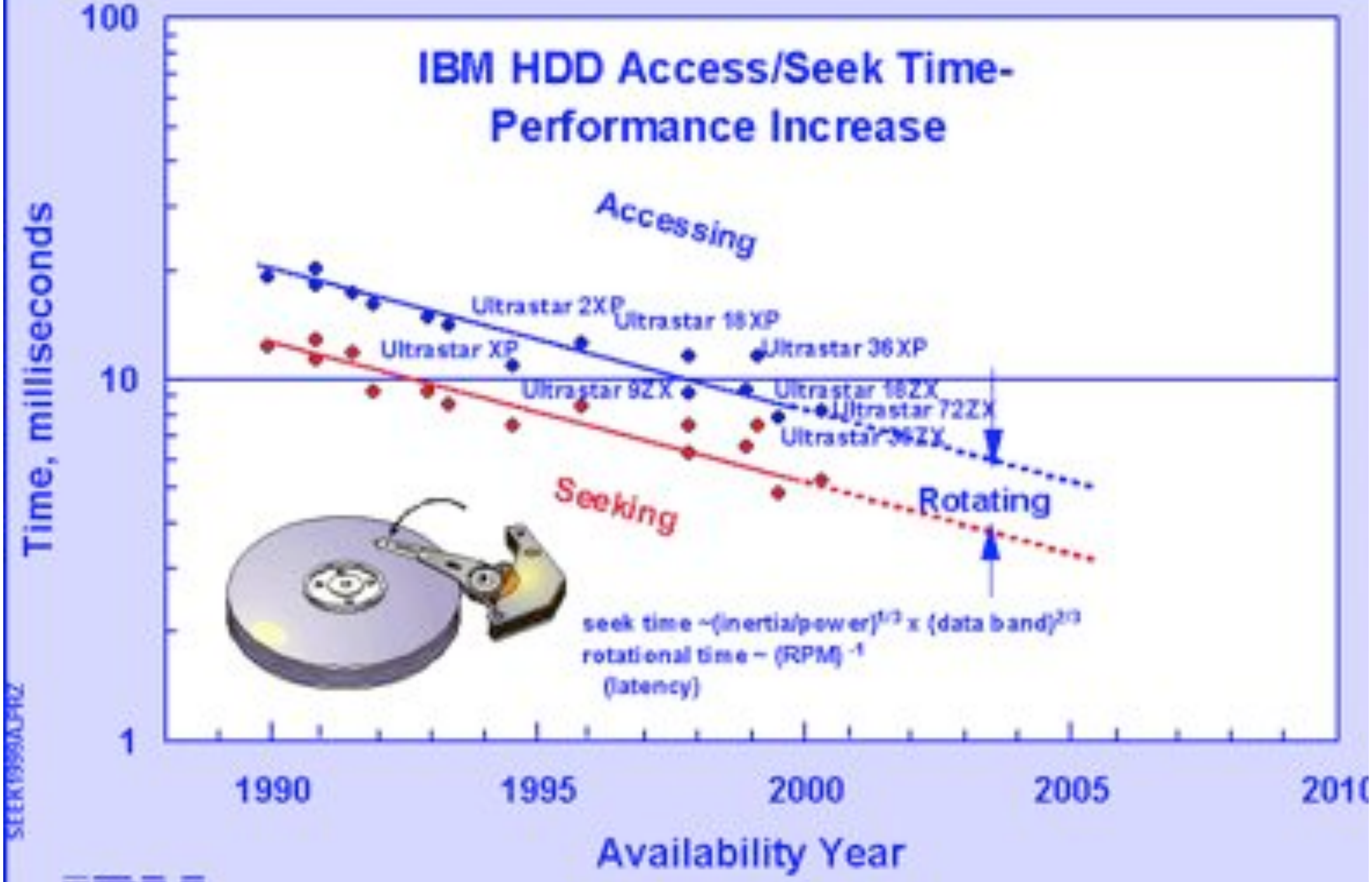
- Seek time
  - accelerate (35-40g)
[coast]
slow down
  - settle
  - single-track seeks
    - “track-switch”
    - special-case performance



- Rotational latency
  - 3600 RPM … 5400 … 7200 … 10,000 … 12,000 …

- Head switches
  - between platters
  - multiple head drives (now extinct)

IBM HDD Access/Seek Time-Performance Increase



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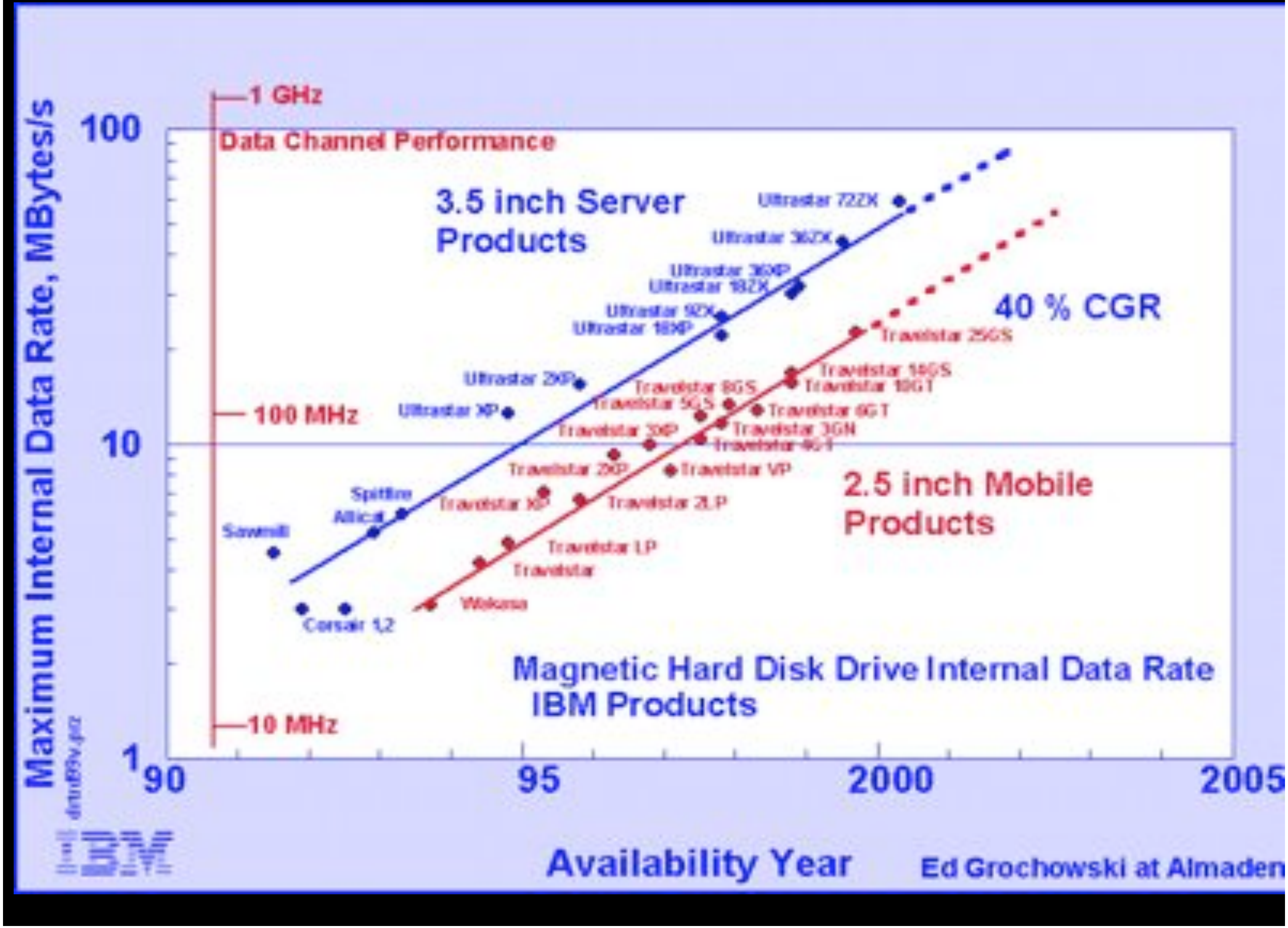


