Topic: Types of “spaces”

• The word **space** is used in mathematics to refer to any set of variables that form metric axes and which therefore allow us to compute a **distance** between points in that space;
  
  – If these variables represent **attributes**, we have a **feature space**.
  – If they represent geographic **coördinates**, we have a **metric geographic** space;

• A non-metric mathematical space can represent topology; if these are geospatial **relations**, we have a **topological geographic** space.
Feature space

This “space” is the metric space (in the mathematical sense) formed by any set of variables:

- **Axes** are the range of each variable;
- **Coördinates** are values of variables, possibly transformed or combined;
- The observations are related in this ‘space’, e.g. the “distance” between them can be calculated.
- We often plot variables in this space, e.g. **scatterplots** in 2D or 3D.
- This is the basis of bi-, tri-, multi-variate analysis

Note: **Feature space** is sometimes referred to as **attribute space**.
This is a **visualisation** of a 2D feature space using a **scatterplot**; two attributes of individual iris flowers as coördinates.

Scatterplot of a 3D feature space

Anderson *Iris* data, three attributes as coordinates.
Spatial concepts, spatial modelling

Geographic space

- “Geo” + “graphy” = “Earth” + “mapping”
- Related somehow to the Earth’s surface
- **metric** vs. **topological**
Spatial concepts, spatial modelling

**Metric geographic space**

- a mathematical space where the axes are *map coördinates* that relate points to some reference location on or in the Earth (or another physical body)

- These coördinates are often in some *geographic coördinate system* that was designed to give each location on (part of) the Earth a unique identification; a common example is the Universal Transmercator (UTM) grid.

- However, a *local coördinate system* can be used, as long as there is a clear relation between locations and coördinates;
  - ungeoreferenced aerial or satellite imagery
  - photograph of microscope slide (not the Earth’s surface but has metric geometry)

- Key point: can compute *distances, angles* of separation, and *areas*.
**Metric space**

- Coördinates represent “true” distances along their axes.

- Axes are 1D **lines**; they almost always have the **same units of measure** (e.g. metres, kilometres . . .)

- **One-dimensional**: coördinates are on a line with respect to some origin (0):
  \[(x_1) = x\]

- **Two-dimensional**: coördinates are on a grid with respect to some origin (0, 0):
  \[(x_1, x_2) = (x, y) = (E, N)\]
  - **Latitude-longitude** (sometimes called “geographic”) coördinates do not have equal distances in the two dimensions; they should be transformed to metric (grid) coördinates for geo-statistical analysis.

- **Three-dimensional**: coördinates are grid and elevation (or depth! a negative elevation) from a reference elevation:
  \[(x_1, x_2, x_3) = (x, y, z) = (E, N, H)\]
Maps of metric space

- Shows features as **abstract** objects (points, lines, polygons, grids);
- The features are **labelled**; these are collected in a **legend**;
- A map shows both **metric geographic** and **feature** (attribute) spaces;
- One map can show many **attributes**
  - Special case: contour maps “2.5D”, show the third geographic dimension (height, depth) on a 2D display
contours; themes: roads (lines); parks & administrative divisions (polygons)
Soil class maps

Dutch soil survey 1:50k sheet 34E; themes: soil class; ground-water level class; subsoil condition (“polkadot” overprint)

SSURGO 1:25k, Edgecombe County NC; theme: soil mapping units n.b. extremely poor, non-connotative, colour scheme

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Navigation maps – 1D and 2D
Topologic geographic space

- Topologic relations are preserved;
  - adjacency, connectivity, containment, intersection . . .

- Distances are not true
True 1D, 2D topology, distorted distances and angles

Note: 3D not correct topology
**Topic: Thinking about spatial analysis**


Cornell access to e-book:

[http://resolver.library.cornell.edu/cgi-bin/EBookresolver?set=Books24x7&id=35218](http://resolver.library.cornell.edu/cgi-bin/EBookresolver?set=Books24x7&id=35218)

Their title term, admittedly “a rather new concept”, is, I think, covered by the common meaning of the existing term *spatial analysis*, which they use in another sense (see following).
O’Sullivan & Unwin’s classification

Four concepts:

1. Spatial data **manipulation**

2. Spatial data **description and exploration**

3. Spatial **statistical analysis**
   - Can a statistical model represent the data?
   - This is not yet understanding, only summarizing as an empirical relation.
   - Requires special techniques to account for spatial relations

