DBMS Implementation Project Phase 2: Graph Database

CSE 510: Database Management System Implementation

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Abstract: In Phase 1 of this project, we described the existing functionality of Minibase, a relational database management system implemented in Java. In this phase, phase 2, we extend the functionalities of Minibase to support a graph database specified by a set of nodes and a set of directed edges. New heap data structures, node heap files and edge heap files, respectively, are created to store the actual nodes and edges. The previously existing BTree data structure is used to index node and edge labels, and edge weights. We create a new Z-Tree index, which creates an ordering based on a Z-curve, to index the 5-dimensional node descriptors. To test the functionality of this new graph database, six queries are implemented: a batch node insert, batch edge insert, batch node delete, batch edge delete, node query, and test query. Each of the batch tests performs a series of insert/delete operations based on an input file, whereas the node/edge queries execute a series of tests that access the database. All tests were completed successfully; a description of each test is provided in the document.
Keywords: Minibase, graph database, Z-trees, database management system, unit testing

1 Introduction

This section details the background of phase 2 of the CSE 510 final project, describing the terminology used within the document, problem specification, and core assumptions made for the project.

1.1 Terminology

DBMS - Database Management System
ID - Identification number
Label - A string that represents the name of a given object
Node - A structure that consists of a label, id, and descriptor. Fundamental unit of a graph. Also known as a vertex.
Edge - A structure that consists of a label, id, descriptor, source node, and destination node. Connects two nodes. For the graph consisted here, the edges will be directed - this means that the source node and the destination node are not interchangeable for a given edge; an edge from Node A to Node B is distinct from an edge going from Node B to Node A.
Graph - A structure that consists of a set of nodes and a set of edges connecting nodes. Since edges in this graph are directed edges, the graph in this database is a directed graph.
Query - an operation performed on the database to add, remove, or retrieve data within the database. The terms “node query” and “edge query” use the more standard definition of query, i.e. accessing the database to retrieve entries in a readable format.
Graph Database - A database which stores data in the form of a graph - i.e. in the form of a set of nodes connected by a set of edges.
B-Tree - A tree-based data structure which is an extension of the binary tree, used for read/write operations on a large set of data.
Z-Curve - A structure which orders objects based on temporal locality.
5D - 5 dimension.

1.2 Problem Specification

In Phase 1 of the CSE 510 project, a relational database management system, Minibase, was explored and tested to understand and evaluate its functionality. In this phase, the original implementation of the Minibase relational DBMS is expanded in order to provide support for graph-based DBMS. As described in the terminology section, a graph consists of a set of nodes and edges, and a graph DBMS stores and allows for access of a set of such nodes and edges. In addition to the standard query functionality of a relational DBMS, a graph DBMS must provide for various additional capabilities that would be expected of a graph-based database: storage of nodes and edges, indexing of node/edge elements, and sorting based on temporal locality of objects. Changes to the database to implement these changes are described in Section 2 of this document.

1.3 Assumptions

For this implementation, we assume that the graph to be implemented is a directed graph, and that the nodes and edges are tuples in the form described in Section 1.1. It is assumed that all input will be of the form described in Section 4 and that no invalid commands will be entered in the test of the program and that no invalid input files will be used. We also assume that the

node insertions are done first on the graph database followed by edge insertions as insertion of edges require scanning the node heap file.

2 Description of the Proposed Solution

This section describes the implementation of the graph DBMS and of the tests used to verify its functionality.

2.1 Implementation

The subsections below describe each individual task to implement the core functionality of the graph DBMS, excluding any of the query operations.

2.1.1 Graph Attribute Description, Expression, and Evaluation

The Graph database created in this phase is a collection of nodes and edges. Each node consists of a node label and a node descriptor. To represent a node descriptor a new data type is created which consists of 5 integers. And each integer may take a value between 0 and 10000. The Descriptor class provides basic functions related to descriptors like set (), get (), distance () and equal (). Minibase supported data types integer, real and string. But the graph database also needs to support attributes of type Descriptor. So, data type attrDesc is added to AttrType.java to support Descriptor data type. The data in the relational database was stored in the form of tuples. Tuples provided getters and setters for all the supported data type fields. We added setDescFld () and getDescfld () to set and get descriptor values respectively. The setter and getter method for descriptors need methods to convert byte stream to descriptor and descriptor to byte stream. So, added getDescValue () and setDescValue () methods in Convert.java.

In a relational database, all the operations are performed on trivial data types but graph database performs operations on descriptor data type which is a 5-D vector. So operand type attrDesc is required to be added in Operand.java to support all operations on descriptor data type.

The relational database does not have any method to compare data of type descriptors. So, modified the CompareTupleWithTuple and CompareTupleWithValue such that if comparison is made between two descriptor types it will return the distance between the two descriptors. Added a distance field in the CondExpr to be used with the operands of type attrDesc. PredEval class is used to determine if two tuples can join or not. The Eval method in this class had support for existing attribute types. So, modified the Eval method to support descriptor types.

