AutoShard – Declaratively Managing Hot Spot Data Objects in NoSQL Document Stores

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ABSTRACT
NoSQL document stores are becoming increasingly popular as backends in web development. Not only do they scale out to large volumes of data, many systems are even custom-tailored for this domain: NoSQL document stores like Google Cloud Datastore have been designed to support massively parallel reads, and even guarantee strong consistency in updating single data objects. However, strongly consistent updates cannot be implemented arbitrarily fast in large-scale distributed systems. Consequently, data objects that experience high-frequent writes can turn into severe performance bottlenecks. In this paper, we present AutoShard, a ready-to-use object mapper for Java applications running against NoSQL document stores. AutoShard’s unique feature is its ability to gracefully shard hot spot data objects to avoid write contention. Using AutoShard, developers can easily handle hot spot data objects by adding minimally intrusive annotations to their application code. Our experiments show the significant impact of sharding on both the write throughput and the execution time.

Categories and Subject Descriptors
H.2.4 [Database Management]: Systems—concurrency, distributed databases, transaction processing

General Terms
Design, Performance, Algorithms

1. INTRODUCTION
NoSQL document stores are highly appealing in web development, especially for applications that require high scalability and high availability. Conveniently, NoSQL data stores are readily available with established web hosting platforms, such as Google App Engine [18]. The flexible data model that these systems commonly provide suits an agile software development style since the database schema does not have to be designed up front. New attributes can be easily added on-the-fly as required by new features. The simple data access methods (i.e., put() and get(key)) and the limited query capabilities are usually sufficient for web applications. Moreover, the sheer scalability of these systems is impressive: Due to a highly distributed architecture, these systems gracefully handle large amounts of users and data.

NoSQL document stores are capable of scaling out over tens of thousands of nodes. With such an architecture, arbitrary transactions with ACID semantics are usually not feasible, and effects of eventual consistency come into play. Yet the application logic often demands strong consistency. Therefore, systems such as Google Cloud Datastore that have been designed with web applications in mind, allow for strongly consistent updates in restricted cases, e.g. when changes affect a single data object only [5].

Yet strongly consistent updates come at the cost of slower writes. With Google Cloud Datastore, the supported limit for writing against a single data object is merely one update per second [4]. This can result in write contention, an effect not unique to this particular system, e.g. [2].

Commonly, web applications are read-intensive, so in the presence of few writes, this limit may not even be noticed. However, there are certain features in web applications that are inherently prone to write contention, such as a global counter recording page visits, or many users hitting a like button on a popular image.

Example 1. Consider crowd sourcing tools such as Google Moderator for ranking user-submitted questions (see Figure 1). In 2008, this tool has been successfully employed in the U.S. presidential debates, with one million votes from 20,000 people in just 48 hours [1]. Thanks to a sophisticated implementation, Google Moderator is highly scalable. However, a naive implementation on a backend such as Google Cloud Datastore may not scale: If the counter tracking positive votes on a question is implemented by a single document, already ten of users concurrently voting on the same popular question will cause write contention. Ultimately, this triggers runtime errors during peak times.

How to deal with so-called hot spot data objects has already been subject of study back in the late 70s and early 80s. Typical use cases in those days were the number of available seats on a plane, or the overall balance of bank accounts. The idea of exploiting the semantics of data items and their transactions has been termed semantics-based transaction processing, and has lead to sophisticated solutions, such as the IMS Fast Path system [16], or the Escrow method [13]. A comprehensive survey can be found in [15].

Yet the challenge of managing hot spot data objects in today’s web applications comes with several novel aspects:
1. NoSQL data stores frequently implement optimistic concurrency control, whereas solutions designed for re-

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http://en.wikipedia.org/wiki/Google_Moderator
Contributions. Our main contributions are:

- We give a systematic overview for sharding hot spot data objects in NoSQL document stores. In particular, we introduce static and dynamic property sharding, as well as entity group sharding.
- We present AutoShard, a novel Java object mapper specifically designed for NoSQL document stores. AutoShard relieves developers from having to deal with low-level property sharding, and thus restores a clearer separation between logical and physical database design. AutoShard is designed for ease-of-use, merely requiring simple declarative annotations in Java classes. Its architecture relies on self-modifying code to transparently generate sharding code.
- We evaluate static property sharding with AutoShard and thereby demonstrate a significant improvement on both the write throughput and the average execution times of writes against hot spot data objects.

