

Notes for STAT 5413 - Spatial Statistics

John Tipton

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Preface

These are the lecture notes for STAT 5413 Fall 2020.

Chapter 1

Day 1

```
library(tidyverse)
```

1.1 Notation

The dimensions of different mathematical objects are very important for the study of spatial statistics. To communicate this, we use the following notation. A scalar random variable is represented by a lowercase alphanumeric letter (x , y , z , etc.), a vector random variable is represented by a bold lowercase alphanumeric letter (\mathbf{x} , \mathbf{y} , \mathbf{z} , etc.), and a matrix random variable is represented by a bold uppercase alphanumeric letter (\mathbf{X} , \mathbf{Y} , \mathbf{Z} , etc.). We use a similar notation for parameters as well where scalar parameters are represented by a lowercase Greek letter (μ , α , β , etc.), a vector parameter is represented by a bold lowercase Greek letter ($\boldsymbol{\mu}$, $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, etc.), and a matrix random variable is represented by a bold uppercase Greek letter (Σ , Ψ , Γ , etc.).

1.2 Probability Distributions

We also need notation to explain probability distributions. We use the notation $[y]$ to denote the probability density function $p(y)$ of the random variable y and $[y|x]$ to denote the probability density function $p(y|x)$ of y given x . For example, if y is a Gaussian random variable with mean μ and standard deviation σ we write

$$[y|\mu, \sigma] = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{1}{2\sigma^2}(y - \mu)^2\right\}.$$

We can also denote that y has a Gaussian (normal) distribution given mean μ and variance σ^2 using the \sim notation

$$y|\mu, \sigma \sim N(\mu, \sigma^2).$$

1.2.1 Example: linear regression

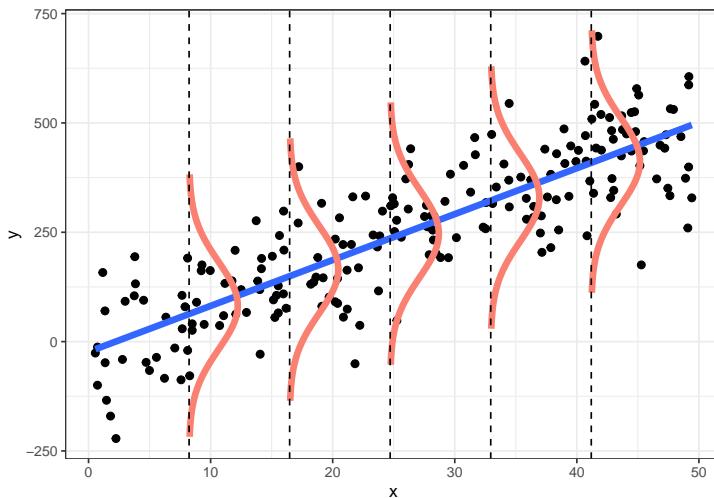
$$\begin{aligned}[y_i|\theta] &\sim N(X_i\beta, \sigma^2) \\ \theta &= (\beta, \sigma^2)\end{aligned}$$

```
## Sample data
set.seed(404)
dat <- data.frame(x=(x=rnorm(200, 0, 50)),
                   y=rnorm(200, 10 * x, 100))

## breaks: where you want to compute densities
breaks <- seq(0, max(dat$x), len=7)[-c(1, 7)]
dat$section <- cut(dat$x, breaks)

## Get the residuals
dat$res <- residuals(lm(y ~ x, data=dat))

## Compute densities for each section, and flip the axes, and add means of sections
## Note: the densities need to be scaled in relation to the section size (2000 here)
ys <- seq(-300, 300, length = 50)
xs <- rep(breaks, each = 50) + 1000 * dnorm(ys, 0, 100)
res <- matrix(0, 50, 5)
for (i in 1:5) {
  res[, i] <- 10 * breaks[i] + ys
}
dens <- data.frame(x = xs, y=c(res),
                     grouping = cut(xs, breaks))
gplot(dat, aes(x, y)) +
  geom_point(size = 2) +
  geom_smooth(method="lm", fill=NA, lwd=2, se = FALSE) +
  geom_path(data=dens, aes(x, y, group = grouping),
            color="salmon", lwd=2) +
  theme_bw() +
  geom_vline(xintercept=breaks, lty=2)
```



1.3 Hierarchical modeling

- Follow Berliner (1996) framework for hierarchical probability models
- Model encodes our understanding of the scientific process of interest
- Model accounts for as much uncertainty as possible
- Model results in a probability distribution
 - Note: nature may be deterministic – often probabilistic models outperform physical models.
 - Example: model individual rain drops vs. probability/intensity of rain
- Update model with data
- Use the model to generate parameter estimates given data

1.3.1 Bayesian Hierarchical models (BHMs)

- Break the model into components:
 - Data Model.
 - Process Model.
 - Parameter Model.

- Combined, the data model, the process model, and the parameter model define a posterior distribution.

$$[\mathbf{z}, \theta_D, \theta_P | \mathbf{y}] \propto [\mathbf{y} | \theta_D, \mathbf{z}] [\mathbf{z} | \theta_P] [\theta_D] [\theta_P]$$

1.3.2 Empirical Hierarchical models (EHMs)

- Break the model into components:
 - Data Model.
 - Process Model.
 - Parameter estimates (fixed values) are substituted before fitting the model
- Combined, the data model and the process model define a predictive distribution. Thus, numerical evaluation of the predictive distribution is typically required to estimate uncertainty (bootstrap, MLE asymptotics)
 - Note: the predictive distribution is not a posterior distribution because the normalizing constant is not known

$$[\mathbf{z} | \mathbf{y}] \propto [\mathbf{y} | \theta_D, \mathbf{z}] [\mathbf{z} | \theta_P]$$

1.3.3 Data Model

$$[\mathbf{y} | \theta_D, \mathbf{z}]$$

- Describes how the data are collected and observed.
- Account for measurement process and uncertainty.
- Model the data in the manner in which they were collected.
- Data \mathbf{y} .
 - Noisy.
 - Expensive.
 - Not what you want to make inference on.
- Latent variables \mathbf{z} .

- Think of \mathbf{z} as the ideal data.
- No measurement error - the exact quantity you want to observe but can't.
- Data model parameters θ_D .

1.3.4 Process Model

$$[\mathbf{z}|\theta_P]$$

- **Where the science happens!**
- Latent process \mathbf{z} is modeled.
- Can be dynamic in space and/or time
- Process parameters θ_P .
- Virtually all interesting scientific questions can be made with inference about \mathbf{z}

1.3.5 Parameter (Prior) Model (BMs only)

$$[\theta_D][\theta_P]$$

- Probability distributions define “reasonable” ranges for parameters.
- Parameter models are useful for a variety of problems:
 - Choosing important variables.
 - Preventing over-fitting (regularization).
 - “Pooling” estimates across categories.

1.3.6 Posterior Distribution

$$[\mathbf{z}, \theta_D, \theta_P | \mathbf{y}] \propto [\mathbf{y} | \theta_D, \mathbf{z}] [\mathbf{z} | \theta_P] [\theta_D | \theta_P]$$

- Probability distribution over all unknowns in the model.
- Inference is made using the posterior distribution.
- Because the posterior distribution is a probability distribution (BMs), uncertainty is easy to calculate. This is not true for EHMs.

1.3.7 Scientifically Motivated Statistical Modeling

- Criticize the model
- Does the model fit the data well?
- Do the predictions make sense?
- Are there subsets of the data that don't fit the model well?
- Make inference using the model.
- If the model fits the data, use the model fit for prediction or inference.

Chapter 2

Day 2

```
library(tidyverse)
library(here)
library(sp)
library(spatstat)
```

2.1 Spatial Data

All data occur at some location in space and time. For now we focus on spatial analyses and will later extend this to spatio-temporal analyses. Let \mathcal{D} represent the spatial domain and let s be a spatial location. In general, we will let $\mathcal{A} \subset \mathcal{D}$ be a subdomain of the spatial region of \mathbf{D} .

Insert Diagram from class here

2.2 Types of spatial data

There are three primary types of spatial data that we are going to consider

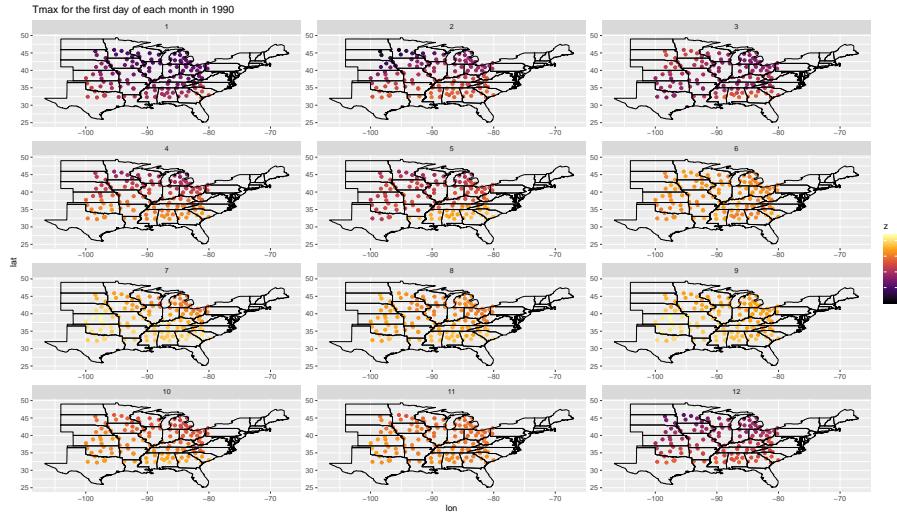
2.2.1 Geostatistical data

- Occur everywhere
- continuous support
- examples: temperature, precipitation

```
data("NOAA_df_1990", package = "STRbook")
glimpse(NOAA_df_1990)
```

```
## Observations: 730,486
## Variables: 10
## $ julian <int> 726834, 726835, 726836, 726837, 726838, 726839, 726840, 7268...
## $ year <int> 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, ...
## $ month <int> 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ...
## $ day <int> 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 1...
## $ id <dbl> 3804, 3804, 3804, 3804, 3804, 3804, 3804, 3804, 3804, 3804, ...
## $ z <dbl> 35, 42, 49, 59, 41, 45, 46, 42, 54, 43, 52, 38, 32, 43, 53, ...
## $ proc <chr> "Tmax", "Tmax", "Tmax", "Tmax", "Tmax", "Tmax", "Tmax", "Tma...
## $ lat <dbl> 39.35, 39.35, 39.35, 39.35, 39.35, 39.35, 39.35, 39.35, 39.3...
## $ lon <dbl> -81.43333, -81.43333, -81.43333, -81.43333, -81.43333, -81.4...
## $ date <date> 1990-01-01, 1990-01-02, 1990-01-03, 1990-01-04, 1990-01-05,...
```

```
## Only plot the states with data
states <- map_data("state")
states <- states %>%
  subset(!region %in% c("washington", "oregon", "california", "nevada", "idaho", "u...
  )
## generate map
NOAA_df_1990 %>%
  subset(year == 1990 & day == 1 & proc == "Tmax") %>%
  ggplot(aes(x = lon, y = lat, color = z)) +
  geom_point() +
  facet_wrap(~ month, scales = "free", nrow = 4) +
  geom_polygon(data = states, aes(x = long, y = lat, group = group),
               inherit.aes = FALSE, fill = NA, color = "black") +
  scale_color_viridis_c(option = "inferno") +
  ggtitle("Tmax for the first day of each month in 1990")
```



