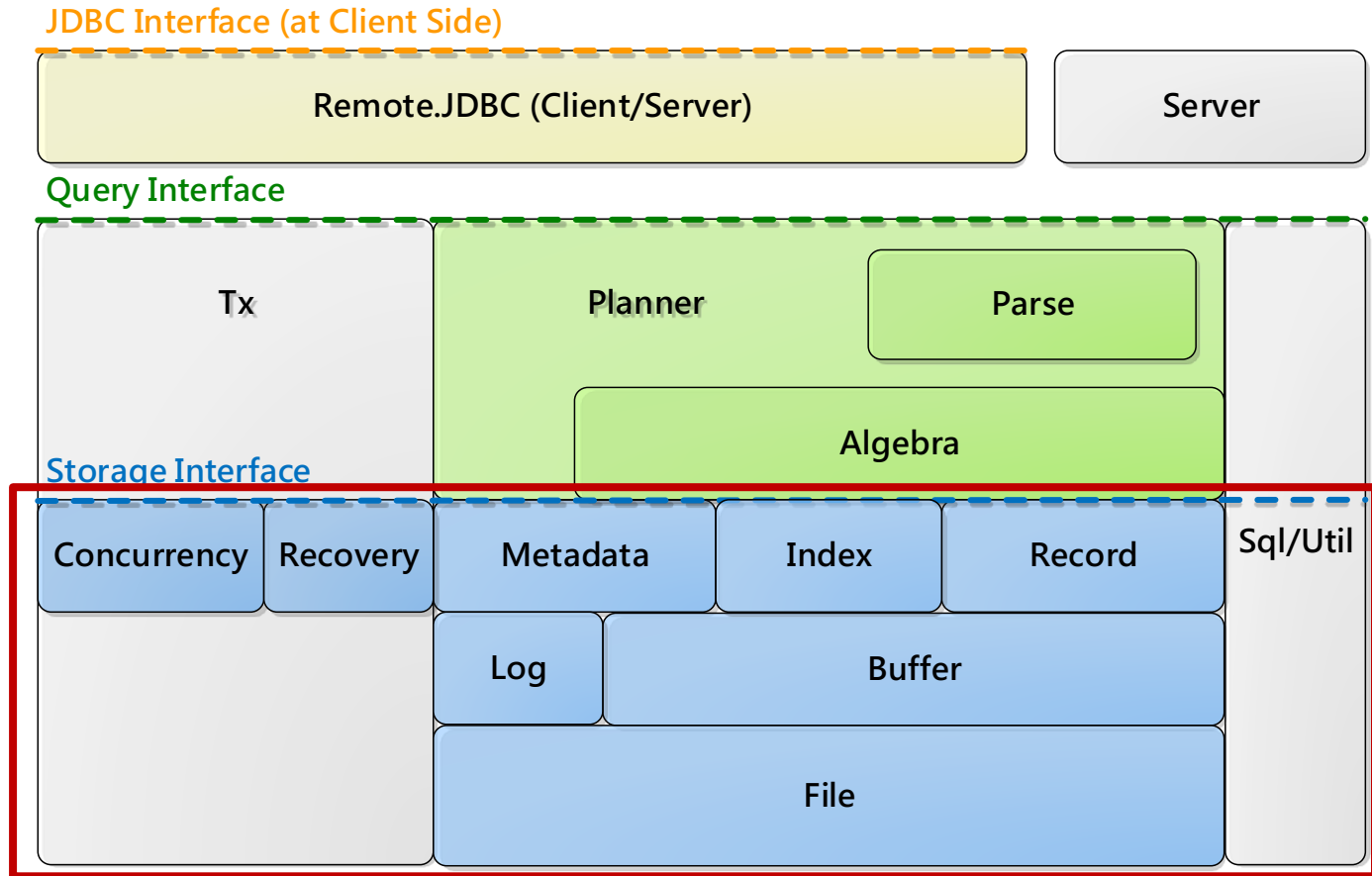


Data Access and File Management

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Storage Engine

VanillaCore



Outline

- Storage engine and data access
- Disk access
 - Block-level interface
 - File-level interface
- File Management in VanillaCore
 - BlockID, Page, and FileMgr
 - I/O interfaces

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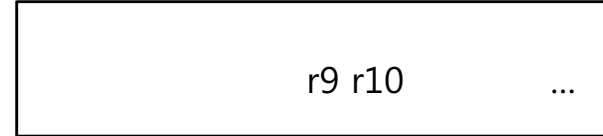
Storage Engine

- Main functions:
- Data access
 - File access (`TableInfo`, `RecordFile`)
 - Metadata access (`CatalogMgr`)
 - Index access (`IndexInfo`, `Index`)
- Transaction management
 - C and I (`ConcurrencyMgr`)
 - A and D (`RecoveryMgr`)