Organization. The remainder of this paper is organized as follows. Section 2 presents various sharding strategies. We discuss the tradeoffs in sharding, i.e. eliminating severe performance bottlenecks and thereby trading in eventual consistency effects that are still tolerable for a large class of practical applications. In Section 3 we introduce AutoShard, our Java object mapper that unburdens developers from writing custom sharding code. Instead, developers conveniently specify which data members are to be sharded by adding annotations to their Java code. We present details on the AutoShard architecture in Section 4. We experimentally evaluate our implementation of AutoShard (Section 5), and conclude with a summary of our work and the directions for future research.

2. SHARDING STRATEGIES

We next give an overview of common sharding strategies as established in the developer community. AutoShard implements two ways of sharding atomic document properties:

- In static property sharding (e.g. [2,9]), the number of shards is fixed, whereas
- in dynamic property sharding (e.g. [8]), the number of shards grows on demand.

Property sharding is applicable to a large class of NoSQL document stores. We illustrate the idea behind these approaches, and further discuss entity group sharding, where sharding is applied to groups of documents. Entity groups are a feature specific to Google Cloud Datastore [18] and its underlying software layer, the Google-internal Megastore [1].

2.1 Static Property Sharding

Let us resume our discussion of building a scalable voting application. An example of a voting question is shown below in JSON format. We refer to persisted objects as entities.

```
{"kind" : "Question", "id" : 42,
  "question" : "How do you plan to improve public education?",
  "author" : "Phil R",
  "responses" : [
    
    
    
    
    "i have earned $1048 dollars just by ad clicks",
    "author" : "twodollarclick"
  ],
  "votes" : 76}
```

Each entity is assigned a kind, which is simply a classification of the entity as a question in this case. Each entity has a unique identifier and further properties (c.f. attributes). Properties may be atomic, multi-valued, structured, and even nested (e.g. like the list of responses above).

The rate at which users may vote on this question is physically limited. In systems such as Google Cloud Datastore, only a minimum write throughput of one write per second per entity is guaranteed (with 5 to 10 concurrent writes...
achieved on average [3]). Yet a controversial question is likely to receive concurrent votes. Write contention then causes runtime errors, and ultimately, results in data loss, since not all updates can be persisted.

The recommended approach is to shard property votes, creating \( n + 1 \) entities instead. One entity stores the question without the votes-property, we refer to it as the main entity. The value of the votes-property is distributed over \( n \) single entities, the shards. This is shown below. The first shard with identifier 42–1 stores the original value of the votes-property, whereas the shard_votes-property in all other shards has been set to zero. We can always obtain the total number of votes for a given question by computing the sum over the shard_votes across all \( n \) shards.

\[
\text{select } \bullet \text{ from Shard where question = 42}
\]

Whenever the question is voted on, a single shard is picked at random, shard_votes is incremented, and the shard is persisted again. This can usually be executed as an atomic action, and effectively distributes concurrent writes across the \( n \) shards, rather than all concurrent updates affecting a single entity. Since addition of integers is commutative and associative, this is mathematically sound.

**Tradeoffs.** By sharding the hot spot counter, we have eliminated a crucial scalability bottleneck in our voting application. As we show in Section 3, sharding significantly improves the write throughput on single entities, while keeping the average transaction time within acceptable bounds. Yet sharding hast two inherent drawbacks, owing to the particularities common to many NoSQL document stores:

1. Range queries over shards may not be supported.
2. The computation of the total number of votes may show eventual consistency effects.

