Chapter 11
Tile Creation using Vector Data

In previous chapters we were primarily concerned with taking an imagery dataset and converting it into tiles. In this chapter we will focus on vector data as the source for creating tiles. Vector data is made up of geometric primitives, such as points, lines, and polygons. As a result, the process of taking vectors and turning them into image tiles brings up a completely different set of issues from the process using an imagery source.

11.1 Vector Data

As stated above, vector data is geospatial data defined by geometric primitives. A vector dataset will be made up of a number of individual vector features. Each vector feature will have a geometry which defines its geometric shape as well as its location geographically. Often, a vector feature will have a simple geometry made up of a single point, polyline, or polygon (see Figure 11.1). More complex geometries are possible as well. A vector feature may be defined by a curve, a conic, having inner rings, or being multi-dimensional. Additionaly, a vector feature may have a complex geometry that is a combination of other geometries. Examples of complex vector features are shown in Figure 11.2.

In general, there is no guarantee that a vector feature may be drawn into an image or on a computer screen. A curve or a circle must be approximated by a polyline or polygon when drawn by a computer. High-dimensional vector features may not even be approximated for rendering by a computer. Of course, in order to be useful as a source for tiled images, a vector feature must be renderable. As a result we will limit our discussion to features which may be rendered into an image. This chapter will not discuss the process of rendering vector data into an image, which is well described in other texts. Instead, we will limit discussion to the effect the tiling process has on the act of rendering vector features, and vice versa.

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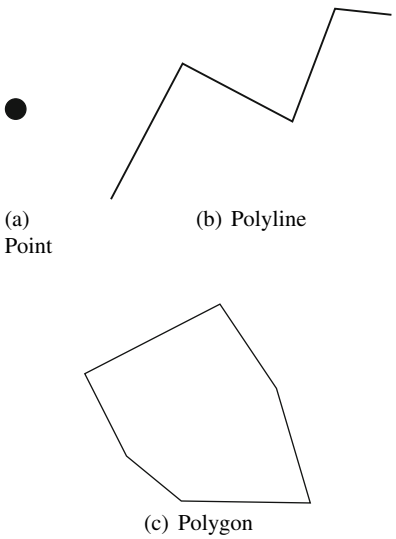


Fig. 11.1 Simple vector features.

11.2 Tile Creation

The overall process for creating tiles from vector source data is not significantly different from the process using imagery source data. The primary difference is that instead of cutting image tiles from source data, the vector data is drawn into tiled images. The tile creation process may be outlined in a few simple steps.

1. Choose a tile to create.
2. Determine the bounding box of the tile.
3. Query the vector data source for all features in the bounding box.
4. Render the vector data to an image with the appropriate tile size.
5. Store/disseminate the tile image.

Most of these steps have already been discussed in reference to tiles created from imagery. However, tiling from vector data does have some unique elements which distinguish it from tiling imagery. To recap, the three primary differences are:

- Storage space: Rendered image tiles require a significant amount of storage space relative to vector map content. A collection of geospatial features might be 100 megabytes in vector form but could grow to several terabytes when rendered over several different scales.
- Processing time: Pre-rendering image tiles requires a significant amount of time, and many of those tiles may be in geographic areas of little interest to users. The