Magnetic Hard Disk Drive Internal Data Rate
IBM Products

Ed Grochowski at Almaden

Magnetic disk drives: a few complications

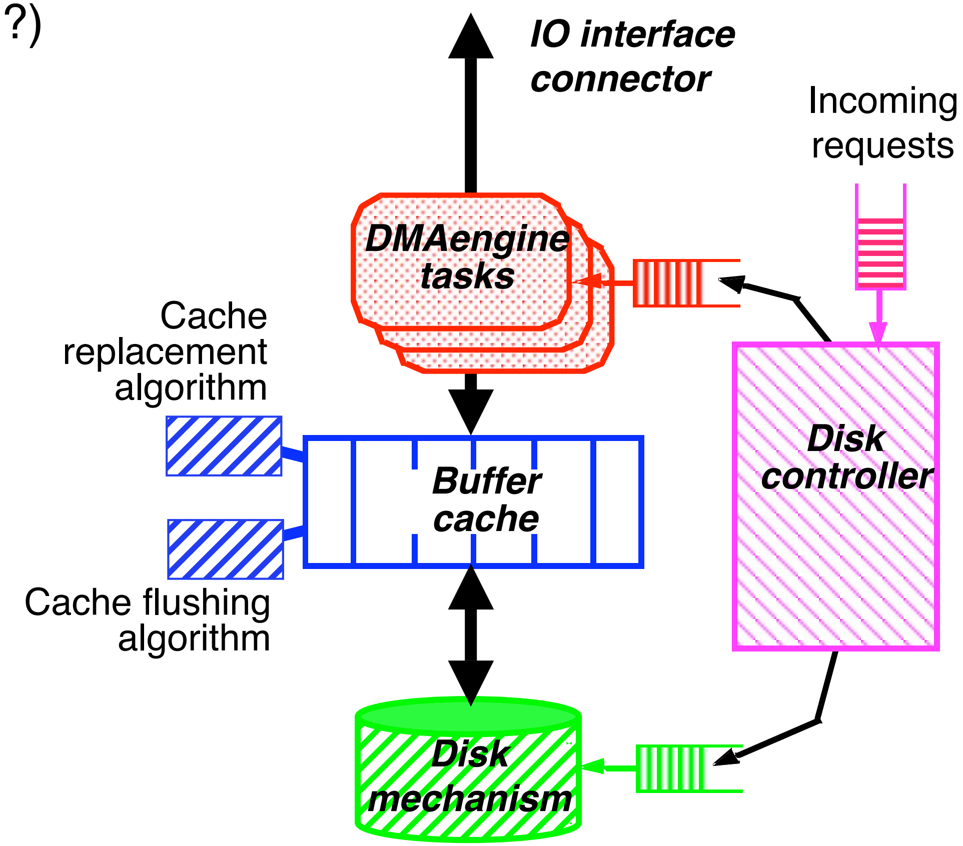
- Zoning
  - outer tracks are longer than inner ones
  - tracks have different capacities
    benefits: increased density, higher data rate

- Track-skew, cylinder-skew
  - slip the start of the next track by the time it takes to switch to it
    benefit: increased sequential transfer performance

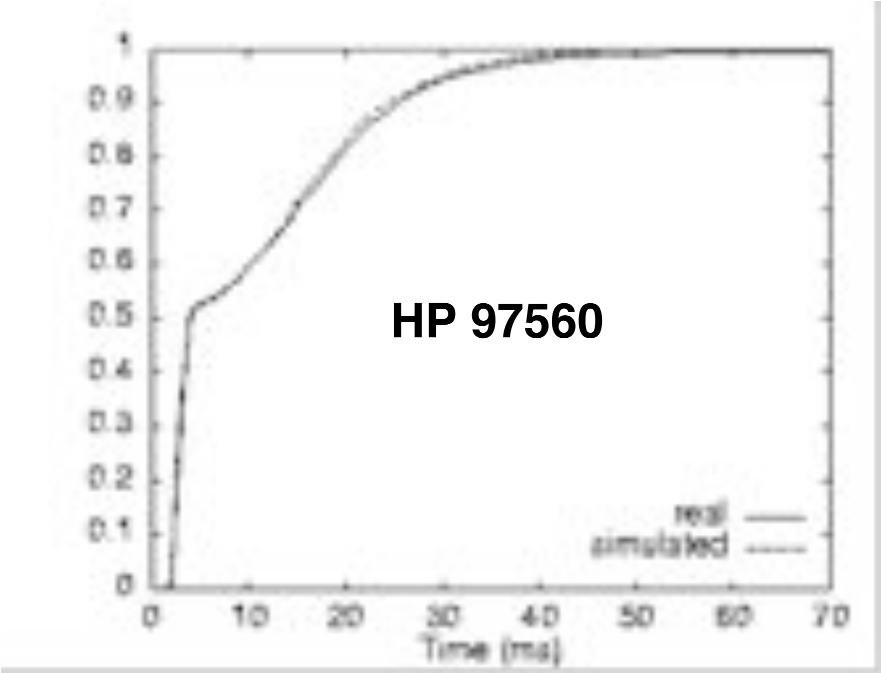
- Sparing
  - leave space for when things go wrong; skip over them

