Modelling spatio-temporal data with R

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Overview

Outline

- Why R?
- R for spatial data analysis
- R for temporal data analysis
- Spatio-temporal data types, processes, models
- R infrastructure for spatio-temporal data analysis
- outlook

Joint work with Roger Bivand, and with help from Michael Sumner and many people at r-sig-geo.

Modelling spatio-temporal data with R

- do we mean *data models* for spatio-temporal phenomena?
- (i.e., how do we represent data in structures)
- .. or statistical modelling of these data?
- (i.e., exploratory data analysis, visualisation, finding patterns, inference, hypothesis testing, predicting / forecasting)

S/T mapping of PCB in North Sea sediment

E Pebesma, R N M Duin (2005) *Spatio-temporal mapping of sea floor sediment pollution in the North Sea.* In: Ph. Renard, and R. Froidevaux, eds. Proceedings GeoENV 2004 – Fifth European Conference on Geostatistics for Environmental Applications; Springer.

Start R, then type

```
> library(gstat)
> demo(pcb)
```

Easy manipulation of data objects

```
> A = log(pcb[pcb$year == 1991, "PCB138"])
> B = log(pcb[pcb$year == 1986, "PCB138"])
> cor(A, B)
```

Handling missing values

- missing values are part of every real data set, and if not
- they get created along the way (cloud removal in RS imagery)
- in low-level programming, handling them properly take a lot of energy ...
- in particular, across all basic types (int, byte, boolean, float, char, ...)

```
> 1/0
[1] Inf
> log(0)
[1] -Inf
> 0/0
[1] NaN
> as.numeric(NA)
[1] NA
> is.nan(NA)
[1] FALSE
> is.na(NA)
[1] TRUE
> mean(c(1, 2, 3, NA))
[1] NA
> mean(c(1, 2, 3, NA), na.rm = TRUE)
[1] 2
```

Handling categorical data

- besides character vectors, R has the `factor`
- internally represented by integers + levels, without coercion it does not yield numbers in numerical manipulation
- it can be used for boolean comparison, mixed with character, to select

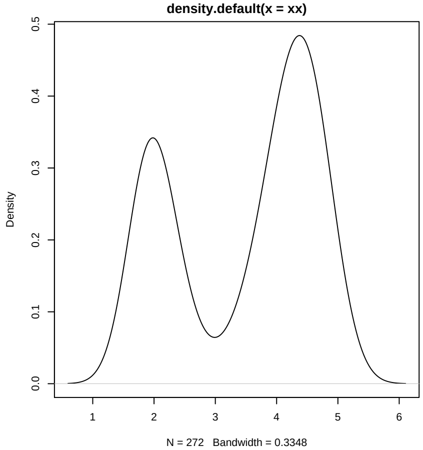
```
> x = c("a", "b", "cc", NA, "b")
> x

[1] "a"  "b"  "cc" NA   "b"

> f = factor(x)
> f

[1] a    b    cc   <NA> b
Levels: a b cc

> as.numeric(f)

[1]  1  2  3 NA  2

> f + 1

[1] NA NA NA NA NA

> f == "b"

[1] FALSE  TRUE FALSE    NA  TRUE

> f %in% c("a", "b", NA)

[1]  TRUE  TRUE FALSE  TRUE  TRUE
```

Why use R? – other voices

```
> xx = faithful$eruptions
> fit1 = density(xx)
> plot(fit1)
```

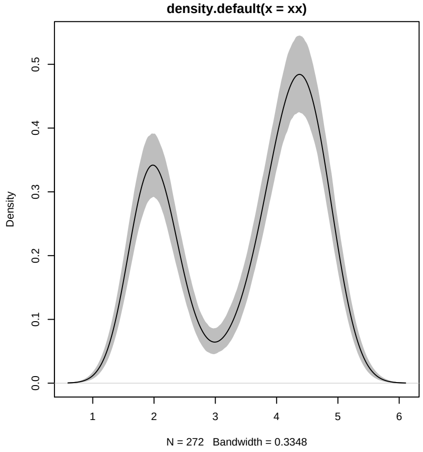
(According to D. Eddenbuettel and R Francois, *Integrating R with C++: Rcpp, RInside, and RProtobuf*, Oct 22, 2010, Google TechTalk[a])

[a] http://www.youtube.com/watch?v=UZkaZhsOfT4



Why use R?

```
> xx = faithful$eruptions
> fit1 = density(xx)
> plot(fit1)
> fit2 = replicate(5000, {
+     x <- sample(xx, replace = TRUE)
+     density(x, from = min(fit1$x),
+         to = max(fit1$x))$y
+ })
> fit3 = apply(fit2, 1, quantile,
+     c(0.025, 0.975))
> plot(fit1, ylim = range(fit3))
> polygon(c(fit1$x, rev(fit1$x)),
+     c(fit3[1, ], rev(fit3[2,
+         ])), col = "grey", border = FALSE)
> lines(fit1)
```



R is not meant as a data base

Typically,

- R sessions start with importing data from a (file, data base, web service)
- a number of commands are executed to reach (or get nearer to) a goal
- output is saved (to file, data base, graph, table,...)
- the set of R commands (.Rhistory) is cleaned, saved to a .R script file, and checked, to safe the analysis for communication or future use.
- (R objects do not have a history, nor time stamps)

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having everything in one place:

- data manipulation / selection options

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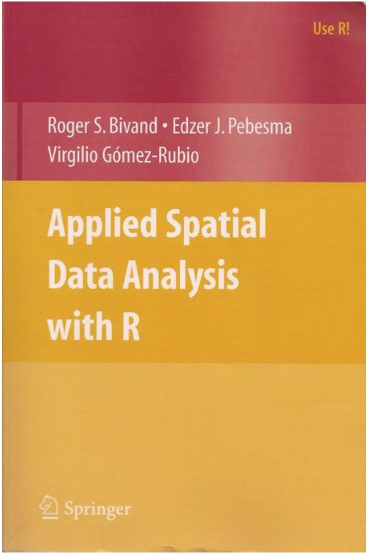
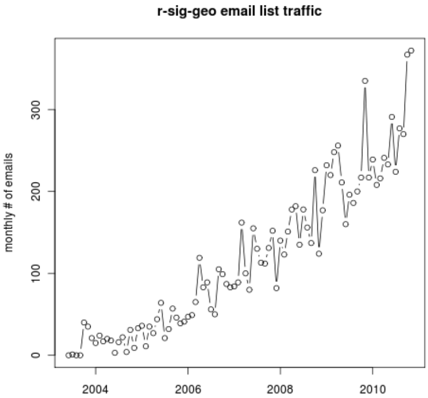
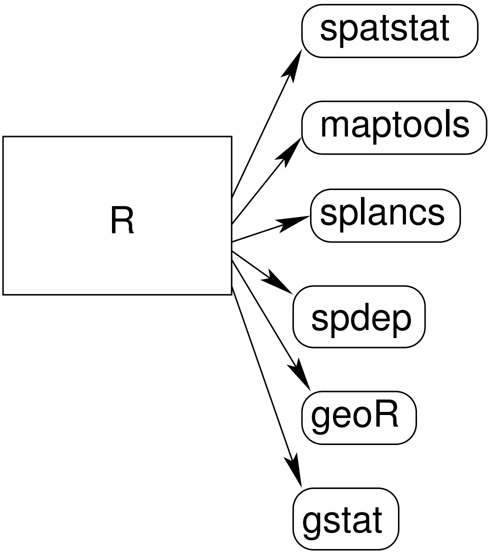
- Sweave: removes need to cut and paste, guarantees consistency
- (arguably:) lingua franca of statistical computation

R spatial

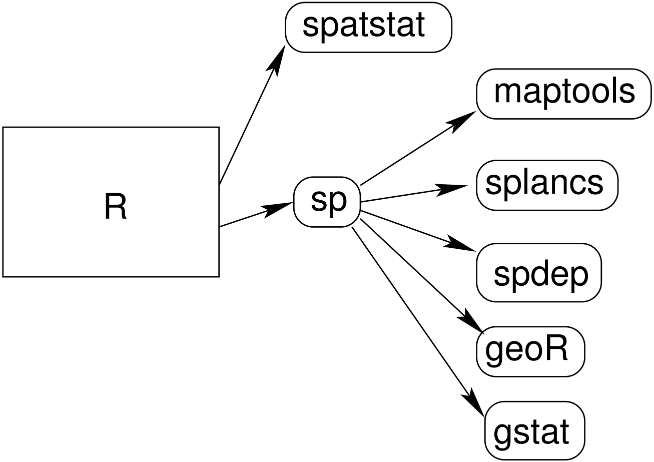

Use R!
Roger S. Bivand • Edzer J. Pebesma
Virgilio Gómez-Rubio
Applied Spatial Data Analysis with R
Springer


r-sig-geo email list traffic
monthly # of emails
0
100
200
300
2004
2006
2008
2010

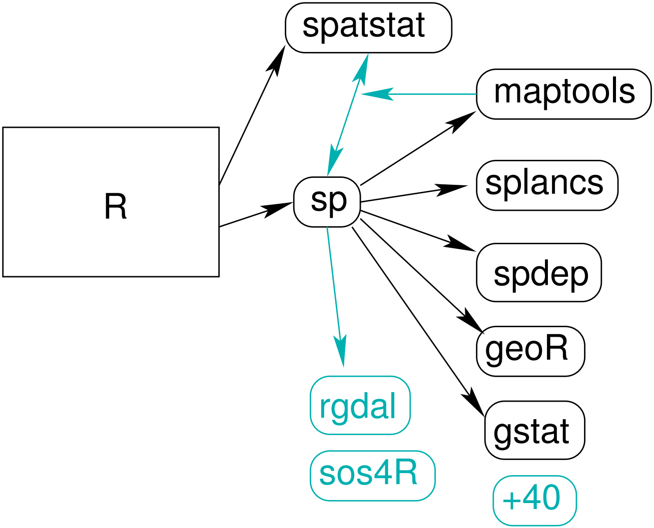
Before 2005



After 2005



2010


R
spatstat
maptools
sp
splancs
spdep
geoR
gstat
rgdal
sos4R
+40

Classes in sp

data type	class	attributes	contains
points	SpatialPoints	No	Spatial*
points	SpatialPointsDataFrame	data.frame	SpatialPoints*
pixels	SpatialPixels	No	SpatialPoints*
pixels	SpatialPixelsDataFrame	data.frame	SpatialPixels* SpatialPointsDataFrame**
full grid	SpatialGrid	No	SpatialPixels*
full grid	SpatialGridDataFrame	data.frame	SpatialGrid*
line	Line	No	
lines	Lines	No	Line list
lines	SpatialLines	No	Spatial*, Lines list
lines	SpatialLinesDataFrame	data.frame	SpatialLines*
rings	Polygon	No	Line*
rings	Polygons	No	Polygon list
rings	SpatialPolygons	No	Spatial*, Polygons list
rings	SpatialPolygonsDataFrame	data.frame	SpatialPolygons*

