Environmental Data Analysis

GIS

Leibniz Universität Hannover

Geodetic Aspects of GIS

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Topics

- General Introduction to Geodesy
- Spatial Modeling (part of Data Modeling)
  - Earth's shape
  - Datums, Projections, coordinate systems
- Data Transformation
  - Geo-referencing of data
- Data Interpolation and Approximation
  - Statistics
  - Common algorithms

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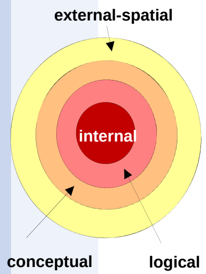
Data Model Views in GIS (preface)



- External-spatial: GUI, visualization(s)
- Conceptual: entity-relation data models (ERD)
- Logical: data-structure - mapping of themes and geometry (vector, raster), determine data model
- Physical (files)

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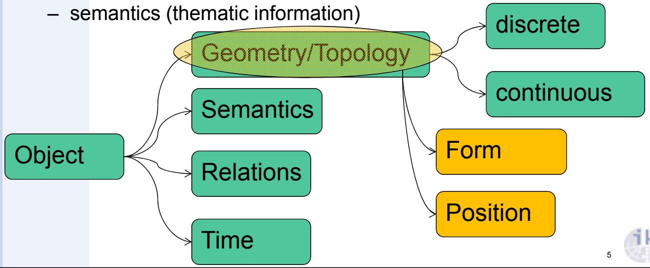
Conceptual Model (preface)

- Conceptual model describes the translation (formation) of the “reality” into given **data structures**; based also on some extent of spatial modeling
- Objects are structured according to:
  - geometry
  - topology (relations)
  - semantics (thematic information)

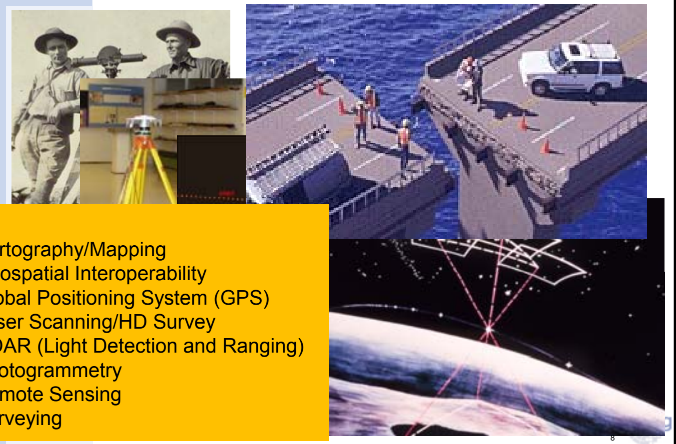


Geodesy

Geodesy

- Earth sciences discipline dealing with technological and practical issues relevant to the measurement and representation of the earth, as well as objects on it – and also their inter-relations.
- Shape, area, length, direction (azimuth), positioning, dynamics,… in large extent (global) as well as zonal (local)
- Gravitational, geomorphomism, geodynamics, precise field measurements, geoinformation, …
- (basically) Does not deal with the earth’s processes, material,…

Geodesy



Cartography/Mapping
Geospatial Interoperability
Global Positioning System (GPS)
Laser Scanning/HD Survey
LiDAR (Light Detection and Ranging)
Photogrammetry
Remote Sensing
Surveying

Geodesy - History

- Earth is not flat – but a globe (Pytagoras, ~ 550 BC),
- Earth is spherical (Aristotle, ~ 350 BC)
- Measuring earth’s size – 16% too big (Eratosthenes, ~200 BC)
- Measuring earth’s size with arc-measurements – 11% too big (Poseidonius, ~70 BC)
- Measuring earth’s size – 3.6% too big (Al Mamun, 827 AD)
- Invention of the telescope (1600’s), logarithms, triangulation,…
- Measuring a meridian – 0.7% longer (Picard, 1670); used by Newton for his theory of universal gravitation
- Geodetic expeditions - earth is flattened at the poles (1735-36)
- First global ellipsoid in with an accuracy of 100 meters (0.002 percent of the Earth's radius) (Helmert, 1906).

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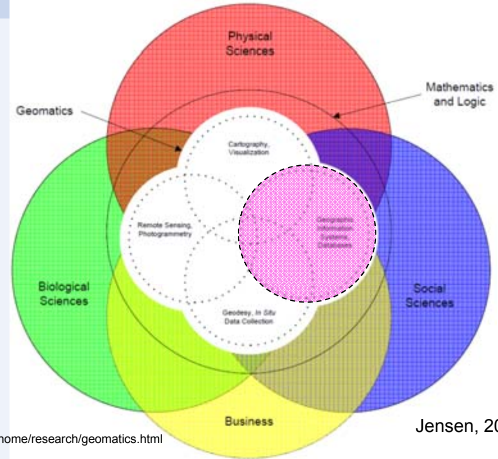
Geodesy – Mapping Sciences



http://cast.uark.edu/home/research/geomatics.html

Jensen, 2005

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(Geo-)Spatial Modeling

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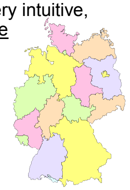
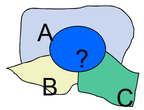
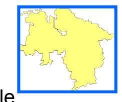
Spatial Reference

