Advanced Geovisualisation

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Welcome

This is the website for "Advanced Geovisualisation" (module **ENVS456**) at the University of Liverpool. This course is designed by Dr. Gabriele Filomena and Dr. Elisabetta Pietrostefani from the Geographic Data Science Lab at the University of Liverpool, United Kingdom.

The website is **free to use** and is licensed under the Attribution-NonCommercial-NoDerivatives 4.0 International. A compilation of this web course is hosted as a GitHub repository that you can access:

- As an html website.
- As a GitHub repository.

Contact 2025-26

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Overview

Aims

This module aims to equip students with an advanced understanding of geovisualisation principles and techniques, combining theoretical knowledge of map design with practical computational skills. Students will apply these skills to address geographic research problems, utilizing the internet as both a source of geographical data and an analytical platform. The module also aims to help students create effective visual narratives on human and physical geography-related issues, by allowing them to employ advanced methods such as network analysis and basic simulation models.

Learning Outcomes

By the end of the module, students will:

- Acquire a deep understanding of theoretical principles in cartography.
- Develop advanced and grounded skills in the design of both static and dynamic maps in computational environments.
- Understand the infrastructure of spatial data formats and web-based applications.
- Master the acquisition and manipulation of data from the web, and the design of web-based visualisation and analysis.

Moreover, at the end of the module, they should able to:

1. Visualise and represent geo-data through static and dynamic maps.
2. Collect Web-based data.
3. Generate interactive maps and dashboards.
4. Understand basic concepts of spatial network analysis.
5. Acquire introductory skills in satellite imagery, spatio-temporal, and mobility data visualisation.
6. Manipulate geo-data through scripting in Python.

Asking for Academic Help:

Verbal face-to-face feedback. Immediate face-to-face feedback will be provided during computer, discussion and clinic sessions in interaction with staff. This will take place in all live sessions during the semester.

Teams Forum. Asynchronous written feedback will be provided via Teams. Students are encouraged to contribute by asking and answering questions relating to the module content. Staff will monitor the forum Monday to Friday 9am-5pm, but it will be open to students to make contributions at all times. Response time will vary depending on the complexity of the question and staff availability.

Direct emails will not be replied to, unless they pertain personal questions.

Queries regarding deadlines, extenuating circumstances requests, etc. should be addressed to: envsci [at] liverpool.ac.uk

Assessment:

Two pieces of coursework (Assignment 1 50% and Assignment 2 50%). See guidilines on the assignment pages, submission and marking criteria here.

Syllabus

Week 1 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: Introduction to the module
- Lab: Powerful examples and Python Refresher

Week 2 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: Geovisualisation: Design Principles and Statistical Visualisation
- Lab: Static Maps in Python.

Week 3 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: Interactive Maps
- Lab: Interactive Maps with Folium.

Week 4 EP Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: The Web's Architecture
- Lab: Web Architectures and APIs in Python.

Week 5 EP Central Teaching Lab: PC Teaching Centre BLUE ZONE (2 - 4pm)

- Lab only: Review & Assignment I clinic.
- **Assignment I Due** 26th February 2.00pm

Week 6 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: OpenStreetMap Data & Spatial Network.
- Lab: Retrieving Data From OpenStreetMap.

Week 7 EP Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: From Pixels to Patterns: Visualising Satellite Image Classification
- Lab: Satellite Image Classification in Python

Week 8

- NO TEACHING

Week 9 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: Simulating agents.
- Lab: Agent-based modelling with Python.

Week 10 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (1 - 4pm)

- Lecture: Time and Flows.
- Lab: Visualising Flows in Python.

Week 11 GF Central Teaching Lab: PC Teaching Centre BLUE ZONE (2 - 4pm)

- Lab only: Review & Assignment II clinic.
- **Assignment II Due (Week 11)* 30th April 2.00pm

Assessments: General Remarks

Submission

Please follow these templates consistently:

- Assignment I
- Assignment II(soon)

Download the template as follows:

and edit them accordingly.

You will submit through Canvas a `.html` file obtained from a Python `.ipynb` Jupyter Notebook file. To do so, in your `.ipynb` file, follow these steps: `File −> Save and Export as.. −> HTML`. Prior to this step, the notebook needs to be rendered (i.e. all the cells should be executed).

Other file formats will not be accepted.

Marking Criteria

This course follows the standard marking criteria (the general ones and those relating to GIS assignments in particular) set by the School of Environmental Sciences. Please make sure to check the student handbook and familiarise with them. In addition to these generic criteria, the following specific criteria will be used in cases where computer code is part of the work being assessed:

Mark Range	Description	Narrative	Map(s) and/or Dashboard Design	Technical Skills	Interactive Map Fully Working (required)	API Call (required) (A1)
0–15	Minimal or no effort; incomplete submission or no functionality.	Problem is unclear or missing; no justification.	Minimal effort; no justification for design choices.	Code does not run; no documentation.	No	No
16–39	Basic attempt with significant issues and/or missing components.	Problem and justification are partially unclear or incomplete.	Design choices lack depth or a clear link to the visualisation's aim.	Code does not run or produces incorrect output. Some documentation is present but unclear or insufficient.	Partially	No
40–49	Minimum requirements met; some functionality and basic clarity.	Problem and justification are clear but weakly integrated into the overall framework.	Basic design choices with a limited link to the visualisation outputs; lacks refinement.	Code runs and produces expected output. Documentation is present but lacks depth and/or proper formatting.	Partially	No

Mark Range	Description	Narrative	Map(s) and/or Dashboard Design	Technical Skills	Interactive Map Fully Working (required)	API Call (required) (A1)
50–59	Meets expectations with functional output and clear structure.	Clear problem identification and justification, but limited integration across components.	Reasonable design choices with some consideration of usability and presentation.	Code runs and produces expected output. Extensive documentation explains the logic.	Partially	Yes
60–69	Good overall quality with functional, thoughtful design.	Problem and justification are clear, with some integration across the framework.	Thoughtful design choices clearly connected to the interactive map (A1) or other visualisation devices (A2), with justification for interactivity	Code runs and produces expected output. Extensive, well-formatted documentation demonstrates good conceptual understanding.	Yes	Yes

Mark Range	Description	Narrative	Map(s) and/or Dashboard Design	Technical Skills	Interactive Map Fully Working (required)	API Call (required) (A1)
70–79	High-quality work showing advanced skills and strong integration.	Problem and justification are clear and well integrated across all components, forming a cohesive narrative.	Excellent design choices, strongly connected to (A1) and/or (A2), with well-justified interactivity (A1/A2).	Code runs and produces expected output. Evidence of advanced skills is demonstrated through code design and implementation.	Yes	Yes
80–100	Exceptional work with innovative contributions and flawless execution.	Problem and justification are expertly presented and fully integrated into a cohesive, professional narrative.	Outstanding, creative design with advanced interactivity and exceptional attention to detail.	Code runs and produces expected output. Extensive, well-formatted documentation includes novel contributions (e.g., optimisations or new methods).	Yes	Yes

DOs and DONTs

- DO NOT include "temporary" maps unless you really need to specifically show something to your reader.

- DO NOT include maps that have no actual differences, apart from few things (e.g. you changed the zoom level).
- DO Mix the accompanying text, in markdown cells, with the code.
- DO NOT include all the text at the beginning.
- DO provide theoretical context and motivation to your topic.
- DO Present 2 or 3 NICE static maps (max) and one final interactive map (Assignment I).

Assignment I

- **Title:** Exploring APIs and Interactive Maps in Python.
- **Type:** Coursework.
- **Due: Thursday February 26th (2.00 pm) - Week 5**.
- 50% of the final mark.
- Submission on Canvas, `.html` files only.

Context, Design, Data, and Assemblage

In this assessment, you will have the opportunity to explore different sources and combine them in a map that can be explored interactively through a web browser. This assignment requires you to identify a research problem from literature, source relevant data from the web in different formats, assemble them, and document the process. To be successful, you will need to demonstrate your understanding not only of the technical aspects involved in the process but also of the conceptual notions underpinning them. Below are the required components for your submission:

1. **Context and Problem**: Identify a research problem with a geographical connotation. Discuss concisely recent research around it in physical or human geography (around 7–8 references). Introduce how you will explore and visualise dimensions of the problem (e.g., gentrification, access to healthy food in cities, urban heat islands, etc.).

2. **Data and Backend**: Draft a list of spatial datasets relevant to your research problem and demonstrate your ability to develop your own API request function in Python. Include datasets containing spatial information or linkable to other spatial sources. Highlight the data/variables worth considering and their role in representing the problem. Demonstrate your understanding of core "backend" web mapping concepts. Include an explanation of how tilesets, client-server architecture, and APIs are implemented and contribute to your map's functionality.

3. **Design**: Create Good Looking static maps to represent your datasets, focusing on spatial units (e.g., buildings, cities). Move onto interactive visualisation with folium, incorporating interactivity for categorical and numerical variables. Seek feedback to refine your ideas. Use inspiration from web map examples discussed in the course to ensure effective representation of data.

4. **Assemblage**: Address design considerations, including the map's extent, zoom levels, and variable visibility at different zoom levels. Ensure consistency and aesthetic appeal to complete this stage successfully.

Expected Content

Text (~1000 words) and Code, alternated:

- ~250 w. introducing the research problem, the context, and existing research on the topic.
- Code: Introductory Static Maps (2), presenting the topic and the context.
- ~250 w. presenting and motivating the chosen data sources.
- Code: An API request written by your own - All the necessary steps for making your API work and for data cleaning/exploration.
- ~200 w. with your description of what your API is, how it works and how it will made your map possible.
- Code: An interactive final map. This should be fed with data obtained through the API request.
- ~200 w. description of how your interactive map works, its components and your design ideas.
- ~100 w. to summarise your research problem and how you tackled it by means of geovisualisation tools (Conclusion).

You CANNOT employ for your main maps the following libraries: Holoviews, Geoviews, and Plotly

Evaulation

The assignment will be evaluated based on 3 main pillars, on which you will have to be successful to achieve a good mark:

1. **Narrative**. The ability to identify and present a research problem, motivate and justify one's map, as well as the ability to bring each component of the assignment into a coherent whole that "fits together".
2. **Map design abilities.** The ability to demonstrate the understanding of geovisualisation and interactivity design principles.
3. **Technical skills**. The ability to master Python scripting and technologies that allow one to create a compelling map, but also to access interesting and sophisticated data sources.

How is this assignment useful?

This assessment includes several elements that will help you improve critical aspects of your web mapping skills:

- **Design**: this is not about making maps, this is about making good maps. And behind every good map there is a set of conscious choices that you will have to think throug to be successful (what map? what data? how to present the data? etc.).
- **Technology**: at the end of the day, building good web maps requires solid understanding of current technology that goes beyond what the average person can be expected to know. In this assignment, you will need to demonstrate you are proficient in a series of tasks manipulating geospatial data in a web environment.
- **Presentation**: in many real-world contexts, your work is as good as it can come across to the audience it is intended to. This means that it is vital to be able to communicate not only what you are doing but why and on what building blocks it is based on.

Setting up the Working Environment

Follow the instructions for your Operating System and test your installation. If you experience any issues, write a message on the MS Teams channel of the module.

Setting up the Python environment is necessary for:

- Executing the Jupyter Notebooks of the Lab sessions of the course.
- Preparing your own Jupyter Notebooks for the assignments (one each).

We will use `Miniconda` to handle our working environment.

Miniconda is a free minimal installer for conda. It is a small bootstrap version of Anaconda that includes only conda, Python, the packages they both depend on, and a small number of other useful packages.

Set up Miniconda (and Python) on MS Windows

Installation

1. Install Miniconda:

   - *Option 1*: On a UoL Machine: Download and install Miniconda from here. This will install Miniconda and Python in `C:\`. If this process is aborted because it requires administrator rights, press `Start`, select `Install University Applications`, type and choose `Miniconda`.
   - *Option 2*, **Recommended**: Install Miniconda on your personal laptop: Follow the instructions here.

2. During the installation, leave the default settings. In particular, when asked whom to "Install Miniconda for", choose "Just for me".

Important: If you do choose to work on University Machines you will have to reinstall `Miniconda` every lab session unless you use a PC where Miniconda has been installed already.

Set up the Directories

1. Create a folder where you want to keep your work conducted throughout this course. For example, call it `geovis`. You can save it wherever you want. If you are working on a university machine, it could be worth creating it in `M:\`, which should be your "virtual" hard-disk.

   Example fictional path (Windows, personal laptop): `C:\Users\YourName\Documents\geovis\`
   Example path (Windows, UoL machine): `M:\geovis\`

2. Download the data and the images for running and rendering the Jupyter notebooks.

3. Unzip the folders and move the nested folders into the folder `geovis`.

4. Create another folder called `labs`.

The folder structure should look like:

```
geovis/
    data/
    labs_img/
    labs/
```

Set up the Python Environment

1. Download the `geovis.yml` from GitHub by clicking `Download raw file`, top right, at this page.

2. Save it in the folder `geovis` created before.

   Example path: `C:\Users\YourName\AnyFolder\geovis\geovis.yml`; **UoL machine example:** `M:\geovis\geovis.yml`

3. Type in the search bar and find the `Anaconda Prompt (miniconda 3)`. Launch it. The terminal should appear.

4. In the **Anaconda Prompt**, run the following, one at the time:

   - `conda install -n base -c conda-forge conda-libmamba-solver -y`
   - `conda config --set solver libmamba`
   - `conda config --set channel_priority strict`
   - `conda env create -f "C:\Users\yourname\AnyFolder\geovis\geovis.yml"`

5. If you are prompted any questions, press `y`. This process will install all the packages necessary to carry out the lab sessions.

6. In the **Anaconda Prompt** write and run: `conda activate geovis`. This activates your working environment.

7. *Necessary on University machines, otherwise optional:* configuration of Jupyter Notebooks

- In the **Anaconda Prompt**, run: `jupyter server --generate-config`. This should create a file at: `C:\Users\YourName\.jupyter\jupyter_server_config.py`

- Open the file with a text editor (e.g. Notepad++). Do a `Ctrl+F` search for: `c.ServerApp.root_dir`

- Uncomment it and set it to your course folder (the folder where you created `geovis`). Example: `c.ServerApp.root_dir = r"M:\geovis"`(use your own path if different).

- Save the file and close it.

Start a Lab Session

1. Download the Jupyter Notebook of the session in your folder. Choose one Jupyter notebook from here and click `Download raw file` as shown below.

2. Save the file in the `labs` folder within your `geovis` folder on your machine.

3. Type in the search bar, find and open the `Anaconda Prompt (miniconda 3)`.

4. In the **Anaconda Prompt** run: `conda activate geovis`

5. (*Recommended*) "Move" into your course folder so Jupyter opens in the right place: `cd "C:\Users\YourName\AnyFolder\geovis\labs"`(or `cd "M:\geovis\labs"` on UoL machines).

6. In the **Anaconda Prompt** run: `jupyter notebook`. This should open Jupyter Notebook in your default browser.

7. Navigate to your course folder and double click on the notebook downloaded in step 1.

8. You can now work on your copy of the notebook.

Follow these instructions and test your installation **prior to the first Lab Session**. If you experience any issues, write a message on the MS Teams channel of the module.

Set up Miniconda (and Python) on Mac

Installation

To install Miniconda on your personal laptop, follow the instructions here. During the installation, leave the default settings. In particular, when asked whom to "Install Miniconda for", choose "Just for me".

Set up the Directories

1. Create a folder where you want to keep your work conducted throughout this course. For example, call it geovis. You can save it wherever you want.

Example fictional path (Mac): /Users/yourname/Documents/geovis/;

Example fictional path (Mac): /Users/yourname/Library/CloudStorage/Dropbox/geovis/

2. Download the data and the images for running and rendering the Jupyter notebooks.

3. Unzip the folders and move the nested folders into the folder geovis.

4. Create another folder called labs.

The folder structure should look like:

```
geovis/
    data/
    labs_img/
    labs/
```

Set up the Python Environment

1. Download the `geovis.yml` from GitHub by clicking `Download raw file`, top right, at this page.

2. Save it in the folder `geovis` created before.

3. Open the **Terminal**.

4. In the **Anaconda Prompt**, run the following, one at the time:

   - `conda install -n base -c conda-forge conda-libmamba-solver -y`
   - `conda config --set solver libmamba`
   - `conda config --set channel_priority strict`
   - `conda env create -f "/Users/yourname/Documents/geovis/geovis.yml"`

5. If you are prompted any questions, press `y`. This process will install all the packages necessary to carry out the lab sessions.

6. Activate the environment: `conda activate geovis`

Start a Lab Session

1. Download the Jupyter Notebook of the session in your folder. Choose one Jupyter notebook from here and click `Download raw file` as shown below.

2. Save the file in the `labs` folder within your `geovis` folder on your machine.

3. Open the **Terminal**.

4. Activate the environment: `conda activate geovis`

5. (*Recommended*) "Move" into your `labs` folder so Jupyter opens in the right place: `cd "/Users/yourname/Documents/geovis/labs"`

6. Start Jupyter Notebook: `jupyter notebook`

7. This should open Jupyter Notebook in your default browser. You should see something like this:

8. Navigate to your folder. You can now work on your copy of the notebook.

1 Introduction & Python Refresher

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

1.1 Part I: Powerful (Web) Mapping Examples

This part of the lab has two main components: 1. The first one will require you to find a partner and work together with them 2. And the second one will involve group discussion.

1.1.1 Paired Activity

In pairs, find **three** examples where web maps are used to communicate an idea. Complete the following sheet for each example:

- **Substantive**

    - `Title`: Title of the map/project
    - `Author`: Who is behind the project?
    - `Big idea`: a "one-liner" on what the project tries to accomplish –
    - `Message`: what does the map try to get accross

- **Technical**

    - `URL`:
    - `Interactivity`: does the map let you interact with it in any way? Yes/No
    - `Zoomable`: can you explore the map at different scales? Yes/No
    - `Design`: what geovisualisation solutions have been adopted?
    - `Basemap`: Is there an underlying map providing geographical context? Yes/No. If so, who is it provided by?
    - `Technology`: can you guess what technology does this map rely on?

Post each sheet as a separate item on the Teams channel for Lab No.1

1.1.1.1 Example

The project "WHO Coronavirus (COVID-19) Dashboard"

- **Substantive**

    - `Title`: WHO Coronavirus (COVID-19) Dashboard
    - `Author`: World Health Organization
    - `Big idea`: Shows confirmed COVID-19 cases and deaths by country to date
    - `Message`: The project displays a map of the world where COVID-19 cases are shown by country. This element is used to show which countries have had more cases (large trends). A drop down button allows us to visualise the map by a) Total per 100,000 population b) % change in the last 7 days c) newly reported in the last 7 days d) newly reported in the last 24 hours.

- **Technical**

    - URL: https://covid19.who.int/
    - `Interactivity`: Yes
    - `Zoomable`: Yes
    - `Tooltips`: Yes
    - `Basemap`: No
    - `Technology`: Unknown

1.1.2 Class discussion

We will select a few examples posted and collectively discuss (some of) the following questions:

1. What makes them powerful, what "speaks" to us?
2. What could be improved, what is counter-intuitive?
3. What design elements do they rely on?
4. What technology do they use?

1.1.3 References

- For an excellent coverage of "visualisation literacy", Chapter 11 of Andy Kirk's "Data Visualisation" is a great start.
- A comprehensive overview of computational notebooks and how they relate to modern scientific work is available on Ch.1 of the GDS book.
- A recent overview of notebooks in Geography is available in Boeing & Arribas-Bel (2021)

1.2 Part II: Python/Pandas (Refresher)

Gabriele Filomena has prepared this notebook by readapting material shared on this repository.
Copyright (c) 2013-2023 Geoff Boeing.

1.2.1 Python

A quick overview of ubiquitous programming concepts including data types, for loops, if-then-else conditionals, and functions.

```python
import numpy as np
import pandas as pd
```

```python
# integers (int)
x = 100
type(x)
```

```
int
```

```python
# floating-point numbers (float)
x = 100.5
type(x)
```

```
float
```

```python
# sequence of characters (str)
x = 'Los Angeles, CA 90089'
len(x)
```

```
21
```

```python
# list of items
x = [1, 2, 3, 'USC']
len(x)
```

```
4
```

```
# sets are unique
x = {2, 2, 3, 3, 1}
x
```

{1, 2, 3}

```
# tuples are immutable sequences
latlng = (34.019425, -118.283413)
type(latlng)
```

tuple

```
# you can unpack a tuple
lat, lng = latlng
type(lat)
```

float

```
# dictionary of key:value pairs
iceland = {'Country': 'Iceland', 'Population': 372520, 'Capital': 'Reykjavík', '% Foreign Po
type(iceland)
```

dict

```
# you can convert types
x = '100'
print(type(x))
y = int(x)
print(type(y))
```

<class 'str'>
<class 'int'>

```
# you can loop through an iterable, such as a list or tuple
for coord in latlng:
    print('Current coordinate is:', coord)
```

Current coordinate is: 34.019425
Current coordinate is: -118.283413

```python
# loop through a dictionary keys and values as tuples
for key, value in iceland.items():
    print(key, value)
```

```
Country Iceland
Population 372520
Capital Reykjavík
% Foreign Population 0.18
```

```python
# booleans are trues/falses
x = 101
x > 100
```

```
True
```

```python
# use two == for equality and one = for assignment
x == 100
```

```
False
```

```python
# if, elif, else for conditional branching execution
x = 101
if x > 100:
    print('Value is greater than 100.')
elif x < 100:
    print('Value is less than 100.')
else:
    print('Value is 100.')
```

```
Value is greater than 100.
```

```python
# use functions to encapsulate and reuse bits of code
def convert_items(my_list, new_type=str):
    # convert each item in a list to a new type
    new_list = [new_type(item) for item in my_list]
    return new_list

l = [1, 2, 3, 4]
convert_items(l)
```

```
['1', '2', '3', '4']
```

1.2.2 `pandas` Series and DataFrames

pandas has two primary data structures we will work with: `Series` and `DataFrame`.

1.2.2.1 Pandas Series

```python
# a pandas series is based on a numpy array: it's fast, compact, and has more functionality
# it has an index which allows you to work naturally with tabular data
my_list = [8, 5, 77, 2]
my_series = pd.Series(my_list)
my_series
```

```
0     8
1     5
2    77
3     2
dtype: int64
```

```python
# look at a list-representation of the index
my_series.index.tolist()
```

```
[0, 1, 2, 3]
```

```python
# look at the series' values themselves
my_series.values
```

```
array([ 8,  5, 77,  2])
```

```python
# what's the data type of the series' values?
type(my_series.values)
```

```
numpy.ndarray
```

```python
# what's the data type of the individual values themselves?
my_series.dtype
```

```
dtype('int64')
```

1.2.2.2 Pandas DataFrames

```
# a dict can contain multiple lists and label them
my_dict = {'hh_income'  : [75125, 22075, 31950, 115400],
           'home_value' : [525000, 275000, 395000, 985000]}
my_dict
```

```
{'hh_income': [75125, 22075, 31950, 115400],
 'home_value': [525000, 275000, 395000, 985000]}
```

```
# a pandas dataframe can contain one or more columns
# each column is a pandas series
# each row is a pandas series
# you can create a dataframe by passing in a list, array, series, or dict
df = pd.DataFrame(my_dict)
df
```

	hh_income	home_value
0	75125	525000
1	22075	275000
2	31950	395000
3	115400	985000

```
# the row labels in the index are accessed by the .index attribute of the DataFrame object
df.index.tolist()
```

```
[0, 1, 2, 3]
```

```
# the column labels are accessed by the .columns attribute of the DataFrame object
df.columns
```

```
Index(['hh_income', 'home_value'], dtype='str')
```

```
# the data values are accessed by the .values attribute of the DataFrame object
# this is a numpy (two-dimensional) array
df.values
```

```
array([[ 75125, 525000],
       [ 22075, 275000],
       [ 31950, 395000],
       [115400, 985000]])
```

1.2.3 Loading data in Pandas

Usually, you'll work with data by loading a dataset file into pandas. CSV is the most common format. But pandas can also ingest tab-separated data, JSON, and proprietary file formats like Excel .xlsx files, Stata, SAS, and SPSS.

Below, notice what pandas's `read_csv` function does:

1. Recognize the header row and get its variable names.
2. Read all the rows and construct a pandas DataFrame (an assembly of pandas Series rows and columns).
3. Construct a unique index, beginning with zero.
4. Infer the data type of each variable (i.e., column).

```python
# load a data file
# note the relative filepath! where is this file located?
# use dtype argument if you don't want pandas to guess your data types
df = pd.read_csv('../data/GTD_2022.csv', low_memory = False)
```

```python
to_replace = [-9, -99, "-9", "-99"]
for value in to_replace:
    df = df.replace(value, np.nan)

df['eventid'] = df['eventid'].astype("Int64")
```

```python
# dataframe shape as rows, columns
df.shape
```

```
(209706, 75)
```

```python
# or use len to just see the number of rows
len(df)
```

```
209706
```

```python
# view the dataframe's "head"
df.head()
```

	eventid	year	date	extended	country	country_txt	region	region_txt
0	201000000000	2005	28/05/2005	1	153	Pakistan	6	South Asia
1	201000000000	2005	29/05/2005	1	95	Iraq	10	Middle East & North Af
2	201000000000	2007	08/06/2007	1	95	Iraq	10	Middle East & North Af
3	201000000000	2010	15/06/2010	1	4	Afghanistan	6	South Asia
4	201000000000	2011	06/01/2011	1	92	India	6	South Asia

```
# view the dataframe's "tail"
df.tail()
```

	eventid	year	date	extended	country	country_txt	region	region_txt
209701	202000000000	2020	31/12/2020	0	228	Yemen	10	Middle East & No
209702	202000000000	2020	31/12/2020	0	228	Yemen	10	Middle East & No
209703	202000000000	2020	31/12/2020	0	75	Germany	8	Western Europe
209704	202000000000	2020	31/12/2020	0	4	Afghanistan	6	South Asia
209705	202000000000	2020	31/12/2020	1	33	Burkina Faso	11	Sub-Saharan Afric

```
# column data types
df.dtypes
```

```
eventid        Int64
year           int64
date             str
extended       int64
country        int64
                ...
INT_LOG      float64
INT_IDEO     float64
INT_MISC     float64
INT_ANY      float64
related          str
Length: 75, dtype: object
```

```
# or
for dt in df.columns[:10]:
    print(dt, type(dt))
```

```
eventid <class 'str'>
```

```
year <class 'str'>
date <class 'str'>
extended <class 'str'>
country <class 'str'>
country_txt <class 'str'>
region <class 'str'>
region_txt <class 'str'>
city <class 'str'>
latitude <class 'str'>
```

1.2.4 Selecting and slicing data from a DataFrame

```
# CHEAT SHEET OF COMMON TASKS
# Operation                      Syntax          Result
#-------------------------------------------------------------
# Select column by name          df[col]         Series
# Select columns by name         df[col_list]    DataFrame
# Select row by label            df.loc[label]   Series
# Select row by integer location df.iloc[loc]    Series
# Slice rows by label            df.loc[a:c]     DataFrame
# Select rows by boolean vector  df[mask]        DataFrame
```

1.2.4.1 Select DataFrame's column(s) by name

```
# select a single column by column name
# this is a pandas series
df['country']
```

```
0          153
1           95
2           95
3            4
4           92
          ...
209701     228
209702     228
209703      75
209704       4
```

```
209705        33
Name: country, Length: 209706, dtype: int64
```

```
# select multiple columns by a list of column names
# this is a pandas dataframe that is a subset of the original
df[['country_txt', 'year']]
```

	country_txt	year
0	Pakistan	2005
1	Iraq	2005
2	Iraq	2007
3	Afghanistan	2010
4	India	2011
...	...	...
209701	Yemen	2020
209702	Yemen	2020
209703	Germany	2020
209704	Afghanistan	2020
209705	Burkina Faso	2020

```
# create a new column by assigning df['new_col'] to some values
# people killed every perpetrator
df['killed_per_attacker'] = df['nkill'] / df['nperps']

# inspect the results
df[['country', 'year', 'nkill', 'nperps', 'killed_per_attacker']].head(15)
```

	country	year	nkill	nperps	killed_per_attacker
0	153	2005	1.0	NaN	NaN
1	95	2005	1.0	NaN	NaN
2	95	2007	15.0	50.0	0.300000
3	4	2010	1.0	NaN	NaN
4	92	2011	1.0	NaN	NaN
5	160	2011	1.0	30.0	0.033333
6	95	2011	1.0	NaN	NaN
7	155	2002	7.0	3.0	2.333333
8	92	2010	5.0	100.0	0.050000
9	153	2011	4.0	NaN	NaN
10	4	2011	1.0	NaN	NaN

	country	year	nkill	nperps	killed_per_attacker
11	153	2011	2.0	NaN	NaN
12	186	2001	12.0	60.0	0.200000
13	4	2006	6.0	NaN	NaN
14	155	2007	0.0	NaN	NaN

1.2.4.2 Select row(s) by label

```
# use .loc to select by row label
# returns the row as a series whose index is the dataframe column names
df.loc[0]
```

```
eventid                  201000000000
year                             2005
date                       28/05/2005
extended                            1
country                           153
                       ...
INT_IDEO                          NaN
INT_MISC                          0.0
INT_ANY                           NaN
related                           NaN
killed_per_attacker               NaN
Name: 0, Length: 76, dtype: object
```

```
# use .loc to select single value by row label, column name
df.loc[15, 'gname'] #group name
```

```
'Taliban'
```

```
# slice of rows from label 5 to label 7, inclusive
# this returns a pandas dataframe
df.loc[5:7]
```

	eventid	year	date	extended	country	country_txt	region	region_txt
5	201000000000	2011	08/01/2011	0	160	Philippines	5	Southeast
6	201000000000	2011	11/04/2011	1	95	Iraq	10	Middle Ea

	eventid	year	date	extended	country	country_txt	region	region_txt
7	200000000000	2002	16/07/2002	0	155	West Bank and Gaza Strip	10	Middle Ea

```python
# slice of rows from label 17 to label 27, inclusive
# slice of columns from country_txt to city, inclusive
df.loc[17:27, 'country_txt':'city']
```

	country_txt	region	region_txt	city
17	India	6	South Asia	Mumbai
18	India	6	South Asia	Mumbai
19	Afghanistan	6	South Asia	Khost
20	India	6	South Asia	Unknown
21	Pakistan	6	South Asia	Lahore
22	Pakistan	6	South Asia	Lahore
23	Pakistan	6	South Asia	Mullazai
24	Colombia	3	South America	El Tambo
25	Nigeria	11	Sub-Saharan Africa	Unknown
26	Pakistan	6	South Asia	Quetta
27	Kenya	11	Sub-Saharan Africa	Nairobi

```python
# subset of rows from with labels in list
# subset of columns with names in list
df.loc[[1, 350], ['country', 'gname']]
```

	country	gname
1	95	Ansar al-Sunna
350	147	Boko Haram

```python
# you can use a column of identifiers as the index (indices do not *need* to be unique)
df_gname = df.set_index('gname')
df_gname.index.is_unique
```

False

```python
df_gname.head(3)
```

	eventid	year	date	extended	country	country_txt	region	region_tx
gname								
Unknown	201000000000	2005	28/05/2005	1	153	Pakistan	6	South As
Ansar al-Sunna	201000000000	2005	29/05/2005	1	95	Iraq	10	Middle E
Al-Qaida in Iraq	201000000000	2007	08/06/2007	1	95	Iraq	10	Middle E

```python
# .loc works by label, not by position in the dataframe
try:
    df_gname.loc[0]
except KeyError as e:
    print('label not found')
```

```
label not found
```

```python
# the index now contains gname values, so you have to use .loc accordingly to select by row
df_gname.loc['Taliban'].head()
```

	eventid	year	date	extended	country	country_txt	region	region_txt	city
gname									
Taliban	201000000000	2010	15/06/2010	1	4	Afghanistan	6	South Asia	Sayd
Taliban	201000000000	2006	26/08/2006	0	4	Afghanistan	6	South Asia	Muqu
Taliban	201000000000	2008	27/04/2008	0	4	Afghanistan	6	South Asia	Muh
Taliban	201000000000	2009	12/05/2009	0	4	Afghanistan	6	South Asia	Khos
Taliban	201000000000	2014	28/03/2014	0	4	Afghanistan	6	South Asia	Kabu

1.2.4.3 Select by (integer) position - Independent from actual Index

```python
# get the row in the zero-th position in the dataframe
df.iloc[0]
```

```
eventid              201000000000
year                         2005
date                   28/05/2005
extended                        1
country                       153
                         ...
INT_IDEO                      NaN
```

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```
INT_MISC                    0.0
INT_ANY                     NaN
related                     NaN
killed_per_attacker         NaN
Name: 0, Length: 76, dtype: object
```

```
# you can slice as well
# note, while .loc is inclusive, .iloc is not
# get the rows from position 0 up to but not including position 3 (ie, rows 0, 1, and 2)
df.iloc[0:3]
```

	eventid	year	date	extended	country	country_txt	region	region_txt
0	201000000000	2005	28/05/2005	1	153	Pakistan	6	South Asia
1	201000000000	2005	29/05/2005	1	95	Iraq	10	Middle East & North Afr
2	201000000000	2007	08/06/2007	1	95	Iraq	10	Middle East & North Afr

```
# get the value from the row in position 3 and the column in position 2 (zero-indexed)
df.iloc[3, 6] #country_txt
```

```
np.int64(6)
```

1.2.4.4 Select/filter by value

You can subset or filter a dataframe for based on the values in its rows/columns.

```
# filter the dataframe by urban areas with more than 25 million residents
df[df['nkill'] > 30].head()
```

	eventid	year	date	extended	country	country_txt	region	region_txt
17	201000000000	2008	26/11/2008	1	92	India	6	South Asia
18	201000000000	2008	26/11/2008	1	92	India	6	South Asia
27	201000000000	2013	21/09/2013	1	104	Kenya	11	Sub-Saharan Africa
38	201000000000	2014	17/07/2014	1	200	Syria	10	Middle East & North A
39	201000000000	2014	24/07/2014	0	200	Syria	10	Middle East & North A

```
# you can chain multiple conditions together
# pandas logical operators are: | for or, & for and, ~ for not
# these must be grouped by using parentheses due to order of operations
df[['country','nkill', 'nwound']][(df['nkill'] > 200) & (df['nwound'] > 10)].head()
# columns on the left-hand side are here used to slice the resulting output
```

	country	nkill	nwound
427	229	339.0	28.0
1000	217	1385.0	10878.0
1001	217	1385.0	10878.0
2780	1004	287.0	400.0
3787	4	266.0	64.0

```
# ~ means not... it essentially flips trues to falses and vice-versa
df[['country','nkill', 'nwound']][~(df['nkill'] > 200) & (df['nwound'] > 10)]
```

	country	nkill	nwound
7	155	7.0	16.0
17	92	68.0	76.0
18	92	32.0	22.0
19	4	9.0	25.0
21	153	29.0	31.0
...	...	...	...
209528	4	10.0	15.0
209547	153	3.0	17.0
209636	4	1.0	13.0
209659	153	0.0	14.0
209681	228	30.0	60.0

1.2.5 Grouping and summarizing

```
# group by terroristic group name
groups = df.groupby('gname')
```

```
# what is the median number of people killed per event across the different groups?
groups['nkill'].median().sort_values(ascending=False)
```

```
gname
Samri militia                                       766.0
Gumuz militia                                       222.0
Dissident Military Mmbrs of Northern Tribal Group   150.0
Ansar al-Din Front                                  103.0
Issa and Gurgura Liberation Front                   100.0
                                                      ...
Western Somalia Liberation Front                      NaN
Workers of the Company                                NaN
World Punishment Organization                         NaN
Zawiya Martyrs Brigade                                NaN
Zimbabwe Guerrillas                                   NaN
Name: nkill, Length: 3725, dtype: float64
```

```
# look at several columns' medians by group
groups[['nkill', 'nwound', 'nperps']].median()
```

	nkill	nwound	nperps
gname			
01-May	0.0	0.0	1.5
09-Feb	0.0	0.0	NaN
14 K Triad	0.0	0.0	8.0
14 March Coalition	5.0	80.0	NaN
14th of December Command	0.0	0.0	NaN
...	...	...	...
Zulu Miners	1.0	10.0	NaN
Zuwar al-Imam Rida	0.0	0.0	4.0
Zviadists	0.0	0.0	NaN
Zwai Tribe	5.0	NaN	NaN
leftist guerrillas-Bolivarian militia	0.0	0.0	NaN

```
# you can create a new dataFrame by directly passing columns between "[[ ]]", after the group
# to do so, you also need to pass a function that can deal with the values (e.g. sum..etc)
western_europe = df[df.region_txt == 'Western Europe']
western_europe.groupby('country_txt')[['nkill', 'nwound']].sum().sort_values('nkill', ascend
```

	country_txt	nkill	nwound
0	United Kingdom	3426.0	6321.0
1	Spain	1289.0	4937.0

	country_txt	nkill	nwound
2	France	565.0	2565.0
3	Italy	420.0	1320.0
4	Greece	264.0	763.0
5	Ireland	108.0	26.0
6	Germany	103.0	735.0
7	West Germany (FRG)	97.0	862.0
8	Belgium	83.0	523.0
9	Norway	80.0	90.0
10	Switzerland	75.0	98.0
11	Cyprus	45.0	41.0
12	Netherlands	41.0	75.0
13	Austria	37.0	150.0
14	Portugal	32.0	95.0
15	Sweden	22.0	83.0
16	Finland	12.0	37.0
17	Malta	5.0	12.0
18	Denmark	5.0	31.0
19	Andorra	0.0	0.0
20	Iceland	0.0	0.0
21	Luxembourg	0.0	6.0
22	Vatican City	0.0	3.0

1.2.6 Indexes

Each `DataFrame` has an index. Indexes do not have to be unique (but that would be for the best)

```
# resetting index (when loading a .csv file pandas creates an index automatically, from 0 to
df.reset_index(drop = True).sort_index().head() # this does not assign the new index though,
```

	eventid	year	date	extended	country	country_txt	region	region_txt
0	201000000000	2005	28/05/2005	1	153	Pakistan	6	South Asia
1	201000000000	2005	29/05/2005	1	95	Iraq	10	Middle East & North Af
2	201000000000	2007	08/06/2007	1	95	Iraq	10	Middle East & North Af
3	201000000000	2010	15/06/2010	1	4	Afghanistan	6	South Asia
4	201000000000	2011	06/01/2011	1	92	India	6	South Asia

```
#this does assign the new index to your df
df = df.reset_index(drop = True).sort_index()
df.head()
```

	eventid	year	date	extended	country	country_txt	region	region_txt
0	201000000000	2005	28/05/2005	1	153	Pakistan	6	South Asia
1	201000000000	2005	29/05/2005	1	95	Iraq	10	Middle East & North Af
2	201000000000	2007	08/06/2007	1	95	Iraq	10	Middle East & North Af
3	201000000000	2010	15/06/2010	1	4	Afghanistan	6	South Asia
4	201000000000	2011	06/01/2011	1	92	India	6	South Asia

```
# index isn't unique
df.index.is_unique
```

```
True
```

```
# you can set a new index
# drop -> Delete columns to be used as the new index.
# append ->  whether to append columns to existing index.
df = df.set_index('eventid', drop=True, append=False)
df.index.name = None # remove the index "name"
df.head()

# this index is not ideal, but it's the original source's id
```

	year	date	extended	country	country_txt	region	region_txt
201000000000	2005	28/05/2005	1	153	Pakistan	6	South Asia
201000000000	2005	29/05/2005	1	95	Iraq	10	Middle East & North Africa
201000000000	2007	08/06/2007	1	95	Iraq	10	Middle East & North Africa
201000000000	2010	15/06/2010	1	4	Afghanistan	6	South Asia
201000000000	2011	06/01/2011	1	92	India	6	South Asia

1.3 Part III: Geospatial Vector data in Python

Gabriele Filomena has prepared this notebook by readapting material shared on this repository.
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```
%matplotlib inline

import geopandas as gpd
```

1.3.1 Importing geospatial data

GeoPandas builds on Pandas types `Series` and `Dataframe`, by incorporating information about geographical space.

- `GeoSeries`: a Series object designed to store shapely geometry object
- `GeoDataFrame`: object is a pandas DataFrame that has a column with geometry (that contains a *Geoseries*)

We can use the GeoPandas library to read many of GIS file formats (relying on the `fiona` library under the hood, which is an interface to GDAL/OGR), using the `gpd.read_file` function. For example, let's start by reading a shapefile with all the countries of the world (adapted from http://www.naturalearthdata.com/downloads/110m-cultural-vectors/110m-admin-0-countries/, zip file is available in the `/data` directory), and inspect the data:

```
countries = gpd.read_file("../data/ne_countries.zip")
# or if the archive is unpacked:
# countries = gpd.read_file("../data/ne_countries.shp")
```

```
countries.head()
```

	iso_a3	name	continent	pop_est	gdp_md_est	geometry
0	AFG	Afghanistan	Asia	34124811.0	64080.0	POLYGON ((61.21082 35.0
1	AGO	Angola	Africa	29310273.0	189000.0	MULTIPOLYGON (((23.9
2	ALB	Albania	Europe	3047987.0	33900.0	POLYGON ((21.02004 40.8
3	ARE	United Arab Emirates	Asia	6072475.0	667200.0	POLYGON ((51.57952 24.
4	ARG	Argentina	South America	44293293.0	879400.0	MULTIPOLYGON (((-66.9

```
countries.plot()
```

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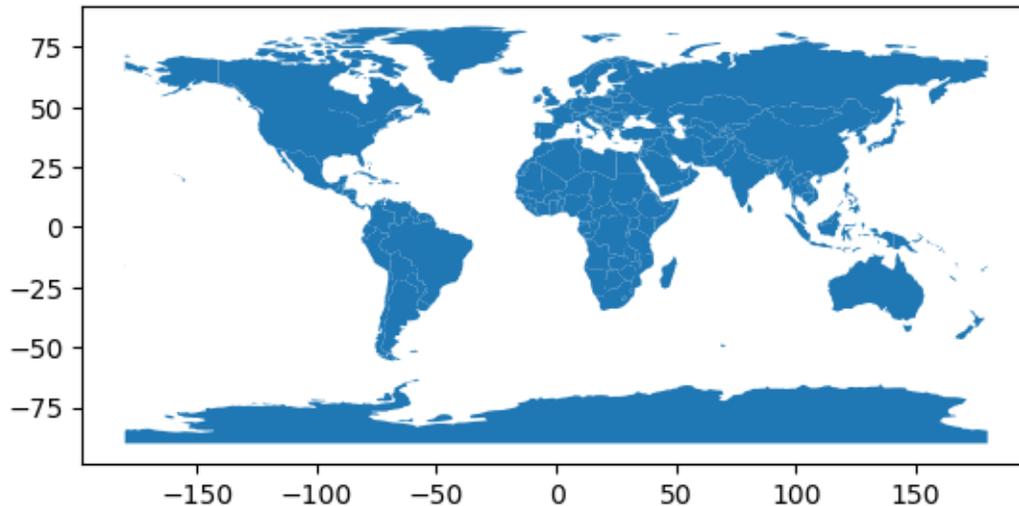
We observe that:

- Using `.head()` we can see the first rows of the dataset, just like we can do with Pandas.
- There is a `geometry` column and the different countries are represented as polygons
- We can use the `.plot()` (matplotlib) method to quickly get a *basic* visualization of the data

1.3.2 What's a GeoDataFrame?

We used the GeoPandas library to read in the geospatial data, and this returned us a `GeoDataFrame`:

```
type(countries)
```

```
geopandas.geodataframe.GeoDataFrame
```

A GeoDataFrame contains a tabular, geospatial dataset:

- It has a 'geometry' column that holds the geometry information (or features in GeoJSON).
- The other columns are the **attributes** (or properties in GeoJSON) that describe each of the geometries.

