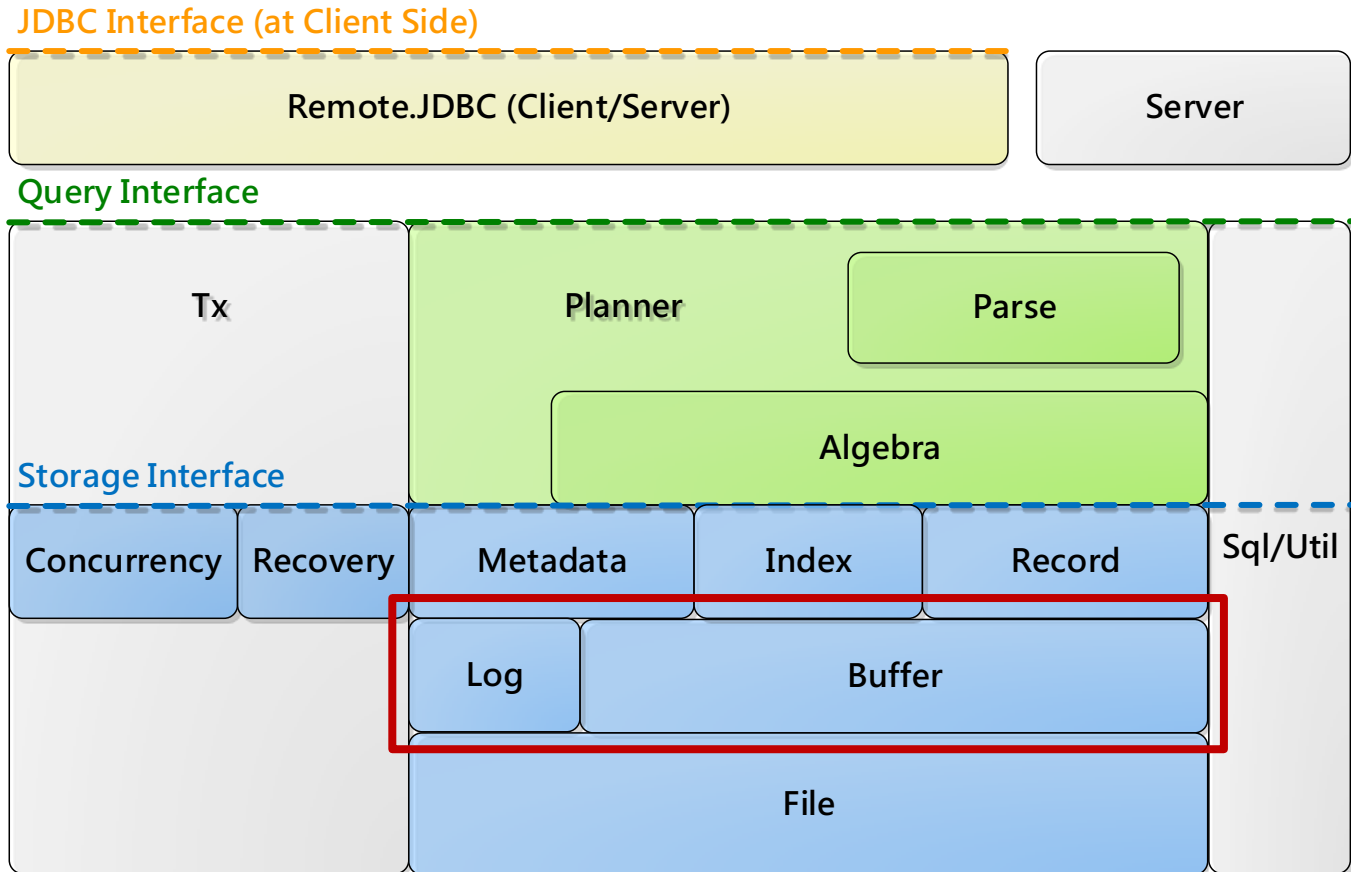


Memory Management

Shan-Hung Wu & DataLab
CS, NTHU

Memory Management

VanillaCore



Outline

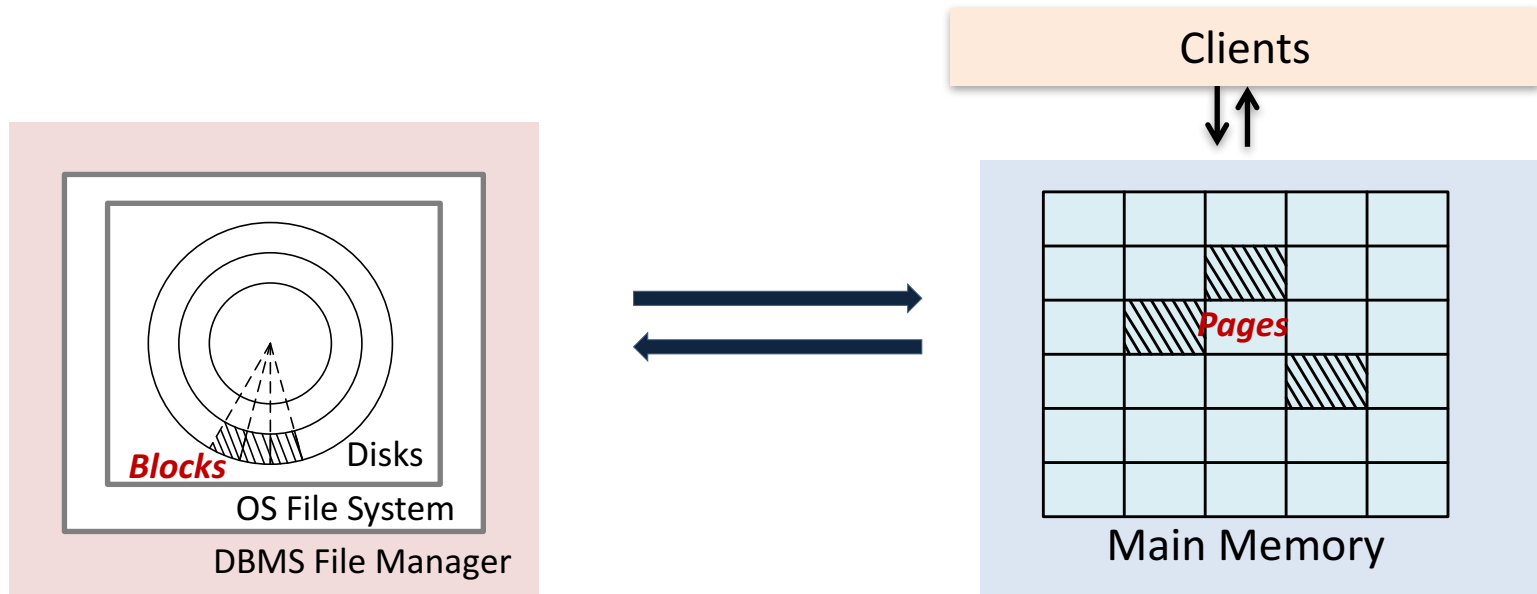
- Overview
- Buffering User Data
- Caching Logs
- Log Manager in VanillaCore
- Buffer Manager in VanillaCore

Outline

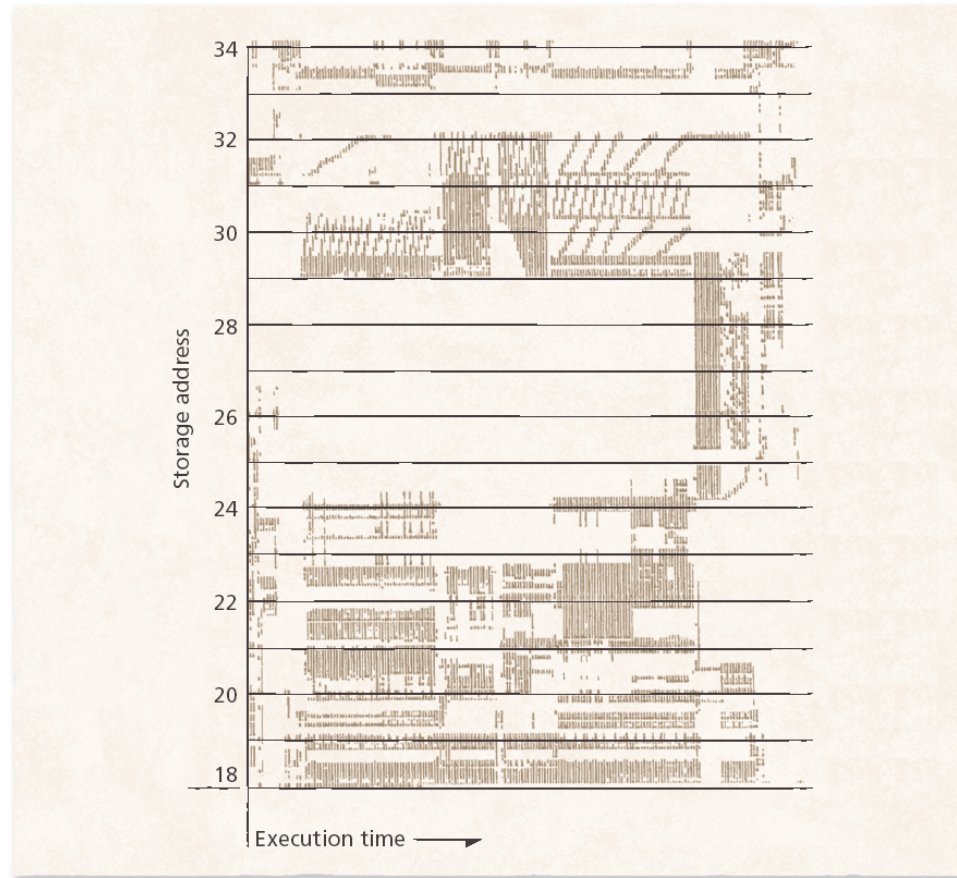
- **Overview**
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- Buffer Manager in VanillaCore

