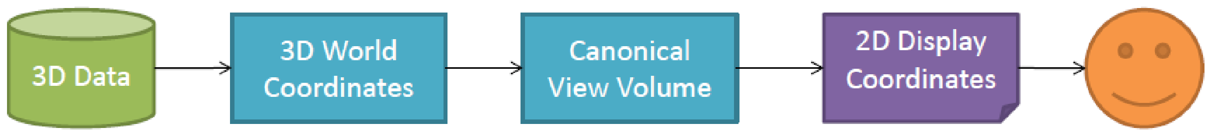
1. Introduction

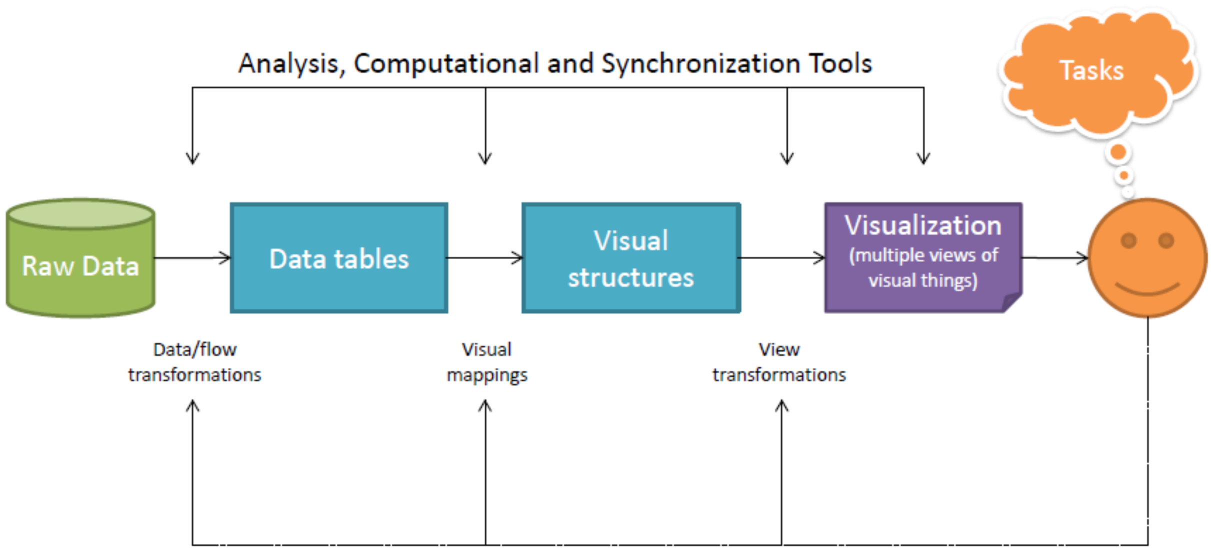
1.1. The Visualization Process

- Analysis of: data type and the information the viewer hopes to extract
- Preprocess the data
- Define a mapping
- Provide interactive controls (if necessary)
- Visualization as port of a larger process:
    - Exploratory data analysis
    - Knowledge discovery
    - Visual analytics
- Goal: Building a model
- Process (data -> image/visualization/model) is called pipeline

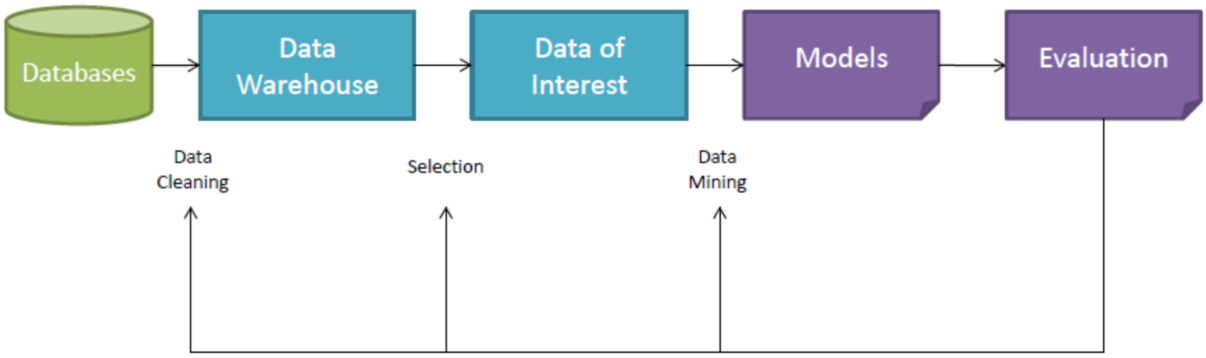
1.2. Computer Graphics Pipeline



1.3. The Visualization Pipeline



1.4. Knowledge Discovery Pipeline



1.5. The Role of the User

- **Presentation:**
    - Starting point: presented facts are a priori
    - Process: choice of appropriate presentation techniques
    - Result: high-quality visualization of data to present facts
- **Confirmatory Analysis**
    - Starting point: hypothesis about the data
    - Process: goal-oriented examination of the hypothesis
    - Result: visualization of data to confirm or reject the hypothesis
- **Exploratory Analysis:**
    - Starting point: no hypothesis about the data
    - Process: interactive, usually undirected search for structures, trends
    - Result: visualization of data to lead to hypothesis about the data

2. Data Foundations

2.1. Types of Data

Data Type	Operation	Example
Nominal	==, !=	Hair color
Ordinal	==, !=, <, >	School Grade
Numeric (Interval)	==, !=, <, >, +, -	Date
Numeric (Ratio)	==, !=, <, >, +, -, /, *	Height of a person

