Interactive Visual Data Analysis

02 – Criteria and influencing factors

Objectives

- What makes a good interactive visual data analysis solution: Learn the criteria to be fulfilled
- What do I need to take into account when designing, developing, or selecting interactive visual data analysis solutions: Learn about the influencing factors based on which decisions can be made

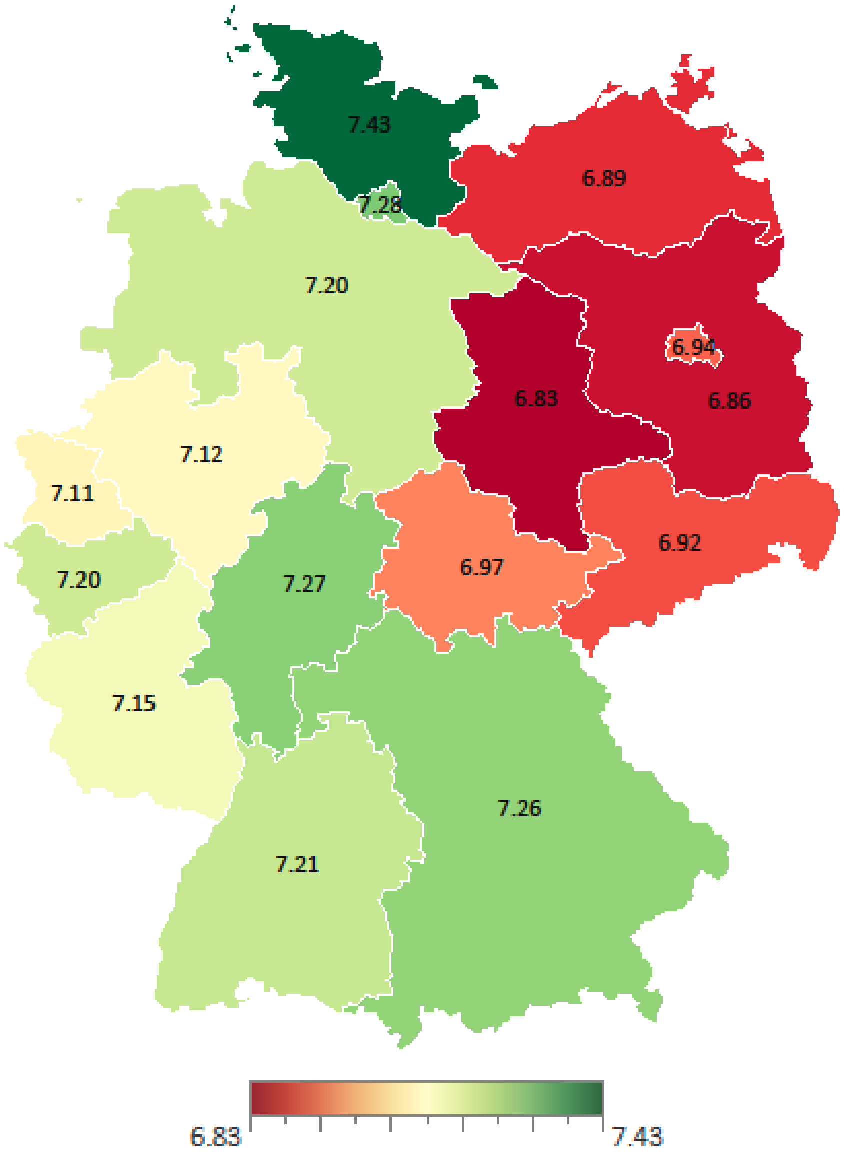
Overview

- Criteria
  - Expressiveness
  - Effectiveness
  - Efficiency
- Influencing factors
  - The subject: Data
  - The objective: Analysis tasks
  - The context: Users and technologies

Motivation

What makes a good visualization?

- Map shows life satisfaction
  - 0 unhappy – 10 very happy
- Think about: What is the first impression conveyed by this visualization and what is truly contained in the data?

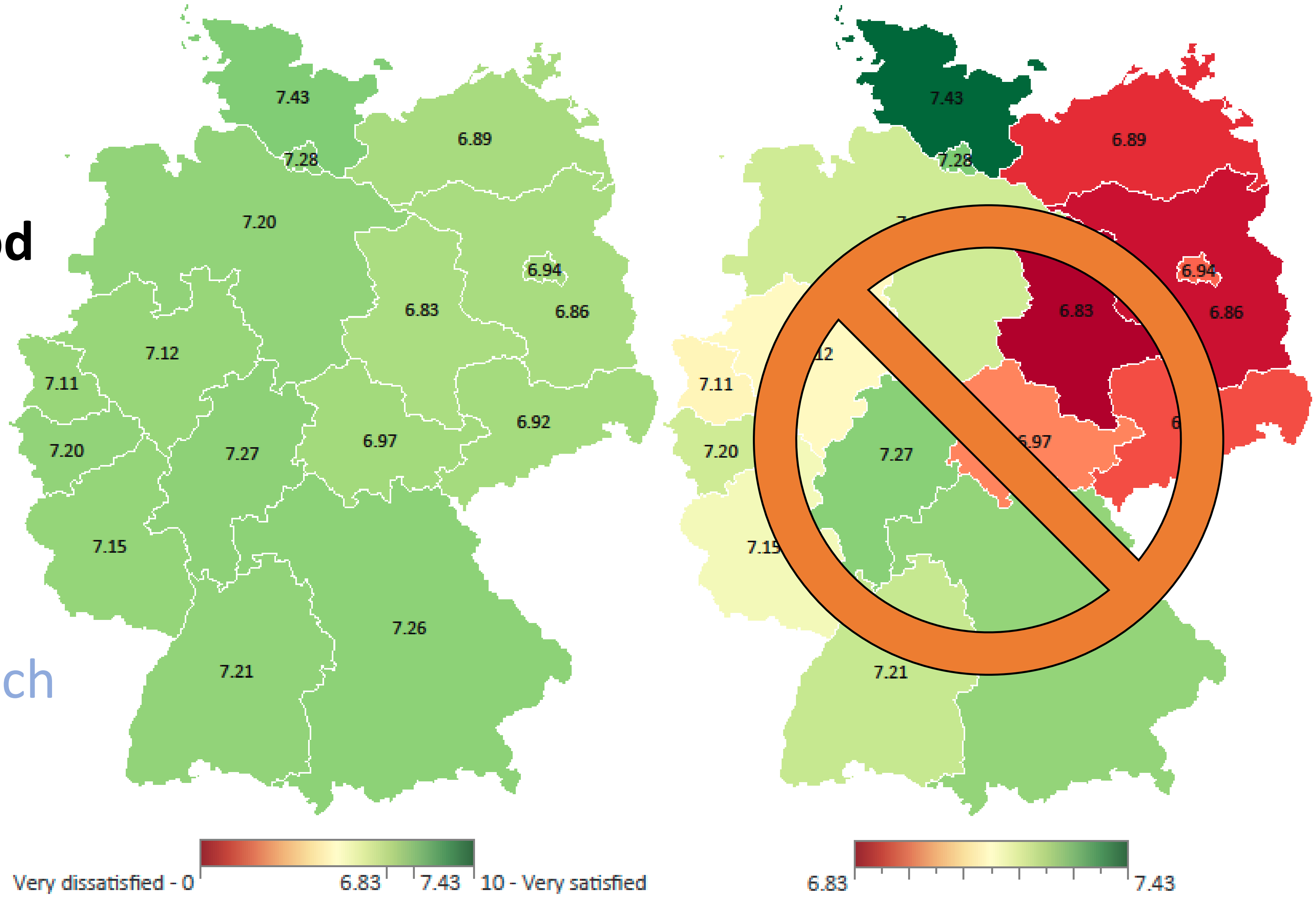


Motivation

What makes a good visualization?