Magnetic disk drives: disk controllers

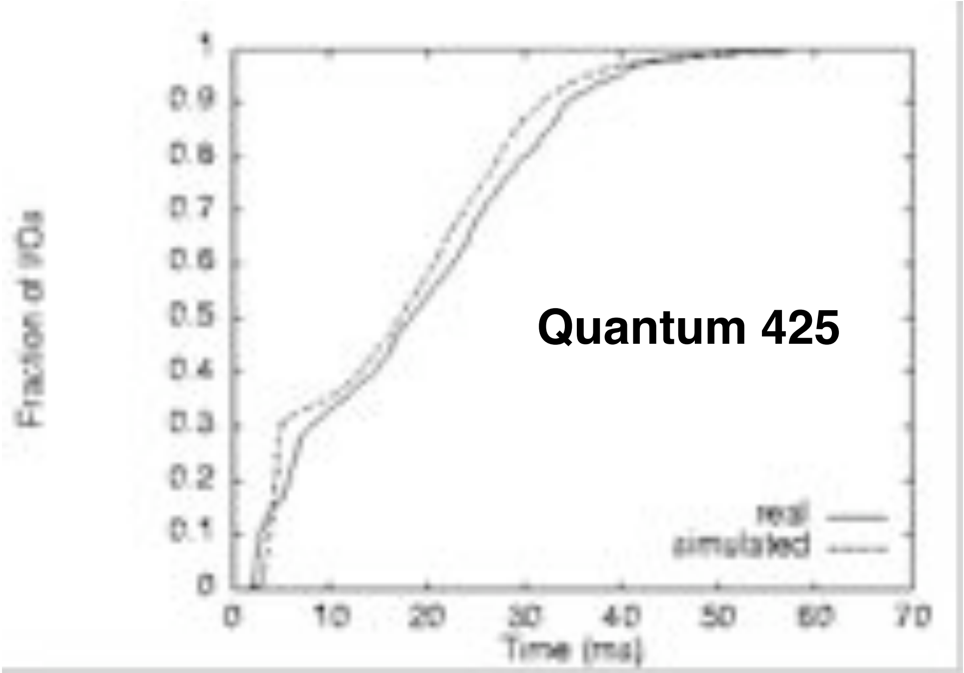
- **Caching**
  - **read-ahead** (multiple streams?)
  - **write behind**
  - **atomicity guarantees (not!)**
- **Controlling the mechanism**
  - **spindle motor**
  - **arm servo-following**
- **Data path management**
  - **DMA control**
  - **protocol sequencing**
  - **request scheduling**



Overall I/O performance under real loads



HP 97560



Quantum 425

- **Real** is traced I/O load from 1992
- **Simulated** is Chris Ruemmler's disk simulator (Pantheon progenitor**)**
- **Demerit figure** is (basically) area between these two curves

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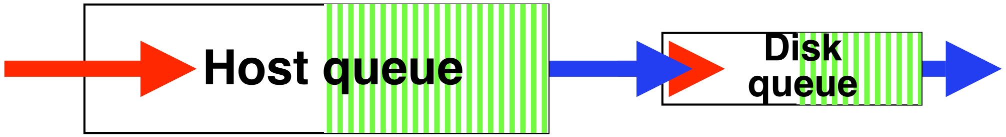
Disk request scheduling

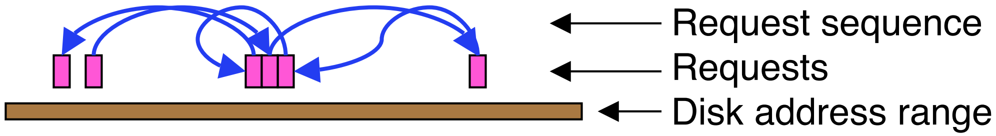
- I/O requests are very bursty
  - queue lengths up to 1000 have been seen
  - especially important for writes
- Queueing takes place in:
  - host device driver
  - disk/array controller
  - in practice: both



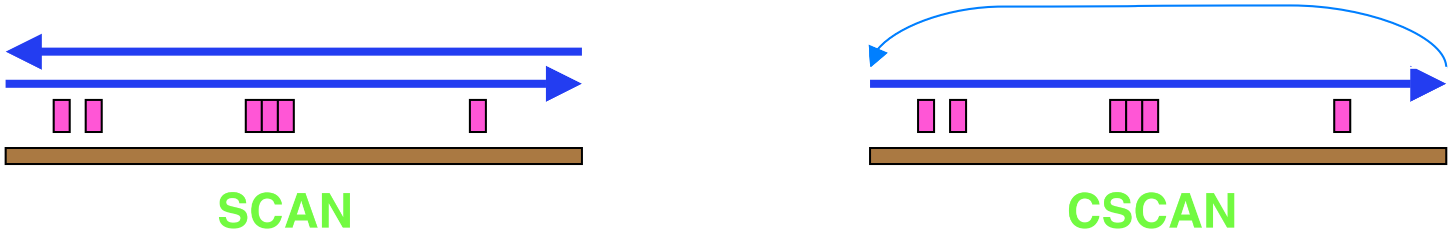
- Traditional 1D schemes: minimize seeks
- Better 2D schemes: include rotational latency, too
  - but have to be done in the disk!

