

Deferred secondary index update with *LSM-trees*

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ABSTRACT

Log-Structured merge-trees (LSM-trees) are becoming more and more widely adopted as a staple data structure in secondary storage database management systems, ending the half-a-century-long dominance of B-trees. The major LSM-tree's advantage is that it writes new data and old data updates on disk always sequentially. It is possible due to LSM-tree's ability to store many versions of the same key - it allows to LSM-based tables do not read and delete old data explicitly from primary index on such operations as deletion or replace to delete old data. Data is deleted by new data during compaction instead. But this advantage is nullified by secondary indexes, because replace/delete-like operations require read and delete old data from each secondary index explicitly. This paper presents a modification for LSM-tree data structure, which allows to do not read any index on replace/delete operations even if there are non-secondary indexes in the table. Experimental research of the modified LSM-tree shows write speed growth 1.5 to 10 times against original LSM-tree on tables with 2-4 non-unique secondary indexes. And the more secondary indexes there are, the faster the new LSM-tree works on write operations.

PVLDB Reference Format:

Vladislav Shpilevoy, Konstantin Osipov, Dmitry Volkanov. Deferred secondary index update with LSM-trees. *PVLDB*, 11 (5): xxxx-yyyy, 2018.

DOI: <https://doi.org/TBD>

1. INTRODUCTION

Log-Structured Merge trees were developed for write-intensive tasks in 1990th and were used in file systems and for reserve copying. But their prevalence was restricted by hidden reads.

These are the reads which accompany writes: e.g. when its necessary to delete old data from a secondary index after an update, or check an unique or a foreign key constraint. A significant amount of reads in a modern database is hidden. Such reads, when followed by a write, cost nearly nothing

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Proceedings of the VLDB Endowment, Vol. 11, No. 5
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DOI: <https://doi.org/TBD>

in a B-tree, but can penalize performance of an LSM-tree based table to an extent when its write advantage becomes completely diluted.

With Solid-State Drive (SSD) appearance cost of random writes had started contribute to overall performance way more heavily than cost of random reads, and nowadays the LSM-tree is considered to be a standard data structure for databases. For example, it is used in LevelDB, RocksDB, Cassandra, Tarantool, BigTable, Hbase, Riak, MySQL (MyRocks).

However SSD does not help in a special case, which is very popular and dilutes LSM-tree's ability to store multiple versions of the same keys. It is linked with LSM-tree compaction algorithm, and appears on tables with multiple indexes.

In a primary LSM-tree based index any replace or delete operation is executed with no hidden reads because of LSM-tree ability to store multiple key versions. A new tuple is just inserted into memory and after some compactions discards old tuples. But it is not possible if there are secondary indexes. If a table contains secondary indexes, any update operation must read an old tuple from a primary index, extract from it secondary keys and delete them from each secondary index explicitly. That is any update of such table produces hidden reads from a primary index.

Primary index read and explicit old tuple deletion can not be avoided in classic LSM-tree, because it deletes old versions of the key only if these versions are equal by the key. If a request changes a secondary key in an existing tuple and does not delete old one, then it is not deleted from a secondary index. LSM-tree considers new and old tuple not to be different versions of the same key, but to be different keys.

The paper describes a new LSM-tree compaction algorithm, a new LSM-tree based table update and read algorithms. Replace and delete operations on the new LSM-tree do not any reads regardless of secondary index number, if all of them are not unique. Experiments show exponential requests number per second (RPS) grow on some loading types and some schemas. For example, on a table with 3 non-unique secondary indexes and replace/delete batched requests RPS increased up to 10 times.

2. BACKGROUND AND MOTIVATION

This section defines some LSM-tree basics: how it is can be stored on disk and in memory, how compaction, update and read works. What LSM-tree parameters are typically configurable.