2.2. Data Preprocessing

- Metadata can help interpreting (format, unit, …)
- Statistical analysis can provide useful information (outliers, clusters, …)

2.2.1. *Missing Values and Data Cleansing*

- **Missing value** is a variable not in the data set, but existing in the real world
- **Empty value** is a variable in the data set without a value in the real world
- Ignore the tuple
- Fill in the missing value manually
- Use global constant or attribute mean to fill
- Use most probable value to fill (determined with regression, interpolation, …)

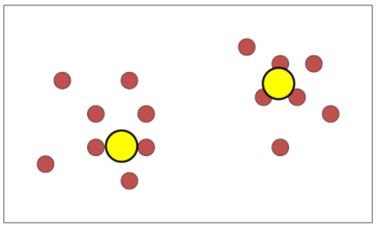
2.2.2. *Normalization*

- Very few outstanding values out of the data set
- Could have huge influence of e.g. a heat-map color mapping
- Linear Mapping: $f_{lin}(v) = \frac{v - min}{\max - min}$

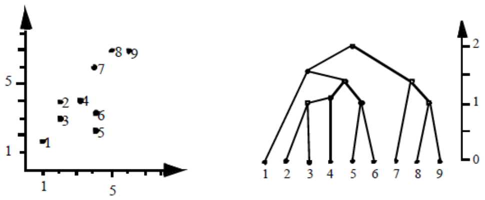
- Square root mapping: $f_{\sqrt{}}(v) = \frac{\sqrt{v}-\sqrt{min}}{\sqrt{max}-\sqrt{min}}$
- Logarithmic mapping is similar

2.2.3. Segmentation

- **Given:** Data set with N d-dimensional data items
- **Task:** determine natural partitioning of the data set into a numbers of clusters (k) and noise
- **Manual Segmentation:**
  - Based upon Attribute values/ranges and topological properties
- **Automatic Segmentation = Clustering Algorithms**
  - K-means



  - Linkage-based methods



  - Kernel density estimation

2.2.4. Sampling and Subsetting

- **Motivation:** data set is much larger than possible to work on
- **Example:** voters of an election (use an representative sample)
- **Important:** subset must represent some well-defined characteristics of whole data set
- **Types:**
  - Non-probabilistic samples: sample on random-basis (volunteers, …)
  - Probabilistic samples: sample on random-basis, but so that every element has equal chance to being selected
    - Simple random sampling: is least biased method
    - Systematic random sampling: elements are numbered 1 to N in some order -> numbers randomly chosen
    - Stratified Random sampling: data set divided into non-overlapping subsets called *strata*, subsets are random
    - Cluster random sampling: sample consists of randomly chosen groups of neighboring elements (clusters)

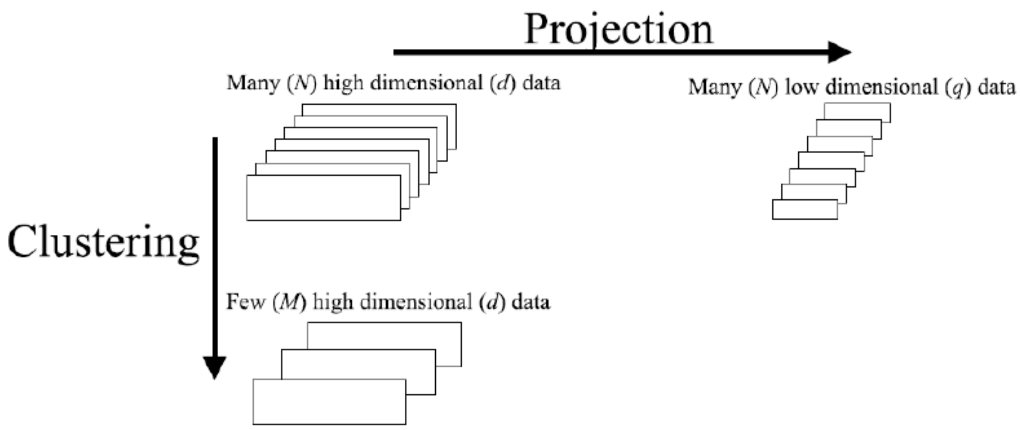
2.2.5. Approximation and Interpolation

- **Approximation:**
  - Problem: spatially random distributed weather stations

- Temperature data approximation based on triangulation
- Regression (linear, quadratic, …)
  - Linear: tries to discover straight line equation, that best fits the data point (y = a +bx), minimizes the least square error
- Interpolation:
  - Polynomial (Lagrange basis, Newton form)
  - Piecewise polynomial (cubic splines, …)
    - Passing single polynomial through many data points can lead to oscillations in the interpolant
    - Interpolant is cubic polynom
  - Orthogonal polynomials (Legendre, …)
  - Trigonometric functions

2.2.6. Dimension Reduction:

- **Major problems**:
  - Large number of features represent an object
  - Data difficult to visualize, especially if some features not characteristic
  - Irrelevant features my cause reduction of algorithm accuracy
- **Idea: Projection =** Identify most important features
  - Simplifies processing without quality loss
  - Directly visualizes two/three most important features



- **Goal:**
  - Discover hidden factors that explain the data
  - Reduce dimensionality of the data
- Similar to cluster centroids

- **PCA:**
  - There are n observations $\boldsymbol{x}_i = (x_{i1}, \dots, x_{ip})^T \in \mathbb{R}^D$
  - Projections are called $\boldsymbol{u}_i \in \mathbb{R}^d$
  - Projection is linear: $\boldsymbol{u} = \boldsymbol{W}\boldsymbol{x}$
  - Assume zero mean, we want to find the **W** which:
    - Decorrelates the projected points **u**
    - Preserves most values of the variance in the data
    - Minimizes reconstruction error
    - Arbeitsannahme: "*Die Richtungen mit der größten Streuung (Varianz) beinhalten die meiste Information.*"