2.2.2 Areal data

- Occur only over discrete areas
- can be thought of as an integral of a continuous process over a subdomain $\mathcal{A} \in \mathcal{D}$
- examples: cases of a disease by counties, votes in an election by congressional district

```
data("BEA", package = "STRbook")
glimpse(BEA)
```

```
## Observations: 116
## Variables: 5
## $ Description <chr> "Per capita personal income (dollars)", "Per capita per...
## $ NAME10      <fct> "Adair, MO", "Andrew, MO", "Atchison, MO", "Audrain, MO...
## $ X1970       <int> 2723, 3577, 3770, 3678, 3021, 2832, 3263, 2508, 2147, 3...
## $ X1980       <int> 7399, 7937, 5743, 8356, 7210, 7445, 8596, 6125, 5431, 9...
## $ X1990       <int> 12755, 15059, 14748, 15198, 12873, 13530, 13195, 11854,...
```

```
data("MOcounties", package = "STRbook")
glimpse(MOcounties)
```

```
## Observations: 214,279
## Variables: 53
## $ long        <dbl> 627911.9, 627921.4, 627923.0, 627947.8, 627956.5, 627994...
## $ lat         <dbl> 4473554, 4473559, 4473560, 4473577, 4473583, 4473612, 44...
```

```

## $ order      <int> 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 1...
## $ hole       <lgl> FALSE, FALSE, FALSE, FALSE, FALSE, FALSE, FALSE, FALSE, ...
## $ piece      <fct> 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ...
## $ id         <chr> "0", "0", "0", "0", "0", "0", "0", "0", "0", "0", "0", "0", "0", ...
## $ group      <fct> 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0...
## $ STATEFP10   <fct> 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, 29, ...
## $ COUNTYFP10  <fct> 045, 045, 045, 045, 045, 045, 045, 045, 045, 045, 045, 045, 045, 0...
## $ COUNTYNS10   <fct> 00758477, 00758477, 00758477, 00758477, 00758477, 00758477, 007584...
## $ GEOID10     <fct> 29045, 29045, 29045, 29045, 29045, 29045, 29045, 29045, 29045, ...
## $ NAME10      <fct> "Clark, MO", "Clark, MO", "Clark, MO", "Clark, MO", "Cla...
## $ NAMELSAD10  <fct> Clark County, Clark County, Clark County, Clark County, ...
## $ LSAD10       <fct> 06, 06, 06, 06, 06, 06, 06, 06, 06, 06, 06, 06, ...
## $ CLASSFP10   <fct> H1, ...
## $ MTFCC10     <fct> G4020, G4020, G4020, G4020, G4020, G4020, G4020, G4020, ...
## $ CSAFP10     <fct> NA, ...
## $ CBSAfp10    <fct> 22800, 22800, 22800, 22800, 22800, 22800, 22800, ...
## $ METDIVFP10  <fct> NA, ...
## $ FUNCSTAT10  <fct> A, ...
## $ ALAND10     <dbl> 1307146971, 1307146971, 1307146971, 1307146971, 13071469...
## $ AWATER10    <dbl> 18473547, 18473547, 18473547, 18473547, 18473547, 184735...
## $ INTPTLAT10 <fct> +40.4072748, +40.4072748, +40.4072748, +40.4072748, +40....
## $ INTPTLON10  <fct> -091.7294720, -091.7294720, -091.7294720, -091.7294720, ...
## $ AREA        <dbl> 1324937990, 1324937990, 1324937990, 1324937990, 13249379...
## $ PERIMETER   <dbl> 161503.6, 161503.6, 161503.6, 161503.6, 161503.6, 161503...
## $ COUNTY10_    <int> 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, ...
## $ COUNTY10_I   <int> 115, 115, 115, 115, 115, 115, 115, 115, 115, 115, 115, 1...
## $ POP90       <int> 7547, 7547, 7547, 7547, 7547, 7547, 7547, 7547, 75...
## $ WHITE90    <int> 7528, 7528, 7528, 7528, 7528, 7528, 7528, 7528, 75...
## $ BLACK90    <int> 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, ...
## $ ASIANPI90  <int> 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, ...
## $ AMIND90    <int> 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, ...
## $ OTHER90    <int> 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, ...
## $ HISP90     <int> 26, 26, 26, 26, 26, 26, 26, 26, 26, 26, 26, 26, 26, ...
## $ POP00       <int> 7416, 7416, 7416, 7416, 7416, 7416, 7416, 7416, 7416, ...
## $ WHITE00    <int> 7329, 7329, 7329, 7329, 7329, 7329, 7329, 7329, 7329, ...
## $ BLACK00    <int> 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, ...
## $ ASIAN00    <int> 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, ...
## $ AMIND00    <int> 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, 15, ...
## $ HAWNPI00  <int> 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, ...
## $ OTHER00    <int> 16, 16, 16, 16, 16, 16, 16, 16, 16, 16, 16, 16, 16, ...
## $ MULTRA00   <int> 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, 45, ...
## $ HISPO0     <int> 52, 52, 52, 52, 52, 52, 52, 52, 52, 52, 52, 52, 52, ...
## $ POP10       <int> 7139, 7139, 7139, 7139, 7139, 7139, 7139, 7139, 71...
## $ WHITE10    <int> 7011, 7011, 7011, 7011, 7011, 7011, 7011, 7011, 70...
## $ BLACK10    <int> 19, 19, 19, 19, 19, 19, 19, 19, 19, 19, 19, 19, 19, ...
## $ ASIAN10    <int> 23, 23, 23, 23, 23, 23, 23, 23, 23, 23, 23, 23, ...

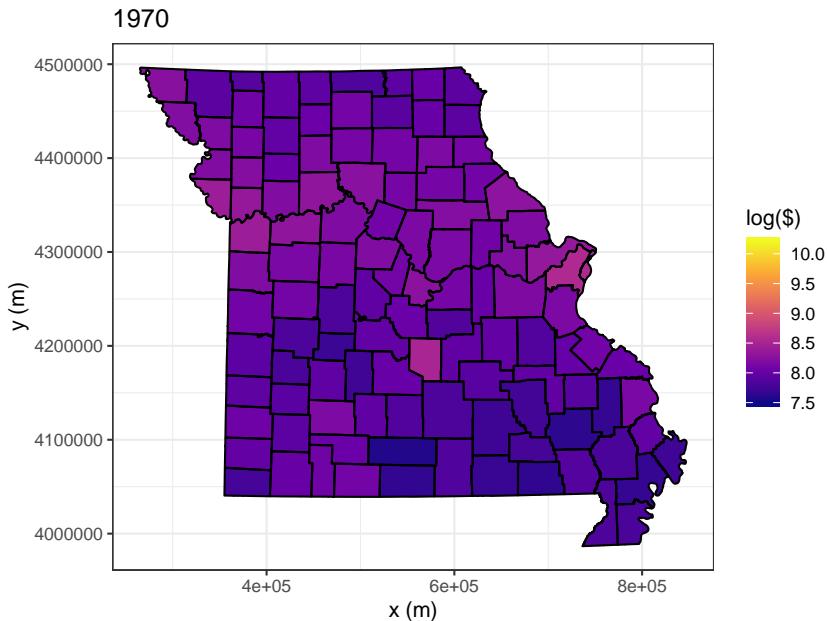
```

```

## $ AMIND10      <int> 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, 9, ...
## $ HAWNPI10    <int> 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, ...
## $ OTHER10     <int> 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, ...
## $ MULTRA10    <int> 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, 72, ...
## $ HISPI10      <int> 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, 42, ...
M0counties <- left_join(M0counties, BEA, by = "NAME10")

ggplot(M0counties) +
  geom_polygon(aes(x = long,
                    y = lat, # county boundary
                    group = NAME10, # county group
                    fill = log(X1970))) + # log of income
  geom_path(aes(x = long, y = lat, group = NAME10)) +
  scale_fill_viridis_c(limits = c(7.5, 10.2), option = "plasma", name = "log($)") +
  coord_fixed() +
  ggtitle("1970") +
  xlab("x (m)") +
  ylab("y (m)") +
  theme_bw()

```



2.2.3 Point process data

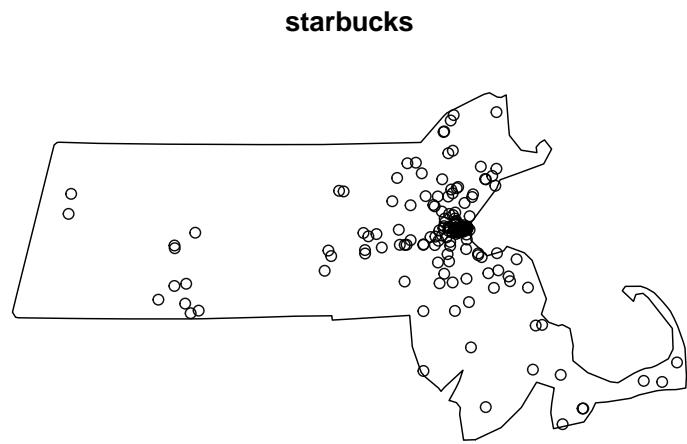
- The count and location of the data are random

