732A54 / TDDE31
Big Data Analytics

Topic: DBMSs for Big Data

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Relational Database Management Systems

- Well-defined formal foundations (*relational data model*)

schema

instance/ state

Relation Name

Attributes

Tuples

STUDENT

Name	Ssn	Home_phone	Address	Office_phone	Age	Gpa
Benjamin Bayer	305-61-2435	(817)373-1616	2918 Bluebonnet Lane	NULL	19	3.21
Chung-cha Kim	381-62-1245	(817)375-4409	125 Kirby Road	NULL	18	2.89
Dick Davidson	422-11-2320	NULL	3452 Elgin Road	(817)749-1253	25	3.53
Rohan Panchal	489-22-1100	(817)376-9821	265 Lark Lane	(817)749-6492	28	3.93
Barbara Benson	533-69-1238	(817)839-8461	7384 Fontana Lane	NULL	19	3.25

Figure from “Fundamentals of Database Systems” by Elmasri and Navathe, Addison Wesley.

Relational Database Management Systems

- Well-defined formal foundations (*relational data model*)
- *SQL* – powerful declarative language
  - querying
  - data manipulation
  - database definition
- Support of transactions with *ACID* properties (***A***tomicity, ***C***onsistency preservation, ***I***solation, ***D***urability)
- Established technology (developed since the 1970s)
  - many vendors
  - highly mature systems
  - experienced users and administrators

Business world has evolved

- Organizations and companies (whole industries) shift to the digital economy powered by the Internet
- Central aspect: new IT applications that allow companies to *run their business* and to *interact with costumers*
  - Web applications
  - Mobile applications
  - Connected devices ("Internet of Things")

Image source: https://pixabay.com/en/technology-information-digital-2082642/

New Challenges for Database Systems

- Increasing numbers of concurrent users/clients
  - tens of thousands, perhaps millions
  - globally distributed
  - expectations: consistently high performance and 24/7 availability (no downtime)
- Different types of data
  - huge amounts (generated by users and devices)
  - data from different sources together
  - frequent schema changes or no schema at all
  - semi-structured and unstructured data
- Usage may change rapidly and unpredictably

Image source: https://www.flickr.com/photos/groucho/5523369279/

``NoSQL”

- Some interpretations (without precise definition):
  - “no to SQL”
  - “not only SQL”
  - “not relational”
- 1998: first used for an RDBMS* that omitted usage of SQL
- 2009: picked up again to name a conference on
  “open-source, distributed, non-relational databases”
- Since then, “NoSQL database” loosely specifies a class of non-relational DBMSs
  - Relax some requirements of RDBMSs to gain efficiency and scalability for use cases in which RDBMSs are a bad fit

*RDBMS = relational database management system

Scalability

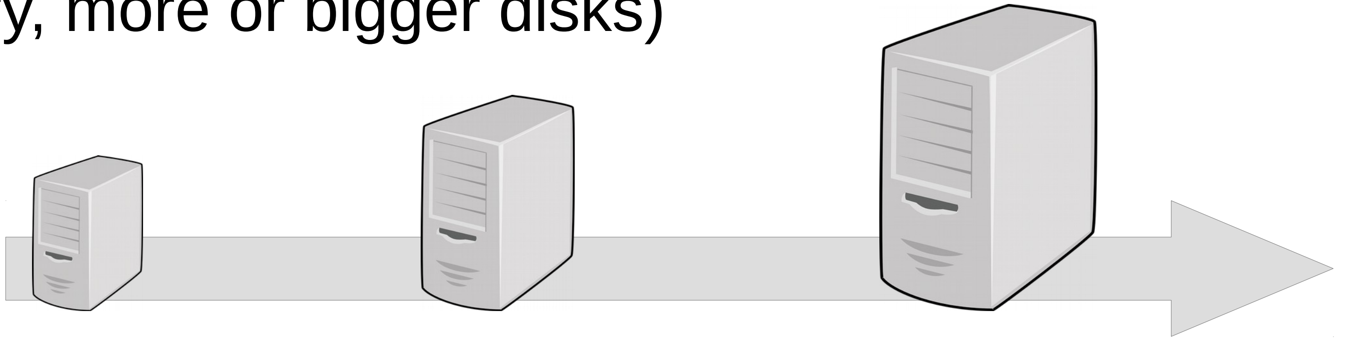
- Data scalability: system can handle
  growing amounts of data
  without losing performance

- Read scalability: system can handle
  increasing numbers of read operations
  without losing performance

- Write scalability: system can handle
  increasing numbers of write operations
  without losing performance

Vertical Scalability *vs.* Horizontal Scalability

- Vertical scalability (“scale up”)
  - Add resources to a server (e.g., more CPUs, more memory, more or bigger disks)



- Horizontal scalability (“scale out”)
  - Add nodes (more computers) to a distributed system