- By coordinates, e.g. exact description: x,y,z (=geo reference)
- Verbal description:
  - Address: e.g. Appelstraße 9a, Hannover; often used, very intuitive, however sometimes not ‘<u>precise</u>’ enough and not <u>unique</u>
  - By Names (e.g. Hannover, Rome, …)
  - Names of extended areas, e.g. Black Forest
  - Property boundaries (e.g. Brazilian cadastre)
- By relative descriptions
  - Adjacent objects (e.g. close to the market place)
  - Spatial relations: in the west of Hannover







- By approximate objects, e.g. minimal enclosing rectangle

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Geometric Aspects of Spatial Reference

Object-Method:

- Discrete: objects can be uniquely distinguished from neighboring objects
- Boundary can clearly be defined (or medial axes, centre point)
- Described by geometric primitives: points, lines, polygons (vector data model)
- One theme within the object boundary

Field-Method:

- Continuous: areal, unlimited, distributed in whole space
- Phenomenon = f(x,y), e.g. terrain surface z = f(x,y)
- Often described via raster data model
- Theme, which varies as a function of position

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Geometric Aspects – Discrete Objects

- Entity with one theme inside object boundary: {e,a,xyz,t}
  - Entity: e
  - Attribute(s): a
  - Position/form: xyz
  - time: t
- Objects can be uniquely distinguished from their neighboring objects, e.g.
  - building: boundary, centre point, type
  - Road: boundary (for cadastre), centre line (for topographic data sets / for navigation purposes)
- Problem: crisp delineation of boundary, e.g.
  - Forest that grows into greenland area
  - Subsurface geological structure
  - Undetermined areas, e.g. „Black Forest“

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Continuous Phenomena – Field View

- Natural phenomena are often continuous (sometimes also with discontinuity)
  - Temperature
  - Terrain height, breaklines
- Described by:
  - {a,xyz,t}
  - Attribute(s), Position, Time
- Phenomenon = f(x,y)
  - E.g. terrain height = f(x,y)
  - Is called 2.5D-representation
- Concept can also be applied for linear phenomena
  - Sediments in river
  - Traffic congestion on road

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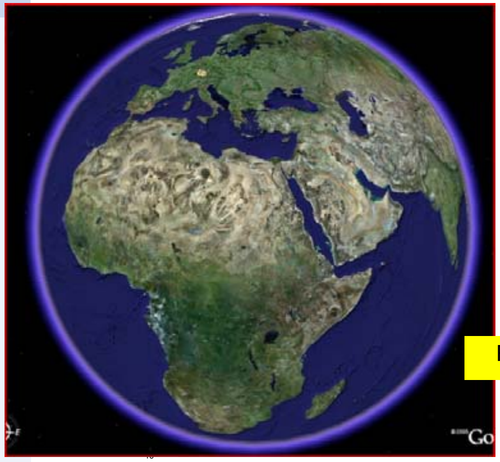
What is 3D-Shape of Earth? Sphere?



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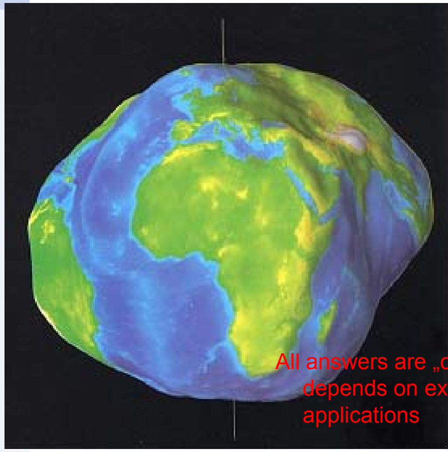
Or is it a plane??

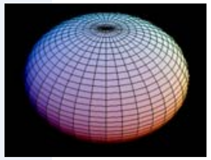
Or is it a „potato" ??



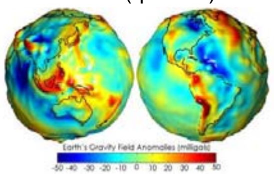
Earth's Shape

- Ellipsoid (spheroid) - a mathematically (and geometrically) defined regular surface that have specific dimensions. A perfectly regular surface (can be described numerically by a continuous function).
- Geoid – a theoretical equal-potential physical surface that coincides if the oceans would conform over the Earth free to adjust to the combined effect of the Earth's mass attractions, i.e., gravitation and rotation (centrifuge). An irregular surface.
- Separations between the two are referred to as undulations (also irregular).

Ellipsoid

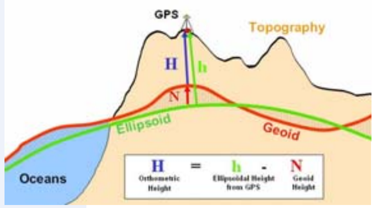


Geoid ("potato")

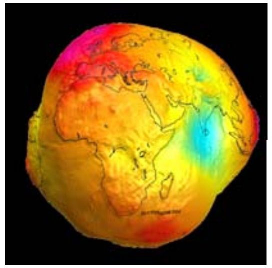


Undulation Model

- Gravitation affects measurements (leveling, …)
- Physical definition of reference "Geoid"
  - Imagine that the sea 'penetrates' through the earth's surface, i.e, continents



Difference |(Geoid – Ellipsoid)| ≤ 100 m



Reference

Plane:

- Suitable for small areas of up to 10x10 km (curvature effects are negligible)

Sphere:

- Best-fitting sphere for small countries

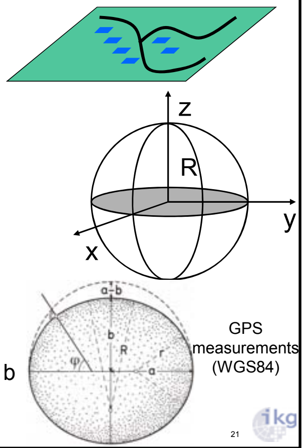
  Radius of earth R≈6,371 km

  Maps scale smaller 1:2,000,000

Ellipsoid:

- Defined by parameter a and b (alternatively by a or b and

  f=(a-b)/a ~1/300; (a-b ~21km))



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Spatial Reference

How to transform 3D objects (the reality, curved-surface) into 2D one (map, screen,…)

Goals:

- Unique determination of objects on earth relating to position and form
  - Coordinate system: e.g. linear one {x,y,(z)},or geographical one {latitude and longitude: φ,λ}
  - Coordinates have to be **fixed** to a given reference system (e.g. where is origin of coordinate system?)
- The aim is to minimize the deformations (always will be) in:
  - Length
  - Area
  - Angle
  - Shape

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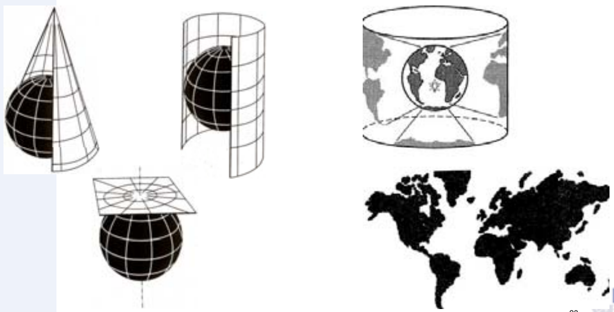
Spatial Reference

- Transforming 3D into 2D via a transforming-plane, e.g. projection.
- Common map projections: Cone (conical), cylinder (cylindrical), plane (azimuthal)



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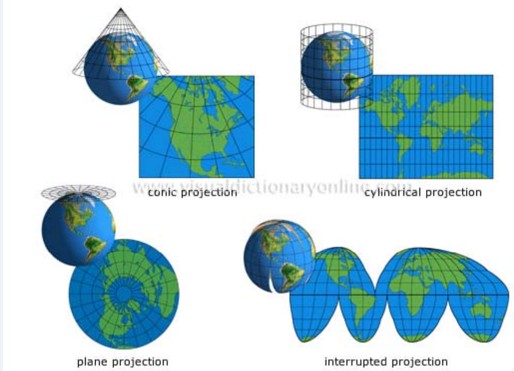
Spatial Reference



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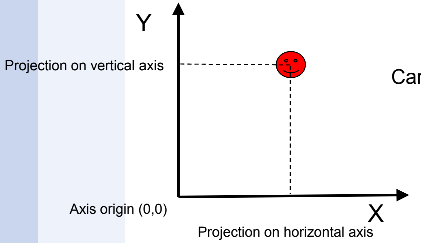
Coordinate Systems

A co-ordinate is a numerical expression for positioning an object that has geographical/geospatial characterization in respect to the space it is in.

In 3D: 3 values/ordinates – {X, Y, Z}, {φ, λ, (h)}, {n, e, u}

In 2D (planar, Cartesian): 2 values/ordinates



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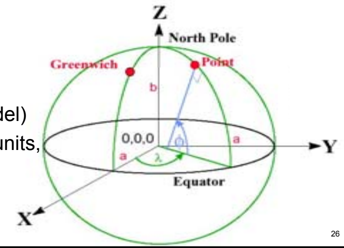
Geographic Coordinates

- Latitude φ (Parallel): from equator northwards (positive: 0°-90° N) and southwards (negative: 0°-(-90°) S). Equator = big circle
- Longitude λ (Meridian): from meridian in Greenwich (λ=0°) eastwards (E) / westwards (W) with +/- 180° (all are big circles)
- Advantage
  - One system for the whole earth
  - Global
  - Intuitive
- Disadvantage
  - Locality
  - Height (undulation model)
  - No metric (Cartesian) units, but angles



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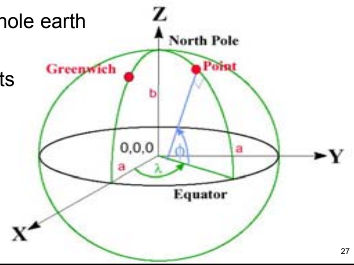
Geocentric Coordinates

- Right hand XYZ Cartesian system.
- XY plan coincides with the equator.
- Z performs a 90° angle with XY, and usually coincides with the rotation axis of the sphere (ellipsoid).
- Origin (0,0,0) coincides with center-of-mass.
- Advantage
  - One system for the whole earth
  - Global
  - Metric (Cartesian) units
- Disadvantage
  - Locality
  - Height
  - Not Intuitive



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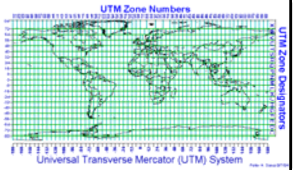
Geodetic Coordinates



- Planar, Cartesian coordinates
  - Metric units
- Examples
  - Gauß-Krüger coordinates (in Germany)
  - UTM-coordinates (worldwide system)
- UTM:
  - Not a single map projection, but a series of sixty zones, each of which is based on a Transverse Mercator (TM) projection
  - Disadvantage: several coordinate systems needed, “moving” between adjacent zones
  - Advantage: easy calculations in metric units

