CS 44800: Introduction To Relational Database Systems

Building a DBMS

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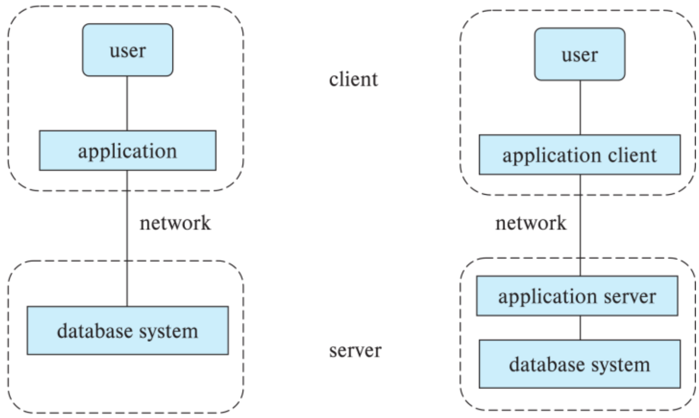
Slides adapted from those developed by the late Stanford University Prof. Hector Garcia-Molina

Database Applications

Database applications are usually partitioned into two or three parts

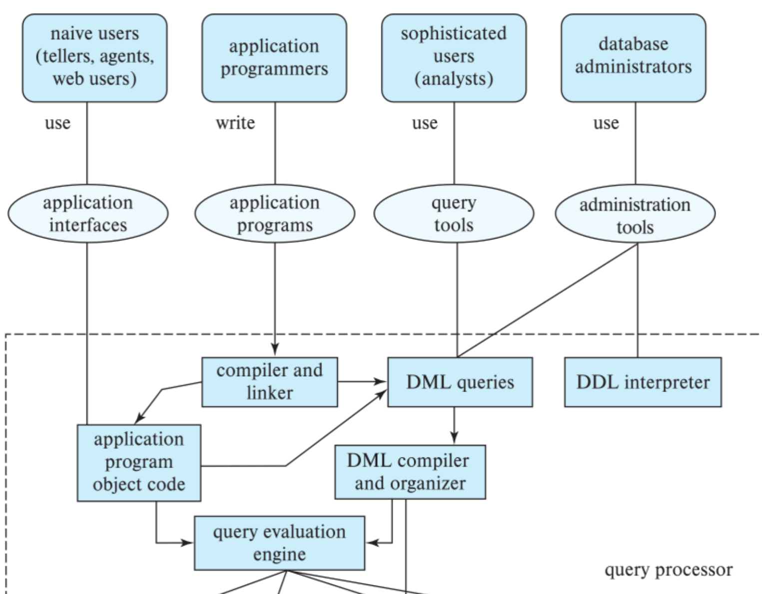
- Two-tier architecture -- the application resides at the client machine, where it invokes database system functionality at the server machine
- Three-tier architecture -- the client machine acts as a front end and does not contain any direct database calls.
  - The client end communicates with an application server, usually through a forms interface.
  - The application server in turn communicates with a database system to access data.

Two-tier and three-tier architectures



(a) Two-tier architecture (b) Three-tier architecture

Database Users



Physical Data Independence

- Physical Data Independence: the ability to modify the physical schema without changing the logical schema
  - Applications depend on the logical schema
  - In general, the interfaces between the various levels and components should be well defined so that changes in some parts do not seriously influence others.
- We've talked about the *logical* schema
  - But what goes underneath?

Database Engine

- A database system is partitioned into modules that deal with each of the responsibilities of the overall system.
- The functional components of a database system can be divided into
  - The storage manager,
  - The query processor component,
  - The transaction management component.

Isn't Implementing a Database System Simple?

Relations ⟹ Statements ⟹ Results

Introducing the

MEGATRON 3000

Database Management System

Megatron 3000 Implementation Details

! First sign non-disclosure agreement !

