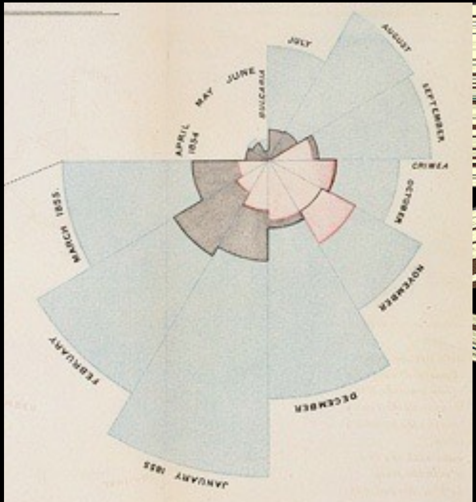
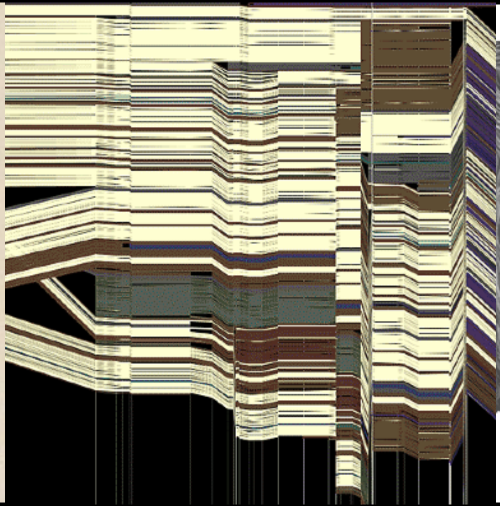
CSE 512 - Data Visualization

Visual Encoding





Jeffrey Heer University of Washington

The Big Picture

task
questions, goals
assumptions

data
physical data type
conceptual data type

domain
metadata
semantics
conventions

processing
algorithms

mapping
visual encoding

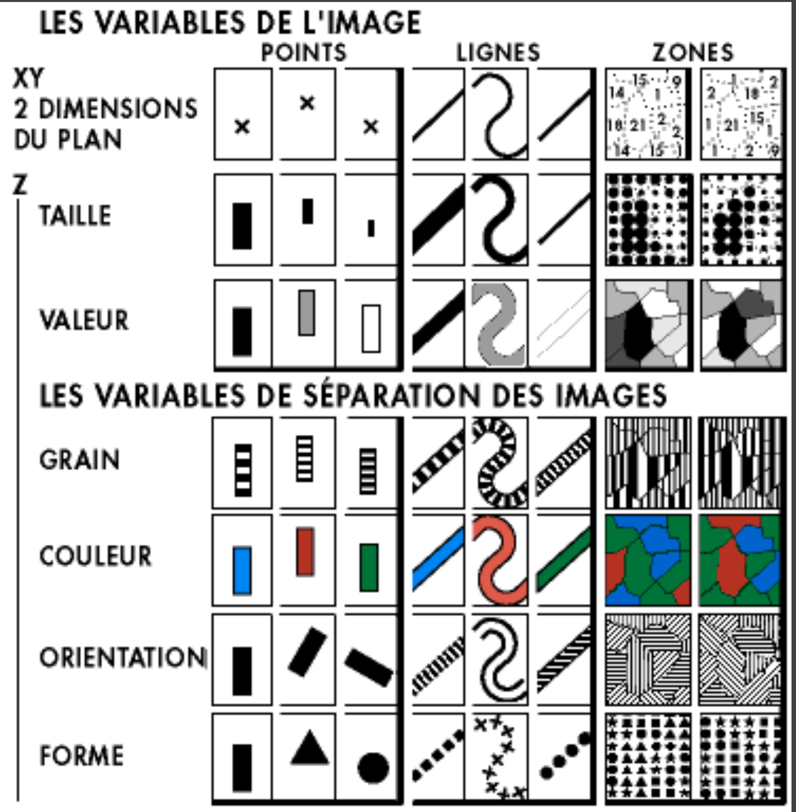
→

image
visual channel
graphical marks

Formalizing Design

Which Channel to Use?

Position (x 2)
Size
Value
Texture
Color
Orientation
Shape



Choosing Visual Encodings

Assume *k* visual encodings and *n* data attributes.
We would like to pick the “best” encoding among a combinatorial set of possibilities of size $(n+1)^k$

Principle of Consistency
The properties of the image (visual variables) should match the properties of the data.

Principle of Importance Ordering
Encode the most important information in the most effective way.

Bertin's Levels of Organization

Position	N	O	Q
Size	N	O	Q
Value	N	O	Q
Texture	N	O	
Color	N		
Orientation	N		
Shape	N		

Nominal

Ordinal

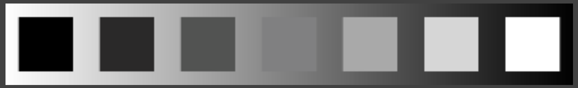
Quantitative

Note: **Q** ⊂ **O** ⊂ **N**

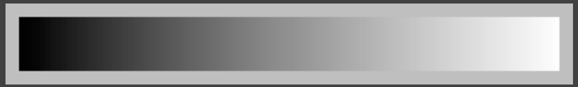
Information in Hue and Lightness

Lightness (“value”) is perceived as ordered

∴ Encode ordinal variables (O)



∴ Encode continuous variables (Q) [not as well]



Hue is normally perceived as unordered

∴ Encode nominal variables (N) using color

Design Criteria [Mackinlay 86]

Expressiveness

A set of facts is *expressible* in a visual language if the sentences (i.e. the visualizations) in the language express all the facts in the set of data, and only the facts in the data.

Effectiveness

A visualization is more *effective* than another visualization if the information conveyed by one visualization is more readily perceived than the information in the other visualization.

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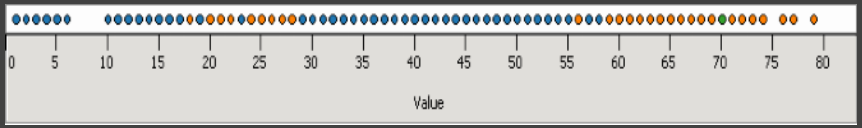
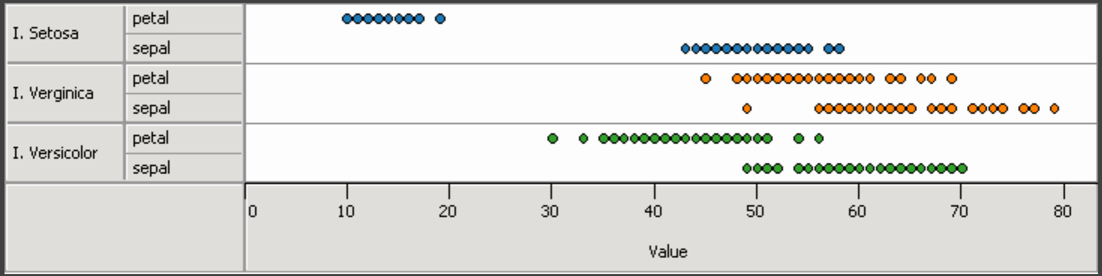
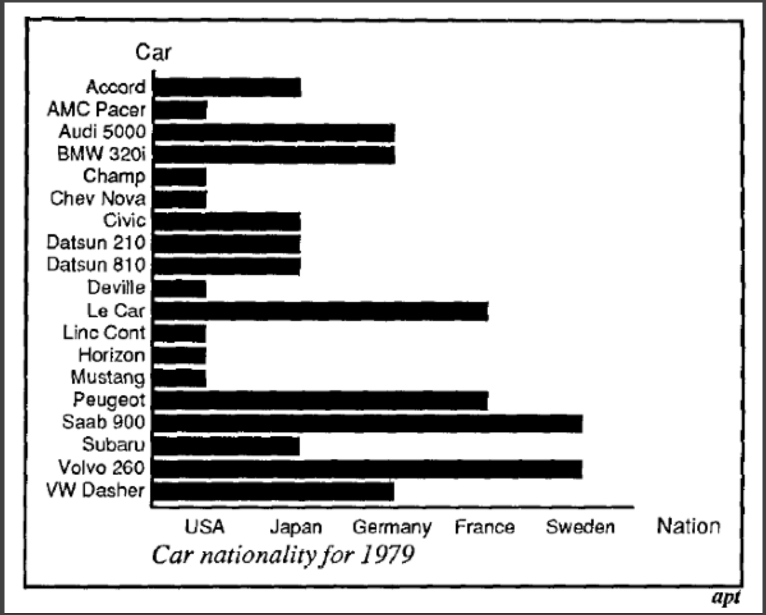
Can not express the facts

A multivariate relation may be *inexpressive* in a single horizontal dot plot because multiple records are mapped to the same position.





Expresses facts not in the data



A length is interpreted as a quantitative value.

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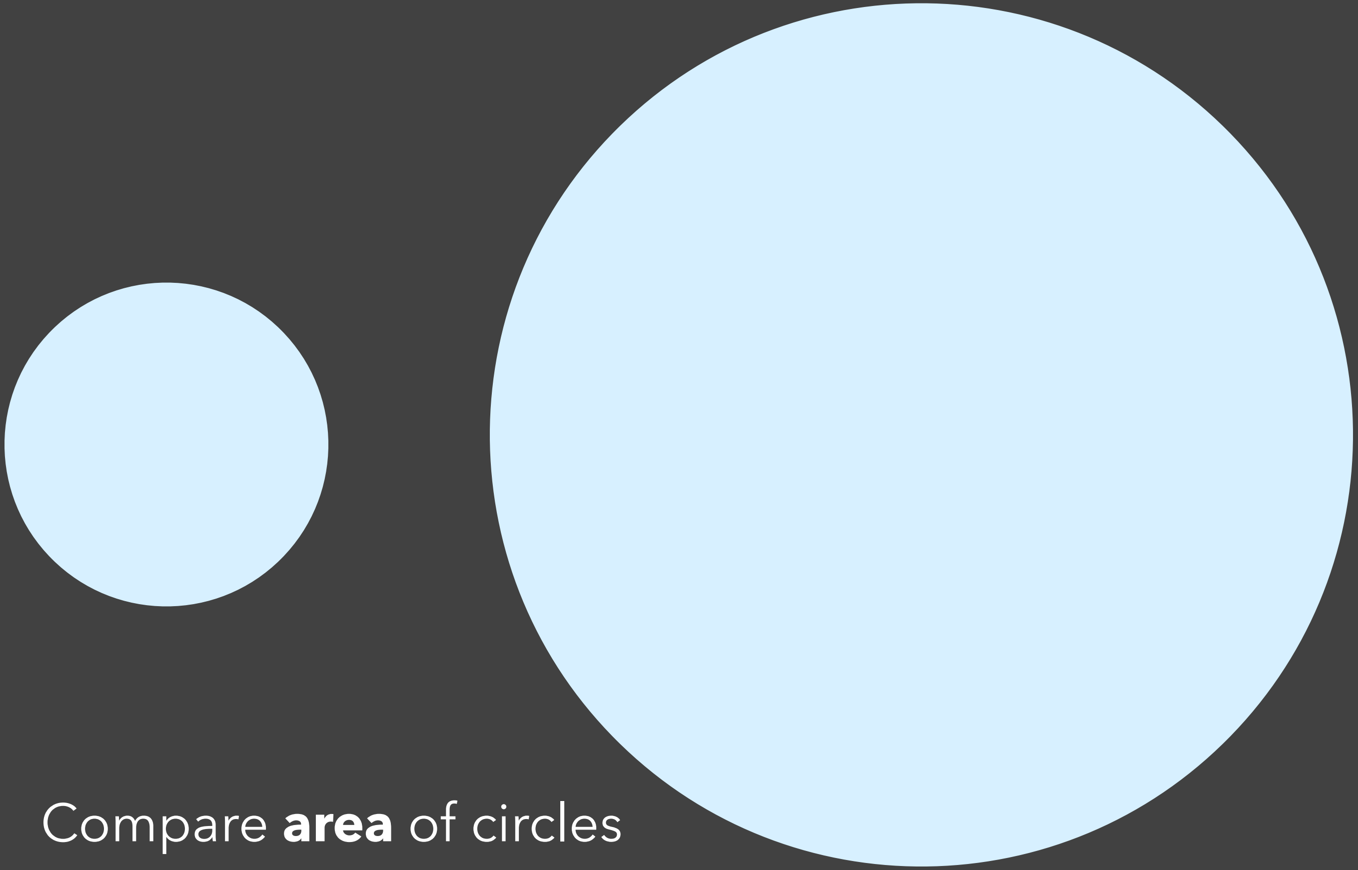
Design Criteria *Translated*

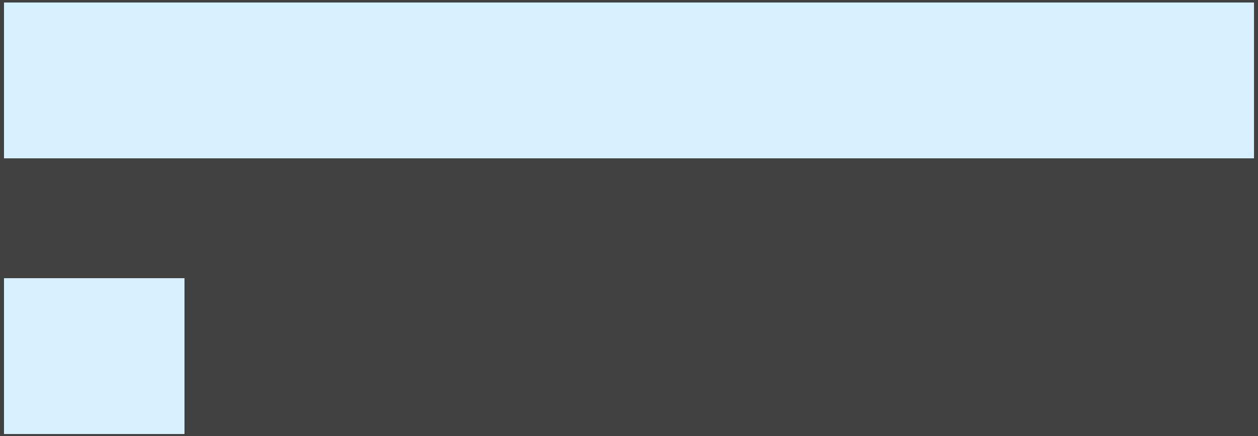
Tell the truth and nothing but the truth
(don't lie, and don't lie by omission)

Use encodings that people decode better
(where better = faster and/or more accurate)

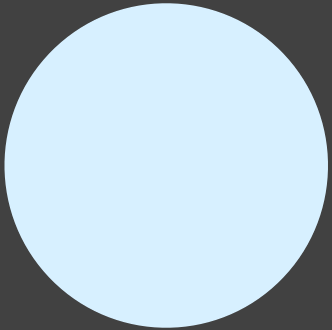
A Quick Experiment…

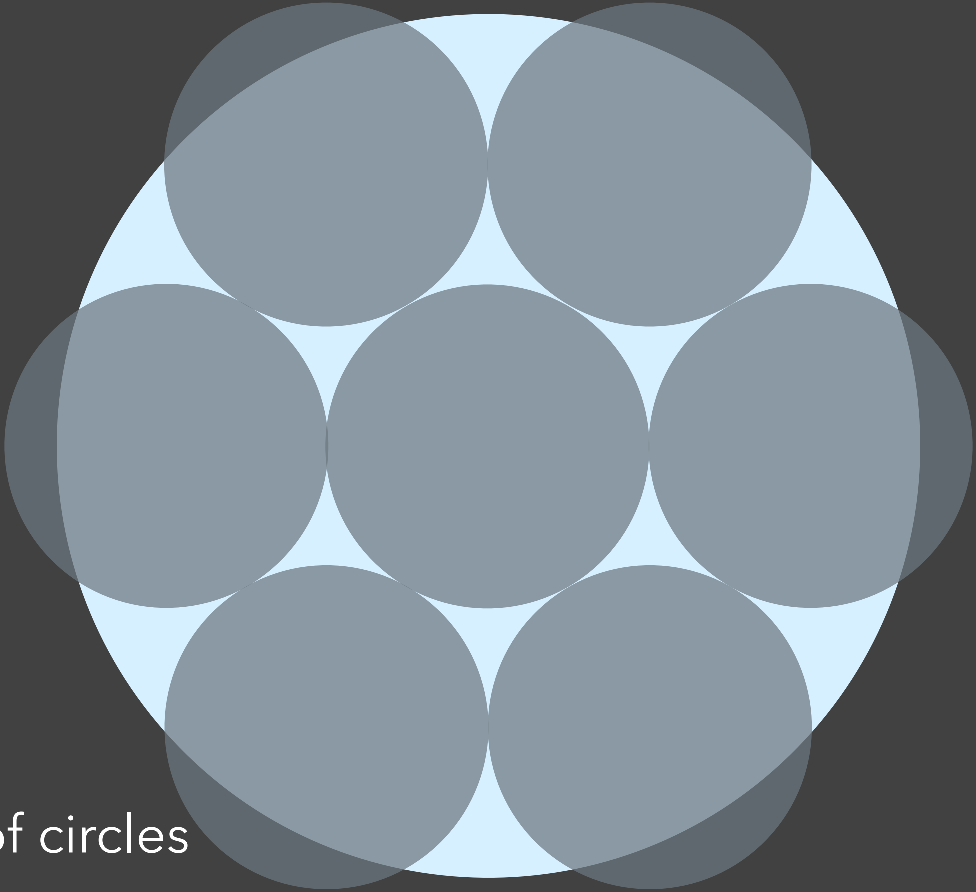


Compare **area** of circles



Compare **length** of bars





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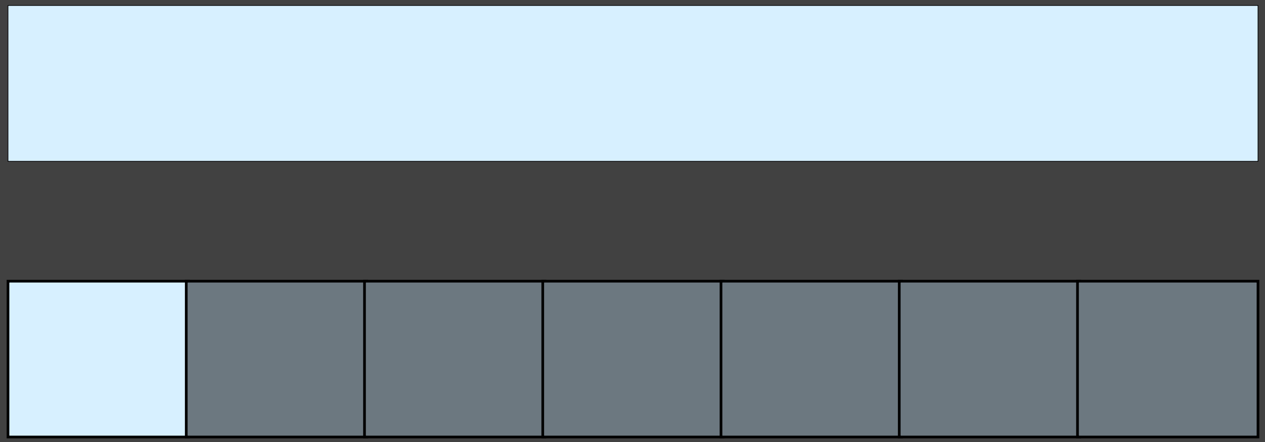
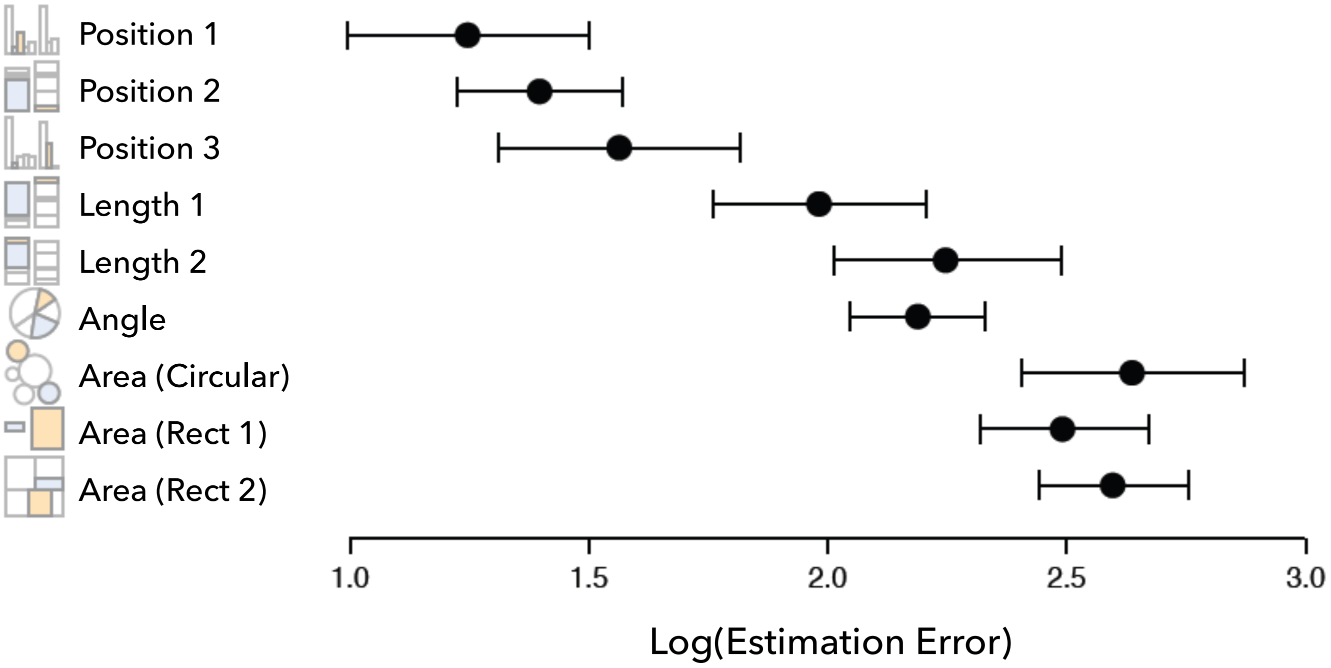


