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Abstract

Many evolving database applications warrant the use of non-traditional indexing mechanisms beyond B+-trees and hash tables. SP-GiST is an extensible indexing framework that broadens the class of supported indexes to include disk-based versions of a wide variety of space-partitioning trees, e.g., disk-based trie variants, quadtree variants, and kd-trees. This paper presents a serious attempt at implementing and realizing SP-GiST-based indexes inside PostgreSQL. Several index types are realized inside PostgreSQL facilitated by rapid SP-GiST instantiations. Challenges, experiences, and performance issues are addressed in the paper. Performance comparisons are conducted from within PostgreSQL to compare update and search performances of SP-GiST-based indexes against the B+-tree and the R-tree for text string and point data sets. Interesting performance results are presented in the paper. Results highlight the potential performance gains of SP-GiST-based indexes as well as several strengths and weaknesses of SP-GiST-based indexes that need to be addressed in future research

1 Introduction

Many emerging database applications warrant the use of non-traditional indexing mechanisms beyond B+-trees and hash tables. Database vendors have realized this need and have initiated efforts to support several non-traditional indexes, e.g., (Oracle [35], and IBM DB2 [1]).

One of the major hurdles in implementing non-traditional indexes inside a database engine is the very wide variety of such indexes. Moreover, there is tremendous overhead that is associated with realizing and integrating any of these indexes inside the engine. Generalized search trees (e.g., GiST [21] and SP-GiST [4, 3]) are designed to address this problem.

Generalized search trees (GiST [21]) and Space-partitioning Generalized search trees (SP-GiST [4, 3]) are software engineering frameworks for rapid prototyping of indexes inside a database engine. GiST supports the class of balanced trees (B+-tree-like trees), e.g., R-trees [7, 20, 32], SR-trees [24], and RD-trees [22], while SP-GiST supports the class of space-partitioning trees, e.g., tries, quadtrees, and k-d trees. Both frameworks have internal methods that furnish general database functionalities, e.g., generalized search and insert algorithms, as well as user-defined external methods and parameters that tailor the generalized index into one instance index from the corresponding index class. GiST has been tested in prototype systems, e.g., in Predator [34] and in PostgreSQL [37], and hence is not the focus of this study.

The purpose of this study is to demonstrate feasibility and performance issues of SP-GiST-based indexes. This work presents a serious attempt at implementing and realizing SP-GiST-based indexes inside PostgreSQL. Using rapid SP-GiST instantiations, several index types are realized inside PostgreSQL that index string and point data types. Performance comparisons are conducted from within PostgreSQL to compare update and search performances of one disk-based trie variant against the B+-tree for a variety of string dataset collections, and one disk-based kd-tree variant against the R-tree for two-dimensional point dataset collections. Other more sophisticated index types can be instantiated using the same SP-GiST platform. We

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plan to release the PostgreSQL version of SP-GiST around the same time we publish this paper.

The contributions of this research can be summarized as follows:

1. We realized SP-GiST inside PostgreSQL to extend the available access methods to include the class of space partitioning trees. Our implementation methodology makes SP-GiST portable. That is, SP-GiST can be realized inside PostgreSQL without recompiling PostgreSQL code.

2. We extended the indexing operations of the space partitioning trees, e.g., the trie, to include more challenging search operations, e.g., the *prefix match* search, and the *regular expression match* search.

3. We conducted extensive experiments from within PostgreSQL to compare the performance of the trie and the kd-tree against the B+-tree and the R-tree, respectively. Our results illustrate that the trie has more than 150% search performance improvement over the B+-tree performance in the case of the *exact match* search. Also, the trie has more than 2 orders of magnitude search performance improvement in the case of the *regular expression match* search. Our experiments also demonstrate that the kd-tree has more than 300% search performance improvement over the R-tree in the case of the *point match* search.

4. We realized the suffix tree index structure using the SP-GiST framework to support the *substring match* searching. Our experiments demonstrate that the suffix tree improves the search performance by more than 3 orders of magnitude over the sequential scan. The other index structures, e.g., B+-tree, and R-tree, do not support the *substring match* search.

5. We identified weaknesses of SP-GiST-based indexes compared to the B+-tree and the R-tree indexes that need to be addressed in future research. Basically, the insertion time and the index size of the SP-GiST-based indexes involve higher overhead than those of the B+-tree and the R-tree indexes.

The rest of this paper proceeds as follows. In Section 2, we highlight related work in the area of extensible indexes and generalized indexing frameworks. In Section 3, we overview space-partitioning trees, the challenges they have from database indexing point of view, and how these challenges are addressed in SP-GiST. Section 4 describes the implementation of SP-GiST inside PostgreSQL. In Section 5, we present the performance results of disk-based tries vs. B+-trees for string data sets and the performance results of disk-based kd-trees vs. R-trees for two-dimensional point data sets. Section 6 contains concluding remarks.