Such a `GeoDataFrame` is just like a pandas `DataFrame`, but with some additional functionality for working with geospatial data: * A `geometry` attribute that always returns the column with the geometry information (returning a `GeoSeries`). The column name itself does not

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necessarily need to be 'geometry', but it will always be accessible as the `geometry` attribute.
* It has some extra methods for working with spatial data (area, distance, buffer, intersection, ...) see here, for example.

```
countries.geometry.head()
```

```
0    POLYGON ((61.21082 35.65007, 62.23065 35.27066...
1    MULTIPOLYGON (((23.90415 -11.72228, 24.07991 -...
2    POLYGON ((21.02004 40.84273, 20.99999 40.58, 2...
3    POLYGON ((51.57952 24.2455, 51.75744 24.29407,...
4    MULTIPOLYGON (((-66.95992 -54.89681, -67.56244...
Name: geometry, dtype: geometry
```

```
type(countries.geometry)
```

```
geopandas.geoseries.GeoSeries
```

```
countries.geometry.area
```

```
C:\Users\gfilo\AppData\Local\Temp\ipykernel_2500\3077649407.py:1: UserWarning: Geometry is i

  countries.geometry.area
```

```
0        63.593500
1       103.599439
2         3.185163
3         7.095047
4       278.923392
           ...
172       0.631326
173      38.475618
174     112.718524
175      62.789498
176      32.280371
Length: 177, dtype: float64
```

It's still a `DataFrame`, so we have all the `pandas` functionality available to use on the geospatial dataset, and to do data manipulations with the attributes and geometry information together. For example, we can calculate the average population over all countries (by accessing the 'pop_est' column, and calling the `mean` method on it):

```
countries['pop_est'].mean()
```

np.float64(41712369.84180791)

```
africa = countries[countries['continent'] == 'Africa']
```

```
africa.plot();
```
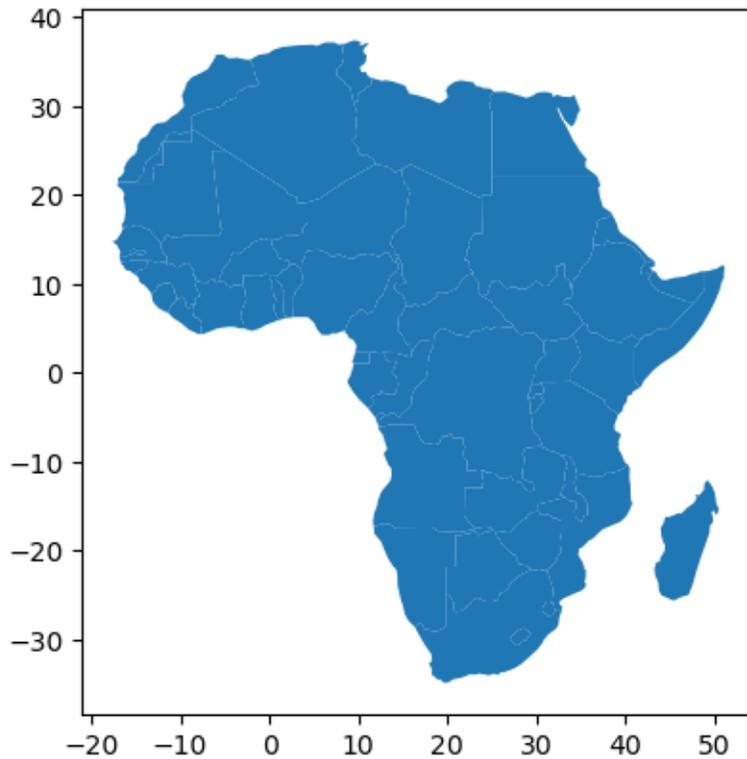

The rest of the tutorial is going to assume you already know some pandas basics, but we will try to give hints for that part for those that are not familiar.

Important:

- A `GeoDataFrame` allows to perform typical tabular data analysis together with spatial operations
- A `GeoDataFrame` (or *Feature Collection*) consists of:
    - **Geometries** or **features**: the spatial objects
    - **Attributes** or **properties**: columns with information about each spatial object

1.3.3 Geometries: Points, Linestrings and Polygons

Spatial **vector** data can consist of different types, and the 3 fundamental types are:

- **Point** data: represents a single point in space.
- **Line** data ("LineString"): represented as a sequence of points that form a line.
- **Polygon** data: represents a filled area.

And each of them can also be combined in multi-part geometries (See https://shapely.readthedocs.io/en/stable/m objects for extensive overview).

For the example we have seen up to now, the individual geometry objects are Polygons:

```python
print(countries.geometry[2])
```

```
POLYGON ((21.0200403174764 40.84272695572588, 20.999989861747224 40.58000397395401, 20.674996
```

Let's import some other datasets with different types of geometry objects.

A dateset about cities in the world (adapted from http://www.naturalearthdata.com/downloads/110m-cultural-vectors/110m-populated-places/, zip file is available in the `/data` directory), consisting of `Point` data:

```python
cities = gpd.read_file("../data/ne_cities.zip")
```

```python
print(cities.geometry[0])
```

```
POINT (12.453386544971766 41.903282179960115)
```

And a dataset of rivers in the world (from http://www.naturalearthdata.com/downloads/50m-physical-vectors/50m-rivers-lake-centerlines/, zip file is available in the `/data` directory) where each river is a `(Multi-)LineString`:

```python
rivers = gpd.read_file("../data/ne_rivers.zip")
```

```python
print(rivers.geometry[0])
```

```
LINESTRING (51.9371337598152 55.70106609892139, 51.880866467313695 55.68625891701544, 51.8203
```

1.3.4 The `shapely` library

The individual geometry objects are provided by the `shapely` library

```python
from shapely.geometry import Point, Polygon, LineString
```

```python
type(countries.geometry[0])
```

```
shapely.geometry.polygon.Polygon
```

To construct one ourselves:

```python
p = Point(0, 0)
```

```python
print(p)
```

```
POINT (0 0)
```

```python
polygon = Polygon([(1, 1), (2,2), (2, 1)])
```

```python
polygon.area
```

```
0.5
```

```python
polygon.distance(p)
```

```
1.4142135623730951
```

Important:

Single geometries are represented by `shapely` objects:

- If you access a single geometry of a GeoDataFrame, you get a shapely geometry object
- Those objects have similar functionality as geopandas objects (GeoDataFrame/GeoSeries). For example:
  - `single_shapely_object.distance(other_point)` -> distance between two points
  - `geodataframe.distance(other_point)` -> distance for each point in the geodataframe to the other point

1.3.5 Plotting

```
%matplotlib inline
import matplotlib
import matplotlib.pyplot as plt

fig, ax = plt.subplots(1, 1, figsize=(15, 10))
countries.plot(ax = ax, edgecolor='k', facecolor='none')
rivers.plot(ax=ax)
cities.plot(ax=ax, color='red')
ax.set(xlim=(-20, 60), ylim=(-40, 40))
```
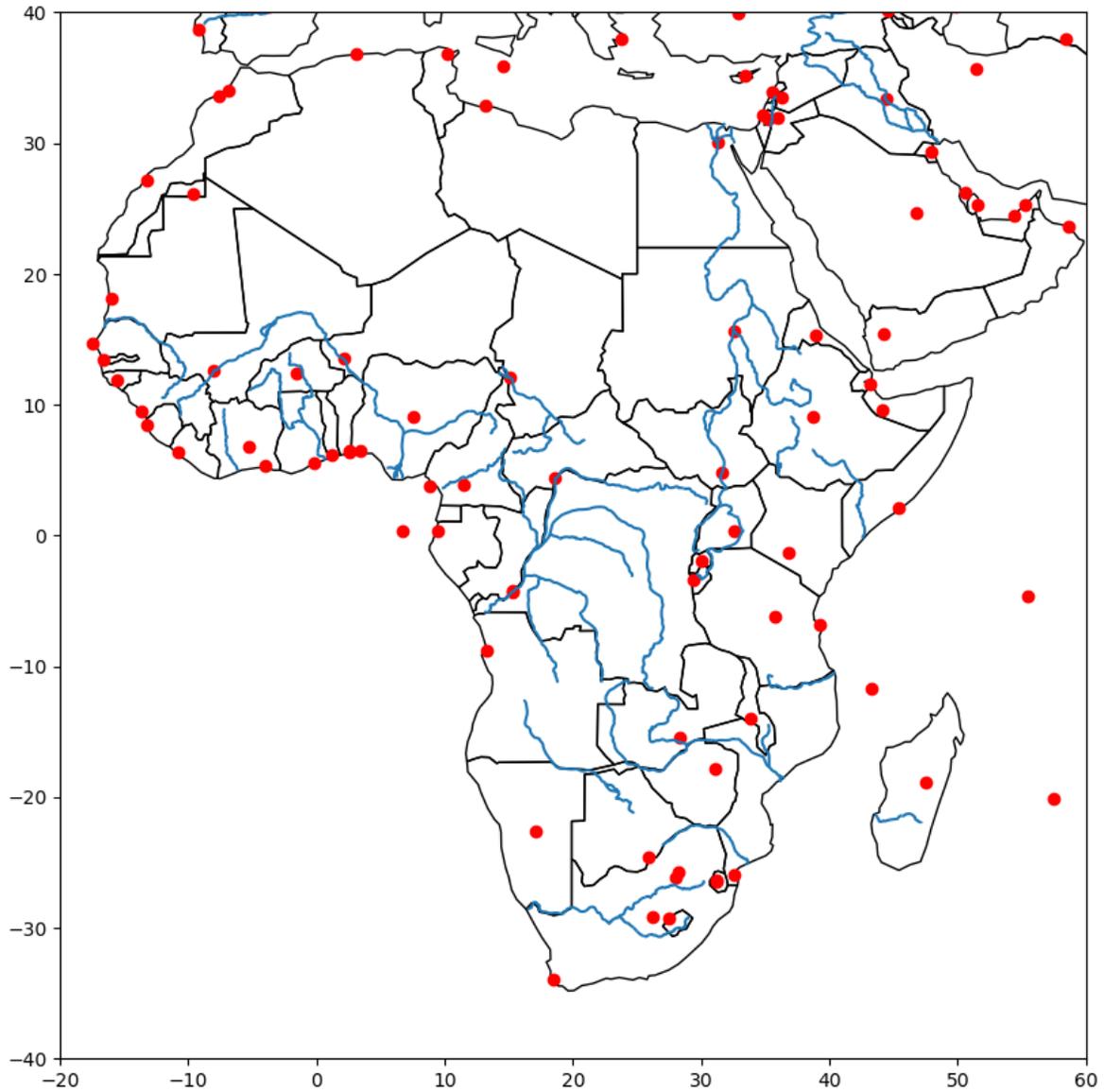
1.3.6 Creating GeoDataFrames (withouth specifying the CRS)

```
gpd.GeoDataFrame({
    'geometry': [Point(1, 1), Point(2, 2)],
    'attribute1': [1, 2],
    'attribute2': [0.1, 0.2]})
```

	geometry	attribute1	attribute2
0	POINT (1 1)	1	0.1
1	POINT (2 2)	2	0.2

```python
# Creating a GeoDataFrame from an existing dataframe
# For example, if you have lat/lon coordinates in two columns:
df = pd.DataFrame(
    {'City': ['Buenos Aires', 'Brasilia', 'Santiago', 'Bogota', 'Caracas'],
     'Country': ['Argentina', 'Brazil', 'Chile', 'Colombia', 'Venezuela'],
     'Latitude': [-34.58, -15.78, -33.45, 4.60, 10.48],
     'Longitude': [-58.66, -47.91, -70.66, -74.08, -66.86]})
```

```python
gdf = gpd.GeoDataFrame(df, geometry=gpd.points_from_xy(df.Longitude, df.Latitude))
gdf
```

	City	Country	Latitude	Longitude	geometry
0	Buenos Aires	Argentina	-34.58	-58.66	POINT (-58.66 -34.58)
1	Brasilia	Brazil	-15.78	-47.91	POINT (-47.91 -15.78)
2	Santiago	Chile	-33.45	-70.66	POINT (-70.66 -33.45)
3	Bogota	Colombia	4.60	-74.08	POINT (-74.08 4.6)
4	Caracas	Venezuela	10.48	-66.86	POINT (-66.86 10.48)

2 Practice

Throughout the exercises in this course, we will work with several datasets about the city of Paris.

Here, we start with the following datasets:

- The administrative districts of Paris (https://opendata.paris.fr/explore/dataset/quartier_paris/): `paris_districts_utm.geojson`
- Real-time (at the moment I downloaded them ..) information about the public bicycle sharing system in Paris (vélib, https://opendata.paris.fr/explore/dataset/stations-velib-disponibilites-en-temps-reel/information/): `data/paris_bike_stations_mercator.gpkg`

Both datasets are provided as spatial datasets using a GIS file format.

Excercise 1:

We will start by exploring the bicycle station dataset (available as a GeoPackage file: `data/paris_bike_stations_mercator.gpkg`)

- Read the stations datasets into a GeoDataFrame called `stations`.
- Check the type of the returned object
- Check the first rows of the dataframes. What kind of geometries does this datasets contain?
- How many features are there in the dataset?

Hints

- Use `type(..)` to check any Python object type
- The `gpd.read_file()` function can read different geospatial file formats. You pass the file name as first argument.
- Use the `.shape` attribute to get the number of features

Exercise 2:

- Make a quick plot of the `stations` dataset.
- Make the plot a bit larger by setting the figure size to (12, 6) (hint: the `plot` method accepts a `figsize` keyword).

Exercise 3:

Next, we will explore the dataset on the administrative districts of Paris (available as a GeoJSON file: `../data/paris_districts_utm.geojson`)

- Read the dataset into a GeoDataFrame called `districts`.
- Check the first rows of the dataframe. What kind of geometries does this dataset contain?
- How many features are there in the dataset? (hint: use the `.shape` attribute)
- Make a quick plot of the `districts` dataset (set the figure size to (12, 6)).

Exercise 4:

What are the largest districts (biggest area)?

- Calculate the area of each district.
- Add this area as a new column to the `districts` dataframe.
- Sort the dataframe by the area column from largest to smallest values (descending).

Hints

- Adding a column can be done by assigning values to a column using the same square brackets syntax: `df['new_col'] = values`
- To sort the rows of a DataFrame, use the `sort_values()` method, specifying the colum to sort on with the `by='col_name'` keyword. Check the help of this method to see how to sort ascending or descending.

2.1 Part IV: Coordinate reference systems & Projections

Gabriele Filomena has prepared this notebook by readapting material shared on this repository. Copyright (c) 2018, Joris Van den Bossche.

```
countries = gpd.read_file("../data/ne_countries.zip")
cities = gpd.read_file("../data/ne_cities.zip")
rivers = gpd.read_file("../data/ne_rivers.zip")
```

2.1.1 Coordinate reference systems

Up to now, we have used the geometry data with certain coordinates without further wondering what those coordinates mean or how they are expressed.

> The **Coordinate Reference System (CRS)** relates the coordinates to a specific location on earth.

For an in-depth explanation, see https://docs.qgis.org/2.8/en/docs/gentle_gis_introduction/coordinate_referen

2.1.1.1 Geographic coordinates

Degrees of latitude and longitude.

E.g. 48°51 N, 2°17 E

The most known type of coordinates are geographic coordinates: we define a position on the globe in degrees of latitude and longitude, relative to the equator and the prime meridian. With this system, we can easily specify any location on earth. It is used widely, for example in GPS. If you inspect the coordinates of a location in Google Maps, you will also see latitude and longitude.

Attention!

in Python we use (lon, lat) and not (lat, lon)

- Longitude: [-180, 180]{{1}}
- Latitude: [-90, 90]{{1}}

2.1.2 Projected coordinates

`(x, y)` coordinates are usually in meters or feet

Although the earth is a globe, in practice we usually represent it on a flat surface: think about a physical map, or the figures we have made with Python on our computer screen. Going from the globe to a flat map is what we call a *projection*.

We project the surface of the earth onto a 2D plane so we can express locations in cartesian x and y coordinates, on a flat surface. In this plane, we then typically work with a length unit such as meters instead of degrees, which makes the analysis more convenient and effective.

However, there is an important remark: the 3 dimensional earth can never be represented perfectly on a 2 dimensional map, so projections inevitably introduce distortions. To minimize such errors, there are different approaches to project, each with specific advantages and disadvantages.

Some projection systems will try to preserve the area size of geometries, such as the Albers Equal Area projection. Other projection systems try to preserve angles, such as the Mercator projection, but will see big distortions in the area. Every projection system will always have some distortion of area, angle or distance.

Projected size vs actual size (Mercator projection):

2.1.3 Coordinate Reference Systems in Python / GeoPandas

A GeoDataFrame or GeoSeries has a `.crs` attribute which holds (optionally) a description of the coordinate reference system of the geometries:

```
countries.crs
```

```
<Geographic 2D CRS: EPSG:4326>
Name: WGS 84
Axis Info [ellipsoidal]:
- Lat[north]: Geodetic latitude (degree)
- Lon[east]: Geodetic longitude (degree)
Area of Use:
- name: World.
- bounds: (-180.0, -90.0, 180.0, 90.0)
Datum: World Geodetic System 1984 ensemble
- Ellipsoid: WGS 84
- Prime Meridian: Greenwich
```

For the `countries` dataframe, it indicates that it uses the EPSG 4326 / WGS84 lon/lat reference system, which is one of the most used for geographic coordinates.

It uses coordinates as latitude and longitude in degrees, as can you be seen from the x/y labels on the plot:

```
countries.plot()
```
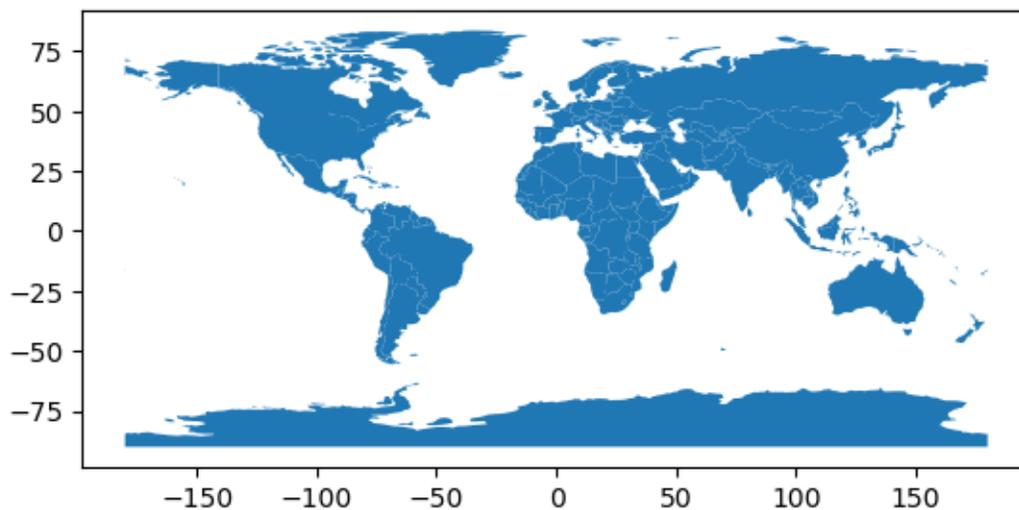
The `.crs` attribute returns a `pyproj.CRS` object. To specify a CRS, we typically use some string representation:

- **EPSG code** Example: `EPSG:4326` = WGS84 geographic CRS (longitude, latitude)

For more information, see also http://geopandas.readthedocs.io/en/latest/projections.html.

2.1.3.1 Transforming to another CRS

We can convert a GeoDataFrame to another reference system using the `to_crs` function.

For example, let's convert the countries to the World Mercator projection (http://epsg.io/3395):

```
# remove Antartica, as the Mercator projection cannot deal with the poles
countries = countries[(countries['name'] != "Antarctica")]
countries_mercator = countries.to_crs(epsg=3395)  # or .to_crs("EPSG:3395")
countries_mercator.plot()
```
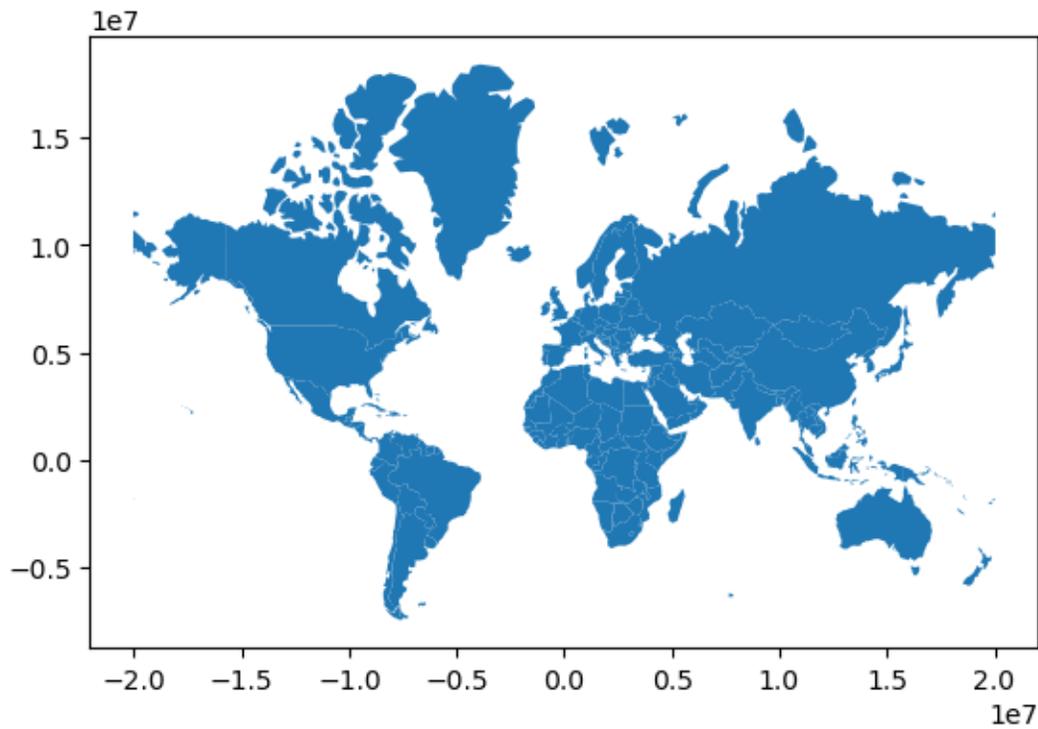

Note the different scale of x and y.

2.1.3.2 Why using a different CRS?

There are sometimes good reasons you want to change the coordinate references system of your dataset, for example:

- Different sources with different CRS -> need to convert to the same crs.

- Different countries/geographical areas with different CRS.
- Mapping (distortion of shape and distances).
- Distance / area based calculations -> ensure you use an appropriate projected coordinate system expressed in a meaningful unit such as meters or feet (**not degrees!**).

Important:

All the calculations (e.g. distance, spatial operations, etc.) that take place in `GeoPandas` and `Shapely` assume that your data is represented in a 2D cartesian plane, and thus the result of those calculations will only be correct if your data is properly projected.

2.2 Practice

Again, we will go back to the Paris datasets. Up to now, we provided the datasets in an appropriate projected CRS for the exercises. But the original data were actually using geographic coordinates. In the following exercises, we will start from there.

Going back to the Paris districts dataset, this is now provided as a GeoJSON file (`"../data/paris_districts.geojson"`) in geographic coordinates.

For converting the layer to projected coordinates, we will use the standard projected CRS for France is the RGF93 / Lambert-93 reference system, referenced by the `EPSG:2154` number.

Exercise: Projecting a GeoDataFrame

- Read the districts datasets (`../data/paris_districts.geojson"`) into a Geo-DataFrame called `districts`.
- Look at the CRS attribute of the GeoDataFrame. Do you recognize the EPSG number?
- Make a plot of the `districts` dataset.
- Calculate the area of all districts.
- Convert the `districts` to a projected CRS (using the `EPSG:2154` for France). Call the new dataset `districts_RGF93`.
- Make a similar plot of `districts_RGF93`.
- Calculate the area of all districts again with `districts_RGF93` (the result will now be expressed in m^2).

Hints

- The CRS information is stored in the `.crs` attribute of a GeoDataFrame.
- Making a simple plot of a GeoDataFrame can be done with the `.plot()` method.
- Converting to a different CRS can be done with the `.to_crs()` method, and the CRS can be specified as an EPSG number using the `epsg` keyword.

3 Static Maps in Python

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

3.1 Part I: Basic Maps

In this session, we will use the libraries `matplotlib` and `contextily` to plot the information represented into different `GeoDataFrames`. We will look into plotting `Point`, `LineString` and `Polygon GeoDataFrames`. Most of the plots here are rather ugly but, at this point, the goal is to get familiar with the parameters of the plot function and what can be done with them.

```python
%matplotlib inline
import matplotlib
import matplotlib.pyplot as plt
import geopandas as gpd
import pandas as pd
import osmnx as ox
import contextily as ctx
import seaborn as sns
```

3.1.1 Plotting Points

Load the data of terrorist attacks 1970-2020 and choose a country. Germany is used as a case study here but feel free to change the country. If you do so, also change the `crs` (see https://epsg.io).

```python
attacks = pd.read_csv("../data/GTD_2022.csv", low_memory = False)
```

Creating the `GeoDataFrame` from the `DataFrame`

```
germany = ['West Germany (FRG)', 'Germany', 'East Germany (GDR)'] # Germany was split till 19
df = attacks[attacks.country_txt.isin(germany)].copy()

# Uncomment the lines below for other countries that haven't changed their denominations/bour
# country = 'France'
# df = attacks[attacks.country_txt == country].copy()#
wgs = 'EPSG:4326'
germany_crs = 'EPSG:4839'
gdf = gpd.GeoDataFrame(df, geometry=gpd.points_from_xy(df.longitude, df.latitude), crs = wgs)
gdf = gdf[~gdf.geometry.is_empty] # remove empty geometries
gdf.to_file("../data/germany.gpkg", driver="GPKG", layer="germany")
gdf = gdf.to_crs(germany_crs)
```

Basic plotting

```
# prepare the axis and coordinate
nr_rows = 1
nr_cols = 1
fig, ax = plt.subplots(nr_cols, nr_rows, figsize=(8, 6))
gdf.plot(ax=ax, color='red', markersize=7)
```
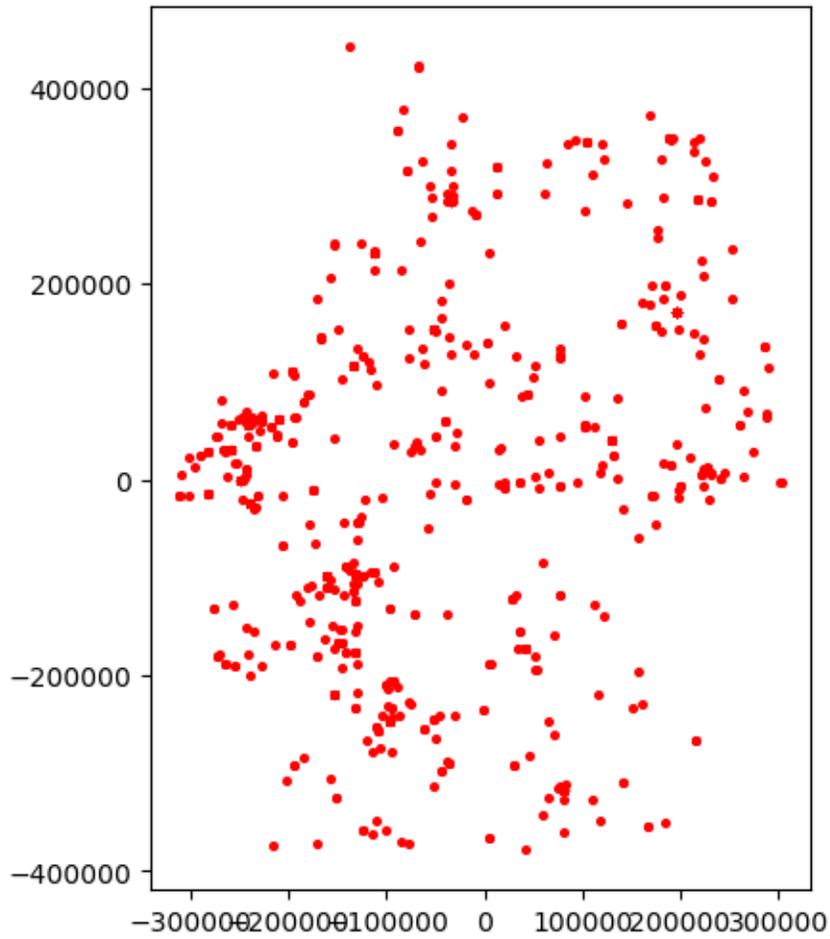
Slightly improving the plot:

```
# removing ticks
ax.xaxis.set_ticklabels([])
ax.yaxis.set_ticklabels([])
ax.tick_params(axis= 'both', which= 'both', length=0)
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Terroristic Attacks in Germany", **title_parameters)
fig
```

Terroristic Attacks in Germany
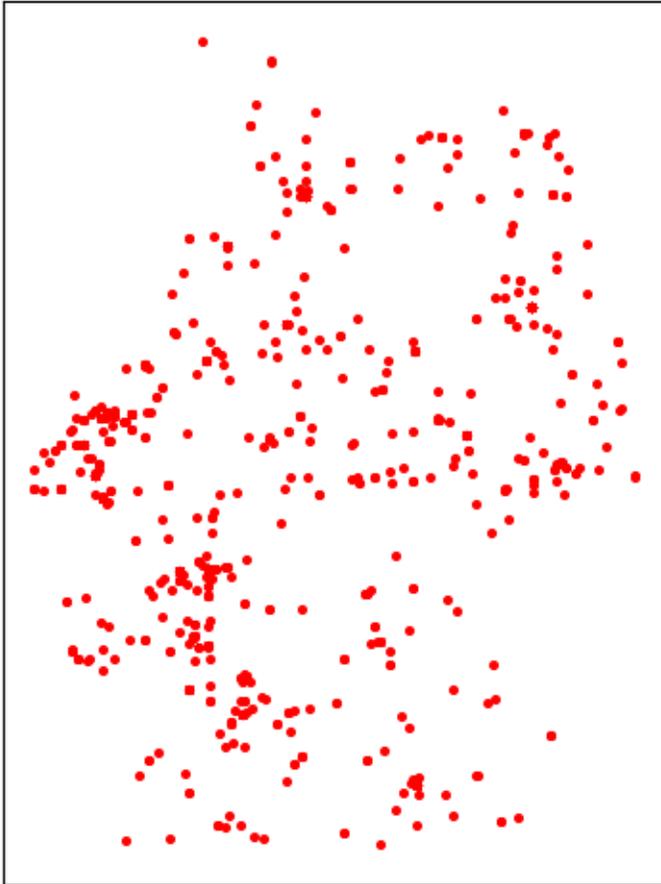
3.1.1.1 Adding some context: Base Maps with `Contextily`

see providers and options here https://xyzservices.readthedocs.io/en/stable/introduction.html

```
source = ctx.providers.CartoDB.Positron
ctx.add_basemap(ax, crs= gdf.crs.to_string(), source= source)
# replot
fig
```

Terroristic Attacks in Germany

```
<Figure size 640x480 with 0 Axes>
```
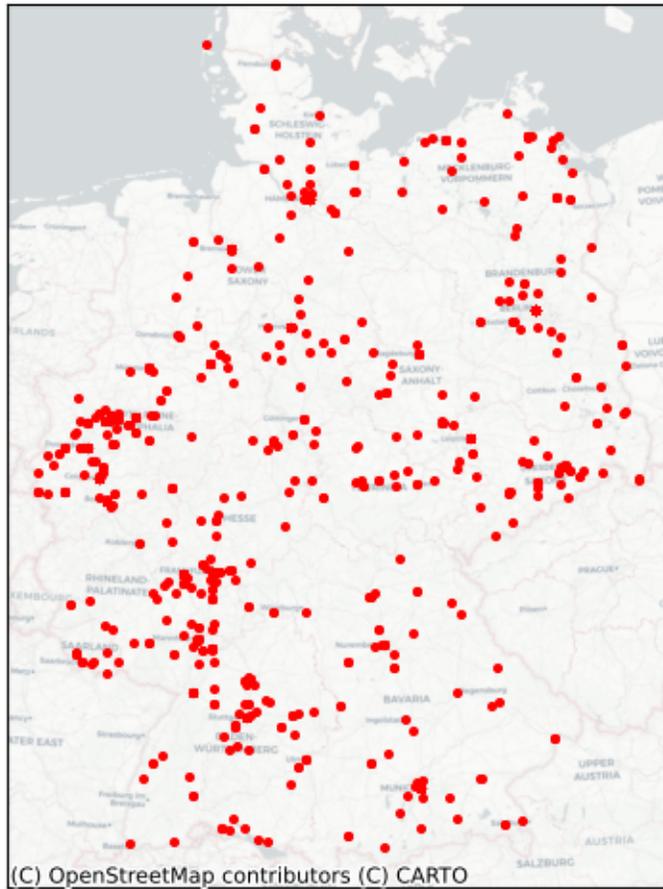
3.1.1.2 Parameters specific to `Point` in the `plot` method

- `markersize`: numerical value (for now)
- `marker`: see https://matplotlib.org/stable/api/markers_api.html

3.1.1.2.1 Other properties, shape independent:

- `color`: https://matplotlib.org/3.1.0/gallery/color/named_colors.html
- `alpha`: regulates transparency of the shape: 0 to 1

```
# first, let's make a function

def ax_ticks_off(ax):
    ax.xaxis.set_ticklabels([])
    ax.yaxis.set_ticklabels([])
    ax.tick_params(axis= 'both', which= 'both', length=0)
```

```
# prepare the axis and coordinate
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf.plot(ax=ax, markersize = 15, color = 'blue', marker = '*', alpha = 0.3)
ctx.add_basemap(ax, crs= gdf.crs.to_string(), source= source)
ax_ticks_off(ax)
```
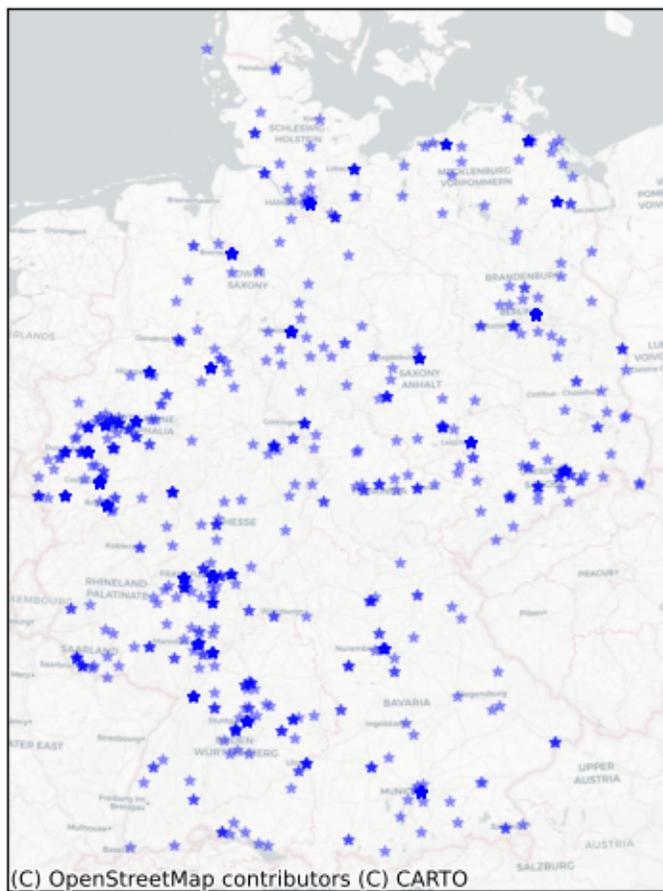
3.1.2 Plotting LineStrings

Let's import railway tracks in the Western Balkans (Slovenia, Croatia, Bosnia & Herzegovina, Montenegro, Serbia, Kosovo)

```
wb_crs = 'EPSG:31277'
lines_gdf = gpd.read_file("..\data\wb_railways.gpkg")
lines_gdf.plot()
```
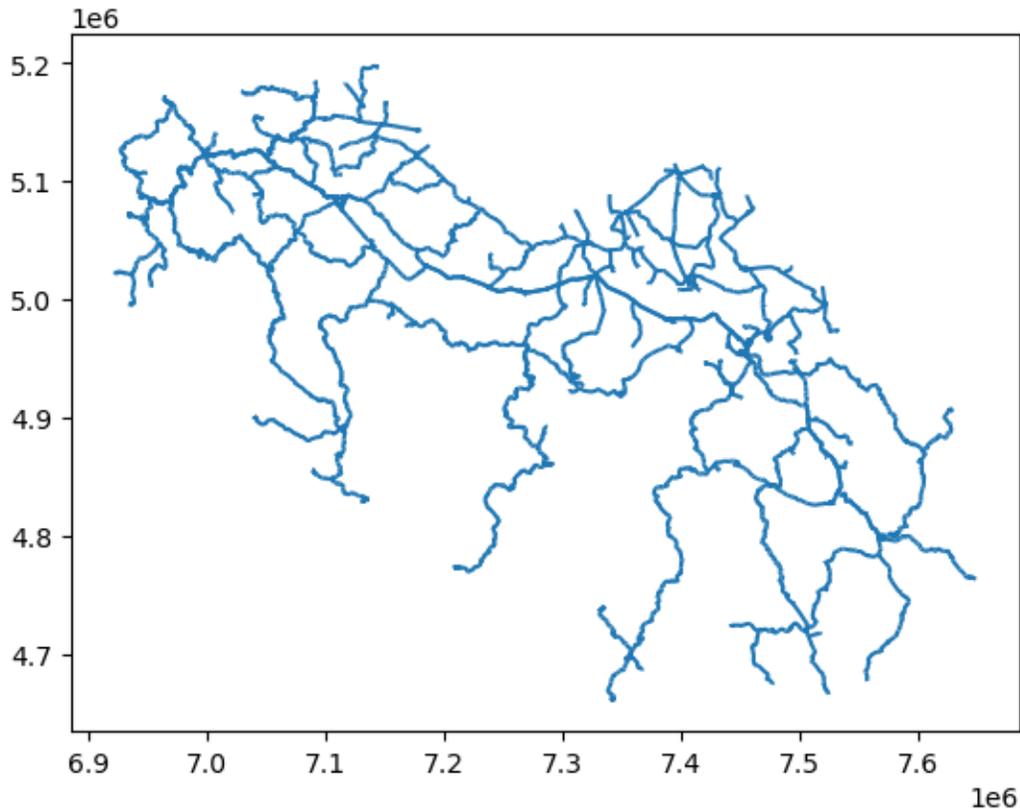


```
# prepare the plot
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
lines_gdf.plot(ax=ax, linewidth = 0.8, color = 'blue', alpha = 1)
ctx.add_basemap(ax, crs= lines_gdf.crs.to_string(), source = ctx.providers.Esri.WorldGrayCan
ax_ticks_off(ax)
ax.set_title("Railway infrastructure in the West Balkans", **title_parameters) #parameters as
```

Text(0.5, 1.0, 'Railway infrastructure in the West Balkans')

Railway infrastructure in the West Balkans

One can also filter prior to plotting, based on the columns in the GeoDataFrame. First we download Serbia's Boundary with `OSMNX`, more on that later on. Then we filter `lines_gdf` with a `within` operation.

```
serbia = ox.geocode_to_gdf('Serbia')
serbia = serbia.to_crs(wb_crs)
serbia_lines = lines_gdf[lines_gdf.geometry.within(serbia.iloc[0].geometry)].copy() #there's
```

```
# prepare the plot
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
serbia_lines.plot(ax=ax, linewidth = 0.8, color = 'blue', alpha = 1)
ctx.add_basemap(ax, crs= lines_gdf.crs.to_string(), source = ctx.providers.Esri.WorldGrayCanv
ax_ticks_off(ax)
ax.set_title("Railway infrastructure in Serbia and Kosovo", **title_parameters) #parameters a
```

```
Text(0.5, 1.0, 'Railway infrastructure in Serbia and Kosovo')
```

Railway infrastructure in Serbia and Kosovo

3.1.2.1 Parameters specific to `LineString`:

- `linewidth`: numerical value (for now).
- `capstyle`: controls how Matplotlib draws the corners where two different line segments meet. See https://matplotlib.org/stable/gallery/lines_bars_and_markers/capstyle.html
- `joinstyle`': controls how Matplotlib draws the corners where two different line segments meet. https://matplotlib.org/stable/gallery/lines_bars_and_markers/joinstyle.html

```
# prepare the plot
fig, ax = plt.subplots(1, 1, figsize=(10, 10))
serbia_lines.plot(ax=ax, linewidth = 0.9, color = 'black', alpha = 1, capstyle = 'round', joi
ax.set_axis_off() # we don't need the ticks function
ax.set_title("Railway infrastructure in Serbia", **title_parameters) #parameters as above
```

Text(0.5, 1.0, 'Railway infrastructure in Serbia')

Railway infrastructure in Serbia

3.1.3 Plotting Polygons

We are again using `OSMNX` to download data from `OpenStreetMap` automatically. In this case, we will get building footprints from the city of Algiers in Alageria.

3.1.3.1 Parameter specific to `Polygon`:

- `edgecolor`: the outline of the polygon, by default = `None` (often better).
- `linewidth`: the width of the outline of the polygon.

```
algeria_crs = 'EPSG:30729'
tags = {"building": True} #OSM tags
buildings = ox.features_from_address("Algiers, Algeria", tags = tags, dist = 2000)
buildings = buildings.reset_index()
 # sometimes building footprints are represented by Points, let's disregard them
buildings = buildings[(buildings.geometry.geom_type == 'Polygon') | (buildings.geometry.geom
buildings = buildings.to_crs(algeria_crs)
```

```
fig, ax = plt.subplots(1, 1, figsize=(15, 10))
ax.set_title("Buildings in Algiers", **title_parameters)
ax.set_axis_off() # we don't need the ticks function
buildings.plot(ax=ax, color = 'orange', edgecolor = 'black', lw = 0.2)
source = ctx.providers.CartoDB.PositronNoLabels
ctx.add_basemap(ax, crs= buildings.crs.to_string(), source= source)
```

Buildings in Algiers

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For polygons, you can also plot just the boundaries of the geometries by:

```
buildings.boundary.plot(lw = 0.5)
```
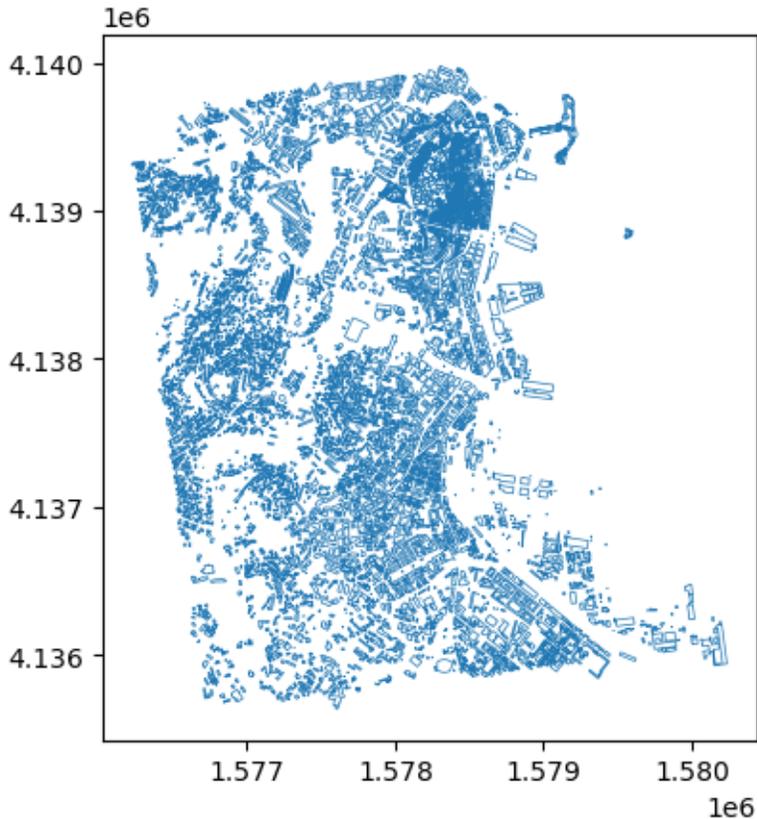
3.1.4 Plotting more than one layer together

Let's also download roads for Algiers

```
tags = {"highway": True} #OSM tags
roads = ox.features_from_address("Algiers, Algeria", tags = tags, dist = 2000)
roads = roads.reset_index()
roads = roads.to_crs(algeria_crs)
 # sometimes building footprints are represented by Points, let's disregard them
roads = roads[roads.geometry.geom_type == 'LineString']
```

And plot everything togehter. It's important to keep in mind that the last layer is always rendered on top of the others. In other words, they may cover the previous ones.