2.1.2 Graph Database Entries (Nodes and Edges)

In order to achieve the target of designing a graph database containing nodes and edges we need to have specialized classes for these types. In a relational database the main task was to handle data in the form of tuples and for that classes like HFpage, scan, Heapfile and tuple were defined. For a graph database, firstly we need a new node ID class which is mainly an extension of RID class with added features such as a label and a descriptor in the node constructor. Secondly, the operations on tuples such as insert and delete were handled by the Heapfile. Therefore, for a node we have created a node heap file which is an extension of the heapfile. This node heap file has added functionalities to handle a node insert and delete along with other operations. Methods such as deleteNode(), getNodeCnt(), getNode(), insertNode() and openScan() were defined to support storing and deleting the nodes in a

node heap file. Next, the node class was defined which is an extension of tuple. This class includes the getters and setters for the node type along with functions such as print (), size (), nodeCopy(), nodeInit() and the constructors. The HFpage was extended into NHFpage. Since it deals with getting next record, current record, previous page and slot related functions, so it was modified for node types. Similarly Nscan was extended from Scan and was modified for node types.
The next task was to make the modifications for the edges. , firstly we need an edge ID class which is mainly an extension of RID class with added features such as source, destination, label and weight. Secondly, the operations on tuples such as insert and delete were handled by the Heapfile. Therefore, for an edge we have created an edge heap file which is an extension of the heapfile. This edge heap file has added functionalities to handle an edge insert and delete along with other operations.

Methods such as deleteEdge(), getEdgeCnt(), getEdge(), insertEdge() and openScan() were defined to support storing and deleting the edges in an edge heap file.

Next, the edge class was defined which is an extension of tuple. This class includes the getters and setters for the edge type along with functions such as print (), size (), edgeCopy(), edgeInit() and the constructors. The return type of source and destination will be NID as they return nodes.

The HFpage was extended into EHFpage. Since it deals with getting next record, current record, previous page and slot related functions, so it was modified for edge types. Similarly Escan was extended from Scan and was modified for edge types.

2.1.3 Graph Tuple Comparisons and Sorting

The task 5 involves modifying the tuple comparison methods. The graph database has a new attribute type, called descriptor which is a 5 – D vector. In order to compare a 5- D vector, The existing methods for tuple comparisons need to be modified to compare the tuples based on the new attribute type too. The CompareTupleWithTuple method is modified by overloading it to include two extra parameters, target descriptor and distance. The method compares The method takes care of the new attribute by modifying the switch case to handle the comparison if the tuple is being compared based on the descriptor attribute. Similarly the CompareTupleWithValue and equal methods are overloaded to accommodate the descriptor attribute.

The task 6 involves changing the classes that use the above modified methods. The TupleUtils.java class is modified for all the methods accessing the tuples. The setValue method is adapted to set up a tuple with the Descriptor field from a given tuple.The sort.java class sorts a given tuple based on a particular attribute by comparing the tuples. In case the sorting has to be done based on the descriptor field, a given target or distance value is passed into the sort constructor to compare the tuples based on the given distance or target . The sort constructor in the sort class is overloaded to take extra parameters, distance and a target. The DuplElim.java, pNodePQ.java classes are modified to accommodate the tuples with a descriptor type attribute.

2.1.4 Z-Tree Index and Access Methods

The database is expected to support indexing over a 5-dimensional vector(Descriptor). This task has been achieved through Z Curve. The system provides a constructor to initialize an index on the Descriptor field. To index the given data, ZCurve class provides API's for insert, delete and scan. When data is inserted into the system, along with all other indexes, it also

creates Z curve index by calling insert method on it. This insert method, converts 5D descriptor field into string of bits. This string of bits is used as key and corresponding data is inserted into the Btree.

Conversation of 5 Dimension to 1 Dimension:
A Utility class in Global package provides a method to convert 5-dimensional descriptor into one dimension string by bit shuffling. The string of bits is used a key for indexing data. There is also and other utility to convert string of bits into 5D vector.

Range Scan:
The range scan on Zcurve is converted into range scan on Btree file by converting the Descriptor to string of bits. It provides two types of scan: A range scan with two keys and a range scan with descriptor and a distance.
A range scan with two keys: ZFileScan(lowKey,HighKey) : It takes two descriptors and performs range scan on Z curve, if null values are passed for low key or high key then [0,0,0,0,0] or [10000, 10000, 10000, 10000, 10000] are set as its values respectively. It returns every point which falls within this range.
The range scan with a descriptor and distance ZFileScan(Descriptor, Distance), uses the distance provided to calculate the low key and high key, and invoke the range scan with two parameters.

Implementation:
There are two implementation of range search currently:
one which does a complete Btree scan between two ranges and checks if descriptor fetched falls within the range of given descriptors. If it does that object will be returned. The other implementation uses the concept of breaking a single query into multiple queries. This is done as described below:

- Initiate a scan with low key and high key.
- Fetches the next element from the btree.
- Checks if the element falls within the range of given 5D descriptor.
- If it does returns the element, Else it increments the missCounter by one
- If the missCounter reaches a threshold, has been set to 32(as its 5D, there are chances that it will come back in the range after 32 misses if it's close to the corners)
- Once it crosses the threshold, it will Invoke Z Divide on the region.
- The Z divide will find the common bit pattern in the key, and cuts the space in a specific dimension, where the 1^{st} bit between the two keys change.
- And it returns a new Little Maximum (max key for the upper space) and Big minimum (and a min key for the lower space).
- If the min is lower than the last reported key, which did not fall in the range. A new scan will be initiated for the lower space, else the upper space is divided again using the Z divide.
- This division is implemented every time when threshold is crossed, once the scan in the upper space is complete, a scan in the lower space will be done.

Possible improvements:

- We are supporting 5D descriptor, with 2 bytes for each, this lead to a key of 80 characters, if bit stream is stored as keys. Instead we can break the bit stream into 32 bit blocks and store 3 Integers concatenated together, which would lead to a key size of 30.
- Range search with Z-divide still has some issues, which we are trying to resolve, hence we have enabled Naive range search for now, which scans Btree from low key to high key.

