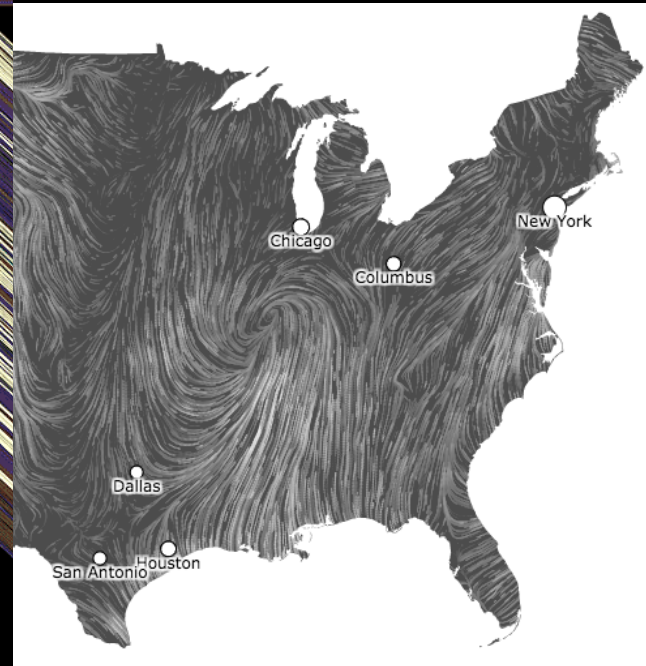
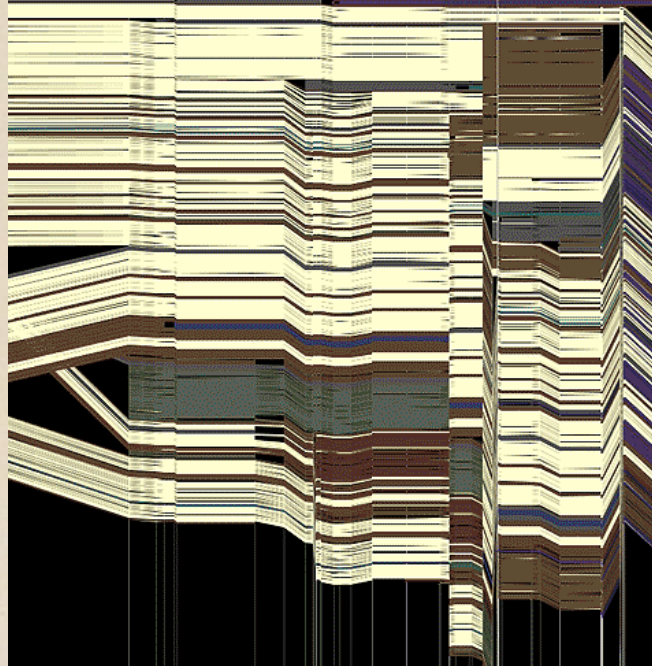
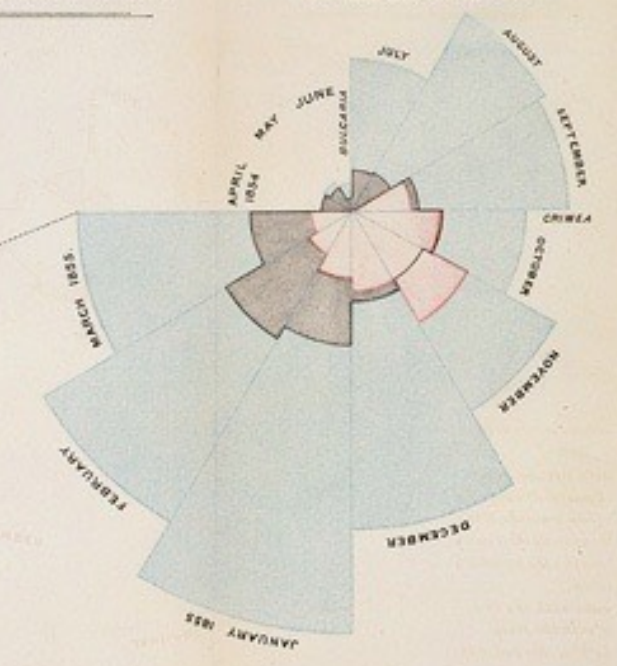


CSE 512 - Data Visualization

# Networks



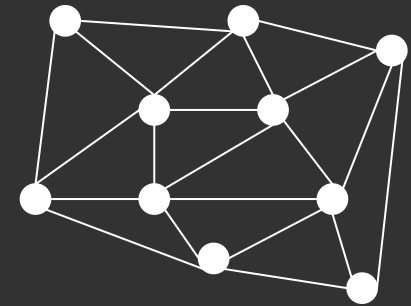
Jeffrey Heer University of Washington

# Graphs and Trees

## Graphs

Model relations among data

*Nodes and edges*

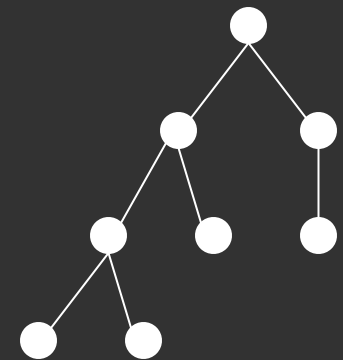


## Trees

Graphs with hierarchical structure

Connected graph with  $N-1$  edges

Nodes as *parents* and *children*



# Spatial Layout

A primary concern of tree/graph drawing is the spatial arrangement of nodes and edges.

Often (but not always) the goal is to effectively depict the graph structure:

- Connectivity, path-following
- Topological distance
- Clustering / grouping
- Ordering (e.g., hierarchy level)

# Applications

Tournaments

Organization Charts

Genealogy

Diagramming (e.g., Visio)

Biological Interactions (Genes, Proteins)

Computer Networks

Social Networks

Simulation and Modeling

Integrated Circuit Design

# Network Analysis Tasks [Pretorius '13]

**Structure-based:** relationships and connectivity

**Attribute-based:** specific node/link attributes

**Browsing:** understand paths in the data

**Estimation:** summarization and temporal changes

# Network Analysis Tasks [Pretorius '13]

**Structure-based:** relationships and connectivity

*Find all of the friends of friends for Taylor.*

*Find all of the people who are friends with Jordan and Alex.*

*Six degrees of separation: shortest path between two individuals.*

**Attribute-based:** specific node/link attributes

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*Find all "students" attending CSE442.*

*Find all the "friends" and "family" of Alex.*

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**Browsing:** understand paths in the data

*Find Alex's friend Taylor, and then Taylor's friend Jordan.*

**Estimation:** summarization and temporal changes



# Network Analysis Tasks [Pretorius '13]

**Structure-based:** relationships and connectivity

*Find all of the friends of friends for Taylor.*

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**Attribute-based:** specific node/link attributes

*Find all "students" attending CSE442.*

*Find all the "friends" and "family" of Alex.*

**Browsing:** understand paths in the data

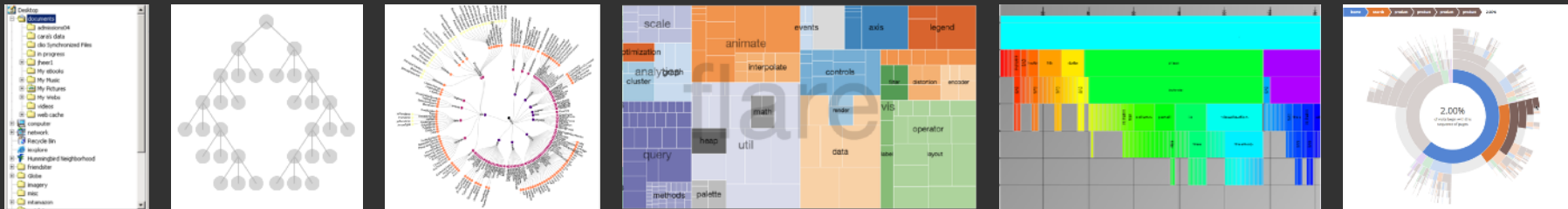
*Find Alex's friend Taylor, and then Taylor's friend Jordan.*

**Estimation:** summarization and temporal changes

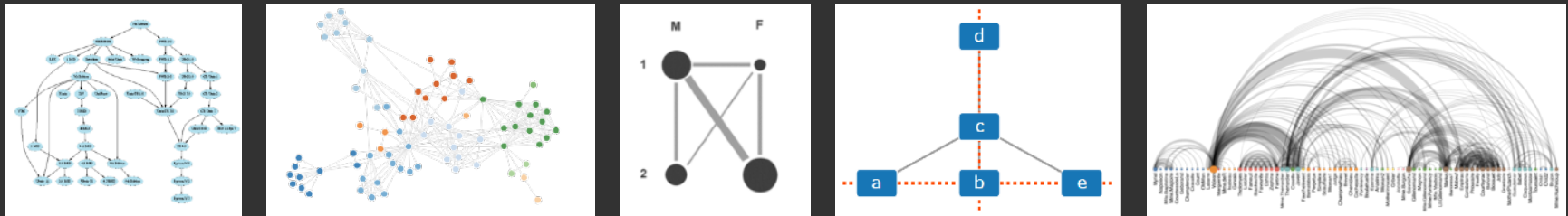
*How does Jordan's friend group change over the course of the year?*

# Topics

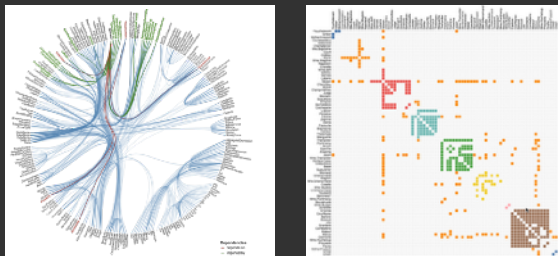
## Tree Visualization



## Graph Layout: Node-Link Diagrams



## Alternative Visualizations and Techniques



Select an image to jump to those slides.

# Tree Visualization

# Tree Visualization

## Indentation

Linear list, indentation encodes depth



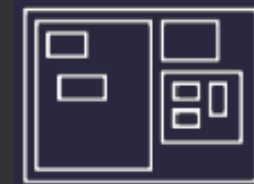
## Node-Link diagrams

Nodes connected by lines/curves



## Enclosure diagrams

Represent hierarchy by enclosure



## Layering

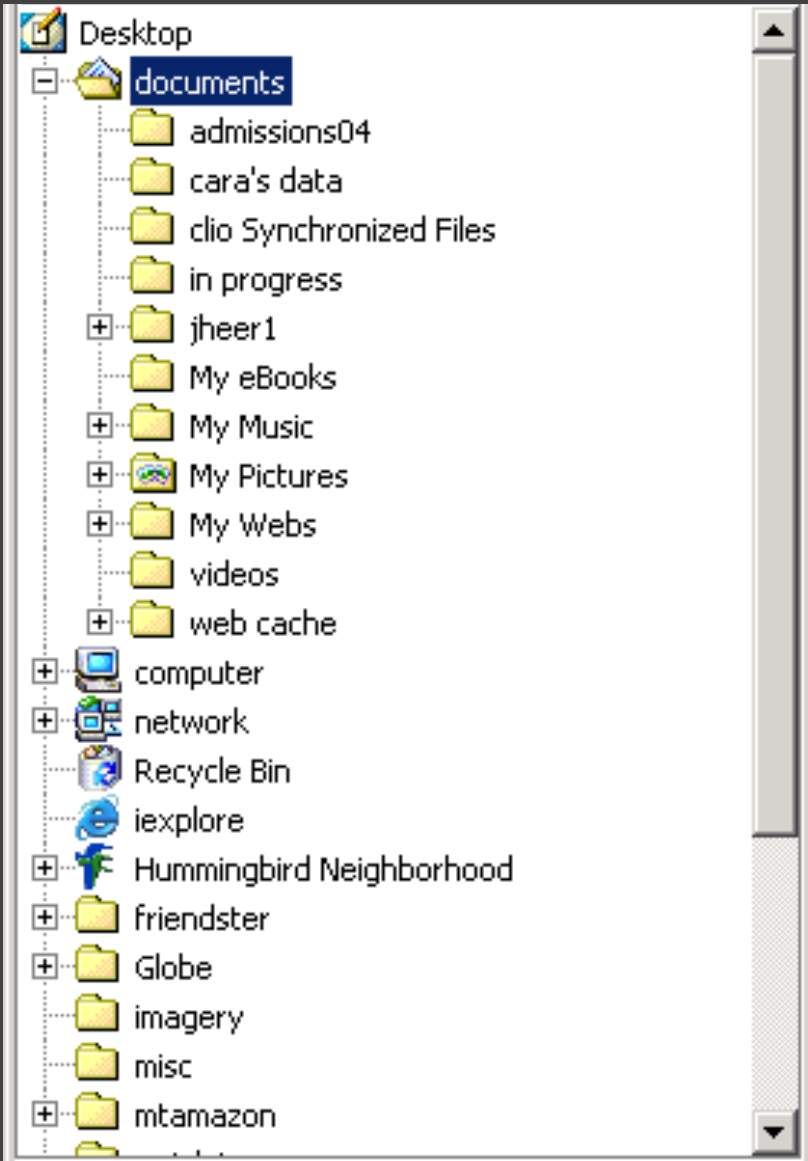
Relative position and alignment



Typically fast:  $O(n)$  or  $O(n \log n)$ , interactive layout

# Indentation

# Indentation



Places all items along vertically spaced rows

Indentation used to show parent/child relationships

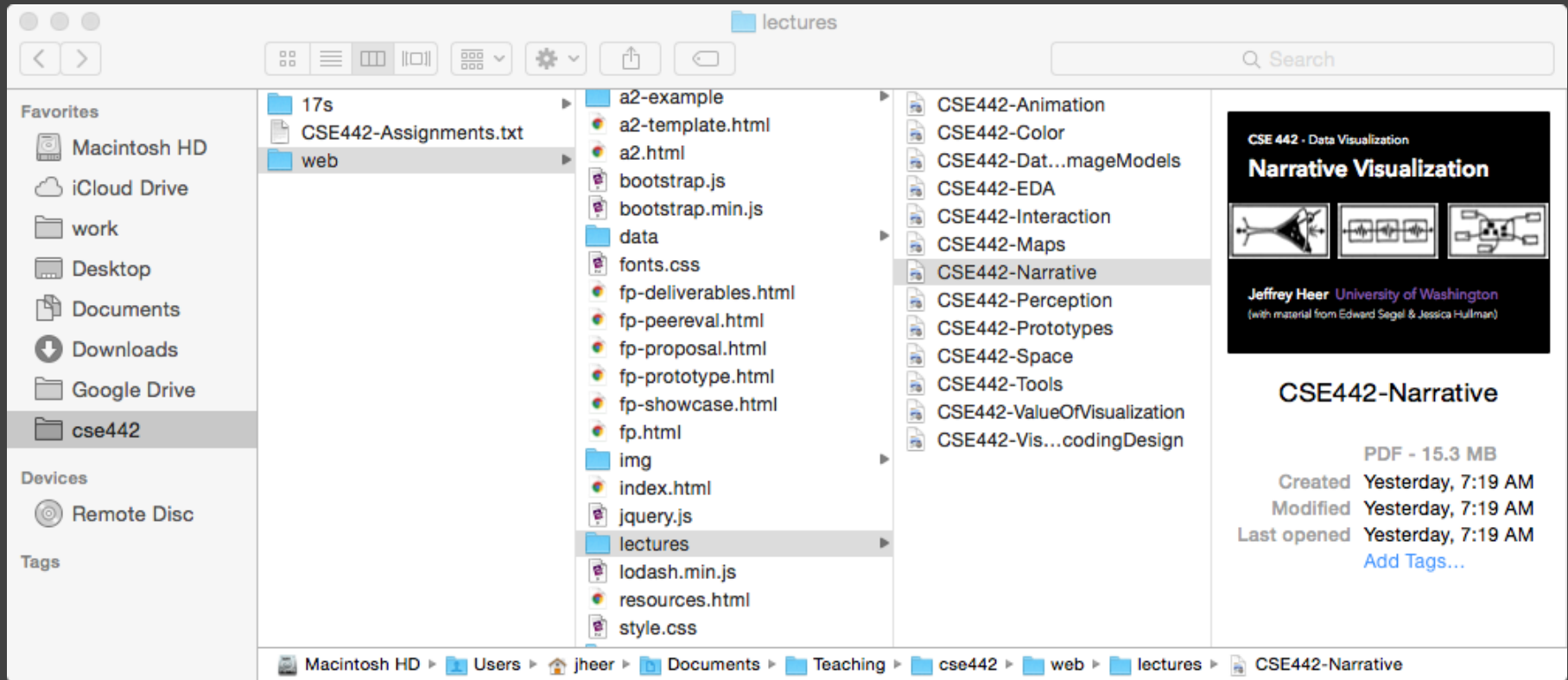
Commonly used as a component in an interface

Breadth and depth contend for space

Often requires a great deal of scrolling

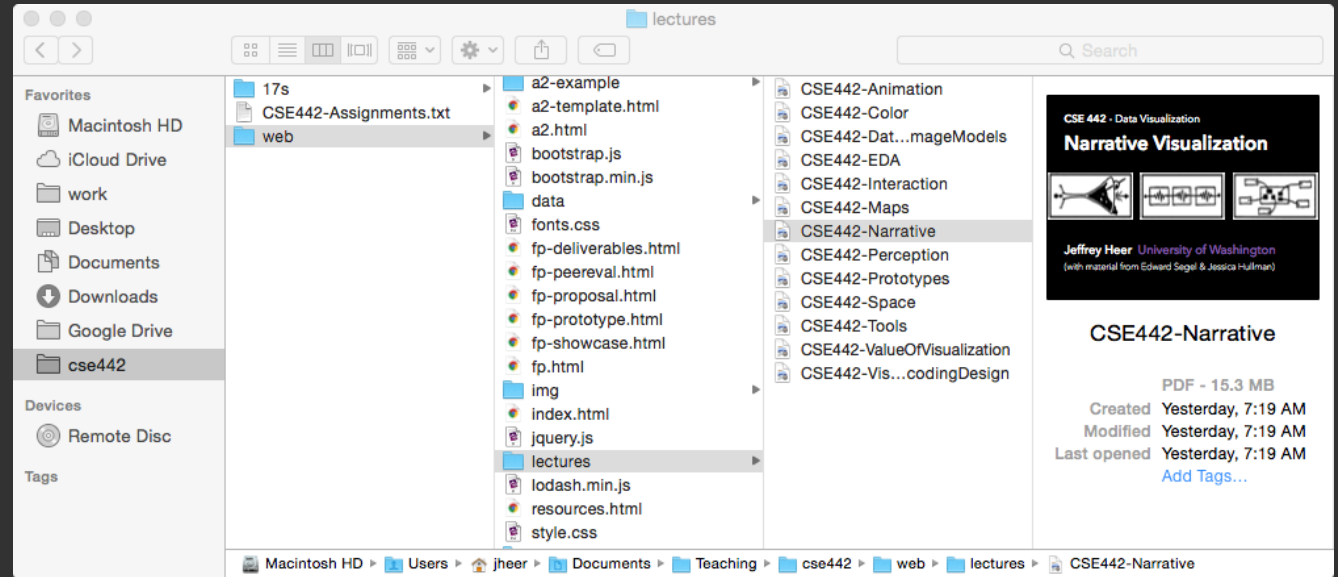
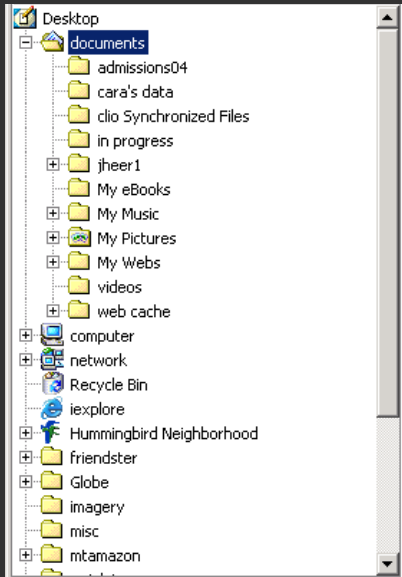


# Single-Focus (Accordion) List



Separate breadth & depth along 2D.  
Focus on a single path at a time.

# What tasks are these good for?



## Benefits:

Navigation + Browsing, Parent-Child Relationships

## Disadvantages:

Estimation, Comparison, Network Overview



# Node-Link Diagrams

# Node-Link Diagrams



Nodes are distributed in space, connected by straight or curved lines

Typical approach is to use 2D space to break apart breadth and depth

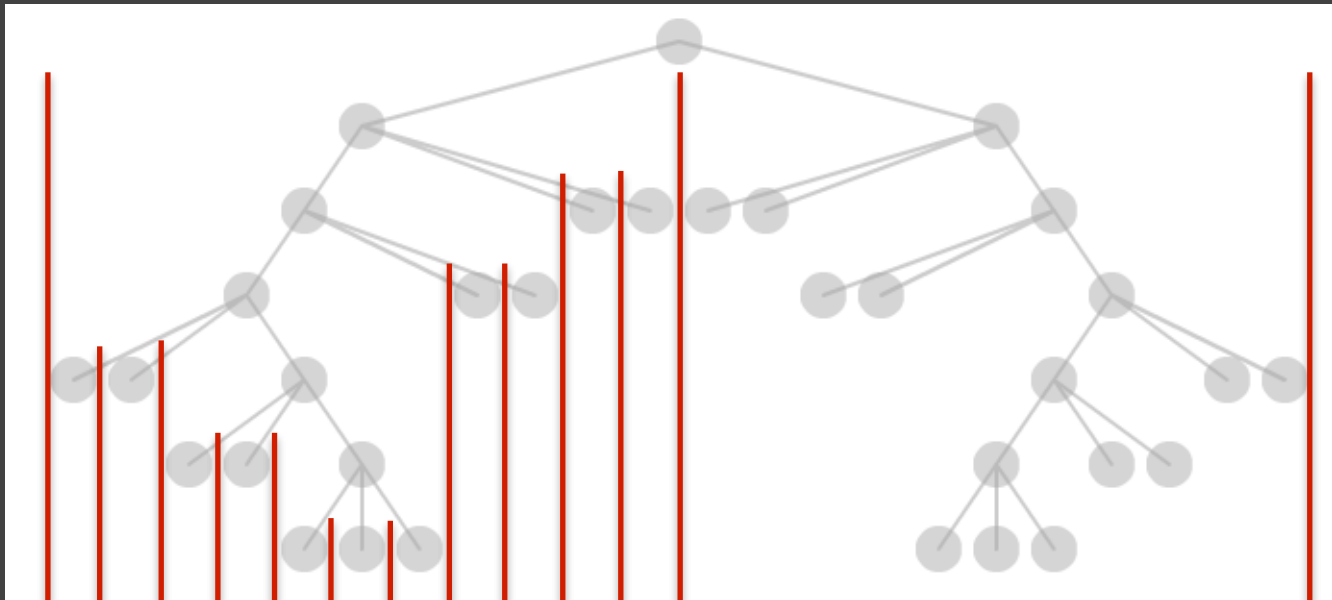
Often space is used to communicate hierarchical orientation (e.g., towards authority or generality)

# Naïve Recursive Layout

Repeatedly divide space for subtrees by leaf count

Breadth of tree along one dimension

Depth along the other dimension



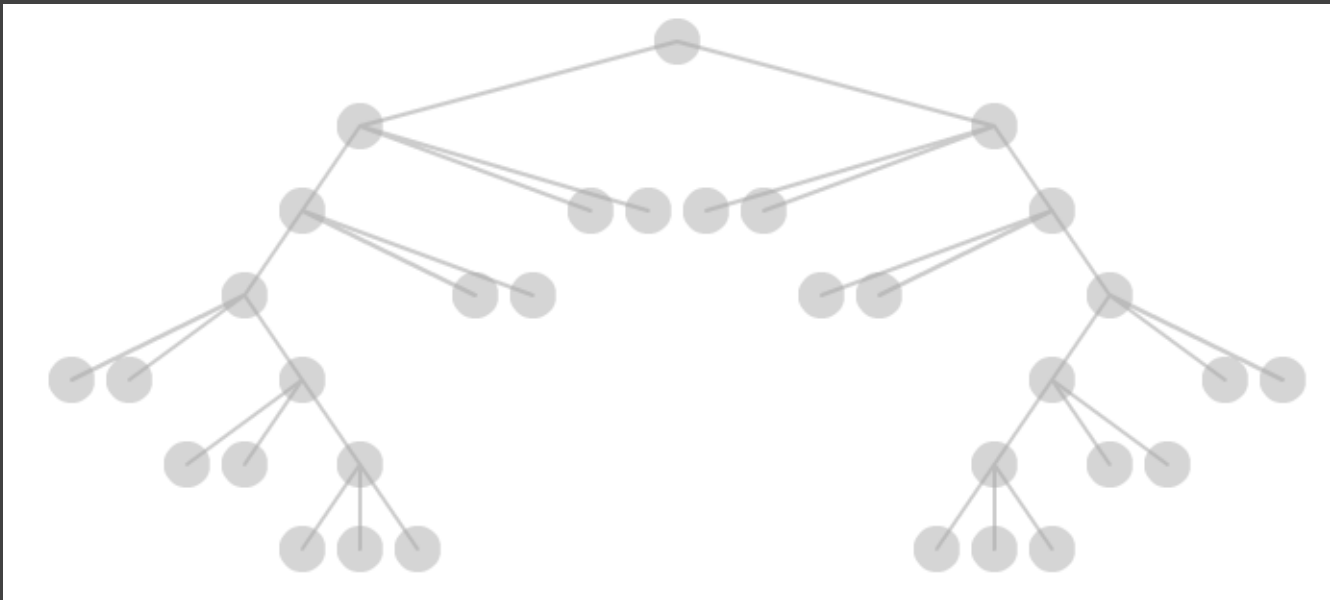
# Naïve Recursive Layout

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Breadth of tree along one dimension