However, you can prevent this by passing arguments to the parameter `zorder` in the `plot` method. The layer with the higher zorder value will be plotted on top.

```
fig, ax = plt.subplots(1, 1, figsize=(15, 10))
ax.set_title("Buildings and Roads in Algiers", **title_parameters)
ax.set_axis_off() # we don't need the ticks function
# only roads within the extent of the buildings layer
roads[roads.geometry.within(buildings.unary_union.envelope)].plot(ax=ax, color = 'grey', lw =
buildings.plot(ax=ax, color = 'orange')
```

C:\Users\gfilo\AppData\Local\Temp\ipykernel_27180\1248606569.py:5: DeprecationWarning: The 'u
  roads[roads.geometry.within(buildings.unary_union.envelope)].plot(ax=ax, color = 'grey', lu

Buildings and Roads in Algiers

3.1.5 Sub-plots

To obtain multiple sub-plots, we manipulate the `nrows`, `ncols` parameters. We can use this approach to: * Plot the same layer with different properties.

```
fig, axes = plt.subplots(1, 2, figsize=(10, 6))
colors = ['red', 'blue']

for n, ax in enumerate(axes):
    gdf.plot(ax=ax, markersize = 4, color = colors[n])
    ax.set_axis_off()
    ctx.add_basemap(ax, crs= gdf.crs.to_string(), source= source)
```
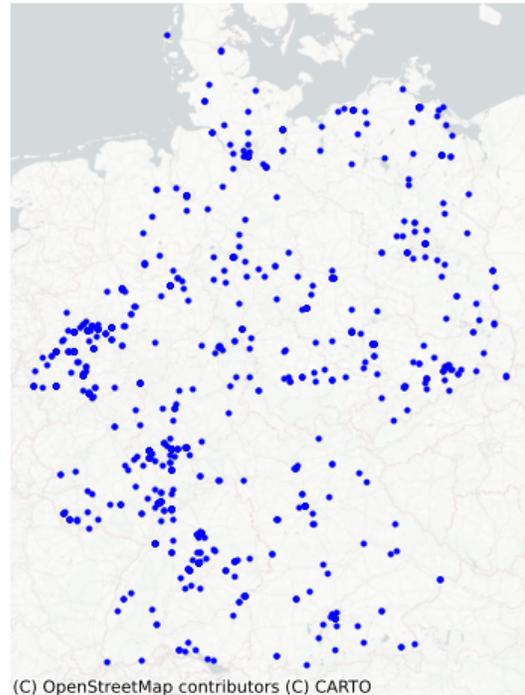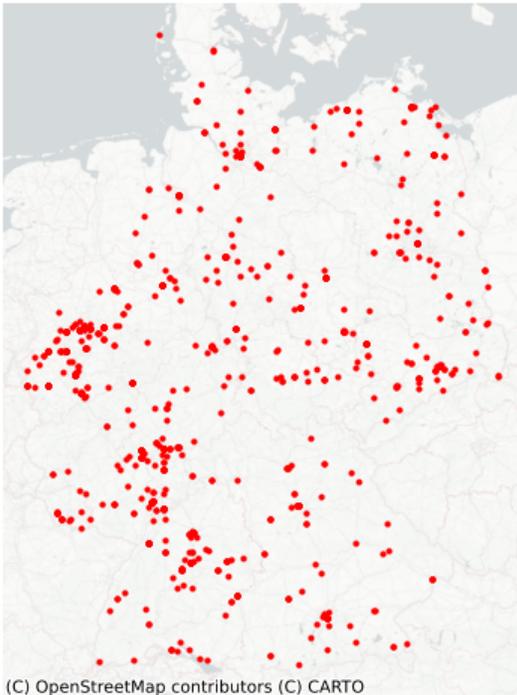

- Plot different layers.

```
fig, axes = plt.subplots(1, 2, figsize=(10, 6))
gdfs = [buildings, roads]
colors = ['orange', 'grey']

buildings.plot(ax=axes[0], color = 'orange', edgecolor = 'none')
roads.plot(ax=axes[1], color = 'gray', lw = 0.5)

for ax in axes:
    ax.set_axis_off()
    ctx.add_basemap(ax, crs= buildings.crs.to_string(), source = source)
```

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- Analyse phenomena across different geographical areas. For example, terrorism in Germany and in the UK.

```python
# let's prepare the gdf for the UK
df_uk = attacks[attacks.country_txt == 'United Kingdom'].copy()
uk_crs = 'EPSG:27700'
gdf_uk = gpd.GeoDataFrame(df_uk, geometry=gpd.points_from_xy(df_uk.longitude, df_uk.latitude)
gdf_uk = gdf_uk.to_crs(uk_crs)
```

```python
fig, axes = plt.subplots(1, 2, figsize=(10, 6))
gdfs = [gdf, gdf_uk]

for n, ax in enumerate(axes):
    gdf_tmp = gdfs[n]
    gdf_tmp.plot(ax=ax, color = 'orange', markersize = 3)
    ax.set_axis_off()
    ctx.add_basemap(ax, crs= gdf_tmp.crs.to_string(), source= source)
```

(C) OpenStreetMap contributors (C) CARTO

(C) OpenStreetMap contributors (C) CARTO
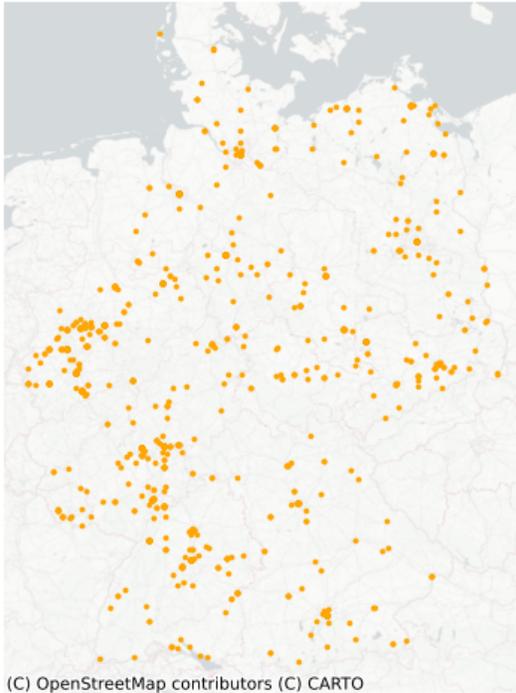
Exercise:

- Think about the plots above and how they could be improved.
- Copy and paste the code and execute the functions playing with the different parameters.
- Produce a neat map using the `GeoDataFrame`s available in this notebook or the ones employed in the previous sessions, making use of the elements/parameters discussed here.
- Try out different tiles for the basemap to familiarise yourself with what's available.

3.2 Part II: Choropleth Mapping

```
import geoplot.crs as gcrs
import geoplot as gplt
```

Data

For this second part of the tutorial, we will use some data at the municipality level for Serbia. The data contains information regarding poverty level, average income, population and tourism. The data is taken from https://data.stat.gov.rs/?caller=SDDB&languageCode=en-US and

can be associated to the polygons representing the administrative boundaries of the municipalities. These boundaries can be found here https://data.humdata.org/dataset/geoboundaries-admin-boundaries-for-serbia?force_layout=desktop. While most of the data refers to 2023, the admin boundaries file traces back to 2017. Thus, it may contain obsolete information (few changes may occur).

Later on, we will go back to the terrorism dataset.

```python
# This will be different on your computer and will depend on where
# you have downloaded the files
serbia_crs = 'EPSG:31277'
wgs = 'EPSG:4326'
serbia_admin = gpd.read_file('../data/serbia_admin.gpkg')
serbia_admin.set_index('townID', inplace = True, drop = True)
serbia_admin = serbia_admin.to_crs(serbia_crs)
```

Let's plot the `GeoDataFrame` following the last session's steps.

```python
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
serbia_admin.plot(ax = ax, color = 'salmon', linewidth = 0.3, edgecolor = 'white')
ax.set_axis_off()
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Serbian Municipalities", **title_parameters) #parameters as above
```

```
Text(0.5, 1.0, 'Serbian Municipalities')
```

Serbian Municipalities
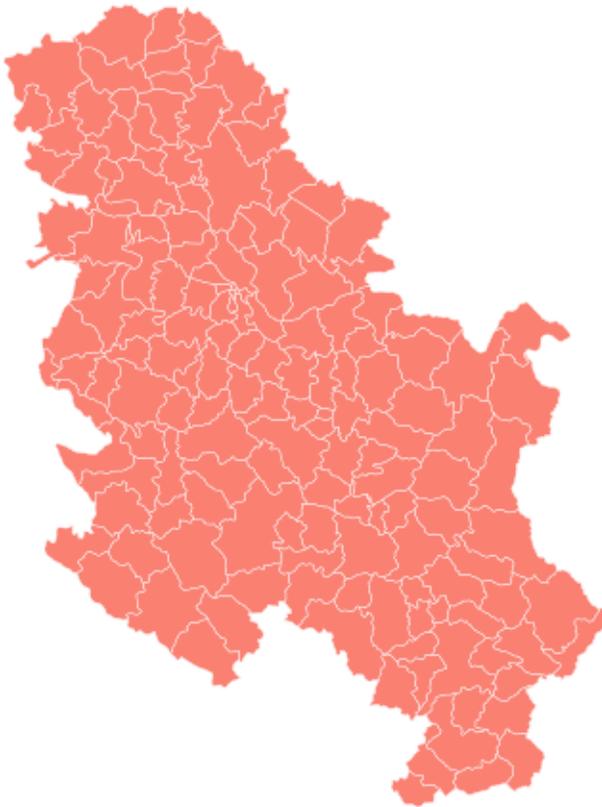
The we load the data and merge it into the `GeoDataFrame`, before getting rid of municipalities that do not have a corresponding shape/record in the GeoDataFrame (probably the result of changes in the national subdivisions).

```
data = pd.read_csv("../data/serbia_data.csv") #some slavic characters
data.drop('name_en', axis = 1, inplace = True)
serbia_admin = pd.merge(serbia_admin, data, left_on = "townID", right_on = "id")
serbia_admin = serbia_admin[serbia_admin.id.notna()]
serbia_admin['id'] = serbia_admin['id'].astype('int64')
serbia_admin.head()

#let's save the so-obtained gdf for later (encoding for dealing with slavic characters).
serbia_admin.to_file("../data/serbia_data.gpkg", encoding='utf-8', driver="GPKG", layer="ser
```

C:\Users\gfilo\AppData\Local\miniconda3\envs\geovis\Lib\site-packages\pyogrio\raw.py:733: Ru

```
ogr_write(
```

Creating a choropleth map is rather straightforward and can ben done by using few other
parameters. Reflect on what you see and whether the map below is informative.

```
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
serbia_admin.plot(ax = ax, column = 'gross', linewidth = 0.3, cmap = 'Greens', legend = True)
ax.set_axis_off()
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Serbian Municipalities", **title_parameters) #parameters as above
```

```
Text(0.5, 1.0, 'Serbian Municipalities')
```
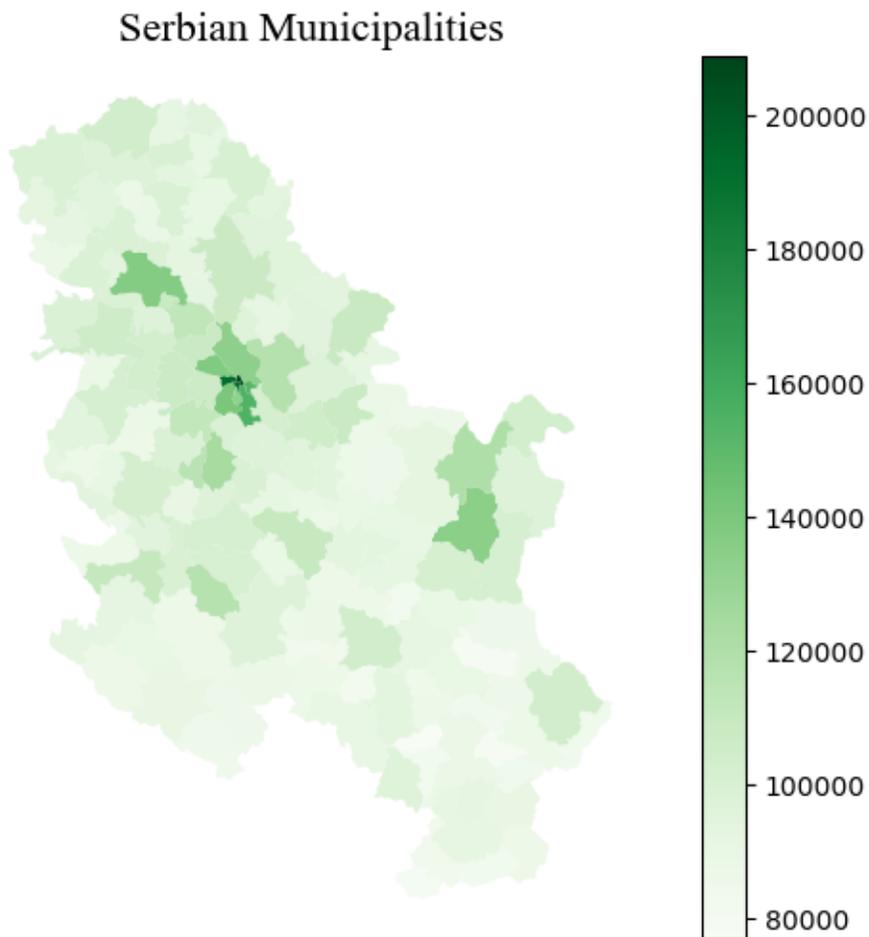
3.2.1 Choropleth Maps for Numerical Variables

We are essentially using the same approach employed for creating basic maps, the method `plot`, but we now need to pass arguments to some new parameters to specify which column is to be represented and how. As an optional argument, one can set legend to `True` and the resulting figure will include a colour bar.

- `column`: the name of the column representing the variable that we want to use to colour-code our shapes.
- `scheme`: the scheme used to colour the shapes based on the variable values.
- `cmap`: the colormap used to show variation.

3.2.1.1 Colormaps

Built-in colour maps can be found here https://matplotlib.org/stable/gallery/color/colormap_reference.html. However one can create new ones as follows from a list of colours:

```python
from seaborn import palplot
from matplotlib.colors import LinearSegmentedColormap

colors = [(0.00, 0.00, 0.00,1), (0.248, 0.0271, 0.569, 1), (0.0311, 0.258, 0.646,1),
          (0.019, 0.415, 0.415,1), (0.025, 0.538, 0.269,1), (0.0315, 0.658, 0.103,1),
          (0.331, 0.761, 0.036,1),(0.768, 0.809, 0.039,1), (0.989, 0.862, 0.772,1),
          (1.0, 1.0, 1.0)]
palplot(colors)
```



```python
kindlmann = LinearSegmentedColormap.from_list('kindlmann', colors)
```

or from colour names:

```python
colors = ["white", "yellow", "red"]
palplot(colors)
```
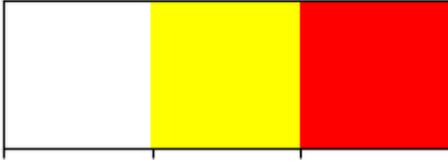
Let's try a new colormap and let's also set a number of classes to divide the data in, through the parameter **k**.

```python
white_to_red = LinearSegmentedColormap.from_list("name", ["yellow","red"])
```

```python
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
serbia_admin.plot(ax = ax, column = 'gross', linewidth = 0.3, cmap = kindlmann.reversed(), le
ax.set_axis_off()
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Serbian Municipalities", **title_parameters) #parameters as above
```

```
Text(0.5, 1.0, 'Serbian Municipalities')
```

Serbian Municipalities
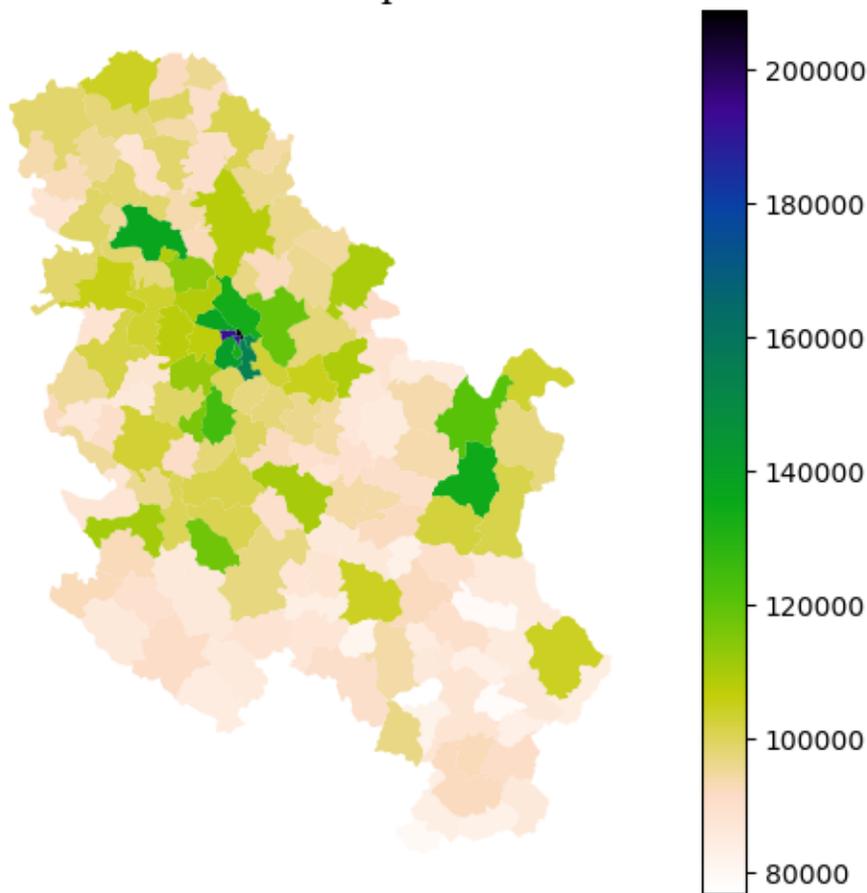
With `GeoPandas`, when you use the `plot` method with `legend=True` the type of legend that appears depends on the data being visualized:

- Continuous Data: For columns with continuous data (like population estimates, temperatures, etc.), a colour bar is generated as the legend. This color bar represents a range of values with a gradient, indicating how data values correspond to colours on the map.
- Categorical Data: For columns with categorical data (like country names, types of land use, etc.), if you specify `legend=True`, `GeoPandas` will try to create a legend that categorizes these distinct values with different colours. However, creating legends for categorical data is not as straightforward as with continuous data and might require additional handling for a clear and informative legend (see below).

3.2.1.2 Scheme

It is important to keep in mind that choropleth maps strongly depend on the scheme that it is passed (or the default one) to classify the data in groups. The plot above only shows one municipality coloured in dark blue.

Look at the following plots and how three different classifiers produce different results for the same data.

Refer to https://geopandas.org/en/stable/gallery/choropleths.html and https://geographicdata.science/book/n for further details

```
# Function for plotting the map and the distribution of the value in bins

from mapclassify import Quantiles, EqualInterval, FisherJenks

def plot_scheme(gdf, column, scheme, figsize=(10, 6)):
    '''
    Arguments
    ---------
    gdf: GeoDataFrame
        The GeoDataFrame to plot
    column: str
        Variable name
    scheme: str
        Name of the classification scheme to use
    figsize: Tuple
        [Optional. Default = (10, 6)] Size of the figure to be created.

    '''
    schemes = {'equal_interval': EqualInterval, 'quantiles': Quantiles, 'fisher_jenks': Fishe
    classification = schemes[scheme](gdf[column], k=7)
    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=figsize)
    # KDE
    sns.kdeplot(gdf[column], fill=True, color='purple', ax=ax1)
    sns.rugplot(gdf[column], alpha=0.5, color='purple', ax=ax1)
    for cut in classification.bins:
        ax1.axvline(cut, color='blue', linewidth=0.75)
    ax1.set_title('Value distribution')
    # Map
    p = gdf.plot(column=column, scheme=scheme, alpha=0.75, k=7, cmap='RdPu', ax=ax2, linewid
    ax2.axis('equal')
    ax2.set_axis_off()
```

```
    ax2.set_title('Geographical distribution')
    fig.suptitle(scheme, size=25)
    plt.show()
```

- The *Equal intervals* method splits the range of the distribution, the difference between the minimum and maximum value, into equally large segments and to assign a different colour to each of them according to a palette that reflects the fact that values are ordered.
- To obtain a more balanced classification, one can use the *Quantiles* scheme. This assigns the same amount of values to each bin: the entire series is laid out in order and break points are assigned in a way that leaves exactly the same amount of observations between each of them. This "observation-based" approach contrasts with the "value-based" method of equal intervals and, although it can obscure the magnitude of extreme values, it can be more informative in cases with skewed distributions.
- Amongst many other, the *Fisher Jenks* dynamically minimises the sum of the absolute deviations around class medians. The Fisher-Jenks algorithm is guaranteed to produce an optimal classification for a prespecified number of classes.

The only additional arguments to pass for producing a choropleth, therefore, are the actual variable we would like to classify and the number of segments we want to create, `k`. This is, in other words, the number of colours that will be plotted on the map so, although having several can give more detail, at some point the marginal value of an additional one is fairly limited, given the ability of the human brain to tell any differences.

```
schemes = ['equal_interval', 'quantiles', 'fisher_jenks']
for scheme in schemes:
    plot_scheme(serbia_admin, 'gross', scheme)
```

equal_interval

Value distribution

Geographical distribution
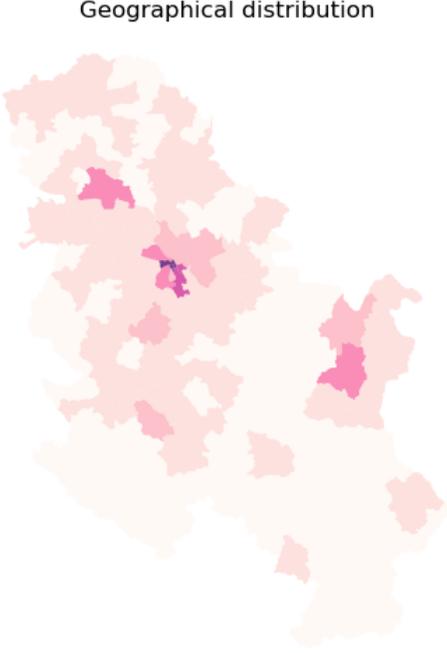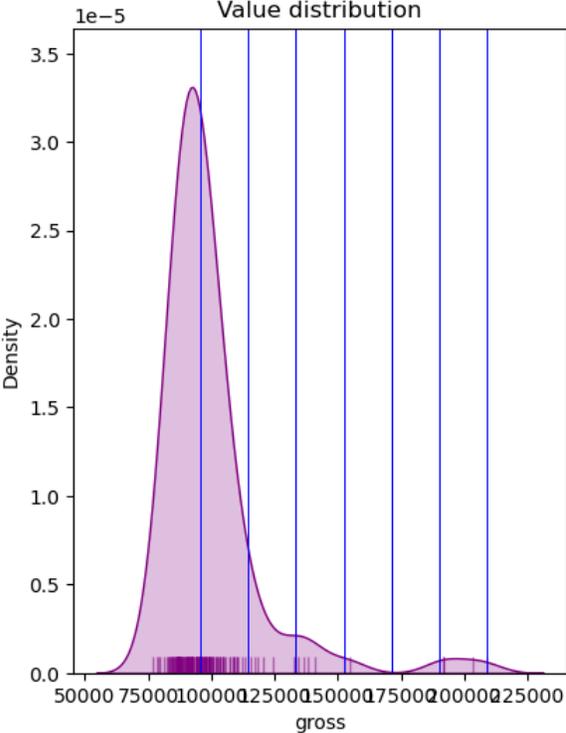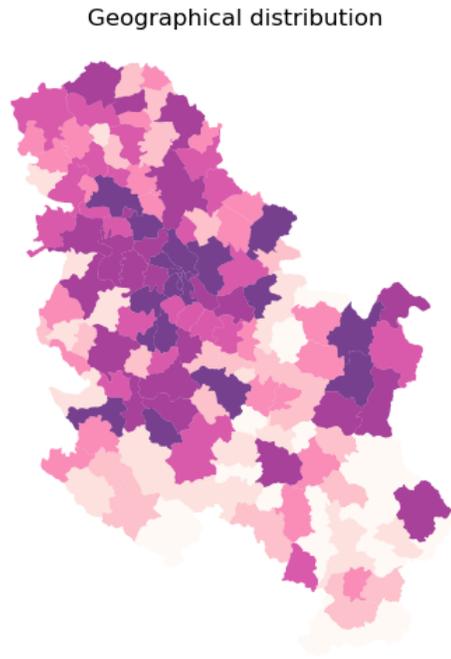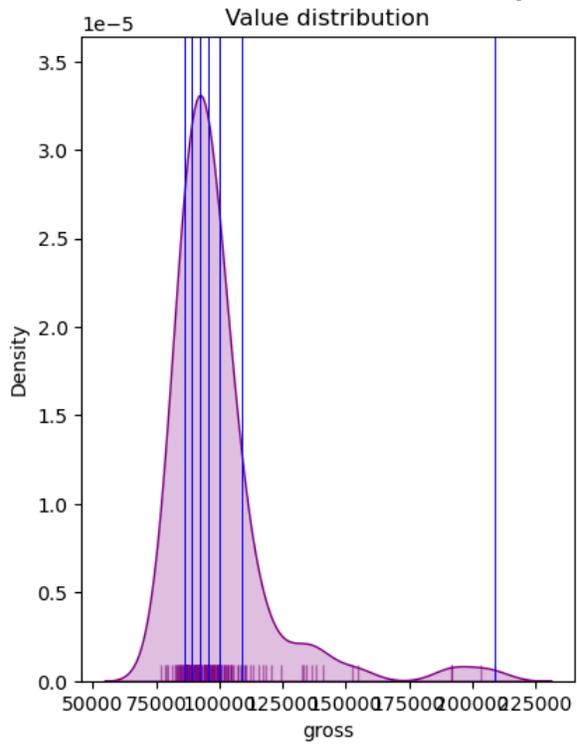
quantiles
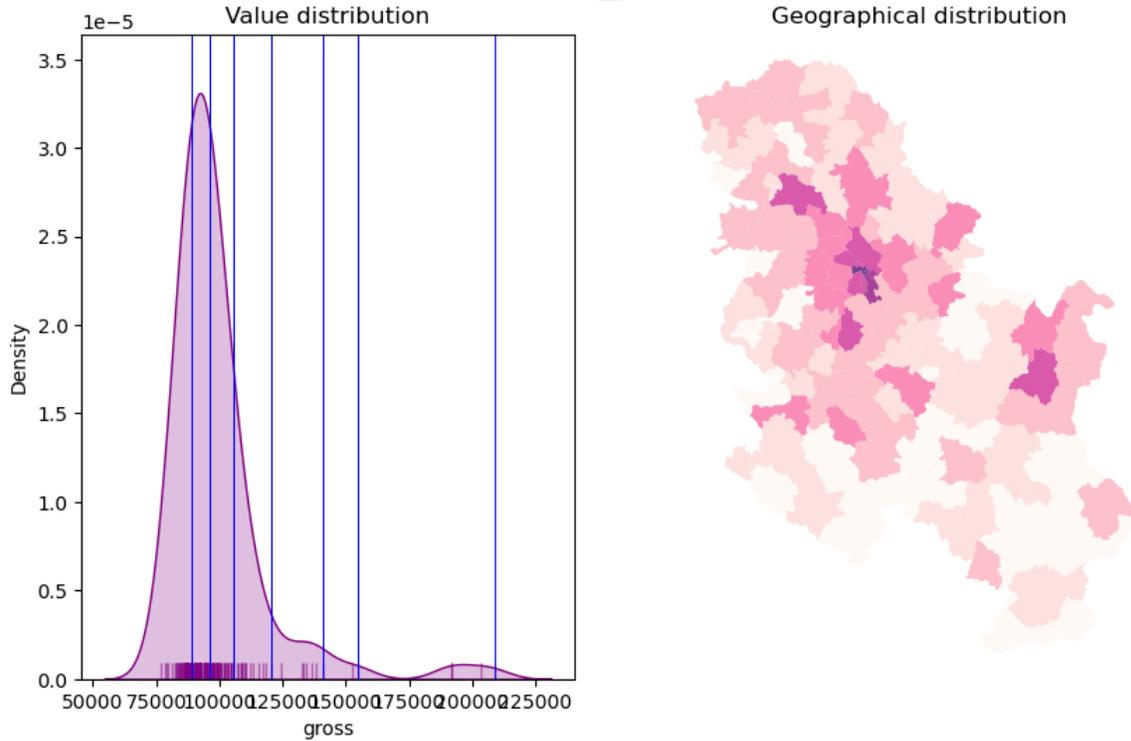
Also consider the Modifiable Areal Unit Problem and how the geographies of the administrative boundaries, in this case, may impact the visualisation.

For example, the most populated area is a municipality in the north that corresponds to the city of Novi Sad. Let's have a look at the data

```
serbia_admin[['name', 'pop', 'Province']].sort_values(by = 'pop', ascending = False).iloc[:10
```

	name	pop	Province
48	Novi Sad	341625.0	Južno-Bački
24	Novi Beograd	186667.0	Grad Beograd
19	Čukarica	154854.0	Grad Beograd
3	Kragujevac	154290.0	Šumadijski
26	Palilula	148292.0	Grad Beograd
34	Zemun	143173.0	Grad Beograd
32	Voždovac	137315.0	Grad Beograd
35	Zvezdara	130225.0	Grad Beograd
39	Leskovac	123201.0	Jablanički

	name	pop	Province
120	Subotica	121250.0	Severno-Bački

In our dataset, the city of Novi Sad is categorised as a municipality by itself, because the administrative boundaries file is not updated. In reality, "since 2002, when the new statute of the city of Novi Sad came into effect, Novi Sad is divided into two city municipalities, Petrovaradin and Novi Sad. From 1989 until 2002, the name Municipality of Novi Sad meant the whole territory of the present-day city of Novi Sad." (see: wikipedia).

On the contrary, Grad Beograd, that is Belgrade, is correctly split into different municipalities and its population, when visualised, is spread out across the different geometries of its municipalities. In other words, our map depends on the geometries of the areas and on how the data was collected. While it could be that these areas were indeed identified by population size in the first place, the point is that the fact that Novi Sad is not split into more areas, as Belgrade is, makes it stound out more clearly from the map (and to some extent a bit unfairly)

This may happen with different types of data, particularly with administrative boundaries and it is crucial to reflect on how Choropleth maps may be impacted. One can look for more granular data or consider to weight the continuous value with the extent of the area (i.e. obtaining density values).

3.2.1.3 An alternative to scheme: ColorMap Normalisation

The `mpl.colors.Normalize` function in `matplotlib` creates a normalization object, which adjusts data values into a range that is ideal for colour mapping in a colormap. This function is particularly beneficial in scenarios where precise control over the mapping of data values to colour representations is needed.

When employed in a plotting function, this normalization object ensures that the data values are scaled to fit a pre-defined range (for instance, `norm = mpl.colors.Normalize(vmin=0, vmax=40)`). Any values falling below 0 are mapped to the lowest colour on the colormap scale, while values exceeding 40 are mapped to the highest colour. This approach is especially useful when aiming to highlight differences within a specific data range; it can significantly enhance the visualization of data, by, for example, emphasizing temperature variations between 0°C and 40°C. This becomes crucial in instances where a few data points with high values (e.g., 50°C) might otherwise lead to a less informative visualization if not 'normalized' and treated as if they corresponded to 40° C values.

For our dataset, we can use as `vmax` the value corresponding to the 90th percentile.

```
serbia_admin['pop'].quantile(0.90)
```

```
np.float64(93014.0)
```

```python
import matplotlib as mpl
fig, ax = plt.subplots(1, 1)
vmin = serbia_admin['pop'].min()
vmax = serbia_admin['pop'].quantile(0.90) #
norm = mpl.colors.Normalize(vmin=vmin, vmax=vmax)
serbia_admin.plot(ax = ax, column='pop', cmap='OrRd', legend=True, norm = norm)
```
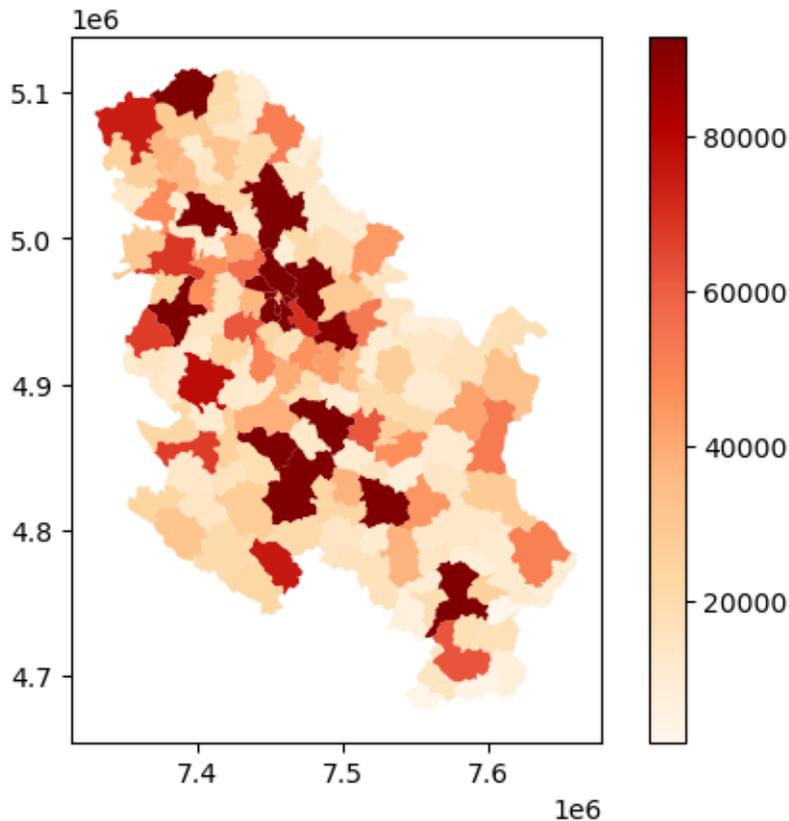

Important:

When passing `norm` in the `plot` method, do not pass the arguments to the `scheme` parameter. For continuous variables, `norm` maps each value directly to a color, making discrete categorization redundant. In other words, it allows for a direct mapping of data values to the color map, eliminating the need for intermediary classification schemes. `norm` ensures a smooth gradient in the color map without artificially segmenting the data.

3.2.1.4 Customising the colorbar

```python
import matplotlib.cm as cm

fig, ax = plt.subplots(1, 1)
cmap = 'YlOrRd'
# we leave the legend out
serbia_admin.plot(column='pop', cmap=cmap, norm = norm, ax=ax)

# we add the colorbar separately passing the norm and cmap
cbar = fig.colorbar(cm.ScalarMappable(norm=norm, cmap=cmap), ax = ax)
cbar.outline.set_visible(False)

# updating ticks VALUES
ticks = [norm.vmin, norm.vmax]
cbar.set_ticks(ticks = ticks)

# updating ticks LABELS
cbar.ax.set_yticklabels([round(t,1) for t in ticks])
cbar.ax.set_yticklabels([round(t,1) if t < norm.vmax else ">= "+str(round(t,1)) for t in cbar
```
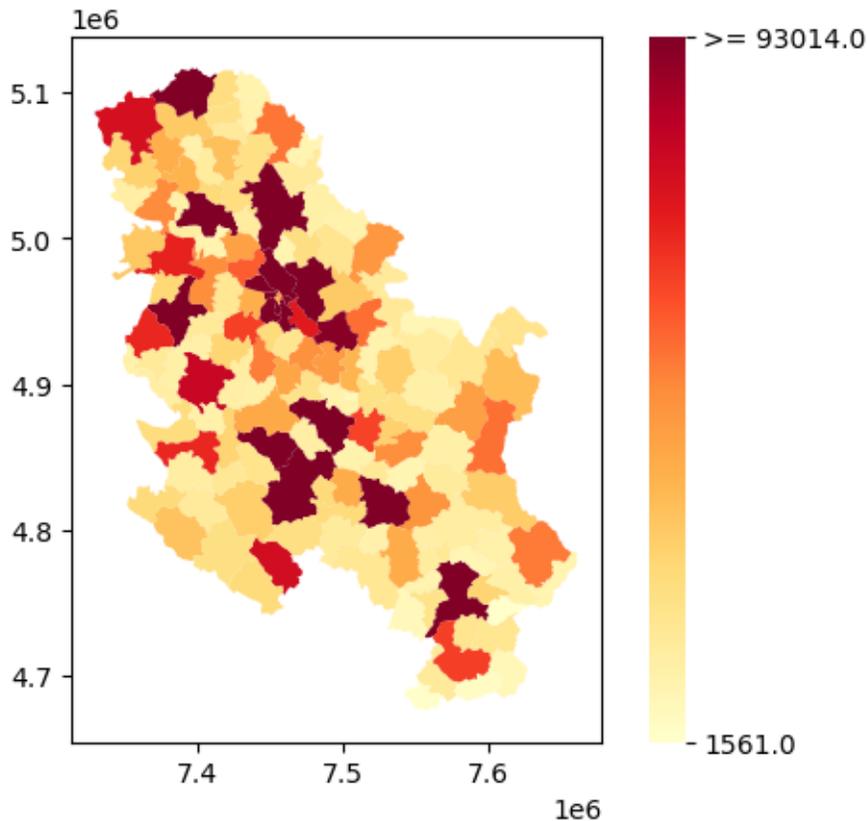
Above, we removed the outline of the color bar. Then we set the tick values to the min and the max population values, based on our norm object. Then, for the vmax value's label we added a ">=" to remind us that other, higher values are displayed with the darkest color.

3.2.1.5 Varying alpha transparency based on an array

Finally, we can also convey variation in a continuous scale through transparency. `alpha` doesn't expect column names, so we cannot just pass the name of the column containing the variable. Instead, we have to create an array from 0.0 to 1.0 values. To so we can a) use normalisation methods, or b) rescale the original values within 0 to 1 based on the original min and max values.

For example, with square root normalization:

```python
# 1. Create an alpha array based on a normalized value (e.g., population)
import numpy as np
pop_max = serbia_admin['pop'].max()
alpha = np.sqrt(serbia_admin['pop'] / pop_max)
```

```
# Plot with varying alpha values
fig, axes = plt.subplots(1, 2, figsize=(10, 6))
serbia_admin.plot(color = 'blue', ax=axes[0], alpha=alpha, edgecolor='black', linewidth = 0.3
serbia_admin.plot(cmap = 'YlOrRd', ax=axes[1], alpha=alpha, edgecolor='red', linewidth = 0.3)
for ax in axes:
    ax.set_axis_off()
```
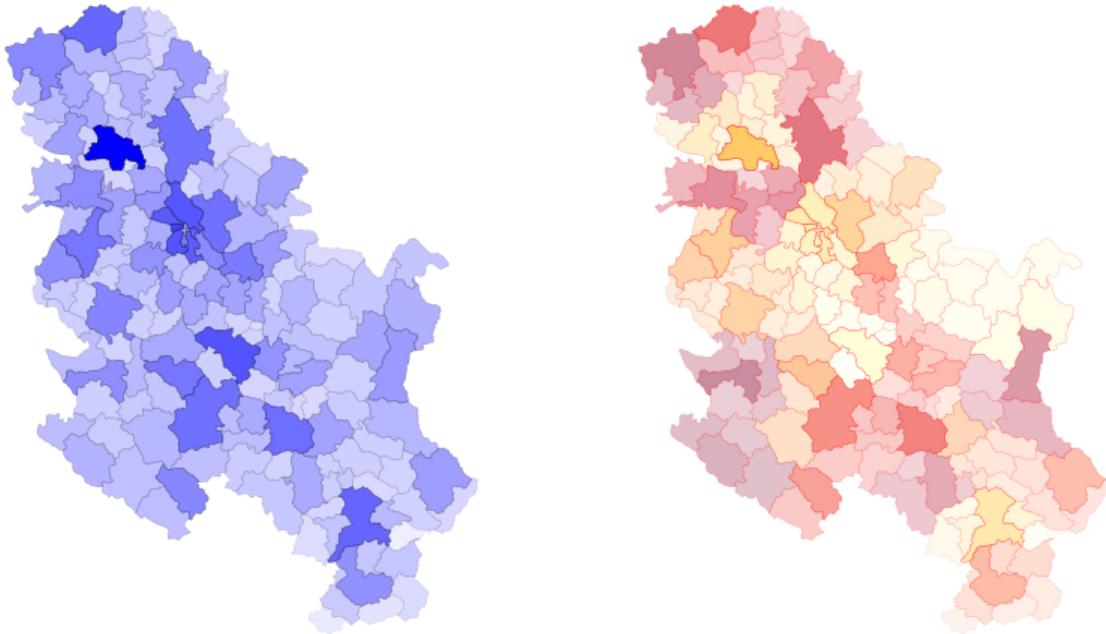

Important:

`matplotlib` would not able to plot a color bar from variations in the alpha value since no column is passed directly. We would need, in this case, to build a color bar manually as demonstrated above.