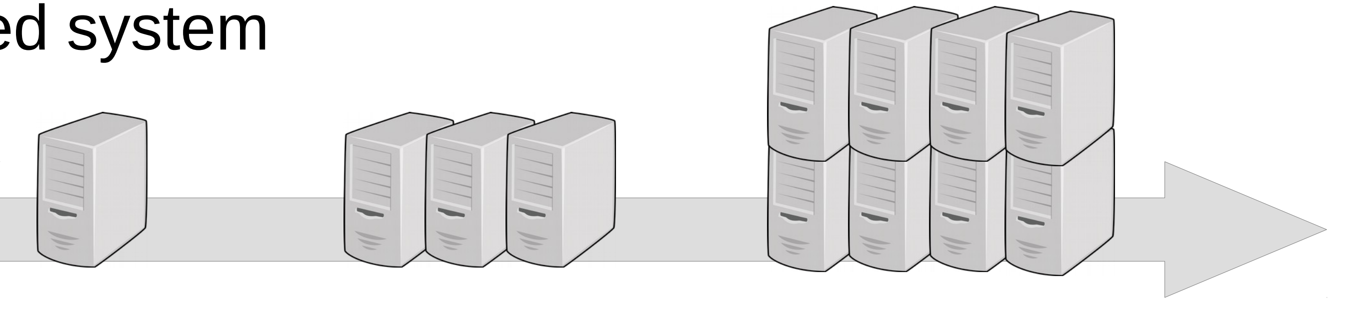


Image source: https://pixabay.com/en/server-web-network-computer-567943/

Typical* Characteristics of NoSQL Systems

- Ability to scale horizontally over many commodity servers with high performance, availability, and fault tolerance
  - achieved by giving up ACID guarantees
  - and by partitioning and replication of data
- Non-relational data model, no requirements for schemas
  - data model limitations make partitioning effective

*Attention, there is a *broad variety* of such systems and not all of them have these characteristics to the same degree

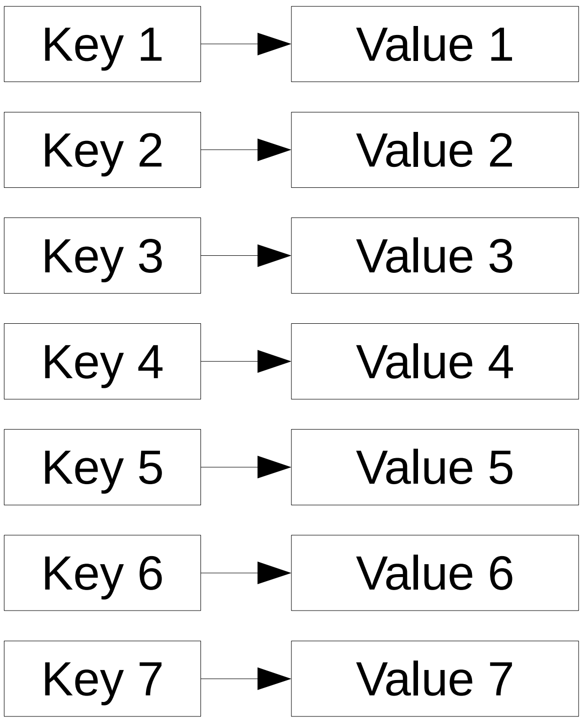
NoSQL Data Models

Data Models

- Key-value model
- Document model
- Wide-column models
- Graph database models

Key-Value Stores: Data Model

- Database is simply a set of key-value pairs
  - keys are unique
  - values of arbitrary data types
- Values are opaque to the system



Example

- Assume a relational database consisting of a single table:

User

login	**name**	**website**	**twitter**
alice12	Alice	http://alice.name/	NULL
bob_in_se	Bob	NULL	@TheBob
charlie	Charlie	NULL	NULL

- How can we capture this data in the key-value model?

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- How can we capture this data in the key-value model?

alice12	→	Alice, http://alice.name/
bob_in_se	→	Bob, , @TheBob
charlie	→	Charlie

Example

- Let's add another table:

Fav

user	favorite
alice12	bob_in_se
alice12	charlie

User

login	name	website	twitter
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alice12	→	Alice, http://alice.name/, , [bob_in_se,charlie]
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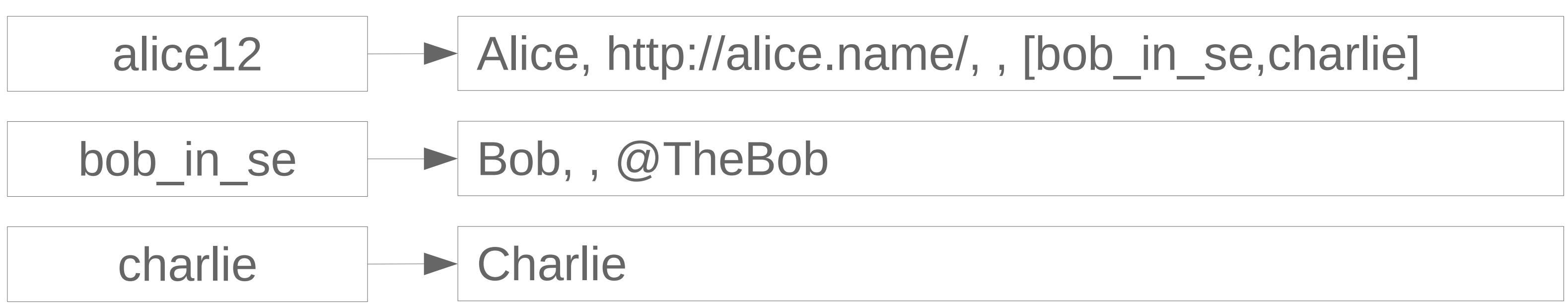
Key-Value Stores: Querying

