

brolgar: An R package to BRowse Over Longitudinal Data Graphically and Analytically in R

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Abstract Longitudinal (panel) data provide the opportunity to examine temporal patterns of individuals, because measurements are collected on the same person at different, and often irregular, time points. The data is typically visualised using a “spaghetti plot”, where a line plot is drawn for each individual. When overlaid in one plot, it can have the appearance of a bowl of spaghetti. With even a small number of subjects, these plots are too overloaded to be read easily. The interesting aspects of individual differences are lost in the noise. Longitudinal data is often modelled with a hierarchical linear model to capture the overall trends, and variation among individuals, while accounting for various levels of dependence. However, these models can be difficult to fit, and can miss unusual individual patterns. Better visual tools can help to diagnose longitudinal models, and better capture the individual experiences. This paper introduces the R package, **brolgar** (BRowse over Longitudinal data Graphically and Analytically in R), which provides tools to identify and summarise interesting individual patterns in longitudinal data.

1 Introduction

This paper is about exploring longitudinal data effectively. By “longitudinal data” we specifically mean individuals repeatedly measured through time. This could include panel data, where possibly different samples from a key variable (e.g. country), are aggregated at each time collection. The important component is a key variable with repeated measurements regularly, or irregularly over time. The inherent structure allows us to examine temporal patterns of individuals, shown in Figure 1, of the average height of Australian males over years. The individual component is country, and the time component is year. The variable country along with other variables is measured repeatedly from 1900 to 1970, with irregular intervals between years.

The full dataset of Figure 1 is shown in Figure 2, showing 144 countries from the year 1700. This plot is challenging to understand because there is overplotting, making it hard to see the individuals. Solutions to this are not always obvious. Showing separate individual plots of each country does not help, as 144 plots is too many to comprehend. Making the lines transparent or fitting a simple model to all the data Figure 2B, might be a common first step to see common trends. However, all this seems to clarify is: 1) There is a set of some countries that are similar, and they are distributed around the center of the countries, and 2) there is a general upward trend in heights over time. We learn about the collective, but lose sight of the individuals.

This paper demonstrates how to effectively and efficiently explore longitudinal data, using the R package, **brolgar**. We examine four problems in exploring longitudinal data:

1. How to sample the data
2. Finding interesting individuals
3. Finding representative individuals

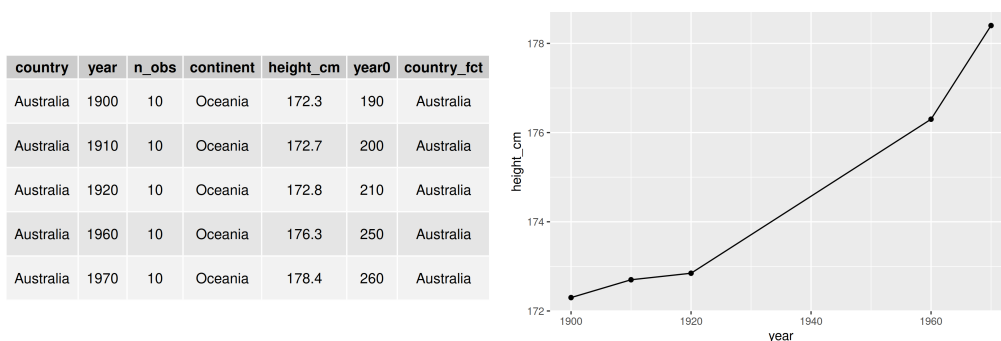


Figure 1: Example of longitudinal data: average height of men in Australia for 1900-1970. The height increase over time, and are measured at irregular intervals.

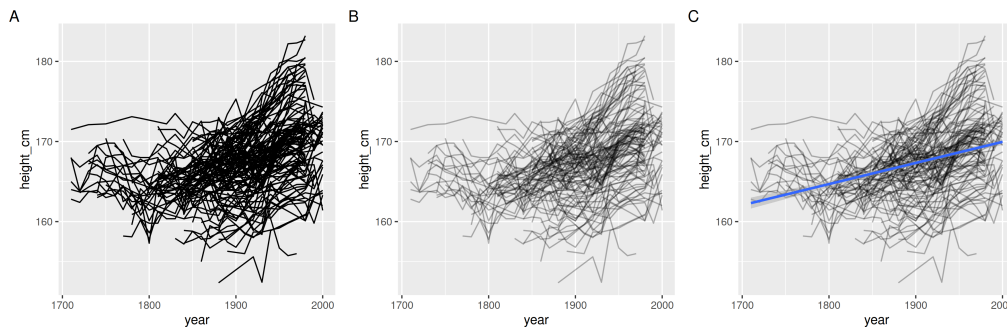


Figure 2: The full dataset shown as a spaghetti plot (A), with transparency (B), and with a linear model overlaid (C). It is still hard to see the individuals.

4. Understanding a model

This paper proceeds in the following way: first, a brief review of existing approaches to longitudinal data, then the definition of longitudinal data, then approaches to these four problems are discussed, followed by a summary.

2 Background

R provides basic time series, `ts`, objects, which are vectors or matrices that represent data sampled at equally spaced points in time. These have been extended through packages such as `xts`, and `zoo` (Ryan and Ulrich 2020; Zeileis and Grothendieck 2005), which only consider data in a wide format with a regular implied time series. These are not appropriate for longitudinal data, which can have indexes that are not time unit oriented, such as “Wave 1...n”, or may contain irregular intervals.

Other packages focus more directly on panel data in R, focussing on data operations and model interfaces. The `pmdplyr` package provides “Panel Manoeuvres” in `dplyr` (Huntington-Klein and Khor 2020). It defines the data structure in as a `pibble` object (`panel tibble`), requiring an `id` and group column being defined to identify the unique identifier and grouping. The `pmdplyr` package focuses on efficient and custom joins and functions, such as `inexact_left_join()`. It does not implement tidyverse equivalent tools, but instead extends their usecase with a new function, for example `mutate_cascade` and `mutate_subset`. The `panelr` package provides an interface for data reshaping on panel data, providing widening and lengthening functions (`widen_panel()` and `long_panel()` (Long 2020)). It also provides model facilitating functions by providing its own interface for mixed effects models. The `plm` package (Millo 2017) for panel data econometrics provides methods for estimating models such as GMM for panel data, and testing, for example for model specification or serial correlation. It also provides a data structure, the `pdata.frame`, which stores the index attribute of the individual and time dimensions, for use within the package’s functions.

These software generally re-implement their own custom panel data class object, as well as custom data cleaning tasks, such as reshaping into long and wide form. They all share similar features, providing some identifying or index variable, and some grouping or key.

3 Longitudinal Data Structures

Longitudinal data is a sibling of many other temporal data forms, including panel data, repeated measures, and time series. The differences are many, and can be in data collection, context and even the field of research. Time series are usually long and regularly spaced in time. Panel data may measure different units at each time point and aggregate these values by a categorical or key variable. Repeated measures typically measure before and after treatment effects. We like to think of longitudinal as measuring the same individual (e.g. wage earner) over time, but this definition is not universally agreed on. Despite the differences, they all share a fundamental similarity: they are measurements over a time period.

This time period has structure - the time component (dates, times, waves, seconds, etc), and the spacing between measurements - unequal or equal. This data structure needs to be respected during analysis to preserve the lowest level of granularity, to avoid for example, collapsing across month when the data is collected every second, or assuming measurements occur at fixed time intervals. These mistakes can be avoided by encoding the data structure into the data itself. This information can then be accessed by analysis tools, providing a consistent way to understand and summarise the

data. This ensures the different types of longitudinal data previously mentioned can be handled in the same way.

