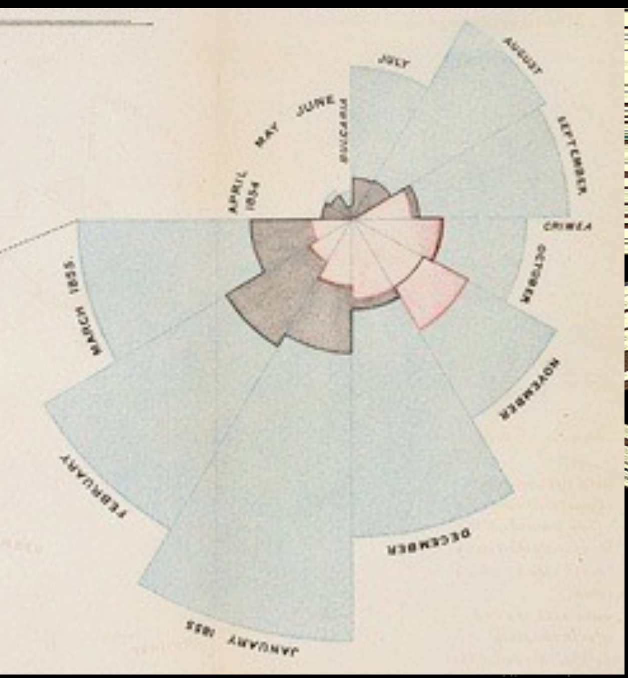
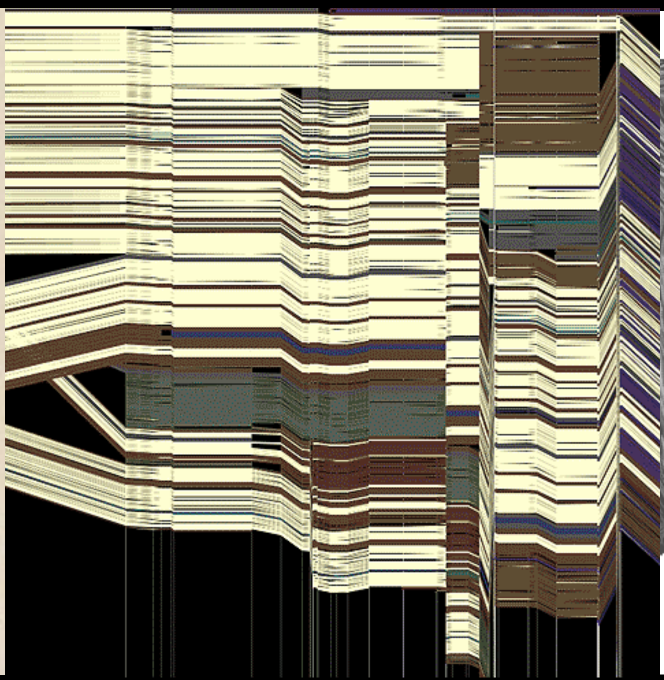
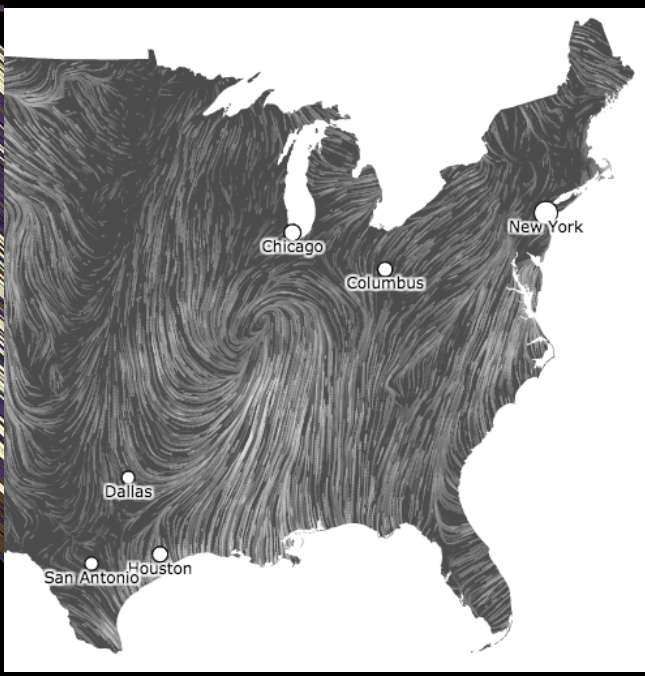
CSE 512 - Data Visualization

Exploratory Data Analysis







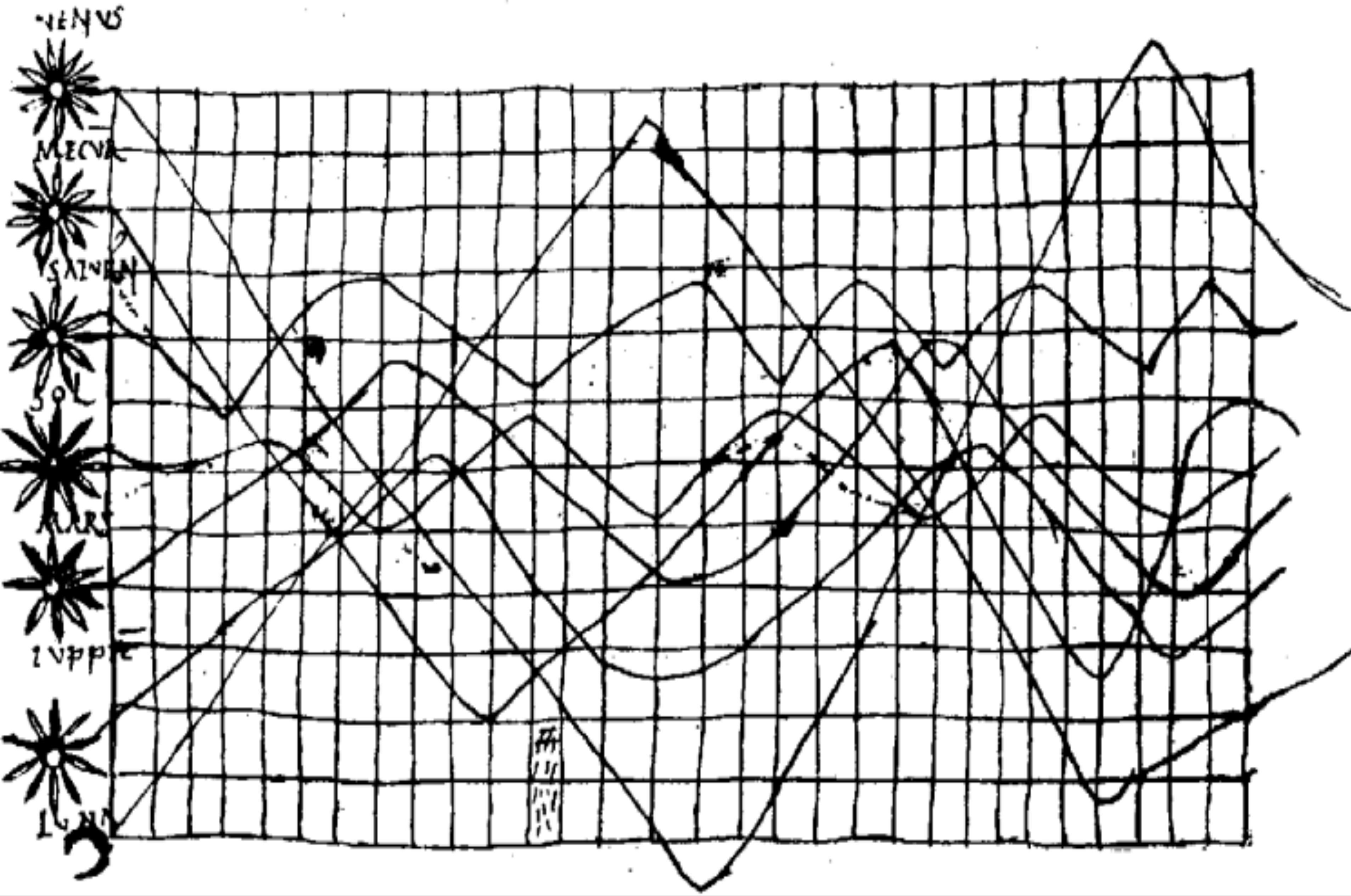
Jeffrey Heer University of Washington

What was the **first** data visualization?