2.1.5 Graph Database Definition and Page Counter

This section covers tasks 8 and 9: creation of a graphDB structure (a graph-based database which inherits from the DB structure), and the implementation of a page counter, respectively. The implementation of the page counter and graph database are described below.

The page counter keeps track of the number of read and write operations performed since the last time the counter was reset. This is used in order to report statistics on the number of pages read and written at the end of the program. Note that all variables and all methods within the page counter (implemented as a class PageCounter) are static, so no variables will need to be passed between databases - but only one page counter can run at a time. In order to reset the value in the page counter, use the initialize() method in the PageCounter class when appropriate.

The graphDB class is an extension of the DB class which provides additional functionality to extend the relational DBMS into a graph DBMS. This function stores the additional structures of a graph database that are not present in a relational database - namely nodes, edges, and indices on the elements of nodes and edges - and functions that act on those elements. Broadly, the function of the graphDB methods fall into one of three categories: access of the database, bookkeeping and tracking of statistics, and handling of graph-based queries to the database. All other features of the graph database are handled by the existing relational framework; the additions are described by category below.

To insert elements (nodes or edges) into or delete elements from the graph database, four functions were needed: one function for inserting nodes, one function for inserting edges, one function for deleting nodes, and one function for deleting edges. For each insert or delete operation, the heap files containing the elements, the index files containing references to an element, and the counters on those elements needed to be updated. Specifically, for every node inserted or removed, the node heap file, node label index, label counter, and node descriptors needed to be modified to add or remove that element. For edges, the edge heap file, edge label index, edge weight index, node source counter, node destination counter, and label counter need to be updated. However, the graphDB insert/delete methods do not delete edges which refer to nodes that no longer exist; this function is performed by the batch node delete handler (which uses this delete function to specify which edges and nodes to delete). To ensure that each piece is properly updated and to avoid index/heap inconsistencies, all insert and delete operations are handled through the graphDB methods.

As mentioned above, the insert and delete methods contain counters which perform bookkeeping on the numbers of unique labels, unique source nodes, and unique destination nodes. This bookkeeping is done in order to avoid a O(n^2) reference for any calculation of unique values over the entire structure. This bookkeeping performed during insert and delete does not increase the O(n) runtime of the original operation, and will allow for O(1) access. The counters themselves are ArrayList objects of tokens containing a reference to the item in

question (an NID for nodes, the label itself for labels) and a reference counter (a token is released when its reference count reaches 0). Inserting into the ArrayList is completed in O(n), and the size of the ArrayList is the number of unique elements within the counter. In addition, the node heap file and edge heap file have methods which give the count of elements within them, which are referenced to obtain that number. In all, five statistical queries are available within the graph database: node count, edge count, unique source node count, unique destination node count, and unique label count.

The last class of structures within the graphDB are the query handlers, objects which are created to access the data structures of the graphDB within a controlled framework. Each of the six tests in Section 2.2 has an associated query handler, which is passed a pointer to the heaps, indices, and the database itself, and called from within the database. The handler then executes all of the relevant operations to the query; the tests themselves consist only of calls to the relevant handlers that perform operations on the internal database structures. This is done to ensure the integrity of the data structures; while each of the tests modifies the graph, the internal structures cannot simply be accessed directly as any changes made without the proper related structures (e.g. the node heap file and the indices and counters associated with the nodes must be changed together).

2.2 Tests

The functionalities used to verify the functionality of the program are given in the subsections below.

2.2.1 Batch Insertion Tests

These tests test insertion of nodes and edges in the graph database. Below are the implementation specifications of the insertion tests.

2.2.1.1 Batch Node Insertion

This test are useful in inserting multiple nodes in the graph database at once provided you have all the nodes data stored in a file in the tests folder in the format <nodelabel1 nodedesc11 nodedesc12 nodedesc13 nodedesc14 nodedesc15>. (Here, nodedesc stands for node descriptor value.) When testcases.java is executed, you can run this test case by entering command line in the format

batchnodeinsert NODEFILENAME GRAPHDBNAME

Upon invocation of the batchnodeinsert program, a graph database with the given name is checked for existence. If the database exists, it is opened otherwise a new database is created using SystemDefs with 1000 number of pages and 100 buffer frames with 'Clock' page replacement policy. SystemDefs invokes graphDB which ensures creation of the database and initialization of all the required data and index files. After the database is opened, the test is started by invoking the corresponding test handler. Both the page counters, PCounter.rcounter and PCounter.wcounter are recorded at the start of the test. The input file is then read line by line and the fields of the node consisting of Node label and Node descriptor are set. The descriptor values are read from the input file as integers, hence, a descriptor is created using Descriptor.set() method defined in Descriptor.java. For setting the node fields, a new node is created and Node.setLabel() and Node.setDesc() are used to set the labels and descriptors of

the node respectively. This node is then inserted into the database by invoking insertNode() function on the graphDB instance. This method ensures insertion of the node in the NodeHeapFile and indexing of the node labels and node descriptors in the corresponding BTree and ZCurve index files. This process is repeated until all the nodes are inserted. To verify the insertion, the node counts and edge counts are printed. Then the page counters are read again and subtracted from the previous values to get the final number of pages read and written during the test and the statistics are printed.

