NDBI040: **Big Data Management and NoSQL Databases**

http://www.ksi.mff.cuni.cz/~svoboda/courses/2016-1-NDBI040/

Lecture 6

Document Databases: MongoDB

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Lecture Outline

Document databases

- General introduction

MongoDB

- Data model
- CRUD operations
  - **Insert**
  - **Update**
  - **Remove**
  - **Find**: projection, selection, modifiers
- Index structures

Document Stores

Data model

- **Documents**
  - Self-describing
  - **Hierarchical tree structures** (JSON, XML, …)
    - Scalar values, maps, lists, sets, nested documents, …
  - Identified by a **unique identifier** (key, …)
- Documents are **organized into collections**

Query patterns

- Create, update or remove a document
- **Retrieve documents according to complex query conditions**

Observation

- Extended key-value stores where the value part is examinable!

Document Stores

Suitable use cases

- Event logging, content management systems, blogs, web analytics, e-commerce applications, …
  - I.e. **for structured documents with similar schema**

When not to use

- **Set operations** involving multiple documents
- Design of document structure is constantly changing
  - I.e. when the required level of granularity would outbalance the advantages of aggregates

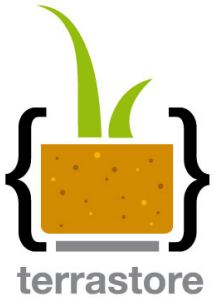
Document Stores

Representatives

- **MongoDB**, **Couchbase**, Amazon **DynamoDB**, **CouchDB**, RethinkDB, RavenDB, Terrastore
- *Multi-model*: **MarkLogic**, **OrientDB**, OpenLink Virtuoso, ArangoDB

Document Stores

Representatives



MongoDB Document Database

MongoDB

JSON document database

- https://www.mongodb.com/
- Features
  - Open source, high availability, eventual consistency, automatic sharding, master-slave replication, automatic failover, secondary indices, …
- Developed by **MongoDB**
- Implemented in C++, C, and JavaScript
- Operating systems: **Windows**, **Linux**, Mac OS X, …
- Initial release in 2009

Example

Collection of movies

```
{
  _id: ObjectId("1"),
  title: "Vratné lahve",
  year: 2006
}
```

```
{
  _id: ObjectId("2"),
  title: "Samotáři",
  year: 2000
}
```

```
{
  _id: ObjectId("3"),
  title: "Medvídek",
  year: 2007
}
```

Query statement

Titles of movies filmed in *2005* and later, sorted by these titles in descending order

```
db.movies.find(
  { year: { $gt: 2005 } },
  { _id: false, title: true }
).sort({ title: -1 })
```

Query result

```
{ title: "Vratné lahve" }
```

```
{ title: "Medvídek" }
```

Data Model

Database system structure

Instance $\rightarrow$ **databases** $\rightarrow$ **collections** $\rightarrow$ **documents**

- Database
- Collection
  - Collection of documents, usually of a similar structure
- Document
  - MongoDB **document** = **one JSON object**
  - Each document…
    - belongs to exactly one collection
    - has a **unique identifier** `_id`

Data Model

MongoDB **document** = **one JSON object**

- Internally stored as BSON (*Binary JSON*)
- Maximal allowed size: 16 MB (in BSON)
  - GridFS can be used to split larger files into smaller chunks

Restrictions on field names

- `_id` (at the top level) is reserved for a primary key
- Field names **cannot start with** `$`
  - Reserved for query operators
- Field names **cannot contain** `.`
  - Used when accessing nested fields

Data Model

Primary Keys

Features of identifiers

- **Unique** within a collection
- **Immutable** (cannot be changed once assigned)
- Can be of **any type** other than an array

Design of identifiers

- Natural identifier
- Auto-incrementing number – not recommended
- UUID (*Universally unique identifier*)
- **ObjectId** – **special 12-byte BSON type** (default option)
  - Small, likely unique, fast to generate, ordered, based on a timestamp, machine id, process id, and a process-local counter

Data Model

Design Questions

Flexible schema

- No document schema is provided, nor expected or enforced
  - However, **documents within a collection are similar in practice**
- MongoDB document = one JSON object
  - I.e. even a complex JSON object with other recursively nested objects, arrays or values

Design challenge

- Balancing application requirements, performance aspects, and data retrieval patterns,
- while considering structure of data and mutual relationships

Two main concepts: references vs. embedded documents

Data Model

Design Questions: Denormalized Data Models

Embedded documents

- **Related data in a single structure** with subdocuments
  - Suitable for **one-to-one** or **one-to-many** relationships
- Brings ability to read / write related data in a single operation
  - I.e. better performance, less queries need to be issued

