

The why of databases

Numbers every programmer should know

Task	Timing (ns)	Timing (μs)
L1 cache reference	0.5	
L2 cache reference	7	
Main memory reference	100	0.1
Random seek SSD	150,000	150
Read 1 MB sequentially from memory	250,000	250
Read 1 MB sequentially from SSD	1,000,000	1,000
Disk seek	10,000,000	10,000
Read 1 MB sequentially from disk	20,000,000	20,000
Send packet CA->Netherlands->CA	150,000,000	150,000

From [jboner/latency.txt](#) & [sirupsen/napkin-math](#)

Jeff Dean's original talk

Implications for big data

Lets imagine we have a 10 GB flat data file and that we want to select certain rows based on a particular criteria. This requires a sequential read across the entire data set.

If we can store the file in memory:

- $10 \text{ } GB \times (250 \text{ } \mu\text{s}/1 \text{ } MB) = 2.5 \text{ seconds}$

If we have to access the file from SSD:

- $10 \text{ } GB \times (1 \text{ } ms/1 \text{ } MB) = 10 \text{ seconds}$

If we have to access the file from disk:

- $10 \text{ } GB \times (20 \text{ } ms/1 \text{ } MB) = 200 \text{ seconds}$

This is just for reading sequential data, if we make any modifications (writing) or the data is

Blocks

Cost: Disk << SSD <<< Memory

Speed: Disk <<< SSD << Memory

So usually possible to grow our disk storage to accommodate our data. However, memory is usually the limiting resource, and if we can't fit everything into memory?

Create blocks - group related data (i.e. rows) and read in multiple rows at a time. Optimal size will depend on the task and the properties of the disk.

Linear vs Binary Search

Even with blocks, any kind of querying / subsetting of rows requires a linear search, which requires $O(N)$ accesses where N is the number of blocks.

We can do much better if we are careful about how we structure our data, specifically sorting some or all of the columns.

- Sorting is expensive, $O(M \log N)$, but it only needs to be done once.
- After sorting, we can use a binary search for any subsetting tasks ($O(\log N)$).
- These "sorted" columns are known as indexes.
- Indexes require additional storage, but usually small enough to be kept in memory while blocks stay on disk.

Databases

SQL

Structures Query Language is a special purpose language for interacting with (querying and modifying) these indexed tabular data structures.

- ANSI Standard but with dialect divergence (MySql, Postgre, sqlite, etc.)
- This functionality maps very closely (but not exactly) with the data manipulation verbs present in dplyr.
- We will see this mapping in more detail next time.
- SQL is likely to be a foundational skill if you go into industry - learn it and put it on your CV

R & databases - the DBI package

Low level package for interfacing R with Database management systems (DBMS) that provides a common interface to achieve the following functionality:

- connect/disconnect from DB
- create and execute statements in the DB
- extract results/output from statements
- error/exception handling
- information (meta-data) from database objects
- transaction management (optional)

RSQLite

Provides the implementation necessary to use DBI to interface with an SQLite database.

```
library(RSQLite)
```

this package also loads the necessary DBI functions as well.

Once loaded we can create a connection to our database,

```
con = dbConnect(RSQLite::SQLite(), ":memory:")
str(con)

## Formal class 'SQLiteConnection' [package "RSQLite"] with 5 slots
##  ..@ Id                  :<externalptr>
##  ..@ dbname               : chr ":memory:"
##  ..@ loadable.extensions: logi TRUE
##  ..@ flags                : int 6
##  ..@ vfs                 : chr ""
```

Example Table

```
employees = data.frame(  
  name = c("Alice", "Bob", "Carol", "Dave", "Eve", "Frank"),  
  email = c("alice@company.com", "bob@company.com",  
           "carol@company.com", "dave@company.com",  
           "eve@company.com", "frank@comany.com"),  
  salary = c(52000, 40000, 30000, 33000, 44000, 37000),  
  dept = c("Accounting", "Accounting", "Sales",  
          "Accounting", "Sales", "Sales"),  
)
```

```
dbWriteTable(con, name = "employees", value = employees)  
## [1] TRUE  
  
dbListTables(con)  
## [1] "employees"
```