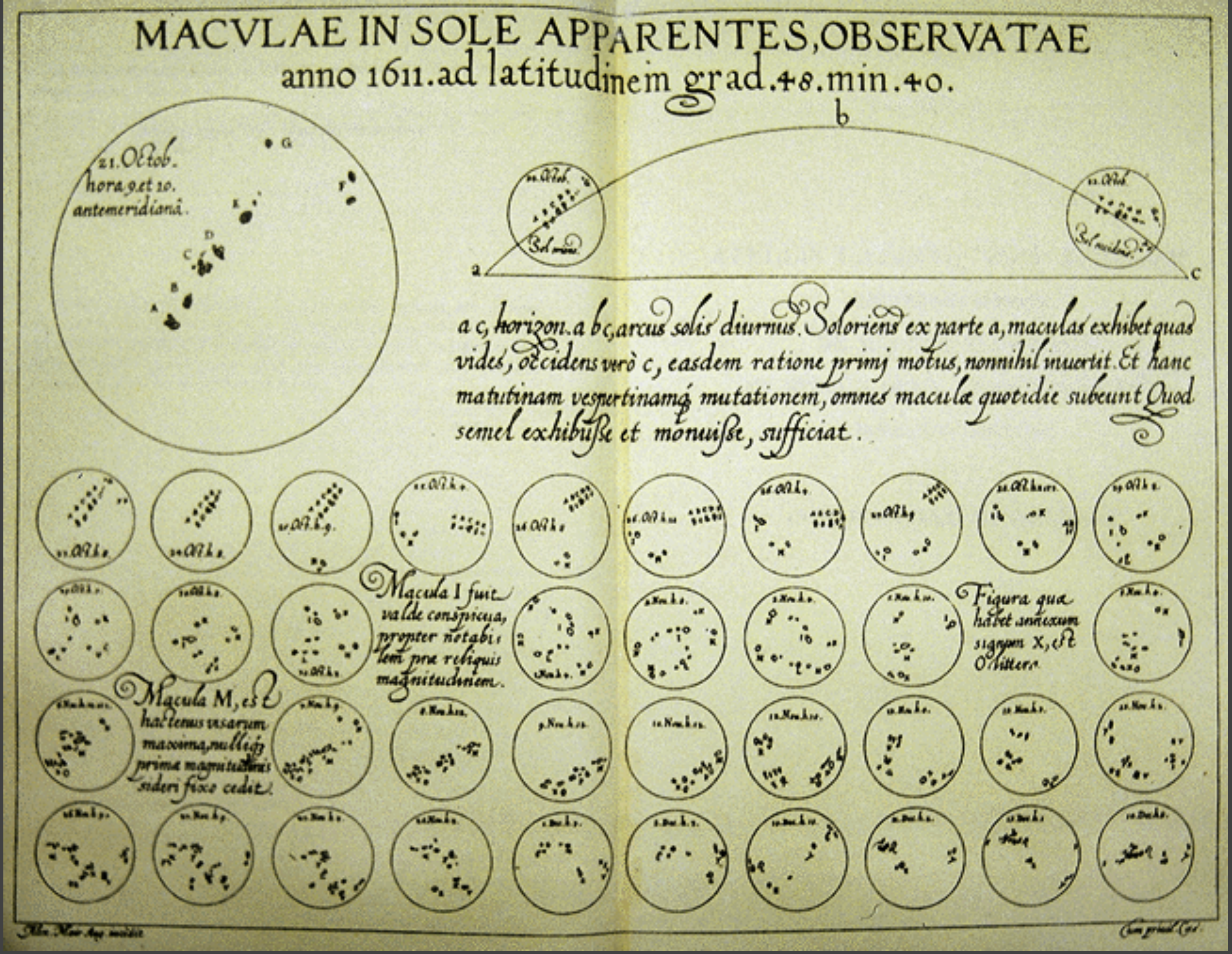
0 BC

~6200 BC Town Map of Catal Hyük, Konya Plain, Turkey

0 BC

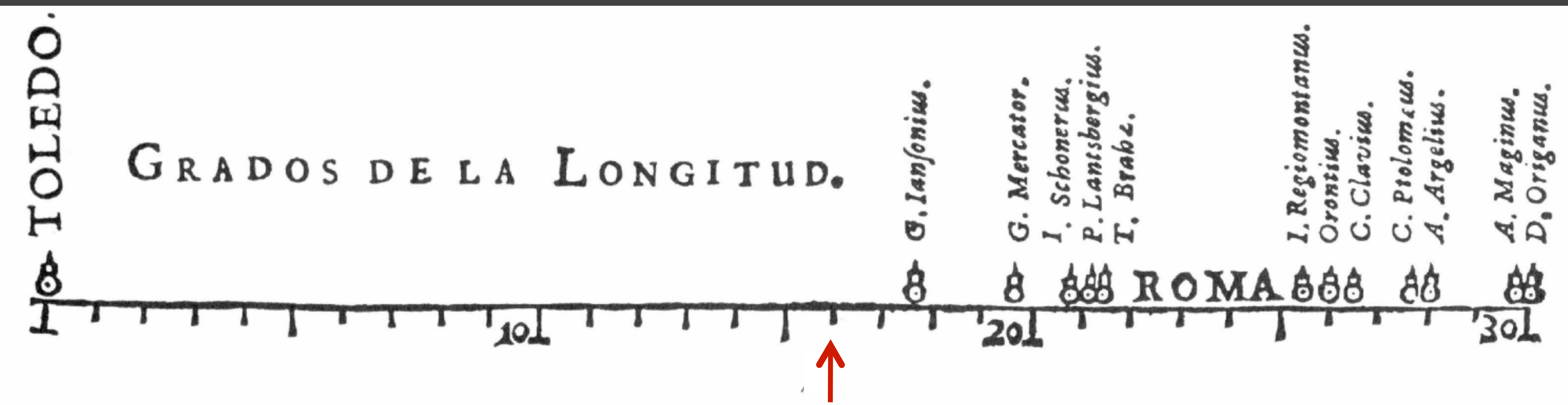


~950 AD Position of Sun, Moon and Planets

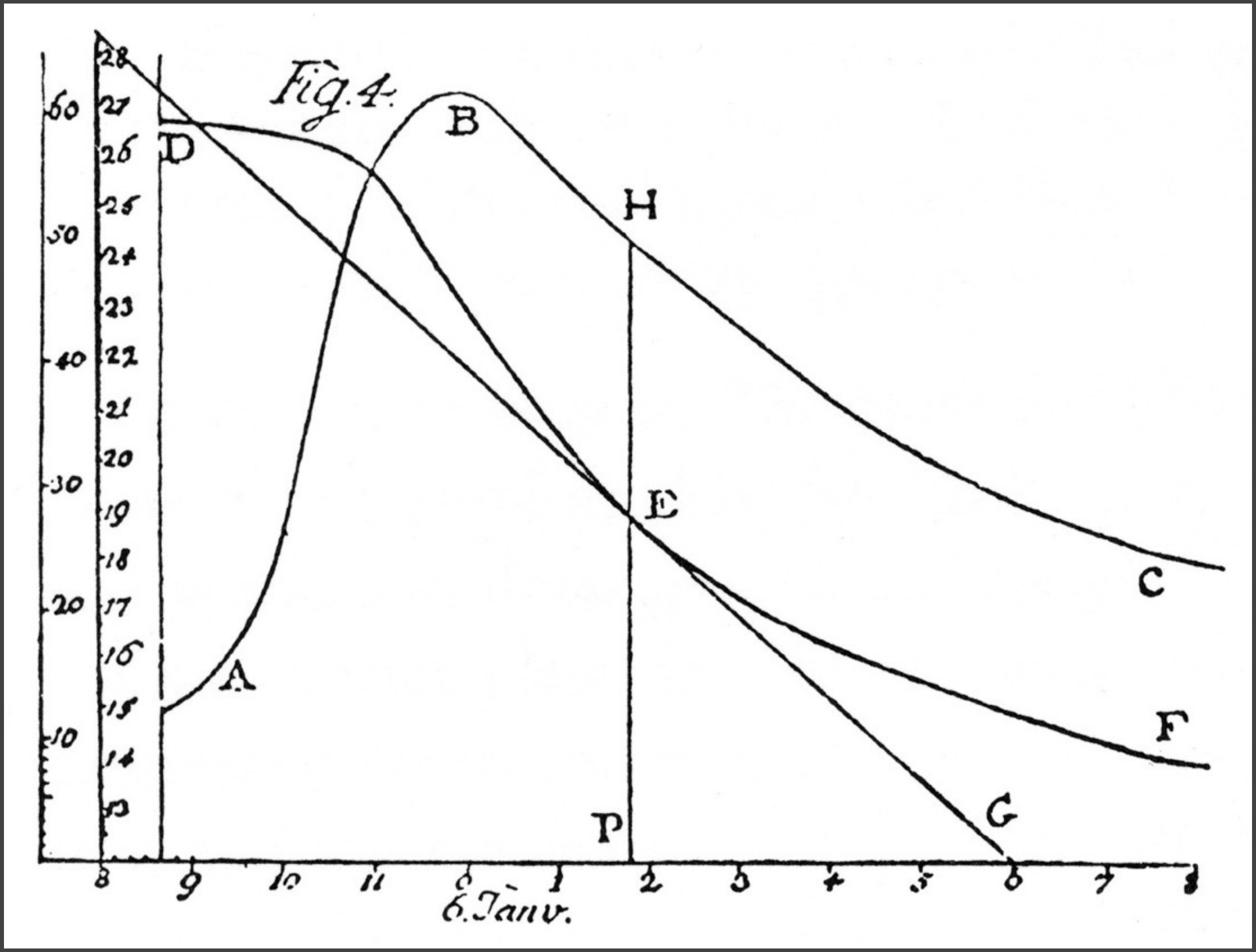


0 BC

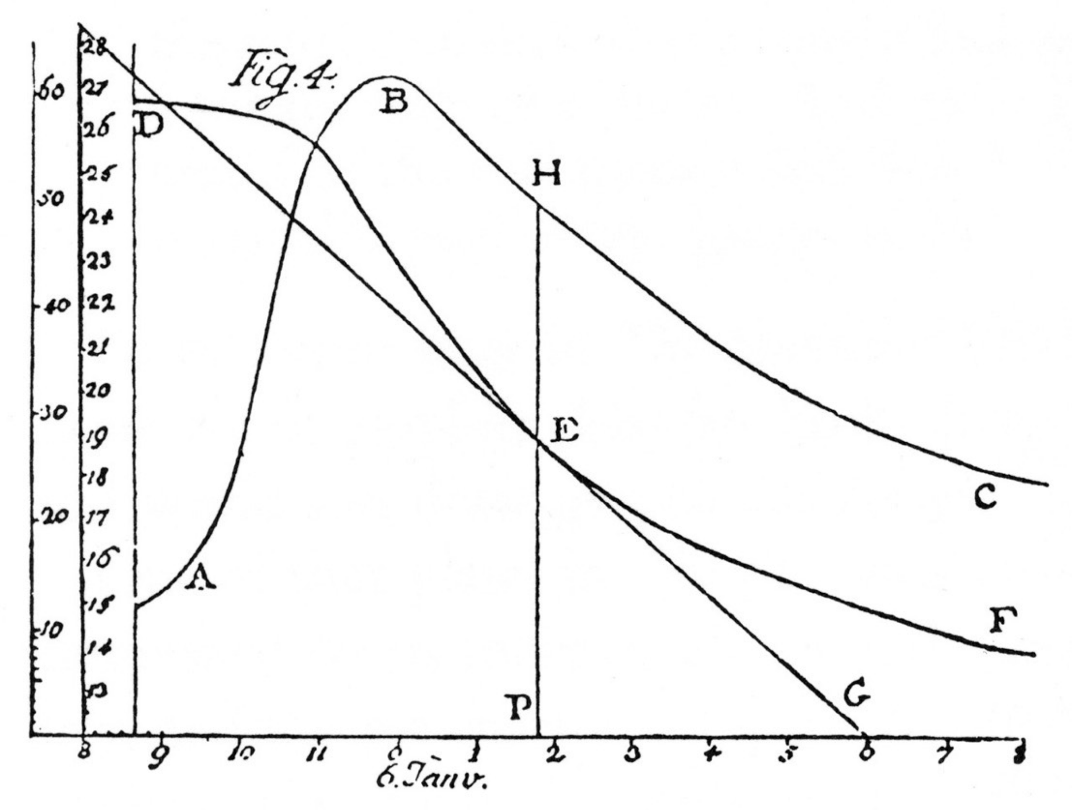
Sunspots over time, Scheiner 1626

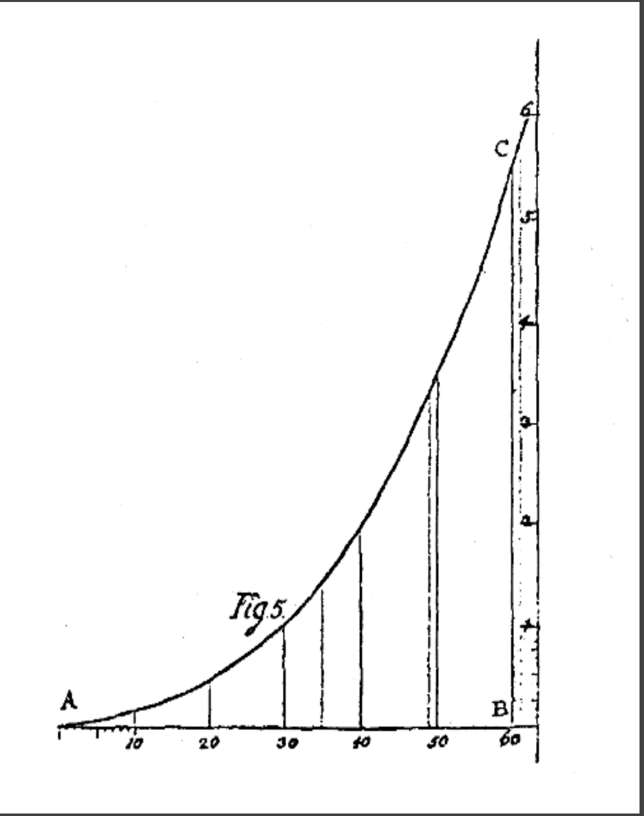


Longitudinal distance between Toledo and Rome, van Langren 1644



The Rate of Water Evaporation, Lambert 1765

