Visualization Analysis & Design

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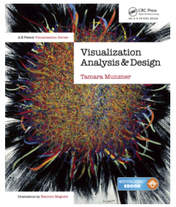


Seminar "Bridging Information Visualization with Machine Learning"
March 1 2015, Schloss Dagstuhl, Wadern DE

http://www.cs.ubc.ca/~tmm/talks.html#vad15dagstuhl

Defining visualization (vis)

Computer-based visualization systems provide visual representations of datasets designed to help people carry out tasks more effectively.

Why?...

Why have a human in the loop?

Computer-based visualization systems provide visual representations of datasets designed to help people carry out tasks more effectively.

Visualization is suitable when there is a need to augment human capabilities rather than replace people with computational decision-making methods.

- don't need vis when fully automatic solution exists and is trusted
- many analysis problems ill-specified
  - don't know exactly what questions to ask in advance
- possibilities
  - long-term use for end users (e.g. exploratory analysis of scientific data)
  - presentation of known results
  - stepping stone to better understanding of requirements before developing models
  - help developers of automatic solution refine/debug, determine parameters
  - help end users of automatic solutions verify, build trust

Why use an external representation?

Computer-based visualization systems provide visual representations of datasets designed to help people carry out tasks more effectively.

- external representation: replace cognition with perception

[CerebralVisualizing Multiple Experimental Conditions on a Graph with Biological Context, Barsky, Munzner, Gardy, and Kincaid. IEEE TVCG (Proc. InfoVis) 14(6):1253-1260, 2008]

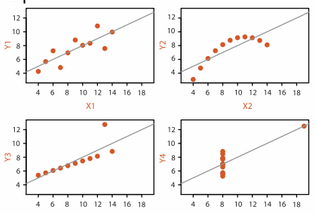
Why represent all the data?

Computer-based visualization systems provide visual representations of datasets designed to help people carry out tasks more effectively.

- summaries lose information, details matter
  - confirm expected and find unexpected patterns
  - assess validity of statistical model

Anscombe's Quartet

Identical statistics	
x mean	9
x variance	10
y mean	8
y variance	4
x/y correlation	1



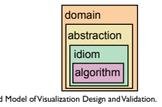
Why are there resource limitations?

Vis designers must take into account three very different kinds of resource limitations: those of computers, of humans, and of displays.

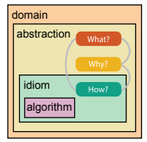
- computational limits
  - processing time
  - system memory
- human limits
  - human attention and memory
- display limits
  - pixels are precious resource, the most constrained resource
  - **information density**: ratio of space used to encode info vs unused whitespace
    - tradeoff between clutter and wasting space, find sweet spot between dense and sparse

Analysis framework: Four levels, three questions

- *domain* situation
  - who are the target users?
- *abstraction*
  - translate from specifics of domain to vocabulary of vis
    - **what** is shown? **data abstraction**
    - **why** is the user looking at it? **task abstraction**
- *idiom*
  - **how** is it shown?
    - **visual encoding idiom**: how to draw
    - **interaction idiom**: how to manipulate
- *algorithm*
  - efficient computation

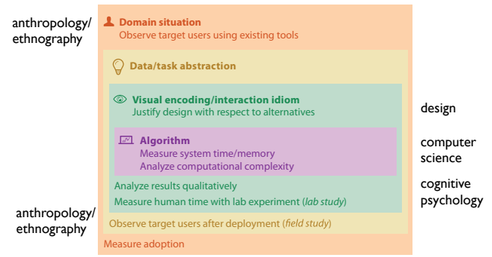


[A Nested Model of Visualization Design and Validation. Munzner. IEEE TVCG 15(6):921-928, 2009 (Proc. InfoVis 2009).]



[A Multi-Level Typology of Abstract Visualization Tasks Brehmer and Munzner. IEEE TVCG 19(12):2376-2385, 2013 (Proc. InfoVis 2013).]

Validation methods from different fields for each level

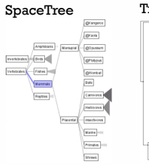


- mismatch: cannot show idiom good with system timings
- mismatch: cannot show abstraction good with lab study

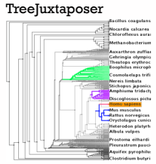
Why analyze?