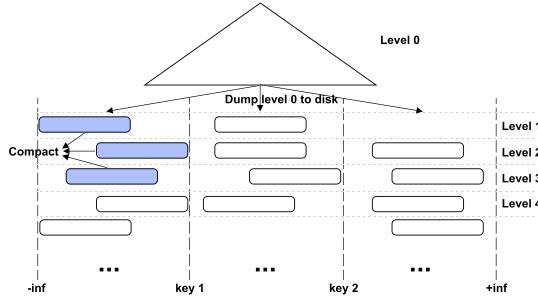


Figure 1: LSM-tree ranges dump and compaction

LSM-tree is a data structure optimized for write-intensive tasks. It has multiple levels: zero-level is stored in a memory and other on a disk. Zero-level amasses updates and periodically is dumped on to a disk to become first level. Zero-level after dump are cleaned up and collects new updates. And so on.

Zero-level usage allows to write updates to a disk in batches regardless of their order, keys, types. Even delete is put in a zero-level as a tuple of a special type.

When level number became too big, the LSM-tree is compacted - several levels are merged in a new one. During compaction new tuples discard old tuples of the same key. For example, delete discards all older data and sometimes itself; replace discards all older data, but not itself.

LSM-tree can store levels in multiple ways. For example, memory level can be B-tree or Red-Black tree. Disk levels can be organized as B-trees or sorted arrays. In the paper sorted arrays on disk and B+ tree in memory are considered.

2.1 Compaction

Each level consists of multiple sublevels. Each sublevel is an array sorted by a key (in a case of LSM-tree index the key consists of index parts) and containing a specific key values range. During compaction some sublevels of each levels are merge-sorted into a new sorted array. It is known, that if one key version is on level i and another on $j < i$, then the key version on level j is newer and another one is discarded when compacted.

Compaction procedure is needed to reduce level count and to discard old tuples to make room for new ones. Compaction frequency is regulated by LSM-tree parameters level size ratio and maximal sublevels count. In each pair of neighbour levels i and $i + 1$ size of a level $i + 1$ must be greater than level i size * level size ratio at least. If maximal sublevels count per level is exceeded or level size ratio is violated, then compaction procedure merges as much sublevels as needed to satisfy both limitations.

In practice, sublevels are produced by memory level dump and by splitting index key values into ranges, when each range stores and maintains its own sublevels independently of other ranges (see Figure 1).

2.2 LSM-tree based table structure

In LSM-tree based table each index is an LSM-tree, sorted by the index parts. It is common pattern, that a table has one primary index and a number of secondary indexes. A primary index always is unique, and stores full tuples, including all indexed and not indexed fields, as they were inserted by an user. A secondary index stores only its own

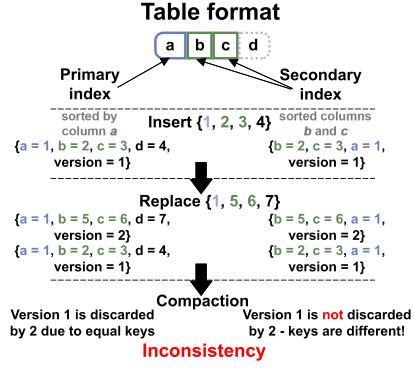


Figure 2: LSM-tree based table inconsistency example

key parts and primary index parts to save memory. Such indexes are called non-covering. Primary parts are used as link to a full tuple in a primary index, when a search uses a secondary index only.

The described pattern is not unique feature of LSM-tree based tables. For example, SQLite secondary indexes based on B-tree are not covering by default too. And each SQLite table has unique primary index even if an user did not specified it explicitly.

Since secondary indexes stores primary index parts, they are linked with primary indexes. And if a tuple does not exist in a primary index, the same tuple can not exist in a secondary index. This is the reason, why hidden reads are indispensable - if a tuple is replaced with another secondary key or deleted from a primary index, then its old version must be deleted from each secondary index by old secondary key, else a table indexes are not consistent.

2.3 Multiple indexes update problem

LSM-tree ability to manage multiple versions of a key allows to avoid hidden reads on such operations as replace or delete which can not break consistency if there is only a primary index in a table and no foreign key constraints. Such operations are known as **blind-writes** [6]. Blind-writes are much faster than non-blind insert or update operations, which read an old tuple in a worst case from a disk to check for duplicate or apply update operations.