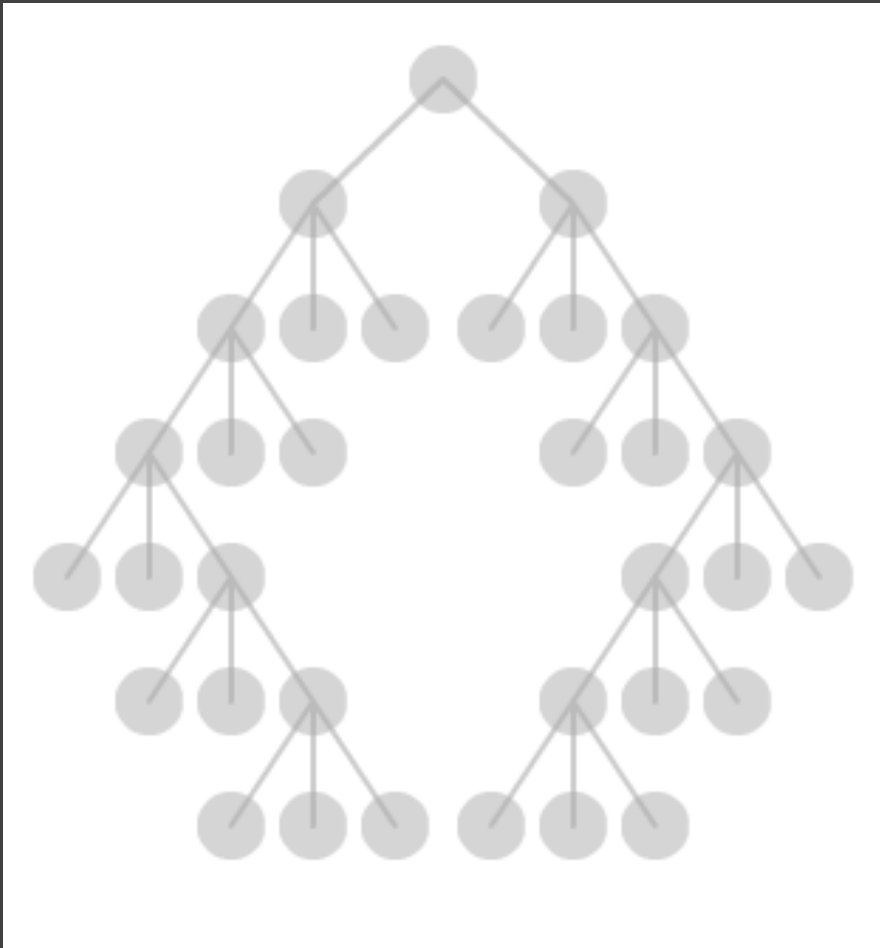
Depth along the other dimension

Problems?





# Reingold & Tilford's "Tidy" Layout

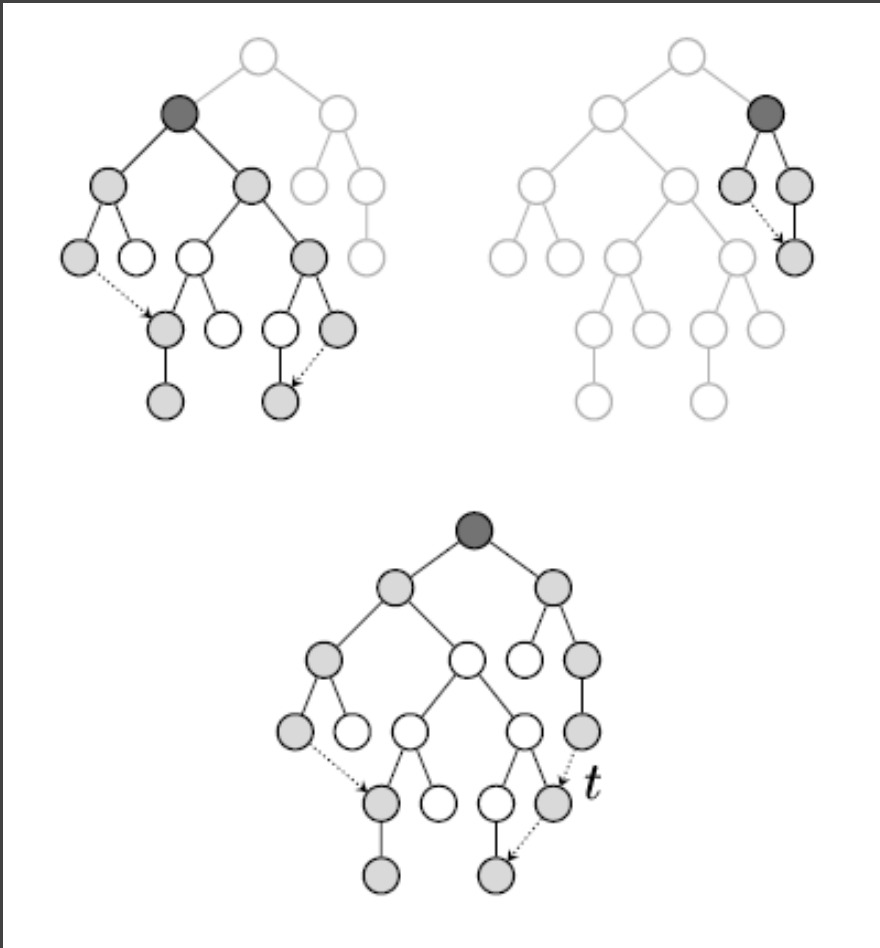


Goal: make smarter use of space, maximize density and symmetry.

Originally binary trees, extended by Walker to cover general case.

Corrected by Buchheim et al. to achieve a linear time algorithm.

# Reingold-Tilford Layout



## Design Considerations

Clearly encode depth

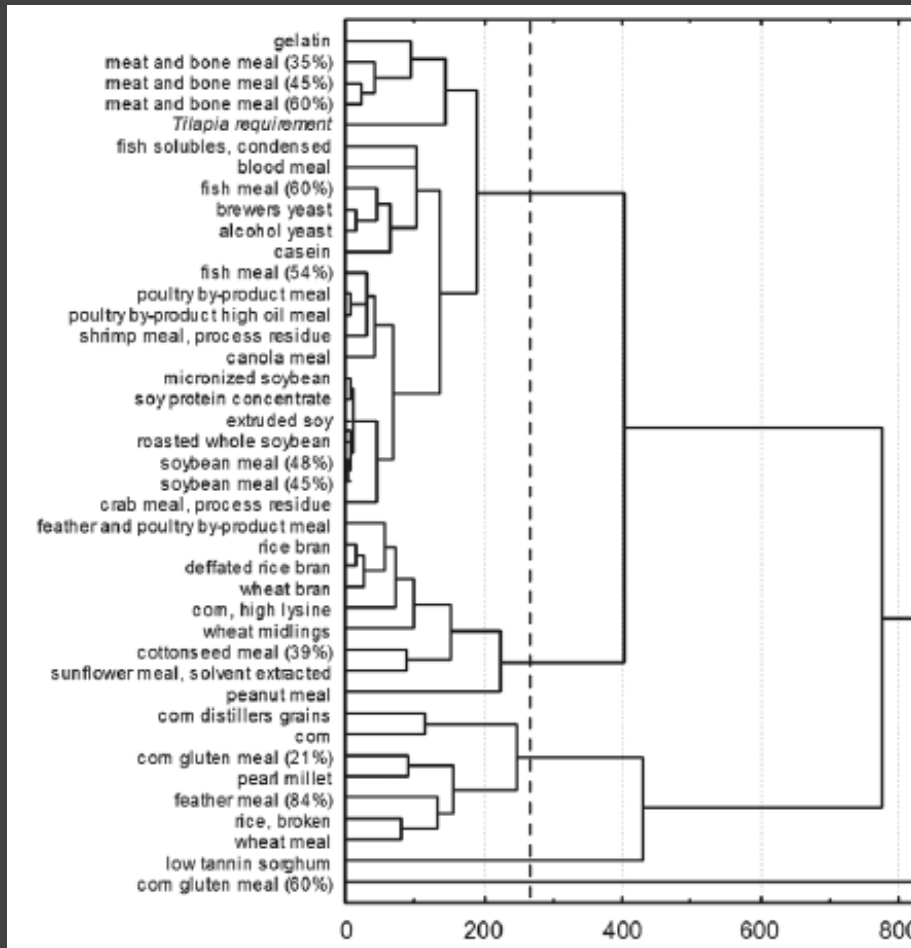
No edge crossings

Draw isomorphic subtrees identically (same shape)

Preserve layout ordering and symmetry

*Compact, space-saving layout (don't waste space)*

# Cluster Dendrograms



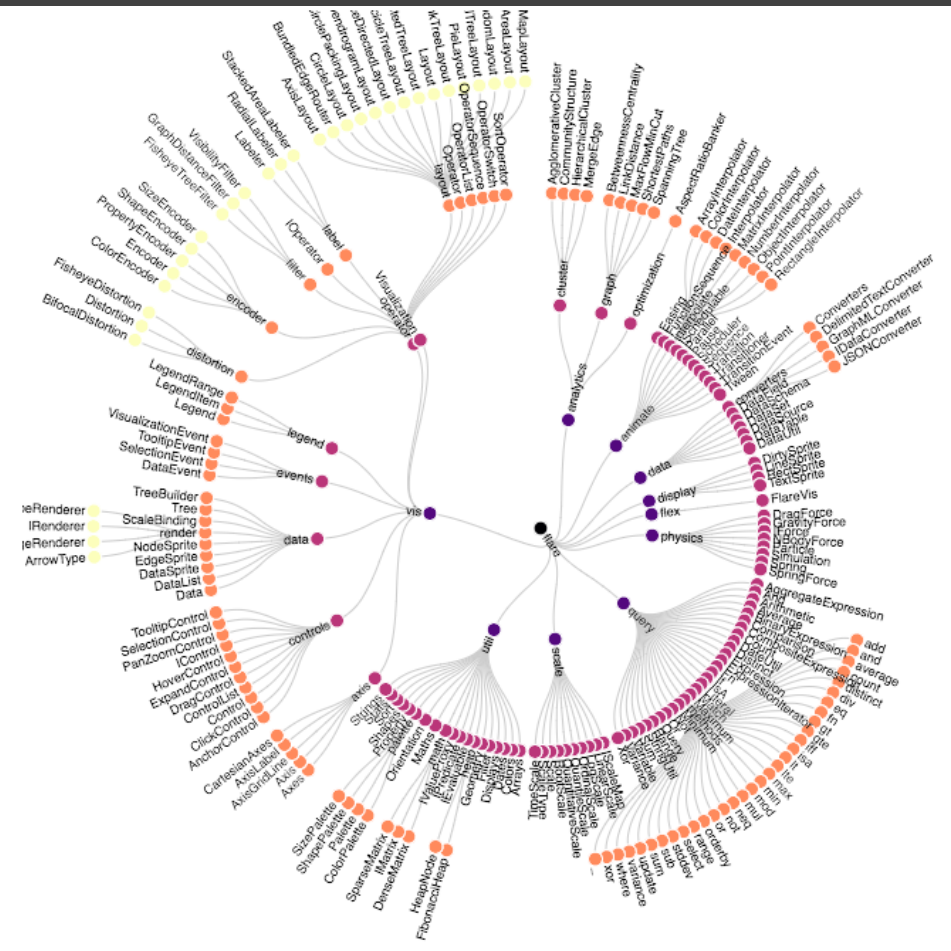
Depicts cluster trees produced by hierarchical clustering algorithms.

Leaf nodes arranged in a line, internal node depth indicates order/value at which clusters merge.

Naïve recursive layout with orthogonal two-segment edges.



# Radial Tree Layout



Node-link diagram in polar co-ordinates.

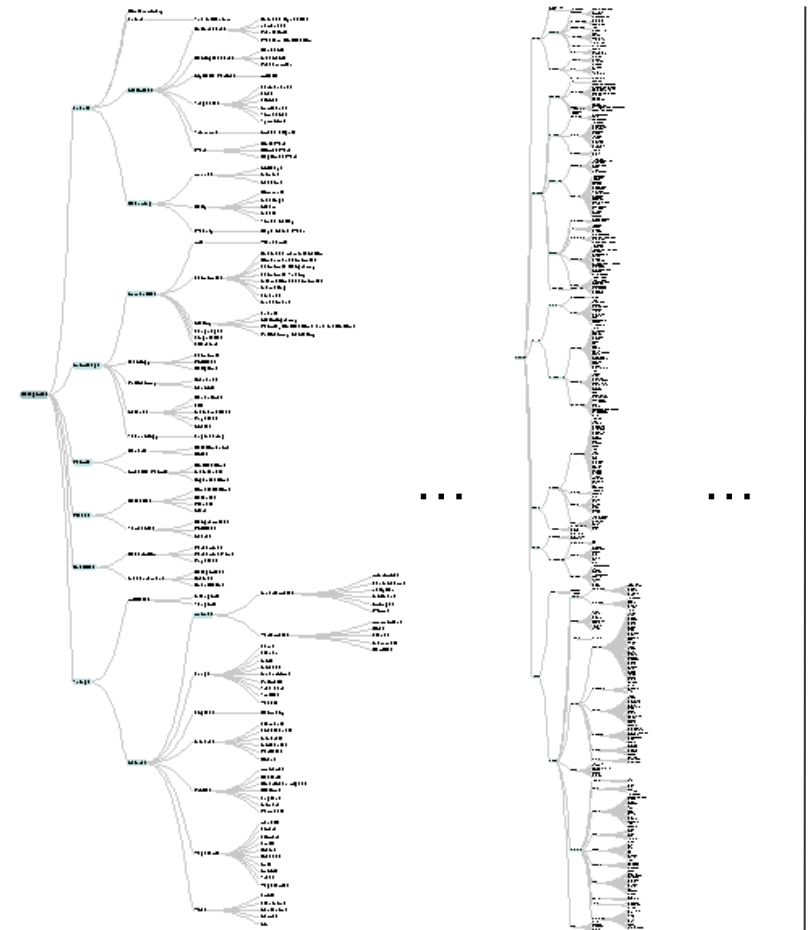
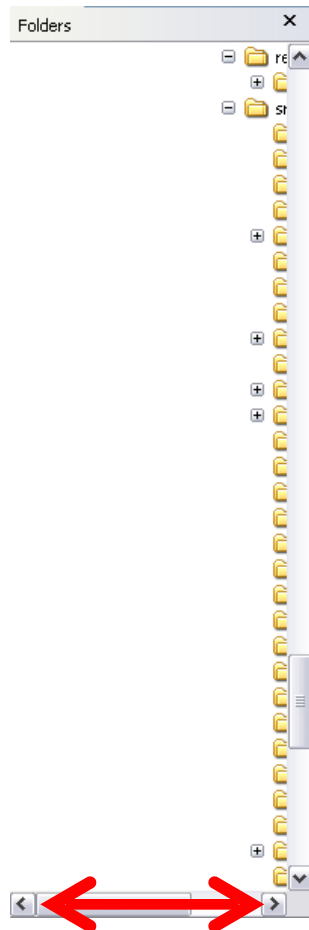
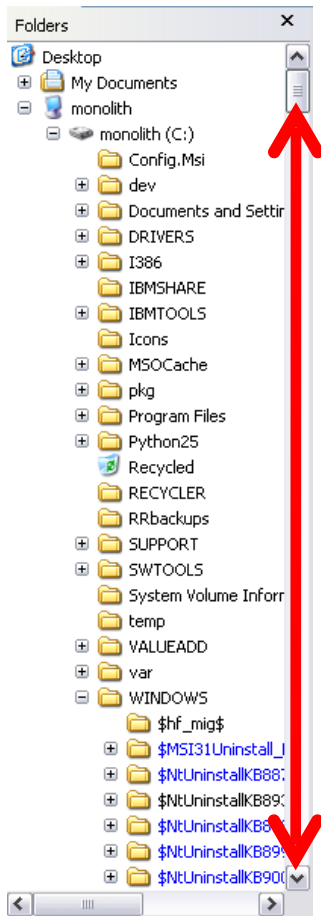
Radius encodes depth, with root in the center.

Angular sectors assigned to subtrees (often with naïve recursive layout).

Reingold-Tilford method can also be applied here.

# Analysis Tasks: Focus+Context

# Visualizing Large Hierarchies



Indented Layout

Reingold-Tilford Layout

# More Nodes, More Problems...

## **Scale**

Tree breadth often grows exponentially  
Even with tidy layout, quickly run out of space

