Independent Skill Development Mission

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EMPOWERING FUTURES, SHAPING TOMORROW

ISDM (INDEPENDENT SKILL DEVELOPMENT MISSION)

SCHEMA DESIGN & DATA MODELING (WEEKS 3-4)

UNDERSTANDING EMBEDDED DOCUMENTS VS. REFERENCES IN MONGODB

CHAPTER 1: INTRODUCTION TO DATA MODELING IN MONGODB

1.1 Why Data Modeling Matters in NoSQL Databases

Data modeling in **MongoDB** is crucial for optimizing **performance, scalability, and maintainability**. Unlike SQL databases, where relationships are defined using **tables and foreign keys**, MongoDB provides **two primary ways** to structure related data:

1. **Embedded Documents (Denormalization)** – Storing related data within a single document.
2. **References (Normalization)** – Storing related data in separate collections with **references (IDs)** linking them.

Choosing the right approach depends on factors such as **query performance, data retrieval efficiency, and application scalability**.

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CHAPTER 2: UNDERSTANDING EMBEDDED DOCUMENTS (DENORMALIZATION)

2.1 What Are Embedded Documents?

In **embedded documents,** related data is **nested inside the main document** instead of being stored in a separate collection. This approach is often called **denormalization** because it avoids separate lookups.

Best Use Cases for Embedded Documents:

✓ When data is **closely related** and frequently accessed together.

✓ When the size of embedded data is relatively **small**.

✓ When data updates are **infrequent** and do not cause redundancy issues.

2.2 Example of Embedded Documents

Consider a scenario where **users** have multiple **addresses**. Using **embedded documents,** we store all addresses inside the user document.

Example: Storing Addresses Inside a User Document

```
{
  "_id": 1,
  "name": "Alice Johnson",
  "email": "alice@example.com",
  "addresses": [
    { "type": "home", "city": "New York", "zip": "10001" },
    { "type": "work", "city": "San Francisco", "zip": "94105" }
  ]
```

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}

✓ **All data is stored in a single document,** making queries faster.
✓ **No need for joins** or multiple queries when retrieving user data.

2.3 Advantages of Embedded Documents

✅ **Fast Read Performance** – Fetching data requires only one query.
✅ **Simpler Queries** – No need for complex joins or additional lookups.
✅ **Better Data Consistency** – Ensures all related data stays together.

2.4 Disadvantages of Embedded Documents

❌ **Increased Document Size** – Large nested documents can slow down performance.
❌ **Redundant Data** – Duplicating embedded information across documents can cause inconsistencies.
❌ **Limited Growth** – Documents exceeding MongoDB's **16MB document size limit** can become problematic.

CHAPTER 3: UNDERSTANDING REFERENCES (NORMALIZATION)

3.1 What Are References?

In the **referencing approach,** related data is stored in **separate collections,** and documents reference each other using **ObjectIDs** or unique identifiers. This is similar to **foreign keys** in relational databases.

Best Use Cases for References:
✓ When related data is **large or frequently updated**.
✓ When related data needs to be **reused across multiple**

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documents.

✓ When documents exceed MongoDB's **document size limit**.

3.2 Example of Using References

Instead of embedding addresses inside the user document, we create a separate addresses collection and store only the **ObjectID reference** in the user document.

User Document (Referencing Approach)

```
{
  "_id": 1,
  "name": "Alice Johnson",
  "email": "alice@example.com",
  "addresses": [101, 102]  // References to Address IDs
}
```

Address Documents (Stored in a Separate Collection)

```
{
  "_id": 101,
  "type": "home",
  "city": "New York",
  "zip": "10001"
}
{
  "_id": 102,
```