Compare **length** of bars

Accuracy of Visual Decoding



Ranking Visual Encodings

Most accurate

Comparing
Proportions

Position (common) scale
Position (non-aligned) scale
Length
Slope
Angle
Area
Volume
Color hue-saturation-density

Least accurate

Effectiveness Rankings [Mackinlay 86]

QUANTITATIVE	ORDINAL	NOMINAL
Position	Position	Position
Length	Density (Value)	Color Hue
Angle	Color Sat	Texture
Slope	Color Hue	Connection
Area (Size)	Texture	Containment
Volume	Connection	Density (Value)
Density (Value)	Containment	Color Sat
Color Sat	Length	Shape
Color Hue	Angle	Length
Texture	Slope	Angle
Connection	Area (Size)	Slope
Containment	Volume	Area
Shape	Shape	Volume

Conjectured *effectiveness* of encodings by data type

Effectiveness Rankings [Mackinlay 86]

QUANTITATIVE	ORDINAL	NOMINAL
Position ················	**Position** ················	**Position**
Length	Density (Value)	Color Hue
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Area (Size)	Texture	Containment
Volume	Connection	Density (Value)
Density (Value)	Containment	Color Sat
Color Sat	Length	Shape
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Slope	Color Hue	Connection
Area (Size)	Texture	Containment
Volume	Connection	Density (Value)
Density (Value)	Containment	**Color Sat**
Color Sat	Length	Shape
Color Hue	Angle	Length
Texture	Slope	Angle
Connection	Area (Size)	Slope
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Area (Size)	Texture	Containment
Volume	Connection	Density (Value)
Density (Value)	Containment	Color Sat
Color Sat	Length	Shape
Color Hue	Angle	Length
Texture	Slope	Angle
Connection	Area (Size)	Slope
Containment	Volume	Area
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Conjectured *effectiveness* of encodings by data type

Mackinlay's Design Algorithm

APT - "A Presentation Tool", 1986

User formally specifies data model and type
Input: ordered list of data variables to show

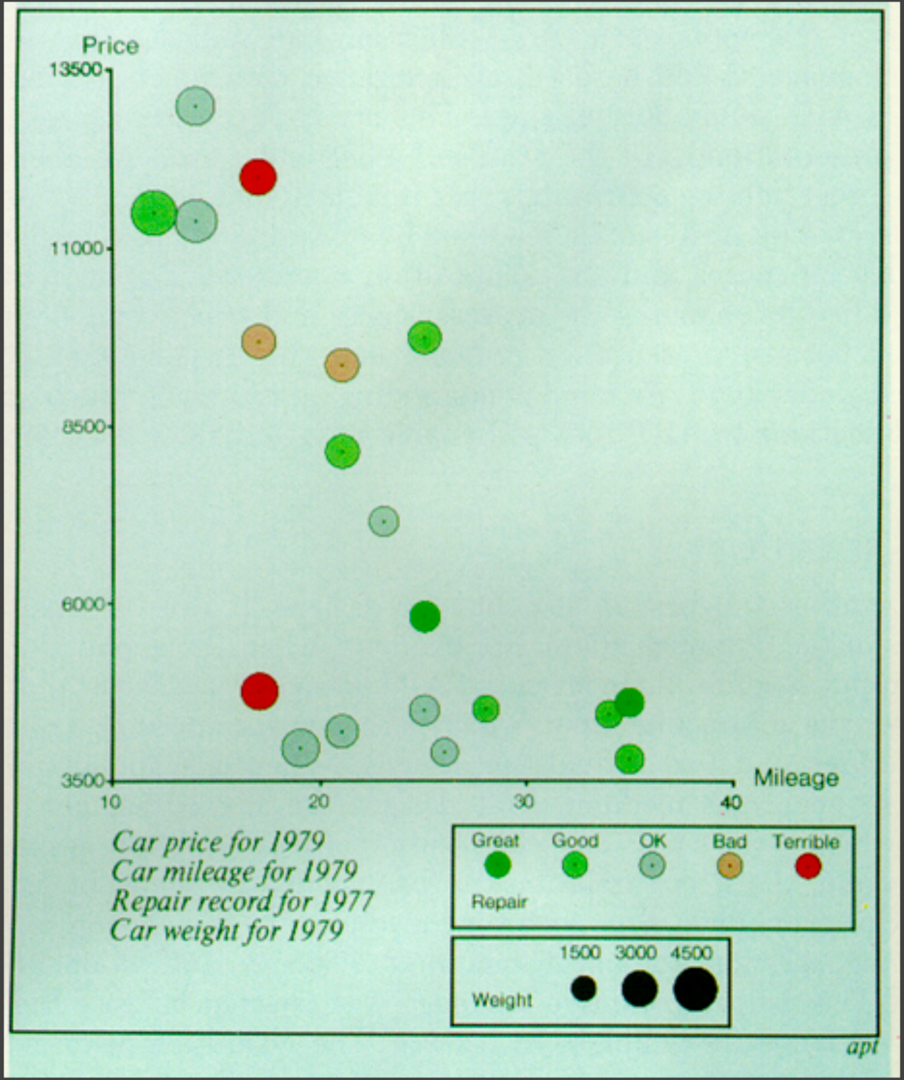
APT searches over design space
Test expressiveness of each visual encoding
Generate encodings that pass test
Rank by perceptual effectiveness criteria

Output the "most effective" visualization

APT

Automatically generate chart for car data

Input variables:
1. Price
2. Mileage
3. Repair
4. Weight



Limitations of APT

Does not cover many visualization techniques
Networks, hierarchies, maps, diagrams
Also: 3D structure, animation, illustration, …

Does not consider interaction

Does not consider semantics / conventions

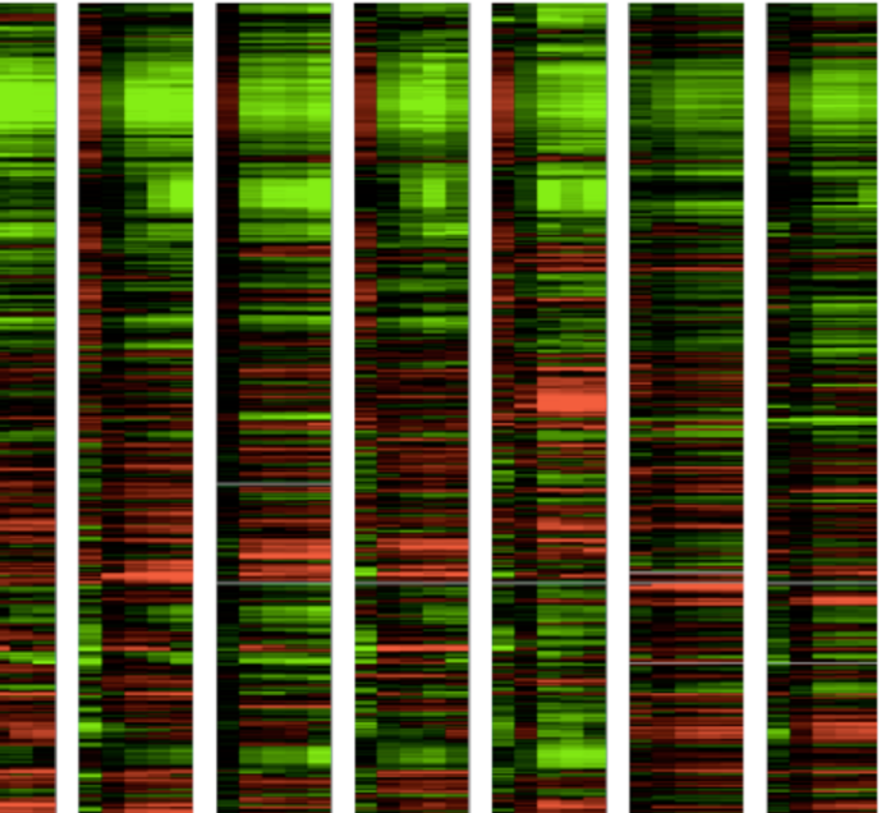
Assumes single visualization as output

Still an active area of research, e.g., the
Draco visualization design knowledge base

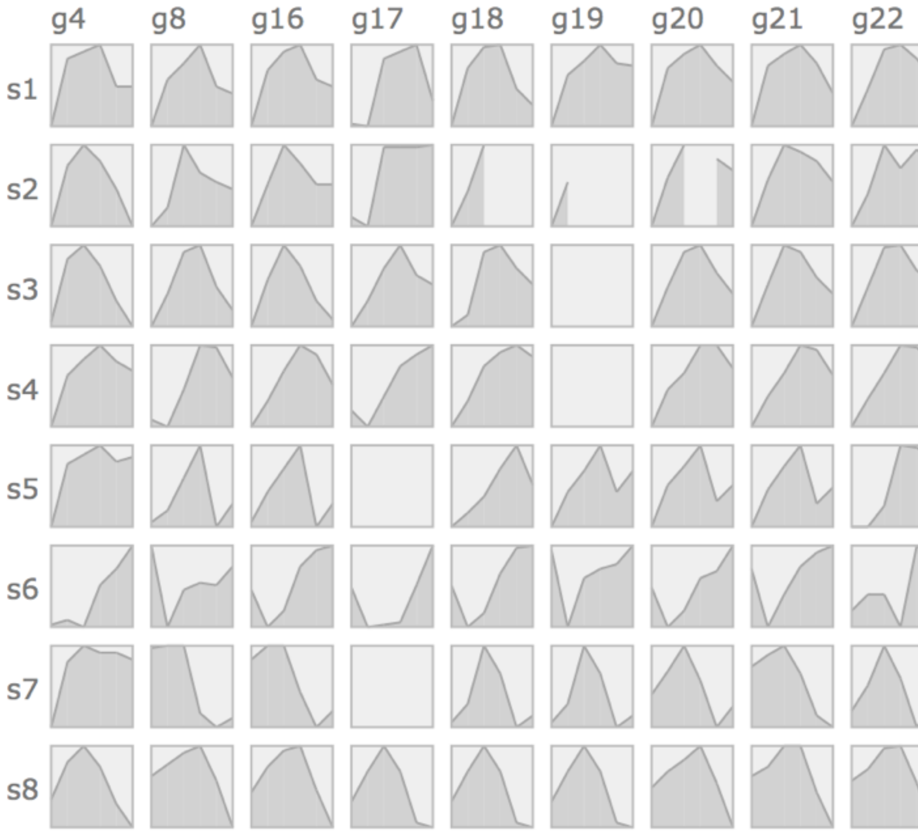
Design Examples

Gene Expression Time-Series [Meyer et al. 2011]

Color Encoding



Position Encoding

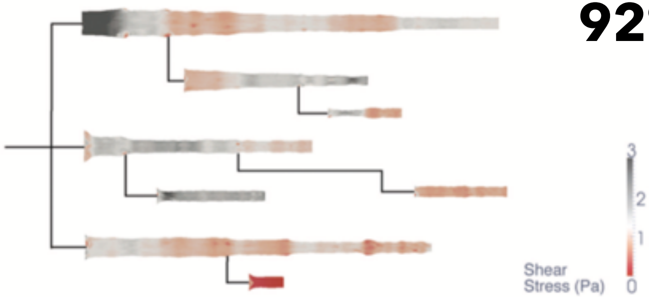


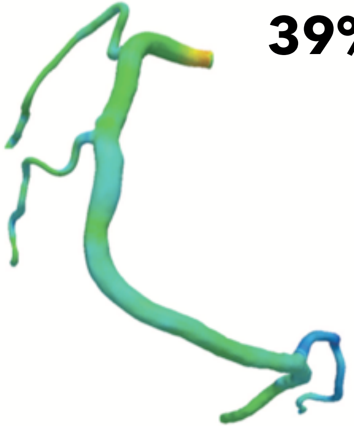
Effectiveness Rankings

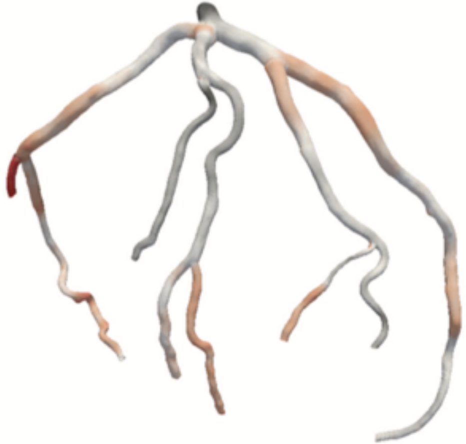
QUANTITATIVE	ORDINAL	NOMINAL
Position	Position	Position
Length	Density (Value)	Color Hue
Angle	Color Sat	Texture
Slope	Color Hue	Connection
Area (Size)	Texture	Containment
Volume	Connection	Density (Value)
~~**Density (Value)**~~	Containment	Color Sat
Color Sat	Length	Shape
~~**Color Hue**~~	Angle	Length
Texture	Slope	Angle
Connection	Area (Size)	Slope
Containment	Volume	Area
Shape	Shape	Volume

Artery Visualization [Borkin et al. 2011]

	Rainbow Palette	Diverging Palette
2D	**62%**	**92%**
3D	**39%**	**71%**







Effectiveness Rankings

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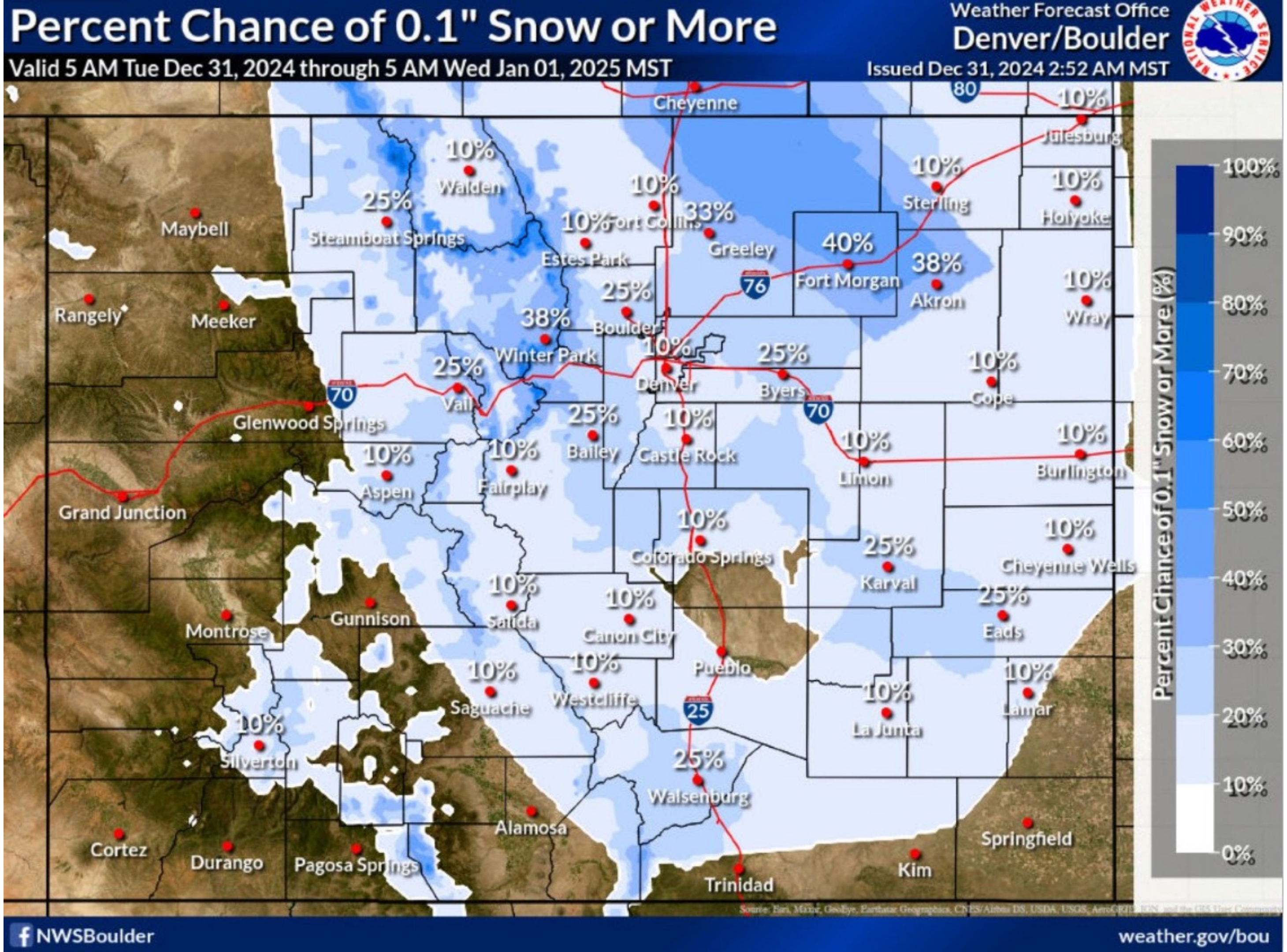
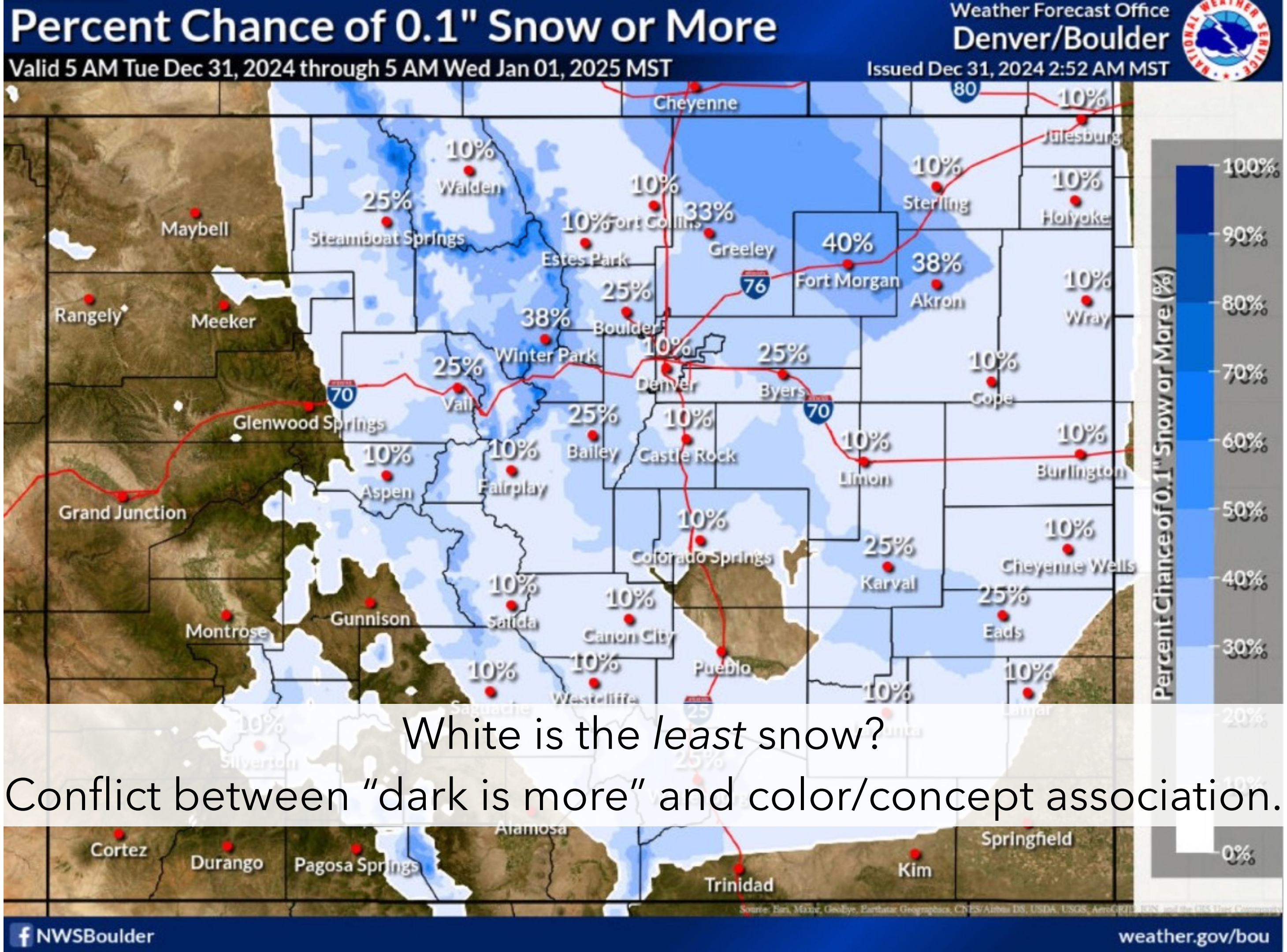
Length	Density (Value)	Color Hue
Angle	Color Sat	Texture
Slope	Color Hue	Connection
Area (Size)	Texture	Containment
Volume	**Connection**	Density (Value)
Density (Value)	Containment	Color Sat
Color Sat	Length	Shape
~~**Color Hue**~~	Angle	Length
Texture	Slope	Angle
Connection	Area (Size)	Slope
Containment	Volume	Area
Shape	Shape	Volume