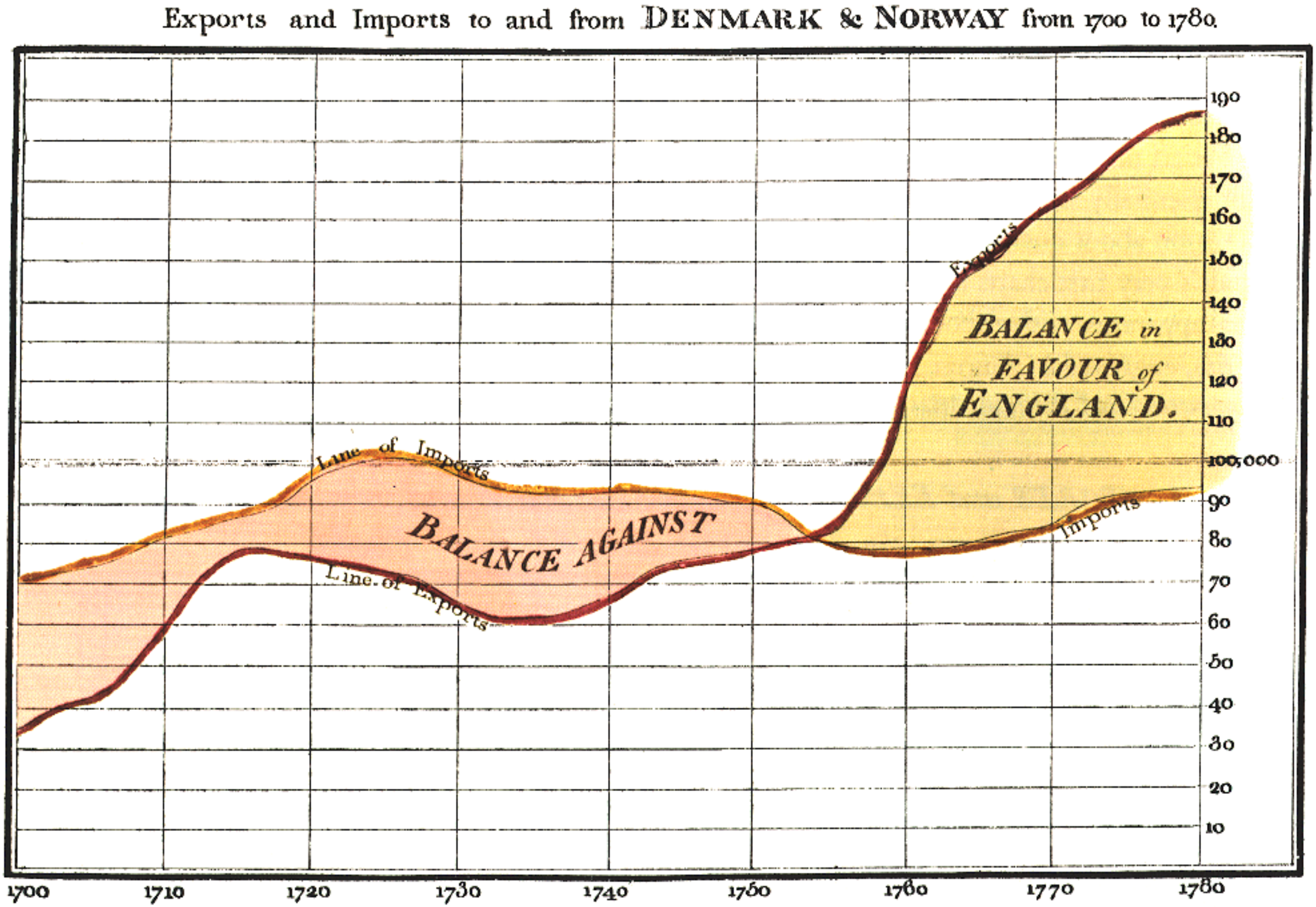




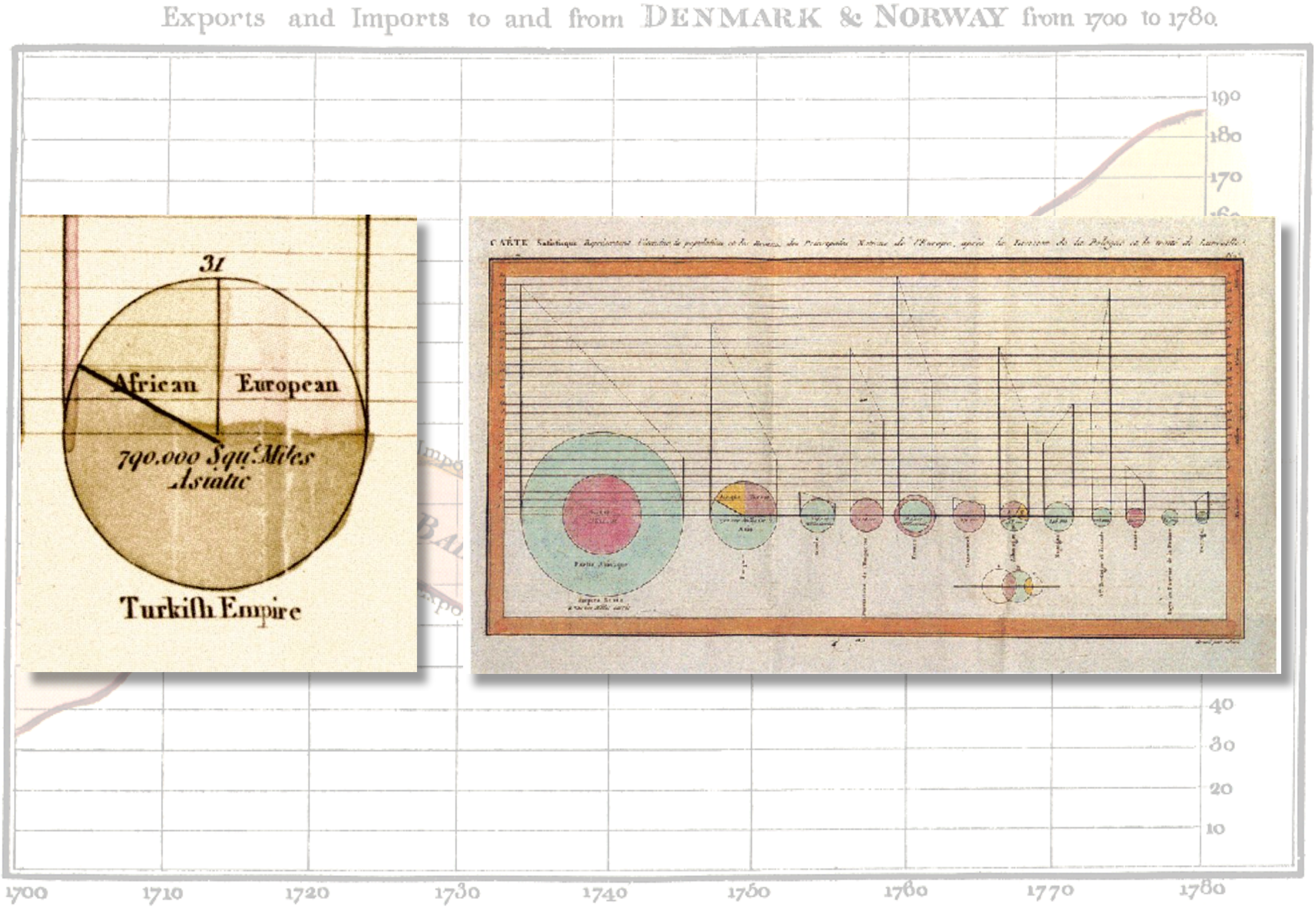
The Rate of Water Evaporation, Lambert 1765

The “**Golden Age**” of Data Visualization

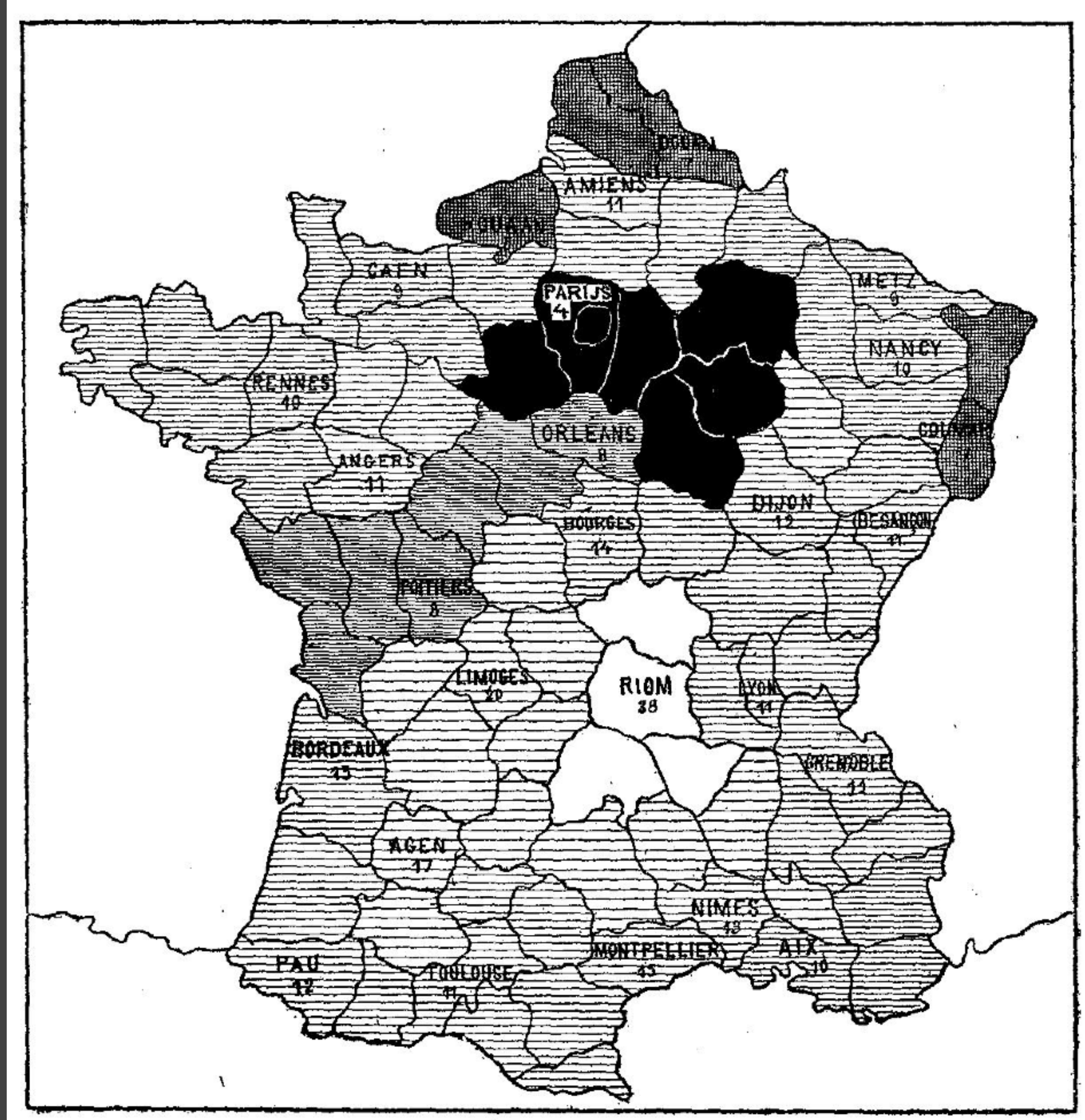
1786 1900



The Commercial and Political Atlas, William Playfair 1786

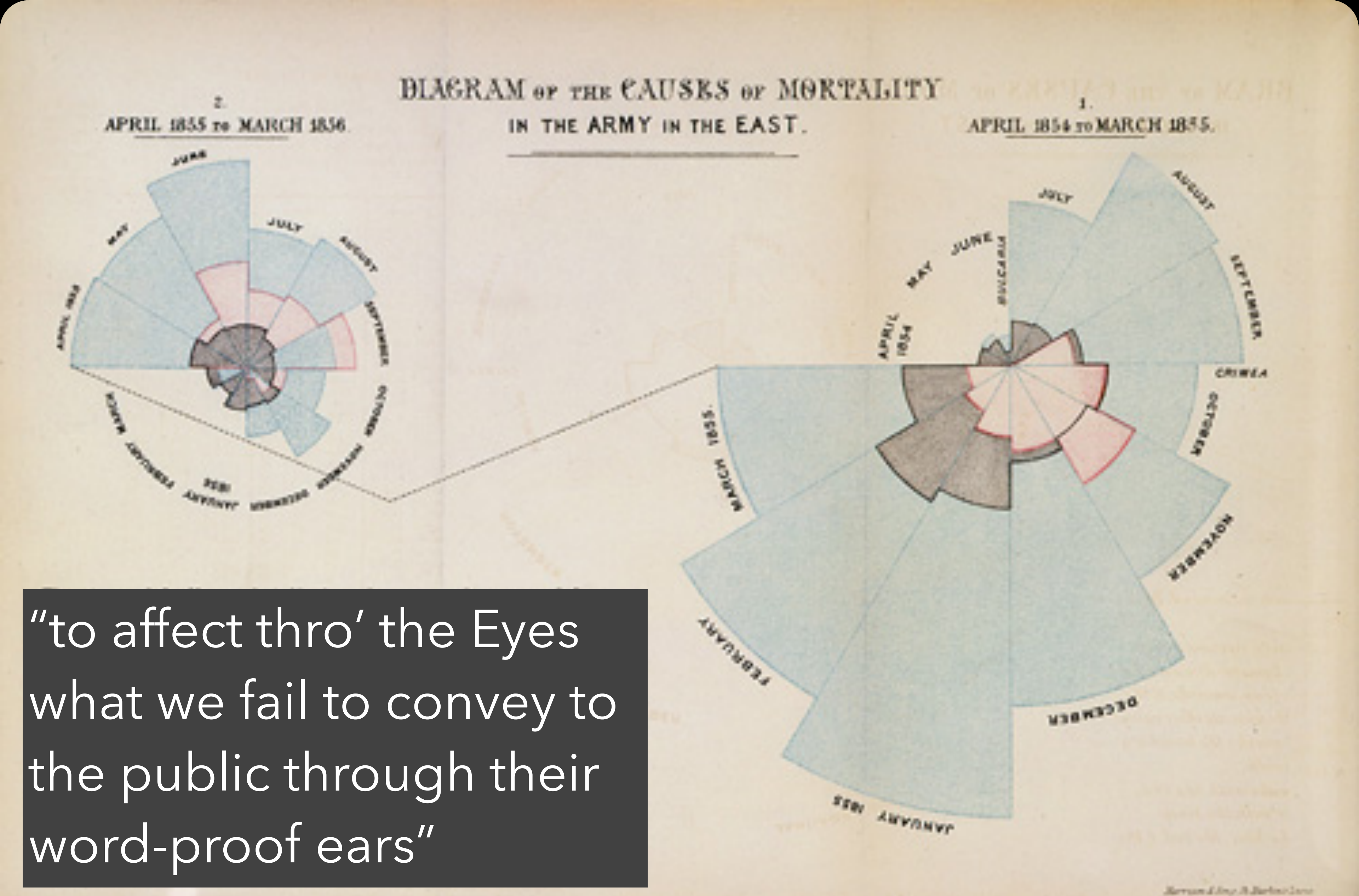


Statistical Breviary, William Playfair 1801



1786

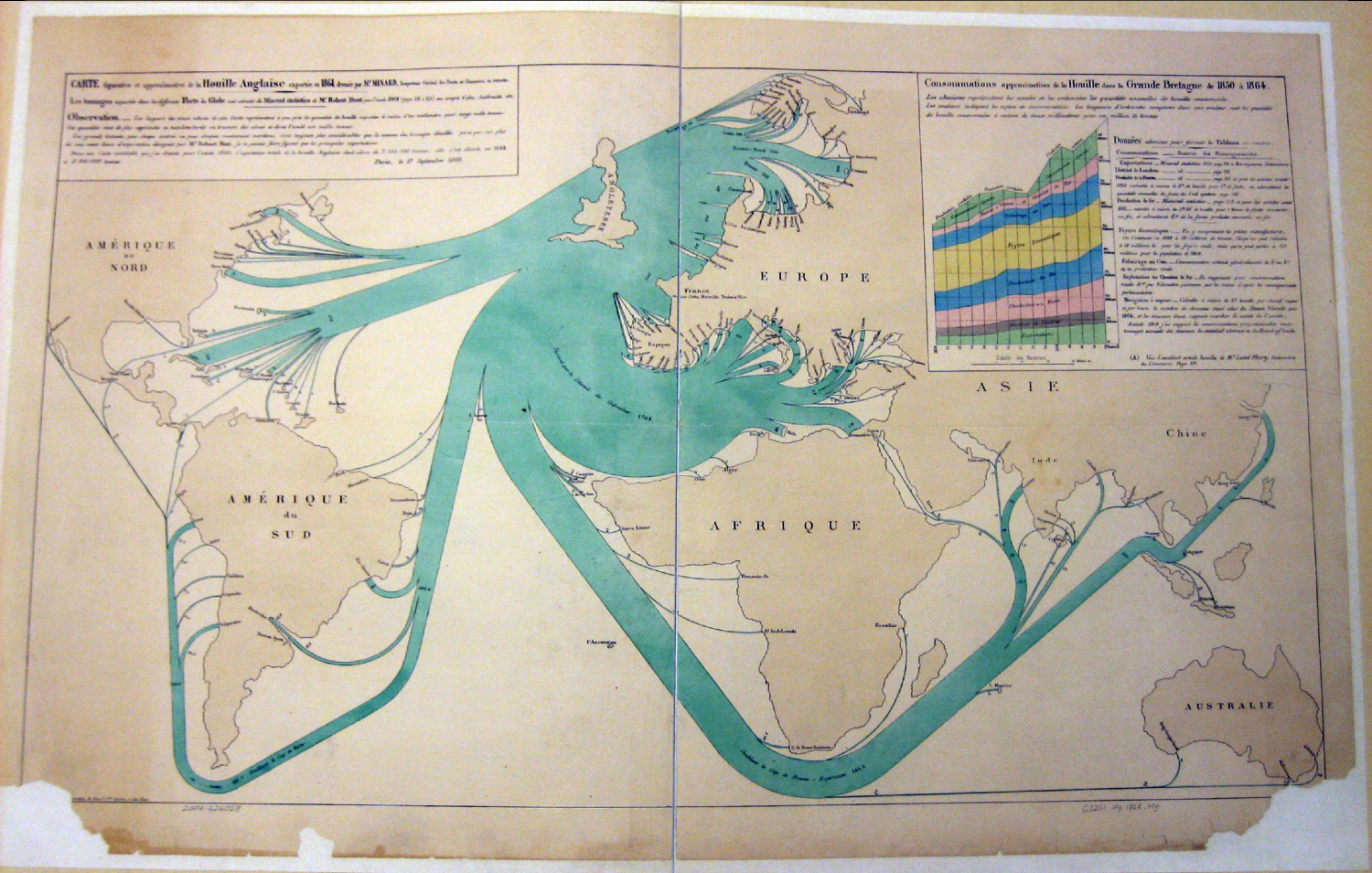
1826(?) Illiteracy in France, Pierre Charles Dupin