- examples: tornados, lightning strikes

```
# uncomment out this line to download the data
# load(url("http://github.com/mgimond/Spatial/raw/master/Data/ppa.RData"))
# save(starbucks, ma, pop, file = here::here("data", "ppa-starbucks.RData"))
load(here::here("data", "ppa-starbucks.RData"))
glimpse(starbucks)
```

```
## List of 5
## $ window      :List of 4
##   ..$ type     : chr "rectangle"
##   ..$ xrange   : num [1:2] 648032 917741
##   ..$ yrange   : num [1:2] 4609785 4748107
##   ..$ units    :List of 3
##     ..$ singular : chr "unit"
##     ..$ plural   : chr "units"
##     ..$ multiplier: num 1
##     ... - attr(*, "class")= chr "unitname"
##   ..- attr(*, "class")= chr "owin"
## $ n           : int 171
## $ x           : num [1:171] 917741 911147 902987 876188 875868 ...
## $ y           : num [1:171] 4637151 4628510 4628982 4616741 4616719 ...
## $ markformat: chr "none"
## - attr(*, "class")= chr "ppp"
```

```
## uses spatstat library
## add the massachusetts polygon
Window(starbucks) <- ma
marks(starbucks) <- NULL
## plot using the plot function from spatstat
plot(starbucks)
```



Chapter 3

Day 3

```
library(tidyverse)
library(here)
library(sp)
```

3.1 Anouncements

- Show GitHub page for site <https://github.com/jtipton25/STAT-5413>
 - Show how to download files and data

3.2 Files for spatial data

- Many different file types for spatial data
- Typically data are in “flat files” like comma-separated value (CSV) files

```
read.csv(here("path", "to", "file.csv"))
```

- “shapefiles” which can be read using *rgdal* or *maptools* packages

```
library(rgdal)
library(maptools)
```

- “NetCDF” files can be read using *ncdf4* or *RNetCDF*

```
library(ncdf4)
library(RNetCDF)
```

3.3 Textbook package

To install the data from the textbook, go to <https://spacetimewithr.org/> and follow the link to the code.

```
# install.packages("devtools")
library(devtools)
install_github("andrewzm/STRbook")
```

Note that this package is relatively large because it contains a decent amount of spatial data.

```
library(STRbook)

##
## Attaching package: 'STRbook'

## The following object is masked _by_ '.GlobalEnv':
##      MOcounties
```

3.4 Spatial Visualization

3.4.1 Spatial visualization using *fields*

- Simulate a process with some random locations

```
library(fields)

## Loading required package: spam

## Loading required package: dotCall164

## Loading required package: grid
```

```
## Spam version 2.5-1 (2019-12-12) is loaded.
## Type 'help( Spam)' or 'demo( spam)' for a short introduction
## and overview of this package.
## Help for individual functions is also obtained by adding the
## suffix '.spam' to the function name, e.g. 'help( chol.spam)'.

##
## Attaching package: 'spam'

## The following objects are masked from 'package:base':
##       backsolve, forwardsolve

## Loading required package: maps

##
## Attaching package: 'maps'

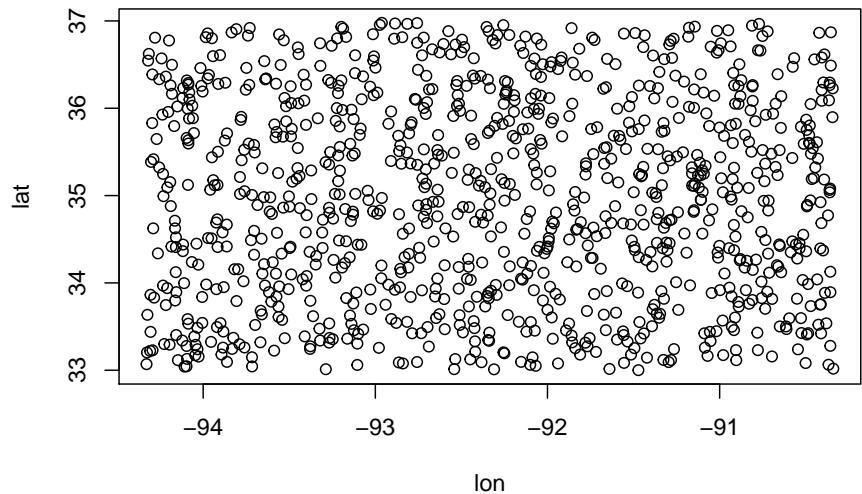
## The following object is masked from 'package:purrr':
##       map

## See https://github.com/NCAR/Fields for
## an extensive vignette, other supplements and source code

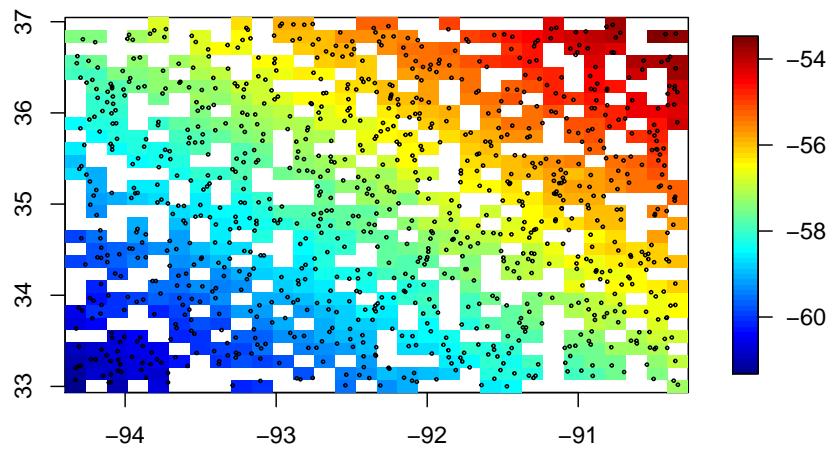
## longitude and latitude of approximately the center of Arkansas
lon_lat_center <- c(-92.33, 35.00)

n   <- 1000
## simulate some random locations
lon  <- runif(n, lon_lat_center[1] - 2, lon_lat_center[1] + 2)
lat  <- runif(n, lon_lat_center[2] - 2, lon_lat_center[2] + 2)
y    <- rnorm(n, lat + lon, .1)

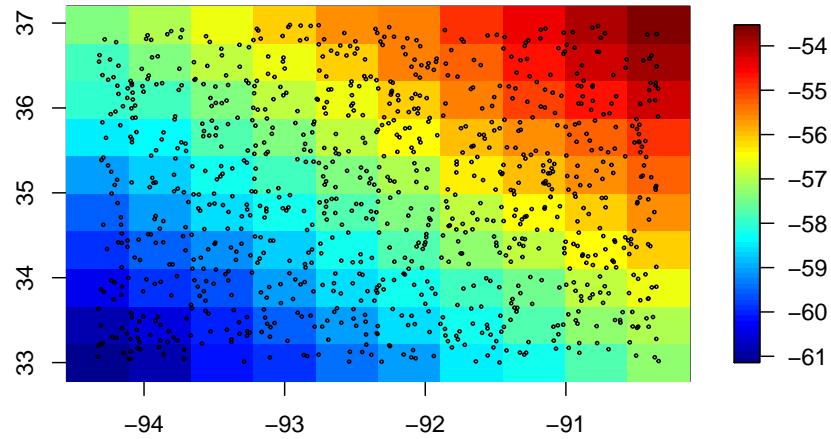
plot(lon, lat)
```



```
quilt.plot(lon, lat, nx = 30, ny = 30)
points(lon, lat, cex = .3)
```



```
quilt.plot(lon, lat, nx = 10, ny = 10)
points(lon, lat, cex = .3)
```



- Simulate a process on a regular grid

```
n <- 50^2
## simulate locations on a grid
lon <- seq(lon_lat_center[1] - 2, lon_lat_center[1] + 2, length = sqrt(n))
lat <- seq(lon_lat_center[2] - 2, lon_lat_center[2] + 2, length = sqrt(n))
s <- expand.grid(lon, lat)

head(lon)

## [1] -94.33000 -94.24837 -94.16673 -94.08510 -94.00347 -93.92184

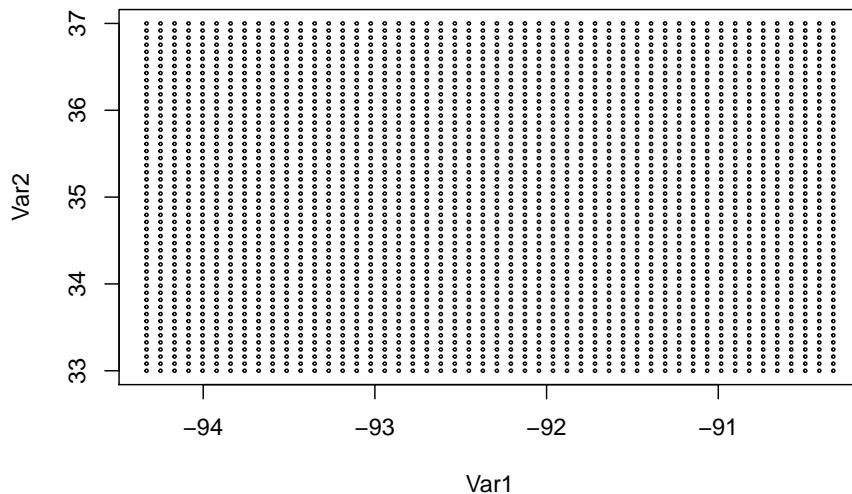
head(lat)

## [1] 33.00000 33.08163 33.16327 33.24490 33.32653 33.40816

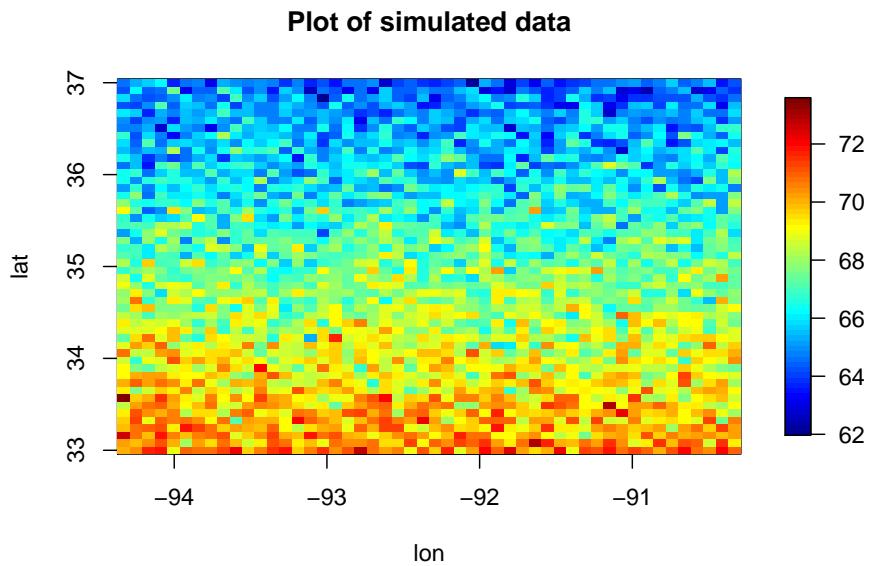
head(s)
```

```
##          Var1 Var2
## 1 -94.33000   33
## 2 -94.24837   33
## 3 -94.16673   33
## 4 -94.08510   33
## 5 -94.00347   33
## 6 -93.92184   33
```