## **Possible Solutions**

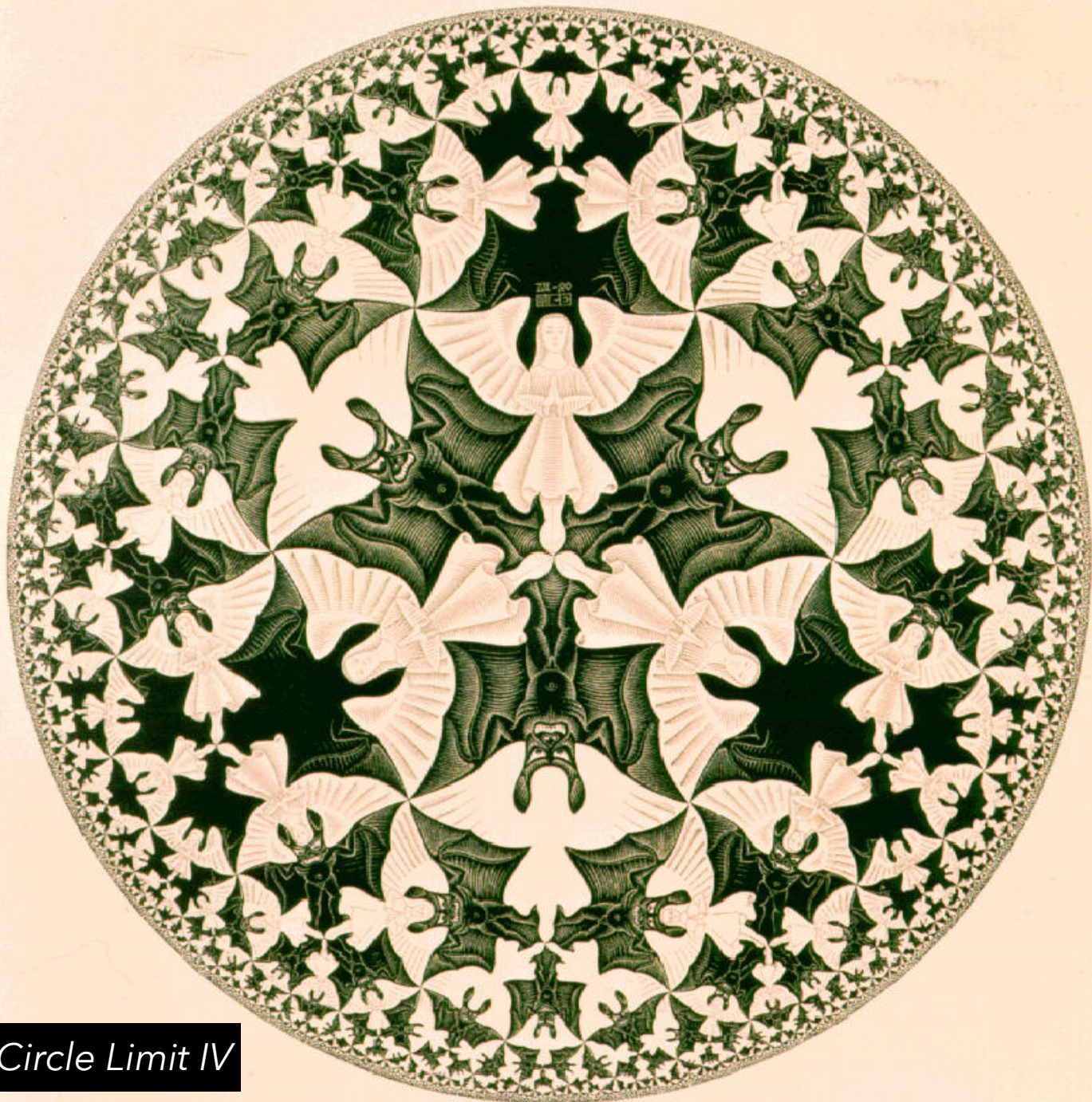
Filtering

Focus+Context

Scrolling or Panning

Zooming

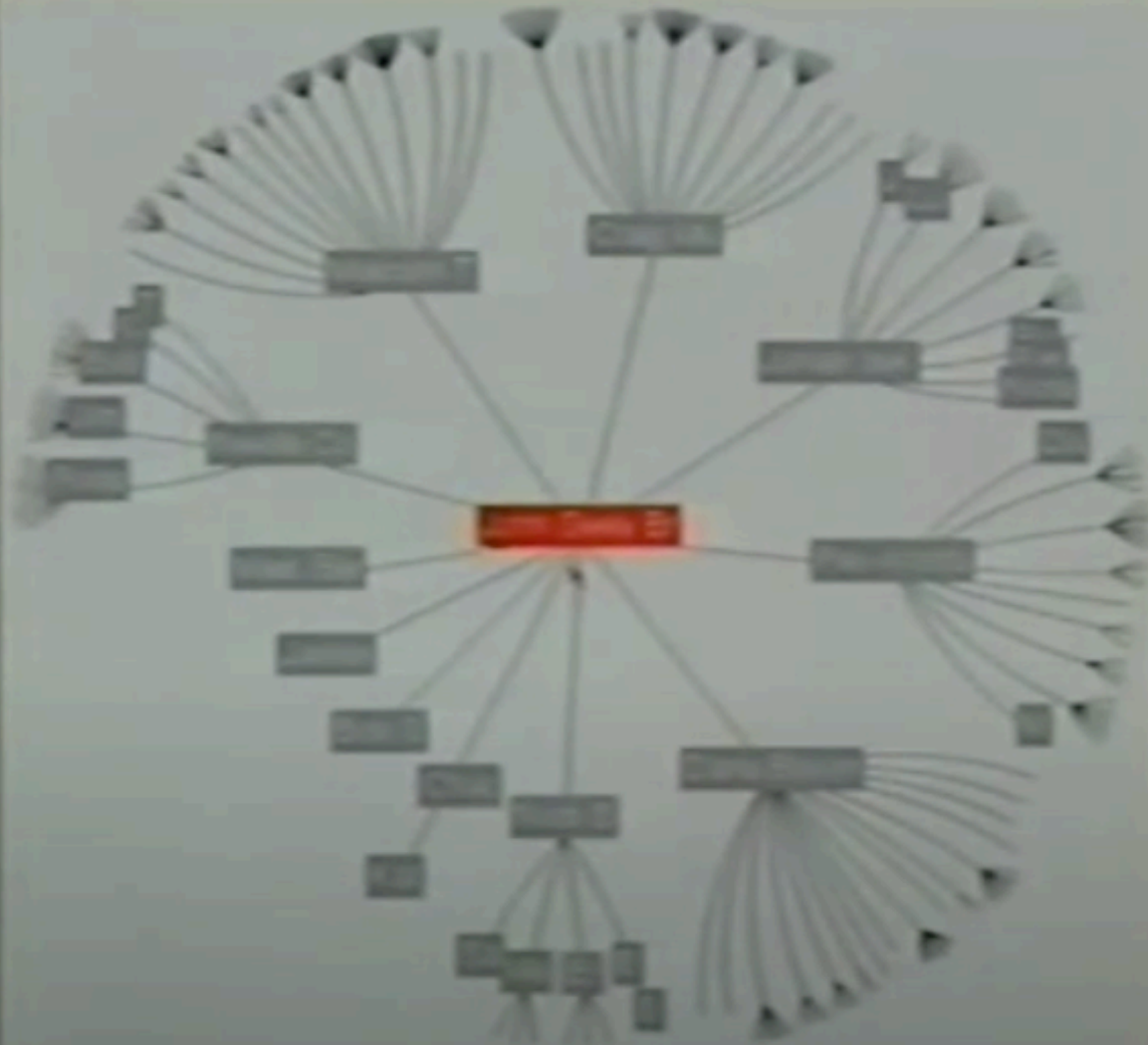
Aggregation



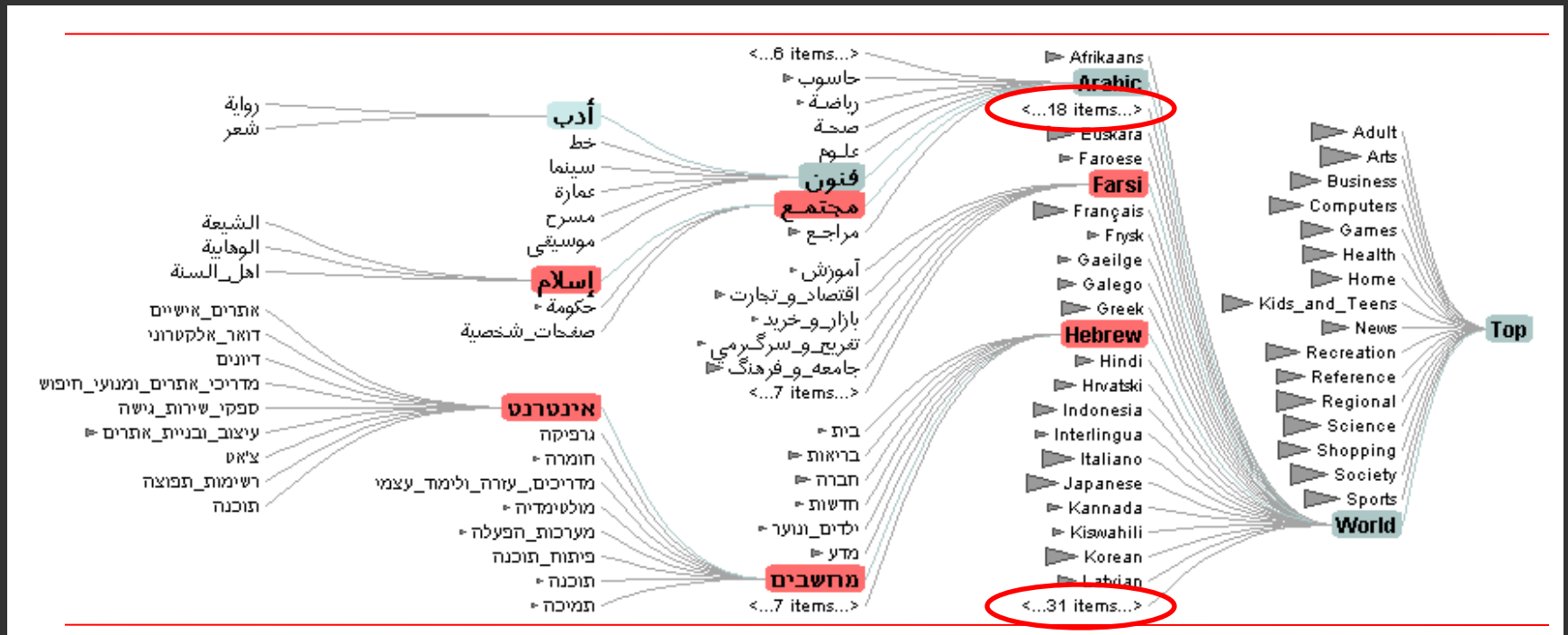
MC Escher, *Circle Limit IV*



# Hyperbolic Layout



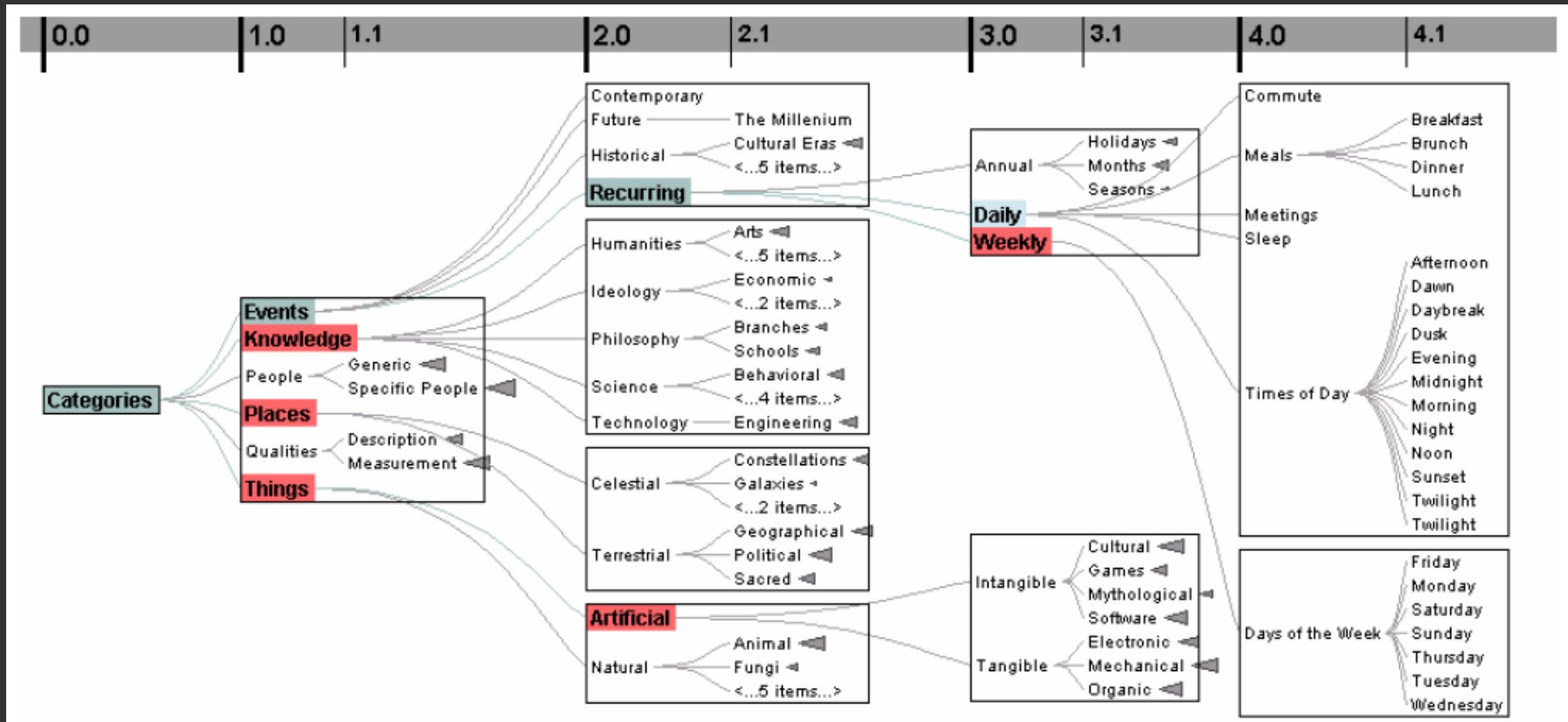
# Degree-of-Interest Trees



Space-constrained, multi-focal tree layout



# Degree-of-Interest Trees



Remove "low interest" nodes at a given depth level until all blocks on a level fit within bounds. Attempt to center child blocks beneath parents.



# Indentation & Node-Link Diagrams

Encode structure in **2D space** (breadth/depth)

## **Benefits**

Clearly depicts node relationships / structure  
Structure-based or browsing tasks

## **Problems**

Even with tidy layout, quickly run out of space

## **Missing**

Attribute-based encodings

**Enclosure**

# Enclosure Diagrams



Encode structure using **spatial enclosure**  
Popularly known as **treemaps**

## Benefits

Provides a single view of an entire tree  
Easier to spot large/small nodes

## Problems

Difficult to accurately read structure / depth

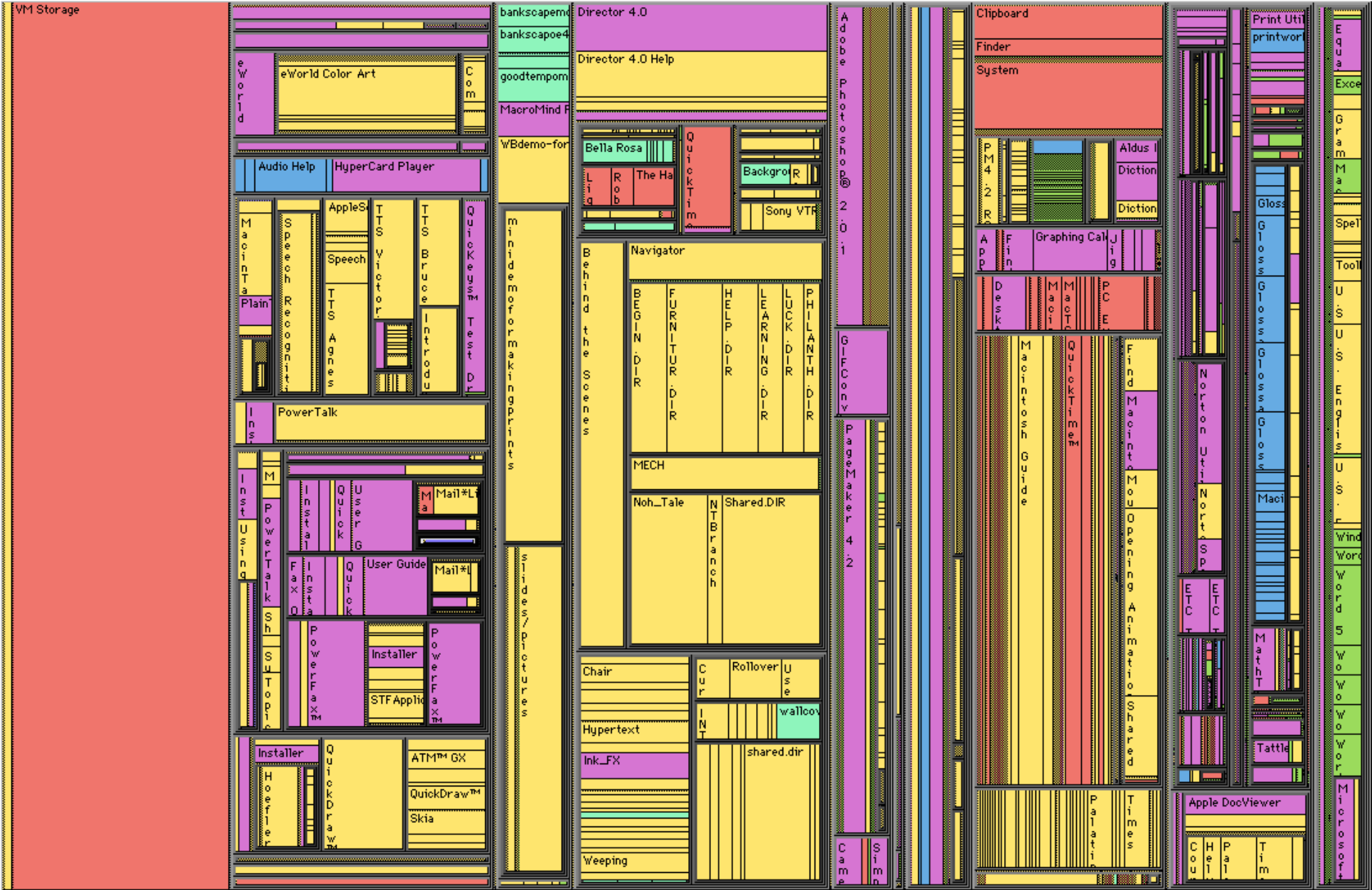


# Treemaps

Hierarchy visualization that emphasizes values of nodes via area encoding.

Partition 2D space such that leaf nodes have sizes proportional to data values.

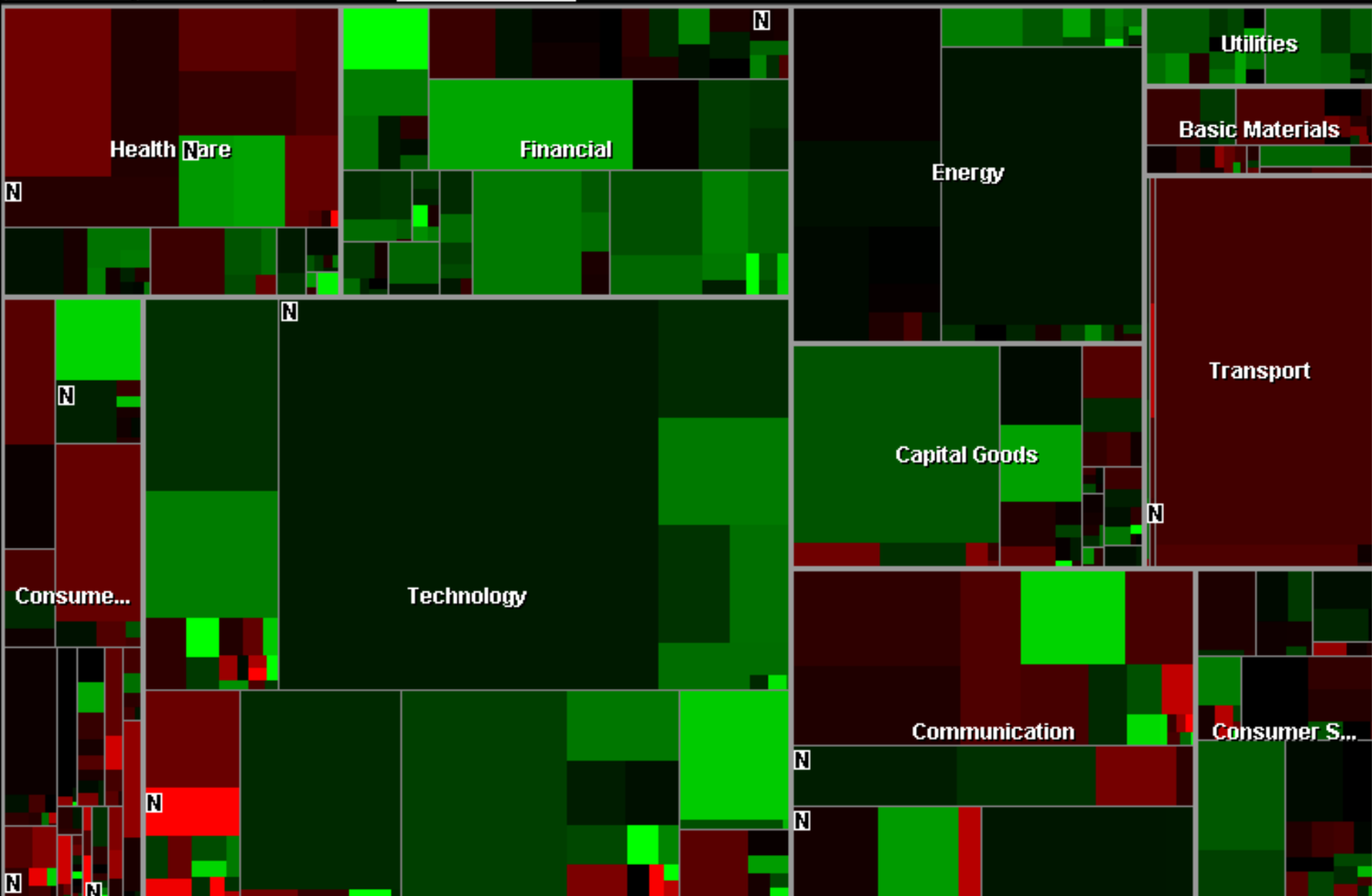
First layout algorithms proposed by Shneiderman et al. in 1990, with focus on showing file sizes on a hard drive.



Name	Size	% Total	Type	Creator	Creation Date	Modification Date
Unknown	Text	Graphics	Archives/Stacks	Programming	Applications	System

*Slice & Dice* layout: Alternate horizontal / vertical partitions.



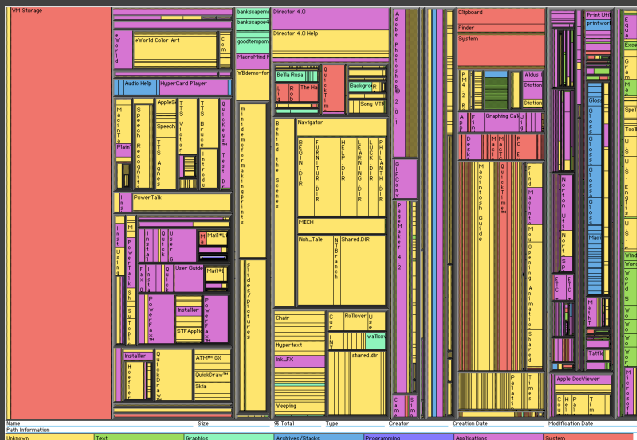


*Squarified* layout: Try to produce square (1:1) aspect ratios

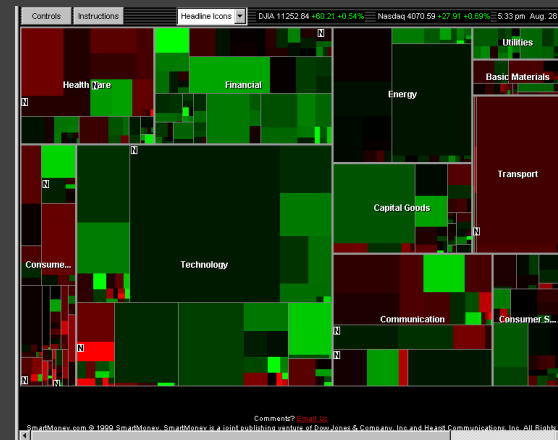
# Squarified Treemaps [Bruls et al. '00]

*Slice & Dice* layout suffers from extreme aspect ratios. How might we do better?

*Squarified* layout: greedy optimization for objective of square rectangles. Slice/dice within siblings; alternate whenever ratio worsens.



VS.

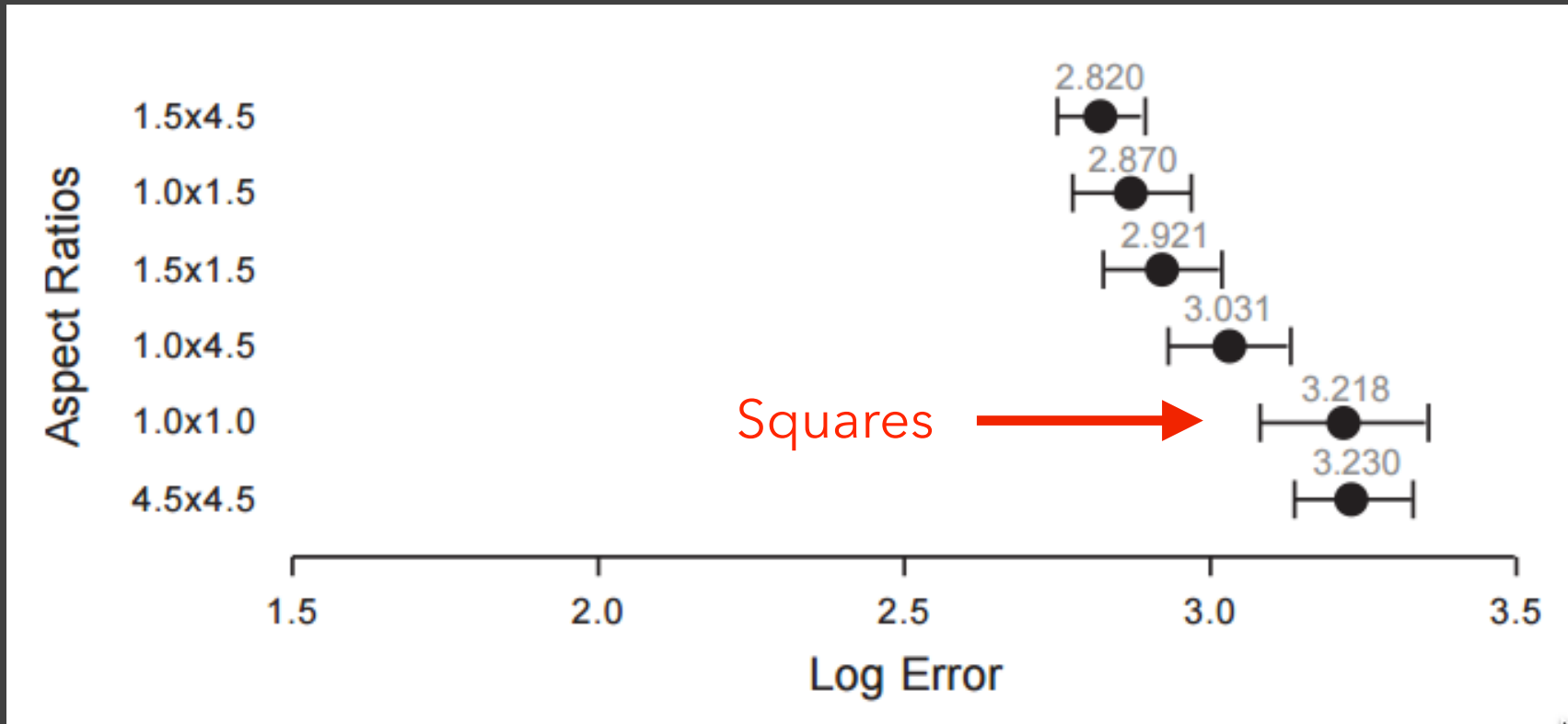


# Why Squares? [Bruls et al. '00]

## Posited Benefits of 1:1 Aspect Ratios

1. Minimize perimeter, reducing border ink.  
*Mathematically true!*
2. Easier to select with a mouse cursor.  
*Validated by empirical research & Fitt's Law!*
3. Similar aspect ratios are easier to compare.  
*Seems intuitive, but is this true?*

# Comparison Error vs. Aspect Ratio



Study by Kong, Heer & Agrawala, InfoVis '10.

Comparison of squares has higher error!

"Squarify" works because it fails to meet its objective?

