

# Databases and duckdb

*VCS, Rice 2025*

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# Load the packages

```
library(here)      # manage file paths
library(socviz)    # data and some useful functions
library(tidyverse) # your friend and mine
library(gapminder) # inescapable

library(DBI) # DBMS interface layer
library(duckdb) # Local database server
```

**“Big” Data**

# What we're talking about

Mostly in this case, datasets that are nominally larger than your laptop's memory.

There are other more specific uses, and truly huge data is beyond the scope of the course. But we can look at methods for working with data that's “big” for all practical purposes.

# Databases

When we're working with data in the social sciences the basic case is a single table that we're going to do something with, like run a regression or make a plot.

```
gapminder
```

```
# A tibble: 1,704 × 6
  country    continent  year lifeExp      pop gdpPercap
  <fct>      <fct>    <int>  <dbl>    <int>    <dbl>
1 Afghanistan Asia      1952   28.8  8425333    779.
2 Afghanistan Asia      1957   30.3  9240934    821.
3 Afghanistan Asia      1962   32.0 10267083    853.
4 Afghanistan Asia      1967   34.0 11537966    836.
5 Afghanistan Asia      1972   36.1 13079460    740.
6 Afghanistan Asia      1977   38.4 14880372    786.
7 Afghanistan Asia      1982   39.9 12881816    978.
8 Afghanistan Asia      1987   40.8 13867957    852.
9 Afghanistan Asia      1992   41.7 16317921    649.
10 Afghanistan Asia      1997   41.8 22227415    635.
# i 1,694 more rows
```

But the bigger a dataset gets, the more we have to think about whether we really want (or even can have) all of it in memory all the time.

# Databases

In addition, much of what we want to do with a specific dataset will involve actually acting on some relatively small subset of it.

```
gapminder ►  
select(gdpPercap, lifeExp)
```

```
# A tibble: 1,704 × 2  
  gdpPercap lifeExp  
    <dbl>    <dbl>  
1     779.     28.8  
2     821.     30.3  
3     853.     32.0  
4     836.     34.0  
5     740.     36.1  
6     786.     38.4  
7     978.     39.9  
8     852.     40.8  
9     649.     41.7  
10    635.     41.8  
# i 1,694 more rows
```

# Databases

In addition, much of what we want to do with a specific dataset will involve actually acting on some relatively small subset of it.

```
gapminder ►  
  filter(continent = "Europe",  
         year = 1977)
```

```
# A tibble: 30 × 6
```

	country <fct>	continent <fct>	year <int>	lifeExp <dbl>	pop <int>	gdpPercap <dbl>
1	Albania	Europe	1977	68.9	2509048	3533.
2	Austria	Europe	1977	72.2	7568430	19749.
3	Belgium	Europe	1977	72.8	9821800	19118.
4	Bosnia and Herzegovina	Europe	1977	69.9	4086000	3528.
5	Bulgaria	Europe	1977	70.8	8797022	7612.
6	Croatia	Europe	1977	70.6	4318673	11305.
7	Czech Republic	Europe	1977	70.7	10161915	14800.
8	Denmark	Europe	1977	74.7	5088419	20423.
9	Finland	Europe	1977	72.5	4738902	15605.
10	France	Europe	1977	73.8	53165019	18293.

```
# i 20 more rows
```

# Databases

In addition, much of what we want to do with a specific dataset will involve actually acting on some relatively small subset of it.

```
gapminder >
  group_by(continent) >
  summarize(lifeExp = mean(lifeExp),
            pop = mean(pop),
            gdpPercap = mean(gdpPercap))
```

```
# A tibble: 5 × 4
  continent lifeExp      pop gdpPercap
  <fct>      <dbl>    <dbl>    <dbl>
1 Africa      48.9  9916003.    2194.
2 Americas    64.7 24504795.    7136.
3 Asia        60.1 77038722.    7902.
4 Europe      71.9 17169765.   14469.
5 Oceania     74.3  8874672.   18622.
```



# Databases

Efficiently storing and querying really large quantities of data is the realm of the database and of Structured Query Languages.