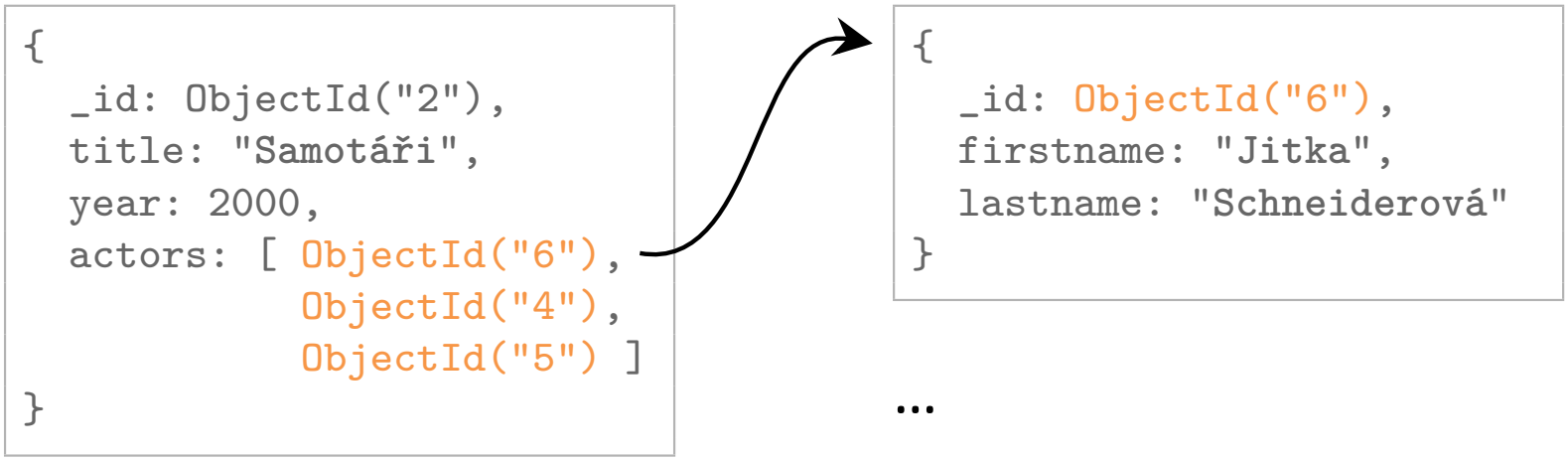
```
{
  _id: ObjectId("2"), title: "Samotáři", year: 2000,
  actors: [
    { firstname: "Jitka", lastname: "Schneiderová" },
    { firstname: "Ivan", lastname: "Trojan" },
    { firstname: "Jiří", lastname: "Macháček" }
  ]
}
```

Data Model

Design Questions: Normalized Data Models

References

- **Directed links between documents**, expressed via identifiers
  - Idea analogous to foreign keys in relational databases
  - Suitable for **many-to-many** relationships
    - Embedding in this case would result in data duplication
- References provide more flexibility than embedding
  - Follow up queries might be needed, however



Sample Data

Collection of **movies**

```
{
  _id: ObjectId("1"),
  title: "Vratné lahve", year: 2006,
  actors: [ ObjectId("7"), ObjectId("5") ]
}
```

```
{
  _id: ObjectId("2"),
  title: "Samotáři", year: 2000,
  actors: [ ObjectId("6"), ObjectId("4"),
            ObjectId("5") ]
}
```

```
{
  _id: ObjectId("3"),
  title: "Medvídek", year: 2007,
  actors: [ ObjectId("5"), ObjectId("4") ]
}
```

Collection of **actors**

```
{ _id: ObjectId("4"),
  firstname: "Ivan",
  lastname: "Trojan" }
```

```
{ _id: ObjectId("5"),
  firstname: "Jiří",
  lastname: "Macháček" }
```

```
{ _id: ObjectId("6"),
  firstname: "Jitka",
  lastname: "Schneiderová" }
```

```
{ _id: ObjectId("7"),
  firstname: "Zdeněk",
  lastname: "Svěrák" }
```

Application Interfaces

`mongo` shell

- **Interactive JavaScript interface to MongoDB**
- `./bin/mongo --username user --password pass --host host --port 28015`

Drivers

- Java, C, C++, C#, Perl, PHP, Python, Ruby, Scala, ...

Query Language

Single JavaScript command / complex **script**

- Each individual command is evaluated over exactly one collection
- Read queries return a **cursor**
  - Allows us to iterate over all the selected documents

Query patterns

- Basic **CRUD** operations
  - Accessing documents via identifiers or **conditions on fields**
- Aggregations: **MapReduce**, **pipelines**, **grouping**

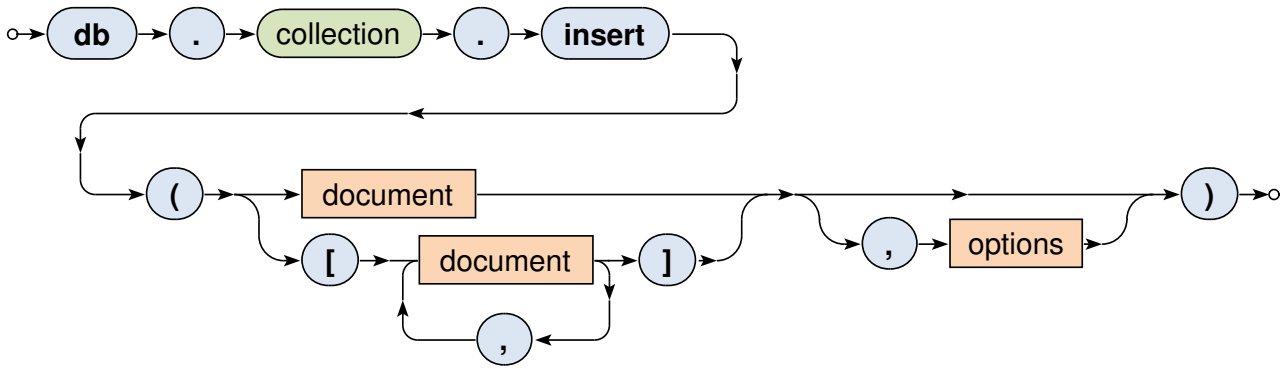
CRUD Operations

Overview

- `db.collection.insert()`
  - Inserts a new document into a collection
- `db.collection.update()`
  - Modifies an existing document / documents or inserts a new one
- `db.collection.remove()`
  - Deletes an existing document / documents
- `db.collection.find()`
  - Finds documents based on filtering conditions
  - Projection and / or sorting may be applied too