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Megatron 3000 Implementation Details

- Relations stored in files (ASCII)
  - e.g., relation R is in /usr/db/R

```
Smith # 123 # CS
Jones # 522 # EE
  :
```

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Megatron 3000 Implementation Details

- Directory file (ASCII) in /usr/db/directory

```
R1 # A # INT # B # STR …
R2 # C # STR # A # INT …
  ⋮
```


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Megatron 3000 Sample Sessions

```
% MEGATRON3000
   Welcome to MEGATRON 3000!
&
  ⋮
& quit
%
```

Megatron 3000
Sample Sessions

```
& select A,B
  from R,S
  where R.A = S.A and S.C > 100 #

   A    B
  123  CAR
  522  CAT

&
```

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Megatron 3000

- To execute "select * from R where condition":
  1) Read dictionary to get R attributes
  2) Read R file, for each line:
     a) Check condition
     b) If OK, display

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Megatron 3000

- To execute "select * from R
  where condition | T":
  1) Process select as before
  2) Write results to new file T
  3) Append new line to dictionary

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Megatron 3000

- To execute "select A,B from R,S where condition":

1) Read dictionary to get R,S attributes
2) Read R file, for each line:
   a) Read S file, for each line:
      i. Create join tuple
      ii. Check condition
      iii. Display if OK

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What's wrong with the Megatron 3000 DBMS?

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- Tuple layout on disk
  - Change string from 'Cat' to 'Cats' and we have to rewrite file
  - ASCII storage is expensive
  - Deletions are expensive
- Search expensive; no indexes
  - Cannot find tuple with given key quickly
  - Always have to read full relation

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What's wrong with the Megatron 3000 DBMS?

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- No buffer manager
  - Need caching
- Brute force query processing
    - select *
      from R,S
      where R.A = S.A and S.B > 1000
  - Do select first?
  - More efficient join?

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What's wrong with the Megatron 3000 DBMS?

- No concurrency control
- No reliability
  - Can lose data
  - Can leave operations half done
- No security
  - File system insecure
  - File system security is coarse

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What's wrong with the Megatron 3000 DBMS?

- No application program interface (API)
  - How can a payroll program get at the data?
- No GUI
- Cannot interact with other DBMSs.
- Poor dictionary facilities
  - How do we know what is in the database?
- Lousy salesman!!

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What do we need to know?

- File & System Structure
  - Records in blocks, dictionary, buffer management,…
- Indexing & Hashing
  - B-Trees, hashing,…
- Query Processing
  - Query costs, join strategies,…
- Crash Recovery
  - Failures, stable storage,…

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What do we need to know?

- Concurrency Control
  - Correctness, locks,…
- Transaction Processing
  - Logs, deadlocks,…
- Security & Integrity
  - Authorization, encryption,…
- Distributed Databases
  - Interoperation, distributed recovery,…

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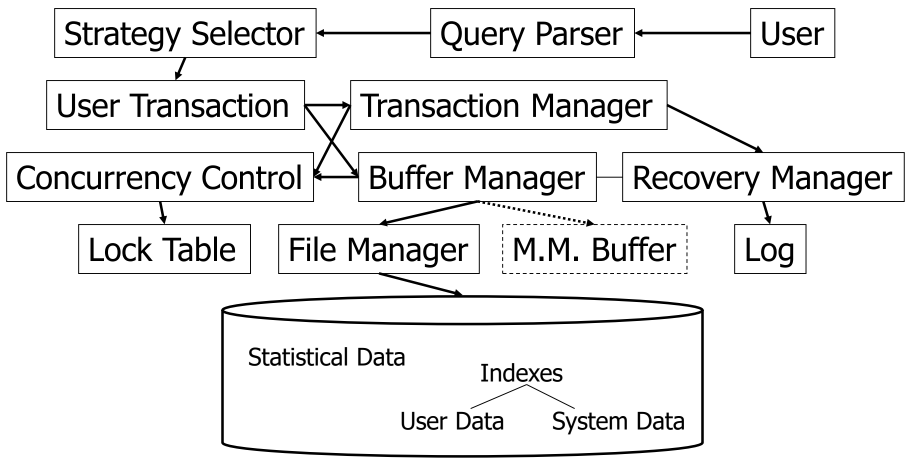
System Structure



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Storage Manager

- A program module that provides the interface between the low-level data stored in the database and the application programs and queries submitted to the system.
- The storage manager is responsible to the following tasks:
  - Interaction with the OS file manager
  - Efficient storing, retrieving and updating of data
- The storage manager components include:
  - Authorization and integrity manager
  - Transaction manager
  - File manager
  - Buffer manager

Storage Manager (Cont.)