Removing Tables

```
dbWriteTable(con, "employs", employees)
## [1] TRUE

dbListTables(con)
## [1] "employees" "employs"

dbRemoveTable(con, "employs")
## [1] TRUE

dbListTables(con)
## [1] "employees"
```

Querying Tables

```
(res = dbSendQuery(con, "SELECT * FROM employees"))
## <SQLiteResult>
##   SQL  SELECT * FROM employees
##   ROWS Fetched: 0 [incomplete]
##           Changed: 0

dbFetch(res)
##      name            email salary      dept
## 1 Alice alice@company.com  52000 Accounting
## 2 Bob   bob@company.com  40000 Accounting
## 3 Carol carol@company.com  30000     Sales
## 4 Dave  dave@company.com  33000 Accounting
## 5 Eve   eve@company.com  44000     Sales
## 6 Frank frank@comany.com  37000     Sales

dbClearResult(res)
## [1] TRUE
```

Creating empty tables

```
dbCreateTable(con, "iris", iris)

(res = dbSendQuery(con, "select * from iris"))
## <SQLiteResult>
##   SQL  select * from iris
##   ROWS Fetched: 0 [complete]
##       Changed: 0

dbFetch(res)
## [1] Sepal.Length Sepal.Width  Petal.Length Petal.Width  Species
## <0 rows> (or 0-length row.names)
```

```
dbFetch(res) %>% as_tibble()
## # A tibble: 0 × 5
## # ... with 5 variables: Sepal.Length <dbl>, Sepal.Width <dbl>, Petal.Length <dbl>,
## #   Petal.Width <dbl>, Species <chr>

dbClearResult(res)
```

Adding to tables

```
dbAppendTable(con, name = "iris", value = iris)
## [1] 150
## Warning message:
## Factors converted to character

(res = dbSendQuery(con, "select * from iris"))
## <SQLiteResult>
##   SQL select * from iris
##   ROWS Fetched: 0 [incomplete]
##       Changed: 0

dbFetch(res) %>% as_tibble()
## # A tibble: 150 x 5
##   Sepal.Length Sepal.Width Petal.Length Petal.Width Species
##       <dbl>       <dbl>       <dbl>       <dbl>   <chr>
## 1         5.1        3.5        1.4        0.2  setosa
## 2         4.9        3.0        1.4        0.2  setosa
## 3         4.7        3.2        1.3        0.2  setosa
## 4         4.6        3.1        1.5        0.2  setosa
## 5         5.0        3.6        1.4        0.2  setosa
## 6         5.4        3.9        1.7        0.4  setosa
## 7         4.6        3.4        1.4        0.3  setosa
## 8         5.0        3.4        1.5        0.2  setosa
```

Ephemeral results

```
res
## <SQLiteResult>
##   SQL  select * from iris
##   ROWS Fetched: 150 [complete]
##           Changed: 0

dbFetch(res) %>% as_tibble()
## # A tibble: 0 x 5
## # ... with 5 variables: Sepal.Length <dbl>, Sepal.Width <dbl>, Petal.Length <dbl>,
## #   Species <chr>

dbClearResult(res)
```

SQL Queries

Connecting

```
cr173@trig2 [class_2021_10_19]$ sqlite3 employees.sqlite
SQLite version 3.34.1 2021-01-20 14:10:07
Enter ".help" for usage hints.
Connected to a transient in-memory database.
Use ".open FILENAME" to reopen on a persistent database.
sqlite>
```

Table information

The following is specific to SQLite

```
sqlite> .tables
```

```
employees
```

```
sqlite> .schema employees
```

```
CREATE TABLE `employees` (
    `name` TEXT,
    `email` TEXT,
    `salary` REAL,
    `dept` TEXT
);
```

```
sqlite> .indices employees
```