Insert Operation

Inserts a new document / documents into a given collection



- **Document identifier** (`_id` field)
  - The provided value must be unique within the collection
  - When missing, it is genereated automatically (ObjectId)
- The collection is created automatically when not yet exists

Insert Operation

Examples

Insert a new actor document

```
db.actors.insert(
  {
    firstname: "Anna",
    lastname: "Geislerová"
  }
)
```

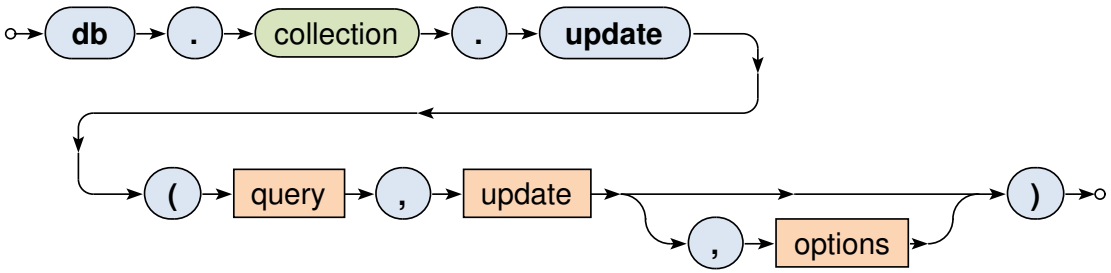
```
{
  _id: ObjectId("8"),
  firstname: "Anna",
  lastname: "Geislerová"
}
```

Insert two new movies

```
db.movies.insert(
  [
    {
      _id: ObjectId("9"), title: "Želary", year: 2003,
      actors: [ ObjectId("4"), ObjectId("8") ]
    },
    { title: "Anthropoid", year: 2016, actors: [ ObjectId("8") ] },
  ]
)
```

Update Operation

Modifies / replaces an existing document / documents



- Parameters
  - **Query**: description of documents to be updated
  - **Update**: modification actions to be applied
- **Just at most one document is updated** by default
  - Unless `{multi: true}` option is specified

Update Operation

Examples

Replace the whole document of at most one specified actor

```
db.actors.update(
  { _id: ObjectId("8") },
  { firstname: "Aňa",
    lastname: "Geislerová" }
)
```

```
{
  _id: ObjectId("8"),
  firstname: "Aňa",
  lastname: "Geislerová"
}
```

Update all the movies filmed in 2015 or later

```
db.movies.update(
  { year: { $gt: 2015 } },
  {
    $set { new: true },
    $inc { rating: 3 }
  },
  { multi: true }
)
```

Update Operation

Update / replace behavior

- **Replace**
  when the `update` parameter contains no update operators
  - `$set`, `$unset`, `$inc`, `$mul`, ...
- **Update**
  otherwise
  - It must then only have update operators and no value fields!
  - I.e. mutual combinations of the both are not allowed

Update Operation: Upsert

Upsert behavior

- **New single document is inserted** when
  - `{upsert: true}` option is specified, and, at the same time, no document was updated
- The new document contains
  - *when replacement takes place*
    all the (value) fields from the `update` parameter, or
  - *otherwise*
    all the value fields from the `query` parameter
    (i.e. comparison operations are omitted) +
    the outcome of all the update operations
    from the `update` parameter,
  - and a newly generated `_id` if necessary

Update Operation: Upsert

Examples

Unsuccessful update of a movie resulting to an insertion

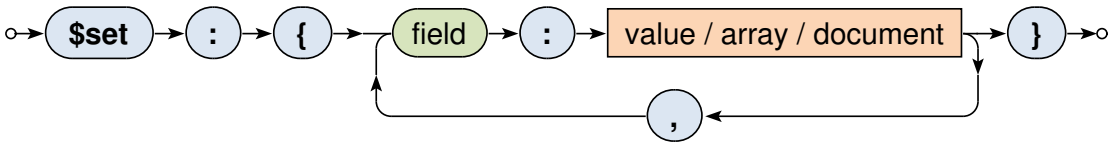
```
db.movies.update(
  { title: "Tmavomodrý svět", year: { $gt: 2000 } },
  {
    $set: {
      director: { firstname: "Jan", lastname: "Svěrák" },
      year: 2001
    },
    $inc: { rating: 2 }
  },
  { upsert: true }
)
```

```
{ _id: ObjectId("11"),
  title: "Tmavomodrý svět",
  director: { firstname: "Jan", lastname: "Svěrák" },
  year: 2001,
  rating: 2 }
```