Consequences of Slow I/Os

- Architecture that minimizes I/Os:
 - Block access to/from disks
 - Self-managed caching of blocks
 - Choose the plan that costs least (fewest block I/Os)



Storage Access Patterns



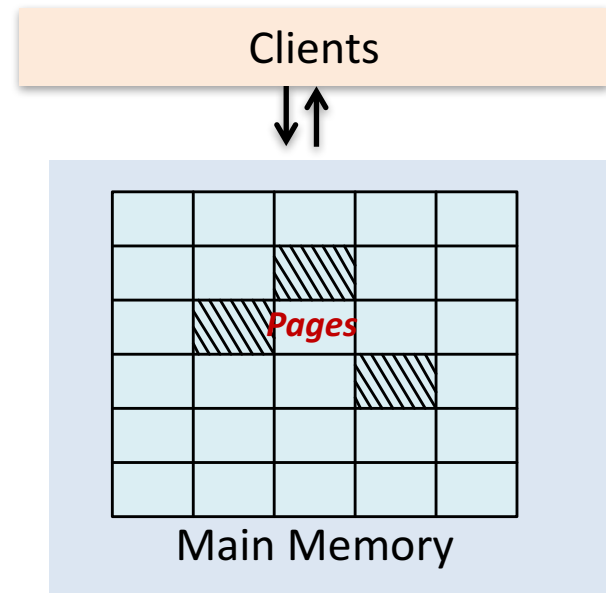
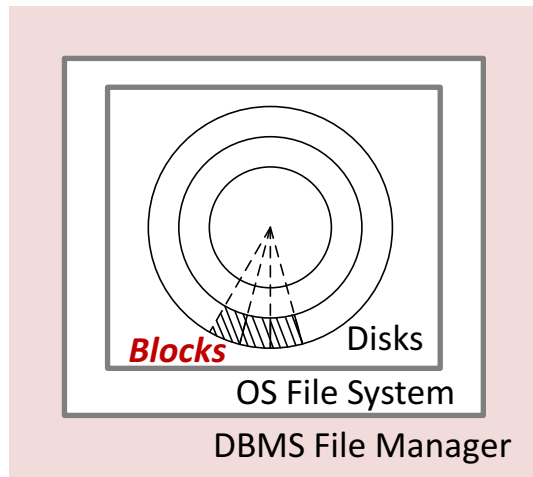
IBM Systems Journal, 1971

Storage Access Patterns

- ***Spatial locality***: each client (e.g., scan) focuses on a small number of blocks a time
 - Despite ending up with huge block accesses
 - E.g., to produce the next output record, a product scan needs only two blocks a time (left and right)
- ***Temporal locality***: recently used blocks are likely to be used in the near future
 - E.g., blocks of catalogs

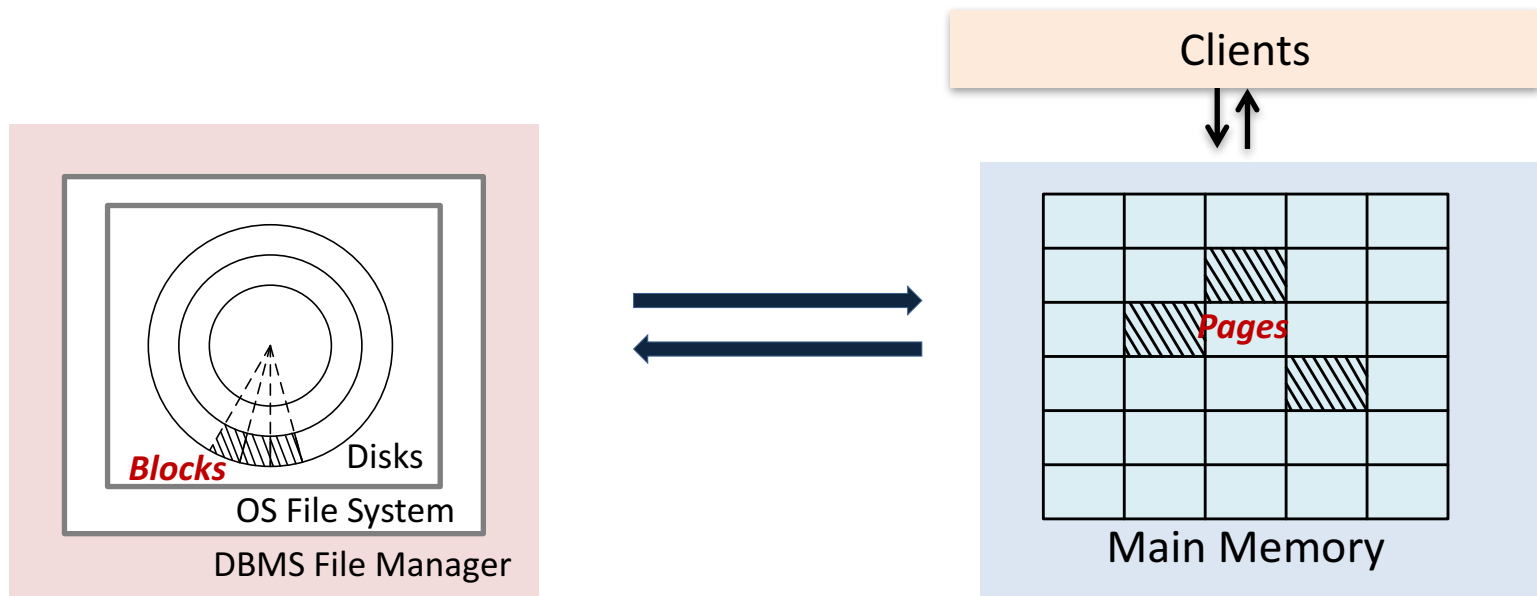
Minimizing Disk Access by Caching

- Idea: to reserve a pool of pages that keep the contents of most currently used blocks
 - To *swap in/out* blocks only when there's no empty page left in the pool



Benefits

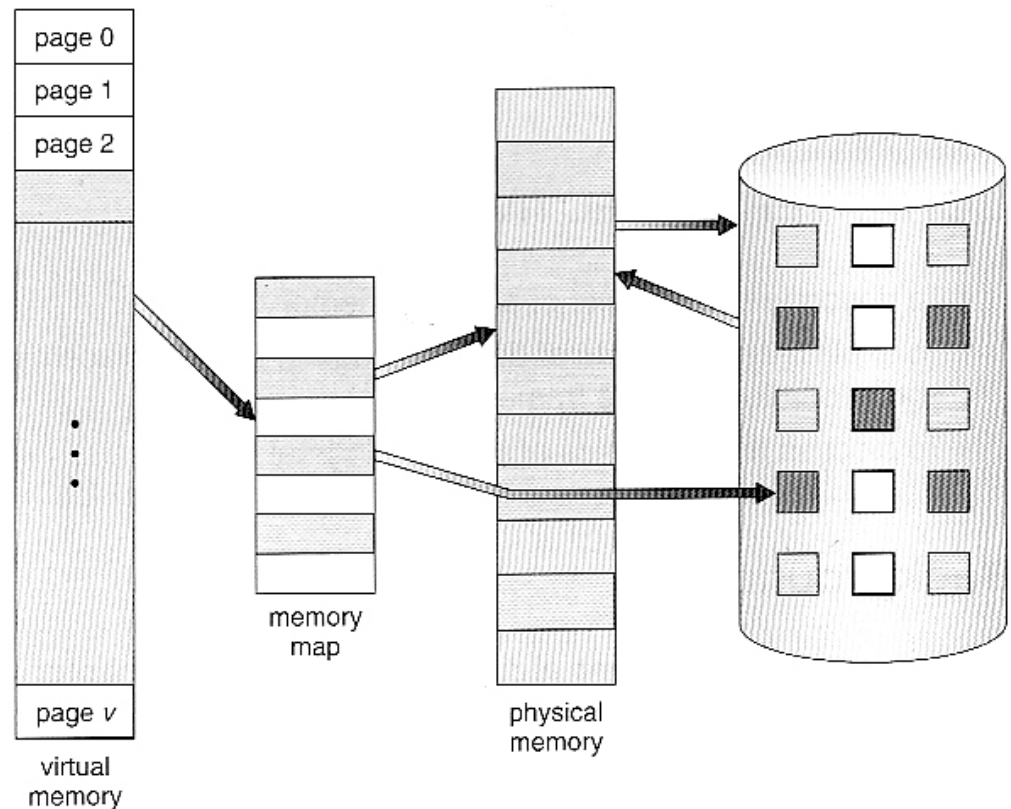
- Economic: only small memory space required
- Saves reads (if a requested block hits a page)
- Saves writes: all values set to a block only need to be written once upon swapping



Why not virtual memory?

