

storage engines: *log-structured* storage engines, and *page-oriented* storage engines such as B-trees.

Data Structures That Power Your Database

Consider the world's simplest database, implemented as two Bash functions:

```
#!/bin/bash

db_set () {
    echo "$1,$2" >> database
}

db_get () {
    grep "^$1," database | sed -e "s/^$1,//" | tail -n 1
}
```

These two functions implement a key-value store. You can call `db_set key value`, which will store key and value in the database. The key and value can be (almost) anything you like—for example, the value could be a JSON document. You can then call `db_get key`, which looks up the most recent value associated with that particular key and returns it.

And it works:

```
$ db_set 123456 '{"name":"London","attractions":["Big Ben","London Eye"]}'

$ db_set 42 '{"name":"San Francisco","attractions":["Golden Gate Bridge"]}'

$ db_get 42
{"name":"San Francisco","attractions":["Golden Gate Bridge"]}
```

The underlying storage format is very simple: a text file where each line contains a key-value pair, separated by a comma (roughly like a CSV file, ignoring escaping issues). Every call to `db_set` appends to the end of the file, so if you update a key several times, the old versions of the value are not overwritten—you need to look at the last occurrence of a key in a file to find the latest value (hence the `tail -n 1` in `db_get`):

```
$ db_set 42 '{"name":"San Francisco","attractions":["Exploratorium"]}'

$ db_get 42
{"name":"San Francisco","attractions":["Exploratorium"]}
```

```
$ cat database
123456,{"name":"London","attractions":["Big Ben","London Eye"]}
42,{"name":"San Francisco","attractions":["Golden Gate Bridge"]}
42,{"name":"San Francisco","attractions":["Exploratorium"]}
```

Our `db_set` function actually has pretty good performance for something that is so simple, because appending to a file is generally very efficient. Similarly to what `db_set` does, many databases internally use a *log*, which is an append-only data file. Real databases have more issues to deal with (such as concurrency control, reclaiming disk space so that the log doesn't grow forever, and handling errors and partially written records), but the basic principle is the same. Logs are incredibly useful, and we will encounter them several times in the rest of this book.



The word *log* is often used to refer to application logs, where an application outputs text that describes what's happening. In this book, *log* is used in the more general sense: an append-only sequence of records. It doesn't have to be human-readable; it might be binary and intended only for other programs to read.

On the other hand, our `db_get` function has terrible performance if you have a large number of records in your database. Every time you want to look up a key, `db_get` has to scan the entire database file from beginning to end, looking for occurrences of the key. In algorithmic terms, the cost of a lookup is $O(n)$: if you double the number of records n in your database, a lookup takes twice as long. That's not good.

In order to efficiently find the value for a particular key in the database, we need a different data structure: an *index*. In this chapter we will look at a range of indexing structures and see how they compare; the general idea behind them is to keep some additional metadata on the side, which acts as a signpost and helps you to locate the data you want. If you want to search the same data in several different ways, you may need several different indexes on different parts of the data.

An index is an *additional* structure that is derived from the primary data. Many databases allow you to add and remove indexes, and this doesn't affect the contents of the database; it only affects the performance of queries. Maintaining additional structures incurs overhead, especially on writes. For writes, it's hard to beat the performance of simply appending to a file, because that's the simplest possible write operation. Any kind of index usually slows down writes, because the index also needs to be updated every time data is written.

This is an important trade-off in storage systems: well-chosen indexes speed up read queries, but every index slows down writes. For this reason, databases don't usually index everything by default, but require you—the application developer or database administrator—to choose indexes manually, using your knowledge of the application's typical query patterns. You can then choose the indexes that give your application the greatest benefit, without introducing more overhead than necessary.

Hash Indexes

Let’s start with indexes for key-value data. This is not the only kind of data you can index, but it’s very common, and it’s a useful building block for more complex indexes.

Key-value stores are quite similar to the *dictionary* type that you can find in most programming languages, and which is usually implemented as a hash map (hash table). Hash maps are described in many algorithms textbooks [1, 2], so we won’t go into detail of how they work here. Since we already have hash maps for our in-memory data structures, why not use them to index our data on disk?