1D request scheduling: minimize seeks

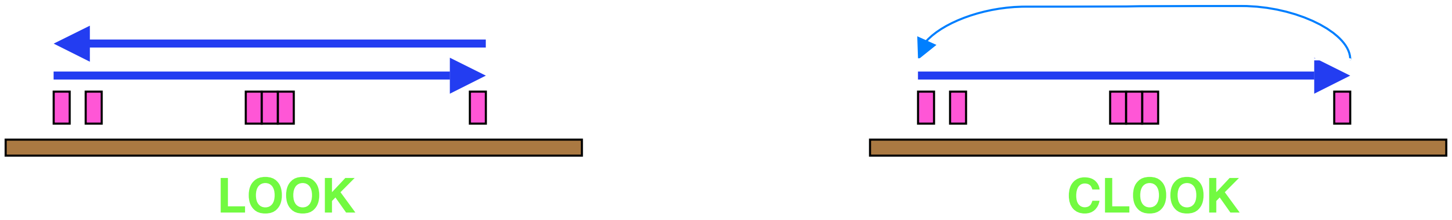
- **FCFS/FIFO: first-in first-out (terrible!)**



- **SCAN: start at one end of the disk, sweep to the other, then reverse direction. CSCAN: at end, go straight back to start.**

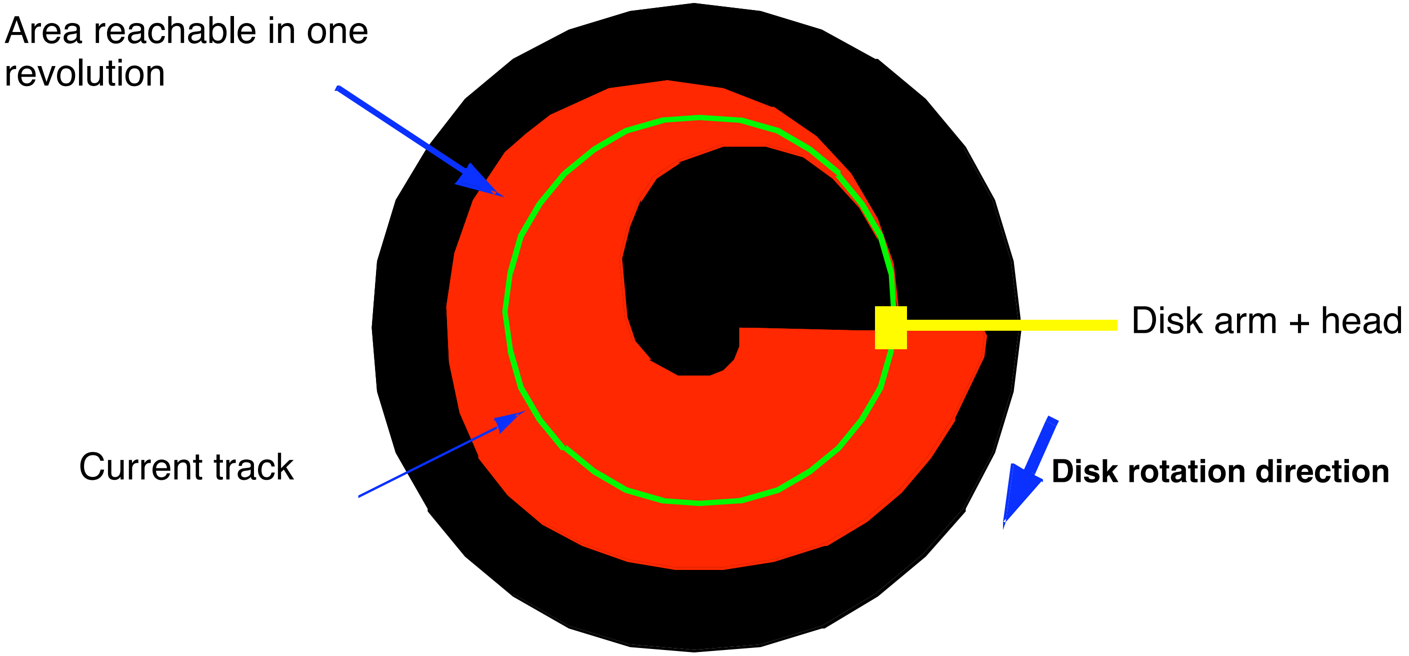


- **[C]LOOK: like [C]SCAN, but go back to first *request*, not start of disk**

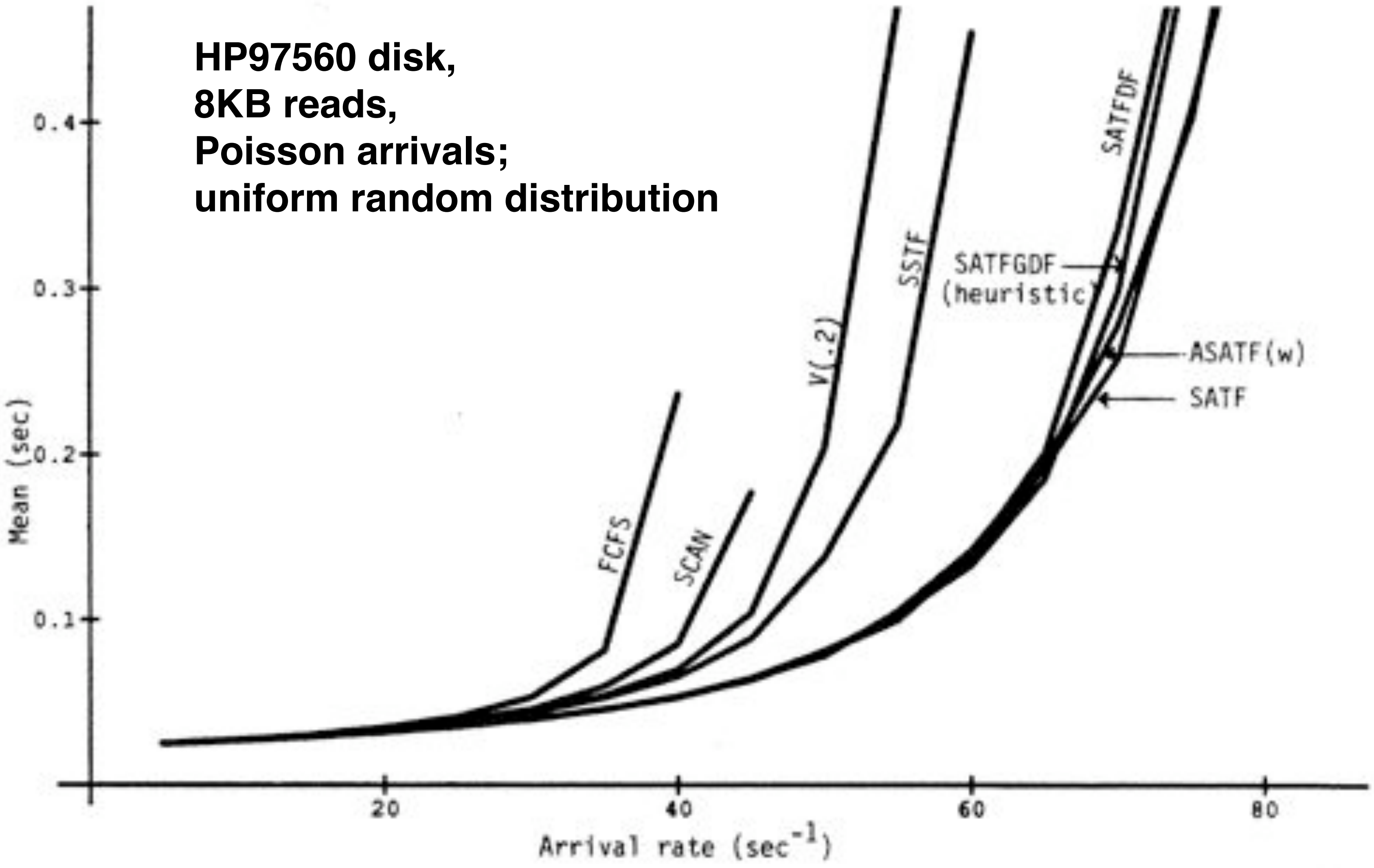


2D disk request scheduling: min(seek+rotation)

- **Shortest Positioning Time First** (aka Shortest Access Time First)
- **Like cpu scheduling: "do the shortest jobs first"**
  - **you do well almost all of the time**