Virtual Memory

- Modern OSs support *virtual memory*
- Illusion: a very large address space for each process
 - Larger than physical memory



Don't Rely on Virtual Memory (1/2)

- Problem 1: bad page replacement algorithms
 - E.g., FIFO, LRU, etc.
- OS has no idea which blocks will definitely be used by a process in the near future
 - E.g., in a product scan, DBMS knows it's best to hold a left-child block at all time during scanning the right-child (as a select)
 - But OS doesn't

Don't Rely on Virtual Memory (2/2)

- Problem 2: uncontrolled delayed writes
 - Swapping is automatic
- When powered off, dirty pages may gone
 - Impairs the DBMS ability to recover after a system crash
 - Hurts durability of committed transactions
- Immediate writes?
 - Impairs the caching
 - Data may still corrupt due to partial writes upon crash
- Meta-writes (of logs) are needed

Self-Managed Pages in DBMS

- Pros:
- Controlled swapping
 - Fewer I/Os than VM via better replacement strategy
 - DBMS can tell which page must/cannot be flushed
- Supports meta-writes
 - DBMS can write logs to recover from crashes

What Blocks to Cache?

- Those of user data (DBs, including catalogs)
 - Pages for these blocks are managed by the *buffer manager*
- Those of logs
 - In meta-writes
 - Pages managed by the *log manager*

Outline

- Overview
- **Buffering User Data**
- Caching Logs
- Log Manager in VanillaCore
- Buffer Manager in VanillaCore

Access Pattern to User Blocks


- **Random** block reads and writes
 - From clients directly
 - Even from sequential scans (if above OS file system)
- Concurrent access to **multiple** blocks by multiple threads
 - Each thread per, e.g., JDBC client
- **Predictable** access to certain blocks
 - Each scan needs certain blocks a time
 - In particular, a table scan need one block a time and can forget what just read

Buffer Manger

- To reduce I/Os, the buffer manager allocates a pool of pages, called *buffer pool*
 - Caching multiple blocks
 - Implement swapping
- Pages should be the direct I/O buffers held by the OS
 - Avoids swapping by VM
 - Eliminates the redundancy of double buffering
 - E.g., `ByteBuffer.allocateDirect()`

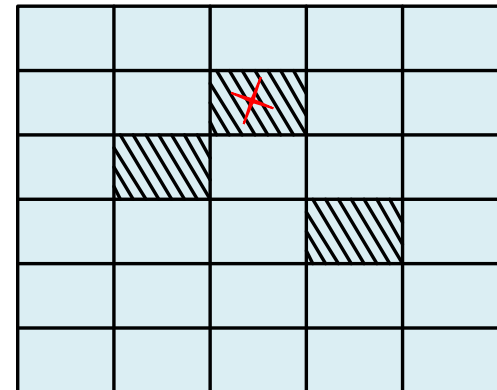
How do make use of predictable block accesses to further reduce I/Os?

Pinning Blocks

- Each table scan needs one block a time
 - The semantic of blocks is hidden behind the associated `RecordFile`
- It is the `RecordFile` instances that talk to memory manager about which blocks are needed
 - One instance per thread/client
- Through *pinning* 

Pinning Blocks

- When a `RecordFile` needs a block
 1. Asks buffer manager to **pin** (read-in) a block in some page
 2. Client accesses the contents of the page
 3. When the client is done with the block, it tells the buffer manager to **unpin** the block
- When swapping, only pages containing the **unpinned** blocks can be swapped out



Pinning Pages

- Results of pinning:
 1. A hit, no I/O
 2. Swapping: there exists at least one *candidate page* in the buffer pool holding unpinned block
 - Need to flush the page contents back to disk if the page is dirty
 - Which candidate page? *replacement strategies*
 - Then read in the desired block
 3. Waiting: all pages in the buffer pool are pinned
 - Wait until some other unpins a page

Buffers

- Each page in the buffer pool needs to associate with additional information:
 - Is contained block pinned?
 - Is contained block modified (dirty)?
 - Information required by the replacement strategy
- A *buffer* wraps a page and hold this information
- A block can be pinned and accessed by multiple clients
 - Buffer must be thread safe (same as page)
 - DBMS needs other mechanism (i.e., concurrency control) to serialize conflict operations to a buffer

Example API

BufferMgr
<u><<final>> # BUFFER_SIZE : int</u>
+ BufferMgr() <<synchronized>> + pin(blk : BlockId, txNum : long) : Buffer <<synchronized>> + pinNew(filename : String, fmtr : PageFormatter, txnum : long) : Buffer <<synchronized>> + unpin(txnum : long, buffs : Buffer[]) + flushAll(txnum : long) + available() : int

Buffer
~ Buffer() <<synchronized>> + getVal(offset : int, type : Type) : Constant <<synchronized>> + setVal(offset : int, val : Constant , txnum : long, lsn : long) <<synchronized>> + block() : BlockId <<synchronized>> ~ flush() <<synchronized>> ~ pin() <<synchronized>> ~ unpin() <<synchronized>> ~ isPinned() : boolean <<synchronized>> ~ isModifiedBy(txNum : long) : boolean <<synchronized>> ~ assignToBlock(b : BlockId) <<synchronized>> ~ assignToNew(filename : String, fmtr : PageFormatter)

- A block can be pinned multiple times
- There's no guarantee that `pin()`'s on the same block will return the same buffer instance

Buffer Replacement Strategies

- All buffers in the buffer pool begin unallocated
- Once all buffers are loaded, buffer manager has to replace the unpinned block in some *candidate buffer* to serve new pin request
- Best candidate?
 - The buffer containing block that will be unused for the longest time
 - Maximizes the hit rate of pins

Buffer Replacement Strategies

- However, as in VM, access of blocks in unpinned buffers is not determinable
- Heuristics needed:
 - Naïve
 - FIFO
 - LRU
 - Clock
- Some commercial systems use different heuristics for different *buffer type*
 - E.g., catalog buffers, index buffers, buffers for full table scan, etc.

Example

- A sequence of operations
 - `pin(10); pin(20); pin(30); pin(40);`
`unpin(20); pin(50); unpin(40);`
`unpin(10); unpin(30); unpin(50);`
- There are 4 buffers in buffer pool

Buffer	0	1	2	3
Block Id				
time read in				
time unpinned				

Example

- A sequence of operations
 - `pin(10); pin(20); pin(30); pin(40);`
`unpin(20); pin(50); unpin(40);`
`unpin(10); unpin(30); unpin(50);`
- There are 4 buffers in buffer pool

Buffer	0 ✖	1	2 ✖	3 ✖
Block Id	10	20	30	40
time read in	1	2	3	4
time unpinned		5		

Example

- A sequence of operations
 - `pin(10); pin(20); pin(30); pin(40);`
`unpin(20); pin(50); unpin(40);`
`unpin(10); unpin(30); unpin(50);`
- There are 4 buffers in buffer pool

Buffer	0 ✗	1	2 ✗	3 ✗
Block Id	10	20	30	40
time read in	1	2	3	4
time unpinned		5		

Example

- A sequence of operations
 - `pin(10); pin(20); pin(30); pin(40);`
`unpin(20); pin(50); unpin(40);`
`unpin(10); unpin(30); unpin(50);`
- There are 4 buffers in buffer pool

Buffer	0 ✗	1 ✗	2 ✗	3 ✗
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned		5		

Example

- A sequence of operations
 - `pin(10); pin(20); pin(30); pin(40);`
`unpin(20); pin(50); unpin(40);`
`unpin(10); unpin(30); unpin(50);`
- There are 4 buffers in buffer pool

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned	8	10	9	7

Example

- Suppose that there are two more pin requests coming:
 - `pin(60); pin(70);`
- Let's see how different replacement strategies work

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned	8	10	9	7

The Naïve Strategy

- Traverses the buffer pool sequentially from beginning
- Replaces the first unpinned buffer met
 - `pin(60); pin(70);`
- Easy to implement, but?

Buffer	0	1	2	3
Block Id	60	70	30	40
time read in	11	12	3	4
time unpinned	8	10	9	7

The Naïve Strategy

- Problem: buffers are not evenly utilized
 - `pin(60); unpin(60); pin(70);`
`unpin(70); pin(60); unpin(60); ...`
- Low hit rate
 - Some buffers may contain stale data

Buffer	0	1	2	3
Block Id	60	50	30	40
time read in	15	6	3	4
time unpinned	16	10	9	7

The FIFO Strategy

- Chooses the buffer that contains the least-recently-read-in block
 - Each buffer records the *time a block is read in*
- Unpinned buffers can be maintained in a priority queue
 - Finds the target unpinned buffer in $O(1)$ time

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned	8	10	9	7

The FIFO Strategy

- Chooses the buffer that contains the least-recently-read-in block
 - Each buffer records the *time a block is read in*
- Unpinned buffers can be maintained in a priority queue
 - Finds the target unpinned buffer in $O(1)$ time

Buffer	0	1	2	3
Block Id	60	50	70	40
time read in	11	6	12	4
time unpinned	8	10	9	7

The FIFO Strategy

- Assumption: the older blocks are less likely to be used in the future
- Valid?
- Not true for, e.g., catalog blocks

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned	8	10	9	7

The LRU Strategy

- Chooses the buffer that contains the least recently used block
 - Each buffer records the *time the block is unpinned*

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	3	4
time unpinned	8	10	9	7

The LRU Strategy

- Choose the buffer that contains the least recently used block
 - Each buffer records the *time the block is unpinned*