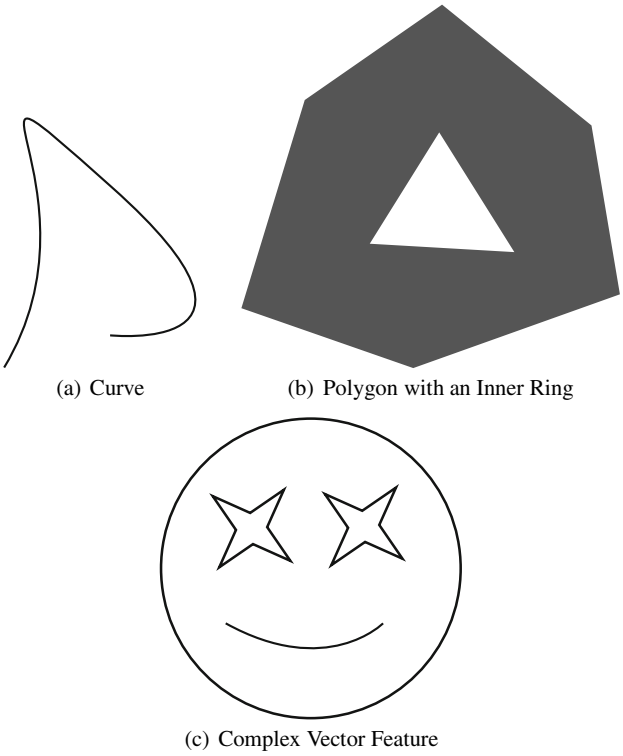


Fig. 11.2 More complicated vector features.

most efficient way to decide what tiles to render is to wait until they are requested by actual users.

- Overview images: Overview images, i.e., very low scale images, can be rendered directly from geospatial vectors. Unlike raster-based tile systems, there is no need to render the high scale views first and then generate scaled down versions.

These differences allow a modification of how the resulting tiles created from vectors are used. For imagery, all the tiles are created ahead of time and stored permanently for distribution. However, because of the above three differences in tiled imagery, it does not make sense to pre-render all tiles ahead of time. Instead, the tiles may be rendered as they are requested by users. By rendering tiles just-in-time, only the tiles which users request are ever generated. On-the-fly rendering reduces storage requirements significantly but will reduce performance of the system. Speed is improved if the rendered tiles are cached on disk after they are first requested. Each tile is only rendered once (or until the underlying data changes). The most commonly viewed tiles will be cached so performance will be good.

11.3 Queries

Querying, and ultimately the storage system for vector data, will be the primary focus of this chapter. Only one query is important to the process of tiling vector features. Each time a tile must be created, the tiling system will request all vector features that lie within the tile bounds. Only requiring one basic query is useful because the queries used in tile creation are completely deterministic. A complete list of queries used in tile creation may be created ahead of time, and the list will not change over repeated tile creation runs. Since the tile scheme is known ahead of time, the geographic bounds used in the query will be known ahead of time as well. Therefore, improving query performance is actually only important for the subset of queries which request data lying within tile bounds. While this may seem obvious, most techniques for improving geospatial query performance tend to be generalized to support any geospatial query. Since the variations in our queries are so small, we can improve upon the standard techniques.

Feature selection based on map scale is a possible variation to the geospatial queries which is important. Consider the case where roads are the vector data used for tiling. For tiles that cover a large area, such as the entire United States, it would be unreasonable to try and draw every road feature that lies within the tile. The results of such a query may be all or a large percentage of the roads in the overall dataset. Performing the query would be slow, if not impossible, and the rendered tile cluttered and unreadable. Rather than draw every feature lying in the tile, only a subset of the features should be drawn. For the roads example, it would make sense to draw only interstates and major highways at the map scale where the entire United States is visible. In general, in cases where the vector data source is quite large, consideration should be given to selecting features to draw based on the map scale of the destination tile. For roads, we may choose to have interstates and major highways drawn at all zoom levels, minor highways drawn at zoom level 5 and above, and all roads drawn at zoom level 8 and above. Using map scale, or zoom level, to select features does add complexity the queries used to generate tiles. However, it will generally improve performance because lower zoom level tiles will have fewer features to retrieve. Filtering features based on scale also does not change the fact that the tiling queries are completely deterministic. The determinism makes it possible to design a highly targeted storage methodology for tiling vector data.

11.4 Storage

There are two primary methods of storing vector data for tiling: database storage and file system storage. Database storage of vector data is more common than file storage when the data is to be retrieved using geospatial queries. File storage is more commonly used for archival and distribution of vector data as fixed data sets. We will describe a file storage system which is designed to support high performance tile creation from vector data.

11.4.1 Database Storage

Most modern database systems provide support for geospatial data, including storing geometries as first class data types, supporting complex geospatial queries, and providing geospatial indexes. Common examples include Oracle with the Spatial extension, PostgreSQL/PostGIS, and MySQL. Normally, vector data is stored in a database with each attribute of the feature appearing as a field in a database table, including the geometry. Because database tables have a fixed schema, features must have the same attributes to be stored in the same table. As a result, there is usually a direct mapping between geospatial layers and database tables. Many tools exist to import data from geospatial file formats directly into tables (such as shp2pgsql for PostgeSQL).