- **Various age-weighting tricks to avoid starvation**



Scheduling algorithms: performance



HP97560 disk,
8KB reads,
Poisson arrivals;
uniform random distribution

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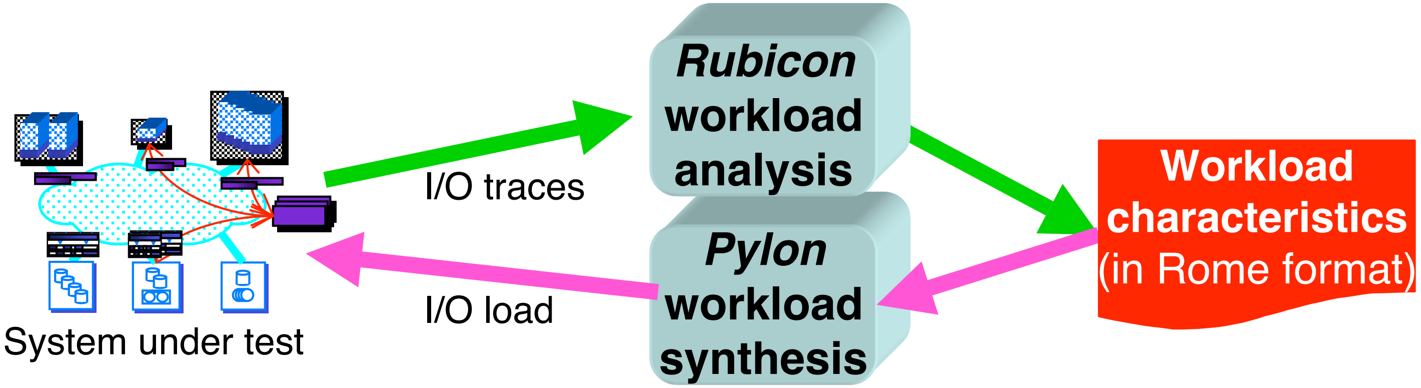
Workload characterization - why?

- System monitoring
  - What’s going on?
- Improve storage system designs
  - “What if?” design questions
  - Predicting effects of new or “scaled” workloads
- Generate synthetic workloads
  - To test performance of new designs
  - To compare existing systems

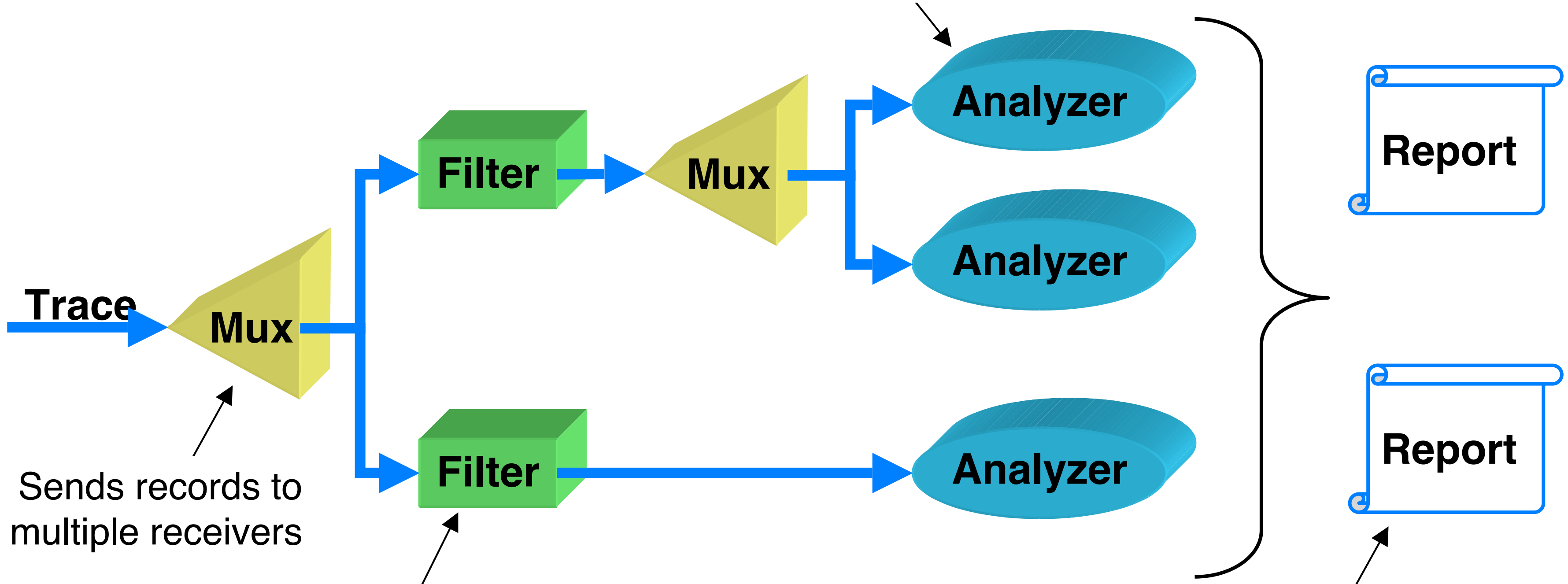
Workload characterization: Rubicon (+ Pylon)

