Data Access and File Management

vanilladb.org

Outline

- Storage engine and data access
- Disk access
  - Block-level interface
  - File-level interface
- File Management in VanillaCore
  - BlockID
  - Page
  - FileMgr

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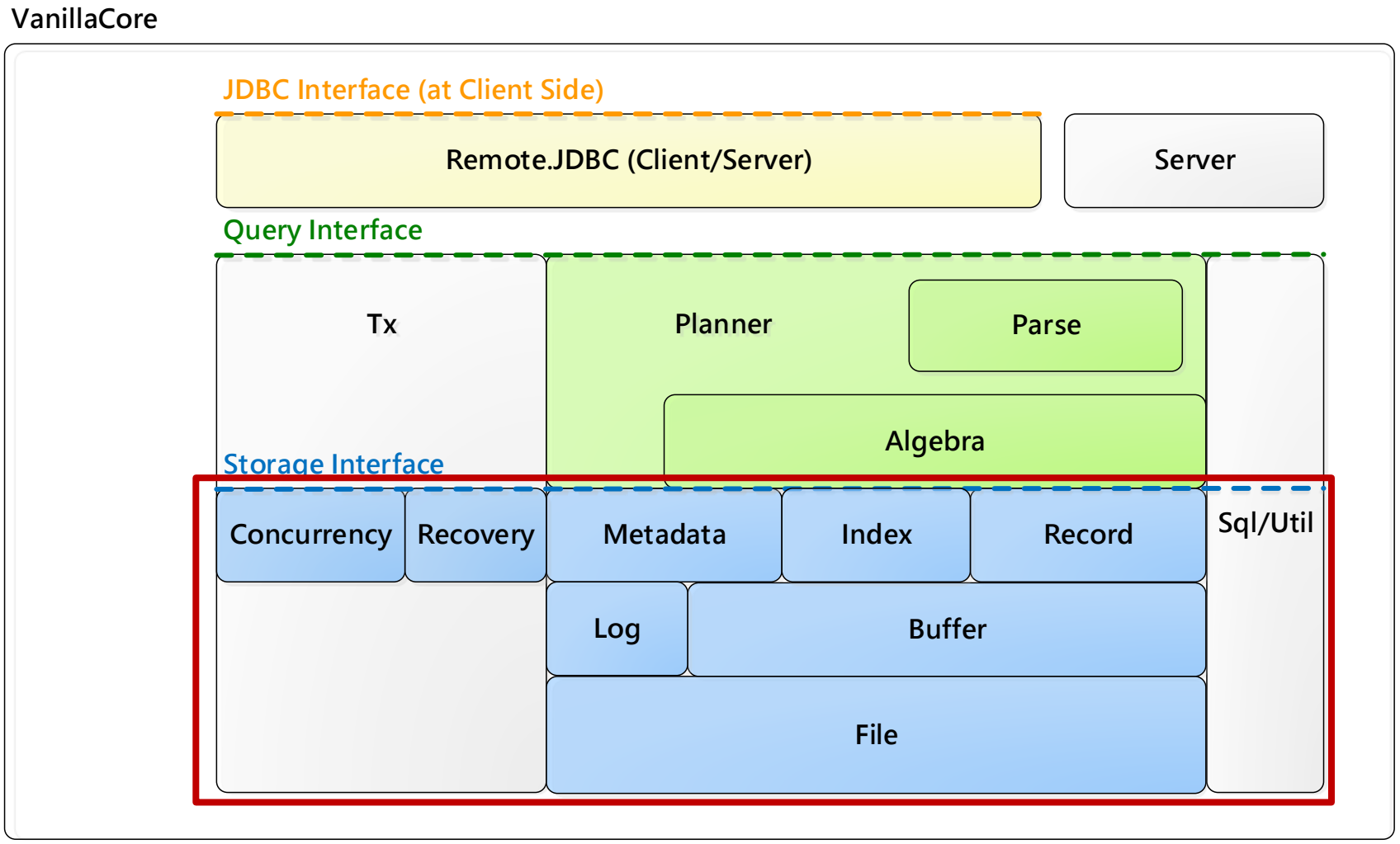
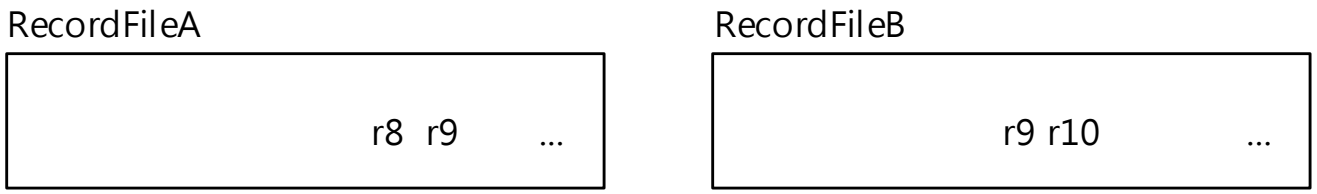
Storage Engine