RecordFileA



RecordFileB

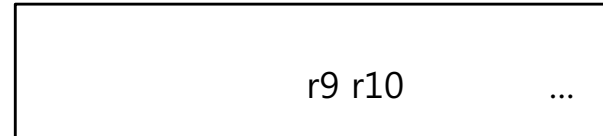


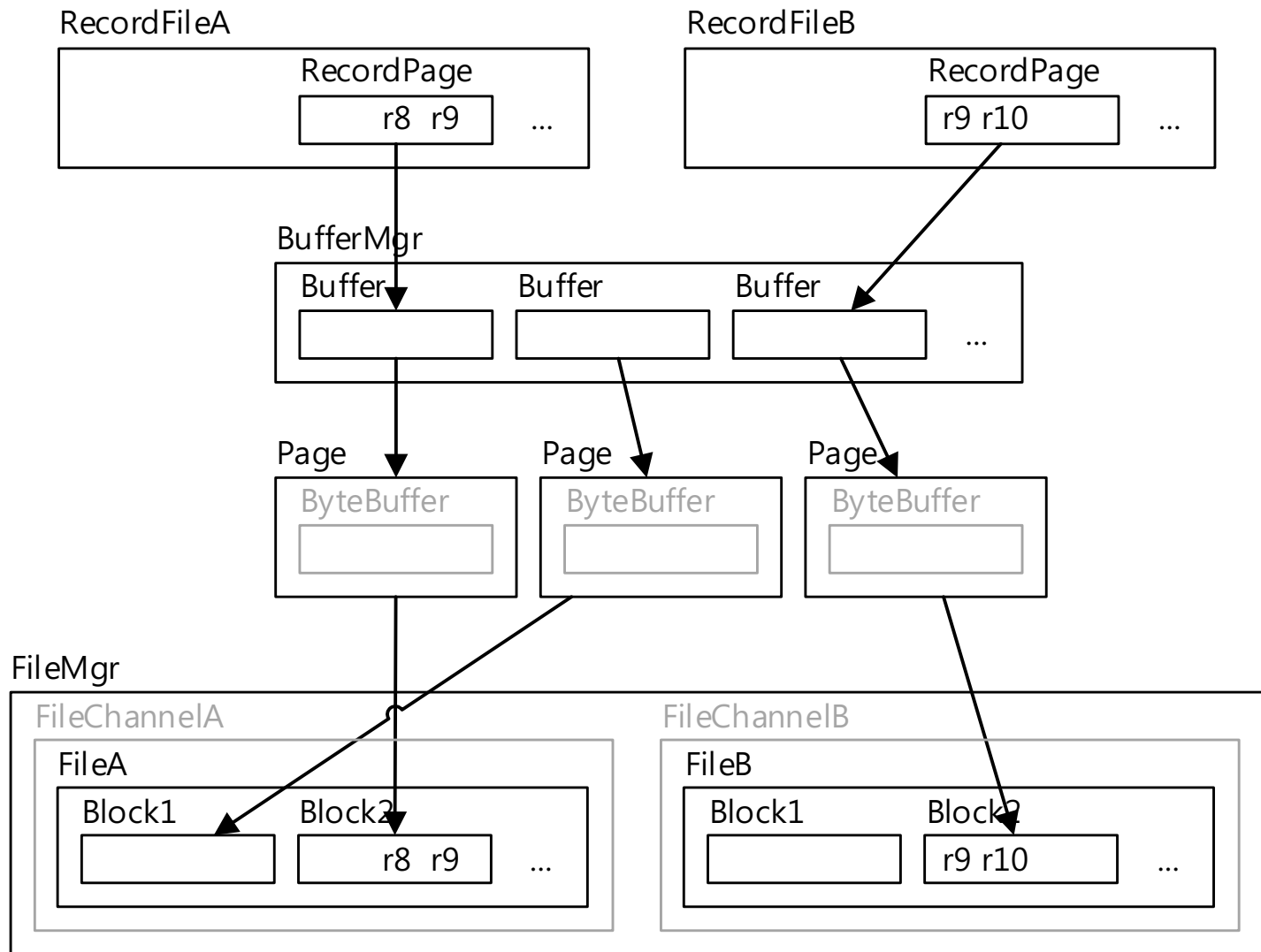
How does a `RecordFile` map to an Actual File on Disk?