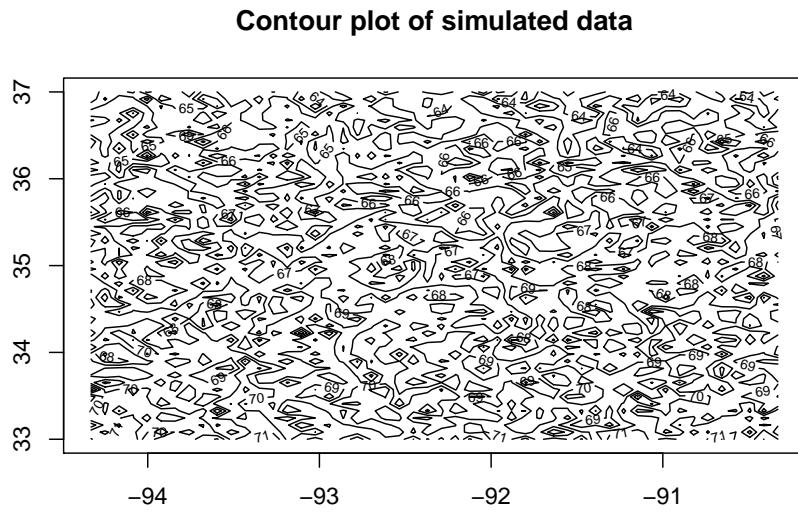
```
plot(s, cex = 0.3)
```



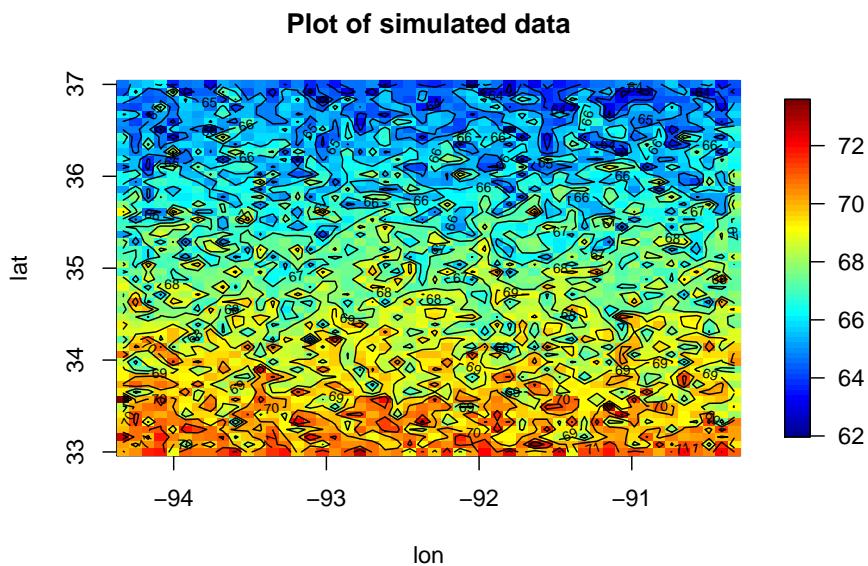
```
## simulate some fake data with a north/south trend
y <- 120 - 1.5 * s[, 2] + matrix(rnorm(n), sqrt(n), sqrt(n))
image.plot(lon, lat, y, main = "Plot of simulated data")
```



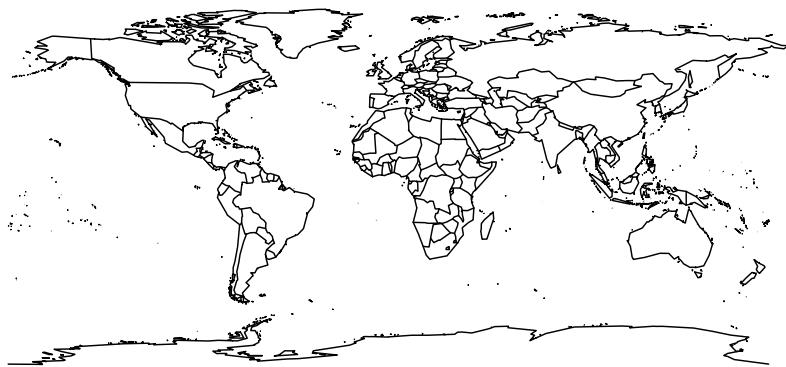
```
contour(lon, lat, y, main = "Contour plot of simulated data")
```



```
image.plot(lon, lat, y, main = "Plot of simulated data")
contour(lon, lat, y, main = "Contour plot of simulated data", add = TRUE,
        nlevels = 10)
```



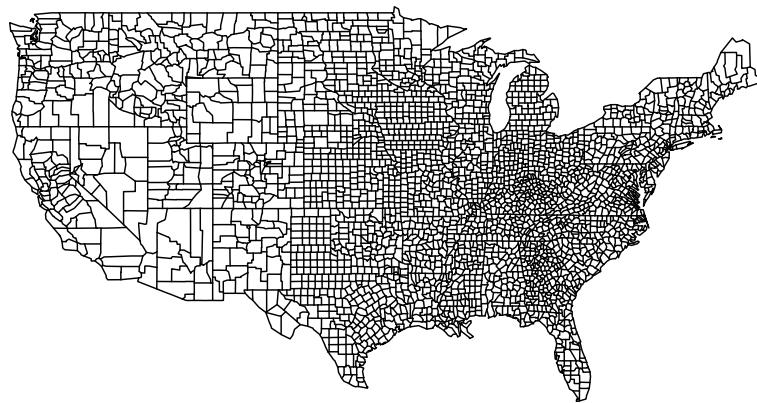
```
## adding in maps
library(maps)
maps::map("world")
```



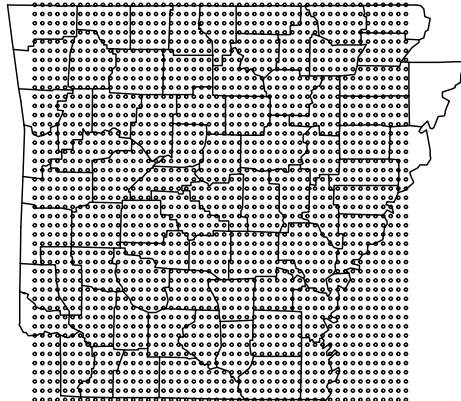
```
maps::map("state")
```



```
maps::map("county")
```



```
maps::map("county", "Arkansas")
points(s, cex = 0.3)
```



```
state <- map.where("state", x = s[, 1], y = s[, 2])
head(state)

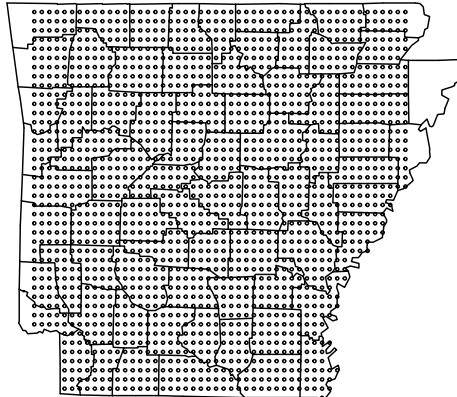
## [1] "texas"      "texas"      "texas"      "texas"      "louisiana"  "louisiana"

table(state)

## state
##   arkansas    louisiana mississippi    missouri      texas
##       1903          34         180          351          32

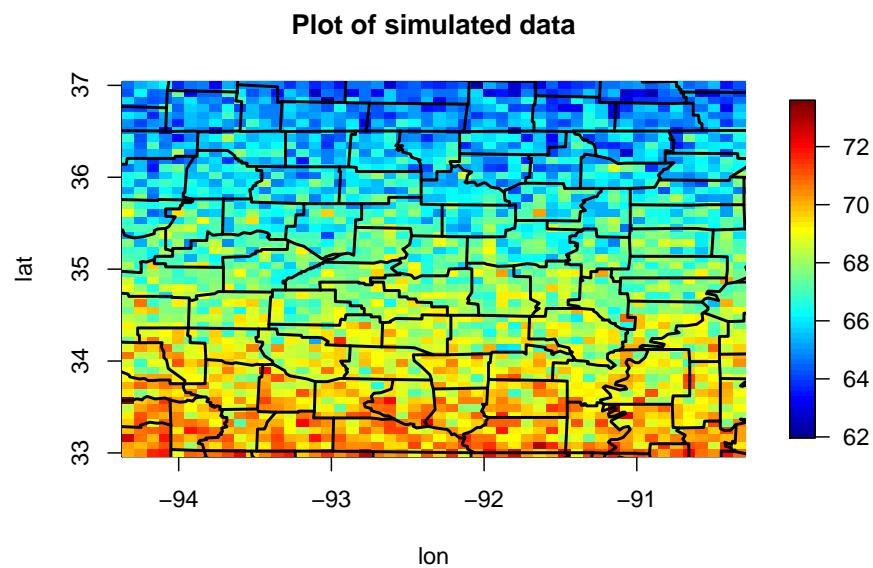
## subset only points in arkansas
dat <- data.frame(
  lon   = s[, 1],
  lat   = s[, 2],
  state = state
)

maps::map("county", "Arkansas")
dat %>%
  subset(state == "arkansas") %>%
  points(cex = 0.3)
```