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```
  "type": "work",
  "city": "San Francisco",
  "zip": "94105"
}
```

3.3 Advantages of References

✅ **Reduces Document Size** – Prevents bloated documents by keeping related data separate.
✅ **Better Scalability** – Works well when handling large datasets.
✅ **Eliminates Redundant Data** – Prevents storing the same data multiple times.

3.4 Disadvantages of References

❌ **Slower Read Performance** – Requires multiple queries ($lookup) to fetch related data.
❌ **More Complex Queries** – Requires joins between collections using $lookup.
❌ **Increased Query Overhead** – Fetching related data requires additional processing.

CHAPTER 4: CHOOSING BETWEEN EMBEDDED DOCUMENTS AND REFERENCES

4.1 Key Differences Between Embedded Documents and References

Feature	Embedded Documents	References

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Data Storage	Nested inside a document	Stored in a separate collection
Query Performance	Fast (Single query)	Slower (Requires multiple queries)
Document Size	Larger	Smaller
Data Consistency	Harder to maintain (duplication)	Easier (single source of truth)
Use Case	Best for small, closely related data	Best for large, frequently changing data

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4.2 When to Use Embedded Documents vs. References

Scenario	Best Approach
User Profiles with Small Addresses	✅ Embedded Documents
Product Catalog with Category Data	✅ References (Category used in multiple products)
Real-Time Chat Messages	✅ Embedded (Messages inside user document)
E-Commerce Orders with Items	✅ References (Items stored separately)

Case Study: How Amazon Uses Embedded & Referenced Data Modeling

Background

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Amazon processes **millions of customer orders,** each containing **multiple products, shipping details, and payment records**.

Challenges

- **Balancing fast read operations with efficient storage.**
- **Ensuring product data remains consistent across millions of orders.**
- **Optimizing storage for frequently updated user order histories.**

Solution: Hybrid Approach Using Embedded & Referenced Data

✓ **Embedded Documents:** User orders **embed shipping addresses** for fast retrieval.
✓ **References:** Product details are **stored separately** to maintain consistency across orders.
✓ **Indexing & Aggregation:** Used for **fast order lookups** without redundant data storage.

This hybrid model ensures **Amazon can handle millions of transactions** efficiently.

Exercise

1. **Embed** an array of orders inside a users document, where each order has product, price, and date.
2. **Create a referenced model** where users store an orderID pointing to an external orders collection.
3. Compare the performance of findOne() when using **embedded vs. referenced** orders.

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Conclusion

In this section, we explored:

✓ **How embedded documents store related data within a single document**.

✓ **How references store related data separately to prevent redundancy**.

✓ **Advantages and disadvantages of both approaches**.

✓ **How Amazon optimizes NoSQL data modeling for e-commerce scalability**.

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ONE-TO-ONE, ONE-TO-MANY & MANY-TO-MANY RELATIONSHIPS IN MONGODB

CHAPTER 1: INTRODUCTION TO RELATIONSHIPS IN MONGODB

1.1 Understanding Data Relationships in NoSQL Databases

Unlike **SQL databases,** which use **foreign keys** to establish relationships between tables, **MongoDB (NoSQL)** manages relationships using **embedding (denormalization)** and **referencing (normalization)**.

✓ **Embedding (Denormalization)** – Stores related data **inside a document** for faster queries.
✓ **Referencing (Normalization)** – Stores **only references** (ObjectId) to related documents, improving flexibility and reducing redundancy.

1.2 Types of Relationships in MongoDB

MongoDB supports three major types of relationships:

1. **One-to-One (1:1)** – A single document is related to only one other document.
2. **One-to-Many (1:N)** – A single document is related to multiple documents.
3. **Many-to-Many (M:N)** – Multiple documents are related to multiple documents.

Each type of relationship can be implemented using **embedding or referencing** depending on the use case.

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CHAPTER 2: IMPLEMENTING ONE-TO-ONE (1:1) RELATIONSHIPS

2.1 What is a One-to-One Relationship?

A **One-to-One (1:1) relationship** means that each document in one collection **directly corresponds** to exactly one document in another collection.

✓ **Example Use Cases:**

- **User and Profile** – A user has only one profile.
- **Employee and ID Card** – Each employee has a single ID card.

2.2 Implementing One-to-One Using Embedding

In **embedding,** related data is stored **inside the same document**.

Example: Storing a User Profile Inside the User Document

```
const userSchema = new mongoose.Schema({
  name: String,
  email: String,
  profile: {
    age: Number,
    bio: String,
    address: String
  }
});
```

✓ The profile fields (age, bio, address) are stored **within the same document**.
✓ This improves **read performance** but **increases document size**.

2.3 Implementing One-to-One Using Referencing

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In **referencing,** related data is stored in **a separate collection,** with an ObjectId reference.

Example: Using References for User and Profile

```
const mongoose = require('mongoose');

const userSchema = new mongoose.Schema({
  name: String,
  email: String,
  profile: { type: mongoose.Schema.Types.ObjectId, ref: 'Profile' }
});

const profileSchema = new mongoose.Schema({
  age: Number,
  bio: String,
  user: { type: mongoose.Schema.Types.ObjectId, ref: 'User' }
});

const User = mongoose.model('User', userSchema);
const Profile = mongoose.model('Profile', profileSchema);
```

To fetch a user **with their profile**:

```
User.findOne({ email: "john@example.com" }).populate('profile')
  .then(user => console.log(user))
  .catch(err => console.error(err));
```

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✓ **Referencing** keeps documents **lightweight** but requires **multiple queries**.

CHAPTER 3: IMPLEMENTING ONE-TO-MANY (1:N) RELATIONSHIPS

3.1 What is a One-to-Many Relationship?

A **One-to-Many (1:N) relationship** means that one document **relates to multiple** documents.

✓ **Example Use Cases:**

- **User and Posts** – A user can have multiple blog posts.
- **Product and Reviews** – A product can have multiple customer reviews.

3.2 Implementing One-to-Many Using Embedding

Example: Storing All User Posts Inside a User Document

```
const userSchema = new mongoose.Schema({
  name: String,
  email: String,
  posts: [{
    title: String,
    content: String,
    date: { type: Date, default: Date.now }
  }]
});
```

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✓ Improves **performance** by reducing queries.
✓ Not ideal for large **datasets** (e.g., a user with thousands of posts).

3.3 Implementing One-to-Many Using Referencing

Example: Storing Posts in a Separate Collection and Referencing Users

```
const postSchema = new mongoose.Schema({
  title: String,
  content: String,
  user: { type: mongoose.Schema.Types.ObjectId, ref: 'User' }
});
```

To fetch a user **with their posts**:

```
User.findOne({ email: "john@example.com" }).populate('posts')
  .then(user => console.log(user))
  .catch(err => console.error(err));
```

✓ **Referencing is scalable**, making it ideal for large datasets.
✓ Queries require **joining data across collections**.

CHAPTER 4: IMPLEMENTING MANY-TO-MANY (M:N) RELATIONSHIPS

4.1 What is a Many-to-Many Relationship?

A **Many-to-Many (M:N) relationship** means that **multiple documents** in one collection are related to **multiple documents** in another.

✓ **Example Use Cases:**

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- **Students and Courses** – A student can enroll in multiple courses, and a course can have multiple students.
- **Tags and Articles** – An article can have multiple tags, and a tag can belong to multiple articles.

4.2 Implementing Many-to-Many Using Referencing

Example: Students and Courses Relationship

```
const studentSchema = new mongoose.Schema({
  name: String,
  courses: [{ type: mongoose.Schema.Types.ObjectId, ref: 'Course' }]
});

const courseSchema = new mongoose.Schema({
  title: String,
  students: [{ type: mongoose.Schema.Types.ObjectId, ref: 'Student' }]
});

const Student = mongoose.model('Student', studentSchema);
const Course = mongoose.model('Course', courseSchema);
```

4.3 Querying Many-to-Many Data

To fetch all **courses a student is enrolled in**:

```
Student.findOne({ name: "Alice" }).populate('courses')
  .then(student => console.log(student))
```

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```
  .catch(err => console.error(err));
```

To fetch all **students enrolled in a course**:

```
Course.findOne({ title: "Math 101" }).populate('students')
  .then(course => console.log(course))
  .catch(err => console.error(err));
```

✓ **Referencing is preferred for many-to-many relationships,** as embedding would create **redundant data**.