# Why Squares? [Bruls et al. '00]

## Posited Benefits of 1:1 Aspect Ratios

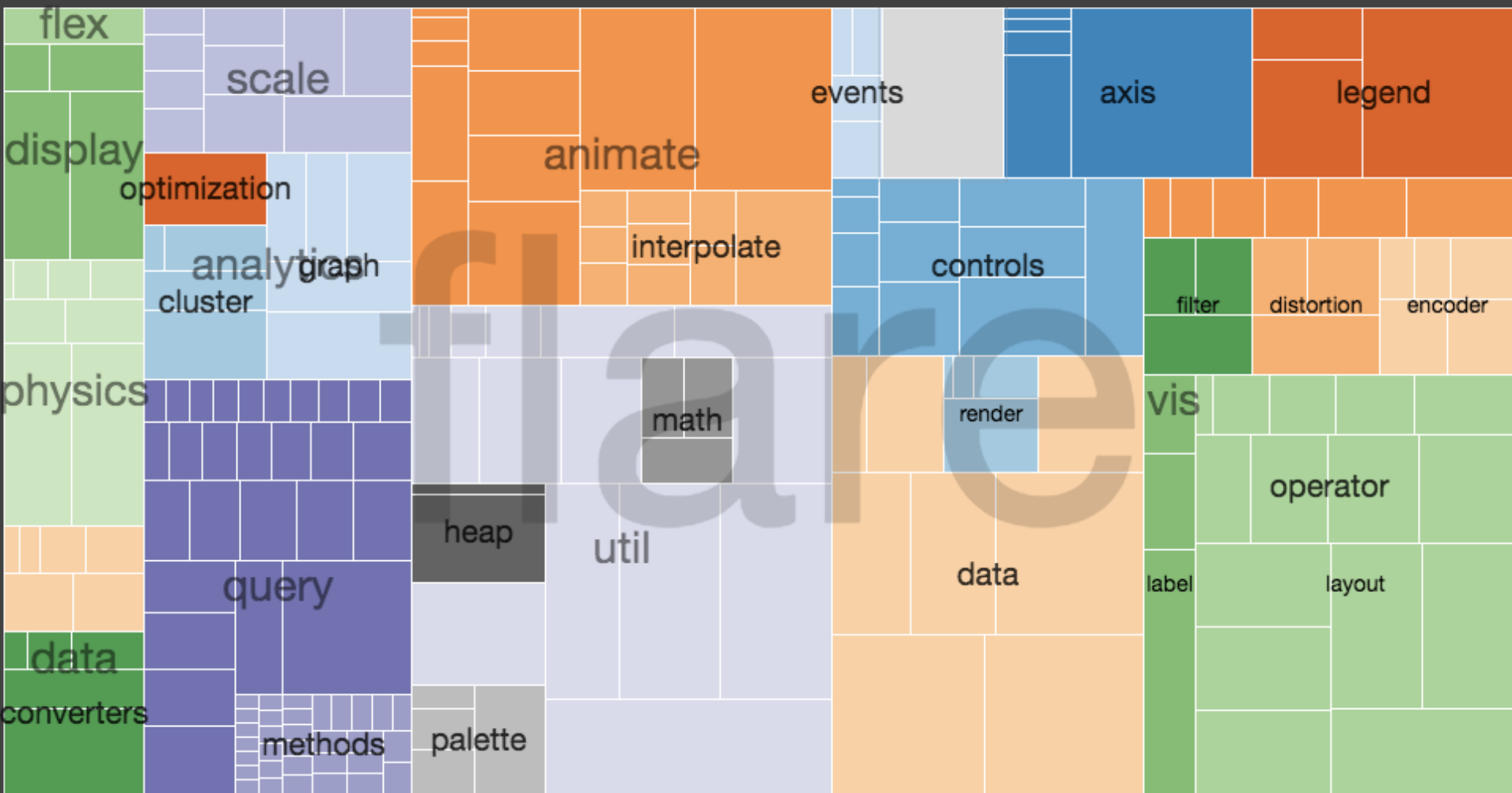
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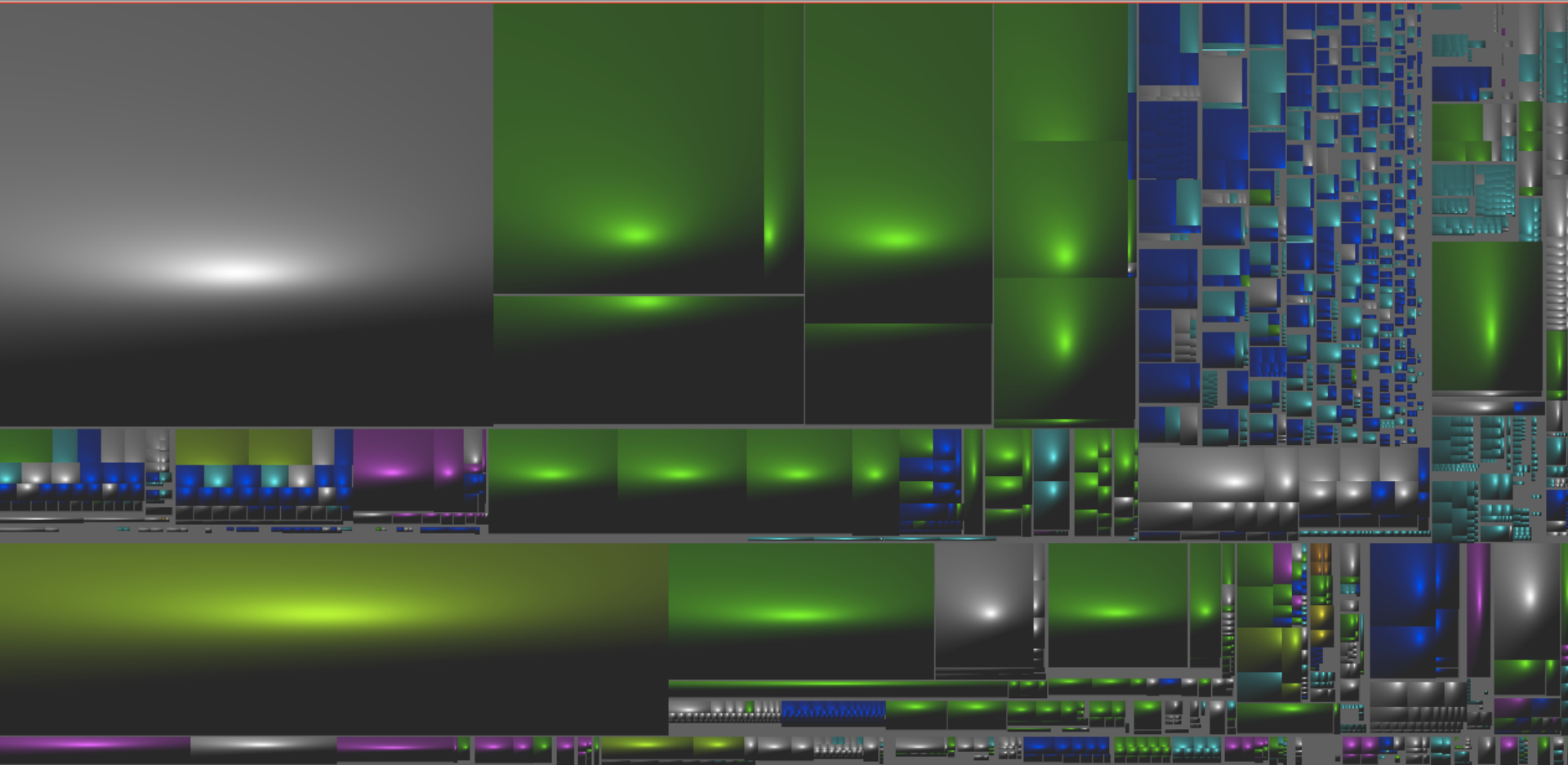
## Posited Benefits of 1:1 Aspect Ratios

1. Minimize perimeter, reducing border ink.  
*Mathematically true!*
2. Easier to select with a mouse cursor.  
*Validated by empirical research & Fitt's Law!*
3. ~~Similar aspect ratios are easier to compare.~~  
*Extreme ratios & squares-only more inaccurate.  
Balanced ratios better? Target golden ratio?*

# Interactive Example...



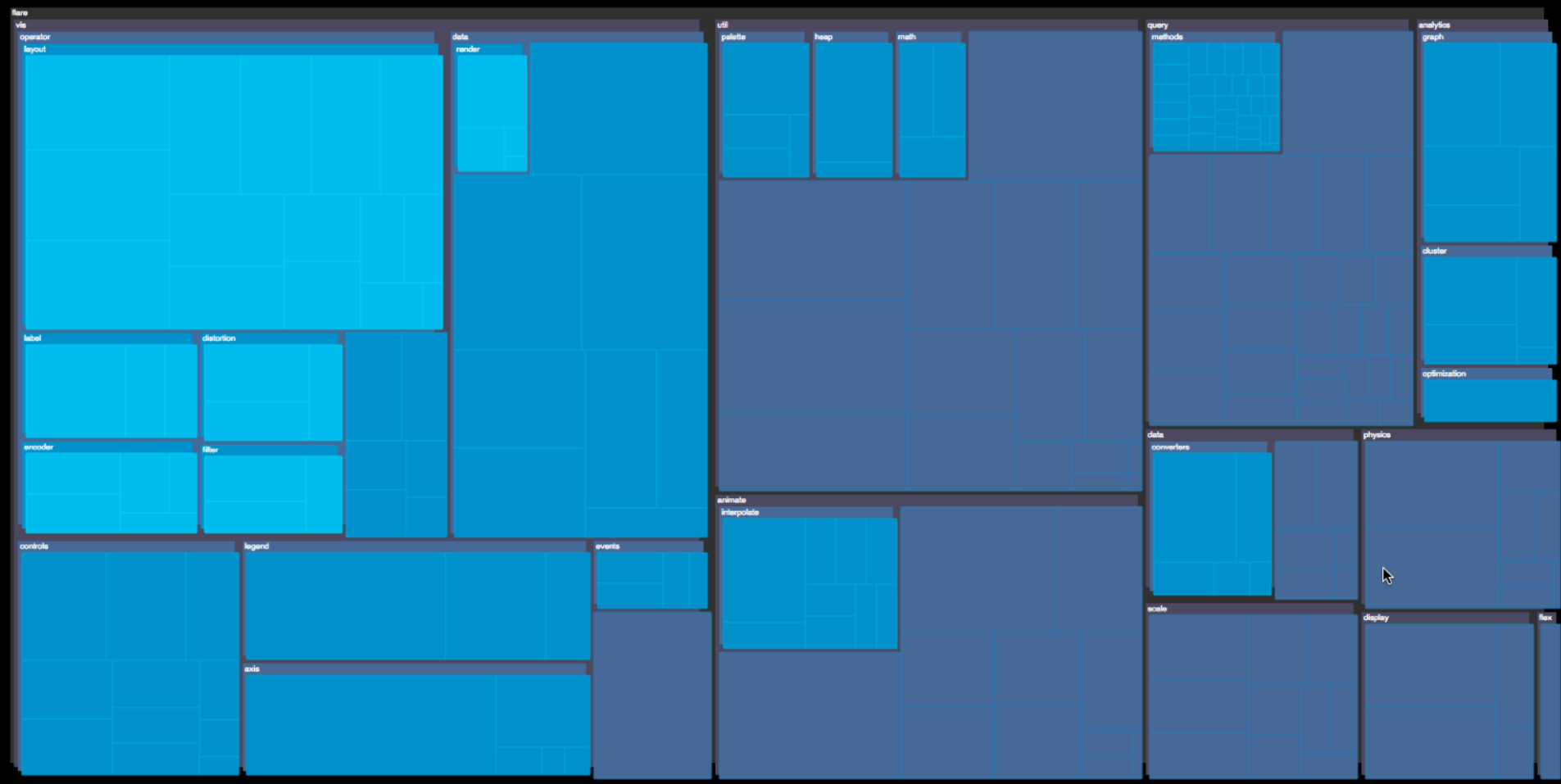
# Cushion Treemaps [van Wijk & Wetering '99]



Uses shading to emphasize hierarchal structure.



# Cascaded Treemaps [Lü & Fogarty '08]

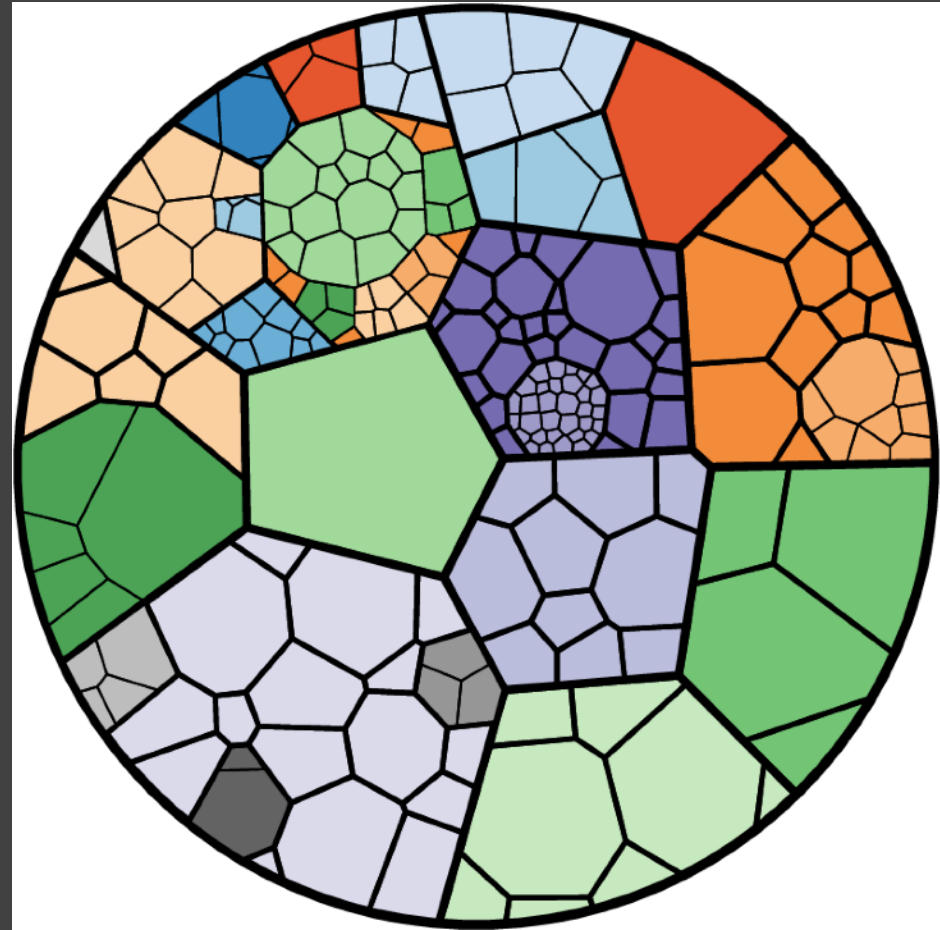


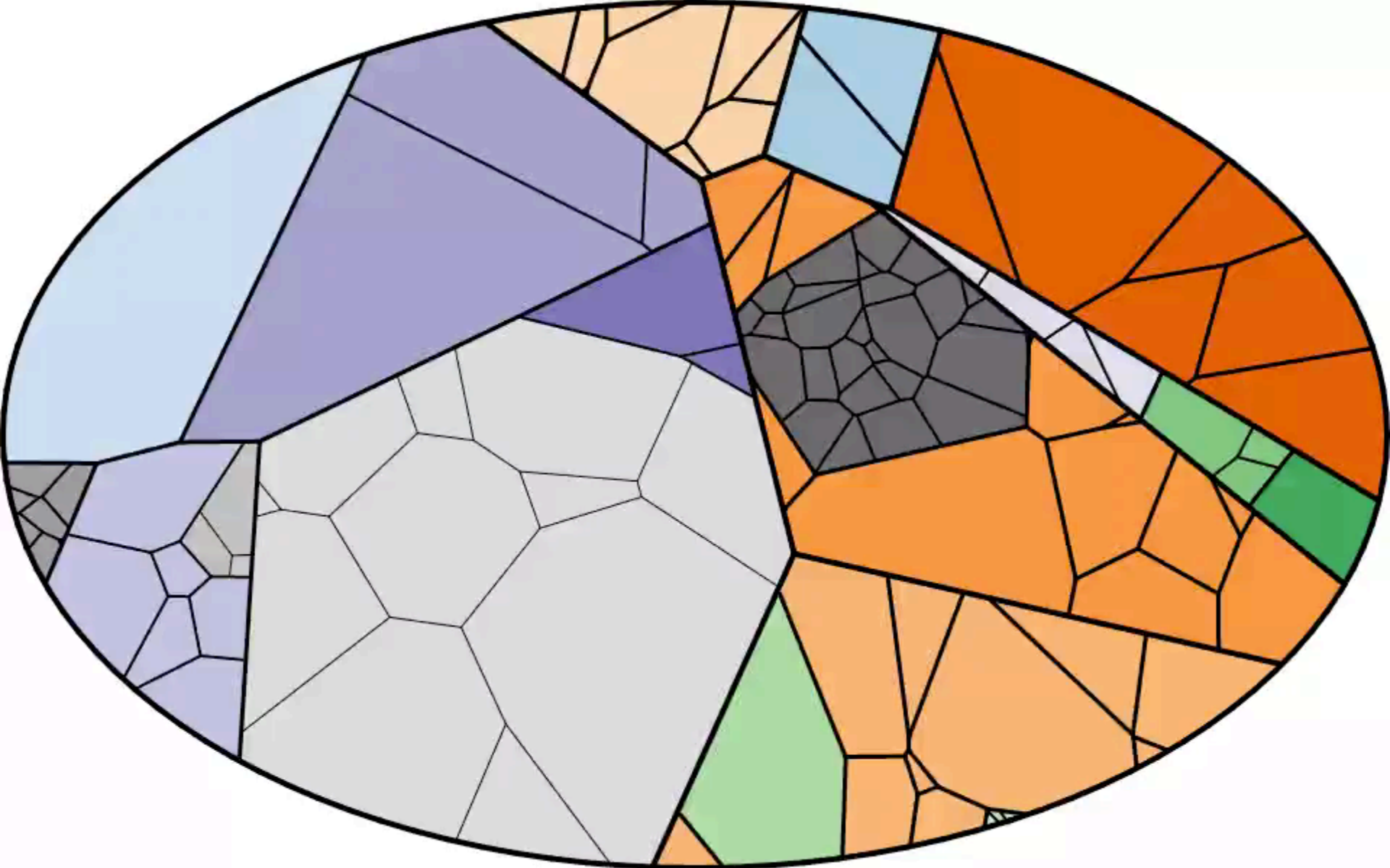
Uses 2.5D effect to emphasize hierarchy relations.

# Voronoi Treemaps [Balzer et al. '05]

Instead of rectangles, create treemaps with arbitrary polygonal shapes and boundary.

Use iterative, weighted Voronoi tessellations to achieve cells with value-proportional areas.

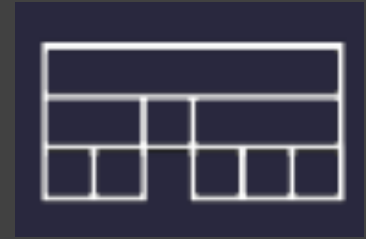




Iterative Voronoi Tessellations [Jason Davies]

# Layering

# Layered Diagrams



Signify tree structure using:

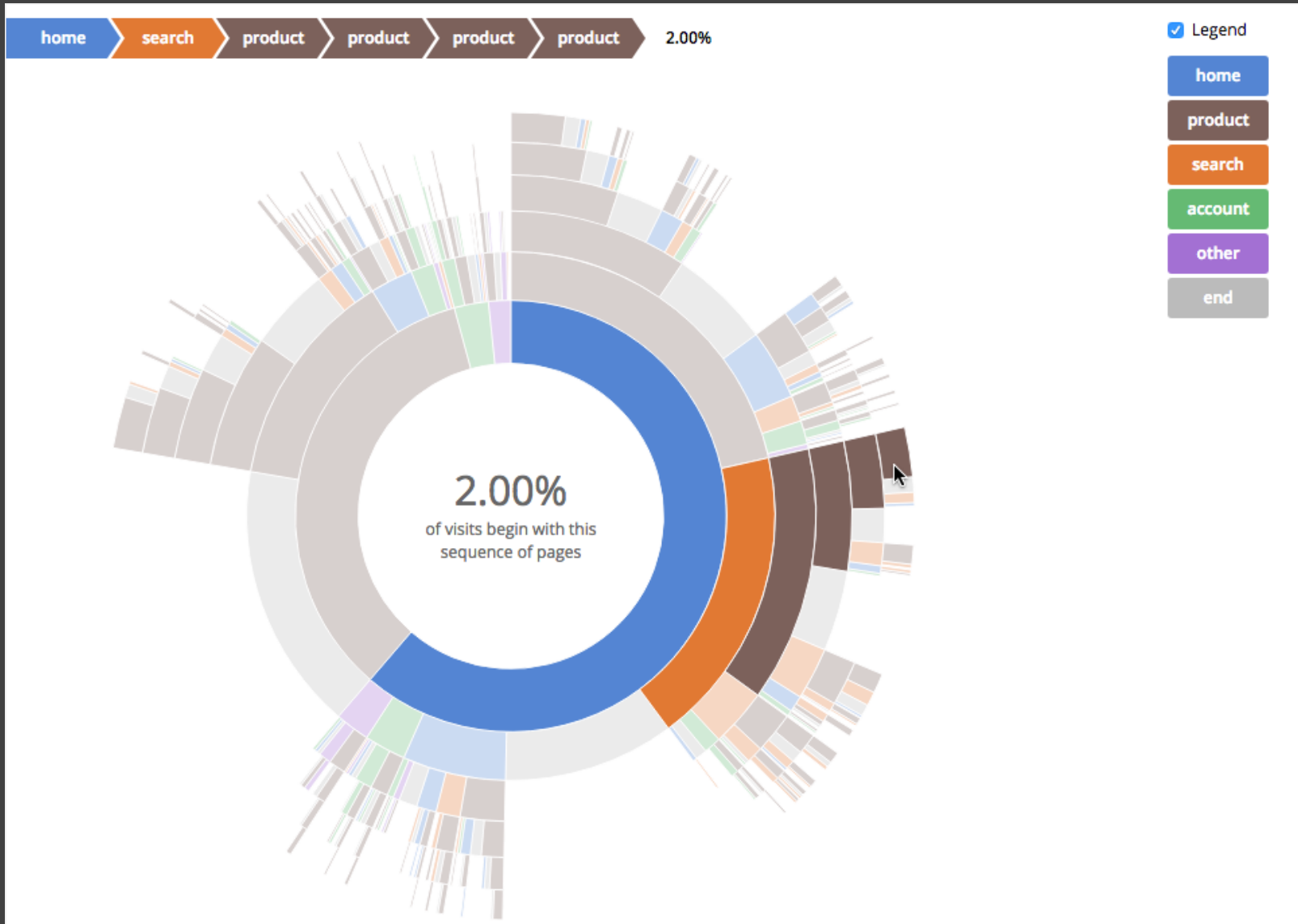
- Layering
- Adjacency
- Alignment

Involves recursive sub-division of space.

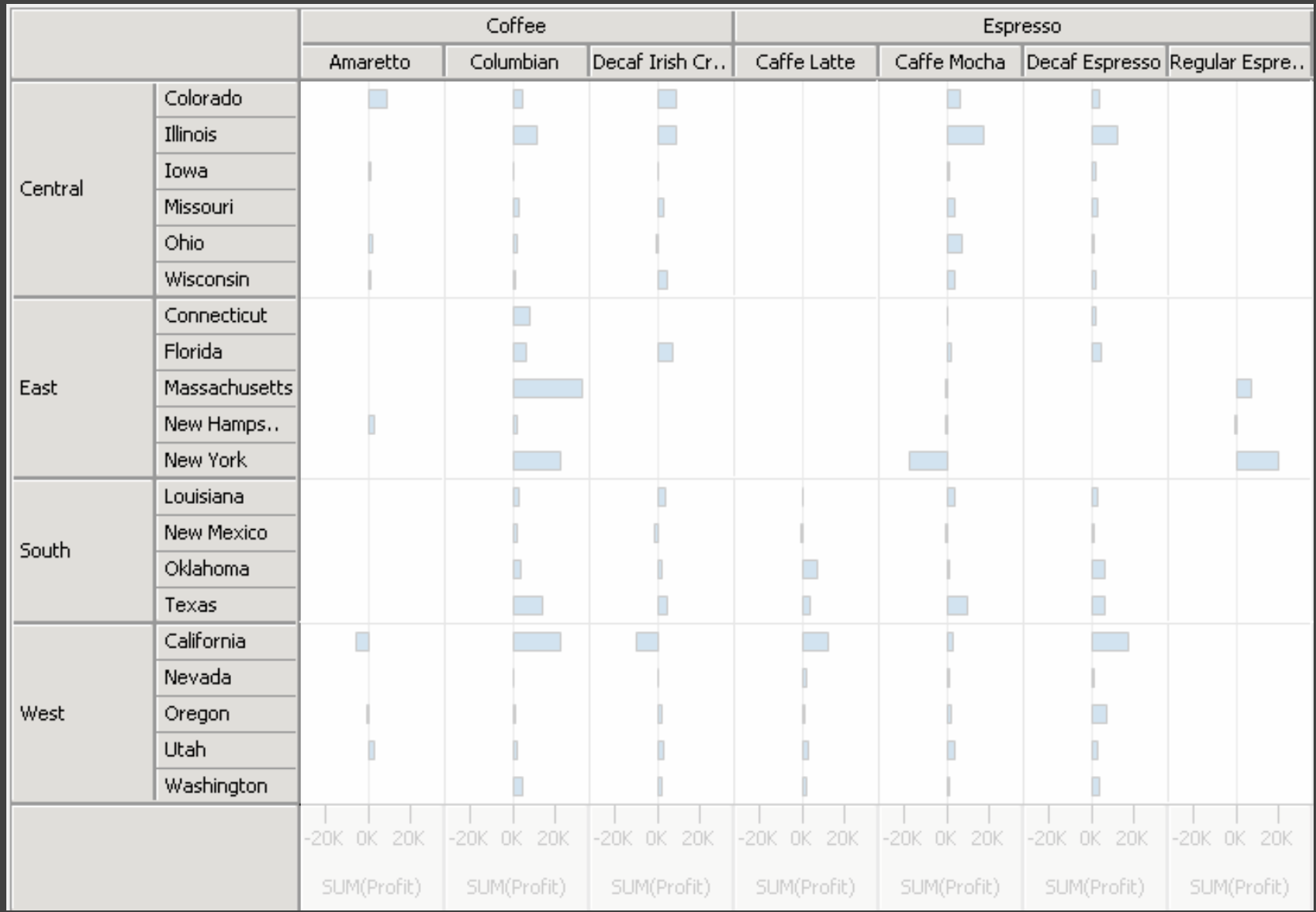
Leaf nodes may be sized by value, parent size visualizes sum of descendant leaf values.



# "Sunburst" Trees: Polar Partition



# Layered Trees Useful Elsewhere...





# Administrivia

# Final Project Schedule

~~Proposal~~ ————— ~~Fri May 10~~

**Prototype**                      **Wed May 22**

*Demo Video*                      Wed May 29

*Video Showcase*              Thu May 30 (in class)

*Deliverables*                      Mon June 3

## **Logistics**

Final project description posted online

Work in groups of up to 4 people

Start determining your project topic!

# Milestone Prototype

Publish work to GitLab pages for others to examine and share feedback. You **are not** expected to have complete, polished content at this point.

You **are** expected to provide prototype work that communicates your design goals. For example: initial visualizations, sketches, storyboards, and text annotations / idea descriptions.

