

Database Programming (Part 3)

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Princeton University

Objectives

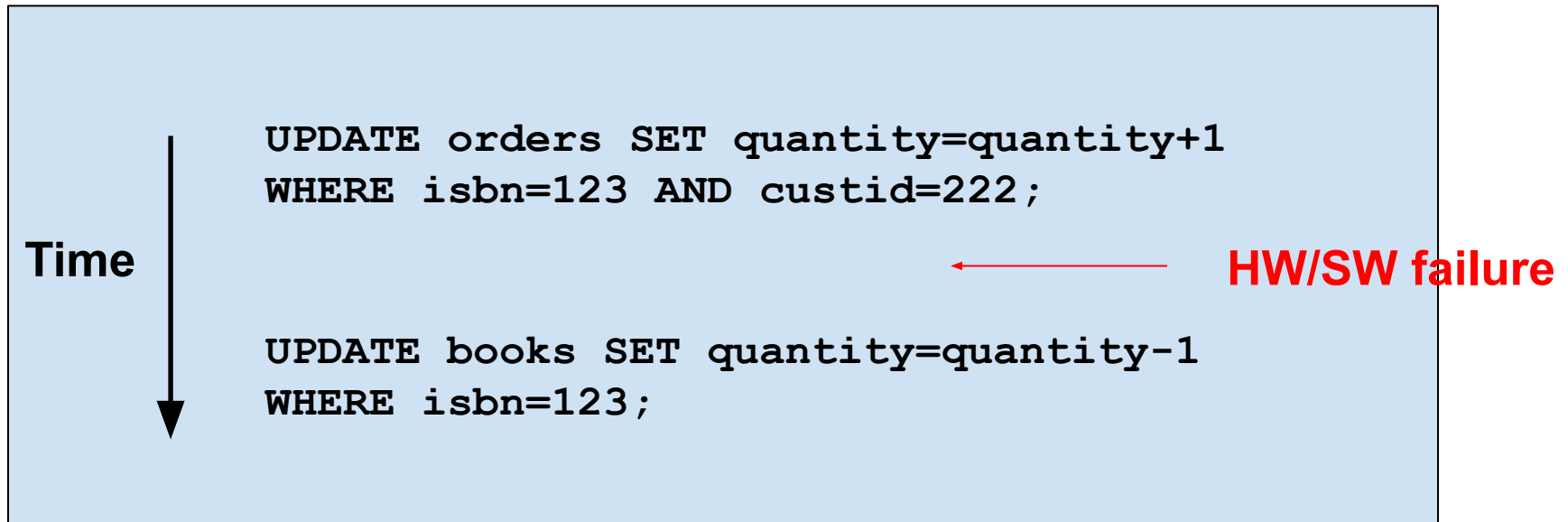
- We will cover:
 - **Databases (DBs) and database management systems (DBMSs)...**
 - With a focus on **relational** DBs and DBMSs...
 - With a focus on the **SQLite** DBMS...
 - With a focus on **programming** with SQLite

Agenda

- **Relational DB transactions: atomicity**
- Relational DB transactions: locking
- Relational DB design

DB Transactions: Atomicity

Customer 222 purchased 1 copy of book 123



DB Transactions: Atomicity

Preserve consistency with
HW/SW failures



Requires

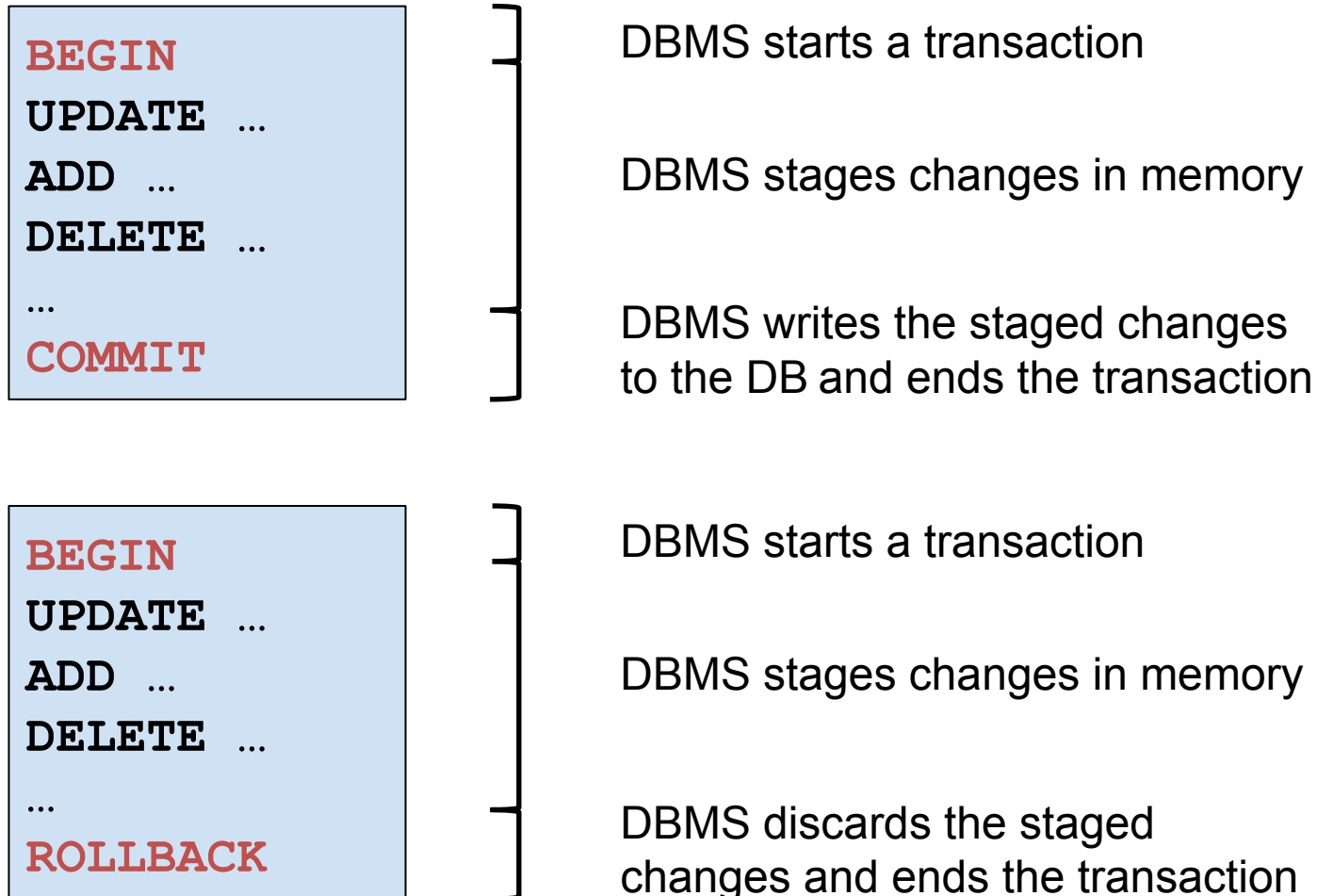
Atomicity



Implemented by

Transactions

DB Transactions: Atomicity



DB Transactions: Atomicity

- See **purchase.py**

```
$ python display.py
-----
books
-----
('123', 'The Practice of Programming', 500)
...
-----
orders
-----
('123', '222', 20)
...
$ python purchase.py 123 222
Transaction committed.
```

```
$ python display.py
-----
books
-----
('123', 'The Practice of Programming', 499)
...
-----
orders
-----
('123', '222', 21)
...
$
```

Aside: Isolation Level

```
connect (DATABASE_URL,  
        isolation_level=None, uri=True
```

“You can disable the sqlite3 module’s implicit transaction management by setting `isolation_level` to `None`. This will leave the underlying sqlite3 library operating in autocommit mode. You can then completely control the transaction state by explicitly issuing `BEGIN`, `ROLLBACK`, `SAVEPOINT`, and `RELEASE` statements in your code.”

<https://docs.python.org/3/library/sqlite3.html>

DB Transactions: Atomicity

- See **recovery.py**

```
$ python display.py
-----
books
-----
('123', 'The Practice of Programming', 500)
...
-----
orders
-----
('123', '222', 20)
...
$
```

DB Transactions: Atomicity

- See **recovery.py**
(cont.)

```
$ python recovery.py
Transaction 0 committed.
Transaction 1 committed.
Transaction 2 committed.
Transaction 3 committed.
Transaction 4 committed.
Simulated failure with i = 5
Transaction 5 rolled back.
Transaction 6 committed.
Transaction 7 committed.
Transaction 8 committed.
Transaction 9 committed.
Transaction 10 committed.
Simulated failure with i = 11
Transaction 11 rolled back.
Transaction 12 committed.
Simulated failure with i = 13
Transaction 13 rolled back.
Transaction 14 committed.
Transaction 15 committed.
Transaction 16 committed.
Transaction 17 committed.
Transaction 18 committed.
Transaction 19 committed.
$
```

DB Transactions: Atomicity

- See recovery.py (cont.)