Case Study: How a Learning Platform Used MongoDB for Course Management

Background

An online learning platform needed a scalable **database solution** to manage **students, courses, and enrollments**.

Challenges

✓ **Complex relationships** between students and courses.
✓ **Slow query performance** when retrieving enrolled students.
✓ **Duplicate data issues** with embedded documents.

Solution: Using Many-to-Many Referencing

The development team:

✓ Created **separate collections** for students and courses.
✓ Used **ObjectId referencing** to establish many-to-many relationships.
✓ Indexed the **student and course fields** for faster lookups.

Results

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- **Query response times reduced by 60%**.
- **Scalability improved,** handling **millions of students**.
- **Better data consistency,** reducing redundancy.

By using **MongoDB's flexible relationship modeling,** the platform efficiently **managed student enrollments and courses**.

Exercise

1. Create a **One-to-One** relationship between **users and addresses**.
2. Implement a **One-to-Many** relationship where a **user can have multiple orders**.
3. Model a **Many-to-Many** relationship where a **student can enroll in multiple courses**.

Conclusion

In this section, we explored:

✓ **One-to-One, One-to-Many, and Many-to-Many relationships in MongoDB**.

✓ **Embedding vs. Referencing for handling relationships**.

✓ **How to implement and query different relationships using Mongoose**.

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CHOOSING THE RIGHT SCHEMA DESIGN FOR APPLICATIONS

CHAPTER 1: INTRODUCTION TO SCHEMA DESIGN IN MONGODB

1.1 Understanding Schema Design

Schema design in **MongoDB** defines how data is structured within a database. Unlike relational databases, MongoDB uses a **document-oriented** approach where data is stored in **JSON-like BSON documents**.

Choosing the right schema design is crucial for:

✓ **Performance optimization** – Faster queries and indexing.
✓ **Data integrity** – Ensuring consistency across collections.
✓ **Scalability** – Supporting large-scale applications with minimal overhead.

Schema design depends on the application type:

- **E-commerce** – Requires an efficient way to store orders, products, and customers.
- **Social media** – Needs relationships between users, posts, and comments.
- **Real-time applications** – Focus on speed and scalability.

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CHAPTER 2: UNDERSTANDING MONGODB SCHEMA DESIGN APPROACHES

2.1 Embedded vs. Referenced Schema Design

MongoDB offers two primary ways to design schemas:

- **Embedded (Denormalized) Schema** – Stores related data within a single document.
- **Referenced (Normalized) Schema** – Stores related data in separate collections and links them using ObjectId.

Each approach has advantages and trade-offs depending on **query performance, scalability, and data consistency**.

CHAPTER 3: EMBEDDED SCHEMA DESIGN (DENORMALIZATION)

3.1 What is Embedded Schema Design?

In **embedded schema design,** related data is **nested inside the parent document**. This reduces the number of database queries, improving read performance.

✓ **Faster Reads** – Data is retrieved in a single query.
✓ **Reduces Joins** – No need for multiple lookups.
✓ **Ideal for small, tightly coupled relationships**.

3.2 Example: Storing Order Details in an E-Commerce App

```
const mongoose = require('mongoose');


const orderSchema = new mongoose.Schema({
  customerName: String,
  items: [
    {
      productName: String,
```

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```
        quantity: Number,
        price: Number
      }
    ],
    orderDate: { type: Date, default: Date.now }
});

const Order = mongoose.model('Order', orderSchema);
```

✓ Each order **contains all purchased items** inside the same document.
✓ This structure **avoids multiple queries** when fetching order details.

3.3 When to Use Embedded Schema Design

Use **embedded schema** when:

✓ Data is **frequently accessed together** (e.g., orders and items).
✓ The dataset is **relatively small** (avoiding large documents).
✓ No need to **query subdocuments separately**.

CHAPTER 4: REFERENCED SCHEMA DESIGN (NORMALIZATION)

4.1 What is Referenced Schema Design?

In **referenced schema design**, related data is **stored in separate collections** and linked using an **ObjectId reference**.

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✓ **Saves Storage** – No duplicated data across documents.
✓ **Efficient for Large Datasets** – Smaller document sizes improve performance.
✓ **Ideal for many-to-many relationships** (e.g., users and posts).

4.2 Example: Users and Posts in a Social Media App

```
const userSchema = new mongoose.Schema({
  name: String,
  email: String
});

const postSchema = new mongoose.Schema({
  title: String,
  content: String,
  author: { type: mongoose.Schema.Types.ObjectId, ref: 'User' }
});

const User = mongoose.model('User', userSchema);
const Post = mongoose.model('Post', postSchema);
```

✓ Posts reference users by **storing the user's ObjectId**.
✓ This allows **efficient querying of user-specific posts**.

To fetch a post **with author details**, use .populate():