- Only CRUD operations in terms of keys
  - CRUD: create, read, update, delete
  - put(*key*, *value*); get(*key*); delete(*key*)
- No support for value-related queries
  - Recall that values are opaque to the system (i.e., no secondary index over values)
- Accessing multiple items requires *separate requests*
  - Beware: often no transactional capabilities



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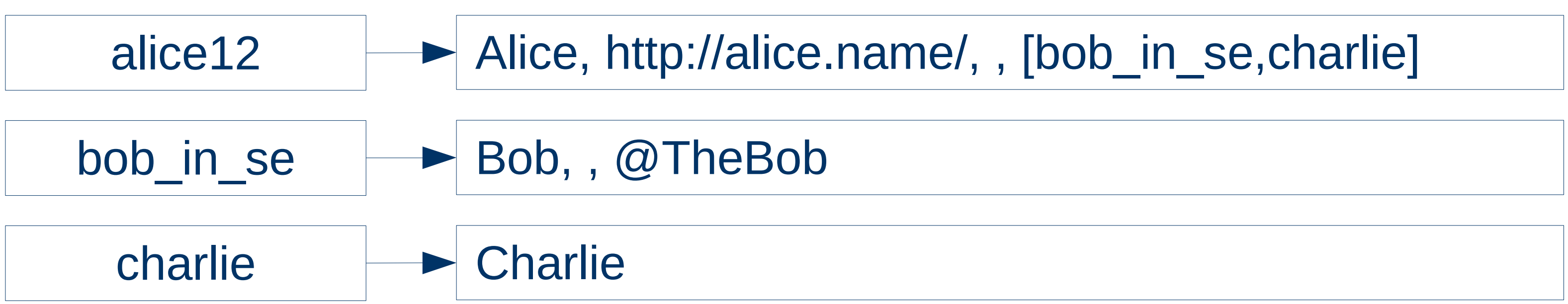
- Accessing multiple items requires *separate requests*
  - Beware: often no transactional capabilities
- Advantage of these limitations: partition the data based on keys (*"horizontal partitioning"*, also called *"sharding"*) and distributed processing can be very efficient

Example (cont'd)

- Assume we try to find all users for whom Bob is a favorite
- It is possible (how?), but very inefficient
- What can we do to make it more efficient?



Example (cont'd)

- Assume we try to find all users for whom Bob is a favorite
- It is possible (how?), but very inefficient
- What can we do to make it more efficient?
  - Add redundancy (downsides: more space needed, updating becomes less trivial and less efficient)

alice12	→	Alice, http://alice.name/, , [bob_in_se,charlie], [ ]
bob_in_se	→	Bob, , @TheBob, [ ], [alice12]
charlie	→	Charlie, , , [ ], [alice12]

Key-Value Stores: Use Cases

- Whenever values need to be accessed only via keys
- Examples:
  - Storing Web session information
  - User profiles and configuration
  - Shopping cart data
  - Caching layer that stores results of expensive operations (e.g., complex queries over an underlying database, user-tailored Web pages)

Examples of Key-Value Stores

- In-memory key-value stores
  - Memcached
  - Redis
- Persistent key-value stores
  - Berkeley DB
  - Voldemort
  - RiakDB

Data Models

- Key-value model
- Document model
- Wide-column models
- Graph database models

Image source: https://pxhere.com/en/photo/1188160

Document Stores: Data Model

- Document: a set of fields consisting of a name and a value
  - field names are unique within the document
  - values are scalars (text, numeric, boolean) or lists

login : "alice12"
name : "Alice"
website : "http://alice.name/"
favorites : ["bob_in_se", "charlie"]

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  - in some systems, values may also be other documents

```
login : "alice12"
name : "Alice"
website : "http://alice.name/"
favorites : [ "bob_in_se", "charlie" ]
address : {
        street : "Main St"
        city : "Springfield"
 }
```

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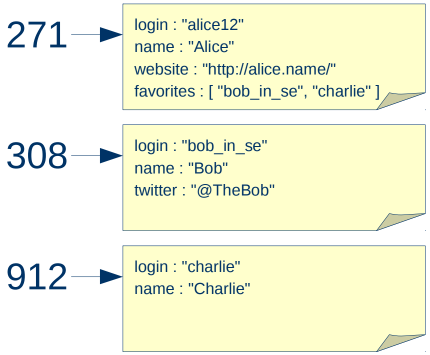
- Database is a set of documents (or multiple such sets)
  - each document additionally associated with a unique identifier (typically system-generated)
  - *schema free*: different documents may have different fields