Percent Chance of 0.1" Snow or More
Valid 5 AM Tue Dec 31, 2024 through 5 AM Wed Jan 01, 2025 MST
Weather Forecast Office
Denver/Boulder
Issued Dec 31, 2024 2:52 AM MST
NATIONAL WEATHER SERVICE
Cheyenne
10% Julesburg
10% Walden
25% Steamboat Springs
Maybell
10% Fort Collins
33% Greeley
10% Estes Park
10% Sterling
10% Holyoke
40% Fort Morgan
38% Akron
10% Wray
Rangely
Meeker
25% Boulder
38% Winter Park
10% Denver
25% Byers
10% Cope
25% Vail
Glenwood Springs
25% Bailey
10% Castle Rock
10% Limon
10% Burlington
10% Aspen
10% Fairplay
Grand Junction
10% Colorado Springs
25% Karval
10% Cheyenne Wells
25% Eads
10% Salida
10% Canon City
Gunnison
Montrose
Pueblo
10% Saguache
10% Westcliffe
10% La Junta
10% Lamar
10% Silverton
25% Walsenburg
Alamosa
Cortez
Durango
Pagosa Springs
Trinidad
Kim
Springfield
80
76
70
25
Percent Chance of 0.1" Snow or More (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
NWSBoulder
weather.gov/bou

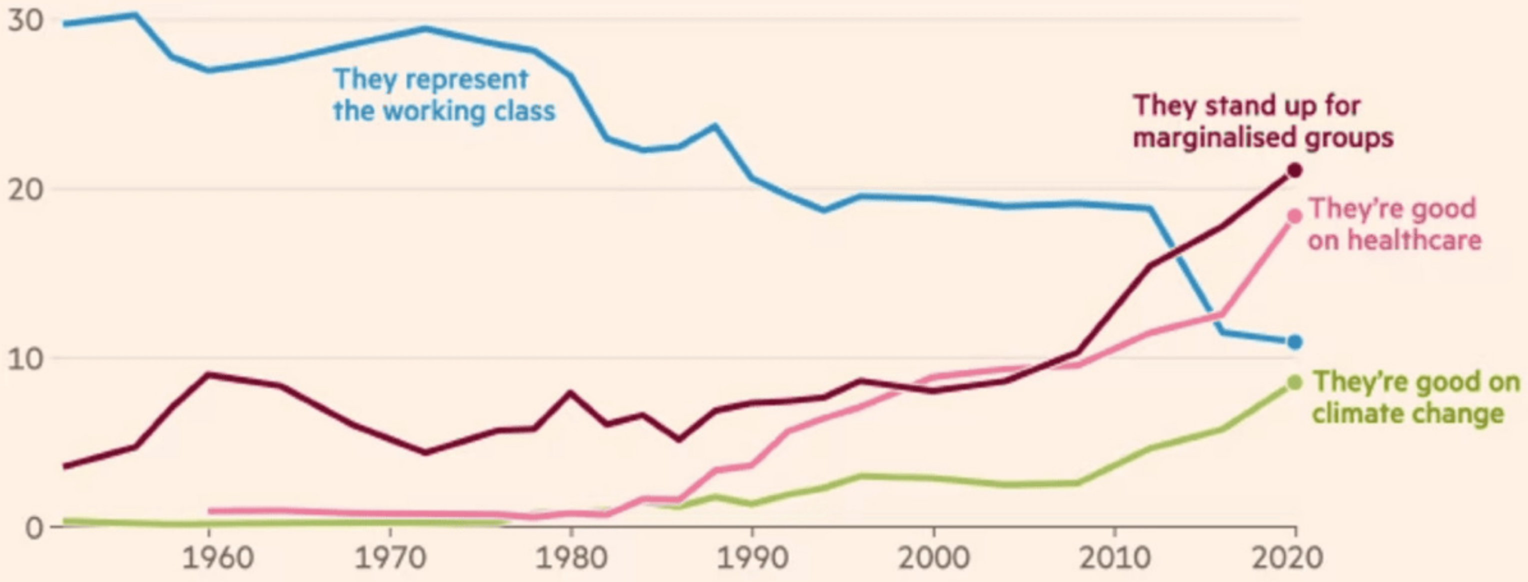


White is the *least* snow?

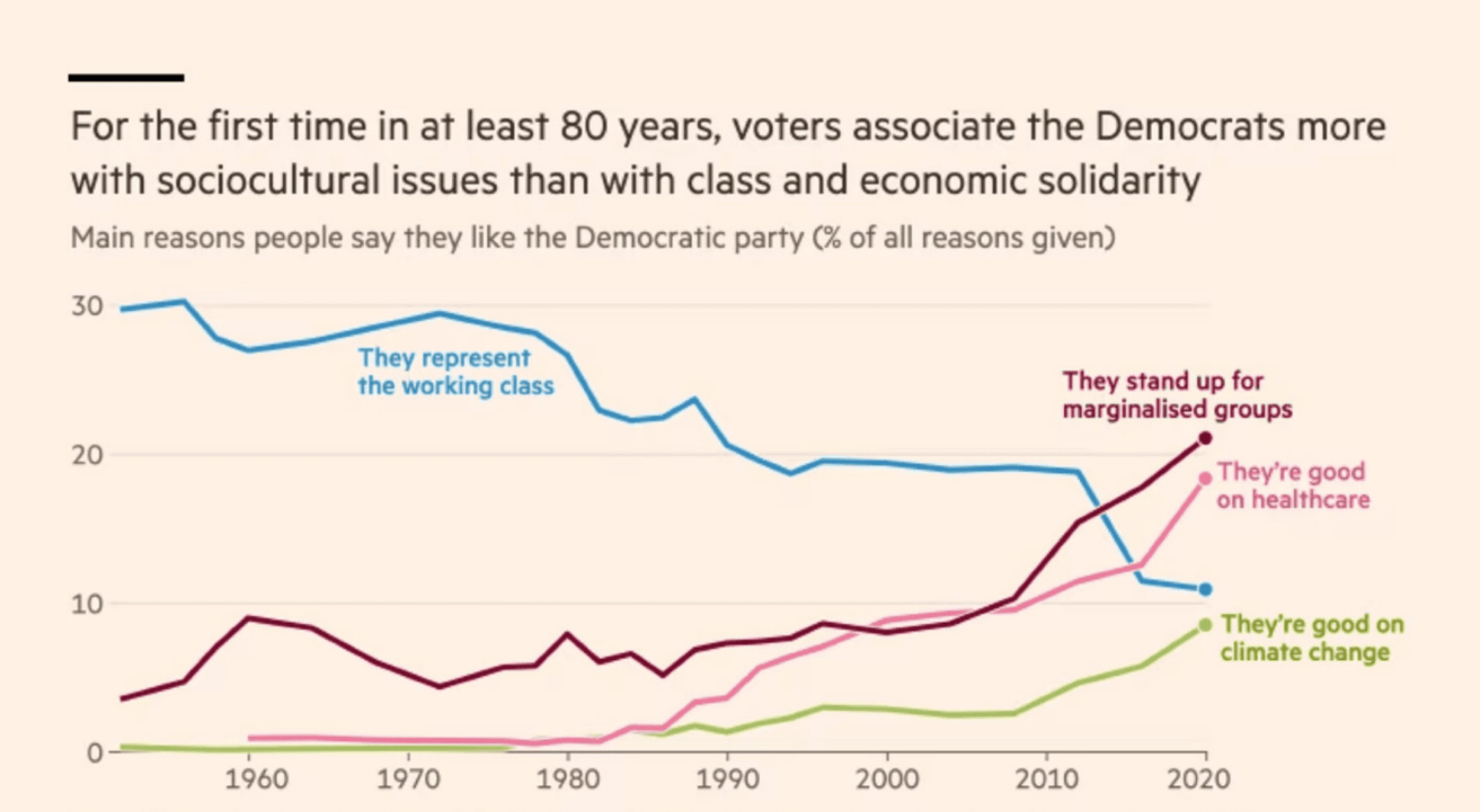
Conflict between “dark is more” and color/concept association.

For the first time in at least 80 years, voters associate the Democrats more with sociocultural issues than with class and economic solidarity

Main reasons people say they like the Democratic party (% of all reasons given)

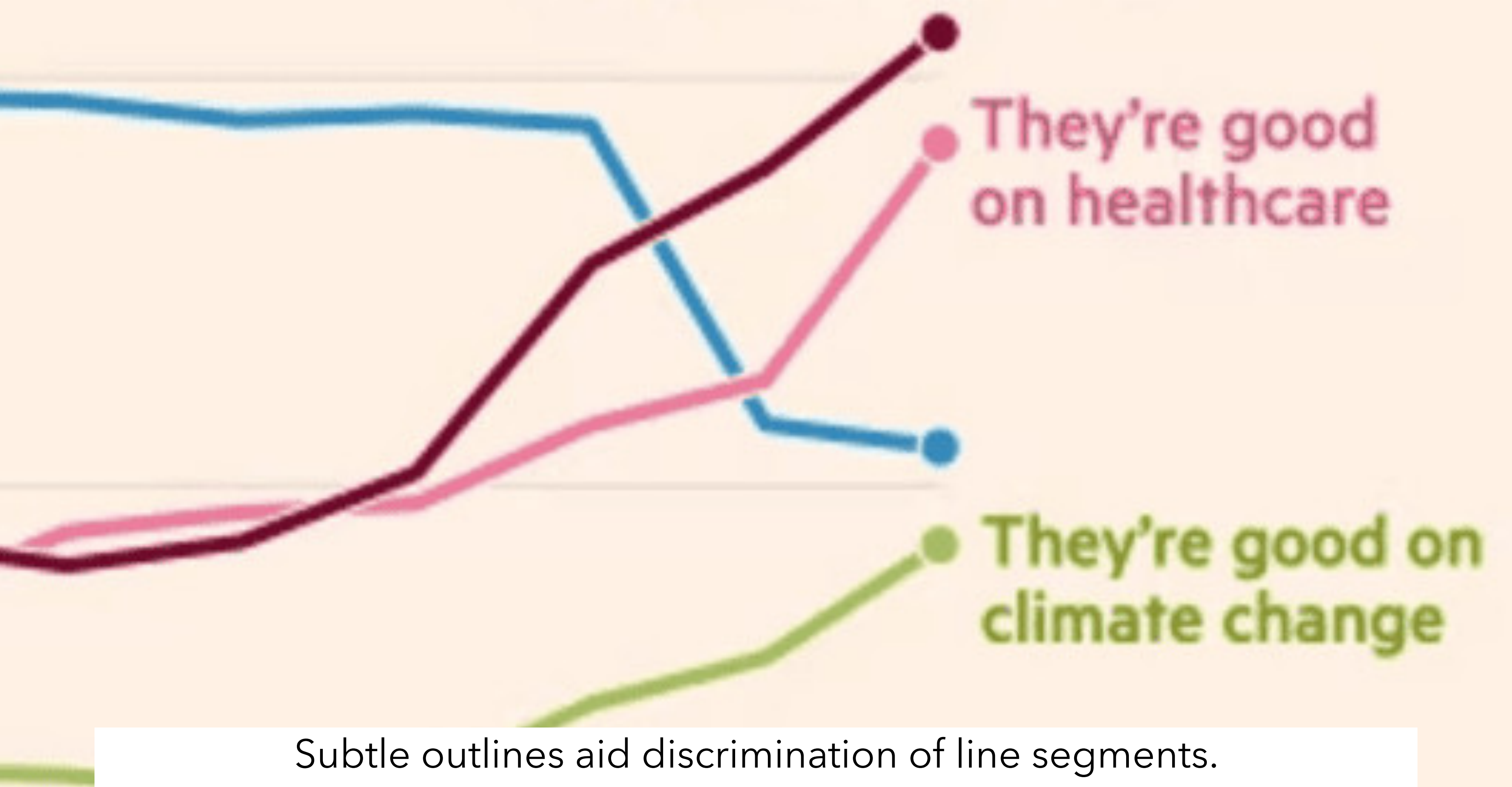


Source: FT analysis of American National Election Studies, based on Party Images in the American Electorate (Brewer, 2008)
FT graphic: John Burn-Murdoch / @jburnmurdoch



Direct labels, rather than legend. (But y-axis units?)

Title and subtitle convey context and steer interpretation.



Subtle outlines aid discrimination of line segments.

A Design Space
of Visual Encodings

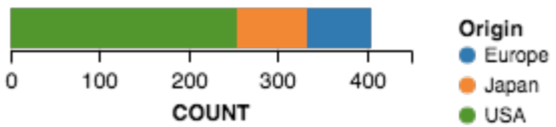
Mapping Data to Visual Variables

Assign **data fields** (e.g., with *N, O, Q* types) to **visual channels** (*x, y, color, shape, size, …*) for a chosen **graphical mark** type (*point, bar, line, …*).

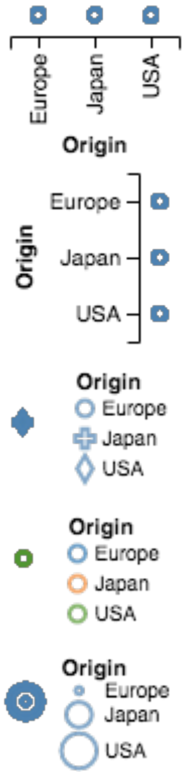
Additional concerns include choosing appropriate **encoding parameters** (*log scale, sorting, …*) and **data transformations** (*bin*, *group, aggregate, …*).

These options define a large combinatorial space, containing both useful and questionable charts!

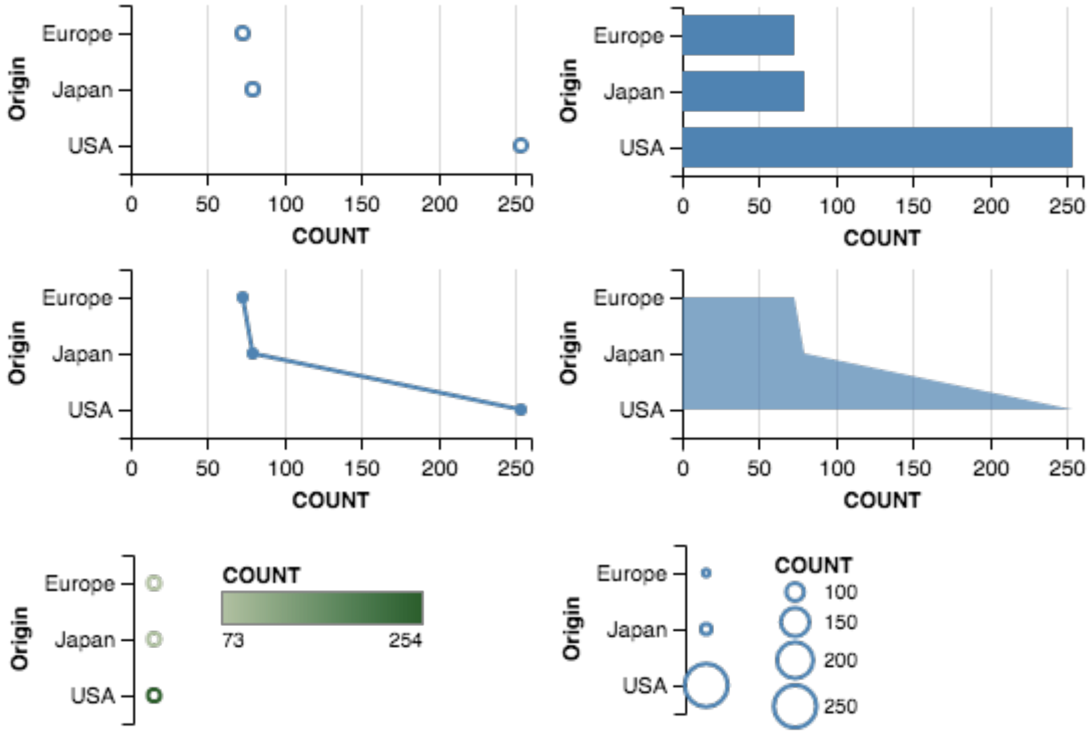
1D: Nominal



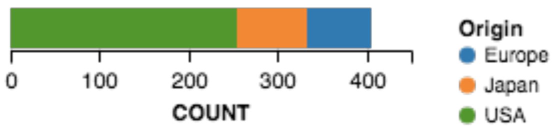
Raw



Aggregate (Count)

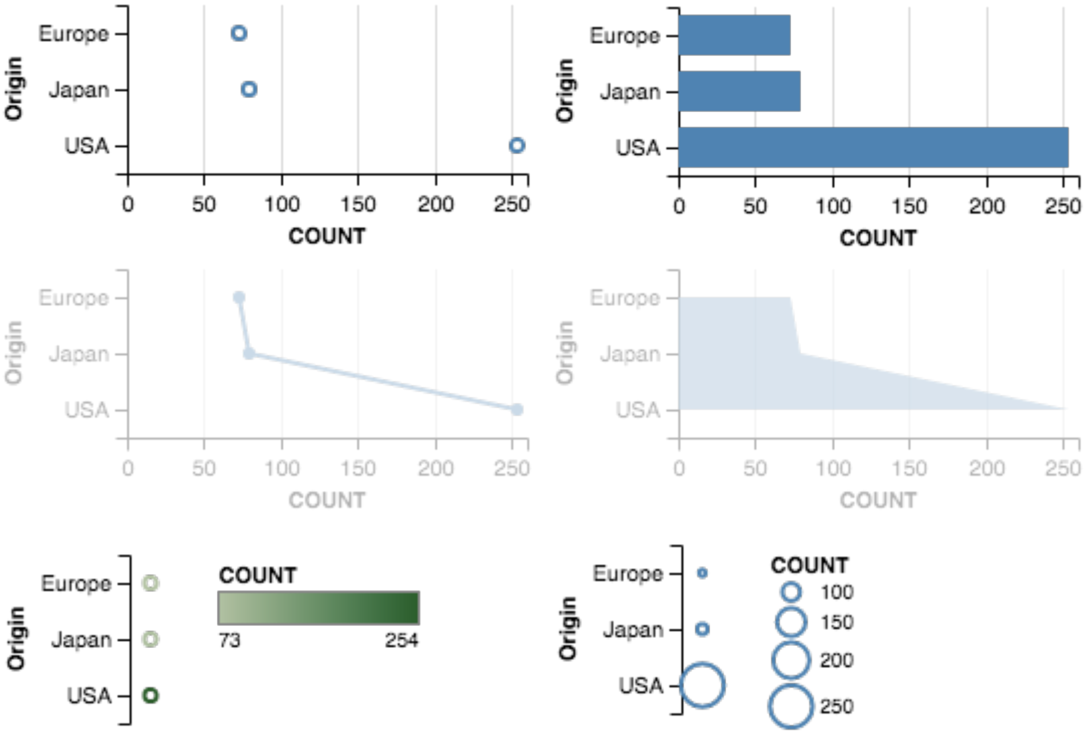


Expressive?