- Same data, different visual encoding

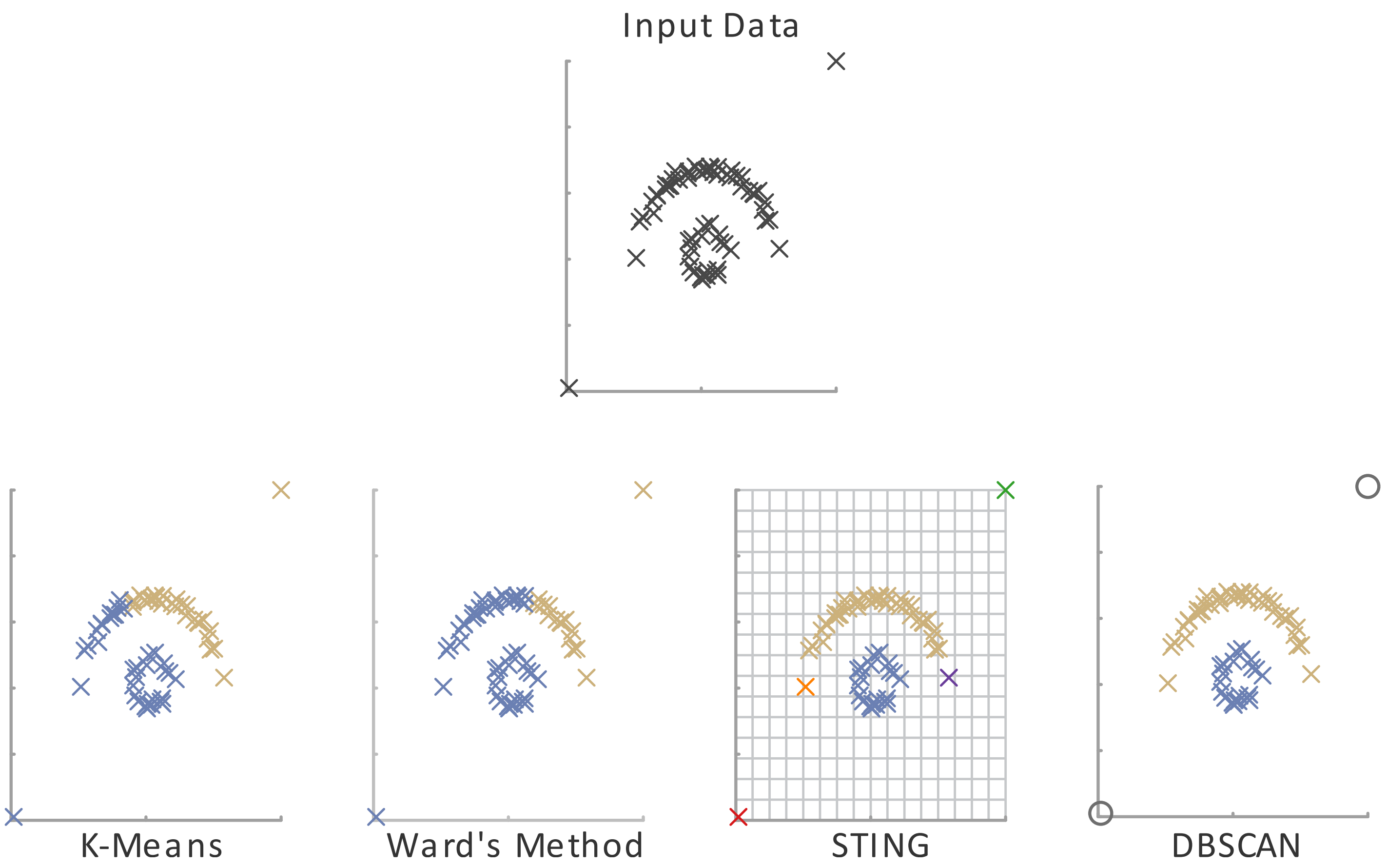
- Think about: Which version is better?



Motivation

Which computational method should be used?

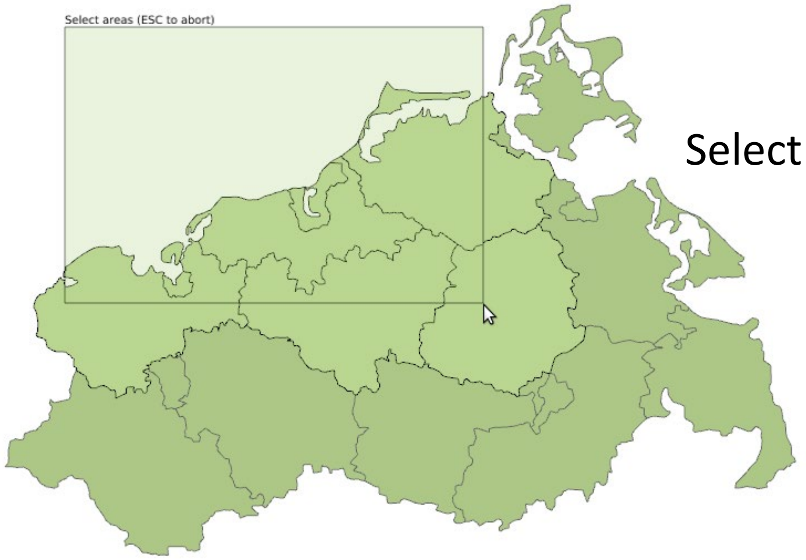
- Consider the plotted data
- Four different algorithms computed data clusters
- Think about: Which algorithm would you choose?



Motivation

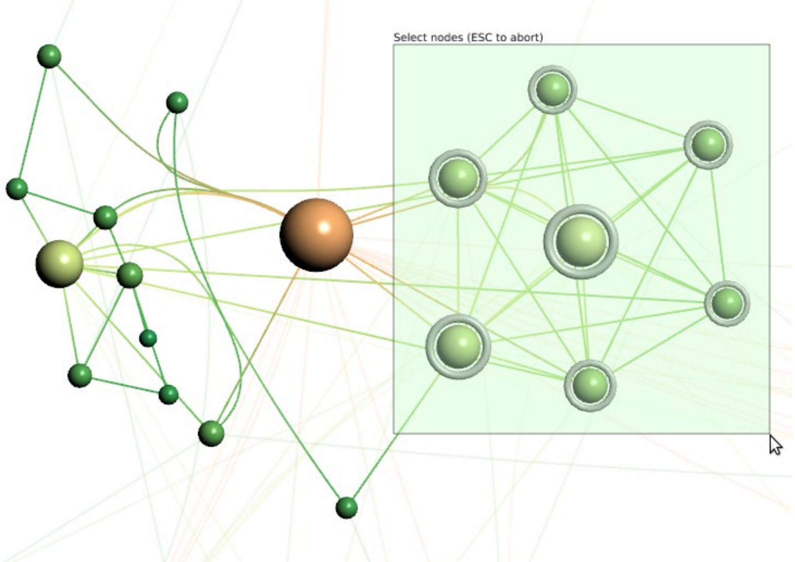
How to interact with the data?

- Two alternative interactions for selecting data items
  - Intersect: Select data items that **intersect** with rectangle
  - Include: Select data items that are fully **included** in rectangle
- Think about: Which variant would you prefer?



Select by intersecting

Select by including



Criteria

We see that some solutions are seemingly better than others. To better characterize what makes a good solution, we define **3** quality **criteria**:

- **Expressiveness**
- **Effectiveness**
- **Efficiency**

Criteria

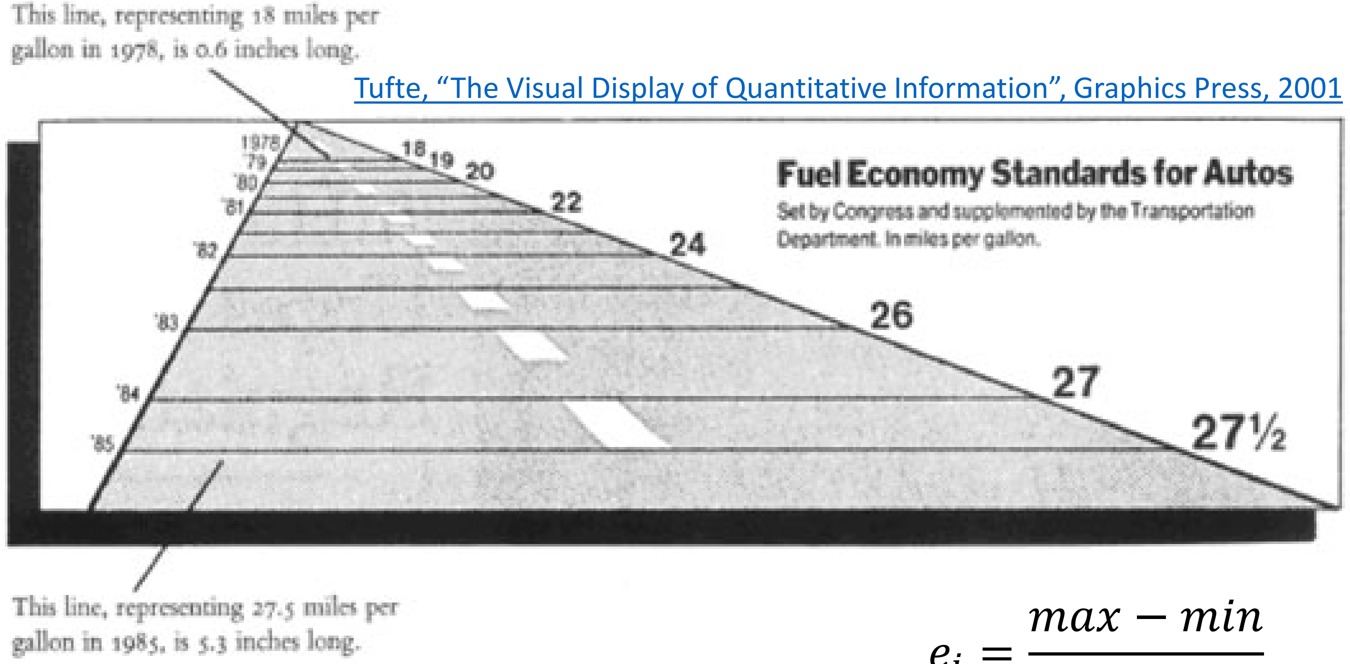
Expressiveness

- Relates to faithfulness
- An interactive visual data analysis solution is **expressive**
  - **if it communicates the relevant information** contained in the data, and only this information. No information is fabricated, no information is withheld.
  - **if it allows users to carry out the actions needed** to acquire the desired information, and only these actions. Users are enabled to do exactly what is necessary for the task at hand.

Criteria

Expressiveness: Lie Factor

- Perceived effect e_v should correspond to the effect in the data e_d
- Lie factor $l = \frac{e_v}{e_d}$
- Example:
  - $e_v = \frac{5.3-0.6}{0.6} = 7.83 \approx 783\%$
  - $e_d = \frac{27.5-18}{18} = 0.53 \approx 53\%$
  - $l = \frac{783\%}{52\%} = 14.77$



[Tufte, "The Visual Display of Quantitative Information", Graphics Press, 2001]

$$e_i = \frac{max - min}{min}$$

Also see https://www.vislies.org

Criteria

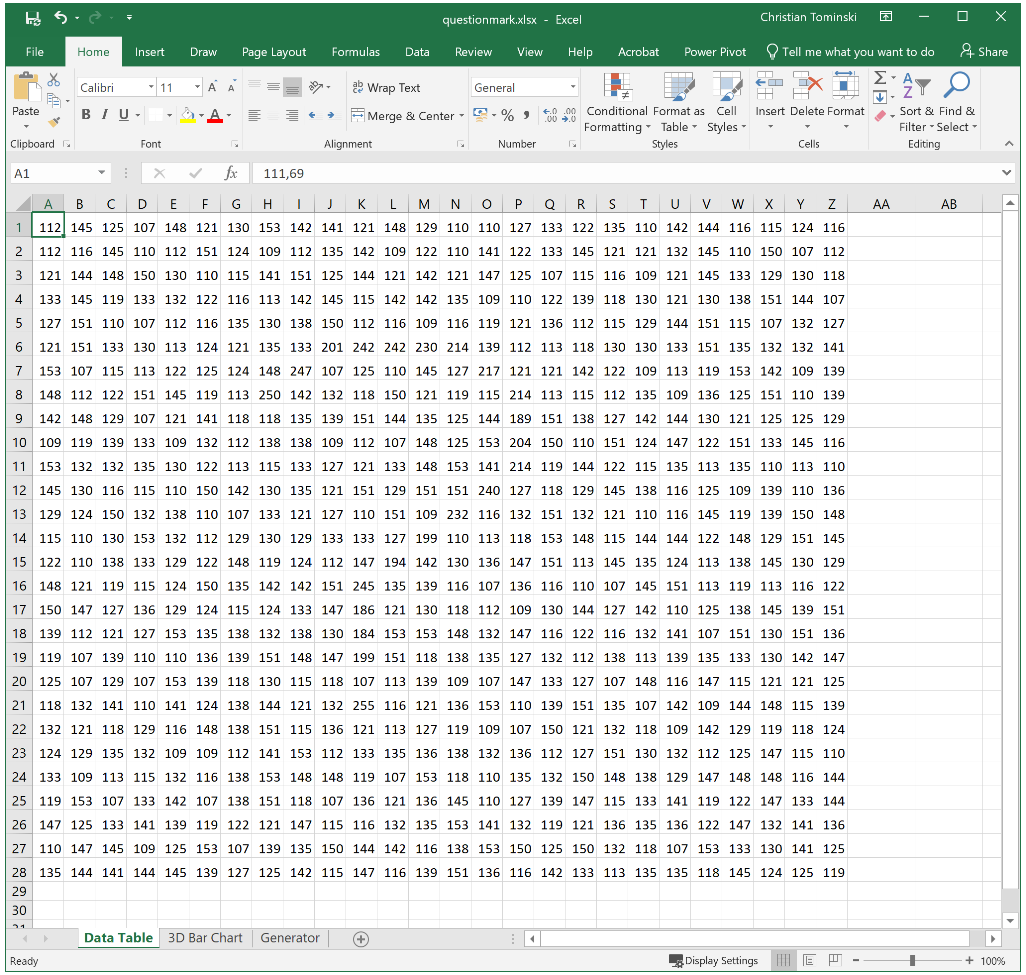
Effectiveness

- Relates to the degree to which users can achieve tasks
- An interactive visual data analysis solution is **effective if it is geared to the human sensory and motor system**
  - How well can users digest the depicted information (visual)
  - How well can users convey their intent to change (interactive)

Criteria

Effectiveness: Illustrating example

- Let's visualize a data table!



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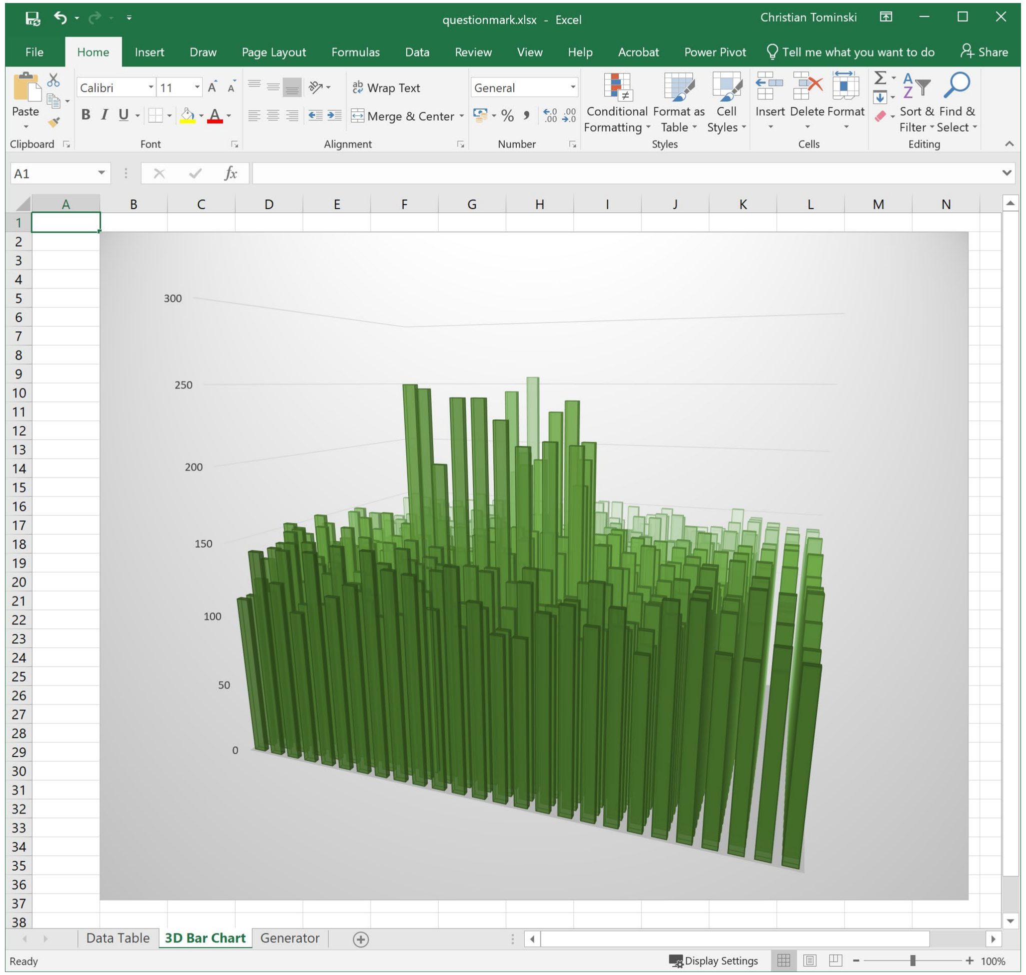
Criteria