Building on a tsibble

Since longitudinal data can be thought of as “individuals repeatedly measured through time”, they can be considered as a type of time series, as defined in Hyndman and Athanasopoulos (2018): “Anything that is observed sequentially over time is a **time series**”. This definition has been realised as a time series `tsibble` in (Wang, Cook, and Hyndman 2020). These objects are defined as data meeting these conditions:

1. The index: the time variable
2. The key: variable(s) defining individual groups (or series)
3. The index and key (1 + 2) together determine a distinct row

If the specified key and index pair do not define a distinct row - for example, if there are duplicates in the data, the `tsibble` will not be created. This helps ensure the data is properly understood and cleaned before analysis is conducted, removing avoidable errors that might have impacted downstream decisions.

We can formally define our heights data from Figure 1 as a `tsibble` using, `as_tsibble`:

```
heights_brolgar <- as_tsibble(heights_brolgar,
                             index = year,
                             key = country,
                             regular = FALSE)
```

The index is `year`, the key is `country`, and `regular = FALSE` since the intervals in the years measured are not regular. Using a `tsibble` means that the index and key time series information is recorded only **once**, and can be referred to many times in other parts of the data analysis by time-aware tools.

In addition to providing consistent ways to manipulate time series data, further benefits to building on `tsibble` are how it works within the tidyverse ecosystem, as well as the tidy time series packages called “tidyverts”, containing `fable` (O’Hara-Wild, Hyndman, and Wang 2020a), `feasts`, (O’Hara-Wild, Hyndman, and Wang 2020b). For example, `tsibble` provides modified tidyverse functions to explore implicit missing values in the index (e.g., `has_gaps()` and `fill_gaps()`), as well as grouping and partitioning based on the index with `index_by()`. For full details and examples of use with the tidyverts time series packages, see Wang, Cook, and Hyndman (2020).

The `brolgar` package uses `tsibble` so users can take advantage of these tools, learning one way of operating a data analysis that will work and have overlap with other contexts.

Characterising Individual Series

Calculating a feature

We can summarise the individual series by collapsing their many measurements into a single statistic, such as the minimum, maximum, or median, with one row per key. We do this with the `features` function from the `fabletools` package, made available in `brolgar`. This provides a summary of a given variable, accounting for the time series structure, and returning one row per key specified. It can be thought of as a time-series aware variant of the `summarise` function from `dplyr`. The feature function works by specifying the data, the variable to summarise, and the feature to calculate. A template is shown below

```
features(<DATA>, <VARIABLE>, <FEATURE>)
```

or, with the pipe:

```
<DATA> %>% features(<VARIABLE>, <FEATURE>)
```

For example, to calculate the minimum height for each key (`country`), in `heights`, we specify the `heights` data, then the variable to calculate features on, `height_cm`, then the feature to calculate, `min` (we write `c(min = min)` so the column calculated gets the name “min”):

```
heights_min <- features(.tbl = heights_brolgar,
                       .var = height_cm,
                       features = c(min = min))
```

```
heights_min
```

```
#> # A tibble: 119 x 2
#>   country      min
#>   <chr>      <dbl>
#> 1 Afghanistan 161.
#> 2 Algeria      166.
#> 3 Angola       159.
#> 4 Argentina   167.
#> 5 Armenia     164.
#> 6 Australia   170.
#> 7 Austria     162.
#> 8 Azerbaijan  170.
#> 9 Bangladesh  160.
#> 10 Belgium    163.
#> # ... with 109 more rows
```

We call these summaries features of the data. We can use this information to summarise these features of the data, for example, visualising the distribution of minimum values (Figure 3A).

We are not limited to one feature at a time, many features can also be calculated, for example:

```
heights_three <- heights_brolgar %>%
  features(height_cm, c(
    min = min,
    median = median,
    max = max
  ))
```

```
heights_three
```

```
#> # A tibble: 119 x 4
#>   country      min median  max
#>   <chr>      <dbl> <dbl> <dbl>
#> 1 Afghanistan 161.  167. 168.
#> 2 Algeria      166.  169. 171.
#> 3 Angola       159.  167. 169.
#> 4 Argentina   167.  168. 174.
#> 5 Armenia     164.  169. 172.
#> 6 Australia   170.  172. 178.
#> 7 Austria     162.  167. 179.
#> 8 Azerbaijan  170.  172. 172.
#> 9 Bangladesh  160.  162. 164.
#> 10 Belgium    163.  166. 177.
#> # ... with 109 more rows
```

These can then be visualised together (Figure 3).

These sets of features can be pre-specified, for example, `brolgar` provides a five number summary (minimum, 25th quantile, median, mean, 75th quantile, and maximum) of the data with `feat_five_num`:

```
heights_five <- heights_brolgar %>%
  features(height_cm, feat_five_num)
```

```
heights_five
```

```
#> # A tibble: 119 x 6
#>   country      min  q25  med  q75  max
#>   <chr>      <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1 Afghanistan 161.  164. 167. 168. 168.
```

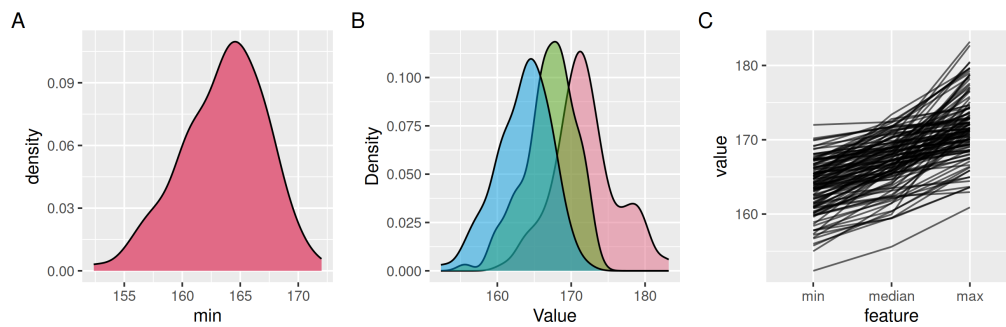


Figure 3: Three plots showing the distribution of minimum, median, and maximum values of height in centimeters. Part A shows just the distribution of minimum, part B shows the distribution of minimum, median, and maximum, and part C shows these three values plotted together as a line graph. We see that there is overlap amongst all three statistics. That is, some countries minimum heights are taller than some countries maximum heights.

```
#> 2 Algeria      166. 168. 169 170. 171.
#> 3 Angola       159. 160. 167. 168. 169.
#> 4 Argentina   167. 168. 168. 170. 174.
#> 5 Armenia     164. 166. 169. 172. 172.
#> 6 Australia   170. 171. 172. 173. 178.
#> 7 Austria     162. 164. 167. 169. 179.
#> 8 Azerbaijan  170. 171. 172. 172. 172.
#> 9 Bangladesh  160. 162. 162. 163. 164.
#> 10 Belgium    163. 164. 166. 168. 177.
#> # ... with 109 more rows
```

This takes the heights data, pipes it to features, and then instructs it to summarise the height_cm variable, using feat_five_num. There are several handy functions for calculating features of the data that brolgar provides. These all start with feat_, and include:

- feat_ranges(): min, max, range difference, interquartile range;
- feat_spread(): variance, standard deviation, median absolute distance, and interquartile range;
- feat_monotonic(): is it always increasing, decreasing, or unvarying?;
- feat_diff_summary(): the summary statistics of the differences amongst a value, including the five number summary, as well as the standard deviation and variance;
- feat_brolgar(), which will calculate all features available in the **brolgar** package.
- Other examples of features from the **feasts** package.