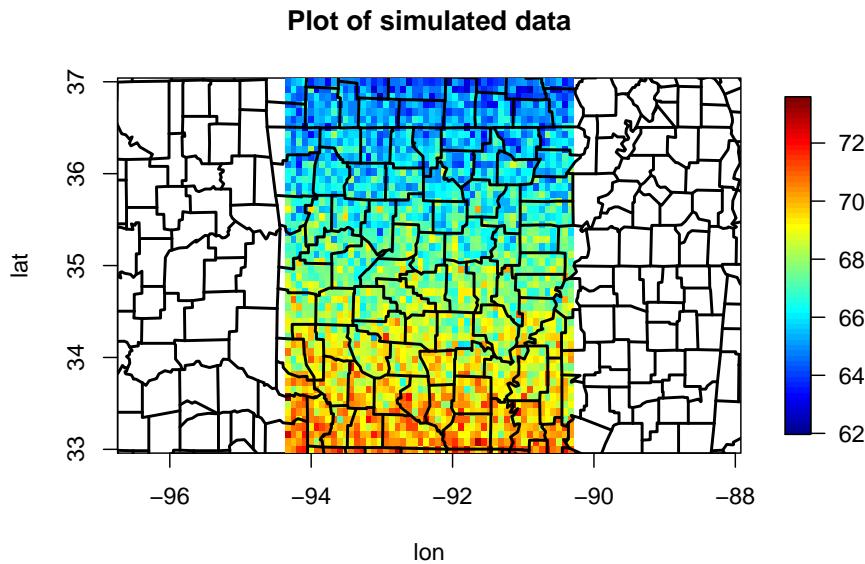


Plot the simulated data with the county boundaries

```
image.plot(lon, lat, y, main = "Plot of simulated data")
maps::map("county", add = TRUE, lwd = 2)
```



```
## change the aspect ratio
image.plot(lon, lat, y, main = "Plot of simulated data", asp = 1.3)
maps::map("county", add = TRUE, lwd = 2)
```



3.4.2 Spatial visualization using *fields*

```
nx <- 100
ny <- 100

library(maps) # for map.where

# Corner of the USA
corners <- c(-124.733056, -66.947028, 24.520833, 49.384472)

# create grid
grid <- expand.grid(
  seq(corners[1], corners[2], length = nx),
  seq(corners[3], corners[4], length = ny)
)

dat <- data.frame(
  lon = grid[, 1],
```

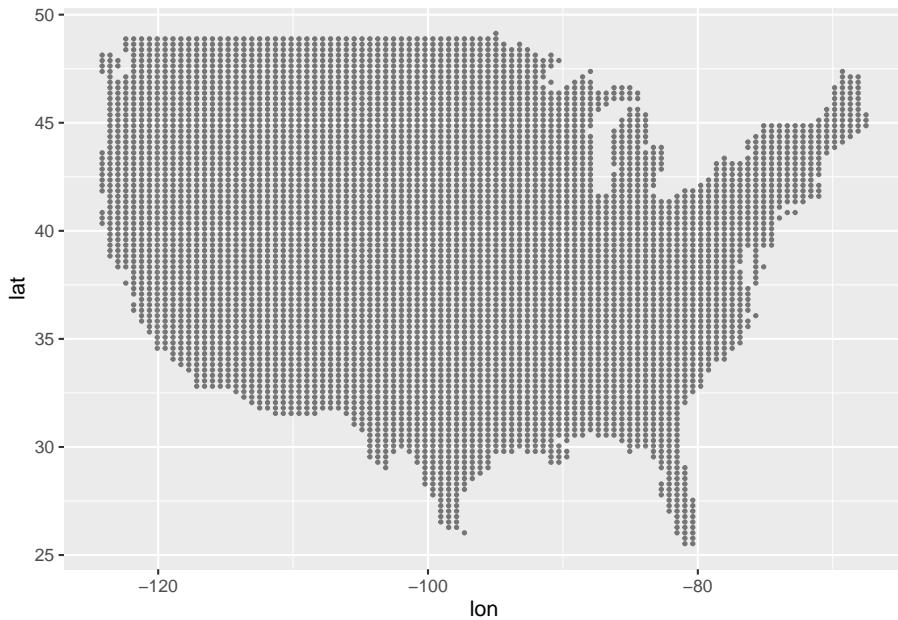
```

lat  = grid[, 2],
inUS = ifelse(is.na(map.where("usa", x = grid[, 1], y = grid[, 2])), FALSE, TRUE)
)

## Plot only points in the us

dat %>%
  subset(inUS) %>% ## this selects only the true values
  ggplot(aes(x = lon, y = lat)) +
  geom_point(size = 0.6, alpha = 0.5)

```

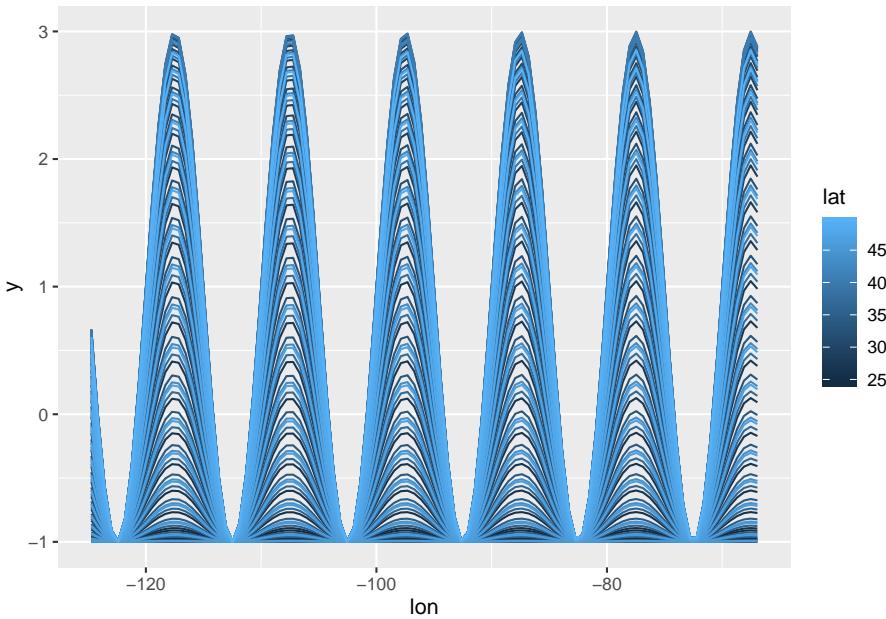


```

## Simulate some data over the grid
dat$y <- sin(2 * pi * dat$lon / 10) + cos(2 * pi * dat$lat / 10) +
  sin(2 * pi * dat$lon / 10) * cos(2 * pi * dat$lat / 10)

## plot each of the responses grouped by latitude
dat %>%
  ggplot(aes(x = lon, y = y, group = lat, color = lat)) +
  geom_line()

```



```
## Function to generate maps
map_points <- function (dat,
                         color_low = "white", color_high = "darkred",
                         color_na = gray(0.9), zeroiswhite = FALSE,
                         xlim = NULL, ylim = NULL, zlim = NULL,
                         mainTitle = NULL, legendTitle = "") {
  library(ggplot2)

  ## check if the data.frame dat contains the correct variables
  if (is.null(dat$lon)) { stop('The data.frame dat must contain a "lon" variable') }
  if (is.null(dat$lat)) { stop('The data.frame dat must contain a "lat" variable') }
  if (is.null(dat$y)) { stop('The data.frame dat must contain a "y" variable') }

  # Store the base data of the underlying map
  states <- map_data("state")

  # Set limits for x, y, z if not specified as parameters
  if (is.null(xlim)) { xlim <- range(dat$lon, na.rm = TRUE) }
  if (is.null(ylim)) { ylim <- range(dat$lat, na.rm = TRUE) }
  if (is.null(zlim)) { zlim <- range(dat$y, na.rm = TRUE) }

  # Create the plot
  p <- ggplot(dat, aes(x = lon, y = lat)) +
    theme_bw()
  p <- p + theme(plot.title = element_text(size = rel(1.5)))
}
```

```

p <- p + geom_point(aes(colour = y))
## add in the map
p <- p + geom_polygon(data = states, aes(x = long, y = lat, group = group),
                       colour = "black", fill = NA)
## a 1.3 coordinate ratio is visually appealing
p <- p + coord_fixed(ratio = 1.3, xlim = xlim, ylim = ylim)
p <- p + labs(title = paste(mainTitle, "\n", sep=""), x = "", y = "")
if(zeroiswhite){
  p <- p + scale_colour_gradient2(
    low      = color_low,
    high     = color_high,
    na.value = color_na,
    limits   = zlim,
    name     = legendTitle
  )
}
if(!zeroiswhite){
  p <- p + scale_colour_gradient(
    low      = color_low,
    high     = color_high,
    na.value = color_na,
    limits   = zlim,
    name     = legendTitle
  )
}
return(p)
}

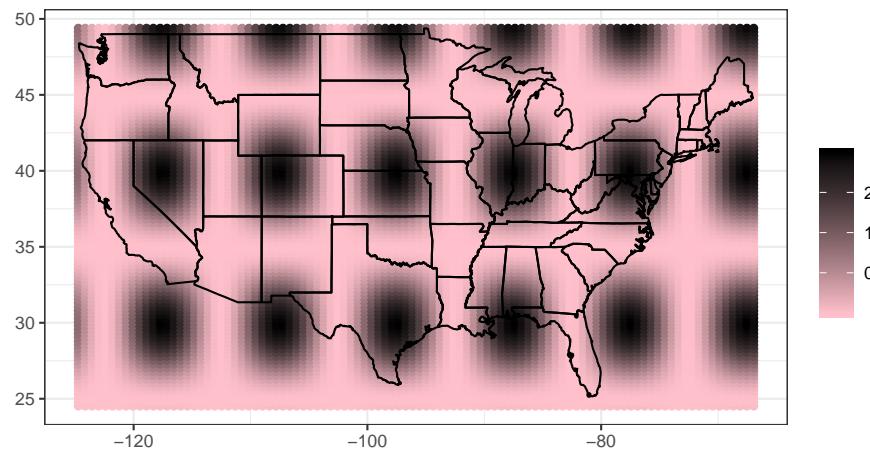
```

```

## Let's make some plots
dat %>%
  map_points(
    color_low  = "pink",
    color_high = "black",
    mainTitle  = "Entire United States"
  )

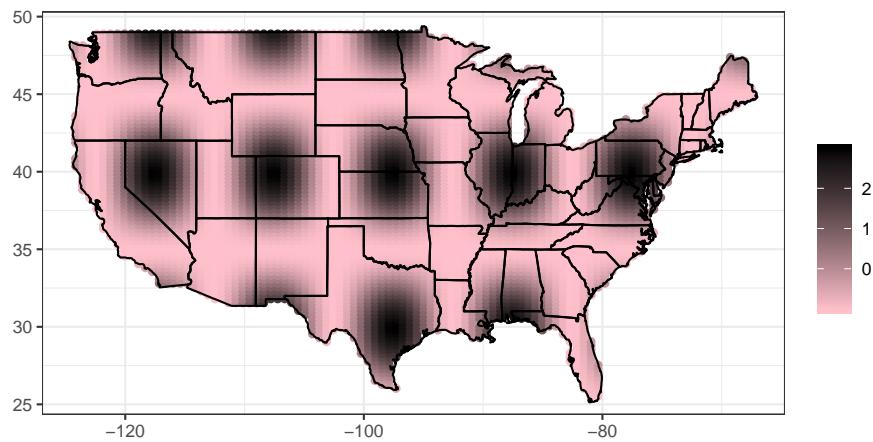
```