As with everything in information technology there is a long and interesting story about various efforts to come up with a good theory of data storage and retrieval, and efficient algorithms for it. If you are interested, watch e.g. [this lecture from a DBMS course](#) from about twelve minutes in.

# Where's the database?

Local or remote?

On disk or in memory?

The important thing from the database admin's point of view is that the data is stored *efficiently*, that we have a means of *querying* it, and those queries rely on some search-and-retrieval method that's *really fast*.

There's no free lunch. We want storage methods to be efficient and queries to be fast because the datasets are gonna be gigantic, and accessing them will take time.

# Database layouts

A real database is usually not a single giant table. Instead it is more like a list of tables that are partially connected through keys shared between tables. Those keys are indexed and the tables are stored in a tree-like way that makes searching much faster than just going down each row and looking for matches.

From a social science perspective, putting things in different tables might be thought of a matter of logically organizing entities at different *units of observation*. Querying tables is a matter of assembling tables ad hoc at various *units of analysis*.

# Database layouts

```
gapminder_xtra ← read_csv(here("examples", "gapminder_xtra.csv"))
gapminder_xtra
```

```
# A tibble: 1,704 × 13
  country    continent  year lifeExp      pop gdpPercap area_pct pop_pct
  <chr>      <chr>    <dbl>  <dbl>    <dbl>    <dbl>    <dbl>    <dbl>
1 Afghanistan Asia      1952   28.8  8425333    779.    29.8    59.4
2 Afghanistan Asia      1957   30.3  9240934    821.    29.8    59.4
3 Afghanistan Asia      1962   32.0 10267083    853.    29.8    59.4
4 Afghanistan Asia      1967   34.0 11537966    836.    29.8    59.4
5 Afghanistan Asia      1972   36.1 13079460    740.    29.8    59.4
6 Afghanistan Asia      1977   38.4 14880372    786.    29.8    59.4
7 Afghanistan Asia      1982   39.9 12881816    978.    29.8    59.4
8 Afghanistan Asia      1987   40.8 13867957    852.    29.8    59.4
9 Afghanistan Asia      1992   41.7 16317921    649.    29.8    59.4
10 Afghanistan Asia      1997   41.8 22227415    635.    29.8    59.4
# i 1,694 more rows
# i 5 more variables: gm_countries <dbl>, country_fr <chr>, iso2 <chr>,
#   iso3 <chr>, number <dbl>
```

Again, in social science terms, the redundancies are annoying in part because they apply to different levels or units of observation. From a Database point of view they are also bad because they allow the possibility of a variety of errors or anomalies when updating the table, and they make things really inefficient for search and querying.

# Database normalization

A hierarchical set of rules and criteria for ensuring the integrity of data stored across multiple tables and for reducing redundancy in data storage.

Tries to eliminate various sources of error — so-called Insertion, Update, and Deletion anomalies — particularly ones that will pollute, damage, or corrupt things beyond the specific change.

Redundancy and error are minimized by breaking the database up into a series of linked or related tables. Hence the term “relational database”

# Normal Forms

*0NF*: No duplicate rows!

*1NF*: Using row order to convey information is not allowed; Mixing data types in the same column is not allowed; No table without a primary key is not allowed. Primary keys can be defined by more than one column though.

*2NF*: Each non-key attribute must depend on the entire primary key

*3NF*: Every non-key attribute should depend wholly and only on the key.

Think of these rules in connection with ideas about “tidy data”.