Effectiveness: Illustrating example

- Think about:
  - Is this visualization expressive?
  - Is this visualization effective?

- Arguably, yes, it is expressive, because all data are represented visually?
- But, it is not effective, because we can hardly interpret the data.

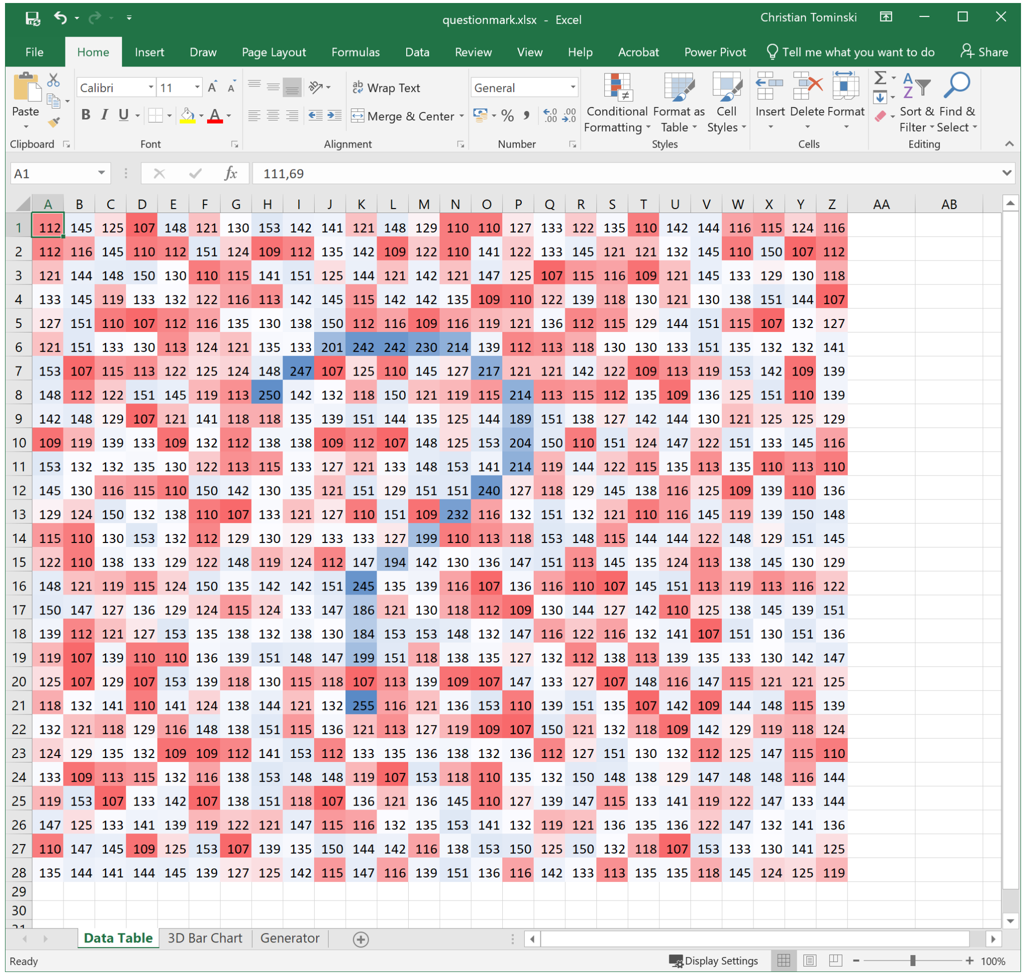


Criteria

Effectiveness: Illustrating example

- Think about:
  - Is this visualization expressive?
  - Is this visualization effective?

- Yes, expressive and effective! All data are depicted faithfully and we can easily discern a pattern from the otherwise noisy data.



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Criteria

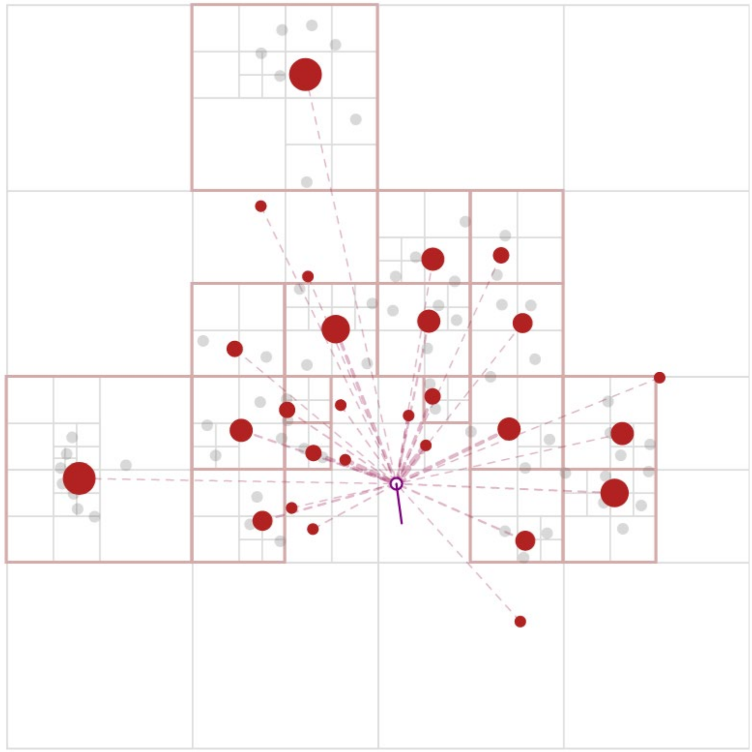
Efficiency

- Relates to the balance of benefits and costs
- An interactive visual data analysis solution is **efficient if its benefits outweigh the costs** in terms of computational and human resources
  - How much time and memory does it take?
  - How much display space is needed?
  - How much eye movement is required?
  - How long does it take to decipher the visual representation?
  - How difficult is it to interact?

Criteria

Illustrating example: Efficiency

- Force-directed layout for graph visualization
  - Attracting forces between connected nodes
  - Repelling forces between all nodes
- Computational costs:
  - Naïve $O(n^2)$
  - Barnes-Hut $O(n \log n)$



https://jheer.github.io/barnes-hut/

Criteria

Criterion	Concern
Expressiveness	Faithfully map data and tasks
Effectiveness	Enable users to accomplish task
Efficiency	Balance benefits and costs

Discussion

- Criteria capture conceptual ideas, and as such, are difficult to evaluate formally
- Some aspects easy to quantify: Computation time, display space, …
- Others hard to pin down:
  - Expressiveness: What is the “relevant” information to be depicted faithfully?
  - Effectiveness: How well can a complex data analysis system be operated?
  - Efficiency: What are the benefits of using an interactive visual solution?
- Nonetheless, the 3 criteria provide essential guidelines for designing interactive visual data analysis solutions!