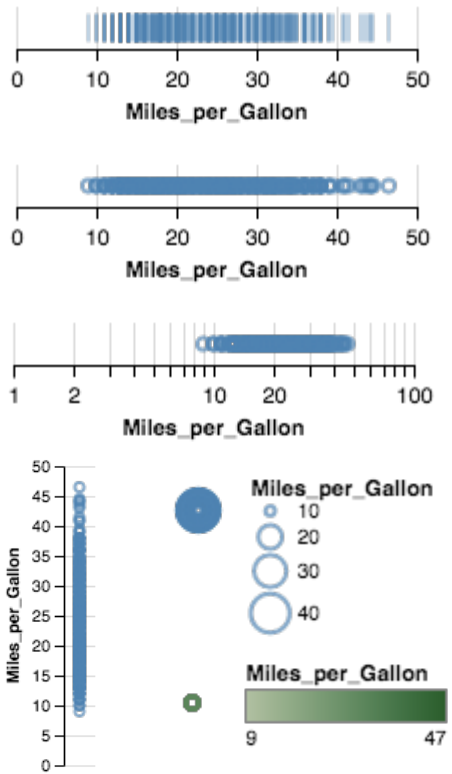
Raw

Aggregate (Count)

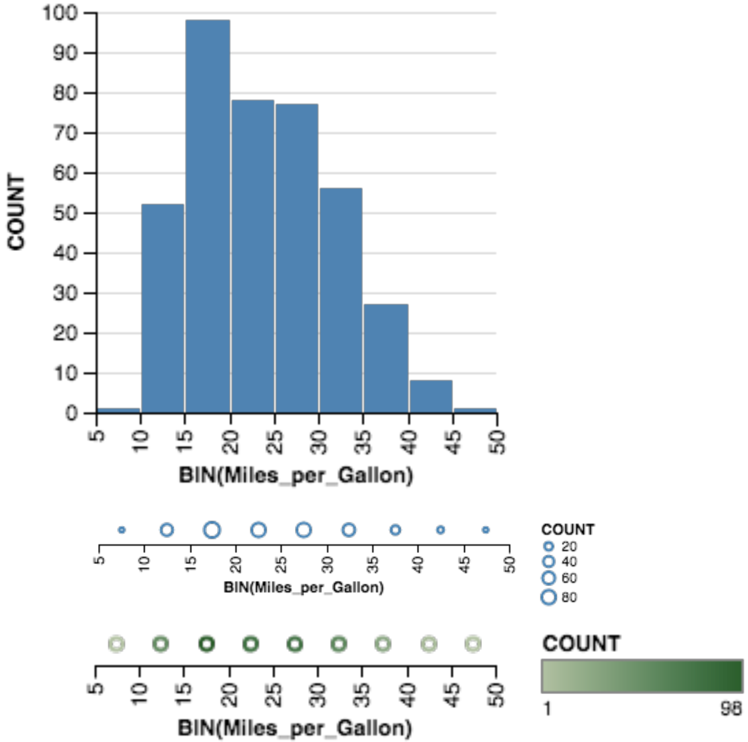


1D: Quantitative

Raw

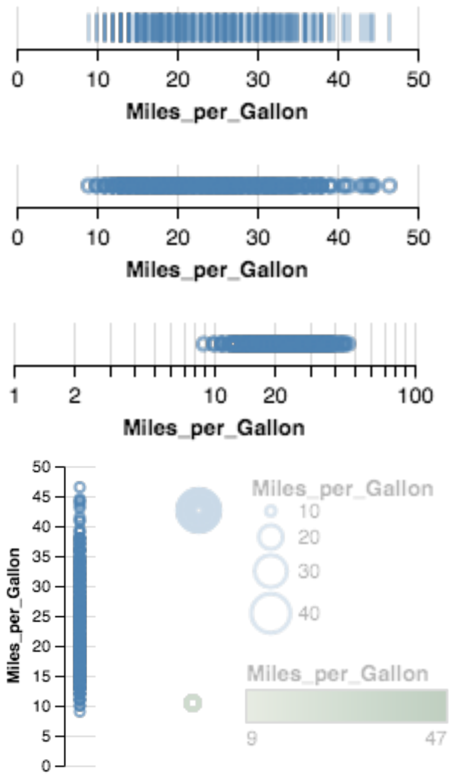


Aggregate (Count)

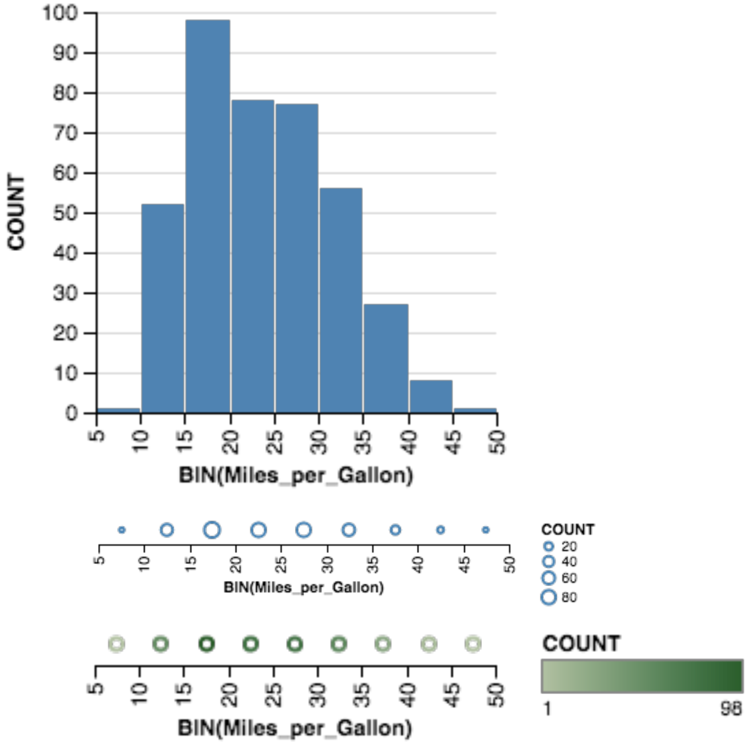


Expressive?

Raw

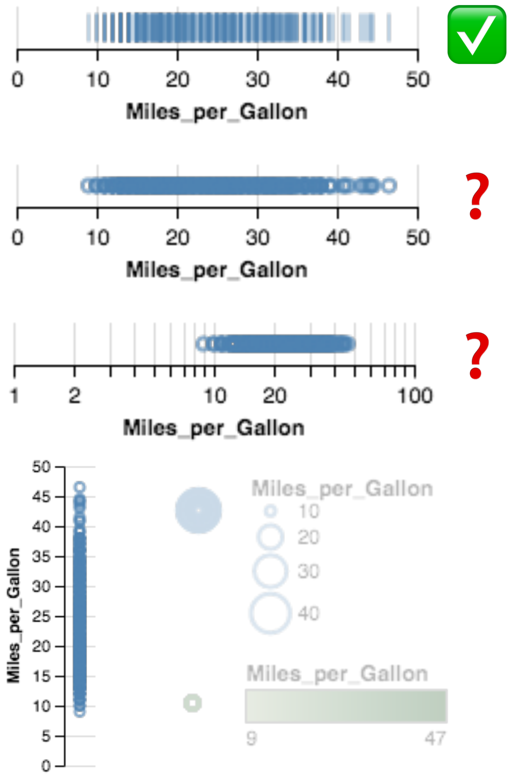


Aggregate (Count)

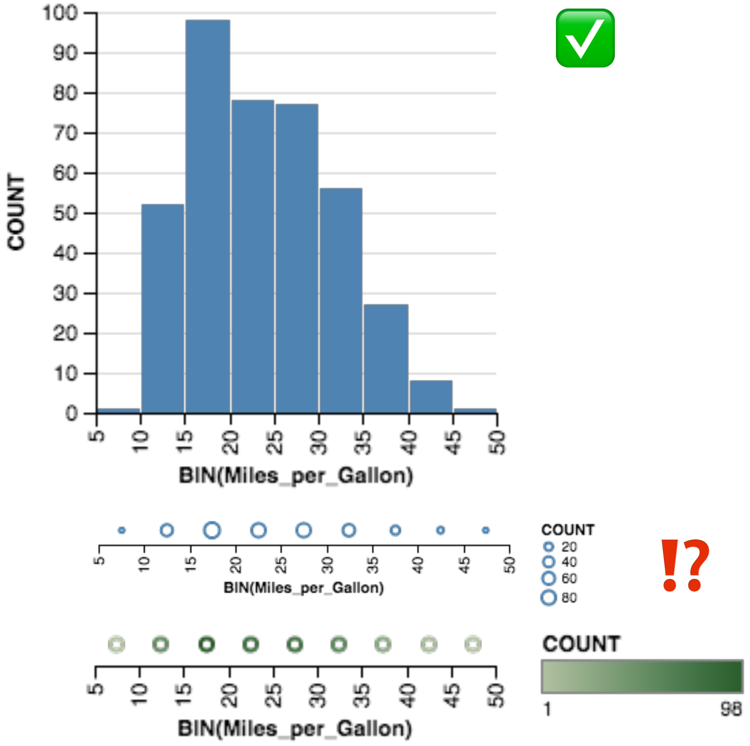


Effective?

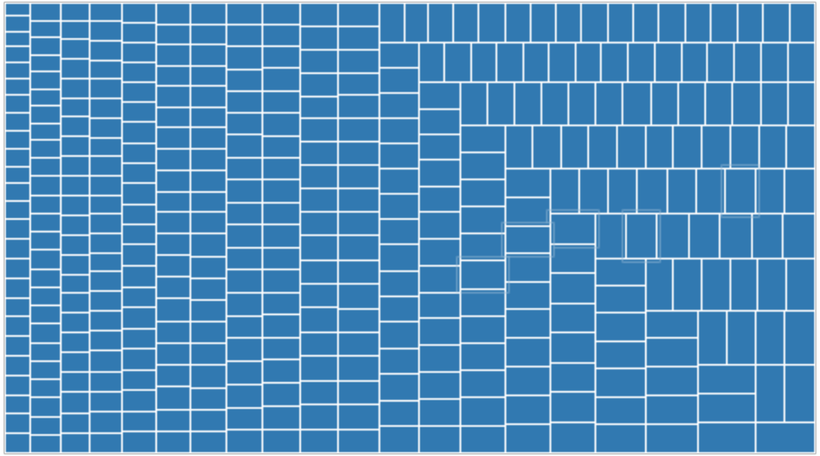
Raw



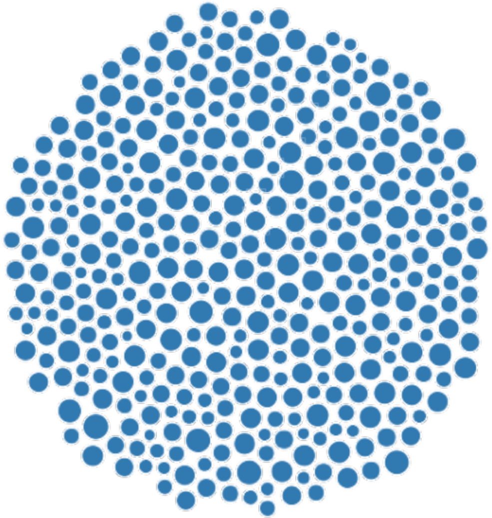
Aggregate (Count)



Raw (with Layout Algorithm)

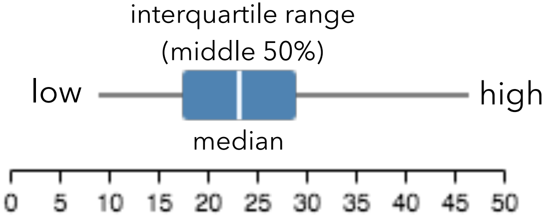


Treemap

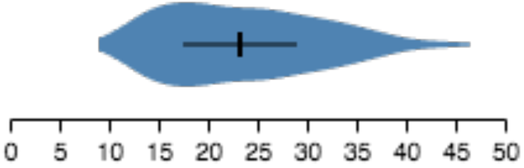


Bubble Chart

Aggregate (Distributions)



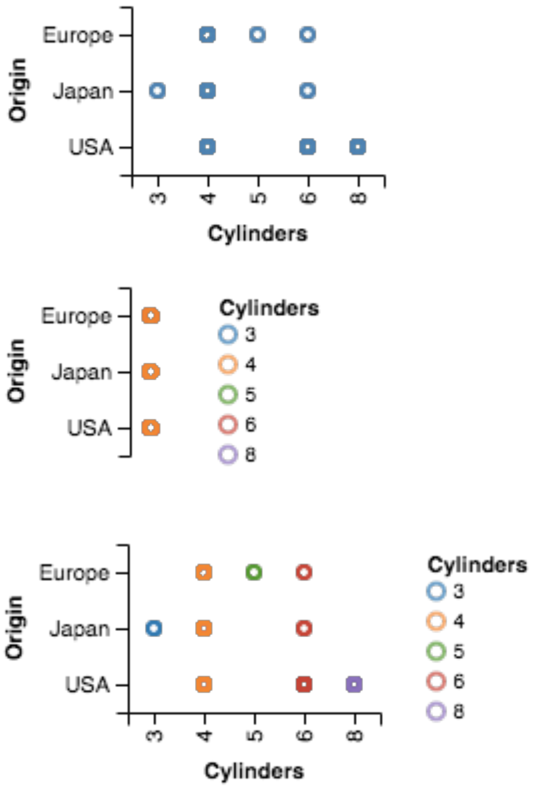
Box Plot



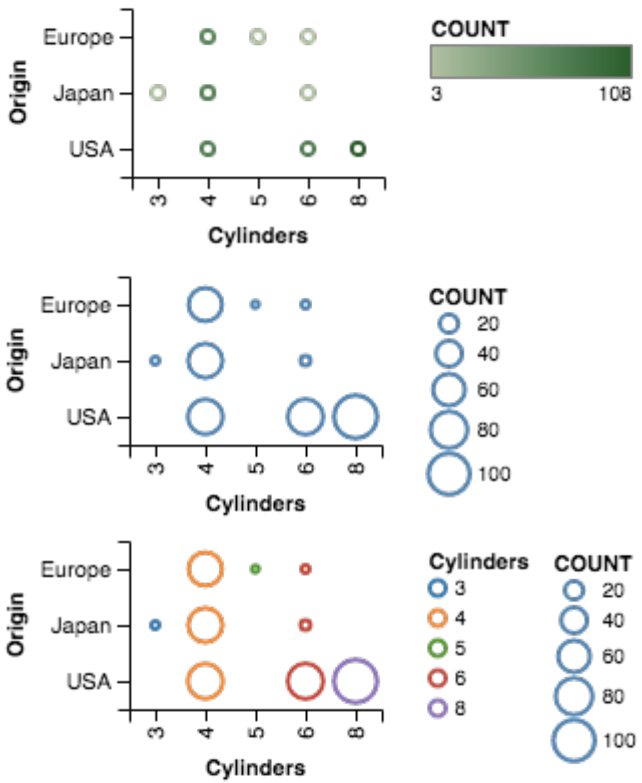
Violin Plot

2D: Nominal x Nominal

Raw

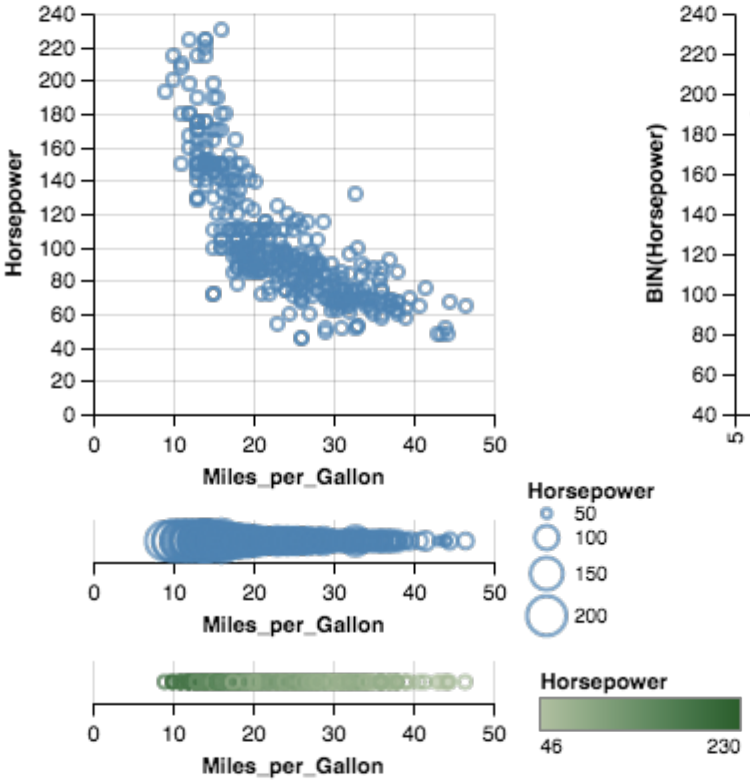


Aggregate (Count)

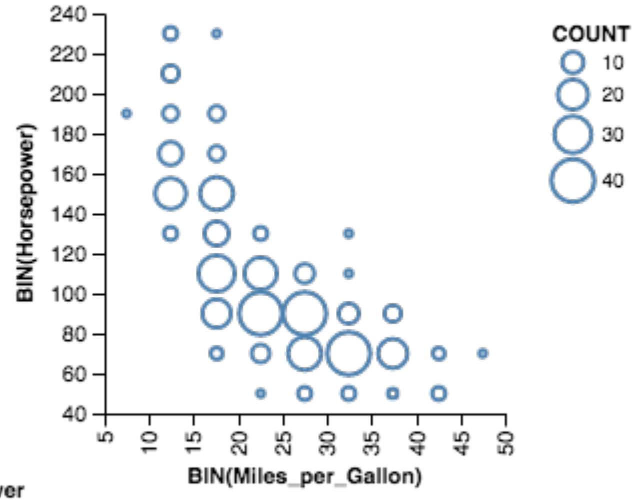


2D: Quantitative x Quantitative

Raw

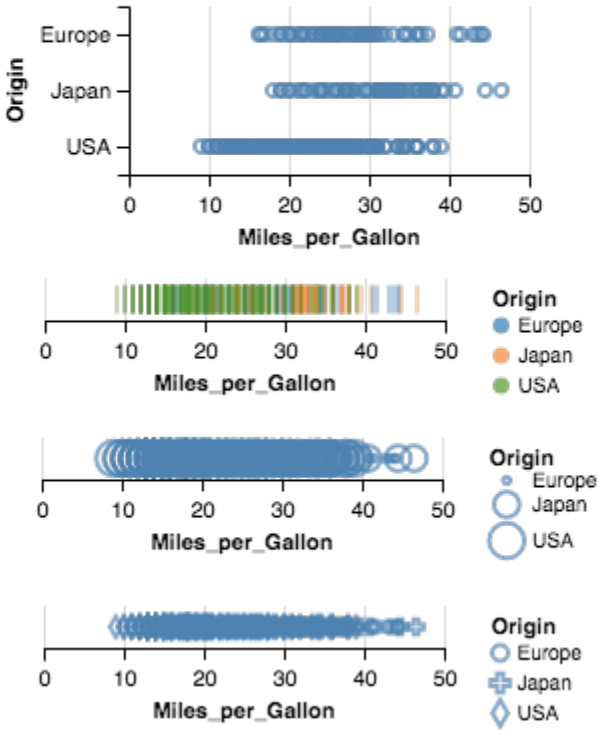


Aggregate (Count)