2.2.1.2 Batch Edge Insertion

This test is used for testing insertion of multiple edges in the graph database at once given that the edges data is stored in a file in the 'tests' directory in the format <sourcelabel1 destlabel1 edgelabel1 edgeweight1> where sourcelabel and destlabel is the label of the source node and destination node respectively whereas edgelabel and edgeweight represents the label and the weight of the edge. The program can be invoked by executing testcases.java and by entering the command line in the format

batchedgeinsert EDGEFILENAME GRAPHDBNAME

Upon invocation, the test is started by invoking the test in batch edge insert handler. At the start of the test, we record both page counters, PCounter.rcounter and PCounter.wcounter to keep track of number of pages read and written during the test. We then read the file line by line. Each line is separated by whitespaces and the appropriate fields are obtained from it. As all the labels in the graph database are converted into a fixed length label, the source and destination node labels obtained from the input data are also converted into fixed length. This proves to be useful while performing the comparisons in the file scans. For setting the source and destination of labels, the methods Edge.setSource() and Edge.setDestination() take node ID of type NID as a parameter. Hence, a scan is initiated on the node heap file in the database to find the source and destination nodes and get their node IDs. We create a new node ID and call getNext() on it to start the scan from the start of the file. The file is scanned using NScan() till it finds both the source and destination labels or it reaches the end of the file. During scanning, the label of each scanned node is compared with source and destination labels and if matched, the appropriate node ID is recorded. Now since all the required data for the edge fields is obtained, the fields are set using Edge.setLabe(), Edge.setSource(), Edge.setSource(), Edge.setDestination(), Edge.setWeight(). Then this newly created node is inserted into the database by using graphDB.insertEdge(). This function ensures that the edge is inserted in the edge heap file and edge labels and edge weights are inserted in the corresponding BTree index files. Then the final page counters are obtained by subtracting the updated ones from the ones which were recorded earlier. All the relevant database statistics, node count, edge count, number of pages read and written are then printed which can be analyzed to ensure the proper functioning of the implementation.

2.2.2 Batch Deletion Tests

These tests perform deletion of nodes and edges in the graph database. Below are the implementation specifications of the batch deletion tests. During both the deletion test, a PCounter object is created to give the statistics of number of pages read and write performed while performing the query.

2.2.2.1 Batch Node Deletion

This test is used for testing deletion of multiple nodes in the graph database at once given that the edges data is stored in a file in the 'tests' directory in the format <nodelabel> where nodelabel is the label of the node to be deleted from the database. The program can be invoked by executing testcases.java and by entering the command line in the format.

batchnodedelete NODEFILENAME GRAPHDBNAME

The program which performs the subsequent tasks takes one input from the NODEFILENAME file at a time. Each input is of type String and contains nodelabel. A new temporary node is created for each nodelabel. The setLabel() method is invoked for this node and the parameter passed in the setLabel() method is the nodelabel obtained from the File. This creates a temporary node which has the nodelabel string as its label. To delete a node from the database which has the nodelabel given in the file, the NID of the node is required. This is provided by initiating a nodeHeapFile NScan using the openScan() method of the NodeHeapFile class. The NodeHeapFile object used is the one initiated by graphDB and passed to the program. The scan is run until a node with the nodeLabel same as the Label of temporary node is not found. Once the required node is found, a EdgeHeapFile scan is started. This is done to find the edges which has the obtained node as its source or destination node. All the edges which have the given node as its source or destination node are removed by finding their EID(Edge ID) using the EScan. Once the edges are removed, EScan is closed and the node found earlier is deleted from the database. Once this is finished, the NScan is closed using closescan function.

Next String is read from the NODEFILENAME file and all the steps described above are performed. This is performed until all the Strings in NODEFILENAME are not read.

2.2.2.2 Batch Edge Deletion

This test is used for testing insertion of multiple edges in the graph database at once given that the edges data is stored in a file in the 'tests' directory in the format <sourcelabel1 destlabel1 edgelabel1 edgeweight1> where sourcelabel and destlabel is the label of the source node and destination node respectively whereas edgelabel and edgeweight represents the label and the weight of the edge. The program can be invoked by executing testcases.java and by entering the command line in the format

batchnodedelete EDGEFILENAME GRAPHDBNAME

Implemented by first reading the file and obtaining one line of the EDGEFILENAME File's content. Each line is split into 3 strings which correspond to EdgeLabel, SourceNode NID, Destination Node NID. An EScan is run on the Edge heap file to search for the corresponding which needs to be deleted. The scan first just checks for the edge Label. The Label obtained from EDGEFILENAME is not used directly as during formation of an edge the formatting of the String Label is changed by adding 0's to obtained constant number of bytes for each Label. Hence a temporary Edge is created for which the setLabel() is used with the input obtained from the EDGEFILENAME as the parameter. The edge obtained is used to search for the edge

with Label consistent with input. Once found, the Source Node NID and Destination Node NID is cross checked with the one obtained in the input File. Once they are cross checked, it proves that this is the edge which needs to be deleted. The edge obtained is deleted by passing its EID to deleteEdge function. The Escan is closed.
The above steps are performed for each line of input in the EDGEFILENAME file given in the command line.

2.2.3 Node and Edge Queries

Implemented by the program nodequery. The program expects the input in the below format:
nodequery GRAPHDBNAME NUMBUF QTYPE INDEX [QUERYOPTIONS]
Once the program nodequery is called it checks for the QTYPE and INDEX in the query and based on that information call the relevant method from the NodeQueryHandler class.
The functionality of each node query handler function is described using query examples below.

➔ nodequery GRAPHDBNAME NUMBUF 0 0

This query calls method nodeHeapTest0() of NodeQueryHandler class. This query requires printing all the node data in the order it appears in the node heap file. To read all the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.
Once scan is opened, it iterates through a loop until all the Node objects are consumed and printed.