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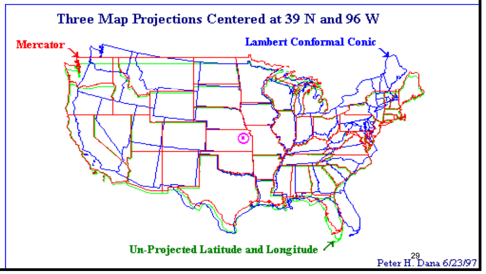
Reference System Definition

- Reference system definition requires several parameters to be declared for the **unique** transformation from 3D to 2D, as well as orientation derived by the chosen ellipsoid:
  - 3 parameters of center of origin (0,0,0)
  - 3 axis – rotation-axis (Z) and equator plane (X, Y)
  - Projection parameters

Aim: to minimize distortions and deformations while 'moving' from 3D to 2D



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Geodetic Reference Systems: Local

DHDN (Deutsches Hauptdreiecksnetz)

- Reference system of German National Mapping Agencies
- Central Point: Rauenberg
- Ellipsoid: Bessel 1841
- Also called: **Potsdam Datum, Zentralpunkt Rauenberg**

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Geodetic Reference System, global: ITRS

- ITRF / ITRS (International Terrestrial Reference Frame/System)
  - ITRS – System (conceptional)
  - **ITRF89** – Realization (using measurements)
- Realized by different measuring systems
  - GPS / LLS (Lunar Laser Ranging) / SLR (Satellite Laser Ranging) / VLBI (Very Long Baseline Interferometry)
- Accuracy: 3 cm
- 180 stations worldwide

Fixed 1989 (due to plate Tectonics) -> ITRF 89

GPS stations of ITRS

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Reference System - global

- World Geodetic System 1984 = **WGS84**
  - Reference system for GPS coordinate measurements
  - Globally best fitting reference ellipsoid

DHDN
Potsdam Datum (local)

	a	b	f
Bessel-Ellipsoid 1841	6,377,397.155 m	6,356,078.965 m	1 : 299.152
Erd-Ellipsoid WGS 84	6,378,137.000 m	6,356,752.315 m	1 : 298.257

Geodetic datum +
Referece ellipsoid (global)

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Weblinks Reference Systems

- ITRS/ITRF
  - http://www.iers.org
  - http://itrf.ensg.ign.fr
- ETRF/ETRS
  - http://www.euref.eu
- DHDN, ETRF, ETRS
  - http://crs.bkg.bund.de
  - http://www.adv-online.de
- WGS
  - http://earth-info.nga.mil/GandG/publications/tr8350.2/tr8350_2.html
  - http://earth-info.nga.mil/GandG/wgs84/index.html

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Coordinate Systems

Cartesian coordinate system:

- Origin of all axis is known and singular
- Scale is usually unified for all axis
- Moving between positions is always feasible, and achieved by geometric formulas (distances and angles)

Ratio between angular and metric units on sphere (earth):

1° (deg) = 60' (min) = 3600" (sec)

1° ≈ 111 km

1' ≈ 1.85 km

1" ≈ 30 m

Approximate distance on sphere of Hannover (position = 52°22′N, 9°43′E) from Equator and Greenwich:

52 * 111 + 22 * 1.85 = 5,812.7 km

9* 111 + 43 * 1.85 = 1,078.55 km

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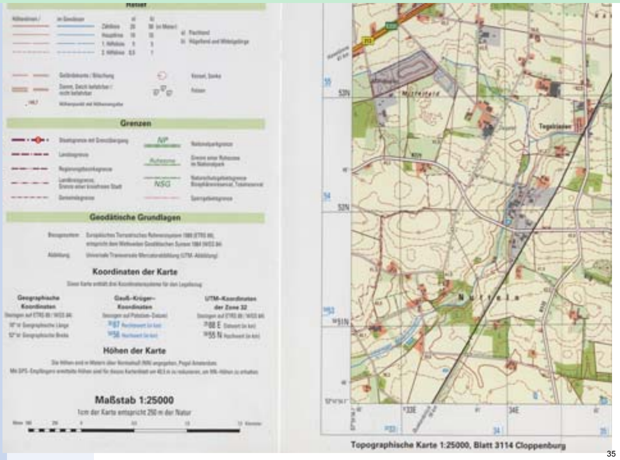
Reference systems in practice: e.g. topographic maps



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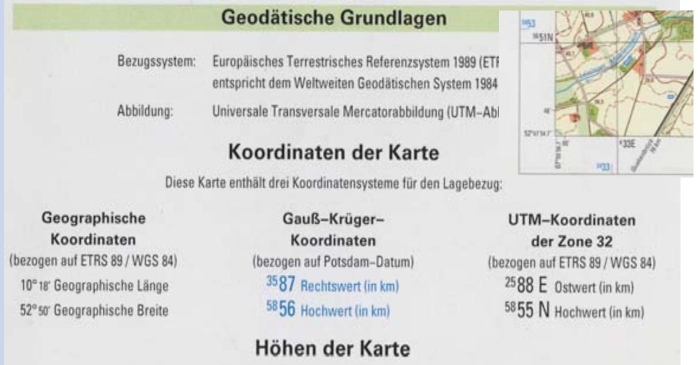
Reference systems in practice: e.g. topographic maps



Between different coordinate systems geodetic spatial transformation(s) is needed

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Data Transformation

Data Transformation – Geo-referencing

- Determining the precise position of existing information (layers, raster) on Earth, i.e., ‘translation’ from pixel space to the object one.
- Rectification – alignment of entities in pixel space so they will coincide with a certain reference system/frame (e.g. Geodetic)
- Registration – alignment of entities in pixel space so they will coincide with each other
- Both geometric processes are carried out mathematically via a **geo-referencing** process.