*One should get a sense of what you intend to ultimately submit! Also feel free to post questions.*

# Node-Link Graph Layout

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout** - arranged by depth

**Force-Directed Layout** - physical simulation

**Attribute-Driven Layout** - arranged by value

**Constraint-Based Layout** - optimization

**Arc Diagrams** - aligned layout

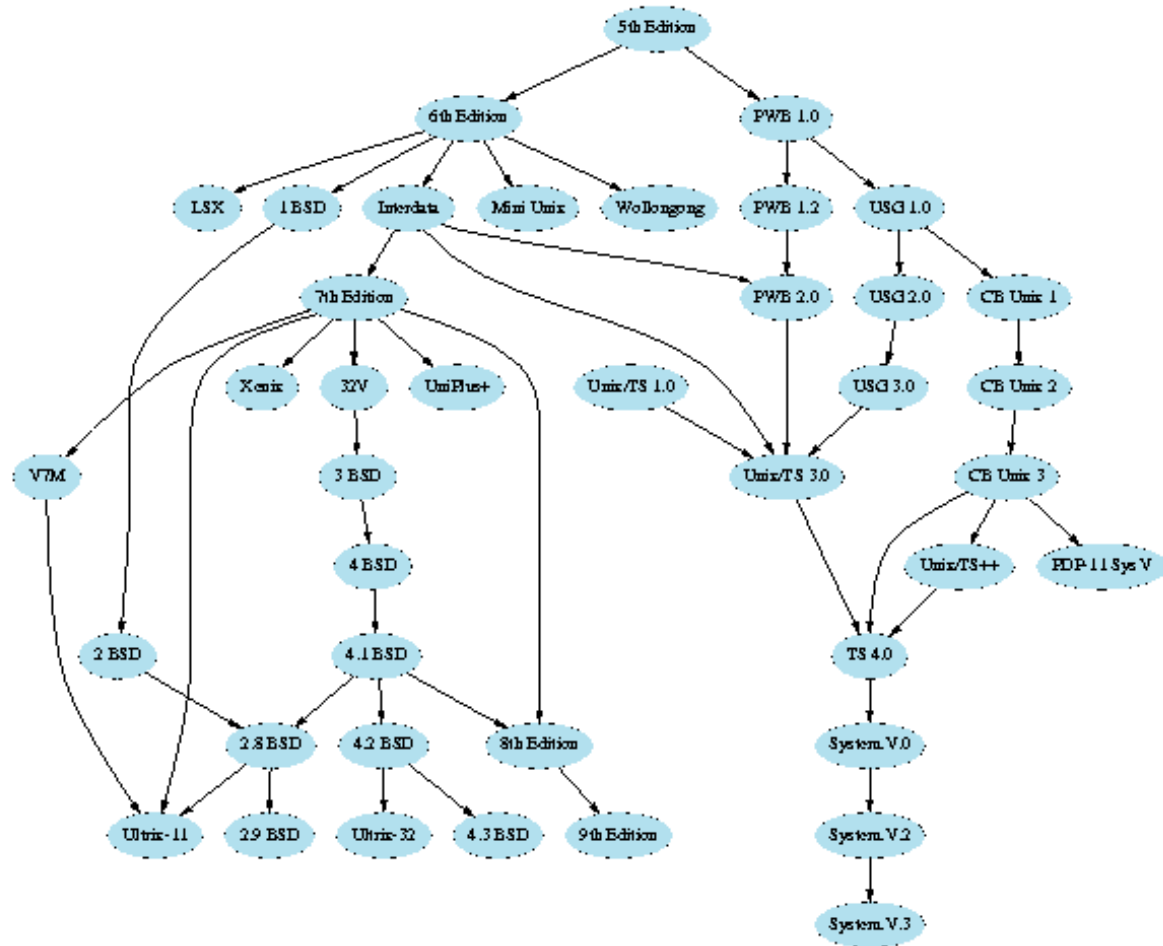
# Sugiyama-Style Layout

# Sugiyama-Style Layout

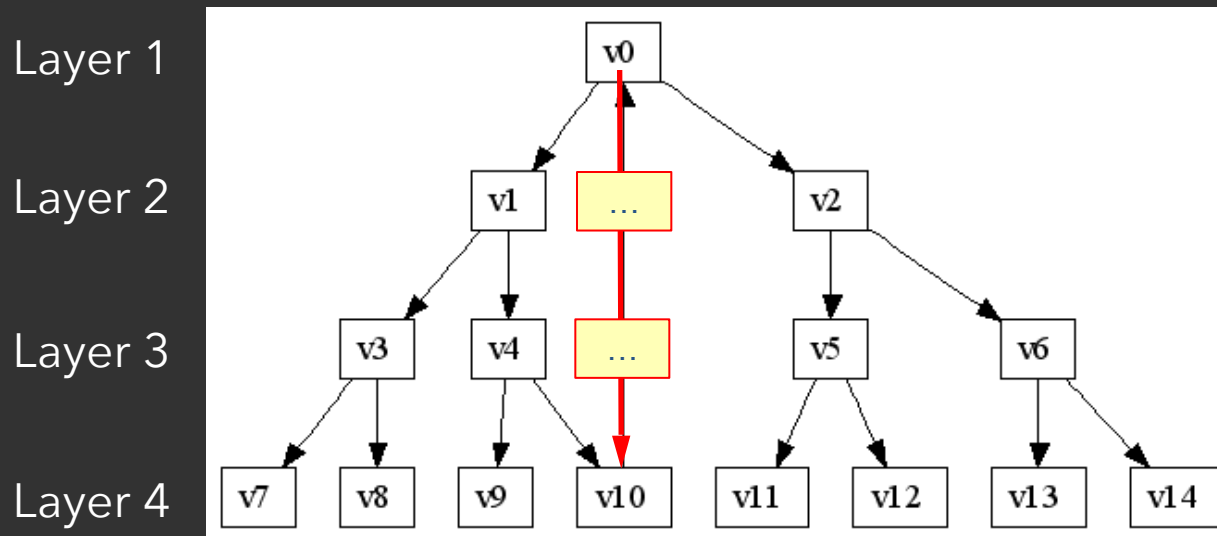
Evolution of the UNIX operating system

Hierarchical layering based on descent

GraphViz package!



# Sugiyama-Style Layout



Reverse edges to remove cycles

Assign nodes to hierarchy layers

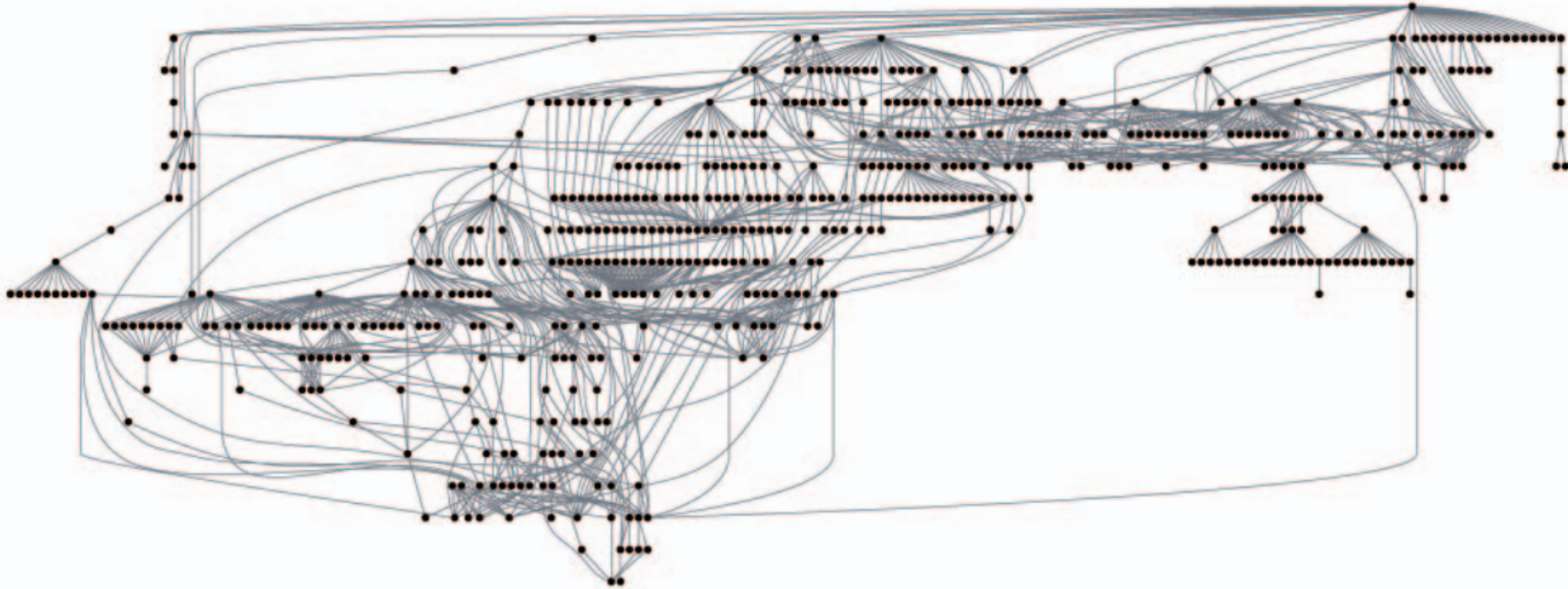
Create dummy nodes to "fill in" missing layers

Arrange nodes within layer, minimize edge crossings

Route edges - layout splines if needed

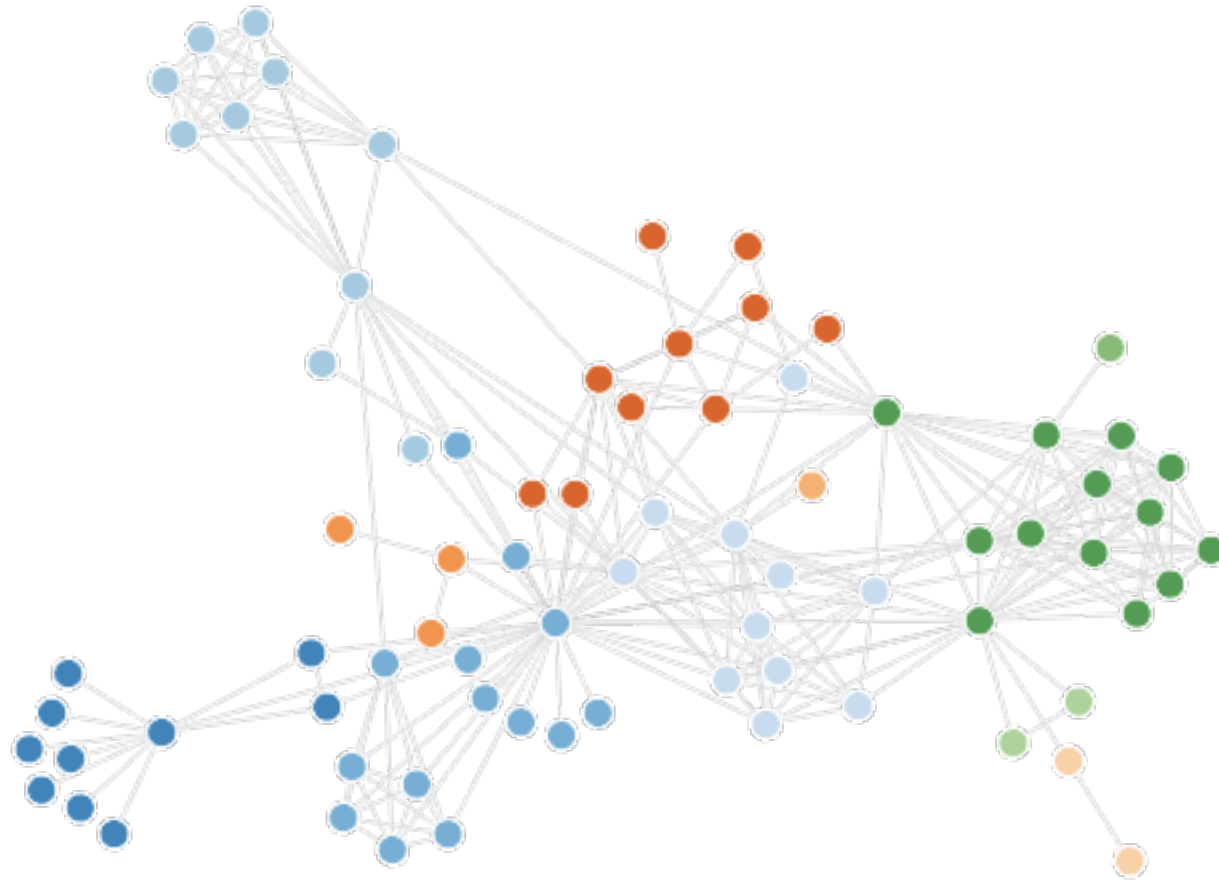


# Produces Hierarchical Layouts

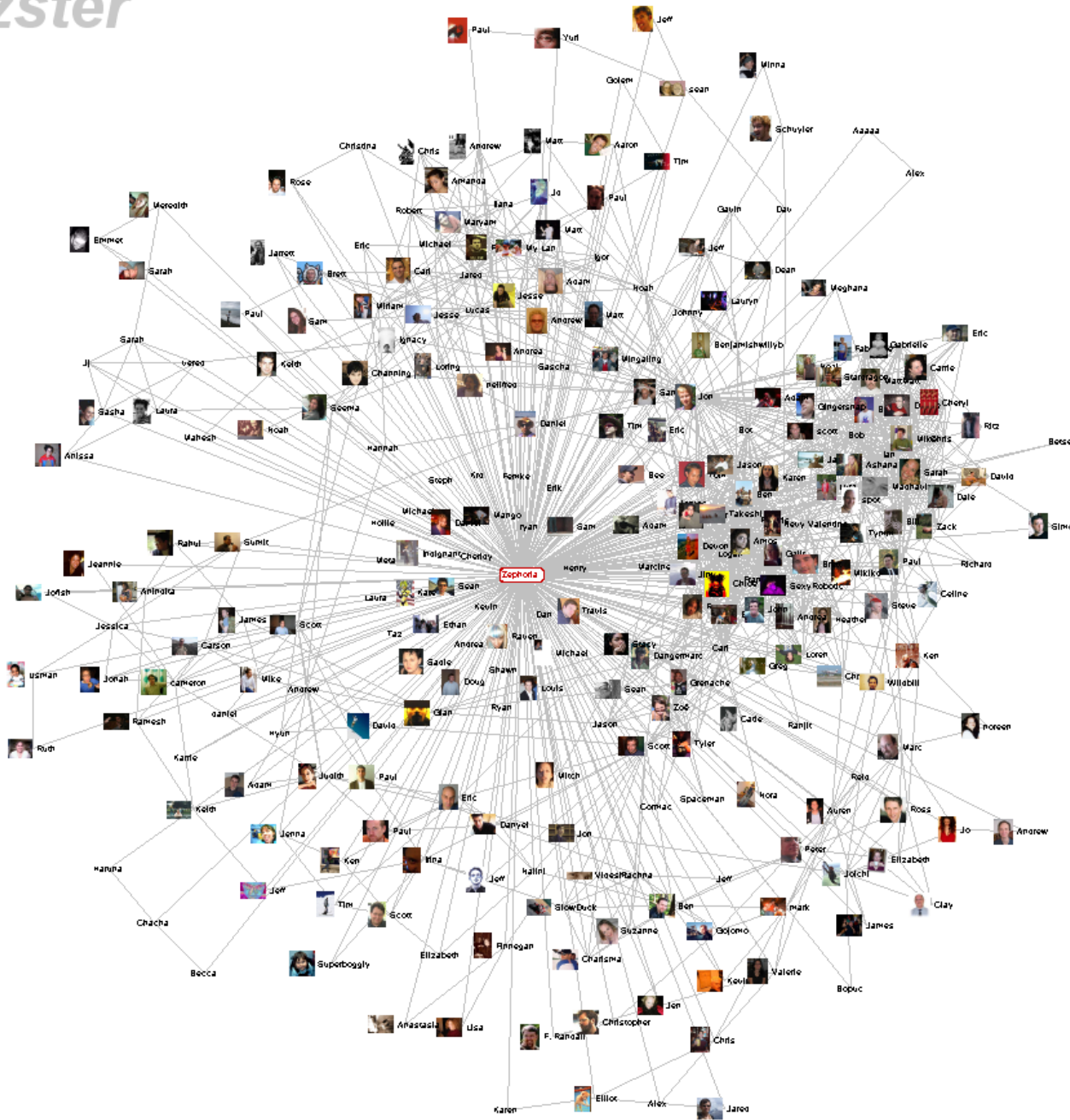


Sugiyama-style layout emphasizes hierarchy. However, cycles in the graph may mislead. Long edges can impede perception of proximity.

# Force-Directed Layout



**Interactive Example: Configurable Force Layout**



**User ID** 21721  
**Friends** 266  
**Age** ??  
**Gender**  Female  
**Status**  Single

**Location** San Francisco, CA  
**Hometown** Lancaster, PA  
**Occupation** researcher: social networks, identity, context

**Interests** apophenia, observing people, culture, questioning power, reading, buddhism, ipseity, computer-mediated communication, social networks, technology, anthropology, stomping

**Music** psytrance/goa/trance [Infected Mushroom, Son Kite... Iboga/Digital Structures], Ani Difranco, downtempo, Thievery Corporation, Beth Orton, Morcheeba, Ween, White Stripes

**Books** Authors: Erving Goffman, Stanley Milgram, Jeanette Winterson, Eric Schlosser, Leslie Feinberg, Dorothy Allison, Italo Calvino, Hermann Hesse

**TV Shows** ??  
**Movies** Koyaanisqatsi, Amelie, Waking Life, Tank Girl, The Matrix, Clockwork Orange, American Beauty, Fight Club, Boys Don't Cry

**Member Since** ??  
**Last Login** 2003-10-21  
**Last Updated** 2003-10-21  
**About** [Some know me as danah..]

I'm a geek, an activist and an academic, fascinated by people and society. I see life as a very large playground and enjoy exploring its intricacies. I revel in life's chaos, while simultaneously providing my own insane element.

My musings:  
<http://www.zephoria.org/thoughts/>

**Want to Meet** Someone who makes life's complexities seem simply elegant

# Use the Force!

<http://mbostock.github.io/d3/talk/20110921/>

# Layout by Physics Simulation

Nodes = charged particles  $F = q_i * q_j / d_{ij}^2$

with air resistance  $F = -b * v_i$

Edges = springs  $F = k * (L - d_{ij})$

At each timestep, calculate forces acting on nodes.  
Integrate for updated velocities and positions.

D3's force layout uses **velocity Verlet** integration.

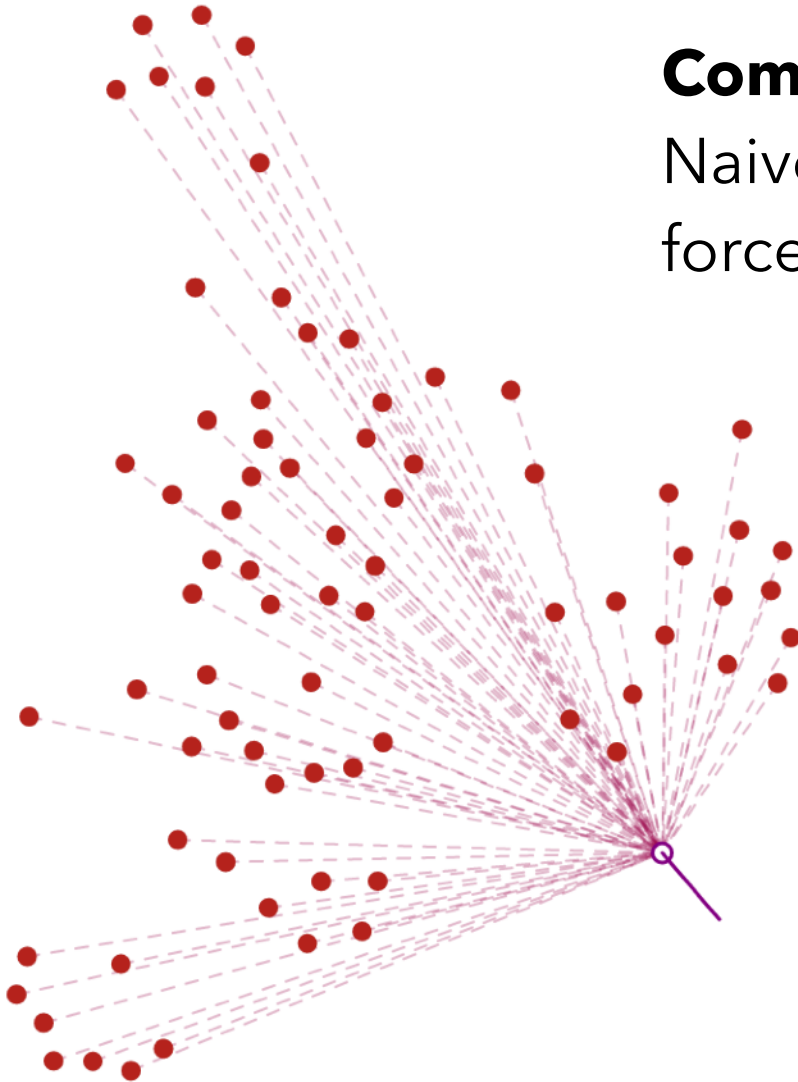
Assume uniform mass ***m*** and timestep  **$\Delta t$** :

$$F = ma \rightarrow F = a \rightarrow F = \Delta v / \Delta t \rightarrow F = \Delta v$$

*Forces simplify to velocity offsets!*

## Computing N-Body Forces

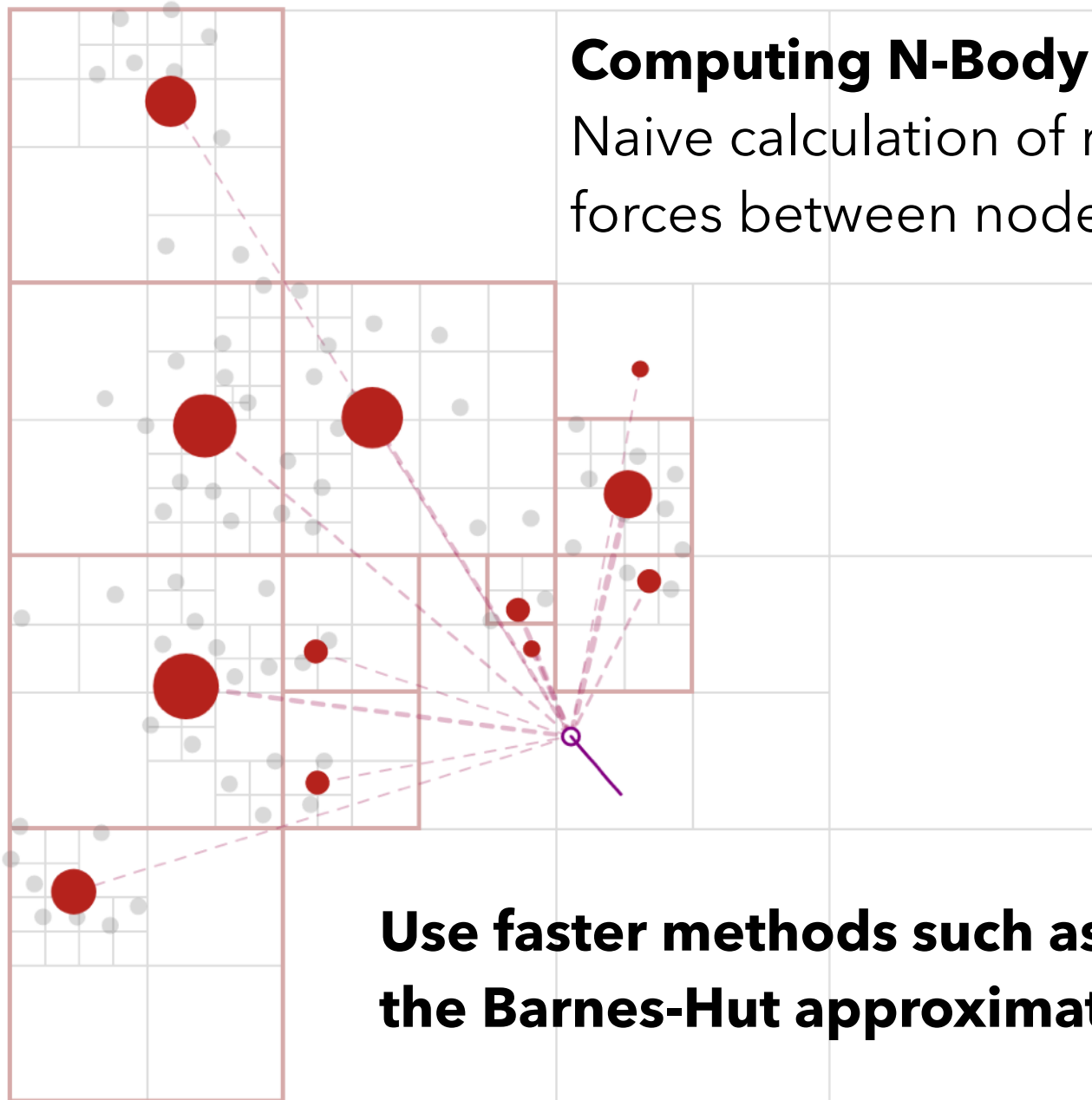
Naive calculation of repulsive forces between nodes is  $O(n^2)$



Naive calculation of forces at a point uses sum of forces from all other  $n-1$  points.

