SimpleDBM Documentation

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CHAPTER 1

SimpleDBM Overview

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Overview

Introduction

SimpleDBM is a transactional database engine, written in Java. It has a very small footprint and can be embedded in the address space of an application. It provides a simple Java application programming interface (API), which can be learned very quickly.

Features

SimpleDBM implements the following features:

- *Transactional* - SimpleDBM fully supports ACID transactions. A STEAL and NO-FORCE buffer management strategy is used for transactions which is optimum for performance.
- *Multi-threaded* - SimpleDBM is multi-threaded and supports concurrent reads and writes of data.
- *Write Ahead Log* - SimpleDBM uses a write ahead log to ensure transaction recovery in the event of system crashes.
- *Lock based concurrency* - SimpleDBM uses row-level shared, update and exclusive locks to manage concurrency.
- *Multiple Isolation Levels* - SimpleDBM supports read committed, repeatable read, and serializable isolation levels.
- *B-Tree Indexes* - SimpleDBM implements B-plus Tree indexes, that fully support concurrent reads, inserts and deletes. SimpleDBM B-Trees continually rebalance themselves, and do not suffer from fragmentation.
- *Tables* - SimpleDBM supports tables, but for maximum flexibility, treats table rows as blobs of data. Table rows can have any internal structure as you like, and can span multiple disk pages. Standard table rows with multiple columns are supported via add-on modules.
- *Latches and Locks* - SimpleDBM uses latches for internal consistency, and locks for concurrency. Latches are more efficient locking mechanisms that do not suffer from deadlocks.
- *Deadlock detection* - SimpleDBM has support for deadlock detection. A background thread periodically checks the lock table for deadlocks and aborts transactions to resolve deadlocks.
- *Network API* - From release 1.0.18 a network client server implementation is included that allows SimpleDBM servers to run standalone and remote clients to connect via TCP/IP. Only Java bindings available right now.

Non-Features

- SimpleDBM is not an SQL engine.
- There is no support for distributed transactions (XA).

Status

SimpleDBM is fully usable, and is available via Maven Central. If you discover a bug, please report it - I will do my best to fix any bugs. Enhancements are currently not being done as I have no time available.

Getting Started

See Getting Started for instructions on how to start using SimpleDBM in your application.

Architecture

The core database engine of SimpleDBM is the RSS (named in honor of the first IBM Relational Database prototype System-R Relational Storage System). The RSS provides the underlying storage structures for transactions, locking, b-trees etc. The functions of the RSS subsystem will be based upon the description of the System-R RSS component in *[ASTRA-76]*.

> The Relational Storage Interface (RSI) is an internal interface which handles access to single tuples of base relations. This interface and its supporting system, the Relational Storage System (RSS), is actually a complete storage subsystem in that it manages devices, space allocation, storage buffers, transaction consistency and locking, deadlock detection, backout, transaction recovery, and system recovery. Furthermore, it maintains indexes on selected fields of base relations, and pointer chains across relations.

The RSS API is however, somewhat low level for ordinary users. It is meant to be used by people interested in building their own Database Engines on top of RSS.

To provides users with a simplified API, three additional modules are available.

The first one is the SimpleDBM TypeSystem module, which adds support for typed data values and multi-attribute row objects.

The second module, the Database API. This module implements a high level Database API and uses the TypeSystem module on top of the RSS.

Finally there is the Network API that provides a Client / Server model.

Technology

SimpleDBM is written in Java and uses features available since version 5.0 of this language.

Third party libraries

SimpleDBM has no run-time dependency on external libraries as it uses only out of the box Java 1.6 functionality. For test cases there is a dependency on JUnit.

Using SimpleDBM

SimpleDBM is available in three levels of abstraction.

The Network API modules allow SimpleDBM to be deployed in a simple Client / server configuration.

The add-on modules SimpleDBM-Database and SimpleDBM Type-System provide a high level API wth support for data dictionary, and the ability to create tables with traditional row/column structure. Indexes can be associated with tables. Details of how to use this API can be found in the document SimpleDBM Database API.

The lower level RSS module works at the level of containers and arbitrary types. The document named RSS User Manual provides instructions on how to develop using the RSS. Note that this is for advanced users who want to implement their own type system and data dictionary.

Developing SimpleDBM

The instructions in this section are for those who wish to develop SimpleDBM.

Obtaining SimpleDBM

SimpleDBM source code can be obtained from the SimpleDBM Project site. Source code is maintained in a Mercurial repository, so you will need a Mercurial client on your computer.

The SimpleDBM SCM repository is organized as follows:

```
projects +--- simpledbm-rss            This is the core database engine - named RSS
         |                             after IBM's research prototype. The RSS offers
         |                             a low level API - most users will prefer to
         |                             use the higher level API offered by
         |                             simpledbm-database.
         |
         +--- simpledbm-common         This contains basic utilities that are
         |                             shared by all projects.
         |
         +--- simpledbm-typesystem     This contains a simple typesystem
         |                             that can be used with SimpleDBM.
         |
         +--- simpledbm-database       This contains a higher level DB
         |                             API that makes life easier for
         |                             users. It uses the typesystem
         |                             component.
         |
         +--- simpledbm-network-framework  implements an NIO server over TCP/IP.
         |
         +--- simpledbm-network-common     contains code that is common to client
         |                                 and server.
         |
         +--- simpledbm-network-server     contains the network server implementation.
         |
         +--- simpledbm-network-client     contains the network client implementation.
         |
         +--- simpledbm-samples        This contains some sample programs
         |                             that demonstrate how to use SimpleDBM.
         |
         +--- simpledbm-docs           Contains the documentation sources.
```

Build Instructions

Pre-requisites

SimpleDBM uses Maven for build management. You will need to obtain a copy of Maven 3. Install Maven and set up your PATH so that Maven can be executed by typing the following command.

```
mvn
```

SimpleDBM development is being done using Eclipse. You can use any IDE of your choice, but you may need to find ways of converting the maven projects to the format recognized by your IDE.

You will need a Git client in order to checkout the code for SimpleDBM.

SimpleDBM requires Java SE 1.6 or above.

Instructions for Eclipse

The following instructions are for the simpledbm-rss project. However, the same instructions apply for the other projects.

1. Use the Mercurial command line tools to create a local clone of the SimpleDBM Repository:

   ```
   git clone https://github.com/dibyendumajumdar/simpledbm.git
   ```

2. Import the SimpleDBM Maven projects into Eclipse. The parent pom file is in the `build` folder. This is a multi-module pom file and will generate sub projects below it.

Maven commands

You can also compile, test and do other operations using maven commands. The following maven commands are commonly used.

To run the test cases.

```
cd build
mvn test
```

To create the package and install it in the local repository.

```
mvn install
```

Please visit the SimpleDBM project Wiki pages for additional platform specific instructions.

Building releases

SimpleDBM releases are published to Maven Central. Please contribute your changes to SimpleDBM maintainer (admin@simpledbm.org) as releases can only be performed by the maintainer.

Coding and Design Principles

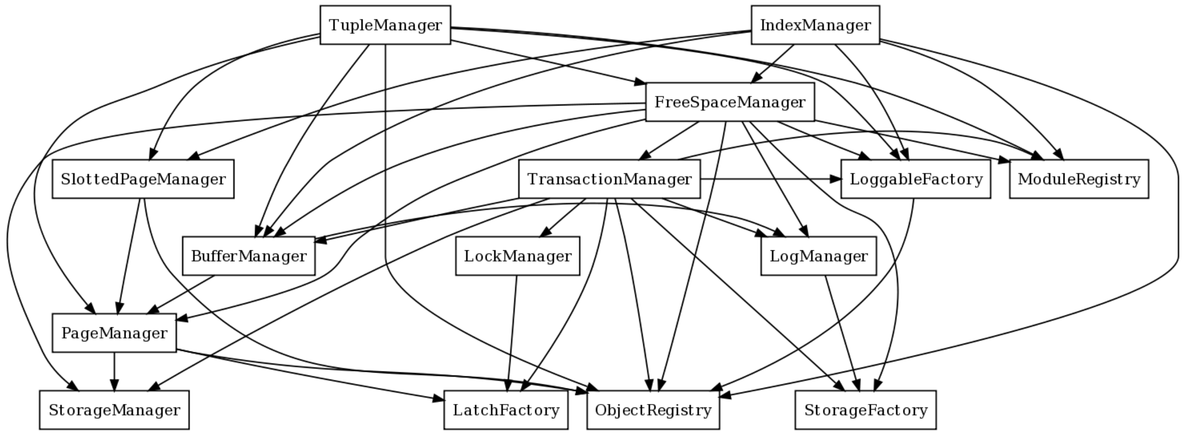
Modular design

SimpleDBM RSS is made up of several modules. Each module implements a particular component, and is contained in its own package.

Each module has a public API, which is specified via a set of Java interfaces. Classes are generally not used as part of the public API, though there are a few exceptional cases.

To make the modules reusable and as independent of each other as possible, the interface of a module is deliberately specified in general terms. Where possible, direct dependence between modules is avoided. The only permissible way for one module to interact with another is to go via the public interfaces of the other module. Modules are not allowed to depend upon implementation specifics of other modules.

A strict rule is that two modules cannot have cyclic dependency. Module dependencies are one-way only, higher level modules depend upon lower level modules. This is illustrated below.



SimpleDBM uses constructor based dependency injection to link modules. It is being designed in such a way that a third-party IoC (Inversion of Control) container may be used to manage the dependencies.

Java coding standards

Where possible, classes are made immutable. This helps in improving the robustness of the system. The serialization mechanism used by SimpleDBM is designed to work with immutable objects.

In the interest of concurrency, fine-grained locking is used as opposed to coarse-grained synchronization. This makes the code complex in some cases, as careful ordering of locks is required for deadlock avoidance. Also, the correctness of synchronization logic is of paramount importance.

Unchecked exceptions are used throughout. Due to the nature of unchecked exceptions, the code that throws the exception has the responsibility of logging an error message at the point where the exception is thrown. This ensures that even if the exception is not caught by the client, an error message will be logged to indicate the nature of the error.

All error messages are given unique error codes.

The code relies upon the efficiency of modern garbage collectors and does not attempt to manage memory. Rather than using object pools, SimpleDBM encourages the use of short-lived objects, on the basis that this aids the garbage collector in reclaiming space more quickly. The aim is to keep permanently occupied memory to a low level.

JUnit based test cases are being added constantly to improve the test coverage. Simple code coverage statistics are not a good indicator of the usefulness of test cases, due to the multi-threaded nature of most SimpleDBM components.

Where possible, test cases are created to simulate specific thread interactions, covering common scenarios.

Particular attention is paid to cleaning up of resources. To ensure that resources are cleaned up during normal as well as exceptional circumstances, finally blocks are used.

Debug messages are used liberally - and are executed conditionally so that if debug is switched off, there is minimal impact on performance.

A special Trace module is used to capture runtime trace. This module is designed to be lock-free, and is very low overhead, so that trace can be collected with negligible overhead. This feature is still being implemented across modules; the intention is that when fatal errors occur, the last 5000 trace messages will be dumped to help debug the error condition.

Documentation

Most of the documentation for SimpleDBM is written in reStructuredText. HTML and PDF versions are generated from the source documents. There is a generous amount of comments in the source code as well.

Being an educational project, producing good documentation is high priority.

The design of most modules is based upon published research. References are provided in appropriate places, both in this document, and in the source code. This acts as another source of information.

Following documents are recommended as starting points:

- SimpleDBM Overview - provides an overview of SimpleDBM
- Database API - describes the Database API
- SimpleDBM TypeSystem - useful if you want to know more about the type system

For advanced stuff, read:

- SimpleDBM RSS User Manual - describes the low level API of RSS
- SimpleDBM RSS Developers Guide - covers internals of RSS, the SimpleDBM database engine
- BTree Space Management - describes some implementation issues with BTree space management

CHAPTER 2

SimpleDBM Database API

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Contents

Introduction

This document describes the SimpleDBM Database API.

Intended Audience

This documented is targetted at users of SimpleDBM.

Pre-requisite Reading

Before reading this document, the reader is advised to go through the SimpleDBM Overview document.

Getting Started

A SimpleDBM server is a set of background threads and a library of API calls that clients can invoke. The background threads take care of various tasks, such as writing out buffer pages, writing out logs, archiving older log files, creating checkpoints, etc.

A SimpleDBM server operates on a set of data and index files, known as the SimpleDBM database.

Only one server instance is allowed to access a SimpleDBM database at any point in time. SimpleDBM uses a lock file to detect multiple concurrent access to a database, and will refuse to start if it detects that a server is already accessing a database.

Multiple simultaneous threads can access SimpleDBM. Multiple transactions can be executed in parallel. SimpleDBM is fully multi-threaded and supports concurrent reads and writes.

Internally, SimpleDBM operates on logical entities called Storage Containers. From an implementation point of view, Storage Containers are mapped to files.

Tables and Indexes are stored in Containers known as TupleContainers and IndexContainers, respectively. Each container is identified by a numeric ID, called the Container ID. Internally, SimpleDBM reserves the container ID zero (0), so the first available ID is one (1).

The SimpleDBM database initially consists of a set of transaction log files, a lock file and a special container (ID 0) used internally by SimpleDBM.

SimpleDBM binaries

SimpleDBM makes use of Java 5.0 features, hence you will need to use JDK1.6 or above if you want to work with SimpleDBM.

Following Maven dependencies are required to access the Database API.

```
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-common</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-rss</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-typesystem</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-database</artifactId>
  <version>1.0.23</version>
</dependency>
```

Creating a SimpleDBM database

A SimpleDBM database is created by a call to DatabaseFactory.create(), as shown below:

```
import org.simpledbm.database.api.DatabaseFactory;
...
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "5242880");
properties.setProperty("log.buffer.size", "5242880");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "30");
properties.setProperty("log.disableFlushRequests", "true");
properties.setProperty("storage.createMode", "rw");
properties.setProperty("storage.openMode", "rw");
properties.setProperty("storage.flushMode", "noforce");
properties.setProperty("bufferpool.numbuffers", "1500");
properties.setProperty("bufferpool.writerSleepInterval", "60000");
properties.setProperty("transaction.ckpt.interval", "60000");
properties.setProperty("logging.properties.type", "jdk");
properties.setProperty("logging.properties.file",
  "classpath:simpledbm.logging.properties");
properties.setProperty("lock.deadlock.detection.interval", "3");
properties.setProperty("storage.basePath",
  "demodata/DemoDB");

DatabaseFactory.create(properties);
```

The DatabaseFactory.create() method accepts a Properties object as the sole argument. The Properties object can be used to pass a number of parameters. The available options are shown below. Note that some of the options have an impact on the performance and reliability of the server - especially those that control how SimpleDBM treats file IO.

Server Options

Property Name	Description
`log.ctl.{n}`	The fully qualified path to the log control file. The first file should be specified as `log.ctl.1`, second as `log.ctl.2`, and so on. Up to a maximum of 3 can be specified. Default is 2.
`log.groups.{n}.path`	The path where log files of a group should be stored. The first log group is specified as `log.groups.1.path`, the second as `log.groups.2.path`, and so on. Up to a maximum of 3 log groups can be specified. Default number of groups is 1. Path defaults to current directory.
`log.archive.path`	Defines the path for storing archive files. Defaults to current directory.
`log.group.files`	Specifies the number of log files within each group. Up to a maximum of 8 are allowed. Defaults to 2.
`log.file.size`	Specifies the size of each log file in bytes. Default is 2 KB.
`log.buffer.size`	Specifies the size of the log buffer in bytes. Default is 2 KB.
`log.buffer.limit`	Sets a limit on the maximum number of log buffers that can be allocated. Default is 10 * log.group.files.
`log.flush.interval`	Sets the interval (in seconds) between log flushes. Default is 6 seconds.
`log.disableFlushRequests`	Boolean value, if set, disables log flushes requested explicitly by the Buffer Manager or Transaction Manager. Log flushes still occur during checkpoints and log switches. By reducing the log flushes, performance is improved, but transactions may not be durable. Only those transactions will survive a system crash that have all their log records on disk.
`storage.basePath`	Defines the base location of the SimpleDBM database. All files and directories are created relative to this location.
`storage.createMode`	Defines mode in which files will be created. Default is `"rws"`.
`storage.openMode`	Defines mode in which files will be opened. Default is `"rws"`.
`storage.flushMode`	Defines mode in which files will be flushed. Possible values are noforce, force.true (default), and force.false
`bufferpool.numbuffers`	Sets the number of buffers to be created in the Buffer Pool.
`bufferpool.writerSleepInterval`	Sets the interval in milliseconds between each run of the BufferWriter. Note that BufferWriter may run earlier than the specified interval if the pool runs out of buffers, and a new page has to be read in. In such cases, the Buffer Writer may be manually triggered to clean out buffers.
`lock.deadlock.detection.interval`	Sets the interval in seconds between deadlock scans.
`logging.properties.file`	Specifies the name of logging properties file. Precede `classpath:` if you want SimpleDBM to search for this file in the classpath.
`logging.properties.type`	Specify `"log4j"` if you want to SimpleDBM to use Log4J for generating log messages.
`transaction.lock.timeout`	Specifies the default lock timeout value in seconds. Default is 60 seconds.
`transaction.ckpt.interval`	Specifies the interval between checkpoints in milliseconds. Default is 15000 milliseconds (15 secs).

The DatabaseFactory.create() call will overwrite any existing database in the specified storage path, so it must be called only when you know for sure that you want to create a database.

Opening a database

Once a database has been created, it can be opened by creating an instance of Database, and starting it. The same properties that were supplied while creating the database, can be supplied when starting it.

Here is a code snippet that shows how this is done:

```
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "5242880");
properties.setProperty("log.buffer.size", "5242880");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "30");
properties.setProperty("log.disableFlushRequests", "true");
properties.setProperty("storage.createMode", "rw");
properties.setProperty("storage.openMode", "rw");
properties.setProperty("storage.flushMode", "noforce");
properties.setProperty("bufferpool.numbuffers", "1500");
properties.setProperty("bufferpool.writerSleepInterval", "60000");
properties.setProperty("transaction.ckpt.interval", "60000");
properties.setProperty("logging.properties.type", "jdk");
properties.setProperty("logging.properties.file",
  "classpath:simpledbm.logging.properties");
properties.setProperty("lock.deadlock.detection.interval", "3");
properties.setProperty("storage.basePath",
  "demodata/DemoDB");

Database db = DatabaseFactory.getDatabase(properties);
db.start();
try {
  // do some work
}
finally {
  db.shutdown();
}
```

Some points to bear in mind when starting SimpleDBM databases:

1. Make sure that you invoke `shutdown()` eventually to ensure proper shutdown of the database.
2. Database startup/shutdown is relatively expensive, so do it only once during the life-cycle of your application.
3. A Database object can be used only once - after calling `shutdown()`, it is an error to do any operation with the database object. Create a new database object if you want to start the database again.

Performance impact of server options

Some of the server options impact the performance or recoverability of SimpleDBM. These are discussed below.

log.disableFlushRequests Normally, the write ahead log is flushed to disk every time a transaction commits, or there is a log switch, or a checkpoint is taken. By setting this option to true, SimpleDBM can be configured to avoid flushing the log at transaction commits. The log will still be flushed for other events such as log switches or checkpoints. This option improves the performance of SimpleDBM, but will have a negative impact on recovery of transactions since the last checkpoint. Due to deferred log flush, some transaction log records may not be persisted to disk; this will result in such transactions being aborted during restart.

storage.openMode This is set to a `mode` supported by the standard Java `RandomAccessFile`. The recommended setting for recoverability is "rws", as this will ensure that modifications to the file are persisted on physical storage as soon as possible. The setting "rw" may improve performance by allowing the underlying operating system to buffer file reads/writes. However, the downside of this mode is that if there is a crash, some of the file contents may not be correctly reflected on physical storage. This can result in corrupted files.

storage.flushMode This setting influences how/whether SimpleDBM invokes `force()` on underlying `FileChannel` when writing to files. A setting of "noforce" disables this; which is best for performance. A setting of "force.true" causes SimpleDBM to invoke `force(true)`, and a setting of "force.false" causes SimpleDBM to invoke `force(false)`. As for the other settings, this setting can favour either performance or recoverability.

While changing the default settings for above options can improve perfomance, SimpleDBM, like any database management system, requires high performance physical storage system to get the best balance between performance and recoverability.

A few other settings that affect the performance or scalability are discussed below.

bufferpool.numbuffers This setting affects the bufferpool size, and hence impacts the performance of the buffer cache. A bigger size is preferable; some experimentation may be required to determine the optimum size for a particular workload. Suggested default: 1000.

log.file.size SimpleDBM will not span log records across log files. Hence the maximum log file size affects the maximum size of an individual log record. See also the note on `log.buffer.size`. The maximum size of a log record limits the size of data operations (insert, update or delete). Suggested default: 5MB.

log.buffer.size For performance reasons, log records are buffered in memory. SimpleDBM will not span log records across log buffer boundaries, hence the maximum log buffer size restricts the size of a log record. Together, this option and the `log.file.size` setting dictate the maximum size of a log record. Suggested default: 5MB.

Problems starting a database

SimpleDBM uses a lock file to determine whether an instance is already running. At startup, it creates the file at the location `_internal\lock` relative to the path where the database is created. If this file already exists, then SimpleDBM will report a failure such as:

```
SIMPLEDBM-EV0005: Error starting SimpleDBM RSS Server, another
instance may be running - error was: SIMPLEDBM-ES0017: Unable to create
StorageContainer .._internal\lock because an object of the name already exists
```

This message indicates either that some other instance is running, or that an earlier instance of SimpleDBM terminated without properly sutting down. If the latter is the case, then the `_internal/lock` file may be deleted enabling SimpleDBM to start.

Managing log messages

SimpleDBM has support for JDK 1.4 style logging as well as Log4J logging. By default, if Log4J library is available on the classpath, SimpleDBM will use it. Otherwise, JDK 1.4 util.logging package is used.

You can specify the type of logging to be used using the Server Property `logging.properties.type`.

The configuration of the logging can be specified using a properties file. The name and location of the properties file is specified using the Server property `logging.properties.file`. If the filename is prefixed with the string "classpath:", then SimpleDBM will search for the properties file in the classpath. Otherwise, the filename is searched for in the current filesystem.

A sample logging properties file is shown below.

```
############################################################
#       JDK 1.4 Logging
############################################################
handlers= java.util.logging.FileHandler, java.util.logging.ConsoleHandler
.level= INFO

java.util.logging.FileHandler.pattern = simpledbm.log.%g
java.util.logging.FileHandler.limit = 50000
java.util.logging.FileHandler.count = 1
java.util.logging.FileHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.FileHandler.level = ALL

java.util.logging.ConsoleHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.ConsoleHandler.level = ALL

org.simpledbm.registry.level = INFO
org.simpledbm.bufmgr.level = INFO
org.simpledbm.indexmgr.level = INFO
org.simpledbm.storagemgr.level = INFO
org.simpledbm.walogmgr.level = INFO
org.simpledbm.lockmgr.level = INFO
org.simpledbm.freespacemgr.level = INFO
org.simpledbm.slotpagemgr.level = INFO
org.simpledbm.transactionmgr.level = INFO
org.simpledbm.tuplemgr.level = INFO
org.simpledbm.latchmgr.level = INFO
org.simpledbm.pagemgr.level = INFO
org.simpledbm.rss.util.level = INFO
org.simpledbm.util.level = INFO
org.simpledbm.server.level = INFO
org.simpledbm.trace.level = INFO
org.simpledbm.database.level = INFO
```

By default, SimpleDBM looks for a logging properties file named "simpledbm.logging.properties".

Transactions

Most SimpleDBM operations take place in the context of a Transaction. Following are the main API calls for managing transactions.

Creating new Transactions

To start a new Transaction, invoke the `Database.startTransaction()` method as shown below. You must supply an `IsolationMode`, try `READ_COMMITTED` to start with.:

```
import org.simpledbm.database.api.Database;
import org.simpledbm.rss.api.tx.IsolationMode;
import org.simpledbm.rss.api.tx.Transaction;

Database database = ...;
```

```
// Start a new Transaction
Transaction trx = database.startTransaction(IsolationMode.READ_COMMITTED);
```

Isolation Modes are discussed in more detail in *Isolation Modes*.

Working with Transactions

Transaction API

The Transaction interface provides the following methods for clients to invoke:

```
public interface Transaction {

  /**
   * Creates a transaction savepoint.
   */
  public Savepoint createSavepoint(boolean saveCursors);

  /**
   * Commits the transaction. All locks held by the
   * transaction are released.
   */
  public void commit();

  /**
   * Rolls back a transaction upto a savepoint. Locks acquired
   * since the Savepoint are released. PostCommitActions queued
   * after the Savepoint was created are discarded.
   */
  public void rollback(Savepoint sp);

  /**
   * Aborts the transaction, undoing all changes and releasing
   * locks.
   */
  public void abort();

}
```

A transaction must always be either committed or aborted. Failure to do so will lead to resource leaks, such as locks, which will not be released. The correct way to work with transactions is shown below:

```
// Start a new Transaction
Transaction trx = database.startTransaction(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  // do some work and if this is completed succesfully ...
  // set success to true.
  doSomething();
  success = true;
}
finally {
  if (success) {
    trx.commit();
  }
  else {
    trx.abort();
  }
}
```

Transaction Savepoints

You can create transaction savepoints at any point in time. When you create a savepoint, you need to decide whether the scans associated with the transaction should save their state so that in the event of a rollback, they can be restored to the state they were in at the time of the savepoint. This is important if you intend to use the scans after you have performed a rollback to savepoint.

Bear in mind that in certain IsolationModes, locks are released as the scan cursor moves, When using such an IsolationMode, rollback to a Savepoint can fail if after the rollback, the scan cursor cannot be positioned on a suitable location, for example, if a deadlock occurs when it attempts to reacquire lock on the previous location. Also, in case the location itself is no longer valid, perhaps due to a delete operation by some other transaction, then the scan may position itself on the next available location.

If you are preserving cursor state during savepoints, be prepared that in certain IsolationModes, a rollback may fail due to locking, or the scan may not be able to reposition itself on exactly the same location.

Note that the cursor restore functionality has not been tested thoroughly in the current release of SimpleDBM.

Tables and Indexes

SimpleDBM provides support for tables with variable length rows. Tables can have associated BTree indexes. In this section we shall see how to create new tables and indexes and how to use them.

Limitations

SimpleDBM supports creating tables and indexes but there are some limitations at present that you need to be aware of.

- All indexes required for the table must be defined at the time of table creation. At present you cannot add an index at a later stage.
- Table structures are limited in the type of columns you can have. At present Varchar, Varbinary, DateTime, Number, Integer and Long types are supported. More data types will be available in a future release of SimpleDBM.
- Null columns cannot be indexed.
- There is no support for referential integrity constraints or any other type of constraint. Therefore you need to enforce any such requirement in your application logic.
- Generally speaking, table rows can be large, but be aware that large rows are split across multiple database pages. The SimpleDBM page size is 8K.
- An Index key must be limited in size to about 1K in storage space.

Creating a Table and Indexes

You start by creating the table's row definition, which consists of an array of `TypeDescriptor` objects. Each element of the array represents a column definition for the table.

You use the `TypeFactory` interface for creating the `TypeDescriptor` objects as shown below.:

```
Database db = ...;
TypeFactory ff = db.getTypeFactory();
TypeDescriptor employee_rowtype[] = {
  ff.getIntegerType(), /* primary key */
  ff.getVarcharType(20), /* name */
  ff.getVarcharType(20), /* surname */
  ff.getVarcharType(20), /* city */
  ff.getVarcharType(45), /* email address */
  ff.getDateTimeType(), /* date of birth */
  ff.getNumberType(2) /* salary */
};
```

The next step is to create a `TableDefinition` object by calling the `Database.newTableDefinition()` method.:

```
TableDefinition tableDefinition = db.newTableDefinition("employee.dat", 1,
  employee_rowtype);
```

The `newTableDefinition()` method takes 3 arguments:

1. The name of the table container.
2. The ID for the table container. IDs start at 1, and must be unique.
3. The `TypeDescriptor array` that you created before.

Now you can add indexes by invoking the `addIndex()` method provided by the `TableDefinition` interface.:

```
tableDefinition.addIndex(2, "employee1.idx", new int[] { 0 }, true, true);
tableDefinition.addIndex(3, "employee2.idx", new int[] { 2, 1 }, false,
  false);
tableDefinition.addIndex(4, "employee3.idx", new int[] { 5 }, false, false);
tableDefinition.addIndex(5, "employee4.idx", new int[] { 6 }, false, false);
```

Above example shows four indexes being created.

The `addIndex()` method takes following arguments.

1. The ID of the index container. Must be unique, and different from the table container ID.
2. The name of the index container.
3. An array of integers. Each element of the array must refer to a table column by position. The table column positions start at zero. Therefore the array { 2, 1 } refers to 3rd column, and 2nd column of the table.
4. The next argument is a boolean value to indicate whether the index is the primary index. The first index must always be the primary index.
5. The next argument is also a boolean value to indicate whether duplicate values are allowed in the index. If set, this makes the index unique, which prevents duplicates. The primary index must always be unique.

Now that you have a fully initialized `TableDefinition` object, you can proceed to create the table and indexes by invoking the `createTable()` method provided by the Database interface.:

```
db.createTable(tableDefinition);
```

Tables are created in their own transactions, and you have no access to such transactions.

It is important to bear in mind that all container names must be unique. Think of the container name as the file name. Also, the container IDs are used by SimpleDBM to identify each container uniqely. As explained before, SimpleDBM internally uses a special container with ID=0. Any tables and indexes you create must have container IDs >= 1, and you must ensure that these are unique.

Isolation Modes

Before describing how to access table data using scans, it is necessary to describe the various lock isolation modes supported by SimpleDBM.