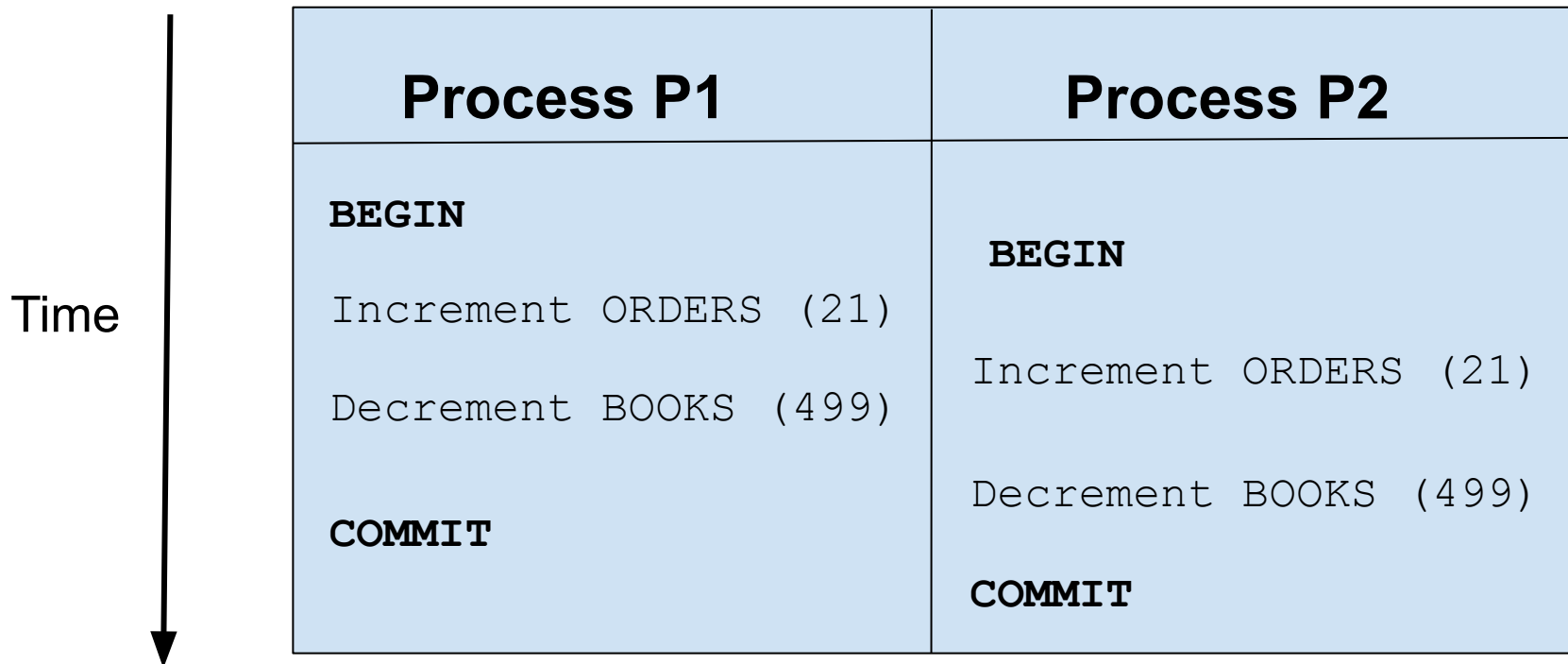
```
$ python display.py
-----
books
-----
('123', 'The Practice of Programming', 483)
...
-----
orders
-----
('123', '222', 37)
...
$
```

Agenda

- Relational DB transactions: atomicity
- **Relational DB transactions: locking**
- Relational DB design

DB Transactions: Locking

Without locking:



DB Transactions: Locking

Preserve consistency with
concurrent updates



Requires

Locking



Implemented by

Transactions

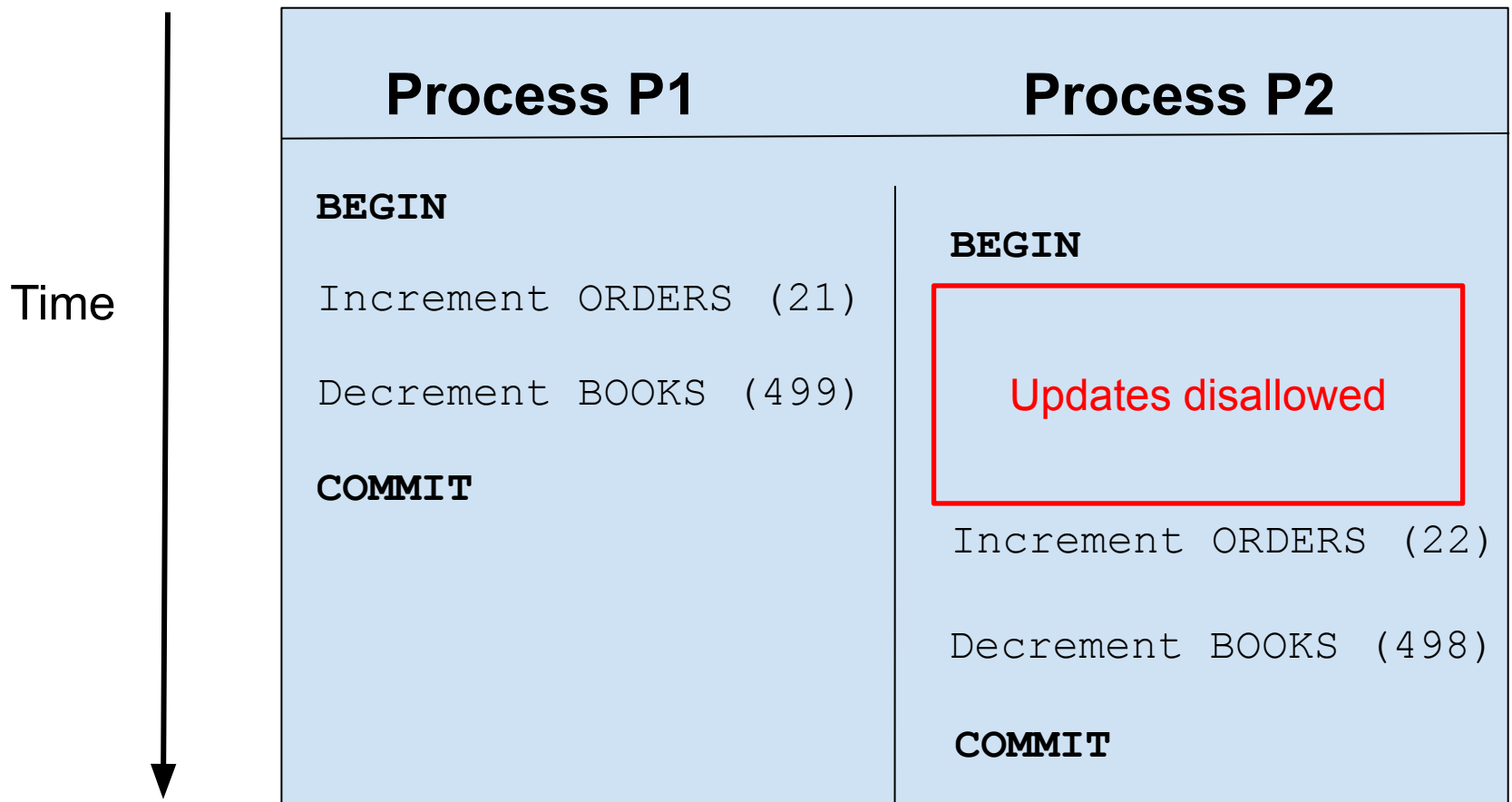
DB Transactions: Locking

Transaction locking in SQLite

After P1 does this on some DB	P2 can do this on that DB
BEGIN	BEGIN SELECT UPDATE ADD DELETE COMMIT ROLLBACK
SELECT UPDATE ADD DELETE	BEGIN SELECT COMMIT ROLLBACK
COMMIT ROLLBACK	BEGIN SELECT UPDATE ADD DELETE COMMIT ROLLBACK

DB Transactions: Locking

With locking:



Process P2 updates are postponed or rejected

DB Transactions: Locking

DBMS	Locking Level
PostgreSQL	row
Oracle	row
SQLServer	row
MySQL	row
SQLite	database

DB Transactions: Locking

Terminal session 1:

```
$ sqlite3 bookstore.sqlite
sqlite> BEGIN;
sqlite> UPDATE books SET quantity = 11111 WHERE isbn = 123;
sqlite>
```

Terminal session 2:

```
$ python purchase.py 123 222
database is locked
$
```

Noticeable delay



DB Transactions: Locking

Terminal session 1 (cont):

```
$ sqlite3 bookstore.sqlite
sqlite> BEGIN;
sqlite> UPDATE books SET quantity = 11111 WHERE isbn = 123;
sqlite> COMMIT;
sqlite>
```