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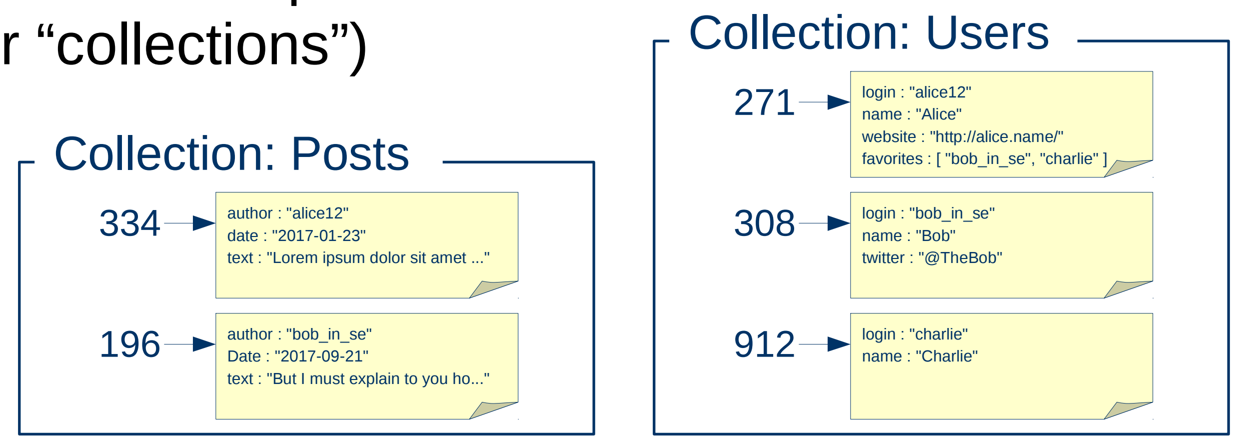

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- Partitioning based on collections and/or on document IDs
- Secondary indexes over fields in the documents possible
  - different indexes per domain/collection of documents

Document Stores: Querying

- Querying in terms of conditions on document content
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- Examples (using MongoDB's query language):
  - Find all docs in collection *Users* whose *name* field is *"Alice"*

    ```
    db.Users.find( {name: "Alice"} )
    ```

  - Find all docs in collection *Users* whose *age* is greater than 23

    ```
    db.Users.find( {age: {$qt: 23}} )
    ```

  - Find all docs about *Users* who favorite Bob

    ```
    db.Users.find( {favorites: {$in: ["bob_in_se"]}} )
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login : "alice12"
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  - Find all docs about *Users* who favorite Bob

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db.Users.find( {favorites: {$in: ["bob_in_se"]}} )
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- However, no cross-document queries (like joins)
  - have to be implemented in the application logic

Document Stores: Use Cases

- Whenever we have items of similar nature but slightly different structure
- Examples:
  - Blogging platforms
  - Content management systems
  - Event logging
- Fast application development

Examples of Document Stores

- Amazon's SimpleDB
- CouchDB
- Couchbase
- MongoDB

Data Models

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- Wide-column models
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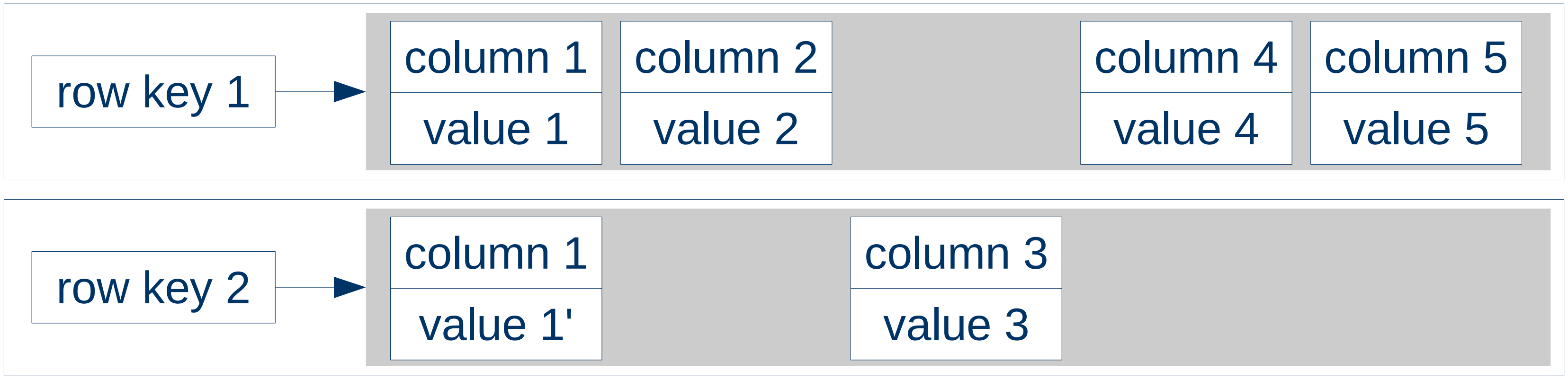
also called
column-family models
or
extensible-record models