FileA



FileB





Data Access Layers (Bottom Up)

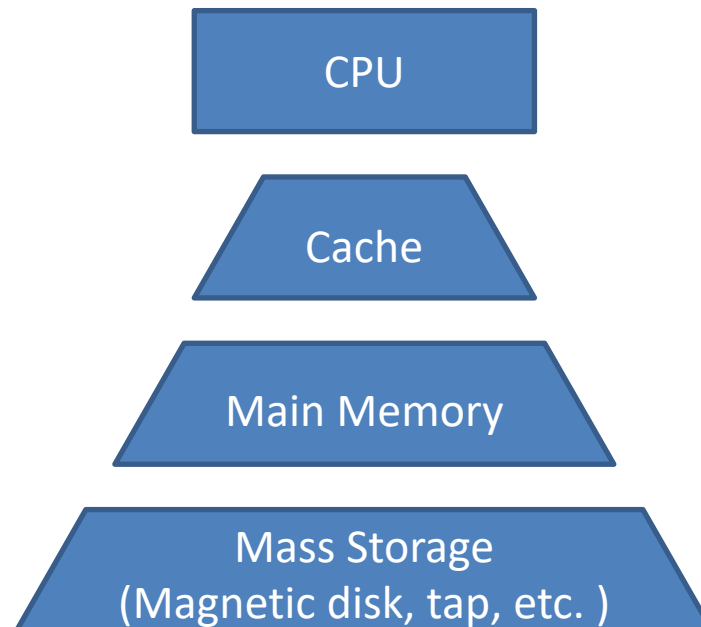
- In `storage.file` package: `Page` and `FileMgr`
 - *Access disks* as fast as possible
- In `storage.buffer` package: `Buffer` and `BufferMgr`
 - *Cache pages*
 - Work with recover manager to ensure A and D
- In `storage.record` package: `RecordPage` and `RecordFile`
 - *Arrange records in pages*
 - *Pin/unpin buffers*
 - Work with recover manager to ensure A and D
 - Work with concurrency manager to ensure C and I
- `Index`
- `CatalogMgr`

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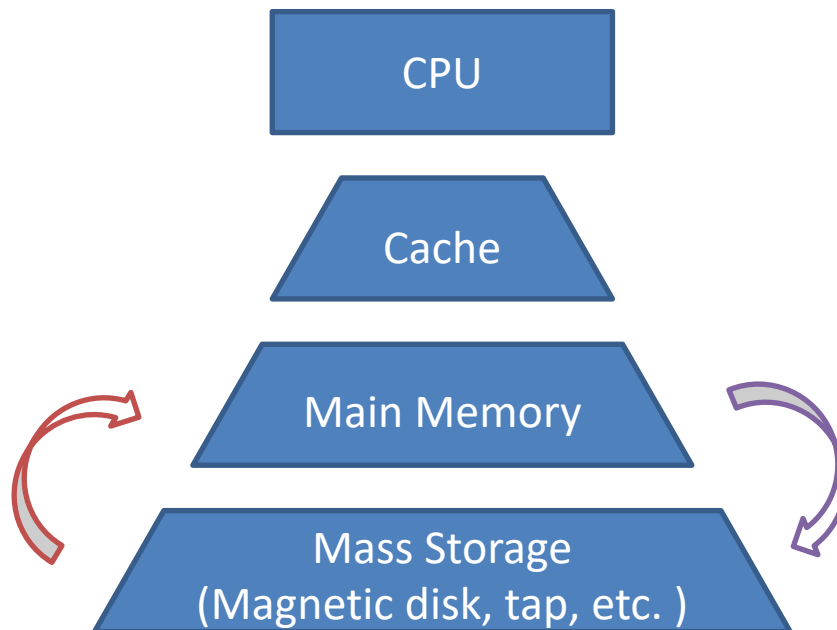
Why Disks?

- The contents of a database must be kept in ***persistent storages***
 - So that the data will not lost if the system goes down, ensuring D