Feature sets

If you want to run many or all features from a package on your data you can collect them all with feature_set. For example:

```
library(fabletools)
feat_set_brolgar <- feature_set(pkgs = "brolgar")
length(feat_set_brolgar)

#> [1] 6
```

You could then run these like so:

```
heights_brolgar %>%
  features(height_cm, feat_set_brolgar)

#> # A tibble: 119 x 46
#>   country      min...1 med...2 max...3 min...4 q25...5 med...6 q75...7 max...8
#>   <chr>         <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1 Afghanistan  161.  167.  168.  161.  164.  167.  168.  168.
#> 2 Algeria      166.  169.  171.  166.  168.  169.  170.  171.
#> 3 Angola       159.  167.  169.  159.  160.  167.  168.  169.
```

```
#> 4 Argentina      167.  168.  174.  167.  168.  168.  170.  174.
#> 5 Armenia        164.  169.  172.  164.  166.  169.  172.  172.
#> 6 Australia      170  172.  178.  170  171.  172.  173.  178.
#> 7 Austria        162.  167.  179.  162.  164.  167.  169.  179.
#> 8 Azerbaijan     170.  172.  172.  170.  171.  172.  172.  172.
#> 9 Bangladesh     160.  162.  164.  160.  162.  162.  163.  164.
#> 10 Belgium       163.  166.  177.  163.  164.  166.  168.  177.
#> # ... with 109 more rows, and 37 more variables: min...9 <dbl>, max...10 <dbl>,
#> #   range_diff...11 <dbl>, iqr...12 <dbl>, var...13 <dbl>, sd...14 <dbl>,
#> #   mad...15 <dbl>, iqr...16 <dbl>, min...17 <dbl>, max...18 <dbl>,
#> #   median <dbl>, mean <dbl>, q25...21 <dbl>, q75...22 <dbl>, range1 <dbl>,
#> #   range2 <dbl>, range_diff...25 <dbl>, sd...26 <dbl>, var...27 <dbl>,
#> #   mad...28 <dbl>, iqr...29 <dbl>, increase...30 <dbl>, decrease...31 <dbl>,
#> #   unvary...32 <dbl>, diff_min <dbl>, diff_q25 <dbl>, diff_median <dbl>, ...
```

To see other features available in the `feasts` R package run `library(feasts)` then `?fabletools::feature_set`.

Creating your own feature

To create your own features or summaries to pass to features, you provide a named vector of functions. These can include functions that you have written yourself. For example, returning the first three elements of a series, by writing our own second and third functions.

```
second <- function(x) nth(x, n = 2)
third <- function(x) nth(x, n = 3)

feat_first_three <- c(first = first,
                      second = second,
                      third = third)
```

These are then passed to features like so:

```
heights_brolgar %>%
  features(height_cm, feat_first_three)

#> # A tibble: 119 x 4
#>   country      first second third
#>   <chr>      <dbl> <dbl> <dbl>
#> 1 Afghanistan 168.  166.  167.
#> 2 Algeria      169.  166.  169
#> 3 Angola       160.  159.  160.
#> 4 Argentina   170.  168.  168
#> 5 Armenia     169.  168.  166.
#> 6 Australia   170  171.  170.
#> 7 Austria     165.  163.  162.
#> 8 Azerbaijan  170.  171.  171.
#> 9 Bangladesh  162.  162.  164.
#> 10 Belgium    163.  164.  164
#> # ... with 109 more rows
```

As well, `brolgar` provides some useful additional features for the five number summary, `feat_five_num`, whether keys are monotonically increasing `feat_monotonic`, and measures of spread or variation, `feat_spread`. Inside `brolgar`, the features are created with the following syntax:

```
feat_five_num <- function(x, ...) {
  c(
    min = b_min(x, ...),
    q25 = b_q25(x, ...),
    med = b_median(x, ...),
    q75 = b_q75(x, ...),
    max = b_max(x, ...)
  )
}
```

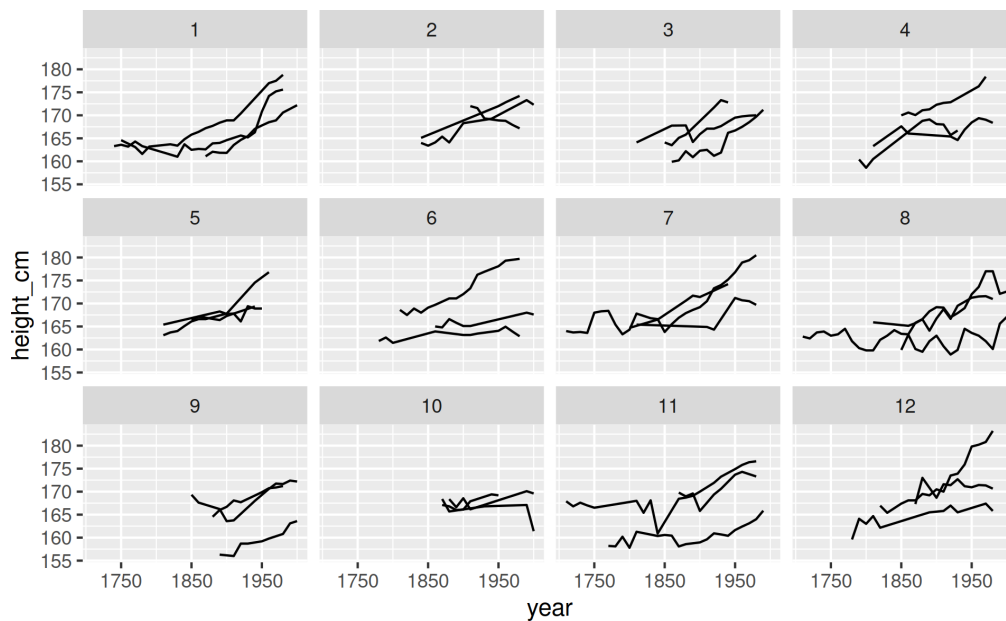


Figure 4: Twelve facets with three keys per facet shown. This allows us to quickly view a random sample of the data.

Here the functions `b_` are functions with a default of `na.rm = TRUE`, and in the cases of quantiles, they use `type = 8`, and `names = FALSE`. What is particularly useful is that these will work on any type of time series data, and you can use other more typical time series features from the `feasts` package, such as autocorrelation, `feat_acf()` and Seasonal and Trend decomposition using Loess `feat_stl()` (O’Hara-Wild, Hyndman, and Wang 2020b).

This demonstrates a workflow that can be used to understand and explore your longitudinal data. The `brlgar` package builds upon this workflow made available by `feasts` and `fabletools`. Users can also create their own features to summarise the data.

4 Breaking up the Spaghetti

Plots like Figure 2 are often called, “spaghetti plots”, and can be useful for a high level understanding as a whole. However, we cannot process and understand the individuals when the data is presented like this.

Sampling

Just how spaghetti is portioned out for consumption, we can sample some of the data by randomly sampling the data into sub-plots with the `facet_sample()` function (Figure 4).

```
ggplot(heights_brolgar,
  aes(x = year,
    y = height_cm,
    group = country)) +
  geom_line() +
  facet_sample() +
  scale_x_continuous(breaks = c(1750, 1850, 1950))
```

This defaults to 12 facets and 3 samples per facet, and provides options for the number of facets, and the number of samples per facet. This means the user only needs to consider the most relevant questions: “How many keys per facet?” and “How many facets to look at?”. The code to change the figure from Figure 2 into 4 requires only one line of code, shown below:

```
ggplot(heights_brolgar,
  aes(x = year,
    y = height_cm,
```