# Database normalization

```
gapminder_xtra
```

```
# A tibble: 1,704 × 13
```

	country	continent	year	lifeExp	pop	gdpPercap	area_pct	pop_pct
	<chr>	<chr>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>	<dbl>
1	Afghanistan	Asia	1952	28.8	8425333	779.	29.8	59.4
2	Afghanistan	Asia	1957	30.3	9240934	821.	29.8	59.4
3	Afghanistan	Asia	1962	32.0	10267083	853.	29.8	59.4
4	Afghanistan	Asia	1967	34.0	11537966	836.	29.8	59.4
5	Afghanistan	Asia	1972	36.1	13079460	740.	29.8	59.4
6	Afghanistan	Asia	1977	38.4	14880372	786.	29.8	59.4
7	Afghanistan	Asia	1982	39.9	12881816	978.	29.8	59.4
8	Afghanistan	Asia	1987	40.8	13867957	852.	29.8	59.4
9	Afghanistan	Asia	1992	41.7	16317921	649.	29.8	59.4
10	Afghanistan	Asia	1997	41.8	22227415	635.	29.8	59.4

```
# i 1,694 more rows
```

```
# i 5 more variables: gm_countries <dbl>, country_fr <chr>, iso2 <chr>,
```

```
# iso3 <chr>, number <dbl>
```

# Database normalization

gapminder

```
# A tibble: 1,704 × 6
```

	country	continent	year	lifeExp	pop	gdpPercap
	<fct>	<fct>	<int>	<dbl>	<int>	<dbl>
1	Afghanistan	Asia	1952	28.8	8425333	779.
2	Afghanistan	Asia	1957	30.3	9240934	821.
3	Afghanistan	Asia	1962	32.0	10267083	853.
4	Afghanistan	Asia	1967	34.0	11537966	836.
5	Afghanistan	Asia	1972	36.1	13079460	740.
6	Afghanistan	Asia	1977	38.4	14880372	786.
7	Afghanistan	Asia	1982	39.9	12881816	978.
8	Afghanistan	Asia	1987	40.8	13867957	852.
9	Afghanistan	Asia	1992	41.7	16317921	649.
10	Afghanistan	Asia	1997	41.8	22227415	635.

```
# i 1,694 more rows
```



# Database normalization

```
continent_tbl ← read_tsv(here("examples", "continent_tab.tsv"))
country_tbl ← read_tsv(here("examples", "country_tab.tsv"))
year_tbl ← read_tsv(here("examples", "year_tab.tsv"))
```

```
continent_tbl
```

```
# A tibble: 5 × 5
```

	continent_id	continent	area_pct	pop_pct	gm_countries
	<dbl>	<chr>	<dbl>	<dbl>	<dbl>
1	1	Africa	20.3	17.6	52
2	2	Americas	28.1	13	25
3	3	Asia	29.8	59.4	33
4	4	Europe	6.7	9.4	30
5	5	Oceania	5.7	0.6	2

```
gapminder
```

```
# A tibble: 1,704 × 6
```

	country	continent	year	lifeExp	pop	gdpPercap
	<fct>	<fct>	<int>	<dbl>	<int>	<dbl>
1	Afghanistan	Asia	1952	28.8	8425333	779.
2	Afghanistan	Asia	1957	30.3	9240934	821.
3	Afghanistan	Asia	1962	32.0	10267083	853.
4	Afghanistan	Asia	1967	34.0	11537966	836.
5	Afghanistan	Asia	1972	36.1	13079460	740.
6	Afghanistan	Asia	1977	38.4	14880372	786.
7	Afghanistan	Asia	1982	39.9	12881816	978.
8	Afghanistan	Asia	1987	40.8	13867957	852.
9	Afghanistan	Asia	1992	41.7	16317921	649.
10	Afghanistan	Asia	1997	41.8	22227415	635.

```
# i 1,694 more rows
```

# Database normalization

continent\_tbl

```
# A tibble: 5 × 5
  continent_id continent area_pct pop_pct gm_countries
    <dbl>    <chr>      <dbl>   <dbl>      <dbl>
1           1 Africa      20.3    17.6         52
2           2 Americas    28.1     13          25
3           3 Asia       29.8    59.4         33
4           4 Europe      6.7     9.4          30
5           5 Oceania     5.7     0.6           2
```

country\_tbl

```
# A tibble: 249 × 8
  country_id continent_id country      iso_country country_fr iso2 iso3 number
    <dbl>      <dbl>    <chr>      <chr>      <chr>      <chr> <chr> <dbl>
1           1           3 Afghanistan Afghanistan Afghanist... AF AFG 4
2           2           4 Albania Albania Albanie (... AL ALB 8
3           3           1 Algeria Algeria Algérie (... DZ DZA 12
4           4           NA <NA> American S... Samoa amé... AS ASM 16
5           5           NA <NA> Andorra Andorre (... AD AND 20
6           6           1 Angola Angola Angola (l... AO AGO 24
7           7           NA Anguilla Anguilla Anguilla AI AIA 660
8           8           NA Antarctica Antarctica Antarctiq... AQ ATA 10
9           9           NA Antigua an... Antigua an... Antigua-e... AG ATG 28
10          10          2 Argentina Argentina Argentine... AR ARG 32
# i 239 more rows
```

