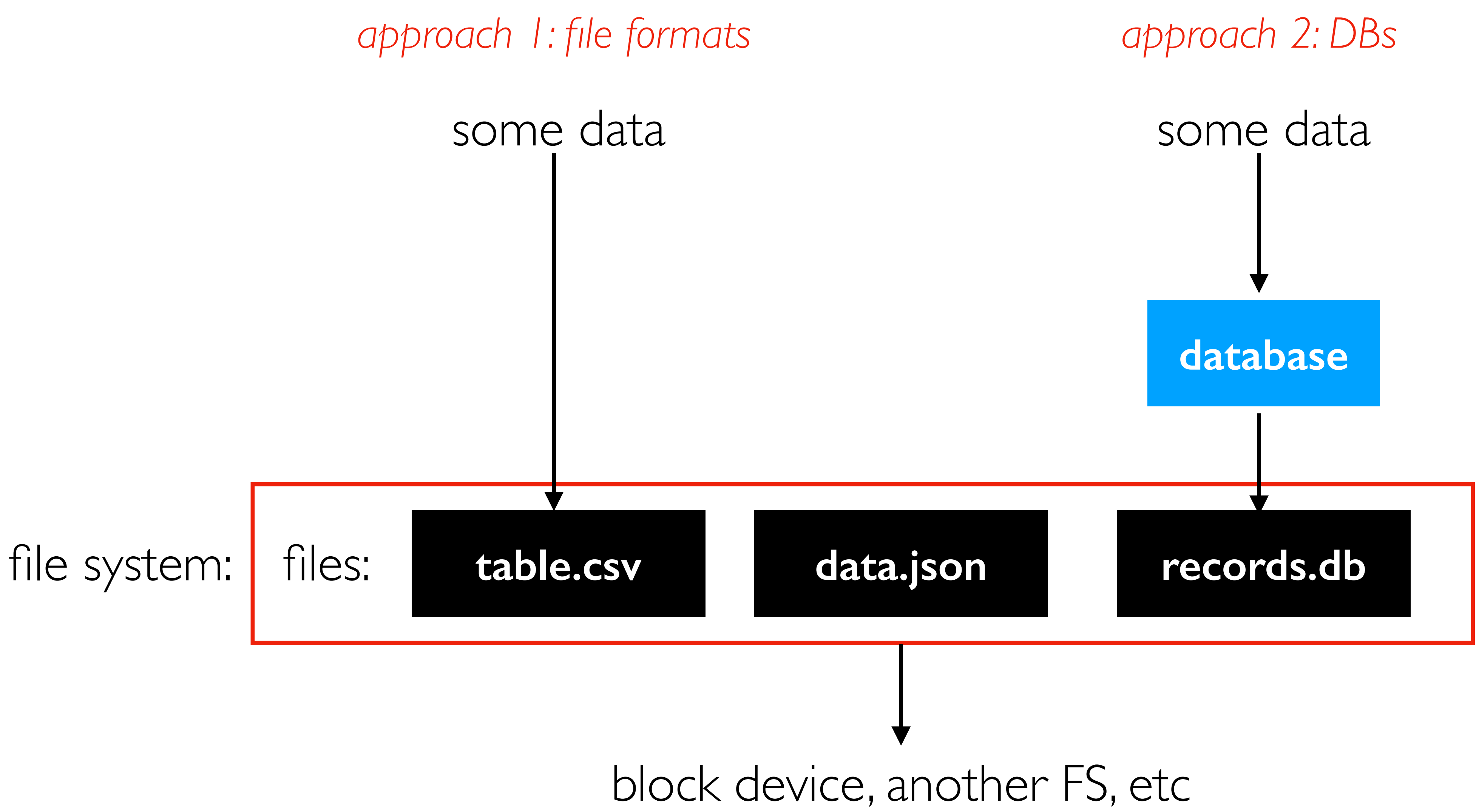
[544] Formats and Databases

Tyler Caraza-Harter

File systems let us give names to sequences of bytes (files) and hierarchically organize those files (via directories). We usually want some structure for those bytes.



Outline

File Formats

- row oriented vs. column oriented
- text vs. binary
- compression
- schemas

Databases

File Layout

Goals

- efficient input/output from storage (large reads/writes, sequential accesses)
- minimize parsing/deserialization computation time

Assumptions

- many file systems will try to map consecutive bytes of a file to consecutive blocks on a storage device
- need to clarify assumptions about how code will access the data (for example, one whole column? a row at a time?)

ACW00011604	17.1167	-61.7833	10.1	ST JOHNS COOLIDGE FLD		
ACW00011647	17.1333	-61.7833	19.2	ST JOHNS		
AE000041196	25.3330	55.5170	34.0	SHARJAH INTER. AIRP	GSN	41196
AEM00041194	25.2550	55.3640	10.4	DUBAI INTL		41194
AEM00041217	24.4330	54.6510	26.8	ABU DHABI INTL		41217
AEM00041218	24.2620	55.6090	264.9	AL AIN INTL		41218
AF000040930	35.3170	69.0170	3366.0	NORTH-SALANG	GSN	40930
AFM00040938	34.2100	62.2280	977.2	HERAT		40938
AFM00040948	34.5660	69.2120	1791.3	KABUL INTL		40948
AFM00040990	31.5000	65.8500	1010.0	KANDAHAR AIRPORT		40990
AG000060390	36.7167	3.2500	24.0	ALGER-DAR EL BEIDA	GSN	60390
AG000060590	30.5667	2.8667	397.0	EL-GOLEA	GSN	60590
AG000060611	28.0500	9.6331	561.0	IN-AMENAS	GSN	60611
AG000060680	22.8000	5.4331	1362.0	TAMANRASSET	GSN	60680
AGE00135039	35.7297	0.6500	50.0	ORAN-HOPITAL MILITAIRE		
AGE00147704	36.9700	7.7900	161.0	ANNABA-CAP DE GARDE		
AGE00147705	36.7800	3.0700	59.0	ALGIERS-VILLE/UNIVERSITE		
AGE00147706	36.8000	3.0300	344.0	ALGIERS-BOUZAREAH		

ghcnd-stations.txt

good: just read the one block containing the row

bad: need to read everything to access any one column

File Layout

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Assumptions

- many file systems will try to map consecutive bytes of a file to consecutive blocks on a storage device
- need to clarify assumptions about how code will access the data (for example, one whole column? a row at a time?)