## Computing N-Body Forces

Naive calculation of repulsive forces between nodes is  $O(n^2)$



**Use faster methods such as the Barnes-Hut approximation!**



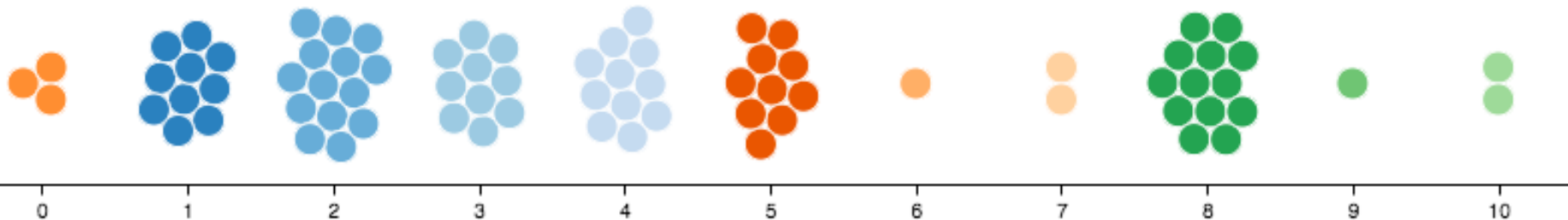
# Customized Force Layouts

Different forces can be composed to create an expressive space of custom layouts.

A **beeswarm plot** can be made by combining:

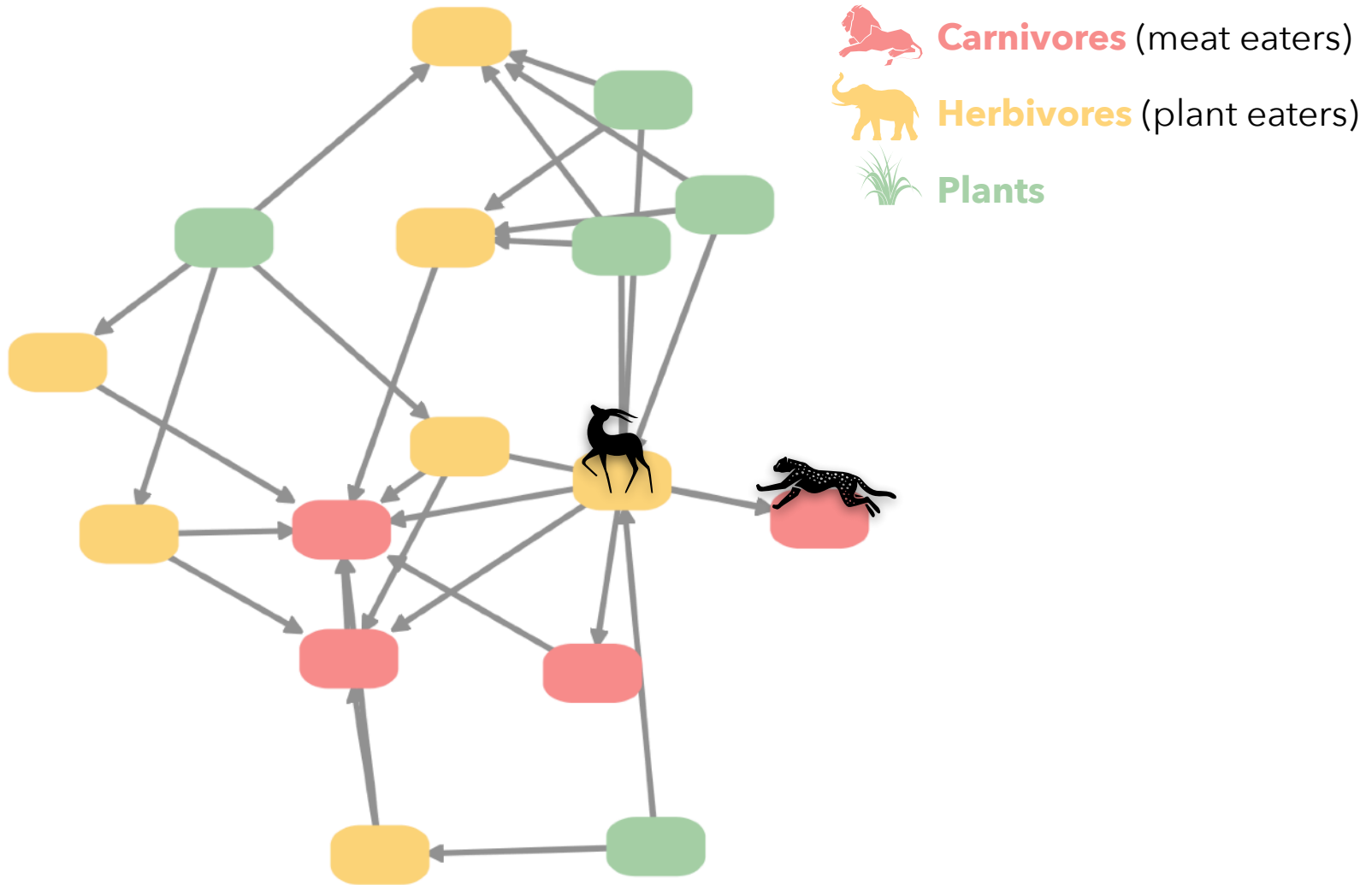
Attractive **X** and **Y** forces to draw nodes of a certain category to a desired point

**Collide** force to detect collision & remove overlap

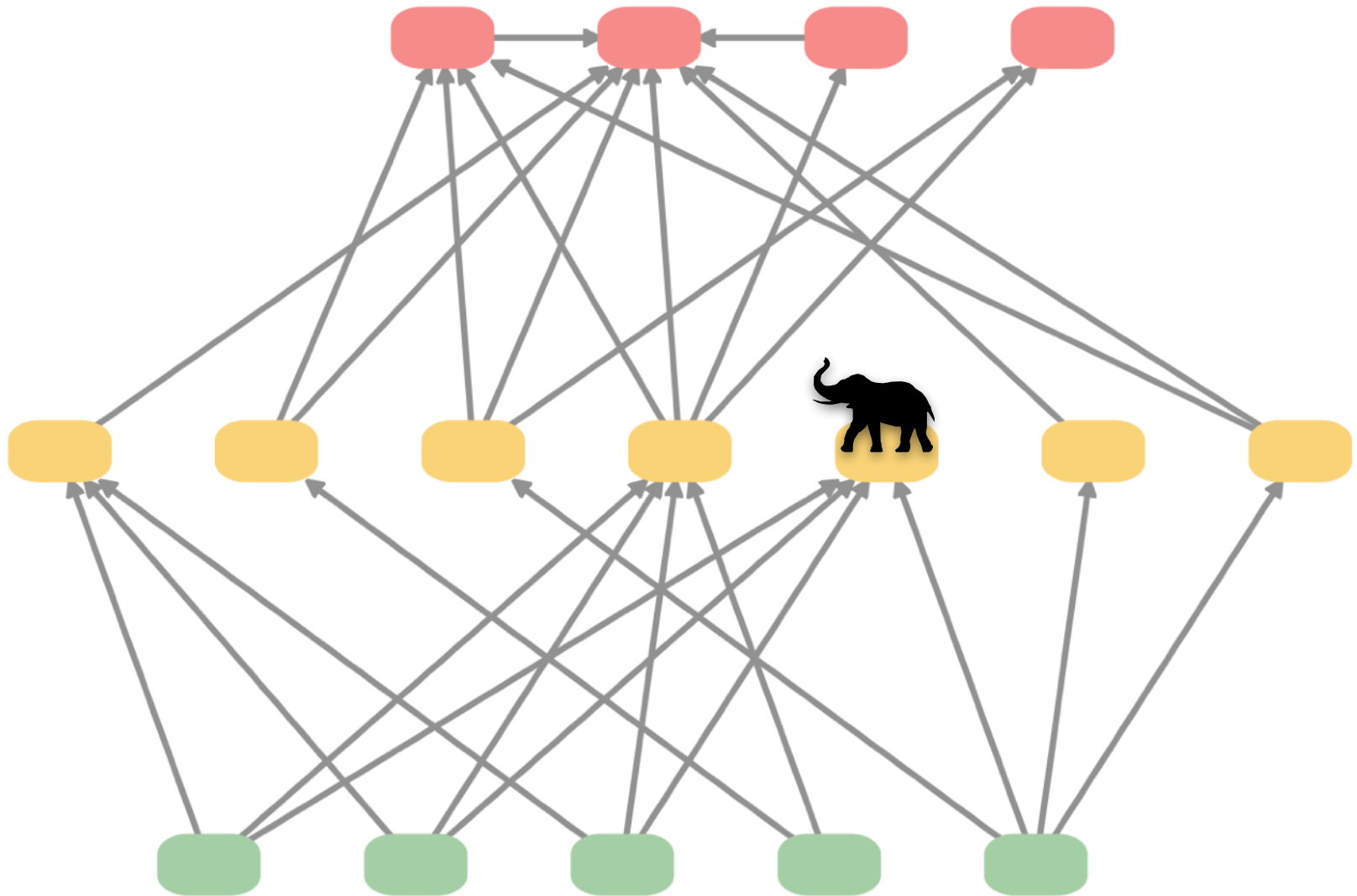


# Attribute-Driven Layout

# How many herbivores have no predators?



How many **herbivores** have no **predators**?



# Attribute-Driven Layout

Large node-link diagrams **get messy!**

Is there additional structure we can exploit?

*Idea:* Use **data attributes** to perform layout

For example, scatter plot based on node values

Attributes may be associated with nodes or edges  
or may be statistical properties of the graph.

Use dynamic queries / brushing to explore...

# Attribute-Driven Layout

The "Skitter" Layout

Internet Connectivity

Radial Scatterplot

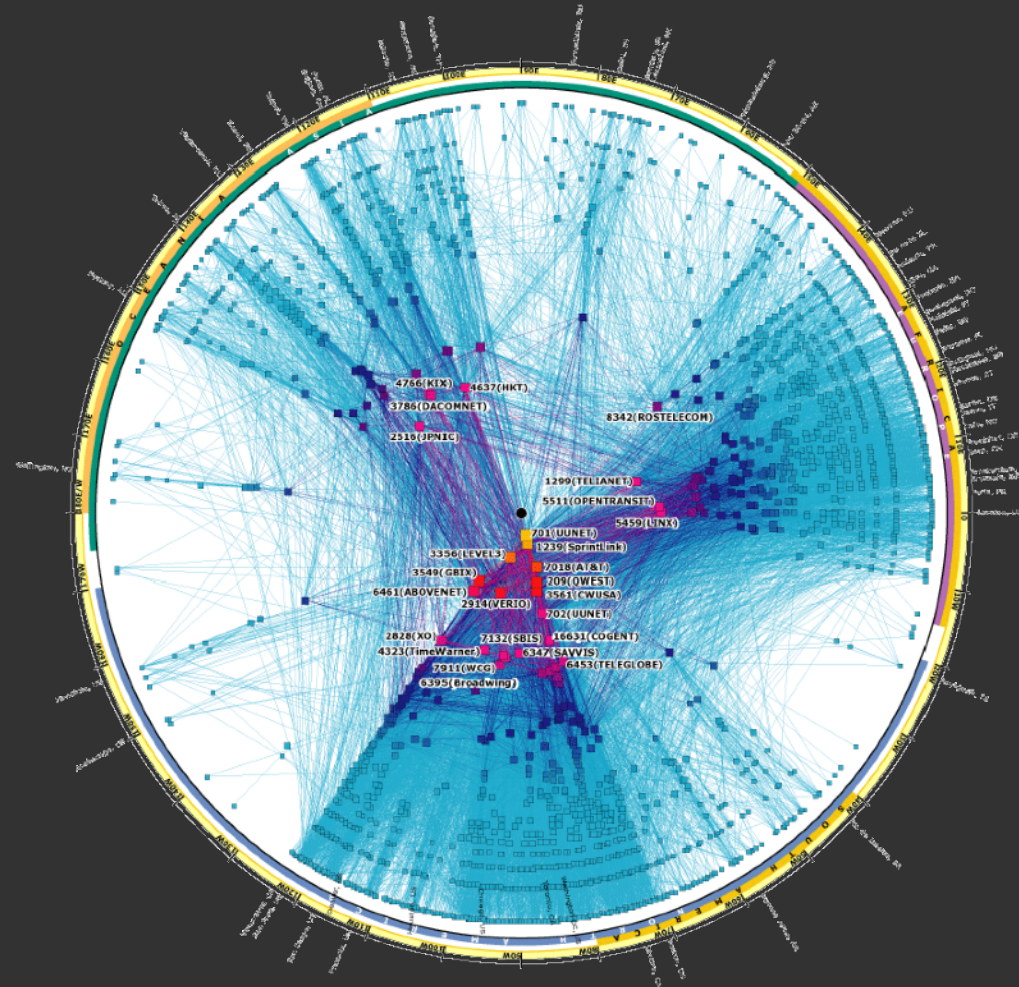
Angle = Longitude

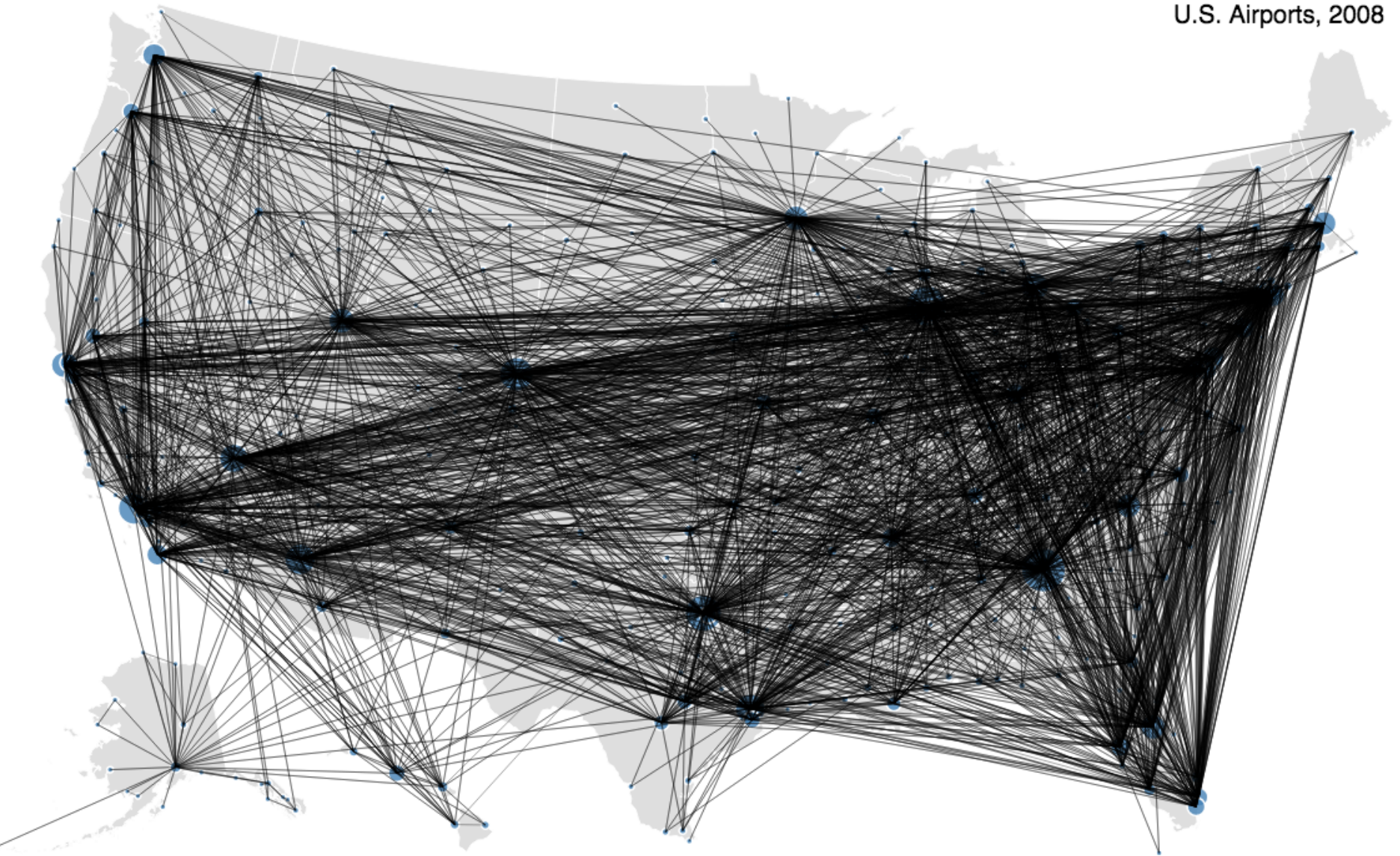
Geography

Radius = Degree

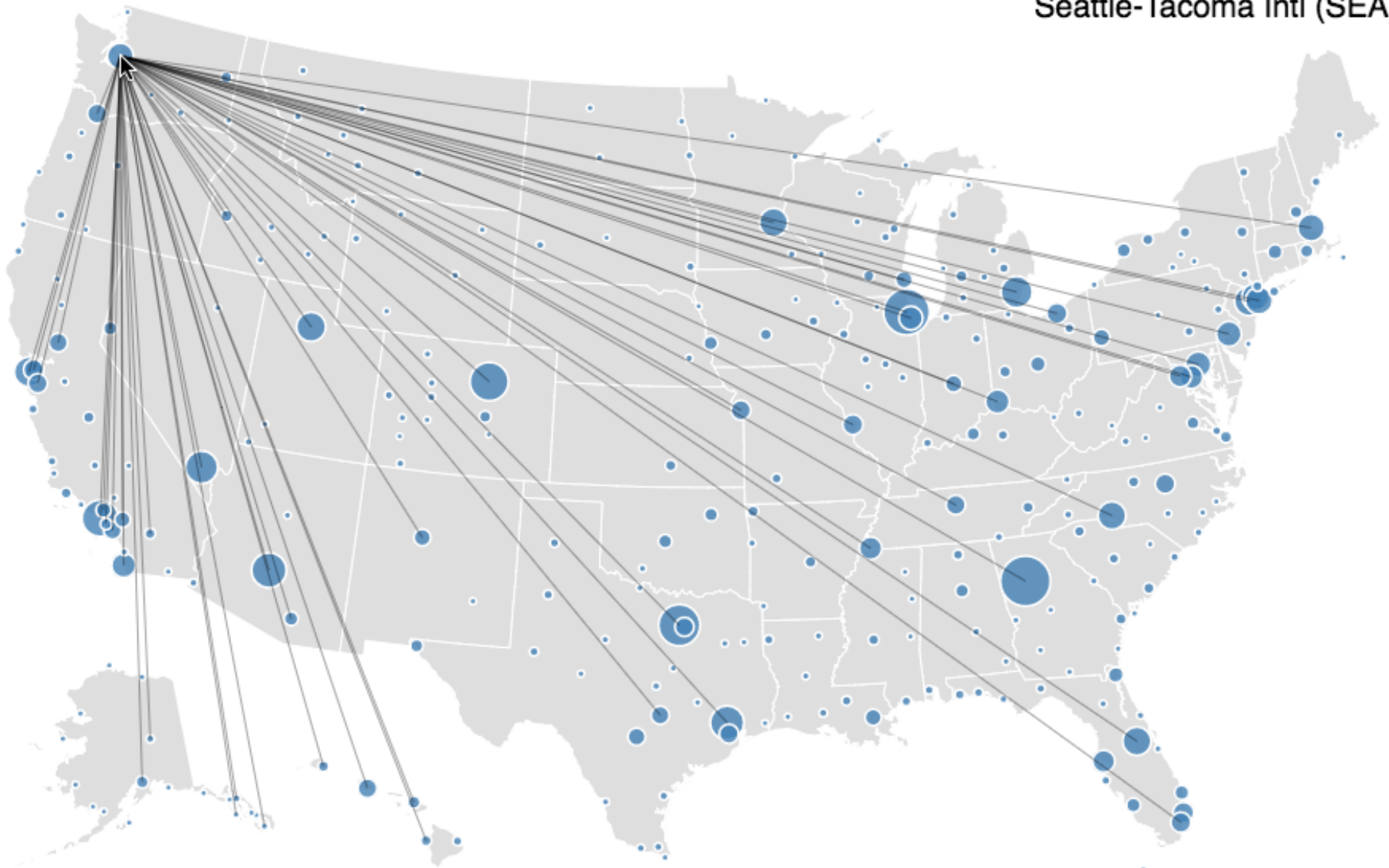
# of connections

(a statistic of the nodes)





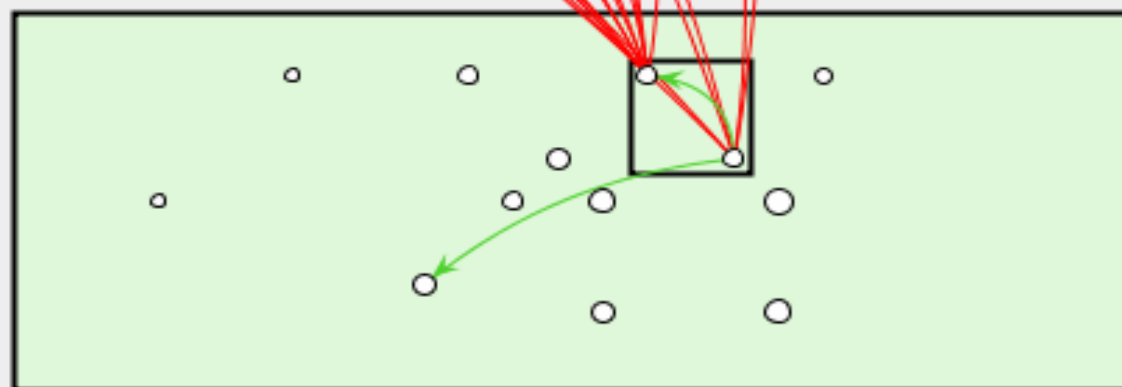
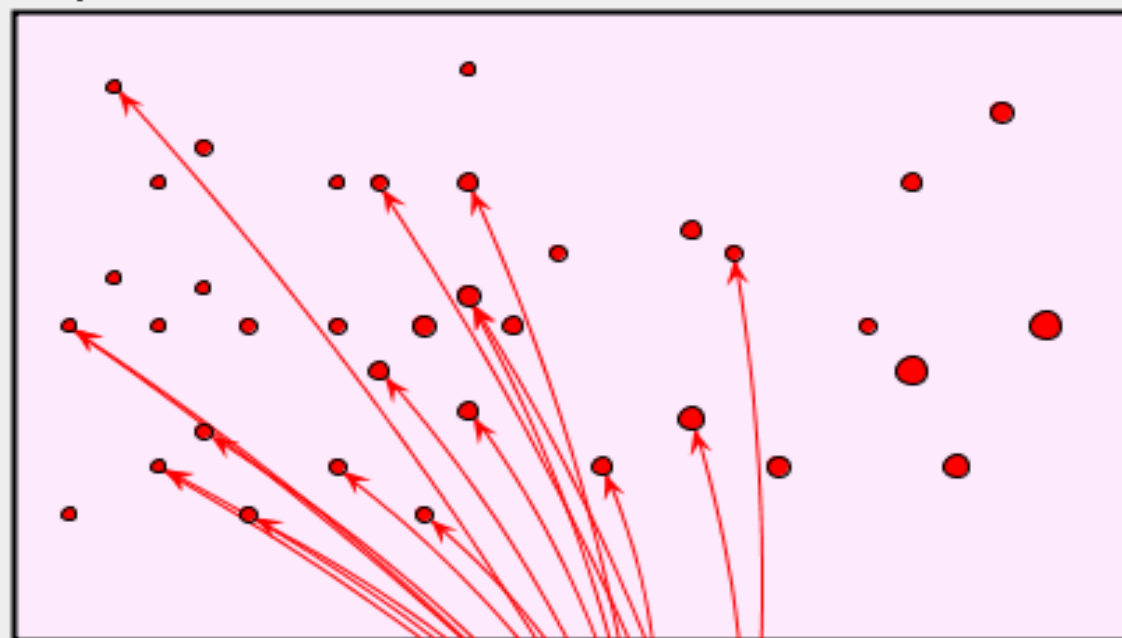
Drawing all edges is not particularly useful here...



