

Population Science

Francisco Rowe, Carmen Cabrera-Arnau, Elisabetta Pietrostefani

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Table of contents

Welcome	5
Contact	5
1 Overview	6
1.1 Aims	6
1.2 Learning Outcomes	6
1.3 Feedback	7
1.4 Computational Environment	7
1.4.1 List of libraries	8
1.5 Assessment	8
1.5.1 Format Requirements	9
2 Data Revolution	11
2.1 Introduction	11
2.2 Defining digital footprint data	12
2.3 Opportunities of digital footprint data	13
2.4 Challenges of digital footprint data	14
2.4.1 Conceptual challenges	14
2.4.2 Methodological challenges	14
2.4.3 Ethical challenges	15
2.5 Conclusion	16
3 Geodemographics	17
3.1 Dependencies	17
3.2 Data	18
3.2.1 Demographic data for Greater London Authority	18
3.2.2 Import the data	18
3.3 Geodemographic classification	19
3.4 Preparing the data for GDC	19
3.4.1 Choice of geographic units	19
3.4.2 Variables of interest	19
3.5 Checking for variable association	22
3.6 Variable standardisation	24
3.6.1 Between areas	24
3.6.2 Between variables	24

3.7	The clustering process	25
3.7.1	K-means	25
3.7.2	Number of clusters	26
3.7.3	Other clustering methods	26
3.8	Dealing with the GDC results	26
3.8.1	Cluster interpretation	26
3.8.2	Testing	26
4	Sequence Analysis	27
4.1	Dependencies	27
4.2	Data	27
4.2.1	Data Wrangling	27
4.3	Application	27
4.3.1	Defining outcome process	27
4.3.2	Optimal matching	27
4.3.3	Clustering	27
4.3.4	Visualising	28
4.4	Questions	28
5	Network Analysis	29
5.1	Dependencies	29
5.2	Data	29
5.2.1	The US Census dataset	29
5.2.2	Import the data	29
5.3	Creating networks	31
5.3.1	Starting from the basics	32
5.3.2	Adding attributes	33
5.4	Reading networks from data files	35
5.4.1	Preparing the data to create an igraph object	35
5.4.2	Filtering the data to create a subgraph	37
5.5	Network visualisation	38
5.5.1	Visualisation with igraph	38
5.5.2	Visualisation of spatial networks	40
5.5.3	Alternative visualisations	42
5.6	Network metrics	42
5.6.1	Density	42
5.6.2	Reciprocity	43
5.6.3	Degree	43
5.6.4	Distances	45
5.6.5	Centrality	45
5.7	Communities	46
5.8	Final visualisation	46

6 Sentiment Analysis	47
6.1 Dependencies	47
6.2 Data	47
7 Topic Modelling	48
8 Modelling Time	49
9 Assessing Interventions	50
10 Machine Learning	51
References	52

Welcome

This is the website for “Population Science”. This is a course designed and delivered by Dr. Francisco Rowe, Dr. Carmen Cabrera-Arnau and Dr. Elisabetta Pietrostefani from the Geographic Data Science Lab at the University of Liverpool, United Kingdom. You will learn applied tools and cutting-edge analytical approaches to use digital footprint data to explore and understand human population trends and patterns, including supervised and unsupervised machine learning approaches, network analysis and causal inference methods.

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 a [download](#) of a .zip file that contains all the materials.
- As an [html website](#).
- As a [pdf document](#)
- As a [GitHub repository](#).

Contact

Francisco Rowe - f.rowe-gonzalez [at] liverpool.ac.uk Senior Lecturer in Quantitative Human Geography Office 507, Roxby Building, University of Liverpool, Liverpool, L69 7ZT, United Kingdom.

Carmen Cabrera-Arnau - c.cabrera-arnau [at] liverpool.ac.uk Lecturer in Geographic Data Science Office 1/016, Roxby Building, University of Liverpool, Liverpool, L69 7ZT, United Kingdom.

Elisabetta Pietrostefani - e.pietrostefani [at] liverpool.ac.uk Lecturer in Geographic Data Science Office 6xx, Roxby Building, University of Liverpool, Liverpool, L69 7ZT, United Kingdom.

1 Overview

The module provides students with an introduction to the use of data science and digital footprint data to analyse human population dynamics. Established approaches to study population dynamics rely on traditional data sources, such as censuses and surveys. Digital footprint data have emerged as a novel source of information providing an opportunity to understand key societal population issues at an unprecedented temporal and spatial granularity at scale (Rowe 2021b). Yet, these data represent major methodological challenges to traditional demographic approaches (Rowe 2021b). Machine learning, artificial intelligence and data science approaches are needed to overcome these methodological challenges.

1.1 Aims

This module aims to:

- provide an introduction to fundamental theories of population science;
- introduce students to novel data and approaches to understanding population dynamics and societal change; and,
- equip students with skills and experience to conduct population science using computational, data science approaches.

1.2 Learning Outcomes

By the end of the module, students should be able to:

- gain an appreciation of relevant demographic theory to help interpret patterns of population change;
- develop an understanding of the types of demographic and social science methods that are essential for interpreting and analysing digital footprint data in the context of population dynamics;
- develop the ability to apply different methods to understand population dynamics and societal change;

- gain an appreciation of how population science approaches can produce relevant evidence to inform policy debates;
- develop critical awareness of modern demographic analysis and ethical considerations in the use of digital footprint data.

1.3 Feedback

Formal assessment of two computational essays. Written assignment-specific feedback will be provided within three working weeks of the submission deadline. Comments will offer an understanding of the mark awarded and identify areas which can be considered for improvement in future assignments.

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.

Online forum. Asynchronous written feedback will be provided via an online forum. 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.

1.4 Computational Environment

To reproduce the code in the book, you need the following software packages:

- R-4.2.2
- RStudio 2022.12.0-353
- Quarto 1.2.280
- the list of libraries in the next section

To check your version of:

- R and libraries run `sessionInfo()`
- RStudio click `help` on the menu bar and then `About`
- Quarto check the `version` file in the quarto folder on your computer.

To install and update:

- R, download the appropriate version from [The Comprehensive R Archive Network \(CRAN\)](#)
- RStudio, download the appropriate version from [Posit](#)

- Quarto, download the appropriate version from [the Quarto website](#)

1.4.1 List of libraries

The list of libraries used in this book is provided below:

- `tidyverse`
- `viridis`
- `viridisLite`
- `ggthemes`
- `patchwork`
- `showtext`
- `RColorBrewer`
- `lubridate`
- `tmap`
- `sjPlot`
- `sf`
- `sp`
- `kableExtra`

You need to ensure you have installed the list of libraries used in this book, running the following code:

```
list.of.packages.cran <- c( "tidyverse", "viridis", "viridisLite", "ggthemes", "patch-
work", "showtext", "RColorBrewer", "lubridate", "tmap", "sjPlot", "sf", "sp",
"kableExtra")

new.packages.cran <- list.of.packages.cran[!(list.of.packages.cran %in% in-
stalled.packages()[,"Package"])] if(length(new.packages.cran)) install.packages(new.packages.cran)

for(i in 1:length(list.of.packages.cran)) { library(list.of.packages.cran[i], charac-
ter.only = T) }
```

1.5 Assessment

The final module mark is composed of the *two computational essays*. Together they are designed to cover the materials introduced in the entirety of content covered during the semester. A computational essay is an essay whose narrative is supported by code and computational results that are included in the essay itself. Each teaching week, you will be required to address a set of questions relating to the module content covered in that week, and to use the material that you will produce for this purpose to build your computational essay.

Assignment 1 (50%) refers to the set of questions at the end of Chapter 2, Chapter 3, Chapter 4 and Chapter 5. You are required to use your responses to build your computational essay. Each chapter provides more specific guidance of the tasks and discussion that you are required to consider in your assignment.

Assignment 2 (50%) refers to the set of questions at the end of Chapter 6, Chapter 7, Chapter 8, Chapter 9 and Chapter 10. You are required to use your responses to build your computational essay. Each chapter provides more specific guidance of the tasks and discussion that you are required to consider in your assignment.

1.5.1 Format Requirements

Both assignments will have the same requirements:

- Maximum word count: 2,000 words, excluding figures and references.
- Up to three maps, plot or figures (a figure may include more than one map and/or plot and will only count as one but needs to be integrated in the figure)
- Up to two tables.

Assignments need to be prepared in “*Quarto Document*” format (i.e. qmd extension) and then converted into a self-contained HTML file that will then be submitted via Turnitin. The document should only display content that will be assessed. Intermediate steps do not need to be displayed. Messages resulting from loading packages, attaching data frames, or similar messages do not need to be included as output code. Useful resources to customise your R notebook can be found on [Quarto’s website](#).

Two Quarto Document templates will be available via [the module Canvas site](#).

Submission is electronic only via Turnitin on Canvas.

1.5.1.1 Marking criteria

The Standard Environmental Sciences School marking criteria apply, with a stronger emphasis on evidencing the use of regression models, critical analysis of results and presentation standards. In addition to these general criteria, the code and outputs (i.e. tables, maps and plots) contained within the notebook submitted for assessment will be assessed according to the extent of documentation and evidence of expertise in changing and extending the code options illustrated in each chapter. Specifically, the following criteria will be applied:

- 0-15: no documentation and use of default options.
- 16-39: little documentation and use of default options.
- 40-49: some documentation, and use of default options.
- 50-59: extensive documentation, and edit of some of the options provided in the notebook (e.g. change north arrow location).