The big problem of LSM-tree based tables is that in presence of secondary indexes all writes become non-blind. See Figure 2 for example of inconsistency if replace is blind and a table has secondary index. Here a table is defined with 4 columns: first is part of a primary index, 2 and 3 are parts of a secondary index, and 4 is not indexed. $\text{Replace}\{1, 5, 6, 7\}$ before executed must read old tuple from a primary index by the key $\{1\}$, extract the secondary key $\{2, 3\}$, delete it from the secondary index, and only then insert the new tuple. If the old tuple is not deleted, then during compaction it becomes garbage with no link to a full tuple in the primary index.

Since disk access is much slower than memory access, secondary index presence destroys LSM-tree versions advantage. In the next section a new LSM-tree update algorithm is presented reviving versions and blind-writes.

3. DESIGN AND IMPLEMENTATION

Below the basics of a new algorithm are described, followed by three sections, each of which unfolds one of enclosed part of the algorithm.

The key idea of the algorithm is that deletion of old data can be deferred until primary index compaction stage. It allows to do not hidden reads during replace and delete by primary key operations since they use hidden reads only to learn and delete old secondary key versions, not to check consistency. It works on tables with non-unique secondary indexes only, because it is impossible to break consistency of non-unique secondary index using delete or replace operations.

Obviously, it is not true if there are unique secondary indexes. For example, consider a table with columns $\{a, b\}$, unique primary index on $\{a\}$ and unique secondary index on $\{b\}$. A table contains two records: $\{1, 1\}$ and $\{2, 2\}$. It is impossible now to do replace $\{1, 2\}$, because it leads to duplicate in the secondary index.

Of course, in MySQL, for example, replace would delete both old records, but such kind of replace can not be deferred because during the primary index compaction there is no way to learn that a new tuple with one primary key discards an old tuple with another primary key without explicitly inserted deletion. This multi-replace must delete old records with another primary keys, and it is not considered under the paper.

The algorithm of deferred update consists of three enclosed parts:

1. Update of a zero-level of all indexes. This is where replace and delete by a primary key are inserted into memory and makes secondary and primary indexes mal-synchronized.
2. Compaction, which differs in primary and secondary indexes. A primary index during compaction detects tuples to discard and sends them to a secondary indexes as a new LSM-tree sublevel. A secondary index on compaction takes into account sublevels received from a primary index.
3. Secondary index reading, that now can see tuples already deleted from a primary index. Existence of a concrete version of a key read from a secondary index must be checked via primary index lookup.

3.1 Deferred update

Only two operations can be deferred: replace and delete by a primary key. At first algorithm of replace execution is presented, and then the delete's one which is very similar.

Consider a table with one primary index and some non-unique secondary indexes. Assume an user executes replace. A tuple specified in the replace is inserted into each index's memory level as is, with no preliminary reading and deletion of an old tuple from secondary indexes.

When this algorithm is used, it is possible and valid, that some secondary indexes consider discarded tuples as not discarded, like in example on Figure 3. In the example there is a tuple with version 3, which is discarded in a primary index by a newer tuple with the same key and version 5. But secondary keys of these tuples are different, and a secondary index sees the tuple with version 3 as a separate non-discarded tuple. Such tuples, visible in a secondary index and not visible in a primary one are called **dirty**.

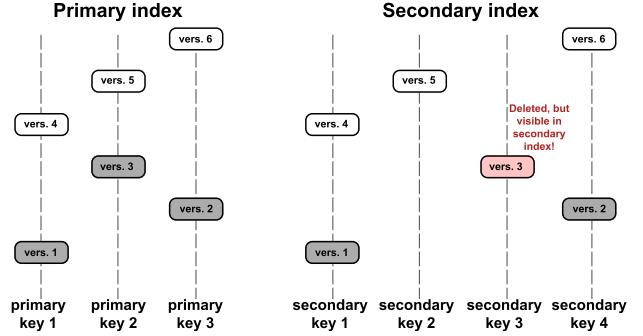


Figure 3: LSM-tree based table if update is deferred

A delete by a primary key is inserted only in a primary index memory. It can not be inserted in a secondary index, because a corresponding secondary key is unknown with no hidden reads. In such a case a tuple, discarded by the delete, becomes dirty.

In the next section the algorithm of deletion of dirty tuples is presented as a part of new LSM-tree compaction procedure.

3.2 Compaction

3.2.1 Primary index

Compaction is triggered by the same signals, as in the classic LSM-tree - by too big number of sublevels, or too big difference in neighbour levels size.

