Spatial Models: A *Quick* Overview
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What this tutorial will cover

- I will explain why spatial models may be useful to scientists in many disciplines.
- I will outline types of spatial data and some basic concepts.
- The idea is to give you enough information so you know when you might have a spatial data problem and where you could look to find help.
What are spatial data?

- Data that have locations associated with them.
- Assumption: their locations are important in how we interpret and analyze the data. The locations themselves may also be central to the scientific questions of interest.
- Dependence is modeled as a function of distance between points, often dependence (or correlation) between data decreases with distance. Can also model process as being attractive (or repulsive) so presence of a data point increases (or reduces) the probability of another data point appearing nearby.
Some reasons to use spatial models

- Fitting an inappropriate model for the data, say by ignoring dependence, may lead to incorrect conclusions. e.g. underestimated variances

- Can lead to superior estimators (e.g. lower mean squared error).

- Sometimes learning about spatial dependence is central to the scientific questions. e.g. when finding spatial clusters, regions of influence/dependence.
Types of Spatial Data

There are three main categories of spatial data (though it is not always obvious how to classify data into these categories):

- **Spatial point processes**: When a spatial process is observed at a set of locations and the locations themselves are of interest. e.g. galaxies in space

- **Geostatistical data**: When a spatial process that varies continuously is observed only at a few points e.g. mineral concentrations at various drilling locations

- **Lattice data**: When a spatial process is observed on a regular or irregular grid. Often this arises due to aggregation of some sort, e.g. averages over a pixel in an image
Spatial Point Process Data examples

Locations of pine saplings in a Swedish forest. Location, diameter of longleaf pines (marked point process). Are they randomly scattered or are they clustered?

(from Baddeley and Turner R package, 2006)
The galaxy distribution: 3D spatial point process

2d location in sky, 1d from redshift as a surrogate for distance.

Shapley concentration: 2D spatial point process

Nearby rich supercluster of galaxies. Several thousand galaxy redshift measurements. Galaxies show statistically significant clustering on small scales (Baddeley, 2008)
Geostatistical (point-referenced) data examples

Spatial analogue to continuous-time time series data.

Wheat flowering dates by location (below):

![Map of wheat flowering dates](image)

Courtesy Plant Pathology, PSU and North Dakota State.
Cosmic microwave background

(ESA and the Planck Collaboration: tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today)
Lattice data example

Spatial analogue to discrete-time data, e.g. images

http://www.scantips.com
Types of Spatial Data

- Spatial point processes
- Geostatistical data
- Lattice data
Spatial Point Processes: Introduction

- **Spatial point process**: The *locations* where the process is observed are random variables, process itself may not be defined; if defined, it is a marked spatial point process.

- Some stochastic mechanism generates the locations/point pattern. Based on the observed locations, we want to learn about the underlying mechanism.

- **Observation window**: the area where points of the pattern can be observed. Important since absence of points in a region within observation window is informative.
Some questions

- What kind of attraction/repulsion exists in the process?
- Is there regular spacing between locations or do locations show a tendency to cluster?
- Does the probability of observing the event vary according to some factors? (Need to relate predictors to observations in a regression type setting.)
- Pattern arose through spread mechanism? e.g. clustering of ‘offspring’ near ‘parents’?
- Can we estimate the overall count from only partial observations?
- Interest in measurements associated with points (“marked patterns”)? e.g. diameter of trees, magnitude of galaxies
Some definitions for spatial point processes

- A spatial point process is a stochastic process, a realization of which consists of a countable set of points \( \{s_1, \ldots, s_n\} \) in a bounded region \( S \in \mathbb{R}^2 \)
- The points \( s_i \) are called events
- For a region \( A \in S \), \( N(A) = \#(s_i \in A) \), \( N(A) \) is random
- The intensity measure \( \Lambda(A) = E(N(A)) \) for any \( A \in S \).
- If \( \Lambda(A) \) can be written as

  \[
  \Lambda(A) = \int_A \lambda(s) ds \quad \text{for all } A \in S,
  \]

  then \( \lambda(s) \) is called the intensity function.
Stationarity and isotropy

- The process is **stationary** if its distribution is invariant to translation in space.

- The process is **isotropic** if its distribution is invariant to rotation in space.

- Hard to assess based on having only a single realization of the process (which is typically the case): stationary process can look non-stationary (or vice-versa) within bounded window.
Intensity of Poisson point process

Let $ds$ denote a small region containing location $s$.