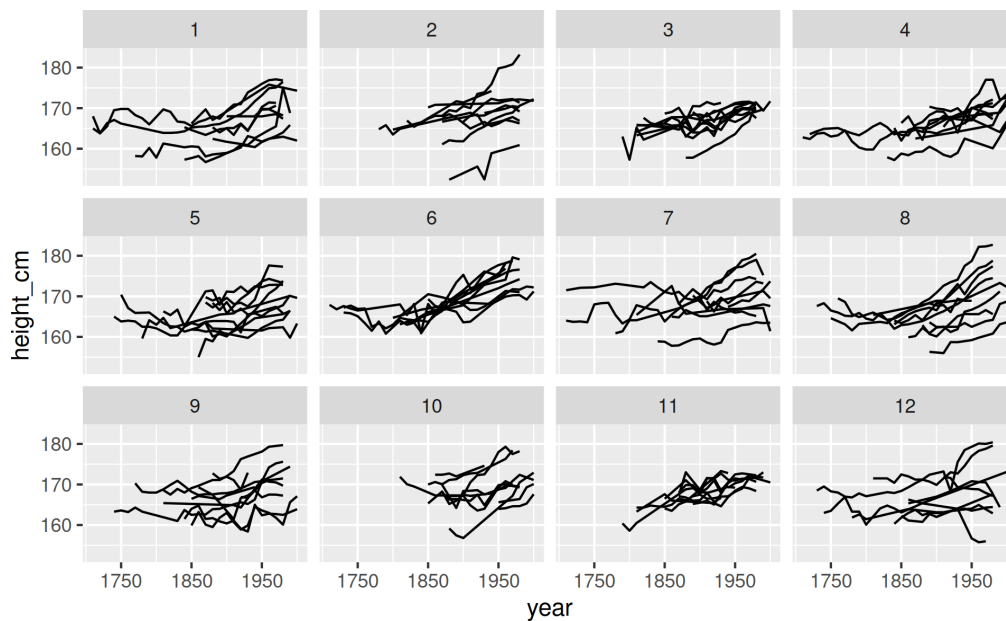


Figure 5: All of the data is shown by spreading out each key across twelve facets. Each key is only shown once, and is randomly allocated to a facet.

```

    group = country)) +
  geom_line() +
  facet_sample()

```

Stratifying

Extending this idea of samples, we can instead look at **all** of the data, spread out equally over facets, using `facet_strata()`. It uses 12 facets by default, controllable with `n_strata`. The code to do so is shown below, creating Figure 5.

```

ggplot(heights_brolgar,
  aes(x = year,
    y = height_cm,
    group = country)) +
  geom_line() +
  facet_strata() +
  scale_x_continuous(breaks = c(1750, 1850, 1950))

```

Featuring

Figure 4 and Figure 5 only show each key once, being randomly assigned to a facet. We can meaningfully place the keys into facets, by arranging the heights “along” a variable, like year, using the `along` argument in `facet_strata` to produce Figure 6:

```

ggplot(heights_brolgar,
  aes(x = year,
    y = height_cm,
    group = country)) +
  geom_line() +
  facet_strata(along = -year) +
  scale_x_continuous(breaks = c(1750, 1850, 1950))

```

We have not lost any of the data, only the order in which they are presented has changed. We learn the distribution and changes in heights over time, and those measured from the earliest times appear to be more similar, but there is much wider variation in the middle years, and then for more recent heights measured from the early 1900s, the heights are more similar. The starting point of each

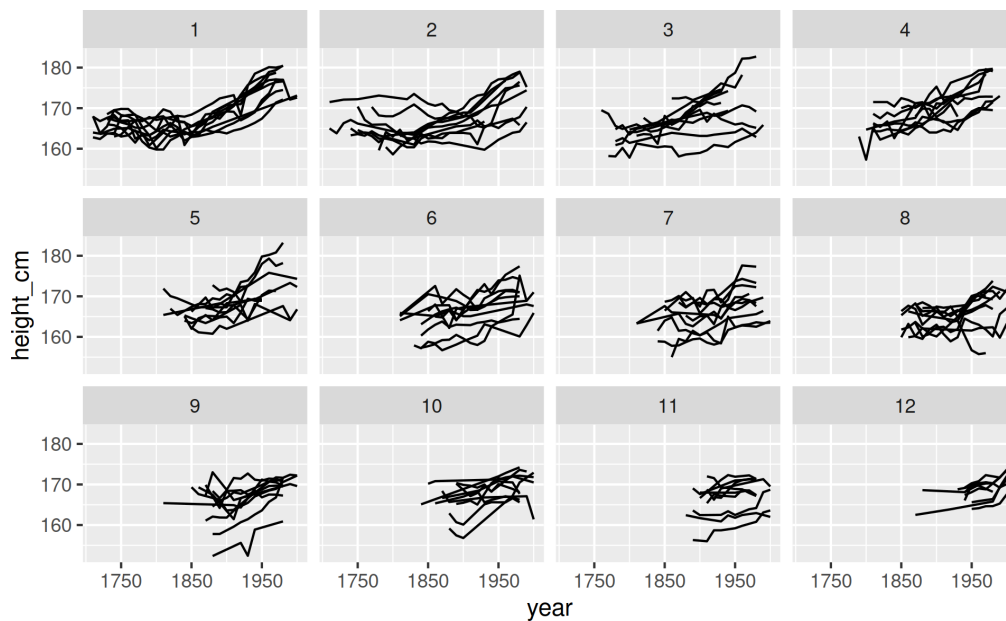


Figure 6: Displaying all the data across twelve facets. Instead of each key being randomly in a facet, each facet displays a specified range of values of year. In this case, the top left facet shows the keys with the earliest starting year, and the bottom right shows the facet with the latest starting year.

of these years seems to increase at roughly the same interval. This informs us that the starting times of the years is approximately uniform.

Together `facet_sample()` and `facet_strata()` allow for rapid exploration, by focusing on relevant questions instead of the minutiae. This is achieved by appropriately randomly assigning while maintaining key structure, keeping the correct number of keys per plot, and so on. For example, `facet_sample()` the questions are: “How many lines per facet” and “How many facets?”, and for `facet_strata()` the questions are: “How many facets / strata?” and “What to arrange plots along?”.

Answering these questions keeps the analysis in line with the analytic goals of exploring the data, rather than distracting to minutiae. This is a key theme of improving tools for data analysis. Abstracting away the parts that are not needed, so the analyst can focus on the task at hand.

Under the hood, `facet_sample()` and `facet_strata()` are powered with `sample_n_keys()` and `stratify_keys()`. These can be used to create data structures used in `facet_sample()` and `facet_strata()`, and extend them for other purposes.

Using a `tsibble` stores important key and index components, in turn allowing for better ways to break up spaghetti plots so we can look at many and all sub-samples using `facet_sample()` and `facet_strata()`.

5 Book-keeping

Longitudinal data is not always measured at the same time and at the same frequency. When exploring longitudinal data, a useful first step is to explore the frequency of measurements of the index. We can check if the index is regular using `index_regular()` and summarise the spacing of the index with `index_summary()`. These are S3 methods, so for `data.frame` objects, the index must be specified, however for the `tsibble` objects, the defined index is used.

```
index_summary(heights_brolgar)
#>   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
#>  1710  1782   1855   1855  1928   2000

index_regular(heights_brolgar)
#> [1] TRUE
```

We can explore how many observations per country by counting the number of observations with features, like so:

```
heights_brolgar %>% features(year, n_obs)
```

```
#> # A tibble: 119 x 2
#>   country      n_obs
#>   <chr>      <int>
#> 1 Afghanistan     5
#> 2 Algeria         5
#> 3 Angola          9
#> 4 Argentina      20
#> 5 Armenia        11
#> 6 Australia      10
#> 7 Austria        18
#> 8 Azerbaijan     7
#> 9 Bangladesh     9
#> 10 Belgium       10
#> # ... with 109 more rows
```

This can be further summarised by counting the number of times there are a given number of observations:

```
heights_brolgar %>% features(year, n_obs) %>% count(n_obs)
```

```
#> # A tibble: 24 x 2
#>   n_obs     n
#>   <int> <int>
#> 1     5    11
#> 2     6    11
#> 3     7    13
#> 4     8     5
#> 5     9    12
#> 6    10    12
#> 7    11     9
#> 8    12     4
#> 9    13     7
#> 10   14     6
#> # ... with 14 more rows
```