Common Behaviour

Following behaviour is common across all lock isolation modes.

1. All locking is on Row Locations (rowids) only. The SimpleDBM Rowid is called a TupleId.
2. When a row is inserted or deleted, its rowid is first locked in EXCLUSIVE mode, the row is inserted or deleted from data page, and only after that, indexes are modified.
3. Updates to indexed columns are treated as key deletes followed by key inserts. The updated row is locked in EXCLUSIVE mode before indexes are modified.
4. When fetching, the index is looked up first, which causes a SHARED or UPDATE mode lock to be placed on the row, before the data pages are accessed.

Read Committed/Cursor Stability

During scans, the rowid is locked in SHARED or UPDATE mode while the cursor is positioned on the key. The lock on current rowid is released before the cursor moves to the next key.

For most use cases, this is the recommended isolation mode as it provides the best concurrency.

Repeatable Read (RR)

SHARED mode locks obtained on rowids during scans are retained until the transaction completes. UPDATE mode locks are downgraded to SHARED mode when the cursor moves.

Serializable

Same as Repeatable Read, with additional locking (next key) during scans to prevent phantom reads.

Inserting rows into a table

To insert a row into a table, following steps are needed.

Obtain a transaction context in which to perform the insert.:

```
Transaction trx = db.startTransaction(IsolationMode.READ_COMMITTED);
boolean okay = false;
try {
```

Get the `Table` object associated with the table. Tables are identified by their container Ids.:

```
int containerId = 1;
Table table = db.getTable(trx, containerId);
```

Create a blank row. It is best to create new row objects rather than reusing existing objects.:

```
Row tableRow = table.getRow();
```

You can assign values to the columns as shown below.:

```
tableRow.setInt(0, i);
tableRow.setString(1, "Joe");
tableRow.setString(2, "Blogg");
tableRow.setDate(5, getDOB(1930, 12, 31));
tableRow.setString(6, "500.00");
```

Any columns you do not assign a value will be set to null automatically. The final step is to insert the row and commit the transaction.:

```
  table.addRow(trx, tableRow);
  okay = true;
} finally {
  if (okay) {
    trx.commit();
  } else {
    trx.abort();
  }
}
```

Accessing table data

In order to read table data, you must open a scan. A scan is a mechanism for accessing table rows one by one. Scans are ordered using indexes.

Opening an TableScan requires you to specify a starting row. If you want to start from the beginning, then you may specify `null` as the starting row. The values from the starting row are used to perform an index search, and the scan begins from the first row greater or equal to the values in the starting row.

In SimpleDBM, scans do not have a stop value. Instead, a scan starts fetching data from the first row that is greater or equal to the supplied starting row. You must determine whether the fetched key satisfies the search criteria or not. If the fetched key no longer meets the search criteria, you should call `fetchCompleted()` with a `false` value, indicating that there is no need to fetch any more keys. This then causes the scan to reach logical `EOF`.

The code snippet below shows a table scan that is used to count the number of rows in the table.:

```
Transaction trx = db.startTransaction(IsolationMode.READ_COMMITTED);
boolean okay = false;
int count = 0;
try {
  Table table = db.getTable(trx, 1);
  /* open a scan with null starting row */
  /* scan will use index 0 - ie - first index */
  TableScan scan = table.openScan(trx, 0, null, false);
  try {
    while (scan.fetchNext()) {
      scan.fetchCompleted(true);
      count++;
    }
  } finally {
    scan.close();
  }
  okay = true;
} finally {
  if (okay) {
    trx.commit();
  } else {
    trx.abort();
  }
}
```

The following points are worth noting.

1. The `openScan()` method takes an index identifier as the second argument. The scan is ordered by the index. Indexes are identified by the order in which they were associated with the table, therefore, the first index is 0, the second is 1, and so on. Note that the index number is not the container ID for the index.
2. The third argument is the starting row for the scan. If `null` is specified, as in the example above, then the scan will start from logical negative infinity, ie, from the first row (as per selected index) in the table.
3. The scan must be closed in a finally block to ensure proper cleanup of resources.

Updating tuples

In order to update a row, you must first set the RowId using a scan. Typically, if you intend to update the tuple, you should open the scan in UPDATE mode. This is done by supplying a boolean true as the fourth argument to `openScan()` method.

Here is an example of an update. The table is scanned from first row to last and three of the columns are updated in all the rows.:

```
Transaction trx = db.startTransaction(IsolationMode.READ_COMMITTED);
boolean okay = false;
try {
  Table table = db.getTable(trx, 1);
  /* start an update mode scan */
  TableScan scan = table.openScan(trx, 0, null, true);
  try {
    while (scan.fetchNext()) {
      Row tr = scan.getCurrentRow();
      tr.setString(3, "London");
      tr.setString(4, tr.getString(1) + "." + tr.getString(2) + "@gmail.com");
      tr.setInt(6, 50000);
      scan.updateCurrentRow(tr);
      scan.fetchCompleted(true);
    }
  } finally {
    scan.close();
  }
  okay = true;
} finally {
  if (okay) {
    trx.commit();
  } else {
    trx.abort();
  }
}
```

The following points are worth noting:

1. If you update the columns that form part of the index that is performing the scan, then the results may be unexpected. As the data is updated it may alter the scan ordering.
2. The update mode scan places UPDATE locks on rows as these are accessed. When the row is updated, the lock is promoted to EXCLUSIVE mode. If you skip the row without updating it, the lock is either released (READ_COMMITTED) or downgraded (in other lock modes) to SHARED lock.

Deleting tuples

Start a table scan in UPDATE mode, if you intend to delete rows during the scan. Row deletes are performed in a similar way as row updates, except that `TableScan.deleteRow()` is invoked on the current row.

The Database API

DatabaseFactory

```
/**
 * The DatabaseFactory class is responsible for creating and obtaining
 * instances of Databases.
 */
public class DatabaseFactory {

      /**
       * Creates a new SimpleDBM database based upon supplied properties.
       * For details of available properties, please refer to the SimpleDBM
       * User Manual.
       */
      public static void create(Properties properties);

      /**
       * Obtains a database instance for an existing database.
       */
      public static Database getDatabase(Properties properties);

}
```

Database

```
/**
 * A SimpleDBM Database is a collection of Tables. The Database runs as
 * an embedded server, and provides an API for creating and
 * maintaining tables.
 * A Database is created using DatabaseFactory.create(). An
 * existing Database can be instantiated using
 * DatabaseFactory.getDatabase().
 */
public interface Database {

      /**
       * Constructs a new TableDefinition object. A TableDefinition object
       * is used when creating new tables.
       *
```

```
     * @param name Name of the table
     * @param containerId ID of the container that will hold the table data
     * @param rowType A row type definition.
     * @return A TableDefinition object.
     */
    public abstract TableDefinition newTableDefinition(String name,
                    int containerId, TypeDescriptor[] rowType);

    /**
     * Gets the table definition associated with the specified container ID.
     *
     * @param containerId Id of the container
     * @return TableDefinition
     */
    public abstract TableDefinition getTableDefinition(int containerId);

    /**
     * Starts the database instance.
     */
    public abstract void start();

    /**
     * Shuts down the database instance.
     */
    public abstract void shutdown();

    /**
     * Gets the SimpleDBM RSS Server object that is managing this database.
     * @return SimpleDBM RSS Server object.
     */
    public abstract Server getServer();

    /**
     * Starts a new Transaction
     */
    public abstract Transaction startTransaction(IsolationMode isolationMode);

    /**
     * Returns the TypeFactory instance associated with this database.
     * The TypeFactory object can be used to create TypeDescriptors
     * for various types that can become columns in a row.
     */
    public abstract TypeFactory getTypeFactory();

    /**
     * Returns the RowFactory instance associated with this database.
     * The RowFactory is used to generate rows.
     */
    public abstract RowFactory getRowFactory();

    /**
     * Creates a Table and associated indexes using the information
     * in the supplied TableDefinition object. Note that the table
     * must have a primary index defined.
     * The table creation is performed in a standalone transaction.
     */
    public abstract void createTable(TableDefinition tableDefinition);
```

```
      /**
       * Drops a Table and all its associated indexes.
       *
       * @param tableDefinition
       *             The TableDefinition object that contains information about the
       *             table to be dropped.
       */
      public abstract void dropTable(TableDefinition tableDefinition);

      /**
       * Gets the table associated with the specified container ID.
       *
       * @param trx Transaction context
       * @param containerId Id of the container
       * @return Table
       */
      public abstract Table getTable(Transaction trx, int containerId);
}
```

TableDefinition

```
/**
 * A TableDefinition holds information about a table, such as its name,
 * container ID, types and number of columns, etc..
 */
public interface TableDefinition extends Storable {

      /**
       * Adds an Index to the table definition. Only one primay index
       * is allowed.
       *
       * @param containerId Container ID for the new index.
       * @param name Name of the Index Container
       * @param columns Array of Column identifiers - columns to be indexed
       * @param primary A boolean flag indicating that this is
       *                the primary index or not
       * @param unique A boolean flag indicating whether the index
       *               should allow only unique values
       */
      public abstract void addIndex(int containerId, String name, int[] columns,
                     boolean primary, boolean unique);

      /**
       * Gets the Container ID associated with the table.
       */
      public abstract int getContainerId();

      /**
       * Returns the Table's container name.
       */
      public abstract String getName();

      /**
       * Constructs an empty row for the table.
       * @return Row
       */
```

```
        public abstract Row getRow();

        /**
         * Returns the number of indexes associated with the table.
         */
        public abstract int getNumberOfIndexes();

        /**
         * Constructs an row for the specified Index. Appropriate columns
         * from the table are copied into the Index row.
         *
         * @param index The Index for which the row is to be constructed
         * @param tableRow The table row
         * @return An initialized Index Row
         */
        public abstract Row getIndexRow(int indexNo, Row tableRow);
}
```

Table

```
/**
 * A Table is a collection of rows. Each row is made up of
 * columns (fields). A table must have a primary key defined
 * which uniquely identifies each row in the
 * table.
 * <p>
 * A Table is created by Database.createTable().
 * Once created, the Table object can be accessed by calling
 * Database.getTable() method.
 */
public interface Table {

        /**
         * Adds a row to the table. The primary key of the row must
         * be unique and different from all other rows in the table.
         *
         * @param trx The Transaction managing this row insert
         * @param tableRow The row to be inserted
         * @return Location of the new row
         */
        public abstract Location addRow(Transaction trx, Row tableRow);

        /**
         * Updates the supplied row in the table. Note that the row to be
         * updated is identified by its primary key.
         *
         * @param trx The Transaction managing this update
         * @param tableRow The row to be updated.
         */
        public abstract void updateRow(Transaction trx, Row tableRow);

        /**
         * Deletes the supplied row from the table. Note that the row to be
         * deleted is identified by its primary key.
         *
         * @param trx The Transaction managing this delete
         * @param tableRow The row to be deleted.
         */
        public abstract void deleteRow(Transaction trx, Row tableRow);

        /**
         * Opens a Table Scan, which allows rows to be fetched from the Table,
         * and updated.
         *
         * @param trx Transaction managing the scan
         * @param indexno The index to be used for the scan
         * @param startRow The starting row of the scan
         * @param forUpdate A boolean value indicating whether the scan will
         *                  be used to update rows
         * @return A TableScan
         */
        public abstract TableScan openScan(Transaction trx, int indexno,
                        Row startRow, boolean forUpdate);

        /**
         * Constructs an empty row for the table.
         * @return Row
         */
        public abstract Row getRow();

        /**
         * Constructs an row for the specified Index. Appropriate columns from the
         * table are copied into the Index row.
         *
         * @param index The Index for which the row is to be constructed
         * @param tableRow The table row
         * @return An initialized Index Row
         */
        public abstract Row getIndexRow(int index, Row tableRow);
}
```

TableScan

```
/**
 * A TableScan is an Iterator that allows clients to iterate through the
 * contents of a Table. The iteraion is always ordered through an Index.
 * The Transaction managing the iteration defines the Lock Isolation level.
 */
public interface TableScan {

        /**
         * Fetches the next row from the Table. The row to be fetched depends
         * upon the current position of the scan, and the Index ordering of
         * the scan.
         * @return A boolean value indicating success of EOF
         */
        public abstract boolean fetchNext();

        /**
         * Returns a copy of the current Row.
         */
        public abstract Row getCurrentRow();
```

```
      /**
       * Returns a copy of the current Index Row.
       */
      public abstract Row getCurrentIndexRow();

      /**
       * Notifies the scan that the fetch has been completed
       * and locks may be released (depending upon the
       * Isolation level).
       * @param matched A boolean value that should be true
       *   if the row is part of the search criteria match result.
       *   If set to false, this indicates that no further
       *   fetches are required.
       */
      public abstract void fetchCompleted(boolean matched);

      /**
       * Closes the scan, releasing locks and other resources
       * acquired by the scan.
       */
      public abstract void close();

      /**
       * Updates the current row.
       */
      public abstract void updateCurrentRow(Row tableRow);

      /**
       * Deletes the current row.
       */
      public abstract void deleteRow();
}
```

CHAPTER 3

SimpleDBM Network API

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Contents

Introduction

This document describes the SimpleDBM Network API.

Intended Audience

This documented is targetted at users of SimpleDBM.

Pre-requisite Reading

Before reading this document, the reader is advised to go through the SimpleDBM Overview document.

Getting Started

SimpleDBM binaries

SimpleDBM makes use of Java 5.0 features, hence you will need to use JDK1.6 or above if you want to work with SimpleDBM.

The following maven dependencies give you access to the server jars.

```
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-network-server</artifactId>
  <version>1.0.23</version>
</dependency>
```

The following maven dependencies are needed for the client application.

```
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-network-server</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-network-framework</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-network-common</artifactId>
  <version>1.0.23</version>
</dependency>
<dependency>
```

```
  <groupId>org.simpledbm</groupId>
  <artifactId>simpledbm-typesystem</artifactId>
  <version>1.0.23</version>
</dependency>
```

Summary of Steps Required

1. Write your client application, using the SimpleDBM Network Client API.
2. Create a new SimpleDBM database.
3. Start the SimpleDBM Network Server.
4. Run your application.

Writing your Application

At present only Java language bindings are available, therefore you must write your application in Java. All you need is the SimpleDBM Network Client jar, which includes required SimpleDBM modules for interacting with the server.

This document will in future contain a tutorial on how to use the Client API. For now, the Java Interface for the API is described in the Appendix. An example client interaction is given below:

```
Properties properties = parseProperties("test.properties");
```

An example test.properties file is given in the next section. Start a session:

```
SessionManager sessionManager = sm = SessionManager.getSessionManager(properties,
  "localhost", 8000,
  (int) TimeUnit.MILLISECONDS.convert(5 * 60, TimeUnit.SECONDS));
```

The last parameter is the socket timeout in milliseconds. The socket will timeout when reading/writing when the specified timeout period is exceeded and there is no response from the server.

Each SessionManager instance maintains a single network connection to SimpleDBM Server. In order to interact with the server, you need to open sessions. Each session is simply a transaction context, allowing you to have one active transaction per session.

Here we open a session, obtain the type factoy and create a table definition:

```
// Get the type factory
TypeFactory ff = sessionManager.getTypeFactory();
// Open a session
Session session = sessionManager.openSession();
try {
 // create a table definition
 TypeDescriptor employee_rowtype[] = { ff.getIntegerType(), /* pk */
 ff.getVarcharType(20), /* name */
 ff.getVarcharType(20), /* surname */
 ff.getVarcharType(20), /* city */
 ff.getVarcharType(45), /* email address */
 ff.getDateTimeType(), /* date of birth */
 ff.getNumberType(2) /* salary */
 };
 // the table will be assigned container ID 1.
 // Containers identify the files that will store the
 // data and therefore must be unique.
```

```
TableDefinition tableDefinition = sessionManager
  .newTableDefinition("employee", 1, employee_rowtype);
// define a few indexes
tableDefinition.addIndex(2, "employee1.idx", new int[] { 0 }, true,
  true);
tableDefinition.addIndex(3, "employee2.idx", new int[] { 2, 1 },
  false, false);
tableDefinition.addIndex(4, "employee3.idx", new int[] { 5 },
  false, false);
tableDefinition.addIndex(5, "employee4.idx", new int[] { 6 },
  false, false);
```

Now we can create the table in the database. This is done in an internal transaction that you cannot control.:

```
session.createTable(tableDefinition);
```

Now that the table has been created, we can initiate a transaction and insert a row:

```
// Start transaction
session.startTransaction(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
 /*
  * Each table is identified the container ID that was
  * assigned when defining the table. So in this
  * case the container ID is 1.
  */
 Table table = session.getTable(1);
 // Get a blank row
 Row tableRow = table.getRow();
 // Initialize the row
 tableRow.setInt(0, 1);
 tableRow.setString(1, "Joe");
 tableRow.setString(2, "Blogg");
 tableRow.setDate(5, getDOB(1930, 12, 31));
 tableRow.setString(6, "500.00");
 // Insert the row
 table.addRow(tableRow);
```

In the same transaction, let us scan through the rows in the table:

```
// The first parameter of the scan is the index
// The second parameter is the search row. In this case
// we want to scan all rows. The last argument is whether
// we intend to update rows.
TableScan scan = table.openScan(0, null, false);
try {
 // Get the next row
 Row row = scan.fetchNext();
 while (row != null) {
  System.out.println("Fetched row " + row);
  // Lets change one of the fields
  row.setString(6, "501.00");
  // Update the current row
  scan.updateCurrentRow(row);
  // Get the next row
  row = scan.fetchNext();
 }
} finally {
 scan.close();
}
success = true;
```

Finally we commit the transaction:

```
} finally {
 if (success) {
  session.commit();
 } else {
  session.rollback();
 }
}
```

Now lets delete the newly added row. First start a new transaction:

```
session.startTransaction(IsolationMode.READ_COMMITTED);
success = false;
try {
 Table table = session.getTable(1);
```

Scan the table and delete all rows:

```
TableScan scan = table.openScan(0, null, false);
try {
 Row row = scan.fetchNext();
 while (row != null) {
  System.out.println("Deleting row " + row);
  scan.deleteRow();
  row = scan.fetchNext();
 }
} finally {
 scan.close();
}
success = true;
```

Commit the transaction:

```
 } finally {
  if (success) {
   session.commit();
  } else {
   session.rollback();
  }
 }
} catch (Exception e) {
 e.printStackTrace();
```

Finally, close the session:

```
} finally {
 session.close();
}
```

Note that you can only have one transaction active in the context of a session. If you need to have more than one transaction active, each should be given its own session context.

When you close a session, any pending transaction will be aborted unless you have already committed the transaction. It is always preferable to explicitly commit or abort transactions.

The server also has a session timeout feature which enables it to clean up sessions that are idle for a while. It is not a good idea to leave a session idle for long; you can close the session once you are done and open a new one when necessary.

Creating a SimpleDBM database

The database configuration is defined in a properties file. Example of the properties file:

```
logging.properties.file = classpath:simpledbm.logging.properties
logging.properties.type = log4j
network.server.host = localhost
network.server.port = 8000
network.server.sessionTimeout = 300000
network.server.sessionMonitorInterval = 120
network.server.selectTimeout = 10000
log.ctl.1 = ctl.a
log.ctl.2 = ctl.b
log.groups.1.path = .
log.archive.path = .
log.group.files = 3
log.file.size = 5242880
log.buffer.size = 5242880
log.buffer.limit = 4
log.flush.interval = 30
log.disableFlushRequests = true
storage.basePath = testdata/DatabaseTests
storage.createMode = rw
storage.openMode = rw
storage.flushMode = noforce
bufferpool.numbuffers = 1500
bufferpool.writerSleepInterval = 60000
transaction.ckpt.interval = 60000
lock.deadlock.detection.interval = 3
```

Notice that most of these properties are the standard options supported by SimpleDBM. An example of the logging properties file can be found in the SimpleDBM distribution.

The additional properties that are specific to the network server are described below:

network.server.host DNS name or ip address of the server

network.server.port Port on which the server is listening for connections

network.server.sessionTimeout The session timeout in milliseconds. If a session is idle for longer than this duration, it will be closed. Any pending transaction will be aborted.

network.server.sessionMonitorInterval The frequency (in seconds) at which the server checks for idle sessions.

network.server.selectTimeout The network server uses the select() facility to poll for network requests. Rather than blocking indefinitely, it uses the specified timeout value. This allows the server to wake up every so often; the default value of 10000 milliseconds is fine and need not be changed.

To create your new database, invoke SimpleDBM Network Server as follows:

```
java -jar simpledbm-network-server-1.0.23.jar create <properties file>
```

This will create an empty database in the location specified by the property *storage.basePath*.

Note that you can obtain the jar above from Maven Central - the link is SimpleDBM NetWork Server 1.0.23.

Starting a database

Once a database has been created, it can be started using the following command (the command is wrapped into two lines but is a single command):

```
java -Xms128m -Xmx1024m -jar simpledbm-network-server-1.0.23.jar
   open <properties file>
```

To stop the database server, simply press Control-C. It may take a few seconds for the server to acknowledge the shutdown request.

Problems starting a database

SimpleDBM uses a lock file to determine whether an instance is already running. At startup, it creates the file at the location `_internal\lock` relative to the path where the database is created. If this file already exists, then SimpleDBM will report a failure such as:

```
SIMPLEDBM-EV0005: Error starting SimpleDBM RSS Server, another
instance may be running - error was: SIMPLEDBM-ES0017: Unable to create
StorageContainer .._internal\lock because an object of the name already exists
```

This message indicates either that some other instance is running, or that an earlier instance of SimpleDBM terminated without properly sutting down. If the latter is the case, then the `_internal/lock` file may be deleted enabling SimpleDBM to start.

Managing log messages

SimpleDBM has support for JDK 1.4 style logging.

The configuration of the logging can be specified using a properties file. The name and location of the properties file is specified using the Server property `logging.properties.file`. If the filename is prefixed with the string "classpath:", then SimpleDBM will search for the properties file in the classpath. Otherwise, the filename is searched for in the current filesystem.

A sample logging properties file is shown below. Note that this sample contains both JDK style and Log4J style configuration.:

```
############################################################
#       JDK 1.4 Logging
############################################################
handlers= java.util.logging.FileHandler, java.util.logging.ConsoleHandler
.level= INFO

java.util.logging.FileHandler.pattern = simpledbm.log.%g
java.util.logging.FileHandler.limit = 50000
java.util.logging.FileHandler.count = 1
java.util.logging.FileHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.FileHandler.level = ALL

java.util.logging.ConsoleHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.ConsoleHandler.level = ALL
```

```
org.simpledbm.registry.level = INFO
org.simpledbm.bufmgr.level = INFO
org.simpledbm.indexmgr.level = INFO
org.simpledbm.storagemgr.level = INFO
org.simpledbm.walogmgr.level = INFO
org.simpledbm.lockmgr.level = INFO
org.simpledbm.freespacemgr.level = INFO
org.simpledbm.slotpagemgr.level = INFO
org.simpledbm.transactionmgr.level = INFO
org.simpledbm.tuplemgr.level = INFO
org.simpledbm.latchmgr.level = INFO
org.simpledbm.pagemgr.level = INFO
org.simpledbm.rss.util.level = INFO
org.simpledbm.util.level = INFO
org.simpledbm.server.level = INFO
org.simpledbm.trace.level = INFO
org.simpledbm.database.level = INFO
org.simpledbm.network.level = INFO
org.simpledbm.network.server.level = INFO
```

By default, SimpleDBM looks for a logging properties file named “simpledbm.logging.properties”.

The Network API

SessionManager

```
/**
 * The SessionManager manages the connection to the SimpleDBM Network Server,
 * and initiates sessions used by the clients. Each SessionManager maintains
 * a single connection to the server. Requests sent over a single connection
 * are serialized.
 */
public abstract class SessionManager {

  /**
   * Obtains an instance of the SessionManager for the specified connection
   * parameters. The client should allow for the fact that the returned
   * instance may be a shared one.
   *
   * @param properties A set of properties - at present only logging parameters
   *                   are used
   * @param host       The DNS name or IP address of the server
   * @param port       The port the server is listening on
   * @param timeout    The socket timeout in milliseconds. This is the
   *                   timeout for read/write operations.
   * @return A Session Manager object
   */
  public static SessionManager getSessionManager(
              Properties properties,
              String host,
              int port,
              int timeout);

  /**
```

```
     * Gets the TypeFactory associated with the database.
     */
    public abstract TypeFactory getTypeFactory();

    /**
     * Gets the RowFactory for the database.
     */
    public abstract RowFactory getRowFactory();

    /**
     * Creates a new TableDefinition.
     *
     * @param name Name of the table's container
     * @param containerId ID of the container; must be unique
     * @param rowType The row definition as an arry of TypeDescriptors
     * @return A TableDefinition object
     */
    public abstract TableDefinition newTableDefinition(
                    String name, int containerId,
                    TypeDescriptor[] rowType);

    /**
     * Starts a new session.
     */
    public abstract Session openSession();

    /**
     * Gets the underlying connection object associated with
     * this SessionManager.
     *
     * The connection object must be handled with care, as
     * its correct operation is vital to the client server
     * communication.
     */
    public abstract Connection getConnection();

    /**
     * Closes the SessionManager and its connection with the database,
     * releasing any acquired resources.
     */
    public abstract void close();
}
```

Session

```
/**
 * A Session encapsulates an interactive session with the server. Each session
 * can only have one active transaction at any point in time. Clients can open
 * multiple simultaneous sessions.
 *
 * All sessions created by a SessionManager share a single network connection
 * to the server.
 */
public interface Session {

    /**
```

```
   * Closes the session. If there is any outstanding transaction, it will
   * be aborted. Sessions should be closed by client applications when no
   * longer required, as this will free up resources on the server.
   */
  public void close();

  /**
   * Starts a new transaction. In the context of a session, only one
   * transaction can be active at a point in time, hence if this method will
   * fail if there is already an active transaction.
   *
   * @param isolationMode Lock isolation mode for the transaction
   */
  public void startTransaction(IsolationMode isolationMode);

  /**
   * Commits the current transaction; an exception will be thrown if
   * there is no active transaction.
   */
  public void commit();

  /**
   * Aborts the current transaction; an exception will be thrown if
   * there is no active transaction
   */
  public void rollback();

  /**
   * Creates a table as specified. The table will be created using its own
   * transaction independent of the transaction managed by the session.
   *
   * @param tableDefinition The TableDefinition
   */
  public void createTable(TableDefinition tableDefinition);

  /**
   * Obtains a reference to the table. The Table container will be
   * locked in SHARED mode.
   *
   * @param containerId The ID of the table's container
   * @return A Table object
   */
  public Table getTable(int containerId);

  /**
   * Gets the SessionManager that is managing this session.
   */
  public SessionManager getSessionManager();

  /**
   * Gets the unique id associated with this session.
   */
  public int getSessionId();
}
```

Table

```
/**
 * A Table represents a collection of related containers, one of which is
 * a Data Container, and the others, Index Containers. The Data Container
 * hold rows of table data, and the Index Containers provide access paths to
 * the table rows. At least one index must be created because the database
 * uses the index to manage the primary key and lock isolation modes.
 *
 * @author Dibyendu Majumdar
 */
public interface Table {

 /**
  * Starts a new Table Scan which allows the client to iterate through
  * the table's rows.
  *
  * @param indexno The index to be used; first index is 0, second 1, etc.
  * @param startRow The search key - a suitable initialized table row.
  *                 Only columns used in the index are relevant.
  *                 This parameter can be set to null if the scan
  *                 should start from the first available row
  * @param forUpdate A boolean flag to indicate whether the client
  *                  intends to update rows, in which case this parameter
  *                  should be set to true. If set, rows will be
  *                  locked in UPDATE mode to allow subsequent updates.
  * @return A TableScan object
  */
  public TableScan openScan(int indexno, Row startRow,
       boolean forUpdate);

  /**
   * Obtains an empty row, in which all columns are set to NULL.
   * @return
   */
  public Row getRow();

  /**
   * Adds the given row to the table. The add operation may fail
   * if another row with the same primary key already exists.
   * @param row Row to be added
   */
  public void addRow(Row row);
}
```

TableScan

```
/**
 * A TableScan is used to traverse the rows in a table, ordered
 * by an Index. The initial position of the scan is determined by
 * the keys supplied when the scan is opened. The table scan
 * respects the lock isolation mode of the transaction.
 *
 * As rows are fetched, the scan maintains its position. The current
 * row may be updated or deleted.
 */
```

```
public interface TableScan {

  /**
   * Fetches the next row. If EOF is reached, null will
   * be returned.
   */
  public Row fetchNext();

  /**
   * Updates the current row.
   *
   * @param tableRow New value for the row
   */
  public void updateCurrentRow(Row tableRow);

  /**
   * Deletes the current row.
   */
  public void deleteRow();

  /**
   * Closes the scan, releasing any locks that are not required.
   */
  public void close();

  /**
   * Obtains the session that is associated with this scan.
   */
  Session getSession();
}
```

CHAPTER 4

SimpleDBM TypeSystem

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Version 1.0.x

Date 05 July 2008

Contents

Introduction

This document describes the SimpleDBM TypeSystem module.

Intended Audience

This documented is targetted at users of SimpleDBM.

Pre-requisite Reading

Before reading this document, the reader is advised to go through the SimpleDBM Overview document.

SimpleDBM TypeSystem

Introduction

SimpleDBM has a modular architecture. The core of the database engine is in the RSS module. A feature of the engine is that it has no knowledge of data types. This is deliberate, to ensure the greatest flexibility. The RSS only cares about the "sortability" and "persistability" of data. It doesn't really care about the internal structure of the data.