# Database normalization

country\_tbl

```
# A tibble: 249 × 8
  country_id continent_id country      iso_country country_fr iso2 iso3 number
  <dbl>         <dbl> <chr>      <chr>      <chr>      <chr> <chr> <dbl>
1         1           3 Afghanistan Afghanistan Afghanist... AF    AFG     4
2         2           4 Albania      Albania      Albanie (... AL    ALB     8
3         3           1 Algeria       Algeria      Algérie (... DZ    DZA    12
4         4           NA <NA>         American S... Samoa amé... AS    ASM    16
5         5           NA <NA>         Andorra       Andorre (... AD    AND    20
6         6           1 Angola       Angola       Angola (l... AO    AGO    24
7         7           NA Anguilla     Anguilla     Anguilla    AI    AIA   660
8         8           NA Antarctica  Antarctica  Antarctiq... AQ    ATA    10
9         9           NA Antigua an... Antigua an... Antigua-e... AG    ATG    28
10        10          2 Argentina    Argentina    Argentine... AR    ARG    32
# i 239 more rows
```

year\_tbl

```
# A tibble: 1,704 × 5
  year country_id lifeExp      pop gdpPercap
  <dbl>      <dbl>   <dbl>   <dbl>   <dbl>
1  1952         1    28.8  8425333    779.
2  1957         1    30.3  9240934    821.
3  1962         1    32.0 10267083    853.
4  1967         1    34.0 11537966    836.
5  1972         1    36.1 13079460    740.
6  1977         1    38.4 14880372    786.
7  1982         1    39.9 12881816    978.
8  1987         1    40.8 13867957    852.
9  1992         1    41.7 16317921    649.
10 1997         1    41.8 22227415    635.
# i 1,694 more rows
```

**Talking to databases**

# The main idea

Ultimately, we query databases with SQL. There are several varieties, because there are a variety of database systems and each has their own wrinkles and quirks.

We try to *abstract away* from some of those quirk by using a DBI (DataBase Interface) layer, which is a generic set of commands for talking to some database. It's analogous to an API.

We also need to use a package for the DBMS we're talking to. It translates DBI instructions into the specific dialect the DBMS speaks.

# Talking to databases

Some databases are small, and some are far away.

*Client-server* databases are like websites, serving up responses to queries. The database lives on a machine somewhere in the building, or on campus or whatever.

*Cloud* DBMSs are like this, too, except the database lives on a machine in someone else's building.

*In-process* DBMSs live and run on your laptop. We'll use one of these, `duckdb` for examples here.

# Talking to databases

We need to open a *connection* to a database before talking to it. Conventionally this is called **con**.

Once connected, we ask it questions. Either we use functions or packages designed to translate our R / dplyr syntax into SQL, or we use functions to pass SQL queries on directly.

We try to minimize the amount of time we are actually making the database do a lot of work.

The key thing is that when working with databases our queries are *lazy* — they don't actually do anything on the whole database unless its strictly necessary or they're explicitly told to.

**Example: flights**



# The nice example

Where everything is lovely and clean.

# duckdb and DBI

```
# library(DBI)  
con ← dbConnect(duckdb::duckdb(), path = ":memory:")
```

Here we open a connection to an in-memory duckdb database (rather than a file we will keep for later). It's empty. We're going to populate it with data from `nycflights13`.

# duckdb and DBI

```
copy_to(  
  dest = con,  
  df = nycflights13::flights,  
  name = "flights",  
  temporary = FALSE,  
  indexes = list(  
    c("year", "month", "day"),  
    "carrier",  
    "tailnum",  
    "dest"  
  )  
)
```

Remember, keys and indexes are what make databases *fast*.

