Introduction to NoSQL Databases

Models, Trade-offs, and Polyglot Persistence

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Lecture Goals and Context

Lecture Goals

By the end of this lecture, you will be able to:

- Explain *why* NoSQL systems emerged historically
- Distinguish the four main NoSQL families
- Compare SQL and NoSQL conceptually
- Discuss **CAP** and **PACELC** trade-offs
- Recognize when *not* to use NoSQL

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Where We Are in the Course

So far we have studied:

- The **relational model**
- **Conceptual design** – Entity-Relationship modeling
- **Logical design** – normalization
- **SQL** – DDL, DML, joins, transactions, ACID

A New Question

What happens when the relational model is no longer the best tool for the job?

This is the question NoSQL tries to answer.

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A Brief History of NoSQL

A Brief Historical Detour

The term **NoSQL** is not as old as you might think.

Timeline

- **2006** – Google BigTable paper
- **2007** – Amazon Dynamo paper
- **2009** – San Francisco meetup coins *"NoSQL"*
- **2010s** – Explosion of non-relational systems
- **2020s** – Convergence: NoSQL adopts ACID

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NoSQL Was Not a Revolution

Key Principle

NoSQL was **not** an ideological revolt against SQL.

It was a **pragmatic response** to scale problems that relational systems struggled to solve.

Why Relational Was Challenged

Web-scale applications in the late 2000s faced new pressures:

- **Volume** – petabytes, not gigabytes
- **Velocity** – millions of writes per second
- **Variety** – semi-structured data, JSON
- **Distribution** – global users, global data
- **Evolution** – schemas changing every week

Where Relational Still Excels

The relational model is **still the right choice** for most enterprise systems.

Typical Domains

- Banking and accounting
- ERP and CRM
- University and government records
- Inventory and order management

Any domain where **transactional integrity** is non-negotiable.

Where Relational Struggles

Some scenarios push the relational model to its limits:

- **Social networks** – deep graph traversals
- **IoT and sensors** – high-velocity time series
- **Content platforms** – heterogeneous documents
- **Recommendation engines** – complex similarity
- **Real-time analytics** – sub-second latency

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What is NoSQL?

What is NoSQL?

The acronym is widely interpreted as:

Definition

"Not Only SQL"

- NoSQL is **not a single technology**.
- It is a **family** of database systems.

Common Traits of NoSQL Systems

Shared characteristics

- Non-relational data models
- Flexible or schema-less storage
- Designed for horizontal scalability
- Often distributed by default
- Trade-offs on classical ACID guarantees

Flexible Schema

Relational vs NoSQL

- In a **relational** database, the schema is *declared upfront* and enforced on every row.
- In most **NoSQL** systems, each record can have a *different structure*.

Flexible Schema – Example

```
{ "id": 1, "name": "Alice", "email": "alice@example.com" }
```

```
{ "id": 2, "name": "Bob",   "phone": "+39 333 1234567" }
```

```
{ "id": 3, "name": "Carol", "tags": ["vip", "newsletter"] }
```

Consequence

This shifts the burden of consistency to the **application layer**.

Horizontal Scalability

Two ways to grow a database:

Vertical scaling

Bigger CPU, more RAM.

Easy, but expensive and bounded.

Horizontal scaling

Add more machines.

Cheaper at scale, but more complex.

Insight

Most NoSQL systems are designed for **horizontal scaling from day one**.

Distribution and Availability

Once data is **distributed** across many nodes:

- The system tolerates **hardware failures**
- It can serve requests **closer to users**
- It can handle **higher throughput**

But distribution introduces new challenges.

New Challenges of Distribution

- Network partitions
- Replica synchronization
- Trade-offs between consistency and availability

This is where the **CAP theorem** enters the picture.

Distribution Trade-offs

CAP and PACELC

The CAP Theorem

Origin

Formulated by **Eric Brewer** (2000). Proved by Gilbert and Lynch (2002).

Three desirable properties:

- **C** – every read sees the most recent write
- **A** – every request gets a response
- **P** – the system works despite network failures

The CAP Trade-off

In a distributed system, **partitions will happen**.

So the real choice is:

The Real Question

*When the network splits, do we prefer **consistency** or **availability**?*

CAP – A Common Misconception

You will often hear:

Popular Phrasing

"Pick two out of three."