- imposes a structure on huge design space
  - scaffold to help you think systematically about choices
  - analyzing existing as stepping stone to designing new

SpaceTree

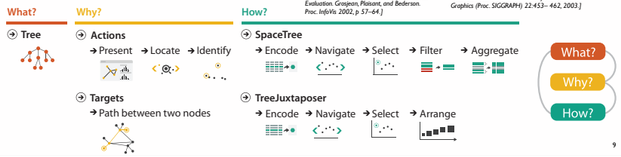


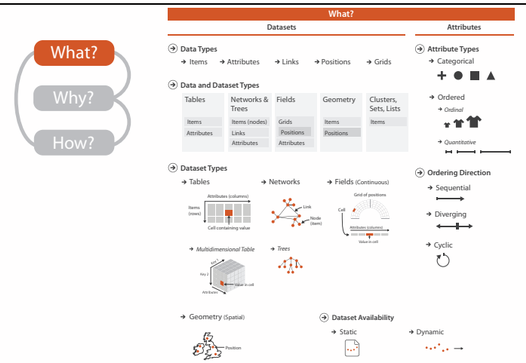
TreeJuxtaposer



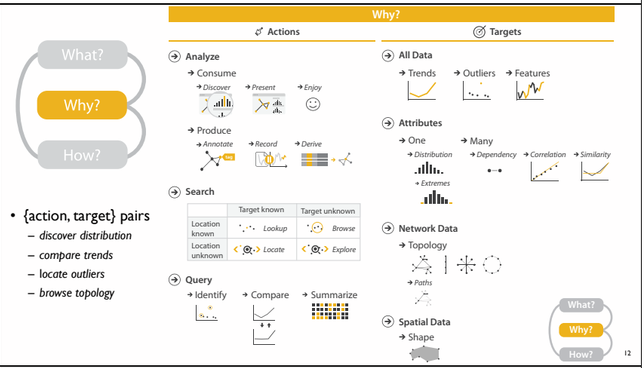
[SpaceTree: Supporting Exploration in Large Node Link Tree, Design Evolution and Empirical Evaluation. Grosjean, Plaisant, and Bederson. Proc. InfoVis 2002, p. 57–64.]

[TreeJuxtaposer: Scalable Tree Comparison Using Focus +Context With Guaranteed Visibility. ACM Trans. on Graphics (Proc. SIGGRAPH) 22:453– 462, 2003.]





Dataset and data types



- {action, target} pairs
  - *discover distribution*
  - *compare trends*
  - *locate outliers*
  - *browse topology*

Actions 1: Analyze

- consume
  - discover vs present
    - classic split
    - aka explore vs explain
  - enjoy
    - newcomer
    - aka casual, social
- produce
  - annotate, record
  - derive
    - crucial design choice

Actions II: Search

- what does user know?
  - target, location

Search

	Target known	Target unknown
Location known	Lookup	Browse
Location unknown	Locate	Explore

Actions III: Query

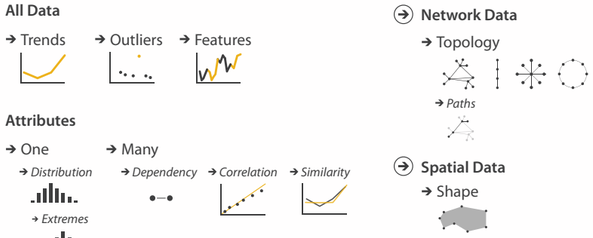
- what does user know?
  - target, location
- how much of the data matters?
  - one, some, all

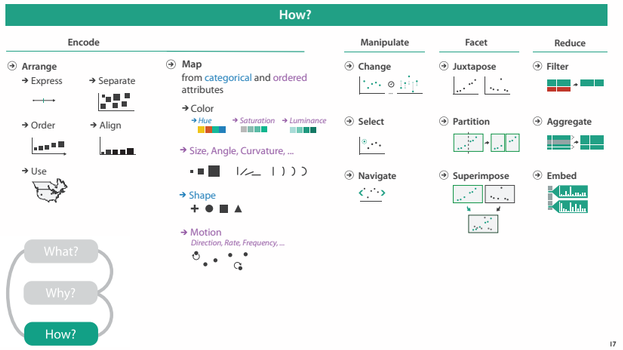
Search

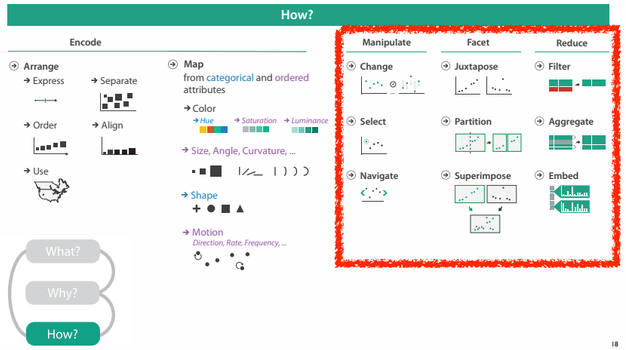
	Target known	Target unknown
Location known	Lookup	Browse
Location unknown	Locate	Explore