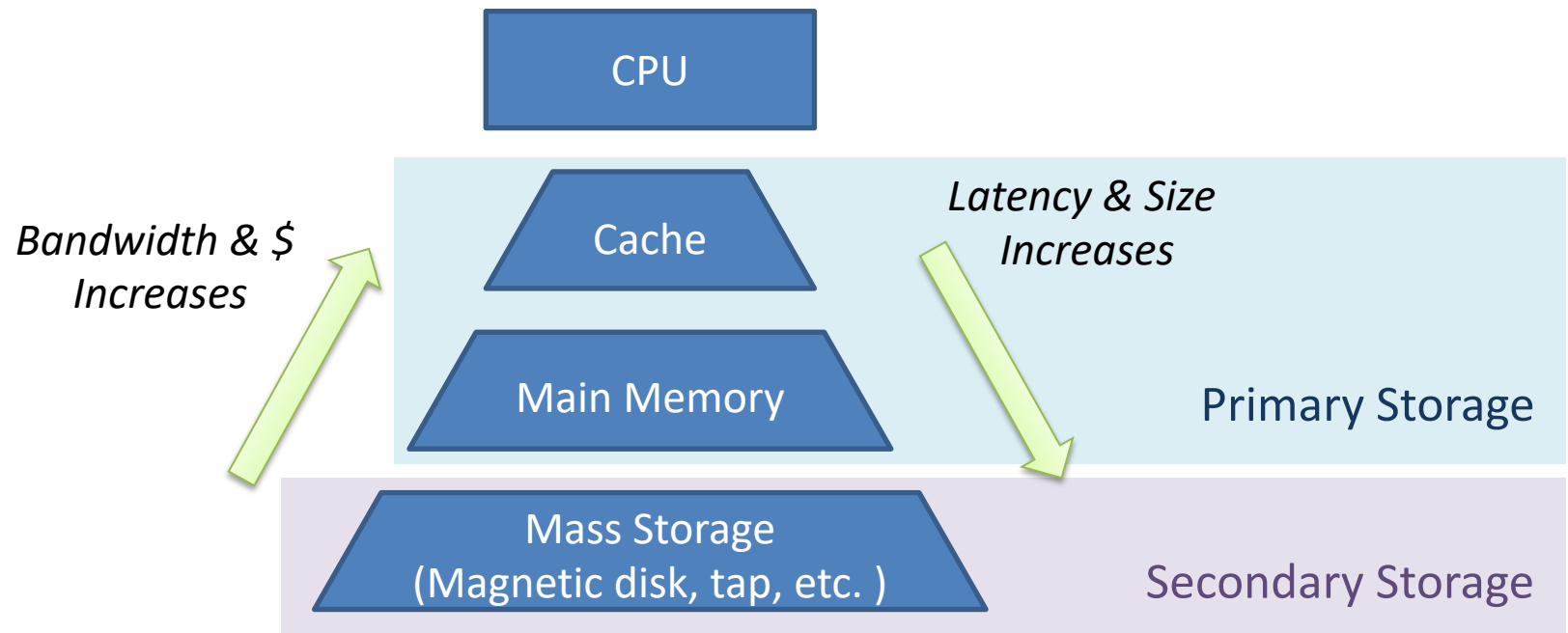
Disk and File Management

- I/O operations:
 - **Read**: transfer data from disk to main memory (RAM)
 - **Write**: transfer data from RAM to disk



Speed and \$

- Primary storage is fast but small
- Secondary storage is large but *slow*

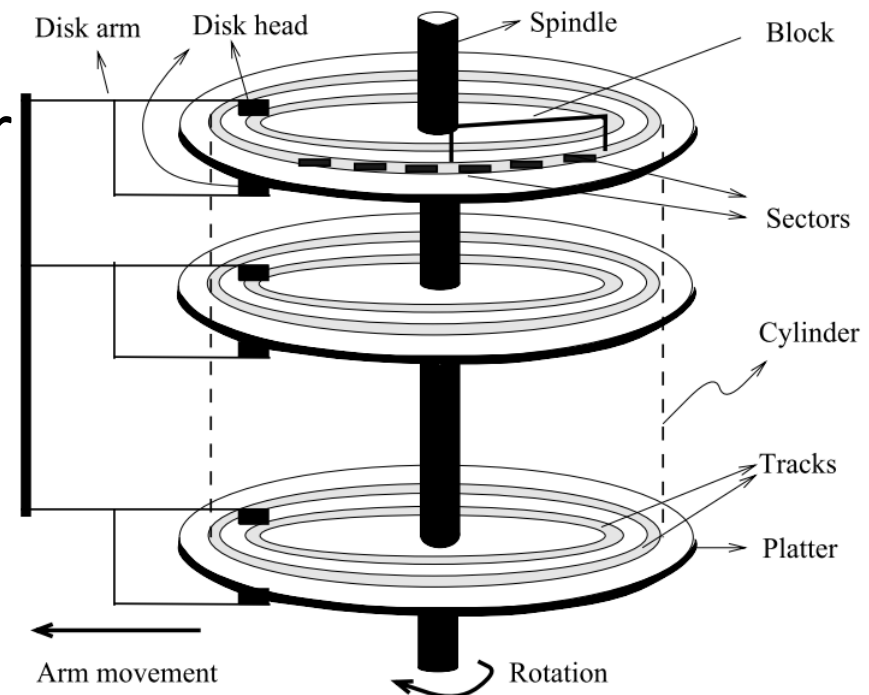


How Slow?

- Typically, accessing a block requires
 - ~60ns on RAMs
 - ~6ms on HDDs
 - ~0.06ms on SSDs
- HDDs are 100,000 times slower than RAMs!
- SSDs are 1,000 times slower than RAMs!

Understanding Magnetic Disks

- Data are stored on disk in units called **sectors**
- **Sequential access** is faster than **random access**
 - The disk arm movement is slow
- Access time is the sum of the **seek time**, **rotational delay**, and **transfer time**



From Database Management System 2/e, Ramakrishnan.