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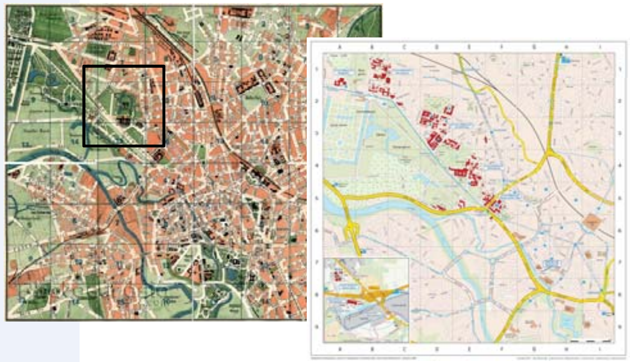
Data Transformation – Geo-referencing



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Data Transformation – Geo-referencing

- Two basic approaches exist:
- Homogenous – a unique and unified mathematical transformation of data through four principal geometric actions. Each pixel/entity is transformed with the same magnitude and behavior. Usually implemented for map referencing or transformation between two given systems (commonly used: **Affine** transformation):
  - Translation
  - Rotation
  - Scaling
  - {Skew (in case axes are not perpendicular)}
- Differential stretch (Rubber-Sheeting) – a non-unified transformation of the area – different zones are fixed and referenced independently. Usually implemented for creating map-series (mosaic) or deformed data.

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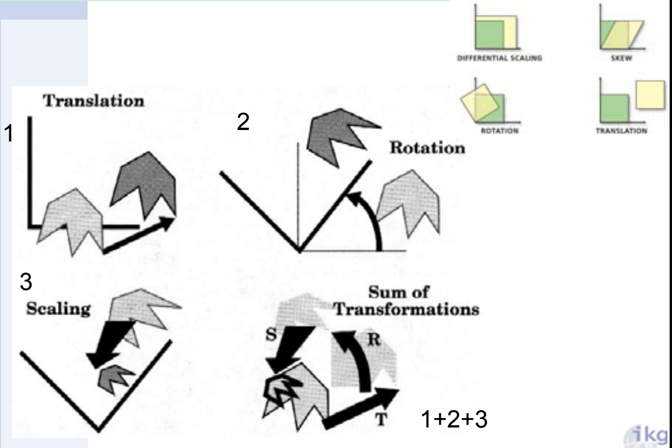
Affine Transformation



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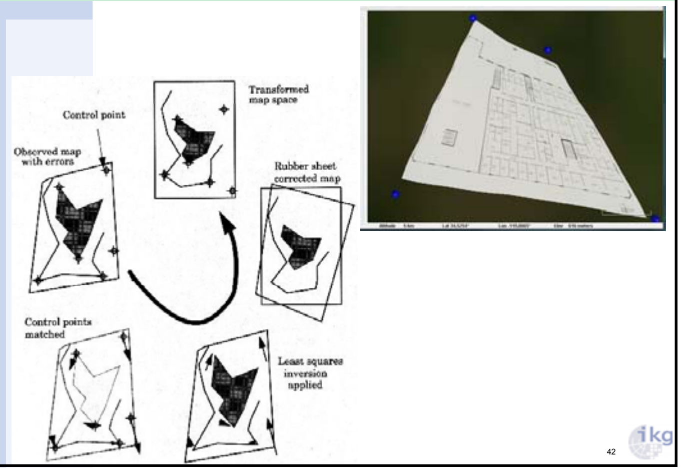
Rubber Sheeting



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Affine Transformation

- Physical geometric and mathematical actions that 'translate' the pixel-frame position to the "real" geodetic reference-frame (map, datum) one:
  - Translation – shifting between the pixel-origin and reference one:
    - 2D – two values (x,y)
    - 3D – three values (x,y,z)
  - Rotation – rotating the pixel-frame to the "true north":
    - 2D – one value (z-axis)
    - 3D – three values (x-, y-, z-axis)
  - Scaling – a unified (or differential) transformation in size:
    - 2D – one or two values ({x,y},xy)
    - 3D – one, two, or three values (x,y,z,{xy,z},{x,yz},…)
  - Skew – in case there is no perpendicularity of both references:
    - 2D – one value (xy)
    - 3D – three values (xy, xz,yz)

A combination of any of the four

Affine Transformation

- 2D affine transformation mathematical concept.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} dX \\ dY \end{bmatrix} + \begin{bmatrix} \lambda 1 \\ \lambda 2 \end{bmatrix} \cdot \begin{bmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix} \cdot \begin{bmatrix} V \\ U \end{bmatrix}$$

Reference positioning (reality) – Translation – Scaling – Rotation matrix *R=f(α)* – Local positioning (pixel)

$$X = dX + V \cdot \lambda 1 \cdot \cos(\alpha) - U \cdot \lambda 2 \cdot \sin(\alpha)$$

$$Y = dY + V \cdot \lambda 1 \cdot \sin(\alpha) + U \cdot \lambda 2 \cdot \cos(\alpha)$$

(X,Y) - reference coordinates with certain datum (geodetic)
(U,V) - pixel coordinates (local map)
$\lambda_{1,2}$ – scaling(s) (sometimes referred to as *s*)
α – rotation angle
… also compatible the "other way"