Query

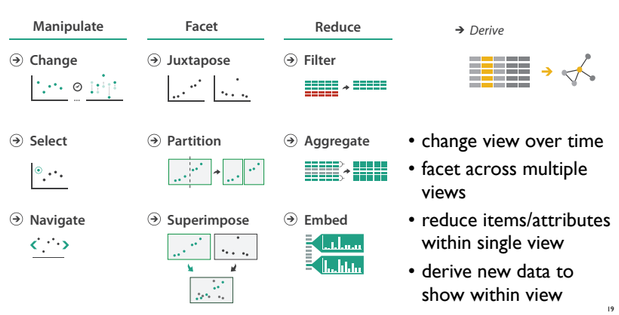
Targets







How to handle complexity: 3 more strategies + 1 previous



- change view over time
- facet across multiple views
- reduce items/attributes within single view
- derive new data to show within view

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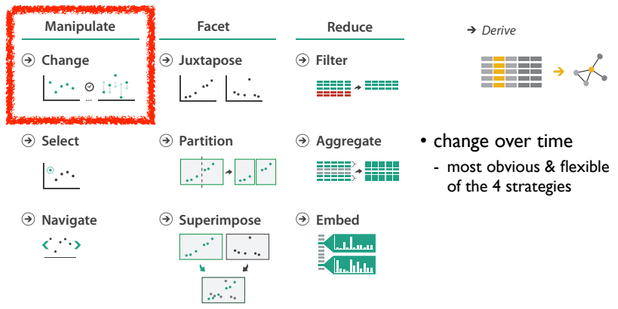
How to handle complexity: 3 more strategies + 1 previous



- change over time
  - most obvious & flexible of the 4 strategies

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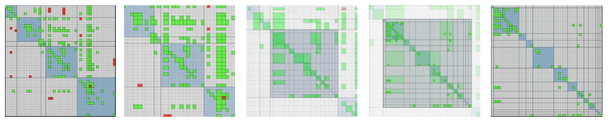
Idiom: **Animated transitions**

- smooth transition from one state to another
  - alternative to jump cuts
  - support for item tracking when amount of change is limited
- example: multilevel matrix views
  - scope of what is shown narrows down
    - middle block stretches to fill space, additional structure appears within
    - other blocks squish down to increasingly aggregated representations



[Using Multilevel Call Matrices in Large Software Projects. van Ham. Proc. IEEE Symp. Information Visualization (InfoVis), pp. 227–232, 2003.]

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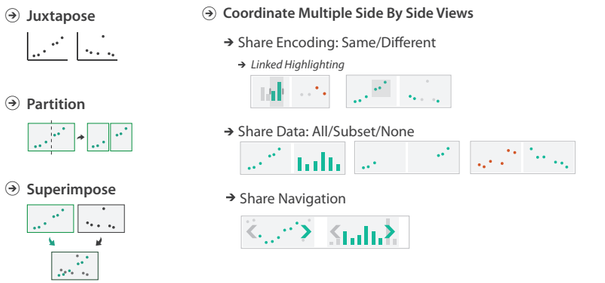
Facet



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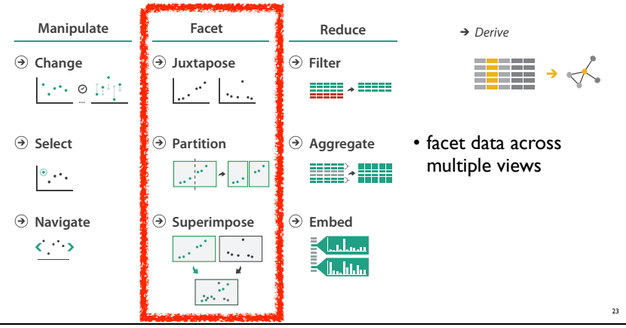
How to handle complexity: 3 more strategies + 1 previous



- facet data across multiple views

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Idiom: **Linked highlighting** System: **EDV**

- see how regions contiguous in one view are distributed within another
  - powerful and pervasive interaction idiom
- encoding: different
  - ***multiform***
- data: all shared

[Visual Exploration of Large Structured Datasets. Wills. Proc. New Techniques and Trends in Statistics (NTTS), pp. 237–246. IOS Press, 1995.]

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Idiom: **bird's-eye maps** System: **Google Maps**

- encoding: same
- data: subset shared
- navigation: shared
  - bidirectional linking
- differences
  - viewpoint
  - (size)
- ***overview-detail***

[A Review of Overview+Detail, Zooming, and Focus+Context Interfaces. Cockburn, Karlson, and Bederson. ACM Computing Surveys 41:1 (2008), 1–31.]

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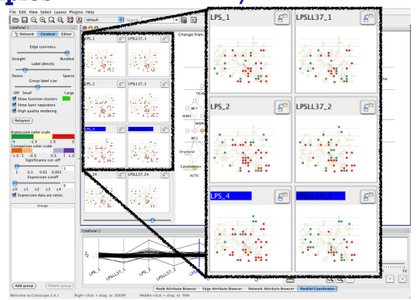
Idiom: **Small multiples** System: **Cerebral**

- encoding: same
- data: none shared
  - different attributes for node colors
  - (same network layout)
- navigation: shared



[Cerebral: Visualizing Multiple Experimental Conditions on a Graph with Biological Context. Barsky, Munzner, Gardy, and Kincaid. IEEE Trans. Visualization and Computer Graphics (Proc. InfoVis 2008) 14:6 (2008), 1253–1260.]