```
Post.find().populate('author', 'name email').then(posts => console.log(posts));
```

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4.3 When to Use Referenced Schema Design

Use **referenced schema** when:

✓ Data is **accessed independently** (e.g., users and their posts).
✓ There are **many relationships** between different collections.
✓ Data **size is large,** requiring efficient storage and retrieval.

CHAPTER 5: HYBRID SCHEMA DESIGN (BEST OF BOTH WORLDS)

5.1 What is a Hybrid Schema?

A **hybrid schema** combines both **embedded and referenced** approaches based on data access patterns.

✓ **Embed frequently accessed data** for fast reads.
✓ **Reference large or independent data** to maintain storage efficiency.

5.2 Example: E-Commerce Products and Reviews

```
const productSchema = new mongoose.Schema({
  name: String,
  price: Number,
  description: String,
  reviews: [{ user: String, rating: Number, comment: String }]
});

const orderSchema = new mongoose.Schema({
```

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```
  customer: { type: mongoose.Schema.Types.ObjectId, ref: 'User' },
  products: [{ type: mongoose.Schema.Types.ObjectId, ref: 'Product' }]
});

const Product = mongoose.model('Product', productSchema);
const Order = mongoose.model('Order', orderSchema);
```

✓ **Products store embedded reviews** because reviews are always accessed with products.
✓ **Orders reference products** because they can be reused across multiple orders.

5.3 When to Use Hybrid Schema Design

Use **hybrid schema** when:

✓ Some data is **frequently accessed together** (e.g., product details and reviews).
✓ Other data **needs separate access** (e.g., products in multiple orders).
✓ Balancing **performance and scalability** is important.

Case Study: How an Online Marketplace Optimized Database Performance

Background

A leading online marketplace faced **slow performance issues** due to improper schema design.

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Challenges

✓ **Large orders collection** led to slow read performance.
✓ **Duplicated product data** increased database size.
✓ **Complex joins** in queries reduced scalability.

Solution: Implementing a Hybrid Schema Design

✓ **Orders referenced products** instead of embedding them.
✓ **Product reviews were embedded** for quick access.
✓ Used **indexed fields** to improve query speed.

Results

- **50% faster queries,** improving user experience.
- **Reduced database size,** improving efficiency.
- **Scalable architecture,** handling **1M+ products**.

This case study shows how **choosing the right schema design improves performance and scalability**.

Exercise

1. Design a schema for a **blogging platform** with:
    - **Users** who can write multiple blog posts.
    - **Posts** that store comments inside the document.
    - **Authors referenced** in posts to avoid duplication.
2. Implement the **schema using Mongoose** and write a query to fetch:
    - A post **with comments**.
    - All posts written by a **specific author**.

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Conclusion

✓ **Choosing the right schema** is crucial for **performance and scalability**.
✓ **Embedded schemas** improve read speed but may cause **large documents**.
✓ **Referenced schemas** reduce duplication but require **joins**.
✓ **Hybrid schemas** balance both approaches **for optimal performance**.

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DESIGNING EFFICIENT INDEXING STRATEGIES

CHAPTER 1: INTRODUCTION TO INDEXING IN DATABASES

1.1 What is Indexing?

Indexing is a **database optimization technique** used to speed up data retrieval operations. Just like an index in a book helps locate topics quickly, a database index allows the database engine to find records faster without scanning the entire dataset.

Indexes are **critical for large-scale applications** where queries must be optimized for speed and efficiency. Without proper indexing, database queries may become slow and resource-intensive, affecting application performance.

1.2 How Indexing Works

Indexes store a **sorted version** of a specific column's values, making it easier to locate data. Instead of scanning an entire table, the database **searches the index**, finds the location of the desired data, and retrieves it efficiently.

Example: Without an Index (Full Table Scan)

```
SELECT * FROM users WHERE email = 'john@example.com';
```

- The database searches every row in the users table to find the match (slow for large datasets).

Example: With an Index

```
CREATE INDEX idx_email ON users(email);

SELECT * FROM users WHERE email = 'john@example.com';
```

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- The database uses the **index** on email to quickly locate the required row (much faster).

CHAPTER 2: TYPES OF INDEXES IN DATABASES

2.1 Primary and Unique Indexes

- **Primary Index** – Automatically created on the **primary key** of a table.
- **Unique Index** – Prevents duplicate values in a column (e.g., ensuring unique emails in a user table).

Example: Creating a Unique Index

```
CREATE UNIQUE INDEX idx_email ON users(email);
```

This prevents duplicate emails from being inserted into the table.

2.2 Single-Column vs. Multi-Column Indexes

- **Single-Column Index** – Created on a **single field** to optimize searches on that field.
- **Multi-Column (Composite) Index** – Created on **multiple fields** to speed up queries that filter by more than one column.

Example: Single-Column Index

```
CREATE INDEX idx_lastname ON users(last_name);
```

- Optimizes searches like:
- SELECT * FROM users WHERE last_name = 'Smith';

Example: Multi-Column Index

```
CREATE INDEX idx_name_email ON users(first_name, email);
```

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- Optimizes queries using **both** columns:
- SELECT * FROM users WHERE first_name = 'John' AND email = 'john@example.com';
- But **not** queries using only email:
- SELECT * FROM users WHERE email = 'john@example.com';

⚠ **Multi-column indexes should be used carefully,** as their effectiveness depends on the order of columns.

2.3 Full-Text Indexes

Full-text indexes are used for **searching large text fields** (e.g., searching product descriptions or blog articles).

Example: Creating a Full-Text Index in MySQL

```
CREATE FULLTEXT INDEX idx_description ON products(description);
```

Example: Using a Full-Text Index in Queries

```
SELECT * FROM products WHERE MATCH(description) AGAINST('smartphone');
```

- Optimized for **natural language searches,** unlike LIKE '%keyword%', which is slower.