2.2.7. Mapping Nominal Dimensions to Numbers

- Find mapping which not introduces artificial relationships that not exists
- Low number of different values (color, shape, …)
- Use multi-dimensional scaling (MDS) to map different nominal values to positions
- Only one nominal attribute: label the graphical elements

2.2.8. Aggregation and Summarization

- **Count** the items in the data set
- **Sum** the items in a list
- **Average (avg)** of all items in a data set
- **Measurement and Error:**
    - Random + systematic error + the true value gives the observation result
    - Only random error (noise) does not affect average
    - Only systematic error (bias) affect the average

2.2.9. Smoothing and Filtering

- Smooth & filter data to reduce noise and to blur sharp discontinuities
- Convolution: values that are significantly different from their neighbors will be modified to be more similar
- Binning
- Smoothing Noisy Data
    - Noise: random error or variance in a measured attribute
    - Causes:
        - Faulty data collection instruments
        - Data entry problems
        - Data transmission problems
        - Technology limitation
        - Inconsistency in naming convention
    - Binning:
        - Sort data and partition into (equi-depth) bins
        - Smooth by bin means, bin median, bin boundaries, etc.
    - Regression:
        - Smooth by fitting a regression function
    - Clustering:
        - Detect and remove outliers
    - Combined computer and human inspection:
        - Detect suspicious values and check by human

2.2.10. Raster to Vector Conversion

- Why?
    - Compressing the contents for transmission
    - Comparing the contents of two or more images
    - Transforming and/or segmenting the data

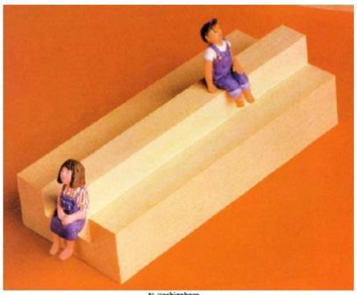
- How?
    - Tresholding: Identify values to break data into regions – boundaries can be traced to generate edges and vertices
    - Region-growing: merge pixels into clusters if they are sufficiently similar
    - Boundary-detection: convolve the image with particular pattern matrix
    - Thinning: Reduce wide linear features, such as arteries, to a single pixel width

2.2.11. Summary of data preprocessing

- Preprocessing can improve the effectiveness of the visualization.
- Convey to the user that these processes have been applied to the data.
- This helps interpreting the results.
- Otherwise, misinterpretation or erroneous conclusions can be drawn from the data.

3. Human Perception and Information Processing

3.1. Definitions


N. Yoshigahara

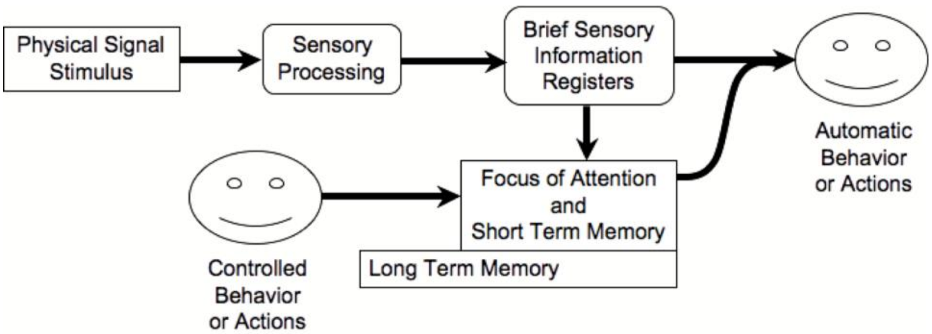
- **Perception:** Process of organizing sensory data, deriving (dt.: ableiten) structure from the complex pattern of energy impinging on our sensory receptors.
- **Cognition:** Is the act or process of knowing including both awareness and judgment; also: a product if this act

3.2. Physiology

- **Sensory of vision:** involves the gathering and recording of light from objects in the surrounding scene, and the forming of a two dimensional function on the photoreceptors.

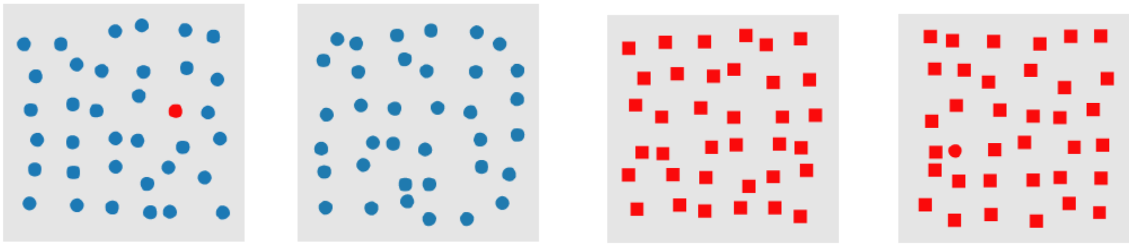
3.3. Perceptual Processing

- **Classic Model** of the flow of sensory data for cognition:

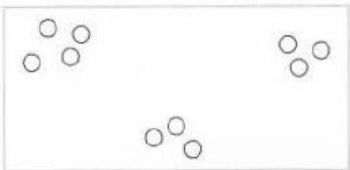


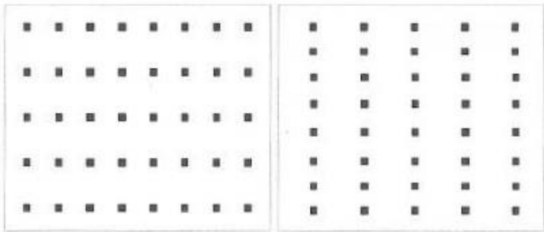
3.3.1. *Preattentive Processing*

- Perception of visual features managed by the low-level visual machinery
- Extremely fast: < 200 msec (eyes take more than that time) -> proceed parallel
- Preattentive = before attention takes place? -> Attention plays a role!!