2 Related Work

Multidimensional searching is a fundamental operation for many database applications. Several index structures beyond B-trees [6, 11], and hash tables [14, 29], have been proposed to manage the update and search operations over spatial and multidimensional data, e.g., [17, 27, 31, 33]. These index structures include the R-tree, and its variants [7, 20, 32], the quadtree, and its variants [15, 18, 25, 39], the kd-tree [8], the disk based kd-tree variants, e.g., [9, 30], and the trie structure, and its variants [2, 10, 16]. Extensions to the B-tree have been also proposed to address indexing multidimensional attributes, such as the universal B-tree [5], and the hB-tree [13]. Extensible indexing frameworks have been proposed to instantiate a variety of index structures in an efficient way and without modifying the database engine. Extensible indexing frameworks are first proposed in [36]. GiST (*Generalized Search Trees*) is an extensible framework for B-tree-like indexes [21]. SP-GiST (*Space Partitioning Generalized Search Trees*) is an extensible framework for the family of space partitioning trees [4, 3]. An extensible bulk loading algorithm for SP-GiST is proposed in [19]. Extensible indexing structures gain more importance in the context of the object relational database management systems (ORDBMS) that are designed primarily to support new types of data and applications. The implementation of GiST in *Informix Dynamic Server with Universal Data Option* (IDS/UDO) is presented in [26]. Current commercial databases have also supported the extensible indexing frameworks, e.g., IBM DB2 [1], and Oracle [35]. The performance of the various index structures have been studied extensively. For example, a model for the R-tree performance is proposed in [38]. A comparison between quadtree and R-tree indexes in Oracle spatial is presented in [28]. Another comparative study among the R-tree variants and the PMR quadtree is presented in [23].

3 Space-partitioning Trees: Overview, Challenges, and SP-GiST

The main characteristic of space-partitioning trees is that they partition the multi-dimensional space into disjoint (non-overlapping) regions. Refer to Figures 1, 2, and 3, for a few examples of space-partitioning trees. Partitioning can be either (1) space-driven (e.g., Figure 2), where we decompose the space into equal-sized partitions regardless of the data distribution, or (2) data-driven (e.g., Figure 3), where we split the data set into equal portions based on some criteria, e.g., based on one of the dimensions.

There are many various types of trees in the class of space-partitioning trees. They differ from each other in various ways. These variations were proposed to enhance the performance of the space-partitioning trees.

Without loss of generality, and for the simplicity of this discussion, we highlight below some of the important variations in the context of the trie data structure.

- **Node Shrinking** (refer to Figure 2) - The problem is that with space-driven partitions, some partitions may end up being empty. So, the question is: Do we allow that empty partitions be omitted? For example, the difference between the standard trie (Figure 2(a)) and the forest trie (Figure 2(b)) is that the latter allows for empty partitions to be eliminated.

- **Path Shrinking** (refer to Figure 1) - The problem here is that we may want to avoid lengthy and skinny paths from a root to a leaf. Paths of one child can be collapsed into one node. For example, the Patricia trie allows for leaf-shrinking (Shrinking single child nodes at the leaf level nodes, e.g.,Figure 1(b)), while it is also possible to allow for path-shrinking (Shrinking single child nodes at the non-leaf level nodes, e.g., Figure 1(c)), or even no shrinking at all (Figure 1(a)).

- **Clustering** - This is one of the most serious issues when addressing disk-based space-partitioning trees. The problem is that tree nodes do not map directly to disk pages. In fact, tree nodes are usually much smaller than disk pages. So, the question is: How do we pack tree nodes together into disk pages with the objective of reducing disk I/Os while performing tree operations (e.g., search or insert)? An optimal and practical node-packing algorithm already exists that solves this issue [12].

Other characteristics of importance to space-partitioning trees include the bucket size of leaf nodes, the resolution of the underlying space, the support for various data types, the splitting of nodes (when to trigger a split and how node splitting is performed), and how concurrency control of space-partitioning trees is performed. For more discussion on these issues as they relate to space-partitioning trees, the reader is referred to [4, 3].

3.1 SP-GiST

SP-GiST is an extensible indexing framework that broadens the class of supported indexes to include disk-based versions of a wide variety of space-partitioning trees, e.g., disk-based trie variants, quadtree variants, and kd-trees.

SP-GiST provides a set of methods, called *internal methods*, that are shared among all the space partitioning trees. The internal methods include a method for the insertion, i.e., *Insert()*, a method for the search, i.e., *Search()*, and a method for the deletion, i.e.,*Delete()*. The internal methods are the core

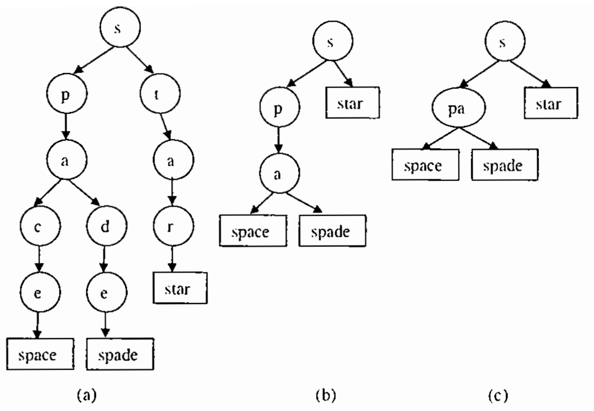


Figure 1: Variant trie structures. (a) No tree shrink, (b) Leaf shrink, (c) Path shrink.

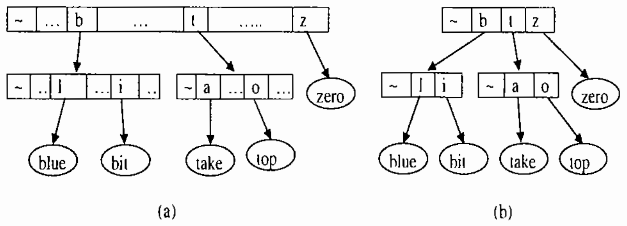


Figure 2: Variant trie structures. (a) No node shrink, (b) Node shrink.

of SP-GiST, and they implement the common features among the space partitioning trees.

To handle the differences among the various index structures, SP-GiST provides for the developers, a set of parameters, called *interface parameters*, and a set of methods, called *external methods*.

The interface parameters include:

- *NodePredicate:* This parameter specifies the predicate type at the index nodes.