Let’s say our data storage consists only of appending to a file, as in the preceding example. Then the simplest possible indexing strategy is this: keep an in-memory hash map where every key is mapped to a byte offset in the data file—the location at which the value can be found, as illustrated in **Figure 3-1**. Whenever you append a new key-value pair to the file, you also update the hash map to reflect the offset of the data you just wrote (this works both for inserting new keys and for updating existing keys). When you want to look up a value, use the hash map to find the offset in the data file, seek to that location, and read the value.

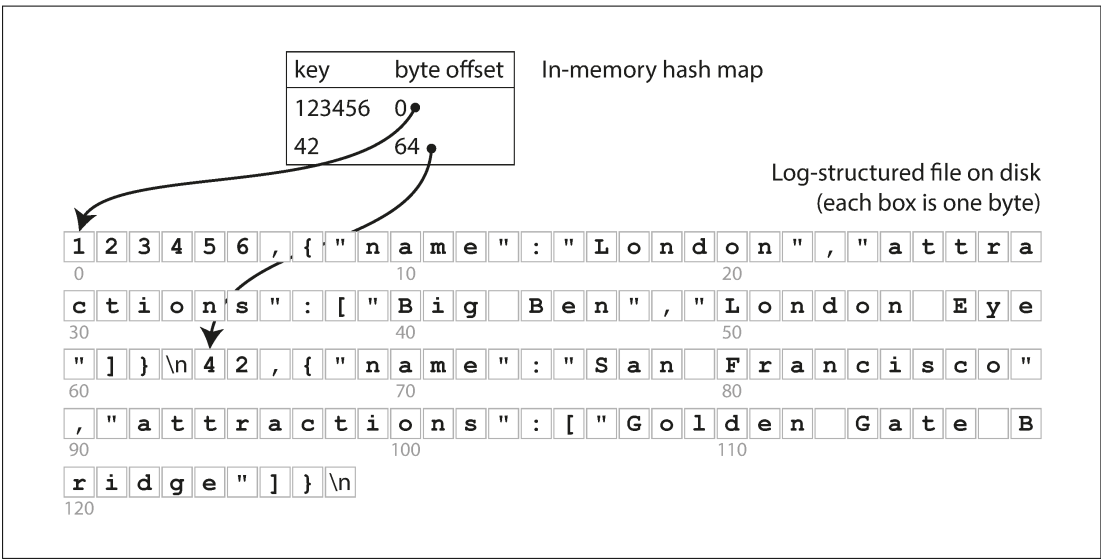


Figure 3-1. Storing a log of key-value pairs in a CSV-like format, indexed with an in-memory hash map.

This may sound simplistic, but it is a viable approach. In fact, this is essentially what Bitcask (the default storage engine in Riak) does [3]. Bitcask offers high-performance reads and writes, subject to the requirement that all the keys fit in the available RAM, since the hash map is kept completely in memory. The values can use more space than there is available memory, since they can be loaded from disk with just one disk

seek. If that part of the data file is already in the filesystem cache, a read doesn't require any disk I/O at all.

A storage engine like Bitcask is well suited to situations where the value for each key is updated frequently. For example, the key might be the URL of a cat video, and the value might be the number of times it has been played (incremented every time someone hits the play button). In this kind of workload, there are a lot of writes, but there are not too many distinct keys—you have a large number of writes per key, but it's feasible to keep all keys in memory.

As described so far, we only ever append to a file—so how do we avoid eventually running out of disk space? A good solution is to break the log into segments of a certain size by closing a segment file when it reaches a certain size, and making subsequent writes to a new segment file. We can then perform *compaction* on these segments, as illustrated in [Figure 3-2](#). Compaction means throwing away duplicate keys in the log, and keeping only the most recent update for each key.