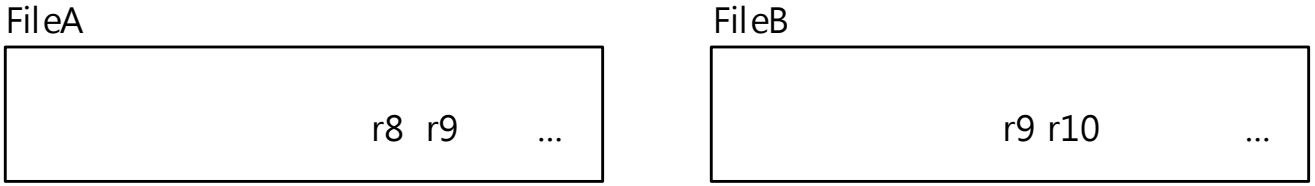


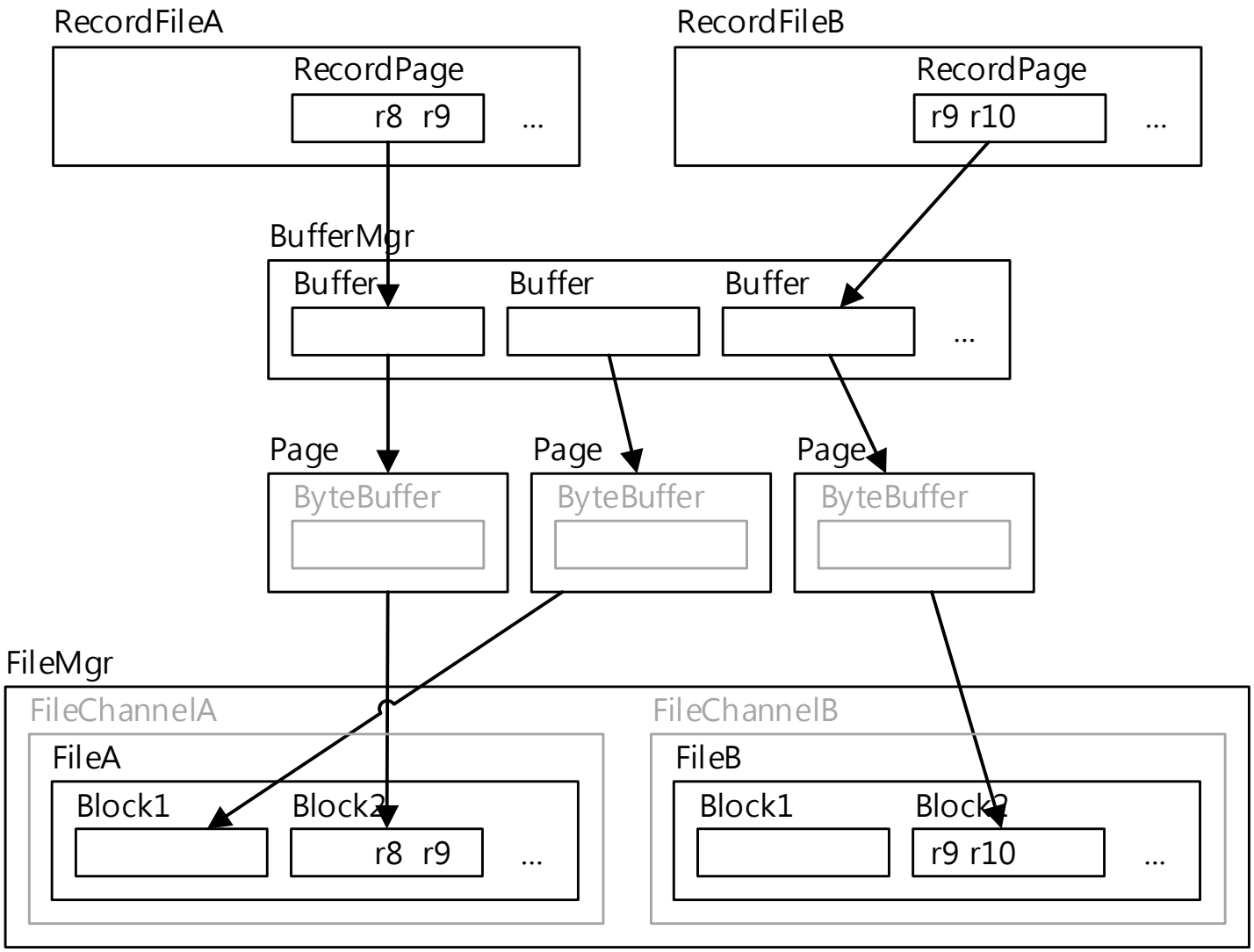
Storage Engine

- 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`)



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




RecordFileA
RecordPage
r8 r9
...
RecordFileB
RecordPage
r9 r10
...
BufferMgr
Buffer
Buffer
Buffer
...
Page
Page
Page
ByteBuffer
ByteBuffer
ByteBuffer
FileMgr
FileChannelA
FileChannelB
FileA
Block1
Block2
r8 r9
...
FileB
Block1
Block2
r9 r10
...

Why So Complicated?

- We need to store data in disks
- But I/O is (very) slow
  - Potentially slow scans
- Target: to minimize the frequency of I/Os required by each scan
- Design choices:
  - Block data access
  - Manage the caching of blocks by DBMS itself

Data Access Layers (Bottom Up)

- `Page` and `FileMgr`
  - ***Block-level disk access***
  - In `storage.file` package
- `Buffer` and `BufferMgr`
  - ***Cache pages***
  - Work with recover manager to ensure A and D
  - In `storage.buffer` 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
  - In `storage.record` package
- `Index`
- `CatalogMgr`