Because we are exploring the temporal patterns, we cannot reliably say anything about those individuals with few measurements. The data used, `heights_brolgar` has less than 5 measurements. This was done using `add_n_obs()`, which adds the number of observations to the existing data. Overall this drops 25 countries, leaves us with 119 out of the original 144 countries.

```
heights_brolgar <- heights %>%
  add_n_obs() %>%
  filter(n_obs >= 5)
```

We can further explore when countries are first being measured using `features` to find the first year for each country number of starting years with the `first` function from `dplyr`, and explore this with a visualisation (Figure 7).

```
heights_brolgar %>%
  features(year, c(first = first))
```

```
#> # A tibble: 119 x 2
#>   country      first
#>   <chr>      <dbl>
#> 1 Afghanistan 1870
#> 2 Algeria     1910
#> 3 Angola      1790
#> 4 Argentina   1770
#> 5 Armenia     1850
#> 6 Australia   1850
#> 7 Austria     1750
```

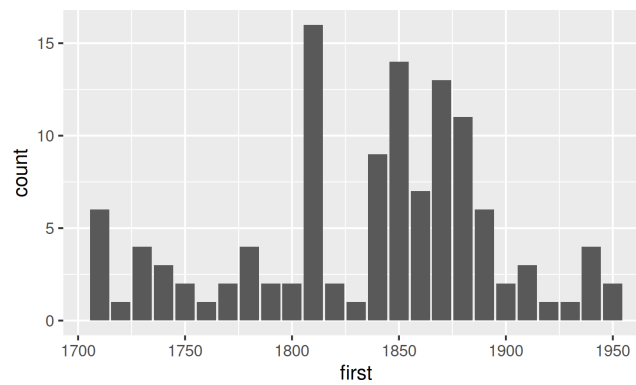


Figure 7: Distribution of starting years of measurement. The data is already binned into 10 year blocks. Most of the years start between 1840 and 1900.

```
#> 8 Azerbaijan 1850
#> 9 Bangladesh 1850
#> 10 Belgium 1810
#> # ... with 109 more rows
```

```
heights_brolgar %>%
  features(year, c(first = first)) %>%
  ggplot(aes(x = first)) +
  geom_bar()
```

We can explore the variation in first year using `feat_diff_summary`. This combines many summaries of the differences in year.

```
heights_diffs <- heights_brolgar %>%
  features(year, feat_diff_summary)
```

```
heights_diffs
```

```
#> # A tibble: 119 x 10
#>   country    diff_min diff_q25 diff_~1 diff_~2 diff_~3 diff_~4 diff_~5 diff_sd
#>   <chr>      <dbl>    <dbl>  <dbl>  <dbl>  <dbl>  <dbl>  <dbl>  <dbl>
#> 1 Afghanistan 10      10      30    32.5  55.8   60    692.  26.3
#> 2 Algeria     10      10      10    22.5  39.2   60    625   25
#> 3 Angola      10      10      10    17.5  10     70    450   21.2
#> 4 Argentina  10      10      10    11.6  10     40    47.4  6.88
#> 5 Armenia     10      10      10    15    20.8   30    72.2  8.50
#> 6 Australia  10      10      10    13.3  10     40    100   10
#> 7 Austria     10      10      10    13.5  10     40    74.3  8.62
#> 8 Azerbaijan 10      10      10    25    25.8   90   1030  32.1
#> 9 Bangladesh 10      10      10    18.8  15.8   70   441.  21.0
#> 10 Belgium    10      10      10    16.7  23.3   40   125   11.2
#> # ... with 109 more rows, 1 more variable: diff_iqr <dbl>, and abbreviated
#> #   variable names 1: diff_median, 2: diff_mean, 3: diff_q75, 4: diff_max,
#> #   5: diff_var
```

This is particularly useful as using `diff` on year would return a very wide dataset that is hard to explore:

```
heights_brolgar %>%
  features(year, diff)
```

```
#> # A tibble: 119 x 30
#>   country    ...1 ...2 ...3 ...4 ...5 ...6 ...7 ...8 ...9 ...10 ...11
#>   <chr>      <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
#> 1 Afghanistan 10    50    60    10    NA    NA    NA    NA    NA    NA    NA
#> 2 Algeria     10    10    60    10    NA    NA    NA    NA    NA    NA    NA
```

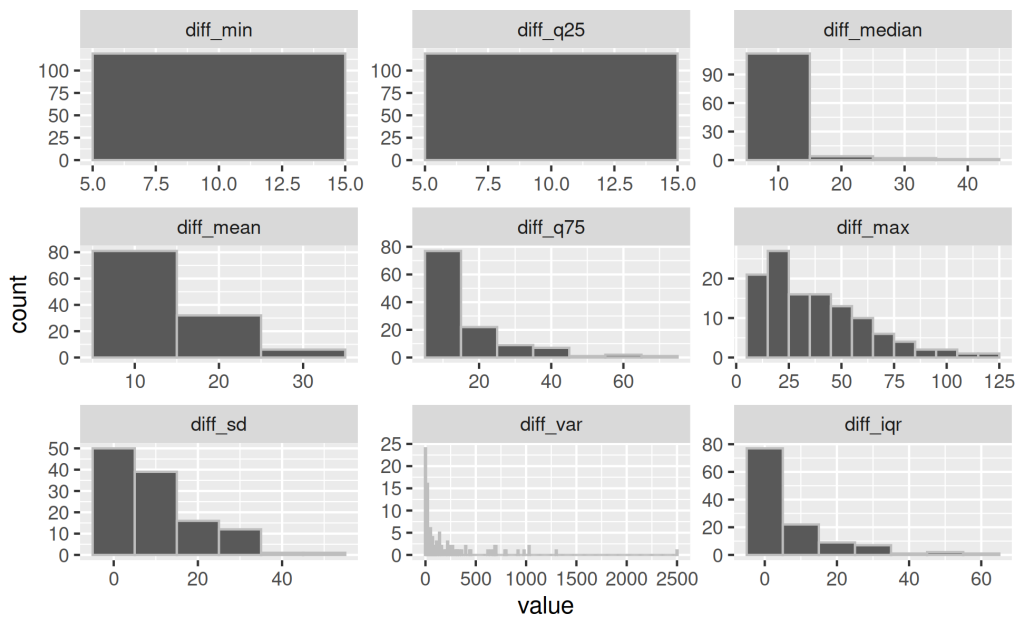


Figure 8: Exploring the different summary statistics of the differences amongst the years. We learn that the smallest interval between measurements is 10 years, and the largest interval is between 10 and 125 years, and that most of the data is measured between 10 and 30 or so years.

```
#> 3 Angola      10  10  70  10  10  10  10  10  NA  NA  NA
#> 4 Argentina  10  10  10  10  10  10  10  10  10  10  10
#> 5 Armenia    10  30  10  10  30  20  10  10  10  10  NA
#> 6 Australia  10  10  10  10  10  10  10  40  10  NA  NA
#> 7 Austria    20  10  10  30  10  10  10  10  10  10  10
#> 8 Azerbaijan 10  90  10  10  10  20  NA  NA  NA  NA  NA
#> 9 Bangladesh 10  10  10  70  10  20  10  10  NA  NA  NA
#> 10 Belgium   10  10  10  10  10  10  30  40  20  NA  NA
#> # ... with 109 more rows, and 18 more variables: ...12 <dbl>, ...13 <dbl>,
#> #   ...14 <dbl>, ...15 <dbl>, ...16 <dbl>, ...17 <dbl>, ...18 <dbl>,
#> #   ...19 <dbl>, ...20 <dbl>, ...21 <dbl>, ...22 <dbl>, ...23 <dbl>,
#> #   ...24 <dbl>, ...25 <dbl>, ...26 <dbl>, ...27 <dbl>, ...28 <dbl>,
#> #   ...29 <dbl>
```

We can then look at the summaries of the differences in year by changing to long form and facetting (Figure 8), we learn about the range of intervals between measurements, the smallest being 10 years, the largest being 125, and that most of the data is measured between 10 and 30 years.