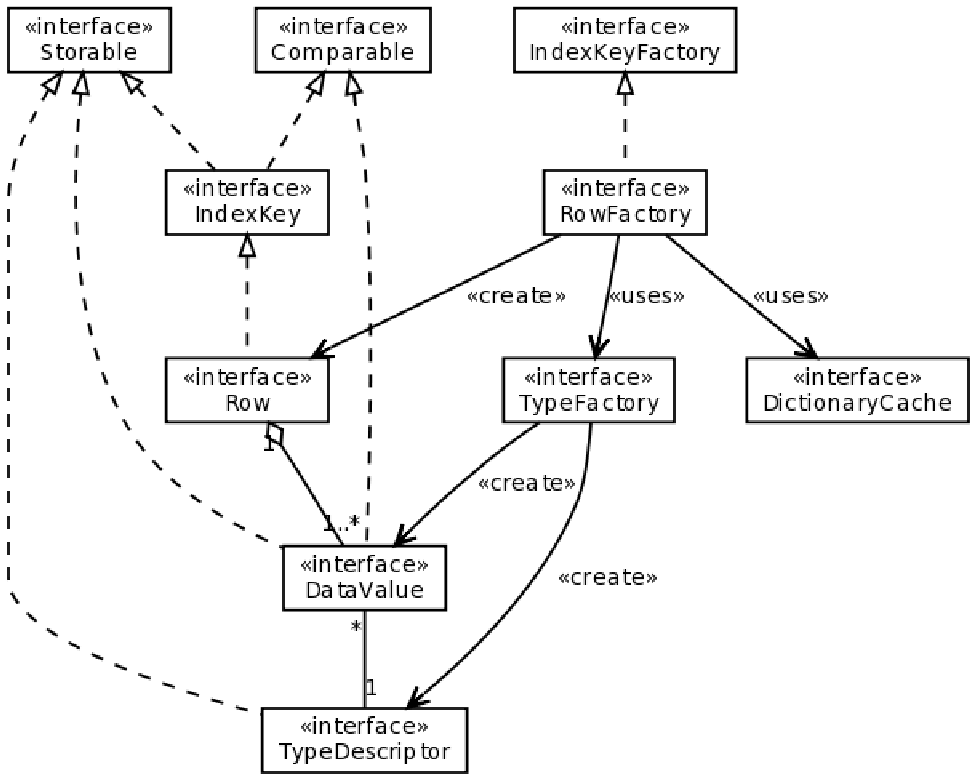
From a user perspective, the RSS is fairly low level. It requires a fair amount of work to use the low level API. For instance, the developer has to worry about how to implement various types, and how to integrate the types into SimpleDBM. This may be exactly what is needed for someone who wishes to use very specialized data types, but for the majority of users, this is too much complexity.

The SimpleDBM-TypeSystem module adds a type system module that can be used with SimpleDBM. It is currently at experimental stage, and is evolving.

The TypeSystem is used by the Database API to provide a higher level interface to SimpleDBM.

TypeSystem Classes

The overall design of the TypeSystem API is shown in a simplified form in the class diagram below:



The main classes and their purposes are described below:

Row represents a table or index row. A row consists of a number of column (Field) objects which are accessed by position.

DictionaryCache implements the Dictionary Cache where row types can be registered, and later on retrieved by container ID.

RowFactory is responsible for instantiating Rows for tables and indexes.

TypeFactory is the main interface for generating column data type descriptors (TypeDescriptor). It provides methods for creating various types.

TypeDescriptor holds details of the type definition. At present, only following four types are available: Varchar, Number, DateTime and Integer.

DataValue this is the column value. Sub-classes implement the actual behavior. DataValue provides a consistent interface for comparison, assignment and reference.

How it all fits together

A client starts by creating an array of TypeDescriptor objects. This array represents the row type for a table or an index container.:

```
TypeFactory typeFactory = TypeSystemFactory.getDefaultTypeFactory();
TypeDescriptor[] rowtype1 = new TypeDescriptor[] {
  typeFactory.getIntegerType(), typeFactory.getVarcharType(10)
};
```

In the example shown above, a row type is created with one integer column and one Varchar column of length 10 characters.

The next step is to register the row type so that it can be accessed by clients. This is done as shown below:

```
RowFactory rowFactory = TypeSystemFactory.getDefaultRowFactory(typeFactory);
rowFactory.registerRowType(1, rowtype1);
```

Here the row type is being registered for container ID 1.

Whenever it is necessary to construct a new Row object for container 1, the following code can be invoked:

```
Row row = rowFactory.newRow(1);
```

By default all the column values in the Row are set to NULL. NULL is a special state in the Field's value.

Column values can be accessed via the getColumnvalue() method provided by the Row interface. The column's value can be changed using one of the setter methods implemented by the underlying DataValue object. Example:

```
DataValue firstColumn = row.getColumnValue(0);
DataValue secondColumn = row.getColumnValue(1);

firstColumn.setInt(5); // set column value
secondColumn.setString("Hello world!");
```

Note that column positions start at 0.

About Data Values

A DataValue can be in one of four states:

Positive Infinity this is a logical value that is greater than any other value of the column.

Negative Infinity the converse of Positive Infinity, this represents the lowest possible value.

Null this represents the Null value.

Value this signifies that there is a real value in the column which is not Null and not one of the Infinity values.

DataValues are sortable. Rows are sortable as well.

Integration with SimpleDBM RSS Module

The TypeSystem integrates with SimpleDBM RSS in following ways:

- RowFactory is a sub-class of IndexKeyFactory. Therefore RowFactory can be used wherever IndexKeyFactory is required.
- Row is a sub-class of IndexKey and Storable. Therefore, Row objects can be used as Tuple values as well as Index key values.
- GenericRowFactory is an implementation of RowFactory that can be registered with SimpleDBM as a factory for index keys and table rows.

Samples

The following samples show how the TypeSystem may be used:

- TupleDemo - demonstrates the raw SimpleDBM RSS API and shows how the TypeSystem may be integrated with it.
- BTreeDemo - demonstrates the standalone use of BTrees.

CHAPTER 5

SimpleDBM RSS User's Manual

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Version 1.0.12

Date 7 April 2009

Contents

Introduction

This document describes the SimpleDBM RSS API.

Intended Audience

This documented is targetted at users of SimpleDBM.

Pre-requisite Reading

Before reading this document, the reader is advised to go through the SimpleDBM Overview document.

SimpleDBM Servers and Databases

Introduction

A SimpleDBM server is a set of background threads and a library of API calls that clients can hook into. The background threads take care of various tasks, such as writing out buffer pages, writing out logs, archiving older log files, creating checkpoints, etc.

A SimpleDBM server operates on a set of data and index files, known as the SimpleDBM database.

Only one server instance is allowed to access a SimpleDBM database at any point in time. SimpleDBM uses a lock file to detect multiple concurrent access to a database, and will refuse to start if it detects that a server is already accessing a database.

Internally, SimpleDBM operates on logical entities called Storage Containers. From an implementation point of view, Storage Containers are mapped to files.

Tables and Indexes are stored in Containers known as TupleContainers and IndexContainers, respectively.

The SimpleDBM database initially consists of a set of transaction log files, a lock file and a special container used internally by SimpleDBM.

Creating a SimpleDBM database

A SimpleDBM database is created by a call to Server.create(), as shown below:

```
import org.simpledbm.rss.main.Server;
...
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "16384");
properties.setProperty("log.buffer.size", "16384");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "5");
properties.setProperty("storage.basePath",
  "demodata/TupleDemo1");
```

```
Server.create(properties);
```

The Server.create() method accepts a Properties object as the sole argument. The Properties object can be used to pass a number of parameters. The available options are shown below:

Server Options

Property Name	Description
`log.ctl.{n}`	The fully qualified path to the log control file. The first file should be specified as `log.ctl.1`, second as `log.ctl.2`, and so on. Up to a maximum of 3 can be specified. Default is 2.
`log.groups.{n}.path`	The path where log files of a group should be stored. The first log group is specified as `log.groups.1.path`, the second as `log.groups.2.path`, and so on. Up to a maximum of 3 log groups can be specified. Default number of groups is 1. Path defaults to current directory.
`log.archive.path`	Defines the path for storing archive files. Defaults to current directory.
`log.group.files`	Specifies the number of log files within each group. Up to a maximum of 8 are allowed. Defaults to 2.
`log.file.size`	Specifies the size of each log file in bytes. Default is 2 KB.
`log.buffer.size`	Specifies the size of the log buffer in bytes. Default is 2 KB.
`log.buffer.limit`	Sets a limit on the maximum number of log buffers that can be allocated. Default is 10 * log.group.files.
`log.flush.interval`	Sets the interval (in seconds) between log flushes. Default is 6 seconds.
`log.disableFlushRequests`	Boolean value, if set, disables log flushes requested explicitly by the Buffer Manager or Transaction Manager. Log flushes still occur during checkpoints and log switches. By reducing the log flushes, performance is improved, but transactions may not be durable. Only those transactions will survive a system crash that have all their log records on disk.
`storage.basePath`	Defines the base location of the SimpleDBM database. All files and directories are created relative to this location.
`storage.createMode`	Defines mode in which files will be created. Default is `"rws"`.
`storage.openMode`	Defines mode in which files will be opened. Default is `"rws"`.
`storage.flushMode`	Defines mode in which files will be flushed. Possible values are noforce, force.true (default), and force.false
`bufferpool.numbuffers`	Sets the number of buffers to be created in the Buffer Pool.
`bufferpool.writerSleepInterval`	Sets the interval in milliseconds between each run of the BufferWriter. Note that BufferWriter may run earlier than the specified interval if the pool runs out of buffers, and a new page has to be read in. In such cases, the Buffer Writer may be manually triggered to clean out buffers.
`lock.deadlock.detection.interval`	Sets the interval in seconds between deadlock scans.
`logging.properties.file`	Specifies the name of logging properties file. Precede `classpath:` if you want SimpleDBM to search for this file in the classpath.
`logging.properties.type`	Specify `"log4j"` if you want to SimpleDBM to use Log4J for generating log messages.
`transaction.lock.timeout`	Specifies the default lock timeout value in seconds. Default is 60 seconds.
`transaction.ckpt.interval`	Specifies the interval between checkpoints in milliseconds. Default is 15000 milliseconds (15 secs).

The `Server.create()` call will overwrite any existing database in the specified storage path, so it must be called only when you know for sure that you want to create a database.

Opening a database

Once a database has been created, it can be opened by creating an instance of SimpleDBM server, and starting it. The same properties that were supplied while creating the database, can be supplied when starting it.

Here is a code snippet that shows how this is done:

```
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "16384");
properties.setProperty("log.buffer.size", "16384");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "5");
properties.setProperty("storage.basePath",
  "demodata/TupleDemo1");

Server server = new Server(properties);
server.start();
try {
  // do some work
}
finally {
  server.shutdown();
}
```

Some points to bear in mind when starting SimpleDBM server instances:

1. Make sure that you invoke `shutdown()` eventually to ensure proper shutdown of the database.
2. Database startup/shutdown is relatively expensive, so do it only once during the life-cycle of your application.
3. A Server object can be used only once - after calling `shutdown()`, it is an error to do any operation with the server object.

Managing log messages

SimpleDBM has support for JDK 1.4 style logging as well as Log4J logging. By default, if Log4J library is available on the classpath, SimpleDBM will use it. Otherwise, JDK 1.4 util.logging package is used.

You can specify the type of logging to be used using the Server Property `logging.properties.type`. If this is set to “log4j”, SimpleDBM will use Log4J logging. Any other value causes SimpleDBM to use default JDK logging.

The configuration of the logging can be specified using a properties file. The name and location of the properties file is specified using the Server property `logging.properties.file`. If the filename is prefixed with the string “classpath:”, then SimpleDBM will search for the properties file in the classpath. Otherwise, the filename is searched for in the current filesystem.

A sample logging properties file is shown below. Note that this sample contains both JDK style and Log4J style configuration.:

```
############################################################
#       JDK 1.4 Logging
############################################################
handlers= java.util.logging.FileHandler, java.util.logging.ConsoleHandler
.level= INFO
```

```
java.util.logging.FileHandler.pattern = simpledbm.log.%g
java.util.logging.FileHandler.limit = 50000
java.util.logging.FileHandler.count = 1
java.util.logging.FileHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.FileHandler.level = ALL

java.util.logging.ConsoleHandler.formatter = java.util.logging.SimpleFormatter
java.util.logging.ConsoleHandler.level = ALL

org.simpledbm.registry.level = INFO
org.simpledbm.bufmgr.level = INFO
org.simpledbm.indexmgr.level = INFO
org.simpledbm.storagemgr.level = INFO
org.simpledbm.walogmgr.level = INFO
org.simpledbm.lockmgr.level = INFO
org.simpledbm.freespacemgr.level = INFO
org.simpledbm.slotpagemgr.level = INFO
org.simpledbm.transactionmgr.level = INFO
org.simpledbm.tuplemgr.level = INFO
org.simpledbm.latchmgr.level = INFO
org.simpledbm.pagemgr.level = INFO
org.simpledbm.rss.util.level = INFO
org.simpledbm.util.level = INFO
org.simpledbm.server.level = INFO
org.simpledbm.trace.level = INFO
org.simpledbm.database.level = INFO

# Default Log4J configuration

# Console appender
log4j.appender.A1=org.apache.log4j.ConsoleAppender
log4j.appender.A1.layout=org.apache.log4j.PatternLayout
log4j.appender.A1.layout.ConversionPattern=%d [%t] %p %c %m%n

# File Appender
log4j.appender.A2=org.apache.log4j.RollingFileAppender
log4j.appender.A2.MaxFileSize=10MB
log4j.appender.A2.MaxBackupIndex=1
log4j.appender.A2.File=simpledbm.log
log4j.appender.A2.layout=org.apache.log4j.PatternLayout
log4j.appender.A2.layout.ConversionPattern=%d [%t] %p %c %m%n

# Root logger set to DEBUG using the A1 and A2 appenders defined above.
log4j.rootLogger=DEBUG, A1, A2

# Various loggers
log4j.logger.org.simpledbm.registry=INFO
log4j.logger.org.simpledbm.bufmgr=INFO
log4j.logger.org.simpledbm.indexmgr=INFO
log4j.logger.org.simpledbm.storagemgr=INFO
log4j.logger.org.simpledbm.walogmgr=INFO
log4j.logger.org.simpledbm.lockmgr=INFO
log4j.logger.org.simpledbm.freespacemgr=INFO
log4j.logger.org.simpledbm.slotpagemgr=INFO
log4j.logger.org.simpledbm.transactionmgr=INFO
log4j.logger.org.simpledbm.tuplemgr=INFO
log4j.logger.org.simpledbm.latchmgr=INFO
```

```
log4j.logger.org.simpledbm.pagemgr=INFO
log4j.logger.org.simpledbm.rss.util=INFO
log4j.logger.org.simpledbm.util=INFO
log4j.logger.org.simpledbm.server=INFO
log4j.logger.org.simpledbm.trace=INFO
log4j.logger.org.simpledbm.database=INFO
```

By default, SimpleDBM looks for a logging properties file named “simpledbm.logging.properties”.

Common Infrastructure

Object Registry

Overview

SimpleDBM uses a custom serialization mechanism for marshalling and unmarshalling objects to/from byte streams. When an object is marshalled, a two-byte code is stored in the first two bytes of the byte stream[1]. This identifies the class of the stored object. When reading back, the type code is used to lookup a factory for creating the object of the correct class.

The SimpleDBM serialization mechanism does not use the Java Serialization framework.

Central to the SimpleDBM serialization mechanism is the `ObjectRegistry` module. The `ObjectRegistry` provides the coupling between SimpleDBM serialization mechanism and its clients. For instance, index key types, table row types, etc. are registered in SimpleDBM’s `ObjectRegistry` and thereby made available to SimpleDBM. You will see how this is done when we discuss Tables and Indexes.

To allow SimpleDBM to serialize and deserialize an object from a byte-stream, you must:

1. Assign a unique 2-byte (short) type code to the class. Because the type code gets recorded in persistent storage, it must be stable, i.e., once registered, the type code association for a class must remain constant for the life span of the the database.
2. Ensure that the class implements a constructor that takes a ByteBuffer argument. The constructor should expect the first two bytes to contain the typecode for the class.
3. Ensure that the class implements the Storable interface. The stored length of an object of the class must allow for the 2-byte type code.
4. Provide an implementation of the `org.simpledbm.rss.api.registry.ObjectFactory` interface, and register this implementation with the `ObjectRegistry`.

An important consideration is to ensure that all the required classes are available to a SimpleDBM RSS instance at startup.

A limitation of the current design is that the type registrations are not held in persistent storage. Since all type mappings must be available to SimpleDBM server when it is starting up (as these may be involved in recovery) you need to ensure that custom type mappings are registered to the `ObjectRegistry` immediately after the server instance is constructed, but before the server is started. Typically this is handled by requiring each module to register its own types.

Type codes between the range 0-1000 are reserved for use by SimpleDBM.

[1] In some cases the type code is not stored, as it can be determined through some other means.

Two Use cases

The `ObjectRegistry` supports two use cases.

- The first use case is where the client registers an `ObjectFactory` implementation. In this case, `ObjectRegistry` can construct the correct object from a byte stream on request. By taking care of the common case, the client code is simplified.
- The second case is when the client has a more complex requirement and wants to manage the instantiation of objects. In this scenario, the client registers a singleton class and associates this with the type code. The `ObjectRegistry` will return the registered singleton object when requested.

Registering an ObjectFactory

In the simple case, an `ObjectFactory` implementation needs to be registered for a particular type code.

In the example shown below, objects of the class `MyObject` are to be persisted:

```
public final class MyObject implements Storable {
  final int value;

  /**
   * Constructs a MyObject from a byte stream.
   */
  public MyObject(ByteBuffer buf) {
    // skip the type code
    buf.getShort();
    // now get the value
    value = buf.getInt();
  }

  /* Storable methods not shown */
}
```

Points worth noting are:

- The `MyObject` class provides a constructor that takes a `ByteBuffer` as an argument. This is important as it allows the object to use final fields, allowing the class to be immutable.
- The constructor skips the first two bytes which contain the type code.

We need an `ObjectFactory` implementation that constructs the `MyObject` instances. The implementation is relatively straightforward:

```
class MyObjectFactory implements ObjectFactory {
  Object getInstance(ByteBuffer buf) {
    return new MyObject(buf);
  }
}
```

Next, we register the `ObjectFactory` implementation with the `ObjectRegistry`.:

```
objectRegistry.registerObjectFactory(1, new MyObjectFactory());
```

Given above registration, it is possible to construct MyObject instances as follows:

```
ByteBuffer buf = ...;
MyObject o = (MyObject) objectRegistry.getInstance(buf);
```

This pattern is used throughout SimpleDBM RSS.

Asymmetry between retrieving and storing objects

The reader may have noticed that the `ObjectFactory` says nothing about how objects are marshalled into a byte stream. It only deals with the unmarshalling of objects.

The marshalling is handled by the object itself. All objects that support marshalling are required to implement the Storable interface.

Storable Interface and Object serialization

Classes that need serialization support should implement the interface `org.simpledbm.rss.api.registry.Storable`. The `Storable` interface requires the object to be able to predict its persistent size in bytes when the `getStoredLength()` method is invoked. It also requires the implementation to be able to stream itself to a `ByteBuffer`.

The Storable interface specification is as follows:

```
/**
 * A Storable object can be written to (stored into) or
 * read from (retrieved from) a ByteBuffer. The object
 * must be able to predict its length in bytes;
 * this not only allows clients to allocate ByteBuffer
 * objects of suitable size, it is also be used by a
 * StorageContainer to ensure that objects can be
 * restored from secondary storage.
 */
public interface Storable {

  /**
   * Store this object into the supplied ByteBuffer in
   * a format that can be subsequently used to reconstruct the
   * object. ByteBuffer is assumed to be setup
   * correctly for writing.
   *
   * @param bb ByteBuffer that will contain a stored
   *           representation of the object.
   */
  void store(ByteBuffer bb);

  /**
   * Predict the length of this object in bytes when
   * stored in a ByteBuffer.
   *
   * @return The length of this object when stored in
   *         a ByteBuffer.
   */
  int getStoredLength();
}
```

The implementation of the `store()` method must be the inverse of the constructor that takes the `ByteBuffer` argument.

A complete example of the `MyObject` class will look like this:

```
public final class MyObject implements Storable {
  final int value;

  /**
   * Constructs a MyObject from a byte stream.
   */
  public MyObject(ByteBuffer buf) {
    // skip the type code
    buf.getShort();
    // now get the value
    value = buf.getInt();
  }

  public int getStoredLength() {
    return 6;
  }

  /**
   * Serialize to a ByteBuffer object.
   */
  public void store(ByteBuffer bb) {
    bb.putShort((short) 1);
    bb.putInt(value);
  }
}
```

Registering Singletons

In some cases, the requirements for constructing objects are complex enough for the client to manage it itself. In this case, the client provides a singleton object that is registered with the `ObjectRegistry`. The `ObjectRegistry.getSingleton(int typecode)` method retrieves the Singleton object. Typically, the singleton is a factory class that can be used to create new instances of objects.

Transactions

Most SimpleDBM operations take place in the context of a Transaction. Following are the main API calls for managing transactions.

Creating new Transactions

To start a new Transaction, invoke the `Server.begin()` method as shown below. You must supply an `IsolationMode`, try `READ_COMMITTED` to start with.:

```
Server server = ...;

// Start a new Transaction
Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
```

Isolation Modes are discussed in more detail in *Isolation Modes*.

Working with Transactions

Transaction API

The Transaction interface provides the following methods for clients to invoke:

```
public interface Transaction {

  /**
   * Creates a transaction savepoint.
   */
  public Savepoint createSavepoint(boolean saveCursors);

  /**
   * Commits the transaction. All locks held by the
   * transaction are released.
   */
  public void commit();

  /**
   * Rolls back a transaction upto a savepoint. Locks acquired
   * since the Savepoint are released. PostCommitActions queued
   * after the Savepoint was created are discarded.
   */
  public void rollback(Savepoint sp);

  /**
   * Aborts the transaction, undoing all changes and releasing
   * locks.
   */
  public void abort();

}
```

A transaction must always be either committed or aborted. Failure to do so will lead to resource leaks, such as locks, which will not be released. The correct way to work with transactions is shown below:

```
// Start a new Transaction
Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  // do some work and if this is completed succesfully ...
  // set success to true.
  doSomething();
  success = true;
}
finally {
  if (success) {
    trx.commit();
  }
  else {
    trx.abort();
  }
}
```

Transaction Savepoints

You can create transaction savepoints at any point in time. When you create a savepoint, you need to decide whether the scans associated with the transaction should save their state so that in the event of a rollback, they can be restored to the state they were in at the time of the savepoint. This is important if you intend to use the scans after you have performed a rollback to savepoint.

Bear in mind that in certain IsolationModes, locks are released as the scan cursor moves, When using such an IsolationMode, rollback to a Savepoint can fail if after the rollback, the scan cursor cannot be positioned on a suitable location, for example, if a deadlock occurs when it attempts to reacquire lock on the previous location. Also, in case the location itself is no longer valid, perhaps due to a delete operation by some other transaction, then the scan may position itself on the next available location.

If you are preserving cursor state during savepoints, be prepared that in certain IsolationModes, a rollback may fail due to locking, or the scan may not be able to reposition itself on exactly the same location.

Tables

TupleContainers

SimpleDBM provides support for tables with variable length records. The container for a table is known as `TupleContainer`. As far as SimpleDBM is concerned, a row in a `TupleContainer` is just a blob of data; it can contain anything you like. SimpleDBM will automatically break up a large row into smaller chunks so the chunks can be stored in individual data pages. This chunking is transparent from a client perspective, as the client only ever sees full records.

Creating a TupleContainer

When you create a `TupleContainer`, you must supply a name for the container, a unique numeric ID which should not be in use by any other container, and the extent size. For efficiency, SimpleDBM allocates space in extents; an extent is simply a set of contiguous pages.:

```
/**
 * Creates a new Tuple Container.
 *
 * @param trx Transaction to be used for creating the container
 * @param name Name of the container
 * @param containerId A numeric ID for the container - must
 *                    be unique for each container
 * @param extentSize The number of pages that should be part
 *                   of each extent in the container
 */
public void createTupleContainer(Transaction trx, String name,
 int containerId, int extentSize);
```

Note that the `createTupleContainer()` method requires a Transaction. Given below is an example of how a tuple container may be created. In this instance, we are creating a TupleContainer named “test.db”, which will be assigned container ID 1, and will have an extent size of 20 pages.:

```
Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  server.createTupleContainer(trx, "test.db", 1, 20);
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Note: When you create a Container it is exclusively locked. The lock is released when you commit or abort the transaction. The exclusive lock prevents any other transaction from manipulating the container while it is being created.

Recommendation: You should create standalone transactions for creating containers, and commit the transaction as soon as the container has been created.

Accessing a TupleContainer

To manipulate a `TupleContainer`, you must first get access to it. This is done by invoking the `getTupleContainer()` method provided by the SimpleDBM Server object. Note that when you access a `TupleContainer` in this way, a shared lock is placed on the container. This prevents other transactions from deleting the container while you are working with it. However, other transactions can perform row level operations on the same container concurrently.:

```
Server server ...

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
try {
  boolean success = false
  TupleContainer container = server.getTupleContainer(trx, 1);
  // do something
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Inserting tuples

SimpleDBM treats tuples (rows) as blobs of data, and does not care about the internal structure of a tuple. The only requirement is that a tuple must implement the `Storable` interface.

An insert operation is split into two steps. In the first step, the initial chunk of the tuple is inserted and a Location assigned to the tuple. At this point, you can do other things such as add entries to indexes.

You complete the insert as a second step. At this point, if the tuple was larger than the space allowed for in the first chunk, additional chunks get created and allocated for the tuple.

The reason for the two step operation is to ensure that for large tuples that span multiple pages, the insert does not proceed until it is certain that the insert will be successful. It is assumed that once the indexes have been successfully updated, in particular, the primary key has been created, then the insert can proceed.

In the example below, we insert a tuple of type `ByteString`, which is a `Storable` wrapper for `String` objects.:

```
Server server ...

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
try {
  boolean success = false
  TupleContainer container = server.getTupleContainer(trx, 1);
  TupleInserter inserter =
    container.insert(trx, new ByteString("Hello World!"));
  Location location = inserter.getLocation();

  // Create index entires here

  inserter.completeInsert();
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Reading tuples

In order to read tuples, you must open a scan. A scan is a mechanism for accessing tuples one by one. You can open Index Scans (described in next chapter) or Tuple Scans. A Tuple Scan directly scans a TupleContainer. Compared to index scans, tuple scans are unordered, and do not support Serializable or Repeatable Read lock modes. Another limitation at present is that tuple scans do not save their state during savepoints, and therefore cannot restore their state in the event of a rollback to a savepoint.:

```
Server server ...

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
try {
  boolean success = false
  TupleContainer container = server.getTupleContainer(trx, 1);
  TupleScan scan = container.openScan(trx, false);
  while (scan.fetchNext()) {
    byte[] data = scan.getCurrentTuple();
    // Do somthing with the tuple data
  }
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Updating tuples

In order to update a tuple, you must first obtain its Location using a scan. typically, if you intend to update the tuple, you should open the scan in UPDATE mode. This is done by supplying a boolean true as the second argument to `openScan()` method.