In sp: mix geometry types:

```
> Netherlands = NUTS1[NUTS1$ID == "NL",]
> Urban_NL = CORINE[Netherlands, "Urban"]
```

would select the Urban grid cells in the Netherlands from the CORINE data base.

```
> AQ_DE = AQ[Germany, ]
```

selects all points from `AQ` inside the polygons object `Germany`
Otherwise: spatial overlay, spatial aggregation

R spatial - new developments (2)

- rgeos: R interface to GEOS topology library

  ```
  > library(maptools)

  Note: polygon geometry computations in maptools
    depend on the package gpclib, which has a
    restricted licence. It is disabled by default;
    to enable gpclib, type gpclibPermit()

  Checking rgeos availability as gpclib substitute:
  FALSE
  ```

- raster: provides manipulation & map algebra on raster data, including those that do not fit in memory.
- Has R now become a GIS?

- primary limitation: objects are stored in RAM.
- several ways around this:
  - read-process-write tiles using data base connections, or rgdal
  - package `raster` (does this for you)
  - package `ff` (uses memory mapping)
- large catalogue of classifiers: discriminant analysis / Max Lik; k-NN; Neural Networks; regression trees; Random Forest; Support Vector Machine...
- large calalogue of cluster algorithms: partitioning, hierarchical, k-means, model-based... (see Task View)
- methods often use similar interface

  ```
  > predict(model(formula, data), newdata)
  ```
- Task view for parallel / clustered setup

R temporal

- naive/implicit: vector, index represents time step
- date/time base types: Date, DateTime, POSIXct
- time series objects: ts, its, zoo, xts
- none of them have explicit time *intervals* as reference
- `xts` allows ISO 8601 interval selection

```
> year = 1990:2000
> year

 [1] 1990 1991 1992 1993 1994 1995
 [7] 1996 1997 1998 1999 2000

> ts(1:20, frequency = 12, start = c(2010,
+     2))

     Jan Feb Mar Apr May Jun Jul
2010       1   2   3   4   5   6
2011  12  13  14  15  16  17  18
     Aug Sep Oct Nov Dec
2010   7   8   9  10  11
2011  19  20

> library(xts)
> x = xts(data.frame(sth = rnorm(4)),
+     Sys.time() + c(0, 1, 4,
+         10) * 3600)
> x["2010-12-8"]

                           sth
2010-12-08 14:23:02  1.2570819
2010-12-08 15:23:02  1.2266700
2010-12-08 18:23:02 -0.7773008
```

Statistical analysis of spatio-temporal data

Questions to data often involve the words *where* and *when*, either implicitly (through covariates / predictors: under which circumstances) or explicitly (i.e., *there* [location] / *then* [time])
Statistical modelling proceeds, as usual, along the line of splitting variability in an understood and a random component (possibly: smooth + rough):

$$\text{observation} = \text{trend} + \text{residual}$$

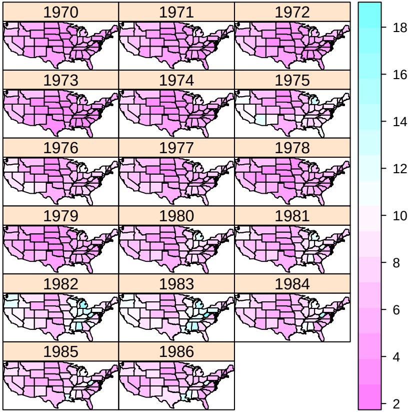
where often the non-random trend relates copes with covariates, and the random residual with correlations in space and time.

Panel data - long format

```
> data("Produc", package = "plm")
> Produc[1:5, ]

    state year     pcap     hwy
1 ALABAMA 1970 15032.67 7325.80
2 ALABAMA 1971 15501.94 7525.94
3 ALABAMA 1972 15972.41 7765.42
4 ALABAMA 1973 16406.26 7907.66
5 ALABAMA 1974 16762.67 8025.52
    water    util       pc   gsp
1 1655.68 6051.20 35793.80 28418
2 1721.02 6254.98 37299.91 29375
3 1764.75 6442.23 38670.30 31303
4 1742.41 6756.19 40084.01 33430
5 1734.85 7002.29 42057.31 33749
     emp unemp
1 1010.5   4.7
2 1021.9   5.2
3 1072.3   4.7
4 1135.5   3.9
5 1169.8   5.5
```

Panel data as ST structure

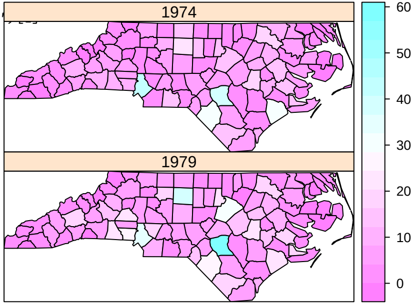
```
> library(maps)
> states.m = map("state", plot = FALSE,
+     fill = TRUE)
> IDs <- sapply(strsplit(states.m$names,
+     ":"), function(x) x[1])
> library(maptools)
> states = map2SpatialPolygons(states.m,
+     IDs = IDs)
> library(plm)

[1] "kinship is loaded"

> data(Produc)
> yrs = 1970:1986
> time = xts(1:17, as.POSIXct(paste(yrs,
+     "-01-01", sep = "")))
> library(spacetime)
> Produc.st = STFDF(states[-8],
+     time, Produc[(order(Produc[2],
+         Produc[1])), ])
> stplot(Produc.st[, , "unemp"],
+     yrs)
```



Wide format 1: NC Sudden infant death syndrome

Wide format: store time instances as columns in the attribute table.