"to affect thro' the Eyes what we fail to convey to the public through their word-proof ears"

1786

1856 "Coxcomb" of Crimean War Deaths, Florence Nightingale

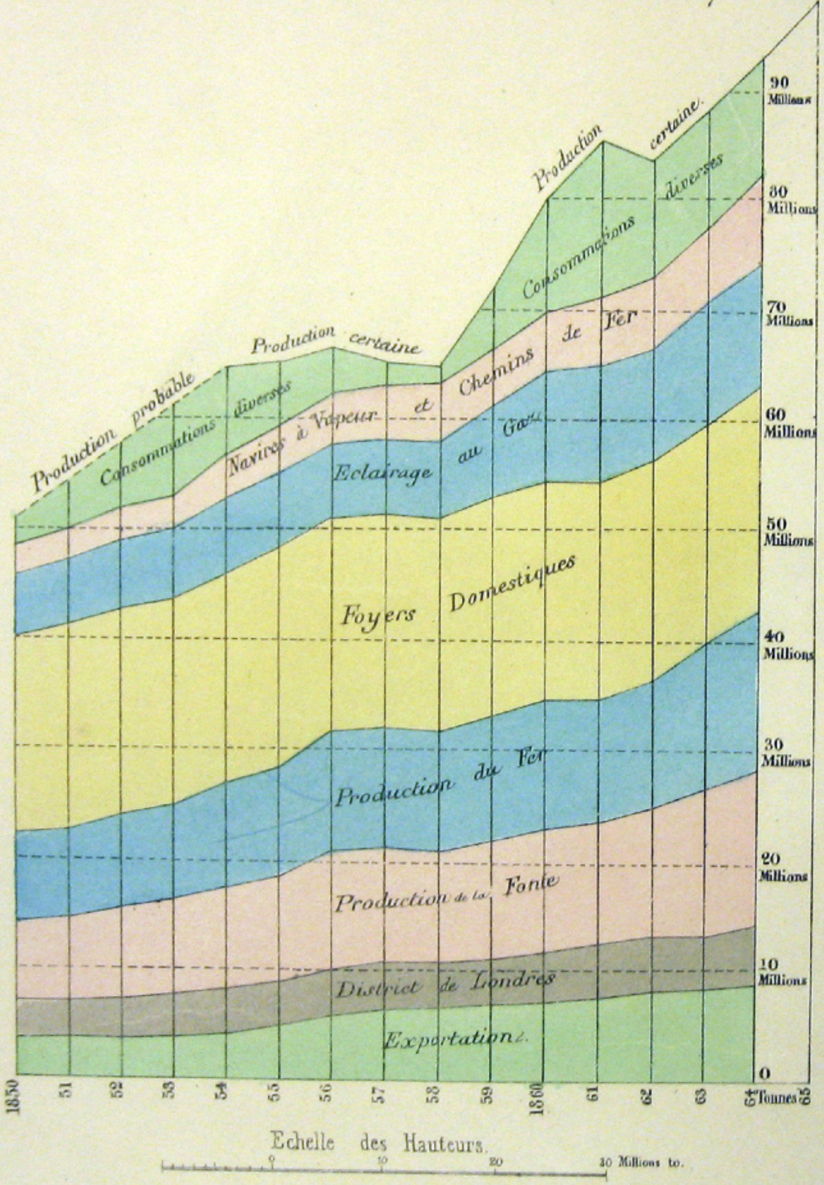


1786

1864 British Coal Exports, Charles Minard

Consommations approximatives de la Houille dans la Grande Bretagne de 1850 à 1864.

Les abscisses représentent les années et les ordonnées les quantités annuelles de houille consommée.
Les couleurs indiquent les espèces de consommations. Les longueurs d'ordonnées comprises dans une couleur sont les quantités de houille consommées à raison de deux millimètres pour un million de tonnes.



Données *admises pour former le* Tableau *ci-contre.*

Consommations. — Sources des Renseignements.

Exportations. — *Mineral statistics 1865 page 214 et Renseignements Parlementaires.*

District de Londres. — *id.* — *page 213*

Produits de la Fonte. — *id* — *page 215 et pour les années avant 1855 calculée à raison de 3to de houille pour 1to de fonte, en admettant les quantités annuelles de fonte du* Coal question *page 192.*

Production du fer — *Mineral statistics — page 215 et pour les années avant 1855 — calculée à raison de 3to35 de houille pour 1 tonne de fonte convertie en fer, et admettant $\frac{9}{10}$^{es} de la fonte produite convertis en fer.*

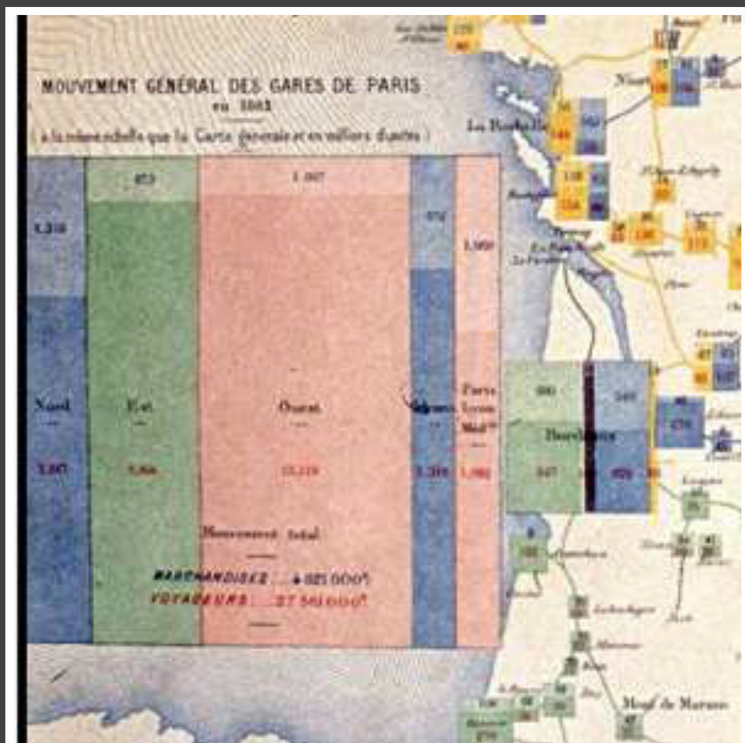
Foyers domestiques. — *En y comprenant les petites manufactures. On l'estimait en 1848 à 19 millions de tonnes, (A) qu'on peut réduire à 18 millions to. pour les foyers seuls, mais qu'on peut porter à 20 millions pour la population de 1864.*

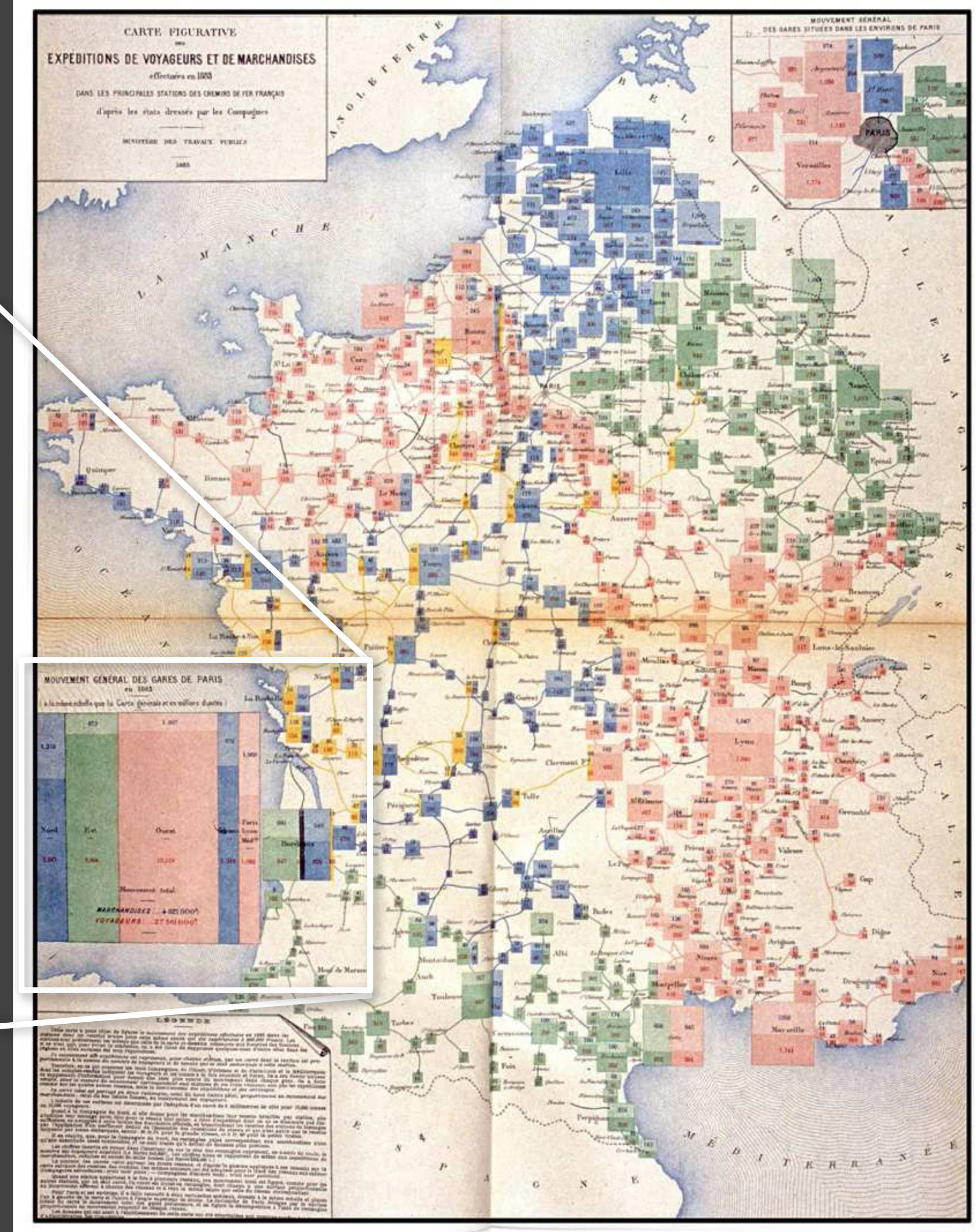
Eclairage au Gaz. — *Consommation estimée généralement du $\frac{1}{3}$^{e} au $\frac{1}{8}$^{e} de la production totale.*

Exploitation des **Chemins** de Fer. — *En supposant pour consommation totale 10^K par Kilomètre parcouru par les trains d'après les renseignements parlementaires.*

Navigation à vapeur. — *Calculée à raison de 5^K houille par cheval vapeur et par heure, le nombre de chevaux étant celui du Steam Vessels pour 1864, et les steamers étant supposés marcher la moitié de l'année;*
Avant 1864 j'ai supposé les consommations proportionnelles aux tonnages annuels des steamers du statistical abstract et du Board of trade.

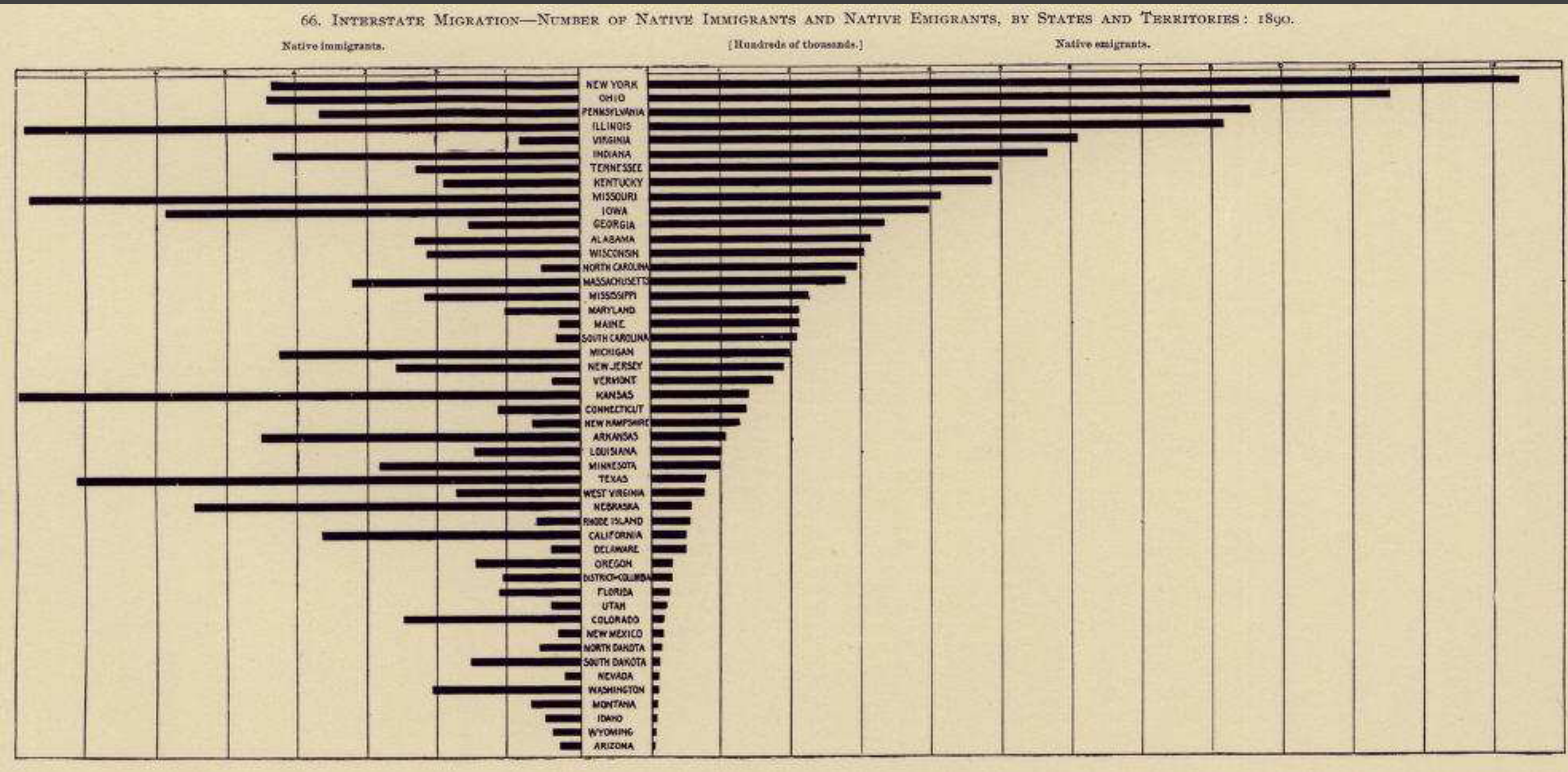
(A) *Voir l'excellent article houille de M^r Lamé Fleury, Dictionnaire du Commerce Page 111.*