- Rubicon is a tool for measuring I/O loads
  - uses HP-UX trace-gathering measurement system
- Pylon is a tool for generating synthetic workloads
  - Rubicon output can be used as Pylon input
- Together … can test for congruence
  - compare effects of synthetic (replayed) workload against original measurements



System under test
I/O traces
I/O load
Rubicon workload analysis
Pylon workload synthesis
Workload characteristics (in Rome format)

Rubicon: sample component tree



Measure stuff; compute workload characterization

Sends records to multiple receivers

Subsets trace records

Output results in multiple formats

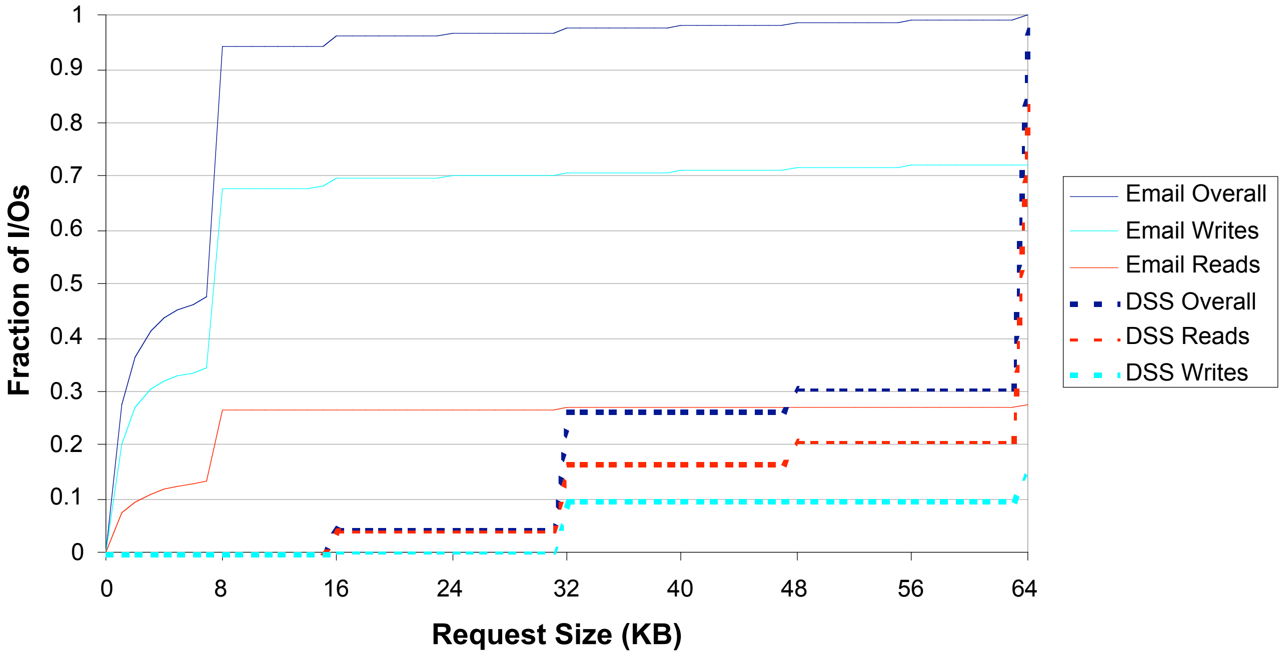
Workload characterization: 2 case studies

- **Electronic mail server**
  - **HP OpenMail**
  - **Peak operation period**
  - **about 1400 active users**

- **Decision support database server**
  - **Oracle**
  - **300 GB TPC-D database**
  - **Presentation focus: TPC-D Q5**

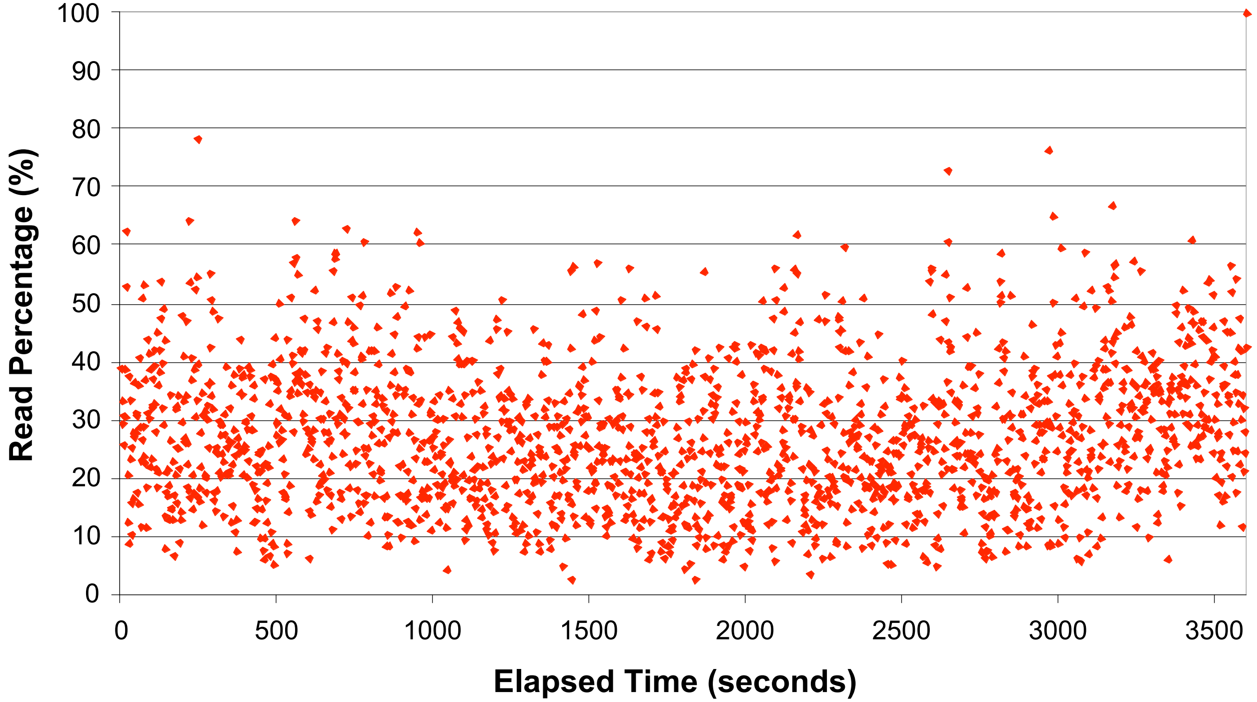
Workload characterization: request size

- Email dominated by small (<= 8 KB) writes
- DSS dominated by larger (64 KB) reads



