

SQL databases and R

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Learning Objectives

- Access a database from R.
- Run SQL queries in R using **RSQLite** and **dplyr**.
- Create an SQLite database from existing .csv files.

Introduction

So far, we have dealt with small datasets that easily fit into your computer's memory. But what about datasets that are too large for your computer to handle as a whole? In this case, storing the data outside of R and organizing it in a database is helpful. Connecting to the database allows you to retrieve only the chunks needed for the current analysis.

Even better, many large datasets are already available in public or private databases. You can query them without having to download the data first.

R can connect to almost any existing database type. Most common database types have R packages that allow you to connect to them (e.g., **RSQLite**, **RMySQL**, etc). Furthermore, the **dplyr** package you used in the previous episode, in conjunction with **dbplyr** supports connecting to the widely-used open source databases **sqlite**, **mysql** and **postgresql**, as well as Google's **bigquery**, and it can also be extended to other database types (a vignette in the **dplyr** package explains how to do it). RStudio has created a website that provides documentation and best practices to work on database interfaces.

Interfacing with databases using **dplyr** focuses on retrieving and analyzing datasets by generating **SELECT** SQL statements, but it doesn't modify the database itself. **dplyr** does not offer functions to **UPDATE** or **DELETE** entries. If you need these functionalities, you will need to use additional R packages (e.g., **RSQLite**). Here we will demonstrate how to interact with a database using **dplyr**, using both the **dplyr**'s verb syntax and the SQL syntax.

The `portal_mammals` database

We will continue to explore the **surveys** data you are already familiar with from previous lessons. First, we are going to install the **dbplyr** package:

```
install.packages(c("dbplyr", "RSQLite"))
```

The SQLite database is contained in a single file `portal_mammals.sqlite` that you generated during the SQL lesson. If you don't have it, you can download it from Figshare into the `data_raw` subdirectory using:

```
dir.create("data_raw", showWarnings = FALSE)
download.file(url = "https://ndownloader.figshare.com/files/2292171",
             destfile = "data_raw/portal_mammals.sqlite", mode = "wb")
```

Connecting to databases

We can point R to this database using:

```
library(dplyr)
library(dbplyr)
mammals <- DBI::dbConnect(RSQLite::SQLite(), "data_raw/portal_mammals.sqlite")
```

This command uses 2 packages that helps `dbplyr` and `dplyr` talk to the SQLite database. `DBI` is not something that you'll use directly as a user. It allows R to send commands to databases irrespective of the database management system used. The `RSQLite` package allows R to interface with SQLite databases.

This command does not load the data into the R session (as the `read_csv()` function did). Instead, it merely instructs R to connect to the `SQLite` database contained in the `portal_mammals.sqlite` file.

Using a similar approach, you could connect to many other database management systems that are supported by R including MySQL, PostgreSQL, BigQuery, etc.

Let's take a closer look at the `mammals` database we just connected to:

```
src_dbi(mammals)
#> src:  sqlite 3.34.1 [/builds/grp-bio-it-workshops/introduction-to-R/data_raw/portal_mammals.sqlite]
#> tbls:  plots, species, surveys
```

Just like a spreadsheet with multiple worksheets, a SQLite database can contain multiple tables. In this case three of them are listed in the `tbls` row in the output above:

- plots
- species
- surveys

Now that we know we can connect to the database, let's explore how to get the data from its tables into R.

Querying the database with the SQL syntax

To connect to tables within a database, you can use the `tbl()` function from `dplyr`. This function can be used to send SQL queries to the database. To demonstrate this functionality, let's select the columns "year", "species_id", and "plot_id" from the `surveys` table:

```
tbl(mammals, sql("SELECT year, species_id, plot_id FROM surveys"))
```

With this approach you can use any SQL queries.

Querying the database with the dplyr syntax

One of the strengths of `dplyr` is that the same operation can be done using `dplyr`'s verbs instead of writing SQL. First, we select the table on which to do the operations by creating the `surveys` object, and then we use the standard `dplyr` syntax as if it were a data frame:

```
surveys <- tbl(mammals, "surveys")
surveys %>%
  select(year, species_id, plot_id)
```