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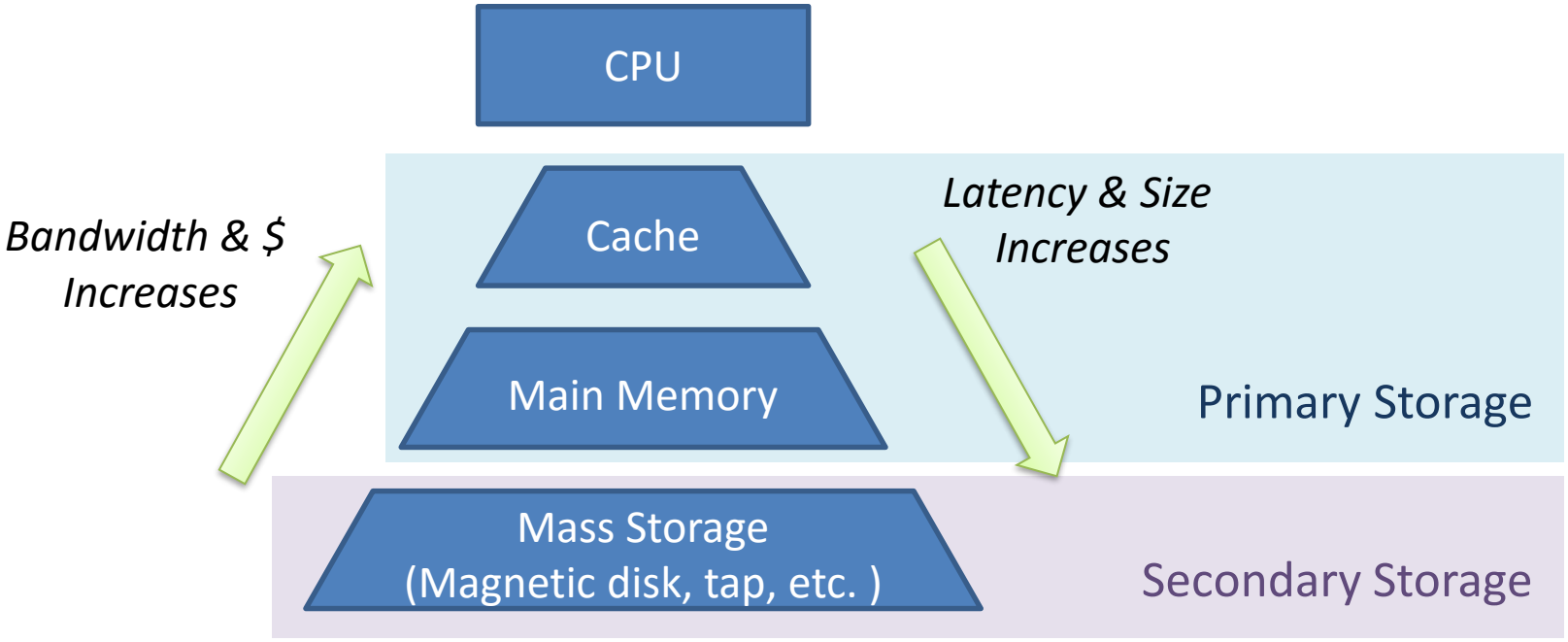
Why Disks?

- 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

The Storage Hierarchy in Computers

- Primary storage is usually volatile
- Secondary storage is usually (very) slow

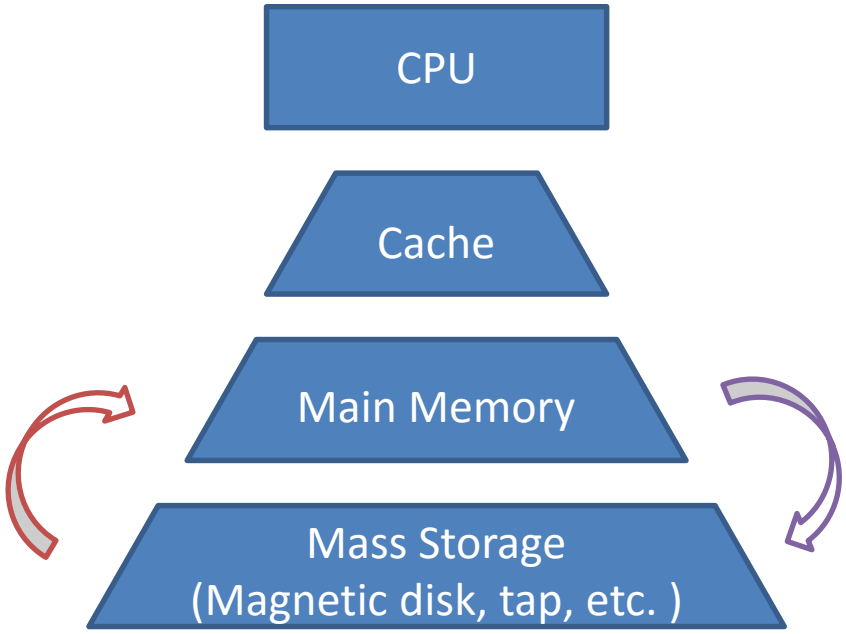


How Slow?

- 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!