3.2.2 Choropleth Maps for Categorical Variables

A choropleth for categorical variables assigns a different color to every potential value in the series based on certain colormaps (`cmap`). We don't need to specify a scheme in this case, but just to the categorical `column`. Using last's week GeoDataFrame, we can plot terrorist attacks in Germany, for example, by group.

```
gdf = gpd.read_file("../data/germany.gpkg").to_crs(germany_crs)
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf.plot(ax = ax, column = 'gname', legend = True)
ax.set_axis_off()
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Terrorist Attacks in Germany, by Group", **title_parameters) #parameters as ab
```

Text(0.5, 1.0, 'Terrorist Attacks in Germany, by Group')

Terrorist Attacks in Germany, by Group

- 2nd of June Movement
- Action Cell Haukur Hilmarsson
- Action Group for the Destruction of the Police State
- Action Struggle Against the World
- Afghans
- Albanian exiles
- Anarchio Scene
- Anarchists
- Animal Liberation Front (ALF)
- Animal Rights extremists
- Anti-AF
- Anti-Abortion extremists
- Anti-American Arab Liberation Front
- Anti-Capitalist Commando
- Anti-Fascist Spring Bremen
- Anti-Government Group
- Anti-Government extremists
- Anti-Immigrant extremists
- Anti-Imperialist Cell (AIZ)
- Anti-Imperialist Fighters for a Free Palestine
- Anti-Iran Government Exiles
- Anti-Muslim extremists
- Anti-Nuclear extremists
- Anti-Roma extremists
- Anti-Semitic extremists
- Anti-globalization extremists
- Arab Revolutionary Army
- Armenian Secret Army for the Liberation of Armenia
- Arsonists
- Asylum Seekers
- Autonomen
- Autonomous Decorators
- Baader-Meinhof Group
- Bahoz
- Basque Fatherland and Freedom (ETA)
- Bavarian Liberation Army
- Black Cells
- Black September
- Census Opponents
- Commando 15th October
- Commando 27 September
- Commando Heinz Neumann
- Commune 1
- Conspiracy of Cells of Fire
- Conspiracy of Vengeful Arsonists
- Conspiracy theory extremists
- Croatian Nationalists
- Croatian Revolutionary Cell-Bruno Busic Dept
- Democratic Front for the Liberation of Palestine (DFLP)
- Democratic Iraqi Opposition of Germany
- Demonstration led by French Anti-Nazi Hunters
- Dev Sol
- Extraparliamentary Opposition (APO)
- Fedayeen Khalq (People's Commandos)
- Fedayeen of the Imperial Iranian Monarchy
- Fire and Flame for the Police (FFdP)
- First of October Antifascist Resistance Group (GRAPO)
- Free Network South (Freies Netz Sued)
- Freital Group
- Friends of Loukanikos
- German Resistance Movement
- Group for a Strong Revolutionary Movement
- Gruppe Haw Weg Den Scheiss
- Hekla Reception Committee-Initiative for More Social Eruptions
- Hizb al-Tahrir al-Islami (HT)
- Hoodie Wearers
- Indigenous People of Biafra (IPOB)
- Informal Anarchist Federation
- Internationalist Cells
- Iranian exiles
- Iranians
- Iraqi extremists
- Irish National Liberation Army (INLA)
- Irish Republican Army (IRA)
- Islamic Golden Army
- Islamic State of Iraq and the Levant (ISIL)
- Israeli extremists
- Jihadi-inspired extremists
- Kurdish Dissidents
- Kurdish Protestors
- Kurdish Separatists
- Kurdish Sympathizers
- Kurdish extremists
- Kurdistan Workers' Party (PKK)
- Kurds
- League of the 18
- Left-Wing Demonstrators
- Left-Wing Guerrillas
- Left-Wing Militants
- Left-Wing Terrorists
- Left-wing extremists
- Liberation Commando Rudolf Hess
- MLA
- May 15 Organization for the Liberation of Palestine
- Militant Cells
- Movement of the Third Reich
- Mujahedin-e Khalq (MEK)
- Muslim extremists
- Mustafa Aktas Fighting Unit
- National Socialist Underground
- Neo-Nazi extremists
- New Armenian Resistance
- Northern Terror Front
- Organization of the Sons of Occupied Territories
- Palestinian Extremists
- Palestinians
- Patriotic Europeans against the Islamization of the West (PEGIDA)
- Plowshares
- Popular Front for the Liberation of Palestine (PFLP)
- Popular Front for the Liberation of Palestine, Gen Cmd (PFLP-GC)
- Proletarian Action Group
- Proletarian Initiative and Offensive for W. Europe
- PVA
- Red Army Faction (RAF)
- Red Cell
- Revolution Chemnitz
- Revolutionary Cells
- Revolutionary Fighting Group 80
- Revolutionary Flames
- Revolutionary Peoples Army
- Right-Wing Youths
- Right-wing extremists
- Robin Food
- Rote Zora
- SFT
- Separatists
- Shutdown G20: Take Hamburg offline!
- Socialist Patients' Collective (SPK)
- Soldiers of the Algerian Opposition
- Students for a Democratic Society (SDS) (German)
- Sympathizers of "Iranian People's Zeda'i"
- Syrians
- Territorial Resistance Army
- The Armed Secret Organization
- The Third Way (Der III. Weg)
- Thomas Muenzer Wild Band
- Turkish Communist Party/Marxist (TKP-ML)
- Turkish Leftists
- Unknown
- Vietnamese
- Vulkangruppe NetzHerrschaft zerreissen
- Wehrsportgruppe Hoffmann
- Yazidi extremists
- Youths

The map above is what you would get from datasets that are not cleaned/manipulated directly or when there are too many categories in the selected column. First, let's get a slimmer slice of the gdf that only contains attacks that cause a number of fatalities and wounded higher than 10.

```
condition = (gdf.nkill + gdf.nwound) > 10
gdf_filtered = gdf[condition].copy()
```

Then, let's build a function that creates a random color map based on the number of categories. This creates random `HUE`-based colors:

```
# Generate random colormap
def rand_cmap(nlabels):
    """
    It generates a categorical random color map, given the number of classes

    Parameters
    ----------
    nlabels: int
        The number of categories to be coloured.
    type_color: str {"soft", "bright"}
        It defines whether using bright or soft pastel colors, by limiting the RGB spectrum.

    Returns
    -------
    cmap: matplotlib.colors.LinearSegmentedColormap
        The color map.
    """
    # Generate color map for bright colors, based on hsv
    randHSVcolors = [(np.random.uniform(low=0.20, high=0.80),
                      np.random.uniform(low=0.20, high=0.80),
                      np.random.uniform(low=0.20, high= 0.80)) for i in range(nlabels)]

    random_colormap = LinearSegmentedColormap.from_list('new_map', randHSVcolors, N=nlabels)

    return random_colormap
```

```
cmap = rand_cmap(len(gdf_filtered.gname.unique()))
cmap
```
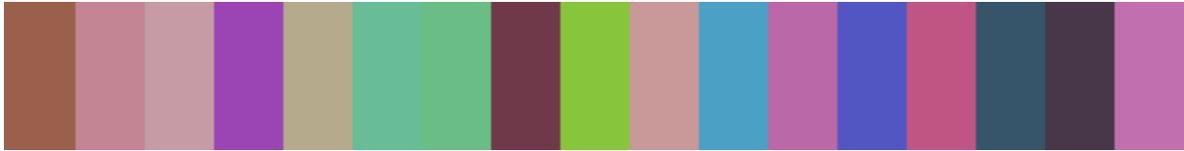
We also place the legend on the centre left. This is done automatically, but the legend and its items can be manipulated directly. Legends in `matplotlib` are extremely complex to personalise. However, do have a look at https://matplotlib.org/stable/api/_as_gen/matplotlib.pyplot.legend.html#ma for both automatic and explicit manipulation.

```
legend_kwds={"loc": "center left", "bbox_to_anchor": (1, 0.5)}
```

```
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf_filtered.plot(ax = ax, column = 'gname', legend = True, cmap = cmap, legend_kwds = legend
title_parameters = {'fontsize':'16', 'fontname':'Times New Roman'}
ax.set_title("Terrorist Attacks in Germany, by Group", **title_parameters) #parameters as abo
ctx.add_basemap(ax, crs= gdf_filtered.crs.to_string(), source = ctx.providers.Esri.WorldGray
```
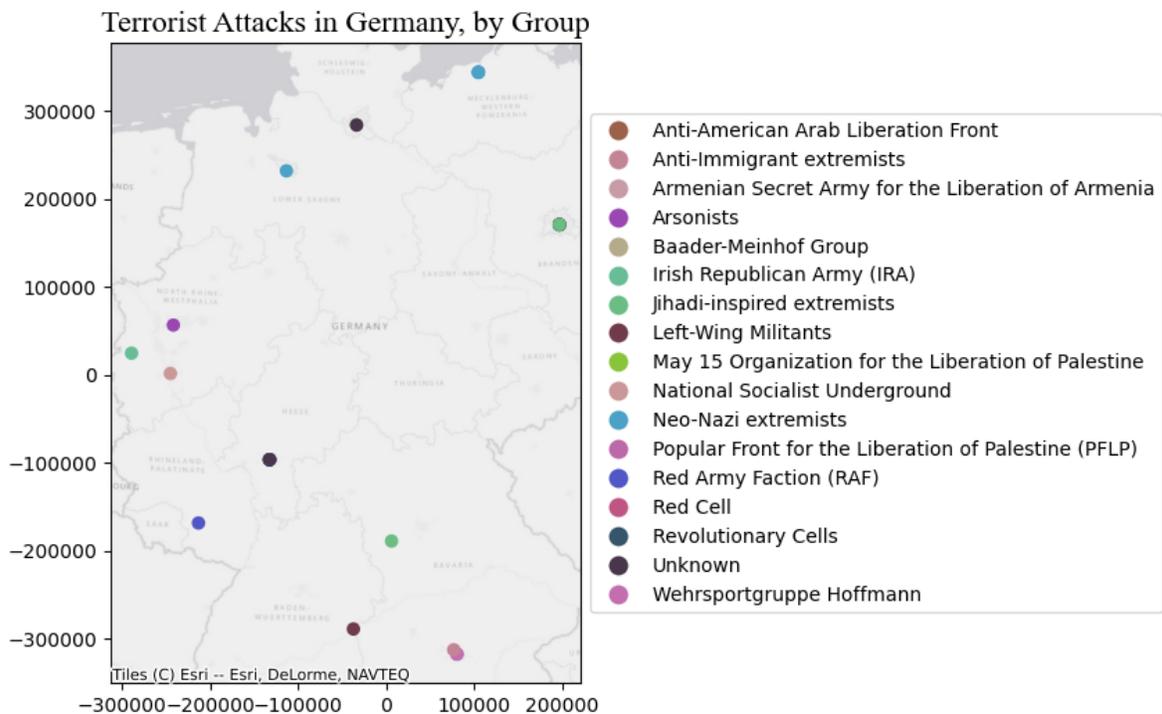

We can also convey the impact of the events through the `markersize`. This introduces the concept of *cartogram* (see below).

```
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf_filtered.plot(ax = ax, column = 'gname', markersize = 'nwound', legend = True, cmap = cma
ax.set_title("Terrorist Attacks in Germany, by Group", **title_parameters) #parameters as ab
ctx.add_basemap(ax, crs= gdf_filtered.crs.to_string(), source = ctx.providers.Esri.WorldGray
ax.set_axis_off()
```


Terrorist Attacks in Germany, by Group
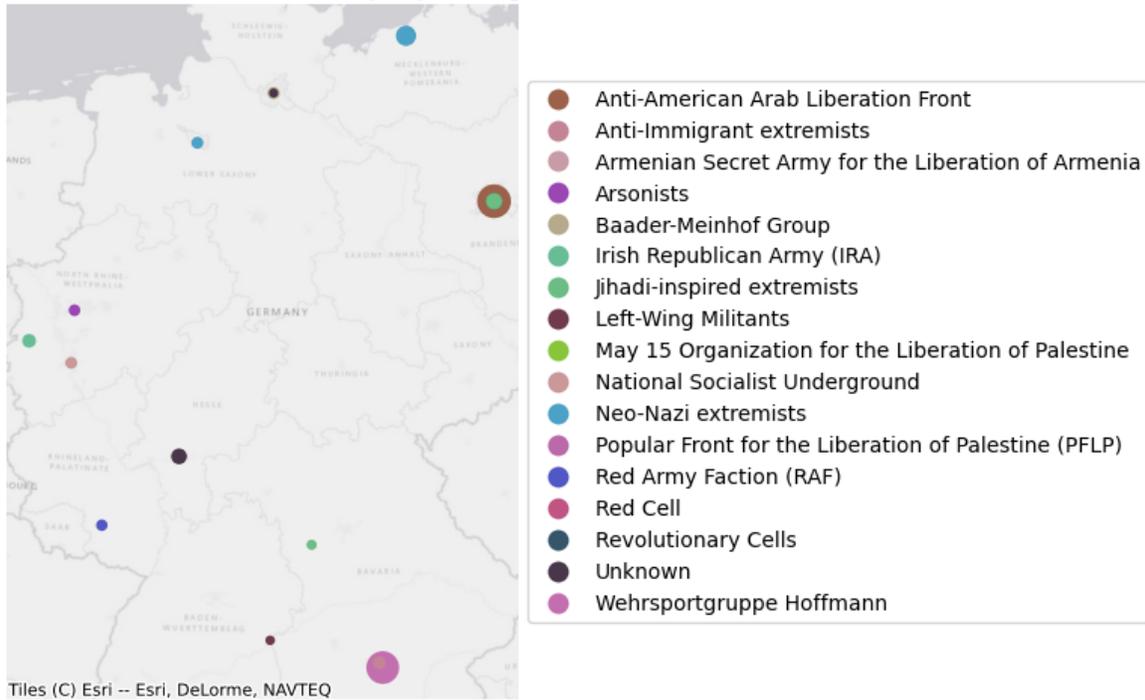
3.3 Part III: Cartograms - Manipulating the Geometry size for showing the magnitude of a value

Cartograms are maps that represent the spatial distribution of a variable not by encoding it in a color palette but rather by modifying geographical objects. There are many algorithms to distort the shapes of geographical entities according to values, some of them are rather complex.

3.3.1 Polygons

You can obtain cartograms for `Polygon` with `geoplot`: see https://residentmario.github.io/geoplot/

geoplot functions pretty much work as `plot`

```
# this library needs the GeoDataFrame to be reverted to WGS
ax = gplt.cartogram(serbia_admin.to_crs(wgs), scale='pop', projection=gcrs.Mercator(), color
# see for projections that work with gplt https://scitools.org.uk/cartopy/docs/v0.15/crs/proj
gplt.polyplot(serbia_admin.to_crs(wgs), facecolor='lightgray', edgecolor='white', ax=ax, lw =
```
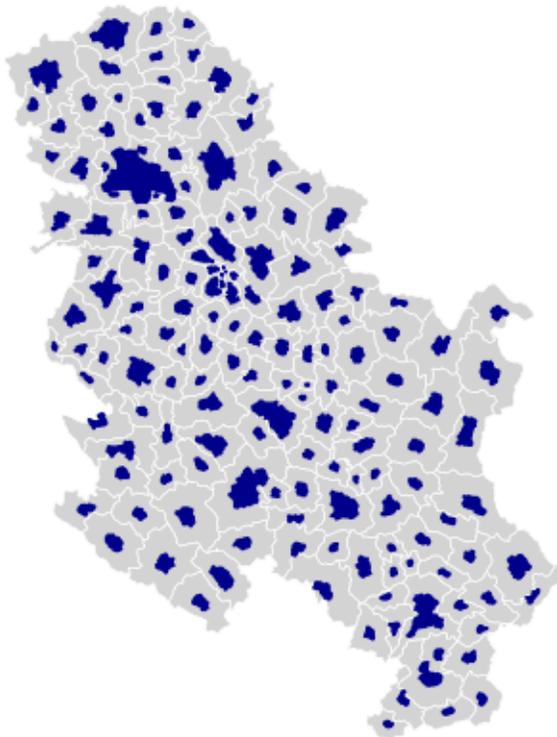

3.3.2 Points

For `Point` GeoDataFrames we can just go back to `plot` and pass a column name to `markersize`.

```
attacks = pd.read_csv("../data/GTD_2022.csv", low_memory = False)
country = 'Germany'
```

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```
df = attacks[attacks.country_txt == country].copy()
wgs = 'EPSG:4326'
germany_crs = 'EPSG:4839'
gdf = gpd.GeoDataFrame(df, geometry=gpd.points_from_xy(df.longitude, df.latitude), crs = wgs)
gdf = gdf.to_crs(germany_crs)
```

```
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf.plot(ax = ax, markersize = 'nwound', color = 'purple', legend = True)
ax.set_axis_off()
```

One can also convert polygons into points by using their centroids, and then define the size of
the dot proportionally to the value of the variable we want to display.

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3.3.3 LineString

For `LineString` we pass the column name to `linewidth`.

Let's load a shapefile of lines. These lines represent frequency of train connections from/to train stations in the region of Liguria (Italy) to other stations within or outside the region. Each line refers to a connection between two specific stations, through a certain type of service and contains information about the frequency of that type of service. For example, the cities of Savona and Finale Ligure might be connected by 5 InterCity trains and 50 regional services. These services correspond to 2 different records.

```
trains_freq = gpd.read_file("../data/trains_fromLiguria.gpkg" )
trains_freq.crs
```

```
<Projected CRS: EPSG:3003>
Name: Monte Mario / Italy zone 1
Axis Info [cartesian]:
- X[east]: Easting (metre)
- Y[north]: Northing (metre)
Area of Use:
- name: Italy - onshore and offshore - west of 12°E.
- bounds: (5.93, 36.53, 12.0, 47.04)
Coordinate Operation:
- name: Italy zone 1
- method: Transverse Mercator
Datum: Monte Mario
- Ellipsoid: International 1924
- Prime Meridian: Greenwich
```

Let's check the type of services contained here.

```
trains_freq['train_type'].unique()
```

```
<StringArray>
['REG', 'IC', 'FB', 'ICN', 'U', 'EC/EN', 'AV']
Length: 7, dtype: str
```

We have: - 'REG': regional trains. - 'IC': intercity trains. - 'FB': similar to IC, but slightly faster. - 'ICN': sleeper trains. - 'U': urban trains (Genoa). - 'EC/EN': international trains. - 'AV': High-speed trains.

Let's keep just regional, intercity, and high-speed trains.

```
to_keep = ['REG', 'IC', 'AV']
trains_freq = trains_freq[trains_freq['train_type'].isin(to_keep)]
```

The usage of `linewdith` is a bit different from `markersize` for some reason. We have to pass an `array` of N values, where N is equal to the GeoDataFrame size. In other words, we have to pass the column we want to use to regulate the line width directly as a list/array. Specifying the column name is not enough.

```
fig, ax = plt.subplots(1, 1, figsize=(10, 15))
trains_freq.plot(ax = ax, linewidth = trains_freq['freq'])
ax.set_axis_off()
```
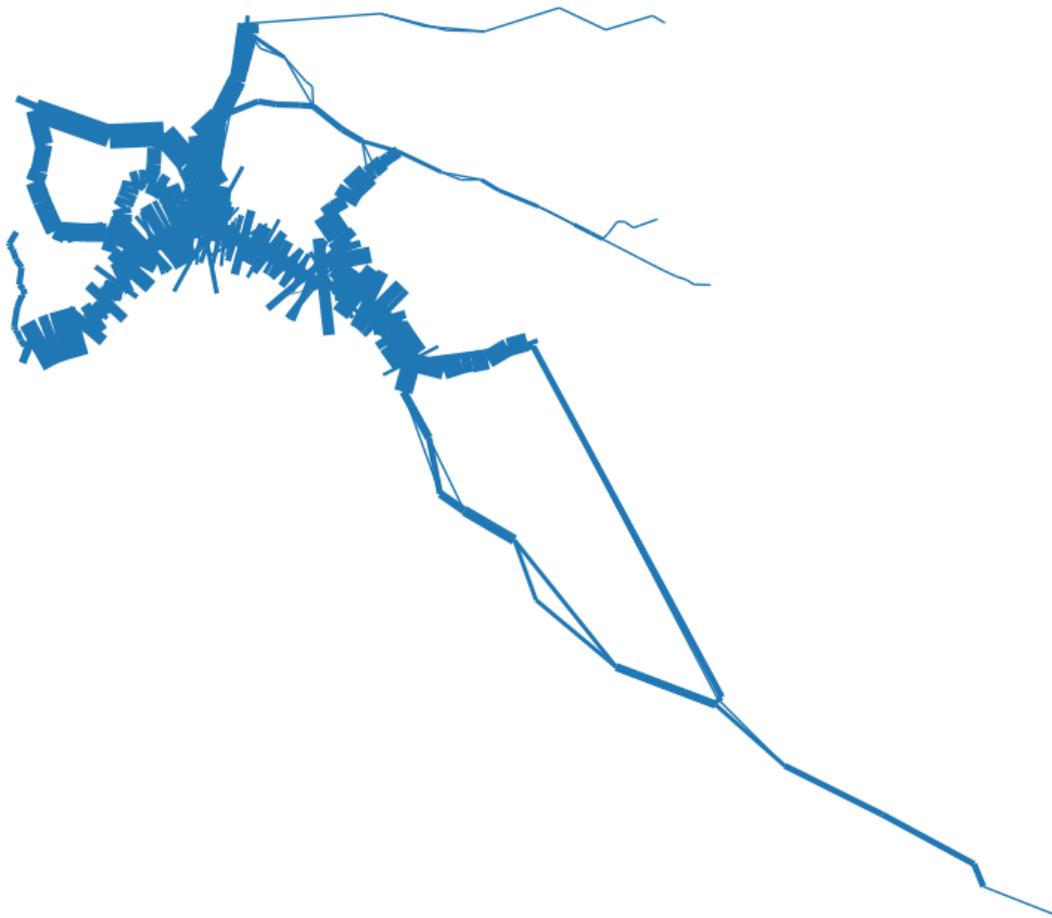
As you can see, the default arguments and simply passing the column values do not produce pretty results. The first thing to look at is the values that are passed to `linewidth`. In some cases, the min and max values, as well as their distribution, are not ideal for visually conveying the magnitude of the variable attached to the geometry. One option is to use a multiplier factor (see below), or to rescale the values from 0 to 1, for example, and then, again, if necessary use a multiplier.

```
fig, ax = plt.subplots(1, 1, figsize=(15, 20))
lw = trains_freq['freq'] * 0.15
trains_freq.plot(ax = ax, linewidth = lw, capstyle = 'round', joinstyle = 'round', column =
ctx.add_basemap(ax, crs= trains_freq.crs.to_string(), source = ctx.providers.Esri.WorldGrayCa
ax.set_axis_off()
```
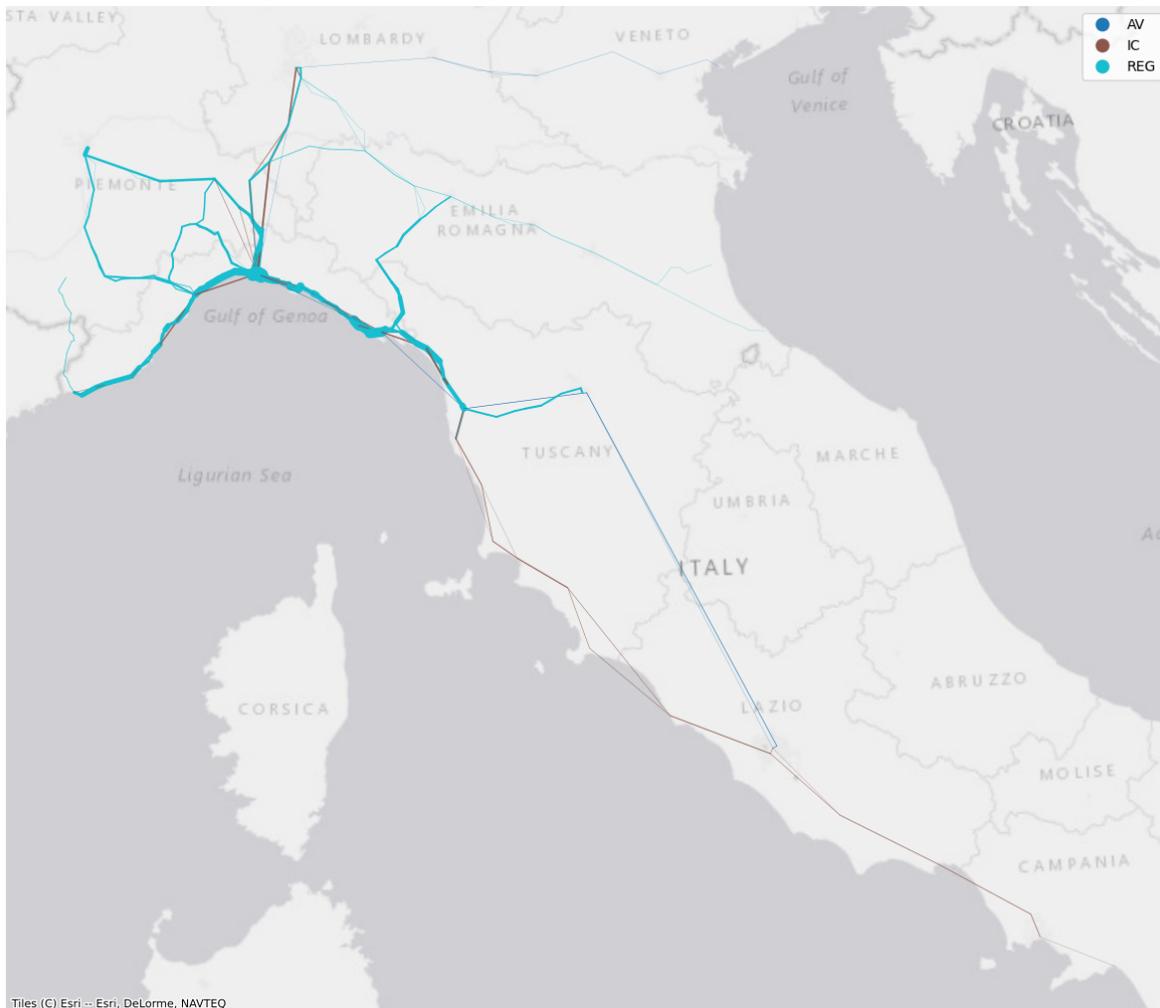
While this looks a bit better, this visualisation is not ideal because the frequencies are not snapped to the actual railway network. The lines represent, instead, connection between train stops and therefore their coordinates only include the ones corresponding to the stations where the different services call at. One can devise approaches to:

- Assigning the frequencies, or any other value, to the corresponding infrastructure's section. For example, the railway section between two stations could be associated with a value representing the total number of regional/local services travelling along it.
- Smoothing the lines representing the services by adding further coordinates along the line.

Both these processes go beyond the scopes of this lab and require several considerations depending on the data, the scale, and what information one wants to displays.

Exercise:

Today we've seen how to exploit `matplotlib` to plot `GeoDataFrame` layers. Go through the notebook again if you feel that there's something you need to review. You are not expected to remember each step/method/parameter. Rather, this notebook should be used as a reference for producing maps in Python. Do keep in mind that most of the maps above have been produced with just a bunch of rows, so each of them can be improved and embellished with some more effort.

Now, if you are not overwhelmed, have a look at the very last map and produce some nice visualisation using the same data. You can further improve its clarity, add a legend that refers to the line width, visualise only a certain type of services, or add information/context, for example. In the folder `\data` you can also find a `.gpkg` file containing all the train stations in Italy, should you need that.

3.3.3.1 Saving figures (check here for details)

```python
fig.savefig("fig1.pdf", dpi='figure', format="pdf", bbox_inches = 'tight')
```

4 Interactive Maps

Gabriele Filomena has readapted parts of this notebook to prepare this notebook. Copyright (c) Henrikki Tenkanen, Vuokko Heikinheimo, Håvard Wallin Aagesen, Christoph Fink, Kamyar Hasanzadeh.

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

Online maps have been interactive for a long time: virtually all online maps allow to zoom in and out, to pan the map extent, and to select map features, or otherwise query information about them. Interactive content in web pages, such as online maps, are typically implemented using *JavaScript/ECMAScript*, a scripting language originally targeted at web pages, primarily, but used for many other applications.

In the open source realm, there exists a number of different *JavaScript* libraries for interactive web cartography, including Leaflet and OpenLayers. We will not write a single line of *JavaScript*; instead, we will take advantage of the *Folium* Python package: it helps create interactive *Leaflet* maps from data stored in `geopandas.GeoDataFrame`. Folium is a library that bridges the capabilities of data manipulation in Python with the interactive mapping strengths of Leaflet, a leading open-source JavaScript library for creating dynamic, interactive maps in the browser. Let's explore both Folium and Leaflet in more detail to understand their roles and relationship.

Leaflet is at the heart of Folium's mapping capabilities. It's an open-source JavaScript library used extensively in web mapping. Known for its simplicity, performance, and ease of use, Leaflet has become a popular choice among developers for embedding maps in web applications. It allows users to create maps with various interactive features like zooming, panning, markers, popups, and different layers.

Folium builds on Leaflet's foundation, bringing its interactive mapping capabilities into the Python environment. This integration is significant for several reasons:

- With Folium, Python users can use libraries like Pandas and directly create interactive Leaflet maps from within Python. This seamless integration means data can be manipulated, analyzed, and visualized using Python, without the need for extensive JavaScript knowledge.
- Folium abstracts the complexity of Leaflet, allowing users to create sophisticated maps using simple Python commands.

- Folium inherits Leaflet's interactivity, enabling the creation of feature-rich maps with various interactive elements such as markers, layers, and choropleths. These maps can be customized and embedded in web applications or Jupyter notebooks, making them highly versatile for data visualization tasks.
- Folium can render maps with different tilesets (like OpenStreetMap, Stamen Terrain), overlay data in various formats, and even incorporate advanced features like heatmaps or GeoJSON layers.

Folium acts as a bridge between Python and Leaflet, enabling Python users to incorporate and develop web maps within their environment. It leverages Leaflet's core functionalities and extends them into the Python ecosystem, making geospatial data visualization both powerful and accessible within Python workflows.

Find more information about the capabilities of the *Folium* package on its official web pages: - Documentation - Example gallery - Quickstart tutorial

```python
import folium
import pandas as pd
import geopandas as gpd
```

4.1 Simple interactive web maps with Folium

We will start by creating a simple interactive web map that contains nothing but a base map. This is so that we can get acustomed to how Folium's syntax works, and which steps we have to take. We create a `folium.Map` object, and specify centred around which `location` and at which initial zoom level (~0-20) a map shall be displayed. By setting `control_scale` to `True`, we make Folium display a scale bar.

```python
location = (39.6508, 66.9654) # Samarkand, Uzbekistan
interactive_map = folium.Map(location=location, zoom_start=13, control_scale=True)
interactive_map
```

```
<folium.folium.Map at 0x1f5a460e810>
```

4.1.0.1 Save the resulting map

To save this map to an HTML file that can be opened in any web browser, use `folium.Map.save()`:

```python
interactive_map.save("base-map.html")
```

4.1.1 Basemap API

Folium, Leaflet.js and `contextily`, the library that we used for adding basemaps to our static maps in the 2nd session, rely on built-in tilesets borrowed from the `xyzservices` package. The XYZ protocol exposes maps as images for portions of the Earth, which we refer to as 'tiles.' The term 'XYZ' originates from the coordinates used to locate a specific tile. Think of the entire planet divided into squares, each identified by a unique combination of X and Y numbers. Now, add a third component (Z) for the zoom level: lower values use fewer tiles to cover the world, while higher zoom levels (higher Z) provide progressively smaller areas with more detail. Most XYZ APIs serve tiles directly over HTTP, enabling us to access them from the browser. In a nuthesell, XYZ Tiles is a method of expressing map tile mosaics, indexed by (x,y) offsets and zoom levels (z).

```python
import xyzservices.providers as xyz
xyz
```

```
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     'html_attribution': '<a target="_blank" href="https://www.swisstopo.admin.ch/">swisstopo</
     'attribution': '© swisstopo',
     'bounds': [[45.398181, 5.140242], [48.230651, 11.47757]],
     'min_zoom': 2,
     'max_zoom': 18,
     'time': 18641231,

```
          'name': 'SwissFederalGeoportal.JourneyThroughTime'}},
      'TopPlusOpen': {'Color': {'url': 'http://sgx.geodatenzentrum.de/wmts_topplus_open/tile/1.0.0
          'max_zoom': 18,
          'html_attribution': 'Map data: &copy; <a href="http://www.govdata.de/dl-de/by-2-0">dl-de/l
          'attribution': 'Map data: (C) dl-de/by-2-0',
          'variant': 'web',
          'name': 'TopPlusOpen.Color'},
        'Grey': {'url': 'http://sgx.geodatenzentrum.de/wmts_topplus_open/tile/1.0.0/{variant}/defau
          'max_zoom': 18,
          'html_attribution': 'Map data: &copy; <a href="http://www.govdata.de/dl-de/by-2-0">dl-de/l
          'attribution': 'Map data: (C) dl-de/by-2-0',
          'variant': 'web_grau',
          'name': 'TopPlusOpen.Grey'}},
      'Gaode': {'Normal': {'url': 'http://webrd01.is.autonavi.com/appmaptile?lang=zh_cn&size=1&sc
          'max_zoom': 19,
          'attribution': '&copy; <a href="http://www.gaode.com/">Gaode.com</a>',
          'html_attribution': '&copy; <a href="http://www.gaode.com/">Gaode.com</a>',
          'name': 'Gaode.Normal'},
        'Satellite': {'url': 'http://webst01.is.autonavi.com/appmaptile?style=6&x={x}&y={y}&z={z}'
          'max_zoom': 19,
          'attribution': '&copy; <a href="http://www.gaode.com/">Gaode.com</a>',
          'html_attribution': '&copy; <a href="http://www.gaode.com/">Gaode.com</a>',
          'name': 'Gaode.Satellite'}},
      'Strava': {'All': {'url': 'https://heatmap-external-a.strava.com/tiles/all/hot/{z}/{x}/{y}.p
          'max_zoom': 15,
          'attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a>',
          'html_attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a
          'name': 'Strava.All'},
        'Ride': {'url': 'https://heatmap-external-a.strava.com/tiles/ride/hot/{z}/{x}/{y}.png',
          'max_zoom': 15,
          'attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a>',
          'html_attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a
          'name': 'Strava.Ride'},
        'Run': {'url': 'https://heatmap-external-a.strava.com/tiles/run/bluered/{z}/{x}/{y}.png',
          'max_zoom': 15,
          'attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a>',
          'html_attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a
          'name': 'Strava.Run'},
        'Water': {'url': 'https://heatmap-external-a.strava.com/tiles/water/blue/{z}/{x}/{y}.png',
          'max_zoom': 15,
          'attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a>',
          'html_attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a
          'name': 'Strava.Water'},
```

```
 'Winter': {'url': 'https://heatmap-external-a.strava.com/tiles/winter/hot/{z}/{x}/{y}.png'
  'max_zoom': 15,
  'attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</a>',
  'html_attribution': 'Map tiles by <a href="https://labs.strava.com/heatmap">Strava 2021</
  'name': 'Strava.Winter'}},
'OrdnanceSurvey': {'Road': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Road_3857/{z}/{x}/
  'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
  'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
  'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/
  'min_zoom': 7,
  'max_zoom': 16,
  'max_zoom_premium': 20,
  'bounds': [[49.766807, -9.496386], [61.465189, 3.634745]],
  'name': 'OrdnanceSurvey.Road'},
 'Road_27700': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Road_27700/{z}/{x}/{y}.png?key=
  'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
  'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
  'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/
  'crs': 'EPSG:27700',
  'min_zoom': 0,
  'max_zoom': 9,
  'max_zoom_premium': 13,
  'bounds': [[0, 0], [700000, 1300000]],
  'name': 'OrdnanceSurvey.Road_27700'},
 'Outdoor': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Outdoor_3857/{z}/{x}/{y}.png?key=
  'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
  'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
  'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/
  'min_zoom': 7,
  'max_zoom': 16,
  'max_zoom_premium': 20,
  'bounds': [[49.766807, -9.496386], [61.465189, 3.634745]],
  'name': 'OrdnanceSurvey.Outdoor'},
 'Outdoor_27700': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Outdoor_27700/{z}/{x}/{y}.pr
  'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
  'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
  'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/
  'crs': 'EPSG:27700',
  'min_zoom': 0,
  'max_zoom': 9,
  'max_zoom_premium': 13,
  'bounds': [[0, 0], [700000, 1300000]],
  'name': 'OrdnanceSurvey.Outdoor_27700'},
```

```
    'Light': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Light_3857/{z}/{x}/{y}.png?key={key]
     'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
     'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
     'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/:
     'min_zoom': 7,
     'max_zoom': 16,
     'max_zoom_premium': 20,
     'bounds': [[49.766807, -9.496386], [61.465189, 3.634745]],
     'name': 'OrdnanceSurvey.Light'},
    'Light_27700': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Light_27700/{z}/{x}/{y}.png?ke
     'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
     'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
     'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/:
     'crs': 'EPSG:27700',
     'min_zoom': 0,
     'max_zoom': 9,
     'max_zoom_premium': 13,
     'bounds': [[0, 0], [700000, 1300000]],
     'name': 'OrdnanceSurvey.Light_27700'},
    'Leisure_27700': {'url': 'https://api.os.uk/maps/raster/v1/zxy/Leisure_27700/{z}/{x}/{y}.pr
     'html_attribution': 'Contains OS data &copy Crown copyright and database right 2025',
     'attribution': 'Contains OS data (C) Crown copyright and database right 2025',
     'key': '<insert your valid OS MapsAPI Key. Get a free key here - https://osdatahub.os.uk/:
     'crs': 'EPSG:27700',
     'min_zoom': 0,
     'max_zoom': 5,
     'max_zoom_premium': 9,
     'bounds': [[0, 0], [700000, 1300000]],
     'name': 'OrdnanceSurvey.Leisure_27700'}},
  'UN': {'ClearMap': {'url': 'https://geoservices.un.org/arcgis/rest/services/ClearMap_WebTop
     'name': 'UN.ClearMap',
     'html_attribution': '&copy; <a href="https://www.un.org/geospatial/mapsgeo/webservices">Ur
     'attribution': 'United Nations'}}}
```

In Folium, you can pass one of the custom `xyzservices.TileProvider` listed above or a
Leaflet-style URL to the tiles parameter: `http://{s}.yourtiles.com/{z}/{x {y}.png`.
You can find a list of free tile providers here: http://leaflet-extras.github.io/leaflet-
providers/preview/. Be sure to check their terms and conditions and to provide attribution
(see below)

```
interactive_map = folium.Map(location=location, zoom_start=13, tiles="CartoDB.DarkMatterNoLal
interactive_map
```

```
<folium.folium.Map at 0x1f5a4870050>
```

Or we can point to a custom *tileset URL*:

```
interactive_map = folium.Map(location=location, zoom_start=12, tiles="https://mt1.google.com,
interactive_map
```

```
<folium.folium.Map at 0x1f5a4ae8fd0>
```

4.1.2 Optional: Mapbox (may be tricky to use - access policies change very often)

Also, the *Mapbox Static Tiles API* serves raster tiles generated from Mapbox Studio styles. Raster tiles can be used in traditional web mapping libraries like Mapbox.js, Leaflet, Open-Layers, and others to create interactive slippy maps. The Static Tiles API is well-suited for maps with limited interactivity or use on devices that do not support WebGL.

Usage of the Mapbox APIs is governed by the Mapbox Terms of Service. Please visit https://www.mapbox.com/legal/tos/ for more information.

```
# Your Mapbox access token
mapbox_access_token = 'YOUR_MAPBOX_ACCESS_TOKEN_HERE'

# Mapbox tile URL
tile_url = f'https://api.mapbox.com/styles/v1/mapbox/light-v9/tiles/{{z}}/{{x}}/{{y}}?access_

# Create a folium map
interactive_map = folium.Map(location=[53.406872, -2.973286], zoom_start=13, tiles = tile_url
interactive_map
```

```
<folium.folium.Map at 0x1f5a460fc10>
```

4.1.3 Add a point marker

To add a single marker to a *Folium* map, create a `folium.Marker`. Supply a `folium.Icon` as the argument of the parameter `icon` to influence how the marker is styled, and set `tooltip` to display a text when the mouse pointer hovers over it.

```
center = folium.Marker(location=location, tooltip="City Centroid", icon=folium.Icon(color="gr
center.add_to(interactive_map)
interactive_map
```

```
<folium.folium.Map at 0x1f5a460fc10>
```

```
# Similarly..
popup = ["Tom", "Kendall", "Sean", "Zachary", "Karla"]

# Longitude and Latitude coordinates
lng = [-3.2031323, -0.2416811, -3.4924087, -4.3725404, -2.6607571]
lat = [53.4118332, 51.5285582, 55.940874, 55.8553807, 51.4684681]

# Creating a folium map
interactive_map = folium.Map(location=[53.4118332, -3.2031323], zoom_start=5, tiles = "NASAG

# Adding markers with popups
for i in range(len(popup)):
    folium.Marker([lat[i], lng[i]], popup=popup[i]).add_to(interactive_map)

interactive_map
```

```
<folium.folium.Map at 0x1f5a474fc10>
```

4.1.4 Add a layer of points

Folium also supports to add entire layers, for instance, as `geopandas.GeoDataFrames`. Folium implements *Leaflet*'s geoJSON layers in its `folium.features.GeoJson` class. We can initialise such a class (and layer) with a GeoDataFrame, and add it to a map. In the example below, we work again with the GeoDataFrame of terrorist attacks in Germany.

```
wgs = 'EPSG:4326'
gdf = gpd.read_file("../data/germany.gpkg")
gdf = gdf.set_crs(wgs)
```

Let's explore the data around Berlin

```
berlin = (52.5200, 13.4050)
interactive_map = folium.Map(location= berlin, zoom_start=10)

attacks_layer = folium.features.GeoJson(gdf, name="Terrorist attacks")
attacks_layer.add_to(interactive_map)
interactive_map
```

```
<folium.folium.Map at 0x1f5a7110550>
```

We can also add a pop-up window to our map which would show some details when clicking on the location of the attacks:

```
popup = folium.GeoJsonPopup(fields=["year", "gname", "nwound"], aliases =["Year", "Terrorist
                            style="background-color: yellow;")
interactive_map = folium.Map(location= berlin, zoom_start=10)
attacks_layer = folium.features.GeoJson(gdf[gdf.nwound.notna()], name="Terrorist attacks", po
attacks_layer.add_to(interactive_map)

interactive_map
```

```
<folium.folium.Map at 0x1f5a464c450>
```

4.1.5 Add a polygon layer

We can do the same with polygons. Let's load municipalities in Serbia.

```
serbia = gpd.read_file("../data/serbia_data.gpkg")
serbia.head()
```

	name	id	poverty	name_sr	arr_dom	arr_int	pop	male	female	net	g
0	Aranđelovac	1	23.3	Aranđelovac	4042.0	958.0	39456.0	19166.0	20290.0	72348.0	1
1	Batočina	2	36.1	Batočina	11.0	0.0	10085.0	4995.0	5090.0	63243.0	8
2	Knić	3	40.1	Knić	753.0	55.0	12533.0	6312.0	6221.0	65463.0	9
3	Kragujevac	4	23.8	Kragujevac	2244.0	2417.0	154290.0	74515.0	79775.0	79415.0	1
4	Lapovo	5	23.9	Lapovo	39.0	36.0	6785.0	3294.0	3491.0	65350.0	9

Important:

We need to project the GeoDataFrame back to the WGS crs; web-maps, because of their interactivity and because users can pan to different areas, work with the WGS projection and cannot handle planar crs.

```
wgs = 'EPSG:4326'
serbia.to_crs(wgs, inplace = True)
```

We will use the `folium.Choropleth` to display arrivals of tourists in July 2023, per municipality. Choropleth maps are more than simply geometries in Folium, which could be displayed as a `folium.features.GeoJson` layer. Rather, this class takes care of categorising data, adding a legend, and a few more small tasks to quickly create beautiful thematic maps.