Let us elaborate on drawback (1): NoSQL document stores commonly provide very restricted query languages. For instance, Google Cloud Datastore would support the following query over the original, unsharded question entity:

\[
\text{select } \bullet \text{ from Question where votes > 50}
\]

Yet the query language is not expressive enough to compute the equivalent query in the presence of shards. Consequently, developers need to write custom code to retrieve these questions. On the good side, queries filtering over unsharded properties can still be expressed.

(2) We next consider compromises in consistency. In many NoSQL data stores, updating a single entity is a strongly consistent action (c.f. [17]). Let us assume that shards 42–2 and 42–3 from our example have been updated concurrently:

\[
\text{select } \bullet \text{ from Shard where question = 42}
\]

This query is evaluated across a large cluster of nodes, and thus may not return a strongly consistent result. Next, we programmatically aggregate over the shard_votes. Due to the effects of eventual consistency, repeatedly executing the query at time of the updates may return the stale results 76 or 77, and eventually will return the consistent value 78.

In an application such as the voting app, temporarily stale results are tolerable, as long as queries return the consistent state by the time that the result is to be utilized (e.g. when the presidential debate actually begins). Therefore, sharding trades strong consistency for scalability in terms of concurrent writes. This is a valid tradeoff for applications where we are mainly interested in a ballpark number (e.g. counting the number of visitors to a website), and where the order of updates does not matter (unlike an auctioning site, for example). After all, the alternative is an application that suffers from runtime errors and data loss at peak times.

### 2.2 Dynamic Property Sharding

We now introduce an alternative approach, which we refer to as dynamic property sharding. The previous discussion of tradeoffs applies here as well. In our running example, we start with a single shard where the property shard_votes is set to the original value of votes.

\[
\text{select } \bullet \text{ from Shard where question = 42}
\]

For each user who increments the counter, we add a new shard and let the NoSQL data store assign a unique key. Thus, when two users increment the counter concurrently, two new shards with shard_votes=1 are added:

\[
\text{select } \bullet \text{ from Shard where question = 42}
\]

Even under immense write load, increments can be executed without any concurrent writes against a single entity. This comes at the cost of higher storage requirements. Again, the total shard value is computed by aggregating over all shards. This may temporarily yield stale results, again due to eventual consistency effects. An independent batch process, e.g., run nightly or when the system is under less load, compacts the shards that have accumulated. This reduces the number of shards, as well as the storage costs. Since there is a single thread writing (or rather, deleting) the shards, this does not cause write contention. Dynamic property sharding scales more gracefully under peak loads, yet amounts to a considerable implementation effort, involving background batch processes or MapReduce jobs.
2.3 Entity Group Sharding

Entity groups are a particular feature of Google Cloud Datastore and Megastore. Entities can be arranged in groups by defining a hierarchy between entities. By physically co-locating the entities inside a group, the system can guarantee ACID updates within the scope of the group.

Different from our original data design of a question with nested responses, we can store the responses in the same group as the question. Below, property parent-id references the question as the root of the hierarchy.

```java
/* ... not showing getters and setters ... */

@Entity class Question {
  @Id private int id;
  private String question;
  private String author;
  private List<Response> responses;

  @Shardable (neutral=0, shards=10)
  private int votes = 0;

  @ShardMethod
  public void voteUp() {
    this.votes++;
  }

  @ShardFold
  public static int foldVotes(int x, int y) {
    return x + y;
  }
}
```

Figure 2: Java class with AutoShard annotations.

3. THE AUTOSHARD OBJECT MAPPER

The main focus of our work is a novel object mapper framework for automatically rewriting annotated Java classes with property sharding. Like other object mappers, (e.g., [6], [11], [12]), AutoShard takes care of the mundane marshalling of persisted entities into Java objects and back, thus greatly simplifying application development. Just like established object mappers, AutoShard relies on Java language metadata annotations.

We show how AutoShard helps with our running example, the voting app. The Java class from Figure 2 represents a Question that can be voted up. In the following, we resolve write contention by property sharding.