Querying for geospatial data is supported by these databases without any extra development. The query for all features in the geospatial bounds of a tile is shown in Listing 11.1.

Listing 11.1 Geospatial query for vector features within a tile's bounding box. Based on PostgreSQL/PostGIS.

```
SELECT * FROM FeaturesTable WHERE feature_geometry && ST_MakeBox2D(ST_Point
    (-90, 0),ST_Point(0, 90));
```

The operator `&&` determines whether the bounding boxes of two geometries overlap. In this example, the query is comparing the feature geometry with the tile `(1, 1)` at zoom level 2.

Indices should be created to provide adequate performance of these queries. The two most commonly used geospatial indices are the R-Tree index (usually the R*-Tree variant) and the Quadtree. The R-Tree index tends to be preferred over the Quadtree because it provides better query performance over a wider variety of geospatial queries. The database controls the creation of indices, though some level of tuning is allowed by the user. Regardless of what type of geospatial index is used, the database tables should be clustered. Clustered data is ordered on disk according to its location in the index. As a result, the database must access only a localized area of the disk when solving a query using the index. Index clustering is essential to query performance when the query is expected to return multiple results. An example of creating a clustered index in PostgreSQL/PostGIS is shown in Listing 11.2.

Listing 11.2 Example SQL for creating a clustered PostGIS R-Tree index in PostgreSQL.

```
CREATE INDEX spatial_index ON FeaturesTable USING GIST ( feature_geometry );
```

Creating the database tables from vector data layers and using clustered indices are sufficient to create a functioning database environment for vector tiling. No changes to the geospatial query are necessary. A database will automatically determine if an index should to be used in the evaluation of a query.

Additional modifications to the geospatial database may be implemented to increase performance. Given the foreknowledge of the query patterns to the database, we can customize the way the features are stored to simplify evaluation for the

known queries. The first case to examine is the one where only a subset of features are used in tiles with low zoom level. A simple modification to the query in Listing 11.2 will add support for this functionality, as seen in Listing 11.3.

Listing 11.3 Geospatial query with filter on zoom level.

```
SELECT * FROM FeaturesTable WHERE feature_geometry && ST_MakeBox2D(ST_Point
    (-90, 0),ST_Point(0, 90)) AND feature_min_zoom_level <= 2;
```

This query will accomplish the goal of retrieving only a subset of the features inside a tile, depending on the scale. However, there is a problem. The query on bounds and scale requires different optimizations depending on the query parameters. When the query zoom level is high and the query bounds are small, a clustered geospatial index will provide the best performance. On the other hand, when the query zoom level is small and the query bounds are large, a clustered zoom level index will provide the best performance. Given that only one index on a table may be clustered, it is inevitable that one of these two sets of queries will not perform as efficiently as possible.

The solution is simple: create multiple tables to hold data for different scales. The key zoom levels where the subset of tiles being rendered changes are known ahead of time. A separate table may be created to hold the features whose minimum display zoom level is less than a particular key zoom levels. For example, if the key zoom levels are zero, eight, and fourteen then our roads layer will have tables `Roads_0`, `Roads_8`, and `Roads_14`. Each of these tables holds all features whose minimum zoom level is less than or equal to the table zoom level. The tiler need only query the table which matches the zoom level of the tile being rendered at the moment. No additional filtering on zoom level need be done in the query because the filtering has been performed ahead of time.

The only drawback to creating multiple tables for each layer is that features will be duplicated between tables. For example, interstates should be represented in all three roads tables. However, additional performance is possible by reducing the resolution (i.e. the number of points in the geometry) of features in the tables with lower zoom level. The reduced resolution will decrease the size of the table and increase the speed of rendering a tile. Creating multiple tables increases the required space to hold the vector data, but disk is cheap, and vector data is relatively small, especially in comparison to imagery. The performance benefits of creating a table for each key zoom level far outweigh the storage costs. Figure 11.3 shows different key zoom levels used by OpenStreetMap.