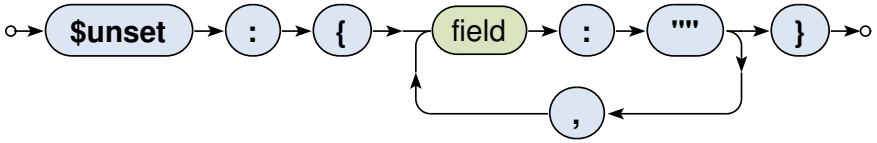
Update Operation: Operators

Field operators

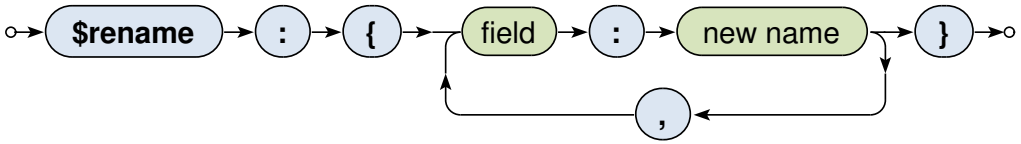
- `$set` – sets the value of a given field / fields



- `$unset` – removes a specified field



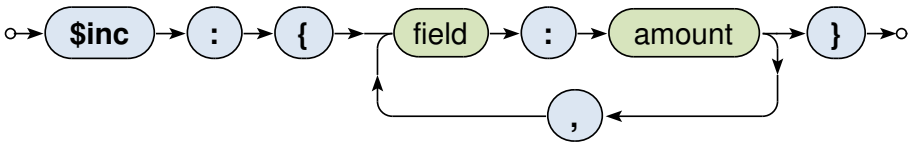
- `$rename` – renames a field



Update Operation: Operators

Field operators

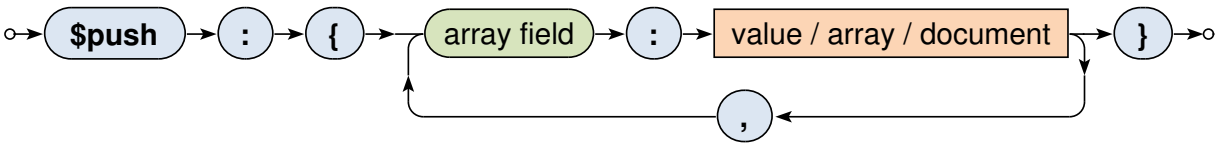
- `$inc` – increments the value of a field by the specified amount



- `$mul` – multiplies the value of a field by the specified amount
- …

Array operators

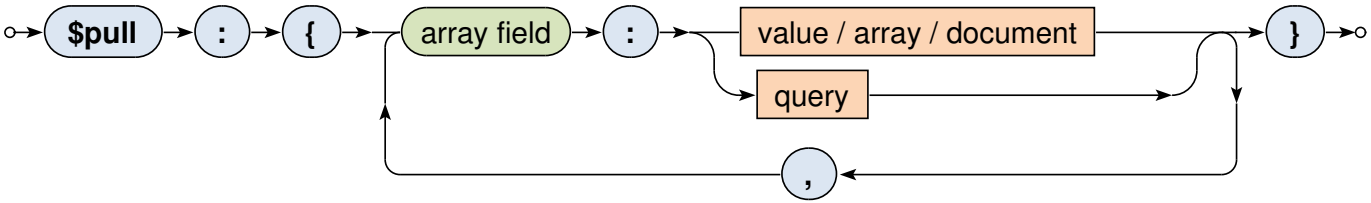
- `$push` – adds one item at the end of an array



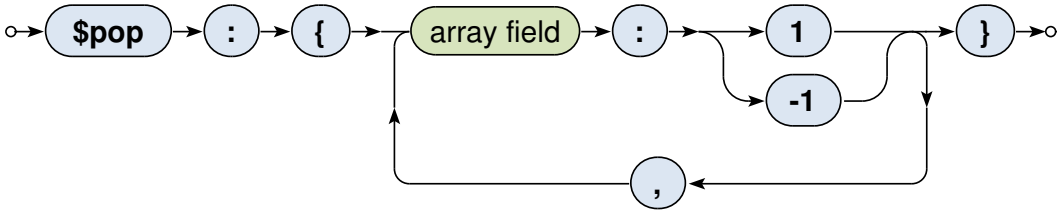
Update Operation: Operators

Array operators

- `$addToSet` – adds a value to an array unless already present
- `$pull` – removes all array items that match a specified query



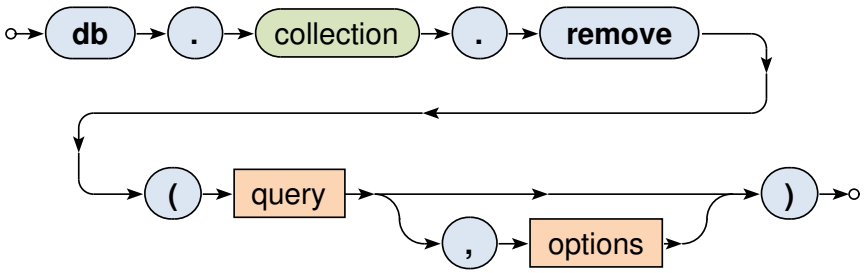
- `$pop` – removes the first / last item of an array



- ...