➔ nodequery GRAPHDBNAME NUMBUF 1 0

This query calls method nodeHeapTest1() of NodeQueryHandler class. This query requires printing all the node data in increasing alphanumerical order of node labels. To read all the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.
Once scan is opened, it iterates through a loop until all the Node objects are consumed then call sort to arrange the Nodes in increasing alphanumerical order of node labels.

➔ nodequery GRAPHDBNAME NUMBUF 2 0 [7 33 35 20 40]

This query calls method nodeHeapTest2() of NodeQueryHandler class. This query requires printing all the node data in increasing distance from the target descriptor provided in the query. To read all the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.
Once scan is opened, it iterates through a loop until all the Node objects are consumed then call sort to arrange the Nodes in order of increasing distance from the target descriptor.

➔ nodequery GRAPHDBNAME NUMBUF 3 0 [7 33 35 20 40 10]

This query calls method nodeHeapTest3() of NodeQueryHandler class. This query requires printing the data for all the nodes which fall within the given distance range from the target descriptor provided in the query. To read all the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.

Once scan is opened, it iterates through a loop until all the Node objects are consumed and prints those nodes whose distance from target descriptor is less than or equal to the distance given in the query.

➔ nodequery GRAPHDBNAME NUMBUF 4 0 [0]

This query calls method nodeHeapTest4() of NodeQueryHandler class. This query requires printing all the data including incoming and outgoing edges for the node label provided in the query, if it exists. To read the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.
Once scan is opened, it iterates through a loop until the node label given in the query is found or all the Node objects are consumed. If the given node label does not exist it prints a relevant message stating this. If the node label is found in the node heap file it creates an Escan object to scan the edge heap files to extract the information about incoming and outgoing edges of the node given in query.
Once the scan is opened, it iterates through a loop until all the edges are scanned and compares the source and destination nodes of the edge to the node given in query.
If a match is found the edge is added to incoming or outgoing edges appropriately.
If the source node of an edge matches to the given node then the edge is added to the list of outgoing edges and if it matches the destination node then the edge is added to the list of incoming edges. After all the information is accumulated, the data is printed.

➔ nodequery GRAPHDBNAME NUMBUF 5 0 [7 33 35 20 40 10]

This query calls method nodeHeapTest5() of NodeQueryHandler class. This query requires printing all the data including incoming and outgoing edges for the nodes that fall within a given distance range from the given target descriptor. To read the node data stored in the node heap file, scan object of type Nscan is created and scan is opened.
Once scan is opened, it iterates through a loop and add all the nodes to a node array whose distance from the target descriptor is less than or equal to the distance given in the query. If the node array is not empty, it creates an Escan object to scan the edge heap files to extract the information about incoming and outgoing edges of the nodes in node array.
Once the scan is opened, it iterates through a loop until all the edges are scanned and compares the source and destination nodes of the edge to the node in node array.
If a match is found the edge is added to incoming or outgoing edges appropriately.
If the source node of an edge matches to the given node then the edge is added to the list of outgoing edges and if it matches the destination node then the edge is added to the list of incoming edges. After all the information is accumulated, the data is printed.

➔ nodequery GRAPHDBNAME NUMBUF 0 1

This query calls method nodeIndexTest0() of NodeQueryHandler class. This query requires printing all the node data in the order it appears in the index file. To read all the node data, scan object of type IndexScan is created for index type Z_Index on node descriptor ZCurve file.
Once scan is opened, it iterates through a loop until all the Node objects are consumed and printed.

➔ nodequery GRAPHDBNAME NUMBUF 1 1

This query calls method nodeIndexTest1() of NodeQueryHandler class. This query requires printing all the node data in increasing alphanumerical order of node labels. Since this query requires data printed in alphanumerical order of node labels, the scan created in this query is on node label index. Scan object of type IndexScan is created for index type B_Index on node labels BTreeFile.
Once scan is opened, it iterates through a loop until all the Node objects are consumed and printed.

➔ nodequery GRAPHDBNAME NUMBUF 2 1 [7 33 35 20 40]

This query calls method nodeIndexTest2() of NodeQueryHandler class. This query requires printing all the node data in increasing distance from the target descriptor provided in the query. To read all the node data, scan object of type IndexScan is created for index type B_Index on node labels BTreeFile.
Once scan is opened, it iterates through a loop until all the Node objects are consumed then call sort to arrange the Nodes in order of increasing distance from the target descriptor.

➔ nodequery GRAPHDBNAME NUMBUF 3 1 [7 33 35 20 40 10]

This query calls method nodeIndexTest3() of NodeQueryHandler class. This query requires printing the data for all the nodes which fall within the given distance range from the target descriptor provided in the query. Scan object of type IndexScan is created for index type Z_Index and the selects parameter to the IndexScan constructor is initialized such that it contains information of the target descriptor and the distance given in the query.
Once scan is opened, it iterates through a loop to return those nodes whose distance from target descriptor is less than or equal to the distance given in the query.

➔ nodequery GRAPHDBNAME NUMBUF 4 1 [0]

This query calls method nodeIndexTest4() of NodeQueryHandler class. This query requires printing all the data including incoming and outgoing edges for the node label provided in the query, if it exists. Scan object of type IndexScan is created for index type B_Index on node labels BTreeFile.
Once scan is opened, it iterates through a loop until the node label given in the query is found or all the Node objects are consumed. If the given node label does not exist it prints a relevant message stating this. If the node label is found in the node heap file it creates a scan object of type IndexScan is created for index type B_Index on edge labels BTreeFile to extract the information about incoming and outgoing edges of the node given in query.
Once the scan is opened, it iterates through a loop until all the edges are scanned and compares the source and destination nodes of the edge to the node given in query.
If a match is found the edge is added to incoming or outgoing edges appropriately.
If the source node of an edge matches to the given node then the edge is added to the list of outgoing edges and if it matches the destination node then the edge is added to the list of incoming edges. After all the information is accumulated, the data is printed.