Terminal session 2 (cont):

```
$ python purchase.py 123 222
database is locked
$ python purchase.py 123 222
Transaction committed.
$
```

Transaction Summary

- DBMSs use **transactions** to:
 - Recover from HW/SW errors
 - Transactions implement **atomicity**
 - Handle concurrent updates
 - Transactions implement **locking**

Agenda

- Relational DB transactions: atomicity
- Relational DB transactions: locking
- **Relational DB design**

Relational DB Design

- Relational DB *normal forms*

Relational DB Design

- Somewhat informally...
- **Def:** A table is in *first normal form* iff no cell of a table is a table
 - All modern relational DBMSs enforce first normal form

Relational DB Design: DB1

DB1:

BOOKS

isbn	title	quantity
123	The Practice of Programming	500
234	The C Programming Language	800
345	Algorithms in C	650

AUTHORS

isbn	author
123	Kernighan
123	Pike
234	Kernighan
234	Ritchie
345	Sedgewick

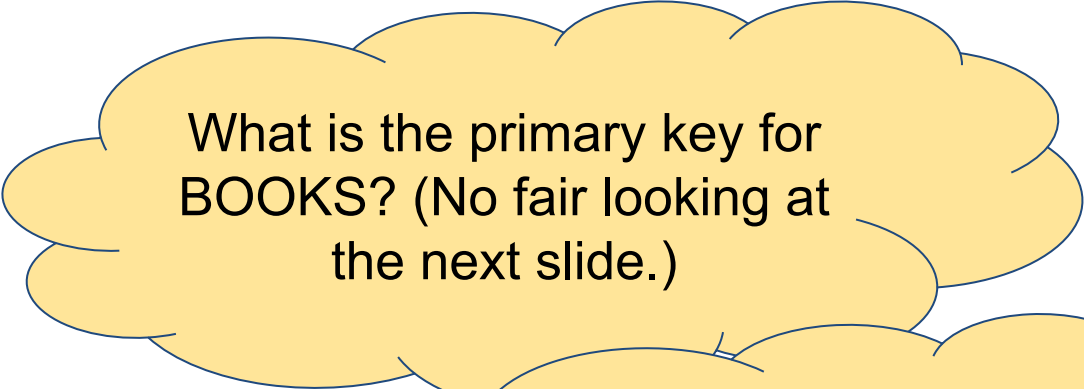
ORDERS

isbn	custid	custname	street	city	state	zipcode	quantity
123	222	Harvard	1256 Mass Ave	Cambridge	MA	02138	20
345	222	Harvard	1256 Mass Ave	Cambridge	MA	02138	100
123	111	Princeton	114 Nassau St	Princeton	NJ	08540	30

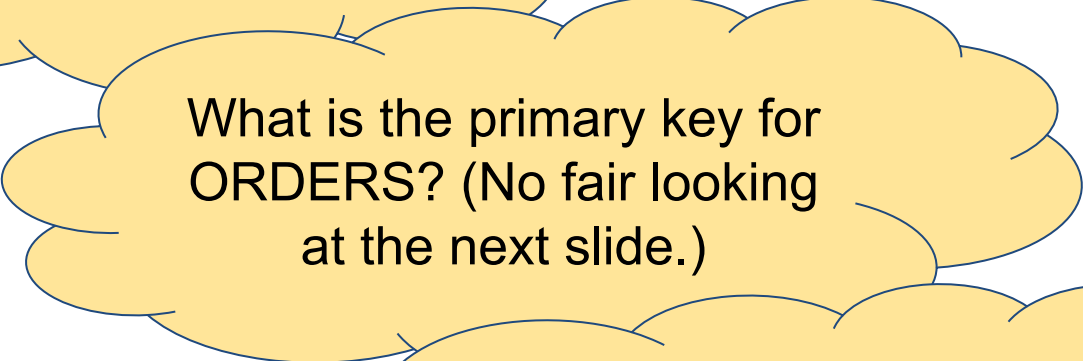
Relational DB Design: DB1

- Somewhat informally...
- **Def:** The *primary key* for a table is the minimal set of columns that uniquely identifies any particular row of that table

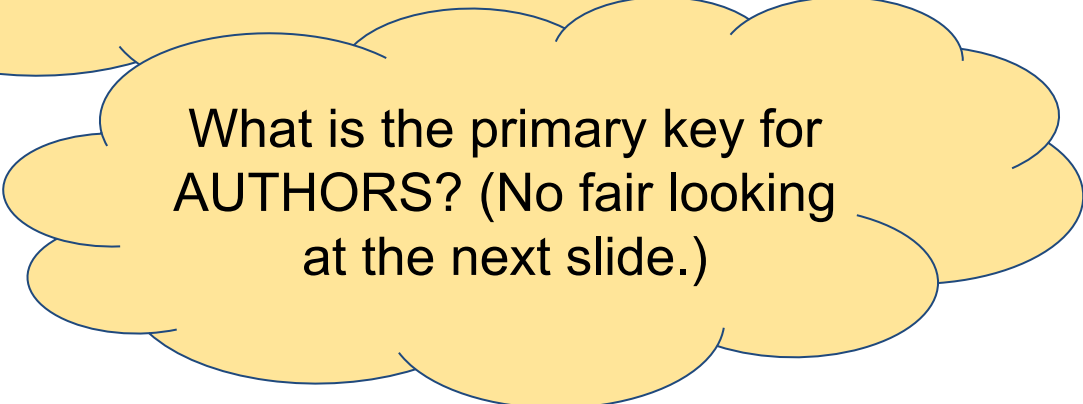
Relational DB Design: DB1



What is the primary key for BOOKS? (No fair looking at the next slide.)



What is the primary key for ORDERS? (No fair looking at the next slide.)



What is the primary key for AUTHORS? (No fair looking at the next slide.)

Relational DB Design: DB1

Primary keys (boldface) in DB1:

BOOKS

isbn	title	quantity
123	The Practice of Programming	500
234	The C Programming Language	800
345	Algorithms in C	650

AUTHORS

isbn	author
123	Kernighan
123	Pike
234	Kernighan
234	Ritchie
345	Sedgewick

ORDERS

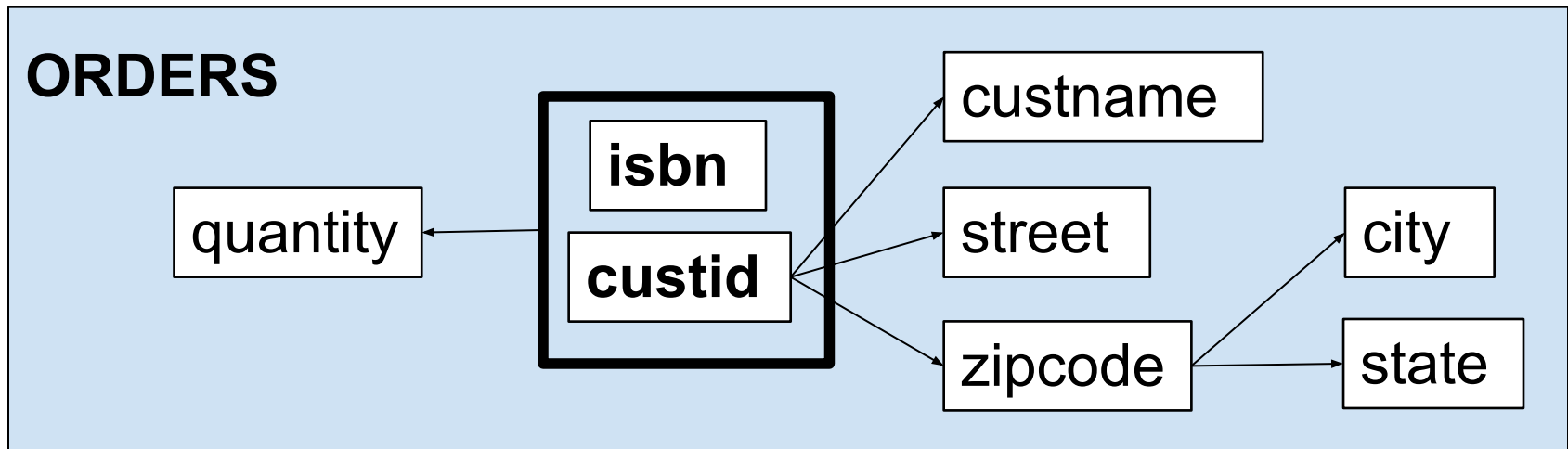
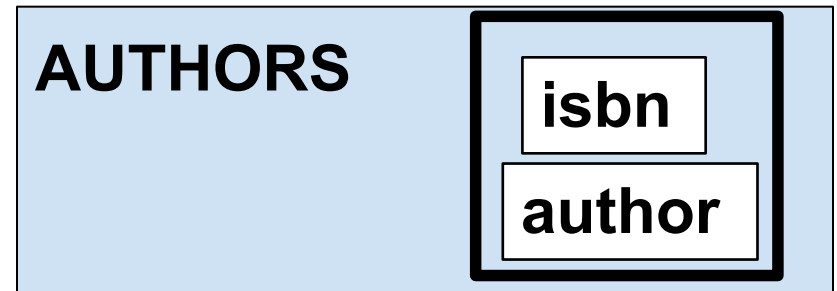
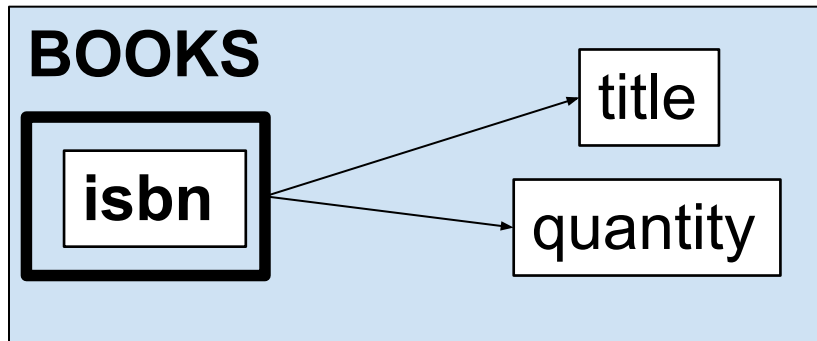
isbn	custid	custname	street	city	state	zipcode	quantity
123	222	Harvard	1256 Mass Ave	Cambridge	MA	02138	20
345	222	Harvard	1256 Mass Ave	Cambridge	MA	02138	100
123	111	Princeton	114 Nassau St	Princeton	NJ	08540	30