Criteria

Summary

“Above all else **show the data**.

— Tufte, 1983

Influencing factors

When designing and developing interactive visual data analysis solutions, we need to take into account **4** key **influencing factors**:

- **Subject** of the data analysis: **Data** (what)
- **Objective** of the data analysis: **Analysis tasks** (why)
- **Context** of the data analysis: **Users and technologies** (who, where, when)

- **Why do they matter?**
  - Depending on the influencing factors, different design choices lead to different degrees of fulfillment of the 3 quality criteria!

Influencing factor: Data

With respect to the **data**, the following data characteristics are relevant

- Data domain (data scale and data type)
- Data structure
- Data space
- Data size
- Data scope
- Meta-data

Influencing factor: Data

Data domain

- Set of values that a datum (or data value) can assume
- Differentiate between different **data scales** and **data types**
- **Data scale**: How are the data scaled?
  - Qualitative data: Nominal and ordinal data
  - Quantitative data: Discrete and continuous data
- **Data type**: How is a datum composed of components?
  - Scalar, vector, tensor

Here, the notion of *data type* is used slightly differently from its use in programming languages.

Influencing factor: Data

Qualitative data

- Nominal data
  - Values for which only the **equality relation** = is defined
  - Also called **categorical** data
  - Example: Names *{John, Mike, Lisa, Monica}*
  - Think about: Give another example of nominal data!
- Ordinal data
  - Values for which an **order relation** < is defined in addition to equality
  - Example: Age groups *{children, youths, adults, elders}*
  - Think about: Give another example of ordinal data!

Influencing factor: Data

Quantitative data

- Discrete data
  - Numeric values whose domain can be equated to the **whole numbers**
  - Countable and **distance** between any two data values is defined
  - Example: Number of people visiting a doctor
- Continuous data
  - Numeric values whose domain can be equated to the **real numbers**
  - **Uncountable**, distance is defined, and **interpolation** is possible
  - Example: Temperature measurements
  - Think about: Why is the uncountable property of relevance here?

Influencing factor: Data

Data scale

- Summary of data scales and possible operations

Operations	Qualitative Data		Quantitative Data	
	Nominal	Ordinal	Discrete	Continuous
Equality	●	●	●	●
Order		●	●	●
Distance			●	●
Interpolation				●
(Count)	●	●	●	

Influencing factor: Data

Data type

In this lecture series, we will focus on scalar data.

- **Scalar:**
  - **Single value**
  - **Example: temperature value**

$$36$$

- Vector:
  - Magnitude and direction
  - Example: 3D vector flow vector

$$\begin{pmatrix}1\\2\\3\end{pmatrix}$$

- Tensor:
  - General multilinear transformations
  - Example: Rank-2, 3D stress tensor

$$\begin{bmatrix}4 & 5 & 6\\8 & 10 & 12\\12 & 15 & 18\end{bmatrix}$$

Influencing factor: Data

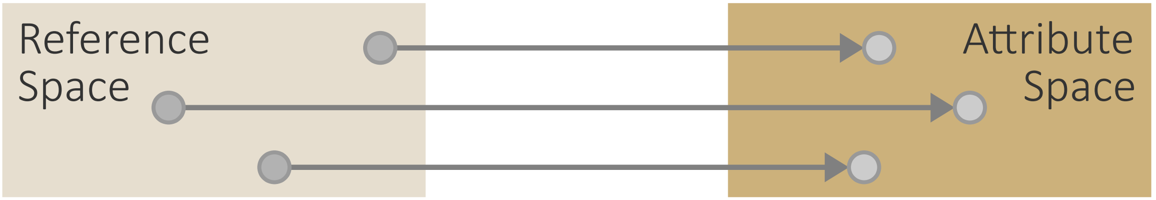
Data structure

- Raw data often “unstructured”
- Data analysis typically requires transforming raw data to a suitable structure
  - **Tabular data: Rows are tuples, columns are variables**
  - Hierarchical data: Parent-child relations, e.g., for different levels of detail
  - Graph data: General model for entities and relations between them
  - (Grid-structured data: Data aligned on different types of grids, for 3D data)

Influencing factor: Data

Data space

- Spanned by variables
  - **Independent** variables: **Dimensions** of the space where data have been collected, observed, or simulated
  - **Dependent** variables: **Attributes** of what has been collected, observed, or simulated
- Describes a functional dependency $f: (D_1 \times D_2 \times \cdots \times D_n) \rightarrow (A_1 \times A_2 \times \cdots \times A_m)$

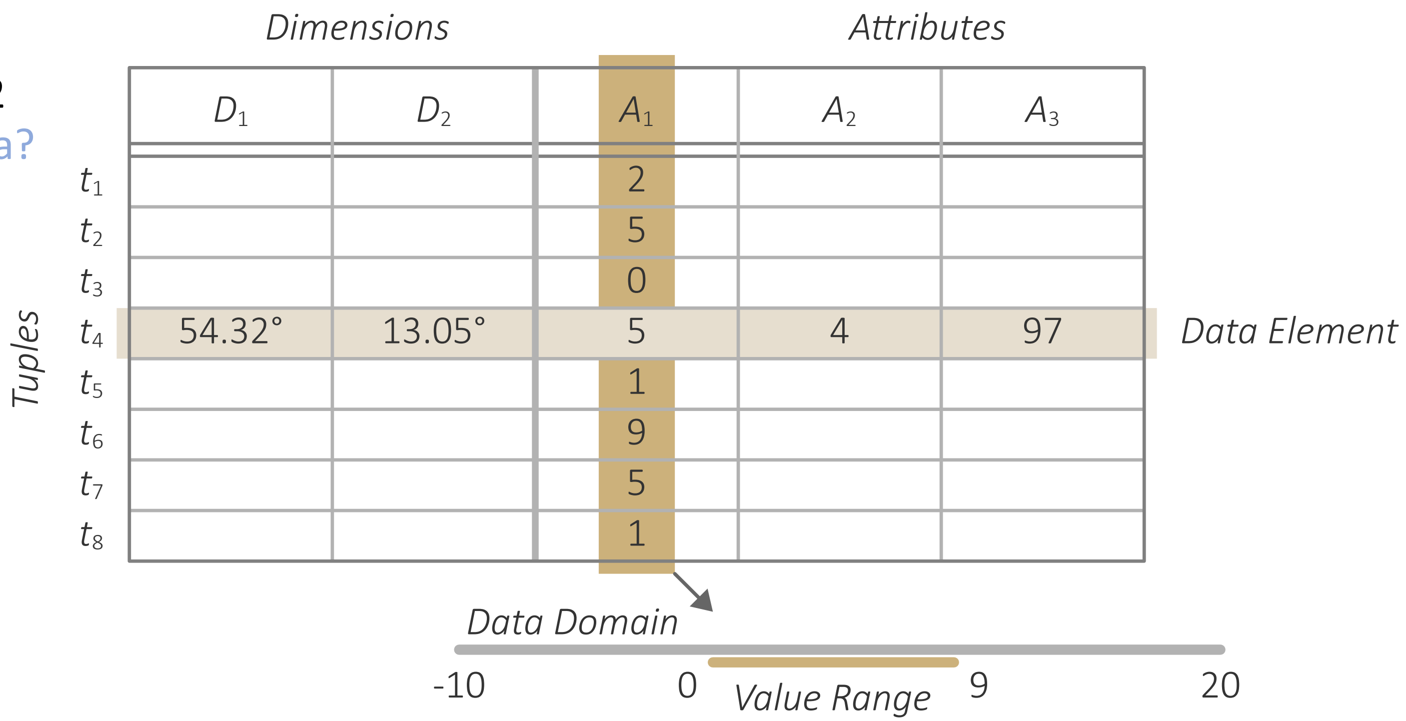


A visualization usually has the goal to make the functional dependencies in the data visible