Node layout determined by geographic location.  
Adjacent edges shown on node selection.



Supreme 1982 1987 1992 1998



Circuit 1982 1987 1992 1998

REGIONS

- 36 ■ Supreme
- 13 ■ Circuit

CITES

- 0 ■ Supreme to Supreme
- 0 ■ Supreme to Circuit
- 18 ■  Circuit to Supreme
- 2 ■  Circuit to Circuit

RANGES

Supreme

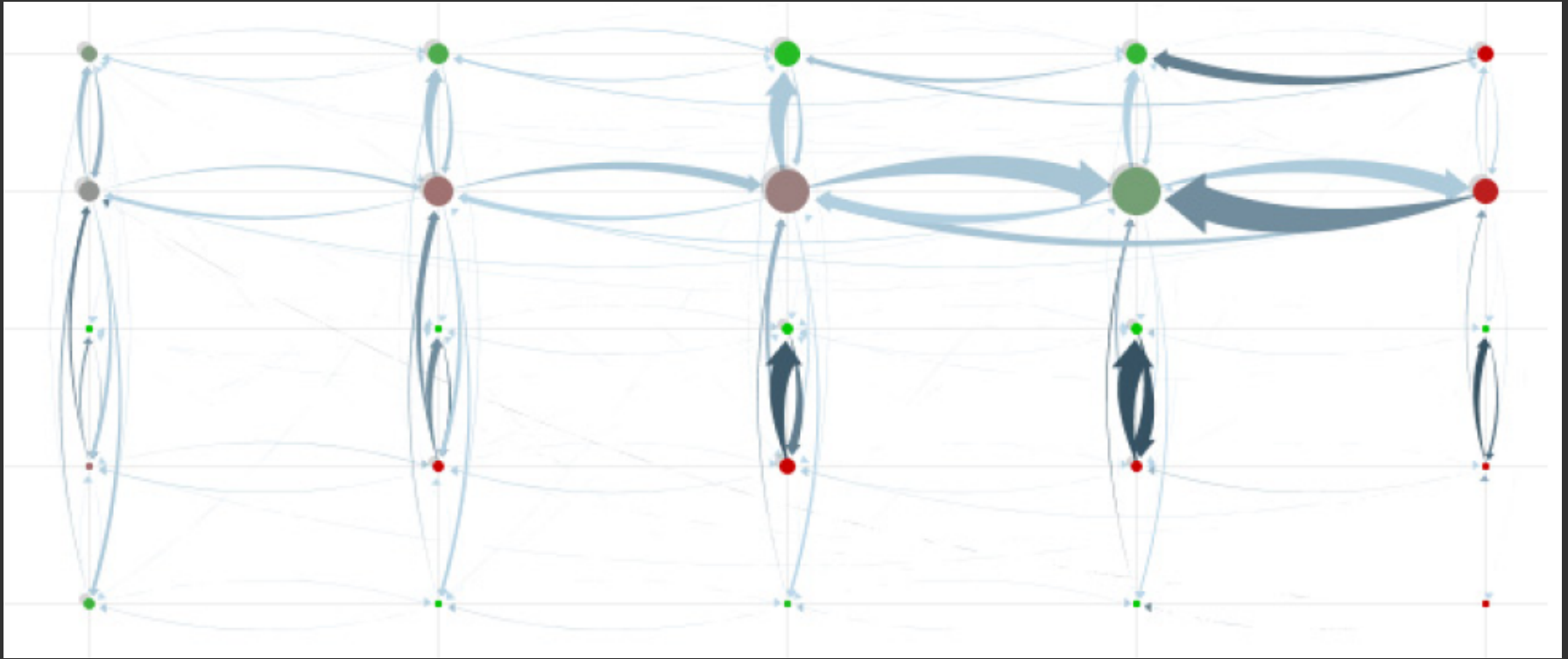
1978 -- 2002

Circuit

1991 -- 1993

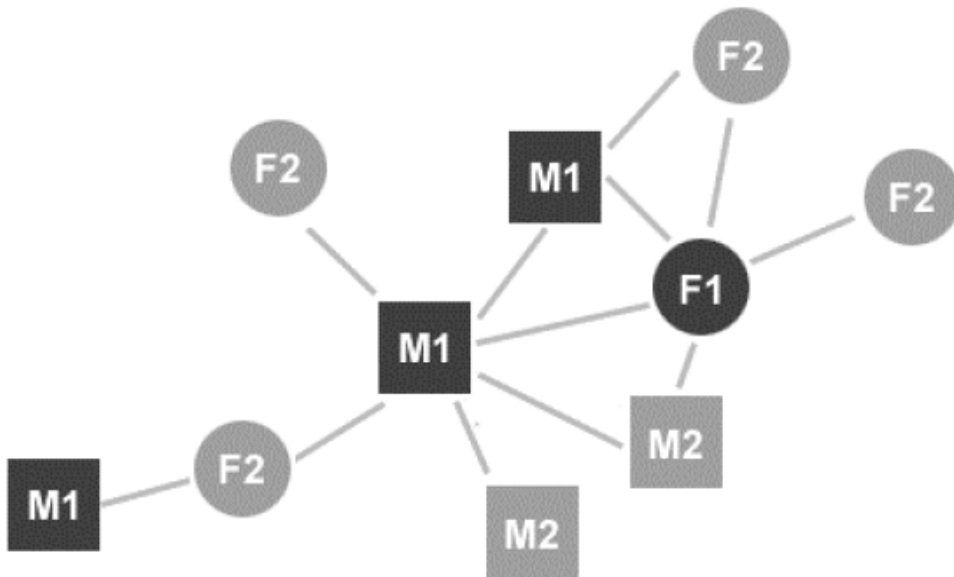


# PivotGraph [Wattenberg '06]

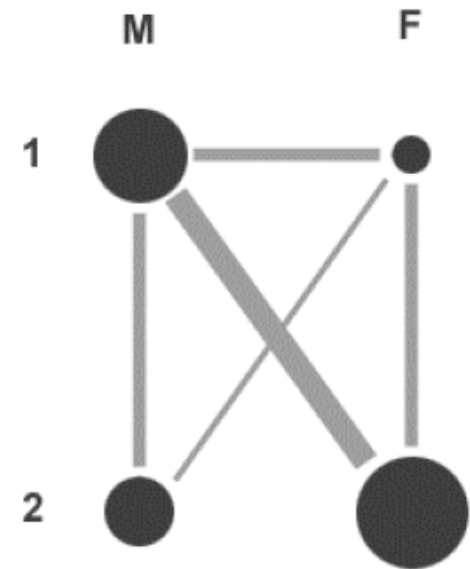


Layout aggregate graphs using node attributes.  
Analogous to pivot tables and trellis display.

# PivotGraph



Node and Link Diagram



PivotGraph Roll-up

X-Axis:

Y-Axis:

**People**

● 25	● 10.0
● 13	● 0.0
● 5	● -10.0
● 3	

**Relationships**

➔ 50	➔ 10.000
➔ 25	➔ 5.000
➔ 10	➔ 2.000
➔ 5	➔ 1.000

**Select:**

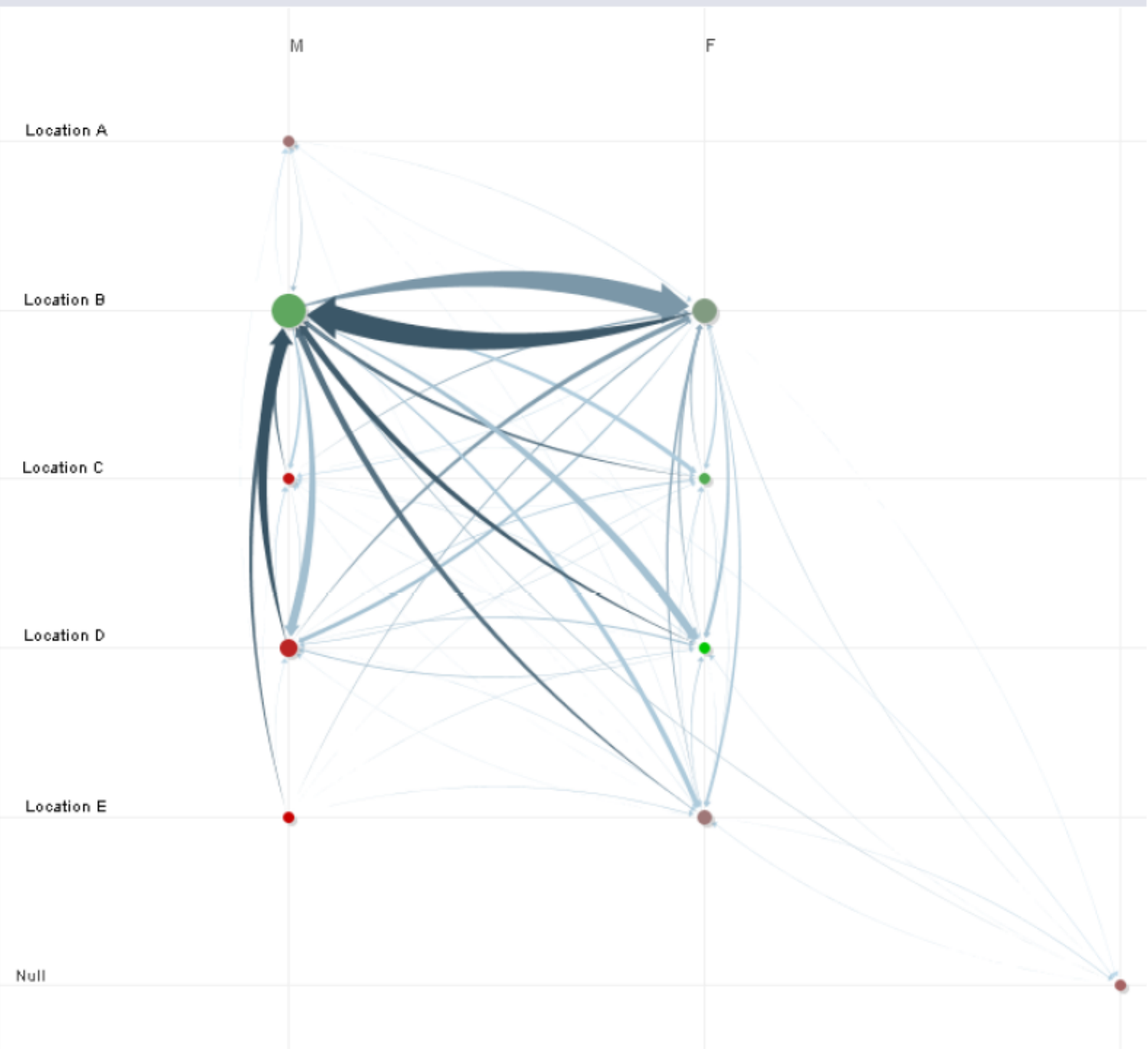
Gender:

Legacy:

Department:

Level:

Location:



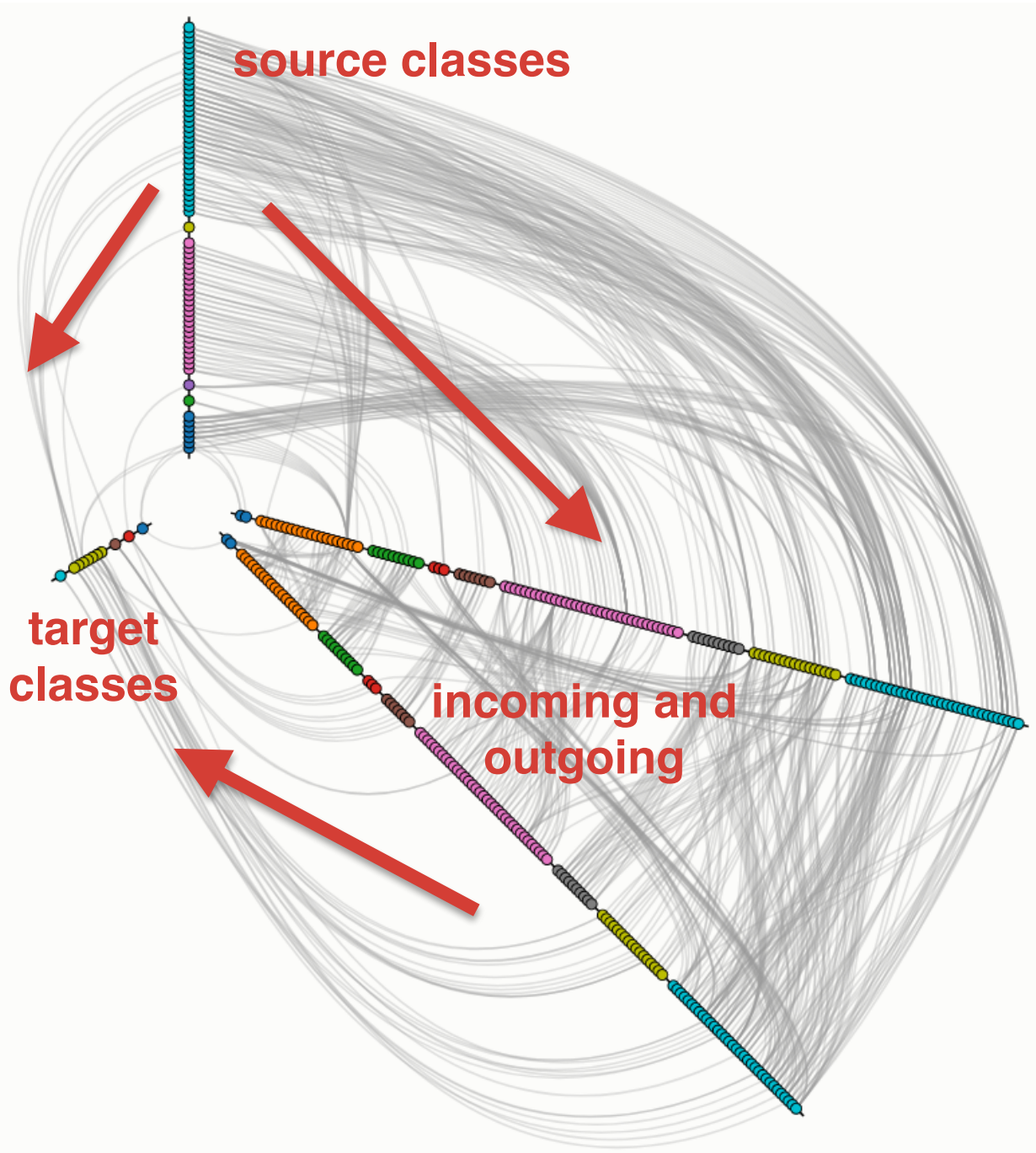


# Limitations of PivotGraph

Only 2 variables (no nesting as in Tableau)

Doesn't support continuous variables

Multivariate edges?



## HivePlots

[Krzywinski '11]

Nodes (dots) may be replicated.

Nodes sorted on radial axes by network statistics (e.g., by degree).

Different axes may contain different subsets of nodes.

[egweb.bcgsc.ca](http://egweb.bcgsc.ca)

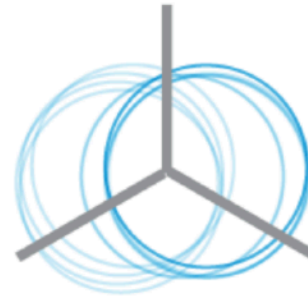
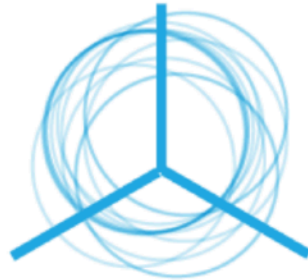
# ORDER NODES BY

LAYER 1

LAYER 2

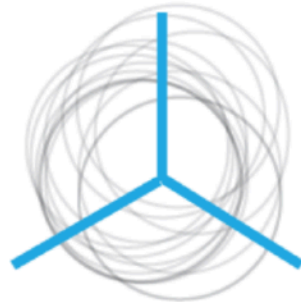
LAYER 3

LAYER 1



DRAW  
EDGES

LAYER 2



LAYER 3





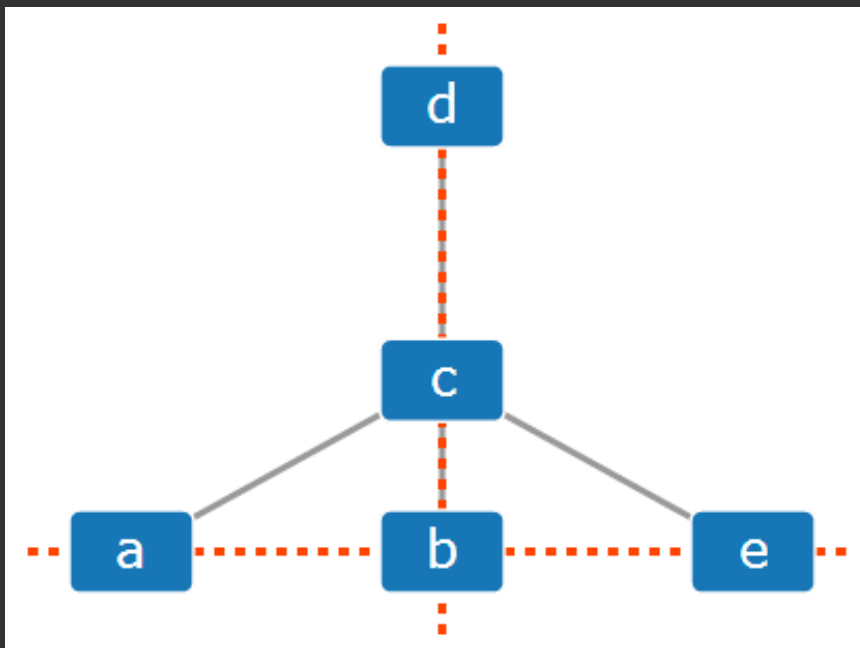
# Constraint-Based Layout

# Constraint-Based Layout

**Treat layout as an *optimization problem***

Define layout using an *energy model* along with *constraints*: equations the layout should obey.

Use optimization algorithms to solve



**Position Constraints:**

*a* must be to the **left** of *b*

*d*, *c*, and *b* must have the same **x position**

*a*, *b*, and *e* must have the same **y position**

# Optimizing Aesthetic Constraints

Minimize edge crossings

Minimize area

Minimize line bends

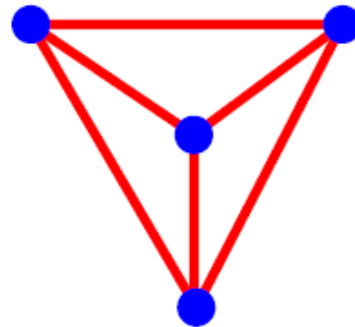
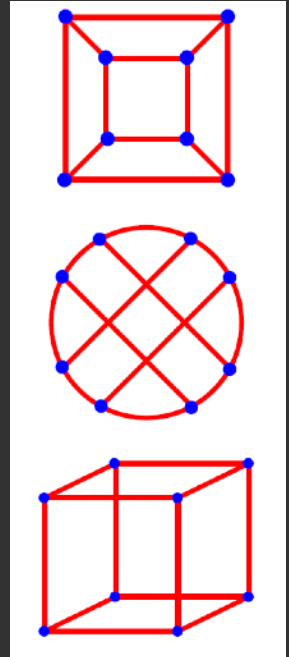
Minimize line slopes

Maximize smallest angle between edges

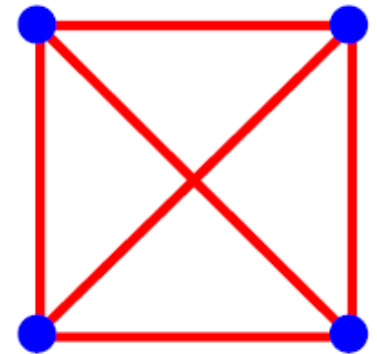
Maximize symmetry

**but, can't do it all.**

Optimizing these criteria is often NP-Hard, requiring approximations.



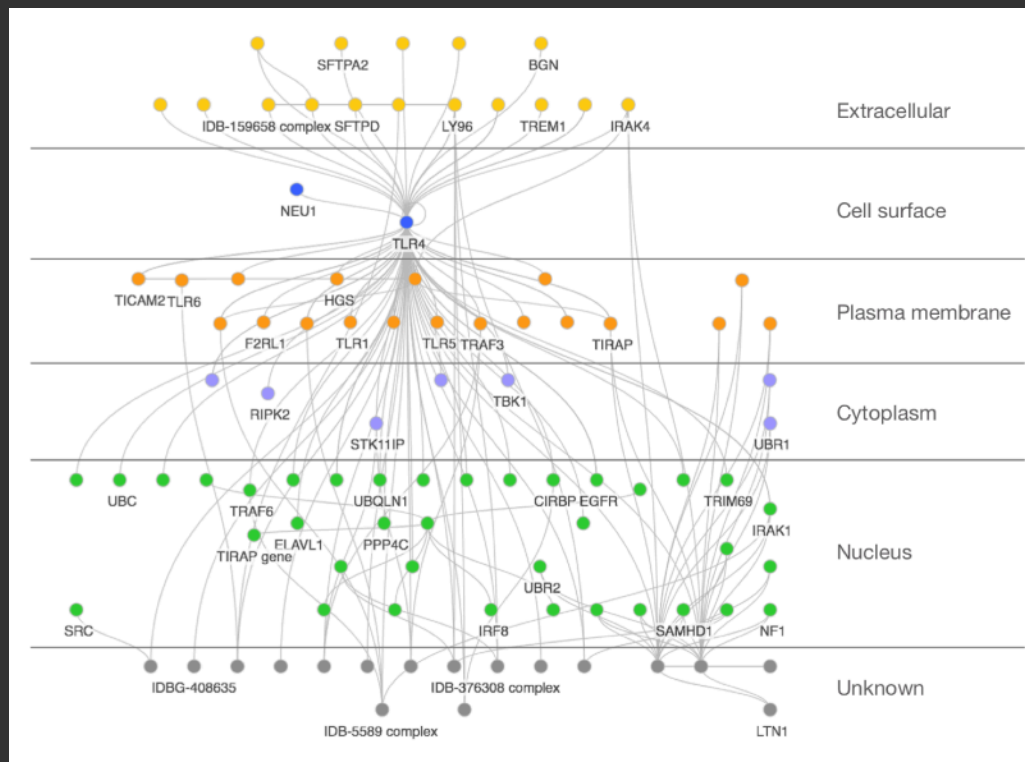
min # crossings



max symmetries

# SetCoLa: High-Level Layout

- (1) Define **sets** of nodes based on attributes.
- (2) Apply **constraints** to set elements.