Wide-Column Stores: Data Model (Basic)

- Database is a set of "rows" each of which …
  … has a unique key, and
  … a set of key-value pairs (called "columns")
- Schema free: different rows may contain different columns



Wide-Column Stores: Data Model

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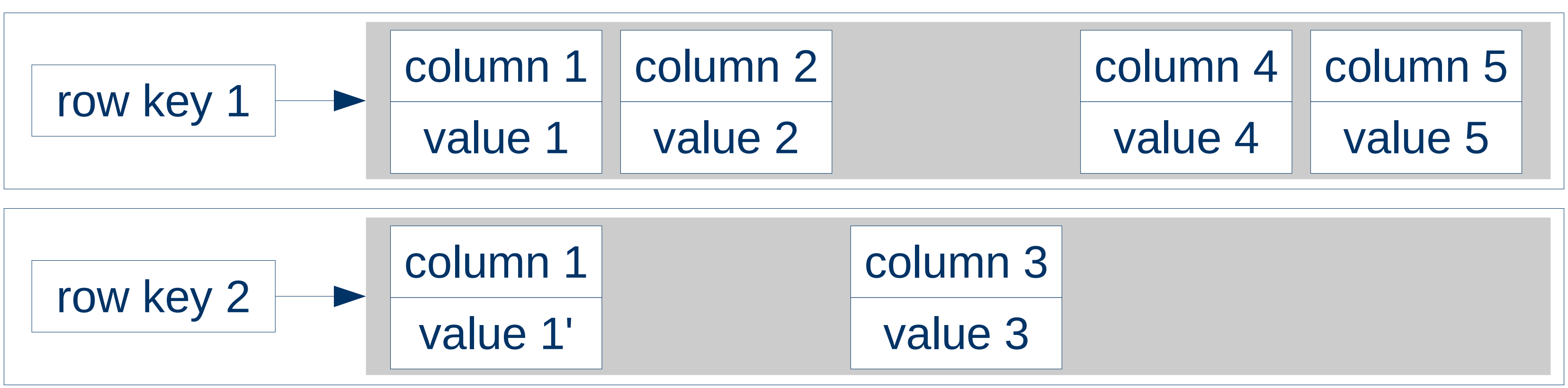
- Like a single, very wide relation (SQL table) that is
  a) extensible, b) schema-free, and c) potentially sparse



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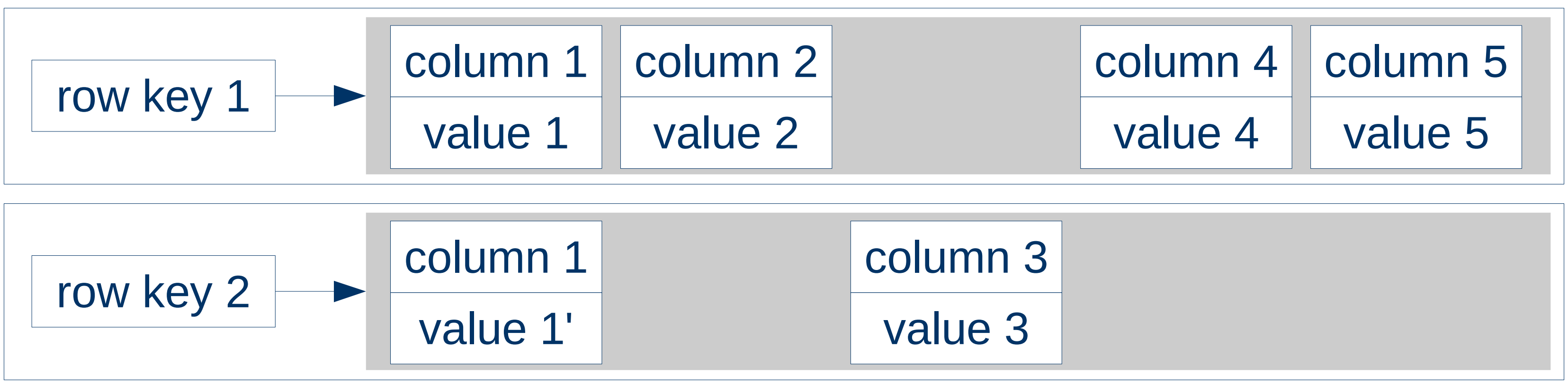
- Like the document model without nesting



Example (cont'd)