Major access patterns

- transactions processing: *reading/changing a row (or few rows) as needed by an application* (note: "transaction" has other meanings for databases as well -- more later...)
- analytics processing: *computing over many rows for specific columns*

Row-Oriented vs. Column-Oriented Layout

col1	**col2**	**col3**
1	5	A
2	6	B
3	7	C
4	8	D

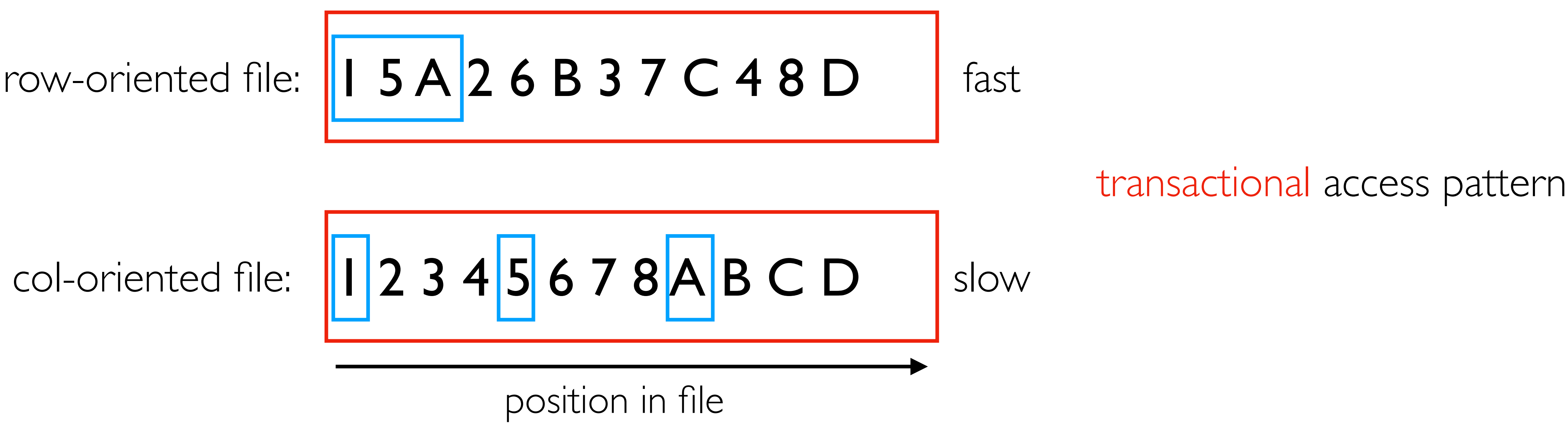
row-oriented file: 1 5 A 2 6 B 3 7 C 4 8 D

col-oriented file: 1 2 3 4 5 6 7 8 A B C D

position in file

Row-Oriented vs. Column-Oriented Layout

col1	col2	col3
1	5	A
2	6	B
3	7	C
4	8	D



Row-Oriented vs. Column-Oriented Layout

col1	**col2**	**col3**
1	5	A
2	6	B
3	7	C
4	8	D

row-oriented file: 1 5 A 2 6 B 3 7 C 4 8 D slow

analytics access pattern

col-oriented file: 1 2 3 4 5 6 7 8 A B C D fast

position in file

Row-Oriented vs. Column-Oriented Layout

col1	col2	col3
1	5	A
2	6	B
3	7	C
4	8	D

row-oriented file: 1 5 A 2 6 B 3 7 C 4 8 D CSV

Demo: CSV vs. parquet...

col-oriented file: 1 2 3 4 5 6 7 8 A B C D Parquet

position in file

Row-Oriented vs. Column-Oriented Layout

TopHat...