- 60-69: extensive well organised and easy to read documentation, and evidence of understanding of options provided in the code (e.g. tweaking existing options).
- 70-79: all above, plus clear evidence of code design skills (e.g. customising graphics, combining plots (or tables) into a single output, adding clear axis labels and variable names on graphic outputs, etc.).
- 80-100: all as above, plus code containing novel contributions that extend/improve the functionality the code was provided with (e.g. comparative model assessments, novel methods to perform the task, etc.).

2 Data Revolution

2.1 Introduction

The digital revolution ushered in the 1990s has unleashed a data revolution. Technological advances in computational power, storage and digital network platforms have enabled the emergence of “Big Data” or “digital footprint data”. These technological developments have enabled the production, processing, analysis and storage of large volumes of digital data. Analysing 1986-2007 data, Hilbert and López (2011) estimated that the world has already passed the point at which more data were being collected than could be physically stored. They estimated that the global general-purpose computing capacity grew at an annual rate of 58 percent between 1986 and 2007, exceeding that of global storage capacity (23 percent). We can now digitally capture and generate data that previously could not easily be recorded and stored.

The unprecedented amount of information that we can now capture through digital technology offers unique opportunities to advance our understanding of *micro* human behaviour and *macro* population processes. Digital footprint data offer a continuous flow of information to capture human population dynamics at unprecedently fine spatial and temporal resolution in real or near real-time comprising entire social systems. We can capture and study micro individual behaviours such as what people watch on Netflix, buy from Amazon, news they like on Twitter, and places they visit. These behaviours can also be aggregated to shed light into macro structural processes and trends, such as urban mobility, consumer demand, transport usage, population ageing and decline. Fundamentally digital footprint data thus have the potential to become a key pillar informing and supporting decision making. They can inform business to increase sales revenue, football clubs to improve team performance and governments to tackle major societal issues, such as the COVID-19 pandemic and global warming, influencing policy, practice and governance structures.

However, the use of digital footprint data also poses major conceptual, methodological and ethical challenges (Rowe 2021b). It is these challenges that motivated this module. Digital footprint data are a by-product of an administrative process or service, and it is not purposely collected for research. Turning raw digital footprint data into actionable, usable information thus requires a unique combination of technical computational expertise and subject-specific knowledge. Traditionally university programmes have tended to focus on providing technical training, such as statistics or on specific knowledge subjects, such as demography. But they are rarely found as a single coherent package. This module aims to fills this gap by offering training

in the access and use of digital footprint data, and sophisticated methodological approaches (including machine learning, artificial intelligence, network science and statistical methods) to tackle important population issues, such as population segmenting, decline and mobility.

The module is labelled “population science” to reflect wide and inclusive perspective. The data revolution has led to the emergence of a range of sub-disciplines, seeking to leverage on the use of digital footprint data to study human behaviour and population processes. These emerging sub-disciplines have tended to focus on discipline-specific issues such as digital demography, or particular methodological approaches, computational social sciences (Lazer et al. 2009) and social physics. Population science seeks to integrate these perspectives and provide a fertile framework for critique, collaboration and co-creation across these emerging areas of scholarship in the study of human population.

Specifically, this chapter aims to discuss key opportunities and challenges of digital footprint data to analyse human population dynamics. We place a particular focus on the challenges relating to privacy, bias and privacy issues. The chapter starts by defining digital footprint data before discussing the key opportunities offered by these data and the challenges they pose.

2.2 Defining digital footprint data

We define digital footprint data as:

the data recorded by digital technology resulting from the interactions of people among themselves or with their social and physical environment.

Data footprint data are distinctive features in their volume, velocity, variety, exhaustiveness, resolution, relational nature and flexibility (). They can take different forms. Traditional data used to be mostly numeric. Digital footprint data has facilitated the collection, storage and analysis of text (e.g. Twitter posts), image (e.g. Instagram photos) and video (e.g. CCTV footage) data.

Multiple digital systems contribute to the storage and generation of digital footprint data. identified three broad systems directed, automated and volunteered systems. Directed systems comprise digital administrative systems operated by a human recording data on places or people e.g. immigration control, biometric scanning and health records. Automated systems involve digital systems which automatically and autonomously record and process data with little human intervention e.g. mobile phone applications, electronic smartcard ticketing, energy smart meter and traffic sensors. Volunteered systems involve digital spaces in which humans contribute data through interactions on social media platforms (e.g. Twitter and Facebook) or crowdsourcing (e.g. OpenStreetMap and Wikipedia).

2.3 Opportunities of digital footprint data

Digital footprint data offer unique opportunities for the analysis of human population patterns. As Rowe (2021b) argues, digital footprint data offer three key promises in relation to traditional data sources, such as surveys and censuses. They generally provide greater spatio-temporal granularity, wider coverage and timeliness.

Digital footprint data offer high geographic and temporal *granularity*. Most digital footprint data are time-stamped and geographically referenced with high precision. Digital technology, such as mobile phone and geographical positioning systems enables the generation of a continuous streams of time-stamped location data. Such information thus provides an opportunity to trace and enhance our understanding human populations over highly granular spatial scales and time intervals, going beyond the static representation afforded by most traditional data sources. Spatial human interactions, and how people use and are influenced by their environment, can be analysed in a temporally dynamic way.

Digital footprint data provide extensive *coverage*. Contrasting to traditional random sampling, digital footprint data promise information on universal or near-universal population or geographical systems. Social media platforms, such as Twitter generate data to capture the entire universe of Twitter users. Satellite technology produces imagery snapshots to composite a representation of the Earth. Electronic smartcard ticketing systems produce information to capture the population of users in the system. Because the information is typically consistently collected and storage, the coverage of digital footprint data offer the potential to study human behaviour of entire systems at a global scale based on harmonised definitions, which is rarely possible using traditional data sources.

Digital footprint data is generated in *real-time*. Unlike traditional systems of data collection and release, digital footprint data can be streamed continuously in real- or near real-time. Commercial transactions are generally recorded on bank ledgers as bank card payments occur at retail shops. Individual mobile phone's location are captured as applications ping cellular antennas. Such information offer an opportunity to monitor and response to rapidly evolving situations, such as the COVID-19 pandemic (Green, Pollock, and Rowe 2021), natural disasters (Rowe 2022) and conflicts (Rowe, Neville, and González-Leonardo 2022).

We should also argue loudly and clearly that while digital footprint data should be seen as a key asset to support government and business decision making processes, they should not be considered at the expenses of traditional data sources. Digital footprint data and traditional data sources should be used to complement each other. As indicated earlier, digital footprint data are the by-product of administrative processes or services. They were not designed with the aim of doing research. They require considerable work of data re-engineering to re-purpose them and turn them into an analysis-ready data product that can be used for further analysis (Arribas-Bel et al. 2021). Yet, as we will discuss below significant challenges remain. As the saying goes “*all data are dirty, but some data are useful*”. This quote used in the data science community to convey the idea that data are often imperfect, but they can still be used to

gain valuable insights. Our message is that digital footprint data and traditional data sources should be triangulated to leverage on their strengths and mitigate their weaknesses.

2.4 Challenges of digital footprint data

Digital footprint data also impose key conceptual, methodological and ethical challenges. In this section, we provide a brief explanation of these challenge areas, focusing particularly on issues around biases, privacy, ethics and new methods. We focus on these issues because they are of practical importance and probably of the most interest to the readers of this book. If you are interested in learning more about the broad areas of challenges, excellent discussions of have been written. We recommend .

2.4.1 Conceptual challenges

Conceptually, the emergence of digital footprint data has led to the rethinking and questioning of existing theoretical social science approaches . On the one hand, digital footprint data provide an opportunity to explore an existing theory or hypothesis through different lens and test the consistency of existing beliefs. For example, economists have historically discussed the existence of temporal and spatial equilibrium. Resulting hypotheses are generally tested through mathematical theoretical models or empirical analyses relying on temporally static data. The existence of equilibrium has thus remained hard to assess. digital footprint data provide an opportunity to empirically test temporal and spatial equilibrium ideas based on suitable temporally dynamic data.

On the other hand, digital footprint data sparked new questions. Digital footprint data provide data on previously unmeasured activities. Data now capture activities that were previously difficult to quantify, such as personal communications, social networks, search and information gathering, and location data. These data offer an opportunity to develop new questions expanding existing theories by looking inside the “black box” of households, organisations and markets. They may also open the door to developing entirely new questions such as the role of digital technology in shaping human behaviour, the role of artificial intelligence on productivity and financial markets.

2.4.2 Methodological challenges

Methodologically, the need for a wide and new set of digital skills and expertise to handle, store and analyse large volumes of data is a key challenge. As indicated earlier, digital footprint data are not created for research purposes. They need to be reengineered for research. Large streams of digital footprint data cannot be stored on local memory. They can rarely be read as a single unit on a local computer and may involve performing the same task numerous

times in regular basis, requiring therefore large storage, computational capacity and computer science expertise. The manipulation and storage of digital footprint data often require technical expertise in data management systems, such as SQL, Google Cloud Storage and Amazon S3, as well as in efficient computing involving expertise in distributed computing systems and parallelisation frameworks. The analysis and modelling of digital footprint data may entail competencies in the application of machine learning and artificial intelligence. While these competencies general form part of a computer science programme, they are rarely taught in an integrated framework focusing on addressing societal or business challenges relating to human populations.