Entire United States



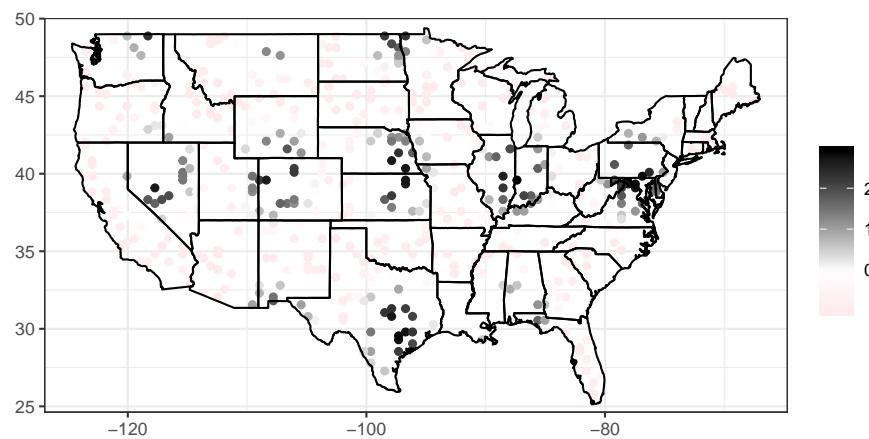
```
## Subset only the US
dat %>%
  subset(inUS) %>%
  map_points(
    color_low  = "pink",
    color_high = "black",
    mainTitle  = "Entire United States"
  )
```

Entire United States



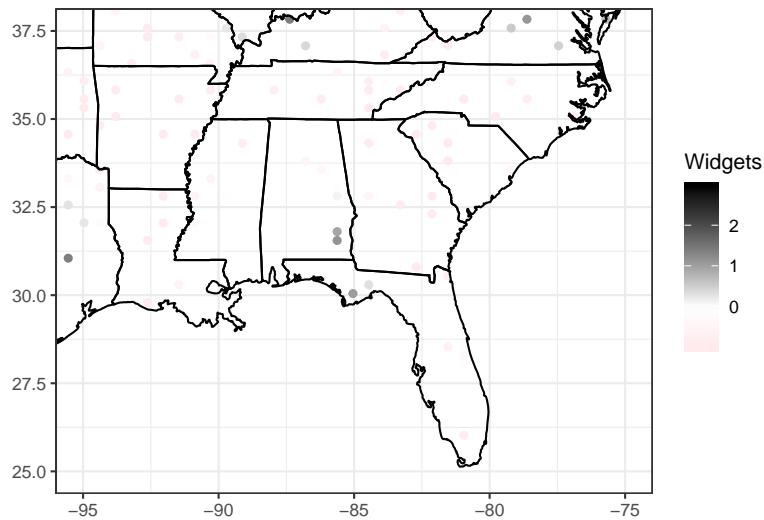
```
## plot only a subset of points
dat %>%
  subset(inUS) %>%
  ## sample 500 points at random
  sample_n(500) %>%
  map_points(
    color_low   = "pink",
    color_high  = "black",
    zeroiswhite = TRUE,
    mainTitle   = "Entire United States"
  )
```

Entire United States



```
## Truncate the southeastern US
dat %>%
  subset(inUS) %>%
  ## sample 500 points at random
  sample_n(500) %>%
  map_points(
    color_low  = "pink",
    color_high = "black",
    zeroiswhite = TRUE,
    xlim       = c(-95, -75),
    ylim       = c(25, 37.5),
    mainTitle  = "Southeastern United States",
    legendTitle = "Widgets"
  )
```

Southeastern United States



Heatmaps can also be used for plotting. In general, there are two ggplot geoms that are useful for spatial data: *geom_tile* is good for irregularly spaced data, *geom_raster* is best for regularly spaced data as it is faster to process.

```
## Function to generate maps
map_heat <- function (dat,
                      color_low = "white", color_high = "darkred",
                      color_na = gray(0.9), zeroiswhite = FALSE,
                      xlim = NULL, ylim = NULL, zlim = NULL,
                      mainTitle = NULL, legendTitle = "",
                      geom = "raster") {
  library(ggplot2)

  ## check if the data.frame dat contains the correct variables
  if (is.null(dat$lon)) { stop('The data.frame dat must contain a "lon" variable') }
  if (is.null(dat$lat)) { stop('The data.frame dat must contain a "lat" variable') }
  if (is.null(dat$y))   { stop('The data.frame dat must contain a "y" variable') }
  if (!geom %in% c("raster", "tile")) { stop('The only options for geom are "raster" or "tile"') }

  # Store the base data of the underlying map
  states <- map_data("state")

  # Set limits for x, y, z if not specified as parameters
  if (is.null(xlim)) { xlim <- range(dat$lon, na.rm = TRUE) }
  if (is.null(ylim)) { ylim <- range(dat$lat, na.rm = TRUE) }
```

```

if (is.null(zlim)) { zlim <- range(dat$y, na.rm = TRUE) }

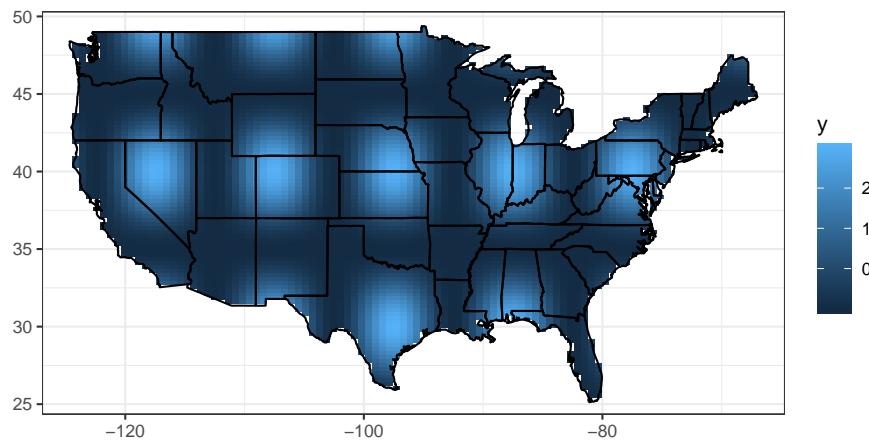
# Create the plot
p <- ggplot(dat, aes(x = lon, y = lat)) +
  theme_bw()
p <- p + theme(plot.title = element_text(size = rel(1.5)))
if (geom == "raster") {
  p <- p + geom_raster(aes(fill = y))
}
if (geom == "tile") {
  p <- p + geom_tile(aes(fill = y))
}
## add in the map
p <- p + geom_polygon(data = states, aes(x = long, y = lat, group = group),
                       colour = "black", fill = NA)
## a 1.3 coordinate ratio is visually appealing
p <- p + coord_fixed(ratio = 1.3, xlim = xlim, ylim = ylim)
p <- p + labs(title = paste(mainTitle, "\n", sep=""), x = "", y = "")
if(zeroiswhite){
  p <- p + scale_colour_gradient2(
    low      = color_low,
    high     = color_high,
    na.value = color_na,
    limits   = zlim,
    name     = legendTitle
  )
}
if(!zeroiswhite){
  p <- p + scale_colour_gradient(
    low      = color_low,
    high     = color_high,
    na.value = color_na,
    limits   = zlim,
    name     = legendTitle
  )
}
return(p)
}

## Subset only the US
dat %>%
  subset(inUS) %>%
  map_heat(
    color_low  = "blue",
    color_high = "yellow",

```

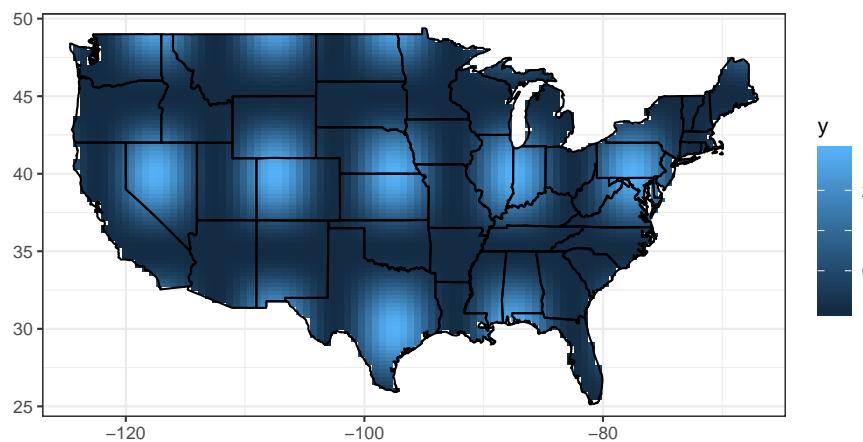
```
    mainTitle = "Entire United States",
    geom = "raster"
)
```