Relational DB Design: DB1

- **Def:** A column C2 of a table is (functionally) *dependent* on a column C1 iff, for each row in the table, the value of C1 determines the value of C2
- In DB1...

Relational DB Design: DB1

Dependencies in DB1:

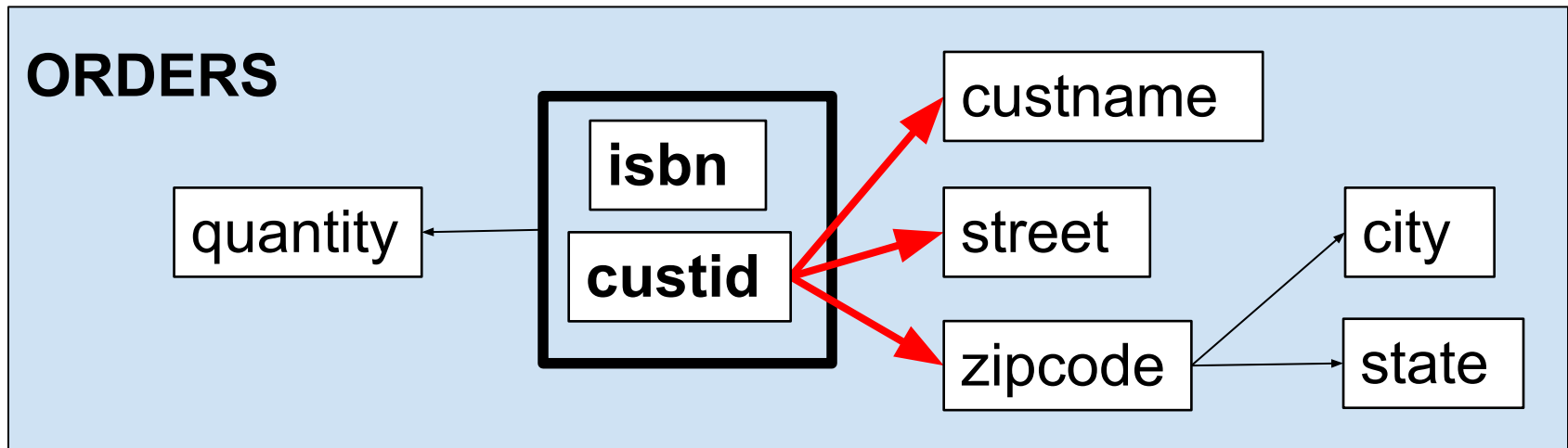
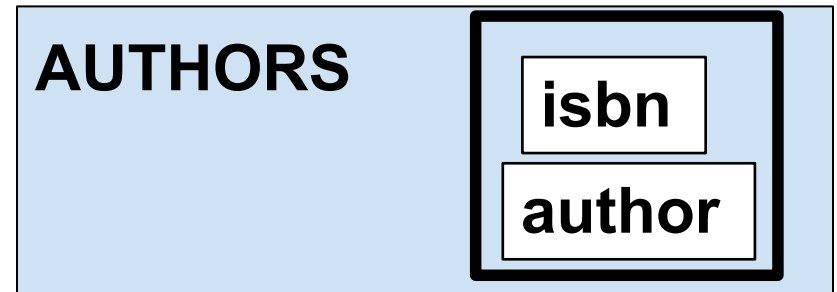
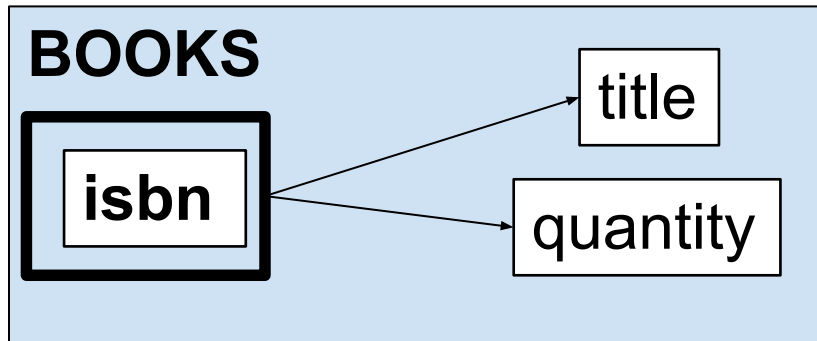


Relational DB Design: DB1

- Somewhat informally...
- A table is in ***second normal form*** iff:
 - It is in first normal form, and
 - Every non-primary-key column is dependent on the **entire** primary key

Relational DB Design: DB1

Dependencies in DB1:



DB1 is not in second normal form

Relational DB Design: DB2

DB2:

BOOKS

isbn	title	quantity
123	The Practice of Programming	500
234	The C Programming Language	800
345	Algorithms in C	650

AUTHORS

isbn	author
123	Kernighan
123	Pike
234	Kernighan
234	Ritchie
345	Sedgewick

ORDERS

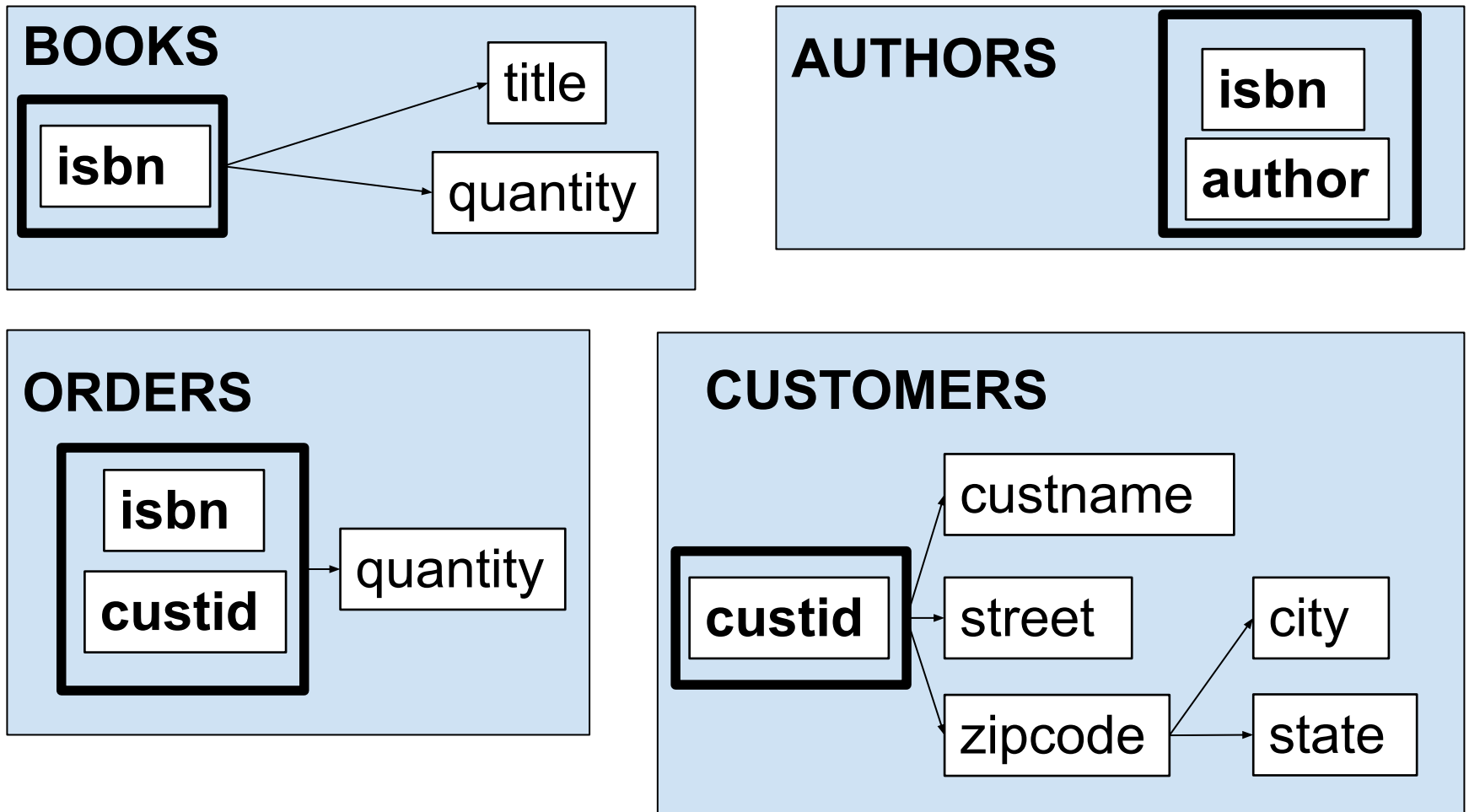
isbn	custid	quantity
123	222	20
345	222	100
123	111	30