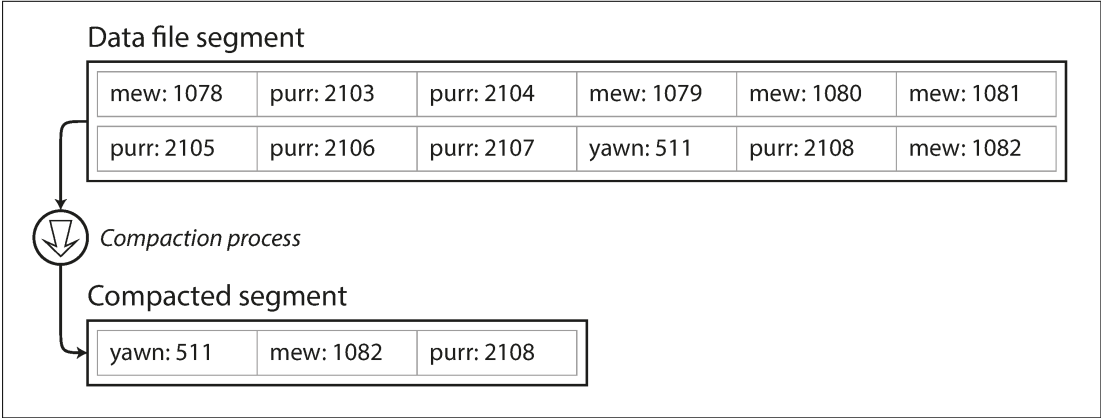


Figure 3-2. Compaction of a key-value update log (counting the number of times each cat video was played), retaining only the most recent value for each key.

Moreover, since compaction often makes segments much smaller (assuming that a key is overwritten several times on average within one segment), we can also merge several segments together at the same time as performing the compaction, as shown in [Figure 3-3](#). Segments are never modified after they have been written, so the merged segment is written to a new file. The merging and compaction of frozen segments can be done in a background thread, and while it is going on, we can still continue to serve read and write requests as normal, using the old segment files. After the merging process is complete, we switch read requests to using the new merged segment instead of the old segments—and then the old segment files can simply be deleted.

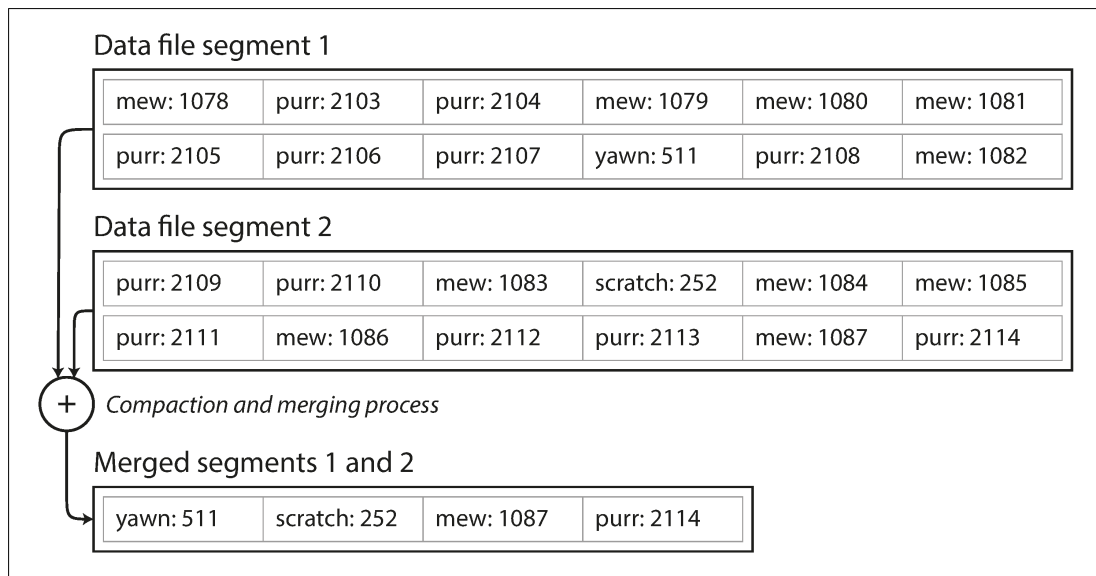


Figure 3-3. Performing compaction and segment merging simultaneously.

Each segment now has its own in-memory hash table, mapping keys to file offsets. In order to find the value for a key, we first check the most recent segment's hash map; if the key is not present we check the second-most-recent segment, and so on. The merging process keeps the number of segments small, so lookups don't need to check many hash maps.

Lots of detail goes into making this simple idea work in practice. Briefly, some of the issues that are important in a real implementation are:

File format

CSV is not the best format for a log. It's faster and simpler to use a binary format that first encodes the length of a string in bytes, followed by the raw string (without need for escaping).

Deleting records

If you want to delete a key and its associated value, you have to append a special deletion record to the data file (sometimes called a *tombstone*). When log segments are merged, the tombstone tells the merging process to discard any previous values for the deleted key.