Buffer	0	1	2	3
Block Id	60	50	30	70
time read in	11	6	3	12
time unpinned	8	10	9	7

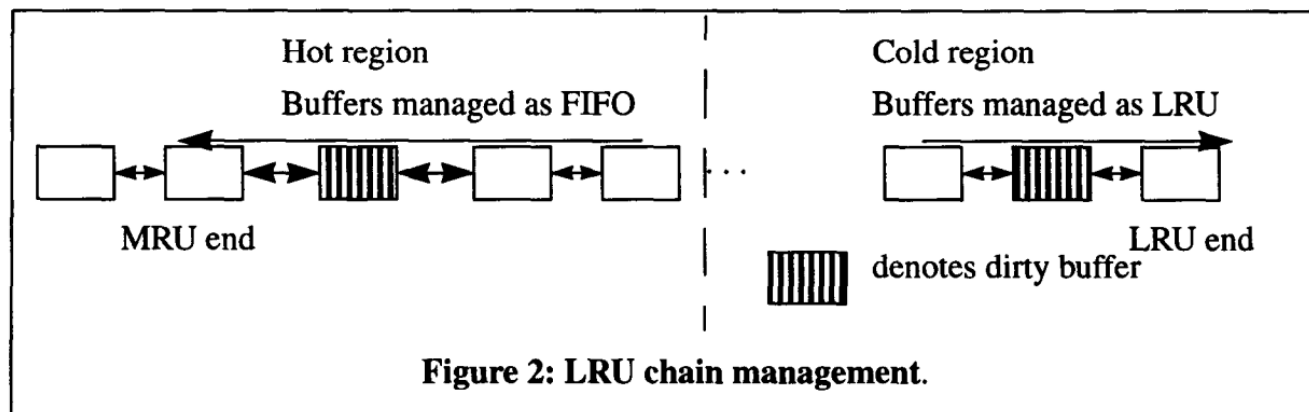
The LRU Strategy

- Assumption: blocks that are not used in the near past will unlikely be used in the near future
 - Valid generally
 - Avoids replacing commonly used pages
- But still not optimal for full table scan
- Most commercial systems use simple enhancements to LRU

Buffer	0	1	2	3
Block Id	60	50	30	70
time read in	11	6	3	12
time unpinned	8	10	9	7

LRU Variants

- In Oracle DBMS, the LRU queue has two logical regions
 - Cold region in front of the hot region
- **Cold: LRU; hot: FIFO**
- For full table scan
 - Puts the just read page into the head (at LRU end)



W. Bridge, A. Joshi, M. Keihl, T. Lahiri, J. Loaiza, and N. MacNaughton, "The oracle universal server buffer," VLDB, 1997.

The Clock Strategy


- Similar to Naïve strategy, but always start traversal from the previous replacement position
- Uses the unpinned buffers as evenly as possible
 - With LRU flavor
- Easy to implement

Last replacement
↓

Buffer	0	1	2	3
Block Id	10	50	30	40
time read in	1	6	5	4
time unpinned	8	10	9	7

The Clock Strategy

- Similar to Naïve strategy, but always start traversal from the last replacement position
 - Buffer manager records the last replacement position
- Uses the unpinned buffers as evenly as possible
 - With LRU flavor
- Easy to implement

Last replacement


Buffer	0	1	2	3
Block Id	10	50	60	70
time read in	1	6	11	12
time unpinned	8	10	9	7

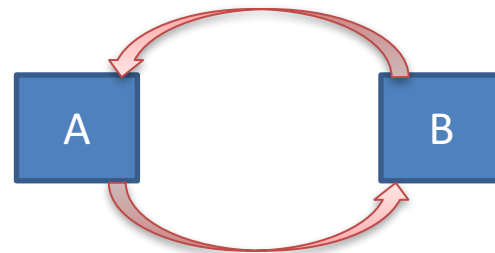
How many pages in buffer pool?

Pool Size

- The set of all blocks that are currently accessed by clients is called the ***working set***
- Ideally, the buffer pool should be larger than the working set
 - Otherwise, ***deadlock*** may happen

Deadlock

- What if there is no candidate buffer when pinning?
 - Buffer manager tells the client to wait
 - Notifies (wakes up) the client to pin again when some other unpins a block
- Deadlock
 - Clients *A* and *B* both want to use two buffers and there remain only two candidate buffers
 - If they both have got one buffer and attempt to get another one, deadlock happens
 - Circularly waiting the others to unpin



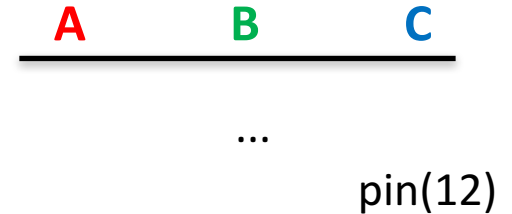
Deadlock

- How to detect deadlock?
 - No buffer becomes available for an exceptionally long time
 - E.g., much longer than executing a query
- How to deal with deadlock?
 - Forces at least one client to
 1. First unpin all blocks it holds
 2. Then re-pins these blocks one-by-one

Waiting: An Example

- Buffer pool size: 10
- Block access from three clients:

- Client A: 1, 2, 3, 4
- Client B: 5, 6, 7, 8
- Client C: 9, 10, 11, 12



Buffer pool



Waiting list



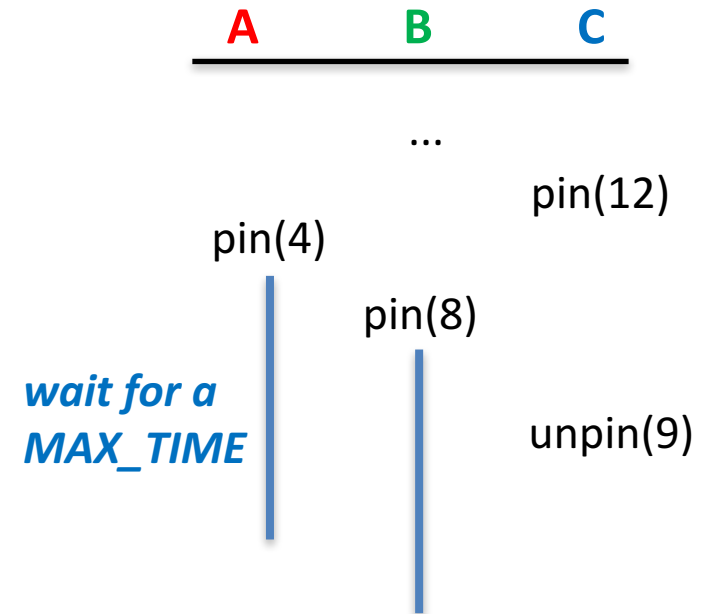
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Buffer pool



Waiting list



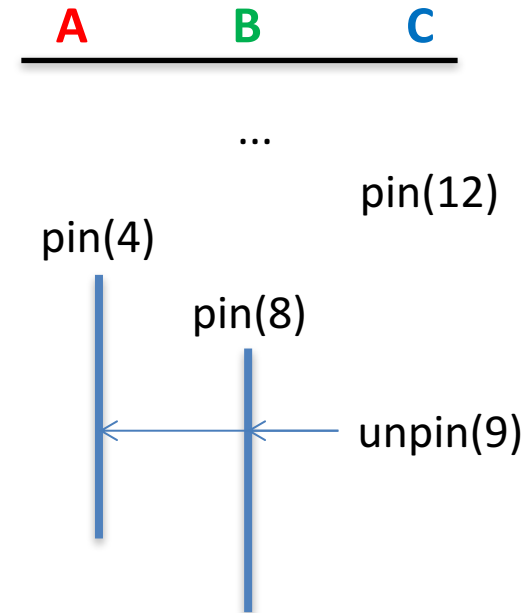
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Buffer pool



Waiting list



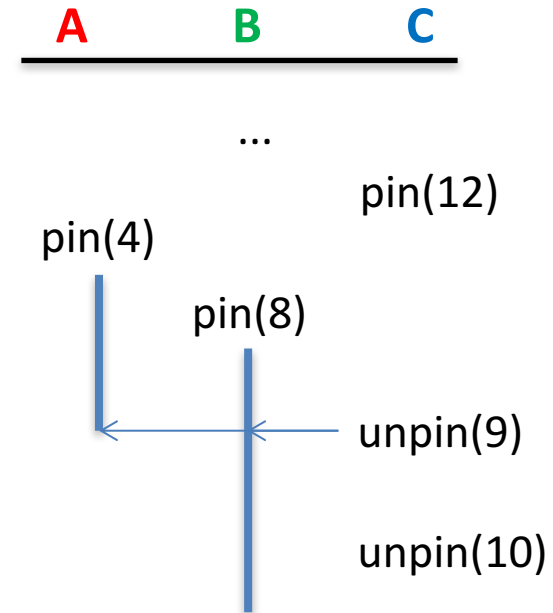
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Buffer pool