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Databases

Text vs. Binary

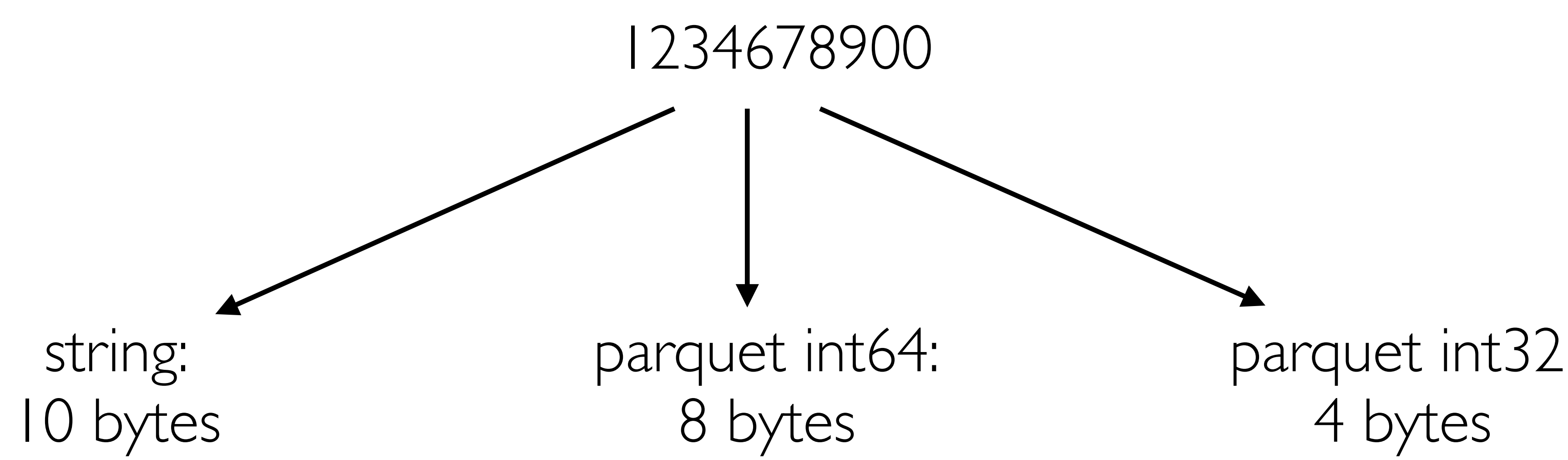
1234678900

string:
???? bytes

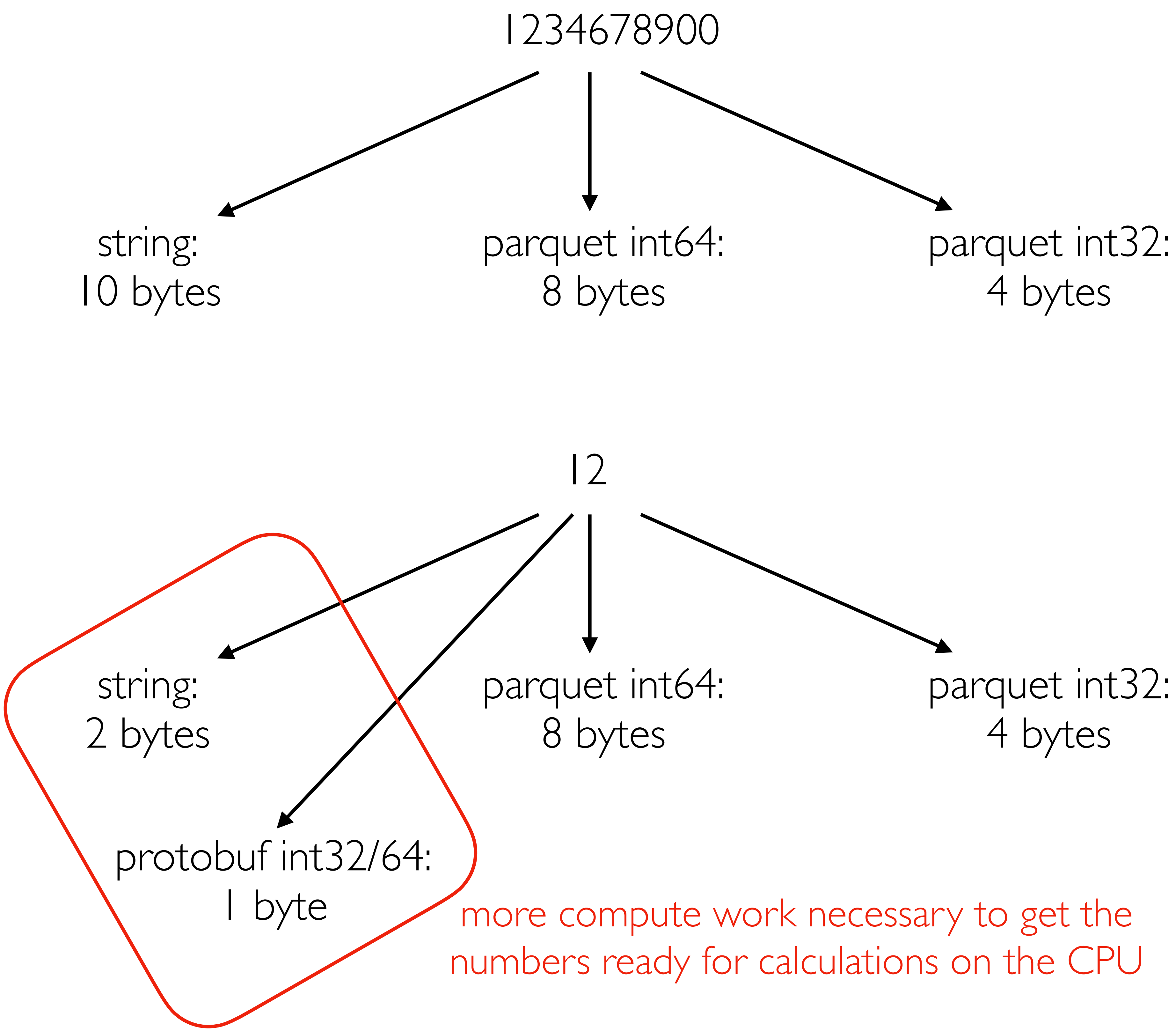
parquet int64:
???? bytes

parquet int32:
???? bytes

Text vs. Binary



Text vs. Binary



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Compression

Idea: avoid repeating yourself

- repetitive datasets are more compressible
- more compute time finding repetition => better compression ratio (original/compressed size)

Example: snappy compression (parquet default):

1210 W Dayton | St, Madison, WI | ; 1202 W Johnson |

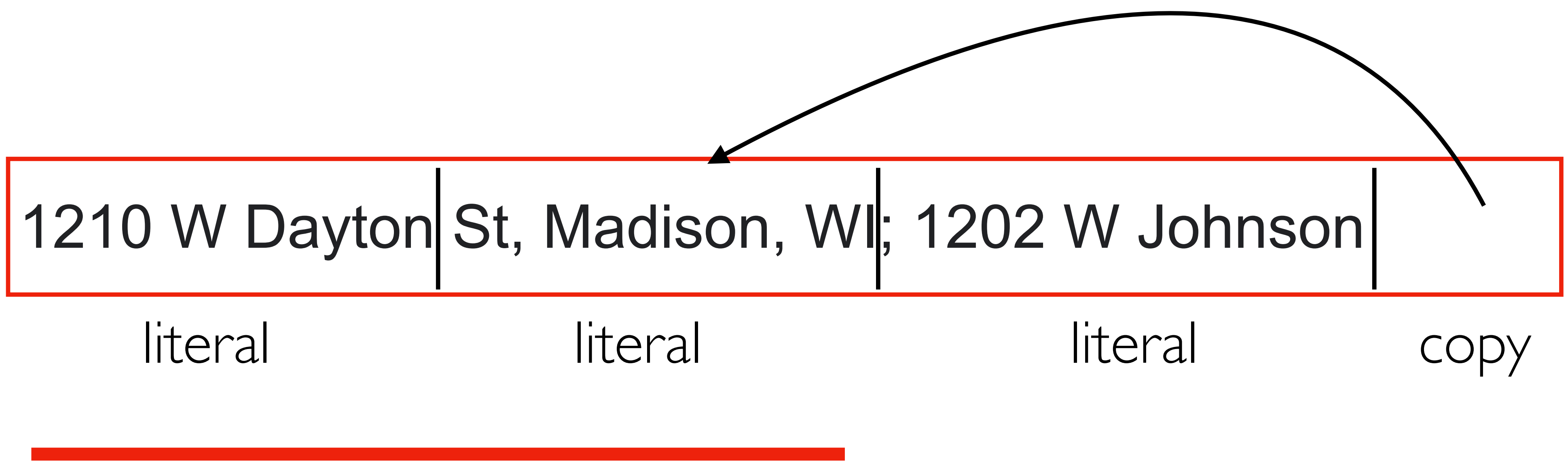
literal literal literal copy

"[Snappy] does not aim for maximum compression, or compatibility with any other compression library; instead, it aims for very high speeds and reasonable compression."

Snappy documentation

- https://github.com/google/snappy
- https://github.com/google/snappy/blob/main/format_description.txt

Challenge: Small Updates



can't just update this first address in isolation
(need to rewrite other parts of the file)

Compression Window/Block

"the current Snappy compressor works in 32 kB blocks and does not do matching across blocks"

row-oriented file: 1 5 A 2 6 B 3 7 C 4 8 D

col-oriented file: 1 2 3 4 5 6 7 8 A B C D

position in file

will compression generally work better for row-oriented formats or column-oriented formats?

Size vs. Compute Tradeoff

DEMO: `df.to_parquet("????.parquet", compression="????")`

- snappy vs. gzip
- measure compute time with %%time
- measure size with "ls -lh"

Time measurements

- wall-clock time: real-world time that passes
- CPU time: time spent running on CPU
- wall clock time > CPU time (maybe I/O time dominates)
- CPU time > wall clock time (maybe multiple cores used)

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Schemas

Schema: "A description of the structure of some data, including its fields and datatypes." -- Kleppmann

schema specified as a dict

CSVs:

- in the file, everything in text
- pd.read_csv("file.csv", dtype={"col1": str, "col2": int, ...}) # specify schema (annoying)
- pd.read_csv("file.csv", dtype=None) # infer schema (slow, error prone!)

parquet files:

- type specification is part of the file
- no need for costly schema inference

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Tables

tbl_purpose

id	loan_purpose
1	Home purchase
2	Home improvement
3	Refinancing

tbl_state

code	abbr	name
1	AL	Alabama
2	AK	Alaska
4	AZ	Arizona
5	AR	Arkansas
6	CA	California
8	CO	Colorado
9	CT	Connecticut
10	DE	Delaware
...	...	...

tbl_action

id	action_taken
1	Loan originated
2	Application approved but not accepted
3	Application denied by financial institution
4	Application withdrawn by applicant
5	File closed for incompleteness
6	Loan purchased by the institution
7	Preapproval request denied by financial
8	Preapproval request approved but not accepted

tbl_loan

id	purpose	action	state	amount	rate
1	2	1	2	20000	5.0
2	1	1	8	300000	3.0
3	1	4	10	450000	3.2
...	...	...	...	...	...

Databases store a collection of tables

- schemas define the columns/types for each table
- IDs/keys let us relate multiple tables
  (for example, the first loan is in Alaska)

Queries

tbl_purpose

id	loan_purpose
1	Home purchase
2	Home improvement
3	Refinancing

tbl_state

code	abbr	name
1	AL	Alabama
2	AK	Alaska
4	AZ	Arizona
5	AR	Arkansas
6	CA	California
8	CO	Colorado
9	CT	Connecticut
10	DE	Delaware
...	...	...