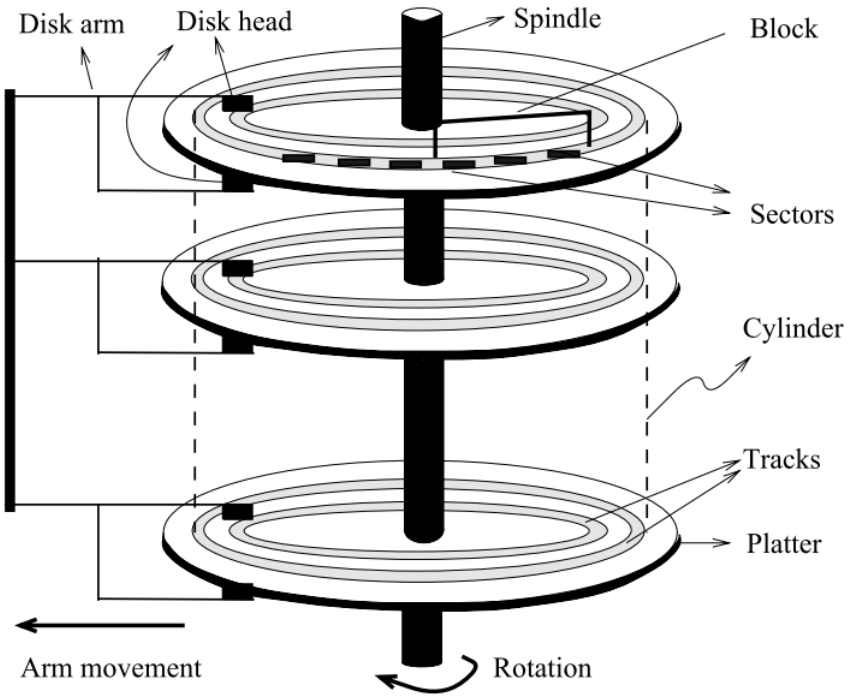
Disk and File Management

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



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

How about SSDs?

- Typically under 0.1 ms delay for random access
- Sequential access may still be faster than random access
  - SSDs 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 Interface

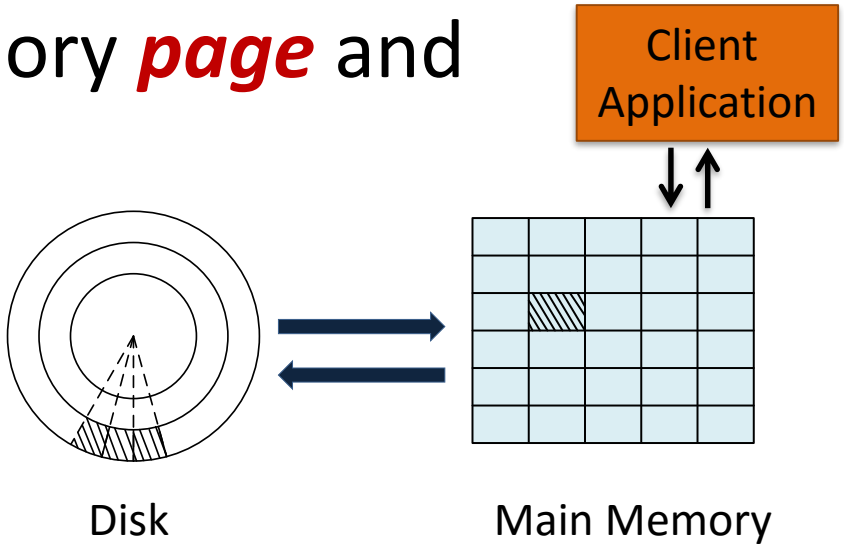
- Disks may have different hardware characteristics
  - In particular, different sector sizes
- OS hides the sectors behind ***blocks***
  - The unit of I/O above OS
  - Size determined by OS

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



Block-Level Interface to the Disk

- Example 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
  - `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
- OS also tracks of which blocks on disk are available for allocation