The class expects an input data set that has an explicit, `str`-type, index column, as it treats the geospatial input and the thematic input as separate data sets that need to be joined (see also, below, how we specify both `geo_data` and `data`). A good approach to create such a column is to copy the data frame's index into a new column, for instance `id_str`.

```
serbia["id_str"] = serbia.index.astype(str)
```

Now we can create the polygon choropleth layer, and add it to a map object. Due to the slightly complex architecture of *Folium*, we have to supply a number of parameters: - `geo_data` and `data`, the geospatial and thematic input data sets, respectively. Can be the same `GeoDataFrame`. - `columns`: a tuple of the names of relevant columns in `data`: a unique index column, and the column containing thematic data - `key_on`: which column in `geo_data` to use for joining `data` (this is basically identical to `columns`, except it's only the first value)

```
# getting the location
centroid = serbia.unary_union.centroid
location = (centroid.coords[0][1], centroid.coords[0][0])
```

```
C:\Users\gfilo\AppData\Local\Temp\ipykernel_36684\1078060503.py:2: DeprecationWarning: The '
  centroid = serbia.unary_union.centroid
```

Let's look at the number of arrivals of tourists across the municipalities. - `arr_dom` indicates the number of domestic tourists (from other areas in Serbia) in july 2023. - `arr_int` indicates the number of international tourists in july 2023.

```
serbia[['arr_dom', 'arr_int', 'Province', 'name']].head()
```

	arr_dom	arr_int	Province	name
0	4042.0	958.0	Šumadijski	Aranđelovac
1	11.0	0.0	Šumadijski	Batočina
2	753.0	55.0	Šumadijski	Knić
3	2244.0	2417.0	Šumadijski	Kragujevac
4	39.0	36.0	Šumadijski	Lapovo

```
interactive_map = folium.Map(location=location, zoom_start=7)
arrivals_choro = folium.Choropleth(geo_data=serbia, data=serbia, columns=("id_str", "arr_int"
                        fill_color="Oranges", line_weight=0.2, line_color='black
                        legend_name="Nr of International Tourists, July 2023",
                        highlight = True) ## look at what this does!
arrivals_choro.add_to(interactive_map)
interactive_map
```

```
<folium.folium.Map at 0x1f5a4addc50>
```

In such an interactive map, it would be nice to display some property of each polygon
when hovering with the mouse over it. `folium.Choropleth` does not support this. Yet, we
can add a "transparent" layer using `folium.features.GeoJson`, and configure it to display
`GeoJsonTooltip`. We can keep the `map` we created above, and simply add the layer to it.

```python
# folium GeoJson layers expect a styling function, that receives each of the map's feature a
# It can, however, also return a static style:
def style_function(feature):
    return {
        "color": "transparent",
        "fillColor": "transparent",
    }


tooltip = folium.features.GeoJsonTooltip(fields=("name",), aliases=("Municipality:",))
tooltip_layer = folium.features.GeoJson(serbia, style_function=style_function, tooltip=toolt
tooltip_layer.add_to(interactive_map)
interactive_map
```

```
<folium.folium.Map at 0x1f5a4addc50>
```

The problem now is that we cannot highlight the polygons and fully figure out the boundaries
of the areas we are hovering on. However, we can also tackle that. First we create again our
map.

```python
# base map
interactive_map = folium.Map(location=[serbia.geometry.centroid.y.mean(), serbia.geometry.cen
```

```
C:\Users\gfilo\AppData\Local\Temp\ipykernel_36684\2597533763.py:2: UserWarning: Geometry is

  interactive_map = folium.Map(location=[serbia.geometry.centroid.y.mean(), serbia.geometry.
```

Then, the choropleth object as before. This time we also set `use_jenks` as `True`. The number
of desired classes needs to be passed by using the parameter `bins`.

```python
# Add the choropleth layer
arrivals_choro = folium.Choropleth(geo_data=serbia, data = serbia, columns=['id_str', 'arr_i
                                   use_jenks = True, bins = 7, fill_color='Oranges',line_we
                                   fill_opacity=0.7, legend_name='Arrivals Intensity').add_
                                   ## no highlight here
```

Then, below, we define two functions that always take a feature as a parameter (each geographic element on the map, the municipality polygons).

1. **`style_function`**:

   - Purpose: Defines the default style for each polygon on the map.
   - Sets the fill color, border color, border weight, and fill opacity for polygons. The provided colors and values are applied to all polygons by default.

2. **`highlight_function`**:

   - Purpose: Changes the style of a polygon when it is hovered over.
   - Alters the fill color and opacity when the mouse hovers over a polygon, making it stand out.

```
# Define style function
def style_function(feature):
    return {
        'fillColor': arrivals_choro.color_scale(feature['properties']['arr_int']),  # fill co
        'color': 'black',  # Border color
        'weight': 0.5, # Border weight
        'fillOpacity': 0.7 # Fill color opacity
    }


# Define highlight function
def highlight_function(feature):
    return {
        'fillColor': '#ff0000',  # Fill color when highlighted
        'color': 'black',  # Border color when highlighted
        'weight': 0.5, # Border weight when highlighted
        'fillOpacity': 1.0 # Fill color opacity
    }
```

Essentially, here, we use the `choropleth`, `arrivals_choro` just to get the colours assigned to the feature, on the basis of the `bins` that we created with the scheme. Then we pass these colors to the same features in the `folium.GeoJson` class below. In this case the layer is not transparent. Finally, as before, we add a `tooltip` and a `popup`.

The popup appears when the polygon is clicked but this aspect can be personalised too.

```
# Add popups and pass styling options
folium.GeoJson(serbia, style_function = style_function,
               highlight_function=highlight_function,
               tooltip= folium.features.GeoJsonTooltip(fields=['name']),
```

```
                popup=folium.features.GeoJsonPopup(fields=['arr_dom', 'arr_int'], aliases = [
    ).add_to(interactive_map)

interactive_map
```

```
<folium.folium.Map at 0x1f5a8affc90>
```

4.2 Interactive Maps and API (more on this next week)

```
import requests
import pandas as pd
import geopandas as gpd
from shapely.geometry import Point

# Request to Transport for London API for BikePoint data
response = requests.get("https://api.tfl.gov.uk/BikePoint/")
bike_stations = pd.DataFrame(response.json())
```

We extract the numeric part from the `id` column

```
bike_stations['stationID'] = [id.split('_')[1] if '_' in id else None for id in bike_stations
bike_stations['stationID'] = bike_stations['stationID'].astype('int64')
```

and we create a `GeoDataFrame`

```
bike_stations_gdf = gpd.GeoDataFrame(bike_stations, geometry=[Point(xy) for xy in zip(bike_st
bike_stations_gdf.set_crs('EPSG:4326', inplace = True)  # Set CRS
bike_stations_gdf.head()
```

	$type	id	url	commonName
0	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_1	/Place/BikePoints_1	River Street , Cle
1	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_2	/Place/BikePoints_2	Phillimore Garden
2	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_3	/Place/BikePoints_3	Christopher Stree
3	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_4	/Place/BikePoints_4	St. Chad's Street.
4	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_5	/Place/BikePoints_5	Sedding Street, Sl

Now let's add some data about trips made by hire bikes. We need to use the station IDs for the beginning and end of the trips. Transport for London publishes online all trips made by hire bikes along many other datasets related to bike usage in London. The files are published weekly. They have information on starting and ending stations, exact time of the trips.

We can download the files for August 2018 and do some cleaning to map the most used routes in London. We first need to filter for completed trips and select trips with different origins/destinations. The next step is to aggregate the trips by pairs of origin and destination stations. The results should be how many trips have originated and ended from a specific pair in August 2018.

```python
import os

# URLs of hire bikes data in August 2018
urls = [
    "https://cycling.data.tfl.gov.uk/usage-stats/121JourneyDataExtract01Aug2018-07Aug2018.csv
    "https://cycling.data.tfl.gov.uk/usage-stats/122JourneyDataExtract08Aug2018-14Aug2018.csv
    "https://cycling.data.tfl.gov.uk/usage-stats/123JourneyDataExtract15Aug2018-21Aug2018.csv
    "https://cycling.data.tfl.gov.uk/usage-stats/124JourneyDataExtract22Aug2018-28Aug2018.csv
    ]

# Destination folder
folder = "../data/tfl"

# Create the destination folder if it doesn't exist
os.makedirs(folder, exist_ok=True)

# Function to download and save a file
def download_file(url, folder):
    response = requests.get(url)
    filename = url.split('/')[-1]
    filepath = os.path.join(folder, filename)
    with open(filepath, 'wb') as file:
        file.write(response.content)

# Download each file
for url in urls:
    download_file(url, folder)
```

The code above performs the following actions:

- Define URLs: A list of URLs is created, each pointing to a CSV file containing data on hire bikes for different weeks in August 2018.

- Destination Folder: It sets a destination folder where the downloaded files will be stored and creates the directory if it doesn't exist
- Define Download Function: `download_file` is a function defined to download a file from a given URL and save it to the specified destination folder. - It uses `requests.get` to fetch the file and writes it to the destination folder.
- Download: A loop goes through each URL in the urls list and calls `download_file` to download and save each file in the defined destination folder.

Now let's load them with `glob`, a library that loads all the files from a directory, and then create the dataframe of journeys.

```python
import glob

# Reading all CSV files in the directory
files = glob.glob(f'{folder}/*JourneyDataExtract*.csv')

# Concatenating the CSV files into a single DataFrame
journeys = pd.concat((pd.read_csv(file) for file in files))
journeys.rename(columns = {"Duration" : "duration", "StartStation Id": "fromStation_id", "En
journeys = journeys[journeys['fromStation_id'] != journeys['toStation_id']] # same station j
journeys.head()
```

	Rental Id	duration	Bike Id	End Date	toStation_id	EndStation Name	S
0	78826223	780	13775	02/08/2018 19:13	291	Claverton Street, Pimlico	
1	78986704	660	3498	06/08/2018 17:45	742	Blenheim Crescent, Ladbroke Grove	
2	78990055	1620	922	06/08/2018 18:36	609	Sugden Road, Clapham	
3	78940313	5340	12074	05/08/2018 17:27	441	Sail Street, Vauxhall	
4	79004458	1440	13220	07/08/2018 07:32	309	Embankment (Savoy), Strand	

Finally, let's get a summary dataframe thanks to `groupby` and other `pandas` functions.

```python
# Filter and aggregate the data
journeys_agg = (
    journeys.dropna(subset=['toStation_id', 'fromStation_id'])
    .query("`fromStation_id` in @bike_stations['stationID'] and `toStation_id` in @bike_stati
    .query("duration > 0 and duration <= 180*60")
    .groupby(['fromStation_id', 'toStation_id'])
    .agg(journeys=('fromStation_id', 'count'), mean_duration=('duration', 'mean'))
    .reset_index()
    .assign(share_trips=lambda x: (100 * x.journeys / x.journeys.sum()))
)
```

What we did above is combining different pandas functions:

- `.dropna(subset=['toStation_id', 'fromStation_id'])`: Removes rows where either the start or end station ID is missing.
- `.query("fromStation_idin @bike_stations['stationID'] and toStation_id in @bike_stations['stationID']")`: Further filters the data to include only those journeys where both the start and end stations are listed in bike_stations.
- `.query("duration > 0 and duration <= 180*60")`: Keeps only those journeys with a duration greater than 0 and less than or equal to 180 minutes.
- `.groupby(['fromStation_id', 'toStation_id'])`: Groups the data by the combination of start and end station IDs.
- `.agg(journeys=('fromStation_id', 'size'), mean_duration=('duration', 'mean'))`: Aggregates each group to calculate the total number (`count`) and average duration (`mean`) of journeys.
- `.reset_index()`: Resets the DataFrame's index, turning the grouped columns back into regular columns.
- `.assign(share_trips=lambda x: 100 * x.journeys / x.journeys.sum())`: Creates a new column `share_trips`, calculating each route's share of total journeys as a percentage.

The `.query()` method in `pandas` allows you to filter a DataFrame using a query string. It's a more concise and readable way to perform filtering compared to traditional Boolean indexing. It takes the following syntax: `.query('expression')` where 'expression' is a string that describes the condition to filter by. Inside the expression, you can refer to DataFrame columns directly by their names and use logical operators (like ==, !=, >, <, in, and, or) to define the conditions. **Example:** `.query('age > 30 and city == "New York"')` filters the DataFrame to include only rows where the 'age' column is greater than 30 and the 'city' column equals "New York"

No need to remember this!

```
journeys_agg[['journeys', 'mean_duration', 'share_trips']].describe()
```

	journeys	mean_duration	share_trips
count	168975.000000	168975.000000	168975.000000
mean	4.885587	1296.924665	0.000592
std	9.669850	927.394412	0.001171
min	1.000000	60.000000	0.000121
25%	1.000000	780.000000	0.000121
50%	2.000000	1120.000000	0.000242
75%	5.000000	1530.000000	0.000606
max	679.000000	10800.000000	0.082249

Most origin/destination pairs have an average of 4.80 trips during the period. The average duration is around 21 min (1297/60). We can then filter our journeys to the top 2 percentiles in terms of counts between two stations. Most pairs do not have any trips (none goes from the furthest station in Hackney down to Oval station).

```python
import numpy as np
from shapely.geometry import LineString

# Calculate the 98th percentile value for the number of journeys
percentile_value = np.percentile(journeys_agg['journeys'], 98)

# Filter out the top 2% of journeys based on the number of journeys
top_journeys = journeys_agg[journeys_agg['journeys'] >= percentile_value]

# Continuing with the merging and creation of desire lines as before
top_journeys = top_journeys.merge(bike_stations, left_on='fromStation_id', right_on='stationI
top_journeys = top_journeys.merge(bike_stations, left_on='toStation_id', right_on='stationID

geometry = [LineString([(row['lon_from'], row['lat_from']), (row['lon_to'], row['lat_to'])])
desire_lines = gpd.GeoDataFrame(top_journeys, geometry=geometry, crs = 'EPSG:4326')

desire_lines.plot()
```
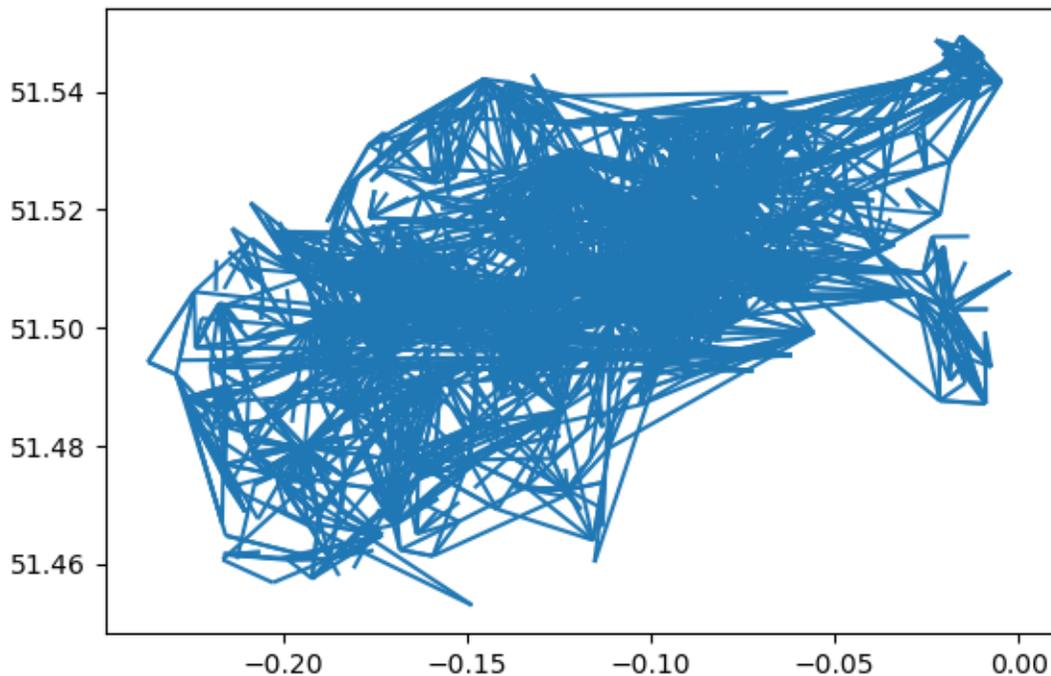
Plotting all lines is quite messy but we can use `folium` again :) Unfortunately, we can't use `Choropleth` for `LineString` geometries. We have to carry out some manual work.

```python
import json
import jenkspy
import matplotlib
import matplotlib.pyplot as plt
# Convert the desire_lines GeoDataFrame to GeoJSON
desire_lines_geojson = desire_lines.to_json()

# breaks with fisher-jenks
breaks = jenkspy.jenks_breaks(desire_lines['journeys'], n_classes=5)

# Use a Matplotlib colormap
cmap = plt.get_cmap('Oranges', len(breaks))  # 'viridis' can be replaced with any Matplotlib

# Generate colors for each break
colors = [matplotlib.colors.rgb2hex(cmap(i)) for i in range(cmap.N)]
cmap
```
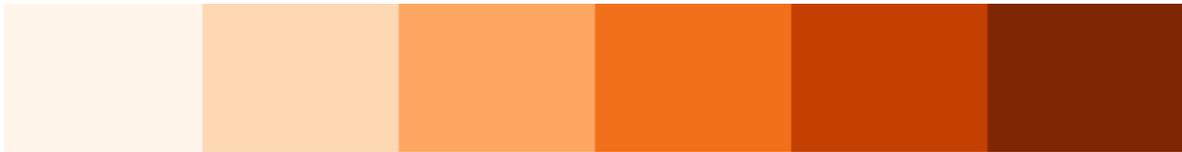
Let's define again a styling function for our lines.

```python
# Define the style function using the generated colors
def assign_color(value):
    for i, break_point in enumerate(breaks[:-1]):
        if value < breaks[i+1]:
            return colors[i]
    return colors[-1]

style_function = lambda feature: {
    'color': assign_color(feature['properties']['journeys']),
    'weight': feature['properties']['share_trips']*150,
    'opacity': max(feature['properties']['share_trips']*25, 0.05)
}
```

```python
# Create and display the Folium map
interactive_map = folium.Map(location=[51.5074, -0.1278], zoom_start=12, tiles="CartoDB.Darkl
```

```
folium.GeoJson(desire_lines_geojson, style_function=style_function).add_to(interactive_map)
interactive_map
```

```
<folium.folium.Map at 0x1f5b7bb7550>
```

Exercise: Look at the documentation for one of the APIs that we discussed last week. - Think of 2 ideas of web maps you could construct from your chosen API/data. - Think about the basemap and the data you would plot on top.

Folium is just one of many packages that provide an easy way to create interactive maps using data stored in (geo-)pandas `DataFrames`. Other interesting libraries include:

- GeoViews.
- Bokeh.
- kepler.gl.
- pydeck.

Nevertheless, Folium allows for a huge degree of personalisation and it's worth exploring further its documentation.

5 Web Architectures and APIs

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

5.1 What do APIs actually do?

In this lab, we will unpack how Application Programming Interfaces ("APIs") work and we cover the basics of accessing an API using Python. Instead of downloading a data set, APIs allow programmers, statisticians (or students) to request data directly from a server to a local machine. When you work with web APIs, two different computers — a client and server — will interact with each other to request and provide data, respectively.

5.1.1 RESTful Web APIs are all around you.

Web APIs

- Allow you query a remote database over the internet
- Take on a variety of formats
- Adhere to a particular style known as Representation State Transfer or REST (in most cases)
- RESTful APIs are convenient because we use them to query database using URLs

Consider a simple Google search:

Ever wonder what all that extra stuff in the address bar was all about? In this case, the full address is Google's way of sending a query to its databases requesting information related to the search term *liverpool top attractions*.

In fact, it looks like Google makes its query by taking the search terms, separating each of them with a **+**, and appending them to the link https://www.google.com/#q=. Therefore, we should be able to actually change our Google search by adding some terms to the URL:

Learning how to use RESTful APIs is all about learning how to format these URLs so that you can get the response you want.

5.1.2 Group activity

Get into groups of 5 or 6 students. Using your friend the internet, look up answers to the following questions. Each group will be assigned one question and asked to present their findings in 5 min to discuss with the entire class.

1. What is a `URL` and how can it help us query data? What is a response status and what are the possible categories?
2. What is a `GET` request? How does a `GET` request work?
3. What are API keys and how do you obtain them? What kinds of restrictions to they impose on users? Find an example of an API key, what does it look like?
4. (For 2 groups) More and more APIs pop up every day. Do a bit of quick research and find 2 different examples of APIs that you would be interested in using. 2 groups, 2 or 3 APIs each.

There are two ways to collect data through APIs in Python:

- **Plug-n-play packages.** Many common APIs are available through user-written Python (or R) Packages. These packages offer functions that conveniently "wrap" API queries and format the response. These packages are usually much more convenient than writing our own query, so it is worth searching for a package that works with the API we need.
- **Writing our own API request.** If no wrapper function is available, web have to write our own API request and format the response ourselves using Python. This is tricky, but definitely doable.

5.2 API Python libraries

Exercise: `census` pair activity:

Some Python packages "wrap" API queries and format the response. Lucky us! In pairs, let's have a look at census, a wrapper or the United States Census Bureau's API You can also have a look at the different APIs available from the United States Census Bureau.

```python
import pandas as pd
from census import Census
```

To get started working, set you Census API key. A key can be obtained from http://api.census.gov/data/key_signup.html.

```python
census_api_key = "" # Replace 'YOUR_CENSUS_API_KEY_HERE' with your actual Census API key.
```

```
# Set API key
c = Census(census_api_key)
```

- Variables in tidycensus are identified by their Census ID, e.g. B19013_001.
- Entire tables of variables can be requested with the table argument, e.g. table = 'B19001'.
- Users can request multiple variables at a time, and set custom names with a named vector.

In Python we can use the library census to access the American Community Survey (ACS) 5-Year Data (2016-2020)

Exercise:

In pairs explore some of the different variables available in the 5-Year ACS (2016-2020). Make a note of 3 variables you would be interested in exploring. The ACS2 variablespage might help.

Let's explore income data for example.

```
# Retrieve income data by state using the ACS table B19001
# Note: The variable 'B19001_001E' represents "Estimate!!Total" in table B19001
income_data = c.acs5.state(('NAME', 'B19001_001E'), Census.ALL, year=2020)
income_data[:10] # just first ten "rows"
```

```
[{'NAME': 'Pennsylvania', 'B19001_001E': 5106601.0, 'state': '42'},
 {'NAME': 'California', 'B19001_001E': 13103114.0, 'state': '06'},
 {'NAME': 'West Virginia', 'B19001_001E': 734235.0, 'state': '54'},
 {'NAME': 'Utah', 'B19001_001E': 1003345.0, 'state': '49'},
 {'NAME': 'New York', 'B19001_001E': 7417224.0, 'state': '36'},
 {'NAME': 'District of Columbia', 'B19001_001E': 288307.0, 'state': '11'},
 {'NAME': 'Alaska', 'B19001_001E': 255173.0, 'state': '02'},
 {'NAME': 'Florida', 'B19001_001E': 7931313.0, 'state': '12'},
 {'NAME': 'South Carolina', 'B19001_001E': 1961481.0, 'state': '45'},
 {'NAME': 'North Dakota', 'B19001_001E': 320873.0, 'state': '38'}]
```

```
income_df = pd.DataFrame(income_data)
income_df.head()
```

	NAME	B19001_001E	state
0	Pennsylvania	5106601.0	42
1	California	13103114.0	06
2	West Virginia	734235.0	54

	NAME	B19001_001E	state
3	Utah	1003345.0	49
4	New York	7417224.0	36

Exercise:

Discuss the format of the data obtained with your partner and then use the function `acs5.state` to explore the 3 variables you discussed in the previous exercise.

You can also get more variables by passing the names in a `tuple`. The code below, for example, fetches all the columns from the B19001 table, which include various income brackets. The tuple in the request generates a list of column names (like 'B19001_001E', 'B19001_002E', …, 'B19001_017E').

```
variables = tuple(f'B19001_{str(i).zfill(3)}E' for i in range(1, 18))
```

5.2.0.1 This is what the line above does:

- `range(1, 18)`: This part generates a sequence of numbers from 1 to 17. In Python, range(start, stop) generates numbers from start up to but not including stop.
- `for i in range(1, 18)`: This is a loop within a comprehension that iterates over each number in the range from 1 to 17.
- `str(i).zfill(3)`: For each number i, this converts i to a string. Then, .zfill(3) pads the string with zeros to make it 3 characters long. For example, if i is 2, `str(i).zfill(3)` becomes '002'.
- `f'B19001_{str(i).zfill(3)}E'`: This is an `f-string`, a way to format strings in Python. It inserts the zero-padded string into a larger string. So, for i = 2, you would get 'B19001_002E'.
- Finally, the comprehension is wrapped in `tuple(...)`, which converts the entire series of strings into a tuple.

```
wide_data = c.acs5.state(('NAME',) + variables, Census.ALL, year=2020)
# Convert to a Pandas DataFrame
wide_df = pd.DataFrame(wide_data)
wide_df.head()
```

	NAME	B19001_001E	B19001_002E	B19001_003E	B19001_004E	B19001_005E	B19001_
0	Pennsylvania	5106601.0	296733.0	206216.0	223380.0	227639.0	226678.0
1	California	13103114.0	614887.0	507398.0	435382.0	474093.0	454373.0
2	West Virginia	734235.0	62341.0	43003.0	45613.0	44635.0	40805.0

	NAME	B19001_001E	B19001_002E	B19001_003E	B19001_004E	B19001_005E	B19001_
3	Utah	1003345.0	36211.0	27395.0	28460.0	32497.0	36116.0
4	New York	7417224.0	471680.0	340614.0	303901.0	298025.0	276764.0

Let's make our query a bit more precise. We are going to query data on median household income and median age by county in the state of Louisiana from the 2016-2020 ACS. We can use the library us to get the code of each of the state by passing their name.

```python
import us
# Get the state object for Louisiana
state_obj = us.states.lookup('Louisiana')
# Get the FIPS code (state code)
code = state_obj.fips
```

```python
# Retrieve wide format data for median income and median age by county in Louisiana for the y
louisiana_data = c.acs5.state_county(('B19013_001E', 'B01002_001E'), code, Census.ALL, year=2
# Convert to a Pandas DataFrame
louisiana_df = pd.DataFrame(louisiana_data)
# Renaming the columns for clarity
louisiana_df.rename(columns={'B19013_001E': 'median_income', 'B01002_001E': 'median_age'}, in
louisiana_df.head()  # Display the first few rows
```

	median_income	median_age	state	county
0	82594.0	36.0	22	005
1	49256.0	37.5	22	011
2	42003.0	37.8	22	017
3	56902.0	44.9	22	023
4	36294.0	37.4	22	029

Let's plot one of our variables.

```python
import matplotlib.pyplot as plt

# Plotting histogram for median income with 15 bins
plt.hist(louisiana_df['median_income'], bins=15, edgecolor='white')
plt.xlabel('Median Income')
plt.ylabel('Frequency')
plt.title('Histogram of Median Income')
plt.show()
```

Histogram of Median Income
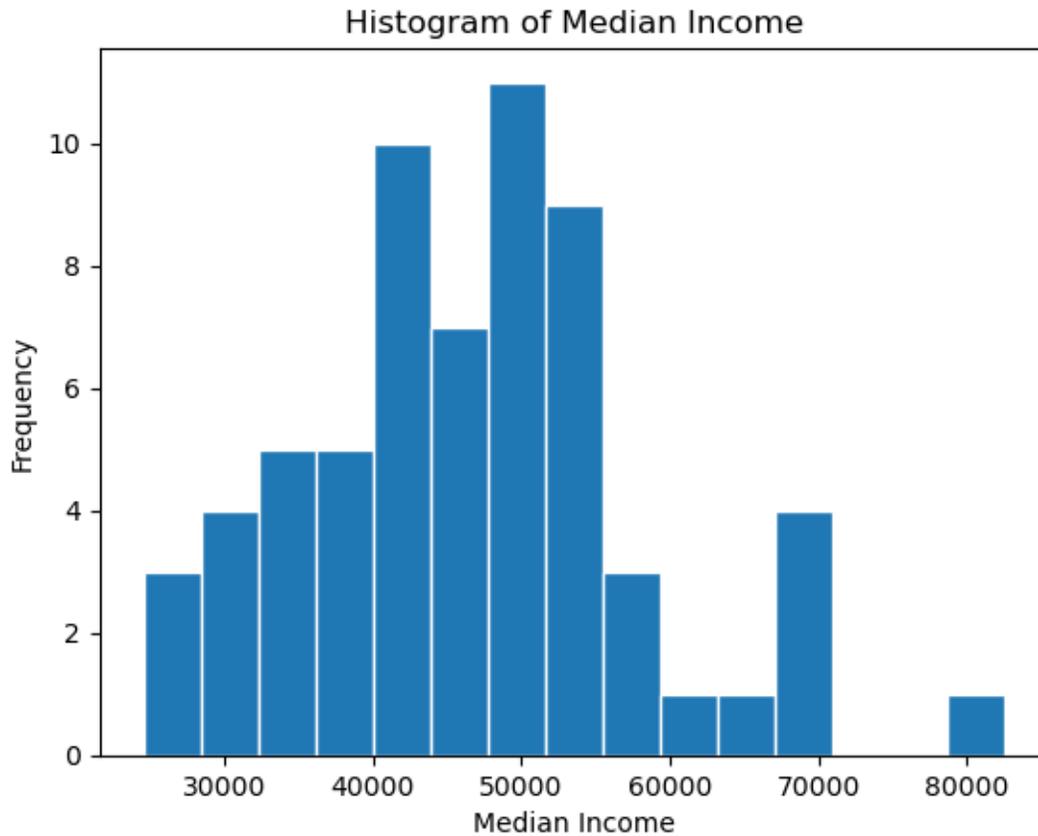
We can also explore correlations between variables. Let's use `seaborn`.

```python
import seaborn as sns

# Creating a scatter plot with a linear regression line
sns.lmplot(x='median_age', y='median_income', data=louisiana_df, aspect=1.5)
plt.xlabel('Median Age')
plt.ylabel('Median Income')
plt.title('Louisiana, Relationship between Income and Age')
plt.show()
```

Louisiana, Relationship between Income and Age
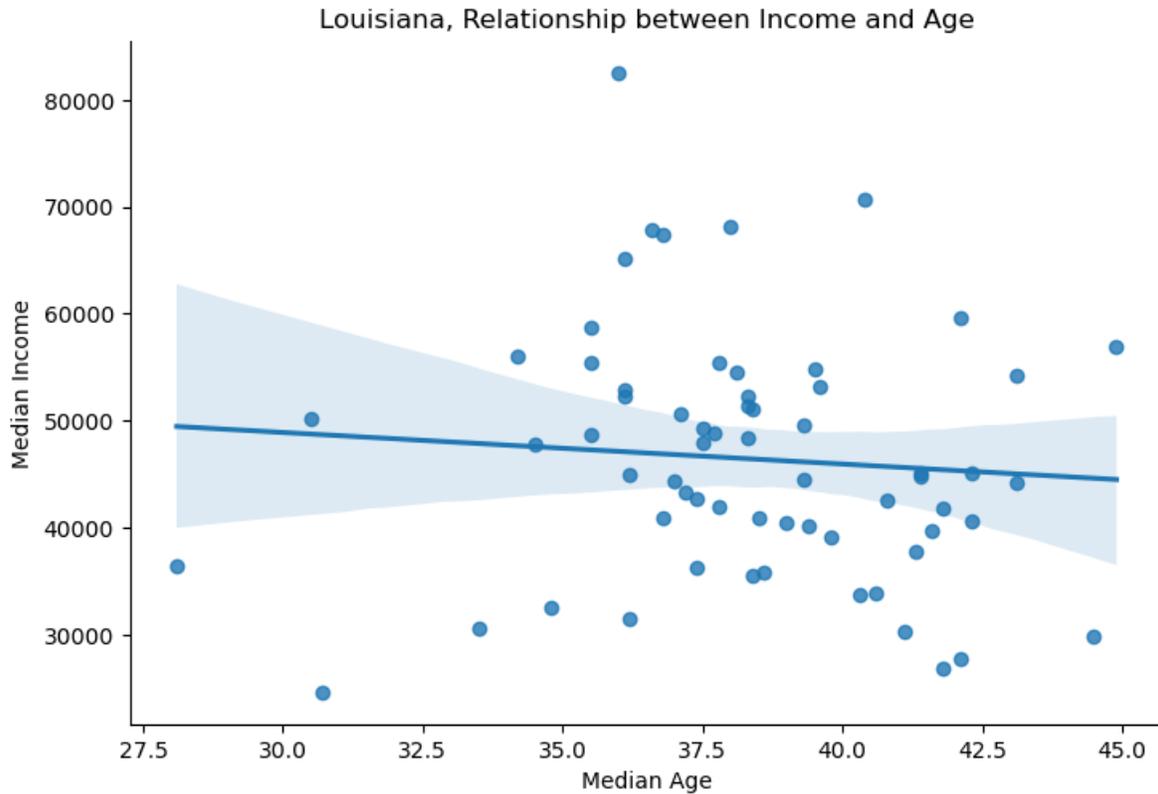
Exercise:

In pairs, modify the state, variables and year parameters following the approach adopted above and produce some other simple scatter plots (cloud of points) that suggest correlations between your variables of interest.

5.3 Your own API request demo

The Python libraries commonly used for API requests are `requests` and `json`.

JSON stands for JavaScript Object Notation. Despite its association with JavaScript, JSON is widely used due to its readability and ease of use by computers, making it the primary format for data transmission through APIs. Most APIs return their responses in JSON format. The `json` library in Python allows you to parse and convert these JSON responses into Python data structures. JSON structures are composed of key-value pairs, similar to Python dictionaries.

In Python, to make an API request and handle the response, you would typically use the `requests` library. A standard API request involves sending a `GET` request to the server's URL, which specifies the data you wish to retrieve. For instance, to request the locations of

all the hire bike stations in London from the **Transport for London** API, you would use the `requests.get()` method. This method requires a URL that directs the request to the appropriate server.

```
import requests
import json

response = requests.get("https://api.tfl.gov.uk/BikePoint/")
response
```

```
<Response [200]>
```

Good! The response code 200 indicates a successful request

Most GET request URLs for API querying have three or four components:

1. Authentication Key/Token: A user-specific character string appended to a base URL telling the server who is making the query; allows servers to efficiently manage database access.
2. Base URL: A link stub that will be at the beginning of all calls to a given API; points the server to the location of an entire database.
3. Search Parameters: A character string appended to a base URL that tells the server what to extract from the database; basically, a series of filters used to point to specific parts of a database.
4. Response Format: A character string indicating how the response should be formatted; usually one of .csv, .json, or .xml.

```
# Making the API request
response = requests.get("https://api.tfl.gov.uk/BikePoint/")

# Parsing the response content as JSON and converting it to a DataFrame
bike_stations = pd.DataFrame(response.json())

# Printing the column names
print(bike_stations.columns)
```

```
Index(['$type', 'id', 'url', 'commonName', 'placeType', 'additionalProperties',
       'children', 'childrenUrls', 'lat', 'lon'],
      dtype='str')
```

```
# Creating a new column 'Station ID' by extracting the numeric part from the 'id' column
bike_stations['Station ID'] = bike_stations['id'].str.extract(r'BikePoints_(\d+)', expand=Fa
bike_stations.head()
```

	$type	id	url	commonName
0	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_1	/Place/BikePoints_1	River Street , Cle
1	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_2	/Place/BikePoints_2	Phillimore Garden
2	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_3	/Place/BikePoints_3	Christopher Stree
3	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_4	/Place/BikePoints_4	St. Chad's Street
4	Tfl.Api.Presentation.Entities.Place, Tfl.Api.P...	BikePoints_5	/Place/BikePoints_5	Sedding Street, SI

By now you should be able to visualise the data that you have obtained through this API.

```
%matplotlib inline
import geopandas as gpd
import contextily as ctx

# Convert DataFrame to GeoDataFrame
gdf = gpd.GeoDataFrame(bike_stations, geometry=gpd.points_from_xy(bike_stations.lon, bike_sta
# Setting the Coordinate Reference System (CRS) to WGS84 (EPSG:4326)
gdf.set_crs(epsg=4326, inplace=True)
# project to British Grid
gdf.to_crs(epsg= 27700, inplace = True)

# Plotting bikepoints on a map
fig, ax = plt.subplots(1, 1, figsize=(8, 6))
gdf.plot(ax = ax, color='red', markersize=5)
source = ctx.providers.CartoDB.Positron
ctx.add_basemap(ax, crs= gdf.crs.to_string(), source= source)
ax.set_title('Bike Points in London')
```

Text(0.5, 1.0, 'Bike Points in London')

Bike Points in London
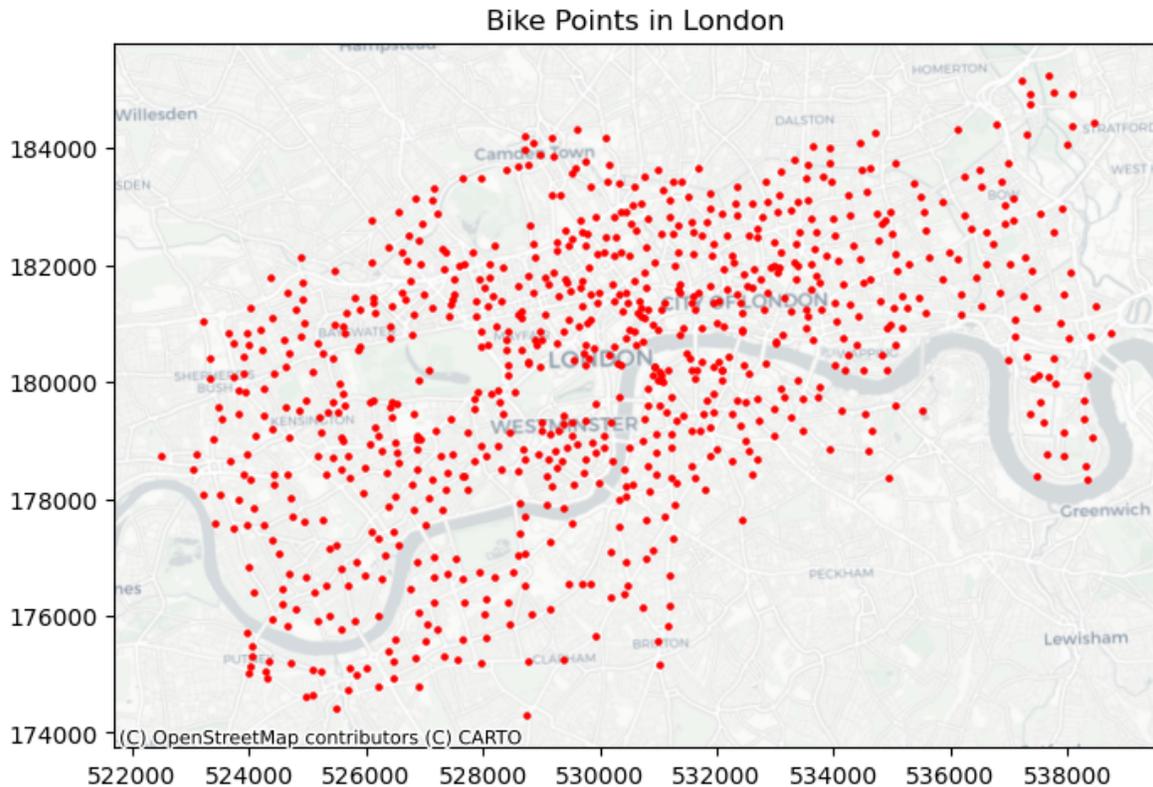
5.4 Geocoding API

Below is a short exploration of a the `geocoder` provided by the library `geopy`. The `geocoder` relies on various external geocoding services. When using `Nominatim`, it accesses data from OpenStreetMap. OpenStreetMap's data includes a vast array of geographical information sourced from contributors globally. This includes street addresses, points of interest, and other location-based data. When you provide an address to the Nominatim geocoder, it queries OpenStreetMap's databases to find the corresponding geographical coordinates.

In your own time, try to use it to automatically embed coordinates between addresses.

```python
from geopy.geocoders import Nominatim
from geopy.extra.rate_limiter import RateLimiter

# Create a DataFrame with addresses
some_addresses = pd.DataFrame({
    'name': ["South Campus Teaching Hub", "Sefton Park", "Stanley Street"],
    'addr': ["140 Chatham St, Liverpool L7 7BA", "Sefton Park, Liverpool L17 1AP", "4 Stanley
```

```
})

geolocator = Nominatim(user_agent="wma-geovis")
geocode = RateLimiter(geolocator.geocode, min_delay_seconds=1, return_value_on_exception=None

lat_longs = some_addresses["addr"].apply(lambda a: geocode(a, timeout=10)).apply(
    lambda loc: pd.Series([loc.latitude, loc.longitude], index=["latitude","longitude"])
    if loc else pd.Series([None, None], index=["latitude","longitude"]) # handle None
)

some_addresses = some_addresses.join(lat_longs)
some_addresses
```

	name	addr	latitude	longitude
0	South Campus Teaching Hub	140 Chatham St, Liverpool L7 7BA	53.400091	-2.964452
1	Sefton Park	Sefton Park, Liverpool L17 1AP	53.386547	-2.932565
2	Stanley Street	4 Stanley St, Liverpool L1 6AA	53.407644	-2.987573

5.4.0.1 Reverse Geocoding

You can also reverse geo-code the data, open the output and see what the result is.

```
# Reverse geocoding (optional)
def reverse_geocode(lat, lon):
    location = geolocator.reverse((lat, lon))
    return location.address

# Apply reverse geocoding
some_addresses[['latitude', 'longitude']].apply(lambda x: reverse_geocode(x['latitude'], x['
```

```
0    152, Chatham Street, Canning / Georgian Quarte...
1    Sefton Park Cricket Club, Croxteth Drive, Wave...
2    Workforce, 14-16, Stanley Street, Pride Quarte...
dtype: str
```

5.4.0.2 Geographic Data through APIs and the web

APIs can help us generate and create spatial data. In this lab, we have both:

- Written **our own API request.**
- Used **Plug-n-play packages.**

There are many APIs where we can get data these days. A few other examples include

- The London DataStore API
- Thames Water API
- London Air API
- Crime data

5.5 *Group activity answers*

1. Uniform Resource Location (`URL`) is a string of characters that, when interpreted via the Hypertext Transfer Protocol (`HTTP`). URLs point to a data resource, notably files written in Hypertext Markup Language (`HTML`) or a subset of a database.

   - 1xx informational response - the request was received, continuing process
   - 2xx successful - the request was successfully received, understood, and accepted
   - 3xx redirection - further action needs to be taken in order to complete the request
   - 4xx client error - the request contains bad syntax or cannot be fulfilled
   - 5xx server error - the server failed to fulfil an apparently valid request

2. `GET` requests a representation of a data resource corresponding to a particular `URL`. The process of executing the `GET` method is often referred to as a `GET request` and is the main method used for querying RESTful databases. `HEAD`, `POST`, `PUT`, `DELETE`: other common methods, though mostly never used for database querying.

   Surfing the web is basically equivalent to sending a bunch of `GET` requests to different servers and asking for different files written in `HTML`. Suppose, for instance, I wanted to look something up on Wikipedia. Your first step would be to open your web browser and type in http://www.wikipedia.org. Once you hit return, you would see the page below. Several different processes occurred, however, between you hitting "return" and the page finally being rendered:

   1. The web browser took the entered character string, used the command-line tool "Curl" to write a properly formatted `HTTP GET` request, and submitted it to the server that hosts the Wikipedia homepage.
   2. After receiving this request, the server sent an `HTTP` response, from which `Curl` extracted the HTML code for the page (partially shown below).
   3. The raw `HTML` code was parsed and then executed by the web browser, rendering the page as seen in the window.