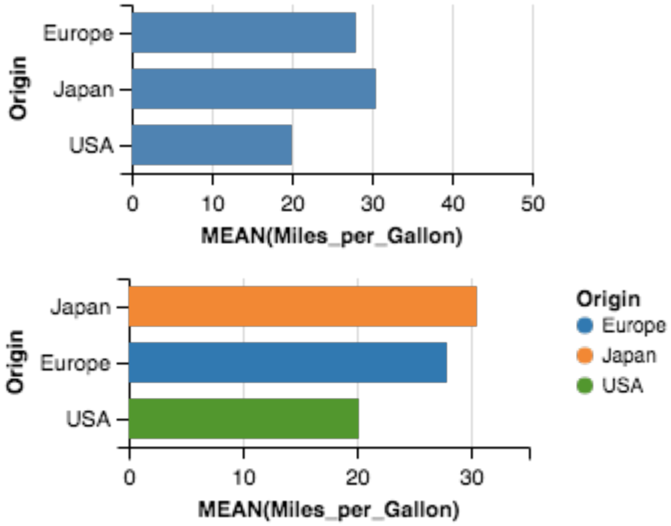


2D: Nominal x Quantitative

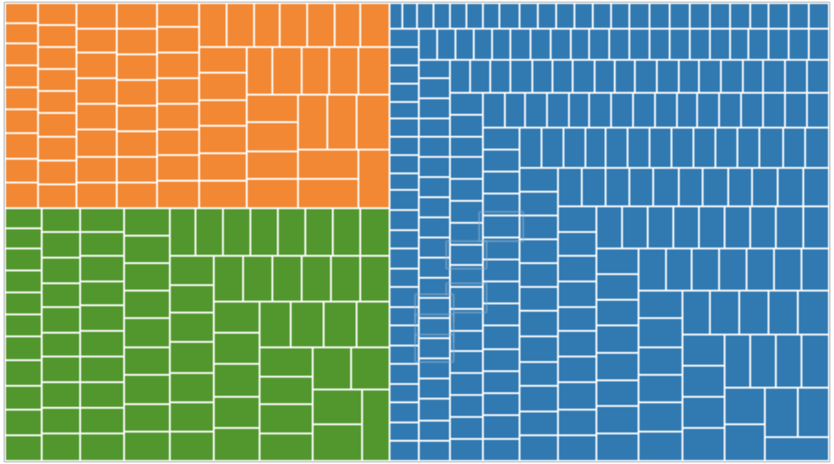
Raw



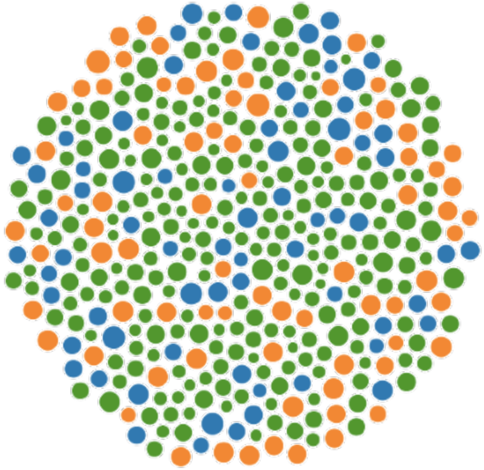
Aggregate (Mean)



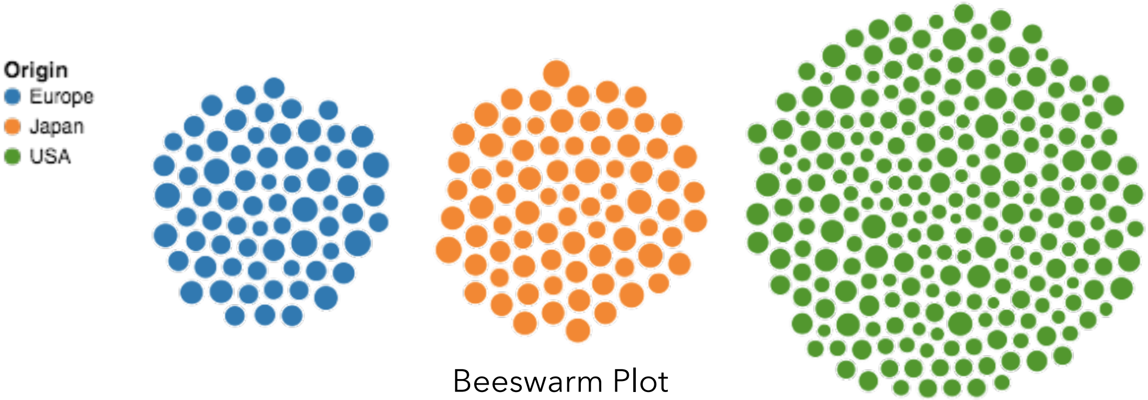
Raw (with Layout Algorithm)



Treemap



Bubble Chart



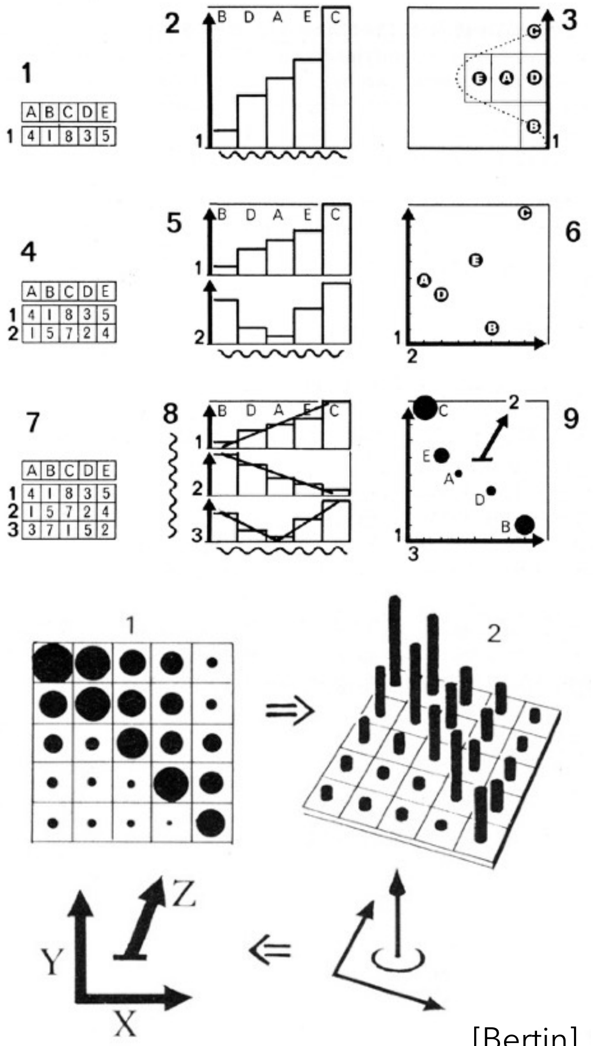
Beeswarm Plot

3D and Higher

Two variables [x, y]
Can map to 2D points.
Scatterplots, maps, …

Third variable [z]
Often use one of size, color, opacity, shape, *etc*. Or, one can further partition space.

What about 3D rendering?



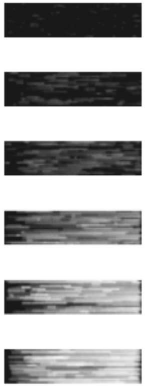
[Bertin]

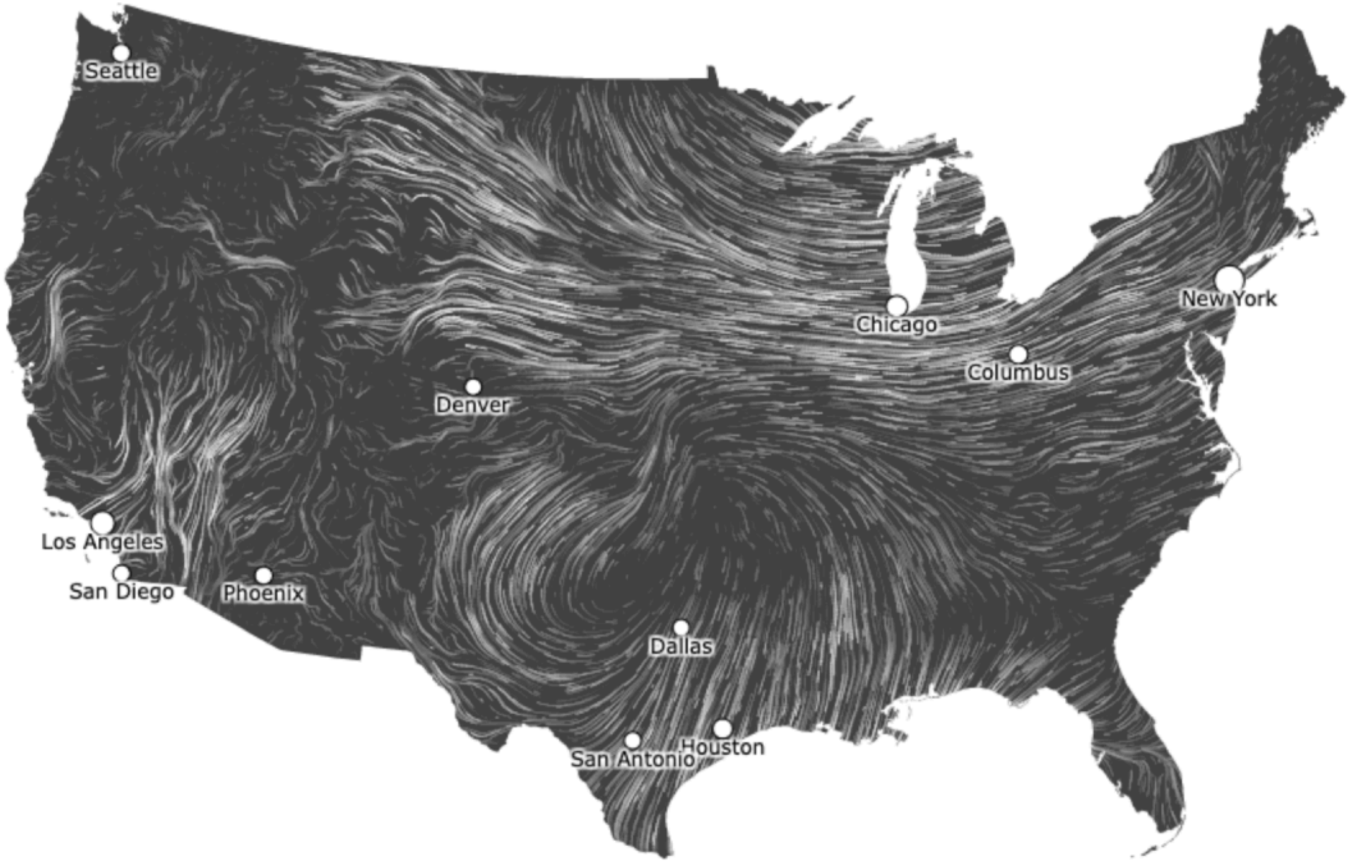
wind map

[Viegas & Wattenberg]

January 13, 2025
12:21 pm EST
(time of forecast download)

top speed: **25.2 mph**
average: **8.1 mph**



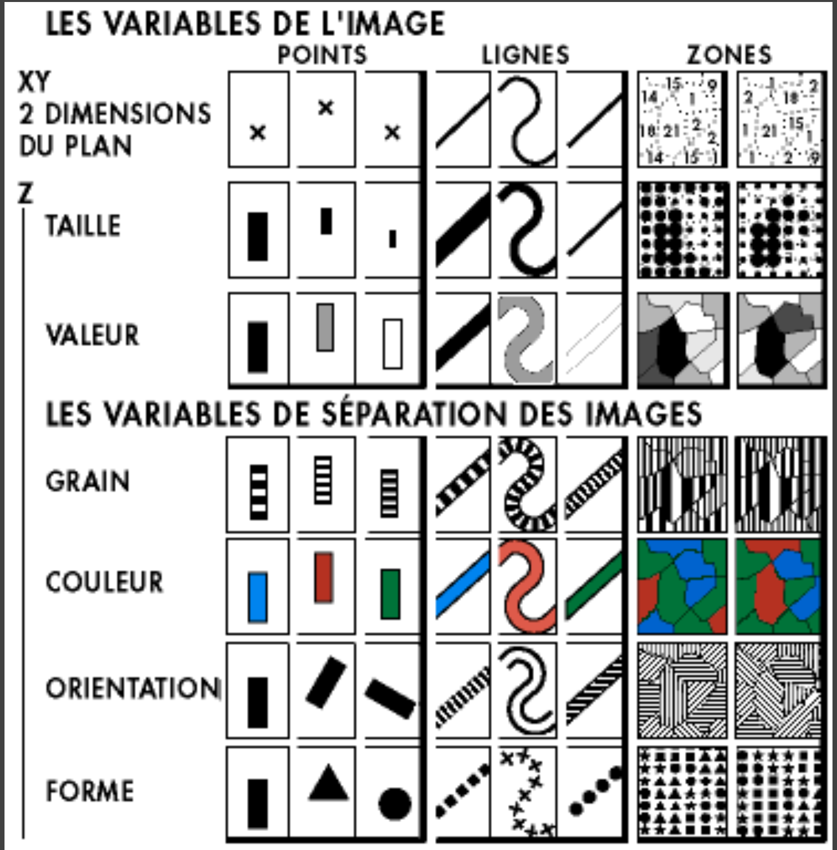


Multidimensional Data

Visual Encoding Channels

Position (X)
Position (Y)
Area
Value
Texture
Color
Orientation
Shape

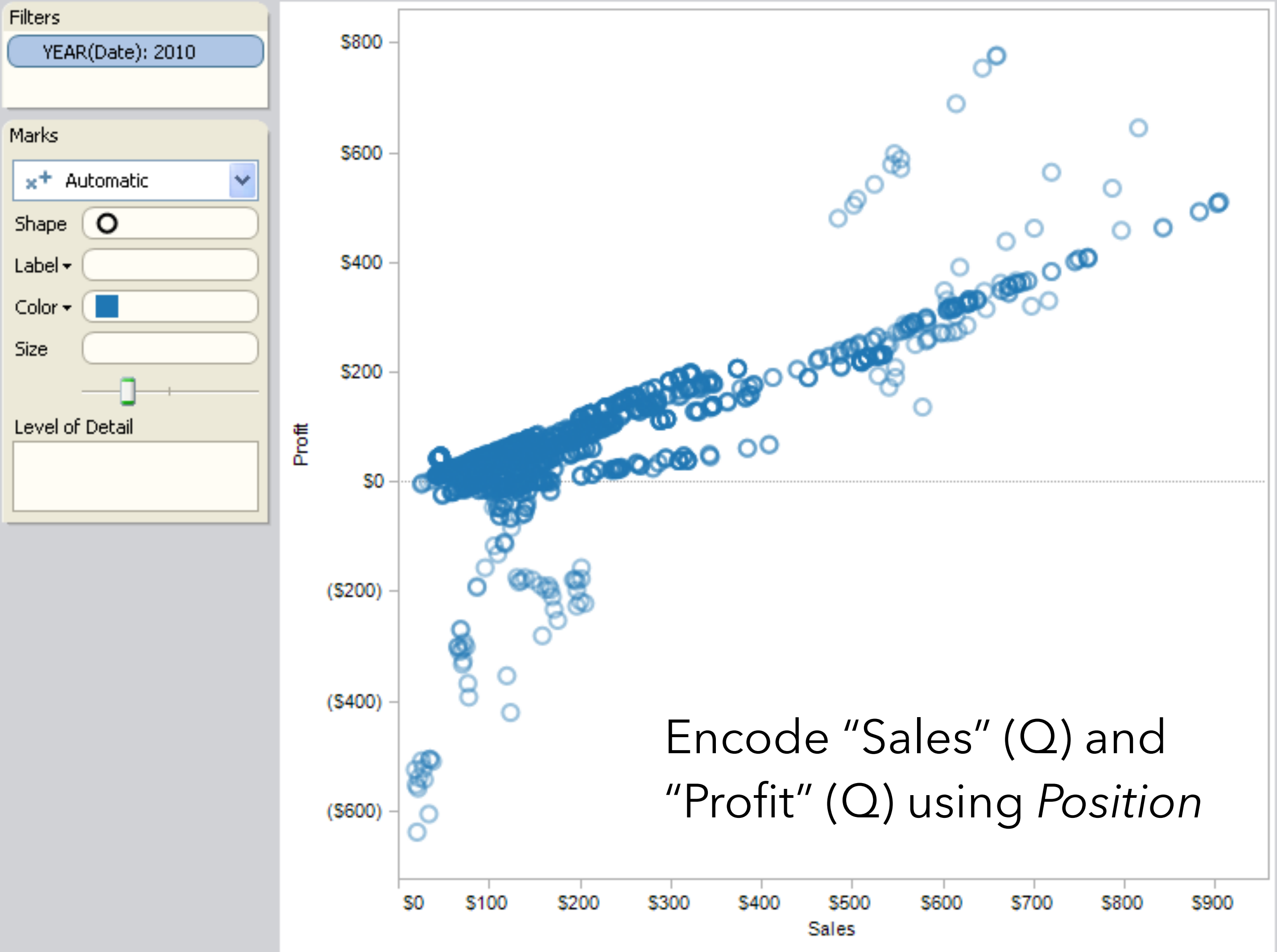
~8 dimensions?