Remove Operation

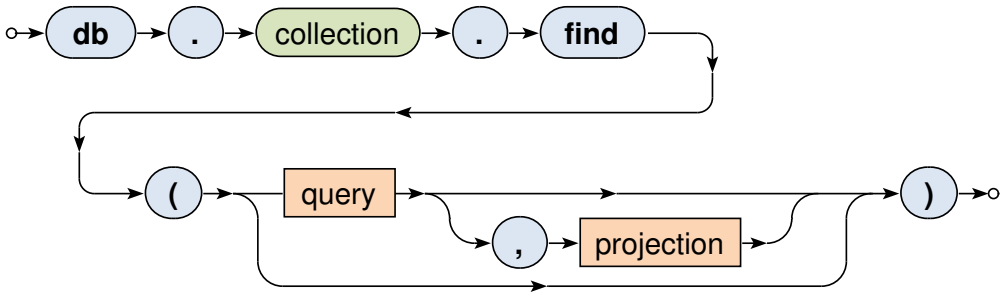
Removes a document / documents from a given collection



- **Query** parameter describes documents to be removed
- All the matching documents are removed
  unless `{ justOne: true }` option is provided in options

Find Operation

Selects documents from a given collection



- `Query` parameter describes documents to be selected
- `Projection` parameter enumerates fields to be included / excluded in / from the result
- Matching documents are returned via an iterable cursor
  - This allows us to chain further `sort`, `skip` or `limit` operations

Find Operation

Examples

Select all the movies from our collection

```
db.movies.find()
```

```
db.movies.find( { } )
```

Select a particular movie based on its document identifier

```
db.movies.find( { _id: ObjectId("2") } )
```

Select all the movies from year *2000* with a rating greater than *1*

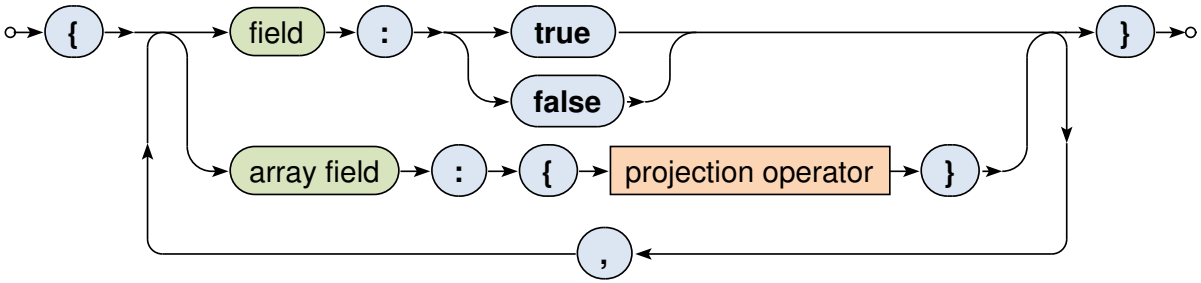
```
db.movies.find( { year: 2000, rating: { $gt: 1 } } )
```

Select all the movies filmed between *2005* and *2015*

```
db.movies.find( { year: { $gte: 2005, $lte: 2015 } } )
```

Find Operation: Projection

Projection allows us to determine the fields returned in the result



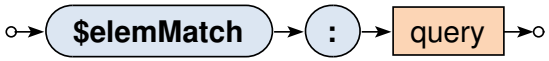
- `true` or `1` for the fields to be **included**
- `false` or `0` for the fields to be **excluded**
- Positive and negative enumerations cannot be combined!
  - The only exception is `_id` which is **included by default**
- **Projection operator**
  - Allows us to select particular items from an array
  - `$elemMatch`, `$slice`, …

Find Operation: Projection

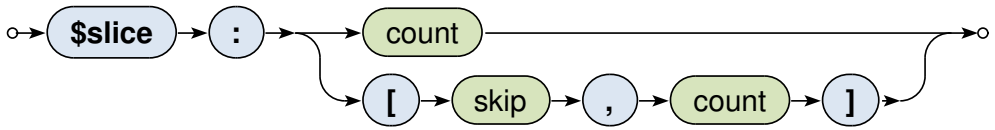
Projection Operators

Projection operators for array fields

- `$elemMatch` – selects the first matching item of an array
  This item must satisfy all the operations included in `query`
  When no matching item is found, the field is not returned at all



- `$slice` – selects the first `count` items of an array (when `count` is positive) / the last `count` items (when negative)
  Certain number of items can also be skipped



- ...

Find Operation: Projection

Examples

Find a particular movie, select its identifier, title and actors

```
db.movies.find(
  { _id: ObjectId("2") },
  { title: true, actors: 1 }
)
```

```
{
  _id: ObjectId("2"),
  title: "Samotáři",
  actors: [ ObjectId("6"),
            ObjectId("4"),
            ObjectId("5") ]
}
```

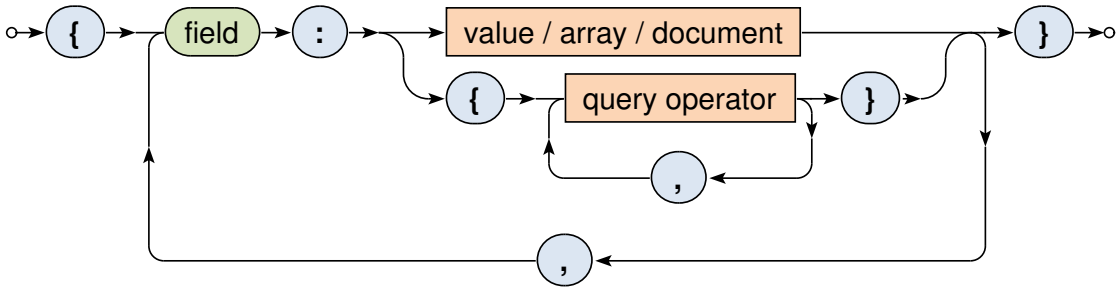
Find all the movies from *2000*, select a title and the last two actors

```
db.movies.find(
  { year: 2000 },
  {
    title: true,
    _id: false,
    actors: { $slice: -2 }
  }
)
```

```
{
  title: "Samotáři",
  actors: [ ObjectId("4"),
            ObjectId("5") ]
}
```