An additional methodological challenge is the presence of biases in digital footprint data. Digital footprint data are representative of a specific segment of the population but little is known which segments and how their representation varies across data sets and digital technology. Digital footprint data may comprise multiple sources of biases. They may reflect differences in the use of a digital device (e.g. mobile phone) and/or a piece of digital technology (e.g. a mobile phone application). They may also reflect differences in *frequency* in the use of digital technology (e.g. number of times an individual uses a mobile phone application) - and this frequency may in turn reflect differences in algorithmic decisions embedded in digital platforms, such as suggesting content based on prior interactions to increase engagement with a given mobile phone application. Some work has been done on assessing biases as well as developing approaches to mitigate their influence .

2.4.3 Ethical challenges

Privacy represents a major ethical challenge. Digital footprint data are highly sensitive, and hence, anonymisation and disclosure control are required. Individual records must be anonymised so they are not identifiable. The high degree of granularity and personal information of these records may and have been used in ethically questionable ways; for example, Cambridge Analytica used information of Facebook users to segment the population and target politically motivated content . Anonymising information, however, imposes a key challenge as there is a trade-off between accuracy and privacy . Anonymisation may reduce the usability of data. The greater the degree of privacy, the lower is the degree of accuracy of the resulting data and *vice versa*. Identifying the optimal point balancing the privacy-accuracy trade-off is the key challenge. If doing incorrectly, we could end up drawing inferences that do not reflect the actual population processes displayed in the data, or have artificially been encoded in the data through noise or reshuffling. The application of data differential privacy to the US census provides a recent good example of this challenge. An emblematic case is [New York's Liberty Island](#) which has no resident population, but official US census reported 48 residents which was the result of adding statistical noise to the data, in order to enhance privacy.

2.5 Conclusion

Digital footprint data present unique opportunities to enhance our understanding of population processes and support individual, business and government decisions to improve targeted processes and outcomes. Businesses have used digital footprint data to segment their consumer populations and improve their targeting of marketing content, products and ultimately increase sales and revenue (Dolega, Rowe, and Branagan 2021). Governments and health care institutions, particularly during the COVID-19 have leverage digital footprint data to monitor the spread of the pandemic and develop appropriate mitigation responses (Green, Pollock, and Rowe 2021). However, the use of digital footprint data poses major conceptual, methodological and ethical challenges - which need to be overcome to unleash their full potential. The aim of this book is to address of the key methodological challenges. In particular, this book seeks to provide applied training on the practical application of commonly used machine learning and artificial intelligence approaches to leverage on digital footprint data in the understanding of human behaviour and population processes.

- Kashyap et al. (2022)
- Kashyap (2021)

3 Geodemographics

3.1 Dependencies

```
library(sf)
```

```
Linking to GEOS 3.10.2, GDAL 3.4.2, PROJ 8.2.1; sf_use_s2() is TRUE
```

```
library(stringr)
library(dplyr)
```

```
Attaching package: 'dplyr'
```

```
The following objects are masked from 'package:stats':
```

```
filter, lag
```

```
The following objects are masked from 'package:base':
```

```
intersect, setdiff, setequal, union
```

```
library(ggplot2)
library(ggcorrplot)
library(viridis)
```

```
Loading required package: viridisLite
```

```
library(plotrix)
```

```
getwd() #Obtain the working directory, where we will save the d  
[1] "/Users/franciscorowe/Dropbox/Francisco/uol/teaching/envs418/202223/r4ps"
```

3.2 Data

3.2.1 Demographic data for Greater London Authority

Data will be from LSOA atlas from GLA. For the session GDC based on some features. For assignment, GDC based on a different set of features. Need to prepare two different datasets.

3.2.2 Import the data

```
# Import LSOA demographic data for GLA  
# Data obtained from link below, but it has been cleaned by Carmen Cabrera-Arnau  
# https://data.london.gov.uk/dataset/lsoa-atlas  
df_LSOA <- read.csv("./data/geodemographics/lsoa-data-clean.csv")  
  
# Import LSOA boundaries for GLA  
# Data obtained from link below  
# https://data.london.gov.uk/dataset/statistical-gis-boundary-files-london  
st_LSOA <- st_read("./data/geodemographics/LSOA_2011_London_gen_MHW/LSOA_2011_London_gen_MH...  
  
Reading layer `LSOA_2011_London_gen_MHW' from data source  
`/Users/franciscorowe/Dropbox/Francisco/uol/teaching/envs418/202223/r4ps/data/geodemograph...  
using driver `ESRI Shapefile'  
Simple feature collection with 4835 features and 14 fields  
Geometry type: MULTIPOLYGON  
Dimension: XY  
Bounding box: xmin: 503574.2 ymin: 155850.8 xmax: 561956.7 ymax: 200933.6  
Projected CRS: OSGB36 / British National Grid
```

3.3 Geodemographic classification

3.4 Preparing the data for GDC

3.4.1 Choice of geographic units

```
plot(st_geometry(st_LSOA), border=adjustcolor("gray20", alpha.f=0.4), lwd=0.6)
```



3.4.2 Variables of interest

```
names(df_LSOA)
```



```
[1] "Lower.Super.Output.Area"
[2] "LSOA11NM"
[3] "MidYearPop"
[4] "MidYearPopAge0to15"
[5] "MidYearPopAge16to29"
[6] "MidYearPopAge30to44"
[7] "MidYearPopAge45to64"
[8] "MidYearPopAge65"
[9] "MidYearPopWorkingAge"
[10] "CensusPop"
[11] "Density2012"
[12] "HouseholdAll"
[13] "HouseholdCoupleWithDepChildren"
[14] "HouseholdCoupleNoDepChildren"
[15] "HouseholdLoneParent"
[16] "HouseholdOnePerson"
[17] "HouseholdOtherMulti"
```

```
[18] "EthnicWhite"
[19] "EthnicMixedMulti"
[20] "EthnicAsianAsianBritish"
[21] "EthnicBlackAfricanCaribbeanBlackBritish"
[22] "EthnicOther"
[23] "EthnicBAME"
[24] "CountryBirthUK"
[25] "CountryBirthNotUK"
[26] "HouseholdEnglishLanguage"
[27] "HouseholdNotEnglishLanguage"
[28] "ReligionChristian"
[29] "ReligionBuddhist"
[30] "ReligionHindu"
[31] "ReligionJewish"
[32] "ReligionMuslim"
[33] "ReligionSikh"
[34] "ReligionOther"
[35] "ReligionNone"
[36] "ReligionNotStated"
[37] "TenureOwnedOutright"
[38] "TenureOwnedMortgageLoan"
[39] "TenureSocialRent"
[40] "TenurePrivateRent"
[41] "DwellingWithUsualResidents"
[42] "DwellingWithNoUsualResidents"
[43] "DwellingDetached"
[44] "DwellingSemiDetached"
[45] "DwellingTerraced"
[46] "DwellingFlat"
[47] "HousePriceMedian"
[48] "HouseSales"
[49] "HouseholdNoAdultInEmploymentWithDependentChildren"
[50] "LoneParentNotInEmployment"
[51] "FullTimeStudent"
[52] "EmploymentRate"
[53] "UnemploymentRate"
[54] "QualificationNone"
[55] "QualificationLevel1"
[56] "QualificationLevel2"
[57] "QualificationApprenticeship"
[58] "QualificationLevel3"
[59] "QualificationLevel4OrAbove"
[60] "QualificationOther"
```

```

[61] "QualificationSchoolchildrenAndFullTimeStudentsOver18"
[62] "HealthDayToDayLimitedALot"
[63] "HealthDayToDayLimitedALittle"
[64] "HealthDayToDayNotLimited"
[65] "HealthVeryGoodOrGood"
[66] "HealthFair"
[67] "HealthBadOrVeryBad"
[68] "HouseholdNoCarOrVan"
[69] "HouseholdOneCarOrVan"
[70] "HouseholdTwoCarOrVan"
[71] "HouseholdThreeCarOrVan"
[72] "HouseholdFourOrMoreCarOrVan"
[73] "CarsPerHousehold"
[74] "PublicTransportAccessibilityAverageScore"
[75] "HouseholdMeanIncome"
[76] "HouseholdMedianIncome"

```

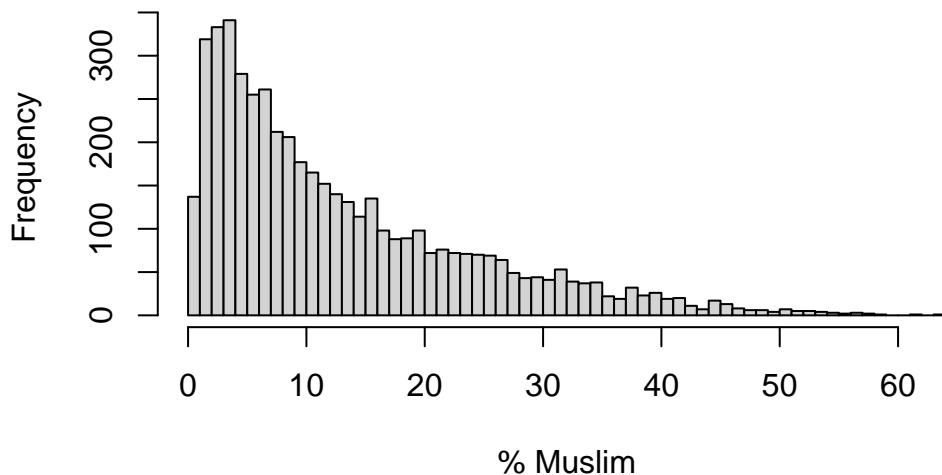
c("LSOA11NM", "EthnicWhite", "EthnicMixedMulti", "EthnicAsianAsianBritish", "EthnicBlackAfricanCaribbeanBlackBritish", "EthnicOther", "EthnicBAME", "CountryBirthUK", "CountryBirthNotUK", "HouseholdEnglishLanguage", "HouseholdNotEnglishLanguage", "ReligionChristian", "ReligionBuddhist", "ReligionHindu", "ReligionJewish", "ReligionMuslim", "ReligionSikh", "ReligionOther", "ReligionNone", "ReligionNotStated", "FullTimeStudent", "EmploymentRate", "UnemploymentRate")

```
df_LSOA <- df_LSOA[, c("LSOA11NM", "EthnicWhite", "EthnicMixedMulti", "EthnicAsianAsianBri
```

```
summary(df_LSOA$EthnicBlackAfricanCaribbeanBlackBritish)
```