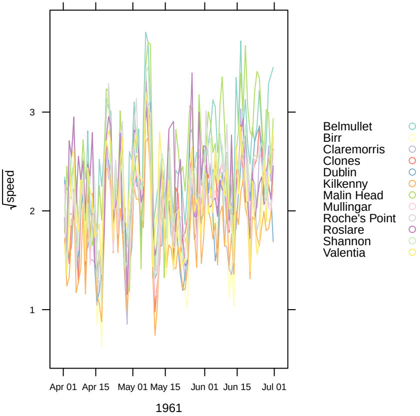
```
> library(maptools)
> fname = system.file("shapes/sids.shp", package="maptools")[1]
> nc = readShapePoly(fname,
+  proj4string=CRS("+proj=longlat +datum=NAD27"))
> as.data.frame(nc[1:5, c("SID74", "SID79")])

  SID74 SID79
0     1     0
1     0     3
2     5     6
3     1     2
4     9     3
```

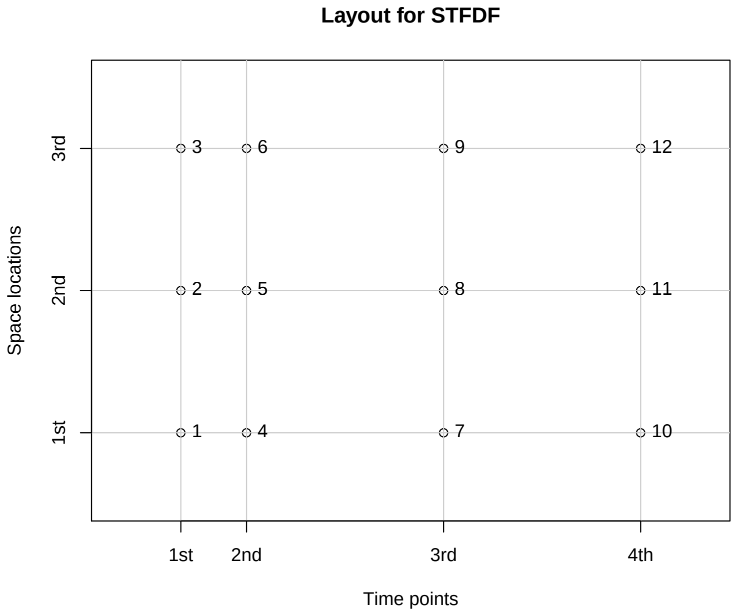


Maybe this is the typical way to do this in regular GIS?
Column (or raster) name needs to encode the time, somehow

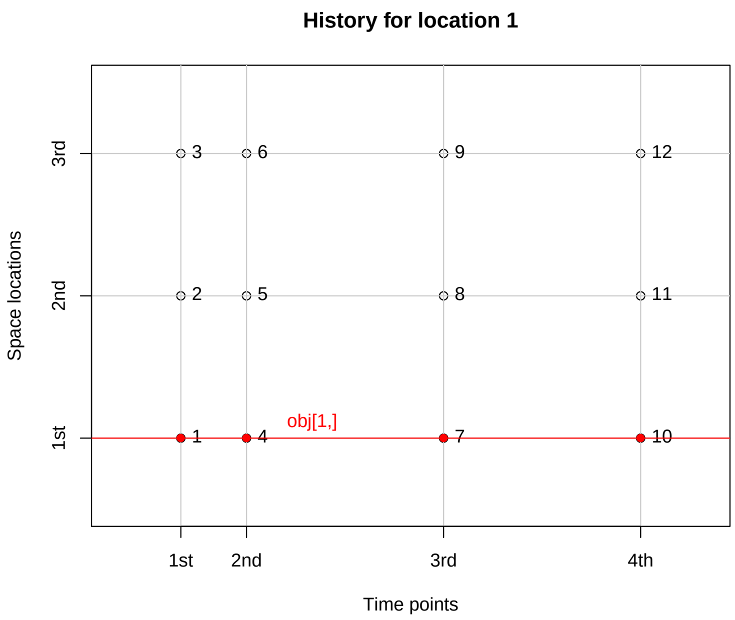
Wide format 2: Irish wind data set

```
> library(gstat)
> data(wind)
> wind[1:5,]

  year month day   RPT   VAL   ROS
1   61     1   1 15.04 14.96 13.17
2   61     1   2 14.71 16.88 10.83
3   61     1   3 18.50 16.88 12.33
4   61     1   4 10.58  6.63 11.75
5   61     1   5 13.33 13.25 11.42
    KIL   SHA  BIR   DUB   CLA
1  9.29 13.96 9.87 13.67 10.25
2  6.50 12.62 7.67 11.50 10.04
3 10.13 11.17 6.17 11.25  8.04
4  4.58  4.54 2.88  8.63  1.79
5  6.17 10.71 8.21 11.92  6.54
    MUL   CLO   BEL   MAL
1 10.83 12.58 18.50 15.04
2  9.79  9.67 17.54 13.83
3  8.50  7.67 12.75 12.71
4  5.83  5.88  5.46 10.88
5 10.92 10.34 12.92 11.83

> wind.loc[1:3,]

      Station Code Latitude
1    Valentia  VAL  51d56'N
2   Belmullet  BEL  54d14'N
3 Claremorris  CLA  53d43'N
  Longitude MeanWind
1   10d15'W     5.48
2   10d00'W     6.75
3    8d59'W     4.32
```