Influencing factor: Data

Data size

- *n* - Number of dimensions
  - n-dimensional data
    - 1D data (e.g., time-series): n = 1
    - 2D data (e.g. geo-spatial data): n = 2
    - Think about: Any idea about 3D data?
    - Multidimensional data: $n > 3$
- *m* - Number of attributes
  - m-variate data
    - Univariate data: m = 1
    - Bivariate data: m = 2
    - Multivariate data: m > 2
- *k* - Number of tuples
  - Small data: k < 1000
  - Big data: k > 100.000



Influencing factor: Data

Data size

- Obviously, the larger *m*, *n*, and *k* are, the more difficult it will be to analyze the data
  - Requires additional effort for transforming, rendering, and interpreting the data
- What are considered large data, depends on the application context
  - Sometimes a graph with hundreds of nodes is large, but graphs exist with millions of nodes!
- Think about: Hardware barriers and data size

Influencing factor: Data

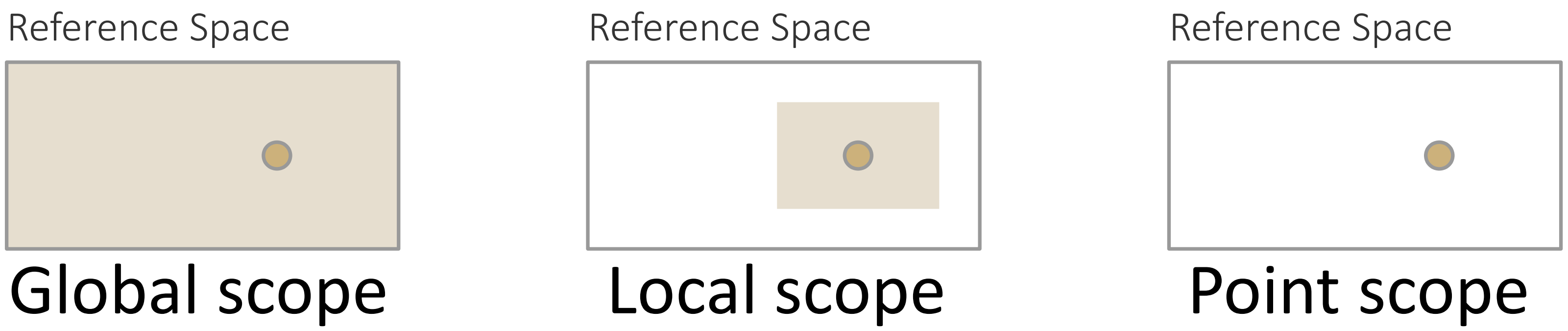
Data size

- Interactive visual data analysis solutions usually target **Big Data**
- Big Data characterized by five Vs
  - **Volume:** Many data points
  - **Velocity:** New data arrive at high speed
  - **Variety:** Many dimensions and attributes covering many different aspects
  - **Variability:** Data must be accessible to diverse user groups
  - **Value:** Monetary costs and benefits of data analysis are considerable

Influencing factor: Data

Data scope

- Characterizes the range in which the data are valid around a point of observation
- Usually cannot be inferred, must be given with the data description/context



Influencing factor: Data

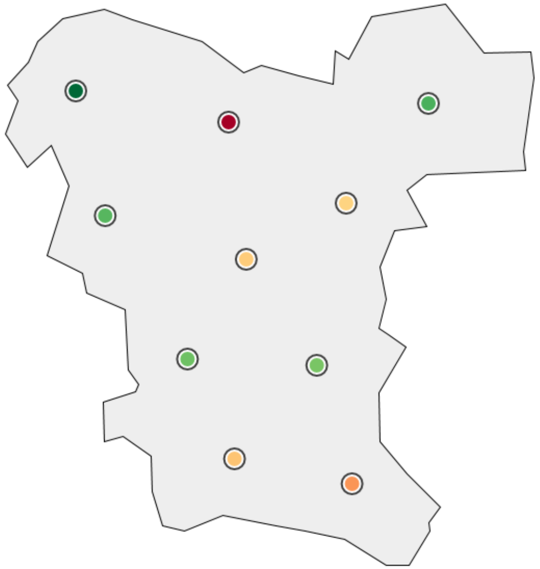
Data scope

- For geo-spatial data, according to Tobler's (1970) first law, the scope is local, because data measured at proximal locations tend to be correlated
- So, (geo-)spatial data are likely to have local scope
- Think about: How to represent local scope visually?

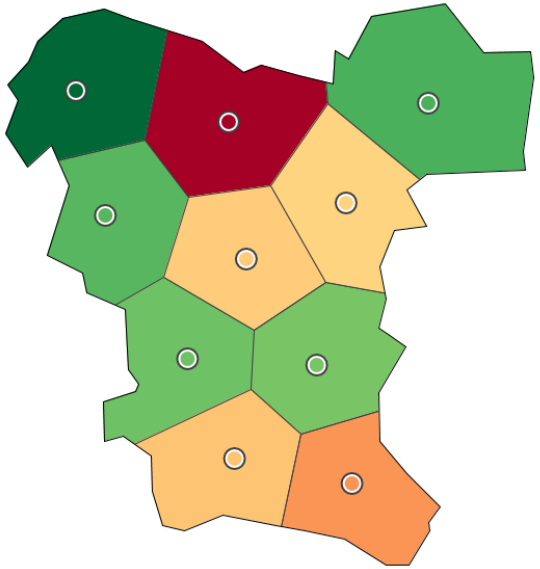
Influencing factor: Data

Data scope

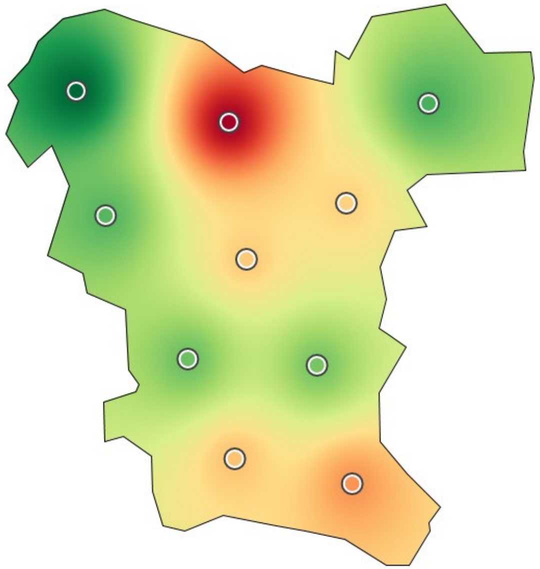
It is time for a demo!



Points only
(invisible local scope)

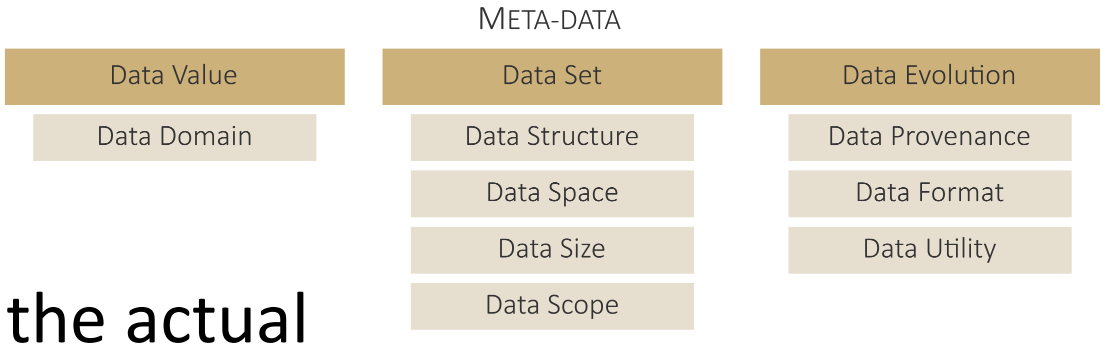


Voronoi partition
(discrete local scope)



Scattered data interpolation
(continuous local scope)

Influencing factor: Data



Meta-data

- Meta-data contain information about the actual data with respect to:
  - Data values: From which data domain are the values?
  - Data set: How is the dataset structured, how does the data space look like, how big are the data, what is their scope?
  - Data evolution:
    - Data Provenance: History of how the data were created?
    - Data Format: How are the data stored presently?
    - Data Utility: How may the data be used in the future?