- First-order intensity function of a spatial point process:

$$
\lambda(s) = \lim_{ds \to 0} \frac{E(N(ds))}{|ds|}.
$$

- Second-order intensity function of a spatial point process:

$$
\lambda^{(2)}(s_1, s_2) = \lim_{ds_1 \to 0} \lim_{ds_2 \to 0} \frac{E\{N(ds_1)N(ds_2)\}}{|ds_1||ds_2|}.
$$

- Covariance density of a spatial point process

$$
\gamma(s_1, s_2) = \lambda^{(2)}(s_1, s_2) - \lambda(s_1)\lambda(s_2).
$$
Spatial point process modeling

Spatial point process models can be specified by:

- A deterministic intensity function
- A random intensity function
- Major classes of models:
  - Poisson Processes: models for no interaction patterns
  - Cox processes: models for aggregated patterns
  - Inhibition processes: models for interacting patterns
  - Markov processes: models for attraction and/or repulsion
- Poisson process: basis for exploratory tools and constructing more advanced point process models.
Poisson Process

Poisson process on $\mathbf{X}$ defined on $S$ with intensity measure $\Lambda$ and intensity function $\lambda$, satisfies for any bounded region $B \in S$ with $\Lambda(B) > 0$:

1. $N(B) \sim \text{Poisson}(\Lambda(B))$.
2. Conditional on $N(B)$, event locations in $B$ are independent and distributed according to pdf proportional to $\lambda(s)$.

• **Homogeneous Poisson process:** The intensity function, $\lambda(s)$ is constant for all $s \in S$.

• **Non-homogeneous Poisson process:** $\lambda(s)$ deterministic, varies with $s$. Example: model $\lambda(s)$ as a function of spatially varying covariates.
Cox Process

Also called *doubly stochastic Poisson process* (Cox, 1955)

- Natural extension of a Poisson process: Consider the intensity function of the Poisson process as a realization of a random field. We assume $\Lambda(A) = \int_A \lambda(s) ds$.
  - Stage 1: $N(A) | \Lambda \sim \text{Poisson}(\Lambda(A))$.
  - Stage 2: $\lambda(s) | \Theta \sim f(\cdot; \Theta)$ so that $\lambda$ is stochastic, a nonnegative random field parametrized by $\Theta$. 


Markov Point Processes

- Point patterns may require a flexible description that allows for the points to interact. Simple: inhibition processes.
- Markov point processes are models for point processes with interacting points (attractive or repulsive behavior can be modeled).
- ‘Markovian’ in that intensity of an event at some location \( s \), given the realization of the process in the remainder of the region, depends only on information about events within some distance of \( s \).
- Origins in statistical physics, used for modeling large interacting particle systems.
Applications to data

- We now have a framework for thinking about spatial point processes.
- Starting point/exploratory data analysis
  - test for complete spatial randomness (Poisson model) say via distance methods, quadrant count method etc. (established literature on point processes)
  - Estimate the intensity function, starting with assuming constant intensity (easy: total count/area of observation)
  - Estimate second order properties: $K$ function, paired correlation, two-point correlation
- Based on results above, possibly fit a model
Exploring homogeneity/clustering

Assume process is stationarity (same intensity everywhere) and isotropic (direction/rotations do not affect the process)

\[ K(d) = \frac{1}{\lambda} E(\text{number of events within distance } d \text{ of an arbitrary event}). \]

- If process is clustered: Each event is likely to be surrounded by more events from the same cluster. \( K(d) \) will therefore be *relatively large* for small values of \( d \).
- If process is randomly distributed in space: Each event is likely to be surrounded by empty space. For small values of \( d \), \( K(d) \) will be *relatively small*.

Can obtain an intuitive estimator for \( K(d) \) for a given data set.
Ripley’s $K$ Function

Let $\lambda$ be the intensity of the process.

- Effective method for seeing whether the process is completely random in space.

$$K(d) = \frac{\text{Mean number of events within distance } d \text{ of an event}}{\lambda}$$

- This can be estimated by

$$\hat{K}(d) = \frac{\sum_{i \neq j} w_{ij} I(d_{ij} \leq d)}{\hat{\lambda}}$$

where $\hat{\lambda} = N/|A|$ with $|A|$ as the total area of the observation window and $N$ is the observed count.

- Note: $K$ can also be viewed as an integral of the two point correlation function as used by astronomers (cf. Martinez and Saar, 2002).
Ripley’s $K$ for homogeneous Poisson Process

Process was simulated with intensity function $\lambda(x, y) = 100$.