This is misleading.

Correction

Partition tolerance is not optional – the network *will* fail.

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CAP – The Correct Reading

The trade-off is **binary and conditional**:

- **During a partition** $\rightarrow$ choose C or A
- **Without a partition** $\rightarrow$ you can have both

Reference

Brewer clarified this in *"CAP Twelve Years Later"* (2012).

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Beyond CAP – PACELC

Daniel Abadi (2012) extended CAP with a more realistic model:

PACELC

- **If Partition** → choose between **A** and **C**
- **Else** → choose between **L**atency and **C**onsistency

PACELC – Real Systems

System	Classification	Priority
Cassandra	PA / EL	Availability + low latency
MongoDB	PA / EC	Availability + consistency at rest
HBase	PC / EC	Consistency always

The Four NoSQL Families

The Four NoSQL Families

Taxonomy

1. **Key-Value stores**
2. **Document databases**
3. **Wide-Column stores**
4. **Graph databases**

Each family targets a different class of problems.

Family 1 – Key-Value Stores

The simplest NoSQL model:

```
key  ->  value
```

- The value is **opaque** to the database.
- Operations are minimal: `GET`, `PUT`, `DELETE`.

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Key-Value – Strengths and Limits

Strengths

- Extreme speed
- Simple horizontal scaling

Limitations

- No querying *inside* values
- No joins, no rich indexing

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Key-Value – Typical Uses

Use cases

- **Session storage** – user_id → session
- **Caching** – query_hash → result set
- **Feature flags** – flag → boolean
- **Leaderboards** – game_id → scores
- **Rate limiting** – ip → count

Technologies

Redis, DynamoDB, Riak, Memcached.

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Key-Value – Example

```
SET user:1001 "{\"name\":\"Alice\",\"age\":21}"
```

```
GET user:1001
```

Returns:

```
{ "name": "Alice", "age": 21 }
```

Note

The database does **not** understand the JSON structure.

Family 2 – Document Databases

Definition

Data is stored as **self-contained documents**, typically in JSON or BSON.

Each document is **identified by a key** *and* **introspectable** by the database.

Document – Example

```
{
  "student_id": 1001,
  "name": "Alice",
  "enrollment_year": 2024,
  "exams": [
    { "course": "Databases",        "grade": 28 },
    { "course": "Machine Learning", "grade": 30 }
  ]
}
```

Insight

You can query, index, and aggregate **inside** the document.

Document vs Relational

The same information in a relational schema:

```
STUDENTS   (student_id, name, enrollment_year)
COURSES    (course_id, course_name)
EXAMS      (student_id, course_id, grade)
```

- A transcript query needs **two joins**.
- In a document model: **one read, no joins**.

Document – Embed vs Reference

The central design decision:

Embed

Nest related data inside the parent.

Reference

Store a pointer (id) to another document.

Embed vs Reference – Guidelines

Heuristics

- **1-to-few** → embed
- **1-to-many, rarely updated** → embed
- **1-to-many, frequently updated** → reference
- **Many-to-many** → reference

This mirrors the *denormalization* decisions of relational design.

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Document – Strengths and Limitations

Strengths

- Natural fit for web apps
- One read = full aggregate
- Schema evolves without migrations
- Excellent for content-heavy apps

Limitations

- Data duplication if embedded aggressively
- Update anomalies across documents
- Cross-document joins are limited

Technologies

MongoDB, CouchDB, DocumentDB, Firestore.

Family 3 – Wide-Column Stores

A common point of confusion – let us be precise:

Three different "column" concepts

- **Row-oriented** – relational DBs (PostgreSQL, MySQL)
- **Column-oriented (analytical)** – Parquet, ClickHouse
- **Wide-column (NoSQL)** – Cassandra, HBase

Warning

Wide-column is **not** the same as column-oriented analytics.

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Wide-Column – Model

A wide-column store is a **sparse, distributed, multi-dimensional map**:

```
(row_key, column_family, column, timestamp) -> value
```

Rows are **sparse** – each row can have completely different columns.