Waiting list



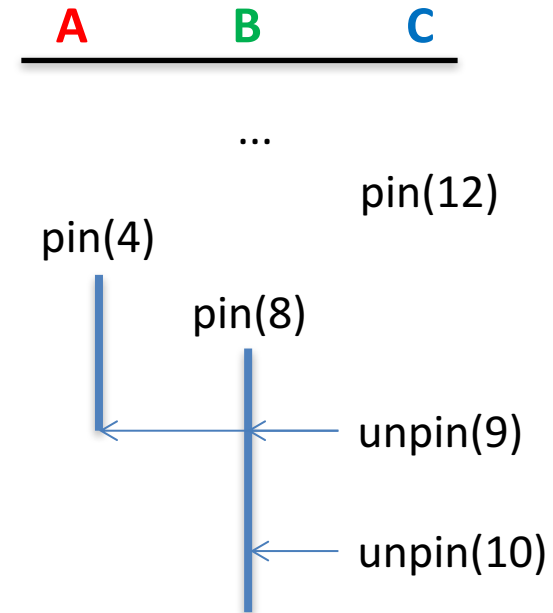
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Buffer pool



Waiting list



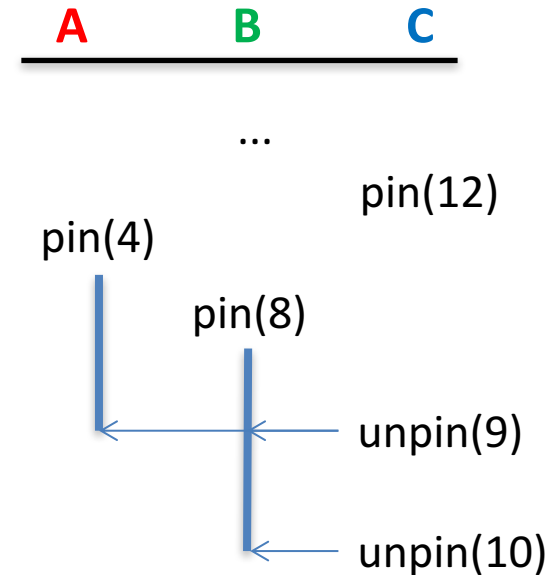
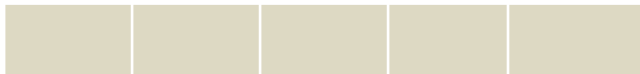
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Buffer pool

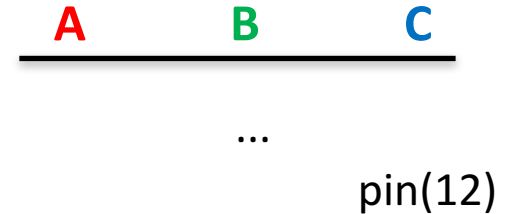


Waiting list



Waiting: Deadlock Case

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Buffer pool



Waiting list



Waiting: Deadlock Case

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Buffer pool

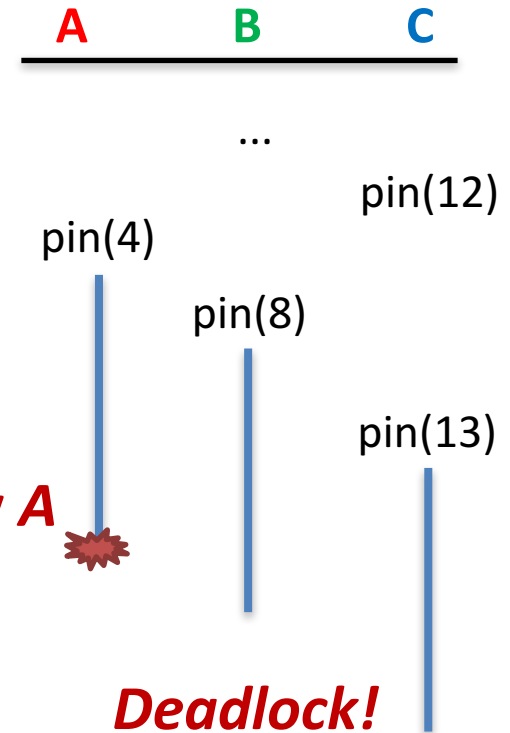


Waiting list



Detected by A

Deadlock!



Waiting: Deadlock Case

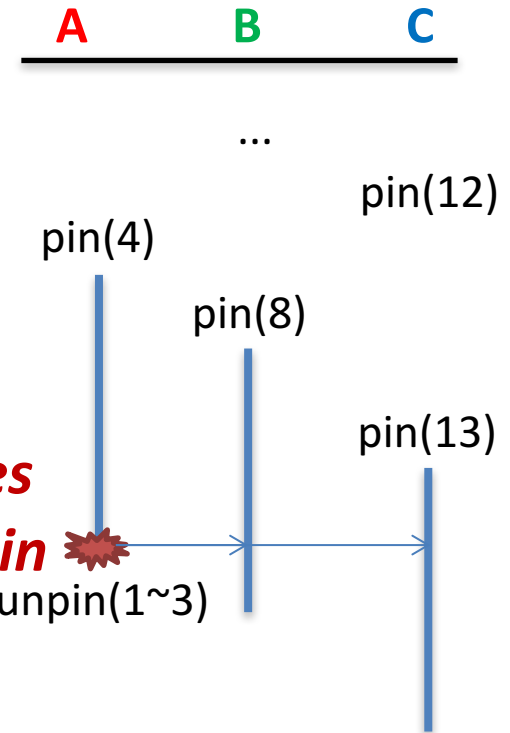
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*Unpin all holding pages
then re-pin again*

Buffer pool



Waiting list



Waiting: Deadlock Case

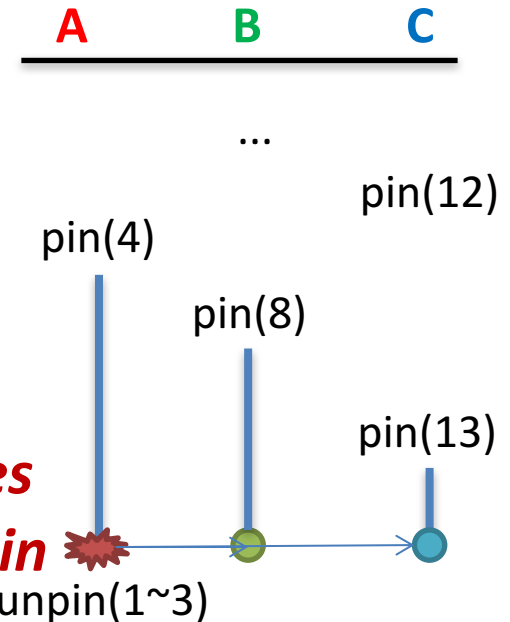
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Buffer pool



Waiting list



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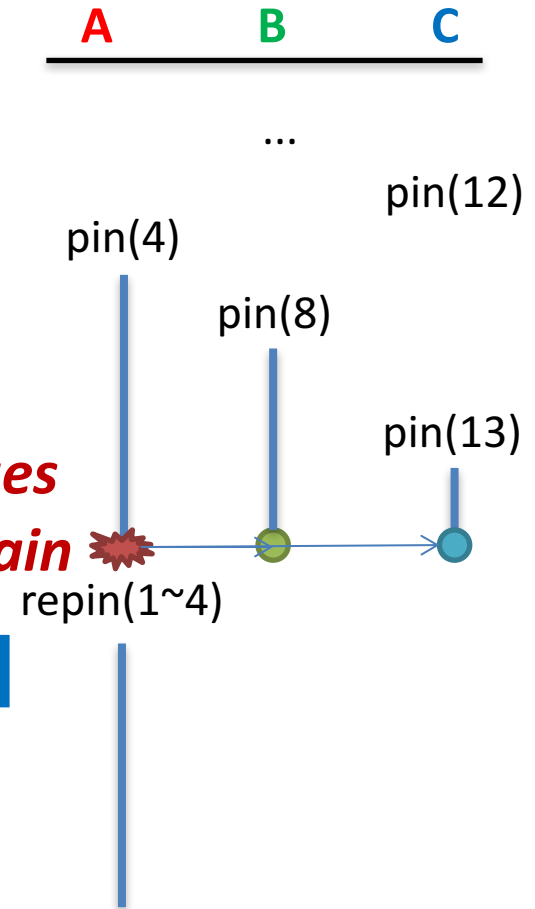
Buffer pool



Waiting list



*Unpin all holding pages
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Waiting: Deadlock Case

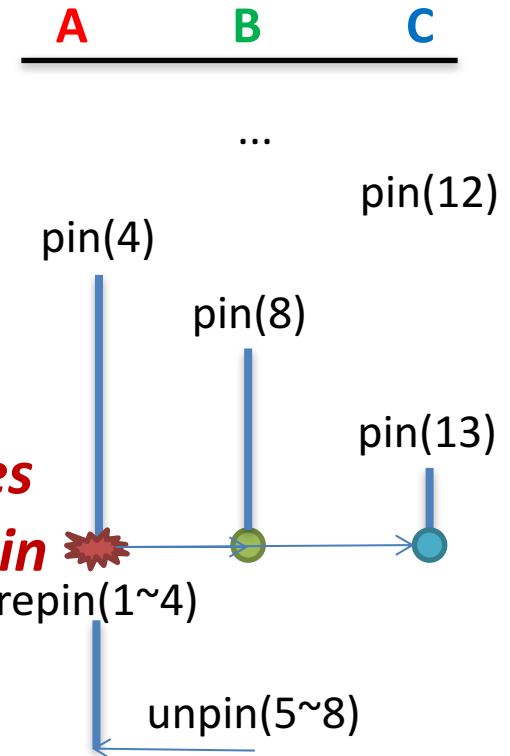
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*Unpin all holding pages
then re-pin again*