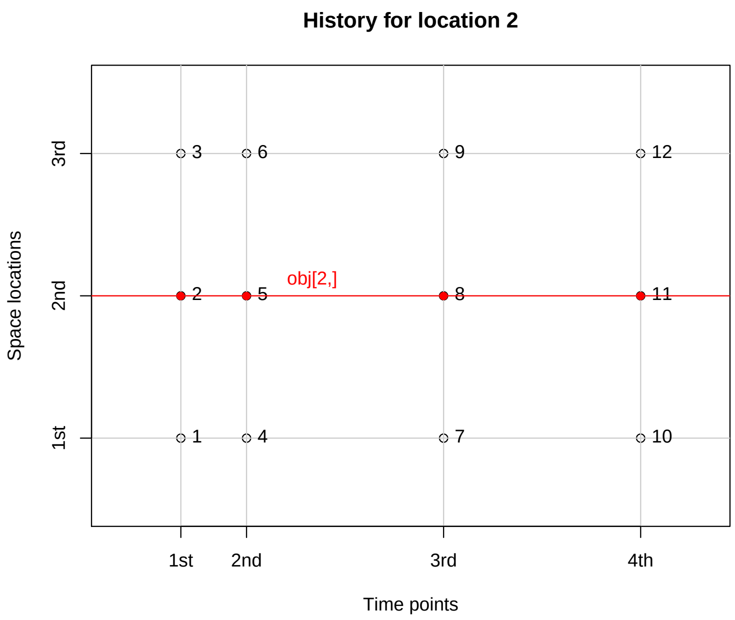


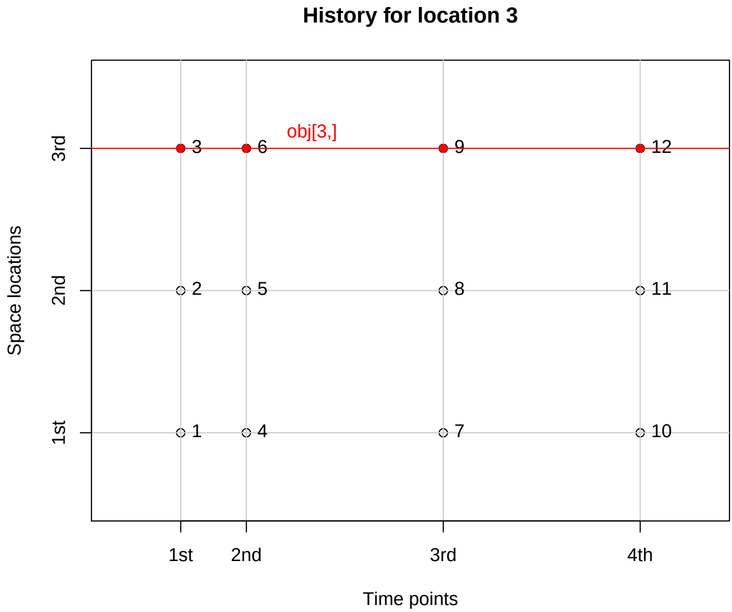


Layout for STFDF
Space locations
1st
2nd
3rd
Time points
1st
2nd
3rd
4th
1
2
3
4
5
6
7
8
9
10
11
12

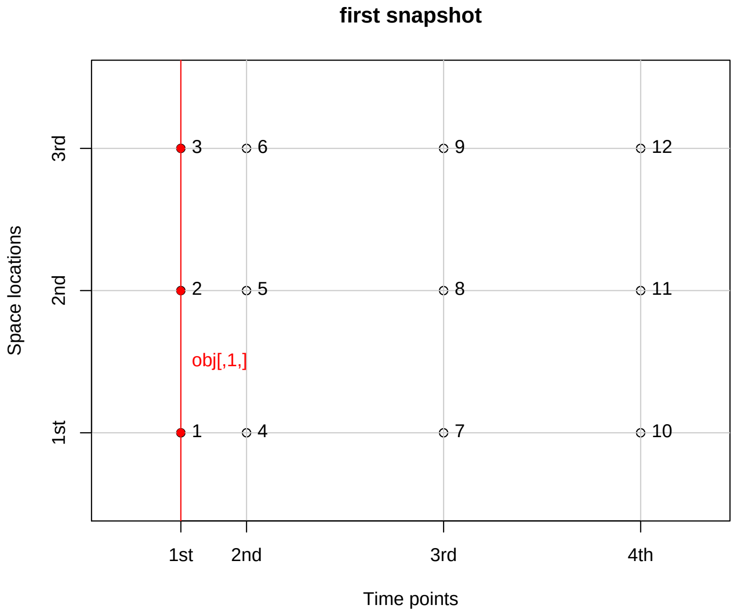


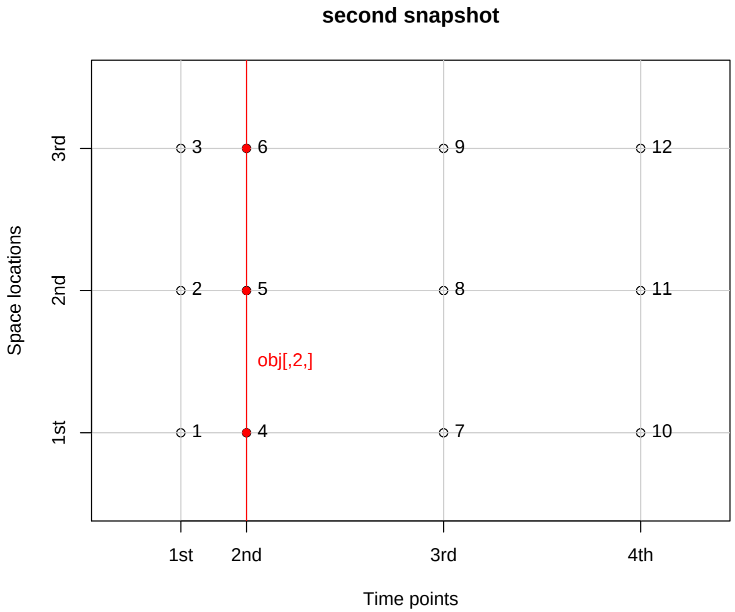
History for location 1
Space locations
1st
2nd
3rd
Time points
1st
2nd
3rd
4th
1
2
3
4
5
6
7
8
9
10
11
12
obj[1,]