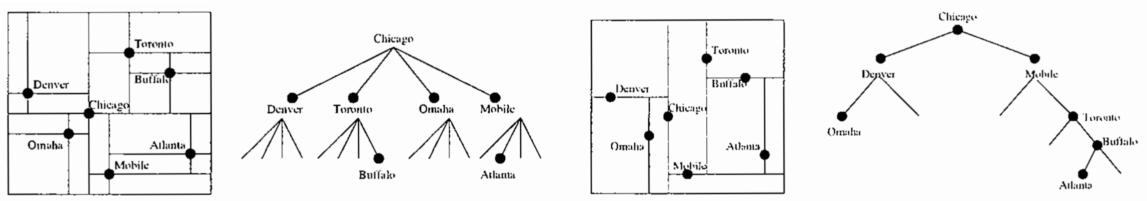
- *KeyType:* This parameter specifies the data type stored at the leaf nodes.

- *NumberofSpacePartitions:* This parameter specifies the number of disjoint partitions produced at each decomposition.

- *Resolution:* This parameter limits the number of space decompositions and is set depending on the required granularity.

- *PathShrink:* This parameter specifies how the index tree can shrink. *PathShrink* takes one of three possible values: *NeverShrik*, *LeafShrink*, and *TreeShrink*.

- *NodeShrink:* A *Boolean* parameter that specifies whether the empty partitions should be kept in the index tree or not.



(a) Point quadtree (b) kd-tree

Figure 3: Example of a point quadtree and a k-d tree.

	trie	k-d tree

Parameters	PathShrink = TreeShrink, NodeShrink = True
	BucketSize = B
	NoOfSpacePartitions = 27
	NodePredicate = letter or blank
	Key Type = String
		PathShrink = NeverShrink, NodeShrink = False
		BucketSize = 1
		NoOfSpacePartitions = 2
		NodePredicate = "left", "right", or blank
		Key Type = Point

Consistent(E,q,level)	If (q[level]==E.letter) OR (E.letter ==blank AND level > length(q)) Return True, else Return False	If (level is odd AND q.x satisfies E.p.x) OR (level is even AND q.y satisfies E.p.y) Return True, else Return False
PickSplit(P,level)	Find a common prefix among words in P Update level = level + length of the common prefix Let P predicate = the common prefix Partition the data strings in P acording to the character values at position "level" If any data string has length < level, Insert data string in Partition "blank" If any of the partitions is still over full Return True, else Return False	Put the old point in a child node with predicate "blank" Put the new point in a child node with predicate "left" or "right" Return False

Table 1: Instantiation of the trie and k-d tree using SP-GiST.

- *BucketSize:* This parameter specifies the maximum number of data items a data node can hold.

For example, to instantiate the trie variants presented in Figure 1(a), (b), and (c), we set *PathShrink* parameter to values *NeverShrink*, *LeafShrink*, and *TreeShrink*, respectively. To instantiate the trie variants presented in Figure 2(a), and (b), we set the *NodeShrink* parameter to values FALSE, and TRUE, respectively. In the case of the quadtree and the kd-tree presented in Figure 3, the *NoOfSpacePartitions* parameter is set to values 4, and 2, respectively.

The SP-GiST external methods include a method to specify how the space is decomposed, and how the data items are distributed over the new partitions, i.e., *PickSplit()*. *PickSplit()* is called by the internal method *Insert()* when a split is needed. The external methods also include a method to specify how to navigate through the index tree, i.e., *Consistent()*. *Consistent()* is called by the internal methods *Insert()*, and *Search()* to guide the tree navigation.

In Table 1, we illustrate the instantiation of the dictionary trie and the kd-tree using SP-GiST framework. Notice that from the developer's point of view, coding of the methods in Table 1 is all what the developer needs to provide.

For the index storage, SP-GiST provides a default clustering technique that maps index nodes into disk pages. The clustering technique is based on [12], and it is proven to generate minimum page-height trees. The clustering technique and the SP-GiST storage layer are discussed in more detail in Section 4.2.

4 Implementation Issues and Challenges

In this section we discuss the challenges and implementation issues of realizing SP-GiST framework inside PostgreSQL. First, we give an overview of the main extensible features of PostgreSQL. Then, we discuss the implementation of SP-GiST.

4.1 PostgreSQL Extensibility

PostgreSQL is an open-source object-relational database management system. The extensibility in PostgreSQL is because most of its functionalities are table-driven. That is, the information about the available data types, access methods, operators, etc., is stored in the system catalog tables. PostgreSQL can also incorporate user-defined functions into the engine through dynamically loadable modules, e.g.,

SP-GiST insert statement	INSERT INTO pg_am VALUES ('SP_GiST', 0, 20, 20, 0, 'f', 'f', 'f', 't', 'spgistgettuple', 'spgistinsert', 'spgistbeginscan', 'spgistrescan', 'spgistendscan', 'spgistmarkpos', 'spgistrestrpos', 'spgistbuild', 'spgistbulkdelete', '-' , 'spgistcostestimate');

Column name	**Column description**	**SP-GiST function/value**
amname	Name of the access method	SP_GiST
amowner	User ID of the owner	0
amstrategies	Max number of operator strategies for this access method	20
amsupport	Max number of support functions for this access method	20
amorderstrategy	The strategy number for entries ordering	0
amcanunique	Support unique index flag	FALSE
amcanmulticol	Support multicolumn flag	FALSE
amindexnulls	Support null entries flag	FALSE
amconcurrent	Support concurrent update flag	TRUE
amgettuple	"Next valid tuple" function	'spgistgettuple'
aminsert	"Insert this tuple" function	'spgistinsert'
ambeginscan	"Start new scan" function	'spgistbeginscan'
amrescan	"Restart this scan" function	'spgistrescan'
amendscan	"End this scan" function	'spgistendscan'
ammarkpos	"Mark current scan position" function	'spgistmarkpos'
amrestrpos	"Restore marked scan position" function	'spgistrestrpos'
ambuild	"Build new index" function	'spgistbuild'
ambulkdelete	Bulk-delete function	'spgistbulkdelete'
amvacuumcleanup	Post-VACUUM cleanup function	—
amcostestimate	Function to estimate cost of an index scan	'spgistcostestimate'

Table 2: pg_am catalog table entry for SP-GiST.

shared libraries. These loadable modules can be used to implement the functionality of new operators or access methods.