4. Most APIs requires a key or other user credentials before you can query their database. Getting credentials for an API requires that you register with the organization. Once you have successfully registered, you will be assigned one or more keys, tokens, or other credentials that must be supplied to the server as part of any API call you make. To make sure users are not abusing their data access privileges (e.g., by making many rapid queries), each set of keys will be given rate limits governing the total number of calls that can be made over certain intervals of time.

3. Most APIs requires a key before you can query their database. This usually requires you to register with the organization. Most APIs are set up for developers, so you will likely be asked to register an "application." All this really entails is coming up with a name for your app/bot/project and providing your real name, organization, and email. Note that some more popular APIs (e.g., Twitter, Facebook) will require additional information, such as a web address or mobile number. Once you have registered, you will be assigned one or more keys, tokens, or other credentials that must be supplied to the server as part of any API call you make. Most API keys limits the total number of calls that can be made over certain intervals of time. This is so users do not busing their data access privileges.

5.6 References

- [Brief History of the Internet](#), by the Internet Society, is a handy (and free!) introduction to how it all came to be.
- Haklay, M., Singleton, A., Parker, C. 2008. ["Web Mapping 2.0: The Neogeography of the GeoWeb"](#). Geography Compass, 2(6):2011–2039
- [A blog post from JoeMorrison](#) commenting on the recent change of licensing for some of the core software from Mapbox
- Terman, R., 2020. [Computational Tools for Social Science](#)

6 Retrieving Data From OpenStreetMap

Gabriele Filomena has readapted parts of this notebook for preparing this notebook. Copyright (c) Michael Szell. Original sources include:

- OSMnx examples: https://github.com/gboeing/osmnx-examples
- pyrosm examples: https://pyrosm.readthedocs.io/en/latest/basics.html#read-street-networks

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

6.1 What is OpenStreetMap?

OpenStreetMap is a free and open map service. It is a collaborative global effort to collect free and open geodata. *Source: wiki.openstreetmap.org.* OpenStreetMap (OSM) is a global collaborative (crowd-sourced) database and project that aims at creating a free editable map of the world containing of information about our environment. It contains data about streets, buildings, different services, and landuse, to mention just a few.

OSM has more than 8 million registered users who contribute around 4 million changes daily. Its database contains data that is described by more than 7 billion nodes (that make up lines, polygons and other objects). While the most well-known side of OpenStreetMap is the map itself, the project is much more than that. OSM's data can be used for many other purposes such as **routing**, **geocoding**, **education**, and **research**. OSM is also widely used for humanitarian response, e.g., in crisis areas (e.g. after natural disasters) and for fostering economic development. Read more about humanitarian projects that use OSM data from the Humanitarian OpenStreetMap Team (HOTOSM) website.

6.1.1 Main tools in this lesson

6.1.1.1 OSMnx

This week we will explore a Python package called `OSMnx` that can be used to retrieve street networks from OpenStreetMap, and construct, analyse, and visualise them. `OSMnx` can also

fetch most of the other data stored in OSM, such as building footprints, transport networks, parks, Points of Interest, etc..OSMNx also includes tools to find routes on a network downloaded from OpenStreetMap, and implements algorithms for finding shortest connections for walking, cycling, or driving.

To get an overview of the capabilities of the package, please refer to the following scientific article describing the package:

> Boeing, G. 2017. "OSMnx: New Methods for Acquiring, Constructing, Analyzing, > and Visualizing Complex Street > Networks." Computers, Environment and Urban Systems 65, 126-139. doi:10.1016/j.compenvurbsys.2017.05.004

6.1.1.2 NetworkX

We will also use `NetworkX` to manipulate and analyse the street network data retrieved from OpenStreetMap. NetworkX is a Python package that can be used to create, manipulate, and study the structure, dynamics, and functions of complex networks. `OSMNx` is built on top `NetworkX` and `GeoPandas`.

```python
import geopandas as gpd
import osmnx as ox
import numpy as np
import networkx as nx
import pandas as pd
import matplotlib.pyplot as plt
```

6.2 Download, manipulate, and visualise OpenStreetMap data with OSMnx

A useful feature of `OSMNx` is its easy-to-use tools to download OpenStreetMap data via the project's OverPass API. In this section, we will learn how to download and visualise the street network and additional data from OpenStreetMap covering different areas of interest.

6.2.1 Boundaries from OpenStreetMap

`OSMnx` lets you download place boundary geometries from OpenStreetMap, project them, and plot them. For a more in-depth demonstration of querying by place, see this notebook.

Important:

Data downloaded from OSM are always in the WGS crs. You need to convert it for any type of spatial operation or computation to the appropriate coordinate reference system.

```
# get the boundary polygon for manhattan, project it, and plot it
city = ox.geocode_to_gdf("Manhattan")
ax = city.plot(fc="gray", ec="none")
ax.axis("off")
```

```
(np.float64(-74.0542289),
 np.float64(-73.8997471),
 np.float64(40.6695361),
 np.float64(40.8921299))
```



```
bulgaria = ox.geocode_to_gdf("Bulgaria")
ax = bulgaria.plot(fc="gray", ec="none")
ax.axis("off")
```

```
(np.float64(22.03062615),
 np.float64(29.21406065),
 np.float64(41.08635925),
 np.float64(44.364547349999995))
```

```
# get boundary polygons for several authorities in the UK, and plot
place_names = ["Merseyside", "Greater Manchester", "Cheshire"]
places = ox.geocode_to_gdf(place_names)
ax = places.plot(fc="gray", ec="red")
_ = ax.axis("off")
```

6.2.2 Download and model Street Networks

The `osmnx.graph`module downloads data to construct a routable road network graph, based on an user-defined area of interest. This area of interest can be specified, for instance, using a place name, a bounding box, or a polygon. In the place name query, OSMnx uses the Nominatim Geocoding API. This means that place names should exist in the OpenStreetMap database (run a test search at openstreetmap.org or nominatim.openstreetmap.org). **OSMnx**, amongst its several functionalities, lets you analyse, plot, and export the network in different file formats. The downloaded street networks are by default **directed** and preserve one-way directionality. For a more in-depth demonstration of creating street networks, see this notebook.

You can download a street network by providing OSMnx any of the following (demonstrated in the examples below): - a bounding box - a lat-lon point plus a distance - an address plus a distance - a place name or list of place names (to automatically geocode and get the boundary of) - a polygon of the desired street network's boundaries - a .osm formatted xml file

You can also specify several different network types: - `drive` - get drivable public streets (but not service roads) - `drive_service` - get drivable streets, including service roads - `walk` - get all streets and paths that pedestrians can use (this network type ignores one-way directionality) - `bike` - get all streets and paths that cyclists can use - `all` - download all non-private

OSM streets and paths (this is the default network type unless you specify a different one) - `all_private` - download all OSM streets and paths, including private-access ones

6.2.2.1 Method #1: Passing a bounding box

This constructs the network from all the OSM nodes and ways within the bounding box. The plot function is built on `Matplotlib`, thus it follows the procedures and methods discussed in session II.

```python
# define a bounding box in San Francisco
north, south, east, west = 37.79, 37.78, -122.41, -122.43

# create network from that bounding box - Bounding box as (left, bottom, right, top).
G = ox.graph_from_bbox([west, south, east, north], network_type="drive_service")
ox.plot_graph(G, node_color="r", figsize=(8, 8))
```

6.2.2.2 Method #2: Passing a lat-lon point and bounding box distance in meters

This creates a bounding box n meters North, South, East, and West of the point, then constructs the network from all the OSM nodes and ways within the bounding box. Here's a useful tool for defining bboxes

```
# define a point at the corner of California St and Mason St in SF
location_point = (37.791427, -122.410018)
# create bikeable network from point, inside bounding box of N, S, E, W each 750m from point
G = ox.graph_from_point(location_point, dist=750, dist_type="bbox", network_type="bike")
ox.plot_graph(G, node_color="r", figsize=(5,5))
```


6.2.2.3 Method #3: Passing a lat-lon point and *network* distance in meters

This creates a bounding box n meters North, South, East, and West of the point, then constructs the network from all the OSM nodes and ways within the bounding box. Then it truncates the network by removing all nodes further than n meters from the point along the network.

```
location_point = (53.40, -2.99)
# create network only of nodes within 750m along the network from point
G1 = ox.graph_from_point(location_point, dist=1000, dist_type="network")
ox.plot_graph(G1, node_color="none", figsize=(5,5))
```


Note the plot above shows the network within 750m (traveling distance along the network) from
the `location_point`. By default, the `network_type` parameter value is `all`, meaning that
we do not filter out paths that restrict certain types of traffic. This also means that one-way
streets are honored as one-way and you cannot travel the wrong direction down them. Thus,
the 750m takes into account only those nodes you can reach within 500m while only traveling
in the allowed direction of the street. Instead (below), we can specify `network_type='walk'`
to build a street network only of paths that walking is allowed on. This also makes every path
bi-directional in the directed network, because you can walk in either direction on the sidewalk
of a one-way street. The 750m now takes into account those nodes you can reach within 750m
while traveling in either direction (even if it's a one-way street).

```
# create network only of nodes within 750m walking along the network from point, only walkab
G2 = ox.graph_from_point(location_point, dist=750, dist_type="network", network_type="walk")
ox.plot_graph(G2, node_color="none", figsize=(5,5))
```
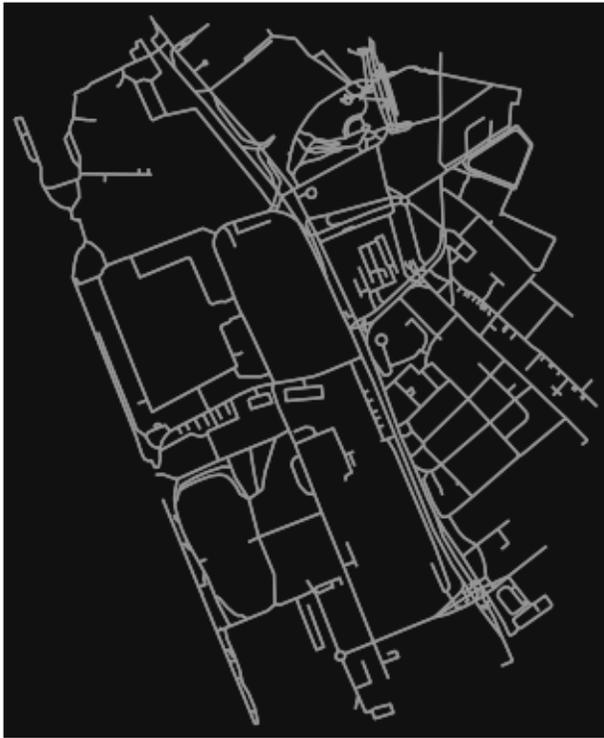
6.2.2.4 Method #4, Passing an address and distance (*bounding box* or *network*) in meters

This geocodes the address, creates a bounding box, downloads the network, then truncates it by network distance (if distance_type='network').

```python
# network from address, including only nodes within 1km along the network from the address
G = ox.graph_from_address(address="350 5th Ave, New York, NY", dist=1000, dist_type="network"
ox.plot_graph(G, node_color="r", figsize=(5,5))
```
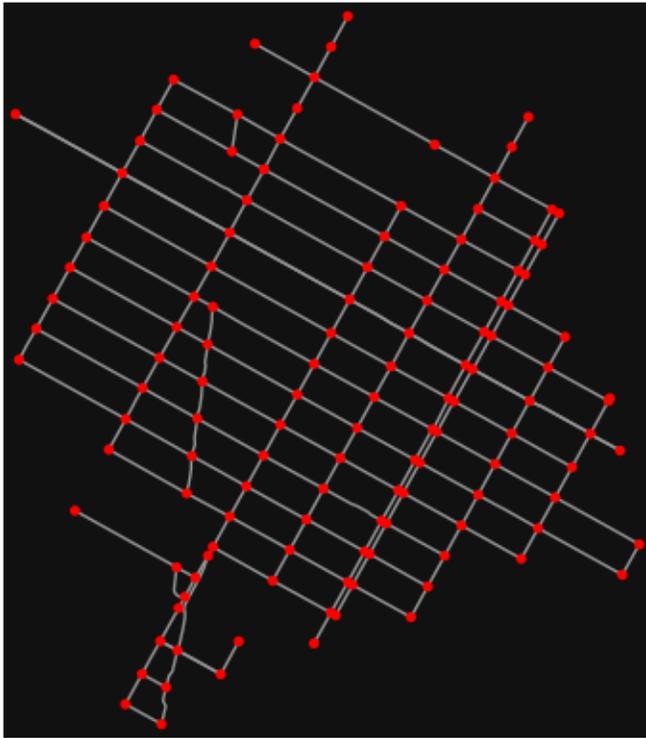
6.2.2.5 Method #5: Passing a place name

This geocodes the place name, gets the place's boundary shape polygon and bounding box, downloads the network within the bounding box, then truncates it to the place's boundary polygon.

```
G = ox.graph_from_place("Bastia, Corsica", network_type="drive")
ox.plot_graph(G, node_color="none") # without plotting nodes
```

Be aware that this is a `MultiDiGraph`, i.e. a multigraph (parallel edges are possible) that is directed. Because there can be multiple links between a pair of nodes, each link is identified with a triple: (node1id, node2id, counter)

```
list(G.edges)[:10]
```

```
[(60370565, 338870652, 0),
 (60370565, 338870615, 0),
```

```
 (60370586, 338870618, 0),
 (60370599, 338870618, 0),
 (60370599, 60370602, 0),
 (60370602, 60370612, 0),
 (60370602, 60370599, 0),
 (60370612, 721266231, 0),
 (60370612, 60370602, 0),
 (60370622, 2358639572, 0)]
```

These values above correspond to u, v and key. More on that later, but, essentially, u is the id of the "from-node" and v the id of the "to-node"

6.2.2.6 Method #6 Passing a Poylgon in the WGS crs

```python
# get the boundary polygon for Sarajevo, and plot it
city = ox.geocode_to_gdf("Sarajevo, Bosnia")
city_proj = ox.projection.project_gdf(city)
ax = city_proj.plot(fc="gray", ec="none")
ax.axis("off");
```



```python
sarajevo = ox.geocode_to_gdf("Sarajevo, Bosnia")
polygon = sarajevo["geometry"].iloc[0]

G = ox.graph_from_polygon(polygon, network_type="drive_service")
ox.plot_graph(G, node_size=0, edge_color="w", edge_linewidth=0.3);
```

6.2.3 Simplifying and Cleaning the Street Network Topology

Simplification is normally done by `OSMnx` automatically under the hood, but we can break it out to see how it works. OpenStreetMap nodes are weird. They include intersections, but they also include all the points along a single block where the street curves. The latter are not nodes in the graph theory sense, so we remove them algorithmically and consolidate the set of edges between "true" network nodes into a single edge. There are two simplification modes, strict and non-strict. The main difference is that unlike strict mode, non-strict mode allows simplification to an "expansion graph" (i.e., if the graph were undirected, nodes with degree 2 as long as the incident edges have different OSM IDs).

```
# create a network around some (lat, lng) point but do not simplify it yet
location_point = (33.299896, -111.831638)
G = ox.graph_from_point(location_point, network_type="drive_service", dist=500, simplify=Fals
ox.plot_graph(G, node_color="r", figsize=(5,5))
```
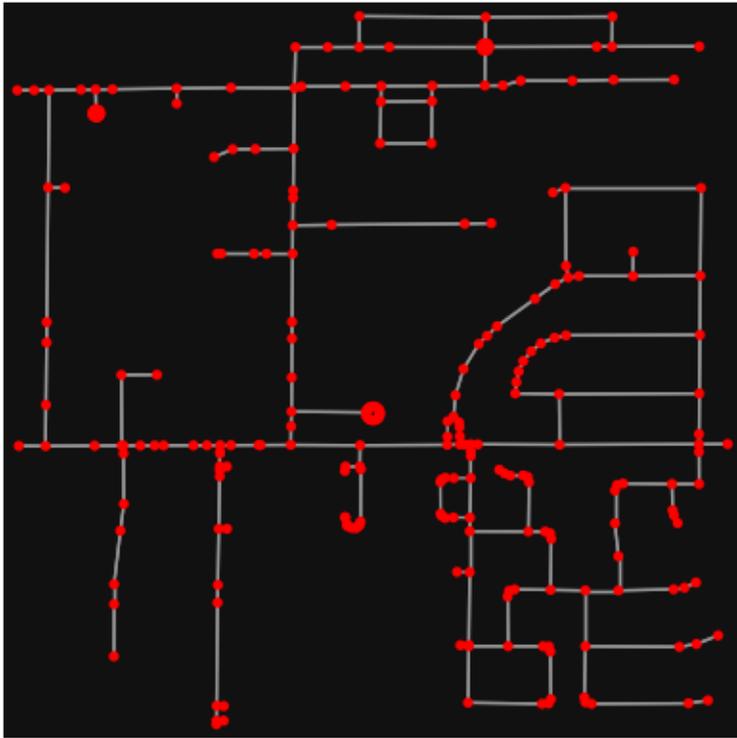
```
# turn off strict mode and see what nodes we'd remove, in yellow
colors = ["r" if ox.simplification._is_endpoint(G, node, node_attrs_include = None, edge_att
fig, ax = ox.plot_graph(G, node_color=colors, figsize=(5,5))
```
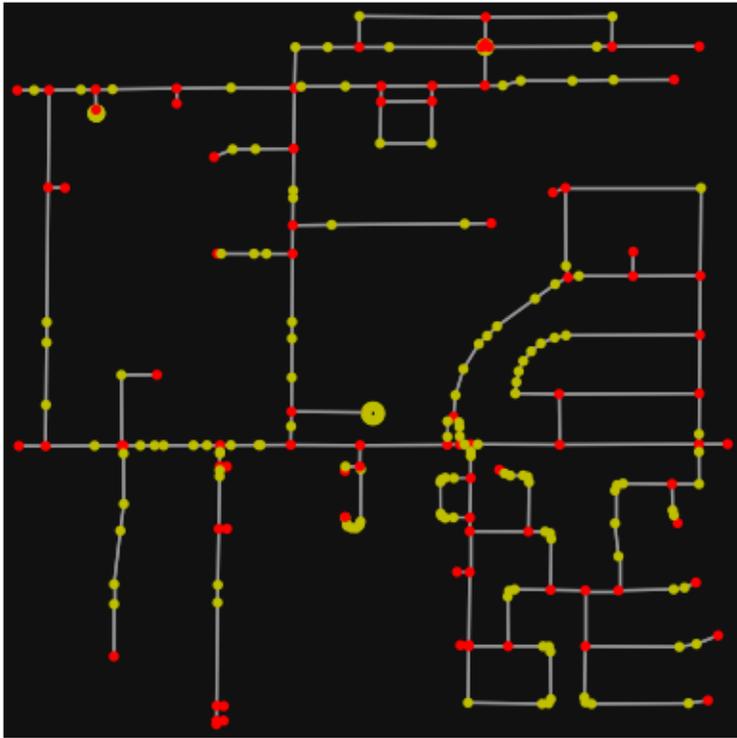
The yellow markers above are OSM nodes. We'll remove the nodes in yellow as they're not real network nodes (intersections/dead-ends).

```
# simplify the network
G = ox.simplify_graph(G)
ox.plot_graph(G, node_color="r", figsize=(5,5))
```
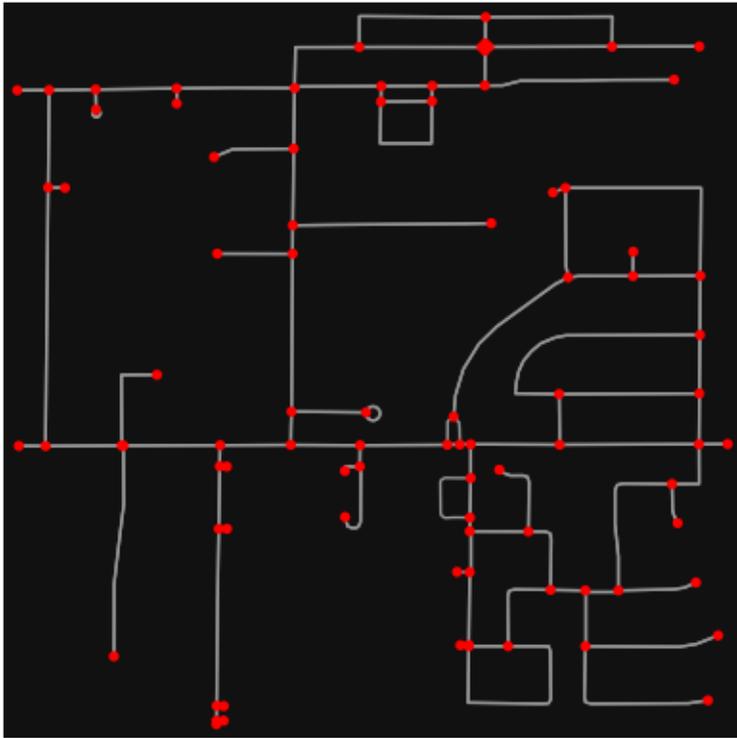
6.2.3.1 Optional: Complex intersection consolidation

Many real-world street networks feature complex intersections and traffic circles, resulting in a cluster of graph nodes where there is really just one true intersection. Similarly, divided roads are often represented by separate centerline edges: the intersection of two divided roads thus creates 4 nodes, representing where each edge intersects a perpendicular edge, but these 4 nodes represent a single intersection in the real world. Traffic circles similarly create a cluster of nodes where each street's edge intersects the roundabout.

`OSMnx` can consolidate nearby intersections and optionally rebuild the graph's topology.

```python
# get a street network and plot it with all edge intersections
point = 55.667708, 12.596266
G = ox.graph_from_point(point, network_type="drive", dist=500)
ox.plot_graph(G, node_color="r", figsize=(5,5))
```

Notice the complex intersections creating clusters of nodes.

We'll specify that any nodes with 15 meter buffers of each other in this network are part of the same intersection. Adjust this tolerance based on the street design standards in the community you are examining, and use a projected graph to work in meaningful units like meters. We'll also specify that we do not want dead-ends returned in our list of consolidated intersections.

```
# get a GeoSeries of consolidated intersections
G_proj = ox.project_graph(G)
intersections = ox.consolidate_intersections(G_proj, rebuild_graph=False, tolerance=15, dead_
# compare to number of nodes in original graph
print(len(intersections), "vs", len(G))
```

```
75 vs 121
```

Note that these cleaned up intersections give us more accurate intersection counts and densities, but do not alter or integrate with the network's topology. To do that, we need to **rebuild the graph**.

```
# consolidate intersections and rebuild graph topology
# this reconnects edge geometries to the new consolidated nodes
cleaned = ox.consolidate_intersections(G_proj, rebuild_graph=True, tolerance=15, dead_ends=Fa
ox.plot_graph(cleaned, node_color="r", figsize=(5,5))
```


Notice how many nodes are merged into a new single centroid node, with edge geometries extended to connect to it. Similar consolidation occurs at the intersection of the divided roads.

Note

Running `consolidate_intersections` with `rebuild_graph=True` may yield somewhat (but not very) different intersection counts/densities compared to `rebuild_graph=False`. The difference lies in that the latter just merges buffered node points that overlap, whereas the former checks the topology of the overlapping node buffers before merging them. This prevents topologically remote but spatially proximate nodes from being merged. For example: - A street intersection may lie directly below a freeway overpass's intersection with an on-ramp. We would not want to merge these together and connect their edges: they are distinct junctions in the system of roads. - In a residential neighbourhood, a bollarded street may create a dead-end immediately next to an intersection or traffic circle. We would not want to merge this dead-end with the intersection and connect their edges.

These examples illustrate (two-dimensional) geometric proximity, but topological remoteness. Accordingly, in some situations we may expect higher intersection counts when using `rebuild_graph=True` because it is more cautious with merging in these cases. The trade-off is that it has higher time complexity than `rebuild_graph=False`.

6.2.4 From OSMNX to NetworkX and Geopandas Classes

Now, we have seen how to use some basic `osmnx` functions to obtain a graph representation of the street network. While this is simple and straightforward, I advise working on the street network represented as `geopandas.GeoDataFrame`s and `networkx` graphs. While at the beginning this may be more tedious, it also gives us much more control, both in terms of visualisation and analysis depth. Before proceeding, it is important to keep in mind what type of graphs can be modelled through OSMNx and NetworkX, and what that means for the infrastructure we are modelling.

Have a look at NetworkX documentation for details.

By default, the graphs obtained through OSMNX are 'MultiDiGraph'

```
siracusa_graph = ox.graph_from_address("Largo XXV Luglio, Siracusa", network_type="all", dist
sicily_epsg = 'EPSG:23030'
nodes = ox.graph_to_gdfs(siracusa_graph, nodes=True, node_geometry=True, edges = False).to_c
edges = ox.graph_to_gdfs(siracusa_graph, nodes=False, edges =  True, fill_edge_geometry=True)
```

```
edges.plot(lw = 0.2, color = 'red')
```
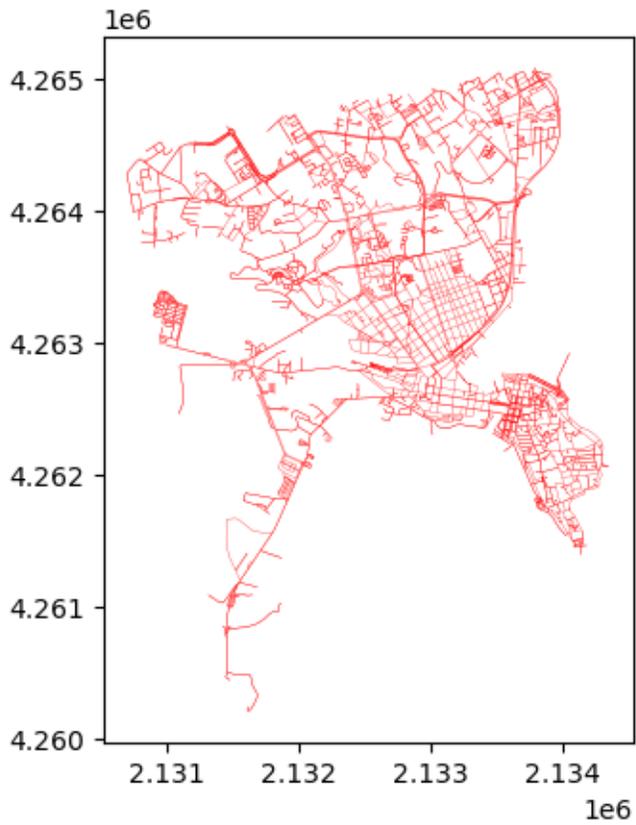
We can visualise major roads on top of the street network:

```
ax = edges[edges.highway.isin(['primary', 'secondary'])].plot()
edges.plot(ax = ax, lw = 0.2, color = 'red')
```

```
edges.head()
```
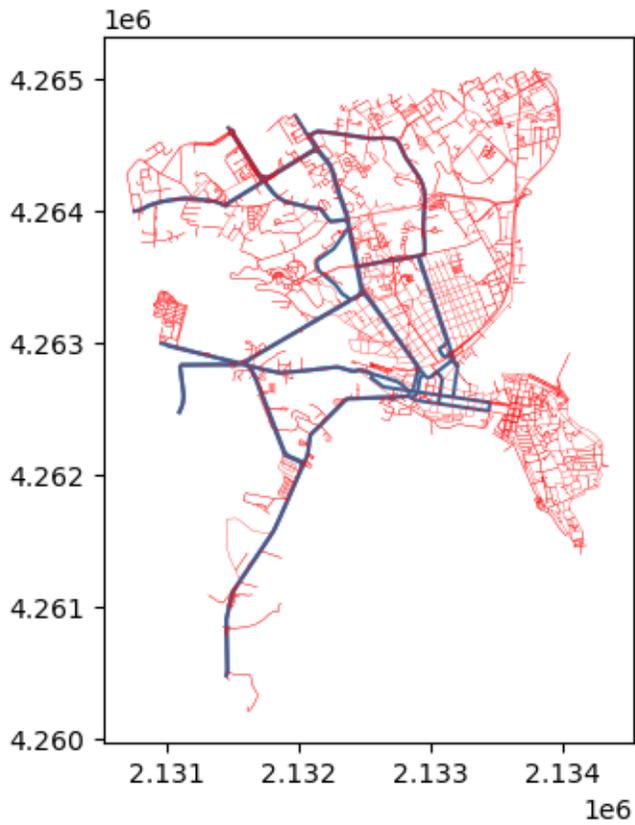
u	v	k
	297074052	0
33566408	9130394527	0
	7876226633	0
	8185067296	0
33566411	33566412	0

```
nodes.head()
```

osmid	y	x	street_count	highway	geometry
33566408	37.068451	15.280819	3	NaN	POINT (2132529.446 4262765.911)
33566411	37.065793	15.287216	4	NaN	POINT (2133165.09 4262581.928)
33566412	37.065258	15.286985	3	NaN	POINT (2133156.199 4262517.746)
33566413	37.064692	15.286909	3	NaN	POINT (2133162.078 4262452.755)
33566854	37.060586	15.293191	3	NaN	POINT (2133819.897 4262104.005)

As you can see an edge's index is a `MultiIndex` given by `u`, `v`, and `key`. `u` and `v` in `networkx` language stand for "from-node" and "to-node". `key`, on the other hand, indicates whether more than one edge links `u` and `v`. When a pair of `u` and `v` nodes have more then one edge, every other edge will have an incremental `key` value (the second one 1, the third one 2, etc., very rare that there are more than two edges per pair of nodes). This means that we are dealing with a `MultiGraph` representation of the street network. In other words, we have two street segments connecting the same two nodes in different directions. This could, for example, indicate that the directionality is accounted for (one-way segments). Based on our objective and analysis, such an aspect might be relevant, or not.

6.2.4.1 (Re)converting to a `MultiGraph`/`MultiDiGraph`

First, we get rid of the `pandas MultiIndex` and we verify whether we are working with bidirectional edges.

```
edges.reset_index(inplace = True)
edges['key'].sum()
```

```
np.int64(117)
```

```
import networkx as nx
Mg = nx.MultiGraph()
Mg.add_nodes_from(nodes.index)
```

Copying the nodes' attributes (this step is not particularly essential unless we need some information associated with the nodes that we want to use when executing `networkx` methods). Anything else we can rely on the information that is in the `GeoDataFrame`.

```
# add the nodes' attributes
attributes = nodes.to_dict()

for attribute_name in nodes.columns:
    if nodes[attribute_name].apply(lambda x: type(x) == list).any():
        continue
    # only add this attribute to nodes which have a non-null value for it
    attribute_values = {k:v for k, v in attributes[attribute_name].items() if pd.notnull(v)}
    nx.set_node_attributes(Mg, name=attribute_name, values=attribute_values)
```

We do something similar for edges. In this case, it is more likely that there is information that we want to copy, e.g. the length of the edges, into the `MultiGraph`.

```
edges['length'] = edges.geometry.length

# add the edges and attributes that are not u, v, key, null, or of type list
## u, v, and key are added directly as you can see from the last line
for row in edges.itertuples():
    attrs = {label: value for label, value in row._asdict().items() if (label not in ['u', '
            (isinstance(value, list) or pd.notnull(value))}
    Mg.add_edge(row.u, row.v, key=row.key, **attrs)
```

6.2.4.2 Converting to a `Graph/DiGraph`

In this case, we need to get rid of the "duplicated" edges. For the sake of simplicity, we remove al the edges with `key` equal to 1. This is a very rough approach.

```
edges_copy = edges[edges.key == 0].copy()
G = nx.Graph()
G.add_nodes_from(nodes.index)
```

Then, we copy the attributes with the same approach used before, although, this time, without adding the `key` value to the edges. The function `add_edge` of the class the `graph` does not take the `key` argument as there could be only one edge between two nodes.

```
# ignore fields containing values of type list
attributes = nodes.to_dict()

for attribute_name in nodes.columns:
    if nodes[attribute_name].apply(lambda x: type(x) == list).any():
```

```
        continue
    # only add this attribute to nodes which have a non-null value for it
    attribute_values = {k: v for k, v in attributes[attribute_name].items() if pd.notnull(v)
    nx.set_node_attributes(G, name=attribute_name, values=attribute_values)

# add the edges and attributes that are not u, v, null, or of type list
## u, and v are added directly as you can see from the last line
for row in edges_copy.itertuples():
    attrs = {label: value for label, value in row._asdict().items() if (label not in ['u', '
    G.add_edge(row.u, row.v, **attrs)
```

And just to be sure:

```
len(list(G.nodes())) == len(nodes)
```

```
True
```

6.3 Routing with NetworkX

Both with `osmnx` and `networkx` we can compute paths across the network, of different kinds,
with different weights and methods (see here. Shortest paths, while they seem to allude to an
explicit reference to distance or time, may be computed in relation to other weights or costs,
based on the purposes of the user.

```
import random
# Get a list of all nodes in the graph
nodes = list(G.nodes())

# Select a random node
origin_node = random.choice(nodes)

while(True):
    destination_node = random.choice(nodes)
    if destination_node != origin_node:
        break

path_nodes = nx.shortest_path(G, source=origin_node, target=destination_node, weight='length
```

`shortest_path`, the simplest function for computing shortest paths in `networkx`, returns the
list of nodes traversed by the path, including the origin and the destination nodes. We have
to transform the sequence of nodes into a sequence of edges to get the corresponding route.

```
path_edges = [(path_nodes[i], path_nodes[i + 1]) for i in range(len(path_nodes) - 1)]
path_edges[0]
```

(305796024, 10582139298)

When we look at the elements of the edges sequence, we can see that this is a tuple containing the index of the u and v nodes that the edge links together. This is the networkx representations of an edge inside a graph.

```
path_edges[0]
```

(305796024, 10582139298)

However, for that edge, we want to get the attribute that refers to the index in the edges_copy GeoDataFrame. For that, We use a list comprehension.

```
G[33566408][297074052]
```

```
{'Index': 421,
 'key': 0,
 'osmid': 828152472,
 'highway': 'secondary',
 'maxspeed': '50',
 'oneway': False,
 'reversed': True,
 'length': 65.91900931714444,
 'geometry': <LINESTRING (2132466.835 4262786.532, 2132529.446 4262765.911)>}
```

```
path_edges = [G.edges[edge]['Index'] for edge in path_edges]
```

And then we can plot the route.

```
ax = edges_copy[edges_copy.index.isin(path_edges)].plot()
edges_copy.plot(ax = ax, lw = 0.2, color = 'red')
```
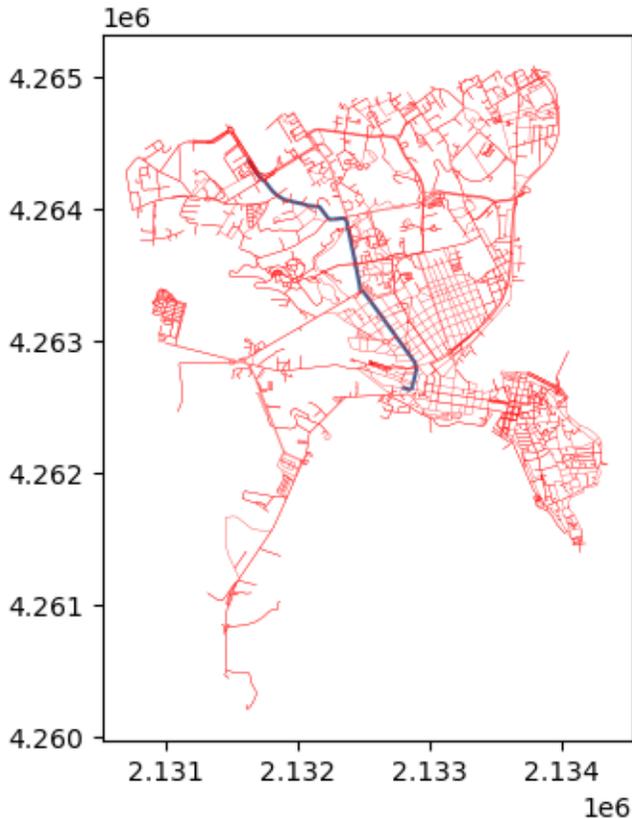
Exercise:

Compute different shortest paths between a node (1) of your choice and a set of 20 other random nodes, for a driver and a walker. Visualise and compare the results. In order to differentiate the users, you are expected to consider their travelling speeds, in relation to the speed limit of the edges. Consider that, at least for the driver, you may want to do that in a `MultiDiGraph`.

You can use as case-study one of the graphs used above for Siracusa (Italy) or Sarajevo (Bosnia). Otherwise, just pick a city you like.

6.4 Fetching other networks with OSMNX

When downloading graphs, one can also pass a `custom_filter` to specify what OSM ways/routes/links they want represented in their graph. This would override the fact that, by default, graph functions in `osmnx` fetch street networks.

From `osmnx` documentation: `custom_filter` (string) – a custom ways filter to be used instead of the network_type presets e.g., `["power"~"line"]` or `["highway"~"motorway|trunk"]`.

This method does not work with bus services, since they are not stored in OpenStreetMap Data as Links but rather relations. See here for more info.

```
# railway infrastructures
place = "Milan, Italy"
G = ox.graph_from_place(place, custom_filter='["railway"~"rail"]')
ox.plot_graph(G, edge_color="c", edge_linewidth=0.5, node_size=0);
```
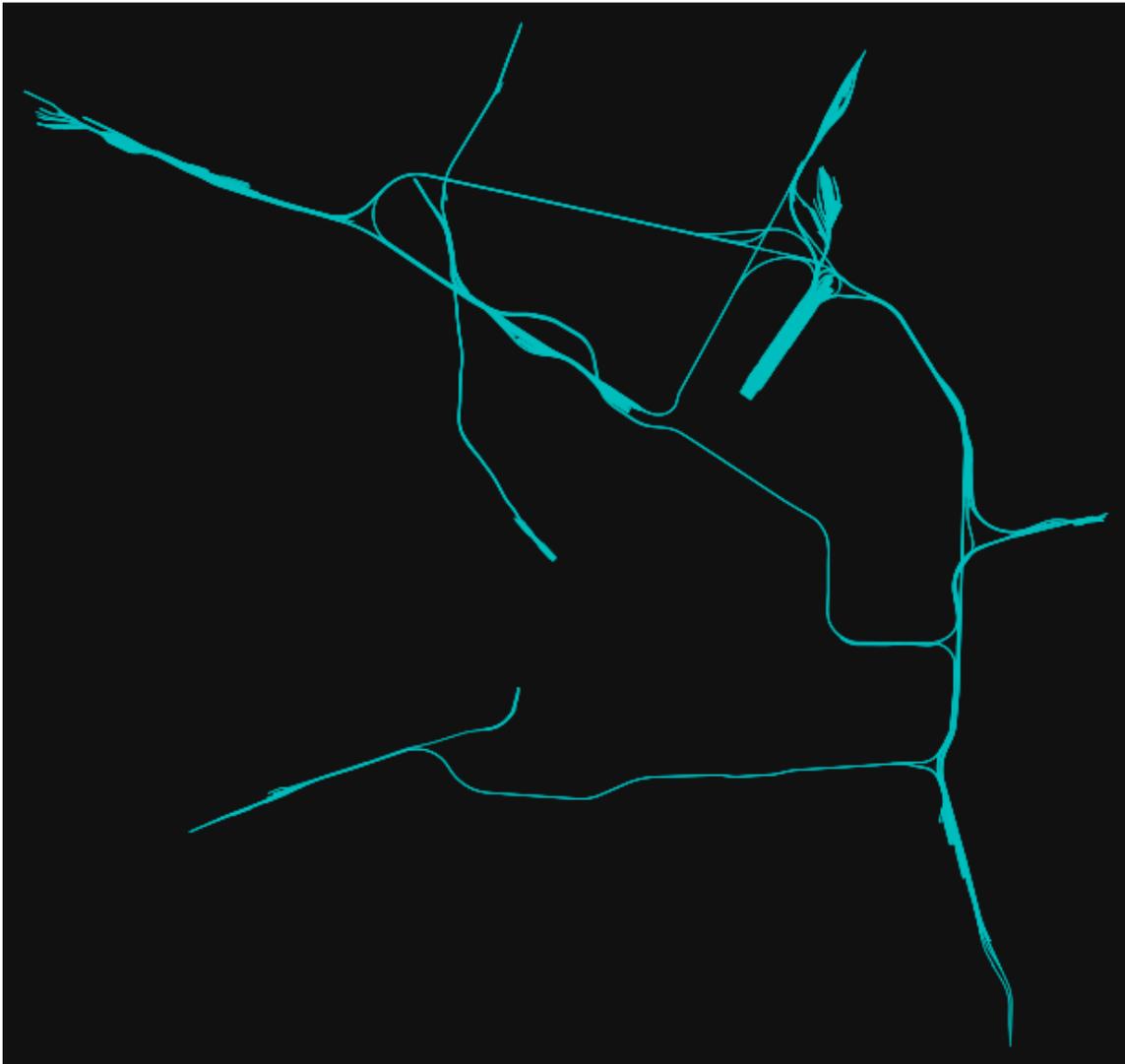
```
# network of canals in Amsterdam
place = "Amsterdam, Netherlands"
G = ox.graph_from_place(place, custom_filter='["waterway"~"canal"]')
ox.plot_graph(G, edge_color="c", edge_linewidth=1, node_size=0);
```


6.5 Retrieving Other OSM data

OSMNx power also lies on the fact that it allows obtaining any other element represented in OpenStreetMap data. You can use the same methods described above for graphs. Instead of using `graph_from_place`, you would use, for example, `features_from_place`, `features_from_address`, etc.