➔ nodequery GRAPHDBNAME NUMBUF 5 1 [7 33 35 20 40 10]

This query calls method nodeIndexTest5() of NodeQueryHandler class. This query requires printing all the data including incoming and outgoing edges for the nodes that fall within a given

distance range from the given target descriptor. Scan object of type IndexScan is created for index type Z_Index and the selects parameter to the IndexScan constructor is initialized such that it contains information of the target descriptor and the distance given in the query.
Once scan is opened, it iterates through a loop to return those nodes whose distance from target descriptor is less than or equal to the distance given in the query.
Each returned node is added to a node array whose distance from the target descriptor is less than or equal to the distance given in the query. If the node array is not empty, it creates a scan object of type IndexScan is created for index type B_Index on edge labels BTreeFile to extract the information about incoming and outgoing edges of the node given in query.
Once the scan is opened, it iterates through a loop until all the edges are scanned and compares the source and destination nodes of the edge to the node in node array.
If a match is found the edge is added to incoming or outgoing edges appropriately.
If the source node of an edge matches to the given node then the edge is added to the list of outgoing edges and if it matches the destination node then the edge is added to the list of incoming edges. After all the information is accumulated, the data is printed.

The edgequery runs with a command line invocation. The qtype decides the nature of query. If the index value is 1, then the query is processed using an index.

- ➔ edgequery GRAPHDBNAME NUMBUF 0 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB ‘s constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. Each edge obtained is subsequently printed.

- ➔ edgequery GRAPHDBNAME NUMBUF 1 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB ‘s constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. For each edge a Source NID is obtained, this NID is used to obtain the Source Node. This Node is passed to an Array of Nodes. Once the entire Array has been created, the Labels of the Array are sorted in alphanumerical order. The Array is printed subsequently.

- ➔ edgequery GRAPHDBNAME NUMBUF 2 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB ‘s constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. For each edge a Destination NID is obtained, this NID is used to obtain the Destination Node. This Node is passed to an Array of Nodes. Once the entire Array has been created, the Labels of the Array are sorted in alphanumerical order. The Array is printed subsequently.

- ➔ edgequery GRAPHDBNAME NUMBUF 3 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB ‘s constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. The edge obtained in each iteration is passed to an

Array containing edges. These edges are passed to sortEdges function with parameter which sorts the edgeLabels of edges in increasing alphanumerical order. The array containing the edges is printed subsequently.

➔ edgequery GRAPHDBNAME NUMBUF 4 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB 's constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. The edge obtained in each iteration is passed to an Array containing edges. These edges are passed to sortWeights function. The function sorts the Array on weights of the edges. The sorted Array is subsequently printed.

➔ edgequery GRAPHDBNAME NUMBUF 5 0 [2 20]

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB 's constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. A check is performed on the edge weights and if they satisfy the condition of being in the lowerbound and upperbound provided in the command line input, subsequently the edges are printed.

➔ edgequery GRAPHDBNAME NUMBUF 6 0

An EScan is run on the object of edgeHeapFile which is initiated by the graphDB 's constructor. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNext function of the EScan object. The source NID and destination NID obtained in each edge is stored in a 2-D array of NIDs. Looping is performed on this array to obtain the edges which have a same vertex. In case the condition is satisfied, the edge labels of both the edges are printed.

➔ edgequery GRAPHDBNAME NUMBUF 0 1

For printing the edges. An IndexScan is run on BTree Index File on edge Labels, in case the file doesn't exist, an index file is created on the edge Label of edges. The Scan is run until the edge obtained in the scan using getNextEdge function is not null. The Edge obtained in each call of getNextEdge function is printed.

➔ edgequery GRAPHDBNAME NUMBUF 1 1

An IndexScan is run on BTree Index File on edge Labels, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. For each edge a Source NID is obtained, this NID is used to obtain the Source Node. This Node is passed to an Array of Nodes. Once the entire Array has been created, the Labels of the Array are sorted in alphanumerical order. The Array is printed subsequently.

➔ edgequery GRAPHDBNAME NUMBUF 2 1

An IndexScan is run on BTree Index File on edge Labels, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. For each edge a Destination NID is obtained, this NID is used to obtain the Destination Node.

This Node is passed to an Array of Nodes. Once the entire Array has been created, the Labels of the Array are sorted in alphanumerical order. The Array is printed subsequently.

➔ edgequery GRAPHDBNAME NUMBUF 3 1

An IndexScan is run on BTree Index File on edge Labels, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. The edge obtained in each iteration is passed to an Array containing edges. These edges are passed to sortEdges function with parameter which sorts the edgeLabels of edges in increasing alphanumerical order. The array containing the edges is printed subsequently.

➔ edgequery GRAPHDBNAME NUMBUF 4 1

An IndexScan is run on BTree Index File on edge Labels, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. The edge obtained in each iteration are printed.

➔ edgequery GRAPHDBNAME NUMBUF 5 1 [2 20]

An IndexScan is run on BTree Index File on edge weights, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. A check is performed on the edge weights and if they satisfy the condition of being in the lowerbound and upperbound provided in the command line input, then the edge is printed.