4. Spatial **modelling**
   - Understand **functional form** of spatial **processes**
   - **Predict** spatial outcomes

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\(^1\) O’S & U call this “spatial data analysis”
Typology of spatial data – views of the world

(O’Sullivan & Unwin – modified)

**Objects** real-world entities: can be *discretely* identified “in the field” and located in geographic space

**Fields** *continuously-varying* properties in space

- Represented in a GIS by some *discretization*, but conceptually continuous
- Measured with some *spatial support* (sample size, instrument field of view, ...), but conceptually continuous

**Networks** *interconnected* line and point objects
It’s not so simple …

- the conceptual definition of the object may be vague (fuzzy definition)
- It may be difficult to identify an object in the field (fuzzy identification)
- Objects may have fuzzy boundaries or locations
- Object concepts may depend on the map scale
  - Roads are conceived of as polygons at large map scale, lines at small map scale
  - Buildings are conceived of as polygons at large map scale, lines at small map scale
- Continuous variables are measured with some spatial support (sample size, instrument field of view, ...); this is a lower limit of the resolution with which we can describe the conceptually-continuous field
Typology of spatial data – conceptual models of spatial objects

**Point** a single point location, defined by coordinates

**Line** a set of ordered points, connected by straight line segments

**Curves** a set of control points (not necessarily on the curve); and a mathematical function of coordinates (e.g., splines)

**Polygon** an area delineated by one or more lines, possibly containing holes (and holes within holes . . .)

**Network** a group of curves connected at points (**vertices**); mathematical “graph”

**Grid** a collection of points or cells, organised in a regular lattice covering an area
19 Spatial concepts, spatial modelling

Polygons

Baarle-**N**assau (NL), Baarle-**H**ertog (**Baerle-Duc**) (B); source Wikimedia commons

“**H**” polygons are B inside NL (i.e., holes in the surround unlabelled “**N**”); “**N**” polygons are N inside B (i.e., holes in a “**H**” polygon).
Grids

40 x 40 m square cells

Cell values could be centre point predictions, block averages, block maxima ...
Typology of spatial data – data models

These are how spatial data are represented inside a GIS – not their conceptual representation

**Vector** exact mathematical form: 0-dimension = points; 1-dimension = line segments (which can be joined); 2-dimension = areas; 3-dimension = volumes

- Note: a Triangulated Irregular Network (TIN) is a vector data model of a 2-D continuous surface conceptual model

**Raster** a regular tessellation (e.g., square or hexagonal grid); fixed resolution

- data values may be grid cell averages, maxima, minima . . . or single values at the centre point
Abstracting and modelling some aspect of a **spatial reality**

- Natural resources
- Built environment
- Social environment
- Conceptual environment (e.g., political divisions)

Does **not** include modelling objects in space without somehow considering their spatial position, i.e., pure feature-space analysis

- Just displaying the results of a feature-space model on a map does not make a spatial analysis
Why model?

• **hypothesis formulation**: a successful model suggests that it realistically represents some real process

• **hypothesis testing**: if we can reproduce some spatial phenomenon with our model based on the hypothesis, the support for the hypothesis is increased
  - any complicated hypothesis is not tested as such, we build up evidence to support, refute or modify it

• **understanding** of “nature”: a successful model increases our confidence that the model structure matches the real structure

• spatial(-temporal) **prediction**: the model results in a map which is then used for **decision-making**

• **scenario** analysis: “what if...”, mainly for decision-making under **uncertainty**
Example – hypothesis formulation and testing

**Observation**: clustering of cholera, relation to water sources

**Hypothesis**: cholera is an infectious disease, caused by an organism which lives in wastewater and cycles through humans.

Types of models – 1

Physical capture the essential behaviour of a physical system with equations; also called **mechanistic**

**Empirical** determine relation between system components, without necessarily knowing the cause

In practice the line is blurry:

- Physical principles are often used to motivate choice of variables in empirical models
  - But, pure **data mining** models, e.g., artificial neural networks (ANN), are purely empirical.