Find Operation: Selection

Query parameter describes the documents we are interested in



- Condition based on **value equality**
  - The actual field value must be identical to the specified value (including, e.g., the order of nested fields or array items)
- Condition based on **query operators**
  - The actual field value must satisfy all the provided operations

Find Operation: Selection

Value Equality Conditions: Examples

Select all the movies having a specific director

```
db.movies.find(
  { director: { firstname: "Jan", lastname: "Svěrák" } }
)
```

```
db.movies.find(
  { director: { lastname: "Svěrák", firstname: "Jan" } }
)
```

Select all the movies having specific actors

```
db.movies.find( { actors: [ ObjectId("7"), ObjectId("5") ] } )
```

```
db.movies.find( { actors: [ ObjectId("5"), ObjectId("7") ] } )
```

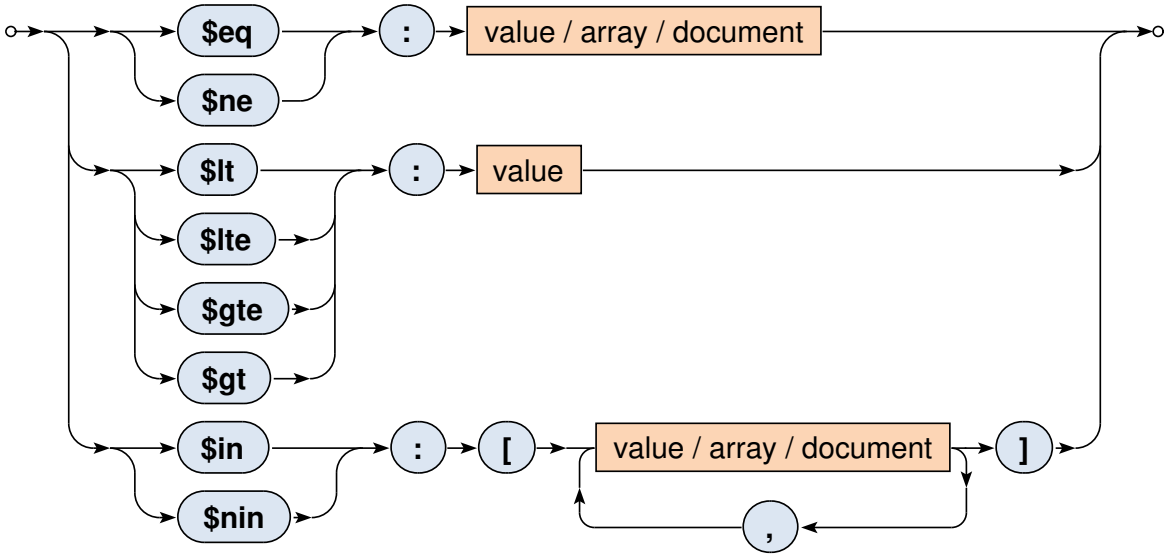
Queries in both the pairs are not equivalent!

Solution: dot notation and `$all` operator respectively (see later)

Find Operation: Selection

Query Operators

Comparison operators



- Comparisons take particular BSON data types into account
- Certain numeric conversions might be automatically applied

Find Operation: Selection

Query Operators

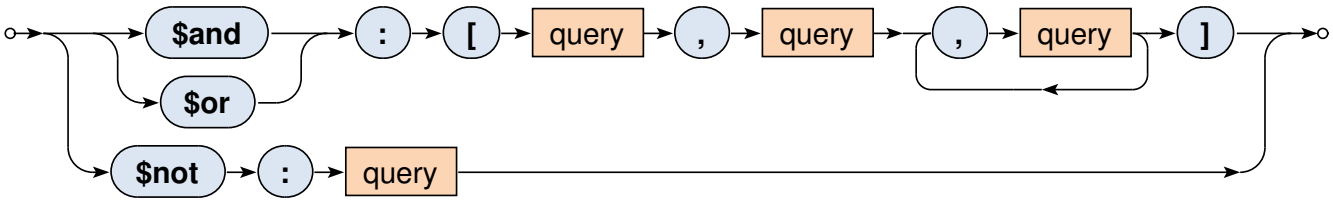
Comparison operators

- `$eq`, `$ne`
  - Tests the actual field value for **equality** / **inequality**
- `$lt`, `$lte`, `$gte`, `$gt`
  - Tests whether the actual field value is **less than** / **less than or equal** / **greater than or equal** / **greater than** the provided value
- `$in`
  - Tests whether the actual field value is equal to **at least one** of the provided values
- `$nin`
  - Negation of `$in`