Entire United States



```
## Subset only the US
dat %>%
  subset(inUS) %>%
  map_heat(
    color_low = "blue",
    color_high = "yellow",
    mainTitle = "Entire United States",
    geom = "tile"
)
```

Entire United States

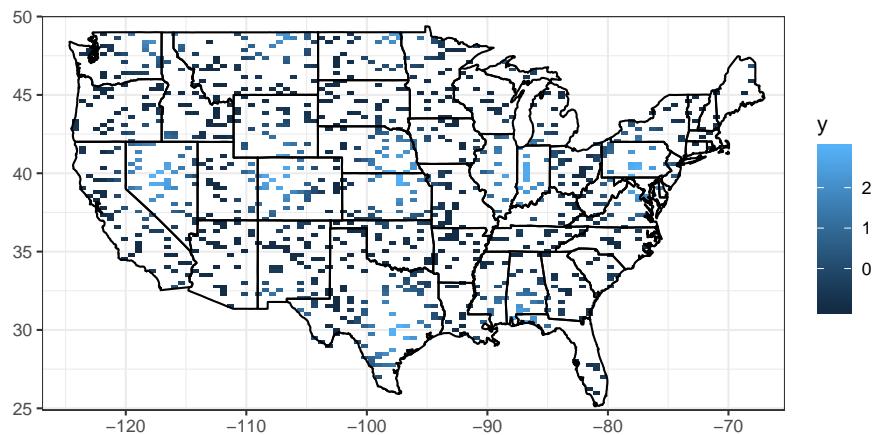


```
## Subsample the data
dat %>%
  subset(inUS) %>%
  sample_n(1000) %>%
  map_heat(
    color_low = "blue",
    color_high = "green",
    mainTitle = "Entire United States",
    geom = "raster"
  )

## Warning in f(...): Raster pixels are placed at uneven horizontal intervals and
## will be shifted. Consider using geom_tile() instead.

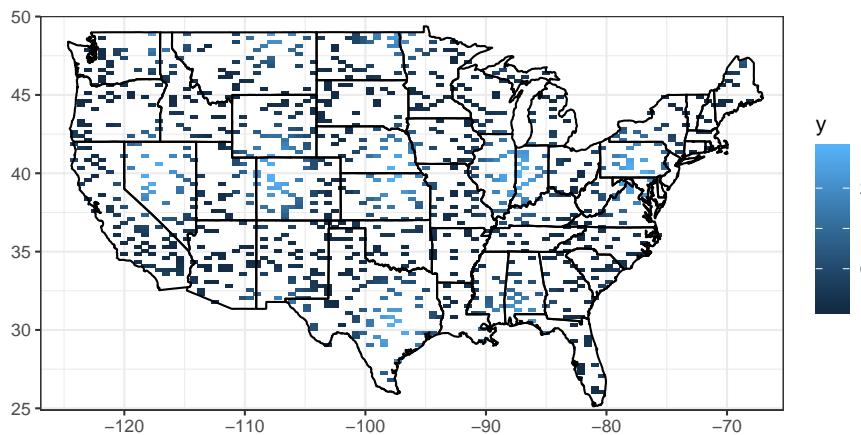
## Warning in f(...): Raster pixels are placed at uneven vertical intervals and
## will be shifted. Consider using geom_tile() instead.
```

Entire United States



```
## Subsample the data
dat %>%
  subset(inUS) %>%
  sample_n(1000) %>%
  map_heat(
    color_low = "pink",
    color_high = "black",
    mainTitle = "Entire United States",
    geom = "tile"
  )
```

Entire United States



- Plotting spatial data using google maps

```
## longitude and latitude of approximately the center of Arkansas
arkansas_center <- c(-92.33, 35.00)

library(maps)
library(ggplot2)
library(ggmap)

## Google's Terms of Service: https://cloud.google.com/maps-platform/terms/.

## Please cite ggmap if you use it! See citation("ggmap") for details.

lon <- arkansas_center[1] + seq(-2, 2, length = 10)
lat <- arkansas_center[2] + seq(-2, 2, length = 10)
s   <- expand.grid(lon, lat)

head(lon)

## [1] -94.33000 -93.88556 -93.44111 -92.99667 -92.55222 -92.10778
```

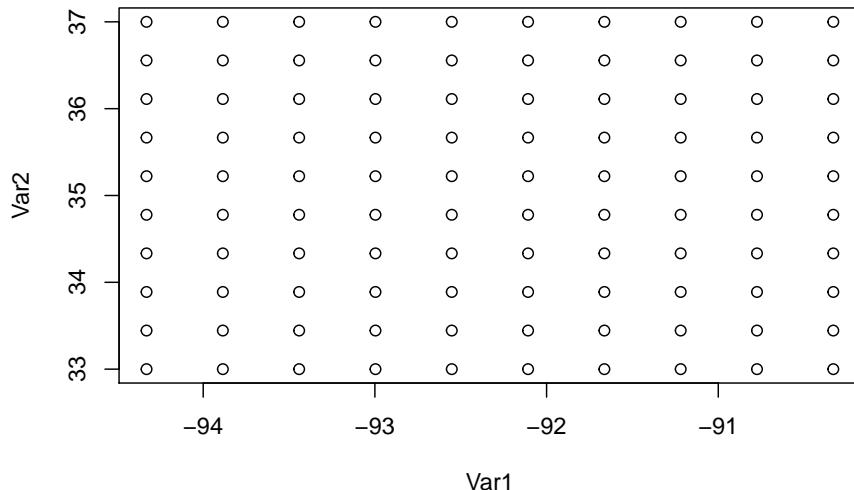
```
head(lat)
```

```
## [1] 33.00000 33.44444 33.88889 34.33333 34.77778 35.22222
```

```
str(s)
```

```
## 'data.frame':   100 obs. of  2 variables:
## $ Var1: num  -94.3 -93.9 -93.4 -93 -92.6 ...
## $ Var2: num  33 33 33 33 33 33 33 33 33 ...
## - attr(*, "out.attrs")=List of 2
##   ..$ dim    : int 10 10
##   ..$ dimnames:List of 2
##     ..$ Var1: chr "Var1=-94.33000" "Var1=-93.88556" "Var1=-93.44111" "Var1=-92.99000"
##     ..$ Var2: chr "Var2=33.00000" "Var2=33.44444" "Var2=33.88889" "Var2=34.33333"
```

```
plot(s)
points(arkansas_center, pch = 19, col = 2)
```



```
dat <- data.frame(lon = lon, lat = lat)
```

Using Google maps requires registration of a key. See <https://www.littlemissdata.com/blog/maps> for details.

- Plotting areal data The example is from <https://www4.stat.ncsu.edu/~reich/SpatialStats/code/Guns.pdf> taken from [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(15\)01026-0/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(15)01026-0/fulltext)

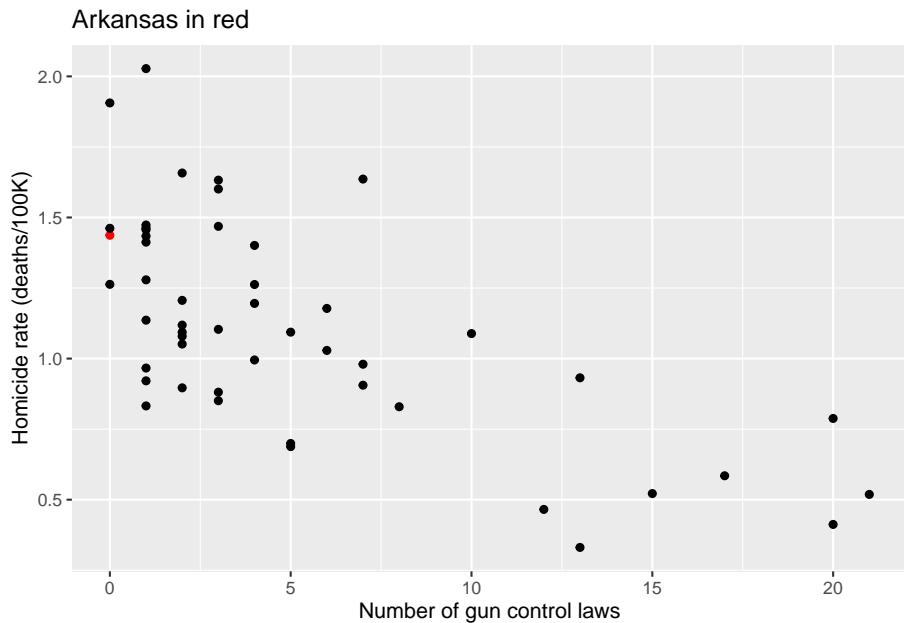
```

## process the guns data
# load(here::here("data", "guns.RData"))
# names(Y)[1:5]
# region <- tolower(names(Y))
# region[1:5]
# rate    <- 10000*Y/N
# numlaws <- rowSums(X)
# crime   <- data.frame(Y=Y, N=N, rate=rate, X=X, numlaws, region=region)
# dat <- data.frame(
#   deaths_2010           = Y,
#   population            = N,
#   deaths_per_10000       = Z[, 1],
#   firearm_quartile      = Z[, 2],
#   unemployment_quartile = Z[, 3],
#   non_firearm_homicide  = Z[, 4],
#   firearm_export_quartile = Z[, 5],
#   numlaws               = apply(X, 1, sum),
#   region                = region
# )
# save(dat, file = here::here("data", "guns_processed.RData"))
load(here::here("data", "guns_processed.RData"))

## mutate a death rate
dat <- dat %>%
  mutate(rate = 10000 * deaths_2010 / population)

dat %>%
  ggplot(aes(x = numlaws, y = rate, color = region == "arkansas")) +
  geom_point() +
  scale_color_manual(values = c("black", "red")) +
  xlab("Number of gun control laws") +
  ylab("Homicide rate (deaths/100K)") +
  ggtitle("Arkansas in red") +
  theme(legend.position = "none")

```



```
lm(rate ~ numlaws, data = dat) %>% summary()
```

```
##
## Call:
## lm(formula = rate ~ numlaws, data = dat)
##
## Residuals:
##      Min       1Q   Median       3Q      Max 
## -0.46715 -0.16720 -0.02576  0.16171  0.72809 
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)    
## (Intercept) 1.344693  0.055145 24.385 < 2e-16 ***
## numlaws     -0.045276  0.007302 -6.201 1.24e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 0.2867 on 48 degrees of freedom
## Multiple R-squared:  0.4448, Adjusted R-squared:  0.4332 
## F-statistic: 38.45 on 1 and 48 DF,  p-value: 1.236e-07
```