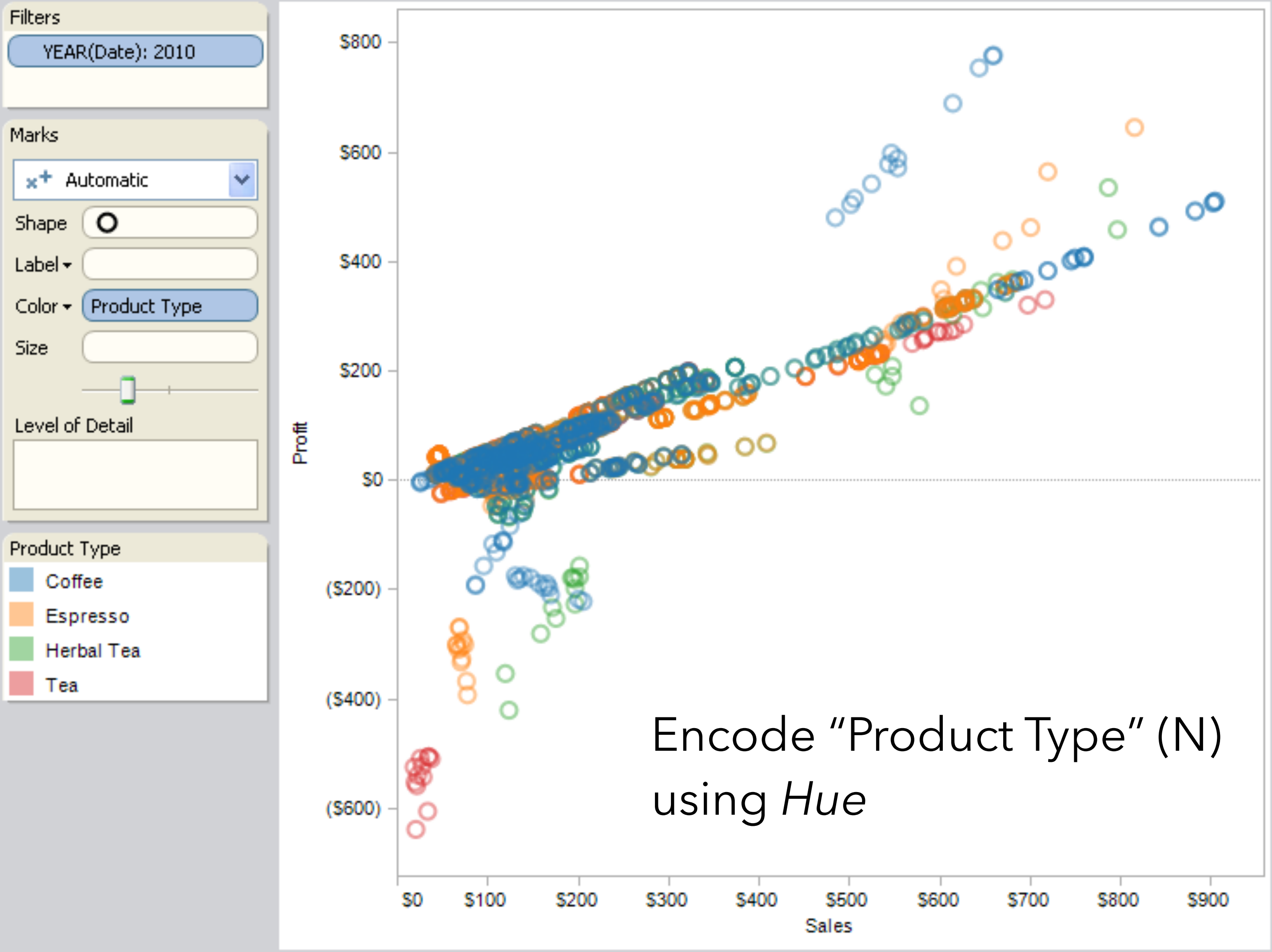
Example: Coffee Sales

Sales figures for a fictional coffee chain

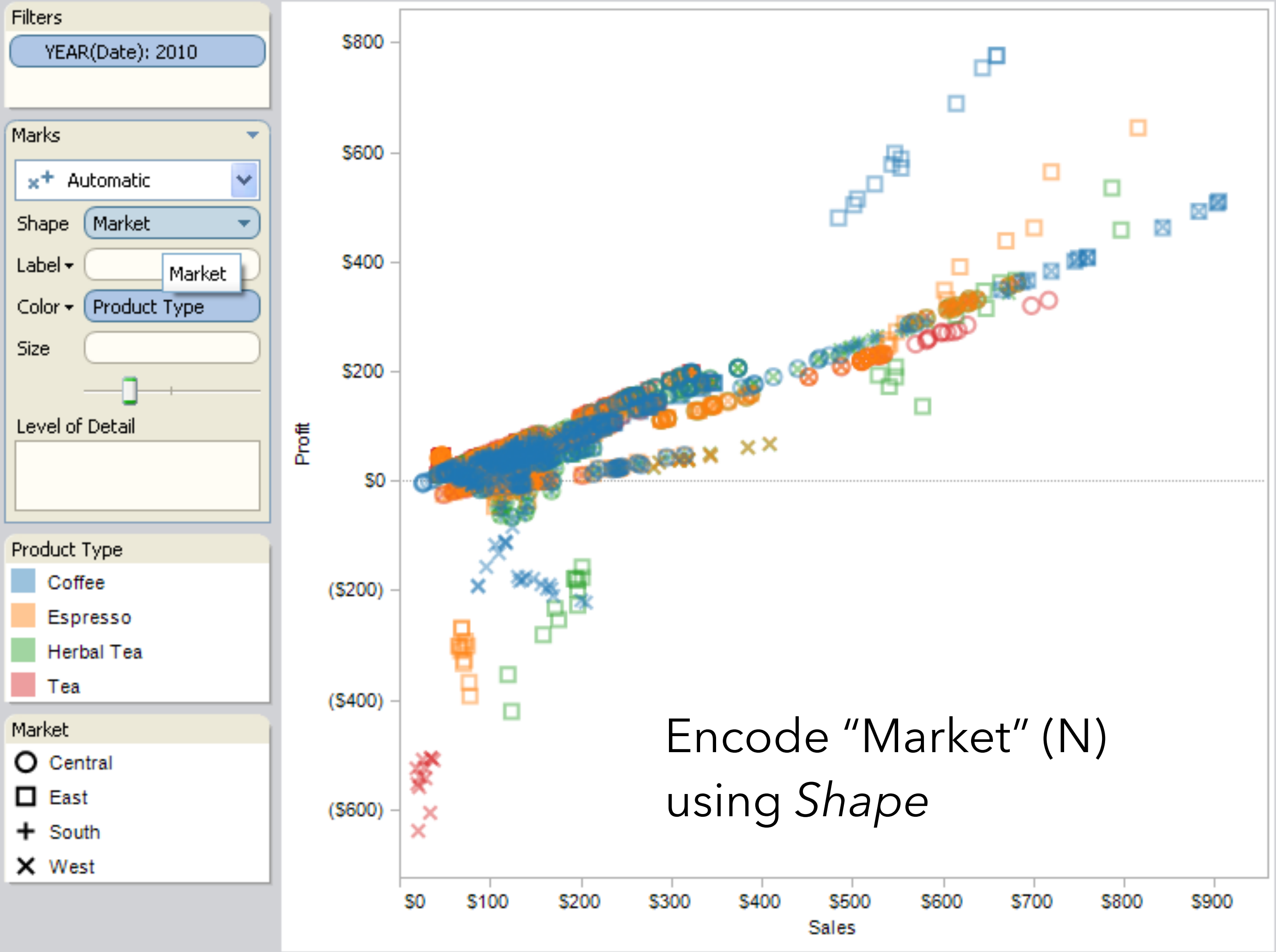
Sales	Q-Ratio
Profit	Q-Ratio
Marketing	Q-Ratio
Product Type	N {Coffee, Espresso, Herbal Tea, Tea}
Market	N {Central, East, South, West}



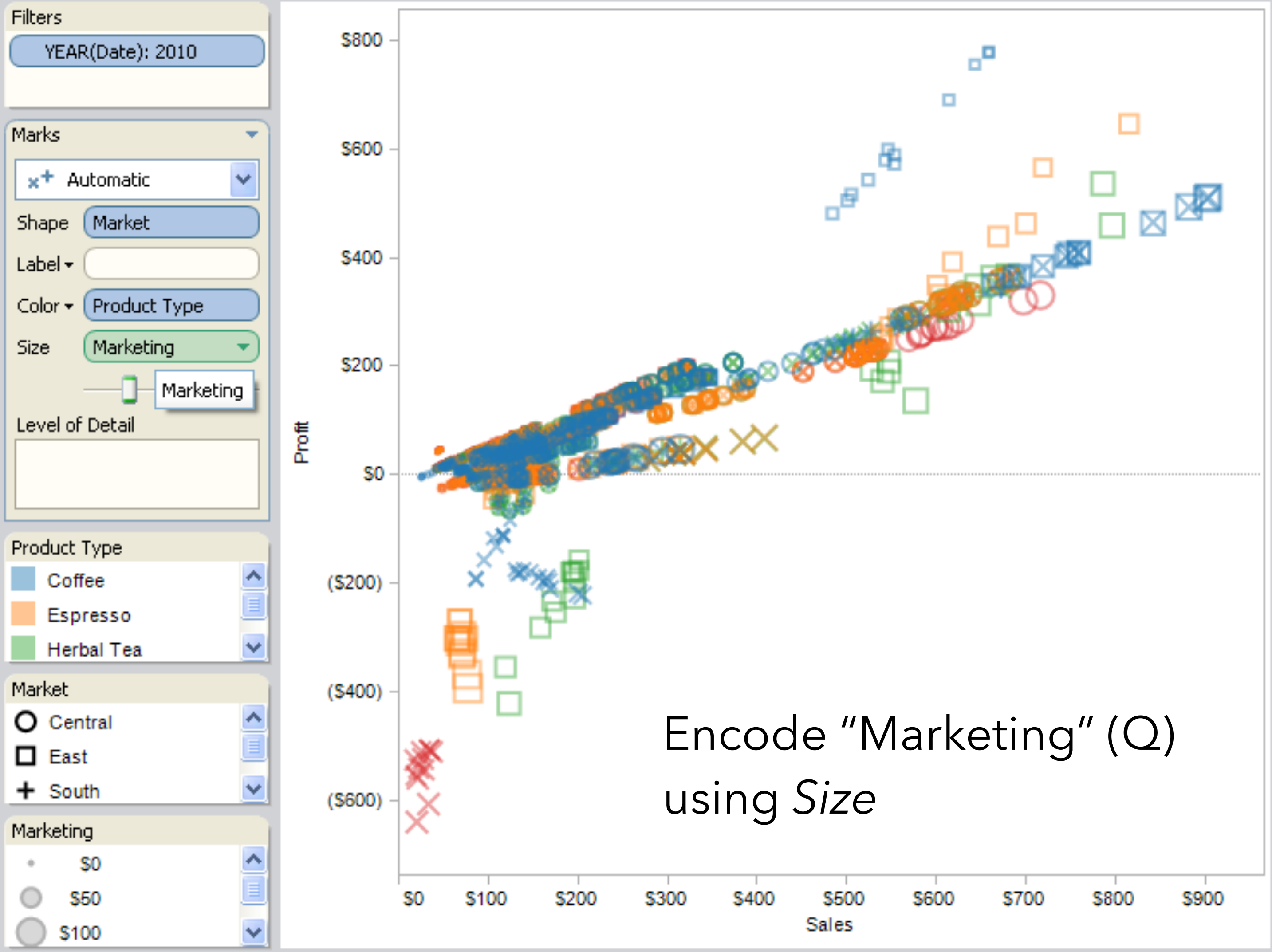
Encode "Sales" (Q) and "Profit" (Q) using *Position*



Encode “Product Type” (N) using *Hue*

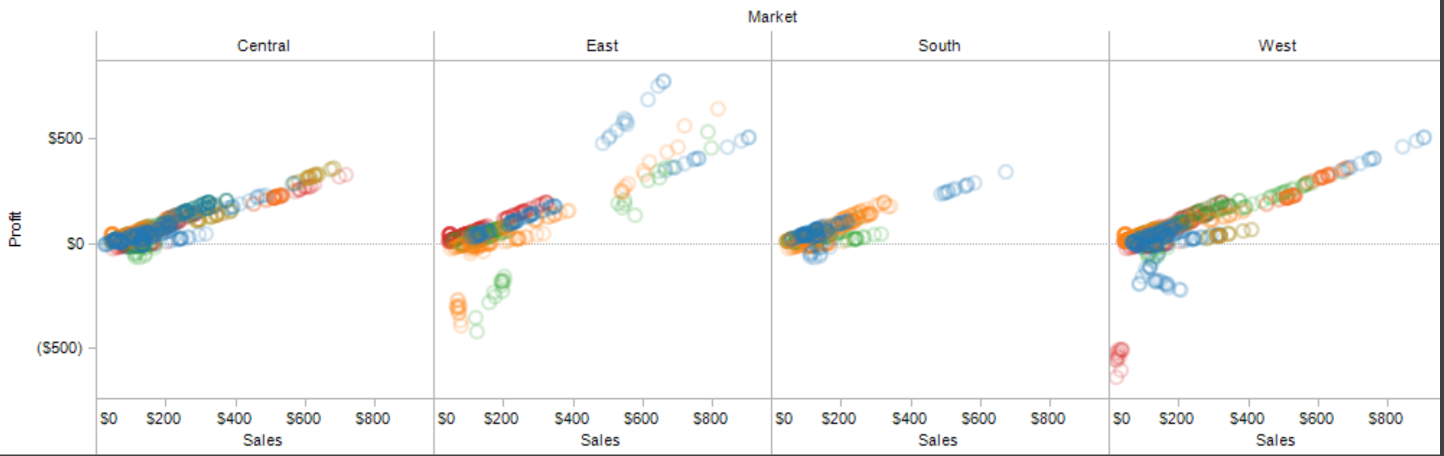


Encode “Market” (N) using *Shape*



Encode “Marketing” (Q) using *Size*

Trellis Plots



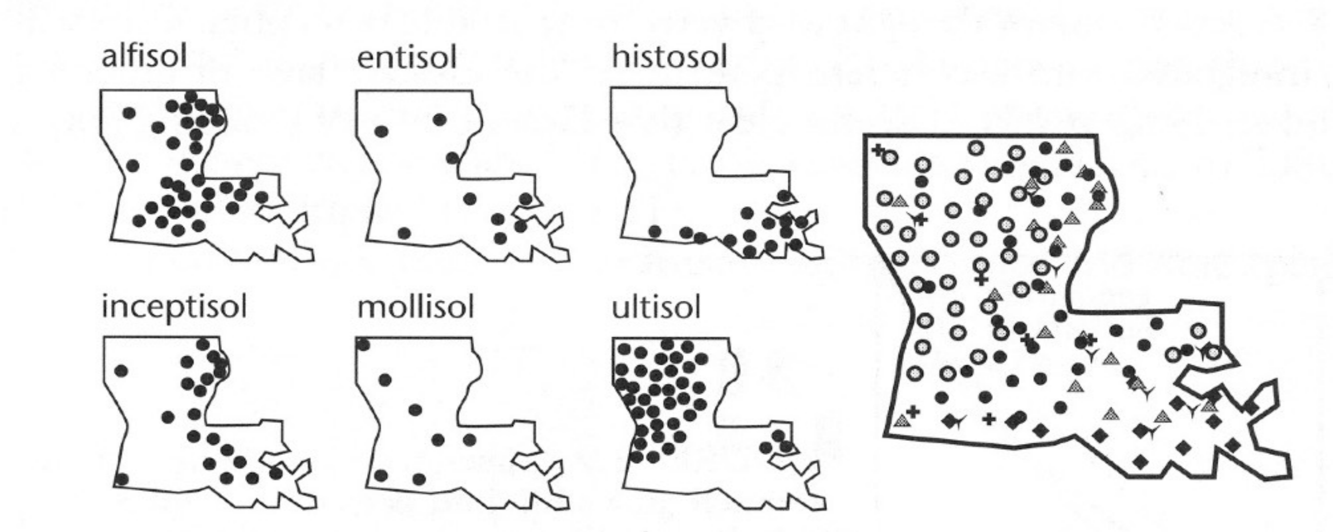
A *trellis plot* subdivides space to enable comparison across multiple plots.

Typically nominal or ordinal variables are used as dimensions for subdivision.

Small Multiples

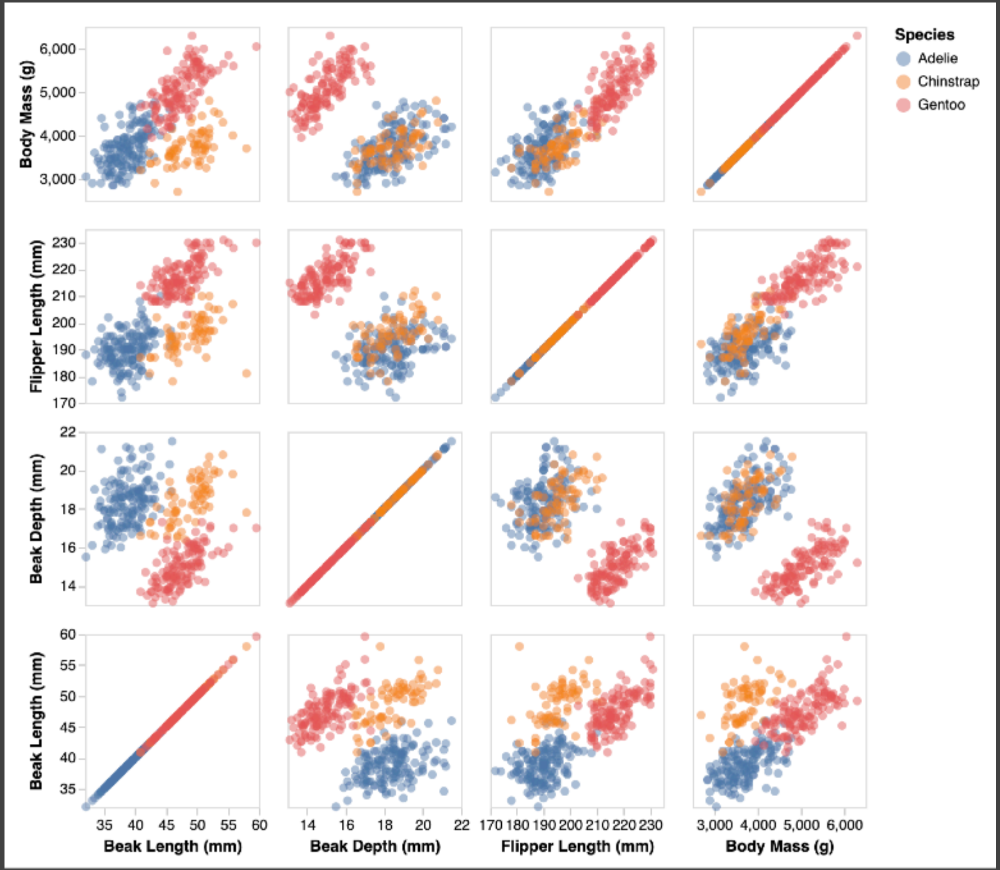
[MacEachren '95, Figure 2.11, p. 38]

Small Multiples



[MacEachren '95, Figure 2.11, p. 38]

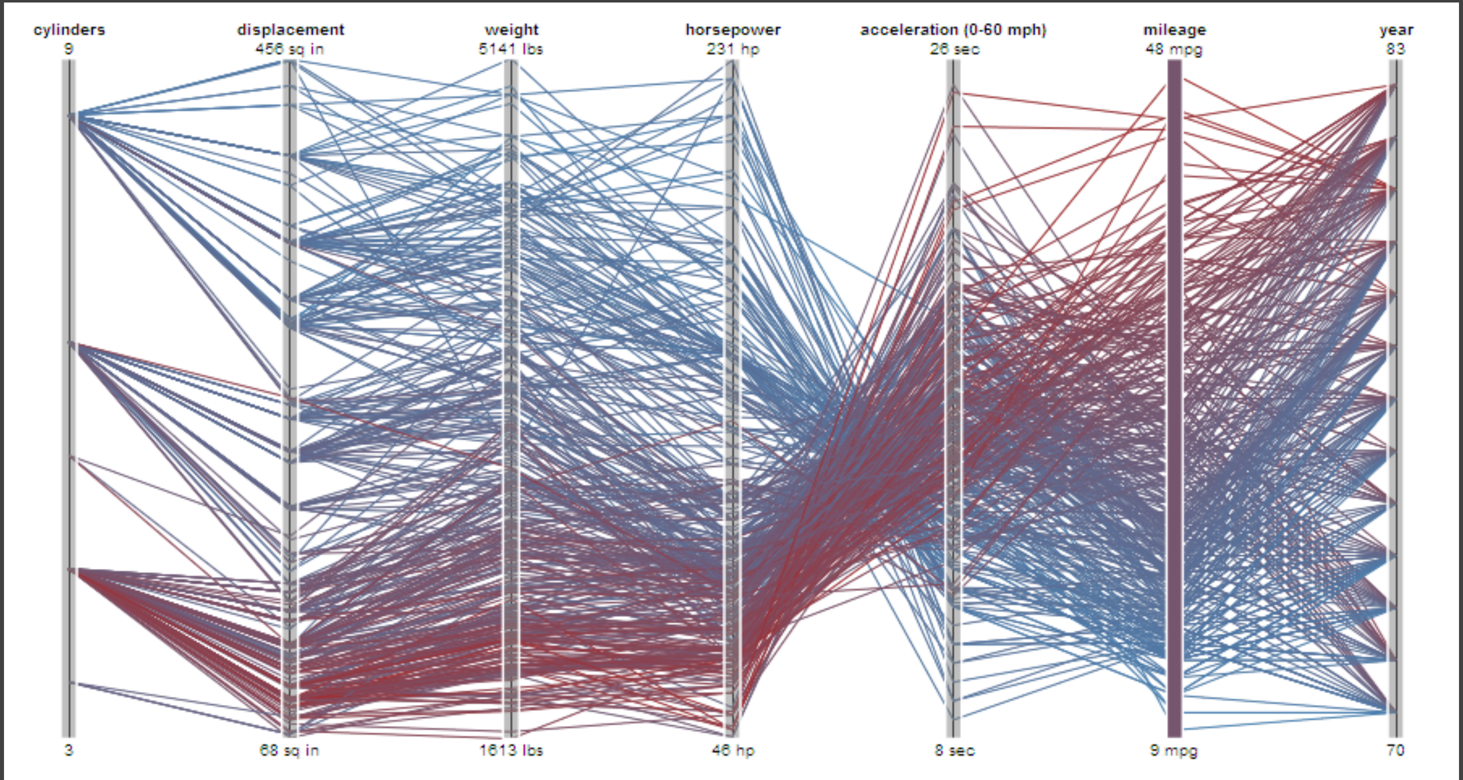
Scatterplot Matrix (SPLOM)



Scatter plots for pairwise comparison of each data dimension.