Buffer pool



Waiting list



Waiting: Deadlock Case

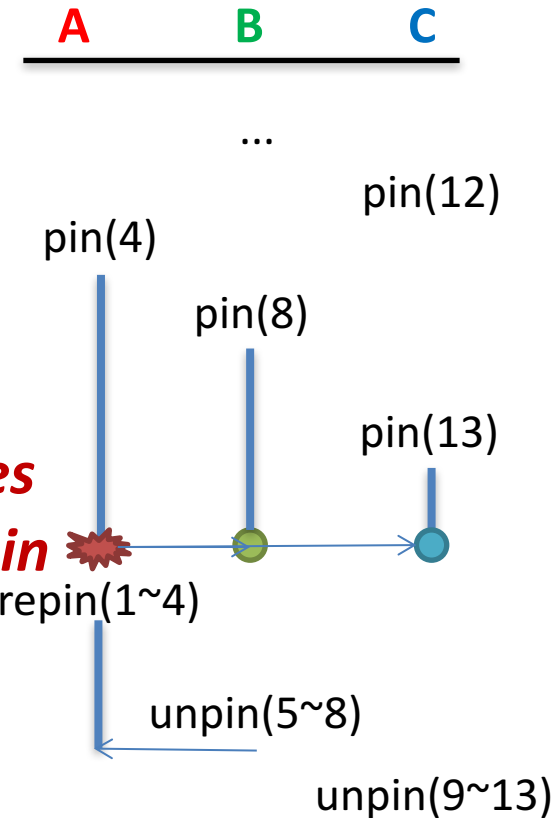
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*Unpin all holding pages
then re-pin again*

Buffer pool



Waiting list



How about Self-Deadlock?

- A client that pins more blocks than a pool can hold
- Happens when
 - The pool is too small
 - The client is malicious (luckily, we write the `clients/RecordFile` ourselves)
- How to handle this?
 - A (fixed-sized) buffer manager has no choice but throwing an exception
- The pool should be large enough to at least hold the working set of a single client
- A good client should pin blocks sparingly
 - Unpins a block immediately when done
 - Call `close()` after iterating a `ResultSet` in JDBC

Outline

- Overview
- Buffering User Data
- **Caching Logs**
- Log Manager in VanillaCore
- Buffer Manager in VanillaCore

Why logging?

Transactions Revisited

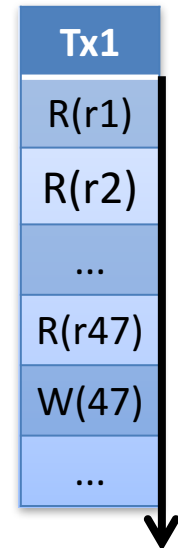
BEGIN TRANSACTION;

...

COMMIT TRANSACTION;



Scans /
record files



ACID

- A database ensures the **ACID** properties of txs
- **Atomicity**
 - All operations in a transaction either succeed (transaction commits) or fail (transaction rollback) together
- **Consistency**
 - After/before each transaction (which commits or rollback), your data do not violate any rule you have set
- **Isolation**
 - Multiple transactions can run concurrently, but cannot interfere with each other
- **Durability**
 - Once a transaction commits, any change it made lives in DB permanently (unless overridden by other transactions)

How?

Naïve C and I

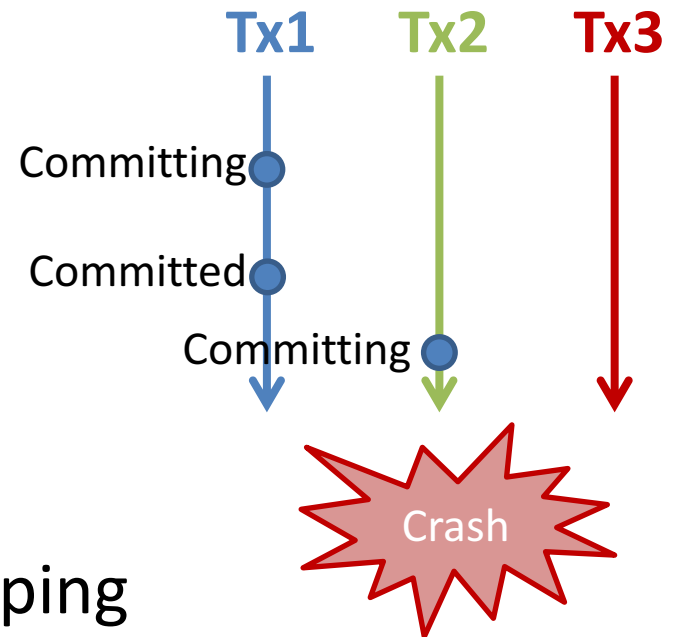
- Observation: there is no tx that accesses data across DBs
- To ensure C and I, each tx can simply lock the entire DB it belongs
 - Acquire lock at start
 - Release lock when committed or rolled back
- Txs for different DBs can execute concurrently

Naïve A and D

- D given buffers?
- Flush all dirty buffers of a tx *before* committing the tx
 - Return to DBMS client after tx commit

Naïve A and D

- What if system crashes and then recovers?
- To ensure A, DBMS needs to rollback uncommitted txs (2 and 3) at start-up
 - Why 3? flushes due to swapping
- Problems:
 - How to determine which txs to rollback?
 - How to rollback all actions made by a tx?



Naïve A and D

- Idea: **Write-Ahead-Logging (WAL)**
 - Record a **log** of each modification made by a tx
 - E.g., <SETVAL, <TX>, <BLK>, <OFFSET>, <VAL_TYPE>, <OLD_VAL> >
 - **In memory** to save I/Os (discussed later)
 - To commit a tx,
 1. Write all associated logs to a log file **before** flushing a buffer
 2. After flushing, write a <COMMIT, <TX>> log to the log file
 - To swap a dirty buffer (in BufferMgr)
 - All logs must be flushed **before** flushing a user block

Naïve A and D

- Which txs to rollback?
 - Observation: txs with COMMIT logs must have flushed all their dirty blocks
 - Ans: those without COMMIT logs in the log file
- How to rollback a tx?
 - Observation: only 3 possibilities for each action **on disk**:
 1. With log and block
 2. With log, but without block
 3. Without log and block
 - Ans: simply **undo** actions that are logged to disk, flush all affected blocks, and then writes a <ROLLBACK, <TX>> log
 - Applicable to self-rollback made by a tx

Naïve A and D

- Assumption of WAL: each block-write either succeeds or fails entirely on a disk, despite power failure
 - I.e., no corrupted log block after crash
 - Modern disks usually store enough power to finish the ongoing sector-write upon power-off
 - Valid if block size == sector size or a journaling file system (e.g., EXT3/4, NTFS) is used
 - Block/physical vs. metadata/logical journals

Caching Logs

- Like user blocks, the blocks of the log file are cached
 - Each tx operation is logged *into memory*
 - Log blocks are flushed only on
 - Tx commit
 - Buffer swapping
- Avoids excessive I/Os

Do we need a buffer pool for the log blocks?

Access Patterns: A Comparison

- User blocks
 - Of multiple files
 - Random reads, writes, and appends
 - Concurrent access by multiple worker threads (each thread per JDBC client)
- Log blocks
 - Of a *single* log file (why not one file per tx?)
 - Always *appends*, by multiple worker threads
 - Always *sequential backward reads*, by a single recovery thread at start-up

Do we need a buffer pool for the log blocks?

No! Two Buffers Are Enough

- For the sequential backward reads
 - The recovery thread “pins” the block being read
 - There is only one recovery thread
 - **Exactly one** buffer is needed
- For (sequential forward) appends
 - All worker threads “pin” the tail block of the same file
 - **Exactly one** buffer is needed
- DBMS needs an additional **log manager**
 - To implement this specialized memory management strategy for log blocks

Example API

LogMgr
<u><<final>> + LAST_POS : int</u> <u><<final>> + logFile : String</u>
+ LogMgr() <<synchronized>> + flush(lsn : long) <<synchronized>> + iterator() : Iterator<BasicLogRecord> <<synchronized>> + append(rec : Constant[]) : long

BasicLogRecord
+ BasicLogRecord(pg : Page, pos : int) + nextVal(type : Type) : Constant

- Each log record has an unique identifier called ***Log Sequence Number (LSN)***
 - Typically block ID + starting position
- `flush(lsn)` flushes all log records with LSNs no larger than `lsn`

Cache Management for Read

- Provides a log iterator that iterates the log records backward from tail
- Internally, the iterator allocates a page, which always holds the block where the current log record resides
- Optimal: more pages do not help in saving I/Os