Access Delay

- Seek time: 1~20ms
- Rotational delay: 0~10ms
- Transfer rate is about 1ms per 4KB page
- Seek time and rotational delay dominate

How about SSDs?

- Typically under 0.1ms delay for random access
- Sequential access may still be faster than random access
 - SSDs *always read/write an entire block* even when only a small portion is needed
- But if reads/writes are all comparable in size to a block, there will be no much performance difference

OS's Disk Access APIs

- OS provides two disk access APIs:
- ***Block-level*** interface
 - A disk is formatted and mounted as a raw disk
 - Seen as a collection of blocks
- ***File-level*** interface
 - A disk is formatted and accessed by following a particular protocol
 - E.g., FAT, NTFS, EXT, NFS, etc.
 - Seen as a collection of files (and directories)

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Block-Level Abstraction

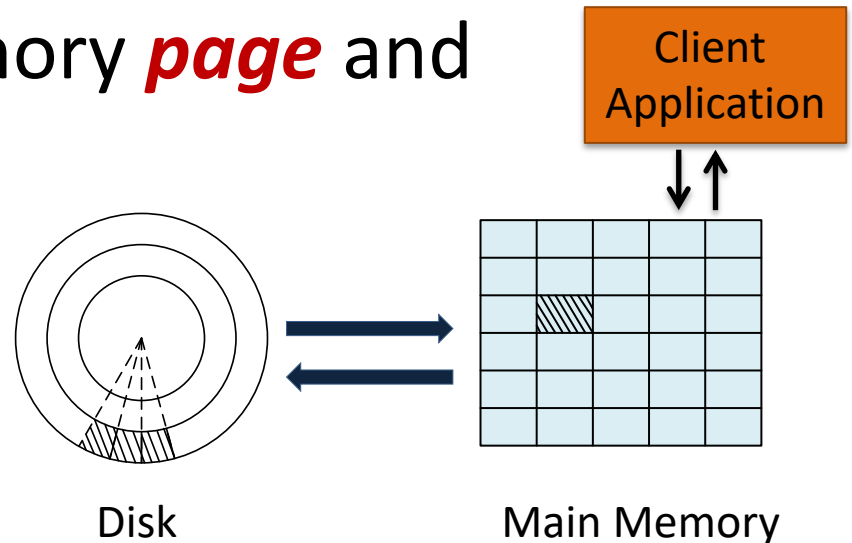
- Disks may have different hardware characteristics
 - In particular, different sector sizes
- OS hides the sectors behind ***blocks***
 - The unit of I/O above OS
 - Size determined by OS

Translation

- OS maintains the mapping between blocks and sectors
- Single-layer translation:
 - Upon each call, OS translates from the ***block number*** (starting from 0) to the actual sector address

Block-Level Interface

- The contents of a block cannot be accessed directly from the disk
 - May be mapped to more than one sectors
- Instead, the sectors comprising the block must first be read into a memory *page* and accessed from there
- *Page*: a block-size area in main memory



API

- `readblock(n, p)`
 - reads the bytes at block n into page p of memory
- `writeblock(n, p)`
 - writes the bytes in page p to block n of the disk
- OS also tracks of which blocks on disk are available for allocation
- `allocate(k, n)`
 - finds k contiguous unused blocks on disk and marks them as used
 - New blocks should be located as close to block n as possible
- `deallocate(k, n)`
 - marks the k contiguous blocks starting with block n as unused

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File-Level Abstraction

- OS provides another, higher-level interface to the disk, called the *file system*
- A file is a sequence of bytes
- Clients can read/write any number of bytes starting at any position in the file
- *No notion of block* at this level

File-Level Interface

- E.g., the Java class `RandomAccessFile`
- To increment 4 bytes stored in the file “file1” at offset 700:

```
RandomAccessFile f = new RandomAccessFile("file1", "rws");

f.seek(700);
int n = f.readInt(); // after reading pointer moves to 704

f.seek(700);
f.writeInt(n + 1);

f.close();
```

Block Access?

- Yes!
 - What does the “s” mode mean?

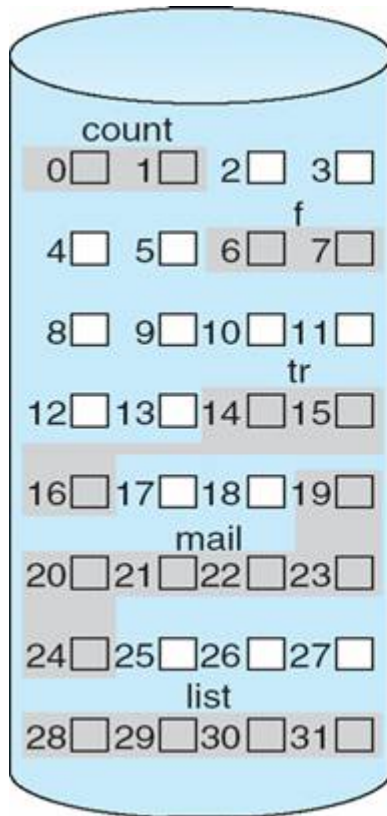
```
RandomAccessFile f =  
    new RandomAccessFile("file1", "rws");  
...  
f.writeInt(...);
```