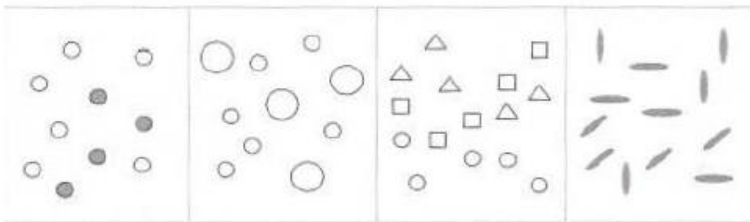


- **Gestalt laws**
  - Perceptual laws about how we **group visual objects** together to form visual entities
  - Law of **Proximity**

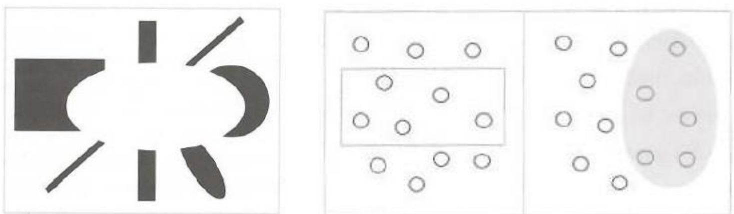




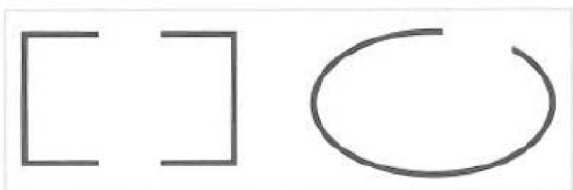
  - Law of **Similarity**



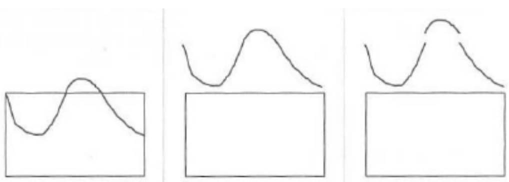
  - Law of **Enclosure**



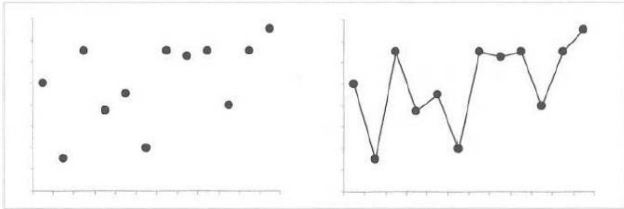
  - Law of **Closure**



  - Law of **Continuity**

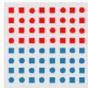


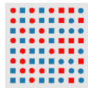
- Law of **Connection**



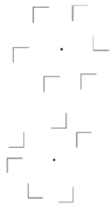
3.3.2. Theories of Preattentive Processing

- Feature Integration Theory
  - Boundary defined by unique feature hue is preattentively classified as horizontal
  - Boundary defined by conjunction of features cannot be preattentively classified as vertical





- Similarity Theory
  - High nontarget-nontarget (N-N) similarity allows easy detection of target L
  - Low N-N similarity increases the difficulty of detecting the target L



3.3.3. Feature Hierarchy

- **Horizontal** hue boundary is preattentively identified when form is held constant
- **Vertical** hue boundary is preattentively identified when form varies randomly in the background
- **Vertical** form boundary is preattentively identified when hue is held constant
- Horizontal form boundary cannot be preattentively identified when hue varies randomly in the background

3.4. <u>Perception in Visualization</u>

- Guidelines for **Color:**
  - Do not over- or underestimate the power of color
  - Always provide a color legend
  - Use color with extreme care and parsimony (Tufte: “above all do no harm”)
  - Learn to love grays and gray scales (grids!)
  - Do not represent unordered data with ordered colors
  - Keep an eye to skewed distribution
  - Do not use the (infamous) rainbow color scale
- **Texture:**
  - Often viewed as a single visual feature
  - Perceptual dimensions: regularity, directionality, contrast, size, etc.
  - Use to represent multiple data attributes

3.5. Metrics – Implications for visualizations

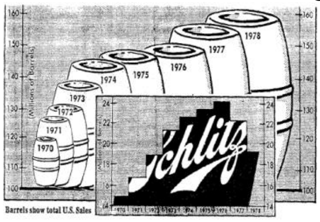
To enhance our absolute judgment

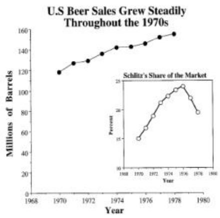
- Reduce graphical representation with one attribute to **4-7 values**
- Or repose problem in **multiple dimension**
- Or reduce problem to **sequence** of small problems
- Or **focus** first on relative judgment, then refine with absolute judgment

4. Visualization Foundations

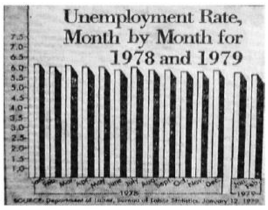
4.1. Bad Visualizations

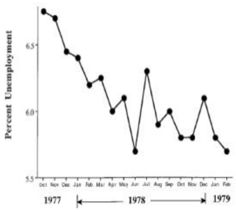
- Use the effect of cubing and get a lie factor of over 131%