In this case, the `surveys` object behaves like a data frame. Several functions that can be used with data frames can also be used on tables from a database. For instance, the `head()` function can be used to check the first 10 rows of the table:

```
head(surveys, n = 10)
```

record_id	month	day	year	plot_id	species_id	sex	hindfoot_length	weight
1	7	16	1977	2	NL	M	32	NA
2	7	16	1977	3	NL	M	33	NA
3	7	16	1977	2	DM	F	37	NA
4	7	16	1977	7	DM	M	36	NA
5	7	16	1977	3	DM	M	35	NA
6	7	16	1977	1	PF	M	14	NA
7	7	16	1977	2	PE	F	NA	NA
8	7	16	1977	1	DM	M	37	NA
9	7	16	1977	1	DM	F	34	NA
10	7	16	1977	6	PF	F	20	NA

This output of the `head` command looks just like a regular `data.frame`: The table has 9 columns and the `head()` command shows us the first 10 rows. Note that the columns `plot_type`, `taxa`, `genus`, and `species` are missing. These are now located in the tables `plots` and `species` which we will join together in a moment.

However, some functions don't work quite as expected. For instance, let's check how many rows there are in total using `nrow()`:

```
nrow(surveys)
```

```
#> [1] NA
```

That's strange - R doesn't know how many rows the `surveys` table contains - it returns `NA` instead. You might have already noticed that the first line of the `head()` output included `??` indicating that the number of rows wasn't known.

The reason for this behavior highlights a key difference between using `dplyr` on datasets in memory (e.g. loaded into your R session via `read_csv()`) and those provided by a database. To understand it, we take a closer look at how `dplyr` communicates with our SQLite database.

SQL translation

Relational databases typically use a special-purpose language, Structured Query Language (SQL), to manage and query data.

For example, the following SQL query returns the first 10 rows from the `surveys` table:

```
SELECT *
FROM `surveys`
LIMIT 10
```

Behind the scenes, `dplyr`:

1. translates your R code into SQL
2. submits it to the database
3. translates the database's response into an R data frame

To lift the curtain, we can use `dplyr`'s `show_query()` function to show which SQL commands are actually sent to the database:

```
show_query(head(surveys, n = 10))
```

The output shows the actual SQL query sent to the database; it matches our manually constructed `SELECT` statement above.

Instead of having to formulate the SQL query ourselves - and having to mentally switch back and forth between R and SQL syntax - we can delegate this translation to `dplyr`. (You don't even need to know SQL to interact with a database via `dplyr`!)

`dplyr`, in turn, doesn't do the real work of subsetting the table, either. Instead, it merely sends the query to the database, waits for its response and returns it to us.

That way, R never gets to see the full `surveys` table - and that's why it could not tell us how many rows it contains. On the bright side, this allows us to work with large datasets - even too large to fit into our computer's memory.

`dplyr` can translate many different query types into SQL allowing us to, e.g., `select()` specific columns, `filter()` rows, or join tables.

To see this in action, let's compose a few queries with `dplyr`.

Simple database queries

First, let's only request rows of the `surveys` table in which `weight` is less than 5 and keep only the `species_id`, `sex`, and `weight` columns.

```
surveys %>%  
  filter(weight < 5) %>%  
  select(species_id, sex, weight)
```

species_id	sex	weight
PF	M	4
PF	F	4
PF	NA	4
PF	F	4
PF	F	4
RM	M	4
RM	F	4
RM	M	4
RM	M	4
RM	M	4
RM	M	4
RM	M	4
RM	F	4
RM	M	4
RM	M	4
RM	M	4
PF	M	4
PP	M	4

Executing this command will return a table with 10 rows and the requested `species_id`, `sex` and `weight` columns. Great!

... but wait, why are there only 10 rows?

The last line:

```
# ... with more rows
```

indicates that there are more results that fit our filtering criterion. Why was R lazy and only retrieved 10 of them?

Laziness

Hadley Wickham, the author of `dplyr` explains:

When working with databases, `dplyr` tries to be as lazy as possible:

- It never pulls data into R unless you explicitly ask for it.
- It delays doing any work until the last possible moment - it collects together everything you want to do and then sends it to the database in one step.

When you construct a `dplyr` query, you can connect multiple verbs into a single pipeline. For example, we combined the `filter()` and `select()` verbs using the `%>%` pipe.

If we wanted to, we could add on even more steps, e.g. remove the `sex` column in an additional `select` call:

```
data_subset <- surveys %>%  
  filter(weight < 5) %>%  
  select(species_id, sex, weight)
```

```
data_subset %>%  
  select(-sex)
```

species_id	weight
PF	4
PF	4
PF	4
PF	4
PF	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
RM	4
PF	4
PP	4

Just like the first `select(species_id, sex, weight)` call, the `select(-sex)` command is not executed by R. It is sent to the database instead. Only the *final* result is retrieved and displayed to you.