Consider the basic compaction, when there are no deferred updates and dirty tuples. Assume the levels consist of sublevels belong to key ranges, and a sublevel is sorted array of versioned keys.

Sublevels are compacted in merge-sorting procedure discarding tuples having older versions among compacting sublevels. That is if a tuple has newer version out of compaction participants, then it is not discarded. Two tuples are considered to be versions of the same key, if they are equal by parts of compacting LSM-tree index. If compaction participants have several versions of a key then during merge-sort they met during one of merge-steps, and only one tuple stays. After merge-sort is finished, a new single sublevel replaces old ones.

Obviously, old tuples are read from disk during compaction. And these reads replace hidden reads of update operations. Actually, the hidden reads are deferred until compaction, where they are done anyway and sequentially - sequential read is at a far quicker than random both on SSD and HDD.

Old tuples going to be discarded are used to extract dirty secondary keys. Extracted keys are resorted into order of a secondary index, and are written as a new sublevel directly into the secondary index. Secondary keys are written as deletes saving the version of the original tuple. New primary index compaction produces sublevels for itself and for each secondary index. When a secondary index compacting, it takes into account sublevels, created for it by a primary index.

Resorting into order of a secondary index is executed to observe LSM-tree index's invariant whereby sublevel of an index is an array tuples sorted by key parts of the index. So sublevels, created for secondary indexes during primary one's compaction, must be resorted into secondary index

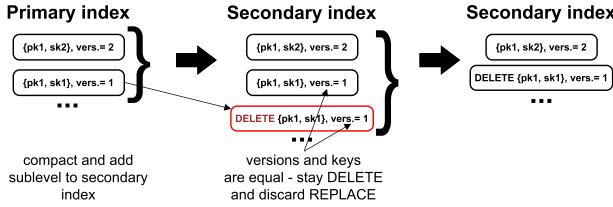


Figure 4: Secondary index compaction example

order. Resorting method depends on implementation, and can be

- in-memory quick sort after all tuples are read from disk;
- in-memory tree-sort, when for each index a tree is created before compaction and it is filled just as tuples are reading from disk. Tree can be of any type: binary, red-black, B-tree. When a primary compaction is finished, the tree is written into a secondary index sublevel as a sorted array. So such a tree is preferred, which can be iterated fast over all keys (B-plus-tree for example - it maintains sorted list of stored values);
- disk merge-sort, which can be used when sublevels compaction discard too many tuples and there are many secondary indexes - they may not fit into memory. The idea is to do in-memory sort of discarded tuples by batches of some fixed size, and dump them as sorted arrays into temporary files. When the primary compaction is finished, the congested temporary sorted arrays are merge sorted into single sublevel intended for a secondary index. Merge-sort of temporary files is executed in the same way as sublevels compaction - read and write files in parts with no reading them all into memory. The described procedure is executed for each secondary index.

3.2.2 Secondary index

Compaction procedure of a secondary index is slightly changed to correctly process the deletes received from a primary index. The point is that the deletes, received from a primary index, have both the same version and the same key as the dirty tuples, for which they are intended, and a compaction procedure must correctly process these versions and keys match.

The only modification of a secondary index compaction is that in a case of versions and keys match of delete and replace tuples the replace tuple must be discarded, and the delete tuple must stay, if it is not **major** compaction. A compaction is major, if all sublevels of all levels are compacted. On the Figure 4 it is presented example of a secondary index compaction with sublevel, received from a primary index. In the example, a primary and secondary indexes stores two tuples: $\{pk1, sk1\}$ and $\{pk1, sk2\}$. In a primary index it is the different versions of the key $pk1$. When a primary index is compacted, a tuple $\{pk1, sk1\}$ is discarded and sent to a secondary index as a DELETE tuple with the same version. During a secondary index compaction this DELETE $\{pk1, sk1\}$ with version 1 meets the dirty tuple $\{pk1, sk1\}$ with version 1 - their keys and versions are

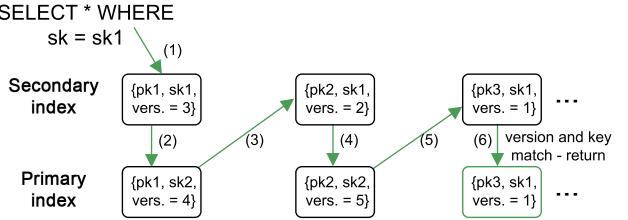


Figure 5: Secondary index read example

equal. It is assumed, that it is not major compaction, so the tuple $\{pk1, sk1\}$ is discarded and the DELETE tuple stays.