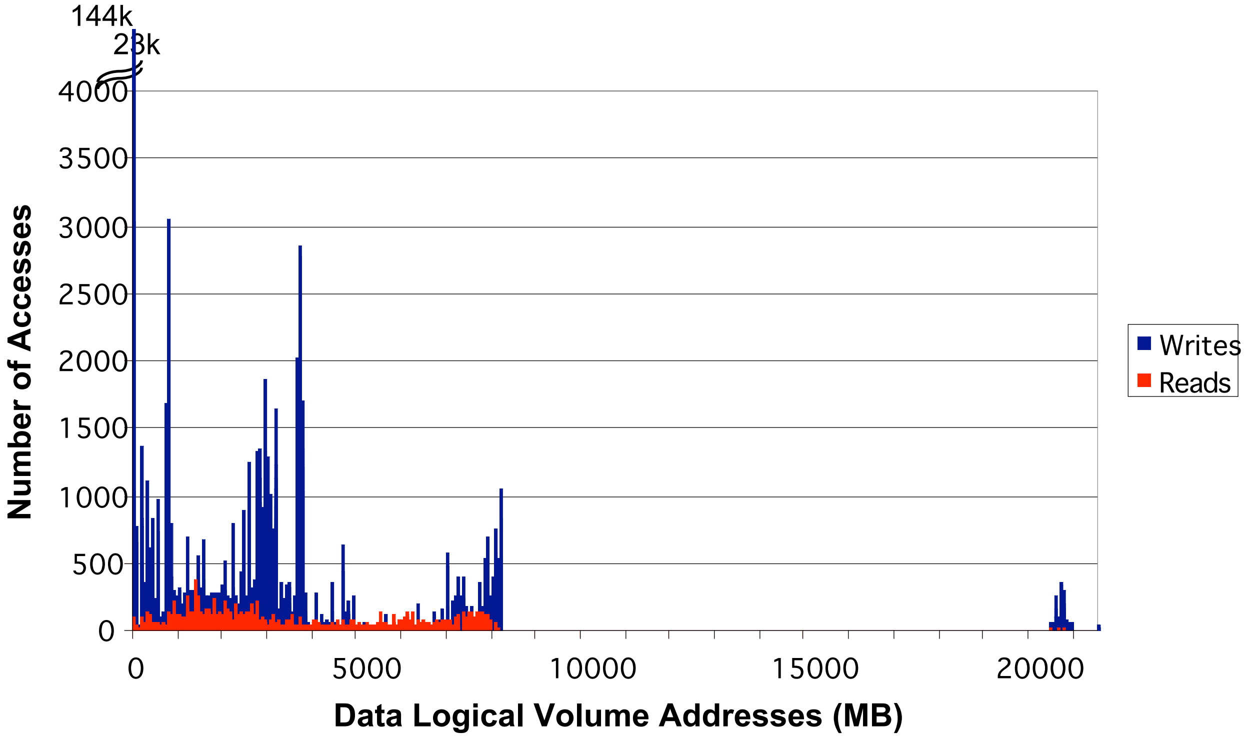
Workload characterization: fraction of reads

- **Email**
  - **average read percent: 28%**
  - **we need distributions, not just averages**



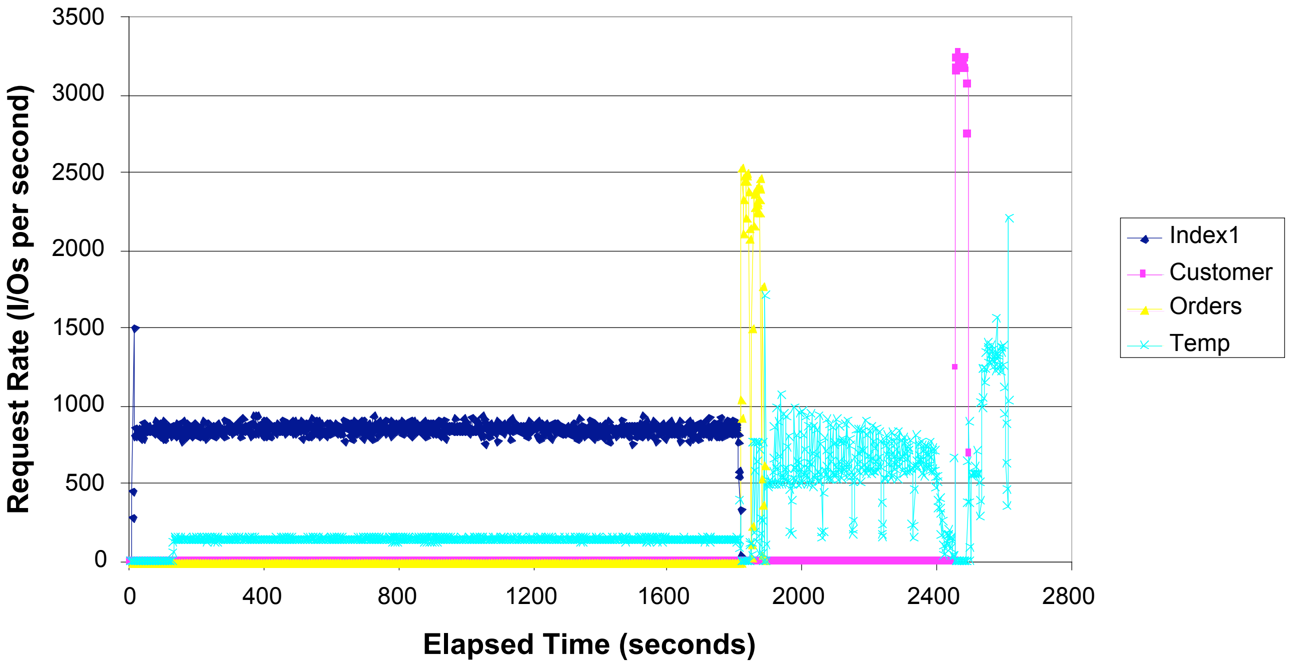
Workload characterization: access locality

- Email
  - Beginning of address range heavily accessed
  - Disk array caching important for performance