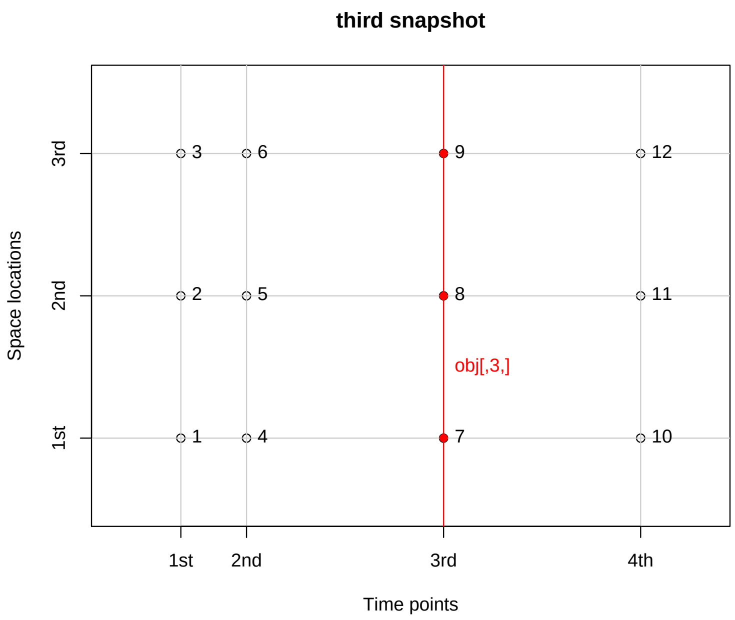

History for location 2
Space locations
3rd
2nd
1st
Time points
1st
2nd
3rd
4th
1
2
3
4
5
6
7
8
9
10
11
12
obj[2,]



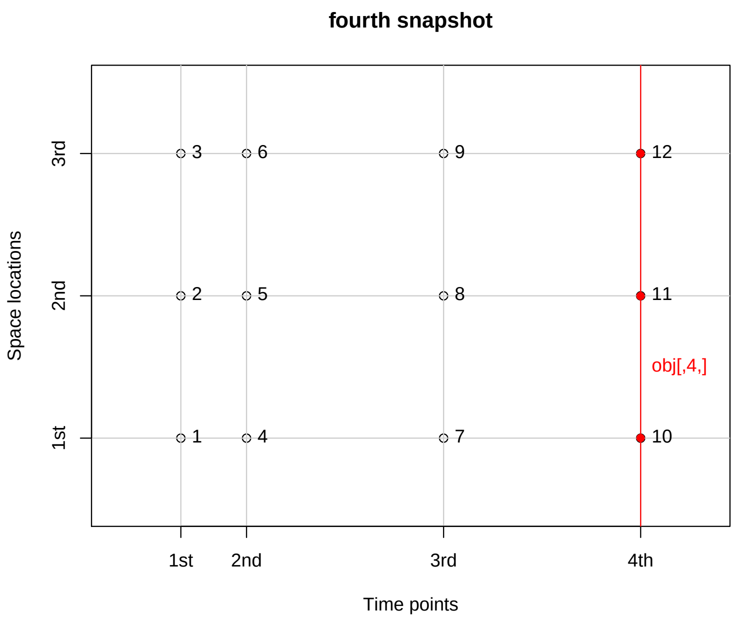
History for location 3
obj[3,]
3
6
9
12
2
5
8
11
1
4
7
10
3rd
2nd
1st
Space locations
1st
2nd
3rd
4th
Time points

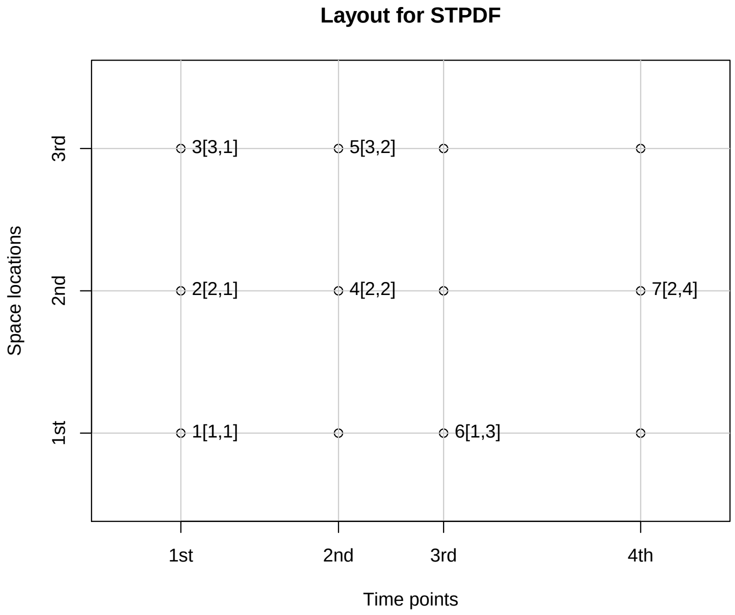

first snapshot
Space locations
3rd
2nd
1st
3
6
9
12
2
5
8
11
obj[,1,]
1
4
7
10
1st
2nd
3rd
4th
Time points