As is customary with object mappers, the annotation @Entity specifies that an instance of class Question is to be persisted as an entity. The annotation @Id marks the unique key of the persisted entity.

The mapping of an instance of class Question onto a persisted entity is straightforward. As discussed previously, a single entity is a performance bottleneck with multiple users voting concurrently on the same question. To solve this problem by sharding, we merely add annotations. The annotation @Shardable specifies that the class member votes is to be sharded. When processing shards, the method annotated with @ShardMethod will be applied to a single shard, rather than the global value of the votes counter. We could even declare several sharding functions (e.g., to increment and decrement votes). Since in this example the shard method is incrementation, we specify zero as the neutral element (see neutral=0). This information is exploited in initializing new shards. Further, we request static property sharding with ten shards (specifying shards=10). If no shard limit is specified, AutoShard shards dynamically.

With annotation @ShardFold, we declare the static function foldVotes as the folding function. This function is called for aggregating over all shards. We may specify even more complex folding operations, as long as they are commutative and associative. It is the responsibility of the developers to correctly annotate their Java classes.

4. THE AUTOSHARD ARCHITECTURE

The AutoShard object mapper is, to our knowledge, the first Java object mapper to shard properties based on simple annotations. Our approach relies on self-modifying code by blending Java code with Groovy technology [10]. Groovy is a dynamic language that runs in the JVM and smoothly inter-operators with Java code. Further, Groovy allows us to annotate code structures for transformations in the abstract syntax tree (AST) during compilation.

Figure 3 shows the architecture of the AutoShard framework. A Java class with AutoShard annotations serves as input. The Groovy parser produces an AST and our AutoShard AST transformer restructures this tree. Class members annotated as @Shardable, as well as the sharding and the folding method, are now transformed.

We consider the modifications required for the class from Figure 2. When compiling for Google Cloud Datastore, AutoShard’s Groovy-based compiler generates the Java class shown in Figure 4. For the sharded property votes, compilation introduces a new (private) attribute shard_votes that stores a single shard value. The body of user-defined method voteUp is transferred to a private method, and the original method is replaced as shown in Figure 4. This new implementation calls the original function both for the shard
value (shard\_votes) and for the actual value (votes). Since the signatures of the class methods do not change, the remaining application code need not be adapted.

At runtime, we use the modified Question class during loading, updating, and saving entities:

**Loading:** When a new instance of a Question is loaded, AutoShard retrieves the main entity to map all unsharded class members. For the sharded class member votes it reads all shards and generates two data members. First, the (regular) data member votes is initialized to the aggregated shard value. AutoShard uses the @ShardFold method (foldVotes for class Question) to aggregate over all shards. Second, the (internal) data member shard\_votes is initialized to the neutral element zero.

**Updates:** When shard method vote\_Up is invoked for updating the counter value, the update is executed on both the (regular) data member votes as well as the (internal) data member shard\_votes. This ensures that whenever the application code accesses votes, it sees the expected value.

**Saving:** When entity Question is persisted after changes have been made, AutoShard first updates the main entity. For the sharded class member a random shard is loaded from storage, as shown in Figure 5. Its value is updated by invoking the @ShardFold (foldVotes for class Question) method on the loaded shard value and on shard\_votes. The shard is persisted within a nested transaction, so that we do not interfere with any transactions that may be running in the remaining code. Since the shard value is re-set to the neutral element, it will capture future updates. Note that the regular property votes still holds the current value.

Persisting entities and retrieving them by key are the main building blocks for web applications when interacting with the NoSQL backend. NoSQL document stores also provide basic query languages. For example, Google Cloud Datastore allows queries on entities of the same kind (or type) using simple property filters. Queries on unsharded properties or entities are not affected by AutoShard compilation. Hence, they can be run without changes (c.f. Section 2.1).