# Make a lazy tibble from it

This says “go to `con` and get the ‘flights’ table in it, and pretend it’s a tibble called `flights_db`.”

```
flights_db ← tbl(con, "flights")
```

```
flights_db
```

```
# Source:   table<flights> [?? x 19]
# Database: DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
  year month   day dep_time sched_dep_time dep_delay arr_time sched_arr_time
  <int> <int> <int>   <int>         <int>         <dbl>   <int>         <int>
1  2013     1     1     517             515           2     830           819
2  2013     1     1     533             529           4     850           830
3  2013     1     1     542             540           2     923           850
4  2013     1     1     544             545          -1    1004          1022
5  2013     1     1     554             600          -6     812           837
6  2013     1     1     554             558          -4     740           728
7  2013     1     1     555             600          -5     913           854
8  2013     1     1     557             600          -3     709           723
9  2013     1     1     557             600          -3     838           846
10 2013     1     1     558             600          -2     753           745
# i more rows
# i 11 more variables: arr_delay <dbl>, carrier <chr>, flight <int>,
#   tailnum <chr>, origin <chr>, dest <chr>, air_time <dbl>, distance <dbl>,
#   hour <dbl>, minute <dbl>, time_hour <dtm>
```

# Run some dplyr-like queries

```
flights_db > select(year:day, dep_delay, arr_delay)
```

```
# Source:   SQL [?? x 5]
# Database: DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
  year month   day dep_delay arr_delay
  <int> <int> <int>    <dbl>    <dbl>
1  2013     1     1         2        11
2  2013     1     1         4        20
3  2013     1     1         2        33
4  2013     1     1        -1       -18
5  2013     1     1        -6       -25
6  2013     1     1        -4        12
7  2013     1     1        -5        19
8  2013     1     1        -3       -14
9  2013     1     1        -3        -8
10 2013     1     1        -2         8
# i more rows
```

# Run some dplyr-like queries

```
flights_db > filter(dep_delay > 240)
```

```
# Source:   SQL [?? x 19]
# Database: DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
  year month   day dep_time sched_dep_time dep_delay arr_time sched_arr_time
  <int> <int> <int>   <int>         <int>         <dbl>   <int>         <int>
1  2013     1     1     848           1835         853     1001           1950
2  2013     1     1    1815           1325         290     2120           1542
3  2013     1     1    1842           1422         260     1958           1535
4  2013     1     1    2115           1700         255     2330           1920
5  2013     1     1    2205           1720         285         46           2040
6  2013     1     1    2343           1724         379         314           1938
7  2013     1     2    1332           904         268     1616           1128
8  2013     1     2    1412           838         334     1710           1147
9  2013     1     2    1607          1030         337     2003           1355
10 2013     1     2    2131          1512         379     2340           1741
# i more rows
# i 11 more variables: arr_delay <dbl>, carrier <chr>, flight <int>,
#   tailnum <chr>, origin <chr>, dest <chr>, air_time <dbl>, distance <dbl>,
#   hour <dbl>, minute <dbl>, time_hour <dtm>
```

# Run some dplyr-like queries

```
flights_db >
  group_by(dest) >
  summarise(mean_dep_delay = mean(dep_delay))
```

```
# Source:   SQL [?? x 2]
# Database: DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
  dest mean_dep_delay
  <chr>          <dbl>
1 SFO             12.9
2 GSP             19.3
3 SJU              9.81
4 GSO             19.4
5 STT              4.61
6 SAN             11.1
7 TYS             28.5
8 EGE             15.5
9 CRW             17
10 MTJ            17.6
# i more rows
```

# Lazy, lazy, lazy

```
tailnum_delay_db ←  
  flights_db ▷  
  group_by(tailnum) ▷  
  summarise(  
    mean_dep_delay = mean(dep_delay),  
    mean_arr_delay = mean(arr_delay),  
    n = n()) ▷  
  filter(n > 100) ▷  
  arrange(desc(mean_arr_delay))
```

This doesn't touch the database.