- “Physical” models have many parameters that must be empirically calibrated (very rarely deriveable from first principles)
Types of models – 2

Explanatory the main purpose of building the model is to understand the process which gave rise to the object of study

- e.g., ecological factors controlling species distribution, based on observations of the species and co-variables
- are not necessarily useful for prediction, but often are

Predictive the main purpose of building the model is to predict at unsampled locations / times (especially the future)

- e.g., areas suitable for a proposed land use, basing the model on areas currently more-or-less successful for that use
- do not necessarily lead to understanding, but often do

For pure prediction, a black-box model may be acceptable and even perform well (e.g., ANN), but such a model is useless for understanding.
Modelled geographical objects

All of these can be model inputs or model outputs:

- points (locations, possibly with attributes)
- lines (same)
- polygons / groups of polygons (same)
- continuous fields (described mathematically or discretized)

Feature-space attributes linked to the geographic features may be part of the model.
Examples of spatial models

- Distribution of rare species in a forest (point pattern, no attributes)
  1. relation to spatially-distributed ecological factors (feature space, but distributed in geographic space)
  2. purely spatial relations, e.g. seed dispersal, allelopathy . . .

- Spread of a disease epidemic
  - point cases, possibly with attributes e.g. age, gender, previous health . . .
  - point or line water sources, possibly with attributes, e.g., water quality
  - point pollution sources, possibly with attributes
  - continuous fields, e.g. soil permeability or hydraulic conductivity

- Distribution of pollutants in soil or groundwater (continuous field)

- “Optimal” location of a new school (etc.), considering spatial factors
Types of processes being modelled

The idea is to **match** the **model** with a **true process** that caused the observations.

Types of processes:

- **fluxes** (flows) driven by “physics”: e.g., diffusion, convection / advection, radiation
  - These can be in “1”D (e.g., along a river, through a road network), 2D (e.g., hillslope), 3D (e.g., soil volume above groundwater)
  - Non-physical processes, e.g., population migrations, could be modelled by physical equations, if assumptions are met

- **known processes**: e.g., plant growth affected by heat, light, nutrients, competition . . .

- **population dynamics**: e.g., birth / death, predator / prey, cooperation / competition

(continued . . .)
Processes (continued)

- "**intelligent**" agents making decisions and interacting

- **decisions** (maybe under uncertainty): try to reproduce the decision-maker’s logic and criteria (e.g., site selection)
Most models have components spread through this diagram. They must be linked, but this brings many problems of concepts / scales.


Three-axis classification

- **degree of complexity**: Mechanistic vs. empirical – see above

- **scale** – see below

- **degree of computation**: Qualitative vs. quantitative

Degre of computation: algorithm / outputs more or less **quantified**

- e.g., “highly suitable” vs. “Net present value for intensive vegetable production $1000 \text{ ha}^{-1}$”
Concepts of “scale”

1. **cartographic** (map) scale: relation of map distances to ground distances
   - “large” = large area of paper needed to represent a given ground area

2. **geographic** scale: size of area being studied
   - “large” = over a wide area

3. **process** scale: spatial extent / variability of process operating on landscape
   - e.g., soil erosion: rill, plot, small catchment, river system . . .

4. **measurement** (observation) scale: size (“support”) of observations
   - e.g., soil ped, core, profile, pit, trench, . . .

5. **modelling** scale: size of fundamental area at which processes or objects are represented in models (“support”)

Temporal scale

The above-mentioned spatial scales can also be used to describe temporal scales.

(Except for “cartographic”).
Matching scales

Key points:

- **modelling** scale should match **process scale**

- **information** at different measurement scales must be **harmonized**
  - e.g., satellite imagery at different resolutions
  - e.g., demographic information at census ward vs. postal code vs. administrative unit (these also at different levels)
  - up-, down-scaling (see below)
Up- and down-scaling

**Upscaling** from detailed scale (e.g., lab. experiments) to coarse scale (e.g., ag. field, region, continent . . .)

**Downscaling** from a coarse scale (e.g., general circulation model of the atmosphere) to a detailed scale (e.g., local weather forecast)

These can be either *spatial* or *temporal* scales.