- The storage manager implements several data structures as part of the physical system implementation:
  - Data files -- store the database itself
  - Data dictionary -- stores metadata about the structure of the database, in particular the schema of the database.
  - Indices -- can provide fast access to data items. A database index provides pointers to those data items that hold a particular value.

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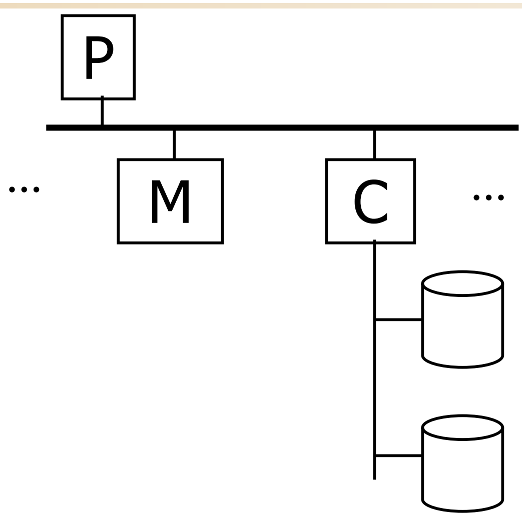

Typical Computer

Secondary Storage

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Processor

Fast, slow, reduced instruction set,
with cache, pipelined…
Speed: 100 → 1000 → 1,000,000 MIPS

Memory

Fast, slow, non-volatile, read-only,…
Access time: 10^{-6} → 10^{-8} sec.
1 μs → 10 ns

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Secondary storage

Many flavors:
- Disk: Floppy (hard, soft)
  Removable Packs
  Winchester
  Ram disks
  Optical, CD-ROM…
  Arrays
  Solid State
- Tape Reel, cartridge
  Robots

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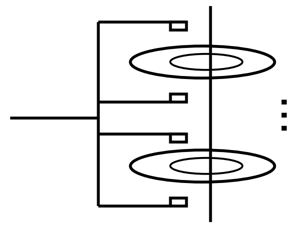
Focus on: "Typical Disk"



Terms: Platter, Head, Actuator
Cylinder, Track
Sector (physical),
Block (logical), Gap

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"Typical" Numbers

Diameter:	1 inch → 15 inches
Cylinders:	100 → 2000
Surfaces: (Tracks/cyl)	1 (CDs) → 2 (floppies) → 30
Sector Size:	512B → 50K
Capacity:	360 KB (old floppy) → TB

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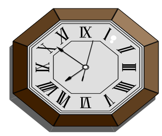
Disk Access Time

I want block X →  → block x in memory

?

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Time = Seek Time +
Rotational Delay +
Transfer Time +
Other

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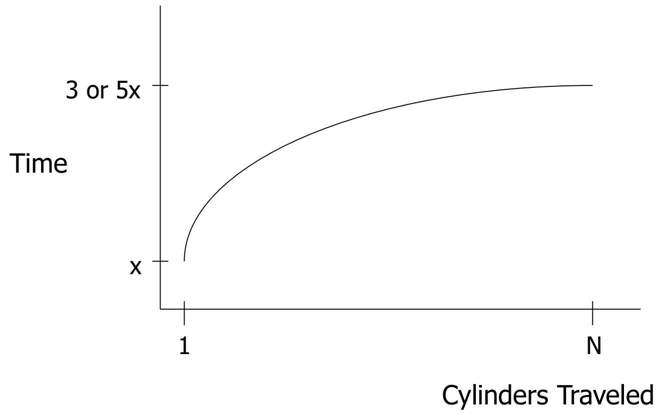
Seek Time



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Average Random Seek Time

$$S = \frac{\sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \text{SEEKTIME}(i \rightarrow j)}{N(N-1)}$$