The implementation of SP-GiST inside PostgreSQL makes use of the following features:

- **Defining New Interface Routines:** Each access method in PostgreSQL has a set of associated functions that perform the functionality of that access method. These functions are called, *interface routines*. The interface routines can be implemented as loadable modules.

- **Defining New Operators:** In the operator definition, we specify the data types on which the operator works. We also specify a set of properties that the query optimizer can use in evaluating the access methods.

- **Defining New Operator Classes:** Operator classes specify the data type and the operators on which a certain access method can work. In addition to linking an access method with data types and operators, operator classes allow users to define a set of functions called *support functions*, that are used by the access method to perform internal functions.

4.2 Realizing SP-GiST Inside PostgreSQL

The access methods currently supported by PostgreSQL (version 8.0.1) are:

1. **Heap access:** Sequential scan over the relation.
2. **B+-tree:** The default index access method.
3. **R-tree:** To support queries on spatial data.
4. **Hash:** To support simple equality queries.
5. **GiST:** Generalized index framework for the B-tree-like structures.

By realizing SP-GiST inside PostgreSQL, we extend the access methods to include the family of space partitioning trees, e.g., the kd-tree, the trie, the quadtree and their variants. Our design objectives are:

1. Fully isolate the definition of the SP-GiST core (i.e., internal methods) from the definition of the extensions (i.e., external methods).
2. Implement SP-GiST as a portable access method. That is, not only SP-GiST extensions be pluggable modules, but also SP-GiST core be a pluggable module.
3. Support a wide range of index operations. For example, we extend the trie operations to include:

Query type	Query Semantic
Equality query	Return the keys that exactly match the query predicate.
Prefix query	Return the keys that have a prefix that matches the query predicate.
Regular expression query	Return the keys that match the query regular expression predicate.
Substring query	Return the keys that have a substring that matches the query predicate.
Range query	Return the keys that are within the query predicate range.

Table 3: The semantic of the query types.

trie		kd-tree	
Equality operator '='	*Prefix match operator* '?='	*Equality operator* '@'	*inside operator* '∧'

CREATE OPERATOR = (
leftarg = VARCHAR,
rightarg = VARCHAR,
procedure = trieword_equal,
commutator = =,
restrict = eqsel,
);
	CREATE OPERATOR ?= (
	leftarg = VARCHAR,
	rightarg = VARCHAR,
	procedure = trieword_prefix,
	restrict = likesel,
	);
		CREATE OPERATOR @ (
		leftarg = POINT,
		rightarg = POINT,
		procedure = kdpoint_equal,
		commutator = @,
		restrict = eqsel,
		);
			CREATE OPERATOR ∧ (
			leftarg = POINT,
			rightarg = BOX,
			procedure = kdpoint_inside,
			restrict = contsel,
			);

Table 4: The trie and kd-tree operators definitions.

the *prefix match* search, and the *regular expression match* search. We also realize the suffix tree to support the *substring match* search.

In the following, we discuss how we achieve our objectives along with the implementation challenges.

- **Realization of SP-GiST Internal Methods**

  SP-GiST internal methods are the core part of the SP-GiST framework, and they are shared among all the space partitioning tree structures. To realize the internal methods, we use PostgreSQL access methods' interface routines (See Section 4.1). A new row is inserted into the *pg_am* table to introduce SP-GiST to PostgreSQL as a new access method (See Table 2). *pg_am* is a system catalog table that stores the information about the available access methods. The internal methods are defined as the interface routines of that access method.

  In Table 2 we illustrate the *pg_am* table's entry for SP-GiST. The name of the new access method is set to 'SP_GiST'. We set the maximum number of the possible strategies (i.e., operators linked to an access method), and the maximum number of possible support functions to 20. Since SP-GiST index entries do not follow a certain order, we set the value of the *amorderstrategy* to 0. This value means that there is no strategy for ordering the index entries. The SP-GiST internal methods (e.g., *spgistgettuple()*, *spgistinsert()*, etc.) are assigned to the corresponding interface routine columns (e.g., *amgettuple*, *aminsert*, etc.).

  Estimating the cost of the SP-GiST index scan is performed by function *spgistcostestimate()*, which is assigned to column *amcostestimate*. *spgistcostestimate()* uses the generic cost estimate functions provided by PostgreSQL. Four cost parameters are estimated:

  1. **Index selectivity:** The index selectivity is the estimated fraction of the underlying table rows that will be retrieved during the index scan. The selectivity depends on the operator being used in the query. We associate with each operator that we define, a procedure that estimates the selectivity of that operator.
  2. **Index correlation:** The index correlation is set to 0 because there is no correlation between the index order and the underlying table order.
  3. **Index startup cost:** The startup cost is the CPU cost of evaluating any complex expressions that are arguments to the index. These expressions are evaluated once at the beginning of the index scan.
  4. **Index total cost:** The total cost is the sum of the startup cost plus the disk I/O cost. The estimated disk I/O cost depends on the index selectivity and the index size.

  SP-GiST internal methods are implemented as a dynamically loadable module that is loaded by the PostgreSQL dynamic loader when the index is first used.