Of course, we could always add on more steps, e.g., we could filter by `species_id` or minimum `weight`. That's why R doesn't retrieve the full set of results - instead it only retrieves the first 10 results from the database by default. (After all, you might want to add an additional step and get the database to do more work...)

To instruct R to stop being lazy, e.g. to retrieve all of the query results from the database, we add the `collect()` command to our pipe. It indicates that our database query is finished: time to get the *final* results and load them into the R session.

```
data_subset <- surveys %>%  
  filter(weight < 5) %>%  
  select(species_id, sex, weight) %>%  
  collect()
```

Now we have all 17 rows that match our query in a `data.frame` and can continue to work with them exclusively in R, without communicating with the database.

Complex database queries

`dplyr` enables database queries across one or multiple database tables, using the same single- and multiple-table verbs you encountered previously. This means you can use the same commands regardless of whether you interact with a remote database or local dataset! This is a really useful feature if you work with large datasets: you can first prototype your code on a small subset that fits into memory, and when your code is ready, you can change the input dataset to your full database without having to change the syntax.

On the other hand, being able to use SQL queries directly can be useful if your collaborators have already put together complex queries to prepare the dataset that you need for your analysis.

To illustrate how to use `dplyr` with these complex queries, we are going to join the `plots` and `surveys` tables. The `plots` table in the database contains information about the different plots surveyed by the researchers. To access it, we point the `tbl()` command to it:

```
plots <- tbl(mammals, "plots")
plots
```

plot_id	plot_type
1	Spectab enclosure
2	Control
3	Long-term Krat Enclosure
4	Control
5	Rodent Enclosure
6	Short-term Krat Enclosure
7	Rodent Enclosure
8	Control
9	Spectab enclosure
10	Rodent Enclosure
11	Control
12	Control
13	Short-term Krat Enclosure
14	Control
15	Long-term Krat Enclosure
16	Rodent Enclosure
17	Control
18	Short-term Krat Enclosure
19	Long-term Krat Enclosure
20	Short-term Krat Enclosure
21	Long-term Krat Enclosure
22	Control
23	Rodent Enclosure
24	Rodent Enclosure

The `plot_id` column also features in the `surveys` table:

```
head(surveys)
```

record_id	month	day	year	plot_id	species_id	sex	hindfoot_length	weight
1	7	16	1977	2	NL	M	32	NA
2	7	16	1977	3	NL	M	33	NA

record_id	month	day	year	plot_id	species_id	sex	hindfoot_length	weight
3	7	16	1977	2	DM	F	37	NA
4	7	16	1977	7	DM	M	36	NA
5	7	16	1977	3	DM	M	35	NA
6	7	16	1977	1	PF	M	14	NA

Because `plot_id` is listed in both tables, we can use it to look up matching records, and join the two tables.

If we have two tables named `x` and `y` with a common column called “ID”, we can join them using ‘join’ functions, two of which are described and illustrated below.

1. `inner_join()` : This returns all rows from `x` where there are matching values in `y`, and all columns from `x` and `y`.
2. `left_join()` : This return all rows from `x`, and all columns from `x` and `y`. Rows in `x` with no match in `y` will have NA values in the new columns.

In both forms of join, if there are multiple matches between `x` and `y`, all combinations of the matches are returned. For the full list of ‘join’ functions, check out the tidyverse join page.

In our example, the two tables we want to join are ‘plots’ and ‘surveys’.