Wide-Column – Use Cases

When to use

- Time-series data
- IoT telemetry
- Write-heavy logs
- Large-scale activity feeds

Technologies

Apache Cassandra, Apache HBase, ScyllaDB, Google BigTable.

Family 4 – Graph Databases

When the **relationships** between entities are as important as the entities themselves.

Two primitives

- **Nodes** – entities
- **Edges** – typed, directed relationships

Both can carry **properties**.

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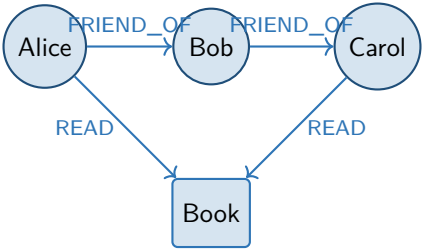
Graph – Visual Example



Edges typed as `FRIEND_OF` and `READ`.

Graph – Why It Matters

Insight

Queries that would require **many recursive joins** in SQL become **natural traversals** in a graph database.

"Friends of friends who read the same book as Alice"
$\rightarrow$ *a few lines of Cypher.*

Graph – Typical Uses

Use cases

- **Social networks** – friends, communities
- **Recommendations** – collaborative filtering
- **Fraud detection** – suspicious patterns
- **Knowledge graphs** – semantic entities
- **Infrastructure mapping** – dependencies

Technologies

Neo4j, Amazon Neptune, ArangoDB, TigerGraph.

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Query Languages

Query Languages – A Quick Tour

Each family has its own query language:

Mapping

- **Relational** → SQL (ISO standard)
- **Document** → MQL, JSONPath
- **Wide-Column** → CQL (SQL-like syntax)
- **Graph** → Cypher, GQL

A Note on CQL and GQL

Beware

CQL *looks* like SQL but does **not** support real joins.
Same syntax, different semantics.

Maturity Signal

GQL (ISO/IEC 39075:2024) is the first ISO standard for graph queries.
A sign of the field's maturity.

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SQL vs NoSQL

SQL vs NoSQL – Schema and Model

Aspect	**SQL**	**NoSQL**
Schema	Fixed, enforced	Flexible
Data model	Tables	Multiple models
Joins	First-class	Limited or absent

SQL vs NoSQL – Scale and Guarantees

Aspect	**SQL**	**NoSQL**
Scaling	Mostly vertical	Mostly horizontal
Transactions	ACID (strong)	Historically BASE
Consistency	Strong default	Often tunable

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SQL vs NoSQL – Best Use

SQL is best for

Structured, transactional workloads.

NoSQL is best for

Large-scale, flexible, distributed workloads.

ACID vs BASE

ACID – A Reminder

The classical guarantees of relational transactions:

ACID

- **A – Atomicity** – all-or-nothing
- **C – Consistency** – valid $\rightarrow$ valid state
- **I – Isolation** – no interference
- **D – Durability** – survives failures

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ACID – A Limitation

Key Point

ACID was designed for **single-node, transactional** workloads.

It does not scale trivially across a distributed cluster.

This led to a weaker, more scalable model.

BASE – The NoSQL Alternative

Early NoSQL systems adopted a relaxed model:

BASE

- **B – Basically Available**
- **S – Soft state**
- **E – Eventual consistency**

BASE – In Practice

Everyday Example

When you “like” a post on a social network, your friends may see the new count **after a few seconds**.

That delay is **eventual consistency** in action.

For many web-scale workloads, this trade-off is acceptable.

ACID vs BASE – The Modern Picture

The strict dichotomy is **outdated**.

Recent evolution

- **MongoDB** – multi-document ACID since 4.0 (2018)
- **Cassandra** – lightweight transactions via Paxos
- **CockroachDB**, **YugabyteDB** – "NewSQL"

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The Real Modern Question

Old Question

"ACID or BASE?"

Better Question

Which consistency guarantees do I need, on which operations, at which cost?

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A Worked Example

The Library System Revisited

A Worked Example – Library

Recall the **library system** from earlier in the course.

Relational design

```
STUDENTS (student_id, name, email)
BOOKS    (book_id, title, author, isbn)
LOANS    (loan_id, student_id, book_id, loan_date)
```

Retrieving active loans requires a **join**.