SELECT Statements

```
sqlite> SELECT * FROM employees;
```

```
Alice|alice@company.com|52000.0|Accounting  
Bob|bob@company.com|40000.0|Accounting  
Carol|carol@company.com|30000.0|Sales  
Dave|dave@company.com|33000.0|Accounting  
Eve|eve@company.com|44000.0|Sales  
Frank|frank@comany.com|37000.0|Sales
```

Pretty Output

We can make this table output a little nicer with some additional SQLite options:

```
sqlite> .mode column  
sqlite> .headers on
```

```
sqlite> SELECT * FROM employees;
```

name	email	salary	dept
Alice	alice@company.com	52000.0	Accounting
Bob	bob@company.com	40000.0	Accounting
Carol	carol@company.com	30000.0	Sales
Dave	dave@company.com	33000.0	Accounting
Eve	eve@company.com	44000.0	Sales
Frank	frank@comany.com	37000.0	Sales

select using SELECT

We can subset for certain columns (and rename them) using SELECT

```
sqlite> SELECT name AS first_name, salary FROM employees;
```

first_name	salary
Alice	52000.0
Bob	40000.0
Carol	30000.0
Dave	33000.0
Eve	44000.0
Frank	37000.0

arrange using ORDER BY

We can sort our results by adding ORDER BY to our SELECT statement

```
sqlite> SELECT name AS first_name, salary FROM employees ORDER BY salary;
```

first_name	salary
Carol	30000.0
Dave	33000.0
Frank	37000.0
Bob	40000.0
Eve	44000.0
Alice	52000.0

We can sort in the opposite order by adding DESC

```
SELECT name AS first_name, salary FROM employees ORDER BY salary DESC;
```

first_name	salary
Alice	52000.0
Eve	44000.0
Bob	40000.0
Frank	37000.0
Dave	33000.0
Carol	30000.0

filter via WHERE

We can filter rows by adding WHERE to our statements

```
sqlite> SELECT * FROM employees WHERE salary < 40000;
```

name	email	salary	dept
Carol	carol@company.com	30000.0	Sales
Dave	dave@company.com	33000.0	Accounting
Frank	frank@comany.com	37000.0	Sales

```
sqlite> SELECT * FROM employees WHERE salary < 40000 AND dept = "Sales";
```

name	email	salary	dept
Carol	carol@company.com	30000.0	Sales
Frank	frank@comany.com	37000.0	Sales

group_by via GROUP BY

We can create groups for the purpose of summarizing using GROUP BY. As with dplyr it is not terribly useful by itself.

```
sqlite> SELECT * FROM employees GROUP BY dept;
```

name	email	salary	dept
Dave	dave@company.com	33000.0	Accounting
Frank	frank@comany.com	37000.0	Sales

```
sqlite> SELECT dept, COUNT(*) AS n FROM employees GROUP BY dept;
```

dept	n
Accounting	3
Sales	3

head via LIMIT

We can limit the number of rows we get by using `LIMIT` and order results with `ORDER BY` with or without `DESC`

```
sqlite> SELECT * FROM employees LIMIT 3;
```

name	email	salary	dept
Alice	alice@company.com	52000.0	Accounting
Bob	bob@company.com	40000.0	Accounting
Carol	carol@company.com	30000.0	Sales

```
sqlite> SELECT * FROM employees ORDER BY name DESC LIMIT 3;
```

name	email	salary	dept
Frank	frank@comany.com	37000.0	Sales
Eve	eve@company.com	44000.0	Sales
Dave	dave@company.com	33000.0	Accounting

Exercise 1

Using sqlite calculate the following quantities,

1. The total costs in payroll for this company
2. The average salary within each department

Import CSV files

```
sqlite> .mode csv  
sqlite> .import phone.csv phone  
sqlite> .tables
```

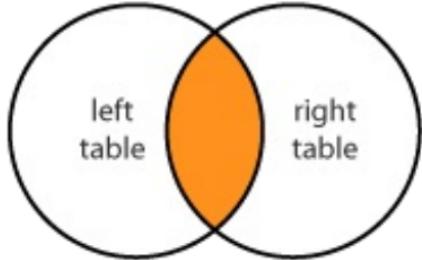
```
employees  phone
```

```
sqlite> .mode column  
sqlite> SELECT * FROM phone;
```