Find Operation: Selection

Query Operators

Logical operators



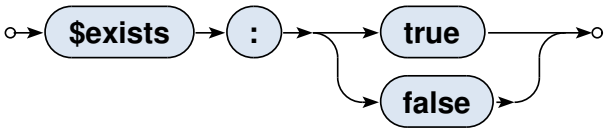
- `$and`, `$or`
  - Logical connectives for **conjunction** / **disjunction**
  - At least 2 involved query expressions must be provided
- `$not`
  - Logical **negation** of right 1 involved query expression
- …

Find Operation: Selection

Query Operators

Element operators

- `$exists` – tests whether a given field **exists** / **not exists**



- …

Evaluation operators

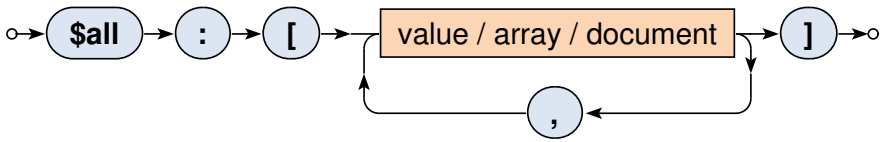
- `$regex` – tests whether the field value matches a **regular expression** (PCRE)
- `$text` – performs **text search** (text index must exists)
- …

Find Operation: Selection

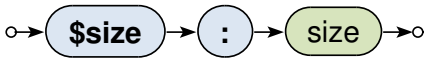
Query Operators

Array operators

- `$all` – tests whether a given array **contains all the specified items** (in any order)



- `$size` – tests the size of a given array against a particular number (and not, e.g., a range, unfortunately)



- `$elemMatch` – tests whether a given array **contains at least one item** that satisfies all the involved query operations

Find Operation: Selection

Dot Notation

The **dot notation** is used when...

- **accessing fields of embedded documents**
  - `"field.subfield"`
    - E.g.: `"director.firstname"`
- **accessing items of arrays**
  - `"field.index"` – used in query selection or projection in order to **access particular array items**, positions start at 0
    - E.g.: `"actors.2"`
  - `"field.$"` – used in query projection in order to **access the very first array item that satisfies the query condition**
    - E.g.: `"actors.$"`

Find Operation: Selection

Value Equality Conditions: Examples Revisited

Select all the movies having a specific director

```
db.movies.find(
  { director: { firstname: "Jan", lastname: "Svěrák" } }
)
```

```
db.movies.find(
  { director.firstname: "Jan", director.lastname: "Svěrák" }
)
```

Select all the movies having specific actors

```
db.movies.find(
  { actors: [ ObjectId("5"), ObjectId("7") ] }
)
```

```
db.movies.find(
  { actors: { $all: [ ObjectId("5"), ObjectId("7") ] } }
)
```

Find Operation: Selection

Querying Arrays

Condition based on **value equality** is satisfied when...

- the given field as a whole is identical to the provided value, or
- at least one item of the array is identical to the provided value

```
db.movies.find( { actors: ObjectId("5") } )
```

```
{ actors: ObjectId("5") }
```

```
{ actors: [ ObjectId("5"), ObjectId("7") ] }
```

Find Operation: Selection

Querying Arrays

Condition based on **query operators** is satisfied when...

- the given field as a whole satisfies all the involved operations, or
- each of the involved operations is satisfied by at least one item of the given array, but this item **might not be the same** for all the individual operations

```
db.movies.find( { ratings: { $gte: 2, $lte: 3 } } )
```

```
{ ratings: 3 }
```

```
{ ratings: [ 3, 7, 5 ] }
```

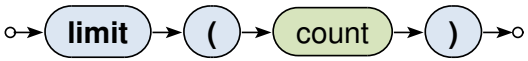
```
{ ratings: [ 1, 4 ] }
```

Note: **use `$elemMatch` when exactly one witnessing item should be found for all the operations**

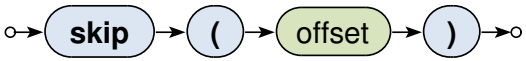
Find Operation: Modifiers

Modifiers change the order and number of returned documents

- `sort` – orders the documents in the result
- `limit` – returns at most the specified number of documents



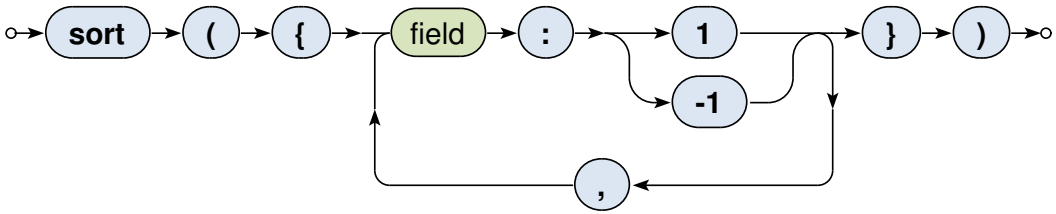
- `skip` – skips the specified number of documents from the beginning



All the modifiers are optional, can be chained in **any mutual order**, but **must be specified before retrieving any documents** via the cursor