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Queries let us

- ask questions about the data
  (like, what is the name of the state with "WI" as an abbreviation)
- make changes to the data
  (like insert Puerto Rico as a row in tbl_state)

SQL

tbl_purpose

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1	Home purchase
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Structure Query Language (SQL)

- most popular/famous query language
- ask questions about the data: SELECT
- make changes to the data: INSERT, UPDATE, DELETE

SQL

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Structure Query Language (SQL)

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- ask questions about the data: SELECT
- make changes to the data: INSERT, UPDATE, DELETE

```
SELECT AVG(rate) FROM tbl_loan;
```

analytics (calculate over many/all rows, few colums)

```
SELECT amount, rate FROM tbl_loan WHERE id = 544;
INSERT INTO tbl_loan (...) VALUES (...);
```

transactions (working with whole row or few rows at a time)

Outline

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Databases

- tables and queries
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Data Base Management Systems

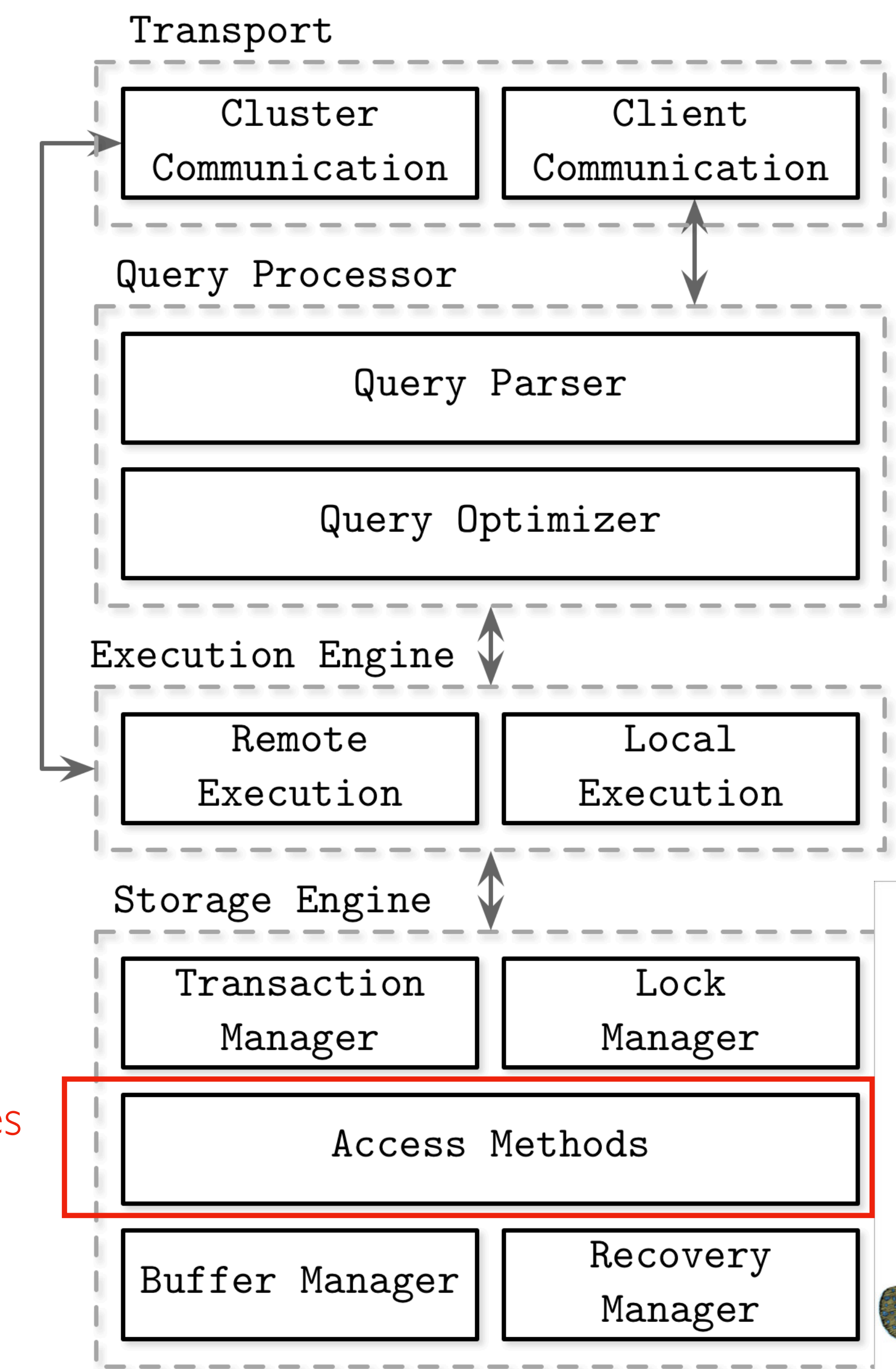
Architecture: *big picture of a system's components/subsystems*

Databases manage all the resources we've learned about:

- storage
- memory
- network
- compute

example database architecture:

storage structures
in files



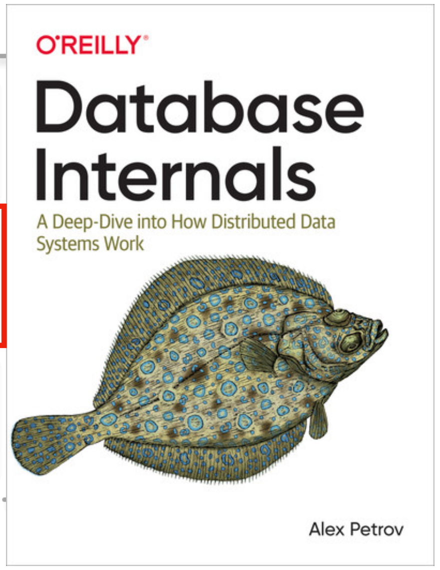


Figure 1-1. Architecture of a database management system
(Chapter 1 of Database Internals, by Petrov)