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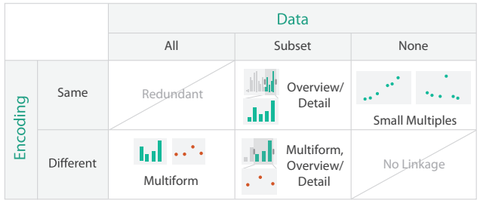
Coordinate views: Design choice interaction



- why juxtapose views?
  - benefits: eyes vs memory
    - lower cognitive load to move eyes between 2 views than remembering previous state with single changing view
  - costs: display area, 2 views side by side each have only half the area of one view

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Partition into views

- how to divide data between views
  - encodes association between items using spatial proximity
  - major implications for what patterns are visible
  - split according to attributes
- design choices
  - how many splits
    - all the way down: one mark per region?
    - stop earlier, for more complex structure within region?
  - order in which attribs used to split
  - how many views

Partition into Side-by-Side Views

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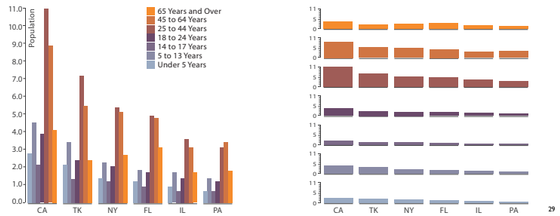
Partitioning: List alignment

- single bar chart with grouped bars
  - split by state into regions
    - complex glyph within each region showing all ages
  - compare: easy within state, hard across ages
- small-multiple bar charts
  - split by age into regions
    - one chart per region
  - compare: easy within age, harder across states



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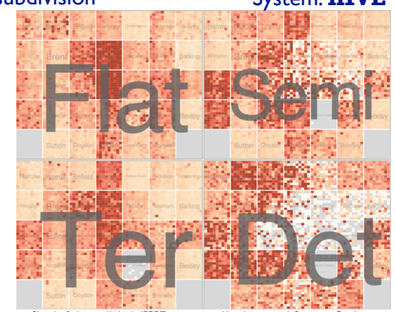
Partitioning: Recursive subdivision System: **HIVE**

- split by type
- then by neighborhood
- then time
  - years as rows
  - months as columns



[Configuring Hierarchical Layouts to Address Research Questions. Slingsby, Dykes, and Wood. IEEE Transactions on Visualization and Computer Graphics (Proc. InfoVis 2009) 15:6 (2009), 977–984.]

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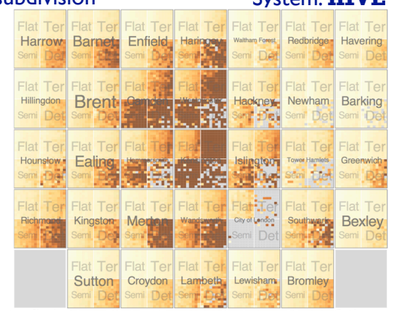
Partitioning: Recursive subdivision System: **HIVE**

- switch order of splits
  - neighborhood then type
- very different patterns



[Configuring Hierarchical Layouts to Address Research Questions. Slingsby, Dykes, and Wood. IEEE Transactions on Visualization and Computer Graphics (Proc. InfoVis 2009) 15:6 (2009), 977–984.]

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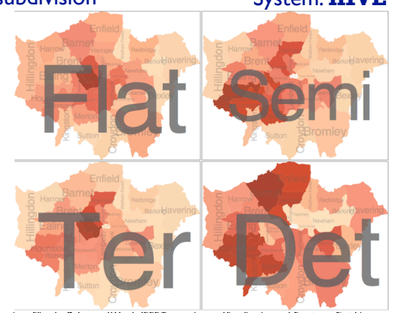
Partitioning: Recursive subdivision System: **HIVE**

- different encoding for second-level regions
  - choropleth maps



[Configuring Hierarchical Layouts to Address Research Questions. Slingsby, Dykes, and Wood. IEEE Transactions on Visualization and Computer Graphics (Proc. InfoVis 2009) 15:6 (2009), 977–984.]