6.5.0.1 Fetching Building Footprints

```
# Specify the location and the data type
place = 'Torino, Italy'
tags = {'building': True}
```

```
# Fetch building footprints
buildings = ox.features_from_place(place, tags=tags)
buildings = buildings[buildings.geometry.geom_type == 'Polygon']

# Plot the building footprints
ax = buildings.plot(figsize=(6, 6), color = 'orange')
ax.set_title('Building Footprints in Torino, Italy')
```

Text(0.5, 1.0, 'Building Footprints in Torino, Italy')

Building Footprints in Torino, Italy
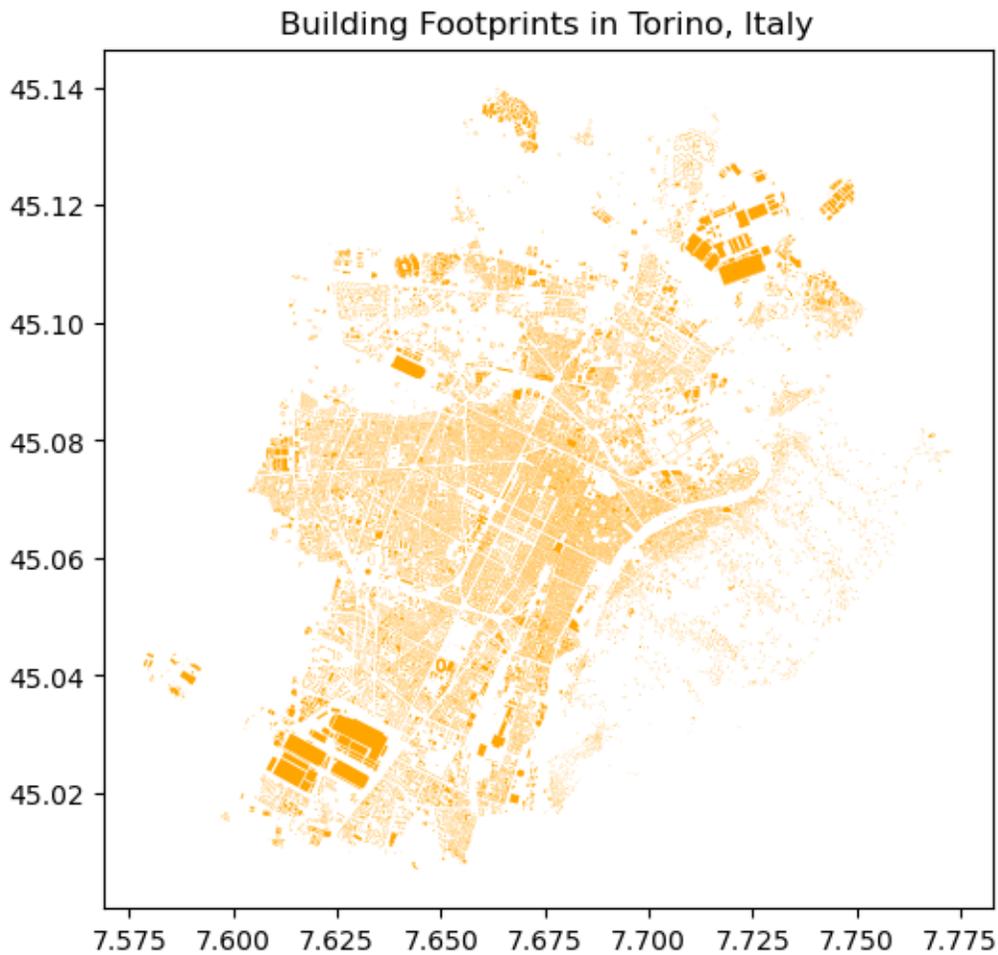
6.5.0.2 Water bodies

```
# Tags for waterbodies
water_tags = {'natural': ['water']}

# Fetch water bodies
waterbodies = ox.features_from_place(place, tags=water_tags)

# Plot water bodies
ax = waterbodies.plot(figsize=(6, 6), color='blue')
ax.set_title('Waterbodies in Torino, Italy')
```

Text(0.5, 1.0, 'Waterbodies in Torino, Italy')
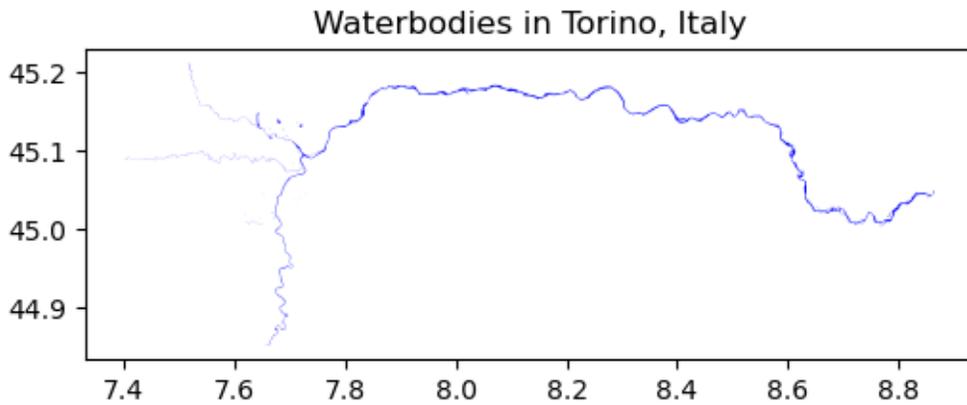
6.5.0.3 POIs

```
# Tags for POIs
poi_tags = {'amenity': True}

# Fetch POIs
pois = ox.features_from_place(place, tags=poi_tags)
pois = pois[pois.geometry.geom_type == 'Point']
# Plot POIs
ax = pois.plot(figsize=(6, 6), color='red', markersize = 0.5)
ax.set_title('Points of Interest in Torino, Italy')
```

```
Text(0.5, 1.0, 'Points of Interest in Torino, Italy')
```


Points of Interest in Torino, Italy
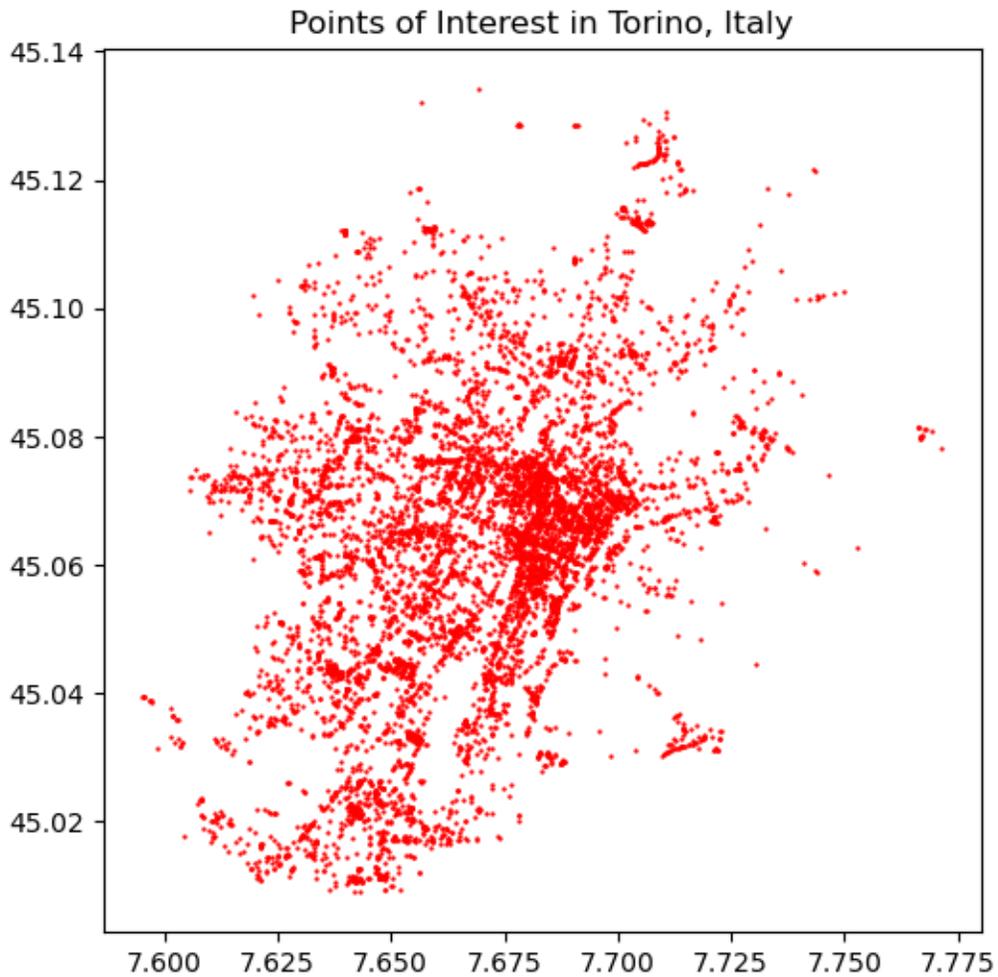
6.5.0.4 Public Transport Bus Stops

```python
# Tags for public transport
tags = {'public_transport': True}

# Fetch public transport routes
pt_stops = ox.features_from_place(place, tags=tags)

# Plot bus routes
```

```
ax = pt_stops.plot(figsize=(6, 6), color='blue', markersize = 0.5)
ax.set_title('Public Transport Stops in Torino, Italy')
```

Text(0.5, 1.0, 'Public Transport Stops in Torino, Italy')

Public Transport Stops in Torino, Italy
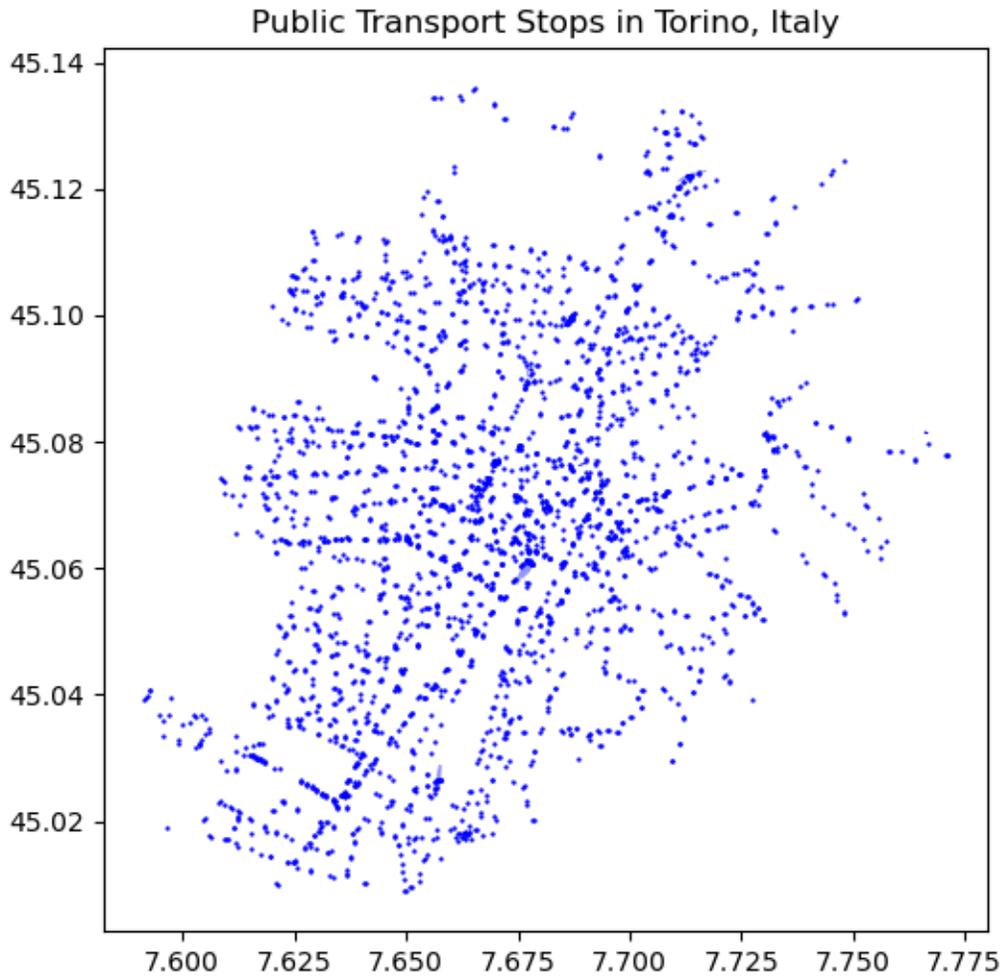
7 From Pixels to Patterns: Visualising Satellite Image Classification

8 From Pixels to Patterns: Visualising Satellite Image Classification

This notebook is based on the tutorial by Sydney Goldstein and adapted to Python by Elisabetta Pietrostefani for this course.

Goals: - Use Landsat 8 data to classify London into **developed, undeveloped, water, and clouds** - Visualise satellite imagery effectively — from greyscale bands to rich composites - Find **resources on the newest frontier in satellite analysis: embeddings** — access ready-to-use data derived from models like Google's SatCLIP / GeoCLIP and Google Embeddings Alpha, which encode entire landscapes into compact vectors that can be compared, searched, and clustered at global scale

We will cover: 1. Crop and mask raster data to a shapefile extent 2. Explore raster properties and load individual bands 3. Visualise true-colour and false-colour composites 4. Calculate NDVI (Normalised Difference Vegetation Index) 5. Supervised classification 6. *(Bonus)* Satellite embeddings — what they are and why the field is excited about them

8.1 Key Python libraries used

Python	R package	Purpose
`rasterio` + `numpy`	`raster`	Read/write/process rasters
`geopandas`	`sf`	Vector shapefiles
`matplotlib` + `earthpy`	`plotRGB` / `mapview`	Visualise composites
`sklearn.tree.DecisionTreeClassifier`	`rpart`	Decision tree classification
`sklearn.tree.plot_tree`	`rpart.plot`	Visualise the decision tree
`sklearn.ensemble.RandomForestClassifier`	`randomForest`	Random forest classification
`sklearn.metrics.ConfusionMatrixDisplay`	`table(confusionMatrix)`	Model evaluation
`matplotlib` + `seaborn`	`ggplot2` / `patchwork`	Plotting & layout
`pandas.melt`	`tidyr::gather`	Reshape data from wide to long

The **Lecture slides** can be found here.

This **lab**'s notebook can be downloaded from here.

8.2 Install & Import Libraries

Run the cell below once to install any missing packages.

```
# Uncomment and run this cell if you need to install the libraries
# !pip install rasterio geopandas earthpy matplotlib numpy pandas seaborn scikit-learn reques
```

```python
import os
import glob
import zipfile
import requests

import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.colors as mcolors
import seaborn as sns

import rasterio
from rasterio.mask import mask as rio_mask
from rasterio.plot import show, show_hist
from rasterio.enums import Resampling
import rasterio.warp as warp

import geopandas as gpd
from shapely.geometry import mapping, box

import earthpy.plot as ep

from sklearn.tree import DecisionTreeClassifier, plot_tree
from sklearn.ensemble import RandomForestClassifier
from sklearn.model_selection import train_test_split
from sklearn.metrics import (
    classification_report, confusion_matrix, ConfusionMatrixDisplay
)

print("All libraries imported successfully!")
```

```
All libraries imported successfully!
```

8.3 Crop and Mask to London Extent

Landsat 8 data covers large swaths of the Earth. Our first step is to **crop** (cut to a bounding box) and **mask** (remove pixels outside a polygon) the imagery to just the London boundary.

We use: - `geopandas` to load the London wards shapefile - `rasterio.mask` to crop and mask each band

8.3.1 Download the London shapefile

Task 1: Before running the code, visit https://earthexplorer.usgs.gov/ and explore what Landsat 8 data includes. What bands are available and what does each measure?

```python
#   Download London Wards shapefile

SHAPEFILE_PATH = "../data/pixels/statistical-gis-boundaries-london/London_ward.shp"
ZIP_PATH = "../data/pixels/statistical-gis-boundaries-london.zip"
URL = (
    "https://data.london.gov.uk/download/statistical-gis-boundary-files-london/"
    "9ba8c833-6370-4b11-abdc-314aa020d5e0/statistical-gis-boundaries-london.zip"
)

os.makedirs("data", exist_ok=True)

if not os.path.exists(SHAPEFILE_PATH):
    print("Downloading London shapefile...")
    response = requests.get(URL, stream=True)
    with open(ZIP_PATH, "wb") as f:
        for chunk in response.iter_content(chunk_size=8192):
            f.write(chunk)
    with zipfile.ZipFile(ZIP_PATH, "r") as zf:
        zf.extractall("data")
    print("Done!")
else:
    print("Shapefile already exists - skipping download.")

# Load wards
wards = gpd.read_file(SHAPEFILE_PATH)
print(f"Loaded {len(wards)} wards | CRS: {wards.crs}")

# Quick plot
fig, ax = plt.subplots(figsize=(8, 6))
```

```
wards.plot(ax=ax, edgecolor="steelblue", facecolor="none", linewidth=0.5)
ax.set_title("London Wards")
ax.set_axis_off()
plt.tight_layout()
plt.show()
```

```
Shapefile already exists - skipping download.
Loaded 649 wards | CRS: PROJCS["OSGB36 / British National Grid",GEOGCS["OSGB36",DATUM["Ordna
```

London Wards

```
#   Crop and mask each Landsat band

# List all raw .TIF files in the data/ folder
tifs = sorted(glob.glob("../data/pixels/*.TIF"))
```

```python
print(f"Found {len(tifs)} TIF files: {[os.path.basename(t) for t in tifs]}")

os.makedirs("../data/pixels/landsat", exist_ok=True)


def crop_and_mask(tif_path: str, shapes, out_dir: str = "../data/pixels/landsat") -> str:
    """
    Crops and masks a single raster to the union of `shapes`.

    Parameters
    ----------
    tif_path : str   Path to the input .TIF file.
    shapes   : list  List of GeoJSON-like geometries (from geopandas).
    out_dir  : str   Folder where the masked raster is saved.

    Returns
    -------
    str  Path to the output raster.
    """
    basename = os.path.basename(tif_path).replace(".TIF", ".tif")
    out_path = os.path.join(out_dir, f"London_{basename}") # Defining them just for London pe

    if os.path.exists(out_path):
        print(f"  Already exists - skipping: {basename}")
        return out_path

    with rasterio.open(tif_path) as src:
        # Re-project the shapefile to match the raster CRS
        shapes_reprojected = shapes.to_crs(src.crs)
        geoms = [mapping(geom) for geom in shapes_reprojected.geometry]

        # Crop (bounding box) + mask (exact polygon)
        out_image, out_transform = rio_mask(src, geoms, crop=True)
        out_meta = src.meta.copy()

    out_meta.update({
        "driver": "GTiff",
        "height": out_image.shape[1],
        "width": out_image.shape[2],
        "transform": out_transform,
    })
```

```
    with rasterio.open(out_path, "w", **out_meta) as dst:
        dst.write(out_image)

    print(f"  Saved: {out_path}")
    return out_path


# Apply to all bands
cropped_paths = [crop_and_mask(t, wards) for t in tifs]
print("\nAll bands cropped and masked!")
```

```
Found 19 TIF files: ['LC08_L2SP_201024_20210418_20210424_02_T1_QA_PIXEL.TIF', 'LC08_L2SP_201(
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_QA_PIXEL.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_QA_RADSAT.ti:
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B1.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B2.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B3.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B4.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B5.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B6.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B7.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_QA_AEROSOI
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_ATRAN.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_B10.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_CDIST.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_DRAD.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_EMIS.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_EMSD.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_QA.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_TRAD.tif
  Saved: ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_ST_URAD.tif

All bands cropped and masked!
```

8.4 Raster Properties & Loading Bands

Answer to Task 1: Landsat 8 carries two sensors — the **Operational Land Imager (OLI)**
and the **Thermal Infrared Sensor (TIRS)** — providing 11 spectral bands in total:

Band	Name	Wavelength	Resolution	What it's good for
1	Ultra Blue (Coastal/Aerosol)	0.43–0.45 µm	**30 m**	Coastal water, aerosol studies — new in Landsat 8
2	Blue	0.45–0.51 µm	**30 m**	Water depth, soil/vegetation distinction
3	Green	0.53–0.59 µm	**30 m**	Peak vegetation reflectance
4	Red	0.64–0.67 µm	**30 m**	Chlorophyll absorption; vegetation vs bare soil
5	Near Infrared (NIR)	0.85–0.88 µm	**30 m**	Biomass, vegetation health, water body edges
6	SWIR-1	1.57–1.65 µm	**30 m**	Soil moisture, snow/cloud differentiation
7	SWIR-2	2.11–2.29 µm	**30 m**	Geology, mineralogy, fire burn scars
8	Panchromatic	0.50–0.68 µm	**15 m**	High-resolution greyscale — pan-sharpening
9	Cirrus	1.36–1.38 µm	**30 m**	Detecting high-altitude cirrus cloud contamination
10	Thermal Infrared (TIRS-1)	10.6–11.19 µm	**100 m**	Surface temperature
11	Thermal Infrared (TIRS-2)	11.50–12.51 µm	**100 m**	Surface temperature (more accurate dual-band retrieval)

What does 30 m resolution actually mean? Each pixel covers a **30 × 30 metre** square on the ground — roughly the footprint of a large house. At 15 m (Band 8), a pixel is about the size of a car parking space. This is coarse compared to commercial satellites (which can reach 0.3 m), but Landsat's free global archive stretching back to 1972 makes it uniquely valuable for long-term change detection.

In this exercise we focus on **Bands 1–7** (all at 30 m).

In Python with `rasterio`, each band is loaded as a 2D `numpy` array — giving us full numerical control for calculations.

Task 2: After loading the bands below, plot them one at a time. What differences do you notice in brightness and range? Why does vegetation appear brighter in Band 5 (NIR)?

```python
#   Load individual bands by explicit filename

BASE = "../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR"

BAND_FILES = {
    "band1": f"{BASE}_B1.tif",
    "band2": f"{BASE}_B2.tif",
    "band3": f"{BASE}_B3.tif",
    "band4": f"{BASE}_B4.tif",
    "band5": f"{BASE}_B5.tif",
    "band6": f"{BASE}_B6.tif",
    "band7": f"{BASE}_B7.tif",
}

bands = {}
band_names = list(BAND_FILES.keys())

for name, path in BAND_FILES.items():
    with rasterio.open(path) as src:
        data = src.read(1).astype("float32")  # read as float for NDVI etc.
        nodata = src.nodata
        if nodata is not None:
            data[data == nodata] = np.nan     # mask no-data pixels
        bands[name] = data

        if name in ("band1", "band7"):        # print metadata for first and last
            print(f"\n{name.upper()} - {path}")
            print(f"  Shape      : {src.shape}")
            print(f"  CRS        : {src.crs}")
            print(f"  Resolution : {src.res} m")
            print(f"  Bounds     : {src.bounds}")
            print(f"  Min / Max  : {np.nanmin(data):.0f} / {np.nanmax(data):.0f}")

# Also keep a list of the paths in band order for rasterio operations later
landsat_tifs = list(BAND_FILES.values())

print("\nAll 7 bands loaded:", band_names)
```

```
BAND1 - ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B1.tif
  Shape      : (1509, 1965)
  CRS        : EPSG:32631
```

```
  Resolution : (30.0, 30.0) m
  Bounds     : BoundingBox(left=256185.0, bottom=5686095.0, right=315135.0, top=5731365.0)
  Min / Max  : 38 / 60798


BAND7 - ../data/pixels/landsat/London_LC08_L2SP_201024_20210418_20210424_02_T1_SR_B7.tif
  Shape      : (1509, 1965)
  CRS        : EPSG:32631
  Resolution : (30.0, 30.0) m
  Bounds     : BoundingBox(left=256185.0, bottom=5686095.0, right=315135.0, top=5731365.0)
  Min / Max  : 6742 / 65454


All 7 bands loaded: ['band1', 'band2', 'band3', 'band4', 'band5', 'band6', 'band7']
```

```python
#   Plot Band 1 and Band 7 with perceptually meaningful colourmaps
#
#   Each band is ONE number per pixel - to add colour we use a colourmap instead.
#   We pick colourmaps that match what each band physically measures:
#   Band 1 (Ultra Blue / coastal aerosol) → 'Blues'  - darker = more scattering
#   Band 7 (SWIR-2 / geology & burn scars) → 'YlOrBr' - warmer = more thermal emission
#
# A linear percentile stretch (vmin/vmax at 2nd-98th percentile) removes
# outlier bright pixels (clouds, water glint) that would otherwise wash out
# the colour range across the rest of the scene.

BAND_CMAPS = {
    "band1": ("Blues",    "Band 1 - Ultra Blue (Coastal/Aerosol)"),
    "band7": ("YlOrBr",   "Band 7 - SWIR-2 (Geology / Burn Scars)"),
}

fig, axes = plt.subplots(1, 2, figsize=(14, 6))

for ax, (bname, (cmap, title)) in zip(axes, BAND_CMAPS.items()):
    data = bands[bname]
    # 2-98th percentile stretch so outliers don't dominate the colour scale
    vmin, vmax = np.nanpercentile(data, [2, 98])
    im = ax.imshow(data, cmap=cmap, vmin=vmin, vmax=vmax)
    ax.set_title(title, fontsize=11, pad=8)
    ax.set_axis_off()
    fig.colorbar(im, ax=ax, fraction=0.03, pad=0.04, label="Reflectance")

plt.suptitle(
    "Individual Landsat 8 Bands - colourmap chosen to match each band's physics",
```

```
    fontsize=12, y=1.02
)
plt.tight_layout()
plt.show()
```

Individual Landsat 8 Bands — colourmap chosen to match each band's physics

Band 1 — Ultra Blue (Coastal/Aerosol)   Band 7 — SWIR-2 (Geology / Burn Scars)
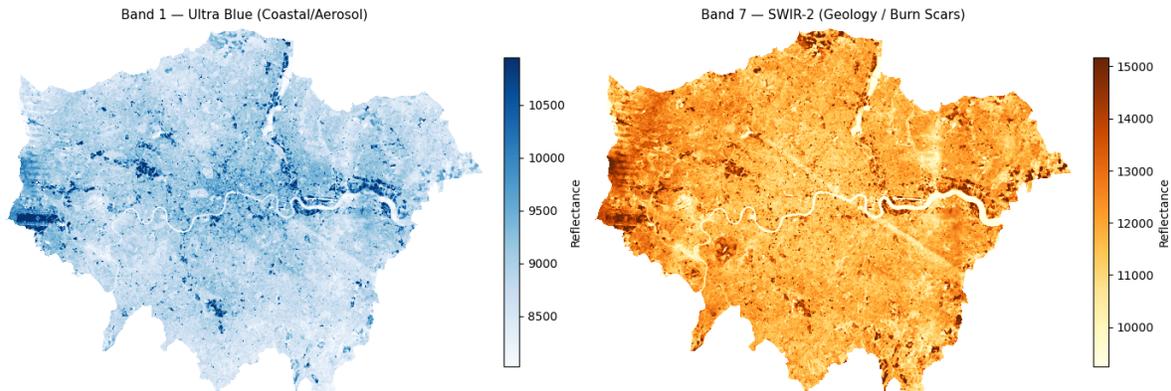
```
#   Plot Bands 2-5 in a 2×2 grid with matched colourmaps
# R equivalent: par(mfrow=c(2,2)); plot(band, col=gray(...))
#
# Colourmap choices:
#   Band 2 Blue  → 'Blues'    - water appears dark, urban bright
#   Band 3 Green → 'Greens'   - vegetation peaks here
#   Band 4 Red   → 'Reds'     - chlorophyll absorption; veg appears dark
#   Band 5 NIR   → 'RdYlGn'   - vegetation bright green, water near-black

BAND_GRID = {
    "band2": ("Blues",   "Band 2 - Blue"),
    "band3": ("Greens",  "Band 3 - Green"),
    "band4": ("Reds",    "Band 4 - Red"),
    "band5": ("RdYlGn",  "Band 5 - NIR (vegetation = bright)"),
}

fig, axes = plt.subplots(2, 2, figsize=(13, 11))

for ax, (bname, (cmap, label)) in zip(axes.flatten(), BAND_GRID.items()):
    data = bands[bname]
    vmin, vmax = np.nanpercentile(data, [2, 98])   # percentile stretch
    im = ax.imshow(data, cmap=cmap, vmin=vmin, vmax=vmax)
```

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```
    ax.set_title(label, fontsize=12)
    ax.set_axis_off()
    fig.colorbar(im, ax=ax, fraction=0.03, pad=0.04, label="Reflectance")

plt.suptitle(
    "Landsat 8 Bands 2-5\n"
    "Notice: vegetation (parks, fields) is bright in NIR (Band 5) but dark in Red (Band 4)",
    fontsize=12, y=1.02
)
plt.tight_layout()
plt.show()
```

Landsat 8 Bands 2–5
Notice: vegetation (parks, fields) is bright in NIR (Band 5) but dark in Red (Band 4)
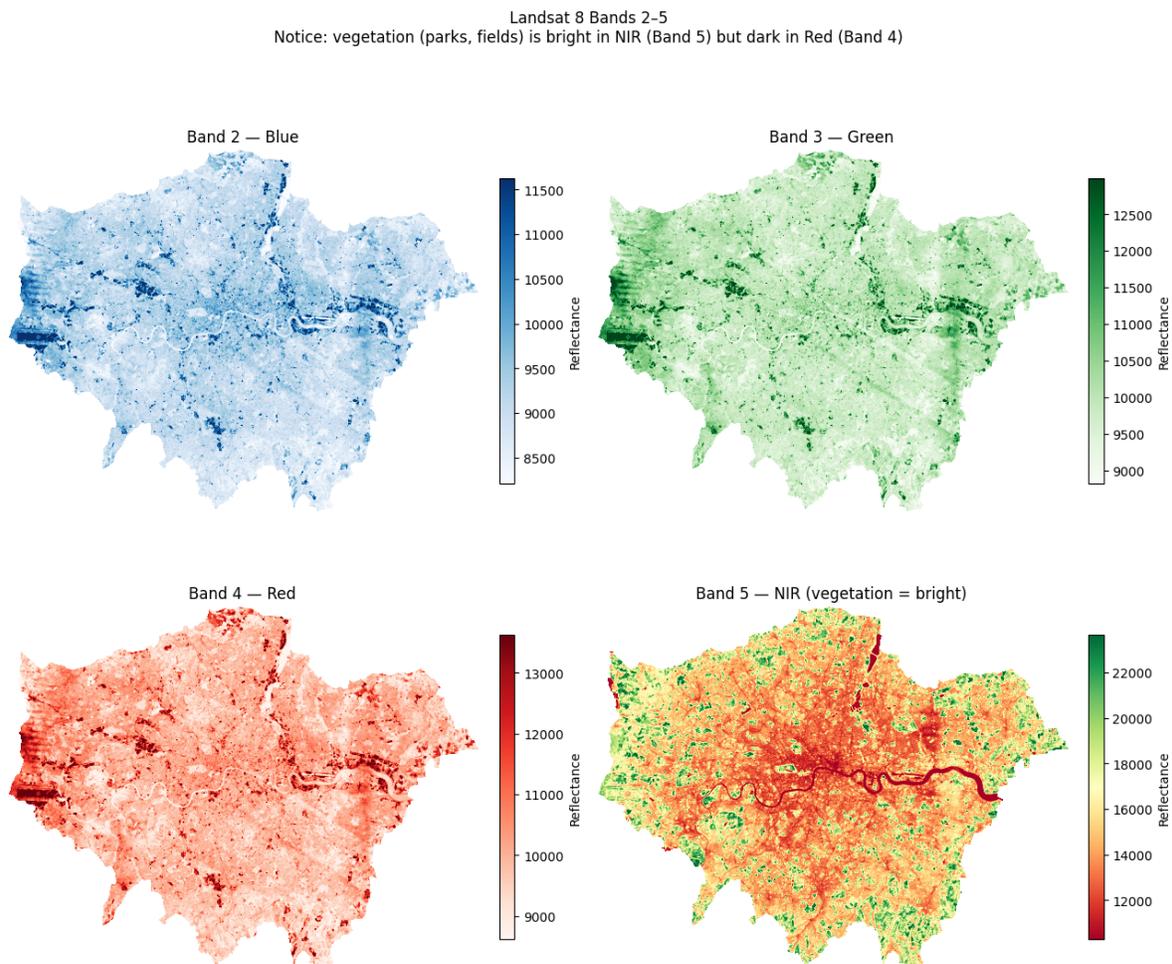
8.5 RGB Composites — True Colour & False Colour

Individual greyscale bands don't convey much on their own. We stack three bands into an **RGB composite**:

Composite	Red channel	Green channel	Blue channel	What it shows
True colour	Band 4 (Red)	Band 3 (Green)	Band 2 (Blue)	How the scene looks to the human eye
False colour (NIR)	Band 5 (NIR)	Band 4 (Red)	Band 3 (Green)	Vegetation appears **red/pink**; built-up appears **cyan/blue**

We use `earthpy.plot.plot_rgb()` which handles normalisation automatically.

```python
#   Stack all 7 bands into a single 3D array (bands × rows × cols)
# This mirrors R's stack() / RasterStack

landsat_stack = np.stack(
    [bands[f"band{i}"] for i in range(1, 8)],
    axis=0
)  # shape: (7, rows, cols)

n_bands, n_rows, n_cols = landsat_stack.shape
print(f"Stack shape : {landsat_stack.shape}")
print(f"Number of bands : {n_bands}")
print(f"Spatial dimensions : {n_rows} rows × {n_cols} cols")
```

```
Stack shape : (7, 1509, 1965)
Number of bands : 7
Spatial dimensions : 1509 rows × 1965 cols
```

```python
#   True Colour Composite
#
# True colour = how the scene looks to the human eye: Red, Green, Blue channels.
# In Landsat 8:  Red = Band 4,  Green = Band 3,  Blue = Band 2
# This is written as '4-3-2' in remote sensing shorthand (R-G-B order).
#
```

```python
# earthpy uses 0-based indexing into the stack, so:
#   Band 4 → stack index 3  (R)
#   Band 3 → stack index 2  (G)
#   Band 2 → stack index 1  (B)
#
# '4-3-2' and rgb=(3,2,1) describe exactly the same composite.

def percentile_stretch(stack, lo=2, hi=98):
    """
    Clip each band in `stack` (shape: bands × rows × cols) to the
    [lo, hi] percentile range and rescale to 0.0-1.0.
    Returns a float32 array of the same shape.
    """
    out = np.zeros_like(stack, dtype="float32")
    for i in range(stack.shape[0]):
        band = stack[i].astype("float32")
        vmin, vmax = np.nanpercentile(band, [lo, hi])
        out[i] = np.clip((band - vmin) / (vmax - vmin + 1e-6), 0, 1)
    return out

landsat_display = percentile_stretch(landsat_stack)   # reuse for all composites
landsat_display = np.nan_to_num(landsat_display, nan=0.0)  # nan → 0 for display only; doesn

fig, ax = plt.subplots(figsize=(10, 8))
ep.plot_rgb(
    landsat_display,
    rgb=(3, 2, 1),    # 0-indexed: band4=index 3, band3=index 2, band2=index 1
    ax=ax,
    title="True Colour Composite (Bands 4-3-2)"
)
ax.set_axis_off()
plt.tight_layout()
plt.show()
```

True Colour Composite (Bands 4-3-2)


```python
#   False Colour / NIR Composite (RGB = Bands 5, 4, 3)
# Vegetation reflects strongly in NIR → appears red/magenta
# Urban surfaces reflect less NIR → appear cyan/blue

fig, ax = plt.subplots(figsize=(10, 8))
ep.plot_rgb(
    landsat_stack,
    rgb=(4, 3, 2),          # 0-indexed: band5=4, band4=3, band3=2
    stretch=True,
    str_clip=0.5,
    ax=ax,
    title="False Colour Composite (Bands 5-4-3) - Vegetation in Red"
)
ax.set_axis_off()
plt.tight_layout()
```

```
plt.show()
```

/opt/miniconda3/envs/envs363_563/lib/python3.11/site-packages/earthpy/spatial.py:561: Runtime
    return (bytedata.clip(low, high) + 0.5).astype("uint8")

False Colour Composite (Bands 5-4-3) — Vegetation in Red
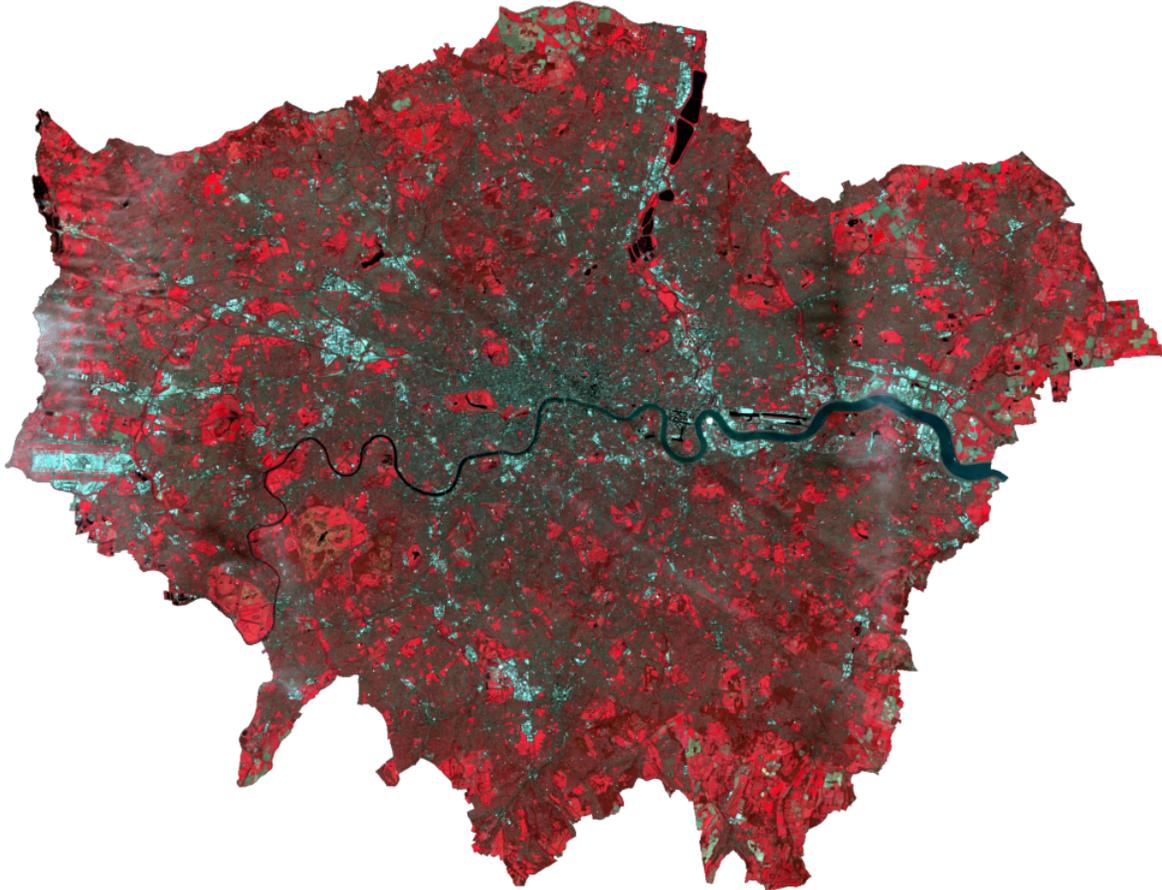

```
#   Side-by-side comparison

fig, axes = plt.subplots(1, 2, figsize=(18, 7))

ep.plot_rgb(landsat_stack, rgb=(3, 2, 1), stretch=True, str_clip=0.5,
            ax=axes[0], title="True Colour (4-3-2)")
ep.plot_rgb(landsat_stack, rgb=(4, 3, 2), stretch=True, str_clip=0.5,
            ax=axes[1], title="False Colour / NIR (5-4-3)")
```

```
for ax in axes:
    ax.set_axis_off()

plt.suptitle("London - Landsat 8 Composites", fontsize=14)
plt.tight_layout()
plt.show()
```


True Colour (4-3-2) London — Landsat 8 Composites False Colour / NIR (5-4-3)
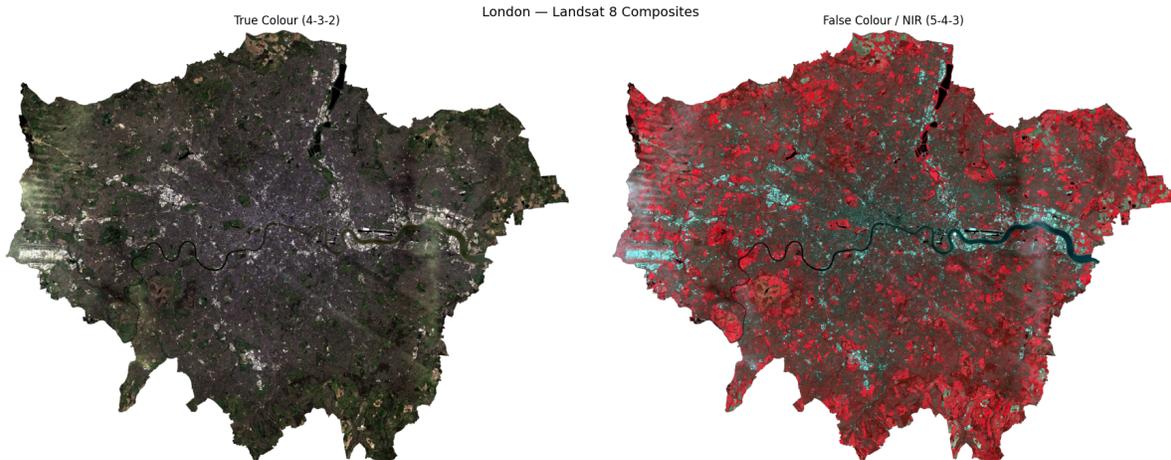
8.6 NDVI — Normalised Difference Vegetation Index

NDVI measures how much **live green vegetation** is present. It exploits the fact that healthy vegetation **absorbs Red light** and **reflects NIR light**:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} = \frac{\text{Band 5} - \text{Band 4}}{\text{Band 5} + \text{Band 4}}$$

NDVI value	Interpretation
< 0	Water, clouds, snow
$0 - 0.2$	Bare soil, urban, rock
$0.2 - 0.5$	Sparse vegetation, shrubs
> 0.5	Dense, healthy vegetation

In Python, this is a simple **vectorised numpy operation** — no loops needed.

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```
#   Calculate NDVI

nir = bands["band5"]    # Near Infrared
red = bands["band4"]    # Red

# Suppress divide-by-zero warnings where NIR + Red == 0
with np.errstate(divide="ignore", invalid="ignore"):
    ndvi = np.where(
        (nir + red) == 0,
        np.nan,
        (nir - red) / (nir + red)
    ).astype("float32")

print(f"NDVI range : {np.nanmin(ndvi):.3f} to {np.nanmax(ndvi):.3f}")
print(f"Mean NDVI  : {np.nanmean(ndvi):.3f}")
```

```
NDVI range : -0.235 to 0.609
Mean NDVI  : 0.197
```

Let's plot this in a "simple" way:

```
#   Simple NDVI vegetation map
# Classify each pixel into just two vegetation categories:
#   Sparse vegetation : 0.2  NDVI < 0.5  (parks, gardens, scrub)
#   Dense vegetation  : NDVI   0.5         (woodland, large parks)

veg_map = np.full_like(ndvi, np.nan)
veg_map[(ndvi >= 0.2) & (ndvi < 0.5)] = 1   # sparse
veg_map[ndvi >= 0.5]                  = 2   # dense

cmap_veg  = mcolors.ListedColormap(["#91cf60", "#1a7837"])
norm_veg  = mcolors.BoundaryNorm([0.5, 1.5, 2.5], cmap_veg.N)

fig, ax = plt.subplots(figsize=(9, 7))
ax.imshow(ndvi, cmap="Greys_r", vmin=-0.2, vmax=0.8, alpha=0.3)   # faint grey base
ax.imshow(veg_map, cmap=cmap_veg, norm=norm_veg)                  # vegetation on top
ax.set_title("Vegetation cover - London (from NDVI)", fontsize=13)
ax.set_axis_off()

# Manual legend
from matplotlib.patches import Patch
```

```
ax.legend(
    handles=[
        Patch(facecolor="#91cf60", label="Sparse vegetation  (NDVI 0.2-0.5)"),
        Patch(facecolor="#1a7837", label="Dense vegetation   (NDVI > 0.5)"),
    ],
    loc="lower left", frameon=False, fontsize=10
)
plt.tight_layout()
plt.show()
```

Vegetation cover — London (from NDVI)
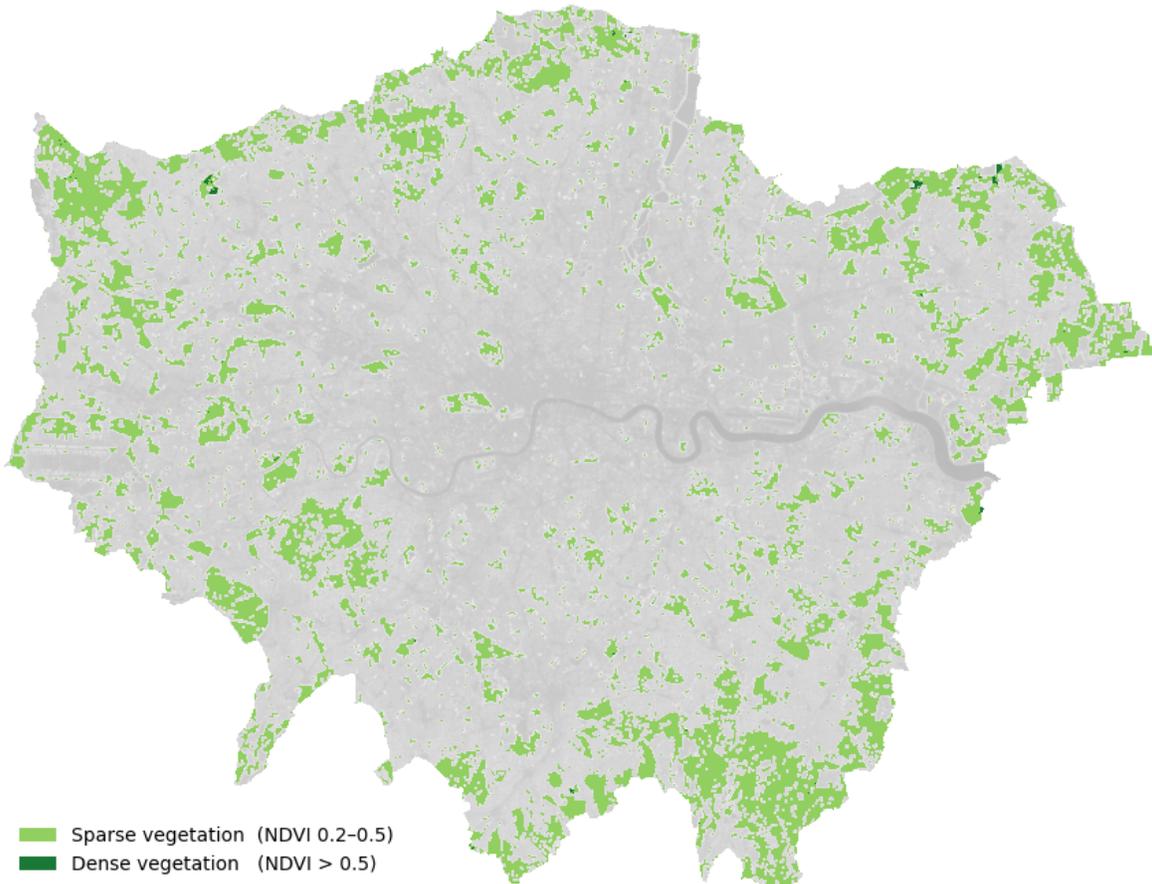
Below is a **full visualisation** (note: the code is fairly complex).