CUSTOMERS

custid	custname	street	city	state	zipcode
111	Princeton	114 Nassau St	Princeton	NJ	08540
222	Harvard	1256 Mass Ave	Cambridge	MA	02138
333	MIT	292 Main St	Cambridge	MA	02142

Relational DB Design: DB2

Dependencies in DB2:



DB2 is in second normal form

Relational DB Design: DB2

DB2:

BOOKS

isbn	title	quantity
123	The Practice of Programming	500
234	The C Programming Language	800
345	Algorithms in C	650

AUTHORS

isbn	author
123	Kernighan
123	Pike
234	Kernighan
234	Ritchie
345	Sedgewick

ORDERS

isbn	custid	quantity
123	222	20
345	222	100
123	111	30

Design of DB2 seems wrong

CUSTOMERS

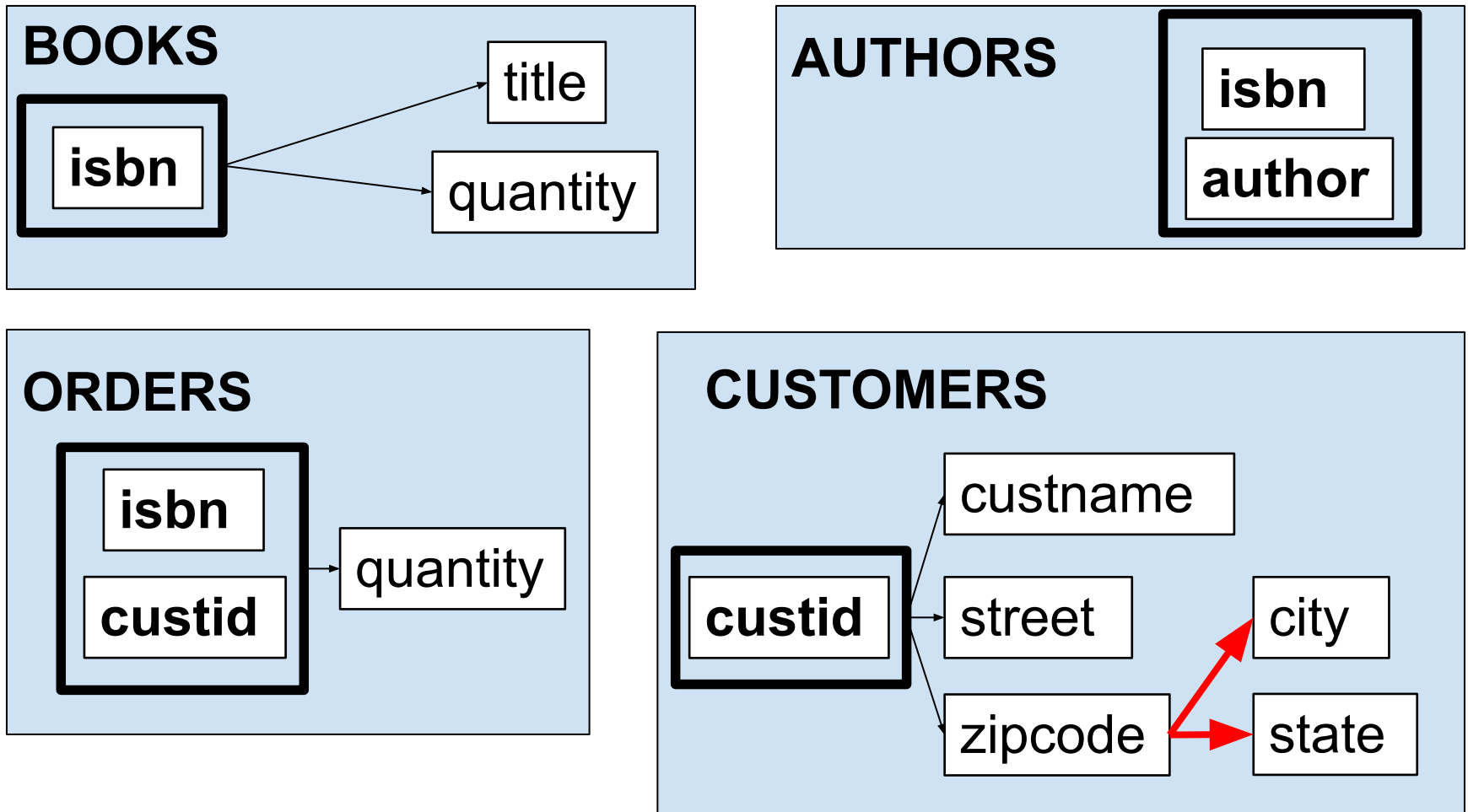
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111	Princeton	114 Nassau St	Princeton	NJ	08540
222	Harvard	1256 Mass Ave	Cambridge	MA	02138
333	MIT	292 Main St	Cambridge	MA	02142

Relational DB Design: DB2

- Somewhat informally...
- A table is in *third normal form* iff:
 - It is in second normal form, and
 - Every non-primary-key column is (non-transitively) **directly** (functionally) dependent on the primary key

Relational DB Design: DB2

Dependencies in DB2:



DB2 is not in third normal form

Relational DB Design: DB3

DB3:

BOOKS

isbn	title	quantity
123	The Practice of Programming	500
234	The C Programming Language	800
345	Algorithms in C	650

ORDERS

isbn	custid	quantity
123	222	20
345	222	100
123	111	30

CUSTOMERS

custid	custname	street	zipcode
111	Princeton	114 Nassau St	08540
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333	MIT	292 Main St	02142