Influencing factor: Data

Data classes

- Data classes pertain to different data aspects
  - **A** – data attributes
  - **T** – time
  - **S** – space
  - **R** – structural relationships
- Based on **A**, **T**, **S**, and **R**, different data classes can be defined
  - Multivariate data, temporal data, spatial data, spatio-temporal data, graph data, …

Influencing factor: Data

Data classes

- **Multivariate data (A)**
  - Data with many attributes (A)
  - Product data, player statistics, gene expressions, simulation runs, etc.
- **Temporal data (T → A)**
  - Data where attributes depend on time (T), a.k.a. time-dependent data
  - Financial data, medical treatment data, sensor data, etc.
- **Spatial data (S → A)**
  - Data being located in space (S), a.k.a. geo-spatial data
  - Election data, distribution of places, land use, etc.

Influencing factor: Data

Data classes

- **Spatio-temporal data ($S \times T \rightarrow A$)**
  - Data depends on space and time
  - Meteorological/climate data, disease spread, movement data, etc.
- **Graph data (R, $R \rightarrow A$, $R \rightarrow S \times T$, or $S \times T \rightarrow R \times A$)**
  - Entities (vertices V) and relations (edges E) between them, graph $G = (V, E)$
  - Entities and relations may be associated with further information (A, S, T)
  - Social networks, biological pathways, connectome data, etc.

Influencing factor: Data

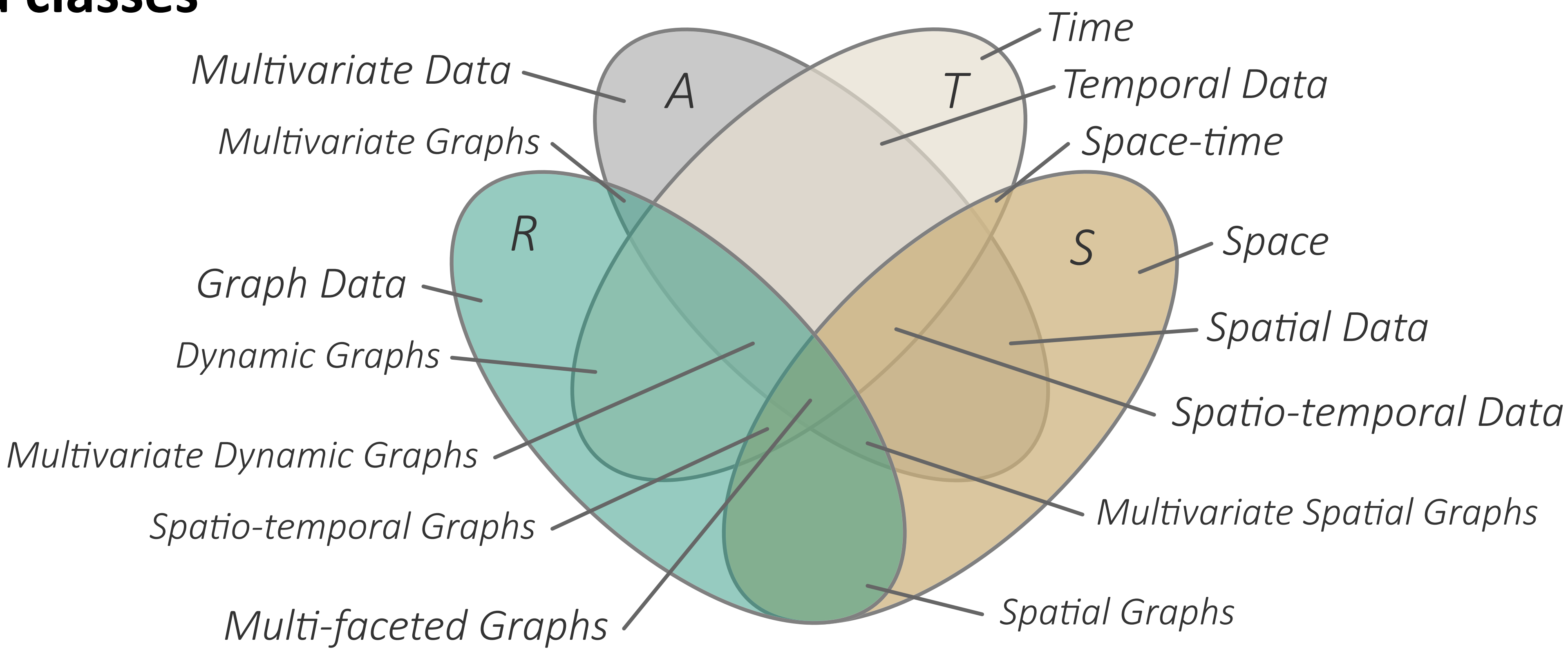
Data classes

- Further data classes
  - Text (A, R)
  - Images (S, A)
  - Flow data (S, A)
  - Volume data (S, A)

Influencing factor: Data

This type of visual representation is called a *Venn-diagram*.

Data classes



Influencing factor: Analysis tasks

With respect to the **analysis tasks**, the following aspects are relevant

- Goals: *Why* do we carry out a task?
- Analytic questions: *What* do we seek to answer?
- Targets: *Where* in the data do we operate?
- Means: *How* do we carry out the task?

Influencing factor: Analysis tasks

Goals: Why?

- **5 goals** are primarily relevant for interactive visual data analysis
  - Exploration
  - Description
  - Explanation
  - Confirmation
  - Presentation
- Goals roughly structure the analysis process
  - We start **exploring** the data and make observations. Next we **describe** findings and try to **explain** them. Then we **confirm** our hypotheses and finally **present** the confirmed analysis results.

Influencing factor: Analysis tasks

Goals: Why?

This goal very much relates to the classic idea of *Exploratory Data Analysis* as formulated by John W. Tukey, 1977.

- **Exploration**
  - Open-ended undirected search
  - "I-know-it-when-I-see-it" approach
  - Make first observations (e.g., gain overview, detect patterns and outliers, …)
- **Description**
  - Characterize observations
  - Derive specifications for observations
  - Example: Describe outliers
    - What are their characteristic values?
    - Where are they located in space and time?

Influencing factor: Analysis tasks

Goals: Why?

- **Explanation**
  - Develop deeper understanding of observations (e.g., by identifying all contributing data, finding main causes, checking re-occurrence, etc.)
  - Formulate hypotheses about the data
- **Confirmation**
  - Verify hypotheses
  - Look for concrete evidence to back up or refute hypothesis
  - Compare different subsets and different visual representations
  - Generate analysis results

Influencing factor: Analysis tasks

Goals: Why?

- **Presentation**
  - Communicate confirmed analysis results
  - Best done by telling a story
  - Convince others

  - Think about: Who are we convincing in explanation and confirmation?

Influencing factor: Analysis tasks

Analytic questions: What?

- Data analysis activities may involve a variety of analytic questions at two distinct levels
  - **Elementary questions**
    - Data elements are studied individually
    - May include one or more individual elements
  - **Synoptic questions**
    - Sets of data elements are studied
    - Consider sets as a whole, not individual elements

Influencing factor: Analysis tasks

Analytic questions: What?

- **Elementary questions**
  - Identify: What is the value?
  - Locate: Where is the value?
  - Compare: Is it less or more?
  - Rank: Is there any order?
  - Connect: Are they related?
  - Distinguish: What makes the difference?

Influencing factor: Analysis tasks

Analytic questions: What?