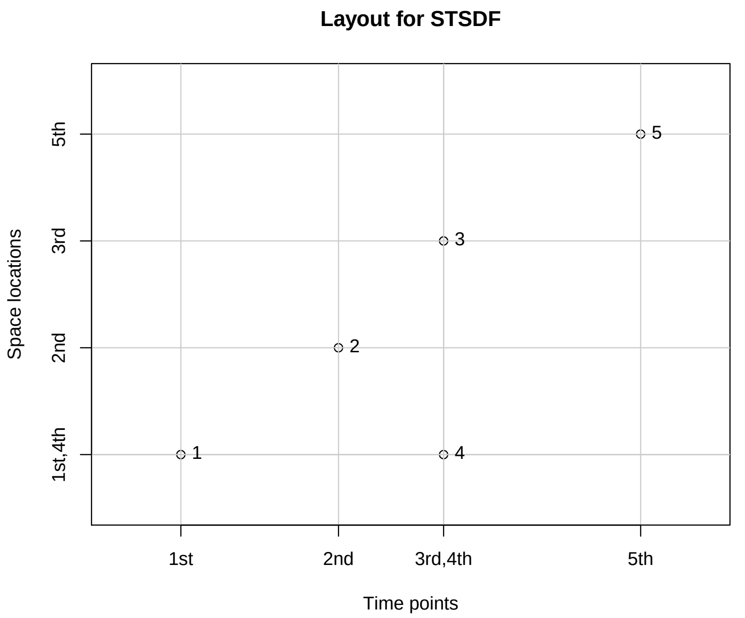

second snapshot
Space locations
1st
2nd
3rd
1
2
3
4
5
6
7
8
9
10
11
12
obj[,2,]
1st
2nd
3rd
4th
Time points



third snapshot
Space locations
3rd
2nd
1st
3
6
9
12
2
5
8
11
obj[,3,]
1
4
7
10
1st
2nd
3rd
4th
Time points


fourth snapshot
Space locations
3rd
2nd
1st
3
6
9
12
2
5
8
11
obj[,4,]
1
4
7
10
1st
2nd
3rd
4th
Time points


Layout for STPDF
3rd
2nd
1st
Space locations
3[3,1]
5[3,2]
2[2,1]
4[2,2]
7[2,4]
1[1,1]
6[1,3]
1st
2nd
3rd
4th
Time points



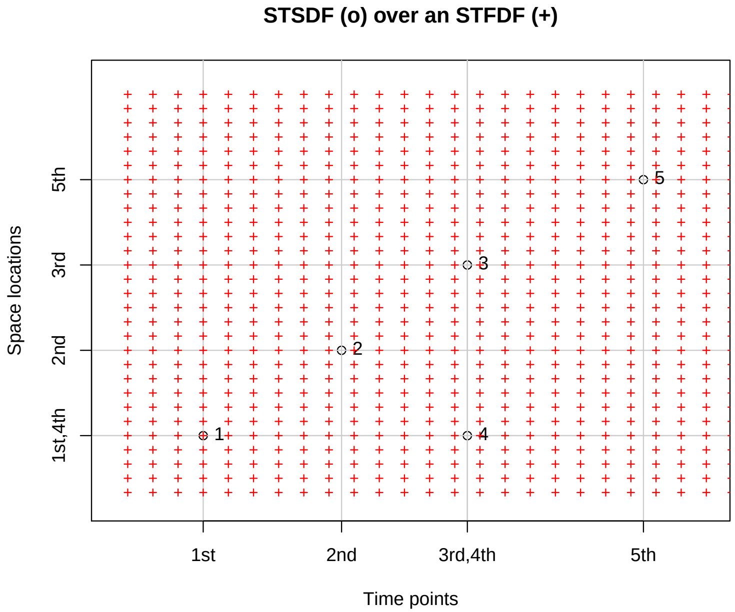
time point 3 and spatial location 1 are duplicated, they appear twice.

Classes in package spacetime

data type	class	attributes	contains
(virtual)	`ST`	No	`Spatial, xts`
full grid	`STF`	No	`ST`
partial grid	`STP`	No	`ST`
sparse grid	`STS`	No	`ST`
full grid	`STFDF`	data.frame	`STF, data.frame`
partial grid	`STPDF`	data.frame	`STP, data.frame`
sparse grid	`STSDF`	data.frame	`STS, data.frame`
trajectories	`STSDFtraj`	data.frame*	`STSDF`

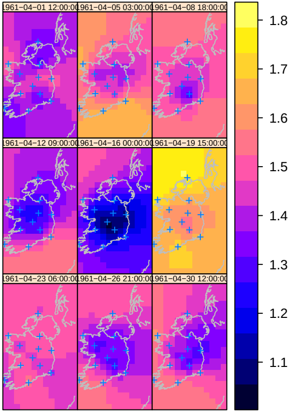
* columns `id` and `burst` reserved for ID (car) and burst (car trip) [see class `ltraj` in package adehabitat].

Methods: coercion, selection (`obj[space,time,attr]`), summary, plot, ...