Note that in the current implementation of SimpleDBM, the space allocated to a tuple is never reduced, even if the tuple grows smaller due to updates.:

```
Server server ...

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
try {
  boolean success = false
  TupleContainer container = server.getTupleContainer(trx, 1);
  TupleScan scan = container.openScan(trx, true);
  while (scan.fetchNext()) {
    Location location = scan.getCurrentLocation();
    byte[] data = scan.getCurrentTuple();
    // Do somthing with the tuple data
    // Assume updatedTuple contains update tuple data.
    Storable updatedTuple = ... ;
    // Update the tuple
    container.update(trx, location, updatedTuple);
  }
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
 }
```

Deleting tuples

Tuple deletes are done in a similar way as tuple updates. Start a scan in UPDATE mode, if you intend to delete tuples during the scan. Here is an example:

```
Server server ...

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
try {
  boolean success = false
  TupleContainer container = server.getTupleContainer(trx, 1);
  TupleScan scan = container.openScan(trx, true);
  while (scan.fetchNext()) {
    Location location = scan.getCurrentLocation();
    container.delete(trx, location);
  }
  success = true;
}
finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Indexes

Index Keys

Index Keys are the searchable attributes stored in the Index. This module specifies Index Keys in a fairly general way:

```
public interface IndexKey
  extends Storable, Comparable<IndexKey> {

  /**
   * Used mainly for building test cases; this method should
   * parse the input string and initialize itself. The contents
   * of the string is expected to match the toString() output.
   */
  void parseString(String string);
}
```

The requirements for an IndexKey are fairly simple. The key must be `Storable` and `Comparable`. Note that this interface does not say anything about the internal structure of the key; in particular it does not specify whether the key contains multiple attributes. This is deliberate, as it makes the Index Manager module more generic.

Depending upon the implementation, there may be restricions on the size of the key. For instance, in the SimpleDBM BTree implementation, the key should not exceed 1/8th of the page size, ie, 1KB in a 8KB page.

Index Key Factories

An Index Key Factory is used to create new keys. In addition to normal keys, an Index Key Factory must be able to create two special type of keys:

MinKey This is a special key that represents negative infinity. All valid keys must be greater than this key.

MaxKey This is a special key that represents positive infinity. All valid keys must be less than this key.

The special keys are used by the Index Manager internally. You can also specify the `MinKey` when opening a scan, to effectively start the scan from the first available key.:

```
public interface IndexKeyFactory {

  /**
   * Generates a new (empty) key for the specified
   * Container. The Container ID is meant to be used as key
   * for locating information specific to a container; for
   * instance, the attributes of an Index.
   *
   * @param containerId ID of the container for which a key
   *                    is required
   */
  IndexKey newIndexKey(int containerId);

  /**
   * Generates a key that represents Infinity - it must be
   * greater than all possible keys in the domain for the key.
   * The Container ID is meant to be used as key
   * for locating information specific to a container; for
   * instance, the attributes of an Index.
   *
   * @param containerId ID of the container for which a key
   *                    is required
   */
  IndexKey maxIndexKey(int containerId);

  /**
   * Generates a key that represents negative Infinity - it
   * must be smaller than all possible keys in the domain for
   * the key. The Container ID is meant to be used as key
   * for locating information specific to a container; for
   * instance, the attributes of an Index.
   *
   * The key returned by this method can be used as an
   * argument to index scans. The result will be a scan of
   * the index starting from the first key in the index.
   *
   * @param containerId ID of the container for which a key
   * is required
   */
  IndexKey minIndexKey(int containerId);
}
```

An implementation is free to use any method it likes for identifying keys that represent `MinKey` and `MaxKey`, as long as it ensures that these keys will obey the contract defined above.

The methods of `IndexKeyFactory` take the container ID as a parameter. In SimpleDBM, each index is stored in a separate container, hence container ID is used as a mechanism for identifying the index. The `IndexKeyFactory` implementation is expected to use the container ID to determine the type of index key to create. For example, it may consult a data dictionary to determine the type of key attributes required by the index key.

Example

Given below is an example of an `IndexKey` implementation. This implementation uses a special byte field to maintain the status information.:

```
public class IntegerKey implements IndexKey {

  private static final byte NULL_FIELD = 1;
  private static final byte MINUS_INFINITY_FIELD = 2;
  private static final byte VALUE_FIELD = 4;
  private static final byte PLUS_INFINITY_FIELD = 8;

  private byte statusByte = NULL_FIELD;
  private int value;

  public IntegerKey() {
    statusByte = NULL_FIELD;
  }

  public IntegerKey(int value) {
    statusByte = VALUE_FIELD;
    this.value = value;
  }

  protected IntegerKey(byte statusByte, int value) {
    this.statusByte = statusByte;
    this.value = value;
  }
```

```
public int getValue() {
  if (statusByte != VALUE_FIELD) {
    throw new IllegalStateException("Value has not been set");
  }
  return value;
}

public void setValue(int i) {
  value = i;
  statusByte = VALUE_FIELD;
}

public void retrieve(ByteBuffer bb) {
  statusByte = bb.get();
  value = bb.getInt();
}

public void store(ByteBuffer bb) {
  bb.put(statusByte);
  bb.putInt(value);
}

public int getStoredLength() {
  return 5;
}

public int compareTo(IndexKey key) {
  if (key == null) {
    throw new IllegalArgumentException("Supplied key is null");
  }
  if (key == this) {
    return 0;
  }
  if (key.getClass() != getClass()) {
    throw new IllegalArgumentException(
        "Supplied key is not of the correct type");
  }
  IntegerKey other = (IntegerKey) key;
  int result = statusByte - other.statusByte;
  if (result == 0 && statusByte == VALUE_FIELD) {
    result = value - other.value;
  }
  return result;
}

public final boolean isNull() {
  return statusByte == NULL_FIELD;
}

public final boolean isMinKey() {
  return statusByte == MINUS_INFINITY_FIELD;
}

public final boolean isMaxKey() {
  return statusByte == PLUS_INFINITY_FIELD;
}
```

```
  public final boolean isValue() {
    return statusByte == VALUE_FIELD;
  }

  public boolean equals(Object o) {
    if (o == null) {
      throw new IllegalArgumentException("Supplied key is null");
    }
    if (o == this) {
      return true;
    }
    if (o == null || !(o instanceof IntegerKey)) {
      return false;
    }
    return compareTo((IntegerKey) o) == 0;
  }

  public void parseString(String s) {
    if ("<NULL>".equals(s)) {
      statusByte = NULL_FIELD;
    } else if ("<MINKEY>".equals(s)) {
      statusByte = MINUS_INFINITY_FIELD;
    } else if ("<MAXKEY>".equals(s)) {
      statusByte = PLUS_INFINITY_FIELD;
    } else {
      value = Integer.parseInt(s);
      statusByte = VALUE_FIELD;
    }
  }

  public String toString() {
    if (isNull()) {
      return "<NULL>";
    } else if (isMinKey()) {
      return "<MINKEY>";
    } else if (isMaxKey()) {
      return "<MAXKEY>";
    } else {
      return Integer.toString(value);
    }
  }

  public static IntegerKey createNullKey() {
    return new IntegerKey(NULL_FIELD, 0);
  }

  public static IntegerKey createMinKey() {
    return new IntegerKey(MINUS_INFINITY_FIELD, 0);
  }

  public static IntegerKey createMaxKey() {
    return new IntegerKey(PLUS_INFINITY_FIELD, 0);
  }
}
```

Shown below is the corresponding `IndexKeyFactory` implementation.:

```
public class IntegerKeyFactory implements IndexKeyFactory {

  public IndexKey maxIndexKey(int containerId) {
    return IntegerKey.createMaxKey();
  }

  public IndexKey minIndexKey(int containerId) {
    return IntegerKey.createMinKey();
  }

  public IndexKey newIndexKey(int containerId) {
    return IntegerKey.createNullKey();
  }
}
```

The example shown above is a simple key. It is possible to create multi-attribute keys as well. For an example of how this can be done, please see the sample `typesystem` package supplied with SimpleDBM, and the sample project `tupledemo`.

Locations

Indexes contain pointers to tuple data. When you insert a tuple in a tuple container, a location is assigned to the tuple. This location can be stored in an index to point to the tuple.

Creating a new index

Following code snippet shows the steps required to create a new index.:

```
int INDEX_KEY_FACTORY_TYPE = 25000;

Server server = ...;
IndexKeyFactory indexKeyFactory = ...;

// Register key factory
server.registerSingleton(INDEX_KEY_FACTORY_TYPE,
  indexKeyFactory);

Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  int containerId = 1;
  int extentSize = 8;
  boolean isUnique = true;
  server.createIndex(trx, "testbtree.dat",
    containerId, extentSize, INDEX_KEY_FACTORY_TYPE,
    isUnique);
  success = true;
} finally {
  if (success)
    trx.commit();
  else
    trx.abort();
}
```

Obtaining index instance

In order to manipulate an index, you must first obtain an instance of the index. This is shown below.

```
Transaction trx = ...;
int containerId = 1;
IndexContainer index = server.getIndex(trx, containerId);
```

This operation causes a SHARED mode lock to be placed on the container ID. This lock is to prevent other transactions from dropping the container. Concurrent insert, delete and scan operations are permitted, however.

Working with keys

Adding a key

The API for inserting new keys is shown below.

```
public interface IndexContainer {
  /**
   * Inserts a new key and location. If the Index is unique,
   * only one instance of key is allowed. In non-unique indexes,
   * multiple instances of the same key may exist, but only
   * one instance of the combination of key/location
   * is allowed.
   *
   * The caller must obtain a Shared lock on the Index
   * Container prior to this call.
   *
   * The caller must acquire an Exclusive lock on Location
   * before this call.
   *
   * @param trx Transaction managing the insert
   * @param key Key to be inserted
   * @param location Location associated with the key
   */
  public void insert(Transaction trx, IndexKey key,
                     Location location);
}
```

To add a key, you need the `IndexKey` instance and the `Location`. The most common use case is to insert the keys after inserting a tuple in a tuple container. An example of this is shown below:

```
Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  TupleContainer table = server.getTupleContainer(
    trx, TABLE_CONTNO);
  IndexContainer primaryIndex =
    server.getIndex(trx, PKEY_CONTNO);
  IndexContainer secondaryIndex =
    server.getIndex(trx, SKEY1_CONTNO);

  // First lets create a new row and lock the location
  TupleInserter inserter = table.insert(trx, tableRow);

  // Insert the primary key - may fail with unique constraint
  // violation
  primaryIndex.insert(trx, primaryKeyRow,
    inserter.getLocation());

  // Insert seconary key
  secondaryIndex.insert(trx, secondaryKeyRow,
    inserter.getLocation());

  // Complete the insert - may be a no-op.
  inserter.completeInsert();
  success = true;
} finally {
  if (success) {
    trx.commit();
  } else {
    trx.abort();
  }
}
```

Above example is taken from the sample `tupledemo`.

Deleting a key

Deleting a key is very similar to adding a key. First lets look at the API.

```
public interface IndexContainer {
  /**
   * Deletes specified key and location.
   *
   * The caller must obtain a Shared lock on the Index
   * Container prior to this call.
   *
   * The caller must acquire an Exclusive lock on Location
   * before this call.
   *
   * @param trx Transaction managing the delete
   * @param key Key to be deleted
   * @param location Location associated with the key
   */
  public void delete(Transaction trx, IndexKey key,
                     Location location);
}
```

Again we take an example from the tupledemo sample (note that the code has been simplified a bit).

```
// Start a new transaction
Transaction trx = server.begin(IsolationMode.READ_COMMITTED);
boolean success = false;
try {
  TupleContainer table =
    server.getTupleContainer(trx, TABLE_CONTNO);
  IndexContainer primaryIndex =
    server.getIndex(trx, PKEY_CONTNO);

  // Start a scan, with the primary key as argument
  IndexScan indexScan = primaryIndex.openScan(trx, primaryKeyRow,
    null, true);
  if (indexScan.fetchNext()) {
    // Scan always return item >= search key, so let's
    // check if we had an exact match
    boolean matched = indexScan.getCurrentKey().equals(
      primaryKeyRow);
    try {
      if (matched) {
        Location location = indexScan.getCurrentLocation();
        // Delete tuple data
        table.delete(trx, location);
        // Delete primary key
        primaryIndex.delete(trx, primaryKeyRow, location);
      }
    } finally {
      indexScan.fetchCompleted(matched);
    }
  }
  success = true;
} finally {
  if (success) {
    trx.commit();
  } else {
    trx.abort();
  }
}
```

Prior to deleting the key, the associated location must be exclusively locked for commit duration. Fortunately, when you delete a tuple, it is locked exclusively, hence in the example shown above, there is no need for the Location to be locked again.

Above example demonstrates also a very common use case, ie, scanning an index in UPDATE mode and then carrying out modifications.

Scanning keys

Isolation Modes

Before describing how to scan keys within an Index, it is necessary to describe the various lock isolation modes supported by SimpleDBM.

Common Behaviour

Following behaviour is common across all lock isolation modes.

1. All locking is on Tuple Locations (rowids) only.
2. When a tuple is inserted or deleted, its Location is first locked in EXCLUSIVE mode, the tuple is inserted or deleted from data page, and only after that, indexes are modified.
3. Updates to indexed columns are treated as key deletes followed by key inserts. The updated row is locked in EXCLUSIVE mode before indexes are modified.
4. When fetching, the index is looked up first, which causes a SHARED or UPDATE mode lock to be placed on the row, before the data pages are accessed.

Read Committed/Cursor Stability

During scans, the tuple location is locked in SHARED or UPDATE mode while the cursor is positioned on the key. The lock on current location is released before the cursor moves to the next key.

Repeatable Read (RR)

SHARED mode locks obtained on tuple locations during scans are retained until the transaction completes. UPDATE mode locks are downgraded to SHARED mode when the cursor moves.

Serializable

Same as Repeatable Read, with additional locking (next key) during scans to prevent phantom reads.

Scanning API

Opening an IndexScan requires you to specify a start condition. If you want to start from the beginning, then you may specify null values as the start key/location.

In SimpleDBM, scans do not have a stop key. Instead, a scan starts fetching data from the first key/location that is greater or equal to the supplied start key/location. You must determine whether the fetched key satisfies the search criteria or not. If the fetched key no longer meets the search criteria, you should call `fetchCompleted()` with a false value, indicating that there is no need to fetch any more keys. This then causes the scan to reach logical EOF.

The API for index scans is shown below:

```
public interface IndexContainer {

  /**
   * Opens a new index scan. The Scan will fetch keys >= the
   * specified key and location. Before returning fetched keys,
   * the associated Location objects will be locked. The lock
   * mode depends upon the forUpdate flag. The IsolationMode
   * of the transaction determines when lock are released.
   *
   * Caller must obtain a Shared lock on the Index Container
   * prior to calling this method.
   *
   * @param trx Transaction that will manage locks obtained
   *            by the scan
   * @param key The starting key to be searched for
   * @param location The starting location to be searched for.
   * @param forUpdate If this set, UPDATED mode locks will
   *                  be acquired, else SHARED mode locks will
   *                  be acquired.
   */
  public IndexScan openScan(Transaction trx, IndexKey key,
    Location location, boolean forUpdate);

}


public interface IndexScan {

  /**
```

```
   * Fetches the next available key from the Index.
   * Handles the situation where current key has been deleted.
   * Note that prior to returning the key the Location
   * object associated with the key is locked.
   * After fetching an index row, typically, data must
   * be fetched from associated tuple container. Locks
   * obtained by the fetch protect such access. After
   * tuple has been fetched, caller must invoke
   * fetchCompleted() to ensure that locks are released
   * in certain lock isolation modes. Failure to do so will
   * cause extra locking.
   */
  public boolean fetchNext();

  /**
   * In certain isolation modes, releases locks acquired
   * by fetchNext(). Must be invoked after the data from
   * associated tuple container has been fetched.
   * If the argument matched is set to false, the scan
   * is assumed to have reached eof of file. The next
   * call to fetchNext() will return false.
   *
   * @param matched If set to true indicates that the
   *                key satisfies search query
   */
  public void fetchCompleted(boolean matched);

  /**
   * Returns the IndexKey on which the scan is currently
   * positioned.
   */
  public IndexKey getCurrentKey();

  /**
   * Returns the Location associated with the current
   * IndexKey.
   */
  public Location getCurrentLocation();

  /**
   * After the scan is completed, the close method
   * should be called to release all resources acquired
   * by the scan.
   */
  public void close();

  /**
   * Returns the End of File status of the scan. Once
   * the scan has gone past the last available key in
   * the Index, this will return true.
   */
  public boolean isEof();
}
```

Following code snippet, taken from the btreedemo sample, shows how to implement index scans.:

```
Transaction trx = ...;
IndexContainer indexContainer = ...;
```

```
IndexScan scan = indexContainer.openScan(trx, null,
  null, false);
try {
  while (scan.fetchNext()) {
    System.err.println("SCAN NEXT=" + scan.getCurrentKey() +
      "," + scan.getCurrentLocation());
    scan.fetchCompleted(true);
  }
} finally {
  if (scan != null) {
    scan.close();
  }
}
```

Another example of an index scan can be found in section *Deleting a key*.

CHAPTER 6

SimpleDBM Developers's Guide

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Contents

Introduction

This document describes the SimpleDBM Internals.

Intended Audience

This documented is targetted at SimpleDBM developers.

Pre-requisite Reading

Before reading this document, the reader is advised to go through the SimpleDBM Overview document.

Data Manager/RSS Components

The Data Manager/Relational Storage system (RSS) consists of the components listed in the table given below.

Module Name	Description
Logging	Provides a Logger interface that hides the implementation details. Can wrap either JDK logging or Log4J.
Utility	Contains miscellaneous utility classes.
Registry	Provides the Object Registry, which is a factory for creating objects based on type code.
Storage Manager	Provides an abstraction for input/output of storage containers similar to files.
Latch	Provides read/write locks that can be used to manage concurrency.
Lock Manager	Implements a Lock Scheduler that allows locking of arbitrary objects. Several different lock modes are supported.
Page Manager	The Page Manager defines the page size and provides mapping of pages to storage containers.
Buffer Manager	The Buffer Manager module implements the Page Cache where recently accessed pages are stored temporarily.
Log Manager	The Write Ahead Log Manager is used for recording changes made to the database for recovery purposes.
Transaction Manager	The Transaction Manager manages transactions, system restart and recovery.
Free Space Manager	The Free Space Manager is responsible for managing free space information in storage containers.
Slotted Page Manager	The Slotted Page Manager provides an common implementation of pages containing multiple records. A slot table is used to provide a level of indirection to the records. This allows records to be moved within the page without affecting clients.
Location	The Location module specifies the interface for identifying lockable records in storage containers.
Index Manager	Provides efficient structures for accessing locations based upon key values.
Tuple Manager	Provides an implementation of tuple containers. A tuple is defined as variable sized blob of data that has a unique identity within the tuple container.
Server	This brings together all the other modules and provides overall management of the SimpleDBM RSS database engine.

Object Registry

Overview

SimpleDBM uses a custom serialization mechanism for marshalling and unmarshalling objects to/from byte streams. When an object is marshalled, a two-byte code is stored in the first two bytes of the byte stream[1]. This identifies the class of the stored object. When reading back, the type code is used to lookup a factory for creating the object of the correct class.

The SimpleDBM serialization mechanism does not use the Java Serialization framework.

Central to the SimpleDBM serialization mechanism is the `ObjectRegistry` module. The `ObjectRegistry` provides the coupling between SimpleDBM serialization mechanism and its clients. For instance, index key types, table row types, etc. are registered in SimpleDBM's `ObjectRegistry` and thereby made available to SimpleDBM. You will see how this is done when we discuss Tables and Indexes.

To allow SimpleDBM to serialize and deserialize an object from a byte-stream, you must:

1. Assign a unique 2-byte (short) type code to the class. Because the type code gets recorded in persistent storage, it must be stable, i.e., once registered, the type code association for a class must remain constant for the life span of the the database.
2. Ensure that the class implements a constructor that takes a ByteBuffer argument. The constructor should expect the first two bytes to contain the typecode for the class.
3. Ensure that the class implements the Storable interface. The stored length of an object of the class must allow for the 2-byte type code.
4. Provide an implementation of the `org.simpledbm.rss.api.registry.ObjectFactory` interface, and register this implementation with the `ObjectRegistry`.

An important consideration is to ensure that all the required classes are available to a SimpleDBM RSS instance at startup.

A limitation of the current design is that the type registrations are not held in persistent storage. Since all type mappings must be available to SimpleDBM server when it is starting up (as these may be involved in recovery) you need to ensure that custom type mappings are registered to the `ObjectRegistry` immediately after the server instance is constructed, but before the server is started. Typically this is handled by requiring each module to register its own types.

Type codes between the range 0-1000 are reserved for use by SimpleDBM.

Two Use cases

The `ObjectRegistry` supports two use cases.

- The first use case is where the client registers an `ObjectFactory` implementation. In this case, `ObjectRegistry` can construct the correct object from a byte stream on request. By taking care of the common case, the client code is simplified.
- The second case is when the client has a more complex requirement and wants to manage the instantiation of objects. In this scenario, the client registers a singleton class and associates this with the type code. The `ObjectRegistry` will return the registered singleton object when requested.

[1] In some cases the type code is not stored, as it can be determined through some other means.

Registering an ObjectFactory

In the simple case, an `ObjectFactory` implementation needs to be registered for a particular type code.

In the example shown below, objects of the class `MyObject` are to be persisted:

```
public final class MyObject implements Storable {
  final int value;

  /**
   * Constructs a MyObject from a byte stream.
   */
  public MyObject(ByteBuffer buf) {
    // skip the type code
    buf.getShort();
    // now get the value
    value = buf.getInt();
  }

  /* Storable methods not shown */
}
```

Points worth noting are:

- The `MyObject` class provides a constructor that takes a `ByteBuffer` as an argument. This is important as it allows the object to use final fields, allowing the class to be immutable.
- The constructor skips the first two bytes which contain the type code.

We need an `ObjectFactory` implementation that constructs the `MyObject` instances. The implementation is relatively straightforward:

```
class MyObjectFactory implements ObjectFactory {
  Object getInstance(ByteBuffer buf) {
    return new MyObject(buf);
  }
}
```

Next, we register the `ObjectFactory` implementation with the `ObjectRegistry`.:

```
objectRegistry.registerObjectFactory(1, new MyObjectFactory());
```

Given above registration, it is possible to construct MyObject instances as follows:

```
ByteBuffer buf = ...;
MyObject o = (MyObject) objectRegistry.getInstance(buf);
```

This pattern is used throughout SimpleDBM RSS.

Asymmetry between retrieving and storing objects

The reader may have noticed that the `ObjectFactory` says nothing about how objects are marshalled into a byte stream. It only deals with the unmarshalling of objects.

The marshalling is handled by the object itself. All objects that support marshalling are required to implement the Storable interface.

Storable Interface and Object serialization

Classes that need serialization support should implement the interface `org.simpledbm.rss.api.registry.Storable`. The `Storable` interface requires the object to be able to predict its persistent size in bytes when the `getStoredLength()` method is invoked. It also requires the implementation to be able to stream itself to a `ByteBuffer`.

The Storable interface specification is as follows:

```
/**
 * A Storable object can be written to (stored into) or
 * read from (retrieved from) a ByteBuffer. The object
 * must be able to predict its length in bytes;
 * this not only allows clients to allocate ByteBuffer
 * objects of suitable size, it is also be used by a
 * StorageContainer to ensure that objects can be
 * restored from secondary storage.
 */
public interface Storable {

  /**
   * Store this object into the supplied ByteBuffer in
   * a format that can be subsequently used to reconstruct the
   * object. ByteBuffer is assumed to be setup
   * correctly for writing.
   *
   * @param bb ByteBuffer that will contain a stored
   *           representation of the object.
   */
  void store(ByteBuffer bb);

  /**
   * Predict the length of this object in bytes when
   * stored in a ByteBuffer.
   *
   * @return The length of this object when stored in
   *         a ByteBuffer.
   */
  int getStoredLength();
}
```

The implementation of the `store()` method must be the inverse of the constructor that takes the `ByteBuffer` argument.

A complete example of the `MyObject` class will look like this:

```
public final class MyObject implements Storable {
  final int value;

  /**
   * Constructs a MyObject from a byte stream.
   */
  public MyObject(ByteBuffer buf) {
    // skip the type code
    buf.getShort();
    // now get the value
    value = buf.getInt();
  }
  public int getStoredLength() {
    return 6;
  }

  /**
   * Serialize to a ByteBuffer object.
   */
  public void store(ByteBuffer bb) {
    bb.putShort((short) 1);
    bb.putInt(value);
  }
}
```

Registering Singletons

In some cases, the requirements for constructing objects are complex enough for the client to manage it itself. In this case, the client provides a singleton object that is registered with the `ObjectRegistry`. The `ObjectRegistry.getSingleton(int typecode)` method retrieves the Singleton object. Typically, the singleton is a factory class that can be used to create new instances of objects.

Historical Note

The initial design of SimpleDBM's `ObjectRegistry` used reflection to create instances of objects. Instead of registering factory classes, the name of the target class was registered.

The unmarshalling of objects was performed in two steps. First, the no-arg constructor was invoked to construct the object. Then a method on the Storable interface was invoked to deserialize the object's fields from the ByteBuffer.

This method was abandoned in favour of the current approach due to following problems.

- Firstly, it required that all classes that participated in the persistence mechanism support a no-arg constructor.
- Fields could not be final, as the fields needed to be initialized post construction. As a result, persistent classes could not be immutable.
- It was difficult to supply additional arguments (context information) to the constructed objects. This was because the object was constructed by a third-party, which had no knowledge about the object.
- It used reflection to construct objects.

The current method overcomes these problems, and has resulted in more robust code.

Comparison with Apache Derby

Apache Derby has a similar requirement to marshall and unmarshall objects to/from a byte stream. The solution used by Derby is different from SimpleDBM in following ways.

- It uses a custom implementation of the Java Serialization mechanism.
- Reflection is used to obtain instances of objects.
- The type code database is hard-coded in a static class. In SimpleDBM, types are added by each module; there is no central hard-coded list of types.

Storage Factory

Overview

Database Managers typically use files to store various types of data, such as log files, data files, etc.. However, from the perspective of a DBMS, the concept of a file is a logical one; all the DBMS cares about is a named storage container that supports random positioned IO. As long as this requirement is met, it is not important whether a container maps to a file or to some other device.

The objective of the StorageFactory package is to provide a level of abstraction to the rest of the DBMS so that the mapping of a container to a file becomes an implementation artefact. If desired, containers may be mapped to raw devices, or to segments within a file.

Storage Containers

A Storage Container is a named entity that supports positioned (random) Input/Output. The default implementation maps a container to a file, but this is an implementation detail, and not a requirement. The rest of the system does not need to know what the storage container maps to.

The operations on storage containers are similar to those that can be performed on files.

In SimpleDBM, each table or index maps to a single storage container. The Write Ahead Log also uses storage containers to store its data. Table and index containers have fixed size pages. The Write Ahead Log contains variable size records.

Storage Container Registry

Container names are usually not good identifiers for the rest of the system. Integer identifiers are better, especially when other objects need to refer to specific containers. Integers take less amount of storage, and also remove the dependency between the container's name and the rest of the system. To support this requirement, the `org.simpledbm.rss.api.st.StorageManager` interface is provided, which maintains a mapping of StorageContainers to integer identifiers. Note that the Storage sub-system does not decide how to map the containers to ids; it merely enables the registration of these mappings and allows StorageContainer objects to be retrieved using their numeric identifiers.

```
StorageContainerFactory storageFactory
   = new FileStorageContainerFactory();
StorageManager storageManager = new StorageManagerImpl();
StorageContainer sc = storageFactory.open("dual");
storageManager.register(0, sc);
```

Above sample code registers the container named "dual" to the storage manager and identifies this with the integer value 0. Other modules may obtain access to the storage container as follows:

