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Scalable Data Management: An In-Depth Tutorial on NoSQL Data Stores

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Abstract: The unprecedented scale at which data is consumed and generated today has shown a large demand for scalable data management and given rise to non-relational, distributed "NoSQL" database systems. Two central problems triggered this process: 1) vast amounts of user-generated content in modern applications and the resulting request loads and data volumes as well as 2) the desire of the developer community to employ problem-specific data models for storage and querying. To address these needs, various data stores have been developed by both industry and research, arguing that the era of one-size-fits-all database systems is over. The heterogeneity and sheer amount of these systems – now commonly referred to as NoSQL data stores – make it increasingly difficult to select the most appropriate system for a given application. Therefore, these systems are frequently combined in polyglot persistence architectures to leverage each system in its respective sweet spot. This tutorial gives an in-depth survey of the most relevant NoSQL databases to provide comparative classification and highlight open challenges. To this end, we analyze the approach of each system to derive its scalability, availability, consistency, data modeling and querying characteristics. We present how each system's design is governed by a central set of trade-offs over irreconcilable system properties. We then cover recent research results in distributed data management to illustrate that some shortcomings of NoSQL systems could already be solved in practice, whereas other NoSQL data management problems pose interesting and unsolved research challenges. In addition to earlier tutorials, we explicitly address how the quickly emerging topic of processing and storing massive amounts of data in real-time can be solved by different types real-time data management systems.

Keywords: NoSQL, Scalability, Distributed Systems, High Availability, Polyglot Persistence, Real-Time Processing, Cloud Data Management

1 Introduction

Traditional relational database management systems (RDBMSs) provide powerful mechanisms to store and query structured data under strong consistency guarantees and have reached an unmatched level of reliability, stability and support through decades of development. In recent years, however, the amount of useful data in some application areas has become so vast that it simply cannot be stored or processed by traditional database solutions [SF12]. User-driven content in social networks or data retrieved from large sensor networks are only two examples of this phenomenon commonly referred to as Big Data [La01]. A class of novel data storage products able to cope with Big Data are subsumed under the term NoSQL databases, many of which offer horizontal scalability and higher availability than traditional relational databases or other useful properties by sacrificing querying options and consistency guarantees [LS13].

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There are dozens of NoSQL database systems, and it is very hard to keep an overview over what these systems provide, where they fail and where they differ. Beyond a mere presentation of prominent NoSQL representatives and their respective features, this tutorial intends to give an overview over the requirements typically posed to NoSQL database systems, the techniques used to fulfill these requirements and the trade-offs that have to be made in the process.

The main problem NoSQL database systems seek to solve is providing storage and query capabilities for specific problem domains. This encompasses specialization in *data models*, *query languages*, *consistency*, *scalability* and *availability* properties, *transactional guarantees*, *schema management*, *low latency*, *analytical* and *real-time processing* as well as *durability*, *reliability* and *elasticity*. While the foundational techniques are often similar (e.g., asynchronous master-slave replication), the resulting systems exhibit very different behavior in both functional and non-functional aspects. Since very different requirements are often found in different parts of the same application, a recent trend is the consolidation of different database systems within a single application (*polyglot persistence*).

Our tutorial discusses the characteristics of NoSQL databases and introduces approaches proposed to address their challenges. To this end, we provide a classification scheme that helps to choose candidate systems for applications based on a set of data management criteria.

Furthermore, we highlight open problems that provide opportunities for contributing to the emerging area of scalable data management and polyglot persistence.

2 Tutorial Outline

Our tutorial is divided into fours parts and structured as follows.

As background, we recall the basics of distributed data management, in particular partitioning, replication, eventual consistency and the different NoSQL data models. We also present the most important impossibility results for distributed databases, e.g. the widely used CAP theorem.

The core survey of NoSQL databases covers the discussion and classification of the different systems. Each system is described in depth and relations to current research are given. We include open-source and commercial NoSQL systems, research systems as well as cloud-based database-as-a-service systems. We classify each system according to functional and non-functional properties.

The third part discusses the new challenge of real-time data management. To this end, different database systems and real-time processing frameworks are analyzed with respect to their capabilities in storing, querying and analyzing data in real-time.

The final part reviews the integration of the discussed systems in polyglot persistence environments, in particular challenges and potential benefits. A short summary of open challenges concludes the tutorial.

3 Intended Audience

We expect the tutorial to appeal to a large portion of the BTW community:

- Students who are looking for novel research topics and orientation
- Experienced researchers in the fields of database systems, cloud computing and distributed systems interested in open challenges and a comparative overview of the NoSQL landscape
- Industry practitioners tackling data management problems who are looking for a survey and classification of existing systems and their respective sweet spots

The tutorial is aimed at balancing practical aspects (e.g., APIs and deployments models) and research approaches (e.g., novel architectures and transaction protocols).

4 Relationship to Prior Tutorials

This tutorial is an extended version of our tutorial from BTW 2015 [GR15] and ICDE 2016 [GR16]. In addition to updates that reflect progress made in both research and practice, we included the topic of real-time data management to account for the quickly emerging trend of serving data for interactive applications.

5 Presenters

Felix Gessert is a Ph.D. student at the databases and information systems group at the University of Hamburg. His main research fields are scalable database systems, transactions and web technologies for cloud data management. His thesis addresses caching and transaction processing for low latency mobile and web applications. He is also founder and CEO of the startup Baqend that implements these research results in a cloud-based backend-as-a-service platform. Since their product is based on a polyglot, NoSQL-centric storage model, he is very interested in both the research and practical challenges of leveraging and improving these systems. He is frequently giving talks on different NoSQL topics.

Wolfram Wingerath is a Ph.D. student under supervision of Norbert Ritter teaching and researching at the University of Hamburg. He was co-organiser of the BTW2015 conference and has held workshop and conference talks on his published work on several occasions. Wolfram is part of the databases and information systems group and his research interests evolve around scalable NoSQL database systems, cloud computing and Big Data analytics, but he also has a background in data quality and duplicate detection. His current work is related to real-time stream processing and explores the possibilities of providing always-up-to-date materialized views and continuous queries on top of existing non-streaming DBMSs.

Norbert Ritter is a full professor of computer science at the University of Hamburg, where he heads the databases and information systems group. He received his Ph.D. from the University of Kaiserslautern in 1997. His research interests include distributed and federated database systems, transaction processing, caching, cloud data management, information integration and autonomous database systems. He has been teaching NoSQL topics in various database courses for several years. Seeing the many open challenges for NoSQL systems, he and Felix Gessert have been organizing the annual SCDM[4] workshop for three years to promote research in this area.

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