3.3 Read

Read of a primary index is not changed, because dirty tuples can appear in secondary indexes only. When a secondary index is read, the dirty tuples are skipped. To check a tuple if it is dirty, its primary key and version are looked up in a primary index. If a primary index contains the same key with the same version, then the tuple is not dirty and can be returned to an user.

It means, that even point reading from a secondary index can lead to multiple lookups in a primary index to exclude dirty tuples. On the Figure 5 a SELECT by a secondary key returns a tuple on a third attempt. At first, it reads $\{pk1, sk1\}$ as the newest known version of this secondary key. It appears to be dirty, because in a primary index a tuple with the same primary key has another version and another secondary key. At second $\{pk2, sk1\}$ is checked as the next by version: it is dirty too - in the primary index this tuple is already replaced by $\{pk2, sk2\}$. At third $\{pk3, sk1\}$ is checked, and in the primary index a tuple is found with the same key and the same version - it means, that this tuple is not dirty and can be returned to an user.

The common algorithm is to read secondary index tuples and lookup each one in a primary index until their versions and keys match.

3.4 Implementation

The developed algorithm is implemented as a patch for Tarantool database's disk engine named Vinyl. Tarantool is DBMS and application server, which supports two storage engines: Memtx in memory and Vinyl on disk. Tables in Tarantool are being called *spaces*. Memtx engine stores data in memory in B-plus-trees, and it is not considered here.

Vinyl engine stores indexes as LSM-trees. LSM-tree based index is split into key ranges. LSM-tree level consists of sublevels, produced by zero-level dump and compactions. Sublevels are files. Ranges are compacted independently of each other. Dump and compaction are executed in background threads, while transaction processing is in a single main thread and it does not heavy operations like disk or network access - it delegates these tasks to worker threads.

Main thread consists of coroutines written in C and called *fibers*. When a main thread wants to do long operation like LSM-tree index dump or compaction, access disk or network, it sends a request to a worker thread and switches to another fiber, while the original one waits for response from the worker. The big advantage of such schema, that there are no locks on internals except inter-thread communication queues.

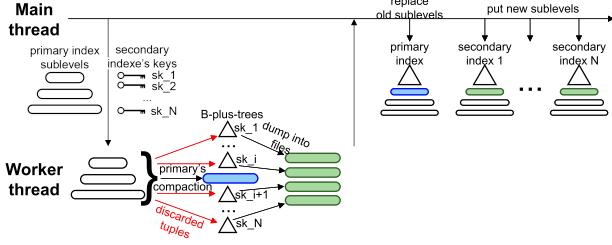


Figure 6: Primary index compaction schema

Implementation of the deferred update algorithm consists of three parts like the algorithm itself: new replace and delete execution, compaction and read.

New replace/delete are quite simple: they just do not hidden reads. Replace is inserted in zero-levels of all indexes of Vinyl space, delete is inserted into a primary one only.

The compaction is the most complex part of the implementation. As applied to Vinyl and LSM-trees, the compaction procedure works as follows before the deferred update:

1. Main thread detects that a compaction is necessary (for example, level size ratio is violated or a level consists of too many sublevels), and sends a request to a worker thread with information, which sublevels need to compact, in which files they are stored;
2. Worker thread sees request and starts compaction. Compaction is executed using merge-sort of sublevels files. Processed files are not deleted or changed by a worker thread, because they may be used now in the main thread for reads. When the worker has finished the work, it has one new sublevel file. The main thread is notified, that the work is done;
3. After a while, one of fibers of the main thread sees the finished worker, gets the new sublevel, puts it in the LSM-tree and deletes old sublevels and their files atomically.