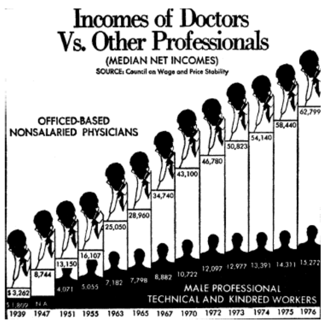


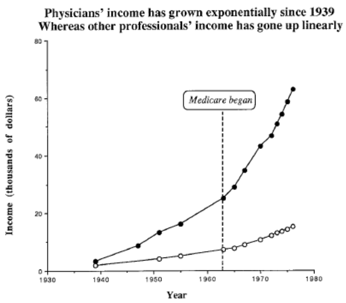
- Display Data out of context (hiding effect by careful choice of scale and origin)



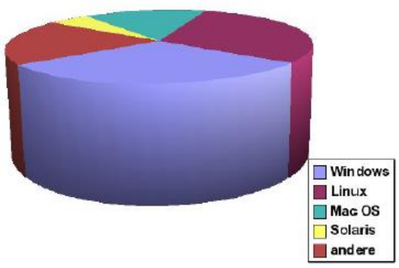


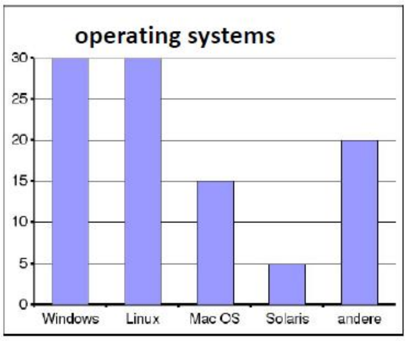
- Change scales in mid-axis to make exponential growth linear



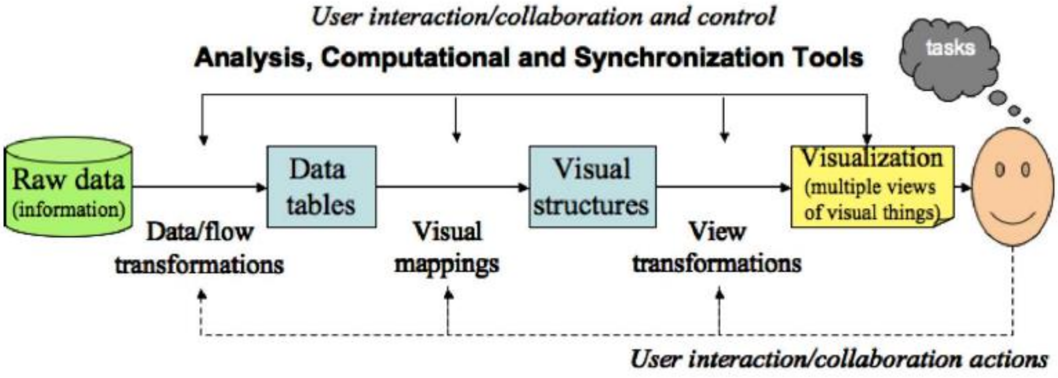


- Make clever use of 3D-effects: difficult to compare sizes of objects





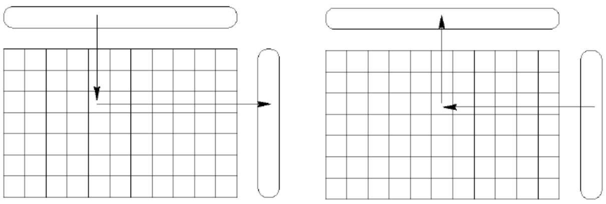
4.2. The Visualization process in detail



- **Expressiveness:** Visualization presents all the information and **only** the information.
- **Important:** Expressing additional information is potentially dangerous because it may not be correct.
- **Effectiveness:** Visualization is effective when it can be interpreted accurately or quickly and when it can be rendered in a cost-effective manner.

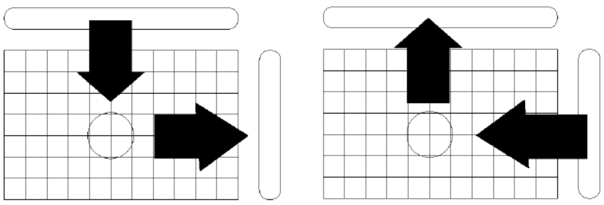
4.2.1. *Levels of information*

- **Level 1:** *Elementary level of information*



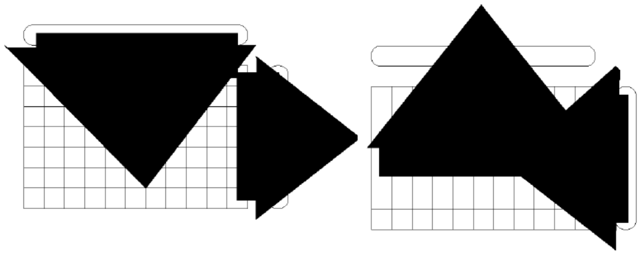
  - Relation between spate objects
  - <u>Question:</u> How many objects of this category exist?
  - Exists even in bad graphics
  - Human memory cannot store the multiplicity of elementary information
  - **Important:** number of elementary information must be reduced, similar elements must be discovered and combined to groups and classes

- **Level 2:** *Middle level of information*



  - Relation between groups/classes
  - <u>Question:</u> Which factors are crucial (entscheidend) ?
  - Analyzes the relationships within a group

- **Level 3:** *Upper level of information (overall information)*



  - Relationships between sets of objects
  - Questions: Which different sets do arise by the totality of all factors?
  - **Important:** The upper level of information is required for decisions!