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Differential Transformation – Rubber Sheeting

- The goal is to try and stretch different locations in different magnitude to align both datasets best
- Usually carried out via polynomial adjustments – each corresponds to different area/zone (via control points)
- Implementing Least Square Matching (LSM) between control points ('observations') in both datasets that aims at minimizing the observations' residuals (corrections to 'reality')
- Requirements (also generally applicable to Homogenous transformation):
  - More control points (observations) – the better the matching will be
  - A good dispersing of control-points on both datasets' area – a more qualitative solution
  - Registration is based solely on identical control points in both datasets

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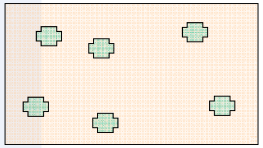
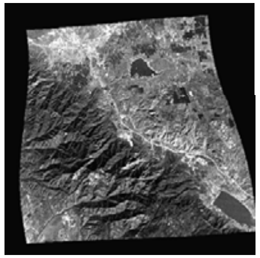
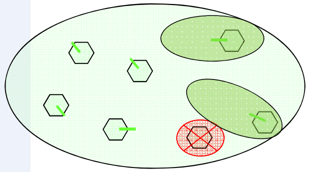
Differential Transformation – Rubber Sheeting

Map positioning





GPS control points



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Data Interpolation

Interpolation

- Motivation:
- Continuous phenomena can only be measured using samples at specific points, e.g. discrete data
- Goal:
  - Derive (predict, approximate) value for phenomena at every point in space via statistical approximation based on a set of known values (observations)
- Example:
  - Terrain is continuous phenomenon
  - Measured at specific data points, e.g. samples (observations)
  - Interpolation to generate a continuous surface description

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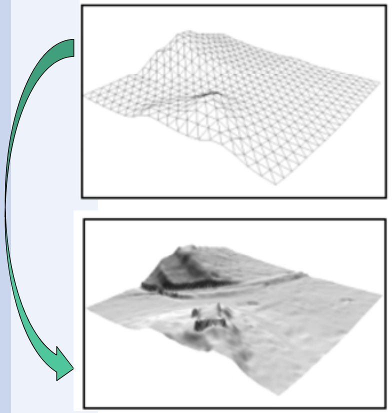
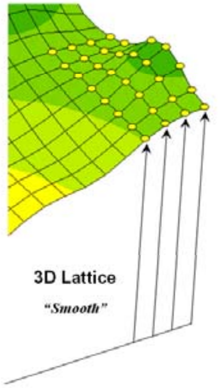
Interpolation





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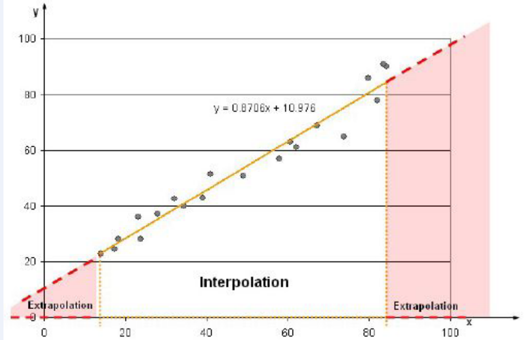
Interpolation / Extrapolation

- 'Inside' measurement (observation) range (set): interpolation
- 'Outside' measurement (observation) range (set): extrapolation



F. Hebeler

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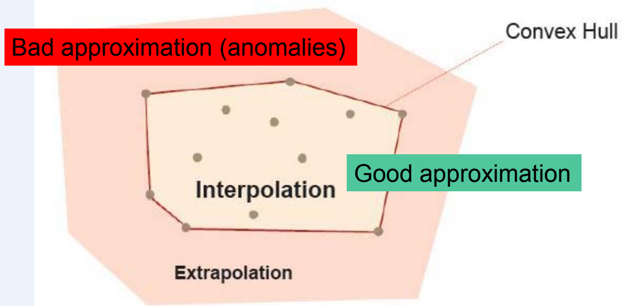
Interpolation / Extrapolation



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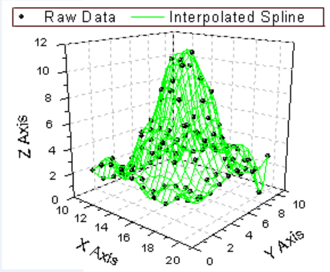
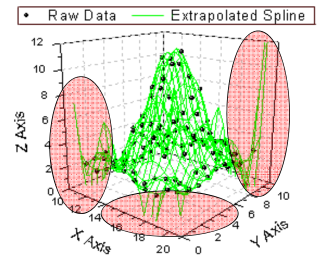
Interpolation / Extrapolation





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Interpolation

- Determine unknown values from known measurement values
- Idea:
  - Values at locations close to measurements will be similar to those of the unknown measurements
  - Different interpolation methods will almost always produce different results
- Tobler's First Law of Geography:
  - "Everything is related to everything else, but near things are more related than distant things"

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Interpolation / approximation

- Different methods:
  - Global vs. local
  - Exact vs. approximated
  - …
- E.g.:
  - Inverse Distance to Weighted (IDW)
  - Polynomial interpolation (mathematical)
  - Spline interpolation
  - Trend surfaces (local neighborhood)
  - Statistical approaches (Kriging)

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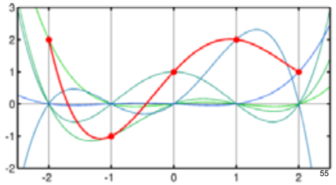
Polynomial interpolation (trend)