- OS hides the pages, called ***I/O buffers***, for file I/Os
- OS also hides the blocks of a file

Hidden Blocks of a File

- OS treats a file as a sequence of *logical blocks*
 - For example, if blocks are 4096 bytes long
 - Byte 700 is in logical block 0
 - Byte 7992 is in logical block 1
- Logical blocks \neq physical blocks (that format a disk)
- Why?

Continuous Allocation



directory		
file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

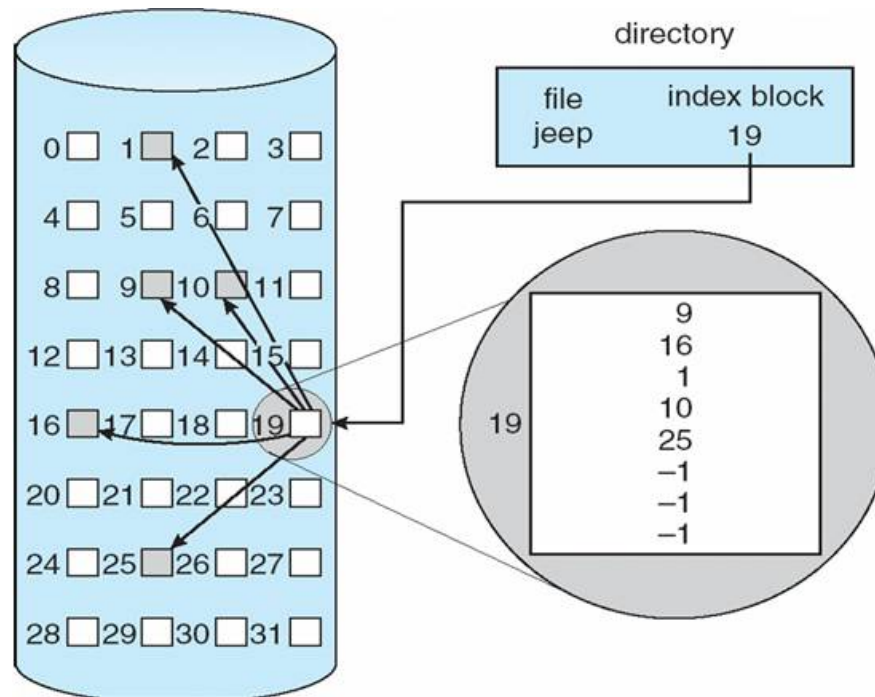
- Stores each file in continuous physical blocks
- Cons:
 - Internal fragmentation
 - External fragmentation

Extent-Based Allocation

- Stores a file as a fixed-length sequence of *extents*
 - An extent is a continuous chunk of physical blocks
- Reduces external fragmentation only

Indexed Allocation

- Keeps a special ***index block*** for each file
 - Which records of the physical blocks allocated to the file