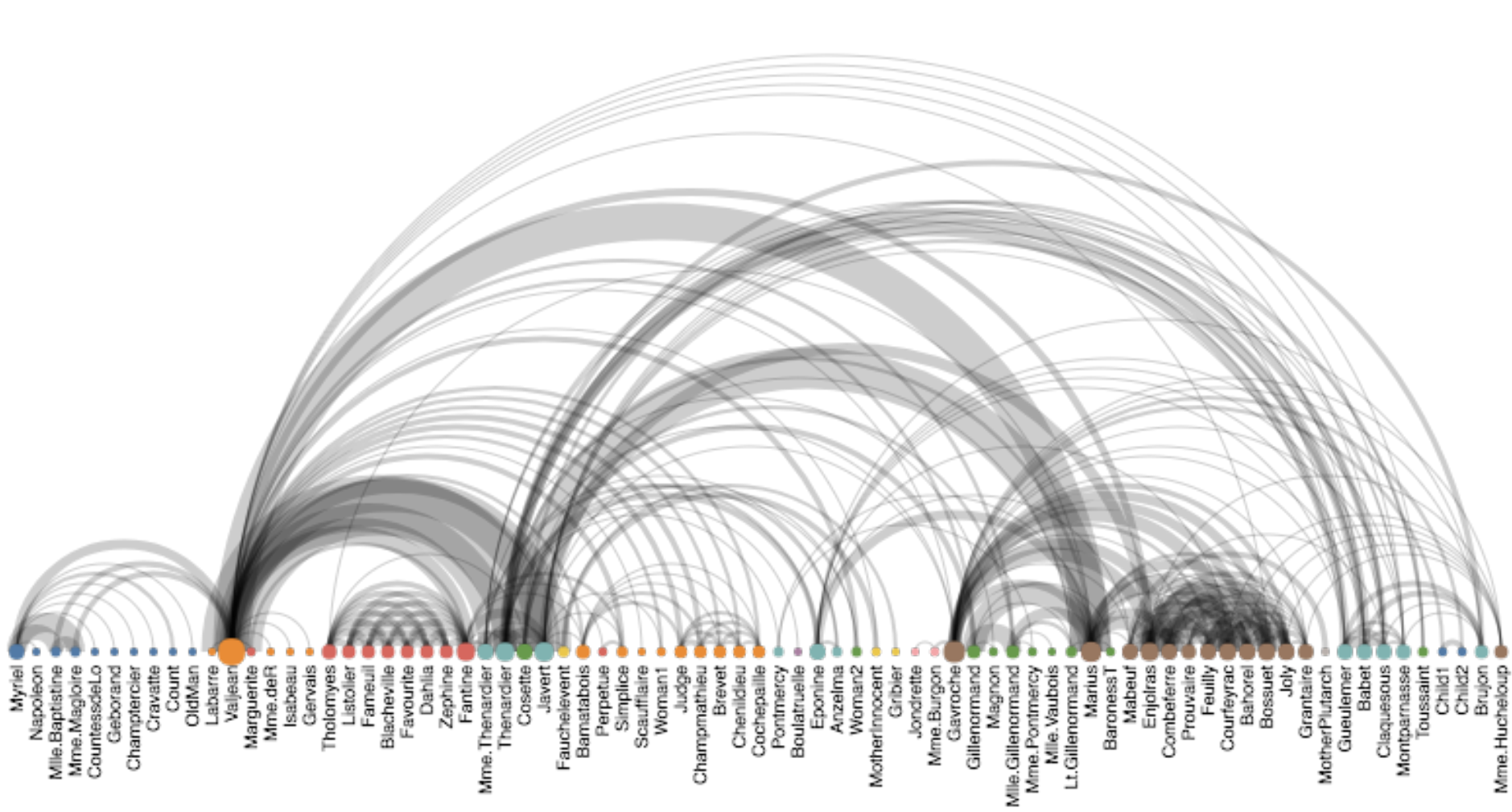


## Layout using SetCoLa:

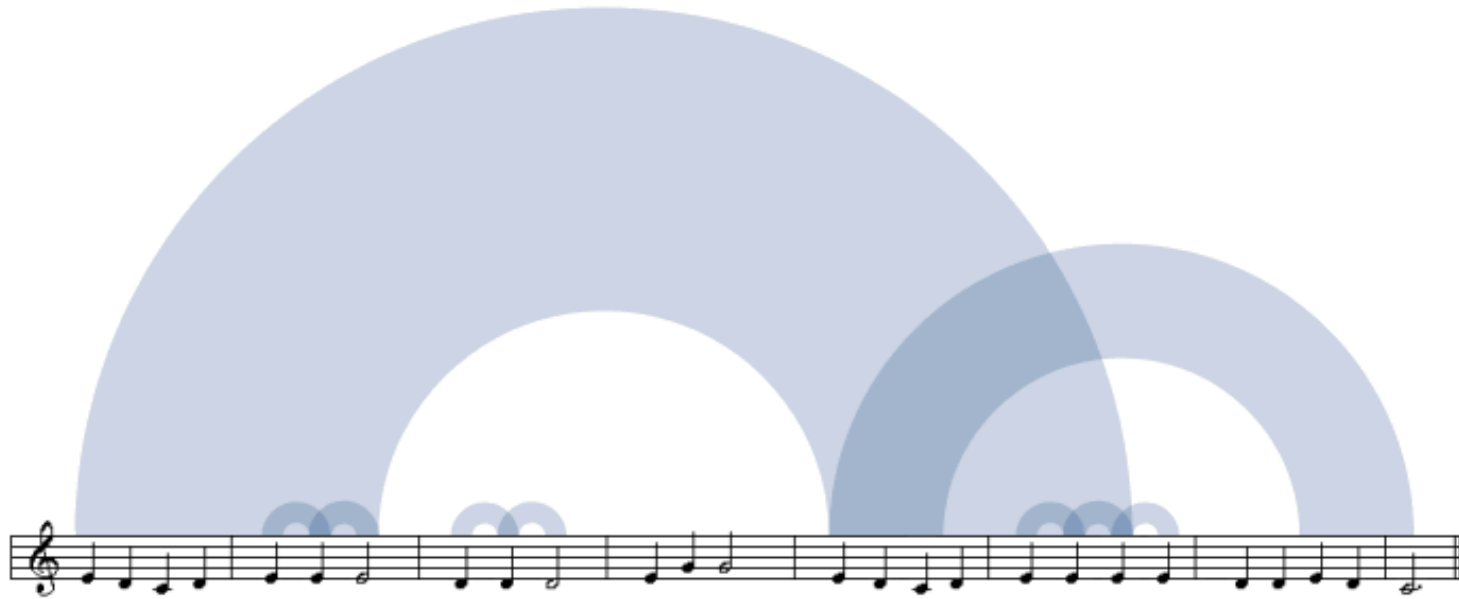
- (1) on all nodes
  - (i) **position** left of "rbound"
  - (ii) **position** right of "lbound"
- (2) partition type
  - (iii) **padding** 18
- (3) compose set from types
  - (iv) **order** by type

[Hoffswell '18]

# Arc Diagrams



Linear node layout, circular arcs show connections.  
 Layout quality sensitive to node ordering!



For example, the picture above was built from the first line of a very simple piece: *Mary Had a Little Lamb*. Each arch connects two identical passages. To clarify the connection between the visualization and the song, in this diagram the score is displayed beneath the arches.

## The Shape of Song

[Wattenberg '01]



This diagram visualizes the refrain from the folk song *Clementine*. As you would expect, the refrain consists of multiple repetitions of the same passage--and that is exactly what the diagram shows. The score isn't shown in this diagram since the notes would be too small to read.

# Task Analysis



# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout** - arranged by depth

**Force-Directed Layout** - physical simulation

**Attribute-Driven Layout** - arranged by value

**Constraint-Based Layout** - optimization

**Arc Diagrams** - aligned layout

# Node-Link Graph Visualization

Nodes connected by lines/curves

## Sugiyama-Style Layout

**The Good:** *Structured-based analysis of hierarchical relationships*

**The Bad:** *Browsing and path following due to long edges*

## Force-Directed Layout

## Attribute-Driven Layout

## Constraint-Based Layout

## Arc Diagrams

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**Constraint-Based Layout**

**Arc Diagrams**

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

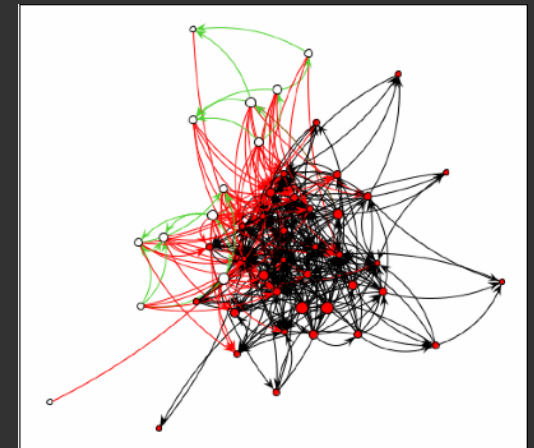
**The Good:** *Structured-based analysis of closely related elements*

**The Bad:** *Browsing and summarization of dense networks*

**Attribute-Driven Layout**

**Constraint-Based Layout**

**Arc Diagrams**



# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**Constraint-Based Layout**

**Arc Diagrams**

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**The Good:** *Attribute-based analysis tasks*

**The Bad (Difficult):** *Designing layouts appropriately*

**Constraint-Based Layout**

**Arc Diagrams**

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**Constraint-Based Layout**

**Arc Diagrams**

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**Constraint-Based Layout**

**The Good:** *Graph layout based on structural/aesthetic properties*

**The Bad (Difficult):** *Selecting constraints appropriately*

**Arc Diagrams**



# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

**Constraint-Based Layout**

**Arc Diagrams**

# Node-Link Graph Visualization

Nodes connected by lines/curves

**Sugiyama-Style Layout**

**Force-Directed Layout**

**Attribute-Driven Layout**

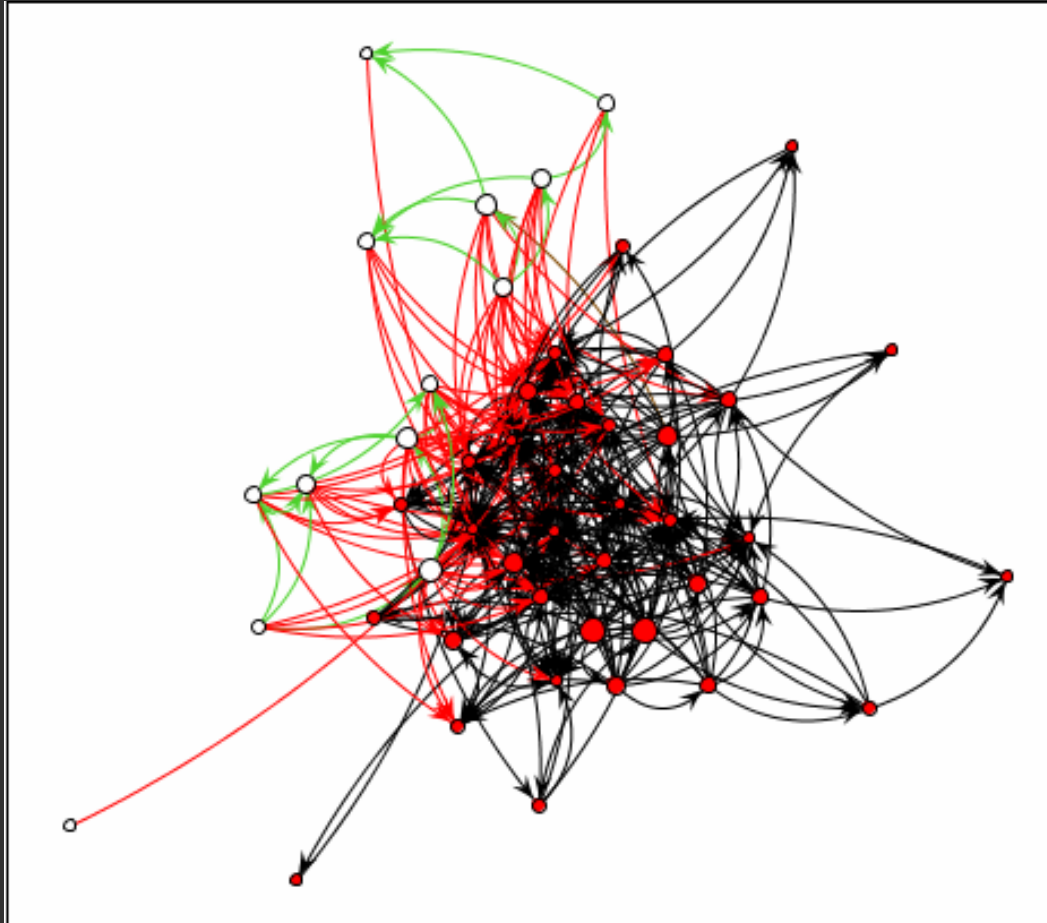
**Constraint-Based Layout**

**Arc Diagrams**

**The Good:** *Summarization and comparison of overall structure*

**The Bad:** *Order matters for node layout; Structure-based and path following*

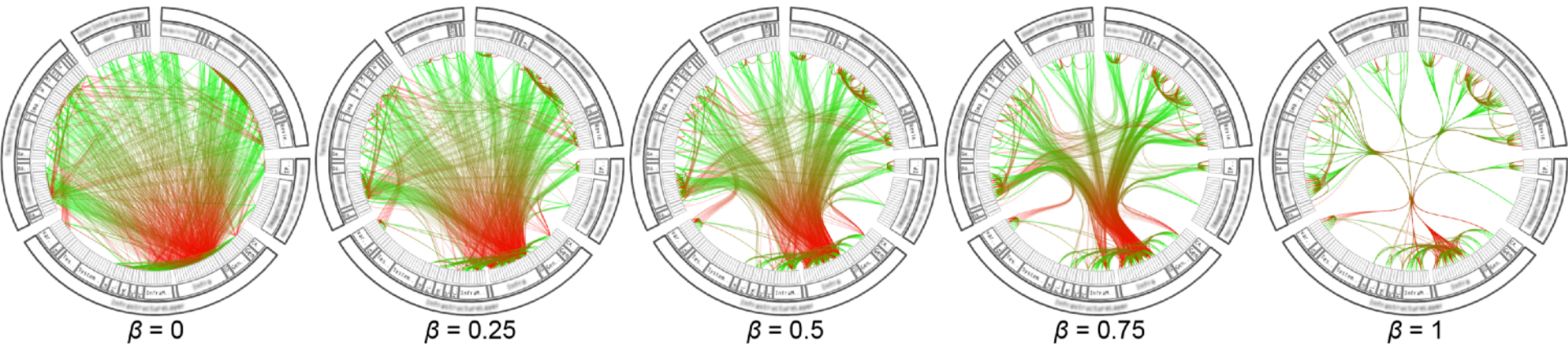
# Limitations of Node-Link Layouts



Edge-crossings and occlusion! Poor scalability....

# Hierarchical Edge Bundling

# Hierarchical Edge Bundling



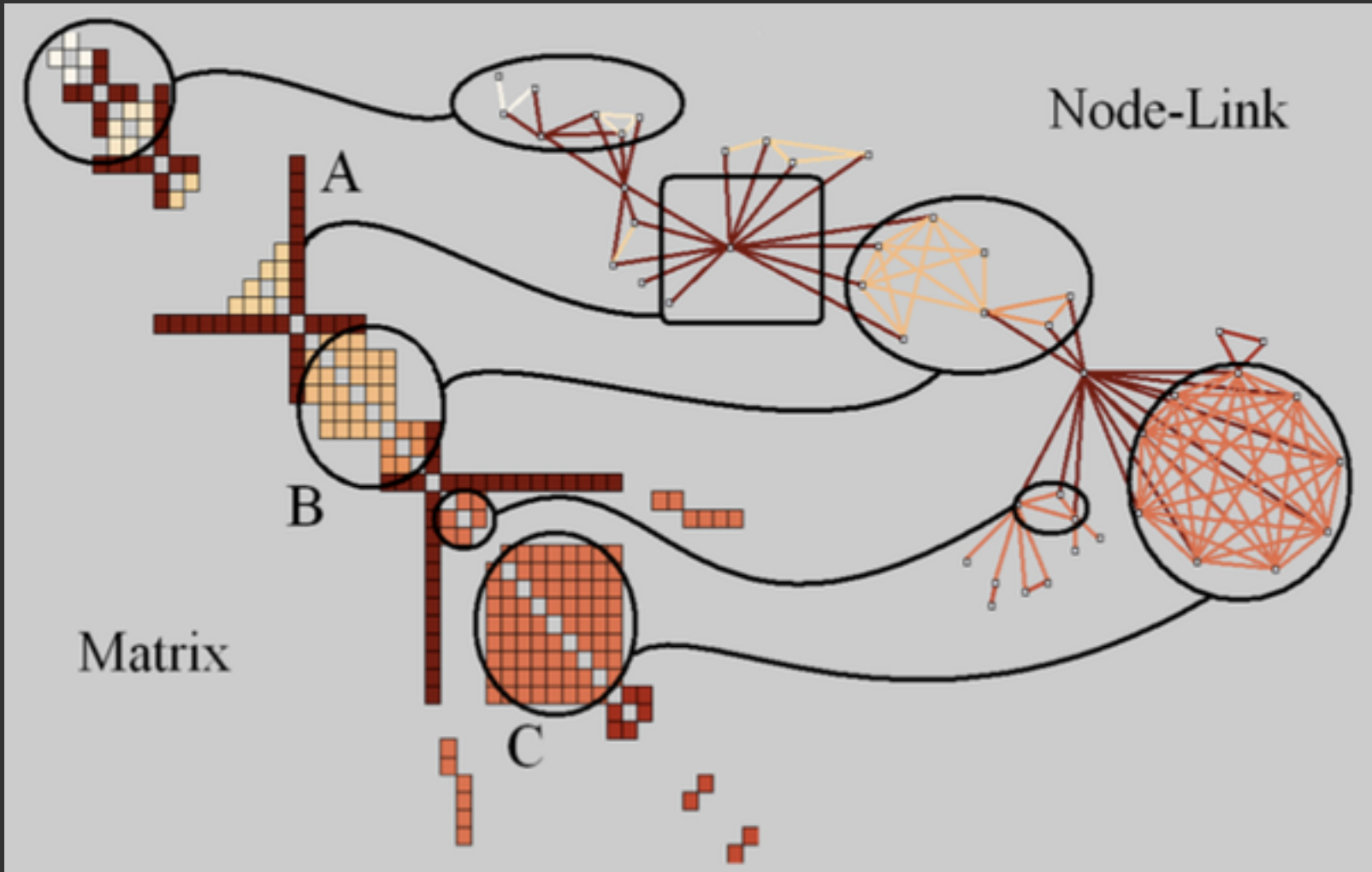
Bundle edges with varying amounts of tension  
Low-level vs. high-level information



# Matrix Diagrams







# Adjacency Matrices

### Graph Viewer

Roll-up by:

All

Visualization:

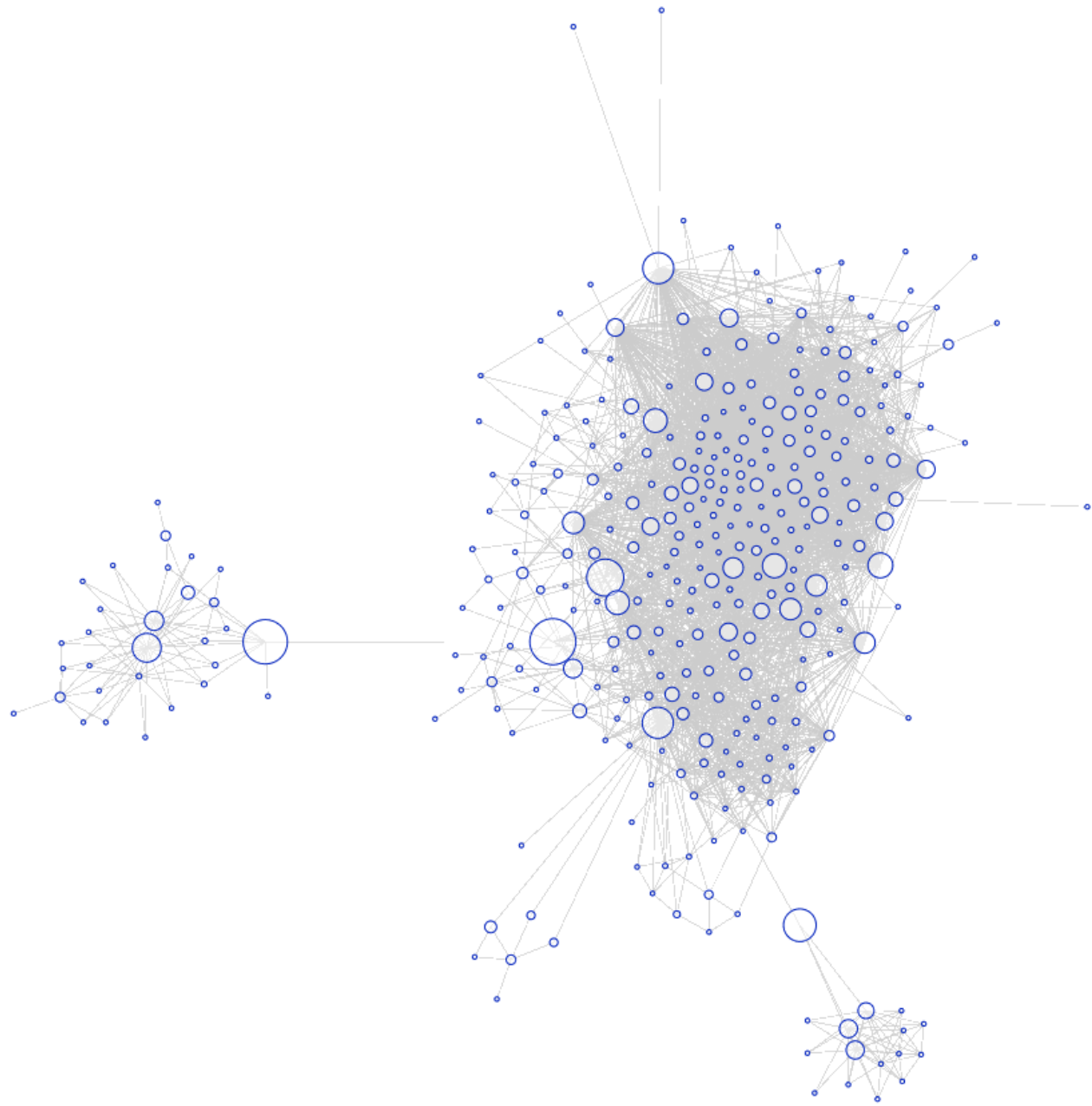
Node-Link

Sort by:

None

Edge centrality filters:

Two horizontal sliders for edge centrality filtering, both currently set to the minimum value.



- Images
- Animate



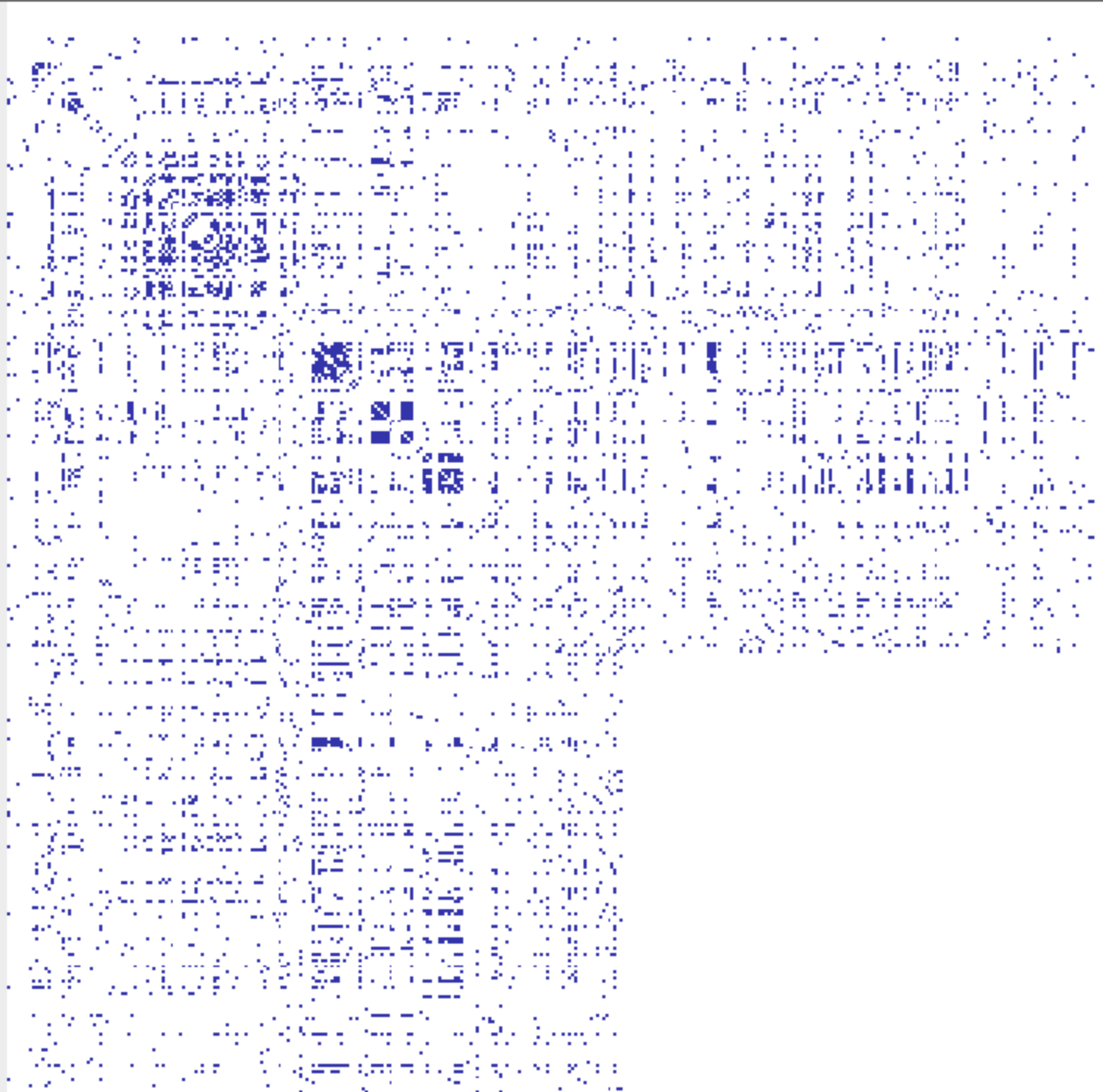
# Graph Viewer

Roll-up by:

Visualization:

Sort by:

Edge centrality filters:



# Summary: Hierarchies & Networks

## **Tree Layout**

Indented / Node-Link / Enclosure / Layers  
Focus+Context techniques for scale

## **Graph Layout**

"Sugiyama" Layout  
Force-Directed Layout  
Attribute-Driven Layout  
Constraint Layout  
Arc Diagrams  
Matrix Diagrams