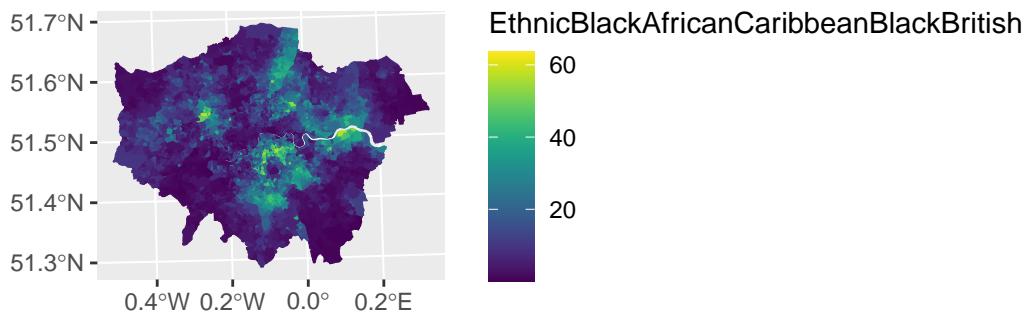
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.10	4.30	9.50	13.05	18.90	63.70

```
hist(df_LSOA$EthnicBlackAfricanCaribbeanBlackBritish, breaks=50, xlab="% Muslim", main=NUL
```



```
join_LSOA <- st_LSOA %>% left_join(df_LSOA, by='LSOA11NM')

join_LSOA %>%
ggplot(aes(fill=EthnicBlackAfricanCaribbeanBlackBritish, color = EthnicBlackAfricanCaribbe
geom_sf() +
scale_fill_viridis(direction = 1) +
scale_color_viridis(direction = 1)
```



3.5 Checking for variable association

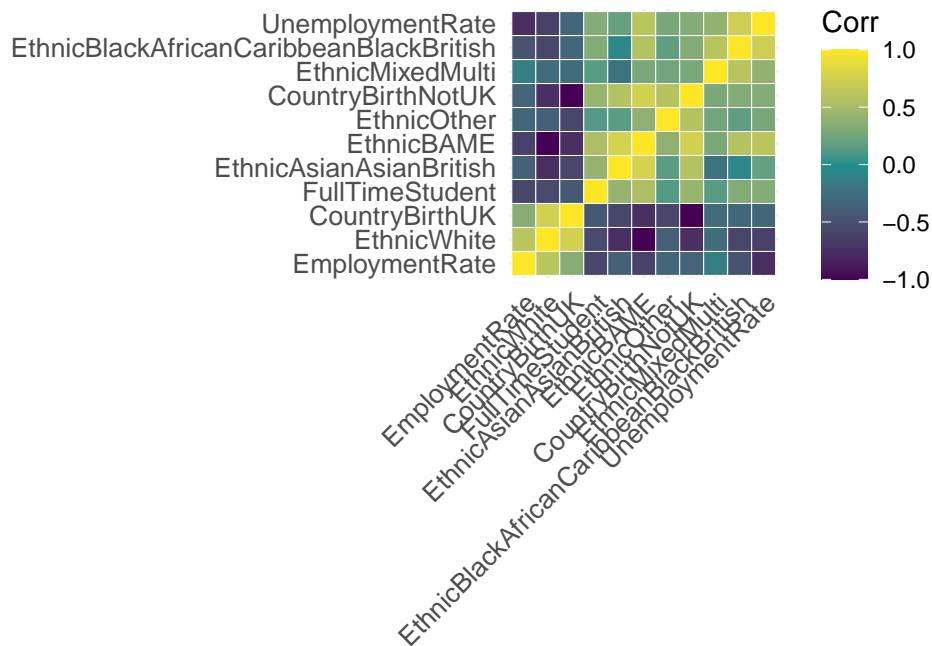
```
colnames_df_LSOA <- colnames(df_LSOA)

# Matrix of Pearson correlation coefficients
corr_mat <- cor(df_LSOA[,c(colnames_df_LSOA[2: ncol(df_LSOA)])], method = "pearson")
```

```

# Matrix of p-values
corr_pmat <- cor_pmat(df_LSOA[,c(colnames_df_LSOA[2: ncol(df_LSOA)])], method = "pearson")
# Barring the no significant coefficient
ggcorrplot(corr_mat, tl.cex=10, hc.order = TRUE, outline.color = "white", p.mat = corr_pma

```



Remove EthnicBAME, HouseholdNotEnglishLanguage, CountryBirthUK, EmploymentRate

```

# Remove EthnicBAME, CountryBirthUK

data <- df_LSOA[, c("LSOA11NM", "EthnicWhite", "EthnicMixedMulti", "EthnicAsianAsianBritish")]

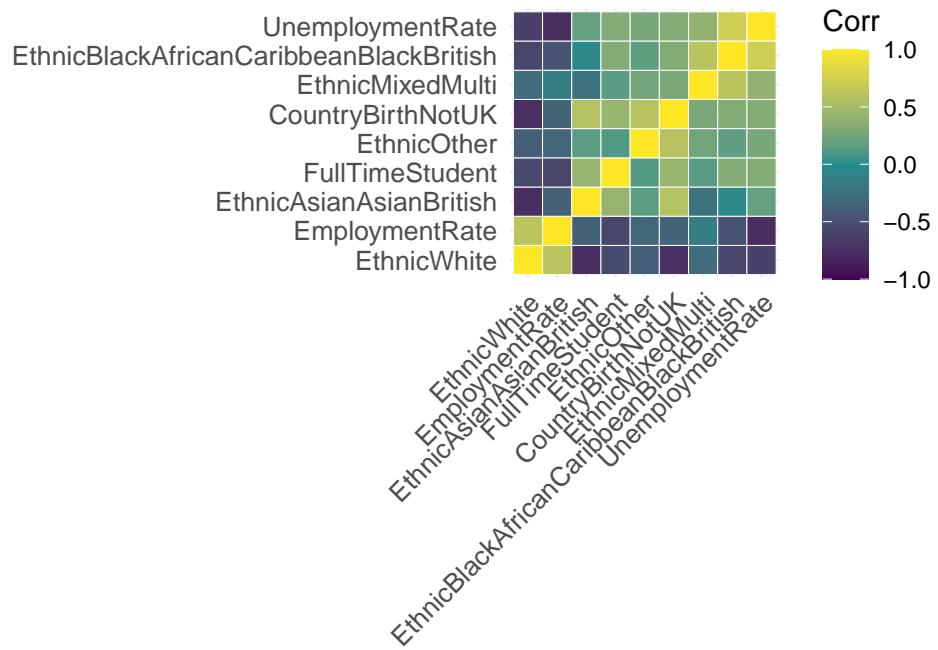
join_data <- st_LSOA %>% left_join(data, by='LSOA11NM')

colnames_data <- colnames(data)

# Matrix of Pearson correlation coefficients
corr_mat_data <- cor(data[,c(colnames_data[2: ncol(data)])], method = "pearson")
# Matrix of p-values
corr_pmat_data <- cor_pmat(data[,c(colnames_data[2: ncol(data)])], method = "pearson")

```

```
# Barring the no significant coefficient
ggcorrplot(corr_mat_data, tl.cex=10, hc.order = TRUE, outline.color = "white", p.mat = cor
```



3.6 Variable standardisation

3.6.1 Between areas

3.6.2 Between variables

```
# creates a new data frame
data_std <- data
# loops columns from position 1 : the last column
for(i in 2: ncol (data_std)){
  data_std[, colnames_data[i]] <- scale(as.numeric(data[, colnames_data[i]]))
}
```