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How to handle complexity: 3 more strategies + 1 previous

Manipulate
- Change
- Select
- Navigate

Facet
- Juxtapose
- Partition
- Superimpose

Reduce
- Filter
- Aggregate
- Embed

→ *Derive*

- reduce what is shown within single view

Reduce items and attributes

- reduce/increase: inverses
- filter
  - pro: straightforward and intuitive
    - to understand and compute
  - con: out of sight, out of mind
- aggregation
  - pro: inform about whole set
  - con: difficult to avoid losing signal
- not mutually exclusive
  - combine filter, aggregate
  - combine reduce, facet, change, derive

Reducing Items and Attributes

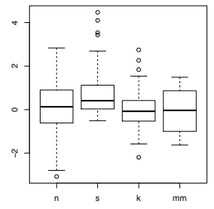
→ **Filter**
→ Items
→ Attributes

→ **Aggregate**
→ Items
→ Attributes

Reduce
→ Filter
→ Aggregate
→ Embed

Idiom: **boxplot**

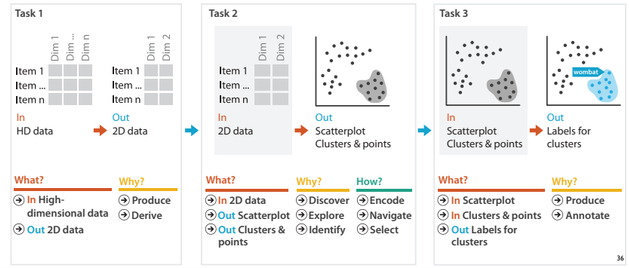
- static item aggregation
- task: find distribution
- data: table
- derived data
  - 5 quant attribs
    - median: central line
    - lower and upper quartile: boxes
    - lower upper fences: whiskers
      - values beyond which items are outliers
  - outliers beyond fence cutoffs explicitly shown

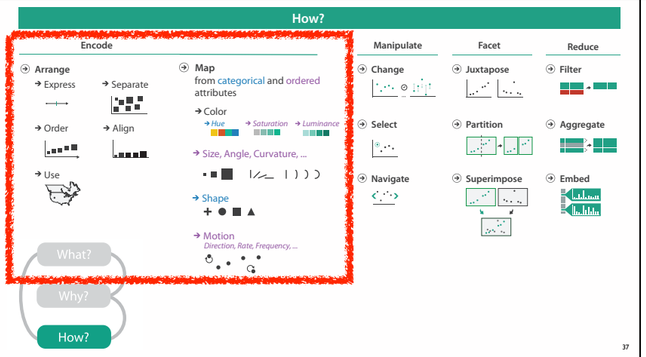


[40 years of boxplots. Wickham and Stryjewski. 2012. had.co.nz]

Idiom: **Dimensionality reduction for documents**

- attribute aggregation
  - derive low-dimensional target space from high-dimensional measured space





How to encode: Arrange space, map channels

Encode

→ **Arrange**
→ Express
→ Separate
→ Order
→ Align
→ Use

→ **Map**
from categorical and ordered attributes
→ Color
→ Hue
→ Saturation
→ Luminance
→ Size, Angle, Curvature, ...
→ Shape
→ Motion
Direction, Rate, Frequency, ...

Encoding visually

- analyze idiom structure

Definitions: Marks and channels

- marks
  - geometric primitives

→ Points
→ Lines
→ Areas

- channels
  - control appearance of marks

→ Position
→ Horizontal
→ Vertical
→ Both
→ Color
→ Shape
→ Tilt
→ Size
→ Length
→ Area
→ Volume

Encoding visually with marks and channels

- analyze idiom structure
  - as combination of marks and channels

1:	2:	3:	4:
vertical position	vertical position horizontal position	vertical position horizontal position color hue	vertical position horizontal position color hue size (area)
mark: line	mark: point	mark: point	mark: point

Channels

Position on common scale	Spatial region
Position on unaligned scale	Color hue
Length (1D size)	Motion
Tilt/angle	Shape
Area (2D size)	
Depth (3D position)	
Color luminance	
Color saturation	
Curvature	
Volume (3D size)	

Same

Channels: Rankings

Magnitude Channels: Ordered Attributes
Position on common scale
Position on unaligned scale
Length (1D size)
Tilt/angle
Area (2D size)
Depth (3D position)
Color luminance
Color saturation
Curvature
Volume (3D size)

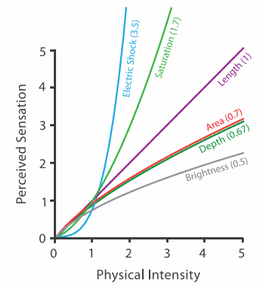
Best
Effectiveness
Least
Same

Identity Channels: Categorical Attributes
Spatial region
Color hue
Motion
Shape

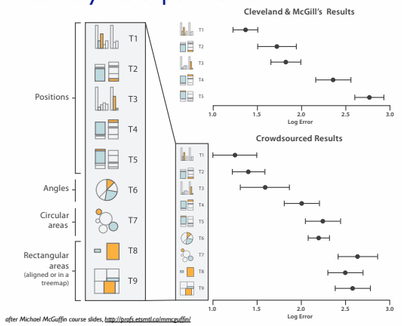
- effectiveness principle
  - encode most important attributes with highest ranked channels
- expressiveness principle
  - match channel and data characteristics

Accuracy: Fundamental Theory

Steven's Psychophysical Power Law: $S = I^N$



Accuracy: Vis experiments



[Crowdsourcing Graphical Perception: Using Mechanical Turk to Assess Visualization Design. Heer and Bostock. Proc ACM Conf. Human Factors in Computing Systems (CHI) 2010, p. 203–212.]

after Michael McGuffin course slides, http://profs.etsmtl.ca/mmcguffin/

How to encode: Arrange position and region

Encode

→ **Arrange**
→ Express
→ Separate
→ Order
→ Align
→ Use

→ **Map**
from categorical and ordered attributes
→ Color
→ Hue
→ Saturation
→ Luminance
→ Size, Angle, Curvature, ...
→ Shape
→ Motion
Direction, Rate, Frequency, ...