Parallel Coordinates

Parallel Coordinates [Inselberg]



Parallel Coordinates [Inselberg]

Visualize up to ~two dozen dimensions at once

1. Draw parallel axes for each variable
2. For each tuple, connect points on each axis

Between adjacent axes: line crossings imply neg. correlation, shared slopes imply pos. correlation.

Full plot can be cluttered. **Interactive selection** can be used to assess multivariate relationships.

Highly sensitive to axis **scale** and **ordering**.

Expertise required to use effectively!

A1: Expository Visualization

Using the given climate data set…

Pick a **guiding question**, use it to title your vis.

Design a **static visualization** for that question.

You are free to **use any visualization tool**.

Deliverables via Gradescope

Image of your visualization (PNG or JPG format)

Short description + design rationale (≤ 4 paragraphs)

Due by **EOD, Tue April 8**.

Scales & Axes

Scale Transforms

$$f\colon D \rightarrow R$$

A **scale** is a function that maps a domain D of data values to a range R of visual values.

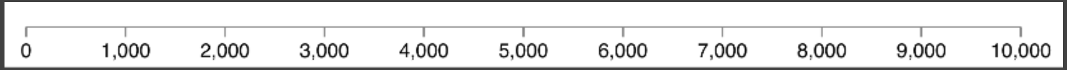
Example ranges: x-position, color, size, angle

Scales are the workhorses of visual encoding!

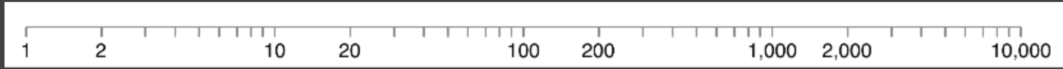
We can modify domains, ranges, transforms (log, etc.), padding, and more…

Positional Scales $R = pixels$

Continuous / Quantitative



linear

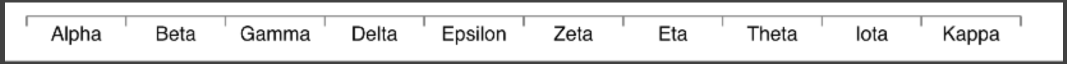


log

sqrt

Discrete / Ordinal

point



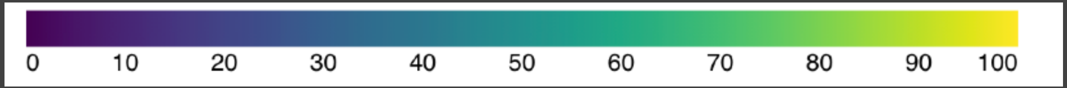
band

Color Scales $R = colors$

Discrete / Categorical

ordinal

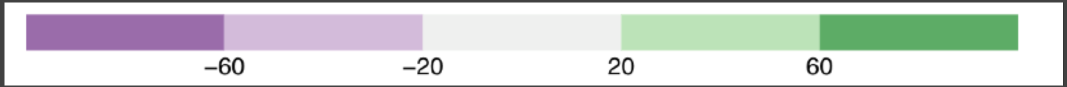
Continuous / Quantitative



sequential

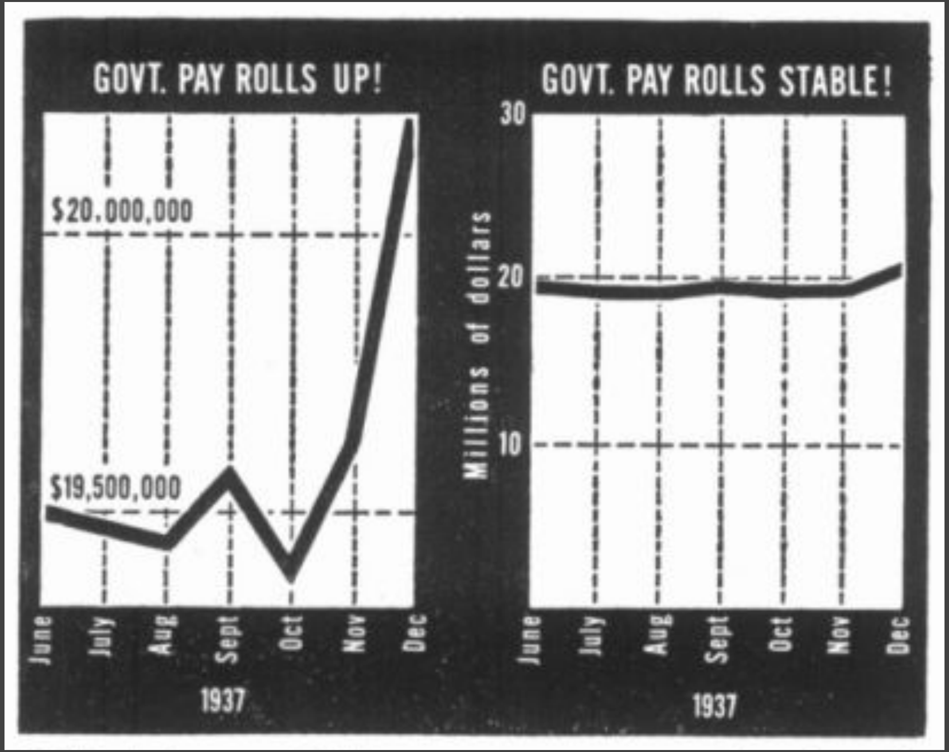
diverging

Discretized / Binned Quantitative



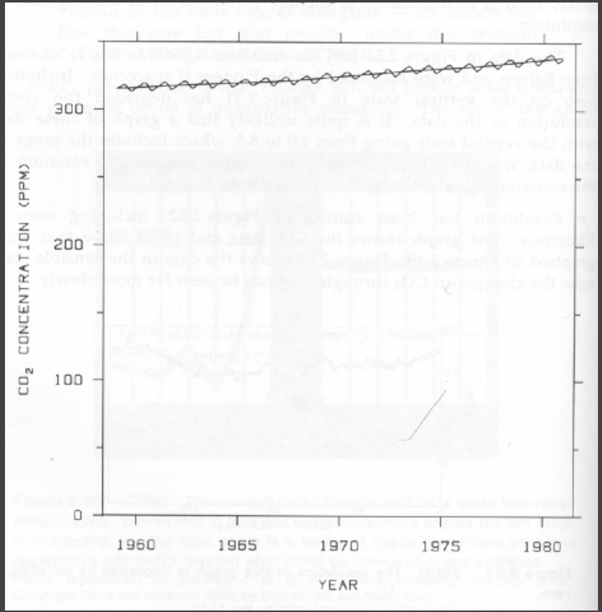
quantize

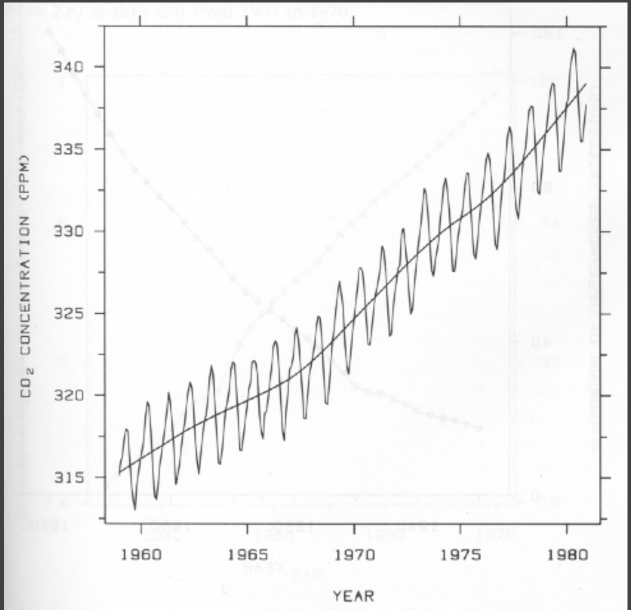
Include Zero in Axis Scale?



Government payrolls in 1937 [How To Lie With Statistics. Huff]

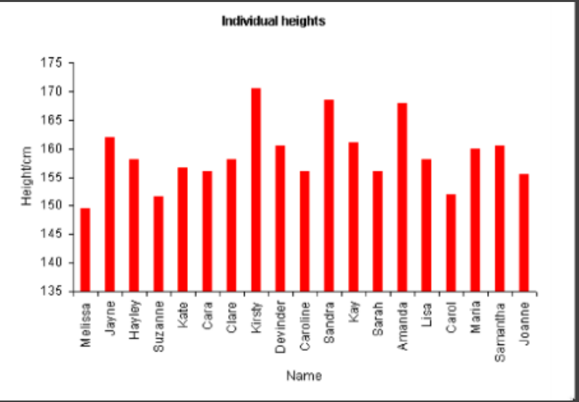
Include Zero in Axis Scale?





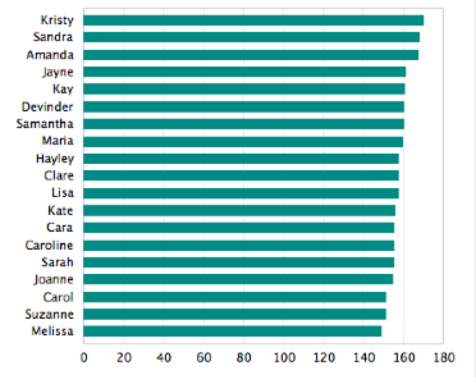
Yearly CO_2 concentrations [Cleveland 85]

Include Zero in Axis Scale?

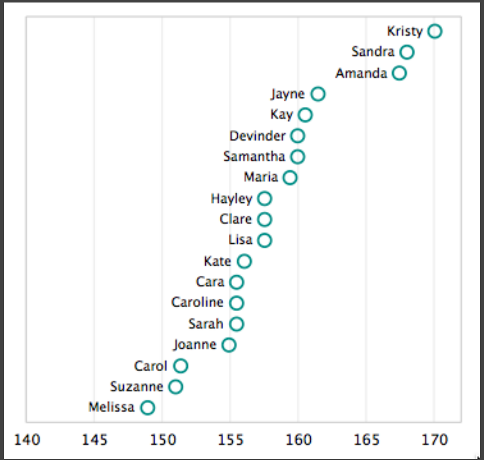


Violates Expressiveness Principle!

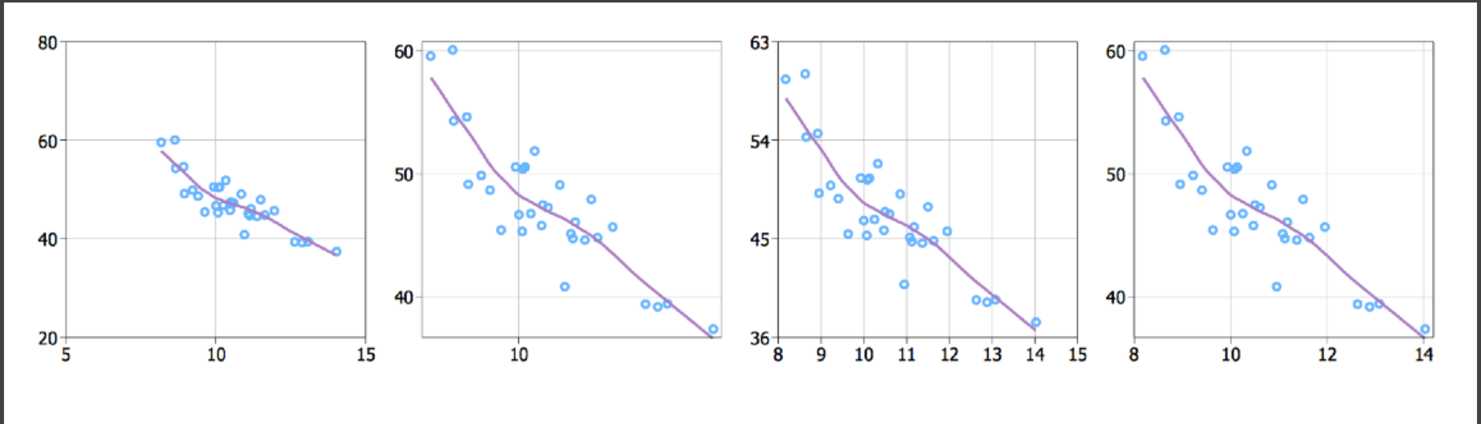
Compare Proportions (Q-Ratio)



Compare Relative Position (Q-Interval)

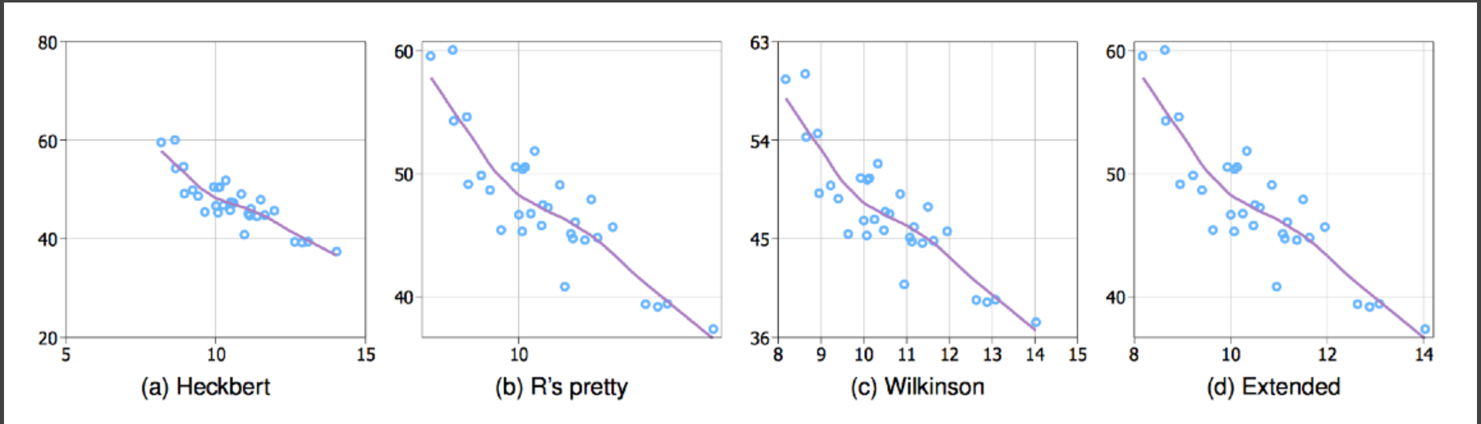


Axis Tick Mark Selection



What are some properties of “good” tick marks?

Axis Tick Mark Selection



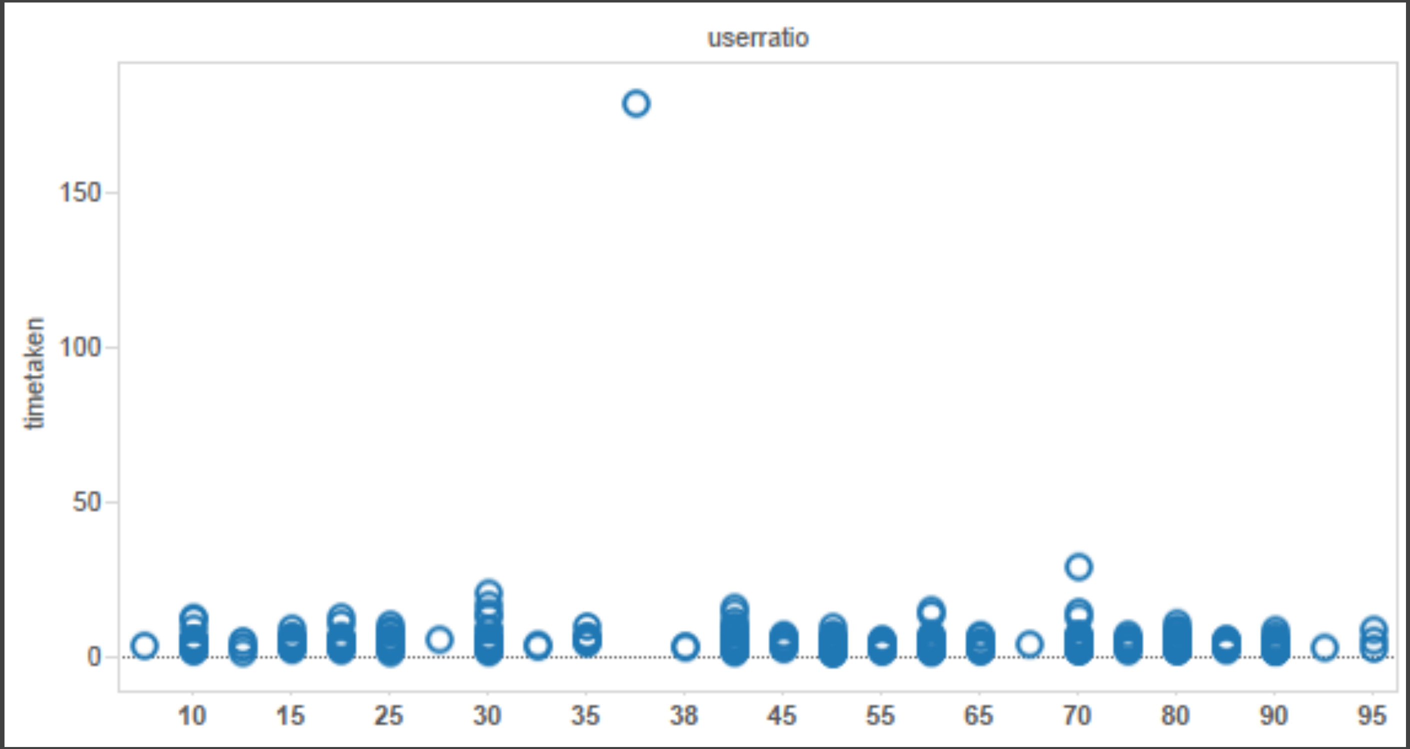
Simplicity - numbers are multiples of 10, 5, 2

Coverage - ticks near the ends of the data

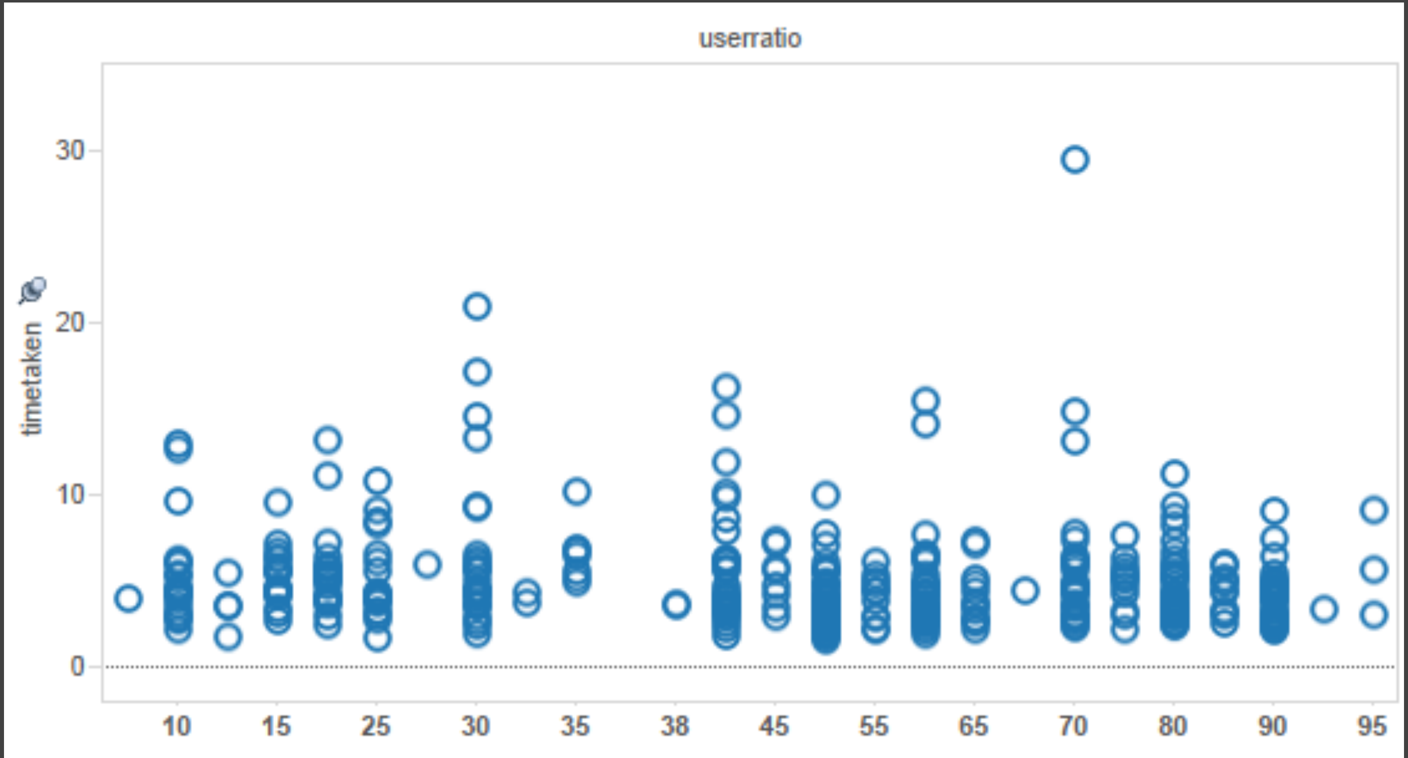
Density - not too many, nor too few

Legibility - whitespace, horizontal text, size

How to Scale the Axis?