6 Finding Waldo

Looking at a spaghetti plot, it can be hard to identify which lines are the most interesting, or unusual. A workflow to identify interesting individuals to start with is given below:

1. Decide upon an interesting feature (e.g., maximum)
2. This feature produces one value per key
3. Examine the distribution of the feature
4. Join this table back to the data to get all observations for those keys
5. Arrange the keys or filter, using the feature
6. Display the data for selected keys

This workflow is now demonstrated. Firstly, we **decide on an interesting feature**, “maximum height”, and whether height is always increasing. We calculate our own “feature”, calculating maximum height, and whether a value is increasing (with `brolgar`’s `increasing` function) as follows:

```
heights_max_in <- heights_brolgar %>%
  features(height_cm, list(max = max,
                           increase = increasing))
```

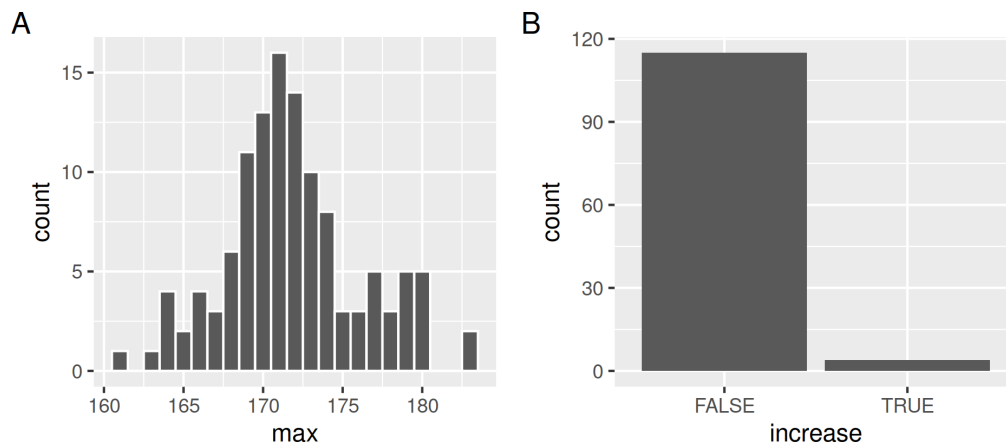


Figure 9: The different distributions of the features - A is depicting the distribution of maximum height, and B displays the number of countries that are always increasing (FALSE), and always increasing (TRUE). We note that the average maximum heights range from about 160cm to 185cm, with most being around 170cm. We also learn that the vast majority of countries are not always increasing in height through time.

```
heights_max_in

#> # A tibble: 119 x 3
#>   country      max increase
#>   <chr>      <dbl> <lgl>
#> 1 Afghanistan 168. FALSE
#> 2 Algeria     171. FALSE
#> 3 Angola      169. FALSE
#> 4 Argentina   174. FALSE
#> 5 Armenia     172. FALSE
#> 6 Australia   178. FALSE
#> 7 Austria     179. FALSE
#> 8 Azerbaijan  172. FALSE
#> 9 Bangladesh  164. FALSE
#> 10 Belgium    177. FALSE
#> # ... with 109 more rows
```

This returns a dataset of **one value per key**. Figure 9 examines the distribution of the features, showing us the distribution of maximum height, and the number of countries that are always increasing.

We can now **join this table back to the data to get all observations for those keys** to move from one key per row to all many rows per key.

```
heights_max_in_full <- heights_max_in %>%
  left_join(heights_brolgar,
            by = "country")

heights_max_in_full

#> # A tibble: 1,406 x 9
#>   country      max increase  year n_obs continent height_cm year0 country_fct
#>   <chr>      <dbl> <lgl>  <dbl> <int> <chr>      <dbl> <dbl> <fct>
#> 1 Afghanistan 168. FALSE  1870     5 Asia      168.  160 Afghanistan
#> 2 Afghanistan 168. FALSE  1880     5 Asia      166.  170 Afghanistan
#> 3 Afghanistan 168. FALSE  1930     5 Asia      167.  220 Afghanistan
#> 4 Afghanistan 168. FALSE  1990     5 Asia      167.  280 Afghanistan
#> 5 Afghanistan 168. FALSE  2000     5 Asia      161.  290 Afghanistan
#> 6 Algeria     171. FALSE  1910     5 Africa    169.  200 Algeria
#> 7 Algeria     171. FALSE  1920     5 Africa    166.  210 Algeria
#> 8 Algeria     171. FALSE  1930     5 Africa    169.  220 Algeria
```

```
#> 9 Algeria      171. FALSE    1990    5 Africa      171.    280 Algeria
#> 10 Algeria     171. FALSE    2000    5 Africa      170.    290 Algeria
#> # ... with 1,396 more rows
```

We can then **arrange the keys or filter, using the feature**, for example, filtering only those countries that are only increasing:

```
heights_increase <- heights_max_in_full %>% filter(increase)
heights_increase

#> # A tibble: 22 x 9
#>   country    max increase  year n_obs continent height_cm year0 country_fct
#>   <chr>      <dbl> <lgl>  <dbl> <int> <chr>      <dbl> <dbl> <fct>
#> 1 Honduras  168. TRUE    1950     6 Americas    164.    240 Honduras
#> 2 Honduras  168. TRUE    1960     6 Americas    164.    250 Honduras
#> 3 Honduras  168. TRUE    1970     6 Americas    165.    260 Honduras
#> 4 Honduras  168. TRUE    1980     6 Americas    165.    270 Honduras
#> 5 Honduras  168. TRUE    1990     6 Americas    165.    280 Honduras
#> 6 Honduras  168. TRUE    2000     6 Americas    168.    290 Honduras
#> 7 Moldova  174. TRUE    1840     5 Europe     165.    130 Moldova
#> 8 Moldova  174. TRUE    1950     5 Europe     172.    240 Moldova
#> 9 Moldova  174. TRUE    1960     5 Europe     173.    250 Moldova
#> 10 Moldova 174. TRUE    1970     5 Europe     174.    260 Moldova
#> # ... with 12 more rows
```

Or tallest country

```
heights_top <- heights_max_in_full %>% top_n(n = 1, wt = max)
heights_top

#> # A tibble: 16 x 9
#>   country    max increase  year n_obs continent height_cm year0 country_fct
#>   <chr>      <dbl> <lgl>  <dbl> <int> <chr>      <dbl> <dbl> <fct>
#> 1 Denmark  183. FALSE    1820    16 Europe     167.    110 Denmark
#> 2 Denmark  183. FALSE    1830    16 Europe     165.    120 Denmark
#> 3 Denmark  183. FALSE    1850    16 Europe     167.    140 Denmark
#> 4 Denmark  183. FALSE    1860    16 Europe     168.    150 Denmark
#> 5 Denmark  183. FALSE    1870    16 Europe     168.    160 Denmark
#> 6 Denmark  183. FALSE    1880    16 Europe     170.    170 Denmark
#> 7 Denmark  183. FALSE    1890    16 Europe     169.    180 Denmark
#> 8 Denmark  183. FALSE    1900    16 Europe     170.    190 Denmark
#> 9 Denmark  183. FALSE    1910    16 Europe     170.    200 Denmark
#> 10 Denmark 183. FALSE    1920    16 Europe     174.    210 Denmark
#> 11 Denmark 183. FALSE    1930    16 Europe     174.    220 Denmark
#> 12 Denmark 183. FALSE    1940    16 Europe     176.    230 Denmark
#> 13 Denmark 183. FALSE    1950    16 Europe     180.    240 Denmark
#> 14 Denmark 183. FALSE    1960    16 Europe     180.    250 Denmark
#> 15 Denmark 183. FALSE    1970    16 Europe     181.    260 Denmark
#> 16 Denmark 183. FALSE    1980    16 Europe     183.    270 Denmark
```

We can then display the data by highlighting it in the background, first creating a background plot and overlaying the plots on top of this as an additional ggplot layer, in Figure 10.