- **Definition of SP-GiST Operators**

  The various SP-GiST index structures have different sets of operators to work on. For the trie index structure, we define the three

trie	kd-tree	suffix tree
CREATE OPERATOR CLASS SP_GiST_trie FOR TYPE VARCHAR USING SP_GiST AS OPERATOR 1 =, AS OPERATOR 2 #=, AS OPERATOR 3 ?=, FUNCTION 1 trie_consistent, FUNCTION 2 trie_picksplit, FUNCTION 3 trie_getparameters;	CREATE OPERATOR CLASS SP_GiST_kdtree FOR TYPE POINT USING SP_GiST AS OPERATOR 1 @, OPERATOR 2 ∧, FUNCTION 1 kdtree_consistent, FUNCTION 2 kdtree_picksplit, FUNCTION 3 kdtree_getparameters;	CREATE OPERATOR CLASS SP_GiST_suffix FOR TYPE VARCHAR USING SP_GiST AS OPERATOR 1 @=, FUNCTION 1 suffix_consistent, FUNCTION 2 suffix_picksplit, FUNCTION 3 suffix_getparameters;

Table 5: The trie, kd-tree and suffix tree operator class definitions.

operators: '=', '#=', and '?=', to support the equality queries, the prefix queries, and the regular expression queries, respectively. For the regular expression queries, the SP-GiST trie supports currently, the wildcard character; '?', that matches any single character. In the case of the kd-tree, we define two operators; '@' and '∧', to support the equality and range queries, respectively. We define one operator for the suffix tree, i.e., '@=', to support the substring match queries. The semantics of the query types is given in Table 3.

An example of the operators' definitions is given in Table 4. Each operator is linked to a procedure that performs the operator's functionality, e.g., *triword_equal()*, *kdpoint_equal()*. Other properties can be defined for each operator. For example, the *commutator* clause specifies the operator that the query optimizer should use, if it decides to switch the original operator's arguments.

Estimating the selectivity of each operator is performed by the procedures defined in the *restrict* clause. We use procedures provided by PostgreSQL, e.g., *eqsel()*, *contsel()*, *likesel()*. *eqsel()* estimates the selectivity of the equality operators. *contsel()* estimates the selectivity of the containment operators (i.e., range search), whereas, *likesel()* estimates the selectivity of the similarity operators, e.g., *LIKE* operator. The query optimizer uses these procedures to estimate the index selectivity and the index scan cost.

- **Realization of SP-GiST External Methods**

The SP-GiST external methods and interface parameters capture the differences among the various types of SP-GiST index structures. To realize the external methods inside PostgreSQL, we use the access methods' support functions. The support functions are provided within the definition of the operator classes (See Section 4.1). The definitions of the trie operator class (*SP-GiST_trie*), the kd-tree operator class (*SP-GiST_kdtree*), and the suffix tree operator class (*SP-GiST_suffix*) are given in Table 5. *SP-GiST_trie*, and *SP-GiST_suffix* use the data type VARCHAR, whereas, *SP-GiST_kdtree* uses the data type POINT. Each operator class defines three support functions. *getparameters()* functions are used to set the index parameters (e.g., *BucketSize, NoOfSpacePartitions*) to their proper values, as illustrated in Table 1.

Two examples for creating and querying the trie and kd-tree indexes are given in Table 6. The *USING* clause in the *CREATE INDEX* statement specifies the name of the access method to be used, that is 'SP_GiST' in our case. We then specify the column name to be indexed, and the corresponding operator class.

SP-GiST external methods are implemented as a dynamically loadable module that is loaded when the index is first used.

In Figure 4, we illustrate the architecture of SP-GiST inside PostgreSQL. The implementation of the SP-GiST core (i.e., internal methods) is fully isolated from the implementation of the SP-GiST extensions (i.e., external methods). The link between the core and the extensions is achieved through PostgreSQL operator classes. The communication among the methods is through the PostgreSQL function manager. The portability is achieved because both the SP-GiST core and extensions are loadable modules. That is, SP-GiST can be realized inside PostgreSQL database without recompiling PostgreSQL code. We extended the internal methods to include functions, i.e., *PostgreSQL storage interface*, to communicate with the PostgreSQL storage manager for the allocation and retrieval of disk pages. We describe the SP-GiST storage layer in more detail in the next section.

- **SP-GiST Storage Layer**

	trie		kd-tree	

Index creation	CREATE TABLE word_data (
	name VARCHAR(50), id INT);
	
	CREATE INDEX sp_trie_index ON word_data
	USING SP_GiST (name SP_GiST_trie);
			CREATE TABLE point_data (
			p POINT , id INT);
			
			CREATE INDEX sp_kdtree_index ON point_data
			USING SP_GiST (p SP_GiST_kdtree);	

	equality query	regular expression query	equality query	range query

Queries	SELECT *
	FROM word_data
	WHERE name = 'random';
		SELECT *
		FROM word_data
		WHERE name ?= 'r?nd?m';
			SELECT *
			FROM point_data
			WHERE p @ '(0,1)';
				SELECT *
				FROM point_data
				WHERE p ∧ '(0,0,5,5)';

Table 6: The trie and kd-tree index creation and querying.