Translation

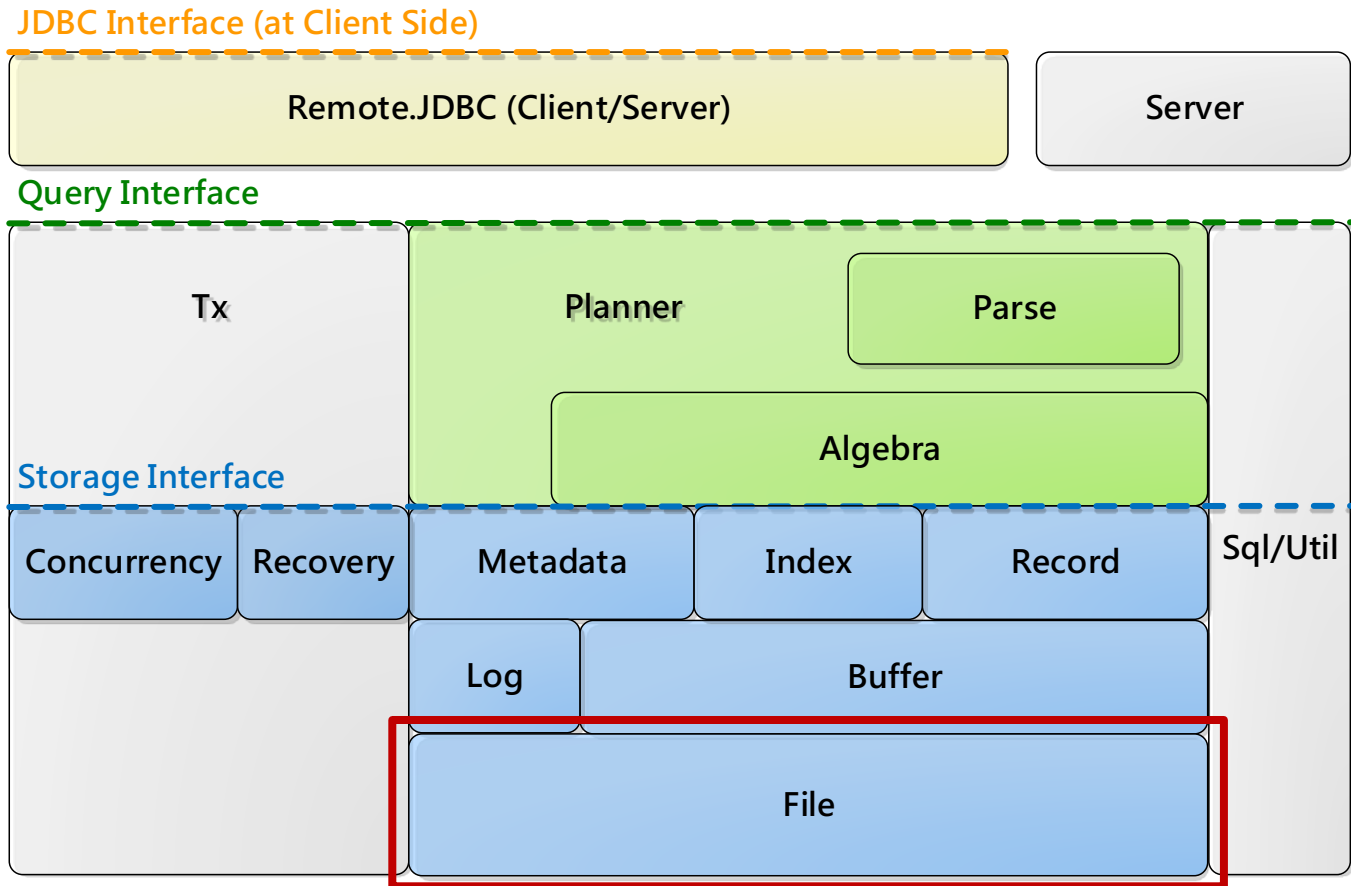
- OS maintains the mapping between logical and physical blocks
 - Specific to file system implementation
- When `seek` is called
- Layer 1: byte position → logical block
- Layer 2: logical block → physical block
- Layer 3: physical block → sectors

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File Manager

VanillaCore



Design Goal

- To access data in disks as fast as possible
- Two choices:
 - Based on the low-level block API
 - Based on the file system
- At which level?

Block-Level Based

- Pros:
 - Full control of physical positions of data
 - E.g., blocks accessed together can be stored nearby on disk, or
 - Most frequent blocks at middle tracks, etc.
 - Avoids OS limitations
 - E.g., larger files (even spanning multiple disks)

Block-Level Based

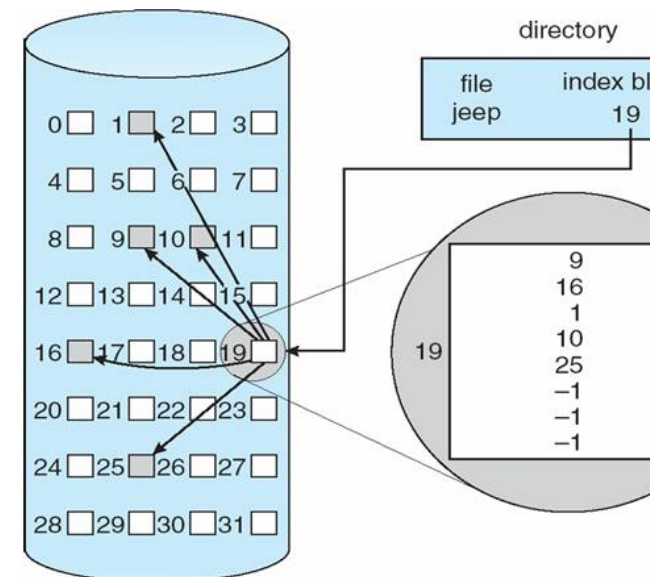
- Cons:
 - **Complex** to implement
 - Needs to manage the entire disk partitions and its free space
 - Inconvenient to some utilities such as (file) backups
 - “Raw disk” access is often OS-specific, which hurts portability
- Adopted by some commercial database systems that offer extreme performance

File-Level Based

- Pros:
 - Easy and convenient
- Cons:
 - Loses control to physical data placement
 - Loses track of pages (and their replacement)
 - Some implementations (e.g., postponed or reordered writes) **destroy correctness** (e.g., WAL)
- DBMS must flush by itself to guarantee ACID

VanillaCore's Choice

- A compromised strategy: at file-level, but access logical blocks directly
- Pros:
 - Simple
 - Manageable locality within a block
 - Manageable flush time (for correctness)
- Cons:
 - Needs to assume random disk access at all time
 - ***Even in sequential scans***
- Fast → minimizing #I/Os
- Adopted by many DBMS too
 - Microsoft Access, Oracle, etc.