# Lazy, lazy, lazy

Even when we ask to look at it, it just does the absolute minimum required.

```
tailnum_delay_db
```

```
# Source:      SQL [?? x 4]
# Database:    DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
# Ordered by: desc(mean_arr_delay)
  tailnum mean_dep_delay mean_arr_delay      n
  <chr>      <dbl>          <dbl> <dbl>
1 N11119      32.6             30.3  148
2 N16919      32.4             29.9  251
3 N14998      29.4             27.9  230
4 N15910      29.3             27.6  280
5 N13123      29.6             26.0  121
6 N11192      27.5             25.9  154
7 N14950      26.2             25.3  219
8 N21130      27.0             25.0  126
9 N24128      24.8             24.9  129
10 N22971     26.5             24.7  230
# i more rows
```

# When ready, use `collect()`

```
tailnum_delay ←  
  tailnum_delay_db ►  
  collect()
```

```
tailnum_delay
```

```
# A tibble: 1,201 × 4  
  tailnum mean_dep_delay mean_arr_delay     n  
  <chr>         <dbl>         <dbl> <dbl>  
1 N11119         32.6         30.3  148  
2 N16919         32.4         29.9  251  
3 N14998         29.4         27.9  230  
4 N15910         29.3         27.6  280  
5 N13123         29.6         26.0  121  
6 N11192         27.5         25.9  154  
7 N14950         26.2         25.3  219  
8 N21130         27.0         25.0  126  
9 N24128         24.8         24.9  129  
10 N22971        26.5         24.7  230  
# i 1,191 more rows
```

Now it exists for realsies.

# Joins

Database systems will have more than one table. We query and join them. The idea is that getting the DBMS to do this will be way faster and more memory-efficient than trying to get `dplyr` to do it.

# Joins

```
## Copy over the "planes" dataset to the same "con" DuckDB connection.
copy_to(
  dest = con,
  df = nycflights13::planes,
  name = "planes",
  temporary = FALSE,
  indexes = "tailnum"
)

## List tables in our "con" database connection (i.e. now "flights" and "planes")
dbListTables(con)
```

```
[1] "flights" "planes"
```

```
## Reference from dplyr
planes_db ← tbl(con, 'planes')
```

See what we did there? It's like `con` the database connection has a list of tables in it.

# Joins

```
# Still not done for realsies!
left_join(
  flights_db,
  planes_db %>% rename(year_built = year),
  by = "tailnum" ## Important: Be specific about the joining column
) ►
select(year, month, day, dep_time, arr_time, carrier, flight, tailnum,
       year_built, type, model)
```

```
# Source:   SQL [?? x 11]
```

```
# Database: DuckDB v1.1.3 [root@Darwin 24.3.0:R 4.4.3/:memory:]
```

	year	month	day	dep_time	arr_time	carrier	flight	tailnum	year_built	type
	<int>	<int>	<int>	<int>	<int>	<chr>	<int>	<chr>	<int>	<chr>
1	2013	2	14	1045	1204	UA	67	N16713	1998	Fixed ...
2	2013	2	14	1048	1412	B6	373	N659JB	2007	Fixed ...
3	2013	2	14	1048	1333	UA	764	N665UA	1998	Fixed ...
4	2013	2	14	1051	1203	US	2171	N747UW	2000	Fixed ...
5	2013	2	14	1057	1244	WN	366	N414WN	2001	Fixed ...
6	2013	2	14	1057	1353	UA	1550	N14228	1999	Fixed ...
7	2013	2	14	1058	1211	EV	4694	N14993	2000	Fixed ...
8	2013	2	14	1058	1337	DL	1647	N689DL	1998	Fixed ...
9	2013	2	14	1105	1210	B6	24	N197JB	2006	Fixed ...
10	2013	2	14	1105	1302	MQ	4485	N711MQ	1976	Fixed ...

```
# i more rows
```

```
# i 1 more variable: model <chr>
```

# Finishing up

Close your connection!

```
dbDisconnect(con)
```