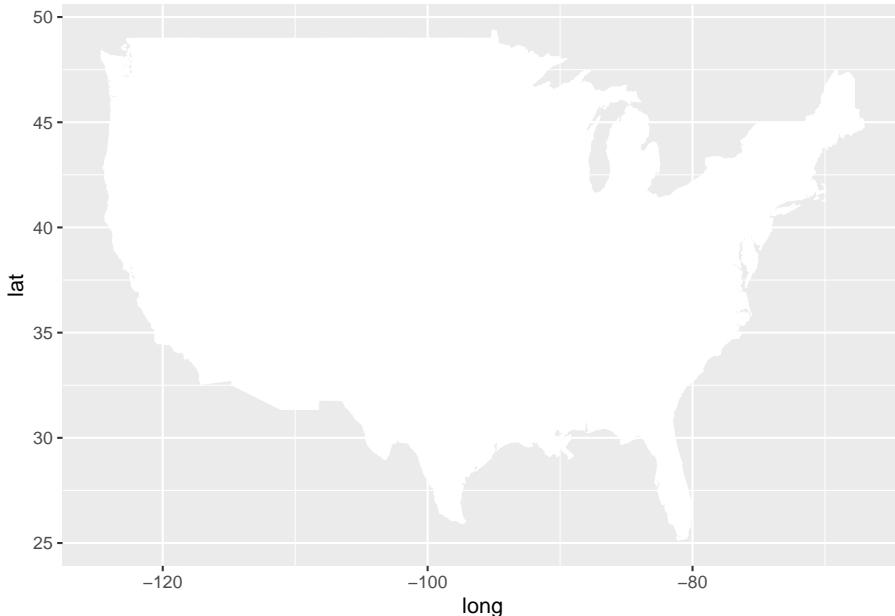
```
us <- map_data("state")
head(us)
```

```
##      long      lat group order  region subregion
## 1 -87.46201 30.38968     1     1 alabama    <NA>
## 2 -87.48493 30.37249     1     2 alabama    <NA>
## 3 -87.52503 30.37249     1     3 alabama    <NA>
## 4 -87.53076 30.33239     1     4 alabama    <NA>
## 5 -87.57087 30.32665     1     5 alabama    <NA>
## 6 -87.58806 30.32665     1     6 alabama    <NA>

gg <- ggplot()
gg <- gg + geom_map(data = us, map = us,
                     aes(x = long, y = lat, map_id = region),
                     fill = "#ffffff", color = "#ffffff", size = 0.15)

## Warning: Ignoring unknown aesthetics: x, y
```

```
gg
```



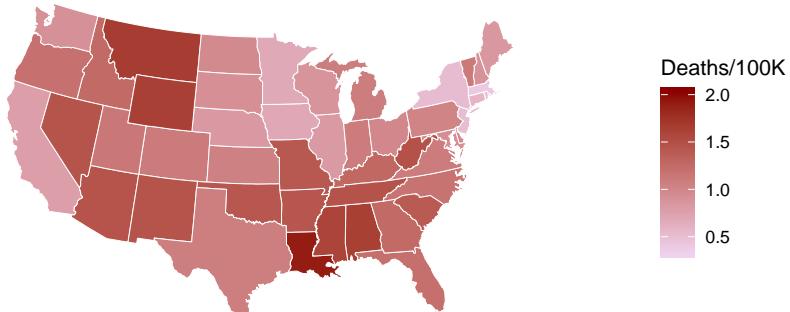
```
gg <- gg + geom_map(
  data = dat,
  map = us,
  aes(fill = rate, map_id = region),
  color = "#ffffff", size = 0.15
)
```

```

gg <- gg + scale_fill_continuous(
  low  = 'thistle2',
  high = 'darkred',
  guide= 'colorbar',
  name = "Deaths/100K"
)
gg <- gg + labs(x = NULL, y = NULL, title = "Homicide rates")
gg <- gg + coord_map("albers", lat0 = 39, lat1 = 45)
gg <- gg + theme(panel.border = element_blank())
gg <- gg + theme(panel.background = element_blank())
gg <- gg + theme(axis.ticks = element_blank())
gg <- gg + theme(axis.text = element_blank())
gg

```

Homicide rates



The map looks right according to

<http://www.deathpenaltyinfo.org/murder-rates-nationally-and-state#MRord>

3.4.3 In Class Activity:

From Lab 2.1 on the textbook site

```

## Wikle, C. K., Zammit-Mangion, A., and Cressie, N. (2019),
## Spatio-Temporal Statistics with R, Boca Raton, FL: Chapman & Hall/CRC
## Copyright (c) 2019 Wikle, Zammit-Mangion, Cressie
##
## This program is free software; you can redistribute it and/or
## modify it under the terms of the GNU General Public License
## as published by the Free Software Foundation; either version 2
## of the License, or (at your option) any later version.
##
## This program is distributed in the hope that it will be useful,
## but WITHOUT ANY WARRANTY; without even the implied warranty of
## MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
## GNU General Public License for more details.

library("dplyr")
library("tidyverse")
library("STRbook")

## -----
locs <- read.table(system.file("extdata", "Stationinfo.dat",
                               package = "STRbook"),
                    col.names = c("id", "lat", "lon"))
Times <- read.table(system.file("extdata", "Times_1990.dat",
                               package = "STRbook"),
                     col.names = c("julian", "year", "month", "day"))
Tmax <- read.table(system.file("extdata", "Tmax_1990.dat",
                               package = "STRbook"))

## -----
names(Tmax) <- locs$id

## -----
Tmax <- cbind(Times, Tmax)
head(names(Tmax), 10)

## -----
Tmax_long <- gather(Tmax, id, z, -julian, -year, -month, -day)
head(Tmax_long)

## -----
Tmax_long$id <- as.integer(Tmax_long$id)

## -----
nrow(Tmax_long)
Tmax_long <- filter(Tmax_long, !(z <= -9998))

```

```

nrow(Tmax_long)

## -----
Tmax_long <- mutate(Tmax_long, proc = "Tmax")
head(Tmax_long)

## -----
data(Tmin_long, package = "STRbook")
data(TDP_long, package = "STRbook")
data(Precip_long, package = "STRbook")

## -----
NOAA_df_1990 <- rbind(Tmax_long, Tmin_long, TDP_long, Precip_long)

## -----
summ <- group_by(NOAA_df_1990, year, proc) %>% # groupings
      summarise(mean_proc = mean(z))           # operation

## -----
NOAA_precip <- filter(NOAA_df_1990, proc == "Precip" & month == 6)
summ <- group_by(NOAA_precip, year, id) %>%
      summarise(days_no_precip = sum(z == 0))
head(summ)

## -----
median(summ$days_no_precip)

## -----
grps <- group_by(NOAA_precip, year, id)
summ <- summarise(grps, days_no_precip = sum(z == 0))

## -----
NOAA_df_sorted <- arrange(NOAA_df_1990, julian, id)

## -----
df1 <- select(NOAA_df_1990, julian, z)
df2 <- select(NOAA_df_1990, -julian)

## -----
NOAA_df_1990 <- left_join(NOAA_df_1990, locs, by = "id")

## -----
Tmax_long_sel <- select(Tmax_long, julian, id, z)
Tmax_wide <- spread(Tmax_long_sel, id, z)
dim(Tmax_wide)

```

```

## -----
M <- select(Tmax_wide, -julian) %>% as.matrix()

## -----
library("sp")
library("spacetime")

## -----
NOAA_df_1990$date <- with(NOAA_df_1990,
                           paste(year, month, day, sep = "-"))
head(NOAA_df_1990$date, 4) # show first four elements

## -----
NOAA_df_1990$date <- as.Date(NOAA_df_1990$date)
class(NOAA_df_1990$date)

## -----
Tmax_long2 <- filter(NOAA_df_1990, proc == "Tmax")
STObj <- stConstruct(x = Tmax_long2,           # data set
                      space = c("lon", "lat"), # spatial fields
                      time = "date")          # time field
class(STObj)

## -----
spat_part <- SpatialPoints(coords = Tmax_long2[, c("lon", "lat")])
temp_part <- Tmax_long2$date
STObj2 <- STIDF(sp = spat_part,
                time = temp_part,
                data = select(Tmax_long2, -date, -lon, -lat))
class(STObj2)

## -----
spat_part <- SpatialPoints(coords = locs[, c("lon", "lat")])
temp_part <- with(Times,
                   paste(year, month, day, sep = "-"))
temp_part <- as.Date(temp_part)

## -----
Tmax_long3 <- gather(Tmax, id, z, -julian, -year, -month, -day)

## -----
Tmax_long3$id <- as.integer(Tmax_long3$id)
Tmax_long3 <- arrange(Tmax_long3, julian, id)

## -----

```

```
all(unique(Tmax_long3$id) == locs$id)

## -----
STObj3 <- STFDF(sp = spat_part,
                 time = temp_part,
                 data = Tmax_long3)
class(STObj3)

## -----
proj4string(STObj3) <- CRS("+proj=longlat +ellps=WGS84")

## -----
STObj3$z[STObj3$z == -9999] <- NA
```

Chapter 4

Day 4

4.1 Interactive visualization (HTML format only)

```
# install.packages("webshot")
# webshot::install_phantomjs()
DT::datatable(iris)
```

Search: <input type="text"/>					
	Sepal.Length	Sepal.Width	Petal.Length	Petal.Width	Species
1	5.1	3.5	1.4	0.2	setosa
2	4.9	3	1.4	0.2	setosa
3	4.7	3.2	1.3	0.2	setosa
4	4.6	3.1	1.5	0.2	setosa
5	5	3.6	1.4	0.2	setosa
6	5.4	3.9	1.7	0.4	setosa
7	4.6	3.4	1.4	0.3	setosa
8	5	3.4	1.5	0.2	setosa
9	4.4	2.9	1.4	0.2	setosa
10	4.9	3.1	1.5	0.1	setosa

Show 10 entries

Previous 1 2 3 4 5 ... 15 Next

Showing 1 to 10 of 150 entries

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Chapter 6

Day 6

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Bibliography

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