```
StorageContainer sc = storageManager.getInstance(0);
```

Default Implementation

The default implementation of the StorageFactory uses a `RandomAccessFile` as the underlying container. A few configuration options are supported to allow changing the behaviour of certain performance sensitive operations. These are listed below.

Option	Description
storage.basePath	This is used to specify the base directory relative to which all storage container instances are to be created.
storage.createMode	This is used to set the `RandomAccessFile` mode that is used when creating a container.
storage.openMode	This is used to set the `RandomAccessFile` mode when a container is opened.
storage.flushMode	The flushMode has two values: force.true causes force(true) to be invoked on the file channel when the container is flushed. force.false causes force(false) to be ivoked. A missing flushMode causes the call to force() to do nothing.

Note that some of the modes can have a big impact on performance of SimpleDBM.

Latch Manager

Overview

A Latch is an efficient lock that is used by the system to manage concurrent access to physical structures. In many ways, Latches are similar to Mutexes, however, latches supports additional lock modes, such as Shared locks and Update locks.

Latch modes

SimpleDBM implements two types of latches. A ReadWrite Latch supports two lock modes:

Shared mode is compatible with Shared mode but incompatible with Exclusive

Exclusive mode incompatible with any other mode.

A ReadWriteUpdate latch is an enhanced version that supports an additional Update mode lock.

Update mode compatible with Shared mode but incompatible with Update or Exclusive modes. Note that the Shared mode locks are incompatible with Update mode locks.

An Update lock may be upgraded to Exclusive lock, and conversely, an Exclusive lock may be downgraded to an Update lock. An Update lock may also be downgraded to a Shared lock.

Implementation and Performance Notes

The SimpleDBM Latch interface is designed to be compatible with the Java 5.0 `ReentrantReadWriteLock` interface. This allows the `ReadWrite` Latch implementation to be based upon the Java primitive.

The `ReadWrite` Latch is likely to be more efficient than the `ReadWriteUpdate` Latch.

The `ReadWriteUpdate` latch implementation uses a subset of the `LockManager` implementation described later in this document. There are a few differences between the two implementations:

- Unlike a Lock, which has to be looked up dynamically in a hash table, a latch is known to its client, and hence no lookup is necessary. Each instance of a latch is a lock. Clients hold a reference to the latch.
- There is no support for various lock durations as these do not make sense here.
- Apart from lock conversions and downgrades, we also support lock upgrades. An upgrade is like a conversion except that it is explicitly requested and does not cause the reference count to go up. Hence the difference is primarily in the way clients use locks. For normal lock conversions, clients are expected to treat each request as

a separate request, and therefore release the lock as many times as requested. Upgrade (and downgrade) requests do not modify the reference count.

- Unlike Lock Manager, the owner for latches is predefined - it is always the requesting thread. Hence there is no need to supply an owner.
- Latches do not support deadlock detection. The implementation uses a timeout of 10 seconds which is a simple way of detecting latch deadlocks. Note that Latch deadlocks are always due to bugs in the code, and should never occur at runtime. Such deadlocks are avoided by ensuring that latches are acquired and released in a specific order.

Obtaining a latch instance

SimpleDBM implements a factory class for creating Latch objects. The factory supports instantiating a ReadWrite latch, or a ReadWriteUpdate latch. There is also a default mode which results in ReadWrite latch.

Log Manager

Overview

The Write Ahead Log plays a crucial role in a DBMS. It provides the basis for recoverability. It is also a critical part of the system that has a massive impact on performance of an OLTP system.

Conceptually, the Log can be thought of as an ever growing sequential file. In the form of Log Records, the Log contains a history of all changes made to the database. Each Log Record is uniquely identified by a number called the Log Sequence Number (LSN). The LSN is designed in such a way that given an LSN, the system can locate the corresponding Log Record quickly. LSNs are assigned in strict ascending order (monotonicity). This is an important property when it comes to recovery.

During the progress of a Transaction, the a DBMS records in the Log all the changes made by the transaction. The Log records can be used to recover the system if there is a failure, or they can be used to undo the changes made by a transaction.

Initially, Log Records are stored in memory. They are flushed to disk during transaction commits, and also during checkpoints. In the event of a crash, it is possible to lose the log records that were not flushed to disk. This does not cause a problem, however, because by definition these log records must correspond to changes made by incomplete transactions. Also, the WAL protocol (described below) ensures that such Log records do not contain changes that have already been persisted within the database.

Write Ahead Log (WAL) Protocol

The WAL protocol requires the following conditions to hold true:

1. All changes made by a transaction must be recorded in the Log and the Log must be flushed to disk before the transaction is committed.
2. A database buffer page may not be modified until its modifications have been logged. A buffer page may not be saved to disk until all its associated log records have been saved to disk.
3. While the buffer page is being modified and the Log is being updated, an Exclusive latch (a type of fast lock) must be held on the page to ensure that order in which changes are recorded in the Log correspond to the order in which they were made.

Consequences of above rules are:

- If a Log Record was not saved to disk, it can be safely ignored, because any changes contained in it are guaranteed to belong to uncommitted transactions. Also, such Log Records cannot represent changes that have been made persistent in the database.
- Log records represent changes to the system in the correct order. The latching protocol ensures that if two Log records represent changes to the same Page, then the ordering of these records reflects the order in which the changes were made to the page.

Advantages of WAL

Typically, in an OLTP system, updates tend to be random and can affect different parts of the disk at a point in time. In comparison, writes to the Log are always sequential. If it were necessary to flush all changes made by the DBMS to disk at commit time, it would have a massive impact on performance because of the randomness of the disk writes. However, in a WAL system, only the Log needs to be flushed to disk at Commit. Thus, the Log has the effect of transforming random writes into serial writes, thereby improving performance significantly.

Usage Notes

The Log Manager interface does not make any assumptions about log records. In fact, it does not specify the format of a log record.

SimpleDBM Implementation of the Log

The SimpleDBM Log maintains control information separately from log files. For safety, multiple copies of control information are stored (though at present, only the first control file is used when opening the Log).

Logically, the Log is organized as a never ending sequence of log records. Physically, the Log is split up into log files. There is a fixed set of online log files, and a dynamic set of archived log files. The set of online log files is called a Log Group.

Each Log Group consists of a set of pre-allocated log files of the same size. The maximum number of groups possible is 3, and the maximum number of log files within a group is 8. Note that each group is a complete set in itself - the Log is recoverable if any one of the groups is available, and if the archived log files are available. If more than one group is created, it is expected that each group will reside on a different disk sub-system.

The Log Groups are allocated when the Log is initially created. The log files within a group are also pre-allocated. However, the content of the online log files changes over time.

Logically, in the same way that the Log can be viewed as a sequence of Log Records, it can also be thought of as a sequence of Log Files. The Log Files are numbered in sequence, starting from 1. The Log File sequence number is called LogIndex. At any point in time, the physical set of online log files will contain a set of logical log files. For example, if there are 3 physical files in a Log Group, then at startup, the set of logical log files would be 1, 2 and 3. After some time, the log file 1 would get archived, and in its place a new logical log file 4 would be created. The set now would now consist of logical log files 2, 3 and 4.

When a log record is written to disk, it is written out to an online log file. If there is more than one group, then the log record is written to each of the groups. The writes happen in sequence to ensure that if there is a write failure, damage is restricted to one Log Group. Note that due to the way this works, having more than 1 group will slow down log writes. It is preferable to use hardware based disk mirroring of log files as opposed to using multiple log groups.

When new log records are created, they are initially stored in the log buffers. Log records are written out to log files either because of a client request to flush the log, or because of the periodic flush event.

During a flush, the system determines which log file to use. There is the notion of Current log file, which is where writes are expected to occur. If the current log file is full, it is put into a queue for archiving, and the log file is switched.

Until an online log file has been archived, its physical file cannot be reused. A separate archive thread monitors archive requests and archives log files in the background.

Only one flush is permitted to execute at any point in time. Similarly, only one archive is permitted to execute at any point in time. However, multiple clients are allowed to concurrently insert and read log records, even while flushing and archiving is going on, except under following circumstances.

1. Log inserts cannot proceed if the system has used up more memory than it should. In that case, it must wait for some memory to be freed up. To ensure maximum concurrency, the memory calculation is approximate.
2. A Log flush cannot proceed if all the online log files are full. In this situation, the flush must wait for at least one file to be archived.
3. When reading a log record, if the online log file containing the record is being archived, the reader may have to wait for the status of the log file to change, before proceeding with the read. Conversely, if a read is active, the archive thread must wait for the read to be over before changing the status of the log file.

If archive mode is ON, log files are archived before being re-used. Otherwise, they can be reused if the file is no longer needed - however this is currently not implemented. By default archive mode is ON.

Limitations of current design

A Log record cannot span log files, and it must fit within a single log buffer. Thus the size of a log record is limited by the size of a log buffer and by the size of a log file. As a workaround to this limitation, clients can split the data into multiple log records, but in that case, clients are responsible for merging the data back when reading from the Log.

Operations

Creating a new Log Instance

Several parameters must be supplied when creating a new log instance. These are specified using a Java Properties object.

Property Name	Description
`log.ctl.{n}`	The fully qualified path to the log control file. The first file should be specified as `log.ctl.1`, second as `log.ctl.2`, and so on. Up to a maximum of 3 can be specified. Default is 2.
`log.groups.{n}.path`	The path where log files of a group should be stored. The first log group is specified as `log.groups.1.path`, the second as `log.groups.2.path`, and so on. Up to a maximum of 3 log groups can be specified. Default number of groups is 1. Path defaults to current directory.
`log.archive.path`	Defines the path for storing archive files. Defaults to current directory.
`log.group.files`	Specifies the number of log files within each group. Up to a maximum of 8 are allowed. Defaults to 2.
`log.file.size`	Specifies the size of each log file in bytes. Default is 2 KB.
`log.buffer.size`	Specifies the size of the log buffer in bytes. Default is 2 KB.
`log.buffer.limit`	Sets a limit on the maximum number of log buffers that can be allocated. Default is 10 * log.group.files.
`log.flush.interval`	Sets the interval (in seconds) between log flushes. Default is 6 seconds.
`log.disableFlushRequests`	Boolean value, if set, disables log flushes requested explicitly by the Buffer Manager or Transaction Manager. Log flushes still occur during checkpoints and log switches. By reducing the log flushes, performance is improved, but transactions may not be durable. Only those transactions will survive a system crash that have all their log records on disk.

Here is an example:

```
LogFactory factory = new LogFactoryImpl();
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "16384");
properties.setProperty("log.buffer.size", "16384");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "30");
factory.createLog(properties);
```

Opening a log instance

Once a Log has been created, it can be opened for use. Opening the log also starts back ground threads that handle periodic log flushes and archival of log files. When the log is closed, the background threads are shut down.

Following sample code shows how this is done:

```
LogFactory factory = new LogFactoryImpl();
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");
properties.setProperty("log.groups.1.path", ".");
properties.setProperty("log.archive.path", ".");
properties.setProperty("log.group.files", "3");
properties.setProperty("log.file.size", "16384");
properties.setProperty("log.buffer.size", "16384");
properties.setProperty("log.buffer.limit", "4");
properties.setProperty("log.flush.interval", "30");
LogMgr log = factory.openLog(properties);
try {
    // do some work
} finally {
    if (log != null)
        log.close();
}
```

Note the use of finally block to ensure that the log is properly closed.

Inserting new log records

The Log Manager does not care about the contents of the log record. It treats the contents as a byte stream. This is illustrated in the following example:

```
LogMgr log = factory.openLog(null);
try {
    String s = "hello world!";
    byte[] b = s.getBytes();
    Lsn lsn = log.insert(b, b.length);
} finally {
    if (log != null)
        log.close();
}
```

Each new log record is assigned a unique sequence number known as the Log Sequence Number (LSN). This can be used later on to retrieve the log record.

Flushing the Log

When new log records are created, initially they are stored in the Log Buffers. The log records are flushed to disk either upon request or by the background thread that periodically flushes the Log. Clients can request the log to be flushed upto a specified LSN. Note that this is a blocking call, i.e., the client will be blocked until the flush is completed.

Example:

```
String s = "hello world!";
byte[] b = s.getBytes();
Lsn lsn = log.insert(b, b.length);
log.flush(lsn);
```

Typically, flush requests are issued by Transaction Manager, when a transaction commits or aborts, or by the Buffer Manager when it is about to write a dirty buffer.

Reading Log records

Log records can be read individually or using a scan. The Log Manager allows both forward and backward scans of the Log. A starting LSN can be specified; if this is not specified then the scanning will begin from the first or last record, depending upon whether it is a forward or backward scan.

Shown below is an example of directly accessing a log record by its LSN:

```
Lsn myLsn = ...;
LogRecord logrec = log.read(myLsn);
byte[] data = logrec.getData();
```

Shown below is an example of using the Log Scan facility:

```
void readAllRecords(LogMgr log) throws Exception {
    LogReader reader = log.getForwardScanningReader(null);
    try {
        for (;;) {
            LogRecord rec = reader.getNext();
            if (rec == null) {
                break;
            }
            printRecord(rec);
        }
    }
    finally {
        if (reader != null)
            reader.close();
    }
}
```

Checkpoint Records

In transactional systems there is often a need to maintain special checkpoint records that contain a snapshot of the system at a point in time. Checkpoint records can be handled in the same way as normal log records, however, the Log Manager also maintains information about the most recent checkpoint record. Whenever a checkpoint record is written, the Log Manager should be informed about its LSN. This ensures that at the next flush, the Log Control files are updated.

```
CheckpointRecord checkpointRec = new CheckpointRecord();
Lsn checkpointLsn = log.insert(checkpointRec.getData(),
        checkpointRec.getLength());
logmgr.setCheckpointLsn(checkpointLsn);
logmgr.flush(checkpointLsn);
```

The LSN of the last checkpoint record can be retrieved at any time using the getCheckpointLsn() method. Note that if the Checkpoint Record is too large and needs to be broken up into smaller records, then the checkpointLsn should be set to the first checkpoint record.

Lock Manager

Introduction

All multi-user transactional systems use some form of locking to ensure that concurrent transactions do not conflict with each other. Depending upon the level of consistency guaranteed by the transactional system the number and type of locks used can vary.

In a single user system, no locking is needed. Transaction are automatically consistent, as only one transaction can execute at any point in time.

Locking Basics

In multi-user systems, transactions must be allowed to proceed concurrently if reasonable performance is to be obtained. However, this means that unless some form of locking is used, data consistency problems will arise. For example, if two transactions update the same record at the same time, one of the updates may be lost.

To prevent this sort of thing from happening, each transaction must lock the data that it updates or reads. A lock is a mechanism by which access to the record is restricted to the transaction that owns the lock. Furthermore, a lock restricts the type of operation that is permitted to occur. For example, a Shared lock can be owned by multiple transactions concurrently and allows read operations. An Exclusive lock permits both read and write operations but can only be granted to one transaction at any point on time. Moreover Shared locks and Exclusive locks are incompatible; this means that if a Shared Lock is held by a transaction on a record, another transaction cannot obtain an Exclusive lock on the same record, and vice-versa.

Two-Phase Locking and Repeatable Read Isolation Level

Not only must a record be locked when it is updated, the transaction must hold the lock until the transaction is committed or aborted. This strategy leads to the basic rule of two-phase locking, which requires that a transaction must manage its locks in two distinct phases. In the first phase, the transaction is permitted to acquire locks, but cannot release any locks. The first phase lasts right up to the moment the transaction is completed, i.e., either committed or aborted. In the second phase, when the transaction is committed or aborted, all locks are released. No further locks can be acquired in this phase. Strict two phase locking ensures that despite concurrent running of transactions, each transaction has the appearance of running in isolation. Strict two-phase locking strategy provides a level of consistency called Repeatable Read.

Read Committed Isolation Level

This basic strategy can be modified to obtain greater concurrency at the cost of data consistency. For example, read locks can be released early to allow other transactions to read data. While this increases concurrency, it does mean that reads are not repeatable, because the original transaction may find that the data it read previously has been modified by the time it is read a second time. This level of consistency is known as Read Committed.

Serializable Isolation Level

Although the Repeatable Read level of consistency prevents data that has been read by one transaction from being modified by another, it does not prevent the problem of phantom reads, which occurs when new records are inserted. For example, if a range of records is read twice by the same transaction, and another transaction has inserted new records in the time interval between the two reads, then the second read will encounter records that did not appear the first time. To prevent this type of phantom reads from occurring, locking has to be made even more comprehensive. Rather than locking one record, certain operations need to lock entire ranges of records, even non-existent ones. This is typically achieved using a logical convention; a lock on a particular data item represents not only a lock on that data, but also the range of data up to and including the data item being locked. For example, if there are two records A and C, then a lock on C would encompass the entire range of data between A and C, excluding A, but including and up to C.

Design choices

The Locking subsystem specified in SimpleDBM requires that locks should be implemented independently of the objects being locked. In order for locking to work, all participants must agree to agree to use the locking system and abide by the rules.

Another design constraint is that the interface is geared towards a memory based implementation. This places a constraint on the number of locks that can be held within the system, because a large number of locks would require a prohibitively large amount of memory.

Some database systems, Oracle, in particular, use markers within the databases disk pages to represent locks. A lock byte is used, for instance, to denote whether a row is locked or not. The advantage of Oracle's approach is that there are no constraints on the number of locks the system can handle. The disadvantage is that the lock status is maintained in persistent storage, therefore changing the lock status can make a page dirty. Oracle overcomes this issue in two ways. Firstly, it uses a multi-version system that does not require read locks. Thus, locks are used only for updates, and since updates cause database pages to be touched anyway, using a lock status byte does not pose a problem. Secondly, Oracle avoids updating the lock status byte when locks are released, by using information about the transaction status to infer that a lock has been released.

The interface for the Locking System specified in this package does not support implementations of the type used in Oracle.

In some systems, locking is based upon facilities provided by the underlying operating system. For instance, most operating systems support some form of file locking. Since database records are laid out into regions within a file system, file system locks can be applied on records. This is not the best way of implementing locks. This is because locking a region in the file would prevent all access to that region, which would cause other problems. Even when systems do use file system locks, typically, some form of logical locking is used. For example, in DBASE III based systems, a single byte in the file represents a record lock. In general, relying upon file system locks can be source of numerous problems, such as portability of the system, performance, etc.

Lock Modes

The SimpleDBM Lock Manager supports the following Lock Modes:

INTENTION_SHARED Indicates the intention to read data at a lower level of granularity.

INTENTION_EXCLUSIVE Indicates the intention to update data at a lower level of granularity.

SHARED Permits readers.

SHARED_INTENTION_EXCLUSIVE Indicates SHARED lock at current level and intention to update data at a lower level of granularity.

UPDATE Indicates intention to update, Permits readers.

EXCLUSIVE Prevents access by other users.

Lock Compatibility Matrix

The lock compatibility matrix for above is given below:

Table 6.1: Lock Compatibility Table

Mode	NONE	IS	IX	S	SIX	U	X
NONE	Y	Y	Y	Y	Y	Y	Y
Intent Shared	Y	Y	Y	Y	Y	N	N
Intent Exclusive	Y	Y	Y	N	N	N	N
Shared	Y	Y	N	Y	N	N	N
Shared Intent Excluive	Y	Y	N	N	N	N	N
Update	Y	N	N	Y	N	N	N
Exclusive	Y	N	N	N	N	N	N

Lock Conversions

SimpleDBM's Lock Manager also supports Lock Conversions. The following table shows how lock conversions are handled:

Table 6.2: Lock Conversion Table

Mode	NONE	IS	IX	S	SIX	U	X
NONE	NONE	IS	IX	S	SIX	U	X
Intent Shared	IS	IS	IX	S	SIX	U	X
Intent Exclusive	IX	IX	IX	SIX	SIX	X	X
Shared	S	S	SIX	S	SIX	U	X
Shared Intent Exclusive	SIX	SIX	SIX	SIX	SIX	SIX	X
Update	U	U	X	U	SIX	U	X
Exclusive	X	X	X	X	X	X	X

Operations

Obtaining an instance of Lock Manager

SimpleDBM provides a factory class for generating instances of the Lock Manager. Note that locks are meaningful only within an instance of the Lock Manager – if there are two Lock Manager instances, each will have its own set of locks.

Following sample code shows how to obtain an instance of the Lock Manager.

```
LockMgrFactory factory = new LockMgrFactoryImpl();
Properties props = new Properties();
LockMgr lockmgr = factory.create(props);
```

The only property that can be set is the Hash Table size.

Lockable objects

Any object can be locked. The only requirement is that the object should implement the `hashCode()` and `equals()` methods. For the system to work correctly, lockable objects should be immutable – once created they must not be modified. Clearly, if the object is modified while it is referenced in the lock tables, then the system will malfunction, as the object will no longer respond to `hashCode()` and `equals()` in a consistent manner.

Lock Owners

Every lock must have an owner. The LockMgr interface allows any object to be lock owner; the only requirement is that the object must implement the `equals()` method.

Lock Durations

Locks can be acquired for an `INSTANT_DURATION` or `MANUAL_DURATION`. Instant duration locks are not acquired in reality – the caller is delayed until the lock becomes available. Manual duration locks are held until they are released. Such locks have a reference count attached to them. If the lock is acquired more than once, the reference count is incremented. The lock will not be released until the reference count becomes zero.

Typically, a Transaction will hold locks until the transaction ends. In some cases, SHARED locks may be released early, for example, in the READ COMMITTED Isolation Level.

Acquiring and releasing locks

Locks can be acquired using the `acquire()` method provided by the LockMgr interface. The acquire method returns a Handle to the lock, which can be used subsequently to release the lock. Example:

```
LockMgr lockmgr = new LockMgrImpl(71);
Object owner = new Integer(1);
Object lockname = new Integer(10);
LockHandle handle = lockmgr.acquire(owner, lockname,
    LockMode.EXCLUSIVE, LockDuration.MANUAL_DURATION, -1);
// do some work
handle.release(false);
```

Algorithm

The main algorithm for the lock manager is shown in the form of use cases. The description here is inspired by a similar description in *[COCKBURN]*.

a001 - lock acquire

Main Success Scenario

1. Search for the lock header
2. Lock header not found
3. Allocate new lock header
4. Allocate new lock request
5. Append lock request to queue with status = GRANTED and reference count of 1.
6. Set lock granted mode to GRANTED

Extensions

2. (a) Lock header found but client has no prior request for the lock.
      i. Do *a003 - handle new request*.
   (b) Lock header found and client has a prior GRANTED lock request.
      i. Do *a002 - handle lock conversion*.

a003 - handle new request

Main Success Scenario

1. Allocate new request.
2. Append lock request to queue with reference count of 1.

3. Check for waiting requests.
4. Check whether request is compatible with granted mode.
5. There are no waiting requests and lock request is compatible with granted mode.
6. Set lock's granted mode to maximum of this request and existing granted mode.
7. Success.

Extensions

5. (a) There are waiting requests or lock request is not compatible with granted mode.
    i. Do *a004 - lock wait*.

a002 - handle lock conversion

Main Success Scenario

1. Check lock compatibility with granted group.
2. Lock request is compatible with granted group.
3. Grant lock request, and update granted mode for the request.

Extensions

2. (a) Lock request is incompatible with granted group.
    i. Do *a004 - lock wait*.

a004 - lock wait

Main Success Scenario

1. Wait for lock.
2. Lock granted.
3. Success.

Extensions

2. (a) Lock was not granted.
    i. Failure!

b001 - release lock

Main Success Scenario

1. Decrease reference count.
2. Sole lock request and reference count is zero.
3. Remove lock header from hash table.
4. Success.

Extensions

2. (a) Reference count greater than zero.
      i. Success.
2. (a) Reference count is zero and there are other requests on the lock.
      i. Remove request from the queue.
      ii. Do *b002 - grant waiters*.

b002 - grant waiters

Main Success Scenario

1. Get next granted lock.
2. Recalculate granted mode.
3. Repeat from 1) until no more granted requests.
4. Get next waiting request.
5. Request is compatible with granted mode.
6. Grant request and wake up thread waiting for the lock. Increment reference count of the granted request and set granted mode to maximum of current mode and granted request.
7. Repeat from 4) until no more waiting requests.

Extensions

1. (a) Conversion request.
      i. Do *b003 - grant conversion request*.
      ii. Resume from 2).
4. (a) "conversion pending" is set (via b003).
      i. Done.
5. (a) Request is incompatible with granted mode.
      i. Done.

b003 - grant conversion request

Main Success Scenario

1. Do *c001 - check request compatible with granted group*.
2. Request is compatible.
3. Grant conversion request.

Extensions

2. (a) Conversion request incompatible with granted group.
    i. Set “conversion pending” flag.

c001 - check request compatible with granted group

Main Success Scenario

1. Get next granted request.
2. Request is compatible with this request.
3. Repeat from 1) until no more granted requests.

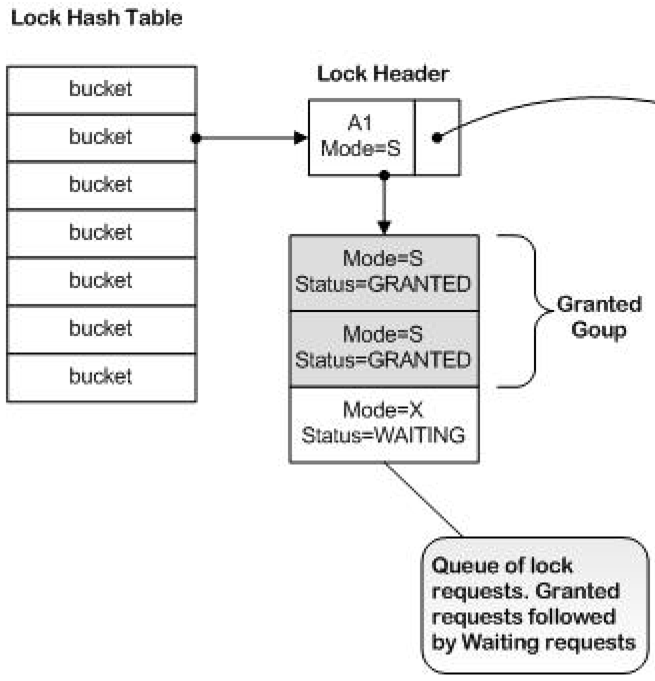
Extensions

1. (a) Request belongs to the caller.
    i. Resume from step 3).
2. (a) Request is incompatible with this request.
    i. Failure!

Data Structures of the Lock Manager

The Lock Manager data structures are based upon the structures described in *[JGRAY]*. A hash table is used to maintain a lookup table for finding lock objects. The buckets in the hash table point to linked lists of lock headers. Each lock header holds housekeeping information about a single lock. A chain of lock requests is attached to the lock header. Each request represents a lock request by a client. At any point in time, a lock may have multiple requests queuing - some in GRANTED state, others waiting for the lock to be GRANTED.

The data structure used by the Lock Manager is depicted below.



Deadlock Detector

The Lock Manager contains a simple Deadlock Detector implemented which is based upon algorithm described in *[JGRAY]*. The deadlock detector runs in a background thread, periodically waking up to check for deadlocks. When a deadlock is detected, one of the transactions (chosen arbitrarily) is aborted.

Page Manager

Overview of Page Manager module

The storage unit of a database system is a Page. In SimpleDBM, pages are contained with logical units called Storage Containers. The default implementation maps containers to Operating System files.

A page is typically a fixed size block within the storage container. The PageManager module encapsulates knowledge about how pages map to containers. It knows about the page size, but delegates the work of reading/writing pages to PageFactory implementations. This division of labour allows all pages to be centrally managed by the PageManager, yet allows new page types to be registered without having to change the PageManager. By isolating the management of pages into the PageManager module, the rest of the system is protected. For example, the BufferManager module can work with different paging strategies by switching the PageManager module.

Note that the PageManager module does not worry about the contents of the page, except for the very basic and common stuff that must be part of every page, such as a checksum, the page Id, page LSN, and the page type. It is expected that other modules will extend the basic page type and implement additional features. The PageManager does provide the base class for all Page implementations.

Interactions with other modules

The Buffer Manager module uses the PageManager module to read/write pages from storage containers and also to create new instances of pages.

The PageManager module requires the services of the Object Registry module in order to obtain PageFactory implementations.

The PageManager uses PageFactory implementations to read/write pages.

The PageManager module also interacts with the StorageManager module for access to Storage Containers.

Each page is allocated a Latch to manage concurrent access to it. The PageManager therefore requires the services of the Latch Manager.

Page class

The page manager provides an abstract Page class that is the root of the Page hierarchy. All other page types derive from this class. The simplest of Page classes that one could create is shown below:

```
public final class RawPage extends Page {
  RawPage(PageManager pageFactory, int type, PageId pageId) {
    super(pageFactory, type, pageId);
  }
  RawPage(PageManager pageFactory, PageId pageId, ByteBuffer bb) {
    super(pageFactory, pageId, bb);
  }
}
```

The constructor that accepts the ByteBuffer argument, should retrieve the contents of the Page from the ByteBuffer.

Page Size and implementation of Storable interface

The Page class implements the Storable interface. However, unlike other implementations, a Page has a fixed length which is defined by the PageManager responsible for creating it. The Page obtains the page size from the PageManager instance and uses that to determine its persistent size. Sub-classes cannot change this value. This means that the page size of all pages managed by a particular PageManager instance is always the same.

Sub-classes of course still need to implement their own store() method and a constructor that can initialize the object from a supplied ByteBuffer object. These methods should always invoke their super class counterparts before processing local content.

Example:

```
public class MyPage extends Page {
     int i = 0;

  MyPage(PageManager pageFactory, int type, PageId pageId) {
    super(pageFactory, type, pageId);
  }

  MyPage(PageManager pageFactory, PageId pageId, ByteBuffer bb) {
    super(pageFactory, pageId, bb);
    i = bb.getInt();
  }

  /**
   * @see org.simpledbm.rss.api.pm.Page#store(java.nio.ByteBuffer)
   */
  @Override
  public void store(ByteBuffer bb) {
    super.store(bb);
    bb.putInt(i);
  }
}
```

How various Page types are managed

Some of the SimpleDBM modules define their own page types. These page types are not known to the BufferManager or the TransactionManager, which must still handle such pages, even read and write them to the disk as necessary. This is made possible as follows:

- Each Page type is given a typecode in the Object Registry. A PageFactory implementation is registered for each Page typecode.
- The typecode is stored in the first two bytes (as a short integer) of the Page when the page is persisted. When reading a page, the first two bytes are inspected to determine the correct Page type to instantiate. Reading and writing various page types is managed by the PageFactory implementation.
- The PageManager looks up the PageFactory implementation in the ObjectRegistry, whenever it needs to persist or read pages.
- The Buffer Manager uses the PageManager to generate new instances of Pages or to read/write specific pages.
- The abstract Page class provides a common interface for all Pages. This interface implements all the functionality that is required by the Transaction Manager module to manage updates to pages.

Page Factory

Creating a page factory is relatively simple:

```
static class MyPageFactory implements PageFactory {

  final PageManager pageManager;

  public MyPageFactory(PageManager pageManager) {
    this.pageManager = pageManager;
  }
  public Page getInstance(int type, PageId pageId) {
    return new MyPage(pageManager, type, pageId);
  }
  public Page getInstance(PageId pageId, ByteBuffer bb) {
    return new MyPage(pageManager, pageId, bb);
  }
  public int getPageType() {
    return TYPE_MYPAGE;
  }
}
```

Note that the PageFactory implementation passes on the PageManager reference to new pages.

The PageFactory provide two methods for creating new instances of Pages. The first method creates an empty Page. The second creates a Page instance by reading the contents of a ByteBuffer - this method is used when pages are read from a StorageContainer.

The PageFactory implementation must be registered with the ObjectRegistry as a Singleton:

```
static final short TYPE_MYPAGE = 25000;
ObjectRegistry objectRegistry = ...;
objectRegistry.registerSingleton(TYPE_MYPAGE, new MyPage.MyPageFactory(pageFactory));
```

Page Manager

Following snippet of code shows how the PageManager instance is created:

```
Properties properties = new Properties();
properties.setProperty("storage.basePath", "testdata/TestPage");
properties.setProperty("logging.properties.file", "classpath:simpledbm.logging.
↪properties");
properties.setProperty("logging.properties.type", "log4j");
platform = new PlatformImpl(properties);
storageFactory = new FileStorageContainerFactory(platform,
  properties);
objectRegistry = new ObjectRegistryImpl(platform, properties);
storageManager = new StorageManagerImpl(platform, properties);
latchFactory = new LatchFactoryImpl(platform, properties);
pageManager = new PageManagerImpl(
  platform,
  objectRegistry,
  storageManager,
  latchFactory,
  properties);
```

Note that the PageManager requires access to the ObjectRegistry, the LatchManager and the StorageManager. PageFactory instances are retrieved indirectly via the ObjectRegistry.

Storing and retrieving Pages

Before pages can be stored or retrieved, the appropriate Storage Containers must be created/opened and registered with the Storage Manager. Also, the Page types must be registered with the Object Registry. Following sample code shows how this may be done:

```
String name = "testfile.dat";
// Create a new storage container called testfile.dat
StorageContainer sc = storageFactory.create(name);
// Assign it a container ID of 1
storageManager.register(1, sc);
// Register the Page Type
objectFactory.register("mypage", TYPE_MYPAGE, MyPage.class.getName());
// Create a new instance of the page
MyPage page = (MyPage) pageFactory.getInstance("mypage", new PageId(1,
    0));
// Store the page in the container
pageFactory.store(page);
// Retrieve the page from the container
page = (MyPage) pageFactory.retrieve(new PageId(1, 0));
```

Checksum

When a page is persisted, its checksum is stored in a field within the page. The checksum is recalculated when a page is read, and compared with the stored checksum. This allows SimpleDBM to detect page corruption.

At present, SimpleDBM will throw an exception when corruption is detected.

Buffer Manager

Overview

The Buffer Manager is a critical component of any DBMS. Its primary job is to cache disk pages in memory. Typically, a Buffer Manager has a fixed size Buffer Pool, implemented as an array of in-memory disk pages. The contents of the Buffer Pool change over time, as pages are read in, and written out. One of the principle tasks of the Buffer Manager is to decide which page should stay in memory, and which should not. The aim is to try to keep the most frequently required pages in memory. The efficiency of the Buffer Manager can be measured by its cache hit-rate, which is the ratio of pages found in the cache, to pages accessed by the system.

In order to decide which pages to maintain in memory, the Buffer Manager typically implements some form of Least Recently Used (LRU) algorithm. In the simplest form, this is simply a linked list of all cached pages, the head of the list representing the least recently used page, and the tail the most recently used. This is based on the assumption that if a page was accessed recently, then it is likely to be accessed again soon. Since every time a page is accessed, it is moved to the MRU end of the list, therefore over time, the most frequently accessed pages tend to accumulate on the MRU side. Of course, if a client reads a large number of temporary pages, then this scheme can be upset. To avoid this, the Buffer Manager may support hints, so that a client can provide more information to the Buffer Manager, which can then use this information to improve the page replacement algorithm. An example of such a hint would be to flag temporary pages. The Buffer Manager can then use this knowledge to decide that instead of the page going to MRU end, it goes to the LRU end.

Interactions with other modules

The Buffer Manager interacts with the Log Manager and the Page Manager modules. It needs the help of the PageFactory in order to instantiate new pages, read pages from disk, and write out dirty pages to disk. In order to support the Write Ahead Log protocol, the Buffer Manager must ensure that all logs related to the page in question are flushed prior to the page being persisted to disk.

The Transaction Manager also interacts with the Buffer Manager. During checkpoints, the Transaction Manager asks for a list of dirty pages. It uses information maintained by the Buffer Manager to determine where recovery should start. After a system restart the Transaction Manager informs the Buffer Manager about the recovery status of disk pages.

Operations

Creating a Buffer Manager instance

A Buffer Manager instance has a dependency on Log Manager and Page Factory. These in turn depend upon a few other modules. The following sample code illustrates the steps required to create a Buffer Manager instance.