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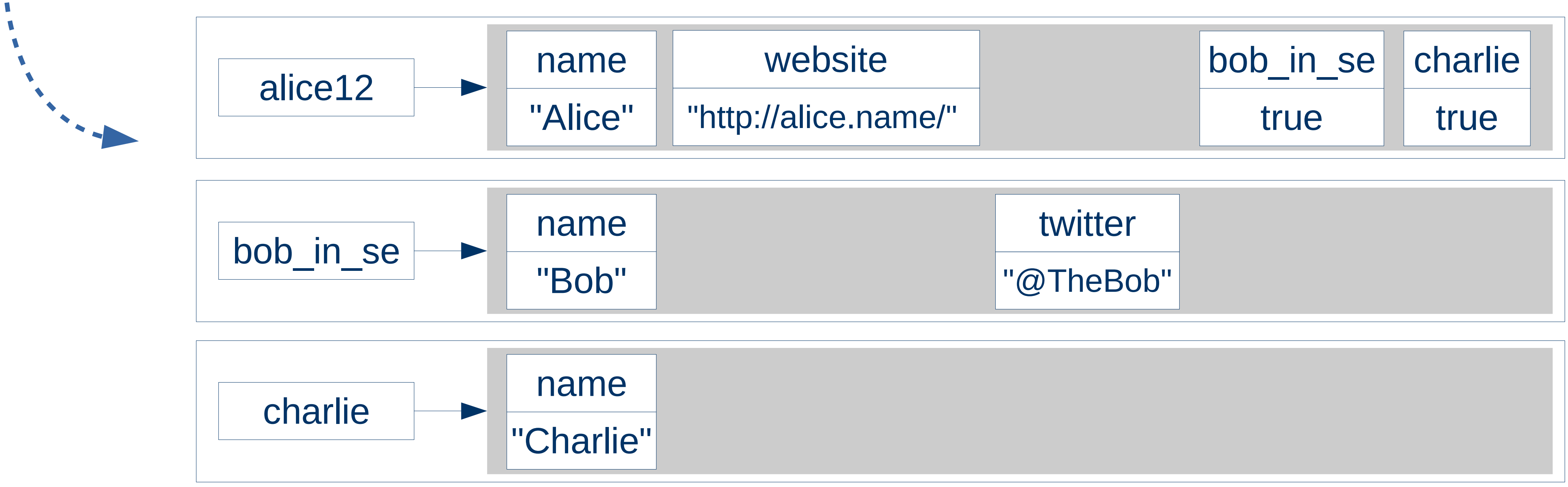
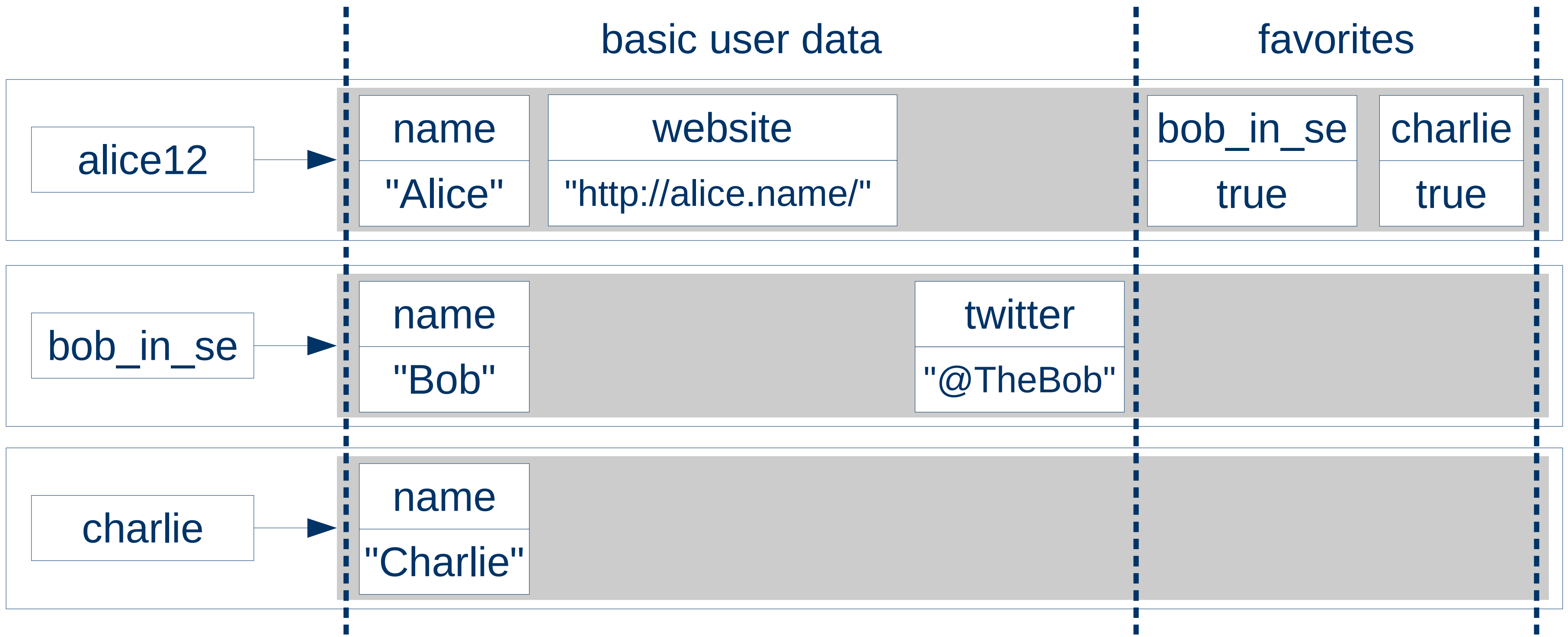