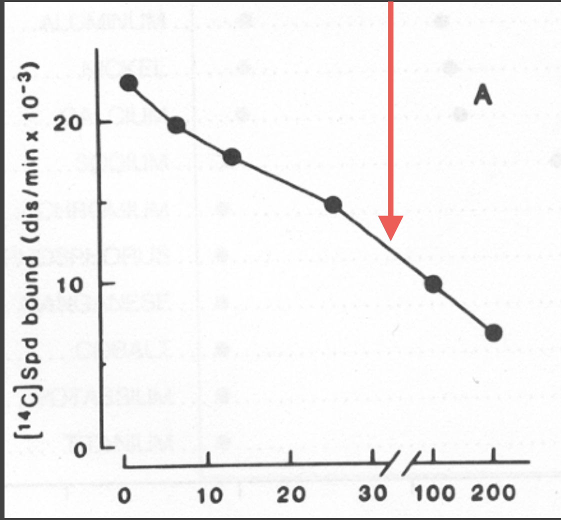


One Option: Clip Outliers

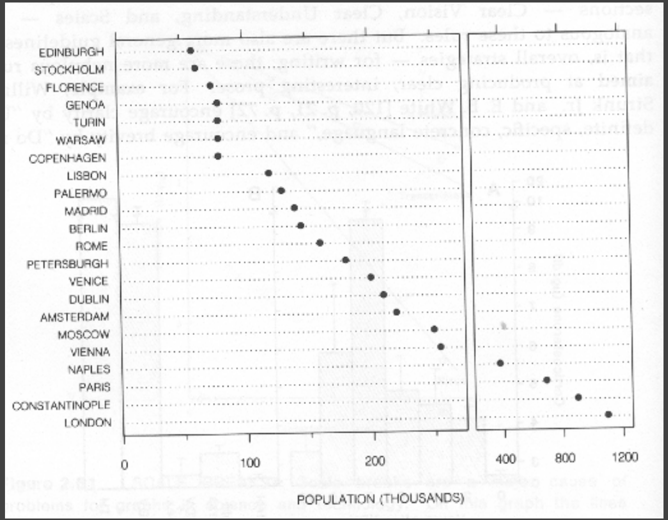


Clearly Mark Scale Breaks

Violates Expressiveness Principle!

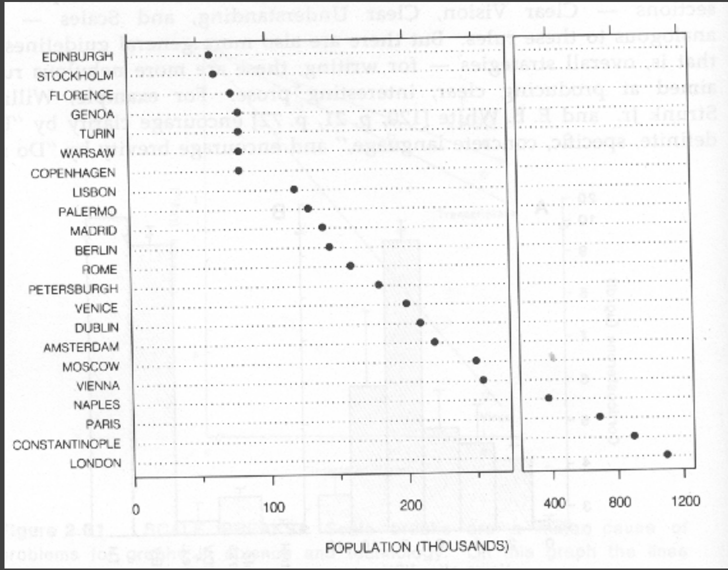


Poor scale break [Cleveland 85]

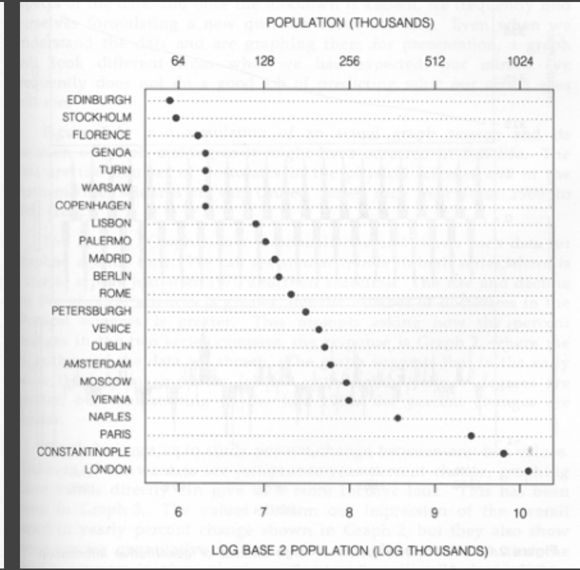


Well-marked scale break [Cleveland 85]

Scale Break vs. Log Scale



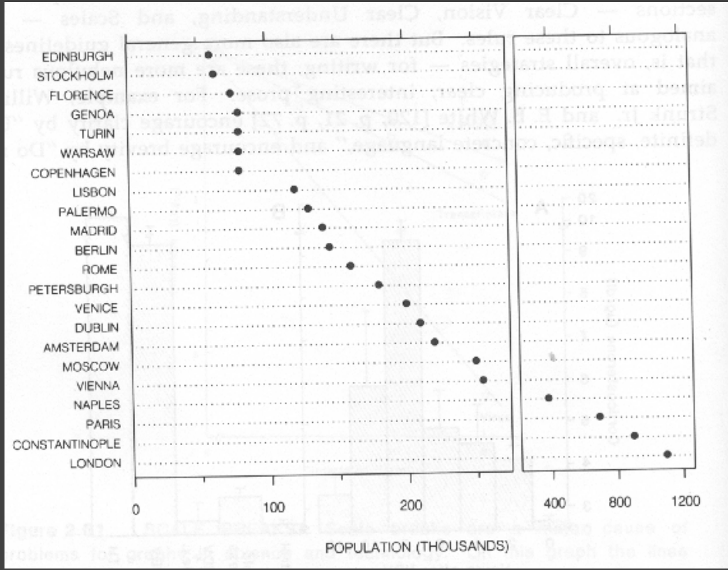
Scale Break

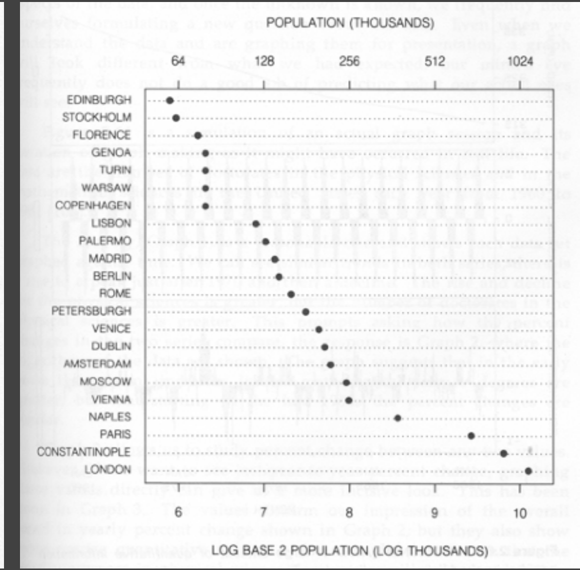


Log Scale

[Cleveland 85]

Scale Break vs. Log Scale





Both increase visual resolution

Scale break: difficult to compare (*cognitive* – not *perceptual* – work)

Log scale: direct comparison of all data

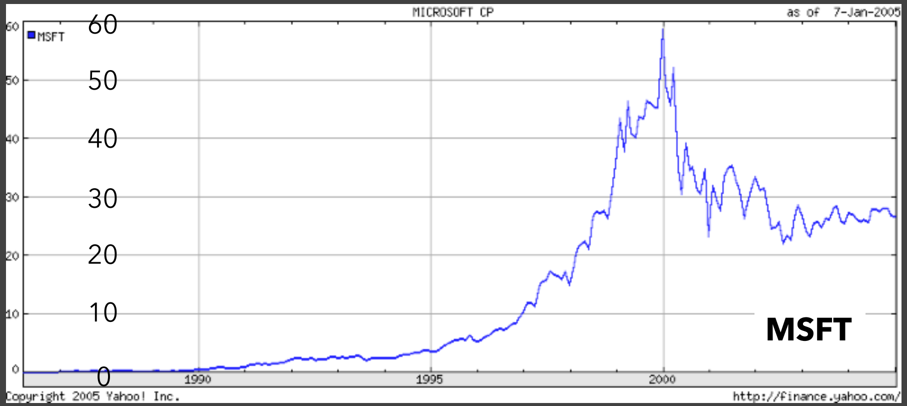
Logarithms turn *multiplication* into *addition*.

$$\log(x\,y) = \log(x) + \log(y)$$

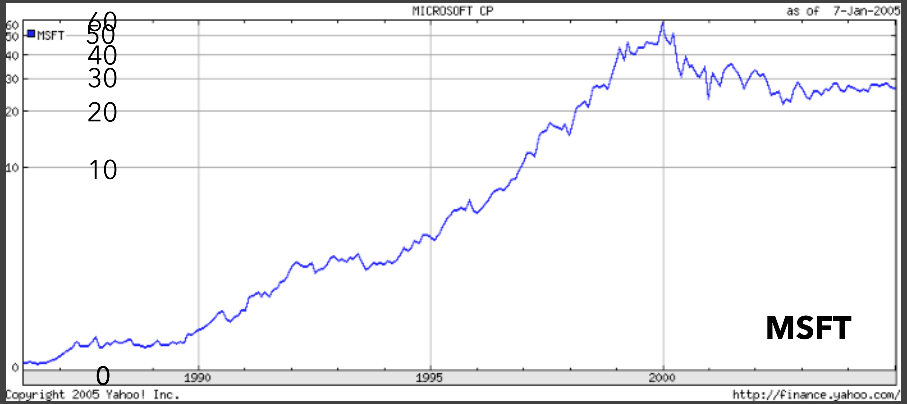
Equal steps on a log scale correspond to equal changes to a multiplicative scale factor.

Linear Scale vs. Log Scale

Linear Scale



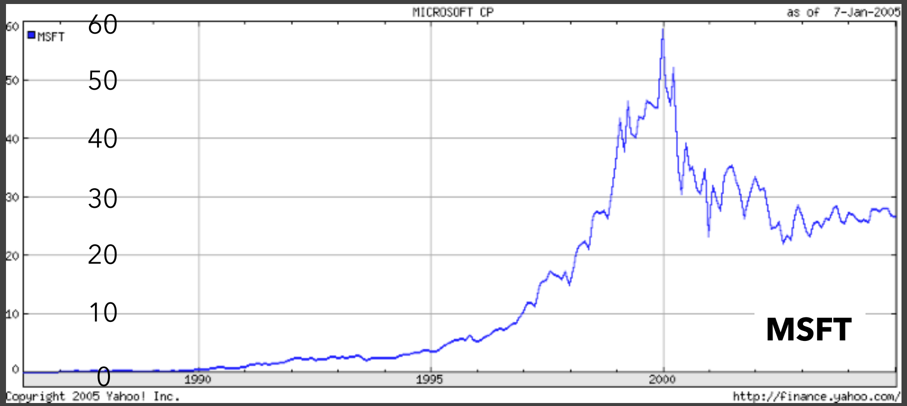
Log Scale



Linear Scale vs. Log Scale

Linear Scale

Absolute change

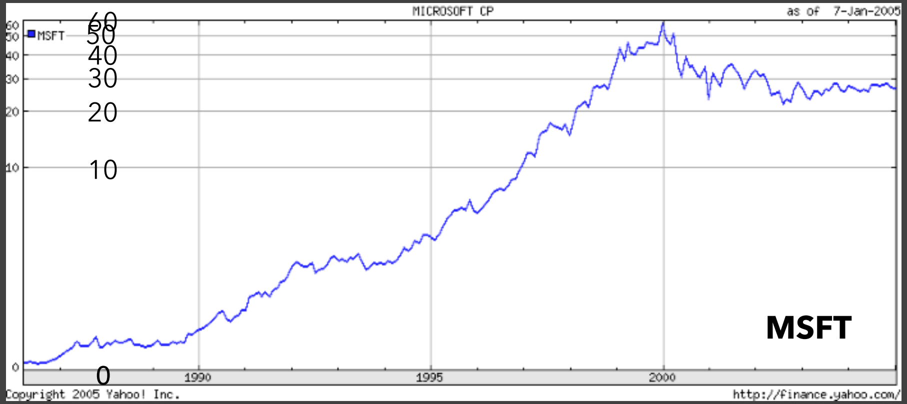


Log Scale

Small fluctuations

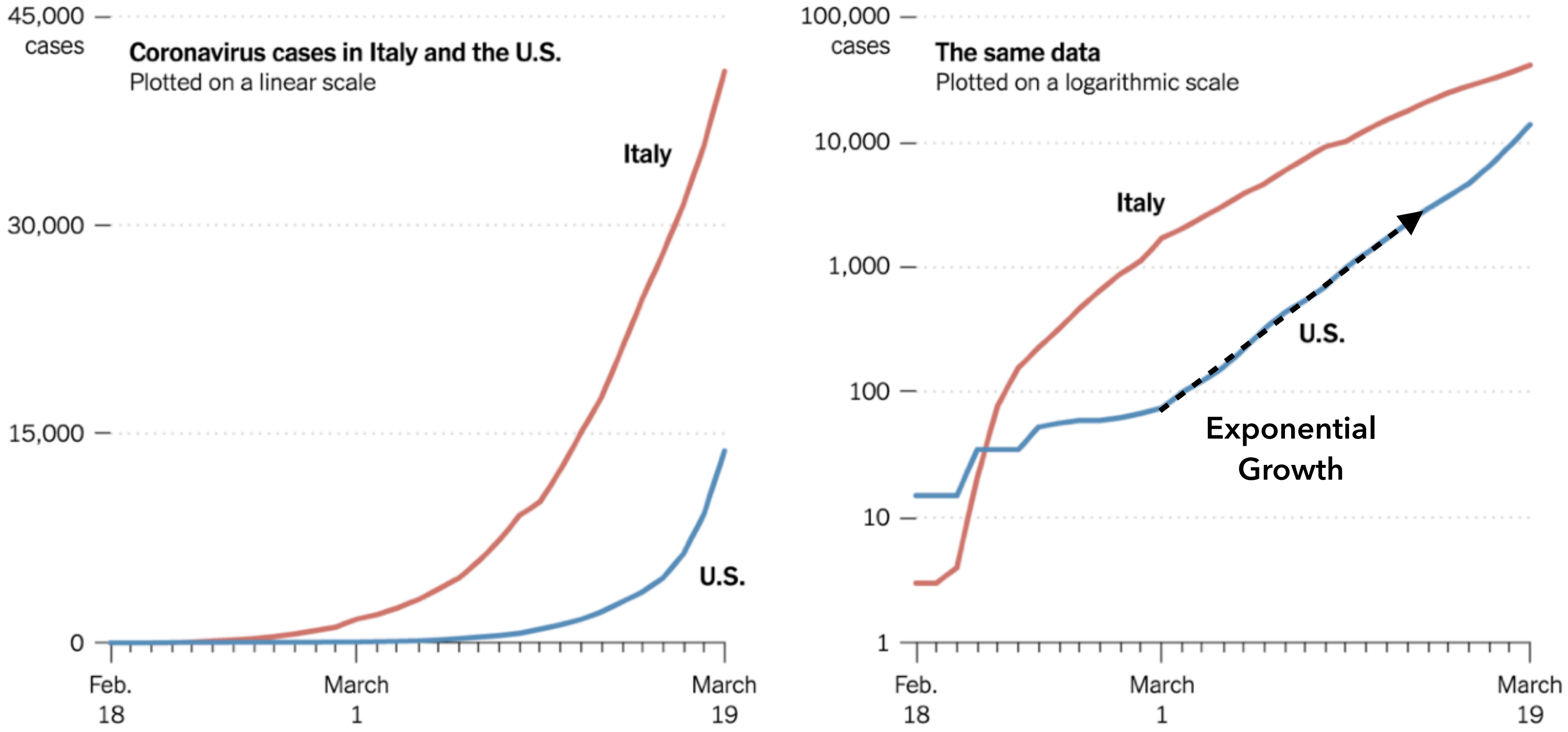
Percent change

d(10,30) > d(30,60)



Bending the Curve

Logarithmic scales can emphasize the rate of change in a way that linear scales do not. Italy seems to be slowing the coronavirus infection rate, while the number of cases in the United States continues to double every few days.



By The New York Times | Data from Worldometer

When To Apply a Log Scale?

Address data skew (e.g., long tails, outliers)

Enables comparison within and across multiple orders of magnitude.

Focus on multiplicative factors (not additive)

Recall that the logarithm transforms **×** to **+**!

Percentage change, not linear difference.

Constraint: **positive, non-zero values**

Constraint: **audience familiarity?**

Visual Encoding Design

Use **expressive** and **effective** encodings
Reduce the problem space
Avoid **over-encoding**
Use **space** and **small multiples** intelligently
Use **interaction** to generate *relevant* views

Rarely does a single visualization answer all questions. Instead, the ability to generate appropriate visualizations quickly is critical!

About the design process…

Visualization draws upon both science and art!

Principles like expressiveness & effectiveness are not hard-and-fast rules, but can assist us to guide the process and articulate alternatives.

They can lead us to think more deeply about our design rationale and prompt us to reflect.

It helps to know "the rules" in order to wisely bend (*or break*) them at the right times!