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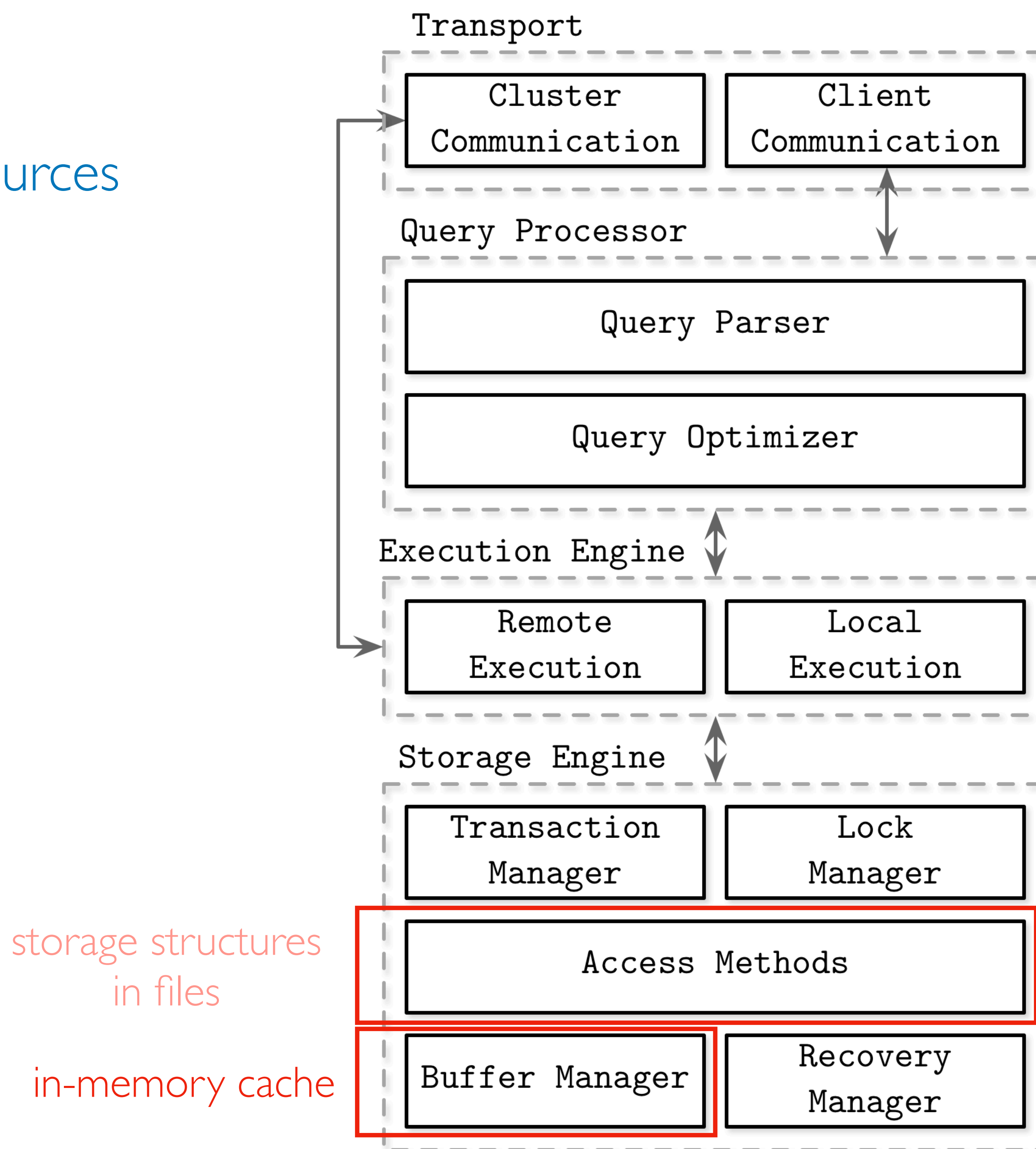

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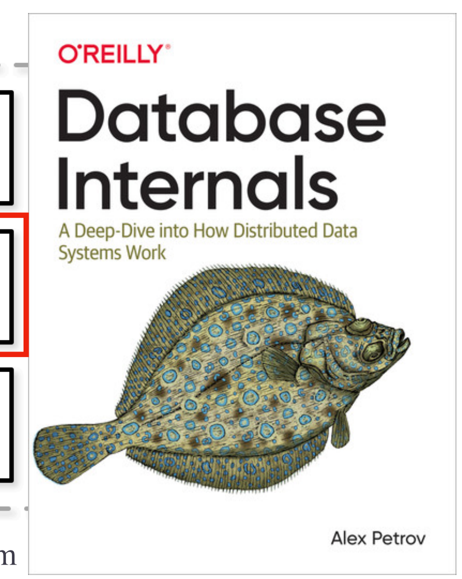

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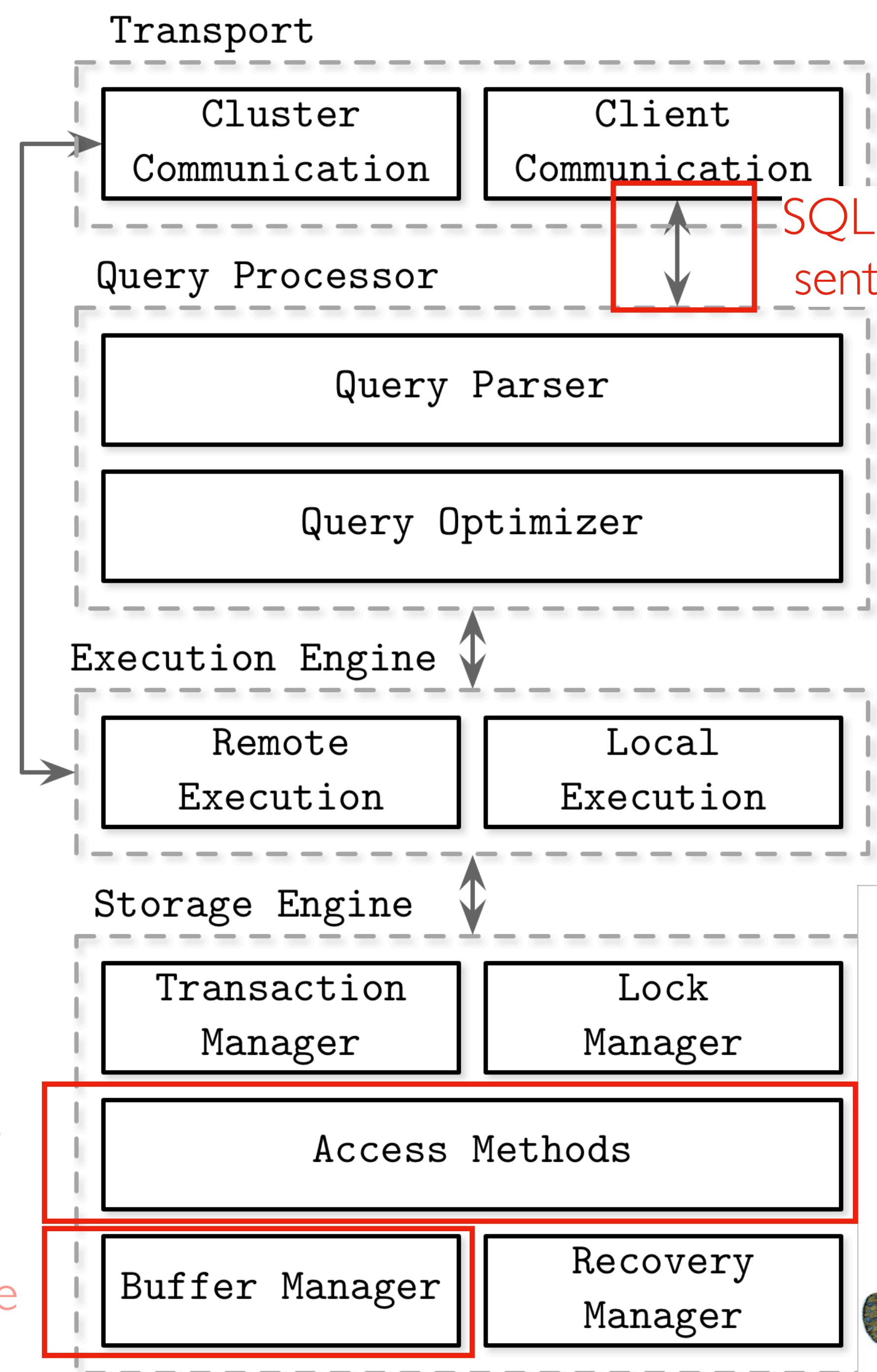