What?
Why?
How?

Arrange tables

→ **Express Values**

→ **Separate, Order, Align Regions**
→ Separate
→ Order
→ Align

→ **Axis Orientation**
→ Rectilinear
→ Parallel
→ Radial

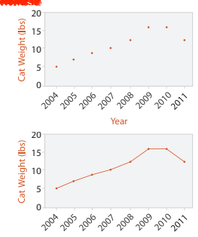
→ **Layout Density**
→ Dense
→ Space-Filling

→ *1 Key* — *List*
→ *2 Keys* — *Matrix*
→ *3 Keys* — *Volume*
→ *Many Keys* — *Recursive Subdivision*

Idioms: **dot chart, line chart**

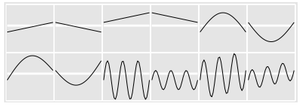
- one key, one value
  - data
    - 2 quant attribs
  - mark: points
    - dot plot: + line connection marks between them
  - channels
    - aligned lengths to express quant value
    - separated and ordered by key attrib into horizontal regions
  - task
    - find trend
      - connection marks emphasize ordering of items along key axis by explicitly showing relationship between one item and the next

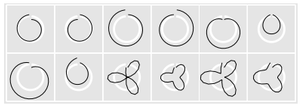
→ *1 Key* — *List*
→ *2 Keys* — *Matrix*
→ *Many Keys* — *Recursive Subdivision*



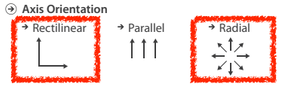
Idiom: **glyphmaps**

- rectilinear good for linear vs nonlinear trends
- radial good for cyclic patterns





Axis Orientation
- Rectilinear
- Parallel
- Radial

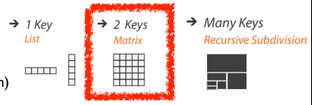


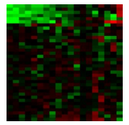
[Glyph-maps for Visually Exploring Temporal Patterns in Climate Data and Models. Wickham, Hofmann, Wickham, and Cook. Environmetrics 23:5 (2012), 382–393.]

Idiom: **heatmap**

- two keys, one value
  - data
    - 2 categ attribs (gene, experimental condition)
    - 1 quant attrib (expression levels)
  - marks: area
    - separate and align in 2D matrix
      - indexed by 2 categorical attributes
  - channels
    - color by quant attrib
      - (ordered diverging colormap)
  - task
    - find clusters, outliers
  - scalability
    - 1M items, 100s of categ levels, ~10 quant attrib levels

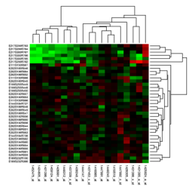
1 Key: List → 2 Keys: Matrix → Many Keys: Recursive Subdivision





Idiom: **cluster heatmap**

- in addition
  - derived data
    - 2 cluster hierarchies
  - dendrogram
    - parent-child relationships in tree with connection line marks
    - leaves aligned so interior branch heights easy to compare
  - heatmap
    - marks (re-)ordered by cluster hierarchy traversal

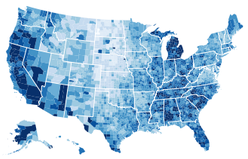


Arrange spatial data

Use Given
- Geometry
  - *Geographic*
  - *Other Derived*
- Spatial Fields
  - *Scalar Fields (one value per cell)*
    - *Isocontours*
    - *Direct Volume Rendering*
  - *Vector and Tensor Fields (many values per cell)*
    - *Flow Glyphs (local)*
    - *Geometric (sparse seeds)*
    - *Textures (dense seeds)*
    - *Features (globally derived)*

Idiom: **choropleth map**

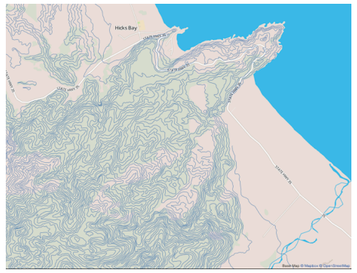
- ***use*** given spatial data
  - when central task is understanding spatial relationships
- data
  - geographic geometry
  - table with 1 quant attribute per region
- encoding
  - use given geometry for area mark boundaries
  - sequential segmented colormap



http://lbl.ocks.org/mbostock/4060606

Idiom: **topographic map**

- data
  - geographic geometry
  - scalar spatial field
    - 1 quant attribute per grid cell
- derived data
  - isoline geometry
    - isocontours computed for specific levels of scalar values