"Typical" S: 5 ms $\rightarrow$ 10 ms

SSD 0.1ms

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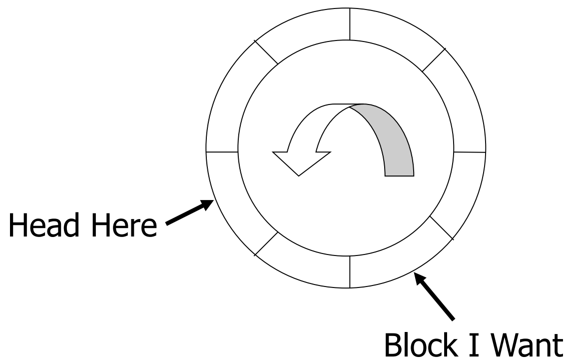
Rotational Delay



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Average Rotational Delay

R = 1/2 revolution

"typical" R = 2 ms (15000 RPM)

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Transfer Rate: t

- “typical” t: 100 $\rightarrow$ 200 MB/second
- transfer time: block size / t
- *SSD: up to 3500 MB/s*
  - But this exceeds architecture transfer limits, so often limited to 300MB/second
  - *Tape drives can match this!*

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Other Delays

- CPU time to issue I/O
- Contention for controller
- Contention for bus, memory

“Typical” Value: 0

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- So far: Random Block Access
- What about: Reading “Next” block?

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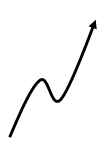
If we do things right

(e.g., Double Buffer, Stagger Blocks…)

Time to get block = Block Size / t + Negligible



- skip gap
- switch track
- once in a while, next cylinder

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Rule of Thumb

Random I/O: Expensive
Sequential I/O: Much less

- Ex: 1 KB Block
  - » Random I/O: ~ 10 ms.
  - » Sequential I/O: ~ 1 ms.

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Curve Balls

- Buffering
  - Disks typically "read ahead" into a buffer
  - Buffer transfer rates typically 300MB/s
- "Moving" blocks
  - Disk controllers mask hardware failures by moving blocks around
  - Sequential reads may not actually be sequential…

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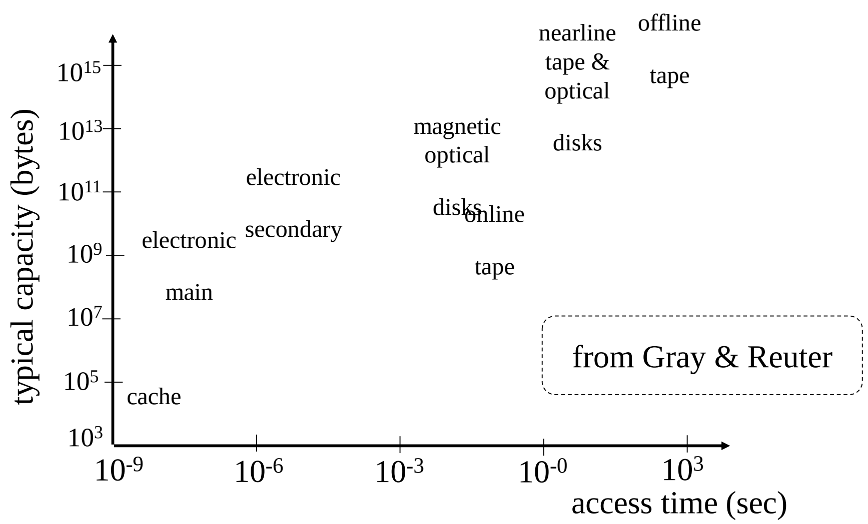
To Modify a Block?