One of the benefits of a database is that it automatically organizes and searches a wide variety of data types. A developer can store data in a database with little or no custom development. The flip side of the automatic and general nature of a database is the limited amount of customization that is possible. The R-Tree index included in a database is a good example of this tradeoff. The R-Tree index is a good geospatial index which increases performance of a wide variety of geospatial queries. However, the database completely manages the organization of data in the R-Tree index. The application developer has no way of guiding the organization of data in the R-Tree. We know ahead of time which vector features lie within which

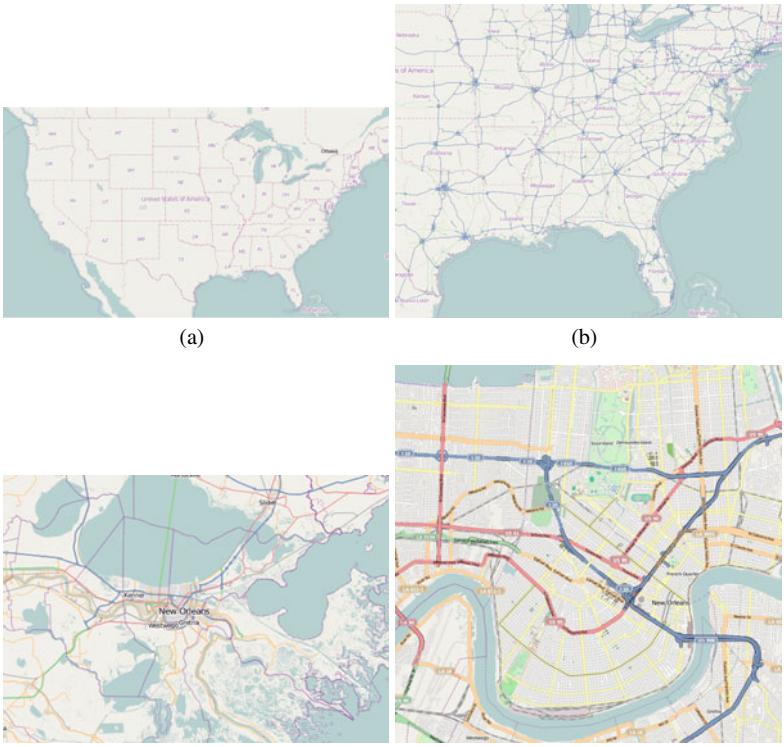


Fig. 11.3 Key zoom levels used by OpenStreetMap when rendering their vector data.

tiles. It would provide a performance benefit if the application developer could ensure that the R-Tree page splits matched tile splits, but this is not possible. Such customization would be difficult even in a Quadtree, which organizes data into tiles by default.

The loss of customization inherent in using a database would be acceptable if the database provided significant advantages for a vector tiling system. However, a tiling system does not require much of the functionality provided by a database. Core database features like advanced locking of data and rollback availability are unnecessary for a vector datastore which is primarily read-only. These database features are not free; they are a core part of the database which are included at a cost to performance. For example, a banking system which requires accuracy in monetary transactions definitely requires atomic transactions in its datastore.

11.4.2 File System Storage

In contrast to a database, file system storage offers little in the way of automatic functionality but provides the developer with the ability to fully customize the storage implementation in the overall system. A tiling system is a good example of an application which can benefit from using a file system for storage. The deterministic nature of the queries performed when tiling features provides an environment which can benefit from the customization allowed by a file system. Using our knowledge of the vector tiling system, we can develop a custom file storage implementation which is optimized for our system.

The first departure in our file storage implementation from the database design is in how vector layers are managed. In the database, each layer is mapped to a separate table. This design is necessary because database tables have a fixed schema which requires all records to share the same columns. In general, different vector layers will not have the same feature attributes (which map to table columns) and, as a result, must be stored in different tables. A custom file format does not have this restriction. The file store may be designed to hold features from many different layers. There is a good reason to store features from multiple layers in the same file. The tile system uses features from multiple layers when drawing tiles. The design of a custom storage system should partition data only when it benefits the overall efficiency of the system. Usually, the performance benefit comes from the query access patterns. Since the queries in the tiling system do not require features partitioned by layers, there is no reason to do so. The simplest way to store features from multiple layers in the same file is to store a variable size list of the attribute names and values for each feature. This method obviously requires more storage space than fixed schema systems. As a means to reduce storage requirements, the attribute names for the different feature layers may be stored once in the file header and linked to each feature. However, storage is generally cheap so the added complexity may not be worth the effort.