Wide-Column Stores: Data Model (cont'd)

- Columns may be grouped into so called "column families"
  - Hence, values are addressed by
    (*row key*, *column family*, *column key*)



Wide-Column Stores: Data Model (cont'd)

- Columns may be grouped into so called “column families”
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- Data may be partitioned …

  … based on row keys (*horizontal partitioning*),

  … but also based on column families (*vertical partitioning*),

  … or even on both

Wide-Column Stores: Data Model (cont'd)

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    (*row key*, *column family*, *column key*)
- Data may be partitioned …
  … based on row keys (*horizontal partitioning*),
  … but also based on column families (*vertical partitioning*),
  … or even on both
- Secondary indexes can be created over arbitrary columns

Wide-Column Stores: Querying

- Querying in terms of keys or conditions on column values
- Queries expressed in a system-specific query language or in terms of program code using an API
  - Conceptually similar to queries in document stores
- No joins
  - Again, must be implemented in the application logic

Wide-Column Stores: Use Cases

- Similar to use cases for document store
- Analytics scenarios
  - Web analytics
  - Personalized search
  - Inbox search

Examples of Wide-Column Stores

- Basic form (no column families):
  - Amazon SimpleDB
  - Amazon DynamoDB
- With column families:
  - Google's BigTable
  - Hadoop HBase
  - Apache Cassandra

Data Models

- Key-value model
- Document model
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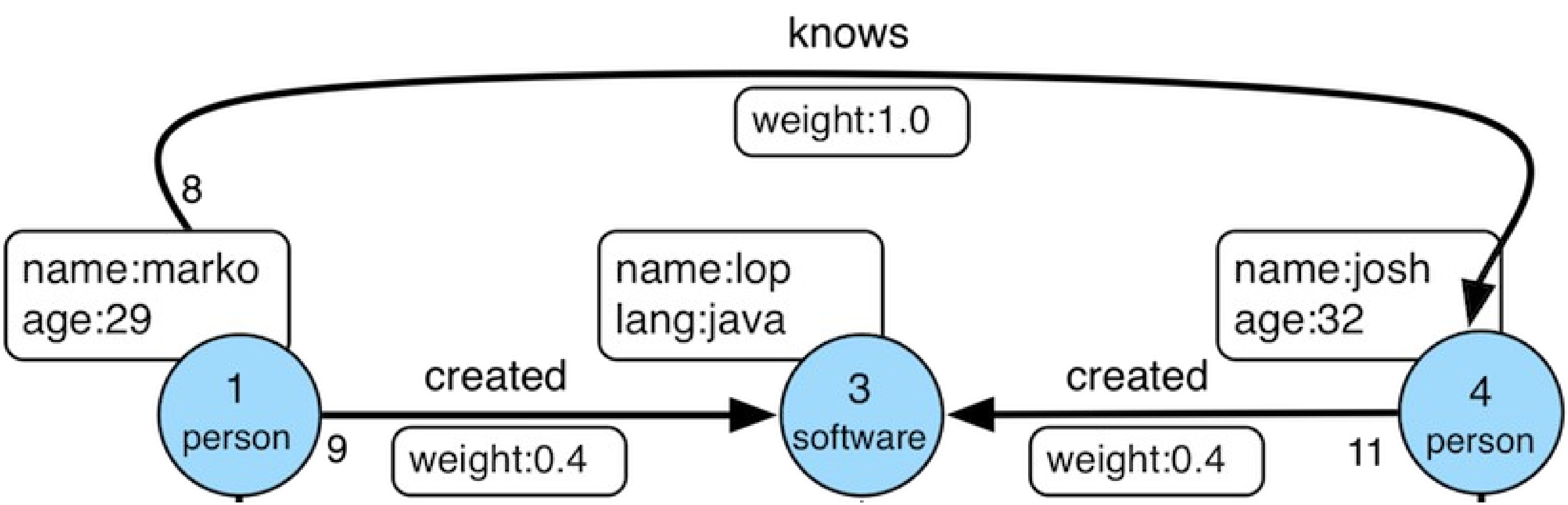
Graph Database Systems: Data Model

- Database is some form of a graph (nodes and edges)
  - plus some extra features
- Prominent example: *Property Graphs* in which any node and any edge may additionally have a label as well as key-value pairs (called "properties")



Graph Database Systems: Querying

- Graph pattern matching
- Traversal queries
  - e.g., shortest paths, navigational expressions
- Graph algorithms
  - e.g., PageRank, connected components, clustering

Graph Database Systems: Use Cases

- Complex networks
  - e.g., social, information, technological, biological
- Concrete example use cases:
  - Location-based services
  - Recommendation
  - Fraud detection