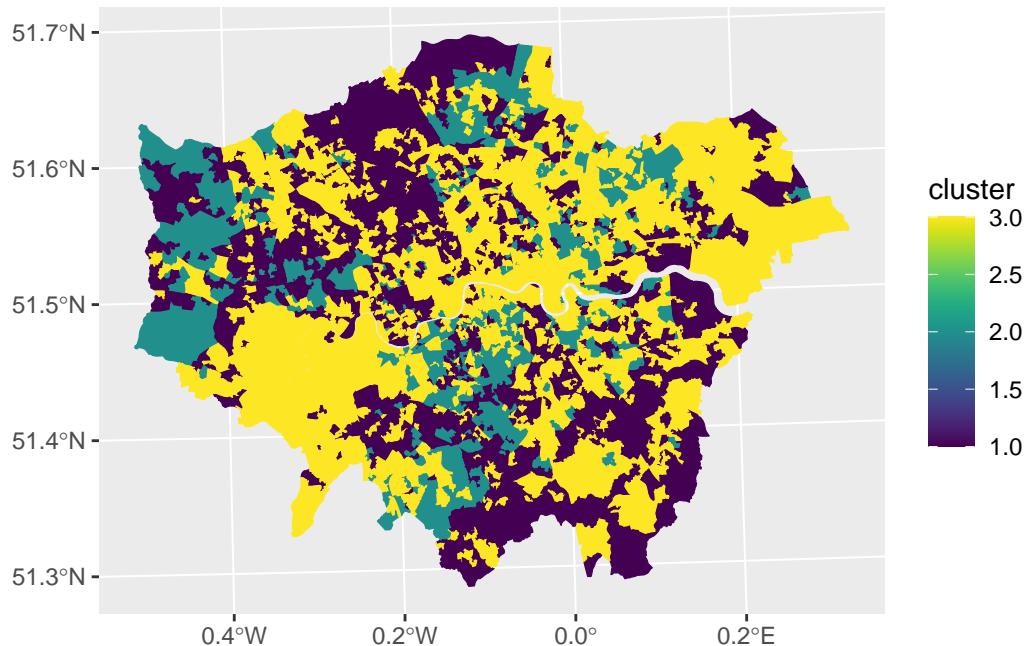
3.7 The clustering process

3.7.1 K-means

```
Km <- kmeans(data_std[,c(colnames_data[2: ncol(data_std)])], 3, nstart = 20, iter.max = 100)

join_data_cluster <- join_data
join_data_cluster$cluster <- Km$cluster

join_data_cluster %>%
  ggplot(aes(fill=cluster, color = cluster)) +
  geom_sf() +
  scale_fill_viridis(direction = 1) +
  scale_color_viridis(direction = 1)
```



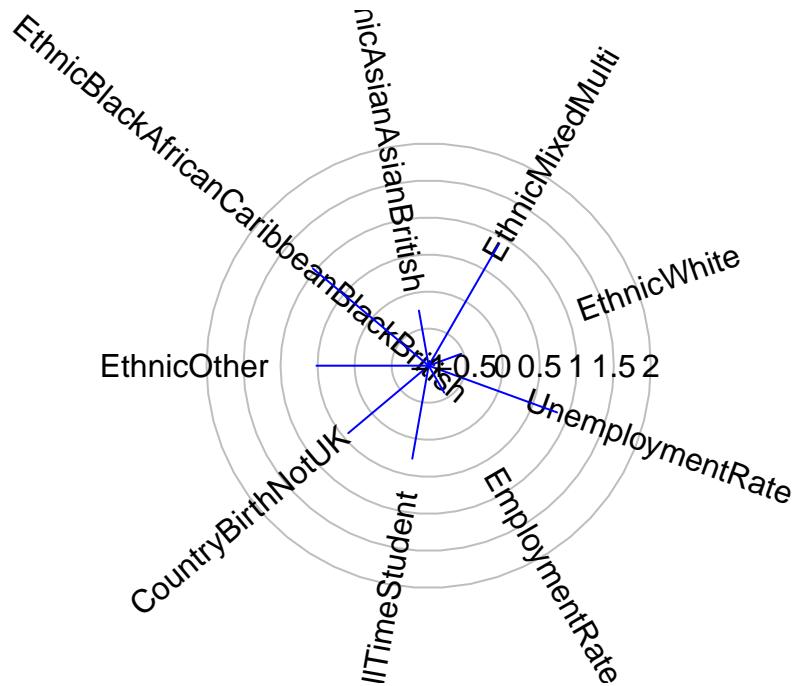
3.7.2 Number of clusters

3.7.3 Other clustering methods

3.8 Dealing with the GDC results

3.8.1 Cluster interpretation

```
# creates a radial plot for the first group [1,]
# the boxed.radial (False) prevents white boxes forming under labels
# radlab rotates the labels
KmCenters <- as.matrix(Km$centers)
KmCenters <- as.data.frame(KmCenters)
radial.plot(KmCenters[1,], labels = colnames(KmCenters),
boxed.radial = FALSE, show.radial.grid = FALSE,
line.col = "blue", radlab = TRUE )
```



3.8.2 Testing

4 Sequence Analysis

4.1 Dependencies

4.2 Data

Aim: to define trajectories of population decline or ageing

Data source: WorldPop 2000-2020

4.2.1 Data Wrangling

Exploratory data analysis to understand the data - time-space data

4.3 Application

Explain intuition and main steps

4.3.1 Defining outcome process

Define the thresholds that should be used to define the extent / pace of acceleration.

4.3.2 Optimal matching

Computation of distance - intuition > indel operators > different OM algorithms > use optimal matching

4.3.3 Clustering

Different cluster algorithms - use of k-meloids

Determining the number of clusters

4.3.4 Visualising

Individual trajectories

Frequency plots

Time spent

Top ten trajectories

4.4 Questions

Francisco to write

This chapter shows the use of sequence analysis to study population decline and draw on the following papers:

- Rowe, Neville, and González-Leonardo (2022)
- Newsham and Rowe (2022)
- Rowe, Robinson, and Patias (2022)

5 Network Analysis

5.1 Dependencies

In this session we need some basic R packages before importing the data.

```
library(magrittr)
library(dplyr)

# An R package for network manipulation and analysis
library(igraph)

getwd() #Obtain the working directory, where we will save the data folder

[1] "/Users/franciscorowe/Dropbox/Francisco/uol/teaching/envs418/202223/r4ps"
```

5.2 Data

5.2.1 The US Census dataset

Describe here the dataset used for this session. It has been cleaned beforehand by myself.

Each row corresponds to a origin-destination pair, the number of rows gives the total number of reported migratory movements.

5.2.2 Import the data

Before we start any analysis with the data, ensure to set the path to the directory where we are working. Please replace in the following line the path to the folder where you have placed the data file.

```
df <- read.csv("./data/networks/metro_to_metro_2015_2019_US_migration.csv")
```

```

#Ensure the MSA code is imported as a character and not as a number
df$MSA_Current_Code <- as.character(df$MSA_Current_Code)

#Include an additional column with the full name of the MSA in the format: Name, State
df$MSA_Previous_Name_State <- paste0(df$MSA_Previous_Name, ', ', df$MSA_Previous_State)
df$MSA_Current_Name_State <- paste0(df$MSA_Current_Name, ', ', df$MSA_Current_State)

#Examine the first few rows of the dataset
head(df)

```

	MSA_Current_Code	MSA_Current_Name	MSA_Current_State
1	10180	Abilene	TX
2	10180	Abilene	TX
3	10180	Abilene	TX
4	10180	Abilene	TX
5	10180	Abilene	TX
6	10180	Abilene	TX
	MSA_Current_Population_1_Year_and_Over_Estimate		
1		168,306	
2		168,306	
3		168,306	
4		168,306	
5		168,306	
6		168,306	
	MSA_Current_Population_1_Year_and_Over_MOE	MSA_Previous_Code	
1	300	10740	
2	300	11100	
3	300	12060	
4	300	12220	
5	300	12420	
6	300	12580	
	MSA_Previous_Name	MSA_Previous_State	
1	Albuquerque	NM	
2	Amarillo	TX	
3	Atlanta-Sandy Springs-Alpharetta	GA	
4	Auburn-Opelika	AL	
5	Austin-Round Rock-Georgetown	TX	
6	Baltimore-Columbia-Towson	MD	
	MSA_Previous_Population_1_Year_and_Over_Estimate		
1		902,213	
2		262,574	
3		5,753,503	

```

4                               153,728
5                               2,045,336
6                               2,766,530
MSA_Previous_Population_1_Year_and_Over_MOE
1                               2,916
2                               1,866
3                               9,607
4                               1,654
5                               5,648
6                               6,154
Movers_Metro_to_Metro_Flow_Estimate Movers_Metro_to_Metro_Flow_MOE
1                               41          47
2                               244         98
3                               118         95
4                               30          40
5                               289         85
6                               8           15
MSA_Previous_Name_State MSA_Current_Name_State
1             Albuquerque, NM      Abilene, TX
2             Amarillo, TX        Abilene, TX
3 Atlanta-Sandy Springs-Alpharetta, GA Abilene, TX
4             Auburn-Opelika, AL   Abilene, TX
5 Austin-Round Rock-Georgetown, TX     Abilene, TX
6 Baltimore-Columbia-Towson, MD       Abilene, TX

```

We can obtain the total number of reported migratory movements with the following command:

```
nrow(df)
```

```
[1] 52930
```

5.3 Creating networks

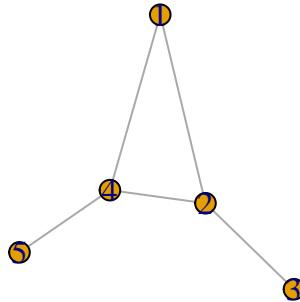
Before we start to analyse the data introduced in Section 5.2, let us first take a step back to consider the main object of study of this Chapter: the so-called networks. In the most general sense, a **network** (also known as a graph) is a structure formed by a set of objects which may have some connections between them. The objects are represented by **nodes** (a.k.a. vertices) and the connections between these objects are represented by **edges** (a.k.a. links). Networks are used as a tool to conceptualise many real-life contexts, such as the friendships between the

members of a year group at school, the direct airline connections between cities in a continent or the presence of hyperlinks between a set of websites. In this session, we will use networks to model the migratory flows between US cities.