After the deferred update is applied, the compaction procedure's second step is completely different. When a primary index is scheduled for compaction, the main thread sends to a worker info not only about a primary index's sublevel, but about each secondary index key parts. They are needed to extract secondary keys from primary index tuples.

While the primary index is being merge-sorted, discarded tuples are stored into in-memory B-plus-trees created for each secondary index. When a primary index compaction is finished and a new sublevel is created, the filled B-plus-trees are dumped into sublevel files for secondary indexes. The dump is fast, because B-plus-tree can be fast iterated due to links between neighbour keys. At this step the worker thread has sublevel files for each index of the table, and it notifies the main thread about finished work.

One of the main thread's fiber replaces compacted sublevels with new one in a primary index, and puts secondary index's sublevels into corresponding indexes at the LSM-tree's first level. Secondary index sublevel received from a primary index is on the LSM-tree's first level, because it can contain any DELETEs from first to last primary index levels and it means, that it can overlap any sublevel stored on

Table 1: Frequency of Special Characters

Non-English or Math	Frequency	Comments
\emptyset	1 in 1,000	For Swedish names
π	1 in 5	Common in math
$\$$	4 in 5	Used in business
Ψ^2	1 in 40,000	Unexplained usage

disk. These DELETEs must overlap dirty tuples for which intended.

3.5 Citations

Citations to articles [1, 3, 2, 4], conference proceedings [3] or books [7, 5] listed in the Bibliography section of your article will occur throughout the text of your article. You should use BibTeX to automatically produce this bibliography; you simply need to insert one of several citation commands with a key of the item cited in the proper location in the .tex file [5]. The key is a short reference you invent to uniquely identify each work; in this sample document, the key is the first author's surname and a word from the title. This identifying key is included with each item in the .bib file for your article.

The details of the construction of the .bib file are beyond the scope of this sample document, but more information can be found in the *Author's Guide*, and exhaustive details in the *LATEX User's Guide*[5].

This article shows only the plainest form of the citation command, using \cite. This is what is stipulated in the SIGS style specifications. No other citation format is endorsed.

3.6 Tables

Because tables cannot be split across pages, the best placement for them is typically the top of the page nearest their initial cite. To ensure this proper “floating” placement of tables, use the environment **table** to enclose the table's contents and the table caption. The contents of the table itself must go in the **tabular** environment, to be aligned properly in rows and columns, with the desired horizontal and vertical rules. Again, detailed instructions on **tabular** material is found in the *LATEX User's Guide*.

Immediately following this sentence is the point at which Table 1 is included in the input file; compare the placement of the table here with the table in the printed dvi output of this document.

To set a wider table, which takes up the whole width of the page's live area, use the environment **table*** to enclose the table's contents and the table caption. As with a single-column table, this wide table will “float” to a location deemed more desirable. Immediately following this sentence is the point at which Table 2 is included in the input file; again, it is instructive to compare the placement of the table here with the table in the printed dvi output of this document.

3.7 Figures

Like tables, figures cannot be split across pages; the best placement for them is typically the top or the bottom of the page nearest their initial cite. To ensure this proper “floating” placement of figures, use the environment **figure** to enclose the figure and its caption.

Table 2: Some Typical Commands

Command	A Number	Comments
\alignauthor	100	Author alignment
\numberofauthors	200	Author enumeration
\table	300	For tables
\table*	400	For wider tables



Figure 7: A sample black and white graphic (.pdf format).



Figure 8: A sample black and white graphic (.pdf format) that has been resized with the `includegraphics` command.

This sample document contains examples of .pdf files to be displayable with L^AT_EX(See Figures 7 and 8). More details on each of these is found in the *Author's Guide*.

As was the case with tables, you may want a figure that spans two columns. To do this, and still to ensure proper “floating” placement of tables, use the environment `figure*` to enclose the figure and its caption (See Figure 9). And don’t forget to end the environment with `figure*`, not `figure`!

Note that only .pdf files were used; if you want to include .ps or .eps formats, you can use the `\epsfig` or `\psfig` commands as appropriate for the different file types.