SQL queries/results sent over network

storage structures in files

in-memory cache

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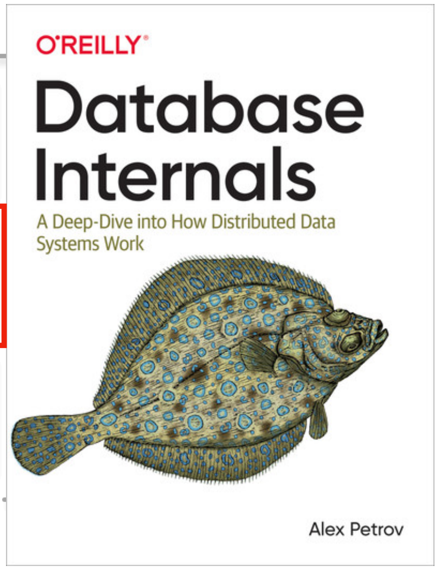

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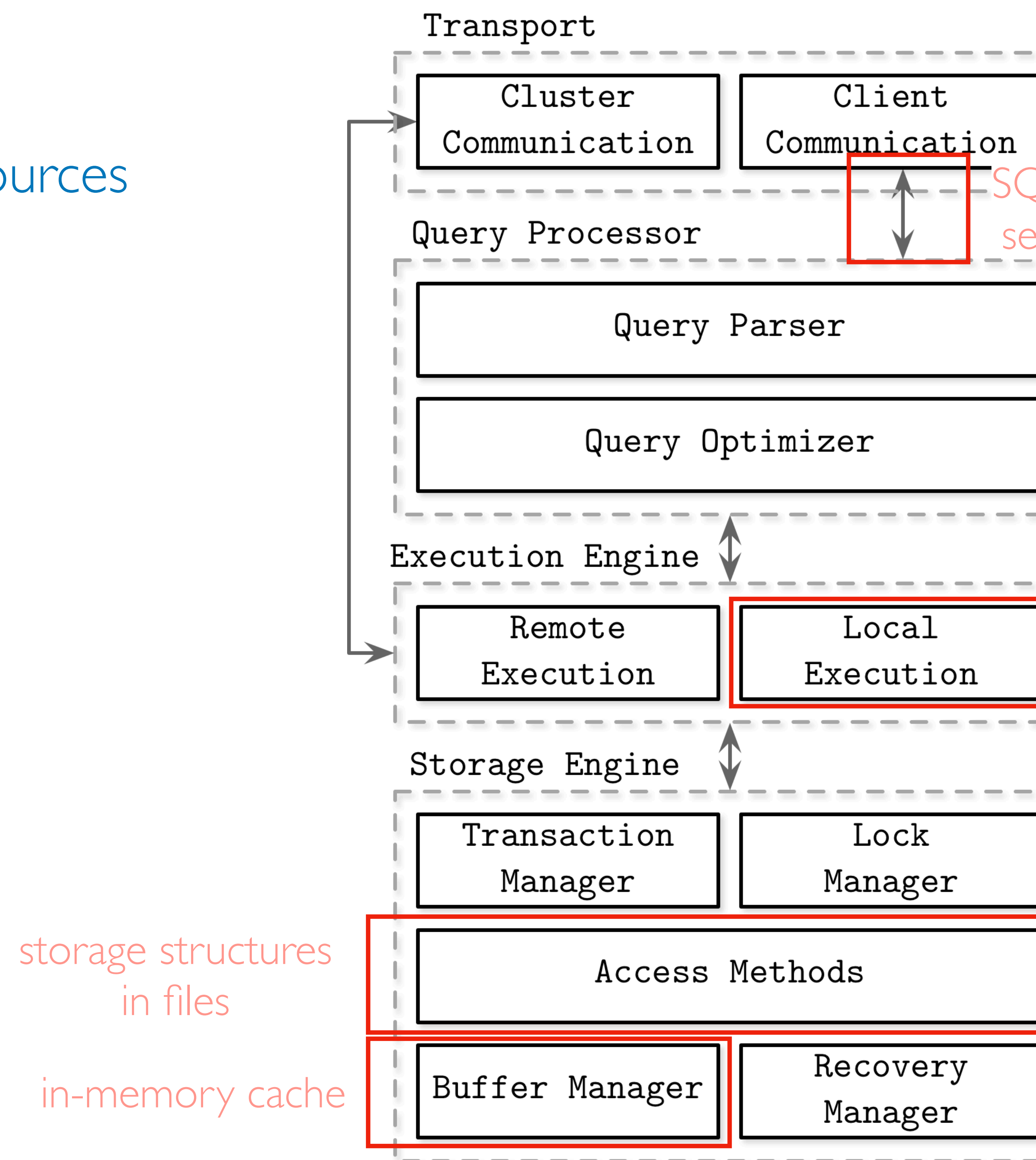

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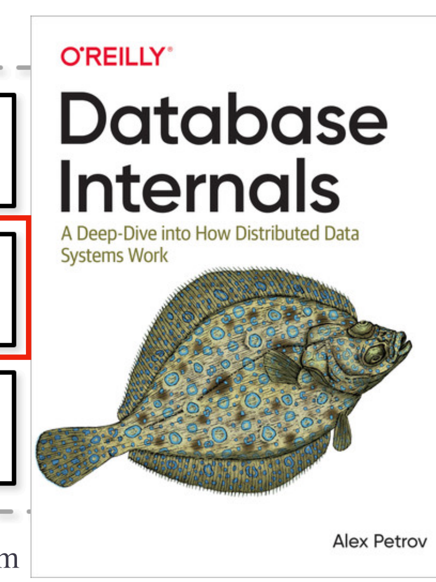
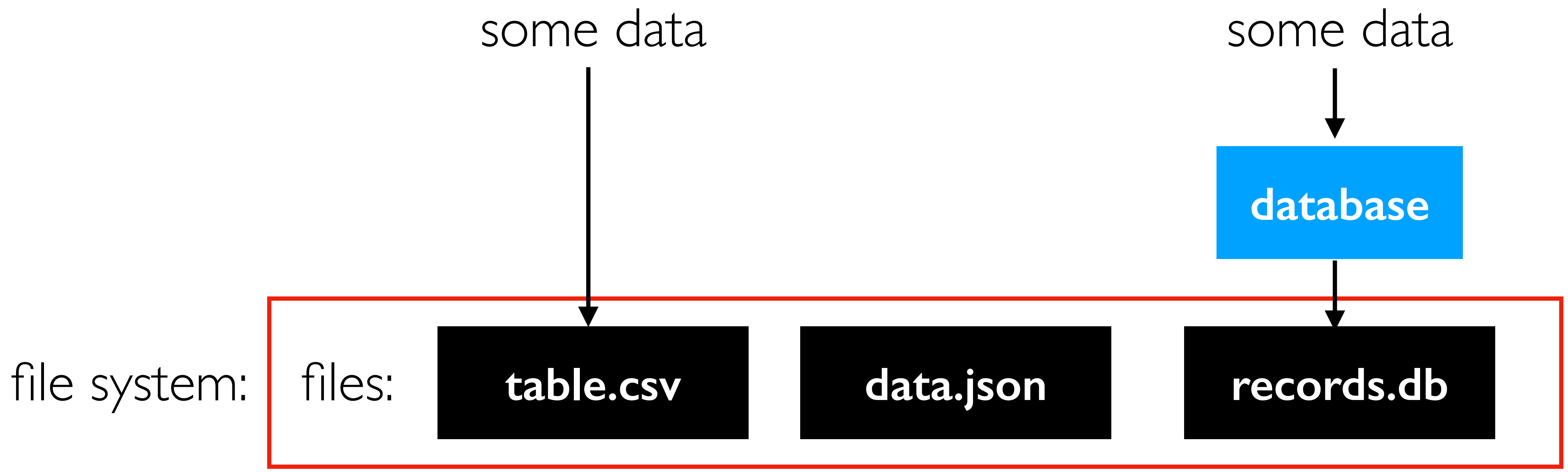
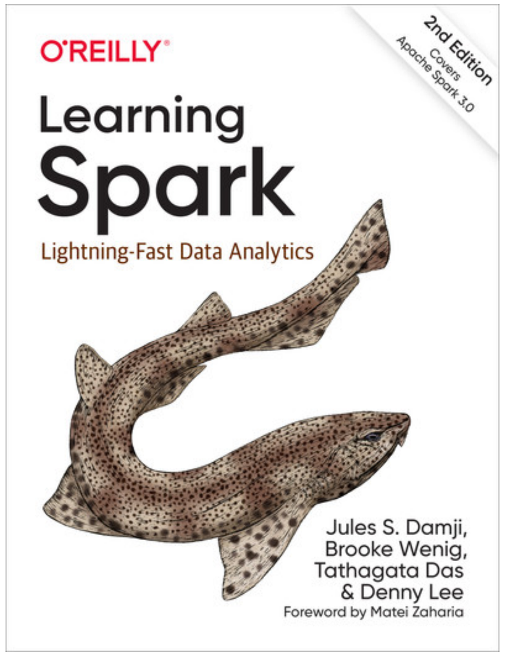