- Given: *n* measured points (observations)
- Goal: compute a function that
  - Goes (exist) through all measured points (exact interpolation), or
  - Approximates points best (approximation, LSM)
- Depending on the number of coefficients of polynomial function (degree), different goals can be achieved
- Number of measurements (observations) ≥ number of polynomial coefficients



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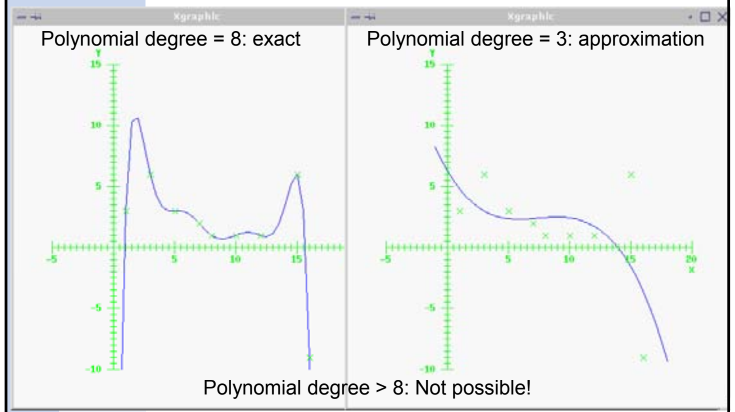
2D Polynomial interpolation: 9 points (observations)



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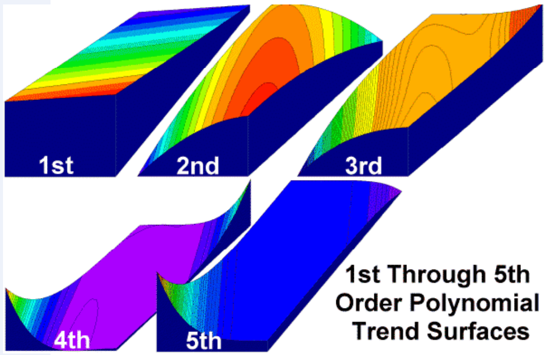
2.5D (Surface) Polynomial interpolation



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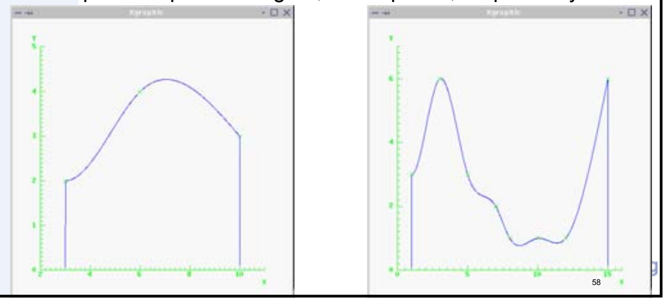
Splines

- Adjacent piecewise low-degree polynomial functions between two measurement points (e.g., interval) fit smoothly together
- Typical: cubic polynomial
- Additional constraints: smooth transitions in measured points
- Example: 2D spline through 3, and 8 points, respectively.



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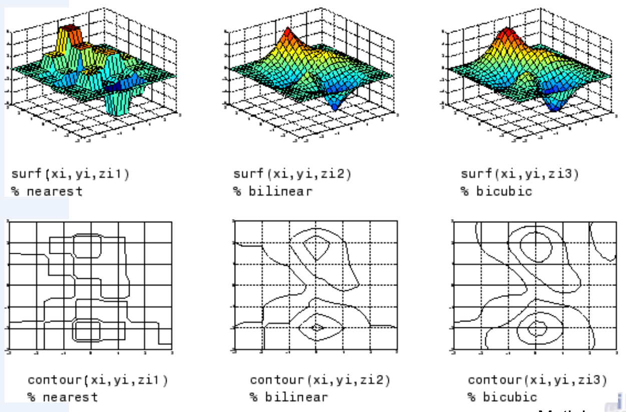
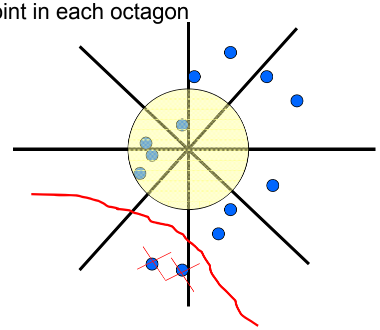
2.5D (Surface) spline interpolation



Matlab

Local Interpolation: selection of points in neighborhood

- Well distributed in neighborhood (i.e., not only the closet ones!)
- E.g. 1 point in each octagon



- No points that lie behind break lines

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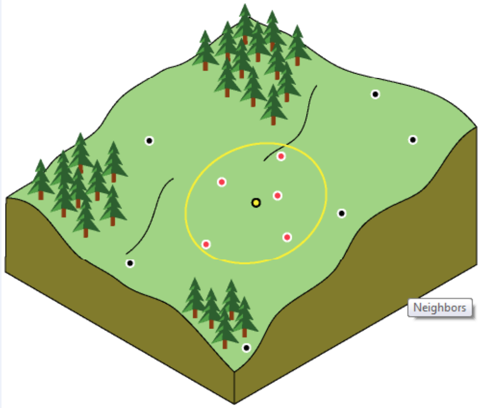
Local Interpolation: selection of points in neighborhood