Cache Management for Append

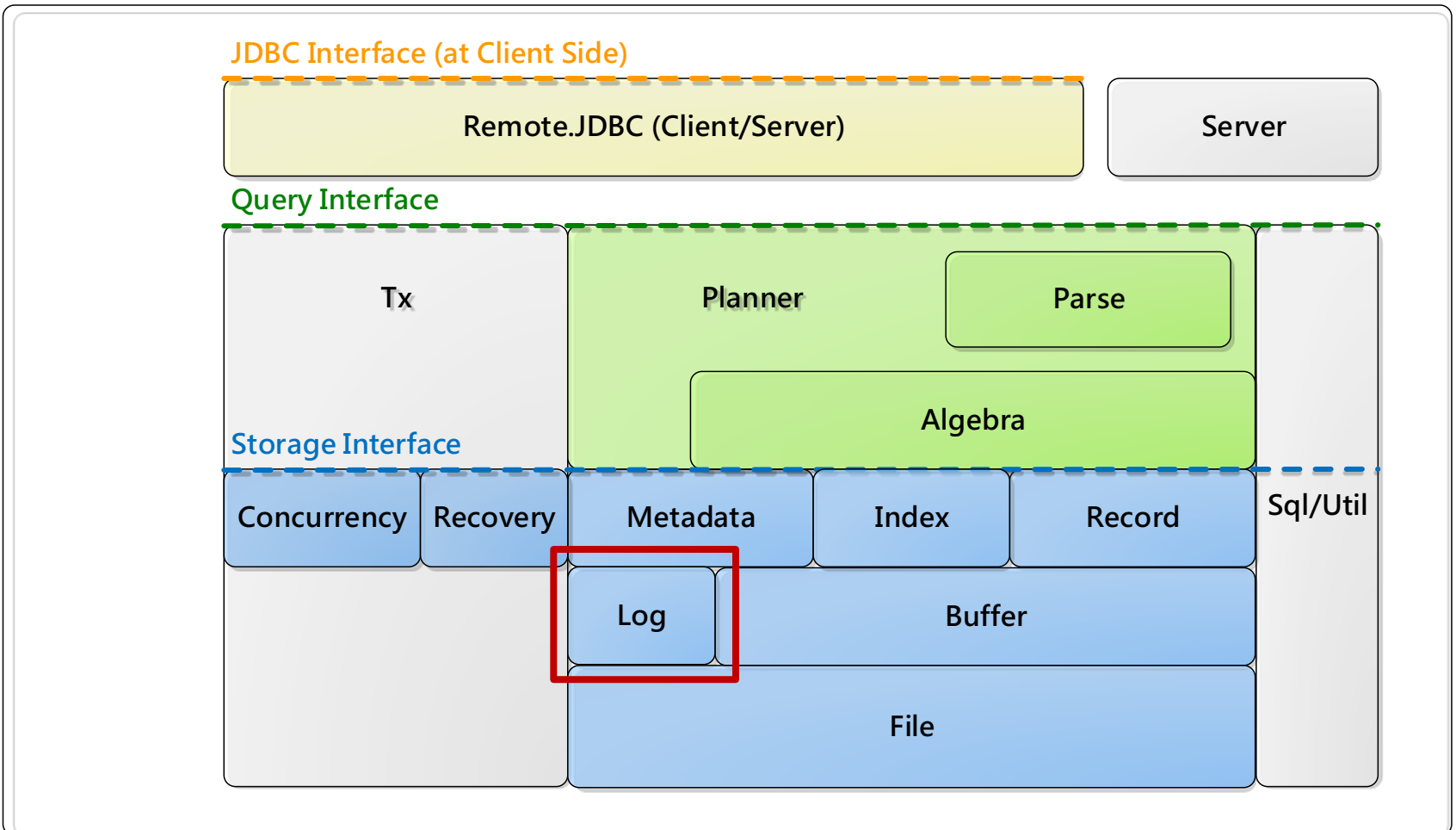
- Permanently allocate a page, P , to hold the tail block of the log file
- When `append(rec)` is called:
 1. If there is no room in P , then write the page P back to disk and clear its contents
 2. Add the new log record to P
- When `flush(lsn)` is called:
 1. If that log record is in P , then write P to disk
 2. Else, do nothing
- Optimal: more pages do not help in saving I/Os

Outline

- Overview
- Buffering User Data
- Caching Logs
- **Log Manager in VanillaCore**
- Buffer Manager in VanillaCore

Log Manager in VanillaCore

VanillaCore



LogMgr

- In `storage.log` package

LogMgr
<u><<final>> + LAST_POS : int</u> <u><<final>> + LOG_File : String</u>
+ LogMgr() <<synchronized>> + flush(lsn : long) <<synchronized>> + iterator() : Iterator<ReversibleIterator> <<synchronized>> + append(rec : Constant[]) : long

LogMgr

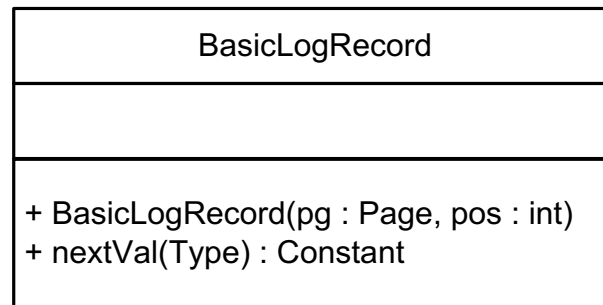
- Singleton
- Constructed during system startup
 - Via `VanillaDb.initFileAndLogMgr(dbname)`
- Obtained via `VanillaDb.logMgr()`
- The method `append` appends a log record to the log file, and returns the record's LSN as long
 - No guarantee that the record will get written to disk
- A client can force a specific log record, *and all its predecessors*, to disk by calling `flush`

LSNs

- Recall that an LSN identifies a log record
 - Typically block ID + starting position
- VanillaCore simplifies the LSN to be a ***block number***
 - Recall: block ID = file name + block number
- All log records in a block are assigned the same LSN, therefore flushed together

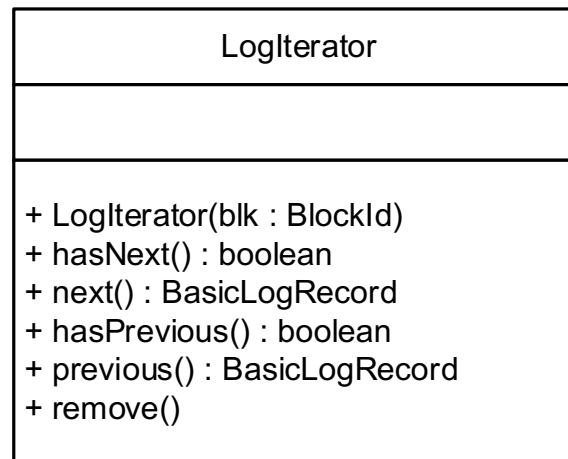
BasicLogRecord

- An iterator of values in an log record
- The log manager only implements the memory management strategy
 - Does **not** understand the contents of the log records
 - It is the **recovery manager** that defines the semantic of a log record



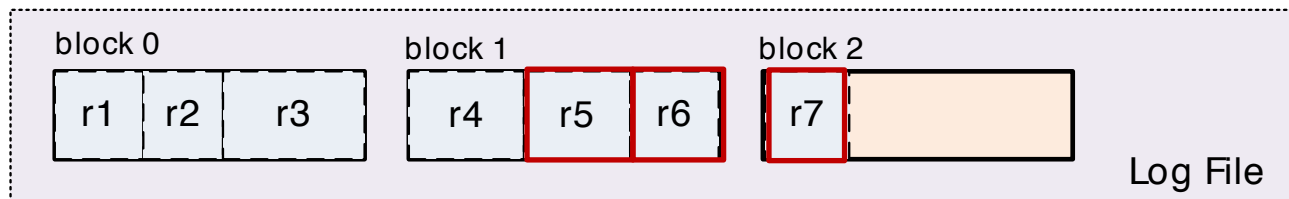
LogIterator

- A client can read the records in the log file by calling the method `iterator` in `LogMgr`
 - Returns a `LogIterator` instance



LogIterator

- Calling `next` returns the next `BasicLogRecord` in **reverse** order from tail
- This is how the recovery manager wants to see the logs



Using LogMgr

```
VanillaDb.initFileAndLogMgr("studentdb");
LogMgr logmgr = VanillaDb.LogMgr();
long lsn1 = logmgr.append(new Constant[] { new IntegerConstant(1),
    new VarcharConstant("abc") });
long lsn2 = logmgr.append(new Constant[] { new IntegerConstant(2),
    new VarcharConstant("kri") });
long lsn3 = logmgr.append(new Constant[] { new IntegerConstant(3),
    new VarcharConstant("net") });
logmgr.flush(lsn3);
```

```
Iterator<BasicLogRecord> iter = logmgr.iterator();
while (iter.hasNext()) {
    BasicLogRecord rec = iter.next();
    Constant c1 = rec.nextVal(Type.INTEGER);
    Constant c2 = rec.nextVal(Type.VARCHAR);
    System.out.println "[" + c1 + ", " + c2 + " ]";
}
```