8.7 Supervised Classification

We now classify each pixel into one of four land cover types:

Class label	Description
0	Water
1	Developed / Urban
2	Undeveloped / Vegetation
3	Cloud

Approach — Random Forest Classifier (scikit-learn): 1. Create training labels by **thresholding NDVI and reflectance values** (a simple rule-based proxy for hand-labelling) 2. Extract the 7-band feature vector for each labelled pixel 3. Train a `RandomForestClassifier` 4. Predict across the full image and visualise the result

In a real project, training labels would come from **digitised ground truth polygons** in a GIS. The rule-based approach below is used here purely for demonstration.

8.7.1 How would you create training points in Python?

This is an approach for **interactive digitising** in Python:

Tool	How
leafmap	Draw points on an interactive Leaflet map in Jupyter, export as GeoJSON
geemap	Same but connected to Google Earth Engine — useful for larger areas
QGIS → GeoJSON	Digitise in QGIS, export as `.geojson` or `.shp`, load with `geopandas`

A `leafmap` workflow would look like this — **you do not need to run this**:

```
# pip install leafmap
import leafmap

m = leafmap.Map()
m.add_basemap('SATELLITE')
m  # displays interactive map – draw your points using the toolbar
```

```
# After drawing:
gdf = m.get_drawn_features()          # returns a GeoDataFrame
gdf['class'] = 'clouds'               # label this batch
# ... repeat for each class, then:
training_points = pd.concat([clouds, developed, undeveloped, water])
training_points.to_file('data/london_trainingPoints_example.shp')
```

For this exercise, **training points have already been prepared** and saved as a shapefile.
We load them directly below.

```
#    Step 1: Load pre-prepared training points

# The shapefile contains hand-digitised points for four land cover classes:
#    id=1   clouds        id=2   developed
#    id=3   undeveloped   id=4   water

training_points = gpd.read_file(
    "../data/pixels/london_trainingPoints/london_trainingPoints.shp"
)
print(f"Loaded {len(training_points)} training points")
print(training_points[["class", "id"]].value_counts().sort_index())

# Reproject to raster CRS for extraction
with rasterio.open(landsat_tifs[0]) as src:
    raster_crs = src.crs
tp_proj = training_points.to_crs(raster_crs)

# Extract band values at each training point
# Equivalent of R: df <- raster::extract(landsat, training_points)
coords = [(geom.x, geom.y) for geom in tp_proj.geometry]

extracted = {}
for name, path in BAND_FILES.items():
    with rasterio.open(path) as src:
        extracted[name] = [v[0] for v in src.sample(coords)]

df_extract = pd.DataFrame(extracted)
df_extract["class"] = training_points["class"].values
df_extract["id"]    = training_points["id"].values
df_extract = df_extract.dropna()
```

```
print(f"\nExtracted band values for {len(df_extract)} points")
print(df_extract.head())
```

```
Loaded 57 training points
class        id
clouds       1.0     9
developed    2.0    12
undeveloped  3.0    14
water        4.0    22
Name: count, dtype: int64


Extracted band values for 57 points
    band1  band2  band3  band4  band5  band6  band7   class   id
0   11636  12300  14071  15659  17048  17925  16451  clouds  1.0
1   13482  14387  15285  15875  16448  16042  14579  clouds  1.0
2   14452  15474  16947  18472  20646  21577  16697  clouds  1.0
3   12589  13673  15304  16322  16906  16274  14316  clouds  1.0
4   12592  13407  15333  16942  19117  19893  17447  clouds  1.0
```

```python
#   Step 2: Plot training points coloured by land use class

CLASS_COLOURS = {
    "clouds":      "cyan",
    "developed":   "burlywood",
    "undeveloped": "darkgreen",
    "water":       "blue",
}

# Load city boundary and reproject everything to the same CRS
city_boundary = gpd.read_file(
    "../data/pixels/statistical-gis-boundaries-london/London_ward.shp"
).dissolve()

# Use the raster CRS as the common reference
with rasterio.open(landsat_tifs[0]) as src:
    plot_crs = src.crs

city_boundary         = city_boundary.to_crs(plot_crs)
training_points_plot = training_points.to_crs(plot_crs)

fig, ax = plt.subplots(figsize=(9, 8))
```

```
city_boundary.plot(ax=ax, color="lightgray", edgecolor="none")

for cls, colour in CLASS_COLOURS.items():
    subset = training_points_plot[training_points_plot["class"] == cls]
    subset.plot(ax=ax, color=colour, markersize=5, label=cls)

ax.set_title("Classification points by land use", fontsize=13)
ax.legend(markerscale=3, frameon=False, fontsize=10, loc="lower left")
ax.set_axis_off()
plt.tight_layout()
plt.show()
```

Classification points by land use
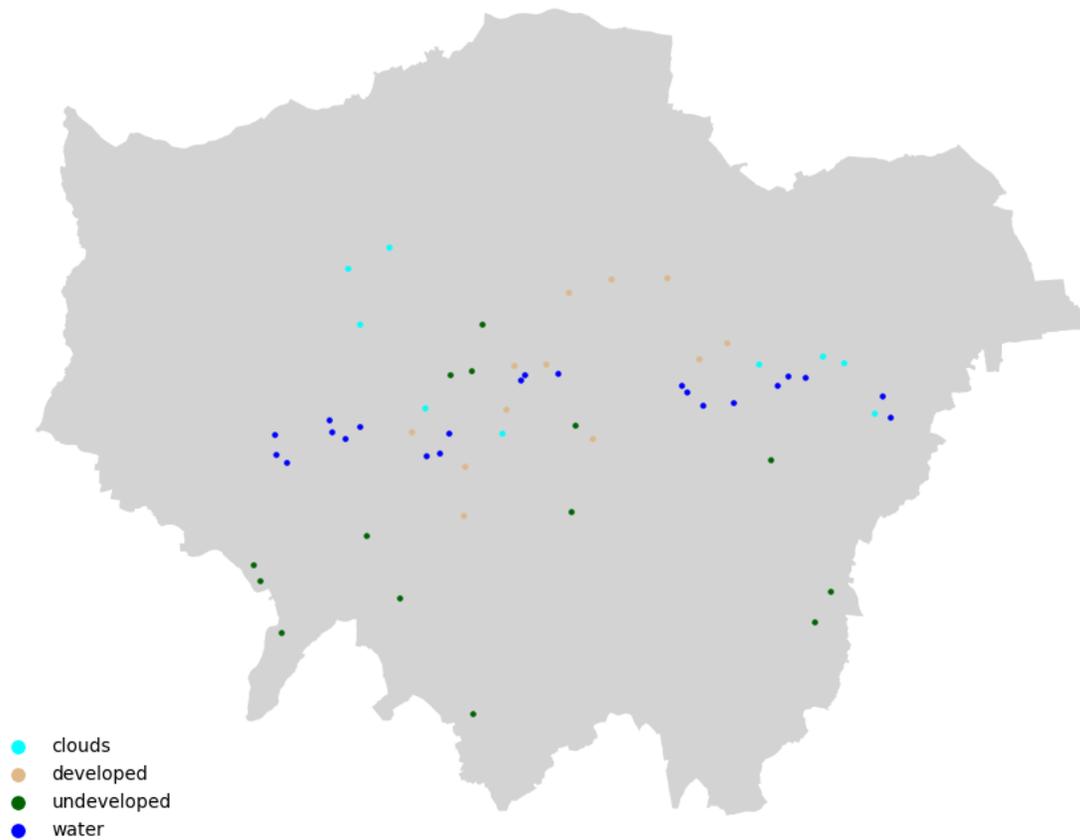

```
#   Step 2: Train Random Forest on the loaded training points
# Build feature matrix X and label vector y from the extracted band values
```

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```python
BAND_COLS = [f"band{i}" for i in range(1, 8)]

X = df_extract[BAND_COLS].values
y = df_extract["class"].values

X_train, X_test, y_train, y_test = train_test_split(
    X, y, test_size=0.2, random_state=42, stratify=y
)
print(f"Training samples : {len(X_train):,}")
print(f"Test samples     : {len(X_test):,}")

# RandomForestClassifier is the Python equivalent of R's randomForest()
rf = RandomForestClassifier(
    n_estimators=100,
    max_features="sqrt",
    n_jobs=-1,
    random_state=42
)
rf.fit(X_train, y_train)
print("\nTraining complete!")

y_pred = rf.predict(X_test)
print("\nClassification Report:")
print(classification_report(y_test, y_pred))
```

```
Training samples : 45
Test samples     : 12

Training complete!

Classification Report:
              precision    recall  f1-score   support

      clouds       1.00      1.00      1.00         2
   developed       1.00      1.00      1.00         2
 undeveloped       1.00      1.00      1.00         3
       water       1.00      1.00      1.00         5

    accuracy                           1.00        12
   macro avg       1.00      1.00      1.00        12
weighted avg       1.00      1.00      1.00        12
```

```
#   Step 3: Predict across the full image

X_full = np.column_stack(
    [bands[f"band{i}"].ravel() for i in range(1, 8)]
)
valid_mask = ~np.isnan(X_full).any(axis=1)
X_valid    = X_full[valid_mask]

predicted_flat = np.full(X_full.shape[0], fill_value="", dtype=object)
predicted_flat[valid_mask] = rf.predict(X_valid)

# Map string class names to integers for visualisation
class_to_int = {"clouds": 1, "developed": 2, "undeveloped": 3, "water": 4}
int_to_class = {v: k for k, v in class_to_int.items()}
class_names  = list(class_to_int.keys())

predicted_int = np.array(
    [class_to_int.get(c, 0) for c in predicted_flat], dtype="float32"
)
predicted_int[~valid_mask] = np.nan
predicted_map = predicted_int.reshape(bands["band1"].shape)

print("Prediction complete!")
for cls, cid in class_to_int.items():
    pct = np.nansum(predicted_map == cid) / np.sum(~np.isnan(predicted_map)) * 100
    print(f"  {cls:12s} : {pct:.1f}% of pixels")
```

```
Prediction complete!
  clouds       :  4.5% of pixels
  developed    : 35.6% of pixels
  undeveloped  : 57.7% of pixels
  water        :  2.2% of pixels
```

```
#   Step 5: Visualise classification result

cmap = mcolors.ListedColormap(["cyan", "burlywood", "darkgreen", "blue"])
bounds = [0.5, 1.5, 2.5, 3.5, 4.5]
norm = mcolors.BoundaryNorm(bounds, cmap.N)

fig, axes = plt.subplots(1, 2, figsize=(18, 7))
```

```
ep.plot_rgb(landsat_display, rgb=(4, 3, 2),
            ax=axes[0], title="False Colour (5-4-3) - Reference")
axes[0].set_axis_off()

im = axes[1].imshow(predicted_map, cmap=cmap, norm=norm)
axes[1].set_title("Random Forest Classification - London", fontsize=13)
axes[1].set_axis_off()
cbar = fig.colorbar(im, ax=axes[1], fraction=0.03, pad=0.04, ticks=[1, 2, 3, 4])
cbar.ax.set_yticklabels(["Clouds", "Developed", "Undeveloped", "Water"])

plt.suptitle("Land Cover Classification from Landsat 8 - Random Forest", fontsize=14)
plt.tight_layout()
plt.show()
```
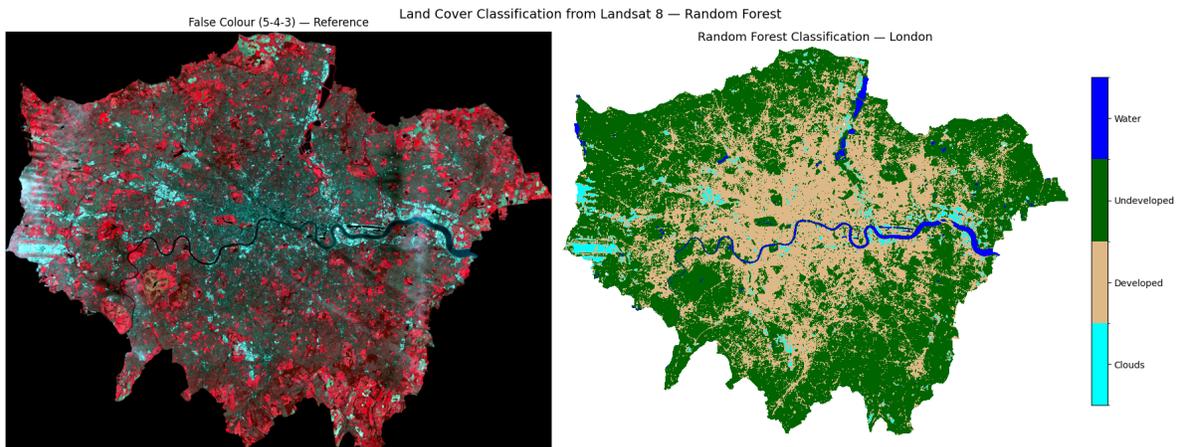

Task 3: Does this classification look correct for London? Consider what you know about the city — are the land cover classes (clouds, developed, undeveloped, and water) distributed where you would expect them to be? Are there any areas that look misclassified?

```
#    Step 6: Feature importance
# Which Landsat band was most useful for classification?

importances = rf.feature_importances_
band_labels_list = [f"Band {i}" for i in range(1, 8)]

fig, ax = plt.subplots(figsize=(8, 4))
bars = ax.barh(band_labels_list, importances, color="steelblue", edgecolor="white")
ax.set_xlabel("Feature Importance (Gini)")
```
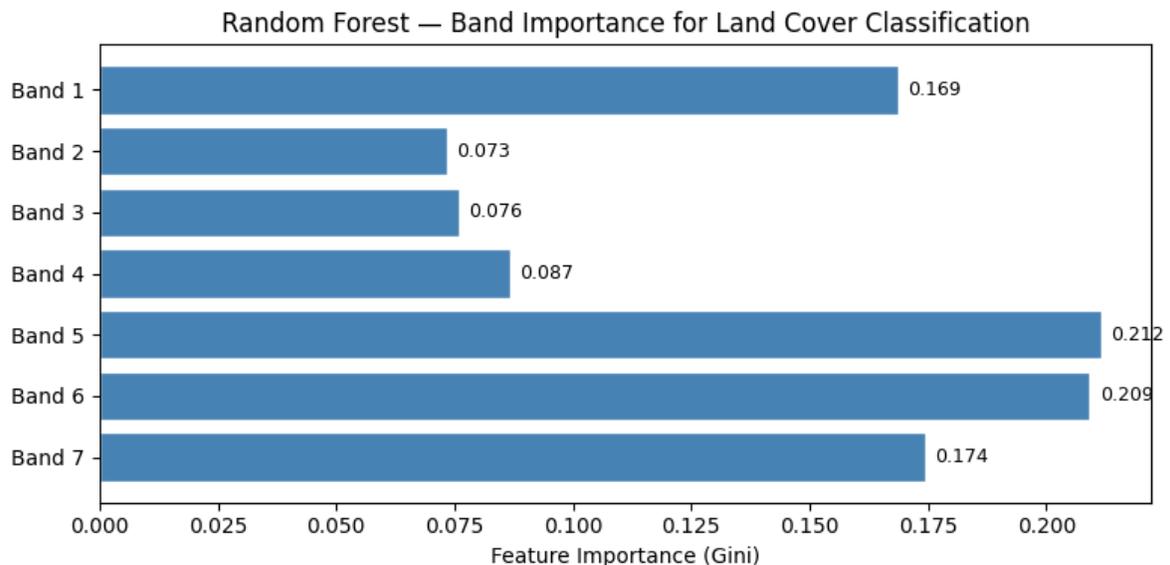
```python
ax.set_title("Random Forest - Band Importance for Land Cover Classification")
ax.invert_yaxis()
for bar, val in zip(bars, importances):
    ax.text(val + 0.002, bar.get_y() + bar.get_height()/2,
            f"{val:.3f}", va="center", fontsize=9)

plt.tight_layout()
plt.show()
```

Random Forest — Band Importance for Land Cover Classification

Band	Feature Importance (Gini)
Band 1	0.169
Band 2	0.073
Band 3	0.076
Band 4	0.087
Band 5	0.212
Band 6	0.209
Band 7	0.174

8.8 Spectral Profile Analysis

Before accepting the classification, we should check whether the four classes are **spectrally separable** — do they reflect light differently across the 7 bands?

We plot two views: 1. **Line plot** — mean reflectance per class across bands (the "spectral signature") 2. **Density plot** — distribution of all reflectance values per class across all bands

> If two classes overlap heavily, the classifier will struggle to tell them apart — the classic example here is **clouds vs developed land**, which both appear bright.

```python
#   Mean spectral profile per class
# Equivalent of R: group_by(id) %>% summarise(mean per band) then ggplot line

BAND_COLS = [f"band{i}" for i in range(1, 8)]
```

```python
profiles = (
    df_extract
    .groupby("class")[BAND_COLS]
    .mean()
    .reset_index()
)

# Wide → long  (equivalent of tidyr::gather)
profiles_long = profiles.melt(
    id_vars="class",
    value_vars=BAND_COLS,
    var_name="band",
    value_name="reflectance"
)

fig, ax = plt.subplots(figsize=(10, 5))
for cls, colour in CLASS_COLOURS.items():
    subset = profiles_long[profiles_long["class"] == cls]
    ax.plot(subset["band"], subset["reflectance"],
            marker="o", linewidth=2, markersize=7,
            color=colour, label=cls)

ax.set_xlabel("Band", fontsize=12)
ax.set_ylabel("Mean Reflectance", fontsize=12)
ax.set_title("Spectral Profile from Landsat 8 Imagery", fontsize=13)
ax.legend(frameon=False)
ax.grid(True, linestyle="--", alpha=0.5)
sns.despine(ax=ax)
plt.tight_layout()
plt.show()
```

Spectral Profile from Landsat 8 Imagery
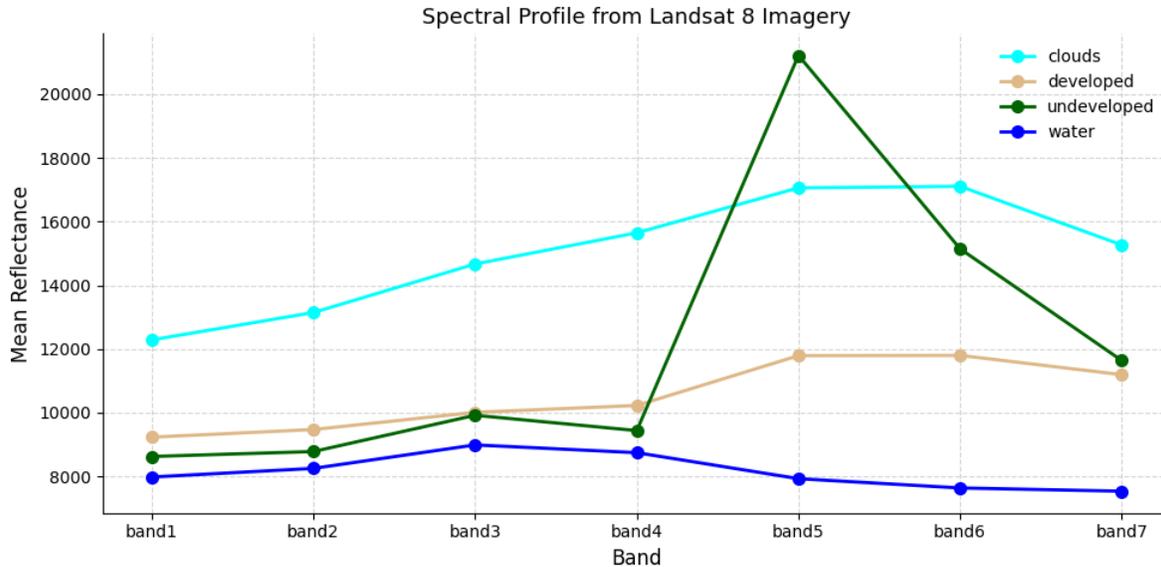
```
#    Density histograms of spectral profiles
# Equivalent of R: geom_density() + geom_vline(grp.mean)
#
# If clouds and developed land overlap heavily, expect the classifier to confuse them.

all_values_long = df_extract.melt(
    id_vars=["class"],
    value_vars=BAND_COLS,
    var_name="band",
    value_name="reflectance"
)
class_means = all_values_long.groupby("class")["reflectance"].mean()

fig, ax = plt.subplots(figsize=(10, 5))
for cls, colour in CLASS_COLOURS.items():
    vals = all_values_long[all_values_long["class"] == cls]["reflectance"]
    vals.plot.kde(ax=ax, color=colour, linewidth=2, label=cls)
    ax.fill_between(
        ax.lines[-1].get_xdata(),
        ax.lines[-1].get_ydata(),
        alpha=0.25, color=colour
    )
    ax.axvline(class_means[cls], color=colour, linestyle="--", linewidth=1.2)

ax.set_xlabel("Reflectance Value", fontsize=12)
```

```
ax.set_ylabel("Density", fontsize=12)
ax.set_title(
    "Density histograms of spectral profiles\n"
    "Dashed lines = mean reflectance per class",
    fontsize=12
)
ax.legend(frameon=False)
ax.grid(True, linestyle="--", alpha=0.4)
sns.despine(ax=ax)
plt.tight_layout()
plt.show()
print("If there is overlap between categories, the model may struggle to differentiate them."
```


Density histograms of spectral profiles
Dashed lines = mean reflectance per class
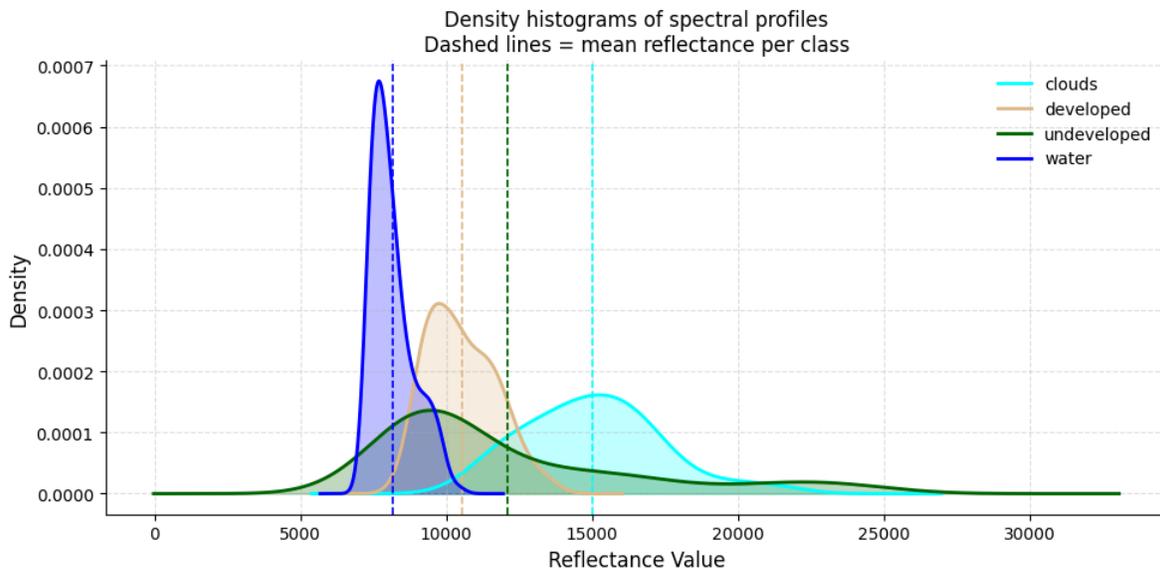
If there is overlap between categories, the model may struggle to differentiate them.

8.9 Decision Tree Classification

As well as Random Forest, we can use a **Decision Tree** (rpart in R → `sklearn.tree.DecisionTreeClassifier` in Python).

A decision tree asks a series of if/else questions about band values — each split is a **node**, each outcome is a **leaf**. Unlike Random Forest you can actually *read* the rules it learned, making it a great teaching tool.

Task 4: After running the classification, comment on the accuracy with your partners. Look at West London — is Heathrow Airport being misclassified as cloud?

```python
#   Train decision tree

X = df_extract[BAND_COLS].values
y = df_extract["class"].values

X_tr, X_te, y_tr, y_te = train_test_split(
    X, y, test_size=0.2, random_state=42, stratify=y
)

dt = DecisionTreeClassifier(max_depth=5, random_state=42)
dt.fit(X_tr, y_tr)
print(f"Tree depth: {dt.get_depth()} | Leaves: {dt.get_n_leaves()}")

#   Visualise the tree
# Equivalent of R: rpart.plot(model.class)
fig, ax = plt.subplots(figsize=(20, 8))
plot_tree(
    dt,
    feature_names=BAND_COLS,
    class_names=dt.classes_,
    filled=True, rounded=True,
    fontsize=9, ax=ax
)
ax.set_title("Classification Tree", fontsize=14)
plt.tight_layout()
plt.show()


#   Predict across the full image (Decision Tree)
predicted_flat_dt = np.full(X_full.shape[0], fill_value="", dtype=object)
predicted_flat_dt[valid_mask] = dt.predict(X_valid)

predicted_int_dt = np.array(
    [class_to_int.get(c, 0) for c in predicted_flat_dt], dtype="float32"
)
predicted_int_dt[~valid_mask] = np.nan
predicted_map_dt = predicted_int_dt.reshape(bands["band1"].shape)
```
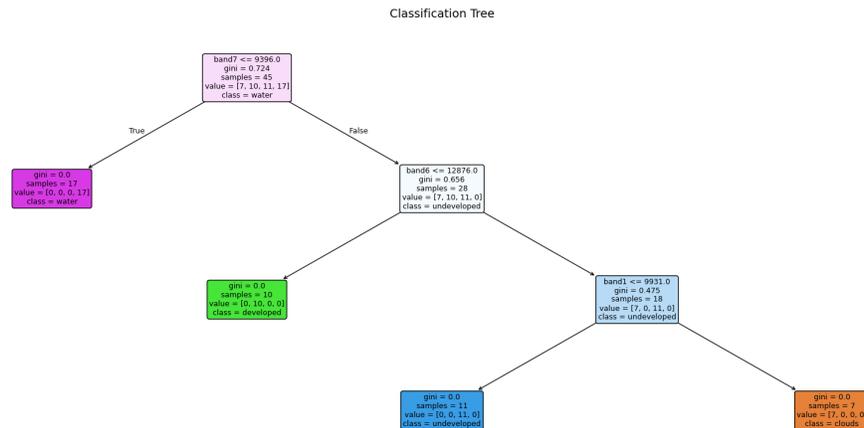
```
print("Decision Tree prediction complete!")
print({cls: int(np.nansum(predicted_map_dt == idx)) for cls, idx in class_to_int.items()})
```

Tree depth: 3 | Leaves: 4

Classification Tree

Decision Tree prediction complete!
{'clouds': 89166, 'developed': 541257, 'undeveloped': 1104408, 'water': 38163}

8.10 Model Evaluation — Confusion Matrix

A confusion matrix compares the **predicted** class to the **observed** (ground-truthed) class.

> **Task 5:** Try and interpret the matrix. Which classes are most often confused? See https://www.geeksforgeeks.org/machine-learning/confusion-matrix-machine-learning/

Key metrics to look for: - **Accuracy** — % of all points classified correctly - **Sensitivity (Recall)** — of points that *are* class X, how many did we catch? - **Specificity** — of points that *aren't* class X, how many did we correctly exclude?

Note: a 100% accuracy on training points is common with few points — it does not mean the full map is perfect!

```
#    Confusion matrix
# Equivalent of R: confusionMatrix(testProbs$obs, testProbs$pred)

y_pred_te = dt.predict(X_te)
print(classification_report(y_te, y_pred_te))

fig, ax = plt.subplots(figsize=(7, 6))
ConfusionMatrixDisplay.from_predictions(
    y_te, y_pred_te,
    display_labels=dt.classes_,
    cmap="Blues", ax=ax
)
ax.set_title("Confusion Matrix - Decision Tree", fontsize=12)
plt.tight_layout()
plt.show()

print("""
Note: You could create more training points using leafmap (see the section above).
More points don't automatically mean better accuracy - the quality and placement
of training points matters more than the quantity.
""")
```
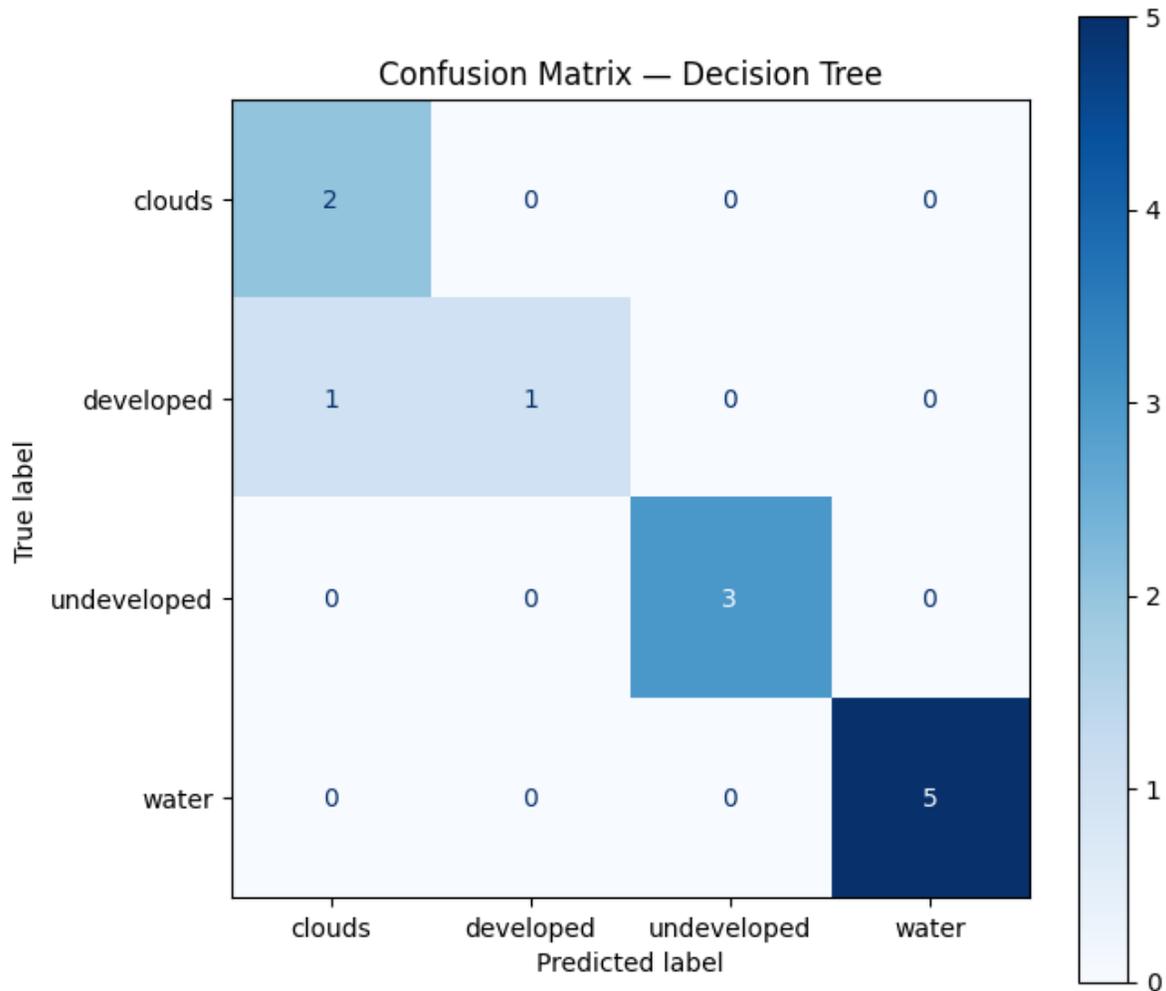
	precision	recall	f1-score	support
clouds	0.67	1.00	0.80	2
developed	1.00	0.50	0.67	2
undeveloped	1.00	1.00	1.00	3
water	1.00	1.00	1.00	5
accuracy			0.92	12
macro avg	0.92	0.88	0.87	12
weighted avg	0.94	0.92	0.91	12

Confusion Matrix — Decision Tree

Note: You could create more training points using leafmap (see the section above).
More points don't automatically mean better accuracy - the quality and placement
of training points matters more than the quantity.

8.11 Final Classification Map

A richer three-panel view of the decision tree classification result for great visualisation.

```
#   Rich 3-panel classification visualisation
# Mirrors the NDVI 3-panel layout: map | pixel count bar | % share bar
```

```python
CLASS_SCHEME = [
    {"label": "Clouds",      "id": 1, "colour": "cyan"},
    {"label": "Developed",   "id": 2, "colour": "burlywood"},
    {"label": "Undeveloped", "id": 3, "colour": "darkgreen"},
    {"label": "Water",       "id": 4, "colour": "#1d6fa4"},
]

total_valid  = int(np.sum(~np.isnan(predicted_map_dt)))
class_counts = [int(np.nansum(predicted_map_dt == c["id"])) for c in CLASS_SCHEME]
pcts         = [n / total_valid * 100 for n in class_counts]
colours      = [c["colour"] for c in CLASS_SCHEME]
labels       = [c["label"] for c in CLASS_SCHEME]

#   Figure layout: map | count bar | % bar
fig = plt.figure(figsize=(20, 7))
gs  = fig.add_gridspec(1, 3, width_ratios=[2, 1, 1], wspace=0.35)
ax_map = fig.add_subplot(gs[0])
ax_cnt = fig.add_subplot(gs[1])
ax_pct = fig.add_subplot(gs[2])

#   Panel 1: classification map with horizontal legend at bottom
from matplotlib.patches import Patch
cmap_cls = mcolors.ListedColormap(colours)
norm_cls = mcolors.BoundaryNorm([0.5, 1.5, 2.5, 3.5, 4.5], cmap_cls.N)
ax_map.imshow(predicted_map_dt, cmap=cmap_cls, norm=norm_cls)
ax_map.set_title("Decision Tree Classification - London", fontsize=13, pad=10)
ax_map.set_axis_off()

# Horizontal patch legend placed below the map
legend_handles = [
    Patch(facecolor=c["colour"], label=c["label"]) for c in CLASS_SCHEME
]
ax_map.legend(
    handles=legend_handles,
    loc="lower center",
    bbox_to_anchor=(0.5, -0.08),
    ncol=4,
    frameon=False,
    fontsize=10,
)

#   Panel 2: pixel count horizontal bar
```

```
bars = ax_cnt.barh(labels, class_counts, color=colours, edgecolor="white", height=0.55)
ax_cnt.set_xlabel("Pixel count", fontsize=11)
ax_cnt.set_title("Pixels per class", fontsize=12)
ax_cnt.set_xlim(0, max(class_counts) * 1.3)
for bar, n in zip(bars, class_counts):
    ax_cnt.text(n + max(class_counts) * 0.02,
                bar.get_y() + bar.get_height() / 2,
                f"{n:,}", va="center", fontsize=9)
ax_cnt.invert_yaxis()
sns.despine(ax=ax_cnt)

#   Panel 3: % share horizontal bar
bars2 = ax_pct.barh(labels, pcts, color=colours, edgecolor="white", height=0.55)
ax_pct.set_xlabel("% of pixels", fontsize=11)
ax_pct.set_title("Land Cover Share", fontsize=12)
ax_pct.set_xlim(0, max(pcts) * 1.3)
for bar, pct in zip(bars2, pcts):
    ax_pct.text(pct + max(pcts) * 0.02,
                bar.get_y() + bar.get_height() / 2,
                f"{pct:.1f}%", va="center", fontsize=9)
ax_pct.invert_yaxis()
sns.despine(ax=ax_pct)

fig.suptitle("Land Cover Classification - London Landsat 8", fontsize=15, y=1.01)
plt.subplots_adjust(top=0.93, wspace=0.35, bottom=0.12)
plt.show()
```


Land Cover Classification — London Landsat 8
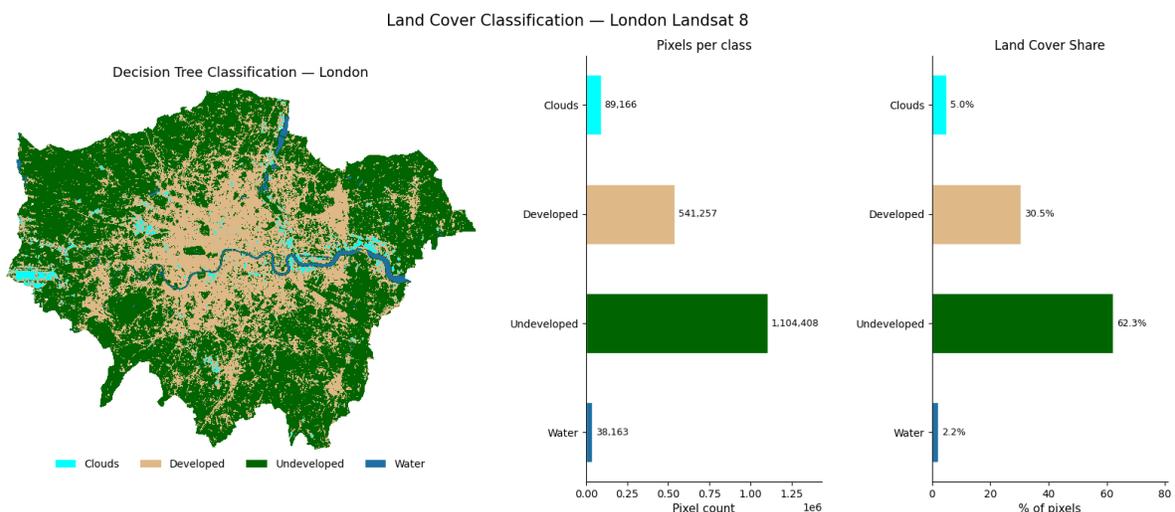
8.12 What's Next? Satellite Embeddings

Everything we have done so far — loading bands, calculating NDVI, training a classifier — treats each pixel as a set of raw reflectance numbers. The next frontier asks a different question: **can we teach a model to *understand* what a landscape looks like, the same way large language models understand text?**

8.12.1 What are embeddings?

An **embedding** is a compact numeric vector (e.g. 512 numbers) that encodes the *meaning* of an image patch — not just its raw pixel values, but what it represents: a park, a motorway interchange, a reservoir, a housing estate. Two patches that look similar will have vectors that are close together in this high-dimensional space, even if they are on opposite sides of the world.

```
Raw Landsat patch (7 bands × 64×64 pixels = 28,672 numbers)
        ↓  foundation model  ↓
Embedding vector  (512 numbers)  ← searchable, comparable, clusterable
```

8.12.2 Why does this matter?

Traditional classification (like what we did above) requires hand-labelled training points for every city and every time period. Embeddings change this. Note that the below points are very simplified (we would need a whole other session to tackle this properly).

- **Zero-shot search** — *"find all patches that look like this neighbourhood"* across a global archive, no labels needed
- **Change detection** — subtract embeddings over time to find where landscapes have changed
- **Cross-city transfer** — a model trained on London embeddings can classify Paris without retraining
- **Multimodal fusion** — combine satellite embeddings with census data, street view, or social media

8.12.3 Where to explore further

EMBED2Social Workshop 2026 — tutorials and materials on using embeddings for social science research:
https://imago-sdruk.github.io/EMBED2Social-Workshop-2026/Materials.html

Imago Data Catalogue — a UK data service for satellite imagery, including pre-computed embedding datasets ready to use:

https://data.imago.ac.uk/datasets?search=embeddings

The Imago data catalogue lets you download embeddings for small admin areas directly — no GPU, no model training needed. You can load them into Python as numpy arrays and immediately run clustering, similarity search, or regression against socioeconomic variables.

> This is the direction the field is moving — from hand-crafted features like NDVI to learned representations that capture the full complexity of what a place looks like from space.

8.13 Summary & Further Exercises

You have successfully: - Cropped and masked Landsat 8 imagery to London using `rasterio` + `geopandas` - Explored raster properties (CRS, resolution, extent) - Plotted true-colour and false-colour composites with `earthpy` - Calculated NDVI using vectorised `numpy` arithmetic - Trained and evaluated a Random Forest classifier with `scikit-learn` - Started evaluating accuracy with a confusion matrix - Produced a rich 3-panel classification map

8.13.1 Do-it-Yourself

1. **Digitise your own points** using leafmap and compare accuracy
2. **More training points** — but remember: quality beats quantity
3. **Add indices** — NDWI `(Green-NIR)/(Green+NIR)` or NDBI `(SWIR-NIR)/(SWIR+NIR)` as extra features
4. **Export** the classified map as a GeoTIFF for use in QGIS

```python
# Hint for exporting:
with rasterio.open("data/landsat/London_classified.tif", "w",
                   driver="GTiff", dtype="int8",
                   width=predicted_map.shape[1],
                   height=predicted_map.shape[0],
                   count=1, crs=src.crs,
                   transform=src.transform) as dst:
    dst.write(predicted_map.astype("int8"), 1)
```