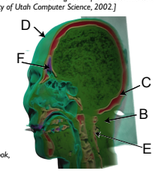
Land Information New Zealand Data Service

Idioms: **isosurfaces, direct volume rendering**

- data
  - scalar spatial field
    - 1 quant attribute per grid cell
- task
  - shape understanding, spatial relationships
- isosurface
  - derived data: isocontours computed for specific levels of scalar values
- direct volume rendering
  - transfer function maps scalar values to color, opacity
    - no derived geometry

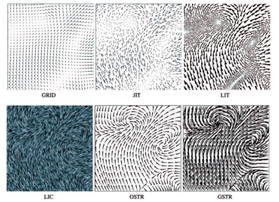
[Multidimensional Transfer Functions for Volume Rendering. Kniss, Kindlmann, and Hansen. In The Visualization Handbook, edited by Charles Hansen and Christopher Johnson, pp. 189–210. Elsevier, 2005.]

[Interactive Volume Rendering Techniques. Kniss. Master's thesis, University of Utah Computer Science, 2002.]



Idioms: **vector glyphs**

- tasks
  - finding critical points, identifying their types
  - identifying what type of critical point is at a specific location
  - predicting where a particle starting at a specified point will end up (advection)

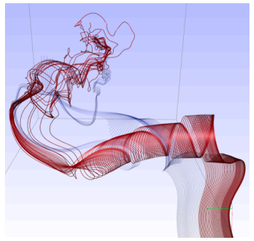


[Comparing 2D vector field visualization methods: A user study. Laidlaw et al. IEEE Trans. Visualization and Computer Graphics (TVCG) 11:1 (2005), 59–70.]

[Topology tracking for the visualization of time-dependent two-dimensional flows. Tricoche, Wischgoll, Scheuermann, and Hagen. Computers & Graphics 26:2 (2002), 249–257.]

Idiom: **similarity-clustered streamlines**

- data
  - 3D vector field
- derived data (from field)
  - streamlines: trajectory particle will follow
- derived data (per streamline)
  - curvature, torsion, tortuosity
  - signature: complex weighted combination
  - compute cluster hierarchy across all signatures
  - encode: color and opacity by cluster
- tasks
  - find features, query shape
- scalability
  - millions of samples, hundreds of streamlines



[Similarity Measures for Enhancing Interactive Streamline Seeding. McLoughlin, Jones, Laramee, Malki, Masters, and Hansen. IEEE Trans. Visualization and Computer Graphics 19:8 (2013), 1342–1353.]

Arrange networks and trees

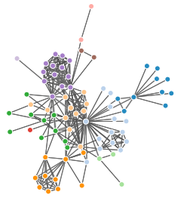
Node–Link Diagrams
Connection Marks
✔ NETWORKS ✔ TREES

Adjacency Matrix
Derived Table
✔ NETWORKS ✔ TREES

Enclosure
Containment Marks
✘ NETWORKS ✔ TREES

Idiom: **force-directed placement**

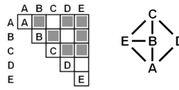
- visual encoding
  - link connection marks, node point marks
- considerations
  - spatial position: no meaning directly encoded
    - left free to minimize crossings
  - proximity semantics?
    - sometimes meaningful
    - sometimes arbitrary, artifact of layout algorithm
    - tension with length
      - long edges more visually salient than short
- tasks
  - explore topology; locate paths, clusters
- scalability
  - node/edge density E < 4N



http://mbostock.github.com/d3/ex/force.html

Idiom: **adjacency matrix view**

- data: network
  - transform into same data/encoding as heatmap
- derived data: table from network
  - 1 quant attrib
    - weighted edge between nodes
  - 2 categ attribs: node list x 2
- visual encoding
  - cell shows presence/absence of edge
- scalability
  - 1K nodes, 1M edges



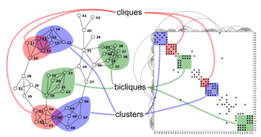
[NodeTrix: a Hybrid Visualization of Social Networks. Henry, Fekete, and McGuffin. IEEE TVCG (Proc. InfoVis) 13(6):1302-1309, 2007.]

[Points of view: Networks. Gehlenborg and Wong. Nature Methods 9:115.]

Connection vs. adjacency comparison

- adjacency matrix strengths
  - predictability, scalability, supports reordering
  - some topology tasks trainable
- node-link diagram strengths
  - topology understanding, path tracing
  - intuitive, no training needed
- empirical study
  - node-link best for small networks
  - matrix best for large networks
    - if tasks don't involve topological structure!