Files vs. Databases (storage+compute coupling)



Databases pros/cons (relative to files):

- "[databases] *tightly couple* *their internal layout of the data and indexes in on-disk files with their highly optimized query processing engines, thus providing very fast computations on the stored data...*"
- "*Databases store data in complex (often proprietary) formats that are typically highly optimized for only that database's SQL processing engine to read. This means other processing tools, like machine learning and deep learning systems, cannot efficiently access the data (except by inefficiently reading all the data from the database).*"



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Transactions vs. Analytics

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analytics (calculate over many/all rows, few colums)

```
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INSERT INTO tbl_loan (...) VALUES (...);
```

transactions (working with whole row or few rows at a time)

SQL (as a language) works great for both transactions and analytics.

Problem: it's hard for a single database (SQL or otherwise) to be efficient at both.

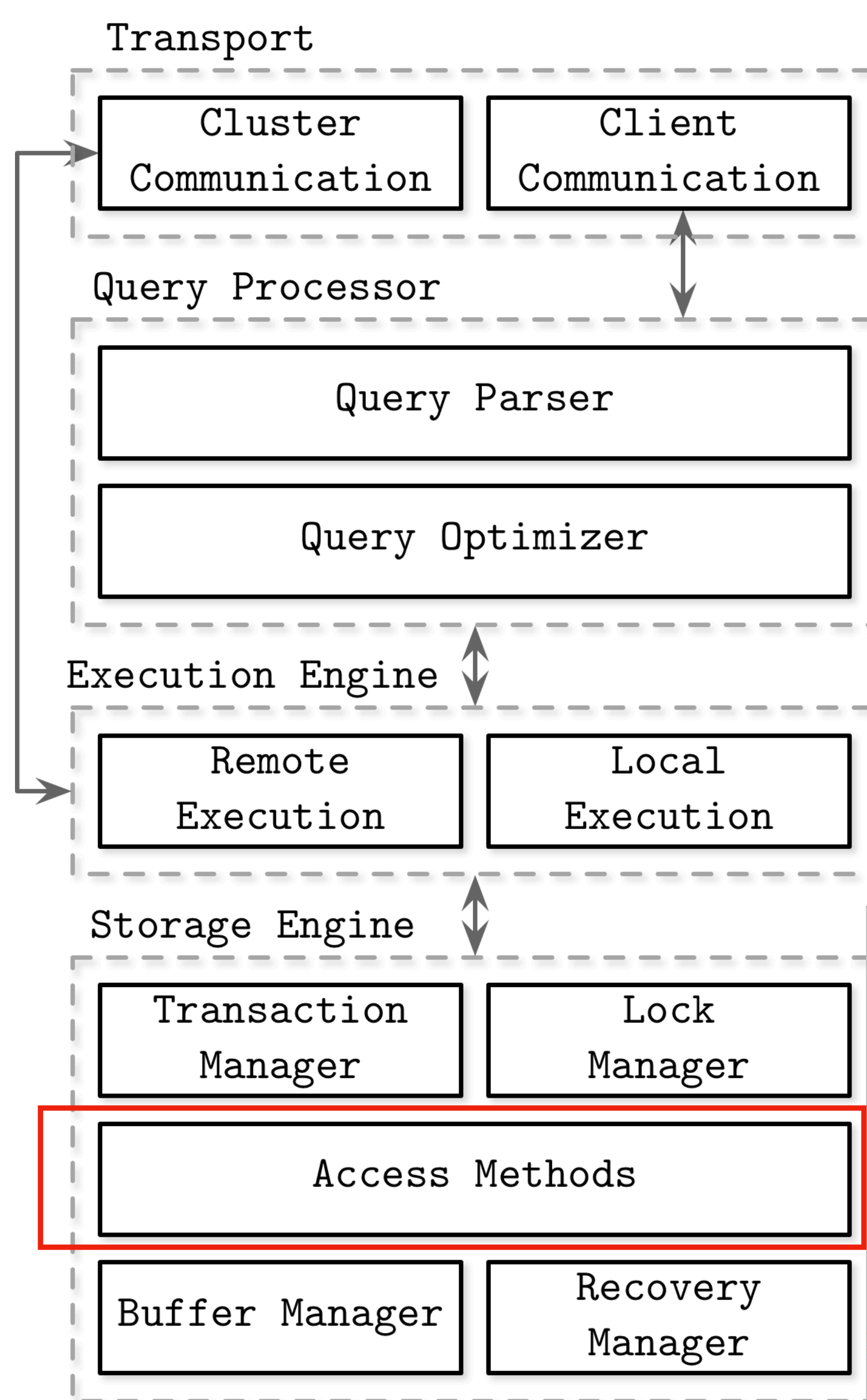
Main database types:

- OLTP (online transactions processing)
- OLAP (online analytics processing)

"The meaning of online in OLAP is *unclear*, it probably refers to the fact that queries are not just for predefined reports, but that analysts use the OLAP system interactively for explorative queries." ~ Kleppmann.

Transactions vs. Analytics

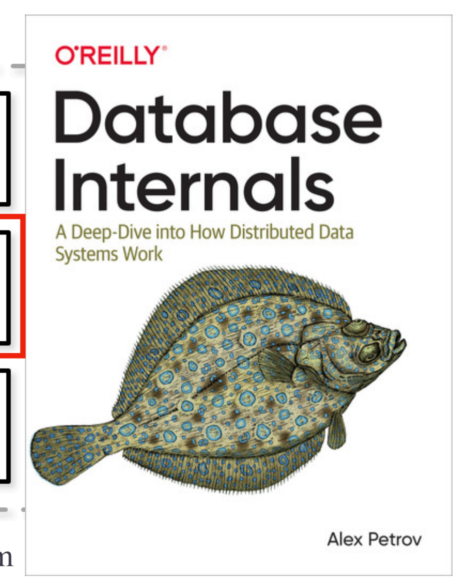
example database architecture:



Typical storage design

OLTP: *row oriented data layout*

OLAP: *col oriented data layout*



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What if you need transactions AND analytics?