## 5. EVALUATION

We investigate the runtime benefits of sharding with AutoShard. We have implemented AutoShard with property sharding for Google Cloud Datastore, a commercial NoSQL document store handling 6.3 trillion daily requests. Our evaluation scenario deals with a Java implementation of a voting tool in the style of Google Moderator. The application is hosted on Google App Engine.

We start with a naive implementation that does not take precautions for handling concurrent writes. A shell script simulates an increasing number of users voting on popular questions, e.g., 75 voting requests per second are equally spread across 16 questions. This causes write contention on the level of persisted entities. As seen in Figure 6 for this naive implementation without any transaction retries (naive “w/o Tx retry”), 25% of the transactions fail due to write contention. This failure rate is obviously unacceptable for real world web applications.

We then repeat the experiment with a sharded version, where we have added the AutoShard annotations from Figure 2 to the code and have recompiled the application. This time, the application experiences only 4% of failed requests (see AutoShard “w/o TxRetry”). This improvement is due to the fact that write contention is reduced by distributing writes across multiple shards. However, a failure rate of 4% can still be considered alarming. Note that in this experiment, we can observe a slight increase in the average transaction time, due to the overhead imposed by sharding.

To ensure that all votes are indeed persisted, we add transaction retries (“w/TxRetry”), so transactions retry until they succeed. This obviously increases execution time. We repeat the experiment with the naive implementation, as well as with the code generated by AutoShard, and visualize the performance results in Figure 6. Both versions show a 100% success rate, yet the average transaction time for the sharded version is clearly superior (300ms vs. 430ms).

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*Quoting Urs Hölzle in his keynote at *Google Cloud Platform Live 2014*, available online at https://cloud.google.com/events/google-cloud-platform-live/*
by AutoShard. Our experiments show the significant impact of property sharding on the throughput of write requests.

In our future work, we are investigating a generic approach to property and entity group sharding that is not specific to a certain data store. Programmers should be able to describe all relevant data store properties (e.g., consistency model, ACID guarantees) so that AutoShard can implement suitable sharding strategies. We will examine how to automatically identify properties that require sharding as well as to automatically determine a suitable number of shards. We are currently extending AutoShard so that queries involving sharded properties or entities are handled transparently (whenever possible). AutoShard is scheduled to be made available as open source software.

6. SUMMARY AND FUTURE WORK

In this paper we have presented AutoShard, a ready-to-use object mapper for Java applications running against NoSQL document stores. In addition to mapping Java objects to persisted entities, AutoShard is capable of sharding properties so that hot spot data objects can be managed gracefully. This form of application-managed sharding ties in with the long tradition of efforts to avoid write contention over hot spot data objects (c.f. [15]).

A main strength of AutoShard is the ease with which data objects may be sharded, namely by merely annotating the Java code. We have demonstrated the merits of AutoShard by contrasting the performance of a naive implementation of a realistic web application with a sharded version generated by AutoShard. Our experiments show the significant impact

This brief evaluation scenario confirms the usefulness of AutoShard, i.e., Automash is capable of gracefully sharding hot spot data objects. An extended evaluation will compare static and dynamic sharding and will analyze the impact of the number of shards on the transaction time.

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Figure 5: Pseudo-code for saving sharded Question entities with AutoShard.

Figure 6: Evaluation of static property sharding where 2,000 users vote on 16 questions. A naive implementation shows an unacceptable failure rate of over 25%. AutoShard reduces the failure rate down to 4% (using 16 shards). When adding a transaction retry mechanism to ensure a 100% success rate, AutoShard significantly reduces the average transaction time compared to the naive implementation.

```java
public void save(Question q) {
    DataStore.put(q); // save the main entity
    BEGIN TRANSACTION
    // read ONE shard value at random
    shard = DataStore.getRandomShard(q);
    // fold shard value with object shard property
    shard.shard_votes = Question.foldVotes(shard.shard_votes, q.shard_votes);
    // save the updated shard
    DataStore.put(shard);
    END TRANSACTION
    // re-initialize local shard_votes data member
    q.shard_votes = 0; // 0 = neutral element
}
```

End Transaction

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