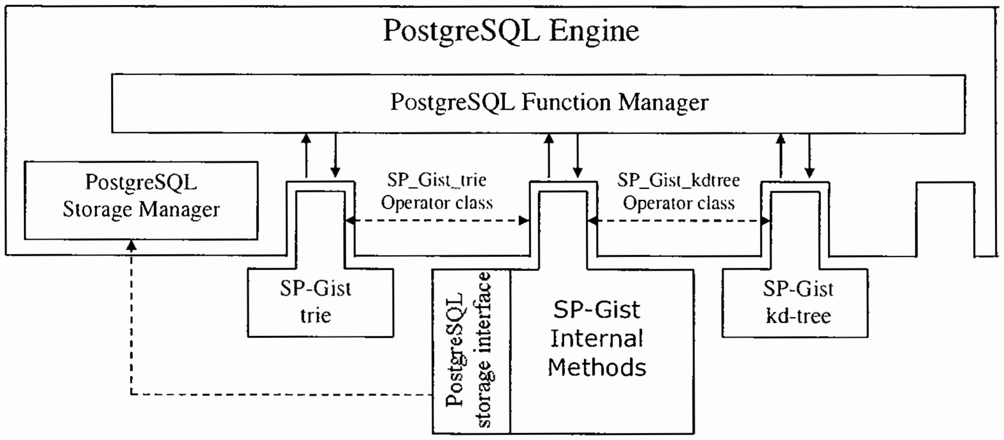

PostgreSQL Engine
PostgreSQL Function Manager
PostgreSQL Storage Manager
SP_Gist_trie Operator class
SP_Gist_kdtree Operator class
SP-Gist trie
PostgreSQL storage interface
SP-Gist Internal Methods
SP-Gist kd-tree

Figure 4: SP-GiST architecture inside PostgreSQL.

SP-GiST manages the disk pages by the internal method *Insert()* and the clustering technique that maps index nodes into disk pages. Although the page allocation and retrieval are performed by PostgreSQL, the page layout is not interpretable by PostgreSQL as it does not follow PostgreSQL page formatting. The clustering technique that SP-GiST uses for mapping index nodes into disk pages is proposed in [12], and it is proven to generate minimum page-height trees. Therefore, it achieves the minimum I/O access in the case of searching. However, our experiments demonstrate that achieving the minimum page-height tree causes the index size to grow rapidly. The reason is that, to always maintain a minimum page-height, the clustering technique has to continuously move the nodes between the pages at each time a split occurs to a node. This continuous change results in increasing the number of pages significantly, and reducing the pages' utilization.

We modified the clustering technique to increase the pages' utilization and hence reduce the index size without significantly degrading the search performance. Although the modified technique is not guaranteed to generate minimum page-height trees, the experiments demonstrate that it performs generally well. The summary of our modifications is as follows. When a tree node splits into multiple nodes, we check:

1. If the newly created nodes can fit into their parent's page, then we store the nodes into that page.

2. If the newly created nodes cannot fit into their parent's page, and the tree page-height will increase, then we store the nodes into a new page and invoke the clustering technique of [12].

3. If the newly created nodes cannot fit into their parent's page, but the tree page-height will not change, then we store the nodes into an existing page, termed *auxiliary_page*. If the *auxiliary_page* is full, we create a new page to be the current *auxiliary_page*.

5 Experiments

In this section, we present our experimental results. We realized three index structures using SP-GiST framework: the trie, the kd-tree, and the suffix tree. The parameters settings of the indexes are as given in Table 1. The *BucketSize* parameter is set to 100 in the case of the trie and the suffix tree. We conduct our experiments from within PostgreSQL. We compare the performance of the SP-GiST trie against the performance of the B+-tree in the context of text string data. We also compare the performance of the SP-GiST kd-tree against the performance of the R-tree in the context of point data. The performance of the suffix tree is compared against the sequential scan because the other access methods do not support the substring match operations.

For the trie versus B+-tree experiments, we generate datasets with size ranges from 500K words to 32M words. The word size (key size) is uniformly distributed over the range [1, 15], and the alphabet letters are from 'a' to 'z'. Our experiments illustrate that the trie has a better search performance than that of the B+-tree. In Figures 5, and 6, we demonstrate the search performance under three search operations; *exact match*, *prefix match*, and *regular expression match*. Figure 5 illustrates that in the case of the *exact match* search, the trie has more than 150% search time improvement over the B+-tree, and that, the trie scales better especially with the increase of the realtion size.

For the *regular expression match* search (Figure 6), our experiments illustrate that the trie achieves more than 2 orders of magnitude search time improvement. Recall that, we only allow for the wildcard, '?', that matches any single character. We notice that the B+-tree performance is very sensitive to the positions of the wildcard; '?' in the search string. For example, if '?' appears in the 2nd or the 3rd positions, then the B+-tree performance will degrade significantly. Moreover, if '?' appears as the first character in the search string, then the B+-tree index will not be used at all, and a sequential scan is performed. The reason for this sensitivity is that the B+-tree makes use only of the search string's prefix that proceeds any wildcards. In contrast, the trie makes use of any non-wildcard characters in the search string to navigate in the index tree. Therefore, the trie is much more tolerant for the *regular expression match* queries. For example, to search for expression '?at?r', the trie matches all the entries of the tree root node with '?', then the 2nd and the 3rd tree levels are filtered based on letters 'a' and 't', respectively. At the 4th level of the tree, the entries of the reached nodes are matched with '?', and then the 5th level is filtered based on letter 'r'.

For the *prefix match* search (Figure 5), our experiments illustrate that the B+-tree has a better performance over the trie. The reason is that having the keys sorted in the B+-tree leaf nodes, allows the B+-tree to answer the *prefix match* queries efficiently. In contrast, the trie has to fork the navigation in the index tree in order to reach all the keys that match the search string.