Often the *inputs* to a model do not have the same scale, so some must be adjusted; and/or the input scale does not match the desired *output* scale.
Issues in spatial scaling

- **Up**scaling: must compress/summarize information
  - e.g., area weighted averaging of properties – but is this meaningful? (e.g., white car in black parking lot → grey pixel)
  - maybe re-run models with coarser scale inputs
  - maybe interpolate including information (somewhat) outside the upscaled resolution

- **Down**scaling: must create new *spatially-explicit* information at a finer scale
  - Just increasing pixel resolution is not creating information!
  - Example: disaggregating a coarse-resolution soil polygon (soil *association* with known landscape relation) to fine-resolution polygons (soil *consociation* = more-or-less homogeneous unit); using expert knowledge + covariates (e.g., terrain classification)

The modifiable areal unit problem

Issue: the same analysis may give different results, i.e., lead to different inferences / conclusions, if the data is aggregated at different scales.

Example: voting patterns by large → small geographic area (polygon size):

- Vote for B.H. Obama vs. W.M. Romney, US President, 2012:
  1. USA (Obama 51.4%)
  2. NY state (Obama 62.6%)
  3. NY 23rd congressional district (Romney wins, Obama 48.4%)
  4. Tompkins County (Obama 68.2%)
  5. City of Ithaca (Obama 83.3%)
  6. 5th ward (Obama 85.2%)
  7. 5th ward 2nd district (Obama 91.6%),

- Summarize predictor variables at the same scales (party registration, census ethnicity, IRS-reported income . . .)

- Do you expect the same predictive model?
Spatial modelling

Several attempts have been made to categorize the *conceptual operations* in spatial models, e.g.:


Some categorizations

• Raster operations:
  - **local**: at a pixel, e.g., transformations
  - **focal**: around a pixel, in its neighbourhood, e.g., filter
  - **zonal**: pixel in some map unit or ‘zone’, e.g. mean value of all pixels in the map unit
  - **global**: all pixels, e.g., distance from a source

• Conceptual:
  - Extract attributes at a location
  - spread attributes or some function over the map, e.g., buffer
  - overlay: combine maps
Steps in modelling

These apply to any sort of model; the terminology here is mostly from empirical-statistical (“regression”) models.

1. Selecting a **functional form**, i.e. the model to be fitted;
   - may try several forms; but these should be “reasonable”, based on possible mechanisms

2. Determining the **parameters** of the model; this is called **calibration** or **parameter estimation**;

3. Determining how well the model describes reality; this is called **validation**.

4. **Criticising** (re-examining) the assumptions and possibly re-cycling.
   - may lead to a modified or completely different **model form**
Examples of functional forms

Grain yield of a cereal crop as affected by N fertilizer:

1. **linear**: one unit of fertilizer is $\beta$ units of grain yield, throughout the range;

2. **linear response with threshold**: same till $\lambda$ units of N, then reaches a plateau;

3. **quadratic**: one unit of fertilizer is $\beta_1 + \beta_2^2$ units of grain yield, throughout the range; $\beta_2$ is negative so after a certain point yield decreases;

4. **negative exponential**: yield increases asymptotically to some limit $\mu$ at some effective range $\rho$.

- The Greek letters indicate **parameters** that must be fit by **calibration**
- All of these have a **plausible physical basis** within a **range of applicability**
The modelling paradigm

**Estimation/fitting**

**Formulation**

Assumptions, model form, prior information,

**Inference**

Fitted model, hypothesis tests, interval estimates

**Criticism**

- after Cook & Weisberg (1982) *Residuals and influence in regression*

Note **criticism** of the **assumptions**, especially **model form**.
Structure vs. noise

- Observations = $f$(Structure, Noise)

- Observations = $f$(model, unexplained variation)

Observations are a subset of Reality, so:

- Reality = $f$(Structure, Noise)

- Reality = $f$(deterministic processes, random variation)

The aim is to match our model with the true deterministic process . . .

. . . and match our estimate of the noise with the actual random variation.

It is equally an error to model the noise (overfit the model) as to not model the process (underfit the model).
Evidence that a model is suitable

Two levels of evidence:

1. **external** to the model:
   (a) what is known or suspected about the *process* that gave rise to the data
   (b) this is the connection to the *reality* that the model is trying to explain or summarise;
   (c) how well the model fits further data from the same population: success of validation against an independent dataset

2. **internal**: from the model itself:
   (a) how well the model fits the data (success of *calibration*);
   (b) how well the fitted model meets the *assumptions* of that functional form (e.g. examination of regression diagnostics).
Example of a spatial modelling exercise

- **Problem**: soil contamination by heavy metals in flood plain of the Maas (Meuse) River near Stein (L), Netherlands

- **Objectives**:
  1. determine where metals came from (**explanation**)  
     - original sediments?  
     - recent atmospheric deposition from industry?  
     - sediments deposited by floods from upstream (B, F)?  
  2. map sediment concentrations over an area (**prediction**)

These objectives are not mutually exclusive! In fact, better explanation often leads to better predictive models.
Fig. 5.2: Meuse data set and values of zinc (ppm): visualized in R (left), and in SAGA GIS (right).