Files

- A VanillaCore database is stored in several files under the database directory
 - One file for each table and index
 - Including catalog files
 - E.g., xxx.tbl, tblcat.tbl
 - Log files
 - E.g., vanilladb.log

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File Management

- BlockId, Page and FileMgr
- In package:
`org.vanilladb.core.storage.file`

BlockId

- Immutable
- Identifies a specific logical block
 - A file name + logical block number
- For example,
 - `BlockId blk = new BlockId("std.tbl", 23);`

BlockId
+ BlockId(filename : String, blknum : long) + fileName() : String + number() : long + equals(Object : obj) : boolean + toString() : String + hashCode() : int

Page

- Holds the contents of a block
 - Backed by an I/O buffer in OS
- **Not** tied to a specific block
- Read/write/append an entire block a time
- Set values are **not** flushed until `write()`

Page
<u><<final>> + BLOCK_SIZE : int</u>
<u>+ maxSize(type : Type) : int</u> <u>+ size(val : Constant) : int</u> + Page() <<synchronized>> + read(blk : BlockId) <<synchronized>> + write(blk : BlockId) <<synchronized>> + append(filename : String) : BlockId <<synchronized>> + getVal(offset : int, type : Type) : Constant <<synchronized>> + setVal(offset : int, val : Constant) + close()

FileMgr

- Singleton, shared by all `Page` instances
- Handles the actual I/Os
- Keeps all opened files of a database
 - Each file is opened once and shared by all worker threads

FileMgr
<u><<final>> + HOME_DIR : String</u> <u><<final>> + LOG_FILE_BASE_DIR : String</u> <u><<final>> + TMP_FILE_NAME_PREFIX : String</u>
+ FileMgr(dbname : String) ~ read(blk : BlockId, bb : IoBuffer) ~ write(blk : BlockId, bb : IoBuffer) ~ append(filename : String, bb : IoBuffer) : BlockId + size(filename : String) : long + isNew() : boolean

Using the VanillaCore File Manager

```
VanillaDb.initFileMgr("studentdb");
FileMgr fm = VanillaDb.fileMgr();

BlockId blk1 = new BlockId("student.tbl", 0);
Page p1 = new Page();
p1.read(blk1);
Constant sid = p1.getVal(34, Type.INTEGER);
Type snameType = Type.VARCHAR(20);
Constant sname = p1.getVal(38, snameType);
System.out.println("student " + sid + " is " + sname);

Page p2 = new Page();
p2.setVal(34, new IntegerConstant(25));
Constant newName = new VarcharConstant("Rob").castTo(snameType);
p2.setVal(38, newName);
BlockId blk2 = p2.append("student.tbl");
```

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I/O Interfaces

- Between VanillaCore and JVM/OS
- Two choices (both at file level):
 - Java New I/O
 - Jaydio (`O_Direct`, Linux only)
- To switch between these implementations, change the value of `USING_O_Direct` property in `vanilladb.properties` file

Java New I/O

- Each page wraps a `ByteBuffer` instance to store bytes
- `ByteBuffer` has two factory methods: `allocate` and **`allocateDirect`**
 - `allocateDirect` tells JVM to use one of the OS's I/O buffers to hold the bytes
 - ***Not*** in Java programmable buffer, no garbage collection
 - Eliminates the redundancy of ***double buffering***

Jaydio

- Provides similar interfaces to Java New I/O
- But with `O_Direct`
 - Some file systems (on Linux) **cache** file pages in its buffers for better performance
 - `O_Direct` tells those file systems **not** to cache file pages as we will implement our own caching policy (to be discussed in the next lecture)
 - Only available on Linux

Assigned Reading

- Java new I/O
 - In `java.nio`
- **Classes:**
 - `ByteBuffer`
 - `FileChannel`

References

- Ramakrishnan Gehrke, Database management System 3/e, chapters 8 and 9
- Edward Sciore, Database Design and Implementation, chapter 12
- Hellerstein, J. M., Stonebraker, M., and Hamilton, J., Architecture of a database system, 2007
- Hussein M. Abdel-Wahab, CS 471 – Operating Systems Slides, <http://www.cs.odu.edu/~cs471w/>