➔ edgequery GRAPHDBNAME NUMBUF 6 1

An IndexScan is run on BTree Index File on edge weights, in case the file doesn't exist, an index file is created on the edge Label of edges. The scan is run until the edge obtained in the scan is not null. Each subsequent edge is obtained using getNextEdge function of the IndexScan object. The source NID and destination NID obtained in each edge is stored in a 2-Dimensional array of NIDs. Looping is performed on this array to obtain the edges which have a same vertex. In case the condition is satisfied, the edge labels of both the edges are printed.

3 Graph DB Interface Specifications

The interface for the graph database will be the same command line interface that was used for the tests performed for the relational DBMS tests for the original Minibase functionality. Invocation of the six tests is described in Section 2.2; each is invoked by a specified input command that is also shown in the menu displayed by the command line interface. Similarly, type "menu" to reprint the menu, or "exit" to exit the tests.

4 System Requirements and Execution Instructions

Similar to the original Minibase code, the instructions to execute the code are as follows:

1. Download and uncompress the file.
2. Modify the makefiles to reflect your own directory structure.
3. In the src directory, run the command "make db" to compile the database.

4. In the src directory, run the command “make test” to run all tests (including the relational DBMS tests) and “make graphtest” to run just the new tests. Input format is described in the menu or in Section 3, above.
5. To record the output, use a typescript.

As with the Minibase program, this is best run on a UNIX machine for access to bash functionality. Java (version 1.7 or later) and Java Development Kit (JDK) need to be installed on your system in order to compile and run this program.

5 Conclusion

The original Minibase DBMS, as analyzed in phase 1 of the project, was extended in this phase (Phase 2) to allow for functionality involving graph databases. This new functionality consisted of both the implementation itself and a series of tests on the implementation to ensure that it works properly. While the relational core is useful for data which can be described in the form of a tabular description, the interconnected nature of graphs (that incorporates both connections between elements and temporal locality) is not well-described by a relational DBMS. As such, this extension is necessary to increase the functionality of the DBMS. The relational core remains; the graphDB inherits from the relational DB class, and all of the old functionality is preserved.

Tasks 1 through 9 dealt with the implementation of the graph DBMS. In these tasks, extensions of relational DBMS classes were created to deal with graph-specific concerns. Specifically, a descriptor (for node descriptors), node and edge ID, Z-tree index, and graph DB were created from Attribute, RID, B-Tree index, and DB classes, respectively. In addition, tuple and attribute comparisons were created to be able to compare and sort values. Finally, for the purpose of tracking page read/writes, a page counter was created.

Tasks 10 through 15 dealt with tests performed on the DBMS that both added querying features (implemented in handlers accessed through graphDB) and test drivers (that called the handlers). The tests included node and edge insertions, deletions, and queries, for a total of six different sets of tests. The running of these tests ensured the proper function of the newly created graph DBMS.

Overall, this project showed how a standard relational DBMS can be build upon in order to improve its capability. While the relational DBMS structure is useful in a wide range of applications, the requirements of the graph database show one of the many cases in which a relational DBMS does not provide sufficient functionality for all the features that such a DBMS would use. This extension is similar to the object-relational DBMS, which uses the core of a relational DBMS and adds object-oriented functionality on top of it. The implementation of the graph DBMS is similar in this addition of a graph functionality on a relational core. However, as of now, while the core functionality of the DBMS has been developed, only unit tests on a database which is destroyed at the end of the program have been performed; a more persistent test of the DBMS would be needed to more effectively evaluate its functionality.

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Appendix A: Individual Contributions by Group Member

Simarpreet Kaur : Completed Task 5 , Task 6 which consisted of modifying the TupleUtils methods and sort.java, DupElim.java and pnodePQ.java classes referring to the tuples, to accommodate the new attribute type Descriptor. Helped Priyekant in Task 14 by completing the index test cases involving the query type 4 and 5. Worked on the report to complete sections related to Task 5, 6, 14 and some common sections.

Prachi Sharma : Completed task 3, task 4 which consisted of defining the nodeheap, edgeheap, edge, node, Nscan, Escan, EHFpage and NHFpage classes so that they are compatible with the functionality of a graph database. Helped Harshdeep in task 15 for the index based test cases. Worked on the report to complete sections related to task 3, 4 and 15.

Jayanth Kumar Melinavolagerehalli Jayaramaiah : Implemented Z curve and ZfileScan Api's, Modified index scan and Index-Utils accordingly. Helped team members in integrating changes and fixing issues. Executed basic functionality test with the team members. Completed the report for Z curves. Added Java documentation for all the new and modified files.

Harshdeep Singh Sandhu: Completed Task 12, 13 and 15. Task 12 and 13 consisted of implementing the batch node delete queries and batch edge delete queries. Task 15 was edgequeries with and without use of index files. Tested the implementation for deleted node and delete edge functions of graphDB. Worked on report to complete sections for Task 12, 13 and 15 and worked on other aspects of report.

Priyekant Aghi : Completed Task 1, Task 2 which consisted of defining the Descriptor class, modifying methods for tuple comparisons and predicate evaluate to accommodate descriptor type arguments. Task 14 which consisted of test cases for node queries based on different query options. Helped team members in integrating changes and fixing issues. Worked on the report to complete the sections related to Task 1, 2, 14 and some common sections. Also created the typescript document.

Shalmali Bhoir: Completed Task 10 and 11 which consisted of test cases for batch insertion of nodes and edges. Tested the functionalities implemented by other group members to check if the node and edge insertions are working fine. The implementations for graph database, heap files, insertion, scanning, page counters for Nodes and Edges and node counters and edge counters were tested and modified according to the requirement in this task. Integrated the code with the handlers designed by Elan. Worked on the report to complete the sections related to Task 10 and 11 and some common sections.