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File-Level Interface

- 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();
```

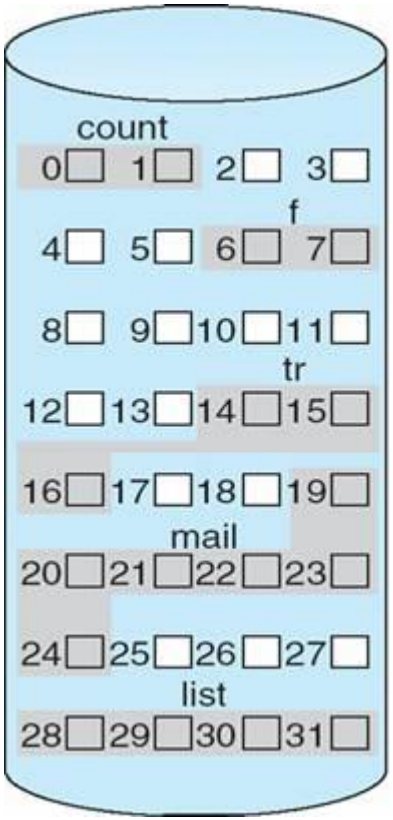
File-Level Interface

- Note that the calls to `readInt` and `writeInt` act as if the disk were being accessed directly
- Block access?
  - Yes
  - What does the “s” mode mean?
- 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 ≠ physical blocks (that format a disk)
- OS maintains the mapping between the logical and physical blocks
  - Specific to file system implementation

Continuous Allocation



directory

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

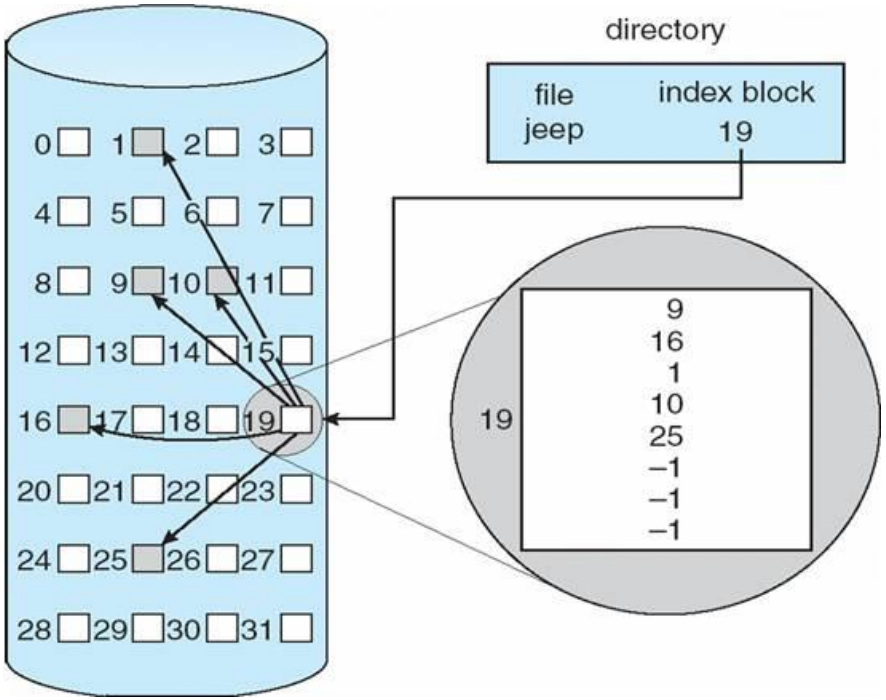
- Stores each file in continuous physical blocks
- Cons:
  - Internal fragmentation
  - External fragmentation

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



From Hussein M. Abdel-Wahab, CS 471 – Operating Systems Slides. http://www.cs.odu.edu/~cs471w/

Translation

- 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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Disk Manager