5.3.1 Starting from the basics

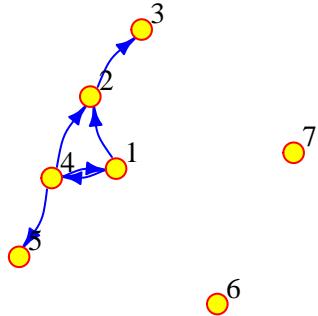
In order to create, manipulate and analyse networks in R, we will use the igraph package, which we imported in Section 5.2. We start by creating a very simple network with the code below. The network contains five nodes and five edges and it is undirected, so the edges do not have orientations. The nodes and edges could represent, respectively, a set of cities and the presence of migration flows between these cities in two consecutive years.

```
g1 <- graph( edges=c(1,2, 1,4, 2,3, 2,4, 4,5), n=5, directed=F ) # Creates an undirected network
# The number of nodes is given by argument n
# In this case, the node labels or IDs are represented by numbers 1 to 5
# The edges are specified as a list of pairs of nodes
plot(g1) # A simple plot of the network allows us to visualise it
```



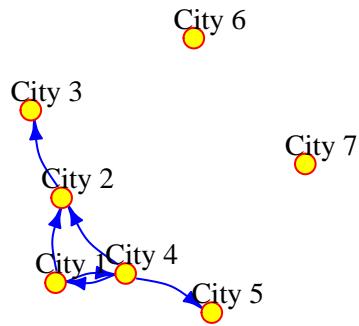
If the connections between the nodes of a network are non-reciprocal, the network is called directed. For example, this could correspond to a situation where there are people moving from city 1 to city 2, but nobody moving from city 2 to city 1. Note that in the code below we have not only added directions to the edges, but we have also added a few additional parameters to the plot function in order to customise the diagram.

```
g2 <- graph( edges=c(1,2, 1,4, 2,3, 4,1, 4,2, 4,5), n=7, directed=T ) # Creates a directed network
# note that we now have edge 1,4 and edge 4,1 and that 2 of the nodes are isolated
plot(g2, vertex.frame.color="red", vertex.label.color="black",
      vertex.label.cex=0.9, vertex.label.dist=2.3, edge.curved=0.3, edge.arrow.size=.5, edge.col
```



The network can also be defined as a list containing pairs of named nodes. Then, it is not necessary to specify the number of nodes but the isolated nodes have to be included. The following code generates a network which is equivalent to the one above.

```
g3 <- graph( c("City 1","City 2", "City 2","City 3", "City 1","City 4", "City 4","City 1",
  plot(g3, vertex.frame.color="red", vertex.label.color="black",
  vertex.label.cex=0.9, vertex.label.dist=2.3, edge.curved=0.3, edge.arrow.size=.5, edge.col
```



5.3.2 Adding attributes

In R, we can add attributes to the nodes, edges and the network. To add attributes to the nodes, we first need to access them via the following command:

```
v(g3)
```

```
+ 7/7 vertices, named, from 96ad3cf:
[1] City 1 City 2 City 3 City 4 City 5 City 6 City 7
```

The node attribute *name* is automatically generated from the node labels that we manually assigned before.

```
V(g3)$name
```

```
[1] "City 1" "City 2" "City 3" "City 4" "City 5" "City 6" "City 7"
```

But other node attributes could be added. For example, the current population of the cities represented by the nodes:

```
V(g3)$population <- c(134000, 92000, 549000, 1786000, 74000, 8000, 21000)
```

Similarly, we can access the edges:

```
E(g3)
```

```
+ 6/6 edges from 96ad3cf (vertex names):
[1] City 1->City 2 City 2->City 3 City 1->City 4 City 4->City 1 City 4->City 2
[6] City 4->City 5
```

and add edge attributes, such as the number of people moving from an origin to a destination city in two consecutive years. We call this attribute the *weight* of the edge, since if there is a lot of people going from one city to another, the connection between these cities has more importance or “weight” in the network.

```
{E(g3)$weight <- c(2000, 3000, 5000, 1000, 1000, 4000)}
```

We can examine the adjacency matrix of the network, which represents the presence of edges between different pairs of nodes. In this case, each row corresponds to an origin city and each column to a destination:

```
g3[] #The adjacency matrix of network g3
```

```
7 x 7 sparse Matrix of class "dgCMatrix"
  City 1 City 2 City 3 City 4 City 5 City 6 City 7
City 1     .    2000      .   5000      .      .      .
City 2     .      .   3000      .      .      .      .
City 3     .      .      .      .      .      .      .
City 4   1000   1000      .      .   4000      .      .
City 5     .      .      .      .      .      .      .
City 6     .      .      .      .      .      .      .
City 7     .      .      .      .      .      .      .
```

We can also look at the existing node and edge attributes.

```
vertex_attr(g3) #Node attributes of g3. Use edge_attr() to access the edge attributes

$name
[1] "City 1" "City 2" "City 3" "City 4" "City 5" "City 6" "City 7"

$population
[1] 134000 92000 549000 1786000 74000 8000 21000
```

Finally, it is possible to add network attributes

```
g3$title <- "Network of migration between cities"
```

5.4 Reading networks from data files

5.4.1 Preparing the data to create an igraph object

At the beginning of the chapter, we defined a data frame called *df* based on some imported data from the US Census about migratory movements between different US cities, or more precisely, between US Metropolitan Statistical Areas. This is a large data frame containing 52,930 rows, but how can we turn this data frame into a network similar to the ones that we generated in Section 5.3. The igraph function **graph_from_data_frame()** can do this for us. To find out more about this function, we can run the following command:

```
help("graph_from_data_frame")
```

As we can see, the input data for **graph_from_data_frame()** needs to be in a certain format which is different from our migration data frame. In particular, the function requires three arguments: 1) *d*, which is a data frame containing an edge list in the first two columns and any additional columns are considered as edge attributes; 2) *vertices*, which is either NULL or a data frame with vertex metadata (i.e. vertex attributes); and 3) *directed*, which is a boolean argument indicating whether the network is directed or not. Our next task is therefore to obtain 1) and 2) from the migration data frame called *df*.

Let us start with argument 1). Each row in *df* will correspond to an edge in the migration network since it contains information about a pair of origin and destination cities for two consecutive years. The names of the origin and destination cities are given by the columns in *df* called *MSA_Prevous_Name* and *MSA_Current_Name*. In addition, the column called *Movers_Metro_to_Metro_Flow_Estimate* gives the number of people moving between the

origin and the destination cities, so this will be the weight attribute of each edge in the migration network. Hence, we can define a data frame of edges which we will call *df_edges* that conforms with the format required by the argument 1) as follows:

```
#The pipe operator used below and denoted by %>% is a feature of the magrittr package, it
# Creates the df_edges data frame with data from df and renames the columns as "origin", "destination" and "weight"
df_edges <- data.frame(df$MSA_Previous_Name_State, df$MSA_Current_Name_State, df$Movers_Mean_Age)
  rename(origin = df.MSA_Previous_Name_State, destination = df.MSA_Current_Name_State, weight = df.Movers_Mean_Age)

#Ensure that the weight attribute is stored as a number and not as character
df_edges$weight <- as.numeric(gsub(",","",df_edges$weight))
```

For argument 2) we can define a data frame of nodes which we will call *df_nodes*, where each row will correspond to a unique node or city. To obtain all the unique cities from *df*, we can firstly obtain a data frame of unique origin cities, then a data frame of unique destinations, and finally, apply the **full_join()** function to these two data frames to obtain their union, which will be *df_nodes*. The name of the unique cities in *df_nodes* is in the column called *label*, the other columns can be seen as the nodes metadata.

```
df_unique_origins <- df %>%
  distinct(MSA_Previous_Name_State) %>%
  rename(name = MSA_Previous_Name_State)

df_unique_destinations <- df %>%
  distinct(MSA_Current_Name_State) %>%
  rename(name = MSA_Current_Name_State)

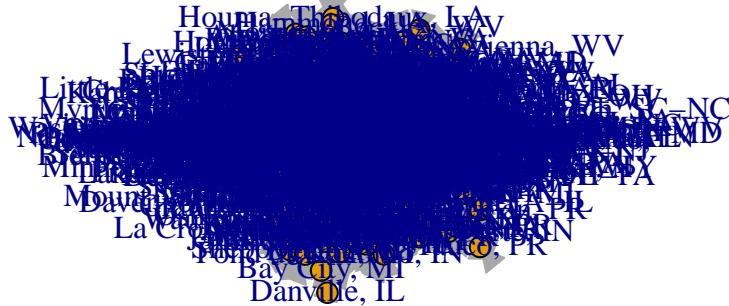
df_nodes <- full_join(df_unique_origins, df_unique_destinations, by = "name")
```

Finally, a directed migration network can be obtained with the following line of code. It should contain 386 nodes and 52,930 edges. You can test this yourself with the functions that you learnt in Section 5.3.

```
g_US <- graph_from_data_frame(d = df_edges,
  vertices = df_nodes,
  directed = TRUE)
```

If we try to plot the network *g3* containing the migratory movements between all the US cities with the **plot()** function as we did before, we obtain a result which is rather undesirable...

```
plot(g_US)
```