**blue** = $K$ function under complete spatial randomness

black (and red, green): versions of $K$ function estimates
Ripley’s $K$ for inhomogeneous Poisson Process (Eg.1)

Process was simulated with intensity function

$$\lambda(x, y) = 100 \exp(3x).$$

Inhomogeneous Poisson Process

Ripley’s K

\[ \text{blue}=K \text{ function under complete spatial randomness} \]

black (and red, green): versions of $K$ function estimates
Ripley’s $K$ for inhomogeneous Poisson Process (Eg.2)

Process was simulated with intensity function

$$\lambda(x, y) = 100 \exp(y).$$

![Inhomogeneous Poisson Process](image)

**Ripley’s K**

*blue* = $K$ function under complete spatial randomness

black (and red, green): versions of $K$ function estimates
Exploring non-homogeneity

- A common way to study spatial point processes is to compare the realization of the process (observations) to a homogeneous Poisson process. This kind of exploratory data analysis or hypothesis test-based approach can be a useful first step.
- Estimating errors on the 2-point correlation or K function has been derived for a random Poisson process (Ripley 1988; Landy & Szalay 1993) or, if a model for the underlying process is known, from a parametric bootstrap (Einsenstein et al. 2005).
- But Poisson errors may be too small for spatially correlated samples.
Exploring non-homogeneity: recent developments

Loh (2008) recommends a ‘marked point bootstrap’ resampling procedure. Figures below show a simulated clustered process, and the resulting 2-point correlation function with Poisson (dashed) and bootstrap (solid) 95% confidence error bands respectively.

Example: Galaxy clustering (Sloan Digital Sky Survey)

Galaxy distribution

Two-point correlation function

Distribution of 67,676 galaxies in two slices of the sky showing strong anisotropic clustering (Tegmark et al. 2004).

Bottom: Two-point correlation function showing the faint feature around 100 megaparsec scales revealing cosmological Baryonic Acoustic Oscillations (Eisenstein et al. 2005).
Inference

- So far exploratory data analysis. Powerful but full inference with a model may provide richer set of tools and scientific conclusions.

- Recently developed algorithms and software (spatstat in R) make it easier to fit at least relatively simple or standard point process models. More advanced models need more specialized code.
Spatial point processes: computing

- **R command:** `spatstat` function `ppm` fits models that include spatial trend, interpoint interaction, and dependence on covariates, generally using MPL.
- Maximum pseudolikelihood (MPL) often works well (Baddeley, 2005) but can work very poorly when there is strong dependence
- Bayesian models are becoming more common but not much software available
Types of Spatial Data

- Spatial point processes
- Geostatistical data
- Lattice data
Continuous-domain/geostatistical data

- We will now talk briefly about models for continuous-domain spatial data: useful for interpolation and for regression with dependent data.

- Important non-spatial use in the context of astronomy: approximating complex computer models (that may take a long time to run) by probabilistic interpolation across computer model runs at a few parameter settings. Given how the computer model behaves at a few sets of inputs (parameters), approximate how the model will behave at other input settings: “Gaussian process emulation”.

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The importance of dependence (contd.)

Toy example: simple linear regression with the correct mean but assuming iid error structure. $Z(s_i) = \beta s_i + \epsilon_i$, where $\epsilon_i$s are iid. Does not capture the data/data generating process well even though trend ($\beta$) is estimated correctly.
The importance of dependence (contd.)

Model: linear regression with correct mean, now assuming dependent error structure. This picks up the ‘wiggles’.

Functions: $f(x) = \sin(x)$ and $f(x) = \exp(-x/5) \sin(x)$.  

Same model used both times: $f(x) = \alpha + \epsilon(x)$, where $
\{\epsilon(x), \ x \in (0, 20)\}$ is a Gaussian process, $\alpha$ is a constant. 
Note: the dependence is being introduced to indirectly capture the non-linear structure, not to model dependence per se.
Spatial (linear) model for geostatistics and lattice data

- Spatial process at location \( s \) is \( Z(s) = \mu(s) + w(s) \) where:
  - \( \mu(s) \) is the mean. Often \( \mu(s) = X(s)\beta \), \( X(s) \) are covariates at \( s \) and \( \beta \) is a vector of coefficients.

- Model dependence among spatial random variables by imposing it on the errors (the \( w(s) \)'s).

- For \( n \) locations, \( s_1, \ldots, s_n \), \( w = (w(s_1), \ldots, w(s_n))^T \) can be jointly modeled via a zero mean Gaussian process (GP), for geostatistics
Gaussian Processes

- Gaussian Process (GP): Let \( \Theta \) be the parameters for covariance matrix \( \Sigma(\Theta) \). Then:

\[
w|\Theta \sim N(0, \Sigma(\Theta)).
\]

This implies:

\[
Z|\Theta, \beta \sim N(X\beta, \Sigma(\Theta))
\]

- We have used the simplest multivariate distribution (the multivariate normal). We will specify \( \Sigma(\Theta) \) so it reflects spatial dependence.