4.3. Semiology of graphical symbols

4.3.1. Symbols and Visualizations

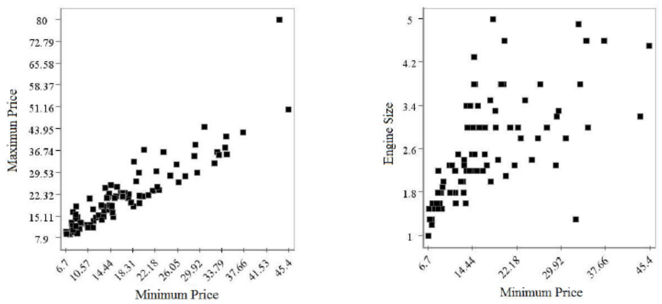
- Without external (cognitive) identification a graphic is unusable
- External identification must be directly readable und understandable
- Meaningful images must have easily interpretable x-, y- and z-dimensions
- Graphics elements of image must be clear
- Similarity in data structures ↔ visual similarity of corresponding symbols
- Order between data items ↔ visual order between corresponding symbols

4.3.2. Features of graphics

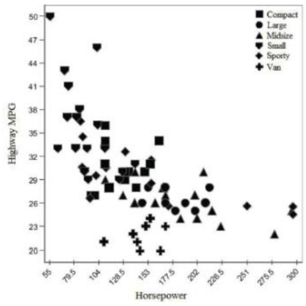
- Aim of graphic is to discover groups of orders in x, and groups of orders in y, that are formed on z-values
- (x, y, z)-construction enables in all cases the discovery of these groups
- Within (x, y, z)-construction, permutations and classifications solve the problem of upper level of information
- Every graphic with more than three factors that differs from the (x, y, z)-construction destroys the unity of graphic and the upper level information
- Pictures must be read and understood by human

4.3.3. The Eight Visual Variables

- **(1) Position:**

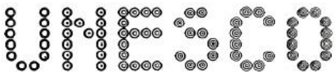


  - Unlike left, there does not appear to be a strong relationship right between the two variables



- **(2) Mark:**
  - Using shapes to distinguish between different types (e.g. of cars) to compare common characteristics (horsepower, MPG)
- **(3) Size (Length, Area and Volume)**
- **(4) Brightness**
- **(5) Color**
- **(6) Orientation** (to adjust mark orientation)
- **(7) Texture**
- **(8) Motion**
  - can be associated with any of th other visual variables
  - common use: varying speed at which a change is occuring, direction

- **Effects of visual variables**



textures

colors

direction

shape

	Position	Size	Shape	Value	Color	Orientation	Texture
Selective	YES	YES	YES	YES	YES	YES	YES
Associative	YES	YES	YES	YES	YES	YES	YES
Quantitative	YES	YES/NO	NO	YES/NO	NO	YES/NO	NO
Order	YES	YES	NO	YES	NO	NO	NO
Length		~ 5		~ 10	8-14	~ 5	

4.4. <u>Taxonomies (Klassifikationen)</u>

- Provides structure and understanding relationships in the large number of visualization techniques
- Reveal gaps (zeigt Lücken)
- Help understanding & to design systems

4.4.1. Taxonomy of visualization goals (Keller & Keller)

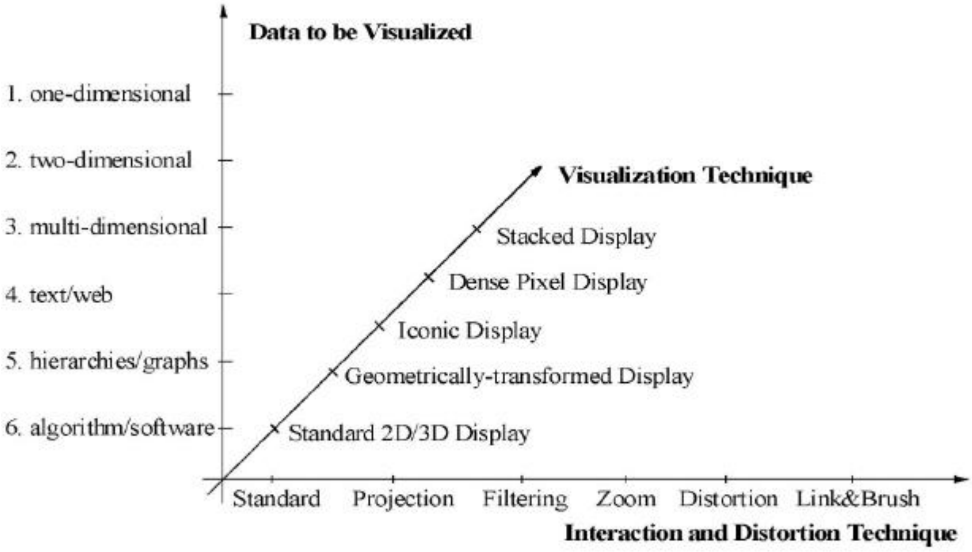
- **Data types:**
  - Scalar (or scalar field)
  - Nominal
  - Direction (or direction field)
  - Shape
  - Position
  - Spatially extended region or object (SERO)
- **Tasks:**
  - *Identify* – establish characteristics by which an object is recognizable
  - *Locate* – ascertain the position (absolute or relative)
  - *Distinguish* – recognize as distinct or different (identification is not needed)
  - *Categorize* – place into division or classes
  - *Cluster* – group similar objects
  - *Rank* – assign an order or position relative to other object
  - *Compare* – notice similarities and differences
  - *Associate* – link or join in a relationship that may or may not be of the same type
  - *Correlate* – establish a direct connection, such as casual or reciprocal