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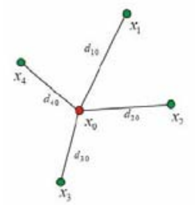
Distance Function: IDW

- Idea: Tobler's law
- Height as weighted mean
  - Weight: inverse proportional to distance
  - i.e., close points have highest influence

$$z(x,y) = \frac{\sum_{p=1}^{R} Z_p d_p^{-n}}{\sum_{p=1}^{R} d_p^{-n}}$$



- With
  - z: unknown height of new point (x_0)
  - R: number of points in neighborhood (=4)
  - z_p: height of neighbor point (x_1 – x_4)
  - d: distance between unknown point and neighbor (d_{10} – d_{40})
  - n: power (typical: n = 1 or 2)

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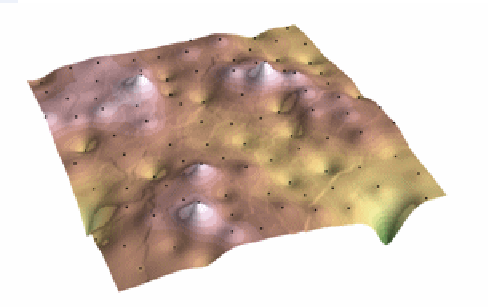
Distance Function: IDW



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Kringing - Geostatistical

- Idea: statistical models that include autocorrelation (correspondence between observations)
- Providing measures of the certainty or accuracy of predictions, e.g., heights.
- Distance (or direction) between samples corresponds to spatial correlation explained by surface variations.
- Appropriate when knowing there is a spatially correlated distance or directional bias in the data (Geology, soil science).

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

- With
  - $Z(s_i)$: measured value at position i
  - λ_i : unknown weight for position i
  - s_0: prediction position
  - N: number of observations

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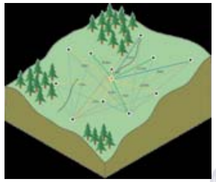

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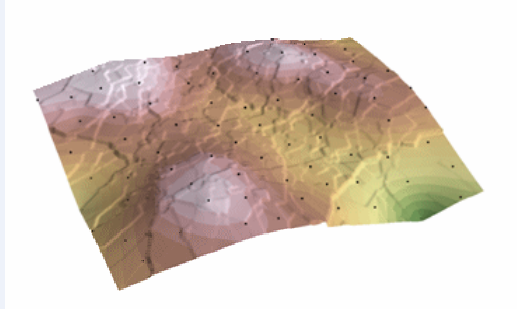

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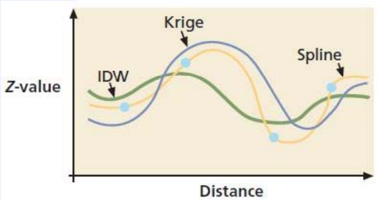
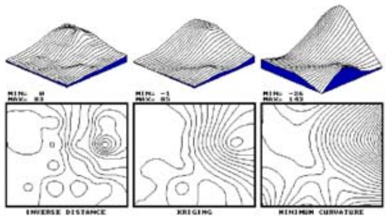
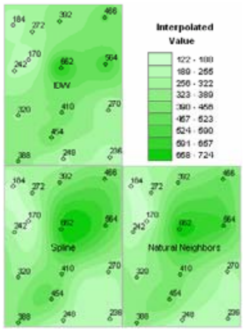
Comparison







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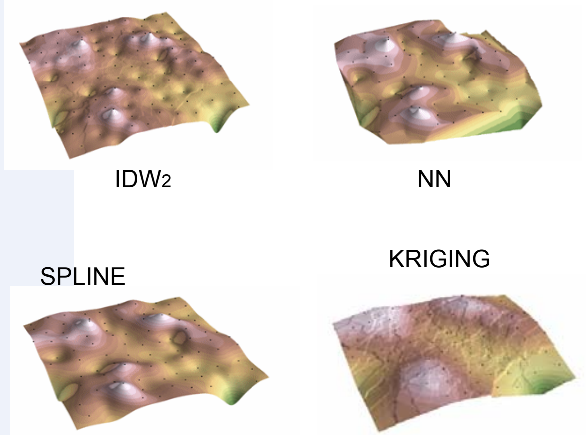
Comparison



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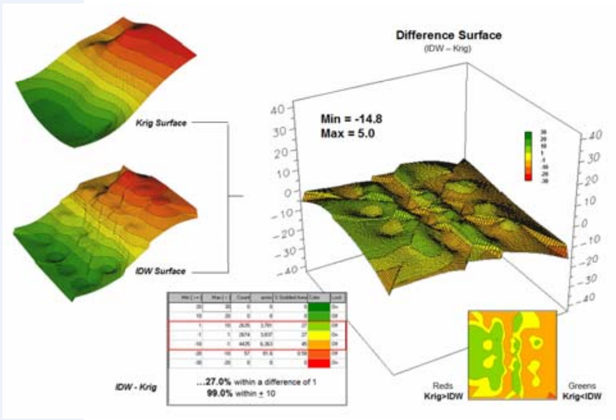
Comparison



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Summary

- Geometric algorithms and statistics are essential for the automatic analysis of spatial data (continuous phenomena)
- Algorithms have to cope with large volumes of data
- Discipline in Computer Science dealing with these problems
  - Computational Geometry
- Ongoing development
  - precise definition of spatial operators
  - implementation in database system (e.g. set operations, buffer, distance, polygon overlay, …) -> e.g. realized in Database Management System Oracle Spatial
  - Analysis-derived (specified) algorithms

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