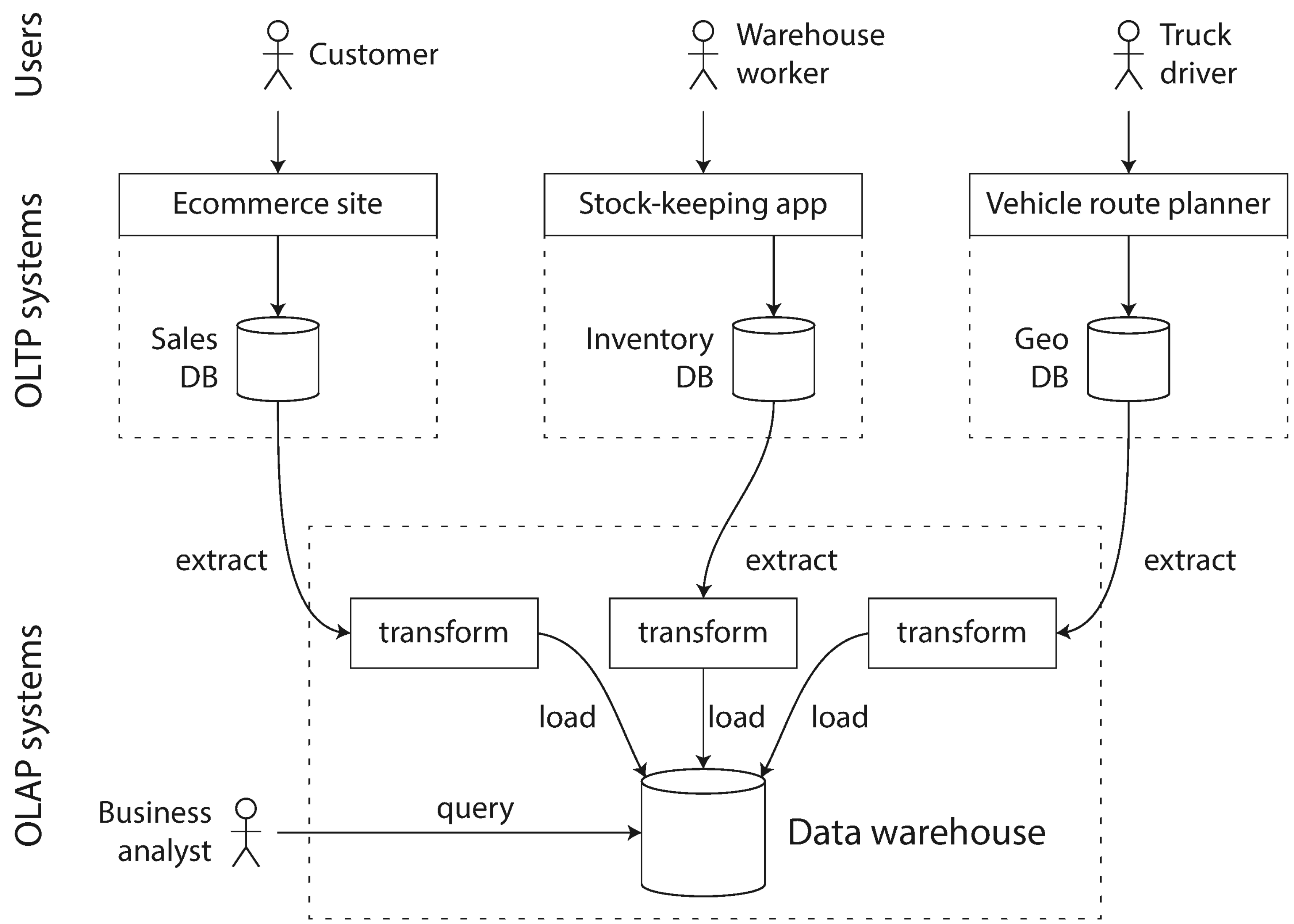
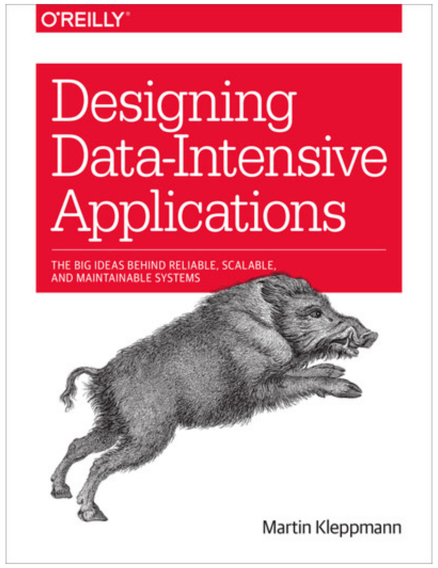


Figure 3-8. Simplified outline of ETL into a data warehouse.
(Chapter 3 of Data-Intensive Applications, by Kleppmann)



Vocab

- Data warehouse: *the OLAP database where we combine data from many sources*
- ETL: *extract-transform-load (process for getting data out of OLTP DBs and into OLAP DB)*

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Data Modeling

Data modeling: deciding how to represent something in an underlying system.

Low-level example (protobufs): how will we represent numbers as bytes being sent over a network?

Traditional Databases: how will we represent things/people/events/etc as rows in tables?

option 1:

tbl_orders

name	book	amount	county	state
Tyler Harter	Designing Data-Intensive Applications	23	Dane	WI
Tyler Harter	Learning Spark	38	Dane	WI
Tyler Harter	Cassandra: The Definitive Guide	39	Dane	WI

Keys and Normalization

SQL keys:

- primary key: uniquely identify a row ("id" in tbl_counties)
- foreign key: reference a primary key ("county_id" in tbl_orders)

In database theory we would say option 2 is "more normalized" (note: there are well-defined normalization levels with formal rules -- we won't get into that in 544)

option 1:

tbl_orders

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option 2:

tbl_orders

name	book	amount	county_id
Tyler Harter	Designing Data-Intensive Applications	23	1
Tyler Harter	Learning Spark	38	1
Tyler Harter	Cassandra: The Definitive Guide	39	1

tbl_counties

id	county	state
1	Dane	WI
2	Milwaukee	WI
3	La Crosse	WI

Normalization Tradeoffs

Benefits of more normalization:

- avoid inconsistencies
- changes in the real world correspond to fewer changes in the DB
- often save space

Downsides of more normalization:

- queries are sometimes slower
- historical record keeping (for example, if you need to reproduce an invoice prior to somebody's name change, you might want the name at time of purchase)

tbl_orders

name	book	amount	county_id
Tyler Harter	Designing Data-Intensive Applications	23	1
Tyler Harter	Learning Spark	38	1
Tyler Caraza-Harter	Cassandra: The Definitive Guide	39	1

tbl_counties

id	county	state_id
1	Dane	55
2	Milwaukee	55
3	La Crosse	55

tbl_states

id	state
55	WI
...	...

Demos

MySQL...