4.4.2. Data Type by task taxonomy (Shneiderman)

- **Data types:**
  - One-dimensional linear
  - Two-dimensional map
  - Three-dimensional world
  - Temporal
  - Multidimensional
  - Tree
  - Network
- **Tasks:**
  - Overview
  - Zoom
  - Filter
  - Details-on-demand
  - Relate
  - History
  - Extract

4.4.3. *Keim's Taxonomy (2002)*

- **Classification Criteria:**



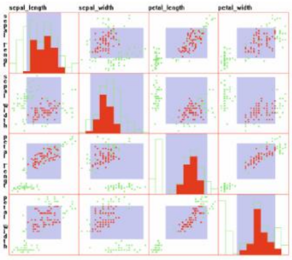
  - Data type to be visualized
    - Dimensionality (1D, 2D, Multidimensional)
    - Complex data types (Text/Web, graphs, etc.)
  - Visualization techniques
    - Support exploration of large data sets
    - Standard 2D/3D display, iconic display, etc.
  - Interaction and distortion techniques
    - User interacts with the data
    - Standard, projection, filtering, etc.
- **Data to be visualized:**
  - One-dimensional data:
    - Termporal data (i.e. news data, stock prices), text documents, …
  - Two-dimensional data:
    - Geographical maps, charts, floorplans, newspaper, layouts, …
  - Multidimensional data:
    - Relational tablets, …
  - Text and hypertext
    - News articles, web documents, …
  - Hirarchies/graphs:
    - Telephone calls, web documents, …
  - Algorithm/software:
    - Debugging operations, …

7. Visualization Techniques or Multivariate Data

7.1. Point-Based Techniques

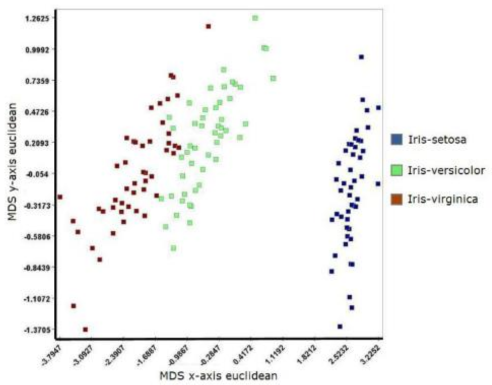
- Project records from n-dimensional data space to an arbitrary k-dimensional display space
- Each record is represented by a visual mark
- Can be structured by various projection techniques

7.1.1. Scatterplots and Scatterplot Matrices



- Scatterplot matrix with diagonal plot showing a histogram of each dimension. (red points and histogram regions indicate selected data)

7.1.2. Force-Based Methods

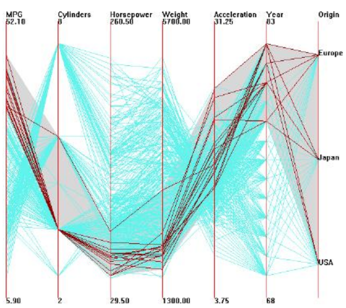


- Maintain the N-dimensional features and chracteristics of the data through the projection process
- Difficult when number of dimension increases
- Unintentional artficats in this visualization but not in the data
- Multidimensional scaling (MDS)

7.2. Line-Based Techniques

- Points are linked toghether with straight or curved lines
- Lines reinforce the relationships among data values
- Convey perceivable features of the data via slope, curvature, crossing, …

7.2.1. Parallel Coordinates

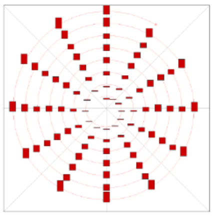


- N equidistant axes which are parallel to one of the screen axes and correspond to the attributes
- Axes are scaled to the [min, max]-range of the corresponding attribute
- Every data item corresponds to a polygonal line which intersects each of the axes at the point which corresponds to the value for the attribute

7.2.2. Radial Axis Techniques

- **Circular line graphs:** the plotted lines are offset from a circular base
- **Polar graphs:** point plots using polar coordinates
- **Circular bar charts:** like (1) but plotting bars on the base line
- **Circular area graphs:** like (1), but area under line filled with a color ort texture

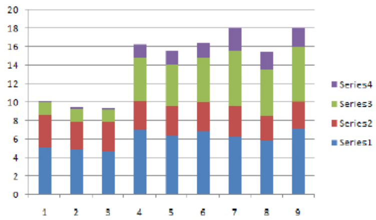
- **Circular bar graphs:** bars that are circular arcs + common center point and base line



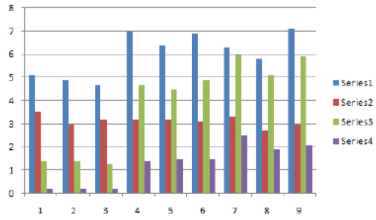
7.3. Region-Based Techniques

- Filled polygons are used to convey values (size, shape, color, …)
- Mostly not showing the real data, but summaries or distributions of the values
- One of the most common: bar chart