Crash recovery

If the database is restarted, the in-memory hash maps are lost. In principle, you can restore each segment's hash map by reading the entire segment file from beginning to end and noting the offset of the most recent value for every key as you go along. However, that might take a long time if the segment files are large, which would make server restarts painful. Bitcask speeds up recovery by storing

a snapshot of each segment's hash map on disk, which can be loaded into memory more quickly.

Partially written records

The database may crash at any time, including halfway through appending a record to the log. Bitcask files include checksums, allowing such corrupted parts of the log to be detected and ignored.

Concurrency control

As writes are appended to the log in a strictly sequential order, a common implementation choice is to have only one writer thread. Data file segments are append-only and otherwise immutable, so they can be read concurrently by multiple threads.

An append-only log seems wasteful at first glance: why don't you update the file in place, overwriting the old value with the new value? But an append-only design turns out to be good for several reasons:

- Appending and segment merging are sequential write operations, which are generally much faster than random writes, especially on magnetic spinning-disk hard drives. To some extent sequential writes are also preferable on flash-based *solid state drives* (SSDs) [4]. We will discuss this issue further in “[Comparing B-Trees and LSM-Trees](#)” on page 83.
- Concurrency and crash recovery are much simpler if segment files are append-only or immutable. For example, you don't have to worry about the case where a crash happened while a value was being overwritten, leaving you with a file containing part of the old and part of the new value spliced together.
- Merging old segments avoids the problem of data files getting fragmented over time.

However, the hash table index also has limitations:

- The hash table must fit in memory, so if you have a very large number of keys, you're out of luck. In principle, you could maintain a hash map on disk, but unfortunately it is difficult to make an on-disk hash map perform well. It requires a lot of random access I/O, it is expensive to grow when it becomes full, and hash collisions require fiddly logic [5].
- Range queries are not efficient. For example, you cannot easily scan over all keys between `kitty00000` and `kitty99999`—you'd have to look up each key individually in the hash maps.

In the next section we will look at an indexing structure that doesn't have those limitations.

SSTables and LSM-Trees

In [Figure 3-3](#), each log-structured storage segment is a sequence of key-value pairs. These pairs appear in the order that they were written, and values later in the log take precedence over values for the same key earlier in the log. Apart from that, the order of key-value pairs in the file does not matter.

Now we can make a simple change to the format of our segment files: we require that the sequence of key-value pairs is *sorted by key*. At first glance, that requirement seems to break our ability to use sequential writes, but we'll get to that in a moment.

We call this format *Sorted String Table*, or *SSTable* for short. We also require that each key only appears once within each merged segment file (the compaction process already ensures that). SSTables have several big advantages over log segments with hash indexes:

1. Merging segments is simple and efficient, even if the files are bigger than the available memory. The approach is like the one used in the *mergesort* algorithm and is illustrated in [Figure 3-4](#): you start reading the input files side by side, look at the first key in each file, copy the lowest key (according to the sort order) to the output file, and repeat. This produces a new merged segment file, also sorted by key.