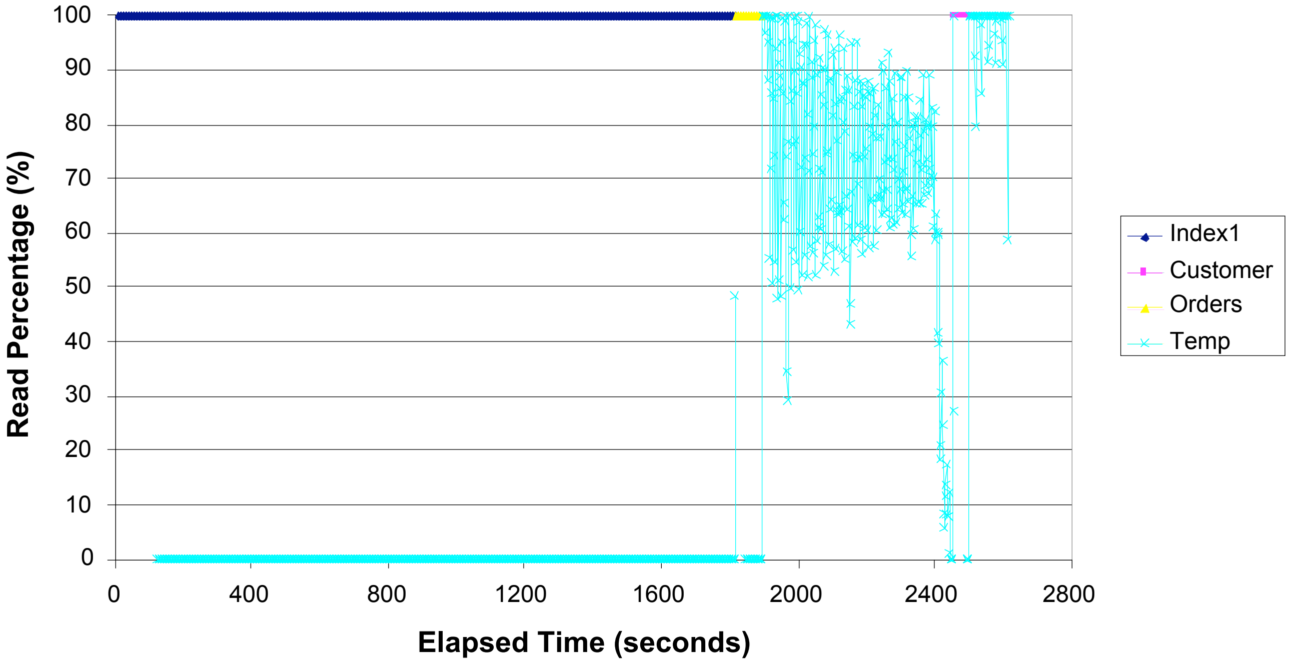
Workload characterization: I/O phasing

- Decision support database: TPC-D query
- Request rates vary widely
- Most multi-table queries have multiple phases



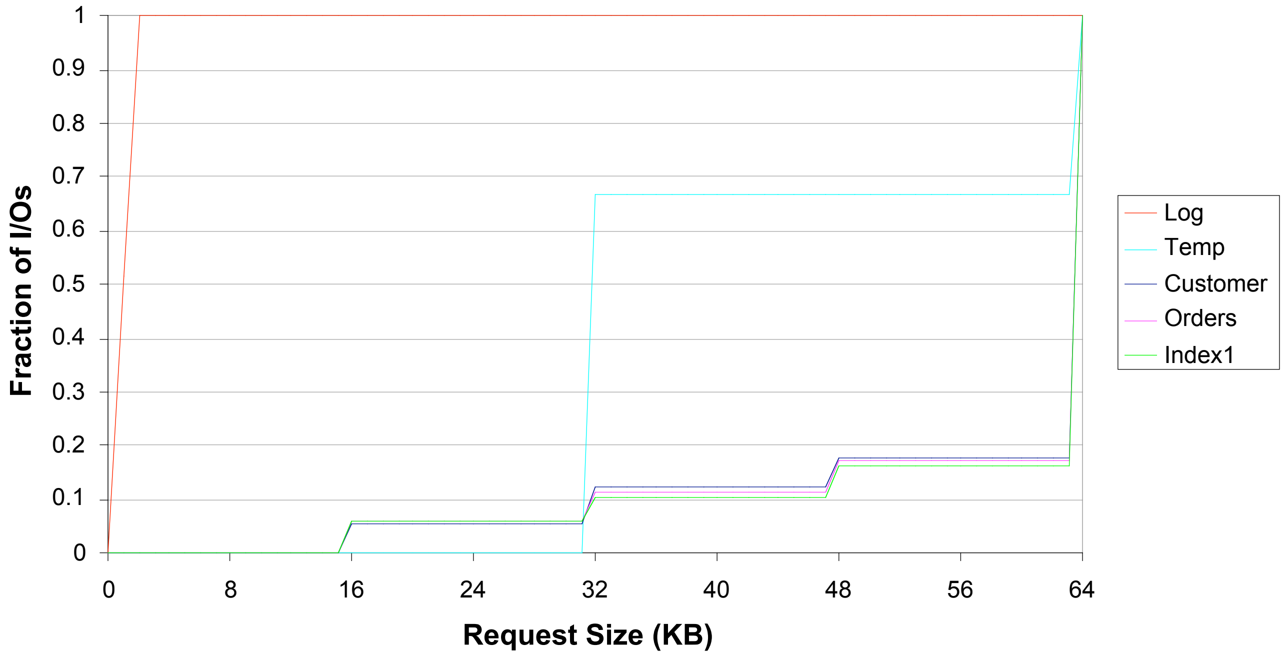
Workload characterization: I/O phasing

- Decision support database: TPC-D query
- “Read-only” workload exhibits writes!



Workload characterization: request size

- Decision support database: TPC-D query
- Different behavior from different parts of the database:
  - table, indices, temp space, log



Workload characterization: lessons learned

- Lessons learned:
  - List of important characteristics is longer than you think
  - Distributions, not averages, are important

- Characteristics of interest:
  - Request size distribution
  - Request rate distribution
  - Read:write ratio
  - Spatial locality (e.g., sequentiality)
  - Temporal locality (e.g., data re-references)
  - Correlation between accesses to different parts of storage system
  - Burstiness
  - Phased behavior

Workload characterization: open problems

- Characterizing workloads
  - correlations
  - burstiness (self-similarity at long term)
  - good spatial locality measures
- Replaying workloads
  - accurate timing is the hard part
- Predicting future loads
  - interleaving/workload merging
  - workload scaling
  - modelling application/dbms effects

Summary so far

- Storage devices: disks, tapes, other
- Performance issues: really important!
- Scheduling is way too much fun!
- Application behavior matters!