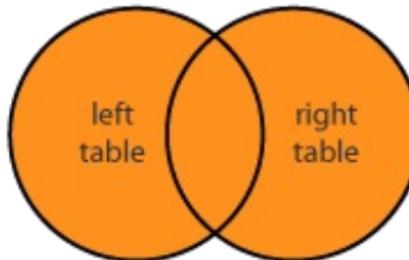
name	phone
Bob	919 555-1111
Carol	919 555-2222
Eve	919 555-3333
Frank	919 555-4444

SQL Joins

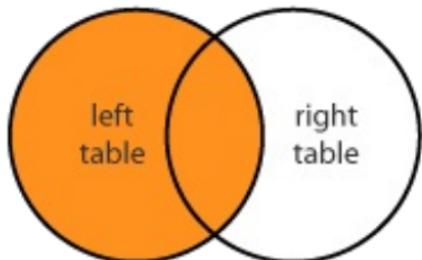
INNER JOIN



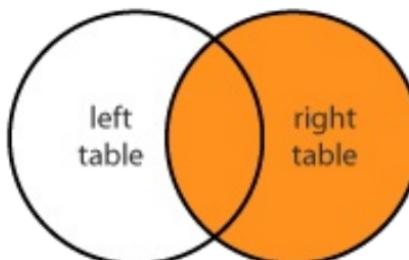
FULL JOIN



LEFT JOIN



RIGHT JOIN



1
2
3

INNER
JOIN

A
B
C

=

2
3
B

A

1
2
3

LEFT
JOIN

A
B
C

=

1
2
3

A

B

1
2
3

RIGHT
JOIN

A
B
C

=

2
3
A
B
C

A

B

C

1
2
3

«FULL»
JOIN

A
B
C

=

1
2
3

A

B

C

1
2
3

CROSS
JOIN

A
B
C

=

1	A
1	B
1	C
2	A
2	B
2	C
3	A
3	B
3	C

Joins - Default

By default SQLite uses a `CROSS JOIN` which is not terribly useful most of the time (similar to R's `expand.grid()`)

```
sqlite> SELECT * FROM employees JOIN phone;
```

name	email	salary	dept	name	phone
Alice	alice@company.com	52000.0	Accounting	Bob	919 555-1111
Alice	alice@company.com	52000.0	Accounting	Carol	919 555-2222
Alice	alice@company.com	52000.0	Accounting	Eve	919 555-3333
Alice	alice@company.com	52000.0	Accounting	Frank	919 555-4444
Bob	bob@company.com	40000.0	Accounting	Bob	919 555-1111
Bob	bob@company.com	40000.0	Accounting	Carol	919 555-2222
Bob	bob@company.com	40000.0	Accounting	Eve	919 555-3333
Bob	bob@company.com	40000.0	Accounting	Frank	919 555-4444
Carol	carol@company.com	30000.0	Sales	Bob	919 555-1111
Carol	carol@company.com	30000.0	Sales	Carol	919 555-2222
Carol	carol@company.com	30000.0	Sales	Eve	919 555-3333
Carol	carol@company.com	30000.0	Sales	Frank	919 555-4444
Dave	dave@company.com	33000.0	Accounting	Bob	919 555-1111
Dave	dave@company.com	33000.0	Accounting	Carol	919 555-2222
Dave	dave@company.com	33000.0	Accounting	Eve	919 555-3333
Dave	dave@company.com	33000.0	Accounting	Frank	919 555-4444

Inner Join

If you want SQLite to find the columns to merge on automatically then we prefix the join with NATURAL.

```
sqlite> SELECT * FROM employees NATURAL JOIN phone;
```

name	email	salary	dept	phone
Bob	bob@company.com	40000.0	Accounting	919 555-1111
Carol	carol@company.c	30000.0	Sales	919 555-2222
Eve	eve@company.com	44000.0	Sales	919 555-3333
Frank	frank@comany.co	37000.0	Sales	919 555-4444