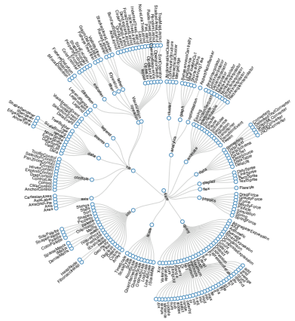
[On the readability of graphs using node-link and matrix-based representations: a controlled experiment and statistical analysis. Ghoniem, Fekete, and Castagliola. Information Visualization 4:2 (2005), 114–135.]



http://www.michaelmcguffin.com/courses/vis/patternsInAdjacencyMatrix.png

Idiom: **radial node-link tree**

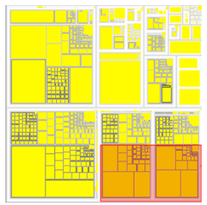
- data
  - tree
- encoding
  - link connection marks
  - point node marks
  - radial axis orientation
    - angular proximity: siblings
    - distance from center: depth in tree
- tasks
  - understanding topology, following paths
- scalability
  - 1K - 10K nodes



http://mbostock.github.com/d3/ex/tree.html

Idiom: **treemap**

- data
  - tree
  - 1 quant attrib at leaf nodes
- encoding
  - area containment marks for hierarchical structure
  - rectilinear orientation
  - size encodes quant attrib
- tasks
  - query attribute at leaf nodes
- scalability
  - 1M leaf nodes

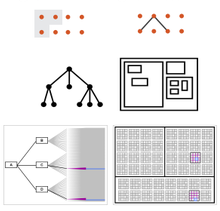


http://tulip.labri.fr/Documentation/3_7/userHandbook/html/ch06.html

Connection vs. containment comparison

- marks as links (vs. nodes)
  - common case in network drawing
  - 1D case: connection
    - ex: all node-link diagrams
    - emphasizes topology, path tracing
    - networks and trees
  - 2D case: containment
    - ex: all treemap variants
    - emphasizes attribute values at leaves (size coding)
    - only trees

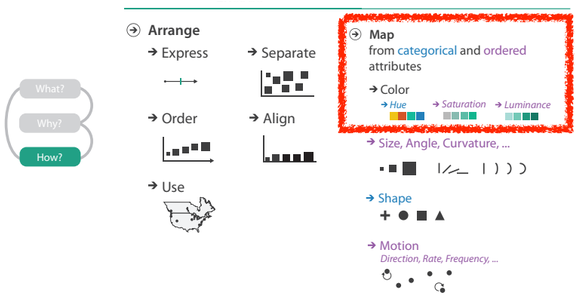
Containment → Connection



Node–Link Diagram | Treemap

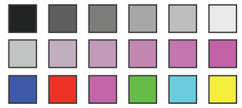
[Elastic Hierarchies: Combining Treemaps and Node-Link Diagrams. Dong, McGuffin, and Chignell. Proc. InfoVis 2005, p. 57-64.]

How to encode: Mapping color



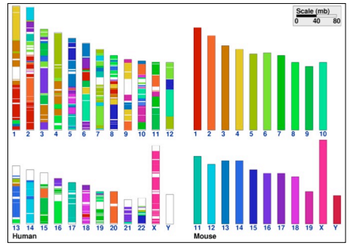
Color: Luminance, saturation, hue

- 3 channels
  - identity for categorical
    - hue
  - magnitude for ordered
    - luminance
    - saturation
- better match for visual encoding than RGB color space from graphics

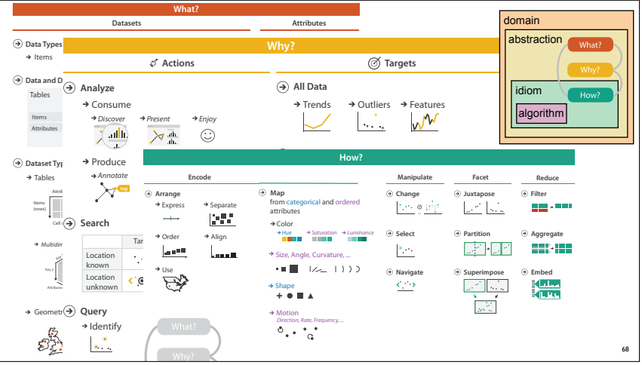


Categorical color: Discriminability constraints

- noncontiguous small regions of color: only 6-12 bins



[Cinteny: flexible analysis and visualization of synteny and genome rearrangements in multiple organisms. Sinha and Meller. BMC Bioinformatics, 8:82, 2007.]



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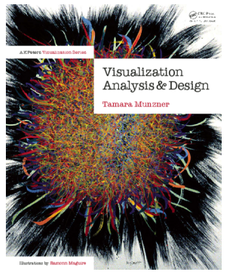

Visualization Analysis and Design.
Munzner. A K Peters Visualization Series, CRC Press, Visualization Series, 2014.