CHAPTER 3: INDEXING STRATEGIES FOR PERFORMANCE OPTIMIZATION

3.1 Choosing the Right Columns for Indexing

Not every column should be indexed. Indexing the right columns **balances speed and storage** while improving performance.

Best Practices for Indexing:

✓ Index **columns frequently used in WHERE conditions**.
✓ Index **columns involved in JOIN operations**.
✓ Index **columns used in ORDER BY and GROUP BY queries**.
✓ **Avoid indexing columns with many duplicate values** (e.g., gender with only M or F).

3.2 Using Partial and Conditional Indexes

Some databases allow **partial indexes,** which index only a subset of rows to save space and improve query efficiency.

Example: Creating a Partial Index (PostgreSQL)

```
CREATE INDEX idx_active_users ON users(status) WHERE status = 'active';
```

- This indexes only **active users,** making queries like this much faster:
- SELECT * FROM users WHERE status = 'active';

3.3 Avoiding Over-Indexing

While indexes improve read performance, they **slow down write operations (INSERT, UPDATE, DELETE)** because the index must also be updated.

⚠ **Common Mistakes to Avoid:**
❌ Indexing **every column** in a table (increases storage and update time).
❌ Creating **duplicate indexes** on the same column.
❌ Using **indexes on small tables,** where full table scans are faster.

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CHAPTER 4: INDEXING IN MONGODB VS. SQL DATABASES

4.1 Creating Indexes in MongoDB

In MongoDB, indexes are created using the createIndex() method.

Example: Single-Field Index in MongoDB

```
db.users.createIndex({ email: 1 });
```

Example: Compound Index in MongoDB

```
db.orders.createIndex({ customerId: 1, orderDate: -1 });
```

- **1 for ascending order, -1 for descending order**.
- Optimizes queries filtering by **both customerId and orderDate**.

4.2 Comparing Indexing in SQL and NoSQL

Feature	SQL Databases (MySQL, PostgreSQL)	NoSQL Databases (MongoDB)
Index Type	B-Trees, Full-Text, Hash Indexes	B-Trees, Compound Indexes
Schema	Fixed, Table-based	Flexible, Document-based
Indexing Speed	Fast for structured data	Optimized for unstructured queries
Use Case	Traditional web apps, Reporting	Real-time analytics, Big Data

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Case Study: How Amazon Optimized Search Performance with Indexing

Background

Amazon handles **billions of product searches daily** and needs to return results instantly.

Challenges

- High volume of search queries slowing down performance.
- Handling large-scale **real-time filtering and sorting**.
- Supporting **millions of concurrent users**.

Solution: Implementing Efficient Indexing

✓ **Used full-text indexes** for product descriptions to improve search speed.
✓ **Created multi-column indexes** on category, price, and ratings to speed up filtering.
✓ **Used indexing with caching (Redis)** to reduce database queries.

Results

- **Search performance improved by 60%**.
- **Reduced database query load,** enabling faster page loads.
- **Higher conversion rates,** as users found products faster.

This case study highlights how **effective indexing can significantly boost database efficiency and user experience**.

Exercise

1. What is the difference between a **single-column index** and a **multi-column index**?

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2. Write an SQL query to create a **unique index** on the email column in a customers table.
3. How do **full-text indexes** improve search performance in large datasets?

Conclusion

In this section, we explored:

✓ **What indexing is and why it's important for databases**.

✓ **Different types of indexes, including primary, unique, and full-text indexes**.

✓ **Best practices for designing efficient indexing strategies**.

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PERFORMANCE OPTIMIZATION TECHNIQUES IN MONGODB

CHAPTER 1: INTRODUCTION TO PERFORMANCE OPTIMIZATION IN MONGODB

1.1 Why Performance Optimization Matters in MongoDB?

MongoDB is a high-performance, scalable **NoSQL database** designed to handle **large datasets and real-time applications**. However, as applications grow, performance bottlenecks can arise due to **slow queries, inefficient indexing, and large document sizes**.

Optimizing MongoDB performance helps:

✓ Improve **query speed** and reduce latency.

✓ Enhance **database scalability** for high-traffic applications.

✓ Reduce **storage and memory usage**, optimizing cost efficiency.

✓ Ensure **faster data retrieval** in real-time applications.

CHAPTER 2: INDEXING STRATEGIES FOR FASTER QUERIES

2.1 Understanding Indexing in MongoDB

An **index** is a data structure that **improves the speed of read operations** by allowing MongoDB to search documents more efficiently. Without an index, MongoDB **scans the entire collection** (full collection scan), which slows down queries.

Types of Indexes in MongoDB:

✓ **Single Field Index** – Indexes a single field for quick lookups.

✓ **Compound Index** – Indexes multiple fields for optimized queries.

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✓ **Multikey Index** – Indexes arrays inside documents.
✓ **Text Index** – Used for full-text search operations.

2.2 Creating and Using Indexes

Example: Creating a Single-Field Index

```
db.users.createIndex({ email: 1 });
```

✓ **Optimizes** queries searching by email.

Example: Using a Compound Index for Faster Queries

```
db.orders.createIndex({ customerId: 1, orderDate: -1 });
```

✓ **Speeds up** searches that filter by customerId and sort by orderDate.

2.3 Checking Query Performance Using explain()

To analyze a query's efficiency, use explain().

```
db.users.find({ email: "alice@example.com"
}).explain("executionStats");
```

✓ **If COLLSCAN appears,** the query is scanning the entire collection (slow).
✓ **If IXSCAN appears,** the query is using an index (optimized).

CHAPTER 3: QUERY OPTIMIZATION TECHNIQUES

3.1 Using Projection to Reduce Data Transfer

By default, MongoDB returns **entire documents,** but using **projection,** we can retrieve only required fields.