```
LogFactory factory = new LogFactoryImpl();
Properties properties = new Properties();
properties.setProperty("log.ctl.1", "ctl.a");
properties.setProperty("log.ctl.2", "ctl.b");

// Create Storage Factory instance
StorageContainerFactory storageFactory =
    new FileStorageContainerFactory();
// Open Log
```

```
LogMgr log = factory.openLog(storageFactory, properties);
// Create Object Registry
ObjectFactory objectFactory = new ObjectFactoryImpl();
// Create Storage Manager instance
StorageManager storageManager = new StorageManagerImpl();
// Create Latch Factory
LatchFactory latchFactory = new LatchFactoryImpl();
// Create Page Factory
PageFactory pageFactory = new PageFactoryImpl(objectFactory,
    storageManager, latchFactory);
// Create a Buffer Manager intance with a Buffer Pool of
// 50 pages and a hash table of 101 buckets
BufMgrImpl bufmgr = new BufMgrImpl(logmgr, pageFactory, 50, 101);
```

Note that when creating a Buffer Manager instance, you can set the size of the Buffer Pool and also the size of the Hash table.

A Buffer Manager instance has a one to one relationship with a Page Factory. Hence all pages managed by the Buffer Manager instance will be of the same size; the page size is determined by the Page Factory.

Fixing Pages in the Buffer Pool

The Buffer Manager provides methods for fixing pages in the Buffer Pool. There are two possibilities:

- Fix a new page.
- Fix an existing page.

It is the client's responsibility to know whether the page is new or existing. If a request is made to fix the page as new, then the outcome may be unexpected. If the page already exists in the Buffer Pool, it will be returned, rather than initializing a new Page.

When fixing a Page, the Page can be locked in one of three modes:

Shared mode allowing multiple clients to access the same Page concurrently for reading.

Update mode which allows one client to access the page in update mode, but other clients may access the same page concurrently in Shared mode.

Exclusive mode in this mode only one client has access to the Page. This mode is used when a client wishes to modify the contents of the Page.

An Update mode request can be upgraded to Exclusive mode. An Exclusive mode request may be downgraded to an Update mode request.

Following code sample shows how page is fixed:

```
// Fix page as New (the second parameter). The page type is mypage.
// This page type should have been registered with the Object Registry
// prior to this call. The page will be latched in Exclusive mode.
// The last parameter is a hint for the LRU replacement algorithm.
BufferAccessBlock bab = bufmgr.fixExclusive(new PageId(1, 0),
  true, "mypage", 0);
```

As shown above, when a page is fixed, the Buffer Manager returns a BufferAccessBlock which contains a reference to the desired page. The Page can be accessed as follows:

```
MyPage page = (MyPage) bab.getPage();
```

Modifying page contents

Note that in order to modify a Page's content, the Page must be fixed in Exclusive mode.

Also, the Write Ahead Log protocol must be obeyed. This requires the modification to proceed as follows:

1. Fix the page in exclusive mode.
2. Generate a log record containing redo/undo information for the modification about to be made.
3. Modify the page contents.
4. Set the Page LSN of the page and mark the page as dirty.
5. Unfix the page.

Failure to follow this protocol may lead to unrecoverable changes.

Changing lock modes

As mentioned before, pages that are locked in Update mode may be upgraded to Exclusive mode. Pages that are locked in Exclusive mode may be downgraded to Update mode. The BufferAccessBlock interface provides methods that allow the lock mode to be upgraded or downgraded.

Unfixing a Page

It is very important to unfix a Page after the client is done with it. Failure to do so may cause the Buffer Pool to become full and the system will potentially come to a halt if further pages cannot be fixed. A fixed page cannot be removed from the Buffer Pool.

It is also advisable to keep pages fixed for a short duration only. If necessary the same page can be fixed again.

Transaction Manager

Introduction

The Transaction Manager is responsible for managing transactions. It provides interfaces for starting new transactions, and for committing or aborting transactions. The SimpleDBM implementation also supports Savepoints. While the view seen by the user is simple, the Transaction Manager is a complex module and has an elaborate interface. This chapter will attempt to unravel the TM interface and with the help of examples, demonstrate how this interface works and how other modules can use this interface to participate in Transactions.

Overview

SimpleDBM's transaction manager is modelled after *[ARIES]*. It makes following assumptions about the rest of the system:

- The system uses the Write Ahead Log protocol when making changes to database containers.
- The unit of change is a disk page. This means that logging is on a per page basis.
- The disk page contains a PageLSN field that can be used to track the last log record that made changes to the page.

- During checkpoints the Transaction Manager does not flush all pages, instead it writes the Buffer Manager's "table of contents" to the Log. The table of contents is the list of dirty pages in the Buffer Pool, along with their Recovery LSNs. The Recovery LSN is the LSN of the oldest log record that could potentially have have a change to the page. For a discussion of the Recovery LSN please refer to Mohan's paper on ARIES and also to section 13.4.4.1 of *[JGRAY]*. *[JGRAY]* refers to Recovery LSNs as `forminlsn`.
- At the end of system restart, the Transaction Manager informs the Buffer Manager the RecoveryLSN status of all dirty pages; the Buffer Manager must therefore provide an interface for updating the Recovery LSN of such pages.
- The Log Manager provides a mechanism for reliably recording the Checkpoint LSN. Also, the Log Manager supports accessing Log Records sequentially from a starting point, as well as randomly using the LSN.
- The Lock Manager provides an interface for acquiring and release locks. The release mode must support a mechanism for forcing the release of a lock.

What is ARIES?

ARIES is a Transaction Logging and Recovery algorithm developed at IBM and published by IBM researcher C. Mohan.

For a full description of ARIES, please see `Mohan, C., Haderle, D., Lindsay, B., Pirahesh, H. , Schwarz, P. ARIES: A Transaction Recovery Method Supporting Fine-Granularity Locking and Partial Rollbacks Using Write-Ahead Logging, ACM Transactions on Database Systems, Vol. 17, No. 1, March 1992, pp94-162.`

A brief overview of ARIES is given below.

ARIES - An Overview

Following is a brief description of the main principles behind ARIES.

Firstly, in ARIES, changes always take the system forward. That is to say, even transaction rollbacks are treated as if they are updates to the system. This is counter-intuitive to what the user thinks, because when a user asks for a transaction to be rolled back, they assume that the system is going back to a previous state of affairs. However, from the perspective of ARIES, there is no such thing as going back. For example, if a transaction changes A to B and then rolls back, ARIES treats the rollback as simply an update that changes B to A. The forward change from A to B (redo) and the reversal of B to A (undo) are both recorded as updates to the system. Changes during normal operations are recorded as Redo-Undo log records. As the name implies, these log records can be 'redone' in case of a system crash, or 'undone' in case a rollback is required. Changes made during rollbacks, however, are recorded as Redo-only log records. These log records are called Compensation Log Records (CLRs). The reason these are redo only is that by definition a rollback does not need to be undone, whereas normal updates need to be undone if the transaction decides to rollback.

The second basic principle of ARIES is that during recovery, history is repeated. This can be explained as follows.

When a system crashes, there would be some transactions that have completed (committed or aborted), and others that are still active. The WAL protocol ensures that changes made by completed transactions have been recorded in the Log. Changes made by incomplete transactions may also be present in the Log, because Log Records are created in the same order as the changes are made by the system.

During recovery, ARIES initially replays the Log to the bring the system back to a state close to that when the crash occurred. This means that ARIES replays the effects of not only those transactions that committed or aborted, but also those that were active at the time of the crash. Having brought the system to this state, ARIES then identifies transactions that were incomplete, and rolls them back. The basic idea is to repeat the entire history upto the point of crash, and then undo failed transactions.

This approach has the advantage that during the redo phase, changes can be replayed at a fairly low level, for example, the level of a disk page. ARIES calls this page oriented redo. This feature is significant because it means that until the redo phase is over, the system does not need to know about higher level data structures such as Indexes. Only during the undo phase, when incomplete transactions are being rolled back, does the system need to know about high level data structures.

Features of ARIES

ARIES includes a number of optimisations to reduce the amount of work required during normal operations and recovery.

One optimisation is to avoid application of log records unnecessarily. The LSN of the most recently generated log record is stored in each disk page. This is known as the PageLsn. The PageLsn allows ARIES to determine during the redo phase, whether the changes represented by a log record have been applied to the page or not.

ARIES chains log records for transactions in such a way that those records that are no longer necessary, are skipped during recovery. For example, if a transaction changed A to B, and then rolled back, generating a log record for changing B to A, then during recovery, ARIES would automatically skip the log record that represents the change from A to B. This is made possible by maintaining a UndoLsn pointer in every Log Record. The UndoLsn normally points to the previous log record generated by the transaction. However, in log records generated during Rollback (known as Compensation Log Records), the UndoLsn is made to point to the Log record preceding the one that is being undone. To take an example, let us assume that a transaction generated log record 1, containing change from A to B, then log record 2 containing change from B to C. At this point the transaction decides to rollback the change from B to C. It therefore generates a new log record 3, containing a change from C to B. The UndoLsn of this log record is made to point at log record 1, instead of log record 2. When following the UndoLsn chain, ARIES would skip log record 2.

ARIES also supports efficient checkpoints. During a checkpoint, it is not necessary to flush all database pages to disk. Instead ARIES records a list of dirty buffer pages along with their RecoveryLsn(s). The RecoveryLsn of a page is the LSN of the earliest log record that represents a change to the page since it was read from disk. By using this list, ARIES is able to determine during recovery, where to start replaying the Log.

ARIES supports nested top-level action concept whereby part of a transaction can be committed even if the transaction aborts. This is useful for situations where a structural change should not be undone even if the transaction aborts. Nested top level actions are implemented using Dummy Compensation Log Records - and make use of the ability to skip logs records using the UndoLsn pointer as described previously.

Key differences from ARIES

The implementation of the Transaction Manager in SimpleDBM is as faithful to ARIES as possible, with a few differences.

- SimpleDBM supports multi-page redo operations where a single log record affects multiple pages.
- SimpleDBM records in the checkpoint records the list of open containers so that it can ensure that these containers are re-opened at startup.
- The transaction manager supports post commit actions for handling of special cases such as deleting a container.
- The transaction manager supports non-page specific log records for operations such as opening/deleting containers.

Transactions and Locks

There is close coordination between the Transaction Manager and the Lock Manager. A Transaction needs to keep track of all locks acquired on its behalf so that it can release them when the Transaction completes. This is why the Transaction interface in SimpleDBM provides methods for acquiring locks. If the Lock Manager is invoked directly by the client then the TM has no way of knowing which locks to release when the Transaction terminates.

While locks can be acquired by a client any time after a Transaction starts, locks are released only on one of the following three occasions:

- If the CURSOR STABILITY Isolation Mode is being used, then a SHARED or UPDATE lock can be released once the cursor moves to the next record. If REPEATABLE READ Isolation Mode is used, then the UPDATE lock can be downgraded to SHARED lock when the cursor moves. Note that the Transaction Manager does not decide when to release or downgrade a lock; it is the responsibility of the client to decide that. However, the Transaction must update its record of the locks when this happens. Therefore, lock release or downgrade requests must be handled via the Transaction interface and not directly between the client and the Lock Manager.
- When a Transaction is rolled back to a Savepoint, any locks acquired after the Savepoint are released. Note that if a lock was acquired before the Savepoint, and upgraded after the Savepoint, it will not be downgraded or released. The Transaction interface manages the release of such locks.
- Finally, when the Transaction completes, all locks held by the transaction are released.

Following sample code shows how a client interacts with the Transaction.

```
// Start new Transaction
Transaction trx = trxmgr.begin();

// Acquire a shared lock
trx.acquireLock(new ObjectLock(1,15), LockMode.SHARED,
   LockDuration.MANUAL_DURATION);

// Upgrade the shared lock
trx.acquireLock(new ObjectLock(1,15), LockMode.UPDATE,
LockDuration.MANUAL_DURATION);

// Downgrade the update lock
trx.downgradeLock(new ObjectLock(1, 15),
   LockMode.SHARED);

// commit the transaction, releasing all locks
trx.commit();
```

Transactions and Modules

The Transaction Manager provides a framework for managing transactions. It provides interfaces to:

1. Start and end transactions
2. Acquire locks on behalf of transactions
3. Create log records on behalf of transactions.

The Transaction Manager itself does not initiate changes to database pages, though it may coordinate the redo or undo of such changes – changes are always initiated by clients. A client in this context is some module within the system that wishes to make changes to the database disk pages as part of a Transaction.

The Transaction Manager does not know in advance what clients it may have to interact with. However, it needs to be able to call upon the clients to redo or undo the effects of log records when required. This is enabled in two ways:

1. Firstly, all clients must implement the TransactionalModule interface. This interface defines the operations that the Transaction Manager may call upon the client to perform.
2. Secondly, all modules must *register* themselves to the Transaction Manager using unique Module IDs. This way, the Transaction Manager knows how to obtain access to a module, and ask it to perform an action.
3. Finally, all log records generated by a Module need to be tagged with the Module's Unique ID. If this is not done, the Transaction Manager would not know which module is responsible for handling a particular log record.

Transactions and Log records

The Transaction Manager works very closely with the Log Manager to ensure the ACID properties of transactions. We saw in the chapter on Log Manager that it does not care about the contents of Log Records. The Transaction Manager, however, does care, and defines a hierarchy of different Log record types that should be used by clients. This is explained below.

The Loggable hierarchy

Loggable is parent interface for all Log Records. The Transaction Manager will only accept Log records that implement this interface. This can be seen from the signature of the logInsert() method provided by the Transaction interface.

The Loggable hierarchy defines the various types of log records that clients can generate. These are further discussed below.

Loggable Hierarchy

The main branches of the Loggable hierarchy are shown below. Note that some of the hierarchy is not visible to outside clients (marked as internal).

Table 6.3: Loggable Hierarchy

Interface	Description
Redoable	All log operations that affect database pages must implement this interface or one of its sub-interfaces. The Transaction Manager expects a valid PageId (s) to be returned by a Redoable log record. Note that Compensation and Undoable log records are sub-interfaces of Redoable.
NonTransaction-RelatedOperation	These represent changes that are not related to specific pages. Since the ARIES algorithm uses page LSNs to track updates caused by log records, changes made by this type of log record are not tracked they are repeated unconditionally at system start. At present, this type of log operation is used to handle opening of containers.
PostCommitAc-tion	Although PostCommitAction is a subinterface of NonTransactionRelatedOperation at present, this may change in future. PostCommitActions are used to schedule actions that must be performed after a successful commit. An example of such an action is the dropping of a container. To avoid logging the full contents of the container, the actual delete of the container must be deferred until it is certain that the Transaction is committing. Note that unlike other NonTransactionRelatedOperations, the Transaction Manager does track the status of PostCommitActions and will execute them at restart if they have not been executed.
ContainerDelete-Operation	The Transaction Manager needs to be aware when containers are deleted, both when a container is dropped or when the creation of a container is aborted. In both cases, the TM uses this marker interface to identify the delete operation and coordinates with the Buffer Manager to clear the cached pages related to the deleted container.
ContainerOpen-Operation	The Transaction Manager needs to be aware when containers are opened between checkpoints so that it can include these in the next checkpoint. The TM uses this marker interface to identify the open operation.

Transaction Manager Internal Log Records

The Transaction Manager uses internal log records to track Transaction completion, and also Checkpoints. These log record types are not available outside the implementation of the TM.

Redoable

Generally speaking, most log records are implementations of Redoable interface or one of its sub-interfaces. A Redoable log record is related to one or more database pages, and can be re-done at System restart. In some cases, the effects of a log record should not be undone; such records are called Redo-only log records and can be created in a number of ways:

- Implement the Redoable interface but not its Undoable sub-interface.
- Implement the Compensation interface. This is a special case, which is discussed later.

An example of a Redo-only log record is the Page Format operation. Newly created pages need to be formatted, but once this is done, it is unnecessary to undo the formatting.

Given below is an example implementation of a Page Format log record:

```
public static class FormatRawPage extends BaseLoggable
  implements Redoable, PageFormatOperation {

  ByteString dataPageType;

  public void init() {
  }
  public final String getDataPageType() {
      return dataPageType.toString();
  }

  public final void setDataPageType(String dataPageType) {
      this.dataPageType = new ByteString(dataPageType);
  }

  public int getStoredLength() {
      return super.getStoredLength() +
          dataPageType.getStoredLength();
  }

  public void retrieve(ByteBuffer bb) {
      super.retrieve(bb);
      dataPageType = new ByteString();
      dataPageType.retrieve(bb);
  }

  public void store(ByteBuffer bb) {
      super.store(bb);
      dataPageType.store(bb);
  }
}
```

As astute reader will notice that the Page Format operation extends the BaseLoggable class and implements both Redoable and PageFormatOperation interfaces. The BaseLoggable class and the PageFormatOperation interface are described further below.

BaseLoggable abstract class

The Transaction Manager provides the BaseLoggable abstract class which implements the Loggable interface. Rather than attempting to implement the Loggable interface from scratch, it is highly recommended that clients sub-class the BaseLoggable class and extend it to add functionality. The reason for making Loggable an interface and not an abstract class like BaseLoggable is that it allows the client to implement its own class hierarchy independently from the Loggable hierarchy.

PageFormatOperation

Operations that format new pages are particularly important because the Transaction Manager must invoke the Buffer Manager FIX AS NEW interface to fix pages affected by them. If the normal fix interface is called, an exception will be thrown because the page may not exist on disk or may be garbage. To allow the Transaction Manager to spot page format operations, all log records that perform such actions should implement the PageFormatOperation interface. This is a marker interface only.

Usually, PageFormatOperations are redo-only.

In SimpleDBM, the page format operations are handled when a container is created or expanded.

MultiPageRedo

Normally a Redoable log record represents changes to a single page. Sometimes, however, it may be necessary for a single log record to contain changes made to multiple pages. In such cases, the Log record should implement the

MultiPageRedo interface.

Note that clients need to follow the following procedure when creating MultiPageRedo log records.

1. Fix all the affected pages.
2. Generate the MultiPageRedo log record.
3. Apply changes to the affected pages.
4. Set the pageLsn of all affected pages to the LSN of the log record.
5. Unfix all affected pages.

Undoable

Logs records that need to be undoable should implement the Undoable interface. The Undoable interface extends the Redoable interface, thus, undoable log records are by definition redoable as well.

An Undoable log record should contain data that can be used to *redo* the changes, as well as to *undo* the changes. Typically, this means that both old and new values must be stored. For example, if the log is to represent changing a field value from A to B, then its old value will be A, and new value will be B.

At system restart, Undoable records are redone. This means that the redo portion of such log records are applied. In the example given above, this would cause the field value to be set to B.

When the Transaction Manager needs to undo the changes represented by an Undoable record, it will ask the client to perform one of following depending upon the type of Undoable record:

- If the Undoable record is an instance of SinglePageLogicalUndo, then the Transaction Manager assumes that the undo operation must be performed against some page other than the one originally affected. However, the undo is known to affect only one page. In this situation the Transaction Manager requests the client to identify the page to which undo should be applied, and then coordinates the generation of undo as normal.
- If the Undoable record is an instance of LogicalUndo, then the Transaction Manager assumes that the undo operation is not an exact inverse of the redo operation and may require updates to one or more pages. It also assumes that the client may generate additional log records. For such log records, the client is given full control over how the undo is to be performed.
- If neither of above are true, then the Transaction Manager assumes that the Undo operation is *physical*, i.e., it is to be applied to the same page that was affected by the original change. In this case, it requests the client to generate the undo information (Compensation) which is then applied as a redo operation.

Following sections describe above in reverse order.

Physical Undos

The simplest case is that of a Physical Undo, where the undo operation affects the same page that was originally modified during forward change (i.e., redo). In this case, the Transaction Manager asks the client to generate a Compensation record for redoing the undo operation. This is then applied to the affected page using the redo interface provided by the client. Following code shows how the Transaction Manager interacts with the client:

```
Compensation clr = module.generateCompensation(undoable);
....
module.redo(page, clr);
```

Thus, for this type of log record, the client must implement the generateCompensation(Undoable) and redo(Page, Redoable) operations.

SinglePageLogicalUndos

SinglePageLogicalUndos are slightly more complex than Physical undos. The undo operation is guaranteed to affect one page only, but it may not be the page originally affected. To handle this scenario, the Transaction Manager first asks the client to identify the page where the undo is to be applied. Once this has been done, the process is identical to that of Physical undos. Following code extract shows how the TM interacts with the client:

```
BufferAccessBlock bab = module.findAndFixPageForUndo(undoable);
...
Compensation clr = module.generateCompensation(undoable);
...
module.redo(bab.getPage(), clr);
...
bab.unfix();
```

What above shows is that the client is responsible for identifying and fixing the appropriate page – the page is unfixed by Transaction Manager once the change has been applied.

LogicalUndos

From the client's perspective the most complex type of undo is where the undo operation may impact several pages, and may result in additional log records being generated.

For such records, the Transaction Manager simply invokes the client's undo interface as follows:

```
module.undo(trx, undoable)
```

It is the client's responsibility to generate appropriate log records and make changes to database pages.

Comments about implementing undo operations

From the discussion above, it should be clear that Physical undos are the easiest to implement. They are also the most efficient. However, in some cases, notably in Index operations, physical undos may not be optimum. This is because in a BTree Index, a key can move from one page to another as a result of page splits or page merges.

In some BTree implementations, such as in Apache Derby, the undo operations are limited to a single page. This is achieved through the use of *logical key deletes*.

Where keys are physically deleted, undo of key deletes may cause page splits. Such undo operations may impact more than one page. The SimpleDBM BTree implementation is an example of this type of operation.

Compensation records

Undo operations are represented using Compensation log records. The benefits of using Compensation log records are explained in detail by Mohan in the ARIES paper. As Mohan explains in his paper, a Compensation record is redo-only – it is never undone. A unique property of ARIES algorithm is that Compensation log records are linked back to the predecessor of the log record that is being undone. This backward chaining allows ARIES to skip processing of undo operations that are already applied.

While Compensation log records are mostly used to represent undo operations, sometimes, they can be effectively used to represent redo operations as well. The system can make use of the backward chaining to allow certain log records to be skipped in the event of an undo. This feature is the basis for the Nested Top Action concept in ARIES. It is also exploited by the SimpleDBM BTree implementation to reduce the amount of logging required for structure modification operations. For further details, please refer to the paper entitled – `Space Management issues in B-Link trees`.

NonTransactionRelatedOperations

A NonTransactionRelatedOperation is one that should be redone without reference to a database page. Note that such operations are discarded after a Checkpoint, i.e, only those records will be redone that are encountered after the last Checkpoint. Is is therefore important to ensure that the effect of these log records are also saved in Checkpoint operations.

In SimpleDBM, the only use of this operation at present is to log opening of containers. After a container is created, a NonTransactionRelatedOperation is logged to ensure that the container will be reopened at system restart. A Checkpoint operation in SimpleDBM includes a list of all open containers, hence, any past open container log records become redundant after the Checkpoint.

PostCommitActions

PostCommitActions are used to defer certain actions until it is known for sure that the Transaction is definitely committing. In SimpleDBM, dropping a container is handled this way. When a request is made by a client to drop a container, a PostCommitAction is scheduled to occur once the transaction commits.

The Transaction Manager tracks the status of PostCommitActions and ensures that once a transaction has committed, its PostCommitActions are executed even if there is a system crash. This is achieved by logging such actions as part of the transaction's Prepare log record. Note that a PostCommitAction may be executed more than once by the TransactionManager, hence it should be coded in such a way that there is no adverse impact if the operation is repeated. For example, if the action is to delete a container, it would be erroneous for the PostCommitAction to complain if the container is already deleted.

ContainerDeleteOperations

Since an ARIES style Transaction Manager operates at the level of disk pages, it is necessary to know when a container has been deleted so that all pages related to the container can be marked invalid. Also, the container needs to be closed to prevent further changes to it. The Transaction Manager uses the ContainerDeleteOperation interface as a marker interface to identify log records that are going to cause containers to be dropped.

ContainerOpenOperations

The TransactionManager maintains a list of open containers in the checkpoint record. At restart, it needs to identify containers created since the last checkpoint; it does this by tracking any ContainerOpenOperation records. A container is reopened if the ContainerOpenOperation is valid, i.e., it has not been superceded by a later ContainerDeleteOperation.

Space Manager

Introduction

The Space Manager module is responsible for managing free space information within a Storage Container. Using free space information, the Space Manager module can find pages that meet space requirements of clients. The Space Manager module also handles creation of new containers and expansion/deletion of existing containers.

Comparison with Storage Manager module

We have previously encountered the Storage Manager module which provides facilities for creating and dropping specific containers. However, these operations are low-level, and not transactional. Containers created by the Storage Manager module are raw, and do not have any structure.

The Space Manager module implements a higher level interface. It differs from the Storage Manager module in following ways:

- Its operations are transactional.
- Containers have a predefined structure and support fixed-size pages.
- The Space Manager module implements special pages within the container where information about other pages is maintained. This information can be used to quickly locate a page with specified amount of storage.

Operations

Obtaining an instance of SpaceMgr

The default implementation of the SpaceMgr module is org.simpledbm.rss.sm.impl.SpaceMgrImpl. As can be seen in the example below, the SpaceMgr module depends upon a number of other modules.

```
SpaceMgr spacemgr = new SpaceMgrImpl(objectFactory, pageFactory,
  logmgr, bufmgr, storageManager, storageFactory,
  loggableFactory, trxmgr, moduleRegistry);
```

Creating a Container

Following sample code demonstrates how to create a Container. Note that for correct operation, the container ID allocated to the new container should be locked exclusively prior to creating the container. This will prevent other transactions from manipulating the same container.

```
SpaceMgr spacemgr = new SpaceMgrImpl(...);
Transaction trx = trxmgr.begin();
boolean okay = false;
try {
  // Create a new Container named testctr.dat and assign it a container
  // ID of 1. This container will use RawPages as its data page.

  int containerId = 1;
  int spaceBits = 1;
  int extentSize = 64;
  spacemgr.createContainer(trx, "testctr.dat", containerId,
     spaceBits, extentSize, pageFactory.getRawPageType());

  okay = true;
}
finally {
  if (okay) {
     trx.commit();
  }
  else {
     trx.abort();
  }
}
```

Note that the container create operation is transactional.

Extending a Container

When a container is initially created, it is allocated an extent of specified size. The extent is the minimum allocation unit for a container; a container is always expanded in extents.