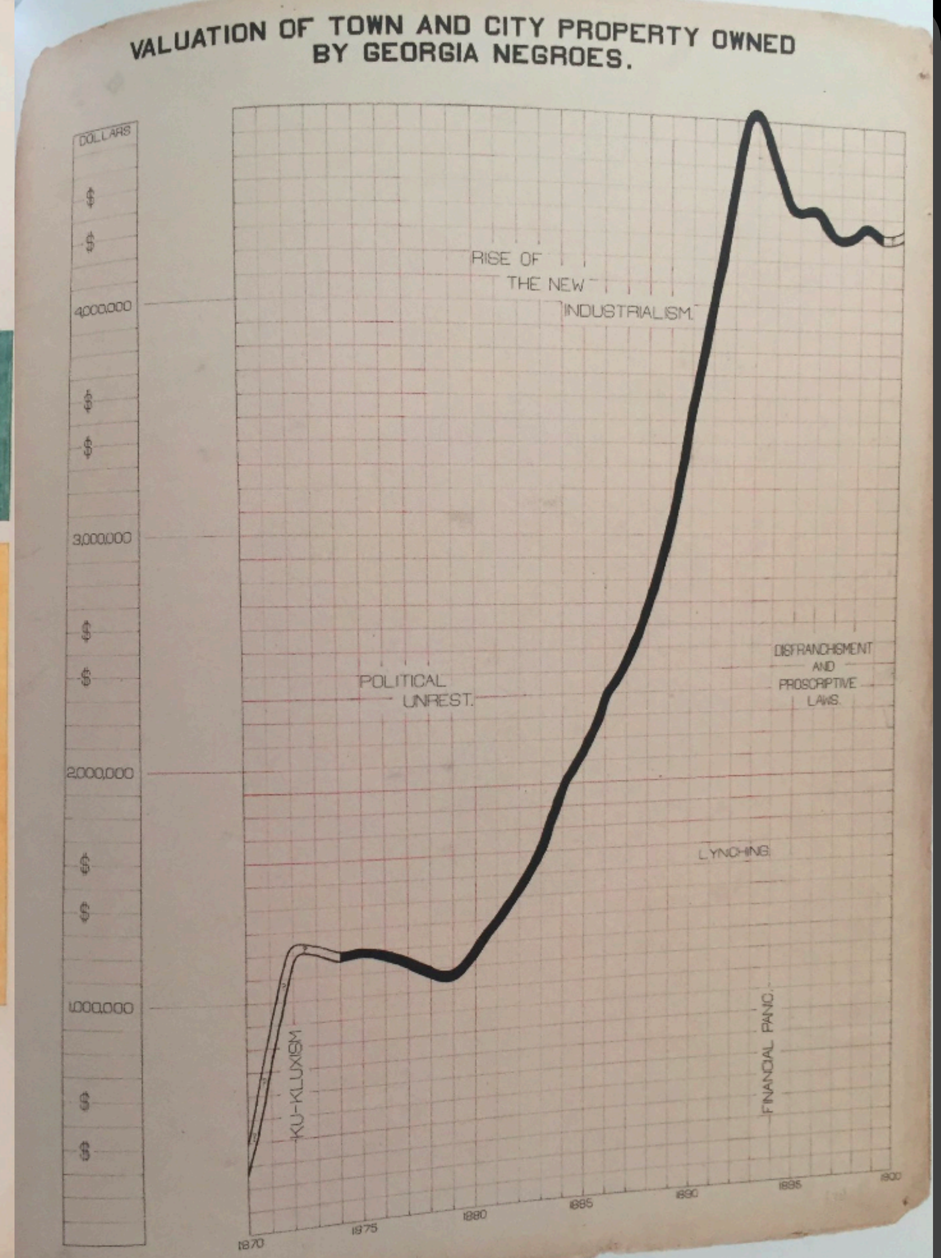
1786

1884 Rail Passengers and Freight from Paris



1786

1890 Statistical Atlas of the Eleventh U.S. Census



1786

1900 Visualizing Black America , W. E. B. DuBois et al.

The Rise of Statistics

1786 1900 1950

Rise of **formal statistical methods** in the physical and social sciences

Little innovation in graphical methods

A period of **application and popularization**

Graphical methods enter textbooks, curricula, and **mainstream use**

1786 1900 1950

1786

Data Analysis & Statistics, Tukey 1962

Four major influences act on data analysis today:

1. The formal theories of statistics.
2. Accelerating developments in computers and display devices.
3. The challenge, in many fields, of more and larger bodies of data.
4. The emphasis on quantification in a wider variety of disciplines.

The last few decades have seen the rise of formal theories of statistics, "legitimizing" variation by confining it by assumption to random sampling, often assumed to involve tightly specified distributions, and restoring the appearance of security by emphasizing narrowly optimized techniques and claiming to make statements with "known" probabilities of error.

While some of the influences of statistical theory on data analysis have been helpful, others have not.

Exposure, the effective laying open of the data to display the unanticipated, is to us a major portion of data analysis. Formal statistics has given almost no guidance to exposure; indeed, it is not clear how the **informality** and **flexibility** appropriate to the **exploratory character of exposure** can be fitted into any of the structures of formal statistics so far proposed.

Nothing - not the careful logic of mathematics, not statistical models and theories, not the awesome arithmetic power of modern computers - nothing can substitute here for the **flexibility of the informed human mind**.

Accordingly, both approaches and techniques need to be structured so as to **facilitate human involvement and intervention**.

Set A		Set B		Set C		Set D	
X	Y	X	Y	X	Y	X	Y
10	8.04	10	9.14	10	7.46	8	6.58
8	6.95	8	8.14	8	6.77	8	5.76
13	7.58	13	8.74	13	12.74	8	7.71
9	8.81	9	8.77	9	7.11	8	8.84
11	8.33	11	9.26	11	7.81	8	8.47
14	9.96	14	8.1	14	8.84	8	7.04
6	7.24	6	6.13	6	6.08	8	5.25
4	4.26	4	3.1	4	5.39	19	12.5
12	10.84	12	9.11	12	8.15	8	5.56
7	4.82	7	7.26	7	6.42	8	7.91
5	5.68	5	4.74	5	5.73	8	6.89

Summary Statistics

$u_X = 9.0$ $\sigma_X = 3.317$

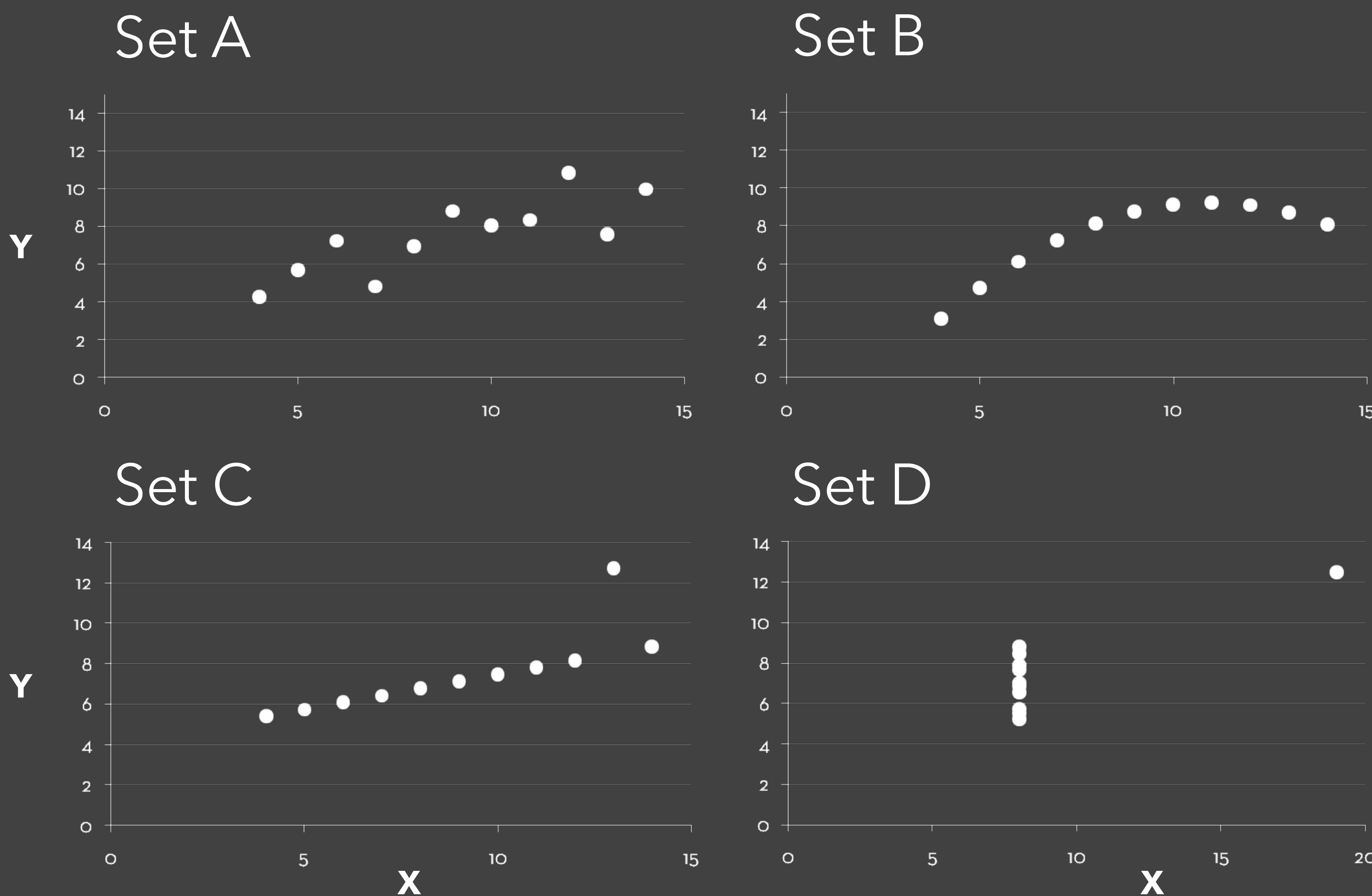
$u_Y = 7.5$ $\sigma_Y = 2.03$

Linear Regression

$Y = 3 + 0.5\ X$

$R^2 = 0.67$

[Anscombe 1973]



[Anscombe 1973]

Topics

Exploratory Data Analysis
Data Wrangling
Exploratory Analysis Examples
Tableau / Polaris

Data Wrangling

I spend more than half of my time integrating, cleansing and transforming data without doing any actual analysis. Most of the time I’m lucky if I get to do any “analysis” at all.

Anonymous Data Scientist

[Kandel et al. ’12]

Big Data Borat
@BigDataBorat

Following

In Data Science, 80% of time spent prepare data, 20% of time spent complain about need for prepare data.