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Example: Fetching Only the name and email Fields

db.users.find({}, { name: 1, email: 1, _id: 0 });

✓ **Reduces network load** and improves response time.

3.2 Optimizing Large Queries with Pagination (limit() and skip())

Large datasets can **slow down queries,** but pagination improves efficiency.

Example: Fetching 10 Users per Page

db.users.find().skip(10).limit(10);

✓ **Ensures only necessary data is loaded** per page.

3.3 Using hint() to Force Index Selection

If MongoDB chooses an inefficient index, use hint() to **manually select the best index**.

db.orders.find({ customerId: 123 }).hint({ customerId: 1 });

✓ **Forces MongoDB to use the customerId index,** improving query speed.

CHAPTER 4: OPTIMIZING DATA STORAGE

4.1 Avoiding Large Documents (Document Size Limit: 16MB)

MongoDB has a **16MB document size limit,** so avoid **storing excessively large documents**.

Solutions:

✓ **Use References Instead of Embedding Large Arrays** – Store

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large related data in separate collections.

✓ **Archive Old Data** – Move historical records to separate collections.

✓ **Compress Data Fields** – Use **shorter field names** to reduce storage size.

4.2 Using TTL (Time-To-Live) Index for Expiring Documents

TTL indexes automatically **delete old documents**, optimizing storage.

Example: Deleting Logs Older Than 7 Days

```
db.logs.createIndex({ createdAt: 1 }, { expireAfterSeconds: 604800 });
```

✓ **Prevents database bloating** with unnecessary logs.

CHAPTER 5: MANAGING HIGH-TRAFFIC WORKLOADS WITH SHARDING & REPLICATION

5.1 Scaling Read & Write Operations with Replication

Replication ensures **data availability and fault tolerance** by **copying data across multiple servers**.

How Replication Helps:

✓ **Load Balancing** – Distributes read operations across replicas.

✓ **Fault Tolerance** – Provides **high availability** in case of failures.

✓ **Automatic Failover** – If the primary node fails, MongoDB switches to a secondary node.

Example: Checking the Status of a Replication Set

```
rs.status();
```

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✓ Displays **health and status** of MongoDB replicas.

5.2 Distributing Data with Sharding

Sharding is used to **split large datasets across multiple servers,** improving query speed and performance.

How Sharding Helps:

✓ **Balances large-scale workloads** across multiple servers.

✓ **Supports high-traffic applications** with millions of records.

✓ **Avoids exceeding the 16MB document limit** by distributing data.

Example: Enabling Sharding in MongoDB

```
sh.enableSharding("myDatabase");

sh.shardCollection("myDatabase.users", { userId: "hashed" });
```

✓ **Distributes user data efficiently** across multiple shards.

Case Study: How Netflix Optimized MongoDB for Streaming Performance

Background

Netflix serves **millions of users worldwide,** requiring **fast data retrieval for personalized recommendations, watch history, and caching**.

Challenges

- **Handling massive volumes of user data efficiently**.
- **Reducing latency for streaming and real-time recommendations**.
- **Ensuring data replication for seamless streaming**.

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Solution: Implementing MongoDB Optimization Techniques

✓ **Used indexing** to speed up **user preference retrieval**.
✓ **Implemented sharding** to distribute watch history data.
✓ **Used replication** to ensure high availability for global users.

By optimizing MongoDB, **Netflix reduced query times by 70%,** enhancing user experience.

Exercise

1. Create an **index** on the users collection for the email field.
2. Use **pagination** to retrieve the first **10 records** from a collection.
3. Set up a **TTL index** to automatically delete logs older than **30 days**.
4. Enable **sharding** for a products collection to distribute data across servers.

Conclusion

In this section, we explored:
✓ **How indexing improves query speed and efficiency.**
✓ **Optimizing large queries using projections, pagination, and hints.**
✓ **Techniques for reducing storage usage and document size.**
✓ **How sharding and replication improve scalability.**
✓ **How Netflix optimized MongoDB to serve millions of users efficiently.**

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USING SCHEMA VALIDATION IN MONGODB

CHAPTER 1: INTRODUCTION TO SCHEMA VALIDATION IN MONGODB

1.1 Understanding Schema Validation in MongoDB

MongoDB is a **schema-less NoSQL database,** meaning documents in the same collection can have **different fields and data types**. While this provides flexibility, it can lead to **data inconsistency** and **unexpected errors**.

To ensure **data integrity,** MongoDB allows **schema validation,** which enforces **rules on fields** in a collection.

✓ **Prevents invalid data** from being inserted or updated.
✓ **Enforces required fields** and specific data types.
✓ **Reduces application-level validation** by handling it at the database level.

1.2 How Schema Validation Works in MongoDB

MongoDB uses **JSON Schema Validation** to define rules for documents. These rules specify:

- **Required fields** – Ensures certain fields are always present.
- **Data types** – Validates field types (e.g., string, number, date).
- **Field restrictions** – Defines **minimum, maximum, and pattern constraints**.

Schema validation is applied at the **collection level** when creating or updating a collection.

CHAPTER 2: DEFINING SCHEMA VALIDATION RULES

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2.1 Creating a Collection with Validation

Schema validation rules are defined when **creating a collection** using the validator parameter.