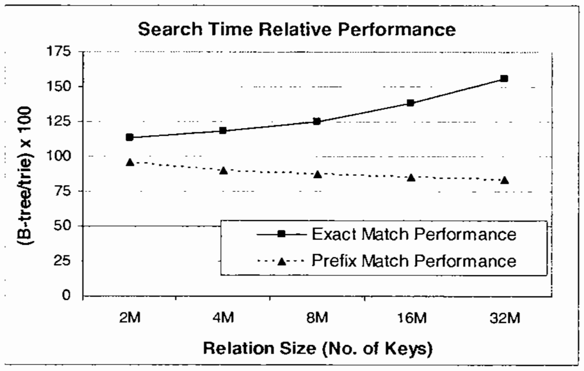


Figure 5: The search performance of the B+-tree vs. the trie.

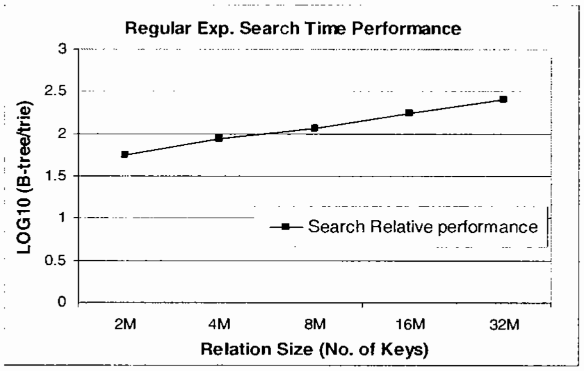


Figure 6: The regular exp. search of the B+-tree vs. the trie.

In Figure 7, we present the search time standard deviation of the trie in the case of the *exact match* search to study the effect of the variation of the tree depth on the search performance. The insertion time and the index size of the B+-tree and the trie are presented in Figures 8 and 9, respectively. The figures demonstrate that the B+-tree scales better with respect to both factors. The reason is that the trie involves a higher number of nodes and a higher number of node splits than the B+-tree because the trie node size is much smaller than the B+-tree node size. In Figures 10 and 11, we present the B+-tree and the trie maximum tree height in nodes and pages, respectively. Although, the trie has higher maximum node-height, as it is an unbalanced tree, the maximum page-height is almost the same as the B+-tree page-height. Recall that SP-GiST uses a clustering technique that tries to minimize the tree maximum page height, which is effective.

For the comparison of the kd-tree against the R-tree, we conduct our experiments over two-dimensional

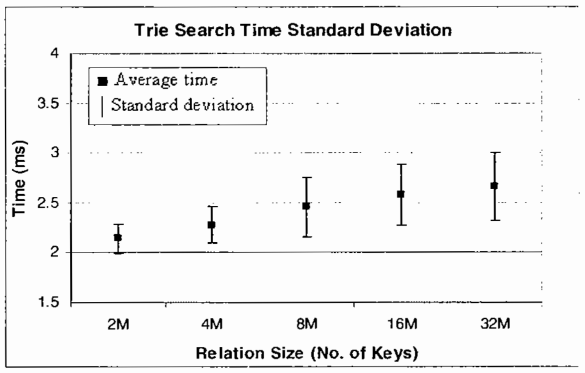


Figure 7: The trie search time standard deviation

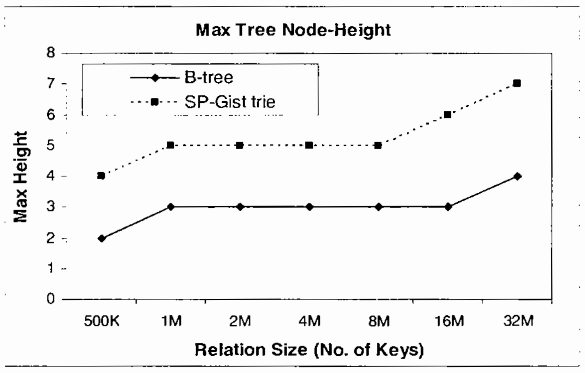


Figure 10: The maximum tree height in nodes.

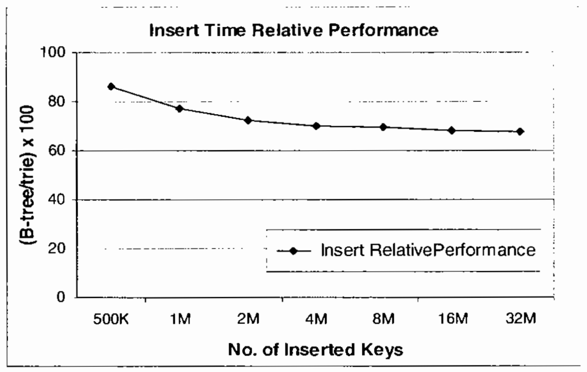


Figure 8: The insert performance of the B+-tree vs. the trie.

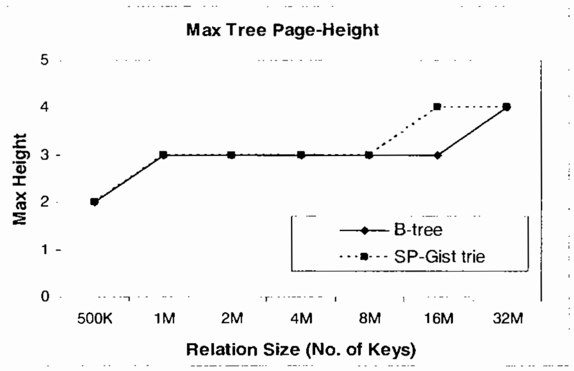


Figure 11: The maximum tree height in pages.