AUTHORS

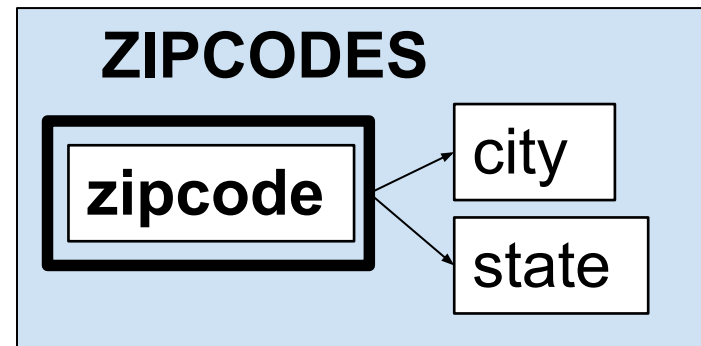
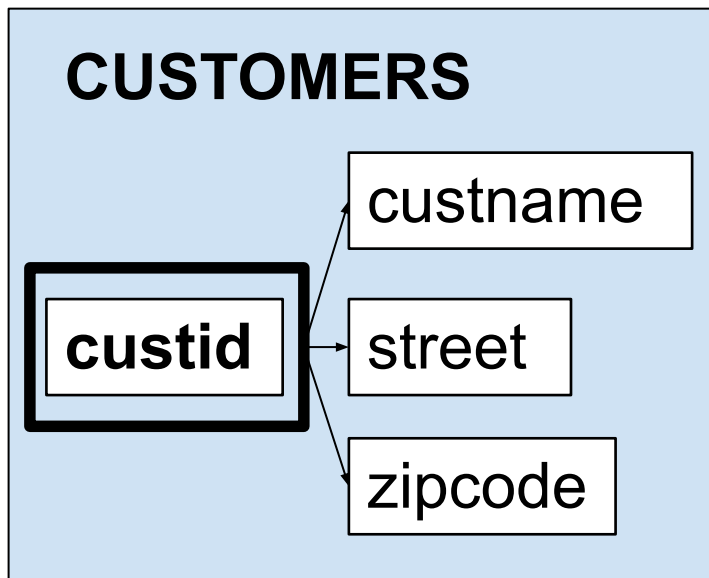
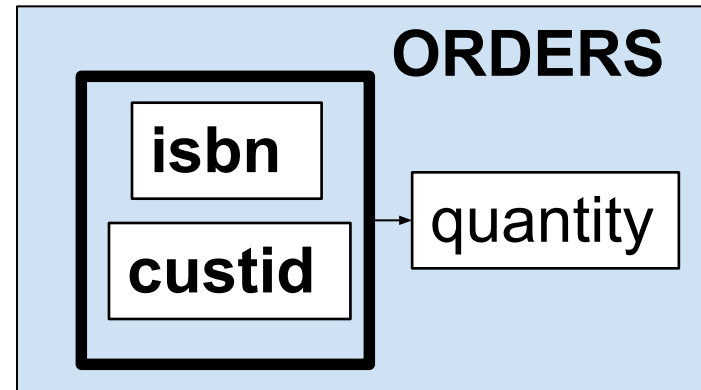
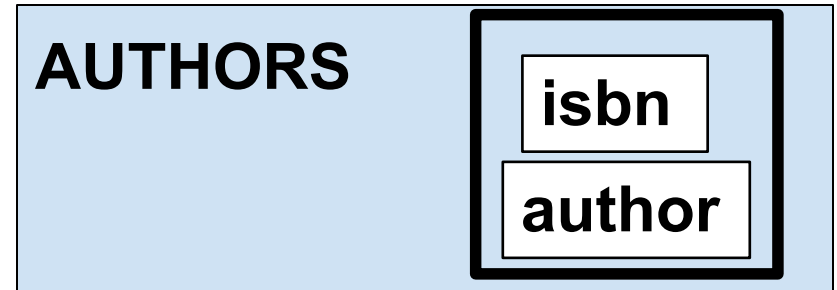
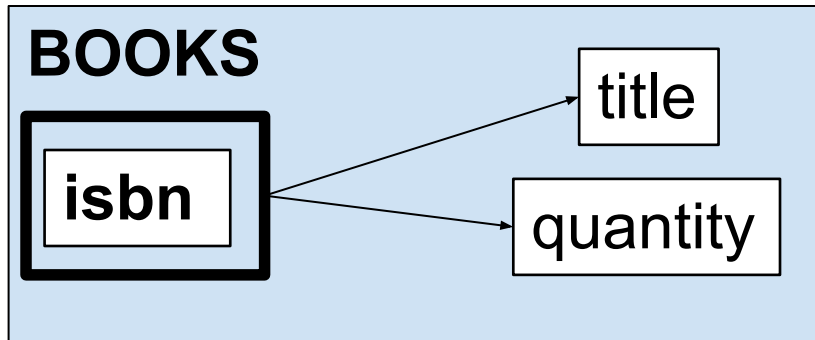
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234	Ritchie
345	Sedgewick

ZIPCODES

zipcode	city	state
08540	Princeton	NJ
02138	Cambridge	MA
02142	Cambridge	MA

Relational DB Design: DB3

Dependencies in DB3:



DB3 is in third normal form

Relational DB Design: Summary

Codd's 1971 Paper

Unnormalized form



Eliminate domains which have relations as elements

First normal form



Eliminate non-full dependence of non-prime attributes on candidate keys

Second normal form



Eliminate transitive dependence of non-prime attributes on candidate keys

Third normal form

Relational DB Design

- Some additional points:
 - Database designers routinely violate normal forms
 - There is a substantial mathematical theory of relational database design
 - DBMS can enforce additional *consistency constraints*
 - See bookstorefancy.sql

Lecture Summary

- In this lecture we covered:
 - Relational DB transactions: atomicity
 - Relational DB transactions: locking
 - Relational DB design

Lecture Series Summary

- In this lecture series we covered:
 - **Databases (DBs) and database management systems (DBMSs)...**
 - With a focus on **relational** DBs and DBMSs...
 - With a focus on the **SQLite** DBMS...
 - With a focus on **programming** with SQLite
- See also...

See Also

- **Appendices**
 - **Appendix 1:** Before relational DBs
 - **Appendix 2:** After relational DBs
- **Optional lecture slide decks**
 - PostgreSQL
 - SQLAlchemy

More Information

- The COS 333 *Lectures* web page provides references to supplementary information

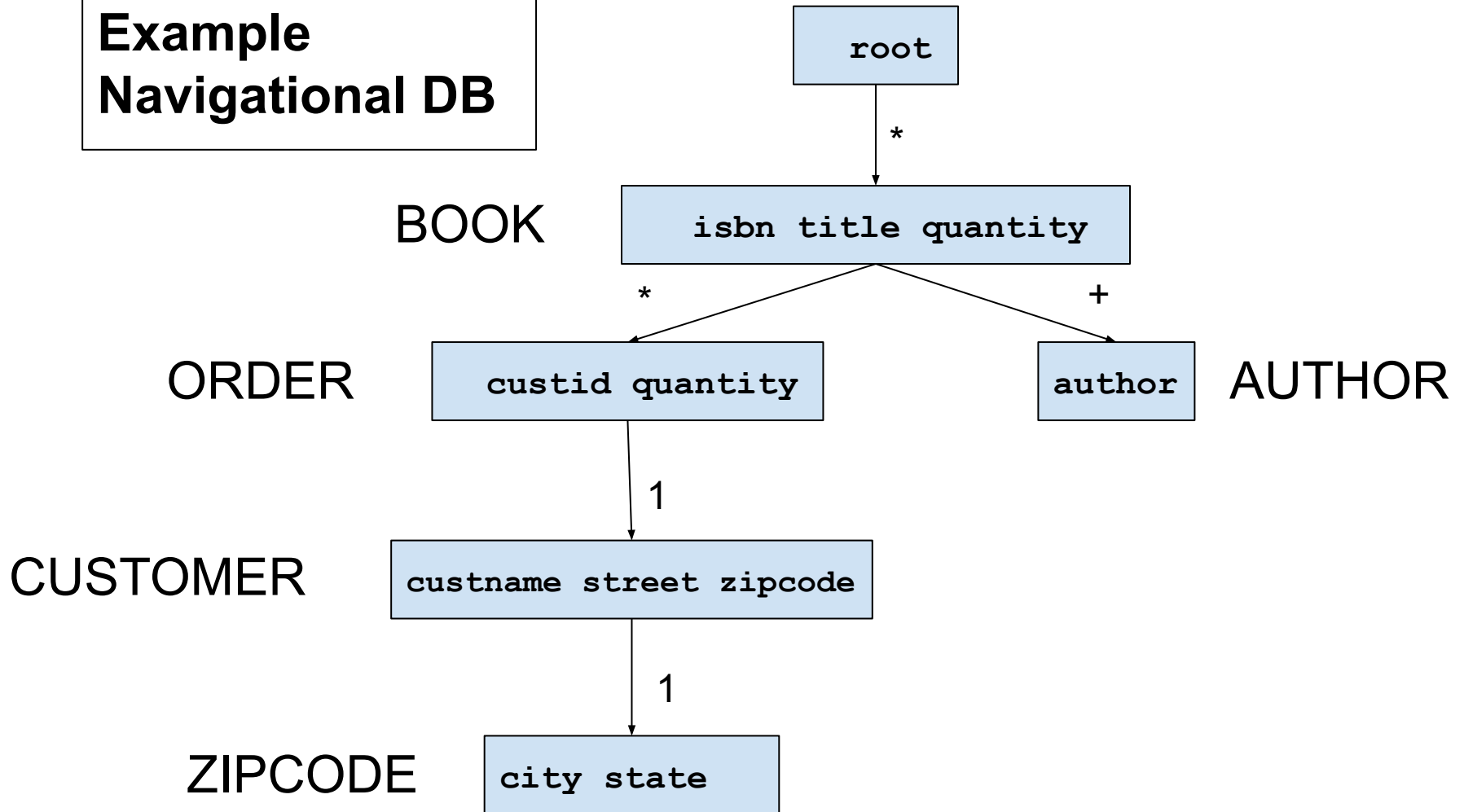
Appendix 1: Before Relational DBs

Before Relational DBs

- Before relational DBs, there were...
- *Navigational* DBs
 - Data are linked into graph structure