- Target: access data in disks as fast as possible
- Two types:
  - Based on the low-level block API
  - Based on the file system

- At which level?

Block-Level Based

- Pros:
  - Full control to the 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

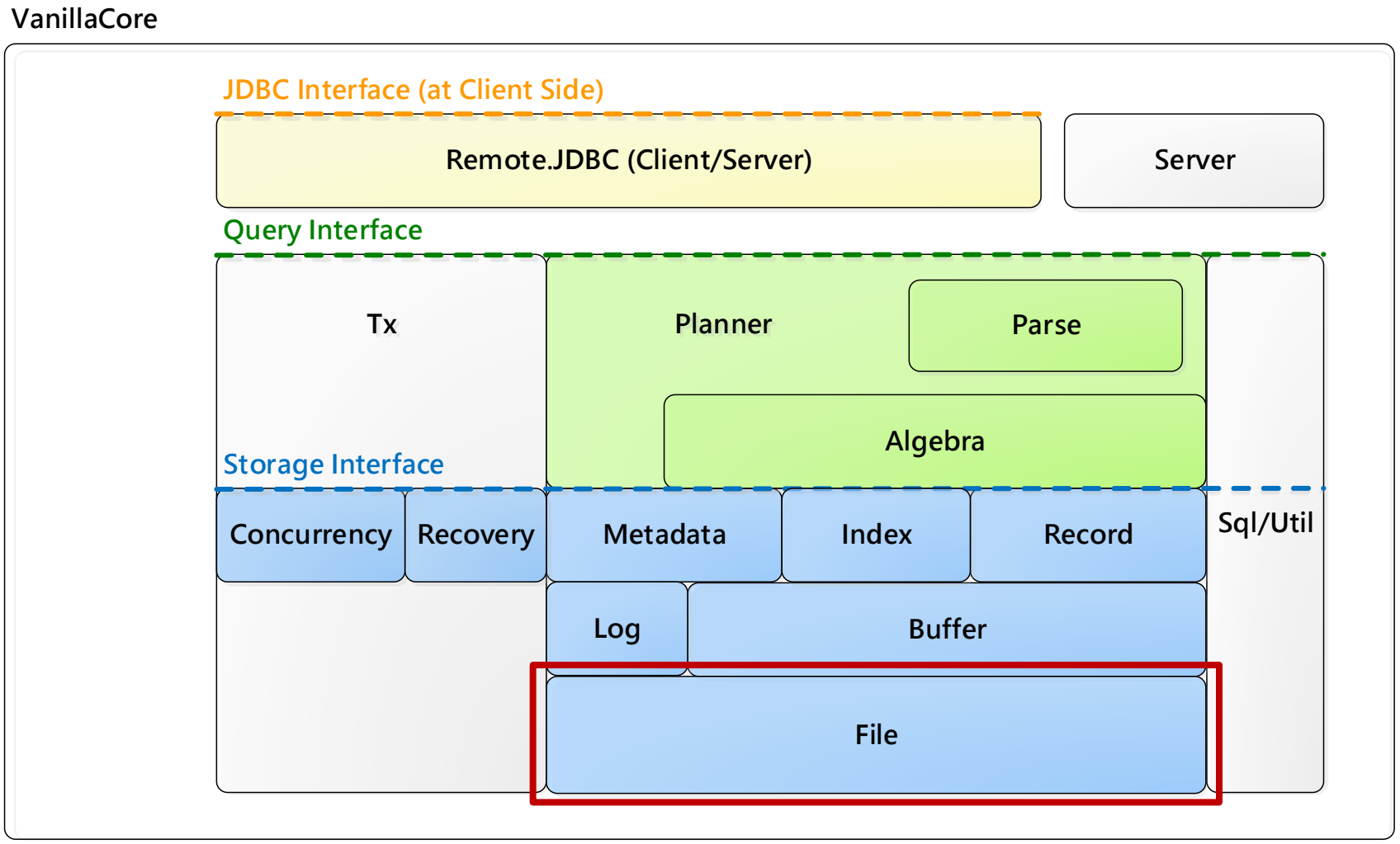
VanillaCore's Choice

- A compromise strategy: at file-level, but access logical blocks directly
- Pros:
  - Simple
  - Manageable locality in a block
  - Manageable pages (provided not swapped by OS)
- Cons:
  - Needs to assume random disk access across blocks
  - ***Even in sequential scans***
- Minimizing I/Os → minimizing block access
- Adopted by many DBMS too
  - Microsoft Access, Oracle, etc.

File Manager

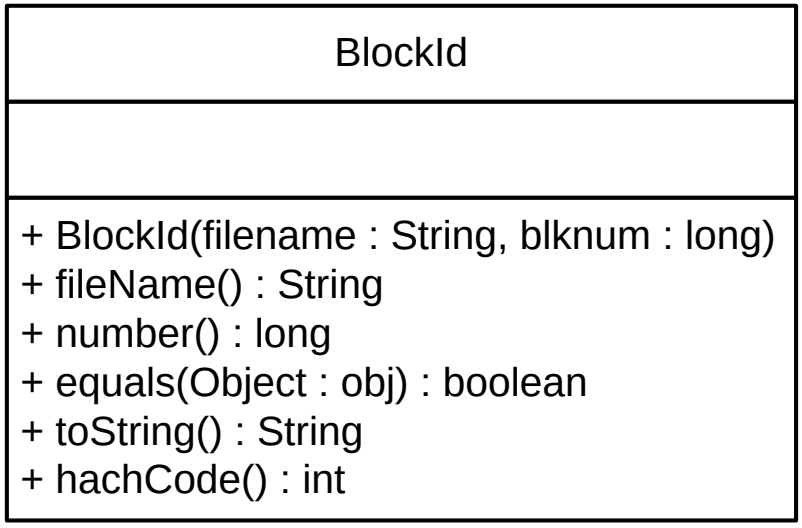
- `BlockId`, `Page` and `FileMgr`
- In package: `org.vanilladb.core.storage.file`

File Manager



BlockId

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



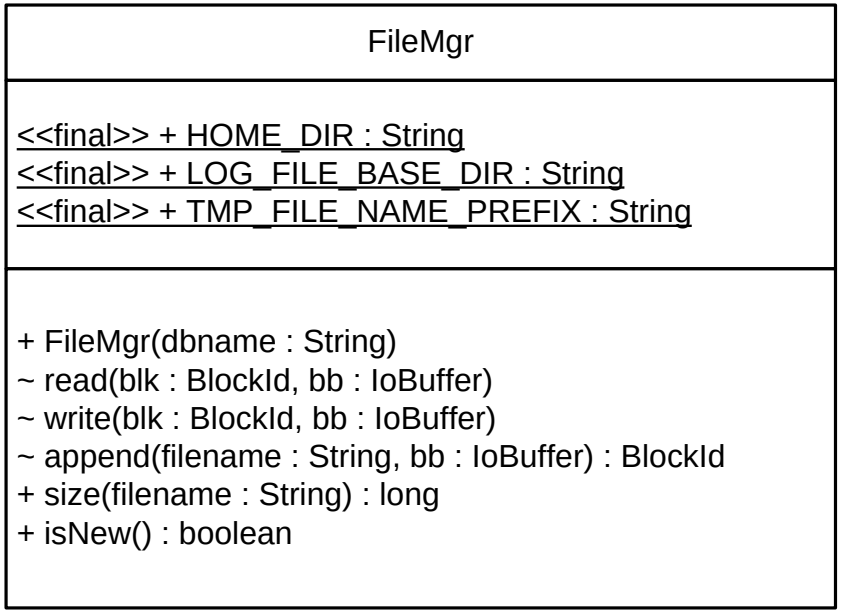
Page

- 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

Page
<<final>> + BLOCK_SIZE : int
+ maxSize(type : Type) : int + size(val : Constant) : int + 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
- Keeps all opened files of a database
  - Each file is opened once and shared by all worker threads
- Wrapped by pages
- Handles the actual I/Os



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");
```

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

I/O Interfaces

- Between VanillaCore and the outside world (i.e., JVM and OS)
- Two implementations:
  - 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

- Java New I/O provides `ByteBuffer` to store bytes and `FileChannel` to access files
- `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

- Jaydio provides similar interfaces to Java New I/O
- The only difference we considered to use it was it provides `O_Direct`
  - Some file systems (on Linux) ***cache*** file pages in its buffers for the performance reason
  - `O_Direct` tells those file systems ***not*** to cache file pages as we have already had our own buffers
  - It is 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/