Examples of (Property) Graph Systems

- Neo4j
- TigerGraph
- InfiniteGraph
- JanusGraph
- Cambridge Semantics' AnzoGraph
- Amazon Neptune

Data Models

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There are also *multi-model NoSQL stores*

Examples:

- OrientDB (key-value, documents, graph)
- ArangoDB (key-value, documents, graph)
- Cosmos DB (key-value, documents, wide-column, graph)

Typical* Characteristics of NoSQL Systems

- Ability to scale horizontally over many commodity servers with high performance, availability, and fault tolerance
  - achieved by giving up ACID guarantees
  - and by partitioning and replication of data
- Non-relational data model, no requirements for schemas
  - data model limitations make partitioning effective

*Attention, there is a *broad variety* of such systems and not all of them have these characteristics to the same degree

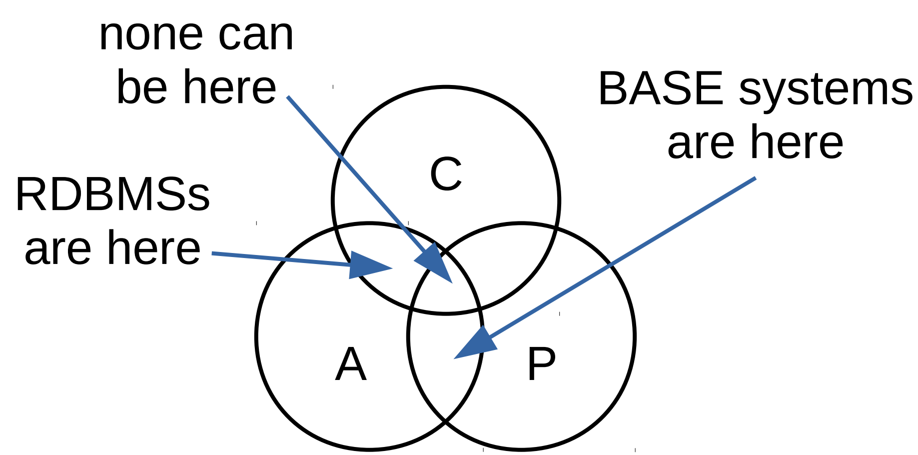
BASE rather than ACID

What is BASE?

- Idea: by giving up ACID guarantees, one can achieve much higher performance and scalability
- ***B***asically ***A***vailable
  - system available whenever accessed, even if parts of it unavailable
- ***S***oft state
  - the distributed data does not need to be in a consistent state at all times
- ***E***ventually consistent
  - state will become consistent after a certain period of time
- BASE properties suitable for applications for which some inconsistency may be acceptable

CAP Theorem

- Only 2 of 3 properties can be guaranteed at the same time in a distributed system with data replication



- ***C***onsistency: the same copy of a replicated data item is visible from all nodes that have this item
  - Note that this is something else than consistency in ACID
- ***A***vailability: all requests for a data item will be answered
  - Answer may be that operation cannot be completed
- ***P***artition Tolerance: system continues to operate even if it gets partitioned into isolated sets of nodes

Consistency Models

- *Strong consistency*: after an update completes, every subsequent access will return the updated value
  - may be achieved without consistency in the CAP theorem
- *Weak consistency*: no guarantee that all subsequent accesses will return the updated value
  - *eventual consistency*: if no new updates are made, eventually all accesses will return the last updated value
  - *inconsistency window*: the period until all replicas have been updated in a lazy manner

Consistency Models (cont'd)

- Let:
  - N be the number of nodes that store replicas
  - R be the number of nodes required for a successful read
  - W be the number of nodes required for a successful write
- Then:
  - Consistency as per CAP requires $W = N$
  - Strong consistency requires $R + W > N$
  - Eventual consistency if $R + W \leq N$
  - High read performance means a great N and $R = 1$
  - Fault tolerance/availability (and relaxed consistency) $W = 1$

Summary

Summary

- NoSQL systems support non-relational data models (key-value, document, wide-column, graph)
  - schema free
  - support for semi-structured and unstructured data
  - limited query capabilities (no joins!)
- NoSQL systems provide high (horizontal) scalability with high performance, availability, and fault tolerance
  - achieved by:
    - data partitioning (effective due to data model limitations)
    - data replication
    - giving up consistency requirements

Reading Material

- **NoSQL Databases: a Survey and Decision Guidance**. F. Gessert. *Blog post*, August 2016.
- **Data Management in Cloud Environments: NoSQL and NewSQL Data Stores.** K. Grolinger et al. *Journal of Cloud Computing 2:22*, 2013
  - Considers not only NoSQL but also NewSQL systems
  - Includes comprehensive comparison of various systems over a large number of dimension
- **Scalable SQL and NoSQL Data Stores.** R. Cattell. *ACM SIGMOD Record 39(4)*, 2011
  - More detailed overview of several example systems
- **NoSQL Databases.** C. Strauch. *Lecture Notes*, 2012
  - Comprehensive discussion of several example systems

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