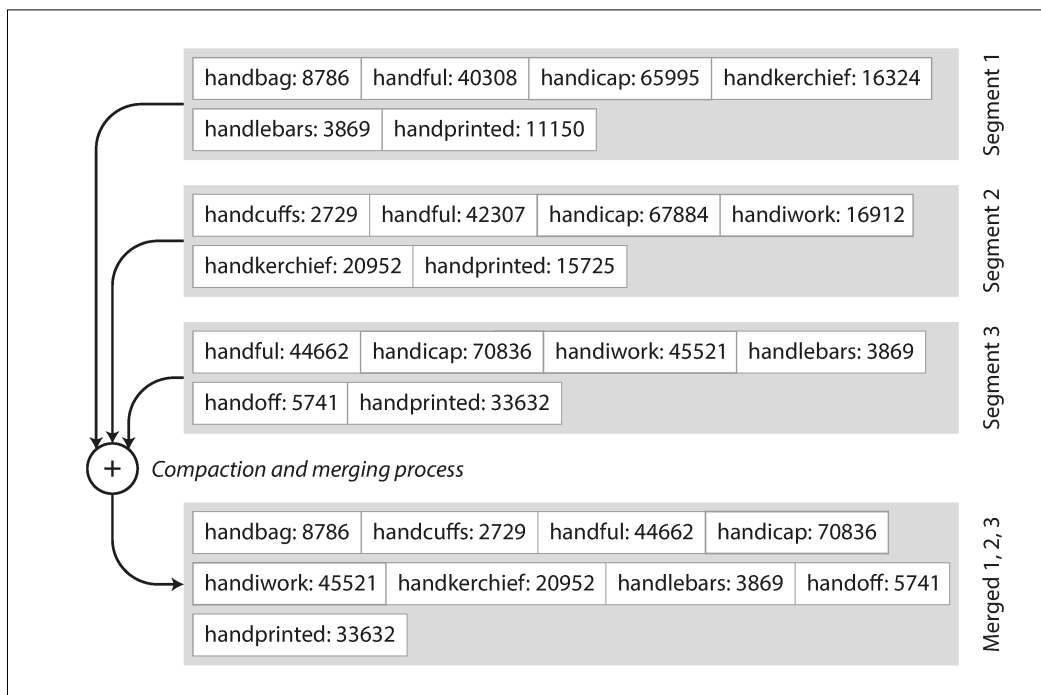


Figure 3-4. Merging several SSTable segments, retaining only the most recent value for each key.

What if the same key appears in several input segments? Remember that each segment contains all the values written to the database during some period of time. This means that all the values in one input segment must be more recent than all the values in the other segment (assuming that we always merge adjacent segments). When multiple segments contain the same key, we can keep the value from the most recent segment and discard the values in older segments.

2. In order to find a particular key in the file, you no longer need to keep an index of all the keys in memory. See [Figure 3-5](#) for an example: say you're looking for the key *handiwork*, but you don't know the exact offset of that key in the segment file. However, you do know the offsets for the keys *handbag* and *handsome*, and because of the sorting you know that *handiwork* must appear between those two. This means you can jump to the offset for *handbag* and scan from there until you find *handiwork* (or not, if the key is not present in the file).

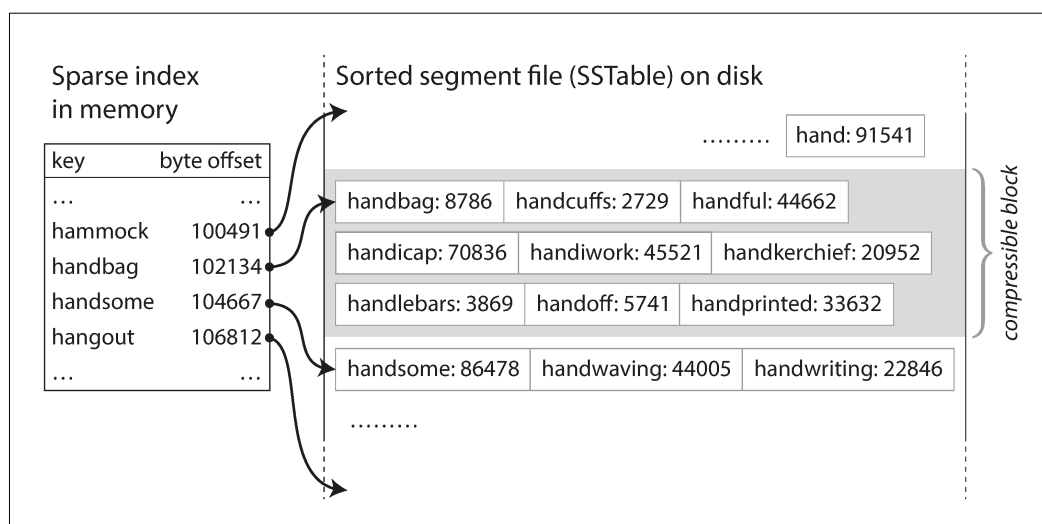


Figure 3-5. An SSTable with an in-memory index.

You still need an in-memory index to tell you the offsets for some of the keys, but it can be sparse: one key for every few kilobytes of segment file is sufficient, because a few kilobytes can be scanned very quickly.ⁱ

3. Since read requests need to scan over several key-value pairs in the requested range anyway, it is possible to group those records into a block and compress it before writing it to disk (indicated by the shaded area in [Figure 3-5](#)). Each entry of the sparse in-memory index then points at the start of a compressed block. Besides saving disk space, compression also reduces the I/O bandwidth use.

i. If all keys and values had a fixed size, you could use binary search on a segment file and avoid the in-memory index entirely. However, they are usually variable-length in practice, which makes it difficult to tell where one record ends and the next one starts if you don't have an index.