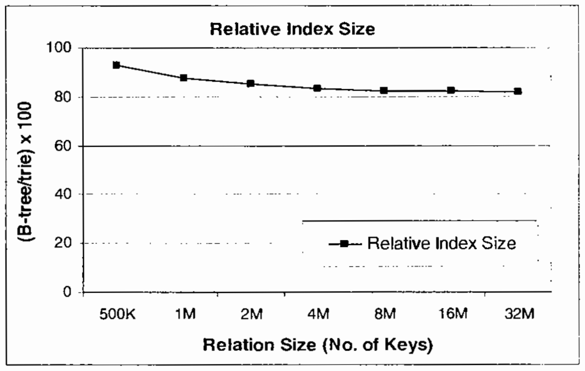


Figure 9: The index size of the B+-tree vs. the trie.

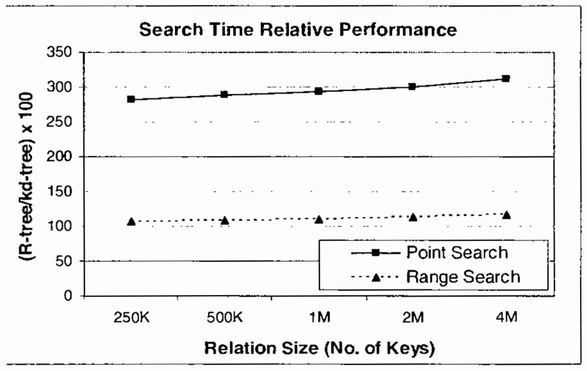


Figure 12: The search performance of the R-tree vs. the kd-tree.

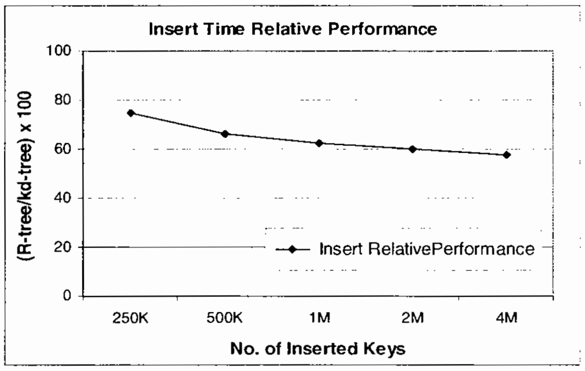


Figure 13: The insert performance of the R-tree vs. the kd-tree.

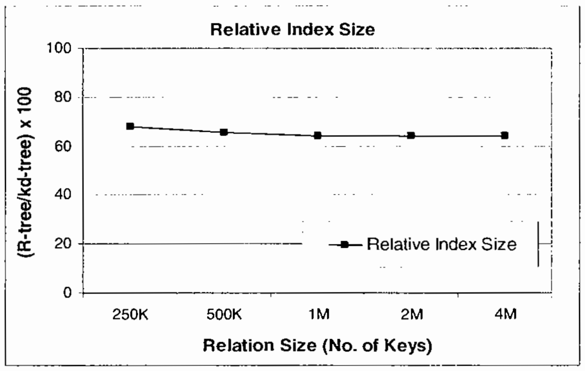


Figure 14: The index size of the R-tree vs. the kd-tree.

point datasets. The x-axis and the y-axis range from 0 to 100. We generate datasets of size that ranges from 250K to 4M two-dimensional points. In Figure 12, we illustrate the search performance under two search operations: the *point match* search, and the *range* search. The figure illustrates that the SP-GiST kd-tree has more than 300% search time improvement over the R-tree in the case of the *point match* search, and it has around 125% performance gain in the case of the *range* search. However, the experiments demonstrate that the R-tree has better insertion time (Figure 13), and better index size (Figure 14) than the kd-tree. The reason is that the kd-tree is a binary search tree, where the node size (*BucketSize*) is 1, and almost every insert results in a node split. Therefore, the number of the kd-tree nodes is very large, and in order for the storage clustering technique to reduce the tree page-height, it has to degrade the index page utilization, which results in an increase in the index size.

With respect to the suffix tree performance, we illustrate in Figure 15, the significant performance gain of using the suffix tree index to support the *substring match* search. The performance gain is more than 3 order of magnitude over the sequential scan search. The other types of index structures, e.g., B+-tree, do not support the *substring match* search.

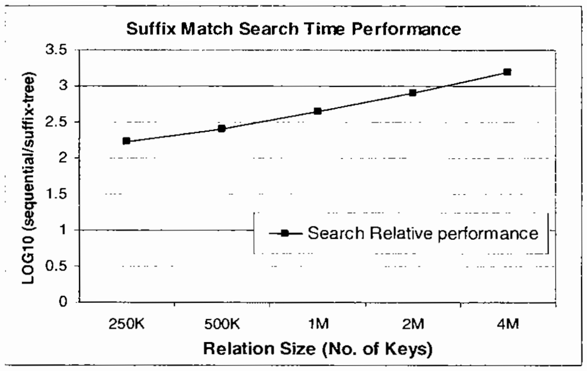


Figure 15: The suffix tree search performance.

6 Conclusion and Future Research

We presented a serious attempt at implementing and realizing SP-GiST-based indexes inside PostgreSQL. We realized three index structures; namely one variant of a forest trie, a kd-tree and a suffix tree. Several implementation challenges, experiences, and performance issues are addressed in the paper. Our experiments demonstrate the potential gain of the SP-GiST indexes. For example, the trie has more than 150% search performance improvement over the B+-tree in the case of the *exact match* search, and it has more than 2 orders of magnitude search performance gain over the B+-tree in the case of the *regular expression match* search. The kd-tree also has more than 300% search performance improvement over the R-tree in the case of the *point match* search. Our experiments demonstrate several weaknesses of SP-GiST indexes that need to be addressed in future research. For example, the insertion time and the index size of the SP-GiST indexes involve higher overhead than those of the B+-tree, and the R-tree indexes.

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