3.8 Theorem-like Constructs

Other common constructs that may occur in your article are the forms for logical constructs like theorems, axioms, corollaries and proofs. There are two forms, one produced by the command `\newtheorem` and the other by the command `\newdef`; perhaps the clearest and easiest way to distinguish them is to compare the two in the output of this sample document:

This uses the `theorem` environment, created by the `\newtheorem` command:

THEOREM 1. Let f be continuous on $[a, b]$. If G is an antiderivative for f on $[a, b]$, then

$$\int_a^b f(t)dt = G(b) - G(a).$$

The other uses the `definition` environment, created by the `\newdef` command:

Definition 1. If z is irrational, then by e^z we mean the unique number which has logarithm z :

$$\log e^z = z$$

Two lists of constructs that use one of these forms is given in the *Author's Guidelines*.

There is one other similar construct environment, which is already set up for you; i.e. you must *not* use a `\newdef` command to create it: the `proof` environment. Here is an example of its use:

PROOF. Suppose on the contrary there exists a real number L such that

$$\lim_{x \rightarrow \infty} \frac{f(x)}{g(x)} = L.$$

Then

$$\begin{aligned} l &= \lim_{x \rightarrow c} f(x) = \lim_{x \rightarrow c} \left[gx \cdot \frac{f(x)}{g(x)} \right] \\ &= \lim_{x \rightarrow c} g(x) \cdot \lim_{x \rightarrow c} \frac{f(x)}{g(x)} = 0 \cdot L = 0, \end{aligned}$$

which contradicts our assumption that $l \neq 0$. \square

Complete rules about using these environments and using the two different creation commands are in the *Author's Guide*; please consult it for more detailed instructions. If you need to use another construct, not listed therein, which you want to have the same formatting as the Theorem or the Definition[7] shown above, use the `\newtheorem` or the `\newdef` command, respectively, to create it.

A Caveat for the T_EX Expert

Because you have just been given permission to use the `\newdef` command to create a new form, you might think you can use T_EX's `\def` to create a new command: *Please refrain from doing this!* Remember that your L^AT_EX source code is primarily intended to create camera-ready copy, but may be converted to other forms – e.g. HTML. If you inadvertently omit some or all of the `\defs` recompilation will be, to say the least, problematic.

4. CONCLUSIONS

This paragraph will end the body of this sample document. Remember that you might still have Acknowledgments or Appendices; brief samples of these follow. There is still the Bibliography to deal with; and we will make a disclaimer about that here: with the exception of the reference to the L^AT_EX book, the citations in this paper are to articles which have nothing to do with the present subject and are used as examples only.

5. ACKNOWLEDGMENTS

This section is optional; it is a location for you to acknowledge grants, funding, editing assistance and what have you. In the present case, for example, the authors would like to thank Gerald Murray of ACM for his help in codifying this *Author's Guide* and the .cls and .tex files that it describes.

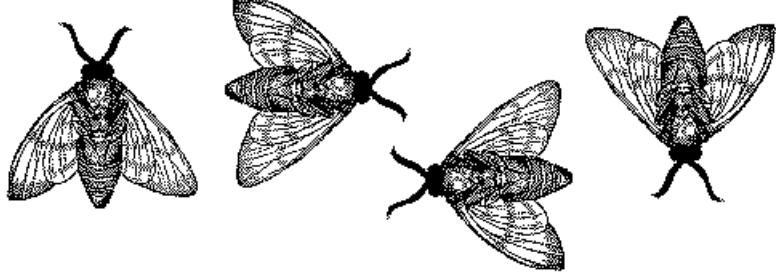


Figure 9: A sample black and white graphic (.pdf format) that needs to span two columns of text.

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6.1 References

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APPENDIX

You can use an appendix for optional proofs or details of your evaluation which are not absolutely necessary to the core understanding of your paper.

A. FINAL THOUGHTS ON GOOD LAYOUT

Please use readable font sizes in the figures and graphs. Avoid tempering with the correct border values, and the spacing (and format) of both text and captions of the PVLDB format (e.g. captions are bold).

At the end, please check for an overall pleasant layout, e.g. by ensuring a readable and logical positioning of any floating figures and tables. Please also check for any line overflows, which are only allowed in extraordinary circumstances (such as wide formulas or URLs where a line wrap would be counterintuitive).

Use the `\balance` package together with a `\balance` command at the end of your document to ensure that the last page has balanced (i.e. same length) columns.