7 Dancing with Models

These same workflows can be used to interpret and explore a model. As the data tends to follow a non linear trajectory, we use a general additive model (gam) with the **mgcv** R package (Wood 2017) using the code below:

```
heights_gam <- gam(
  height_cm ~ s(year0, by = country_fct) + country_fct,
  data = heights_brolgar,
  method = "REML"
)
```

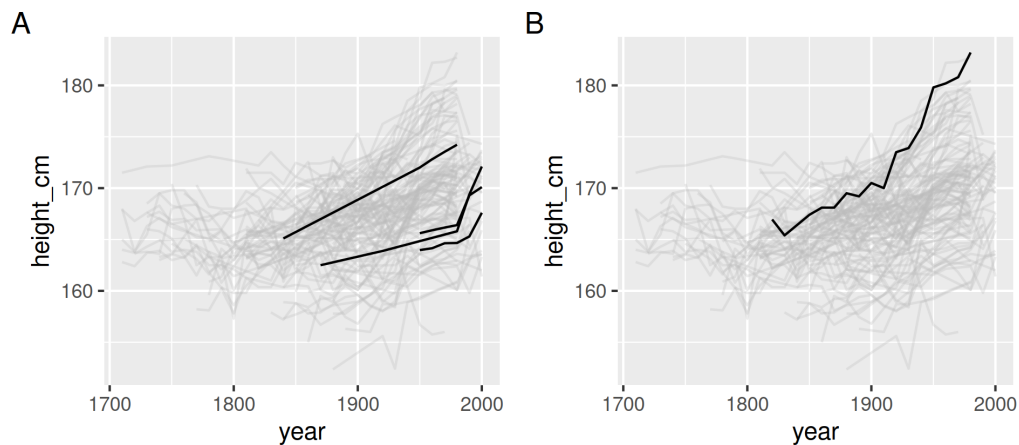


Figure 10: Plots of the data in the background, with the countries that always increase in height through time in A, and the country with the tallest people in B

This fits height in centimetres with a smooth effect for year for each country, with a different intercept for each country. It is roughly equivalent to a random intercept varying slope model. Note that this gam model took approximately 8074 seconds to fit. We add the predicted and residual values for the model below, as well as the residual sums of squares for each country.

```
library(mgcv)
library(modelr)
heights_aug <- heights_brolgar %>%
  add_predictions(heights_gam, var = "pred") %>%
  add_residuals(heights_gam, var = "res") %>%
  group_by_key() %>%
  mutate(rss = sum(res^2)) %>%
  ungroup()
```

We can use the previous approach to explore the model results. We can take a look at a sample of the predictions along with the data, by using `sample_n_keys`. This provides a useful way to explore some set of the model predictions. In order to find those predictions that best summarise the best, and worst, and in between, we need to use the methods in the next section, “Stereotyping”.

```
heights_aug %>%
  sample_n_keys(12) %>%
  ggplot(aes(x = year,
             y = pred,
             group = country)) +
  geom_line(colour = "steelblue") +
  geom_point(aes(y = height_cm)) +
  facet_wrap(~country)
```

8 Stereotyping

To help understand a population of measurements over time, it can be useful to understand which individual measurements are typical (or “stereotypical”) of a measurement. For example, to understand which individuals are stereotypical of a statistic such as the minimum, median, and maximum height. This section discusses how to find these stereotypes in the data.

Figure 12 shows the residuals of the simple model fit to the data in the previous section. There is an overlaid five number summary, showing the minimum, 1st quantile, median, 3rd quantile, and maximum residual value residuals, as well as a rug plot to show the data. We can use these residuals to understand the stereotypes of the data - those individuals in the model that best match to this five number summary.

We can do this using `keys_near()` from `brolgar`. By default this uses the 5 number summary, but any function can be used. You specify the variable you want to find the keys nearest, in this case `rss`, residual sums of squares for each key:

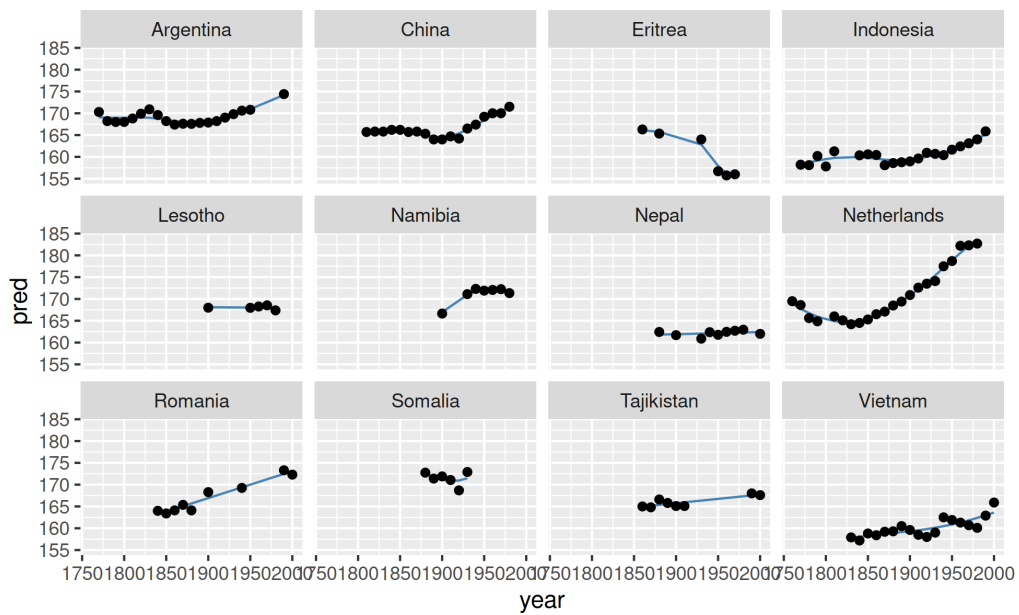


Figure 11: Exploration of a random sample of the data. This shows the data points of 12 countries, with the model fit in blue.

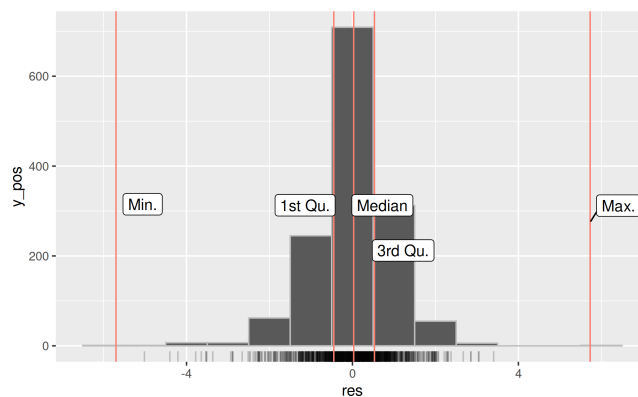


Figure 12: Five number summary of residual values from the model fit. The residuals are centered around zero with some variation.