Constructing and maintaining SSTables

Fine so far—but how do you get your data to be sorted by key in the first place? Our incoming writes can occur in any order.

Maintaining a sorted structure on disk is possible (see “B-Trees” on page 79), but maintaining it in memory is much easier. There are plenty of well-known tree data structures that you can use, such as red-black trees or AVL trees [2]. With these data structures, you can insert keys in any order and read them back in sorted order.

We can now make our storage engine work as follows:

- When a write comes in, add it to an in-memory balanced tree data structure (for example, a red-black tree). This in-memory tree is sometimes called a *memtable*.
- When the memtable gets bigger than some threshold—typically a few megabytes—write it out to disk as an SSTable file. This can be done efficiently because the tree already maintains the key-value pairs sorted by key. The new SSTable file becomes the most recent segment of the database. While the SSTable is being written out to disk, writes can continue to a new memtable instance.
- In order to serve a read request, first try to find the key in the memtable, then in the most recent on-disk segment, then in the next-older segment, etc.
- From time to time, run a merging and compaction process in the background to combine segment files and to discard overwritten or deleted values.

This scheme works very well. It only suffers from one problem: if the database crashes, the most recent writes (which are in the memtable but not yet written out to disk) are lost. In order to avoid that problem, we can keep a separate log on disk to which every write is immediately appended, just like in the previous section. That log is not in sorted order, but that doesn’t matter, because its only purpose is to restore the memtable after a crash. Every time the memtable is written out to an SSTable, the corresponding log can be discarded.

Making an LSM-tree out of SSTables

The algorithm described here is essentially what is used in LevelDB [6] and RocksDB [7], key-value storage engine libraries that are designed to be embedded into other applications. Among other things, LevelDB can be used in Riak as an alternative to Bitcask. Similar storage engines are used in Cassandra and HBase [8], both of which were inspired by Google’s Bigtable paper [9] (which introduced the terms *SSTable* and *memtable*).

Originally this indexing structure was described by Patrick O’Neil et al. under the name *Log-Structured Merge-Tree* (or LSM-Tree) [10], building on earlier work on

log-structured filesystems [11]. Storage engines that are based on this principle of merging and compacting sorted files are often called LSM storage engines.

Lucene, an indexing engine for full-text search used by Elasticsearch and Solr, uses a similar method for storing its *term dictionary* [12, 13]. A full-text index is much more complex than a key-value index but is based on a similar idea: given a word in a search query, find all the documents (web pages, product descriptions, etc.) that mention the word. This is implemented with a key-value structure where the key is a word (a *term*) and the value is the list of IDs of all the documents that contain the word (the *postings list*). In Lucene, this mapping from term to postings list is kept in SSTable-like sorted files, which are merged in the background as needed [14].

Performance optimizations

As always, a lot of detail goes into making a storage engine perform well in practice. For example, the LSM-tree algorithm can be slow when looking up keys that do not exist in the database: you have to check the memtable, then the segments all the way back to the oldest (possibly having to read from disk for each one) before you can be sure that the key does not exist. In order to optimize this kind of access, storage engines often use additional *Bloom filters* [15]. (A Bloom filter is a memory-efficient data structure for approximating the contents of a set. It can tell you if a key does not appear in the database, and thus saves many unnecessary disk reads for nonexistent keys.)

There are also different strategies to determine the order and timing of how SSTables are compacted and merged. The most common options are *size-tiered* and *leveled* compaction. LevelDB and RocksDB use leveled compaction (hence the name of LevelDB), HBase uses size-tiered, and Cassandra supports both [16]. In size-tiered compaction, newer and smaller SSTables are successively merged into older and larger SSTables. In leveled compaction, the key range is split up into smaller SSTables and older data is moved into separate “levels,” which allows the compaction to proceed more incrementally and use less disk space.

Even though there are many subtleties, the basic idea of LSM-trees—keeping a cascade of SSTables that are merged in the background—is simple and effective. Even when the dataset is much bigger than the available memory it continues to work well. Since data is stored in sorted order, you can efficiently perform range queries (scanning all keys above some minimum and up to some maximum), and because the disk writes are sequential the LSM-tree can support remarkably high write throughput.

B-Trees

The log-structured indexes we have discussed so far are gaining acceptance, but they are not the most common type of index. The most widely used indexing structure is quite different: the *B-tree*.