Example: Enforcing Data Validation in a "users" Collection

```
db.createCollection("users", {
  validator: {
    $jsonSchema: {
      bsonType: "object",
      required: ["name", "email", "age"],
      properties: {
        name: {
          bsonType: "string",
          description: "Must be a string and is required"
        },
        email: {
          bsonType: "string",
          pattern: "^[^@\\s]+@[^@\\s]+\\.[^@\\s]+$",
          description: "Must be a valid email address"
        },
        age: {
          bsonType: "int",
          minimum: 18,
          description: "Must be an integer and at least 18"
```

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```
          }
        }
      }
    }
});
```

✓ **Enforces required fields**: name, email, age.
✓ **Validates data types**: name and email must be string, age must be int.
✓ **Applies constraints**: email must match **a valid email pattern,** and age must be **at least 18**.

CHAPTER 3: TESTING SCHEMA VALIDATION

3.1 Inserting Valid Data

The following insert **passes validation**:

```
db.users.insertOne({
  name: "Alice",
  email: "alice@example.com",
  age: 25
});
```

✓ Data **matches validation rules,** so MongoDB **accepts the insert**.

3.2 Inserting Invalid Data

The following insert **fails validation** because age is below 18:

```
db.users.insertOne({
```

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```
  name: "Bob",
  email: "bob@example.com",
  age: 16
});
```

🚨 **Error**: "age" must be at least 18.

Similarly, an invalid email format **also fails validation**:

```
db.users.insertOne({
  name: "Charlie",
  email: "charlie.com",
  age: 22
});
```

🚨 **Error**: "email" must match the pattern of a valid email address.

CHAPTER 4: UPDATING DOCUMENTS WITH SCHEMA VALIDATION

4.1 Ensuring Validation on Updates

Schema validation applies to **both inserts and updates**. To prevent updating a document with **invalid data,** MongoDB enforces validation when using updateOne() or updateMany().

Example: Updating a User's Age

```
db.users.updateOne(
  { name: "Alice" },
  { $set: { age: 17 } }
);
```

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🚨 **Error**: "age" must be at least 18.

4.2 Bypassing Validation for Specific Updates

MongoDB allows **bypassing validation** using bypassDocumentValidation: true:

```
db.users.updateOne(
  { name: "Alice" },
  { $set: { age: 17 } },
  { bypassDocumentValidation: true }
);
```

✓ Used in **migration scenarios**, but **not recommended** for regular updates.

CHAPTER 5: MODIFYING SCHEMA VALIDATION RULES

5.1 Updating an Existing Collection's Schema

To **modify schema validation** for an existing collection, use collMod:

```
db.runCommand({
  collMod: "users",
  validator: {
    $jsonSchema: {
      bsonType: "object",
      required: ["name", "email"],
      properties: {
```

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```
            name: { bsonType: "string" },
            email: { bsonType: "string", pattern:
"^[^@\\s]+@[^@\\s]+\\.[^@\\s]+$" },
            age: { bsonType: "int", minimum: 18, maximum: 100 }
        }
    }
  }
});
```

✓ **Updates validation** to **include a maximum age of 100**.

5.2 Removing Schema Validation from a Collection

To **remove validation**, set validator to {}:

```
db.runCommand({
  collMod: "users",
  validator: {}
});
```

✓ Converts the collection **back to a schema-less structure**.

Case Study: How an E-Commerce Platform Used Schema Validation for Data Integrity

Background

An **e-commerce company** faced issues with **inconsistent data** in their product database. Some products had:

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✓ **Missing fields,** leading to incorrect display on the website.
✓ **Invalid prices** (negative values).
✓ **Duplicate product SKUs,** causing order processing errors.

Solution: Implementing Schema Validation

The development team:

✓ Enforced **required fields** (name, price, SKU).
✓ Added **constraints** (price must be **greater than 0**).
✓ Used a **unique index** to prevent duplicate SKUs.

```
db.createCollection("products", {
  validator: {
    $jsonSchema: {
      bsonType: "object",
      required: ["name", "price", "SKU"],
      properties: {
        name: { bsonType: "string" },
        price: { bsonType: "double", minimum: 0 },
        SKU: { bsonType: "string", unique: true }
      }
    }
  }
});
```

Results

- **Data consistency improved by 95%.**

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- **Reduced errors in product listings**.
- **Faster order processing**, leading to **increased sales**.

By enforcing schema validation, the company **eliminated data inconsistencies** and improved **customer experience**.

Exercise

1. Create a students collection with validation rules:
    - name (required, string).
    - email (required, must follow email pattern).
    - age (integer, between 18-60).
2. Insert a **valid student record**.
3. Try inserting an **invalid student record** (e.g., missing name or invalid email) and observe the error.
4. Modify the schema to **allow a maximum age of 80**.

Conclusion

In this section, we explored:

✓ **How MongoDB schema validation enforces data integrity**.

✓ **How to define validation rules using JSON Schema**.

✓ **How to update, modify, and remove schema validation**.

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ASSIGNMENT:

DESIGN AN OPTIMIZED SCHEMA FOR AN E-COMMERCE APPLICATION AND IMPLEMENT RELATIONSHIPS.

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Solution Guide: Designing an Optimized Schema for an E-Commerce Application & Implementing Relationships

Step 1: Define the Requirements for an E-Commerce Schema

To design an optimized schema, we need to consider:

1. **Users** – Customers and Admins with authentication.
2. **Products** – Product details, categories, and stock management.
3. **Orders** – Tracking purchases, order statuses, and payments.
4. **Reviews** – Customer reviews for products.

Schema Design Approach:

✓ **Users and Orders** – **Referenced** for better scalability.
✓ **Products and Reviews** – **Embedded** for fast retrieval.
✓ **Orders and Products** – **Hybrid approach** to balance efficiency.

Step 2: Set Up the Project and Install Dependencies

2.1 Initialize Node.js Project

mkdir ecommerce-app

cd ecommerce-app

npm init -y

2.2 Install Required Packages

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npm install express mongoose dotenv

✓ **Express.js** – For API creation.
✓ **Mongoose** – ODM for MongoDB.
✓ **dotenv** – To manage environment variables.

Step 3: Configure MongoDB Connection

3.1 Set Up MongoDB Connection

Create **.env** file:

```
MONGO_URI=mongodb://localhost:27017/ecommerceDB
PORT=5000
```

Create **config/db.js**:

```
const mongoose = require('mongoose');
require('dotenv').config();

mongoose.connect(process.env.MONGO_URI, {
  useNewUrlParser: true,
  useUnifiedTopology: true
})
.then(() => console.log('MongoDB Connected'))
.catch(err => console.error('MongoDB Connection Error:', err));

module.exports = mongoose;
```

Step 4: Define the E-Commerce Schema in Mongoose

4.1 User Schema

Create **models/User.js**:

```
const mongoose = require('mongoose');

const userSchema = new mongoose.Schema({
  name: { type: String, required: true },
  email: { type: String, required: true, unique: true },
  password: { type: String, required: true },
  role: { type: String, enum: ['customer', 'admin'], default: 'customer' }
});

module.exports = mongoose.model('User', userSchema);
```

✓ **Users** have different roles (customer/admin).
✓ **Email is unique** to prevent duplicate accounts.

4.2 Product Schema (Embedded Reviews)

Create **models/Product.js**:

```
const mongoose = require('mongoose');

const productSchema = new mongoose.Schema({
  name: { type: String, required: true },
```

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```
  description: String,
  price: { type: Number, required: true },
  category: String,
  stock: { type: Number, default: 0 },
  reviews: [
    {
      user: { type: mongoose.Schema.Types.ObjectId, ref: 'User' },
      rating: { type: Number, min: 1, max: 5 },
      comment: String
    }
  ]
});

module.exports = mongoose.model('Product', productSchema);
```

✓ **Reviews are embedded** to speed up queries.
✓ **User references** help track review authors.

4.3 Order Schema (Hybrid Approach)

Create **models/Order.js**:

```
const mongoose = require('mongoose');

const orderSchema = new mongoose.Schema({
```

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```
  user: { type: mongoose.Schema.Types.ObjectId, ref: 'User', required: true },
  products: [
    {
      product: { type: mongoose.Schema.Types.ObjectId, ref: 'Product' },
      quantity: Number
    }
  ],
  totalPrice: Number,
  status: { type: String, enum: ['pending', 'shipped', 'delivered', 'cancelled'], default: 'pending' },
  orderDate: { type: Date, default: Date.now }
});

module.exports = mongoose.model('Order', orderSchema);
```

✓ **Orders reference users and products** for better scalability.
✓ **Order status** is pre-defined to prevent incorrect values.

Step 5: Implement CRUD Operations for E-Commerce Entities

5.1 Add a New Product

Create **routes/productRoutes.js**:

```
const express = require('express');
const Product = require('../models/Product');
```

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```
const router = express.Router();


// Create a product
router.post('/add', async (req, res) => {
  try {
    const newProduct = new Product(req.body);
    await newProduct.save();
    res.status(201).json(newProduct);
  } catch (error) {
    res.status(500).json({ error: error.message });
  }
});


module.exports = router;
```

✓ **Adds a new product** to the database.

5.2 Fetch All Products

```
router.get('/all', async (req, res) => {
  try {
    const products = await Product.find();
    res.json(products);
  } catch (error) {
```

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```
    res.status(500).json({ error: error.message });
  }
});
```

✓ **Retrieves all products** in the database.

5.3 Place an Order

Create **routes/orderRoutes.js**:

```
const express = require('express');
const Order = require('../models/Order');
const router = express.Router();

// Create an order
router.post('/place', async (req, res) => {
  try {
    const newOrder = new Order(req.body);
    await newOrder.save();
    res.status(201).json({ message: 'Order placed successfully', newOrder });
  } catch (error) {
    res.status(500).json({ error: error.message });
  }
});
```

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```
module.exports = router;
```

✓ Orders are **linked to users** and contain **multiple products**.

5.4 Fetch User Orders

```
router.get('/user/:id', async (req, res) => {
  try {
    const orders = await Order.find({ user: req.params.id }).populate('products.product');
    res.json(orders);
  } catch (error) {
    res.status(500).json({ error: error.message });
  }
});
```

✓ Fetches **all orders placed by a specific user**.

Step 6: Start the Express Server

Create **server.js**:

```
const express = require('express');
const mongoose = require('./config/db');
const productRoutes = require('./routes/productRoutes');
const orderRoutes = require('./routes/orderRoutes');

require('dotenv').config();
```

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```
const app = express();


app.use(express.json());

app.use('/products', productRoutes);

app.use('/orders', orderRoutes);


const PORT = process.env.PORT || 5000;

app.listen(PORT, () => console.log(`Server running on port ${PORT}`));
```

✓ **Registers API routes** for products and orders.

Step 7: Testing the API

7.1 Start the Server

node server.js

7.2 Test API Endpoints Using Postman or cURL

- **Add a Product**
- curl -X POST -H "Content-Type: application/json" -d '{"name":"Laptop", "price":1200, "category":"Electronics"}' http://localhost:5000/products/add
- **Fetch All Products**
- curl -X GET http://localhost:5000/products/all
- **Place an Order**

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- curl -X POST -H "Content-Type: application/json" -d '{"user":"USER_ID","products":[{"product":"PRODUCT_ID","quantity":2}]}' http://localhost:5000/orders/place

---

Conclusion

✓ We **designed an optimized schema** for an e-commerce platform.
✓ We **implemented relationships** between users, products, orders, and reviews.
✓ We **built CRUD APIs** to manage data efficiently.

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