Elan Markov: Completed Task 8, designing the graphDB and the insert/delete functionality. Created the interface for the handler functions which were designed by their respective designers. Designed menu for the test driver and updated the makefile for running the graph tests. Wrote the readme file. Completed Task 9, designing the page counter. Wrote the sections relevant to Task 8 and 9 for the report. Wrote the introduction, interface and runtime details in the report.

Appendix B: Text of Typescript Output

```
Script started on Tue 14 Mar 2017 09:45:21 PM MST
user@user-Linux ~/Documents/CSE510/minjava/javaminibase/src $make graphtest
cd tests; make graph
make[1]: Entering directory
`/home/user/Documents/CSE510/minjava/javaminibase/src/tests'
/usr/lib/jvm/default-java/bin/java  -classpath .:.. tests.testcases
Graph Database Test Cases
Format of command line input:

Batch Node Insert (Task 10 Query):
batchnodeinsert NODEFILENAME GRAPHDBNAME
NODEFILENAME should be a file in tests folder

Batch Edge Insert (Task 11 Query):
batchedgeinsert EDGEFILENAME GRAPHDBNAME
EDGEFILENAME should be a file in tests folder

Batch Node Delete (Task 12 Query):
batchnodedelete NODEFILENAME GRAPHDBNAME
NODEFILENAME should be a file in tests folder

Batch Edge Delete (Task 13 Query):
batchnodeinsert EDGEFILENAME GRAPHDBNAME
EDGEFILENAME should be a file in tests folder

Simple Node Query (Task 14 Query):
nodequery GRAPHDBNAME NUMBUF QTYPE INDEX [QUERYOPTIONS]

Simple Edge Query (Task 15 Query):
edgequery GRAPHDBNAME NUMBUF QTYPE INDEX [QUERYOPTIONS]


Enter menu to print the menu, exit to exit, or a command line input to execute:
batchnodeinsert NodeTestData.txt graphdb1
Replacer: Clock


Running Batch Node Insert tests....

Node Count after batch insertion on graph database: 530
Edge Count after batch insertion on graph database: 0
No. of disk pages read during batch insertion on graph database: 0
No. of disk pages written during batch insertion on graph database: 0

... Batch Node Insert tests completed successfully..

Enter menu to print the menu, exit to exit, or a command line input to execute:
batchnodedelete EdgeTestData.txt graphdb1

Running Batch Edge Insert tests....

Node Count after batch insertion on graph database: 530
Edge Count after batch insertion on graph database: 1060
No. of disk pages read during batch insertion on graph database: 3
No. of disk pages written during batch insertion on graph database: 54

... Batch Edge Insert tests completed successfully..
```

```
Enter menu to print the menu, exit to exit, or a command line input to execute:
batchedgedelete EdgeRemoveData.txt graphdb1
Number of Pages Read: 0
Number of Page writes performed: 0
Total Edge Count: 1057
Total node Count: 530
Enter menu to print the menu, exit to exit, or a command line input to execute:
batchnodedelete NodeTestData.txt graphdb1
Its Running
.............Batch Node Deletion Performed successfully.....
Number of Pages Read: 0
Number of Page writes performed: 0
Number of Total Nodes in the Database are:530
Number of Total Edges in the Database are: 1057
Enter menu to print the menu, exit to exit, or a command line input to execute:
edgequery graphdb1 1000 5 0 2 20
  - Scan the records

[ source label : 0000000001
 destination label : 0000000011
 edge label : 0000001_11 weight : 20 ]
[ source label : 0000000001
 destination label : 0000000355
 edge label : 000001_355 weight : 18 ]
[ source label : 0000000001
 destination label : 0000000047
 edge label : 0000001_47 weight : 7 ]
[ source label : 0000000002
 destination label : 0000000025
 edge label : 0000002_25 weight : 15 ]
[ source label : 0000000002
 destination label : 0000000395
 edge label : 000002_395 weight : 8 ]
[ source label : 0000000006
 destination label : 0000000161
 edge label : 000006_161 weight : 4 ]
[ source label : 0000000007
 destination label : 0000000100
 edge label : 000007_100 weight : 5 ]
[ source label : 0000000007
 destination label : 0000000473
 edge label : 000007_473 weight : 17 ]
[ source label : 0000000008
 destination label : 0000000216
 edge label : 000008_216 weight : 4 ]
[ source label : 0000000009
 destination label : 0000000094
 edge label : 0000009_94 weight : 19 ]
[ source label : 0000000010
 destination label : 0000000172
 edge label : 000010_172 weight : 10 ]
[ source label : 0000000010
 destination label : 0000000139
 edge label : 000010_139 weight : 9 ]
[ source label : 0000000011
 destination label : 0000000227
 edge label : 000011_227 weight : 11 ]
[ source label : 0000000012
 destination label : 0000000412
 edge label : 000012_412 weight : 9 ]
[ source label : 0000000012
```

```
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 edge label : 000012_278 weight : 10 ]
[ source label : 0000000013
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 edge label : 000013_355 weight : 10 ]
[ source label : 0000000014
 destination label : 0000000152
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[ source label : 0000000024
 destination label : 0000000252
 edge label : 000024_252 weight : 10 ]
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 edge label : 000026_191 weight : 15 ]
[ source label : 0000000027
 destination label : 0000000168
 edge label : 000027_168 weight : 4 ]
[ source label : 0000000028
 destination label : 0000000248
```

```
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```

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exit
make[1]: Leaving directory
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user@user-Linux ~/Documents/CSE510/minjava/javaminibase/src $ exit

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