5.4.2 Filtering the data to create a subgraph

We will dedicate the entirety of next section to explore tools that can help us improve the visualisation of networks, since it is one of the most important aspects of network analysis. To facilitate the visualisation in the examples shown in Section 5.5, we will work with a subset of the full network called g_US . A way to create a subnetwork is to filter the original data frame. In particular, we will filter df to only include cities from a state, in this case, Minnesota. To filter, we use the `grepl()` function, which stands for grep logical. Both `grep()` and `grepl()` allow us to check whether a pattern is present in a character string or vector of a character string. While the `grep()` function returns a vector of indices of the element if a pattern exists in that vector, the `grepl()` function returns TRUE if the given pattern is present in the vector. Otherwise, it returns FALSE. In this case, we are filtering the dataset so that only the rows where the field `MSA_Current_State` is WA, which is the official abbreviation for Washington state.

```
df_sub <- df %>% filter(grepl('WA', MSA_Current_State)) %>% filter(grepl('WA', MSA_Previous_N...
```

Then, we can prepare the data as we did before to create gUS . But, instead of basing the network on df , we will generate it from df_sub .

```
df_sub_edges <- data.frame(df_sub$MSA_Previous_Name, df_sub$MSA_Current_Name, df_sub$Mover)
  rename(origin = df_sub.MSA_Previous_Name, destination = df_sub.MSA_Current_Name, weight = df_sub$Weight)

#Split long names into several lines for visualisation purposes
df_sub_edges$origin <- gsub("-", "-\n", df_sub_edges$origin)
df_sub_edges$destination <- gsub("-", "-\n", df_sub_edges$destination)

df_sub_edges$weight <- as.numeric(gsub(",","",df_sub_edges$weight))

df_sub_unique_origins <- df_sub %>%
  distinct(MSA_Previous_Name) %>%
```

```

  rename(name = MSA_Previous_Name)

df_sub_unique_destinations <- df_sub %>%
  distinct(MSA_Current_Name) %>%
  rename(name = MSA_Current_Name)

df_sub_nodes <- full_join(df_sub_unique_origins, df_sub_unique_destinations, by = "name")
df_sub_nodes$name <- gsub("-", "\n", df_sub_nodes$name)

g_sub <- graph_from_data_frame(d = df_sub_edges,
                                vertices = df_sub_nodes,
                                directed = TRUE)

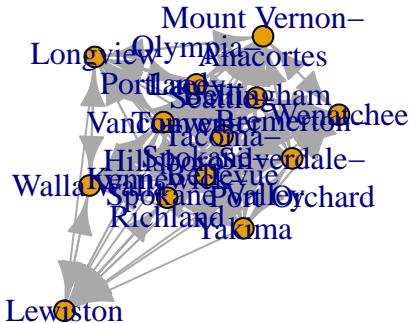
```

5.5 Network visualisation

5.5.1 Visualisation with igraph

Let us start by generating the most basic visualisation of g_{sub} .

```
plot(g_sub)
```

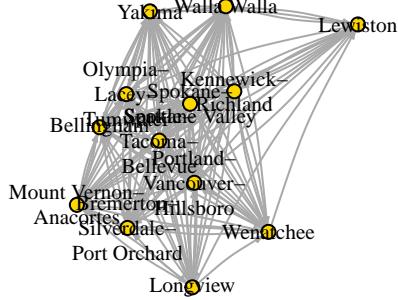


This plot can be improved by changing adding a few additional arguments to the `plot()` function. For example, by just changing the color and size of the labels, the color and size of the nodes and the arrow size of the edges, we can already see some improvements.

```

plot(g_sub, vertex.size=10, edge.arrow.size=.2, edge.curved=0.1,
      vertex.color="gold", vertex.frame.color="black",
      vertex.label=V(g_sub)$name, vertex.label.color="black",
      vertex.label.cex=.65)

```



But there are few more things we can do not only to improve the look of the diagram, but also to include more information about the network. For example, we can set the size of the nodes so that it reflects the total number of people that the corresponding cities receive. We can do this by adding a new node attribute, *inflow*, which is obtained as the sum of the rows of the adjacency matrix of g_{sub} .

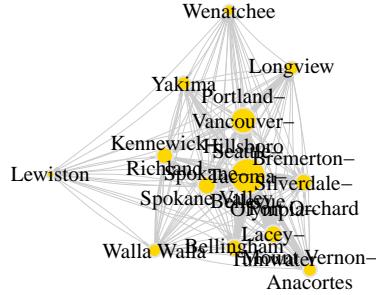
```
V(g_sub)$inflow <- rowSums(as.matrix(g_sub[]))
```

Below we set the node size based on the inflow attribute. Note the formula $0.4 * (V(gsub)$inflow)^{0.4}$, where the power of 0.4 is chosen to scale the size of the nodes in such a way that the largest ones do not get excessively large and the smallest ones do not get excessively small. We also set the edge width based on its weight, which is the total number of people migrating from the origin and destination cities that it connects.

```
# Set node size based on inflow of migrants:  
V(g_sub)$size <- 0.4*(V(g_sub)$inflow)^0.4  
# Set edge width based on weight:  
E(g_sub)$width <- E(g_sub)$weight/1200
```

Run the code below to discover how the aspect of the network has significantly improved with the modifications that we have introduced above.

```
plot(g_sub, vertex.size=V(g_sub)$size, edge.arrow.size=.15, edge.arrow.width=.2, edge.curv  
vertex.color="gold", vertex.frame.color="gray90",  
vertex.label=V(g_sub)$name, vertex.label.color="black",  
vertex.label.cex=.65)
```



5.5.2 Visualisation of spatial networks

Firstly, we will import geographical data for the metropolitan and micropolitan statistical areas in the whole of the US, using the `sf` package. Here, we are only interested in the metropolitan areas so we will filter the data frame `cbsa_us` to keep only the metropolitan areas, i.e. those entries with value M1 for the column named `LSAD`.

```
library(sf)
```

```
Linking to GEOS 3.10.2, GDAL 3.4.2, PROJ 8.2.1; sf_use_s2() is TRUE
```

```
library(stringr)
```

```
#Import core-based statistical areas https://www.census.gov/geographies/mapping-files/time
cbsa_us <- st_read("./data/networks/cb_2020_us_cbsa_500k/cb_2020_us_cbsa_500k.shp")
```

```
Reading layer `cb_2020_us_cbsa_500k' from data source
`/Users/franciscorowe/Dropbox/Francisco/uol/teaching/envs418/202223/r4ps/data/networks/cb_2
using driver `ESRI Shapefile'
Simple feature collection with 939 features and 9 fields
Geometry type: MULTIPOLYGON
Dimension:      XY
Bounding box:  xmin: -178.3347 ymin: 17.88328 xmax: -65.56427 ymax: 65.45352
Geodetic CRS:  NAD83
```

```
msa_us <- cbsa_us %>% filter(grepl('M1', LSAD)) #Filter the original data frame to obtain
```

We will now find the centroid of each MSA polygon and add columns to `msa_us` for the longitude and latitude of each centroid.

```
#Add longitude and latitude corresponding to centroid of each MSA polygon
msa_us$lon_centroid <- st_coordinates(st_centroid(msa_us$geometry))[, "X"]
msa_us$lat_centroid <- st_coordinates(st_centroid(msa_us$geometry))[, "Y"]
```

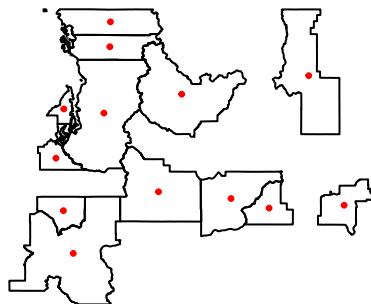
Since we are focusing on Washington state, let us filter *msa_us* so that it only includes data from Washington. This requires some data manipulation via the library stringr:

```
msa_us$NAME_ONLY <- gsub(",.*$", "", msa_us$NAME) #Create a new column with the name of the MSA
#Long names of MSAs are split into lines for visualisation purposes
msa_us$NAME_ONLY <- gsub("-", "-\n", msa_us$NAME_ONLY)
msa_us$STATE <- substr(msa_us$NAME, nchar(msa_us$NAME)-1, nchar(msa_us$NAME)) #Create a new column with the state name

msa_sub <- msa_us %>% filter(grepl('WA', STATE)) #Filter to keep the metro areas belonging to Washington
```

We can now plot the polygons for the MSA belonging to Washington state as well as the centroids:

```
plot(st_geometry(msa_sub))
plot(st_centroid(msa_sub$geometry), add=TRUE, col="red", cex=0.5, pch=20)
```



However, we still need to link this data to the network data that we obtained before. In order to incorporate the geographic information to the nodes of the migration subnetwork, we can join data from two data frames: *msa_sub*, which contains the geographic data, and *df_sub_nodes*, which contains the names of the nodes. To do this, we can use the function **left_join()** and then, select only the columns of interest. For more information on this magical function, check [this link](#).