- Need to ensure that \( \Sigma(\Theta) \) is positive definite for this distribution to be valid, so we assume some valid parametric forms for specifying the covariance.
Gaussian Processes: Example

- Consider the popular \textbf{exponential} covariance function.
- Let $\Sigma(\Theta) = \kappa I + \psi H(\phi)$ where $I$ is the $N \times N$ identify matrix. Note that $\Theta = (\kappa, \psi, \phi)$ and $\kappa, \psi, \phi > 0$.
- The $i, j$th element of the matrix $H$, $H(\|s_i - s_j\|; \phi)_{ij} = \exp(-\phi\|s_i - s_j\|)$.
- Note: covariance between $i, j$th random variables depends only on distance between $s_i$ and $s_j$, and does not depend on the locations themselves (implying \textit{stationarity}) and only depends on the magnitude of the distance, not on direction (implying \textit{isotropy}).
- Extremely flexible models, relaxing these conditions, can be easily obtained though fitting them can be more difficult.
Gaussian Processes: Inference

- The model completely specifies the likelihood, $\mathcal{L}(Z|\Theta, \beta)$.
- This means we can do likelihood-based inference:
  - Estimation using maximum likelihood (MLE) or Bayes (if we place priors on $\Theta, \beta$)
  - Prediction using plug-in MLE or posterior predictive (Bayes).
Gaussian Processes: Computing

- For likelihood based inference: R’s geoR package by Ribeiro and Diggle.
- For Bayesian inference:
  - R’s spBayes package by Finley, Banerjee and Carlin.
  - WINBUGS software by Spiegelhalter, Thomas and Best.
- Very flexible packages: can fit many versions of the linear Gaussian spatial model. Also reasonably well documented.
- Warning: With large datasets (>1000 data points), matrix operations (of order $O(N^3)$) become very slow. Either need to be clever with coding or modeling. Above software (except spBayes in some cases) will not work.
Models for lattice data

- We have not discussed lattice data models here.
- Worth noting that lattice models like Gaussian Markov random fields may have computationally advantages (due to sparse matrices) and hence may be useful for continuous-domain data.
- GeoDa package at https://www.geoda.uiuc.edu/ (free) by Luc Anselin
- R’s spdep package by Roger Bivand et al.
- Bayesian inference: WINBUGS includes GeoBUGS which is useful for fitting such models.
- INLA by H. Rue and co-authors
Useful ideas for non-spatial data

Some spatial modeling techniques may be useful in non-spatial scenarios:

- Gaussian processes: Useful for modeling complex relationships of various kinds. Examples: flexible nonparametric regression, classification. see Rasmussen and Williams (2005) online book
- Fast approximations for complex computer models.
- Ideas for modeling time series, particularly multivariate time series.
Summary: spatial data types and associated models

General spatial process: \( \{Z(s) : s \in D\} \), \( D \) is set of locations.

- **Spatial point process**: \( D = \{s_1, \ldots, s_N\} \) is a random collection of points on the plane. Ordinarily \( Z(s) \) does not exist. For marked point process, \( Z(s) \) is a random variable.
  Usual (basic) models: Poisson process, Cox process.

- **Geostatistics**: \( D \) is a fixed subset of \( \mathbb{R}^2 \) (or \( \mathbb{R}^3 \) in 3D case). \( Z(s) \) is a random variable at each location \( s \in D \).
  Usual (basic) model: Gaussian process.

- **Lattice data**: \( D = \{s_1, \ldots, s_N\} \) is a fixed regular or irregular lattice, on \( \mathbb{R}^2 \) (or \( \mathbb{R}^3 \)).
  \( Z(s) \) is a random variable at each location \( s \in D \).
  Usual (basic) model: Gaussian Markov random field.
References: Geostatistics and Lattice Processes

Geostatistics and Lattice Data:


- Cressie (1994) "Statistics for Spatial Data". This is a comprehensive guide to classical spatial statistics, but it is considerably more technical than the other two references listed here.

- S. Banerjee, B.P. Carlin and A.E. Gelfand (2004) “Hierarchical Modeling and Analysis for Spatial Data”. This is a textbook on Bayesian models for spatial data.
References: Spatial Point Processes


- Baddeley and Turner’s R `spatstat` package.


- P.J.Diggle’s online lecture notes: [http://www.maths.lancs.ac.uk/~diggle/spatialepi/notes.ps](http://www.maths.lancs.ac.uk/~diggle/spatialepi/notes.ps)
References: Spatial Point Processes


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