Bureau of Justice Statistics - Data Online
http://bjs.ojp.usdoj.gov/

Reported crime in Alabama

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	4525375	4029.3	987	2732.4	309.9
2005	4548327	3900	955.8	2656	289
2006	4599030	3937	968.9	2645.1	322.9
2007	4627851	3974.9	980.2	2687	307.7
2008	4661900	4081.9	1080.7	2712.6	288.6

Reported crime in Alaska

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	657755	3370.9	573.6	2456.7	340.6
2005	663253	3615	622.8	2601	391
2006	670053	3582	615.2	2588.5	378.3
2007	683478	3373.9	538.9	2480	355.1
2008	686293	2928.3	470.9	2219.9	237.5

Reported crime in Arizona

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	5739879	5073.3	991	3118.7	963.5
2005	5953007	4827	946.2	2958	922
2006	6166318	4741.6	953	2874.1	914.4
2007	6338755	4502.6	935.4	2780.5	786.7
2008	6500180	4087.3	894.2	2605.3	587.8

Reported crime in Arkansas

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	2750000	4033.1	1096.4	2699.7	237
2005	2775708	4068	1085.1	2720	262
2006	2810872	4021.6	1154.4	2596.7	270.4
2007	2834797	3945.5	1124.4	2574.6	246.5
2008	2855390	3843.7	1182.7	2433.4	227.6

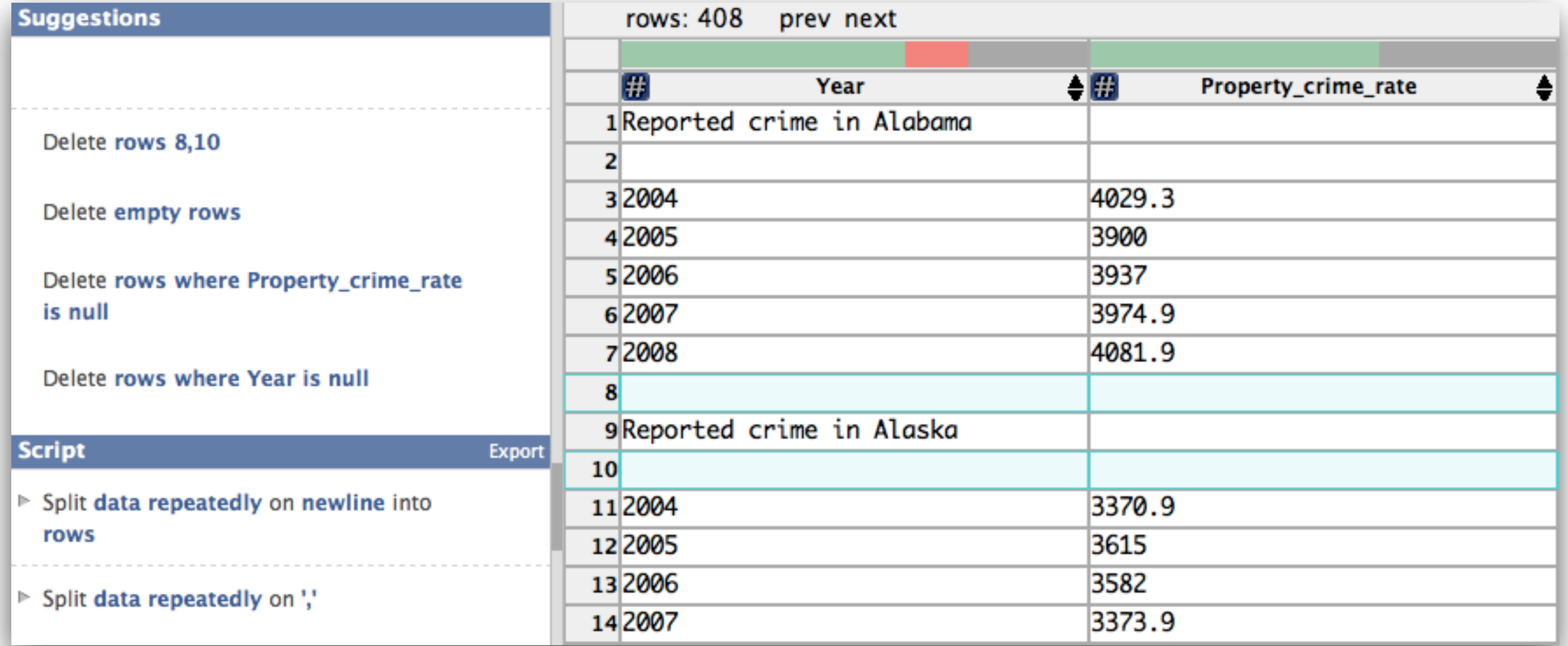
Reported crime in California

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	35842038	3423.9	686.1	2033.1	704.8
2005	36154147	3321	692.9	1915	712
2006	36457549	3175.2	676.9	1831.5	666.8
2007	36553215	3032.6	648.4	1784.1	600.2
2008	36756666	2940.3	646.8	1769.8	523.8

Reported crime in Colorado

Year	Population	Property crime rate	Burglary rate	Larceny-theft rate	Motor vehicle theft rate
2004	4601821	3918.5	717.3	2679.5	521.6

DataWrangler



Wrangler: Interactive Visual Specification of Data Transformation Scripts

Sean Kandel et al. *CHI'11*

Data Wrangling

One often needs to manipulate data prior to analysis. Tasks include reformatting, cleaning, quality assessment, and integration.

Approaches include:
Manual manipulation in spreadsheets
Code: arquero (JS), dplyr (R), pandas (Python)
Tableau Prep
Open Refine

Tidy Data [Wickham 2014]

How do rows, columns, and tables match up with observations, variables, and types? In "tidy" data:

1. Each variable forms a column.
2. Each observation forms a row.
3. Each type of observational unit forms a table.

The advantage is that this provides a flexible starting point for analysis, transformation, and visualization.

Our pivoted table variant was not "tidy"!

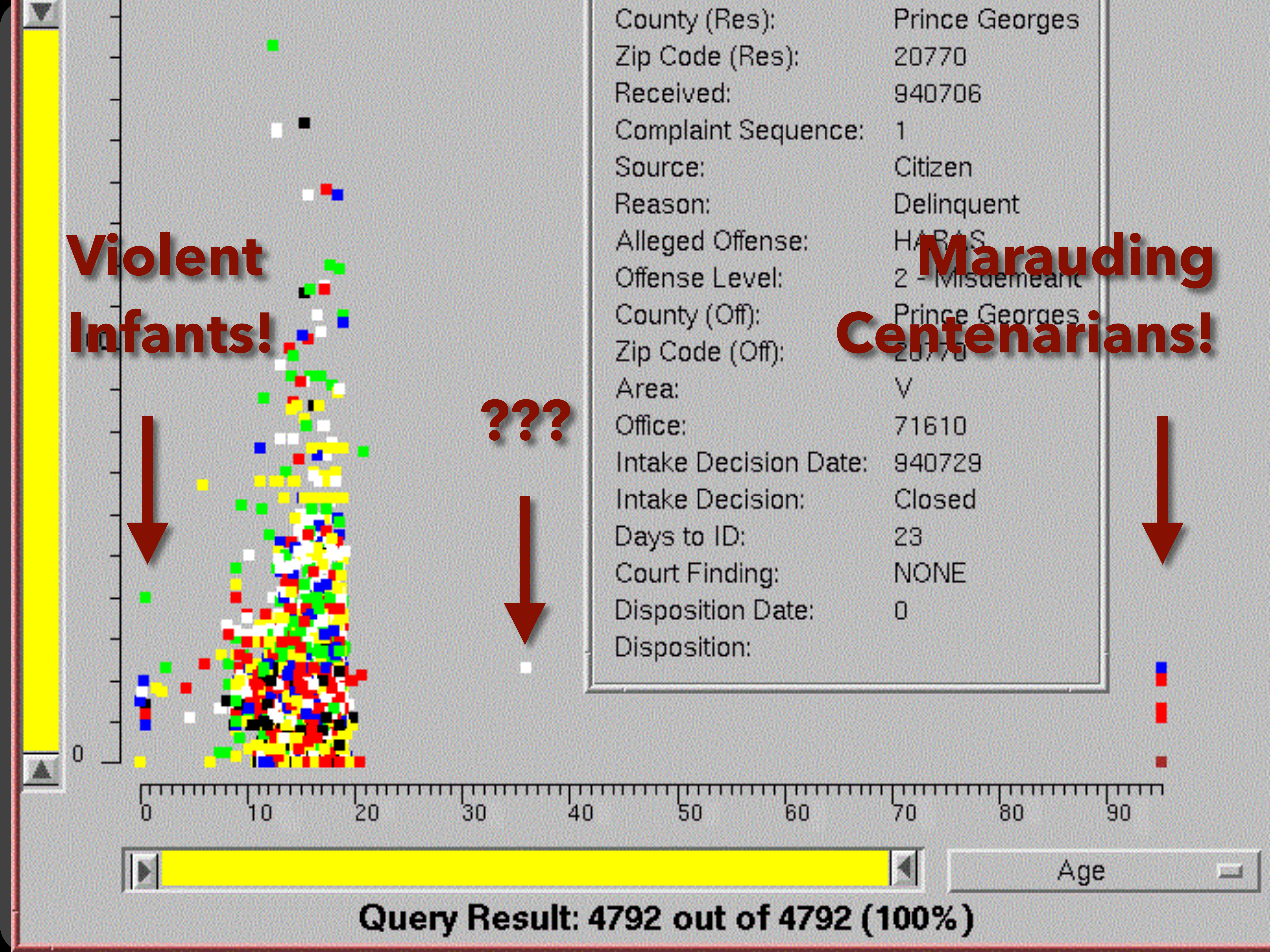
(This is a variant of <u>normalized forms</u> in DB theory)

Data Quality

“The first sign that a visualization is good is that it shows you a problem in your data…

…every successful visualization that I've been involved with has had this stage where you realize, "Oh my God, this data is not what I thought it would be!" So already, you've discovered something.”

Martin Wattenberg



County (Res): Prince Georges
Zip Code (Res): 20770
Received: 940706
Complaint Sequence: 1
Source: Citizen
Reason: Delinquent
Alleged Offense: HARAS
Offense Level: 2 - Misdemeanor
County (Off): Prince Georges
Zip Code (Off): 20770
Area: V
Office: 71610
Intake Decision Date: 940729
Intake Decision: Closed
Days to ID: 23
Court Finding: NONE
Disposition Date: 0
Disposition:
Violent Infants!
???
Marauding Centenarians!
0
0
10
20
30
40
50
60
70
80
90
Age
Query Result: 4792 out of 4792 (100%)

Graph Viewer

Graph Viewer

Roll-up by:

All

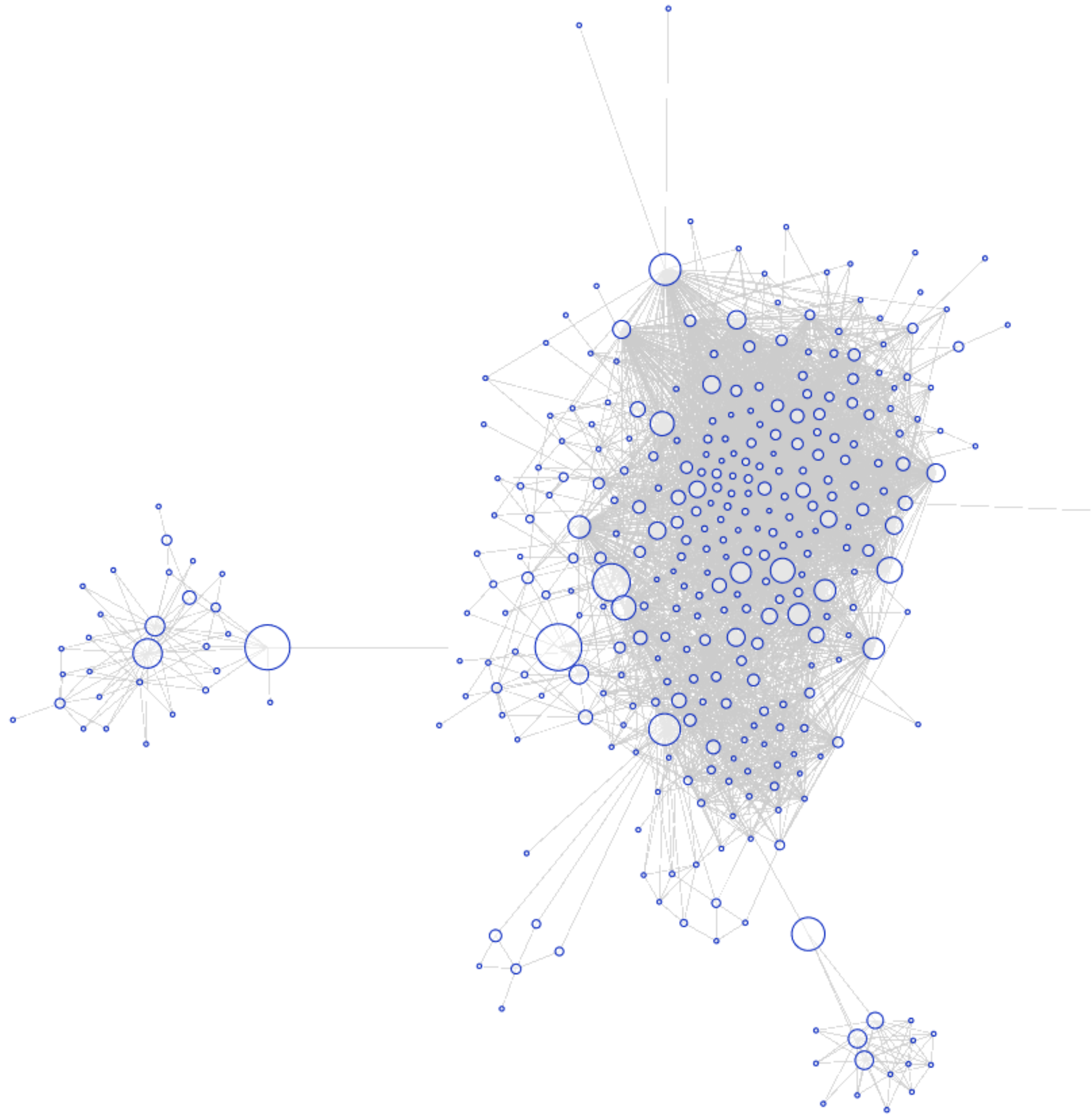
Visualization:

Node-Link

Sort by:

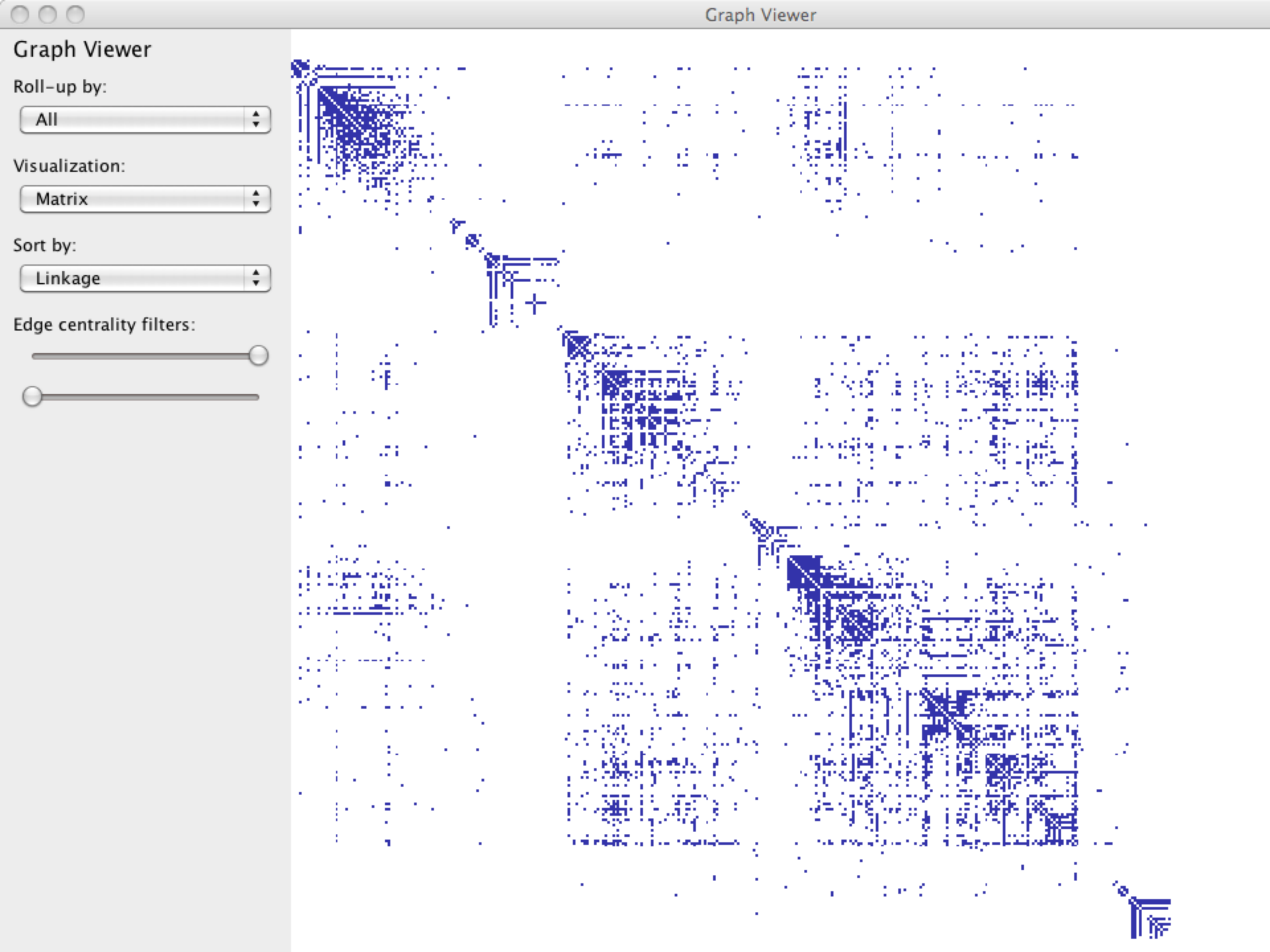
None

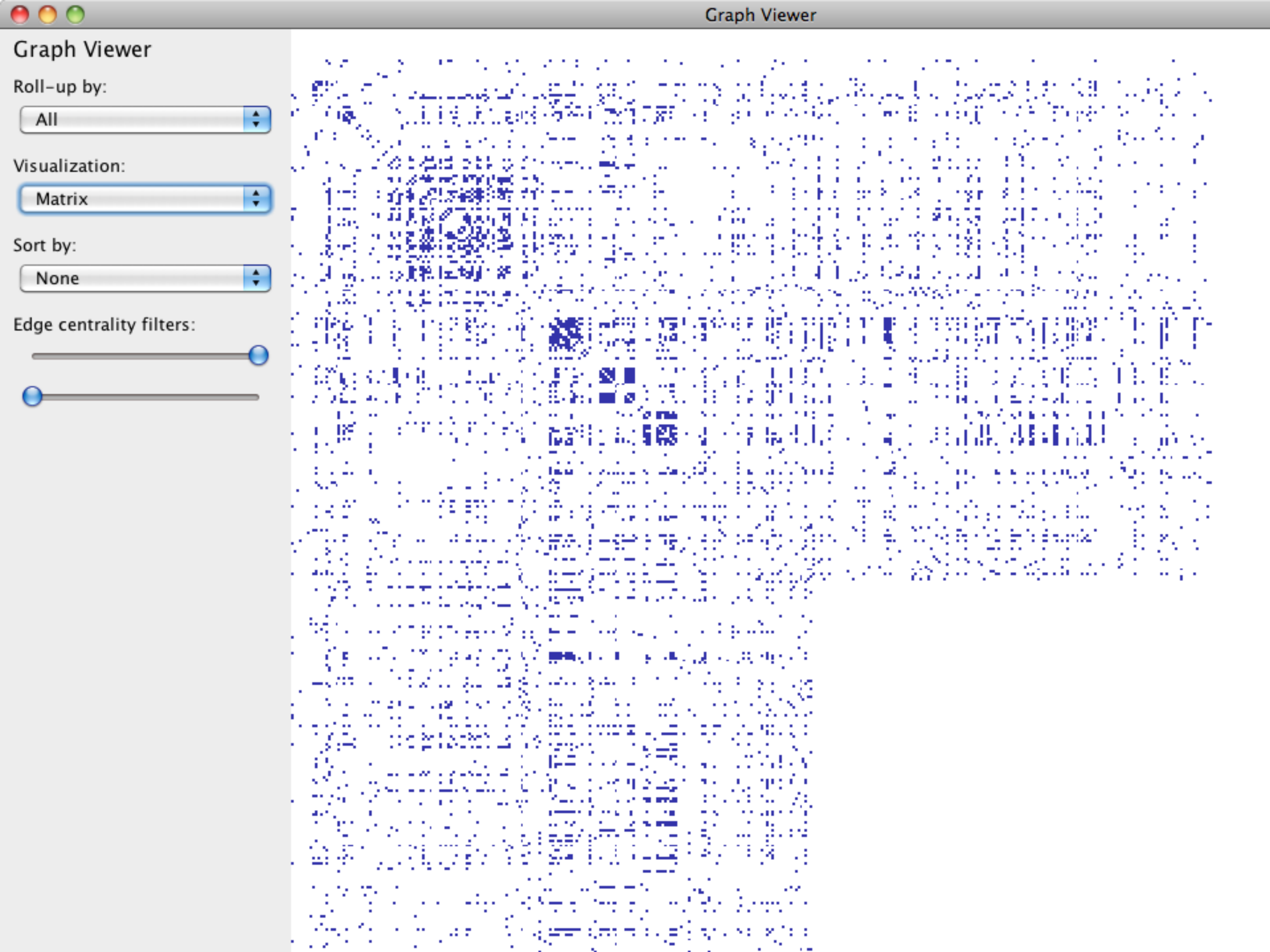
Edge centrality filters:



Images

☑ Animate


Graph Viewer
Graph Viewer
Roll-up by:
All
Visualization:
Matrix
Sort by:
Linkage
Edge centrality filters:


Graph Viewer
Graph Viewer
Roll-up by:
All
Visualization:
Matrix
Sort by:
None
Edge centrality filters:

Visualize Friends by School?

Berkeley |||||||||||||||||||||||||||||||

Cornell ||||

Harvard |||||||||

Harvard University |||||||

Stanford ||||||||||||||||||||

Stanford University ||||||||||

UC Berkeley |||||||||||||||||||||

UC Davis ||||||||||

University of California at Berkeley |||||||||||||||

University of California, Berkeley ||||||||||||||||||

University of California, Davis |||

Data Quality Hurdles

Missing Data	no measurements, redacted, …?
Erroneous Values	misspelling, outliers, …?
Type Conversion	e.g., zip code to lat-lon
Entity Resolution	diff. values for the same thing?
Data Integration	effort/errors when combining data

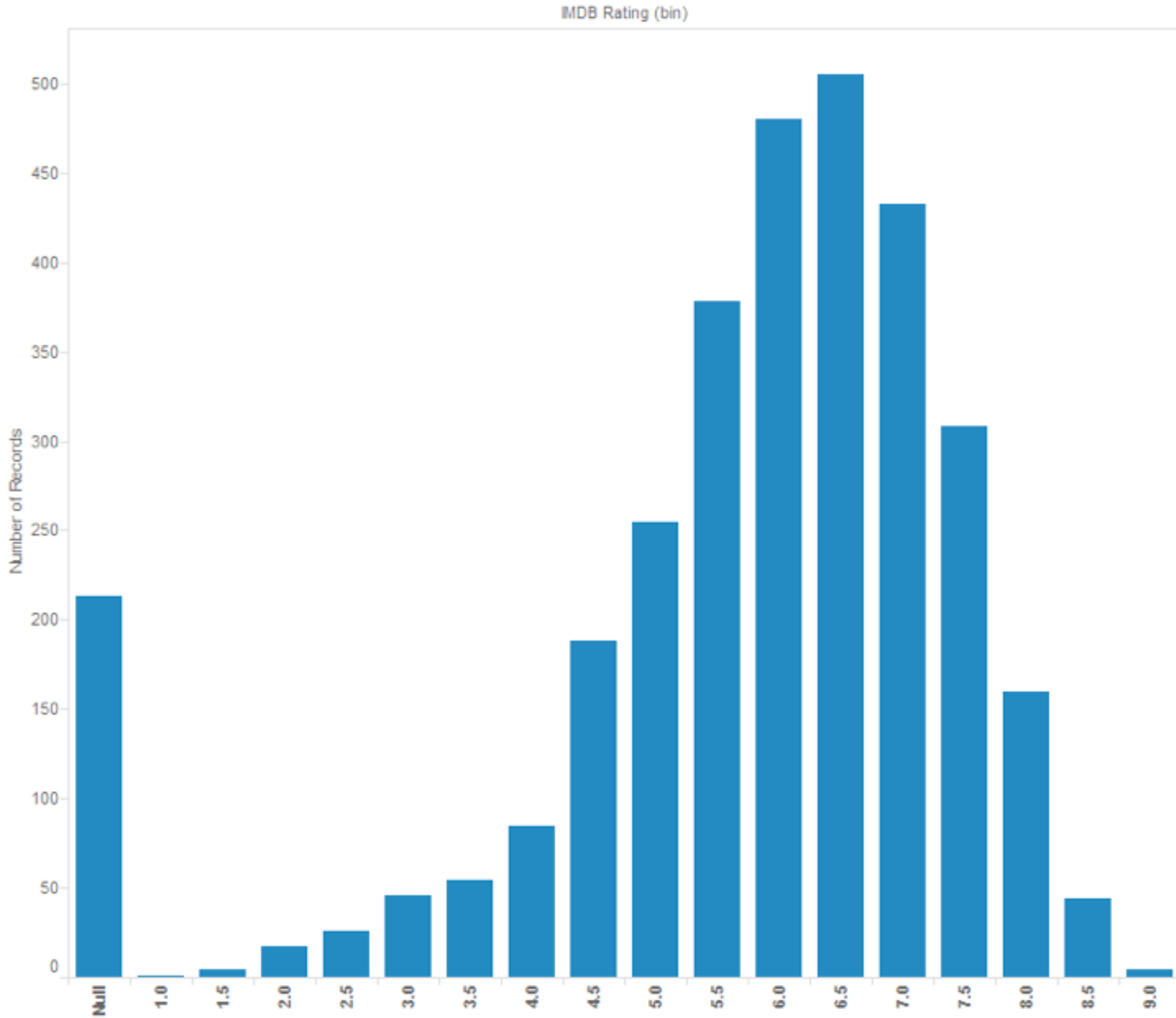
LESSON: Anticipate problems with your data.

Many research problems around these issues!