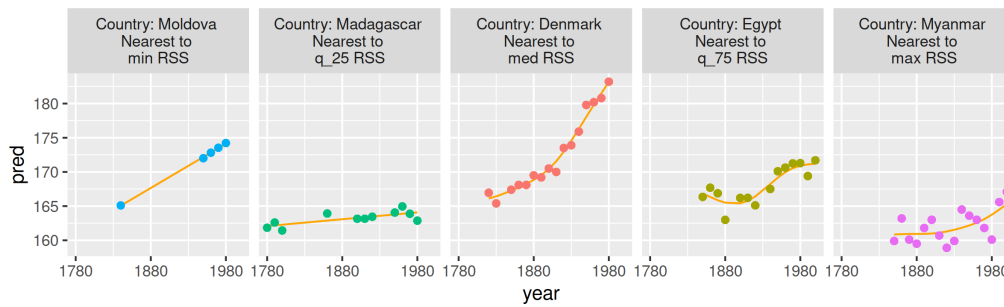


Figure 13: The keys nearest to the five number summary of the residual sums of squares. Moldova and Madagascar are well fit by the model, and are fit by a straight line. The remaining countries with poorer fit have greater variation in height. It is not clear how a better model fit could be achieved.

```
keys_near(heights_aug, var = rss)
```

```
#> # A tibble: 62 x 5
#>   country  rss stat  stat_value stat_diff
#>   <chr>   <dbl> <fct>    <dbl>    <dbl>
#> 1 Denmark  9.54 med      9.54      0
#> 2 Denmark  9.54 med      9.54      0
#> 3 Denmark  9.54 med      9.54      0
#> 4 Denmark  9.54 med      9.54      0
#> 5 Denmark  9.54 med      9.54      0
#> 6 Denmark  9.54 med      9.54      0
#> 7 Denmark  9.54 med      9.54      0
#> 8 Denmark  9.54 med      9.54      0
#> 9 Denmark  9.54 med      9.54      0
#> 10 Denmark 9.54 med      9.54      0
#> # ... with 52 more rows
```

To plot the data, they need to be joined back to the original data, we use a left join, joining by country.

```
heights_near_aug <- heights_aug %>%
  keys_near(var = rss) %>%
  left_join(heights_aug,
    by = c("country"))
```

Figure 13 shows those countries closest to the five number summary. Observing this, we see that the minimum RSS for Moldova fits a nearly perfectly straight line, and the maximum residuals for Myanmar have wide spread of values.

```
ggplot(heights_near_aug,
  aes(x = year,
    y = pred,
    group = country,
    colour = country)) +
  geom_line(colour = "orange") +
  geom_point(aes(y = height_cm)) +
  scale_x_continuous(breaks = c(1780, 1880, 1980)) +
  facet_wrap(~stat + country,
    labeller = label_glue("Country: {country} \nNearest to \n{stat} RSS"),
    nrow = 1) +
  theme(legend.position = "none",
    aspect.ratio = 1)
```

We can also look at the highest and lowest 3 residual sums of squares:

```
heights_near_aug_top_3 <- heights_aug %>%
  distinct(country, rss) %>%
  top_n(n = 3,
```

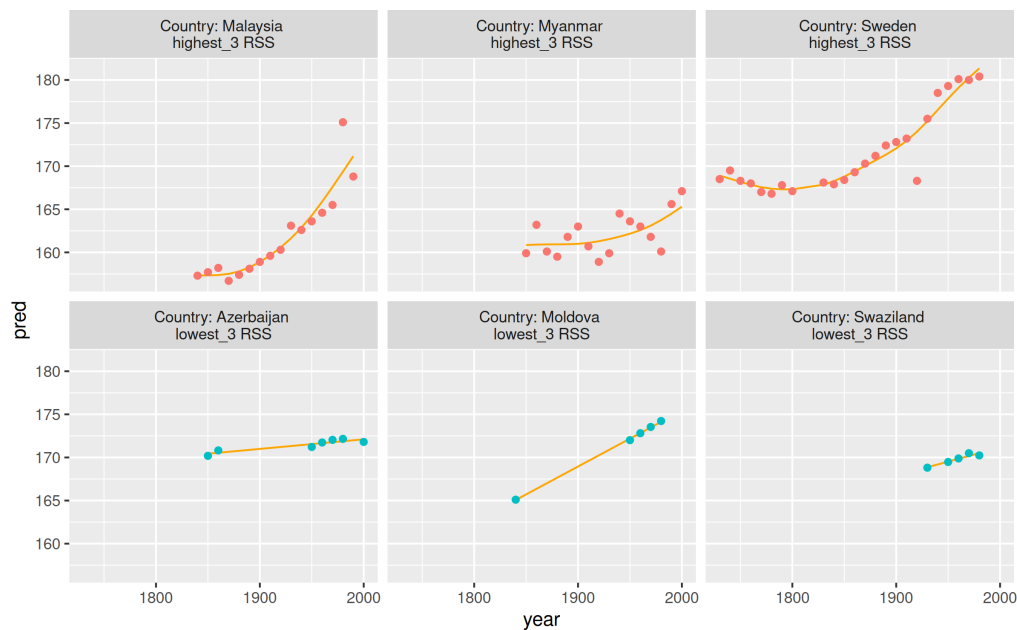


Figure 14: Figure of stereotypes for those keys with the three highest and lowest RSS values. Those that fit best tend to be linear, but those that fit worst have wider variation in heights.

```

    wt = rss)

heights_near_aug_bottom_3 <- heights_aug %>%
  distinct(country, rss) %>%
  top_n(n = -3,
        wt = rss)

heights_near_top_bot_3 <- bind_rows(highest_3 = heights_near_aug_top_3,
                                   lowest_3 = heights_near_aug_bottom_3,
                                   .id = "rank") %>%
  left_join(heights_aug,
            by = c("country", "rss"))

```

Figure 14 shows the same information as the previous plot, but with the 3 representative countries for each statistic. This gives us more data on what the stereotypically “good” and “poor” fitting countries to this model.

9 Getting Started

The **brlgar** R package can be installed from CRAN using

```

# From CRAN
install.packages("brlgar")
# Development version
remotes::install_github("njtierney/brlgar")

```

The functions are all designed to build upon existing packages, but are predicated on working with **tsibble**. The package extends upon **ggplot2** to provide facets for exploration: `facet_sample()` and `facet_strata()`. Extending **dplyr**'s `sample_n()` and `sample_frac()` functions by providing sampling and stratifying based around keys: `sample_n_keys()`, `sample_frac_keys()`, and `stratify_keys()`. New functions are focussed around the use of key, for example `key_slope()` to find the slope of each key, and `keys_near()` to find those keys near a summary statistic. Finally, feature calculation is provided by building upon the existing time series feature package, **feasts**.

To get started with **brlgar** you must first ensure your data is specified as a **tsibble** - discussed earlier in the paper, there is also a vignette “**Longitudinal Data Structures**”, which discusses these ideas. The next step we recommend is sampling some of your data with `facet_sample()`, and

`facet_strata()`. When using `facet_strata()`, facets can be arranged in order of a variable, using the `along` argument, which can reveal interesting features.

To further explore longitudinal data, we recommend finding summary features of each variable with `features`, and identifying variables that are near summary statistics, using `keys_near` to find individuals stereotypical of a statistical value.

10 Concluding Remarks

The **brolgar** package facilitates exploring longitudinal data in R. It builds upon existing infrastructure from **tsibble**, and **feasts**, which work within the tidyverse family of R packages, as well as the newer, **tidyverts**, time series packages. Users familiar with either of these package families will find a lot of similarity in their use, and first time users will be able to easily transition from **brolgar** to the tidyverse or **tidyverts**.

Visualizing categorical or binary data over a time period can be difficult as the limited number of values on the y axis leads to overplotting. This can conceal the number of values present at a given value. The tools discussed in **brolgar** facilitate this in the form of `facet_sample`, and `facet_strata`. Some special methods could be developed to add jitter or noise around these values on the y axis, while still maintaining the graphical axis and tick marks.

Future work will explore more features and stratifications, and stereotypes, and generalise the tools to work for data without time components, and other data types.

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12 Paper Source

The complete source files for the paper can be found at <https://github.com/njtierney/rjournal-brolgar>. The paper is built using **rmarkdown**, **targets** and **capsule** to ensure R package versions are the same. See the README file on the github repository for details on recreating the paper.

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