Inner Join - Explicit

```
sqlite> SELECT * FROM employees JOIN phone ON employees.name = phone.name;
```

name	email	salary	dept	name	phone
Bob	bob@company.com	40000.0	Accounting	Bob	919 555-1111
Carol	carol@company.c	30000.0	Sales	Carol	919 555-2222
Eve	eve@company.com	44000.0	Sales	Eve	919 555-3333
Frank	frank@comany.co	37000.0	Sales	Frank	919 555-4444

to avoid the duplicate name column we can use USING instead of ON

```
sqlite> SELECT * FROM employees JOIN phone USING(name);
```

name	email	salary	dept	phone
Bob	bob@company.com	40000.0	Accounting	919 555-1111
Carol	carol@company.com	30000.0	Sales	919 555-2222
Eve	eve@company.com	44000.0	Sales	919 555-3333
Frank	frank@comany.com	37000.0	Sales	919 555-4444

Left Join - Natural

```
sqlite> SELECT * FROM employees NATURAL LEFT JOIN phone;
```

name	email	salary	dept	phone
Alice	alice@company.com	52000.0	Accounting	
Bob	bob@company.com	40000.0	Accounting	919 555-11
Carol	carol@company.com	30000.0	Sales	919 555-22
Dave	dave@company.com	33000.0	Accounting	
Eve	eve@company.com	44000.0	Sales	919 555-33
Frank	frank@comany.com	37000.0	Sales	919 555-44

Left Join - Explicit

```
sqlite> SELECT * FROM employees LEFT JOIN phone ON employees.name = phone.name;
```

name	email	salary	dept	name	phone
Alice	alice@company.com	52000.0	Accounting		
Bob	bob@company.com	40000.0	Accounting	Bob	919 555-11
Carol	carol@company.com	30000.0	Sales	Carol	919 555-22
Dave	dave@company.com	33000.0	Accounting		
Eve	eve@company.com	44000.0	Sales	Eve	919 555-33
Frank	frank@comany.com	37000.0	Sales	Frank	919 555-44

As above to avoid the duplicate `name` column we can use `USING`, or can be more selective about our returned columns,

```
SELECT employees.* , phone FROM employees LEFT JOIN phone ON employees.name = phone.name;
```

name	email	salary	dept	phone
Alice	alice@company.com	52000.0	Accounting	
Bob	bob@company.com	40000.0	Accounting	919 555-1111
Carol	carol@company.com	30000.0	Sales	919 555-2222
Dave	dave@company.com	33000.0	Accounting	

Other Joins

Note that SQLite does not support directly support an OUTER JOIN (e.g a full join in dplyr) or a RIGHT JOIN.

- A RIGHT JOIN can be achieved by switch the two tables (i.e. A right join B is equivalent to B left join A)
- An OUTER JOIN can be achieved via using UNION ALL with both left joins (A on B and B on A)

Creating an index

```
sqlite> CREATE INDEX index_name ON employees (name);
sqlite> .indices

index_name

sqlite> CREATE INDEX index_name_email ON employees (name,email);
sqlite> .indices

index_name
index_name_email
```

Subqueries

We can nest tables within tables for the purpose of queries.

```
SELECT * FROM (SELECT * FROM employees NATURAL LEFT JOIN phone) WHERE phone IS NULL;
```

name	email	salary	dept	phone
Alice	alice@company.com	52000.0	Accounting	
Dave	dave@company.com	33000.0	Accounting	

```
sqlite> SELECT * FROM (SELECT * FROM employees NATURAL LEFT JOIN phone) WHERE phone IS NOT NULL;
```

name	email	salary	dept	phone
Bob	bob@company.com	40000.0	Accounting	919 555-1111
Carol	carol@company.c	30000.0	Sales	919 555-2222
Eve	eve@company.com	44000.0	Sales	919 555-3333
Frank	frank@comany.co	37000.0	Sales	919 555-4444

Excercise 2

Lets try to create a table that has a new column - abv_avg which contains how much more (or less) than the average, for their department, each person is paid.

Hint - This will require joining a subquery.

`employees.sqlite` is available in the exercises repo.