STSDF (o) over an STFDF (+)
Space locations
5th
3rd
2nd
1st,4th
1
2
3
4
5
1st
2nd
3rd,4th
5th
Time points

Space/time interpolation of Irish wind data

```
> library(maptools)
> library(mapdata)
> m = map2SpatialLines(map("worldHires",
+  xlim = c(-11,-5.4), ylim = c(51,55.5), plot=F))
> proj4string(m) = "+proj=longlat +datum=WGS84"
> m = spTransform(m, utm29)
> # setup grid
> grd = SpatialPixels(SpatialPoints(makegrid(m, n = 300)),
+     proj4string = proj4string(m))
> # select april 1961:
> w = w[, "1961-04"]
> # 10 prediction time points, evenly spread over this month:
> n = 9
> tgrd = xts(1:n, seq(min(index(w)), max(index(w)), length=n))
> # use separable covariance model,
> # exponential with ranges 750 km and 1.5 day:
> v = list(space = vgm(0.6, "Exp", 750000),
+  time = vgm(1, "Exp", 1.5 * 3600 * 24))
> pred = krigeST(sqrt(values)~1, w, STF(grd, tgrd), v)
> wind.ST = STFDF(grd, tgrd,
+  data.frame(sqrt_speed = pred))
```



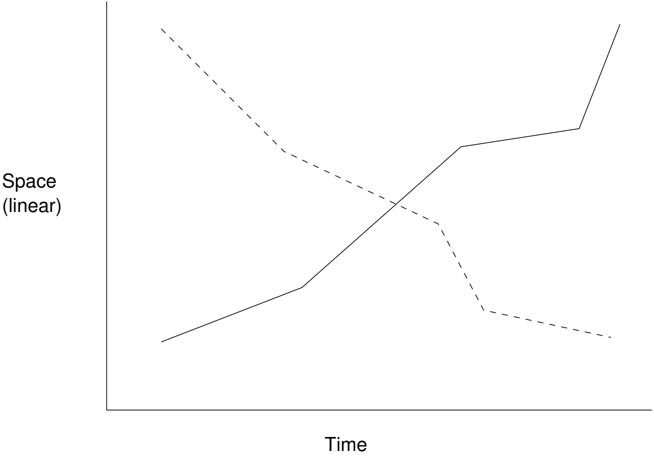
cshapes: changing country shapes

- Package cshapes provides a data base with country shapes, and their change
- data come as a `SpatialPolygonsDataFrame`, with start time and end time for each shape
- conversion to STSDF is done ignoring end time, assuming (i) end of the time series is known, and (ii) no overlapping intervals

```
> library(cshapes)
> cs = cshp()
> class(cs)

[1] "SpatialPolygonsDataFrame"
attr(,"package")
[1] "sp"

> cshp.2002 = cshp(date = as.Date("2002-6-30"),
+     useGW = TRUE)
> t = strptime(paste(cs$COWSYEAR,
+     cs$COWSMONTH, cs$COWSDAY,
+     sep = "-"), "%Y-%m-%d")
> tt = as.POSIXct(t)
> st = STSDF(geometry(cs), tt,
+     as.data.frame(cs))
> pt = SpatialPoints(cbind(7,
+     52), CRS(proj4string(cs)))
> as.data.frame(st[pt, ])[c("CNTRY_NAME",
+     "time")]

               CNTRY_NAME
1 Germany Federal Republic
2                  Germany
        time
1 1955-05-05
2 1990-10-03
```

Spatial geometry changing continuously over time

Use case: space-time prisms, alibi problem, meeting planning (PhD Walied Othman)



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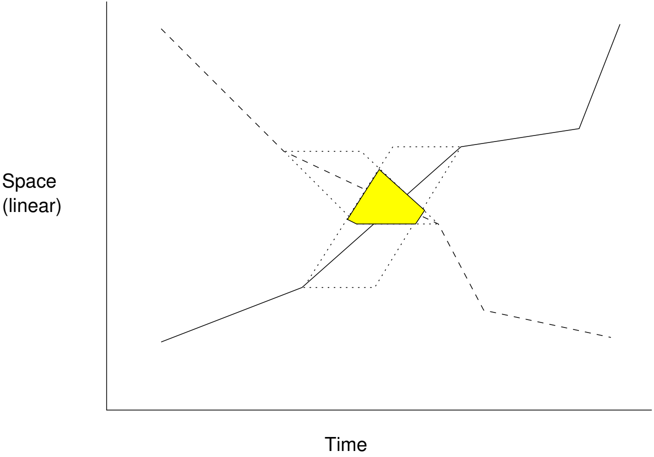

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- implicit assumption for time: length of time step, or explicit (e.g. in Open/High/Low/Close).

geostatistical, point pattern, or lattice data?

do the S/T points carry information in their patterns, or in their sensed values? Or do they form trajectories?

- fields: aggregate, smooth, interpolate, simulate

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- fields: aggregate, smooth, interpolate, simulate
- point patterns: where are clusters? What is the probability distribution over S/T? (kernel densities); given a density, do points interact (e.g. avoid each other)? simulate;
- trajectories: what are the common patterns? How to identify outliers? do multiple trajectories interact? What is the correlation between two trajectories? Primitives / operations of R.H. Güting.

Conclusions (and what's so special about S/T?)

- R (program, packages, mailing lists) provides a rich ecosystem for analyzing data, but also for studying how people analyze data
- spatio-temporal data analysis of all kinds is abundant, convergence based on common classes and methods started, and is under active development
- extending aggregation, disaggregation, and smoothing methods is high priority
- Special about space-time analysis, as opposed to space or time only, is the need to express how proximity, similarity, correlation etc in space relates to that in time ("how many seconds equals one meter?")
- (Although less principled, this was also true for most three-dimensional data analyses.)
- we're building a rich toolbox to deal with the many aspects of *the scale problem*, in space and time