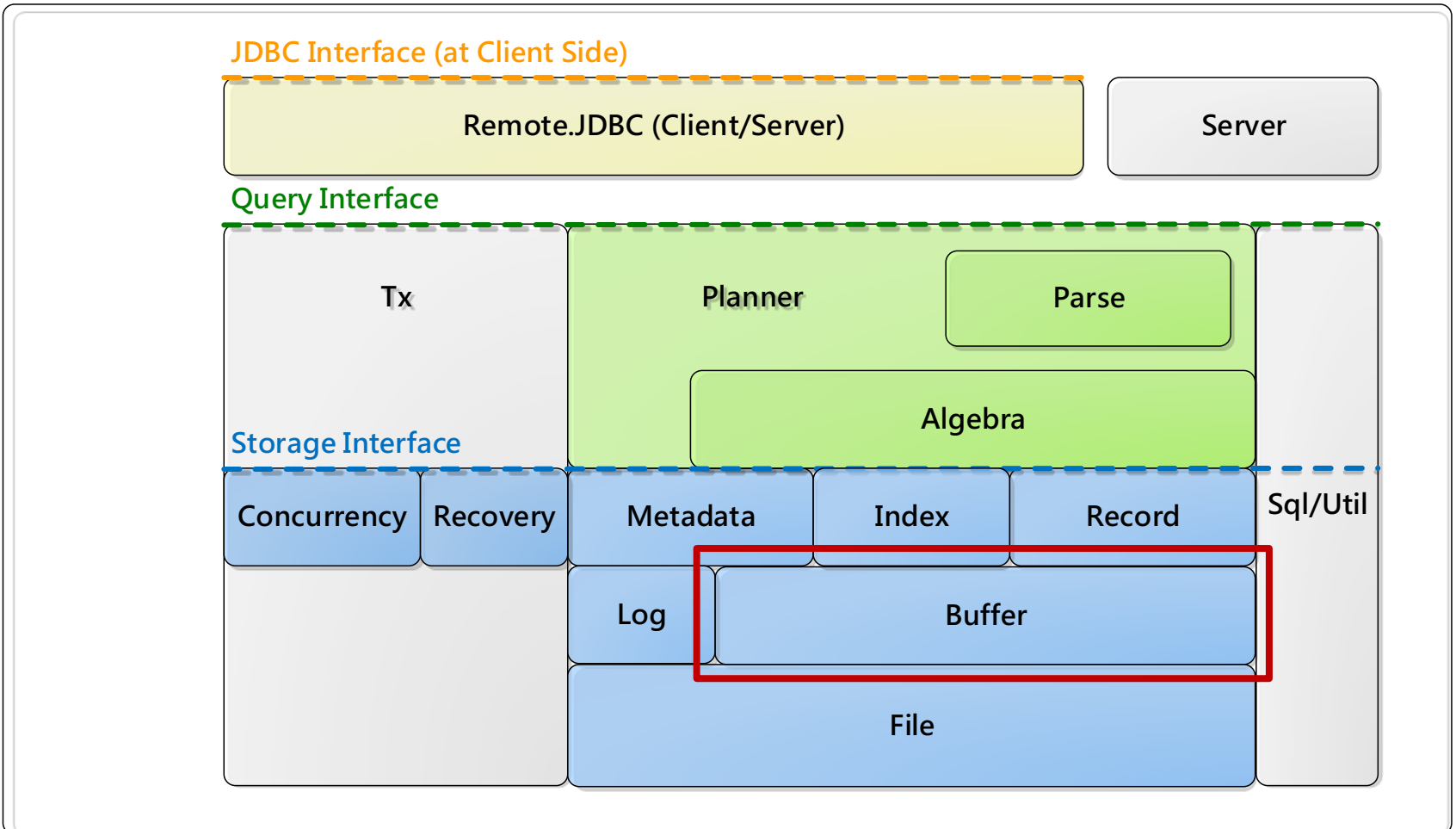
Output:
[3, net]
[2, kri]
[1, abc]

Outline

- Overview
- Buffering User Data
- Caching Logs
- Log Manager in VanillaCore
- **Buffer Manager in VanillaCore**

Buffer Manager in VanillaCore

VanillaCore



BufferMgr

- Each transaction has its own BufferMgr
- Constructed while creating a transaction
 - Via `transactionMgr.newTransaction(...)`
- Obtained via `transaction.bufferMgr()`

BufferMgr : TransactionLifecycleListener
<u><<final>> # BUFFER_POOL_SIZE : int</u>
<pre>+ BufferMgr() + onTxCommit(tx : Transaction) + onTxRollback(tx : Transaction) + onTxEndStatement(tx : Transaction) <<synchronized>> + pin(blk : BlockId) <<synchronized>> + pinNew(filename : String, fmtr : PageFormatter) : Buffer <<synchronized>> + unpin(buffs : Buffer[]) + flush() + flushAll() + available() : int</pre>

BufferMgr

- A `BufferMgr` of a transaction takes care which buffers are pinned by the transaction and make it waiting when there is no available buffer
- `flush()` flushes each buffer modified by the specified tx
- `available()` returns the number of buffers holding unpinned buffers

BufferPoolMgr

- A BufferPoolMgr is a singleton object and it is hidden in `buffer` package to the outside world
- It manages a buffer pool for all pages and implements the *clock* buffer replacement strategy
 - The details of disk access is unknown to client

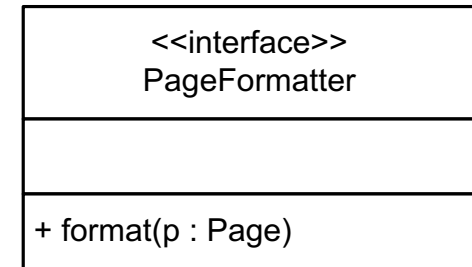
Buffer

- Wraps a page and stores
 - ID of the holding block
 - Pin count
 - Modified information
 - Log information
- ***Supports WAL***
 - `setVal()` requires an LSN
 - Must be preceded by `LogMgr.append()`
 - `flush()` calls `LogMgr.flush(maxLsn)`
 - Called by `BufferMgr` upon swapping

Buffer
<pre>~ Buffer() <<synchronized>> + getVal(offset : int, type : Type) : Constant <<synchronized>> + setVal(offset : int, val : Constant , txnum : long, lsn : long) <<synchronized>> + block() : BlockId <<synchronized>> ~ flush() <<synchronized>> ~ pin() <<synchronized>> ~ unpin() <<synchronized>> ~ isPinned() : boolean <<synchronized>> ~ isModifiedBy(txNum : long) : boolean <<synchronized>> ~ assignToBlock(b : BlockId) <<synchronized>> ~ assignToNew (filename : String, fmtr : PageFormatter)</pre>

PageFormatter

- The `pinNew(fmtr)` method of `BufferMgr` appends a new block to a file
- `PageFormatter` initializes the block
 - To be extended in packages (`storage.record` and `storage.index.btree`) where the semantics of records are defined



```
class ZeroIntFormatter implements PageFormatter {  
    public void format(Page p) {  
        Constant zero = new IntegerConstant(0);  
        int recsize = Page.size(zero);  
        for (int i = 0; i + recsize <= Page.BLOCK_SIZE; i += recsize)  
            p.setVal(i, zero);  
    }  
}
```


Using the Buffer Manager

- Reading value from a buffer

```
// Initialize VanillaDB ...
```

```
Transaction tx =  
VanillaDb.txMgr().newTransaction(Connection.TRANSACTION_SERIALIZABLE,  
    false);  
BufferMgr bufferMgr = tx.bufferMgr();
```

```
BlockId blk = new BlockId("student.tbl", 0);  
Buffer buff = bufferMgr.pin(blk);  
Type snameType = Type.VARCHAR(20);  
Constant sname = buff.getVal(46, snameType);
```

```
System.out.println(sname);
```

```
bufferMgr.unpin(buff);
```

Using the Buffer Manager

```
// Initialize VanillaDB ...
```

```
Transaction tx =  
VanillaDb.txMgr().newTransaction(Connection.TRANSACTION_SERIALIZABLE,  
false);  
BufferMgr bufferMgr = tx.bufferMgr();  
LogMgr logMgr = VanillaDb.LogMgr();  
long myTxnNum = 1;
```

```
BlockId blk = new BlockId("student.tbl", 0);  
Buffer buff = bufferMgr.pin(blk);  
Type snameType = Type.VARCHAR(20);  
Constant sname = buff.getVal(46, snameType);  
Constant[] logRec = new Constant[] { new BigIntConstant(myTxnNum), new  
VarcharConstant("student.tbl"),  
new BigIntConstant(blk.number()), new IntegerConstant(46), sname };
```

```
long lsn = logMgr.append(logRec);  
buff.setVal(46, new VarcharConstant("kay").castTo(snameType), myTxnNum,  
lsn);  
bufferMgr.unpin(buff);
```

```
// [WAL] when buff.flush() is called due to swapping or tx commit,  
// logMgr.flush(lsn) is called first by buff
```

- Writing value into a buffer

You Have Assignment!

Assignment 3 (1/2)

- The current File and Buffer Managers are slow
 - Mainly due to the synchronization (for thread-safety)
- ***Optimize them*** to improve performance
- We provide you a basic implementation of these modules which have bad performance
 - You need to modify them to reach higher throughput or lower latency in our benchmark
- You need to come out at least one optimization for each module
 - `storage.file`
 - `storage.buffer`

Assignment 3 (2/2)

- Use the micro-benchmark we provided to compare performance between the basic and your implementation
- Report
 - Show the throughput and latency of benchmark between those implementation
 - Show what you exactly do for optimization
 - Discuss why your optimization works

Hints

- Critical sections are used in File/BufferManagers to protect some shared resource
- ***Breaks*** a single critical section into multiple ones
 - Avoids unnecessary transaction/thread stalls
- ***Reduce the coverage*** of critical sections
 - reduce the stall duration

References

- W. Bridge, A. Joshi, M. Keihl, T. Lahiri, J. Loaiza, and N. MacNaughton, The oracle universal server buffer, *VLDB*, 1997.
- M. Cyran., Oracle Database Concepts, 10g Release 2 (10.2), 2005.
- Edward Sciore., *Database Design and Implementation*, chapter 13.
- Hellerstein, J. M., Stonebraker, M., and Hamilton, J. Architecture of a database system. *Foundations and Trends in Databases 1, 2*, 2007.
- Hussein M. Abdel-Wahab, CS 471 – Operating Systems Slides, <http://www.cs.odu.edu/~cs471w/>