To Modify Block:

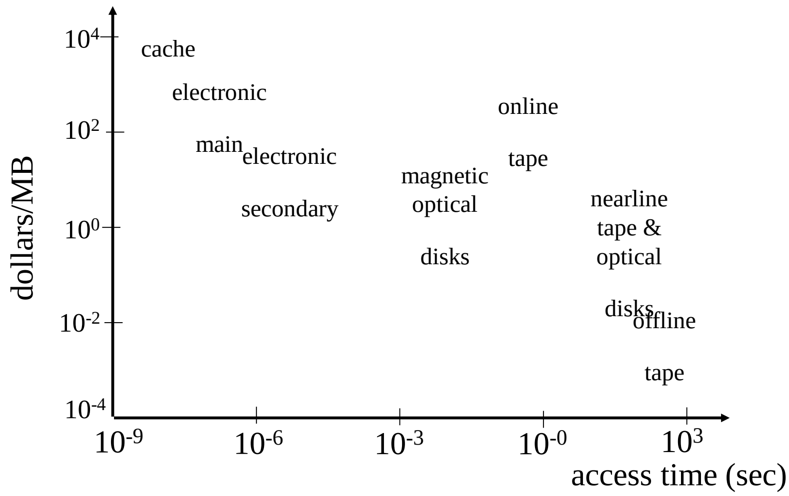
(a) Read Block
(b) Modify in Memory
(c) Write Block
[(d) Verify?]

Storage Cost



Storage Cost

from Gray & Reuter



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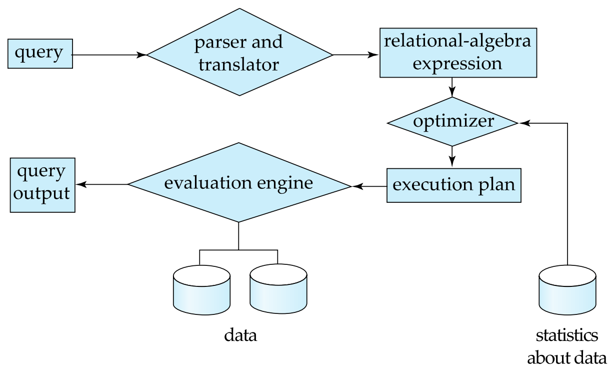
Query Processor

- The query processor components include:
  - DDL interpreter -- interprets DDL statements and records the definitions in the data dictionary.
  - DML compiler -- translates DML statements in a query language into an evaluation plan consisting of low-level instructions that the query evaluation engine understands.
    - The DML compiler performs query optimization; that is, it picks the lowest cost evaluation plan from among the various alternatives.
  - Query evaluation engine -- executes low-level instructions generated by the DML compiler.

Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation



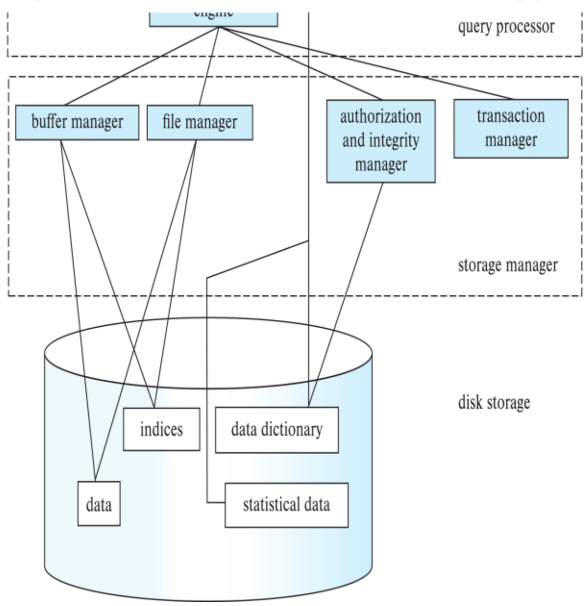
Transaction Management

- A **transaction** is a collection of operations that performs a single logical function in a database application
- **Transaction-management component** ensures that the database remains in a consistent (correct) state despite system failures (e.g., power failures and operating system crashes) and transaction failures.
- **Concurrency-control manager** controls the interaction among the concurrent transactions, to ensure the consistency of the database.

Database Architecture

- Centralized databases
  - One to a few cores, shared memory
- Client-server,
  - One server machine executes work on behalf of multiple client machines.
- Parallel databases
  - Many core shared memory
  - Shared disk
  - Shared nothing
- Distributed databases
  - Geographical distribution
  - Schema/data heterogeneity

Database Architecture (Centralized/Shared-Memory)



Storage Hierarchy (Cont.)