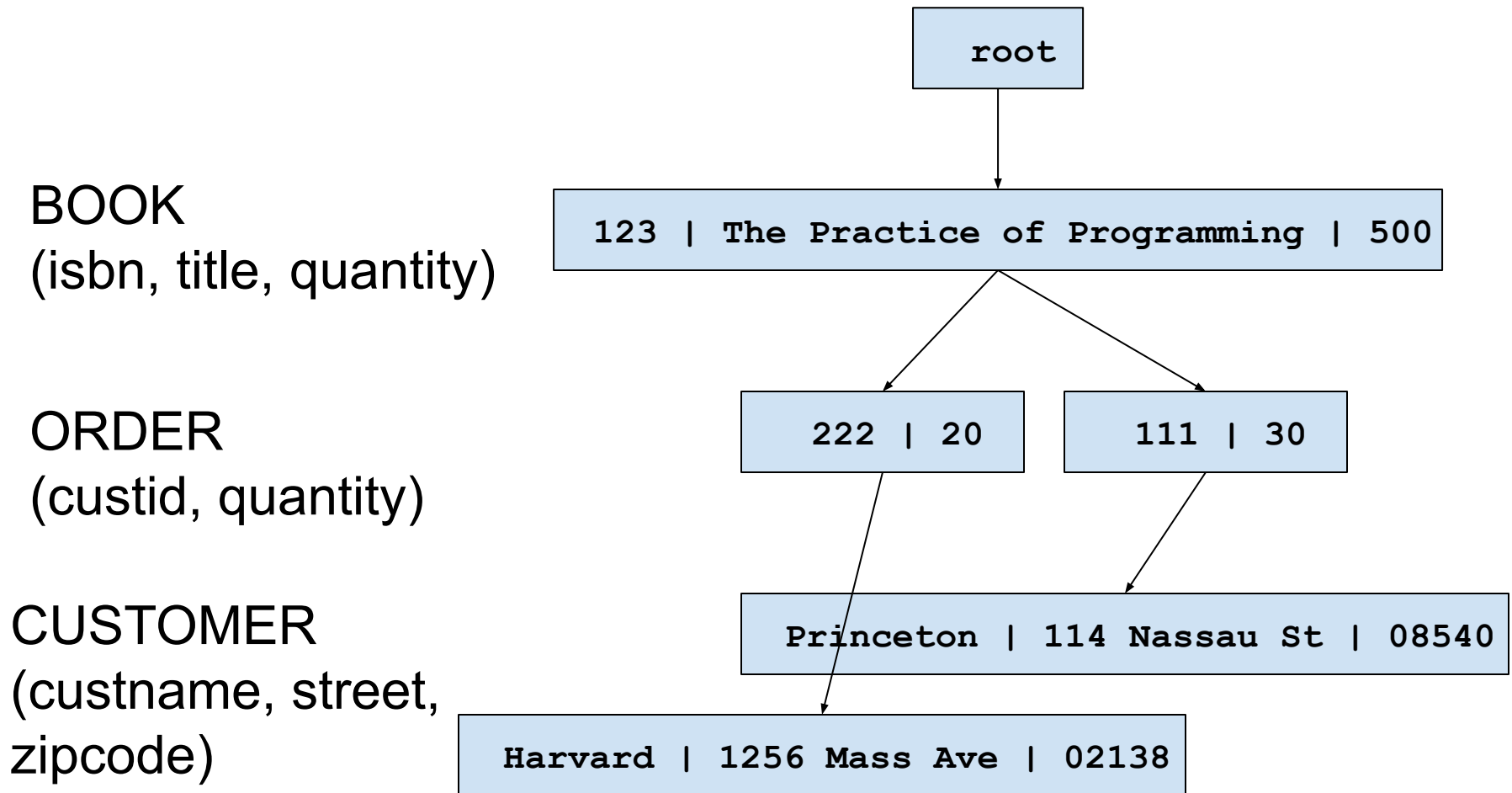
Before Relational DBs

Example Navigational DB



Before Relational DBs

Which customers purchased the book whose ISBN is 123?



Before Relational DBs

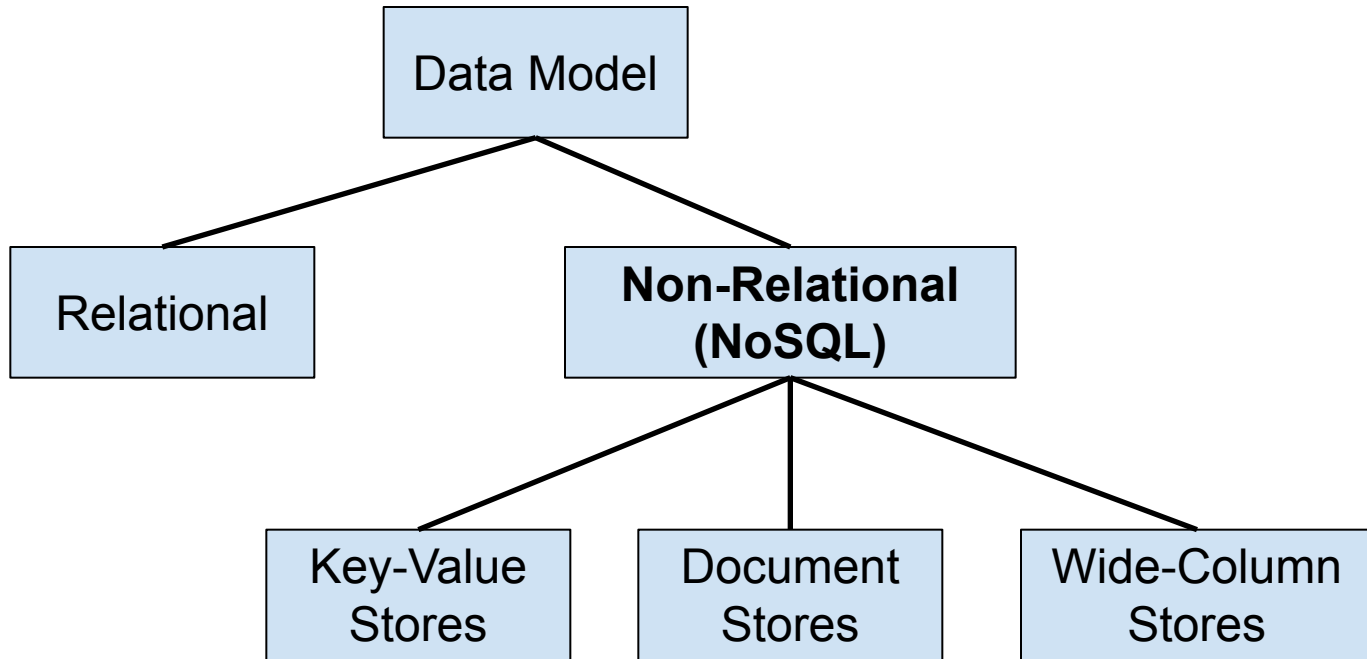
- Navigational DBs
 - Queries are **biased**
 - DB designer must anticipate queries
- Relational DBs
 - Queries are **unbiased**
 - DB designer need not anticipate queries
 - However, DB designer can create indices

Appendix 2: After Relational DBs

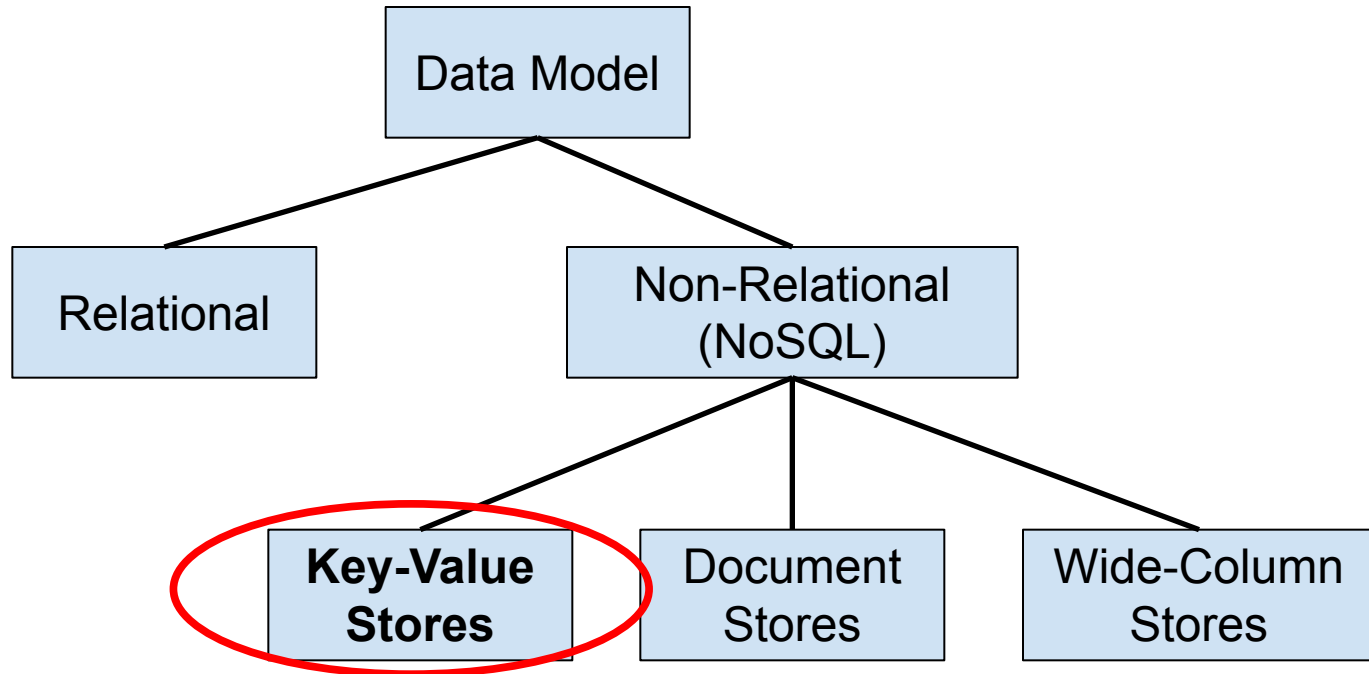
After Relational DBs

- For some apps:
 - Relational DBMSs are more complex than necessary
 - The relational DB model is a poor fit