In contrast, the geospatial area is a property of the vector features that affects query access patterns. Therefore, partitioning data according to location is important for an efficient file storage system. Databases improve the performance of the geospatial queries by using a geospatial index. We already mentioned that by automatically creating these indices, the database would never provide a geospatial index optimized for our tiling application. With a custom file storage implementation, we can optimize storage for our tiling application. We can take advantage of the fact that geospatial queries used by the tiling system always match tile boundaries. As a result, we index and cluster the vector data using tile boundaries.

The simplest index partitions the data into multiple files whose bounds align with the tile bounds at one chosen zoom level. However, as we have seen with image tiles, at high zoom levels the number of files becomes unwieldy. Instead, we partition the data according to tile location but store each partition in one file. The start byte and length of every tile partition is stored separately so that each tile may be accessed independently. A feature is placed into a tile partition if its geospatial bounds overlap the bounds of the file's corresponding tile (see Figure 11.4). It is likely that a few of

the features will overlap multiple tiles. In this case, the features are placed into each overlapping tile partition. The result is a file storage scheme which is by default also a clustered index. Using features stored on the file system is easy. An entire tile partition may be loaded into memory, and the tile it represents is rendered. All subtiles at higher zoom levels may be rendered as well. Alternatively, features may be rendered as they are read from the file system without caching them in memory, allowing lower resource systems to use the same scheme.

To support memory caching, the tile partitions must be sized to fit into memory. Thus, the zoom level which defines the boundaries of the tile partitions should be the lowest zoom level whose tile partitions fit into the memory of the rendering system. Determining the appropriate target zoom level will require some experimentation, but if performance is a concern, the results will be worth it.

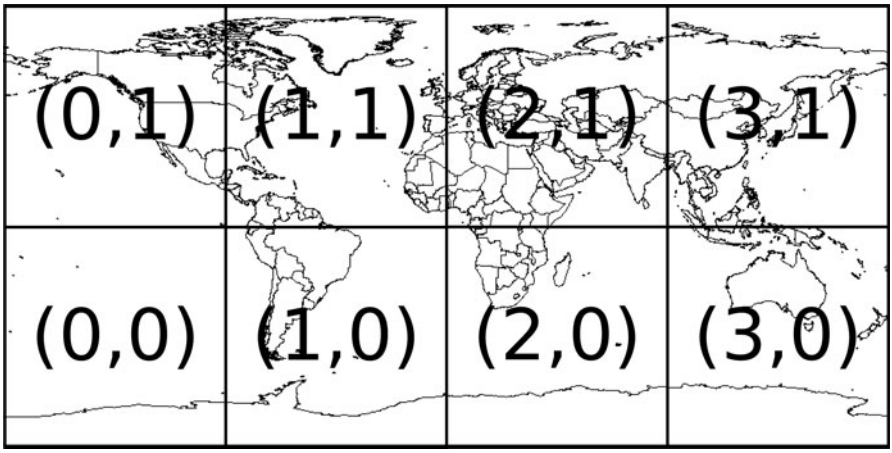


Fig. 11.4 A map made up of polyline vector features. Each polyline is partitioned according to which zoom level 2 tile it lies within. For example, Antarctica would be placed in tiles (0,0), (1,0), (2,0), and (3,0).