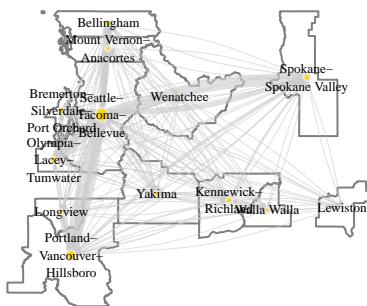
```
#Join the data frame of nodes df_sub_nodes with the geographic information of the centroid
df_sub_spatial_nodes <- df_sub_nodes %>% left_join(msa_sub, by = c("name" = "NAME_ONLY"))
```

```

lo <- as.matrix(df_sub_spatial_nodes[,2:3])

plot(st_geometry(msa_sub), border=adjustcolor("gray50"))
plot(g_sub, layout=lo, add = TRUE, rescale = FALSE, vertex.size=V(g_sub)$size, edge.arrow.
vertex.label=V(g_sub)$name, vertex.label.color="black",
vertex.label.cex=.45)

```



5.5.3 Alternative visualisations

In this session we have based our visualisations on igraph, however, there exist a variety of packages that would also allow us to generate nice plots of networks.

For example, COMPLETE

In addition, migration networks are particularly well-suited to be represented as a chord diagram. If you want to explore this type of visualisation, you can find further information on the [official R documentation](#) and also, for example, on this other link [link](#).

5.6 Network metrics

Here we define some of the most important metrics that help us quantify different characteristics of a network. We will use the migration network for the whole of the US again, g_US . It has more nodes and edges than g_sub and consequently, its behaviour is richer and helps us illustrate better the concepts that we introduce in this section.

5.6.1 Density

The network **density** is defined as the proportion of existing edges out of all the possible edges. In a network with n nodes, the total number of possible edges is $\frac{1}{2}n(n-1)$, i.e. the number of edges if each node was connected to all the other nodes. A density equal to 1 corresponds

to a situation where $n \times (n - 1)$ edges are present. A network with no edges at all would have density equal to 0. The line of code below tells us that the density of g_{sub} is approximately 0.33, meaning that about 33% of all the possible edges are present, or in other words, that there are migratory movements between almost a third of every pair of cities.

```
edge_density(g_US, loops=FALSE)
```

```
[1] 0.3283458
```

5.6.2 Reciprocity

The **reciprocity** in a directed network is the proportion of reciprocated connections between nodes (i.e. number of pairs of nodes with edges in both directions) from all the existing edges.

```
reciprocity(g_US)
```

```
[1] 0.6067259
```

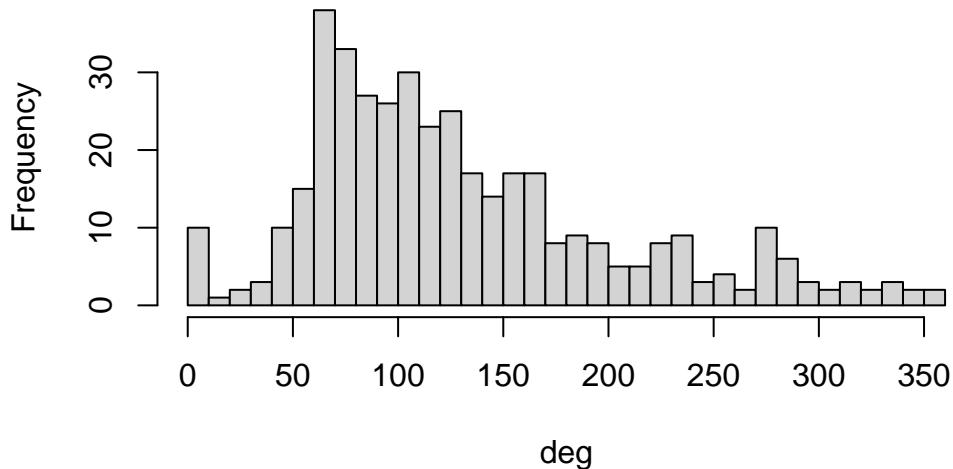
From this result, we conclude that about 62% of the pairs of nodes that are connected have edges in both directions.

5.6.3 Degree

The **total degree** of a node refers to the number of edges that emerge from or point at that node. The **in-degree** of a node in a directed network is the number of edges that point at it whereas the **out-degree** is the number of edges that emerge from it. The **degree()** functions, allows us to compute the degree of one or more nodes and allows us to specify if we are interested in the total degree, the in-degree or the out-degree.

```
# Compute degree of the nodes given by v belonging to graph g_US, in this case the in-degr  
deg <- degree(g_US, v=V(g_US), mode="in")  
  
#Produces histogram of the frequency of nodes with a certain in-degree  
hist(deg, breaks = 30, main="Histogram of node in-degree")
```

Histogram of node in-degree



As we can see in the histogram, many cities receive immigrants from 60-70 different cities. Very few cities receive immigrants from 300 or above cities. We can check which is the city with the maximum in-degree.

```
V(g_US)$name[degree(g_US, mode="in")==max(degree(g_US, mode="in"))]
```

```
[1] "Phoenix-Mesa-Chandler, AZ"  
[2] "Washington-Arlington-Alexandria, DC-VA-MD-WV"
```

We actually obtain a tie between two: the MSA containing Phoenix in Arizona and the MSA containing Washington DC, which actually spans over four states. Their in-degree is 354 as we can see below.

```
degree(g_US, v=c("Phoenix-Mesa-Chandler, AZ"), mode="in")
```

```
Phoenix-Mesa-Chandler, AZ  
354
```

```
degree(g_US, v=c("Washington-Arlington-Alexandria, DC-VA-MD-WV"), mode="in")
```

```
Washington-Arlington-Alexandria, DC-VA-MD-WV  
354
```

Note that the fact that these two cities have the largest in-degree does not necessarily mean that they are the ones receiving the largest number of migrants.

5.6.4 Distances

Shortest path between nodes, mean distance, diameter ,etc.

```
diameter(g_US)
```

```
[1] 36
```

5.6.5 Centrality

```
centr_degree(g_US, mode="in", normalized=T)
```

```
$res
[1] 198 108 330 108 283 275 127 182 116 175 104 66 251 285 187 104 344 198
[19] 259 123 258 231 141 197 345 331 280 174 66 113 237 159 110 78 148 96
[37] 230 63 304 261 220 132 44 73 55 76 300 169 166 95 115 333 115 121
[55] 125 205 297 79 123 66 144 78 291 330 148 67 176 243 237 150 209 240
[73] 311 354 105 96 282 230 277 134 228 101 279 304 276 222 110 204 316 73
[91] 113 110 149 336 73 122 245 81 101 128 45 128 354 78 164 138 157 0
[109] 0 0 0 0 0 172 33 163 276 148 132 271 167 104 103 105 26
[127] 247 128 36 232 286 53 112 200 160 25 113 261 47 20 0 75 70 170
[145] 61 194 202 74 81 113 170 164 72 105 221 65 92 255 92 271 216 192
[163] 55 180 196 181 97 178 170 122 157 117 83 151 232 122 288 228 133 163
[181] 187 70 227 186 71 68 282 64 127 185 222 240 144 54 276 156 274 157
[199] 207 235 219 127 69 88 128 158 103 156 74 116 190 102 100 163 90 237
[217] 104 319 93 67 68 77 179 146 0 0 76 136 68 56 131 166 115 69
[235] 164 88 106 93 217 99 71 140 200 70 82 81 103 94 146 168 155 109
[253] 94 95 62 113 98 103 152 123 62 98 87 165 187 76 66 117 69 93
[271] 85 108 92 90 123 116 88 116 133 213 50 69 110 151 61 99 129 67
[289] 72 74 65 151 161 63 83 154 93 129 117 107 132 115 145 150 155 125
[307] 134 130 178 42 62 139 130 151 185 161 54 86 99 100 52 70 74 108
[325] 75 119 140 128 115 121 134 139 43 52 78 47 68 69 90 87 143 80
[343] 66 83 50 140 159 67 80 106 114 85 117 107 80 123 95 87 93 72
[361] 86 81 81 89 63 83 93 54 66 124 55 134 60 119 75 77 81 107
[379] 77 56 78 113 51 37 74 102 80 145 101 62 87 83 100 64 59 68
[397] 99 67 41 76 51 46
```

```
$centralization  
[1] 0.5544472
```

```
$theoretical_max  
[1] 161202
```

5.7 Communities

5.8 Final visualisation

```
# V(g_US)$inflow <- rowSums(as.matrix(g_US[]))  
# # Set node size based on inflow of migrants:  
# V(g_US)$size <- 0.03*(V(g_US)$inflow)^0.1  
# # Set edge width based on weight:  
# E(g_US)$width <- E(g_US)$weight/1200  
#  
# #Join the data frame of nodes df_sub_nodes with the geographic information of the centros  
# df_spatial_nodes <- df_nodes %>% left_join(msa_us, by = c("name" = "NAME")) %>% select(c  
#  
# lo <- as.matrix(df_spatial_nodes[,2:3])  
#  
# plot(st_geometry(msa_us), border=adjustcolor("gray50"))  
# plot(g_US, layout=lo, add = TRUE, rescale = FALSE, vertex.size=V(g_US)$size, edge.arrow.  
# vertex.label="", vertex.label.color="black",  
# vertex.label.cex=.0)
```

6 Sentiment Analysis

Francisco to write

Chapter 6

This chapter will draw on:

- Rowe (2021a)
- Rowe et al. (2021)

6.1 Dependencies

6.2 Data

7 Topic Modelling

Elisabetta to write

Chapter 7

8 Modelling Time

Elisabetta to write

Tao et al. (2018)

9 Assessing Interventions

Elisabetta to write

10 Machine Learning

Carmen to write

Chapter [10](#)

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