```
Transaction trx = trxmgr.begin();
spacemgr.extendContainer(trx, 1);
trx.commit();
```

Deleting a container

Note that prior to deleting a container, you must acquire an Exclusive lock on the container ID. This will prevent other transactions from accessing the same container.

Deleting a container is as simple an operation as extending it:

```
Transaction trx = trxmgr.begin();
spacemgr.dropContainer(trx, 1);
trx.commit();
```

An important point to note about the container delete operation is that the physical removal of the container is deferred until the transaction commits. This is done to allow the delete operation to be rolled back in case the transaction aborts.

A limitation in the current implementation is that the container is not physically removed. This will be fixed in a future revision of the module.

Searching for free space

At the time of creating a container, you can specify the number of bits that should be used to track space information for each individual page. At present, you can either use a single bit or two bits. If one bit is used, the possible values are 0 and 1, if two bits are used, then the possible values are 0, 1,2 and 3. The SpaceMgr module initializes the space bits with a value of 0, hence this value always means unused or unallocated space. The interpretation of other values is upto the client; SpaceMgr merely provides the mechanism to maintain this data.

As an example, in the BTree module, containers are created with a single bit for each page. The value 0 is used to identify unallocated pages, 1 is used for allocated pages.

In order to search for free space, you first need to obtain a SpaceCursor. The SpaceCursor mechanism allows you to perform following actions:

- Search for page with specified space usage, and fix associated space map page exclusively.
- Update the space map information for a page, and log this operation.
- Fix a specific space map page.
- Unfix the currently fixed space map page.

When you search for free space, you need to provide an implementation of `SpaceChecker`; this will be invoked by SpaceMgr module to check whether a page meets the space requirements of the client.

Here is an example of a search that attempts to locate pages that are unallocated:

```
int pageNumber = spaceCursor.
     findAndFixSpaceMapPageExclusively(new SpaceChecker() {
  public boolean hasSpace(int value) {
     return value == 0;
  }
});
```

If the SpaceCursor cannot locate a suitable page, it returns -1. Otherwise it returns the page that satisfied the space request.

An important point to note is that just because space map information indicates that the page has free space, does not always mean that the page will be able to satisfy the request. Some modules, such as the TupleMgr module, may mark pages as free even though they are still occupied. Please refer to the TupleMgr documentation to understand why this is so. In general, it is upto the client module to ensure that the space map information is accurate and up-to-date.

Usually, if the space map search returns -1, the container needs to be extended and then the search retried.

Updating space information

A successful search will result in the space map page being exclusively latched. Hence, after the search, the client must unfix the page. Failure to do so will cause pages to remain fixed and exhaust the Buffer Pool. The SpaceCursor interface provides an interface for unfixing the currently fixed space map page.

```
Transaction trx = trxmgr.begin();
spaceCursor.updateAndLogRedoOnly(trx, pageNumber, 1);
spaceCursor.unfixCurrentSpaceMapPage();
trx.commit();
```

Above example also shows how to update the space map page information and also log it to the Write Ahead Log.

There will be times when the client wishes to update the space information for a specific page. In this situation it is the client's responsibility to know which space map page contains the associated data.

The SpaceCursor interface supports accessing a specific space map page, provided it is known which page is desired:

```
Transaction trx = trxmgr.begin();
SpaceCursor spcursor = spaceMgr.getSpaceCursor(containerId);
spcursor.fixSpaceMapPageExclusively(spaceMapPageNumber,
  pageNumber);
try {
  pcursor.updateAndLogRedoOnly(trx, pageNumber, spacebits);
} finally {
  spcursor.unfixCurrentSpaceMapPage();
}
trx.commit();
```

Slotted Page Manager

Introduction

SimpleDBM, like most other databases, stores records in fixed size pages. The Slotted Page Manager module provides an enhancement to the Raw Page by allowing records to be inserted, updated and deleted within the page. By providing a common infrastructure, client modules such as the B-Tree Manager or the Tuple Manager can concentrate on higher level functions.

Structure of Slotted Page

From the client perspective, the structure of the Slotted Page is not relevant in its details. What matters is the interface. A key requirement is to be able to access records quickly within the page, using a numeric identifier called Slot Number.

Each record in the page is assigned a Slot Number. Slot Numbers start from 0, ie, the first record in the page can be accessed via Slot Number 0.

In addition to storing the record data, each Slot is also capable of storing a set of flags in a Short integer. The interpretation of these flags is up to the client module.

Records may be inserted at a specific Slot position, updated and deleted. Deleted records leave the Slot unoccupied, but do not shift records. A purge interface is available which completely removes the record specified and also shifts to the left all records to the right of the purged record.

Obtaining instances of Slotted Page

The actual implementation of the Slotted Page is not visible to the outside world. The Slotted Page Manager module *registers* the implementation of SlottedPage to the Object Registry. This enables client modules to obtain new instances of SlottedPage without having to know how this is implemented. Following snippet of code illustrates this:

```
SlottedPageMgr spmgr = new SlottedPageMgrImpl(objectFactory);
SlottedPage page = (SlottedPage)
  pageFactory.getInstance(spmgr.getPageType(), new PageId());
```

Note that the PageFactory is able to instantiate the appropriate Page type using the typecode (`spmgr.getPageType()`) assigned to the implementation by the SlottedPageManager module.

In most cases, clients do not actually invoke the PageFactory as shown above. Instead it is more common to specify the page type when a container is first created; this ensures that the Buffer Manager module can instantiate the correct page type automatically. Here is an example of how to do this:

```
// Create the container and specify SlottedPage as the page
// type.
spaceMgr.createContainer(trx, name, containerId, spacebits,
  extentSize, spmgr.getPageType());

// Fix page 5
BufferAccessBlock bab =
  bufmgr.fixExclusive(new PageId(containerId, 5), false, -1, 0);

// Get access to the page.
SlottedPage page = (SlottedPage) bab.getPage();
```

In the example above, the Space Manager module formats all data pages in the specified container as SlottedPage. This ensures that when the client module accesses the page via the Buffer Manager, the correct page type is automatically instantiated.

Inserting or updating records

The SlottedPage interface supports two insert modes. In the replace mode, the new record will replace any existing record at the same Slot. If replace mode is false, the new record will cause existing records to be shifted to the right to make space for the new record.

```
boolean replaceMode = false;
// Insert item1 at Slot 0
page.insertAt(0, item1, replaceMode);
// Insert item0 at Slot 0
page.insertAt(0, item0, replaceMode);
// Now item1 is at Slot 1
```

When invoking `SlottedPage.insertAt()`, the SlotNumber must be between 0 and `SlottedPage.getNumberOfSlots()`.

Deleting records

As mentioned before, there are two types of delete. The first type removes the record but does not disturb the Slot Numbers. Example:

```
// Insert at slot 0
page.insertAt(0, item0, true);
// Insert at slot 1
page.insertAt(1, item1, true);
// Delete slot 0
page.delete(0)
// Slot 1 still holds item1
```

The second mode is called purge, and in this mode, records to the right of the deleted Slot are moved left to fill up the hole. Example:

```
// Insert at slot 0
page.insertAt(0, item0, true);
// Insert at slot 1
page.insertAt(1, item1, true);
// Delete slot 0
page.purge(0)
// Slot 0 now holds item1
```

Accessing records

The `SlottedPage.getNumberOfSlots()` method returns the number of slots in the page. To access a slot, you invoke `SlottedPage.get()`; you must supply the correct `Storable` object type as the second parameter.

```
// Get the record at Slot 1 as a StringItem.
page.get(1, new StringItem());
```

Miscellaneous operations

It is possible to assign to each Slot a set of flags. Upto 16 bits can be accomodated.

```
// Get the flags for Slot 0
int flags = page.getFlags(0);
// Update the flags for Slot 0
page.setFlags(0, (short)(flags | 1));
```

The total number of Slots in the page is returned by the method `getNumberOfSlots()`. To test whether a particular Slot is deleted, you can use the method `isSlotDeleted()`. There are a few methods that provide space usage data.

Index Manager

Overview

The Index Manager module is responsible for implementing search structures such as BTrees. Indexes are used to enforce primary key constraint and unique constraints in tables, as well as for ensuring speedy retrieval of data.

Challenges with B-Tree Concurrency

It is challenging to implement a B-Tree that supports high concurrency and is also recoverable. The problem occurs because B-Tree traversals occur top-down, whereas the tree grows bottom-up using page splits that are propagated up the tree.

In the following discussion, the term SMO is used to refer to modifications to a B-Tree that causes the Tree's structure to change. By structure we mean the relationships that exist between the nodes in the tree, such as parent- child and sibling relationships.

The key ideas that enable concurrent updates to B-Trees are:

1. Short term locks must be used to prevent interactions between concurrent updaters and traversers to ensure that each process gets a structurally consistent (but not necessarily the same) view of the B-Tree. A considerable amount of research has been devoted to ways of reducing the scope of locking to increase concurrency. Worst case is that the entire Tree must be exclusively locked during an SMO.
2. In B+Tree trees (a variation of B-Tree), all keys are maintained in the leaf pages and the index nodes act as navigation aids. In such trees, completed structural changes to the B-Tree need not be undone even when transactions that initiated them roll back. Only incomplete structural changes must be undone because they will corrupt the B-Tree.
3. Although structural updates occur bottom up, locking must always be top-down. Maximum concurrency is obtained when structural changes can be propagated bottom-up without obtaining locks at multiple levels of the tree.

Survey of algorithms

A popular approach to improving concurrency is based on locking subsets of the Tree top-down during an SMO. For example, if it becomes necessary to split a page, the program gives up any locks on the page to be split, and traverses down the tree from root, obtaining exclusive locks on nodes while moving down the tree. If a node is encountered which is "safe", i.e., has sufficient space for accomodating a split key, then locks on higher level nodes may be released. This process continues until the leaf node is found that is to be split. In the worst case scenario the entire path from the root node to the leaf node will be locked exclusively. Having obtained all the locks, the inserter can proceed splitting the leaf node and propagating the change up the tree.

An undesirable feature of this method is that locks are obtained at multiple levels of the tree, which is bad for concurrency.

ARIES/IM *[MOHA-92]* algorithm tries to avoid locking pages at more than one level simultaneously. SMOs are performed bottom-up rather than top-down for maximum concurrency, but a Tree Lock is used to serialize SMO operations. This means that only one SMO operation can be active at any point in time, but operations that do not cause SMOs, can proceed concurrently. The ARIES/IM algorithm supports key deletions and node consolidations.

Several other approaches to the problem of concurrency in B-Trees are based on the seminal work done by Lehman and Yao in *[LEHMAN-81]*. The B-Link tree structure described by Lehman and Yao has following features:

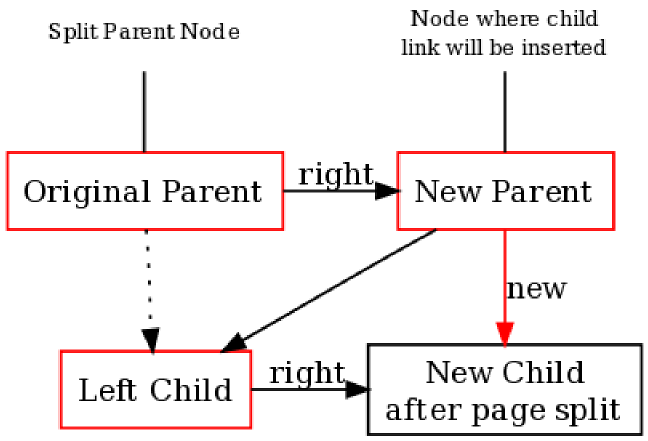
- Nodes are linked to each other from left to right at each level of the Tree.

- Each key in an index node has an associated child pointer which points to a subtree containing keys that are guaranteed to be less or equal to the key value.
- Leaf nodes have an extra key that is known as the *high key* - all keys in the leaf node are guaranteed to be less or equal to the high key.
- The algorithm does not support consolidation or deletion of nodes. Once created, the nodes continue to exist. Key deletes are handled by simply removing keys from the leaf nodes - hence the need for a *high key* as an upper-bound for the key-range within a leaf node. Leaf nodes are allowed to become empty (except for the high key which can never be deleted).
- Page splits always result in a new sibling to be created on the right.
- Page splits always update the sibling pointer first, before updating the parent node. The page split and the sibling pointer update is handled as an atomic action to ensure that no two processes can ever see the Tree in a state where two adjacent nodes are not linked in this way.

The main idea is that while an a page split is in progress, there is a short time window during which the parent lacks a pointer to the newly allocated child node. During this time window, the newly allocated node can be reached via the sibling node to its left.

During navigation, if the search key exceeds the highest value in the node, it indicates that the tree structure has changed, and the traversal must move right to the sibling node to find the search key.

The concurrency of a B-link Tree is improved because in the worst case only three nodes need to be locked during a page split, and page splits are propagated bottom-up rather than top-down.



The diagram above shows the worst case locking, when original parent node, its new sibling, and the left child are all locked before the new link to the right sibling is inserted.

Limitations of Lehman and Yao B-link Trees

Lehman and Yao assumed that each process that accesses a node would read its own copy of the page. In most DBMS implementations, this is not true. Pages are shared between processes via the Buffer Manager. Therefore readers must lock pages in shared mode before accessing them.

Deletions do not support merging of nodes because when propagating a key split up the tree, the algorithm relies on always being able to move right from the current parent node to find the correct node where the child link and split key needs to be inserted.

Suggestion is to use offline process that locks the entire tree in order to compact the tree.

The algorithm does not consider recovery.

Recoverable B-Link Trees

The individual page split operations in a B-Link Tree can be made atomic by using the nested top action features of ARIES. These atomic actions must be independent of regular transactions and must not be undone even if the transaction that triggered them is aborted.

The difficult bit is to ensure that the parent nodes are properly updated even if there is a system crash, say between the split occuring at leaf level and it being propagated to the level above.

In *[DAVI-92]*, the authors provide a solution to this problem. During tree traversals, it is possible to detect that a node lacks a pointer to it from the parent. When this is detected, an action can be initiated to add the missing link into the parent node.

B-Tree algorithm in Apache Derby

In Apache Derby, when an inserter finds during a page split that that it is unable to promote the discriminator key into the parent node because the parent node is full, it releases all locks, and starts a new traversal from the root, splitting all nodes that are too full to accomodate the discriminator key. This is done top-down, and may esult in moe page splits that needed, but the assumption is that the nodes would have to be split eventually anyway.

SimpleDBM B-link Tree

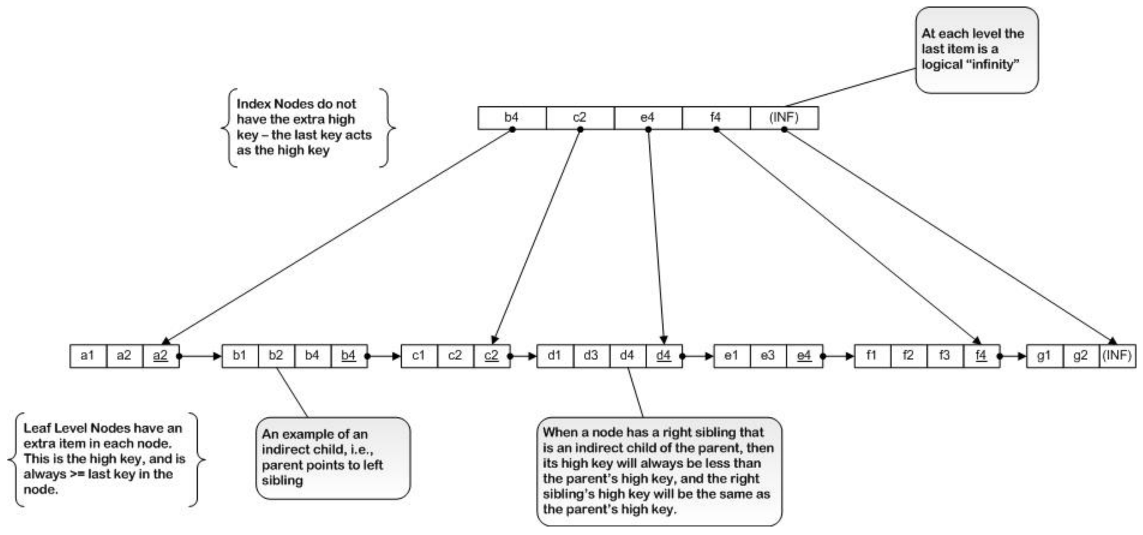
SimpleDBM currently provides a B-Link Tree Index implementation, based upon algorithms described in *[JALUTA-05]*. These algorithms combine the idea of short atomic actions, as in *[DAVI-92]*, with top-down detection and correction of page overflow and underflow conditions. Unlike previous algorithms, these algorithms handle deletes uniformly as inserts, and automatically merge nodes as they become empty.

There are some variations from the published algorithms, noted at appropriate places within the code, and described below.

Structure of the B-link Tree

The tree is contained in a container of fixed size pages. The first page (pagenumber = 0) of the container is a header page. The second page (pagenumber = 1) is the first space map page. These pages are common to all containers that are managed by the Free Space Manager module.

The third page (pagenumber = 2) is allocated as the root page of the tree. The root page never changes.

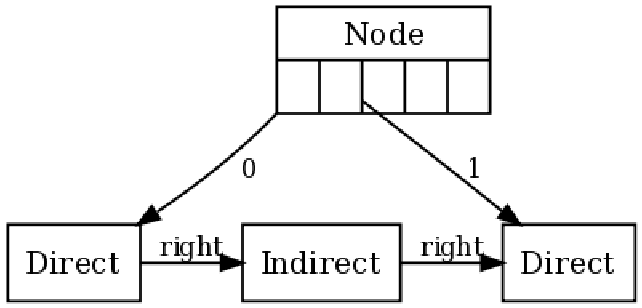

At each level the last item is a logical "infinity"
Index Nodes do not have the extra high key – the last key acts as the high key
b4
c2
e4
f4
(INF)
a1
a2
a2
b1
b2
b4
b4
c1
c2
c2
d1
d3
d4
d4
e1
e3
e4
f1
f2
f3
f4
g1
g2
(INF)
Leaf Level Nodes have an extra item in each node. This is the high key, and is always >= last key in the node.
An example of an indirect child, i.e., parent points to left sibling
When a node has a right sibling that is an indirect child of the parent, then its high key will always be less than the parent's high key, and the right sibling's high key will be the same as the parent's high key.

Pages at all levels are linked to their right siblings. In leaf pages, an extra item called the high key is present. In index pages, the last key acts as the highkey. All keys in a page are guaranteed to be <= than the highkey. Note that in leaf pages the highkey may not be the same as the last key in the page.

The reason for the extra high key in leaf pages is that the high key defines the key space contained within the leaf page, and does not change when the keys within the leaf page are deleted. The highest key in the leaf page cannot be used as the high key because the high key can only change through page split, redistribute or merge (SMO) activities, whereas the highest key may be deleted outside of these operations, for example, as part of a delete key operation.

In index pages, each key is associated with a pointer to a child page. The child page contains keys <= to the key in the index page.

A direct child can be accessed from the parent by following a child pointer. An indirect child is accessed via the direct child's right sibling pointer.



The highkey of the child page will match the index key if the child is a direct child. The highkey of the child page will be < than the index key if the child has a sibling that is an indirect child.

All pages other than root must have at least two items (excluding the highkey in leaf pages).

The root node is allowed to have a right sibling. Eventually, such a situation is resolved by increasing the tree's height. See *Increase Tree Height Operation* for more information.

The rightmost key at any level is a special key containing logical INFINITY. Initially, the empty tree contains this key only. As the tree grows through splitting of pages, the INFINITY key is carried forward to the rightmost pages at each level of the tree. This key can never be deleted from the tree.

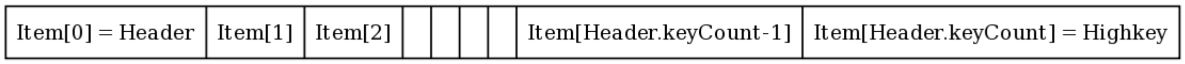
Structure of Nodes

Overview

Nodes at each level of the tree are linked from left to right. The link of the rightmost node at a particular level is always set to null.

Leaf Nodes

Leaf nodes have following structure:



```
[header] [item1] [item2] ... [itemN] [highkey]

item[0] = header
item[1,header.KeyCount-1] = keys
item[header.keyCount] = high key
```

The highkey in a leaf node is an extra item, and may or may not be the same as the last key [itemN] in the page. Operations that change the highkey in leaf pages are Split, Merge and Redistribute. All keys in the page are guaranteed to be <= highkey.

Index Nodes

Index nodes have following structure:

```
[header] [item1] [item2] ... [itemN]
item[0] = header
item[1,header.KeyCount] = keys
```

The last key is also the highkey. Note that the rightmost index page at any level has a special key as the highkey - this key has a value of INFINITY.

Each item in an index key contains a pointer to a child page. The child page contains keys that are <= than the item key.

Limits

The largest key cannot exceed 1/8th size of the page. The published algorithm requires a key to be smaller than 1/6th of a page.

Each page other than root must have at least two keys.

Key Differences from published algorithm

Support for Non-Unique indexes

The published algorithm assumes a unique index. SimpleDBM implementation supports both unique and non-unique indexes. In non-unique indexes, a key/location pair is always the unit of comparison, whereas in unique indexes, only key values are used. There are some differences in how locking is handled for a unique index versus a non-unique index.

Handling of storage map

The published algorithm assumes a single page 0 that contains a bit vector showing the allocated/unallocated status of all pages. In SimpleDBM implementation space allocation is managed using free space pages which are arranged in a linked list and are dynamic.

There is an important concurrency improvement related to handling of the space map. See *[DIBY-05]* for further details.

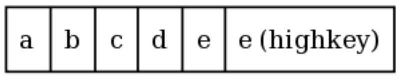
Variable length keys

The implementation differs from the published algorithm in how it determines whether a page is "about to underflow" or "about to overflow". It considers any page with minimum keys (1 for root, and 2 for all other pages) as about to underflow. It checks the available space for the key being inserted to determine whether the page is about to overflow.

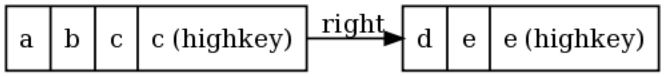
Page Split operation

A page split operation takes a node and splits it into two. A new node is allocated and linked to the old node. This is shown in the example below.

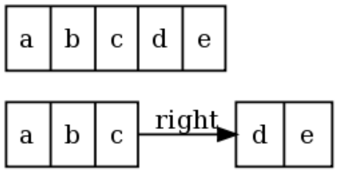
Here's an example of a leaf node. Note the presence of the extra high key.



When the node is split, the keys are divided between the old node and a newly allocated node. The old node's right field is set to point to the newly allocated right sibling. Note that the high key changes in the old node and is set to be the same as the highest key in the node. This may later on change as keys are deleted from the node.



The splitting of an index node is similar, except that the extra high key is not present.



The Split Operation differs from the published algorithm in following ways:

1. Page allocation is logged as redo-undo.
2. Space map page latch is released prior to any other exclusive latch.
3. The split is logged as Muli Page Compensation record, with undoNextLsn set to the LSN prior to the page allocation log record.
4. Information about space map page is stored in new page.
5. The total space occupied by keys as an indicator of key space. For example, when finding the median key, SimpleDBM sums up key lengths to decide where to split.

When implementing the Split operation it became necessary to enhance the transaction manager to support multi-page redo records - ie - one redo record containing data for multiple pages. The published ARIES algorithms do not cater for this.

The published algorithm does not state this requirement but assumes that the transaction manager supports multi-page redo.

Merge Operation

The Merge Operation is the opposite of the Split operation. It joins two existing nodes to create a single node.

The implementation differs from published algorithm in its management of space map update. In the interests of high concurrency, the space map page update is handled as a separate redo only action which is logged after the merge operation.

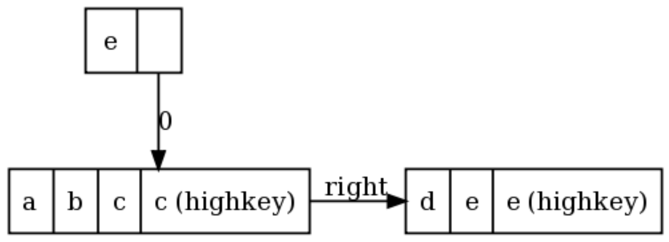
If this space map update log record does not survive a system crash, then the page will end up appearing allocated. However the actual page will be marked as deallocated, and hence can be reclaimed later on, although this is not implemented.

The Merge Operation is logged as a Multi-Page Redo only record.

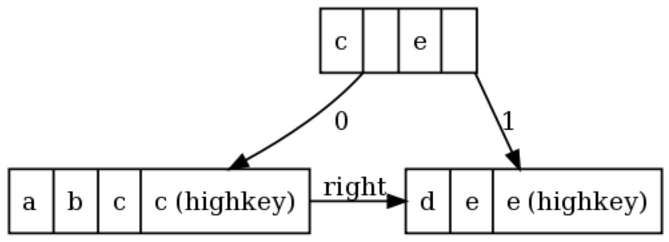
Link Operation

The Link Operation creates a link from a parent node to a child node. Following diagrams illustrate the link operation.

Before the link operation:



After the link operation:



The implementation differs slightly from the published algorithm. The psuedo code for the implementation is shown below.

```
v = highkey of RightNode
u = highkey of LeftNode
Link(ParentNode, LeftNode, RightNode) {
  upgrade-latch(ParentNode);
  n = new index record (u, LeftNode.pageno);
  lsn = log(<unlink, ParentNode, n, LeftNode.pageno, RightNode.pageno>);
  find index record with child pointer = LeftNode.pageno in ParentNode;
  change the child pointer of above to RightNode.pageno;
  insert new index record n before above index record.
  ParentNode.pageLsn = lsn;
  downgrade-latch(ParentNode);
}
```

Unlink Operation

The Unlink Operation is the reverse of the Link operation.

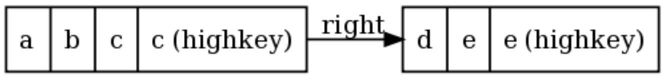
The implementation differs slightly from the published algorithm. The psuedo code is shown below.