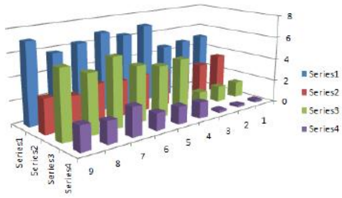
7.3.1. *Bar Charts/Histograms*



Stacked bar chart



Clustered bar chart



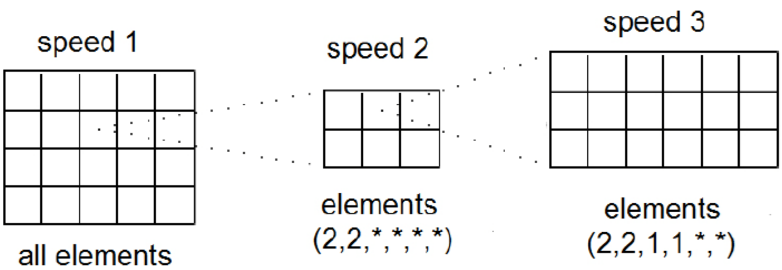
Bar graphs

7.3.2. *Tabular Displays*

- Multivariate data is often stored in tables
- Visualization modeled on this tabular structure
- Color or size/length used to encode data value
- Example shows iris data set

7.3.3. *Dimensional Stacking*

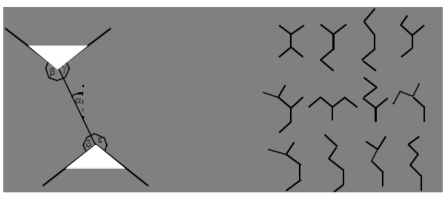
- Mapping data from discrete N-dimensional space to two-dimensional image
- Start with data of dimension 2N+1
- Select finite cardinality for each dimension
- Choose one of the dimensions to be the dependent variable
- The rest will be considered independent



7.4. Combination of Techniques

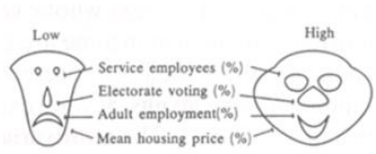
7.4.1. *Glyphs and Icons*

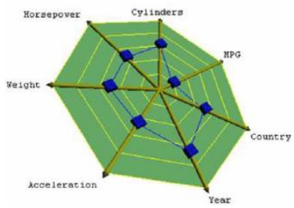
- A glyph is a visual representation of a piece of data or information where a graphical entity and its attributes are controlled by one or more data attributes.
- Stick Figures, Chernoff-Faces & Star Glyphs:



Stick Figure Icon

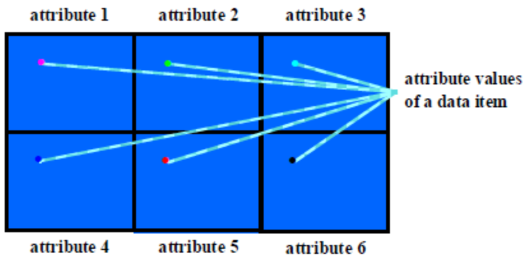
A Family of Stick Figures





7.4.2. *Dense Pixel Displays*

- Basic Idea:
  - Each attribute value is represented by one colored pixel (the vlaue ranges of the attributes are ampped to a fixed color map)
  - Attribute values for each attribute are presented in separate subwindows



7.5. <u>Comparison of the Techniques</u>

7.5.1. *Comparison*

Comparison based on the suitability for certain:

- **task characteristics:** clustering, multi variate hot spots, …
- **data characteristics:** no. of variates, no. of data items, categorical data, …
- **visualization characteristics:** visual overlap, learning curve, …

		cluster-ing	multi-variate hot spot	no. of variates	no. of data items	cate-gorical data	visual overlap	learning curve
Geometric Transformations	Scatterplot Matrices	++	++	+	+	-	o	++
	Landscapes	+	+	-	o	o	+	+
	Prosection Views	++	++	+	+	-	o	+
	Hyperslices	+	+	+	+	-	o	o
	Parallel Coordinates	o	++	++	-	o	--	o
Iconic Displays	Stick Figures	o	o	+	-	-	-	o
	Shape Coding	o	-	++	+	-	+	-
	Color Icon	o	-	++	+	-	+	-
Pixel Displays	Query-Independent	+	+	++	++	-	++	+
	Query-Dependent	+	+	++	++	-	++	-
Stacked Displays	Dimensional Stacking	+	+	o	o	++	o	o
	Worlds-within-Worlds	o	o	o	+	o	o	o
	Treemaps	+	o	+	o	++	+	o
	Cone Trees	+	+	o	+	o	+	+
	InfoCube	o	o	-	-	o	o	+

7.5.2. *Hybrid Approaches*

- **Basic Idea:**
  - Integrated use of multiple techniques in one or multiple windows to enhance the expressiveness of the visualizations.
  - Linking diverse visualizations techniques may provide additional information.
  - Virtually all visualizations techniques are combined with dynamics and interactivity

- **Guidelines for Using Multiple Views:**
    - *Rule of Diversity:* Use multiple views when there is a diversity of attributes, models, user profiles, level of abstraction or genres.
    - *Rule of Complementary:* Use multiple views when different views bring out correlations and/or disparities.
    - *Rule of Decompostion:* Partition complex data into multiple views to create manageable chunks and to provide insight into the interaction among different dimensions.
    - *Rule of Parsimony:* Use multiple views minimally.

      Reasoning:
        - Single view: stable context
        - Multiple views: additional complexity for user
    - *Rule of Space/Time Resource Optimization:* Balance the spacial and temporal costs of presenting multiple views with the spacial and temproal benefits of using the views.
    - *Rule of Self-Evidence:* Use perceptual cues to make relationships among multiple views more apparent to the user.
    - *Rule of Consistency:* Make the interfaces for multiple views consistent and make the states of multiple views consistent.
    - *Rule of Attention Management:* Use perceptual technqiues to focus und the user's attention on the right view at the right time.