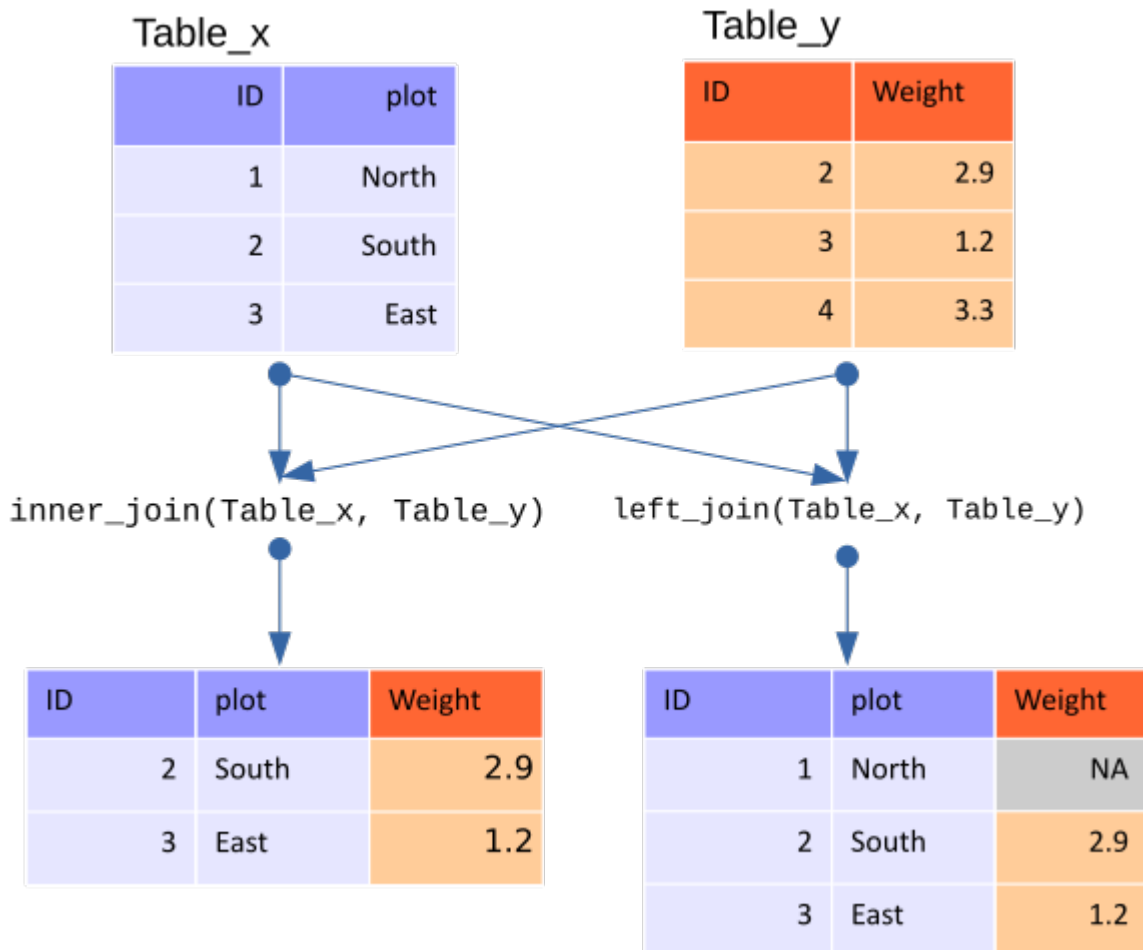


Figure 1: diagram illustrating inner and left joins

For example, to extract all surveys for the first plot, which has `plot_id` 1, we can do:

```
plot_id_surveys <- plots %>%  
  filter(plot_id == 1) %>%  
  inner_join(surveys) %>%  
  collect()
```

```
#> Joining, by = "plot_id"
```

```
head(plot_id_surveys)
```

plot_id	plot_type	record_id	month	day	year	species_id	sex	hindfoot_length	weight
1	Spectab enclosure	6	7	16	1977	PF	M	14	NA
1	Spectab enclosure	8	7	16	1977	DM	M	37	NA
1	Spectab enclosure	9	7	16	1977	DM	F	34	NA
1	Spectab enclosure	78	8	19	1977	PF	M	16	9
1	Spectab enclosure	80	8	19	1977	DS	M	48	NA
1	Spectab enclosure	218	9	13	1977	PF	M	13	4

Important Note: Without the `collect()` statement, only the first 10 matching rows are returned. By adding `collect()`, the full set of 1,985 is retrieved.

Challenge

- 5.1 Write a query that returns the number of rodents observed in each plot in each year.

Hint: Connect to the species table and write a query that joins the species and survey tables together to exclude all non-rodents. The query should return counts of rodents by year.

- Optional: 5.2 Write a query in SQL that will produce the same result. You can join multiple tables together using the following syntax where foreign key refers to your unique id (e.g., `species_id`):

```
SELECT table.col, table.col  
FROM table1 JOIN table2  
ON table1.key = table2.key  
JOIN table3 ON table2.key = table3.key
```

Answer

```
## with dplyr syntax  
species <- tbl(mammals, "species")  
  
left_join(surveys, species) %>%  
  filter(taxa == "Rodent") %>%  
  group_by(taxa, year) %>%  
  tally %>%  
  collect()  
  
#> Joining, by = "species_id"  
  
## with SQL syntax  
query <- paste("  
SELECT a.year, b.taxa, count(*) as count  
FROM surveys a  
JOIN species b  
ON a.species_id = b.species_id  
AND b.taxa = 'Rodent'  
")
```



```
GROUP BY a.year, b.taxa",
sep = "" )

tbl(mammals, sql(query))
```

Challenge

5.3 Write a query that returns the total number of rodents in each genus caught in the different plot types.

Hint: Write a query that joins the species, plot, and survey tables together. The query should return counts of genus by plot type.