Library System – Document Version

```
{
  "student_id": 1001,
  "name": "Alice",
  "active_loans": [
    { "book": "Database Systems",
      "isbn": "978-0136086208",
      "loan_date": "2026-05-14" }
  ]
}
```

Insight

One document, one read, the full active state.

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Library – Document Wins On

Advantages

- Read performance for the most frequent query
- Natural mapping to the application object
- Schema flexibility per student

Library – Document Loses On

Trade-offs

- *"How many copies of book X are on loan?"* $\rightarrow$ must scan all students
- Updating book metadata in one place – duplicated
- Strict referential integrity – no foreign keys

Library – The Lesson

The Lesson

The right model depends on the **dominant access pattern**.

Not on which technology is “newer” or “trendier”.

When Not to Use NoSQL

and Polyglot Persistence

When *Not* to Use NoSQL

Choose a **relational database** when:

- Data is **highly structured** and stable
- **Multi-table transactions** are central
- **Referential integrity** must be enforced
- **Ad-hoc joins** are frequent
- The dataset fits on one large machine

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A Useful Sanity Check

Rule of Thumb

"You probably don't have big data."

PostgreSQL on a well-provisioned server handles **far more** than most projects ever need.

Start simple. Scale when forced to.

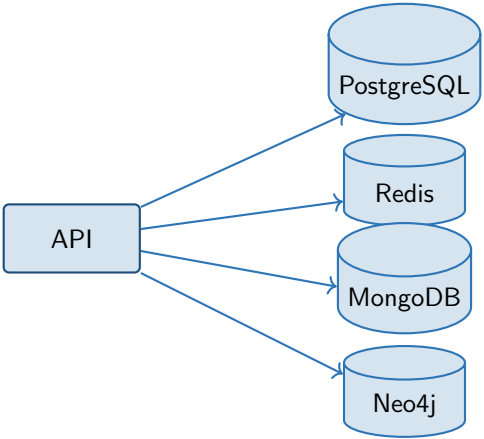
Polyglot Persistence

Definition

Using different databases for different parts of the same application – each chosen for its strengths.

Modern systems rarely commit to a **single** database technology.

Polyglot Persistence – Architecture



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Polyglot – E-commerce Example

Each system does what it does best

- **PostgreSQL** – orders, payments → ACID
- **Redis** – sessions, cache → low latency
- **MongoDB** – product catalog → flexible
- **Neo4j** – recommendations → graph
- **Elasticsearch** – full-text search

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Polyglot – The Cost

Operational Complexity

- More services to deploy
- More systems to monitor
- More integrations to keep in sync

Adopt polyglot only when **justified by evidence**.

Choosing a Database

Choosing a Database – Step 1

First Question

What is the dominant access pattern?

Mapping

- Point lookups → **key-value**
- Aggregate reads by id → **document**
- Heavy writes, time-series → **wide-column**
- Relationship traversal → **graph**
- Joins and ad-hoc queries → **relational**

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Choosing a Database – Step 2

Then ask

- What consistency do I need, on which operations?
- What is my realistic data scale today and in 2 years?
- What operational cost can I afford?

Key Takeaways

Key Takeaways – 1

What NoSQL Is

- NoSQL is a **family** of systems, not one technology
- It emerged as a **pragmatic response** to web-scale
- Four main models: **key-value, document, wide-column, graph**

Key Takeaways – 2

Trade-offs and Design

- **CAP** is a useful intuition; **PACELC** is more realistic
- The **ACID vs BASE** dichotomy has softened
- Relational databases are **still the right default**
- Real architectures often combine technologies – **polyglot persistence**

References

Suggested Readings – Foundational

Books

- Sadalage & Fowler – *NoSQL Distilled*, Addison-Wesley, 2012
- Kleppmann – *Designing Data-Intensive Applications*, O'Reilly, 2017

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Suggested Readings – Original Papers

Seminal papers

- Brewer – *"CAP Twelve Years Later"*, IEEE Computer (2012)
- Abadi – *"Consistency Tradeoffs..."*, IEEE Computer (2012)
- DeCandia et al. – *"Dynamo"*, SOSP (2007)
- Chang et al. – *"Bigtable"*, OSDI (2006)

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Questions?

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Next lecture: course wrap-up and exam preparation.

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