```
Unlink(ParentNode, LeftNode, RightNode) {
  upgrade-latch(P);
  lsn = log(<unlink, ParentNode, LeftNode.pageno, RightNode.pageno>);
  in ParentNode delete the index record with child pointer
     set to LeftNode.pageno;
  change the child pointer of next index record to LeftNode.pageno;
  ParentNode.pageLsn = lsn;
  unfix(ParentNode);
}
```

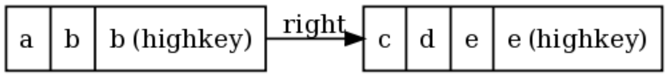
Redistribute Keys Operation

The implementation of this differs from the published algorithm. It moves one key from the overpopulated node to the sibling node, rather than evenly redistributing the keys across the two nodes.

For example, before the Redistribute Operation:



After the Redistribute Operation:



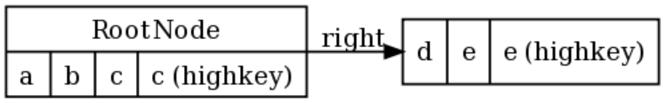
The Redistribute Key operation is logged using a Multi-Page redo only log record.

Increase Tree Height Operation

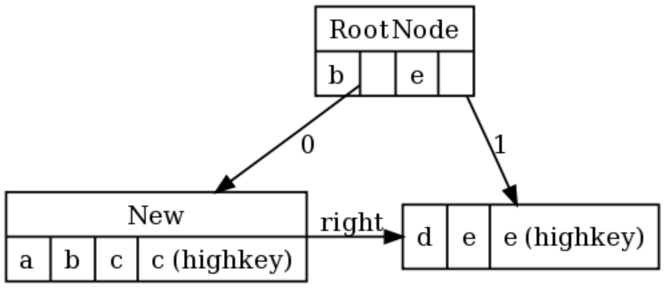
The Increase Tree Height Operation is used to raise the height of the tree. For this to occur, the root must have been split previously and therefore must have a right sibling.

During this operation, a new node is allocated and the contents of the rooot node copied to this new node. The root node is then re-initialized to contain pointers to the new node as its left child and the old right sibling as its right child.

For example, let us consider the following:



This is how it appears after the Increase Tree Height Operation:



The implementation differs from the published algorithm in following ways:

1. Page allocation is logged as redo-undo.
2. Space map page latch is released prior to any other exclusive latch.
3. The Increase Tree Height operatopn is logged as Muli Page Compensation record, with undoNextLsn set to the LSN prior to the page allocation log record.
4. There is no need to format the new page as pages are formatted when they are first created.

Decrease Tree Height Operation

This differs from the published algorithm.

To increase concurrency, the space map page update is logged after the SMO as a separate redo only action. This improves concurrency because the space map page latch is not held exclusively during the SMO. However, it has the disadvantage that if the SMO survives a system crash, and the log for the space map page updates does not survive, then the page will remain allocated on the space map, even though it is no longer in use. It is posible to identify deallocated pages by checking the page flags for the BTreeNode but this is not implemented.

The Decrease Tree Height Operation is logged as Multi Page Redo only log record.

Index Scans

The published algorithm only considers the SERIALIZATION lock isolation mode, but the implementation supports other lock modes. There are differences in when and where locks are acquired and released under various modes.

Simplified Algorithm for Scans

The published algorithm has a complex fetch and fetchnext logic, and attempts to handle both > and >= operators. The implementation does not allow the operator to be specified. It automatically uses >= for the first fetch, and then > than current key for subsequent fetches.

The code for next key locking code is simplified. We don't do all the checks that are in the published algorithm. This means that there is a greater chance that the tree will be rescanned.

The published fetch algorithm does not cater for UPDATEABLE cursors. In general, the paper assumes that the B-Tree is standalone, and contains data records. In SimpleDBM, and in most DBMS implementations, a B-Tree index is a redundant structure - leaf pages contain pointers to data records. The published algorithms are not always the best fit for this. For example:

1. The algorithm suggests locking current key and next key during Inserts and Deletes. In a DBMS, the current key is already locked when an Insert or Delete is issued.
2. In a DBMS a fetch cursor is also used in UPDATE mode. For example, when a DELETE or UPDATE SQL statement is issued, the records must be fetched using UPDATE locks. Then the lock is upgraded to EXCLUSIVE, and the key is deleted. In this scenario, we need to cater for the fact that the current key may be deleted. Therefore, when the fetch next call is issued, the cursor must be able to detect that the key does not exist and rescan. These issues are discussed in detail in *[MOHA-02]*.

SimpleDBM does not implement the optimizations described in [MOHA-02]. Therefore, supposing all keys are deleted during the index scan, after the first page, every delete will cause the tree to be scanned from root to leaf. This can be avoided by using the technique described by Mohan.

Simpler page modification checks

The implementation uses a simpler check to determine whether the page has changed since last it was latched. This may cause unnecessary traversals from root node.

B-Tree index is a secondary structure

Unlike the published algorithm, where the B-Tree index holds the database records in the leaf nodes, the implementation stores pointers (Locations) to tuples (table rows).

Tuple Manager

Overview of Tuple Manager

The Tuple Manager module provides a low-level interface for managing persistence of table rows. It is low-level in the sense that this module has no knowledge of what is contained in a table row. I use the term tuple instead of table row, but even this is not the right term, as a tuple means a collection of attributes.

To the Tuple Manager, tuples are just blobs of data that can span multiple pages. When a tuple is inserted for the first time, it is assigned a unique Location, which is really an abstraction of the ROWID concept in other databases. The Tuple Manager module implements the Location interface, but other modules do not need to know anything about the internal structure of these objects.

Like B-Tree indexes, tuples are stored in containers. A container that is specialized for storing tuples is called a Tuple Container. By design, only one type of tuple may be stored in a particular container. In a higher level module, a tuple can be mapped to a table row, and the container to a table.

The interface of Tuple Manager is made generic by ensuring that it knows very little about tuples. Unfortunately, this means that tuple updates cannot be handled efficiently, specially with regards to logging, as the contents of the both before and after images of the tuple must be logged. A possible optimisation would be to use some form of binary diff algorithm to generate a change vector, and store the change vector only in the log record. Another way is to allow a callback method to calculate the difference between the old and the new tuple.

Design Decisions

Some of the implementation decisions are given below:

Tuple Inserts

Tuple inserts are done in two stages. In the first stage, a new Location is allocated and locked exclusively. Also, the tuple data is inserted into the first page that will be used by the tuple. The rest of the tuple data is inserted in the second stage. The rationale for splitting the insert into two stages is to allow the client to perform other operations in between, such as creating Index keys.

Tuple Segmentation

If a tuple is too large to fit into one page, it is broken into chunks of `TupleManagerImpl.TupleSegment`. Each segment is inserted into a page, and the segments are linked together in a singly linked list. Since the segments are inserted in order, in the first pass the links are not set, and the implementation has to revisit all the pages and update the links between the segments. The last segment/page does not require an update.

At the time of insert, the implementation tries to allocate as much space as possible on each page. When a page is visited, an attempt is made to reclaim any deleted segments within the page.

Tuple Deletes

Deletes are logical, ie, the Tuple Segments are marked with a logical delete flag. Space Map information is updated immediately, however. During deletes, the links between the segments of a tuple are broken. This is because the link is reused to store the tuple's Location. Thus, it is possible to determine the Location of a tuple from any of the deleted segments. This is important because the tuple reclamation logic uses locking to determine whether a logically deleted tuple can be physically removed.

If the delete is undone, the links are restored.

Tuple Updates

When tuples are updated, existing segments are updated with new data. If the new tuple is longer than the old tuple, then additional segments are added. The `TupleInserter#completeInsert()` interface is reused for this purpose. No attempt is made to change the size of existing segments, even if there is additional space available in the page. This is to keep the algorithm simple. Also, segments are never released, even if the new tuple has become smaller and does not occupy all the segments.

Note that due to the way this is implemented, more than one segment of the same tuple can end up in the same page.

Since the structure of the tuple is opaque to this module, updates are not very efficiently handled. Current implementation logs the full before and after images of the tuple being updated. In future, this needs to be made more efficient by using some mechanism to calculate the difference between the old tuple and the new.

Space Reclamation

Space used by deleted tuples is reclaimed when some other transaction visits the affected page and tries to use the space. Locking is used to determine whether the delete was committed. The actual physical removal of the tuple segments are logged. Note that this method of determining whether a segment can be released is conservative and sometimes results in segments being retained even when they are no longer required. Why this happens will become clear with an example. Suppose that a tuple that has 4 segments is deleted. Each segment is marked deleted. Now, some transaction creates a new tuple, reusing the Location of the deleted tuple. However, the new tuple may not reuse all the segments used by the old tuple, in fact, only the first segment is guaranteed to be reused. As a result of the tuple insert, the Location gets exclusively locked. If this transaction or any other transaction encounters the remaining segments that are marked deleted, the reclamation logic will incorrectly assume that the delete is still uncommitted, because the lock on the location will fail. The segments wil get eventually reused, when the transaction that locked the tuple commits.

Tuple Segment Structure

Each Tuple segment contains three fields.

nextPageNumber Used only in segmented tuples. Normally, points to the location of next segment. If a tuple is deleted, this is updated to the page number of the first segment.

nextSlotNumber Used only in segmented tuples. Normally, points to the location of next segment. If a tuple is deleted, this is updated to the slot number of the first segment.

data Data in this segment.

Free Space Information

Both BTrees and Tuple Containers need free space management. By free space management we mean the process of identifying pages where new data can go. In the case of B-Trees, SimpleDBM uses space map pages that use one bit per page. This is okay, because in a BTree, a page is either allocated or not.

In case of Tuple Containers, I am using space map pages that use two bits to store the space information for a single page. This means that we can track the following states: full (3), two-thirds full (2), one-third full (1), and empty (0). Initially pages start out empty, but when they are used, their status changes as required.

There are a couple of issues related to space management that merit discussion. Unfortunately, there are very few papers that go into all the details. Couple of very useful papers are *[MOHA-94]* and *[CAREY-96]*.

The first issue is how to handle deletes. There are two options.

The first option is to delete a tuple physically and update space map page to reflect the change. However, this poses the problem that if the transaction aborts and the tuple needs to be restored, then the restore will fail if some other transaction uses up the released space in the meantime. To prevent this, some extra information needs to be stored in the page to indicate that although the tuple has been deleted, its space is reserved, and cannot be used by any other transaction. One possible approach is to store the transaction id and the amount of space reserved using the space previously occupied by the tuple. If the tuple occupied more than one page, then space must be reserved on all affected pages, since otherwise, when the tuple is to be restored, the pages may no longer have space to hold the tuple data. If logical undo is implemented, then it is possible to avoid reserving space in pages other than the first page, because a logical undo will allow new pages to be commissioned if necessary to accomodate the restored tuple. Since the tuple's unique id (Location) is bound to the first page, this page must always have space available for the tuple to be restored.

If as suggested above, the space map information is updated as soon as the tuple is deleted, then other transactions looking for free space may end up visiting the pages that have been affected by the tuple delete. However, those transactions may discover when they access the page, that space is not actually available. As a solution to this problem, the space map page update could be deferred until the tuple delete is known to have been committed. However, this would be inefficient, as the transaction that performs the delete will have to visit all pages affected by deleted tuples at commit time, and update the free space map information for these pages.

The space map update could also be delegated to the next transaction that needs the space. The problem with this is that if the page remains marked as fully allocated, then no other transaction will visit that page unless the tuples on the page need to be updated. There is the risk that the tuple space will never be reclaimed.

The problem of unnecessary visits to a page containing reserved space can be avoided by techniques described in *[CAREY-96]*. This involves maintaining a cache of recently used pages and avoiding scanning of the free space map as long as there is candidate page available in the cache. When a page is affected by a tuple delete, it is added to the cache provided that its total free space, including the space reserved for deleted tuple, is greater than the fullest page in the cache. If a transaction visits such a page and is unable to use the reserved space, it removes the page from the cache.

In summary then, the preferred option appears to be to update the space map information as soon as the tuple is deleted.

Physically deleting tuples affects the amount of logging that must be performed. Since the tuple's data is removed, the log must contain the entire contents of the deleted tuple. Similarly, when undoing the delete, the Compensation log record must again contain the full content of the tuple. Thus the tuple data gets logged twice potentially, once when the delete occurs, and again if the transaction aborts.

This brings us to the second option, which is to use logical deletes. In this solution, the tuple remains as is, but is marked as deleted. No space reservation is needed, as the tuple still exists. The space map information is updated as before, that is, at the time of tuple being deleted. Using logical deletes makes undo of such deletes a simple matter of resetting the deleted flag. Logging overhead is substantially reduced.

With logical deletes, however, none of the space can be released prior to the transaction commit. In contrast, with physical deletes, if logical undo is implemented, at least some of the space can be immediately released.

Whether logical or physical deletes are used, in both cases, we still have the issue of how to inform other transactions that the tuple space is still needed. In both cases, the solution is the same. The Lock Manager can be used to ascertain whether the deleted tuple is still locked. If not, then the transaction can infer that tuple delete has been committed. The Lock Manager solution works even if the ID of the transaction that deleted the tuple is unknown, as it relies upon the tuple's Location only. If each tuple is tagged with the ID of the last transaction that updated the tuple, then it would be possible to directly query the transaction table for the status of the transaction. However in this case, the system would have to maintain the status of all transactions, even those that have committed or aborted. SimpleDBM maintains the status of only active transactions, and also does not tag tuples with the IDs of transactions. Hence, it is appropriate to use the Lock Manager solution in SimpleDBM.

Latch Ordering

If both data page and free space map page need to be updated, then the latch order is data page first, and then free space map page while holding the data page latch.

Logging of Space Map Page updates

As per *[MOHA-94]*, space map pages should be logged using redo only log records. During normal processing, the data page update is logged first followed by the space map page update. During undo processing, the space map page update is logged first, followed by data page update. Note that this does not change the latch ordering.

CHAPTER 7

Space Management in B-Link Trees

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Abstract Space management operations can drastically reduce the concurrency of B-link tree structure modification operations. This paper examines some of the issues and potential remedies.

Introduction

The B-link tree algorithms described in *[IBRA-05]* require that during certain structure modification operations (SMOs), the space map page be latched exclusively for the duration of the SMO. This is required for the Split, Merge, Increase-tree-height and Decrease-tree-height operations. It is assumed that there is a single space map page M that contains a bit vector describing which pages are allocated and which are unallocated.

The problem with latching the space map page exclusively during SMOs is that it effectively serializes all SMOs. If, as the paper describes, only one space map page is used, then the effect is global. However, if we assume a design where space allocation data is maintained in a number of space map pages, each containing a bit vector for a range of pages, then the impact is restricted to the range covered by the space map page in question. Even with this concession, the impact on concurrency is likely to be severe, as a single space map page of 8K size can hold allocation data for upto 64k pages.

It is desirable therefore to reduce the time for which the space map page is exclusively latched.

Operation	Number of pages latched exclusively	Space Map Page latched
Split	2	Yes
Link	1	No
Unlink	1	No
Merge	2	Yes
Redistribute	2	No
Increase-tree-height	2	Yes
Decrease-tree-height	2	Yes

Using Nested Top Actions

To avoid having to latch the space map page exclusively at the same time as other pages, one option is to break down each SMO into two steps. In case of SMOs involving page allocation, the page allocation step is logged first, followed by the SMO itself. In case of SMOs involving page deallocation, the SMO is logged first, followed by the page deallocation. To make the action atomic, these need to be logged as redo-undo records, followed by a Dummy Compensation log records *[MOHA-92]*.

The problem with using the nested top action approach is that it negates the benefits of using single redo-only log records. Each operation requires a redo-undo log record, as it must be possible to undo the SMO should it not complete successfully.

Separate (de)allocation steps

Another option is to separate the page allocation and deallocation steps into discrete atomic actions. This improves concurrency while retaining the simplicity of the original design, i.e., it allows SMOs to be logged using single redo-only log records. However, it introduces the problem that if the system fails between the page allocation and the SMO, or between the SMO and the page deallocation, then the space map information may incorrectly show some pages as allocated even though they are not part of the B-link tree. It is worth noting here that the discrepancy in the space allocation map does not impact the correctness of the B-link tree structure, it merely leads to some wasted space. As such, this may be an acceptable solution in many cases.

Proposed solution

Ideally we would like a solution that minimizes the duration and frequency of latching space map pages, and yet supports the simplicity of redo-only logging of SMOs. We would also like to avoid the situation where pages end up showing allocated in the space map but are in reality not part of the B-link tree.

The design of the solution is based upon following observations.

1. In ARIES, a Compensation log record is redo-only, and is linked via the undoNextLsn to the predecessor of the undoable log record for which the CLR is compensating *[MOHA-92]*. A Dummy CLR is a special case, as it does not actually compensate for an undo, instead it is used as a linking mechanism to bypass the undo of actions that are part of the nested top action. We note that there is no reason why an ordinary redo-only log record may not also be used as a Dummy CLR. The only difference would be that such a CLR would contain redo information, whereas a Dummy CLR does not contain such information.
2. During page allocation and deallocation, it may be necessary to scan the space map pages in order to locate the correct space map page. We note that the scan during page deallocation can be avoided if we make a note of the appropriate space map page during page allocation.
3. During an operation that deallocates a page, the deallocated page is exclusively latched, and is also a part of the redo-only log record. This provides us an opportunity to add extra information within the deallocated page to indicate its new status.

SMOs involving page allocation

The solution proposes that SMOs that result in page allocation should be handled as nested top actions with the following modifications:

1. The page allocation step should be logged as redo-undo so that in case the SMO aborts, the page allocation will be undone. This ensures that the page allocation is automatically undone at system restart without need for any special action.
2. The SMO should be logged as a Compensation log record. Its undoNextLsn should be set to the Lsn prior to the one that describes the page allocation step. This ensures that the SMO is logged as redo-only, thus avoiding the overhead of supporting undo operation. However, at the same time, we allow the page allocation to be undone in the event that the SMO is not logged.
3. The identity of the space map page responsible for maintaining the allocation status of the new page, should be stored inside the page as a separate field. This makes it possible to avoid searching for the appropriate space map page during page deallocation.
4. A page allocation flag should be set within the newly allocated page to indicate its allocated status. This flag can be used to mark deallocated pages as well, as we shall see in the next section.

SMOs involving page deallocation

The solution proposes that an SMO involving page deallocation should be split into separate discrete atomic actions as described below.

1. The structure modification operation should be logged as a redo-only log record. The deallocated page should be marked as deallocated using the page allocation flag within the page. Also, an action to deallocate the page should be enqueued. The action should specify the page to be deallocated, as well as the space map page that owns allocation data for the page.
2. A background process should be configured to listen on the deallocation queue. When a request for page deallocation arrives, it should generate a redo-only log record for the specified deallocation and then perform the deallocation. This must be committed as an independent transaction. Note that the process may batch together updates to several pages that are managed by the same space map page, rather than handling each update individually.

Garbage collection of deallocated pages

If the system fails before all the pages that are in the deallocation queue have been logged, then some pages will show as allocated in the space map pages but will not be part of the B-link tree. These pages can be recovered using a single scan of all the pages in the B-link tree after system recovery. Since deallocated pages have a flag set within the page, the garbage collection process does not need to inspect any other attribute of the page to determine the status of the page. The garbage collection process simply enqueues a page deallocation request, after checking that there is not already a deallocation request for the same page. This check is necessary to avoid conflicts with other concurrent processes that may be deallocating pages.

Note that the garbage collection process only needs to obtain shared latches on the pages while inspecting them. Ideally, the pages inspected by the garbage collection process should not be made resident in the Buffer cache, to avoid filling up the buffer cache with infrequently accessed pages. If they are to be part of the Buffer cache, then they should be placed at the LRU (least recently used) end of the cache.

The garbage collection process may be started anytime after system recovery has been completed. It needs to scan each B-link tree

only once. It can run in parallel with other processes as a low priority task.

If the system can cope with some amount of wasted space, then the garbage collection process can be run during off-peak periods, possibly at weekends.

Advantages of proposed solution

1. Advantages of logging SMOs as redo-only log records are retained.
2. Page allocations are handled normally as nested top actions, thereby requiring no special action.
3. Deallocations are handled asynchronously. By batching several deallocations together, and by avoiding searches for space map pages, the load on space map pages is reduced.
4. SMOs do not require space map pages to be latched exclusively at the same time as other pages are latched exclusively. This allows multiple SMOs

. to proceed concurrently.

Disadvantages of proposed solution

1. A separate background process is required for handling page deallocation requests. However, this has the benefit that deallocation requests can be batched together to reduce latching of the space map pages.
2. A separate garbage collection process is needed to recover deallocated pages that are incorrectly marked as allocated in the space map page. However, this process can run concurrently with other processes, and needs to only scan a B-link tree once. Also, it does not acquire exclusive latches on any page.

Another approach to page deallocation

In the approach described above, page deallocations are handled asynchronously. With the help of additional locking, it is possible to devise a solution that handles page deallocations synchronously using nested top actions in the same way as page allocations are handled.

The problem with page deallocations is that they must occur after the SMO that generates them. This means that if we implement such operations as nested top actions, then we need to make the SMO undoable. We have already said why this is undesirable.

To avoid this, we can generate the log record for the page deallocation before the SMO. However, this would cause a problem because other processes may consider the page available for re-use before the SMO is completed, thus corrupting the B-link tree. The solution to this problem is to obtain an exclusive lock on the deallocated page before logging the page deallocation. This lock must be obtained from the Lock Manager. By locking the deallocated page, we prevent other processes from accessing the deallocated page until the SMO is complete. Once the SMO has been logged, the lock is released. Thus, page deallocation locks are held for a short period only, and do not conflict with transaction level locks.

SMOs involving page allocation must respect the page lock. Once a page has been identified as available, we need to obtain an instant duration lock *[MOHA-92]* on the page to check whether that page is truly available. There is no need to wait for such a lock, therefore the lock request must be conditional *[MOHA-92]*. If the lock is not available, we can try another page.

In this approach, page deallocations are handled in the same way as page allocations at the expense of additional locking. This approach also avoids the problem of incorrect information in space map pages.

Related Papers

The paper [IBRA-06] presents the algorithms described in this document in more detail.

CHAPTER 8

A Quick Survey of MultiVersion Concurrency Algorithms

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Abstract This document looks at some of the problems with traditional methods of concurrency control via locking, and explains how Multi-version Concurrency algorithms help to resolve some of these problems. It describes the approaches to Multi-Version concurrency and examines a couple of implementations in greater detail.

Contents

Introduction

Database Management Systems must guarantee consistency of data while allowing multiple transactions to read/write data concurrently. Classical DBMS[1] implementations maintain a single version of the data and use locking to manage concurrency. Examples of SVDB implementations are IBM DB2, Microsoft SQL Server, Apache Derby and Sybase.

To understand how Classical DBMS implementations solve concurrency problems with locking, it is necessary to first understand the type of problems that can arise.

Problems of Concurrency

Dirty reads. The problem of dirty read occurs when one transaction can read data that has been modified but not yet committed by another transaction.

Lost updates. The problem of lost update occurs when one transaction over-writes the changes made by another transaction, because it does not realize that the data has changed. For example, if a transaction T1 reads record R1, following which a second transaction T2 reads record R1, then the first transaction T1 updates record R1 and commits the change, following which the second transaction T2 updates R1 and also commits the change. In this situation, the update made by the first transaction T1 to record R1 is "lost", because the second transaction T2 never sees it.

Non-repeatable reads. The problem of non-repeatable read occurs when a transaction finds that a record it read before has been changed by another transaction.

Phantom reads. The problem of phantom read occurs when a transaction finds that the same SQL query returns different set of records at different times within the context of the transaction.

Lock Modes

To resolve the various concurrency problems, Classical Database Systems use locking to restrict concurrent access to records by various transactions. Two types of locks are used:

Shared Locks. Are used to protect reads of records. Shared locks are compatible with other Shared locks but not with Exclusive locks. Thus multiple transactions may acquire Shared Locks on the same record, but a transaction wanting to acquire Exclusive Lock must wait for the Shared locks to be released.

Exclusive Locks. Are used to protect writes to records. Only one transaction may hold an Exclusive lock on a record at any time, and furthermore, Exclusive locks are not compatible with Shared Locks. Thus a record protected by Exclusive Lock prevents both read and write by other transactions.

The various lock modes used by the DBMS, also called Isolation levels, are given below:

Read Committed. In this mode, the SVDB places Commit duration[2] exclusive locks on any data it writes. Shared locks are acquoired on records being read, but these locks are released as soon as the read is over. This mode prevents dirty reads, but allows problems of lost updates, non-repeatable reads, and phantom reads to occur.

Cursor Stability. In addition to locks used for Read Committed, the DBMS retains shared lock on the "current record" until the cursor moves to another record. This mode prevents dirty reads and lost updates.

Repeatable Read. In addition to exclusive locks used for Read Committed, the DBMS places commit duration shared locks on data items that have been read. This mode prevents the problem of non-repeatable reads.

Serializable. In addition to locks used for Repeatable Read, when queries are executed with a search parameter, the DBMS uses key-range locks to lock even non-existent data that would satisfy the search criteria. For example, if a SQL query executes a search on cities beginning with the letter 'A', all cities beginning with 'A' are locked in

[1] DBMS implementations that are based upon the locking protocols of IBM's System R prototype.
[2] A Commit duration lock, once acquired, is only released when the transaction ends.

shared mode even though some of them may not physically exist in the database. This prevents other transactions from creating new data items that would satisfy the search criteria of the query until the transaction running the query either commits or aborts.

Clearly, the different lock modes offer different levels of data consistency, trading off performance and concurrency for greater consistency. Read Committed mode offers greatest concurrency but least consistency. The Serialized mode offers the most consistent view of data, but the lowest concurrency due to the long-term locks held by a transaction operating in this mode.

Problems with Traditional Lock based concurrency

Regardless of the lock mode used, the problem with a SVDB systems is that Writers always block Readers. This is because all writes are protected by commit duration exclusive locks, which prevent Readers from accessing the data that has been locked. Readers must wait for Writers to commit or abort their transactions.

In all lock modes other than Read Committed, Readers also block Writers.

Introduction to Multi-Version Concurrency

The aim of Multi-Version Concurrency is to avoid the problem of Writers blocking Readers and vice-versa, by making use of multiple versions of data.

The problem of Writers blocking Readers can be avoided if Readers can obtain access to a previous version of the data that is locked by Writers for modification.

The problem of Readers blocking Writers can be avoided by ensuring that Readers do not obtain locks on data.

Multi-Version Concurrency allows Readers to operate without acquiring any locks, by taking advantage of the fact that if a Writer has updated a particular record, its prior version can be used by the Reader without waiting for the Writer to Commit or Abort. In a Multi-version Concurrency solution, Readers do not block Writers, and vice versa.

While Multi-version concurrency improves database concurrency, its impact on data consistency is more complex *[HB95]*.

Requirements of Multi-Version Concurrency systems

As its name implies, multi-version concurrency relies upon multiple versions of data to achieve higher levels of concurrency. Typically, a DBMS offering multi-version concurrency (MVDB), needs to provide the following features:

1. The DBMS must be able to retrieve older versions of a row.
2. The DBMS must have a mechanism to determine which version of a row is valid in the context of a transaction. Usually, the DBMS will only consider a version that was committed prior to the start of the transaction that is running the query. In order to determine this, the DBMS must know which transaction created a particular version of a row, and whether this transaction committed prior to the starting of the current transaction.

Challenges in implementing a multi-version DBMS

1. If multiple versions are stored in the database, an efficient garbage collection mechanism is required to get rid of old versions when they are no longer needed.
2. The DBMS must provide efficient access methods that avoid looking at redundant versions.

3. The DBMS must avoid expensive lookups when determining the relative commit time of a transaction.

Approaches to Multi-Version Concurrency

There are essentially two approaches to multi-version concurrency. The first approach is to store multiple versions of records in the database, and garbage collect records when they are no longer required. This is the approach adopted by PostgreSQL and Firebird/Interbase.

The second approach is to keep only the latest version of data in the database, as in SVDB implementations, but *reconstruct* older versions of data dynamically as required by exploiting information within the Write Ahead Log. This is the approach taken by Oracle and MySQL/InnoDb.

The rest of this paper looks at the PostgreSQL and Oracle implementations of multi-version concurrency in greater detail.

Multi-Version Concurrency in PostgreSQL

PostgreSQL is the Open Source incarnation of Postgres. Postgres was developed in University of California, Berkeley, by a team led by Prof. Michael Stonebraker (of INGRES fame). The original Postgres implementation offered a multi-version database with garbage collection. However, it used traditional two-phase locking model that led to the "readers blocking writers" phenomenon.

The original purpose of multiple-versions in the database was to allow time-travel, and also to avoid the need for a Write-Ahead Log. However, in PostgreSQL support for time-travel has been dropped, and the multi-version technology in original Postgres is exploited for implementing a Multi-Version concurrency algorithm. PostgreSQL team also added Row level locking and a Write-Ahead Log to the system.

In PostgreSQL, when a row is updated, a new version (called a tuple) of the row is created and inserted into the table. The previous version is provided a pointer to the new version. The previous version is marked "expired", but remains in the database until it is garbage collected.

In order to support multi-versioning, each tuple has additional data recorded with it:

xmin - The ID of the transaction that inserted/updated the row and created this tuple.

xmax - The transaction that deleted the row, or created a new version of this tuple. Initially this field is null.

To track the status of transactions, a special table called `PG_LOG` is maintained. Since Transaction Ids are implemented using a monotonically increasing counter, the `PG_LOG` table can represent transaction status as a bitmap. This table contains two bits of status information for each transaction; the possible states are in-progress, committed, or aborted.

PostgreSQL does not undo changes to database rows when a transaction aborts - it simply marks the transaction as aborted in `PG_LOG`. A PostgreSQL table therefore may contain data from aborted transactions.

A Vacuum cleaner process is provided to garbage collect expired/aborted versions of a row. The Vacuum Cleaner also deletes index entries associated with tuples that are garbage collected.

Note that in PostgreSQL, indexes do not have versioning information, therefore, all available versions (tuples) of a row are present in the indexes. Only by looking at the tuple is it possible to determine if it is visible to a transaction.

In PostgreSQL, a transaction does not lock data when reading. Each transaction sees a snapshot of the database as it existed at the start of the transaction.

To determine which version (tuple) of a row is visible to the transaction, each transaction is provided with following information:

1. A list of all active/uncommitted transactions at the start of current transaction.

2. The ID of current transaction.

A tuple's visibility is determined as follows (as described by Bruce Momijian in *[BM00]*:

Visible tuples must have a creation transaction id that:

- is a committed transaction
- is less than the transaction's ID and
- was not in-process at transaction start, ie, ID not in the list of active transactions

Visible tuples must also have an expire transaction id that:

- is blank or aborted or
- is greater than the transaction's ID or
- was in-process at transaction start, ie, ID is in the list of active transactions

In the words of Tom Lane:

A tuple is visible if its xmin is valid and xmax is not. "Valid" means "either committed or the current transaction".

To avoid consulting the `PG_LOG` table repeatedly, PostgreSQL also maintains some status flags in the tuple that indicate whether the tuple is "known committed" or "known aborted". These status flags are updated by the first transaction that queries the `PG_LOG` table.

Multi-version Concurrency in Oracle

Oracle does not maintain multiple versions of data on permanent storage. Instead, it recreates older versions of data on the fly as and when required.

In Oracle, a transaction ID is not a sequential number; instead, it is a made of a set of numbers that points to the transaction entry (slot) in a Rollback segment header. A Rollback segment is a special kind of database table where "undo" records are stored while a transaction is in progress. Multiple transactions may use the same rollback segment. The header block of the rollback segment is used as a transaction table. Here the status of a transaction is maintained, along with its Commit timestamp (called System Change Number, or SCN, in Oracle).

Rollback segments have the property that new transactions can reuse storage and transaction slots used by older transactions that have committed or aborted. The oldest transaction's slot and undo records are reused when there is no more space in the rollback segment for a new transaction. This automatic reuse facility enables Oracle to manage large numbers of transactions using a finite set of rollback segments. Changes to Rollback segments are logged so that their contents can be recovered in the event of a system crash.

Oracle records the Transaction ID that inserted or modified a row within the data page. Rather than storing a transaction ID with each row in the page, Oracle saves space by maintaining an array of unique transactions IDs separately within the page, and stores only the offset of this array with the row.

Along with each transaction ID, Oracle stores a pointer to the last undo record created by the transaction for the page. The undo records are chained, so that Oracle can follow the chain of undo records for a transaction/page, and by applying these to the page, the effects of the transaction can be completely undone.

Not only are table rows stored in this way, Oracle employs the same techniques when storing index rows.

The System Change Number (SCN) is incremented when a transaction commits.

When an Oracle transaction starts, it makes a note of the current SCN. When reading a table or an index page, Oracle uses the SCN number to determine if the page contains the effects of transactions that should not be visible to the current transaction. Only those committed transactions should be visible whose SCN number is less than the SCN number noted by the current transaction. Also, Transactions that have not yet committed should not be visible. Oracle checks the commit status of a transaction by looking up the associated Rollback segment header, but, to save time, the first time a transaction is looked up, its status is recorded in the page itself to avoid future lookups.

If the page is found to contain the effects of "invisible" transactions, then Oracle recreates an older version of the page by undoing the effects of each such transaction. It scans the undo records associated with each transaction and applies them to the page until the effects of those transactions are removed. The new page created this way is then used to access the tuples within it.

Since Oracle applies this logic to both table and index blocks, it never sees tuples that are invalid.

Since older versions are not stored in the DBMS, there is no need to garbage collect data.

Since indexes are also versioned, when scanning a relation using an index, Oracle does not need to access the row to determine whether it is valid or not.

In Oracle's approach, reads may be converted to writes because of updates to the status of a transaction within the page.

Reconstructing an older version of the page is an expensive operation. However, since Rollback segments are similar to ordinary tables, Oracle is able to use the Buffer Pool to effectively ensure that most of the undo data is always kept in memory. In particular, Rollback segment headers are always in memory and can be accessed directly. As a result, if the Buffer Pool is large enough, Oracle to able create older versions of blocks without incurring much disk IO. Reconstructed versions of a page are also stored in the Buffer Pool.

An issue with Oracle's approach is that if the rollback segments are not large enough, Oracle may end up reusing the space used by completed/aborted transactions too quickly. This can mean that the information required to reconstruct an older version of a block may not be available. Transactions that fail to reconstruct older version of data will fail.

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