Find Operation: Modifiers

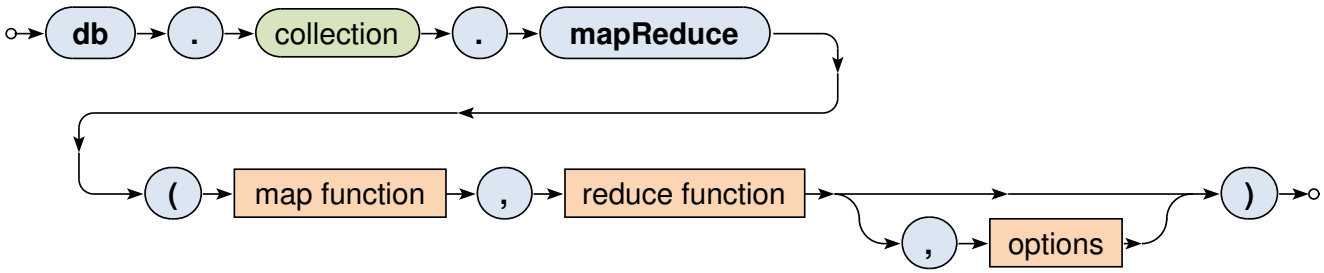
Sort modifier orders the documents in the result



- 1 for **ascending**, −1 for **descending** order
- Multiple fields can be used
- The order of documents is undefined, unless explicitly sorted
- Sorting of larger datasets should be supported by indices
- **Sorting happens before the projection phase**
  - I.e. excluded fields can be used for sorting purposes as well

MapReduce

Executes a **MapReduce** job on a selected collection



- Both map and reduce functions are implemented as ordinary JavaScript functions
  - **Map** function: current document is accessible via `this`, `emit(key, value)` is used for emissions
  - **Reduce** function: key and array of values are provided as arguments, reduced value is published via `return`
- Beside others, `query`, `sort` or `limit` options are accepted
- `out` option determines the output (e.g. a collection name)

MapReduce

Example

Count the number of movies filmed in each year, starting in *2005*

```
db.movies.mapReduce(
  function() {
    emit(this.year, 1);
  },
  function(key, values) {
    return Array.sum(values);
  },
  {
    query: { year: { $gte: 2005 } },
    sort: { year: 1 },
    out: "statistics"
  }
)
```

Index Structures

Motivation

- Full **collection scan** must be performed when searching for the documents matching conditions of a given query, at least **unless an appropriate index exists**

Primary index

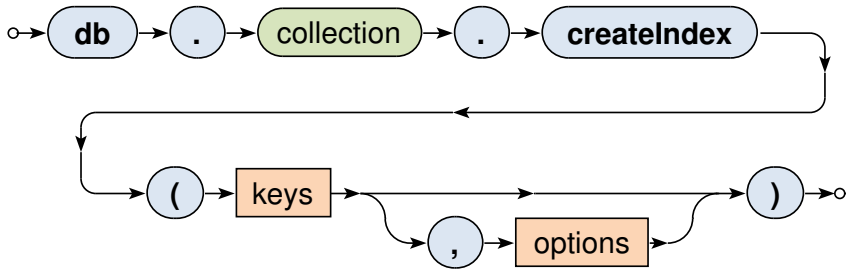
- Unique **index on the _id field**, created automatically

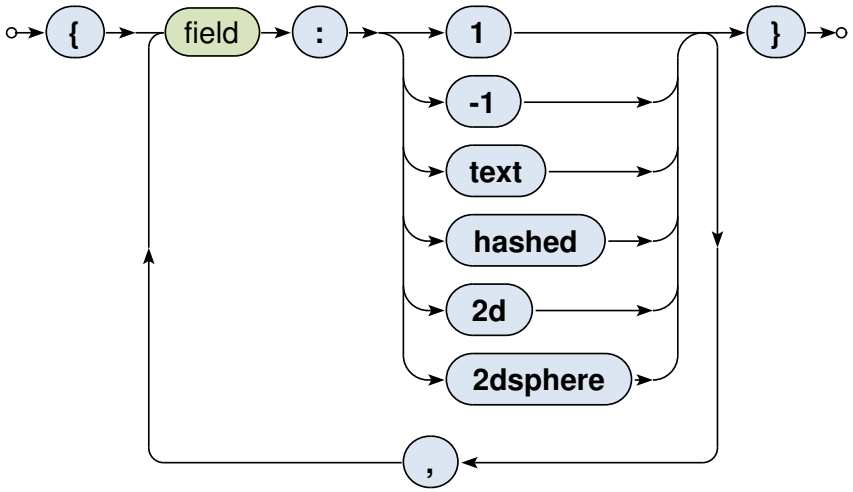
Secondary indexes

- Created manually for a given key field / fields, always on a particular collection

Index Structures

Secondary **index creation**





Index Structures

Index types

- `1`, `-1` – standard ascending / descending value indexes
  - Both scalar values and embedded documents can be indexed
- `hashed` – hash values of a single field are indexed
- `text` – basic full-text index
- `2d` – points in planar geometry
- `2dsphere` – points in spherical geometry

Index Structures

Index forms

- Single field / **composed index** for multiple fields
- Single value / **multi-key index** for multiple values in arrays

Index properties

- **Unique** – duplicate values are rejected (cannot be inserted)
- **Partial** – only selected documents are indexed
- **Sparse** – only documents with the index field are indexed
- **TTL** – documents are removed when timeout elapses

Just some type / form / property combinations can be used!

Conclusion

MongoDB

- **JSON document database**
- **Sharding with master-slave replication architecture**

Query functionality

- CRUD operations
  - **Insert**, **find**, **update**, **remove**
  - Complex filtering conditions
- MapReduce
- Index structures