After Relational DBs



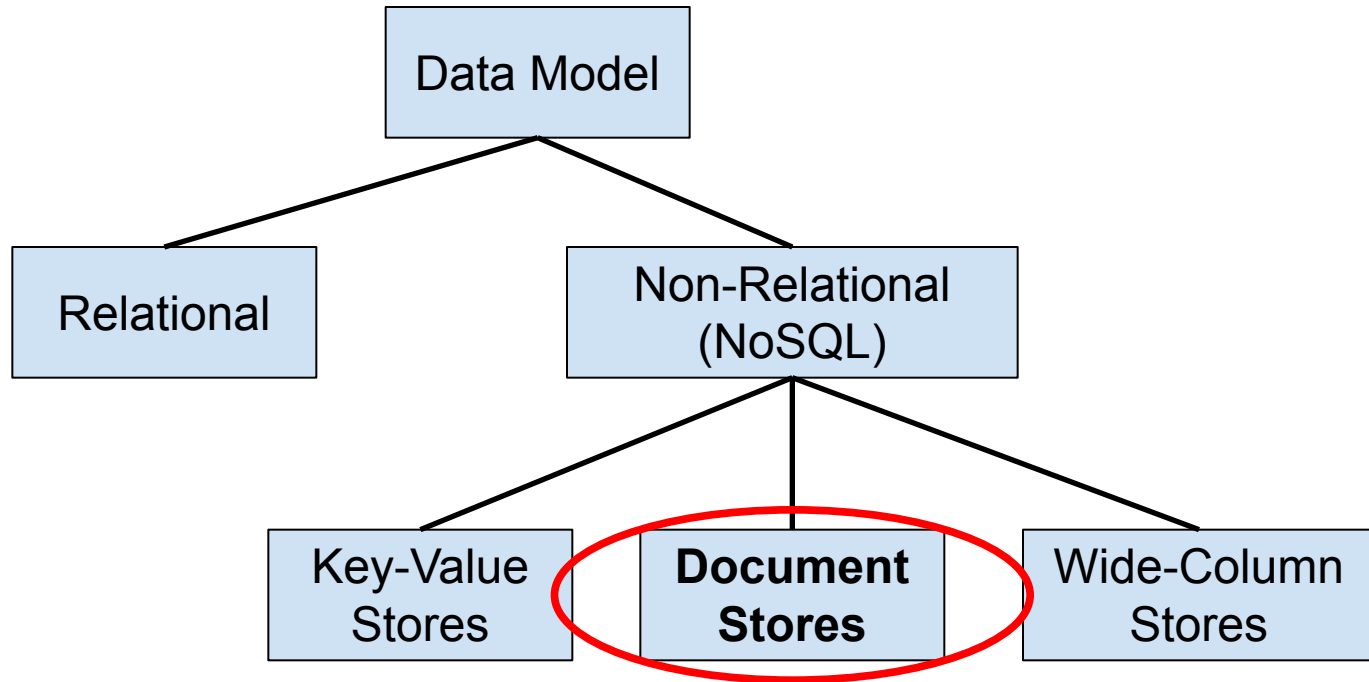
After Relational DBs



After Relational DBs

- ***Key-value store***
 - **Values:** arbitrary bytes
 - **Data structure:** key-value pairs
 - **Access:** by key
 - **Examples:** **Redis**, Memcached, Microsoft Azure Cosmos DB, Hazelcast, Ehcache

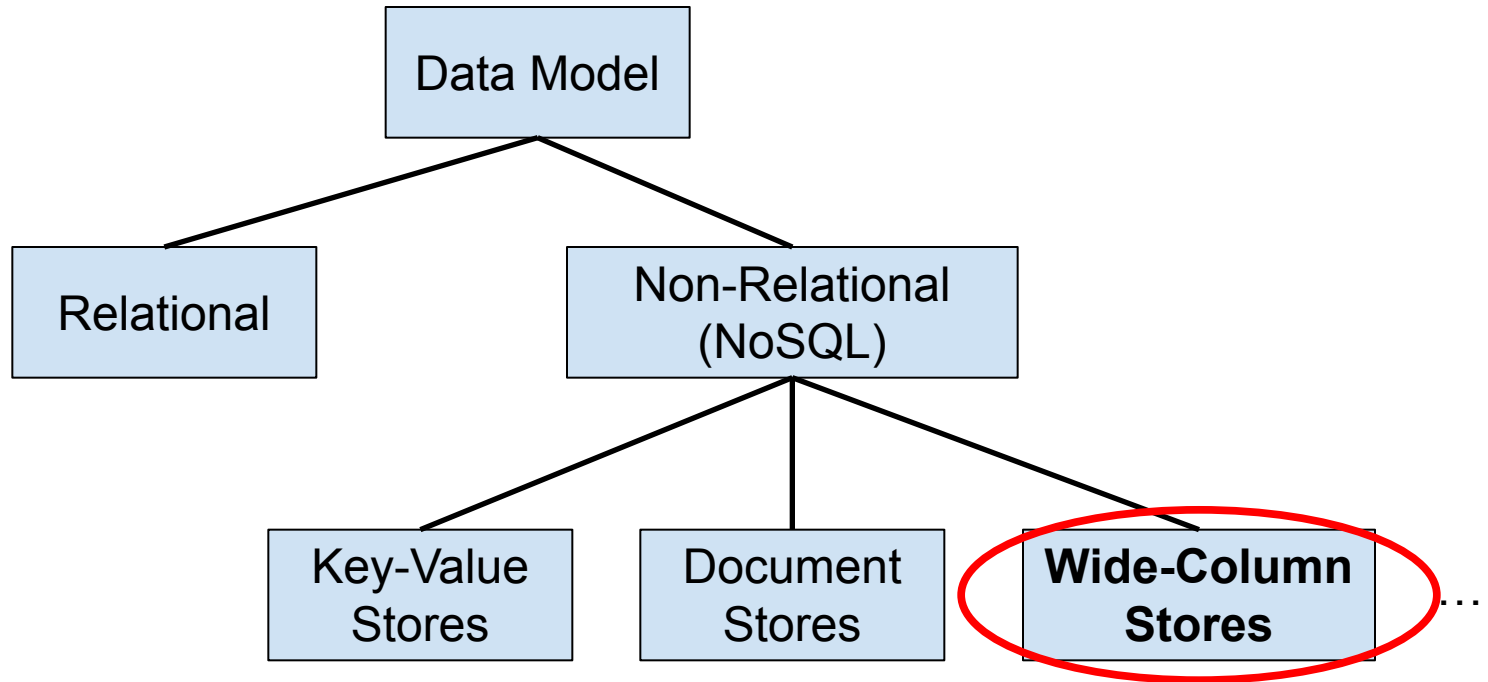
After Relational DBs



After Relational DBs

- ***Document store***
 - **Values:** documents with internal structure (e.g., JSON)
 - **Data structure:** key-value pairs
 - **Access:** by key or content
 - **Examples:** MongoDB, Amazon DynamoDB, Couchbase, CouchDB, MarkLogic

After Relational DBs



After Relational DBs

- ***Wide-column store***
 - **Values:** Arbitrary bytes
 - **Data structure:** Multidimensional associative array
 - **Examples:** Cassandra, HBase, Microsoft Azure Cosmos DB

After Relational DBs

Popular DBMSs, according to
<https://db-engines.com/en/ranking> as of Sept 2025:

Rank	DBMS	DB Data Model	Score
1	Oracle	Relational	1171
2	MySQL	Relational	892
3	Microsoft SQL Server	Relational	717
4	PostgreSQL	Relational	657
5	MongoDB	Document Store	381
6	Snowflake	Relational	190
7	Redis	Key-Value Store	145
...	...	...	...
11	SQLite	Relational	108