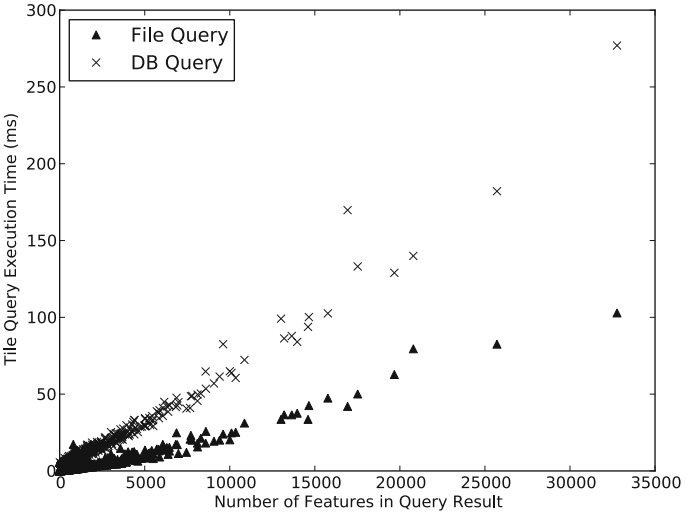
Minimum rendering zoom level is another vector feature property which may be managed by partitioning data. For database storage, a table was made for each key zoom level in the tiling system. The same technique may be used for file storage. Each zoom level which uses a different subset of features for rendering has a separate file to store features. That directory stores the feature file and its index. The files for a key zoom level are used when rendering tiles at that zoom level or higher (until the next higher key zoom level).

As with the database version of this optimization, overall storage cost is increased by redundantly storing features. Conversely, the average amount of data accessed when performing a query is reduced because there are fewer features in each file. The result of this custom vector data store is that all queries are essentially precomputed so that the disk accesses are all predetermined. Each file will only be read off disk once, and all tiles may be rendered by looking at only one file. Once data is in

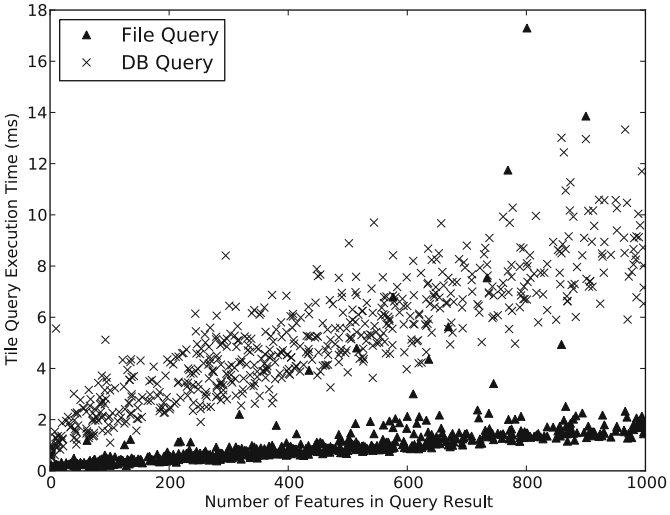
memory, the cost of filtering features to render tiles with smaller geographic areas is small. Disk access is much more costly than in-memory computation.

Experimentation shows that the performance of a file-based feature store out performs a standard database. The feature data used for the testing is the road network of the United States. The data comes from the NAVTEQ corporation and is the same dataset used by the commercial Web-mapping systems. We created a basic file-based storage system with features partitioned at zoom level 11 and stored in a file. We also created a PostgreSQL/PostGIS datasbase to store the same features. The database table was clustered using an R-Tree index on the data. The experiment query requests all the features in a tile. The tests were performed using a random list of tiles from zoom level 11 located in the continental United States. The time to execute each query and the number of features in the queried tile was recorded. The results, as seen in Figure 11.5, show that the queries to the file store are approximately twice as fast as those to the database.

The experimental results make sense because the file-based tile storage scheme is designed specifically for rendering tiles from vector data. Similar optimizations are possible for database stored vector data; splitting tables by key zoom level was already discussed, but data could also be indexed according to precomputed tile location at a specific zoom level. However, with these changes, managing the database storage becomes significantly more complicated, even more than the file-based storage (querying multiple layer tables for data, handling features which cross tile boundaries, etc.). A file store can provide better performance with lower development cost, lower administrative overhead, and better portability than databases.



(a) Results for all tile queries.



(b) Results for tile queries with fewer than 1000 featuers.

Fig. 11.5 Comparison of geospatial query execution times between a database and a file-based feature store. Each geospatial query requests all features in a tile from zoom level 11. The file query outperforms the database, most significantly when the number of features in the query tile grows.