- **primary storage:** Fastest media but volatile (cache, main memory).
- **secondary storage:** next level in hierarchy, non-volatile, moderately fast access time
  - Also called **on-line storage**
  - E.g., flash memory, magnetic disks
- **tertiary storage:** lowest level in hierarchy, non-volatile, slow access time
  - also called **off-line storage** and used for **archival storage**
  - e.g., magnetic tape, optical storage
  - Magnetic tape
    - Sequential access, 1 to 12 TB capacity
    - A few drives with many tapes
    - Juke boxes with petabytes (1000's of TB) of storage

Storage Interfaces

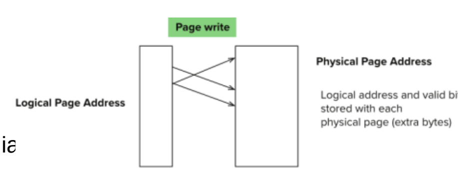
- Disk interface standards families
  - SATA (Serial ATA)
    - SATA 3 supports data transfer speeds of up to 6 gigabits/sec
  - SAS (Serial Attached SCSI)
    - SAS Version 3 supports 12 gigabits/sec
  - NVMe (Non-Volatile Memory Express) interface
    - Works with PCIe connectors to support lower latency and higher transfer rates
    - Supports data transfer rates of up to 24 gigabits/sec
- Disks usually connected directly to computer system
- In **Storage Area Networks (SAN)**, a large number of disks are connected by a high-speed network to a number of servers
- In **Network Attached Storage (NAS)** networked storage provides a file system interface using networked file system protocol, instead of providing a disk system interface

SSD (Flash) Storage

- NOR flash vs NAND flash
- NAND flash
  - used widely for storage, cheaper than NOR flash
  - requires page-at-a-time read (page: 512 bytes to 4 KB)
    - 20 to 100 microseconds for a page read
    - Not much difference between sequential and random read
  - Page can only be written once
    - Must be erased to allow rewrite
- **Solid state disks**
  - Use standard block-oriented disk interfaces, but store data on multiple flash storage devices internally
  - Transfer rate of up to 500 MB/sec using SATA, and up to 3 GB/sec using NVMe PCIe

SSD Storage (Cont.)

- Erase happens in units of **erase block**
  - Takes 2 to 5 millisecs
  - Erase block typically 256 KB to 1 MB (128 to 256 pages)
- **Remapping** of logical page addresses to physical page addresses avoids waiting for erase
- **Flash translation table** tracks mapping
  - also stored in a label field of flash page
  - remapping carried out by **flash translation layer**



- After 100,000 to 1,000,000 erases, erase block becomes unrelia
  - **wear leveling**

RAID

- **RAID: Redundant Arrays of Independent Disks**
  - disk organization techniques that manage a large numbers of disks, providing a view of a single disk of
    - **high capacity** and **high speed** by using multiple disks in parallel,
    - **high reliability** by storing data redundantly, so that data can be recovered even if a disk fails
- The chance that some disk out of a set of *N* disks will fail is much higher than the chance that a specific single disk will fail.
  - E.g., a system with 100 disks, each with MTTF of 100,000 hours (approx. 11 years), will have a system MTTF of 1000 hours (approx. 41 days)
  - Techniques for using redundancy to avoid data loss are critical with large numbers of disks

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Hardware: Key Takeaways

- Database must reside on non-volatile storage
  - Can cache in faster storage
- Non-volatile storage *slow*
  - But accessing a lot not much different than accessing a little
  - Therefore we read/write as large blocks (typically 4kb)
- Abstract performance as: $\alpha + \beta b$
  - α is *seek time* (abstraction of read/write setup overhead)
  - β is *transfer rate*
  - b is *block size*
- Rotating media: seek can dominate (but caching, sequential reads reduce this)
- Solid state: transfer dominates
  - but erasure, protocol overheads make "seek" more than you'd expect
- Writes typically worse than reads
  - *Not "done" until safe in non-volatile storage, so reduces caching benefits*