Answer

```
species <- tbl(mammals, "species")
genus_counts <- left_join(surveys, plots) %>%
  left_join(species) %>%
  filter(taxa == "Rodent") %>%
  group_by(plot_type, genus) %>%
  tally %>%
  collect()
```

This is useful if we are interested in estimating the number of individuals belonging to each genus found in each plot type. But what if we were interested in the number of genera found in each plot type? Using `tally()` gives the number of individuals, instead we need to use `n_distinct()` to count the number of unique values found in a column.

```
species <- tbl(mammals, "species")
unique_genera <- left_join(surveys, plots) %>%
  left_join(species) %>%
  group_by(plot_type) %>%
  summarize(
    n_genera = n_distinct(genus)
  ) %>%
  collect()
```

```
#> Joining, by = "plot_id"
```

```
#> Joining, by = "species_id"
```

`n_distinct`, like the other `dplyr` functions we have used in this lesson, works not only on database connections but also on regular data frames.

Creating a new SQLite database

So far, we have used a previously prepared SQLite database. But we can also use R to create a new database, e.g. from existing `csv` files. Let's recreate the mammals database that we've been working with, in R. First let's download and read in the `csv` files. We'll import `tidyverse` to gain access to the `read_csv()` function.

```
download.file("https://ndownloader.figshare.com/files/3299483",
             "data_raw/species.csv")
download.file("https://ndownloader.figshare.com/files/10717177",
             "data_raw/surveys.csv")
download.file("https://ndownloader.figshare.com/files/3299474",
             "data_raw/plots.csv")

library(tidyverse)
species <- read_csv("data_raw/species.csv")
```

```

#>
#> -- Column specification -----
#> cols(
#>   species_id = col_character(),
#>   genus = col_character(),
#>   species = col_character(),
#>   taxa = col_character()
#> )

surveys <- read_csv("data_raw/surveys.csv")

#>
#> -- Column specification -----
#> cols(
#>   record_id = col_double(),
#>   month = col_double(),
#>   day = col_double(),
#>   year = col_double(),
#>   plot_id = col_double(),
#>   species_id = col_character(),
#>   sex = col_character(),
#>   hindfoot_length = col_double(),
#>   weight = col_double()
#> )

plots <- read_csv("data_raw/plots.csv")

#>
#> -- Column specification -----
#> cols(
#>   plot_id = col_double(),
#>   plot_type = col_character()
#> )

```

Creating a new SQLite database with **dplyr** is easy. You can re-use the same command we used above to open an existing `.sqlite` file. The `create = TRUE` argument instructs R to create a new, empty database instead.

Caution: When `create = TRUE` is added, any existing database at the same location is overwritten *without warning*.

```

my_db_file <- "data/portal-database-output.sqlite"
my_db <- src_sqlite(my_db_file, create = TRUE)

```

Currently, our new database is empty, it doesn't contain any tables:

```

my_db
#> src:  sqlite 3.34.1 [/builds/grp-bio-it-workshops/introduction-to-R/data/portal-
database-output.sqlite]
#> tbls:

```

To add tables, we copy the existing data.frames into the database one by one:

```

copy_to(my_db, surveys)
copy_to(my_db, plots)
my_db

```

If you check the location of our database you'll see that data is automatically being written to disk. R and **dplyr** not only provide easy ways to query existing databases, they also allows you to easily create your own

databases from flat files!

Challenge

5.4 Add the remaining species table to the `my_db` database and run some of your queries from earlier in the lesson to verify that you have faithfully recreated the mammals database.

Note: In this example, we first loaded all of the data into the R session by reading the three `csv` files. Because all the data has to flow through R, this is not suitable for very large datasets.

Summary of functions in this lesson

- `dir.create()` # create a directory
- `download.file()` # download files from the internet to your computer
- `dbConnect()` # create a connection to a database
- `SQLite()` # connect to a SQLite database
- `src_dbi()` # connect dplyr to a DBI-compatible database file
- `tbl` # connect to a table within a database
- `sql()` # combine character vectors into a single SQL expression
- `show_query()` # show which SQL commands are sent to the database
- `collect()` # retrieve all the results from the database
- `inner_join()` # perform an inner join between two tables
- `src_sqlite()` # connect dplyr to a SQLite database file
- `copy_to()` # copy a data frame as a table into a database

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