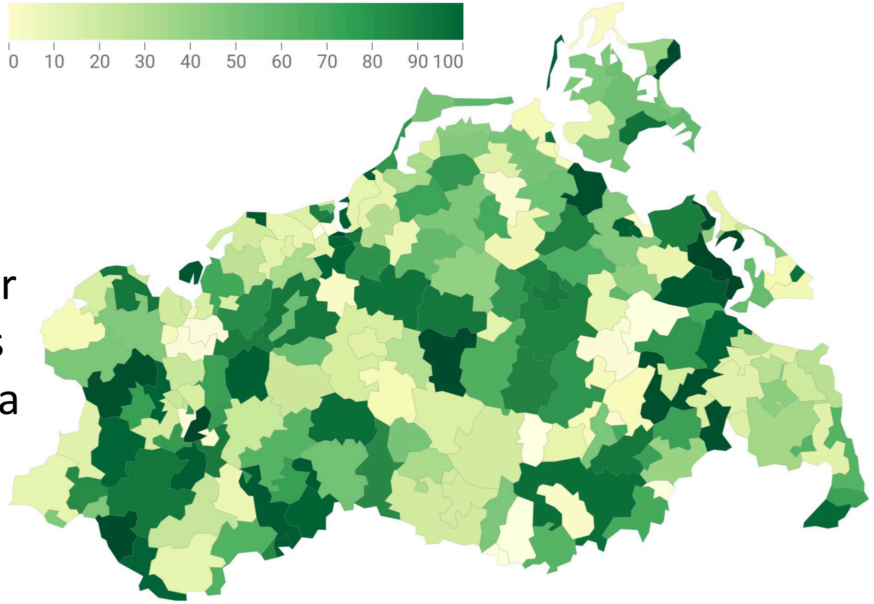
- **Synoptic questions**
  - Group: Do they belong together?
  - Correlate: Are there any dependencies?
  - Trends: Do they develop systematically?
  - Cycles: Do they re-occur periodically?
  - Outliers: Are they special with respect to the rest?
  - Features: What is characteristic for the data?

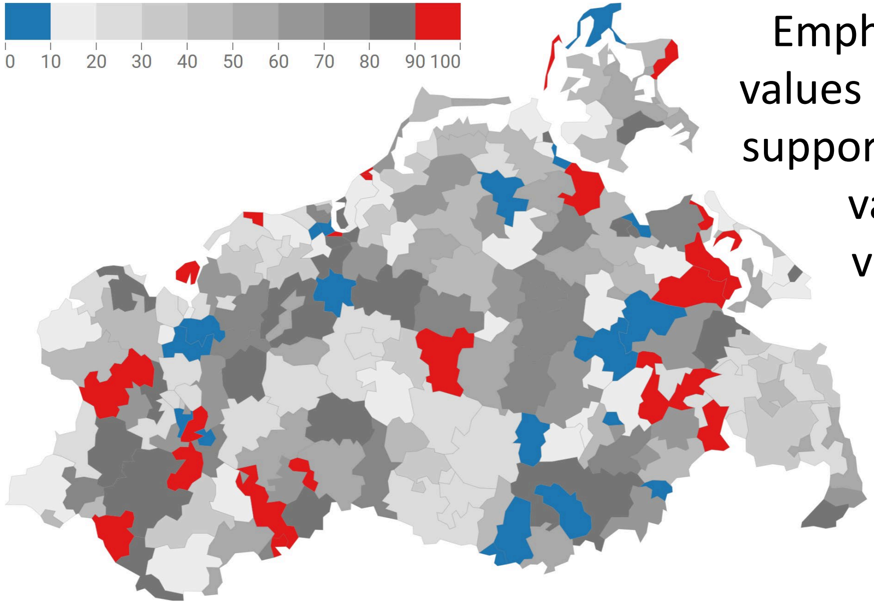
Influencing factor: Analysis tasks

Analytic questions: What?

- Different questions require different visual representations
- Example: Color-coded map for **identification** and **location** tasks

A uniform color scale supports **identifying** data values



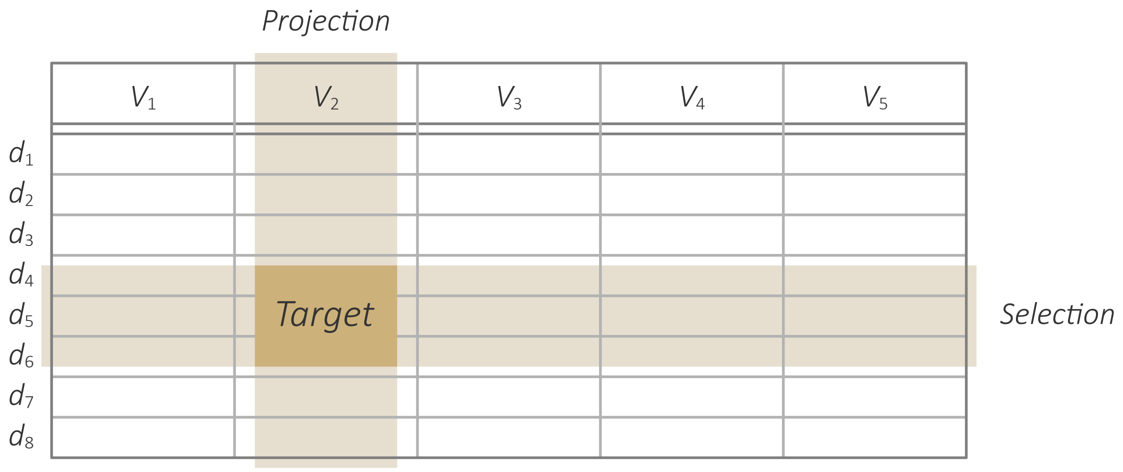


Emphasizing specific values in the color scale supports **locating** these values in the visualization

Influencing factor: Analysis tasks

Targets: Where?

- Define where in the data a task operates
- Knowing the target allows us to focus the analysis on relevant data
  - **Data of interest**
    - Particular data elements: Selection
    - Specific data attributes: Projection
  - **Data granularity**
    - Relevant for hierarchical multi-scale data
    - At what scale does a task operate
      - High level of abstraction: Overview tasks
      - High level of detail: Tasks required fine-grained information



Influencing factor: Analysis tasks

Means: How?

- We have three options for carrying out analysis tasks
  - **Visual means**
    - Tasks rely primarily on the human visual system
    - Example: Detect group of similar data elements
  - **Interactive means**
    - Tasks are carried out primarily through human action
    - Example: Select data elements for detailed inspection
  - **Computational means**
    - Tasks conducted by the machine
    - Example: Cluster similar data elements

Influencing factor: Analysis tasks

Summary

TASKS

Goals	Questions		Targets	Means
	Elementary	Synoptic		
Explore Describe Explain Confirm Present	Identify Locate …	Group Correlate …	Data of Interest Granularity	Visual Interactive Computational

Influencing factor: Analysis tasks

Examples

Goal	Question	Target	Means
Explore	locations of	maximum values	visually.
Describe	groups of	low-value elements	by marking.
Confirm	cyclic behavior	of temperature	by statistics.

Influencing factor: Context

The **context** captures the influencing factors pertaining to the users and the technologies involved in the data analysis

- **Users**
  - Human factors
  - User background and expertise
  - Application domain
  - Single-user and collaborative analysis
- **Technologies**
  - Computational resources
  - Display technologies
  - Input modalities

Summary

- **Criteria** (few)
  - Expressiveness
  - Effectiveness
  - Efficiency
- **Influencing factors** (many)
  - The subject: Data
  - The objective: Analysis tasks
  - The context: Users and technologies

*The **many influencing factors** make the design of interactive visual data analysis solutions a **challenging** endeavor!*

Summary

What can you do with criteria and influencing factors?

- Assess the quality of an interactive visual data analysis solution!
  - Is the solution expressive, effective, and efficient?
- Compare solutions based on criteria!
  - Is one solution more suited than another?
- Ask your customers the right questions!
  - Are your data qualitative or quantitative?
  - How big are your data?
  - What are your goals?
  - Think about: What else might you want to ask?

Assignments

1. Read about the context as influencing factor in detail in Chapter 2 of "Interactive Visual Data Analysis" by Tominski and Schumann!

Questions

1. Name and explain the 3 quality criteria for interactive visual data analysis!
2. What can we learn from the “lie factor”?
3. What factors influence design and selection of adequate methods?
4. How is the data domain characterized?
5. What are independent and dependent variables and how are they related to the reference space and the attribute space?
6. Name different data classes and give corresponding example data sets!
7. Name and explain the 5 primary goals of interactive visual data analysis!
8. How are elementary and synoptic analysis questions characterized? Give examples tasks!
9. How can identification tasks and location tasks be supported by appropriate color-coding?
10. What are selection and projection good for?
11. What is captured by the context as an influencing factor?
12. What would you sensibly ask a customer who approaches you with a data analysis project proposal?