Chosen model forms

(1) **Ordinary kriging (OK):** local spatial dependence (covariance) of *soil property*

- theory: metal is the result of a spatially-autocorrelated random process
- ignores obvious geographic co-variates – a convenient mathematical fiction

(2) **Regression kriging (RK):** combines:

1. **Feature space** model: metal vs. covariables: flooding frequency, distance from river, soil organic matter
   - using multiple linear regression, possibly with some transformations
   - e.g., $\log(\text{zinc}) \sim \text{ffreq} \ast \text{dist}$
   - These predictors expected from theory/previous studies

2. **Geographic space** model: local spatial dependence (covariance) of *residuals* from feature-space model
   - using OK of the residuals – variation not explained by feature-space model
These are distributed in geographic space; and the normalized distance is derived by a geographic-space operation, so in that sense this is a “spatial” model, even though evaluated with a feature-space model.
Modelling results – feature space (1)

R> summary(m <- lm(log(zinc) ~ ffreq*dist, data=meuse))

Residuals:
   Min     1Q Median     3Q    Max
-0.9439 -0.3107 -0.0058  0.2488  1.6676

Coefficients:
                  Estimate Std. Error t value  Pr(>|t|)
(Intercept)       6.7692     0.0702   96.44  < 2e-16
ffreq2           -0.7664     0.1319   -5.81 3.6e-08
ffreq3           -0.5579     0.1954   -2.86  0.00491
dist            -3.0909     0.2885  -10.71  < 2e-16
ffreq2:dist      1.4180     0.4023    3.52  0.00056
ffreq3:dist      0.8281     0.6384    1.30  0.19657

Residual standard error: 0.436 on 149 degrees of freedom
Multiple R-squared: 0.647, Adjusted R-squared: 0.635

**Interpretation:**
(1) reasonably successful model (almost 2/3 variance explained);
(2) Flood frequency 2 & 3 significantly lower levels than 1;
(3) concentration decreases with distance from river;
(4) this effect is less for areas with flood frequency 2.
Modelling results – feature space (2)

After controlling for distance to river and flooding frequency, is there an effect of soil organic matter?

R> summary(m.om <- lm(residuals(m) ~ om, data=meuse))

Residuals:

Min  1Q  Median  3Q  Max
-0.7765 -0.3263 -0.0283 0.2725 1.6762

Coefficients:

Estimate Std. Error  t value Pr(> |t| )
(Intercept)  -0.25022 0.07834   -3.19   0.00171
om           0.03501 0.00953    3.67   0.00033

Multiple R-squared: 0.0821, Adjusted R-squared: 0.076

**Interpretation:** Almost no relation between these soil constituents, once the common (presumed) underlying variables are accounted for.

**Note:** we rely on physical principles to assert that river flooding affects organic matter content, not the other way around!
Modelling results – as prediction maps

**KED−ffreq*dist prediction, log−ppm Zn**

Regression kriging

Clear effect of flood class and distance maps

**ordinary kriging**

One smooth surface

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Modelling results – inferences

What does the model imply about the processes, i.e., what can we infer?

1. Strong relation between metal concentration and (1) flood frequency; (2) interaction of this with distance to river
   - inference: metals are from upstream industry; flood waters spread them on this land

2. No relation with organic matter
   - inference: little or no reaction with soil in short term

3. Strong spatial dependence of residuals
   - inference: local “hot” and “cold” spots of deposition, perhaps from specific flood events in different places?

These inferences are not proven, rather, the evidence allows us to argue their plausibility with respect to competing hypotheses.
Internal model quality: kriging prediction variance

The variance is produced along with the prediction.
External model quality: kriging prediction validation

OK validation errors at undersampled points, log10(Pb)

OK cross-validation errors, log10(Pb)

Prediction errors, applying the model at known points, not used in the prediction.