Analysis Example:
Motion Pictures Data

Motion Pictures Data

Title	String (N)
IMDB Rating	Number (Q)
Rotten Tomatoes Rating	Number (Q)
MPAA Rating	String (O)
Release Date	Date (T)


IMDB Rating (bin)
Number of Records
0
50
100
150
200
250
300
350
400
450
500
Null
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
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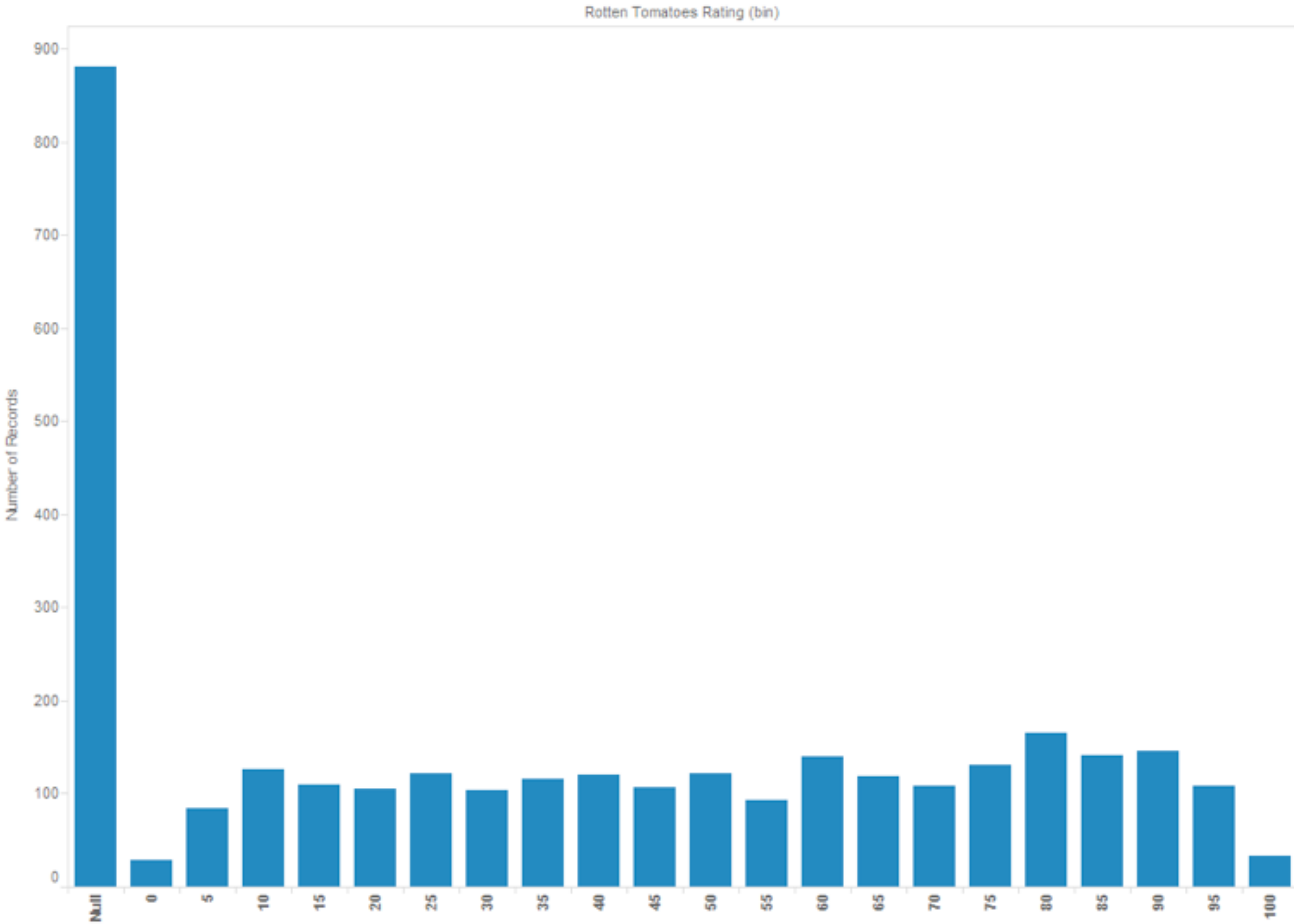
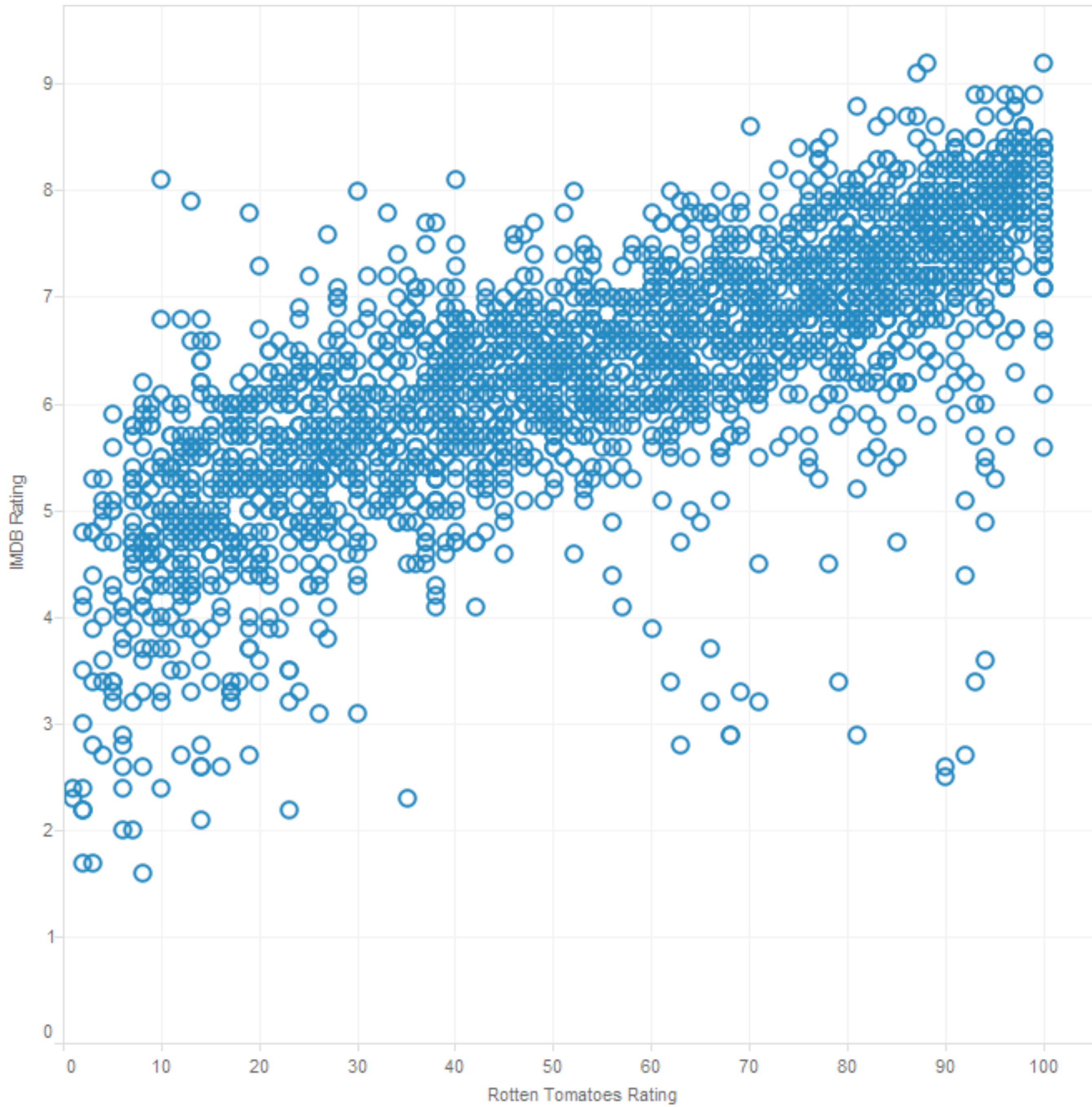
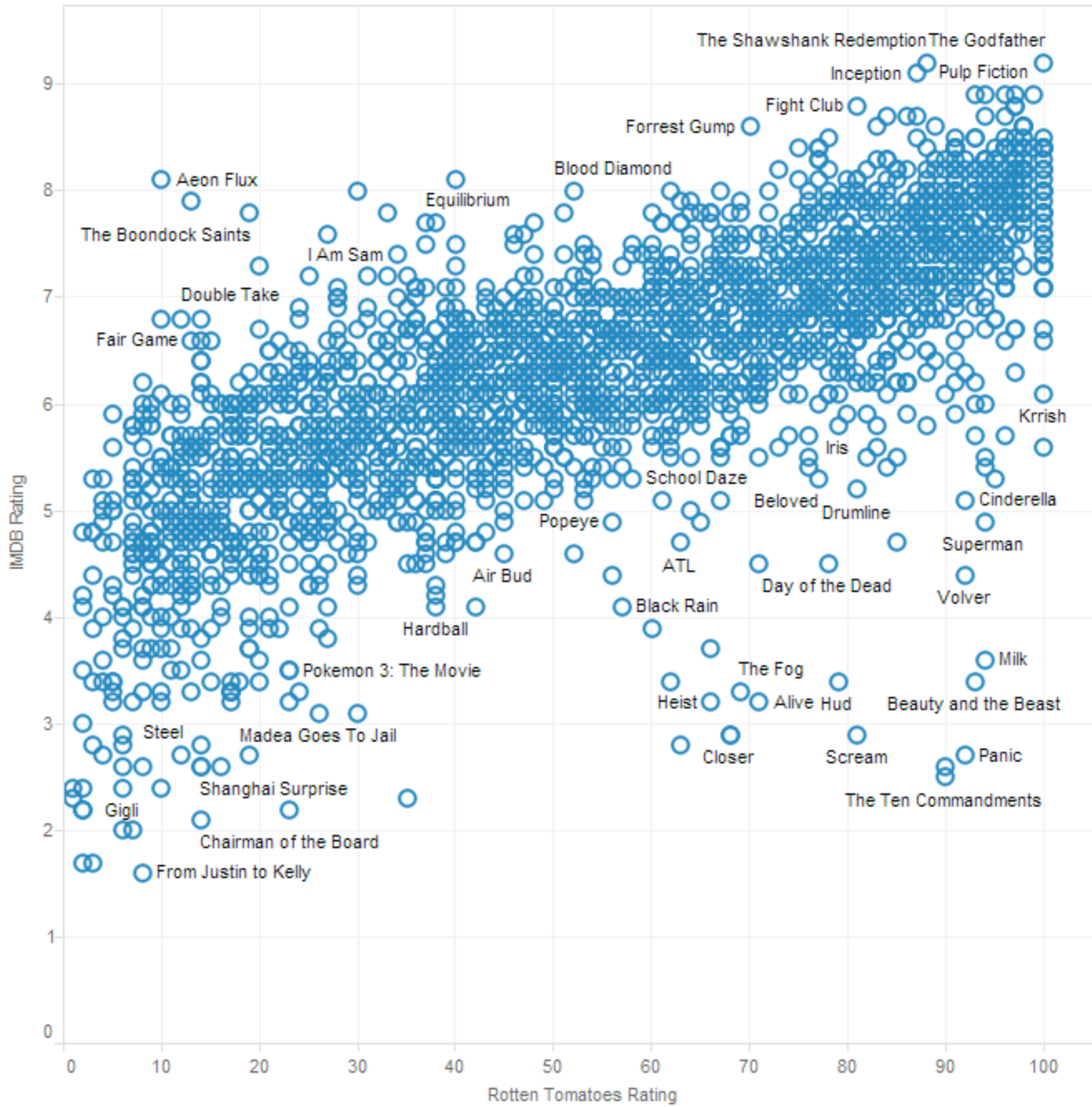
8.0
8.5
9.0



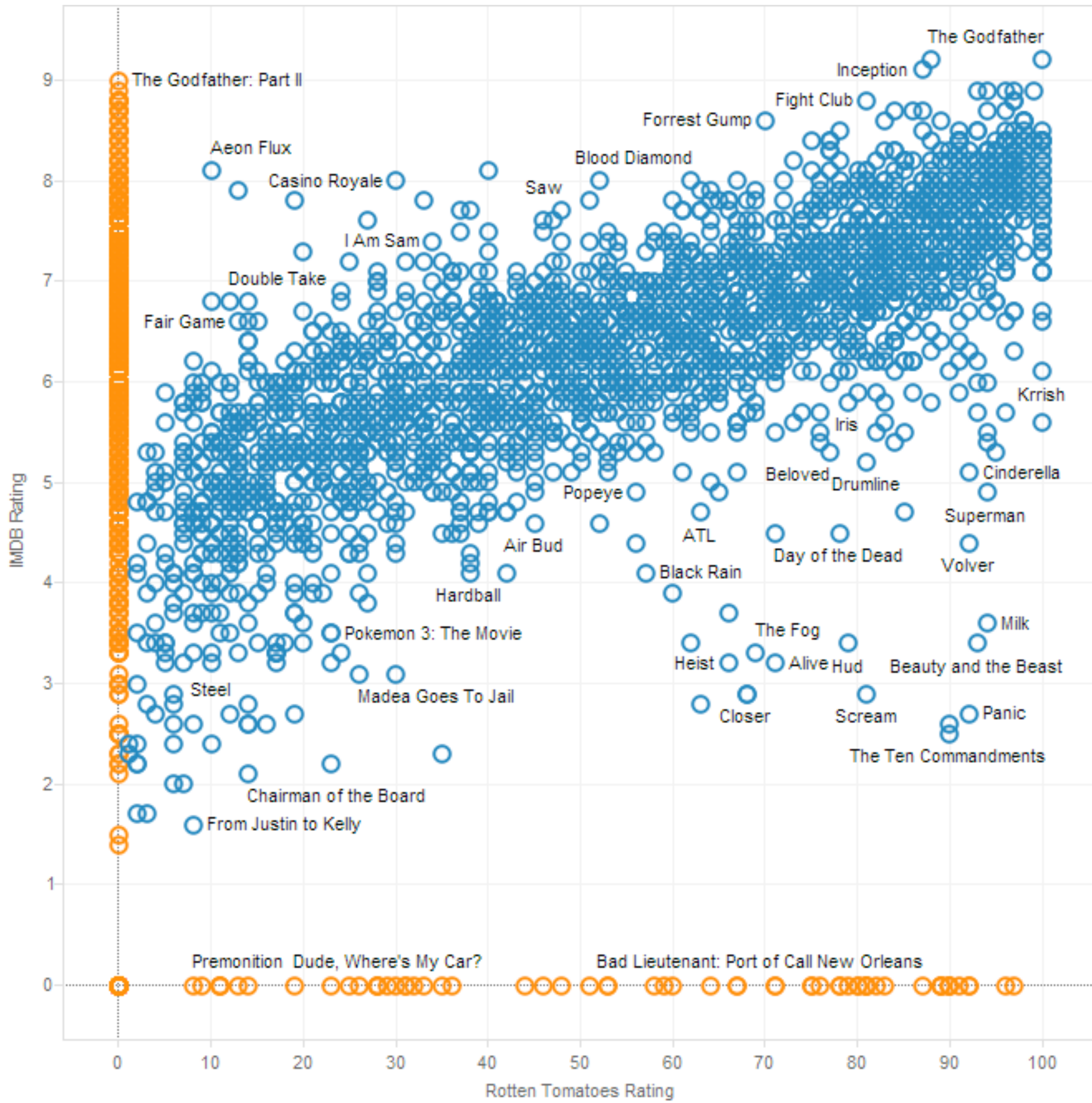
Rotten Tomatoes Rating (bin)
Number of Records
900
800
700
600
500
400
300
200
100
0
Null
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100



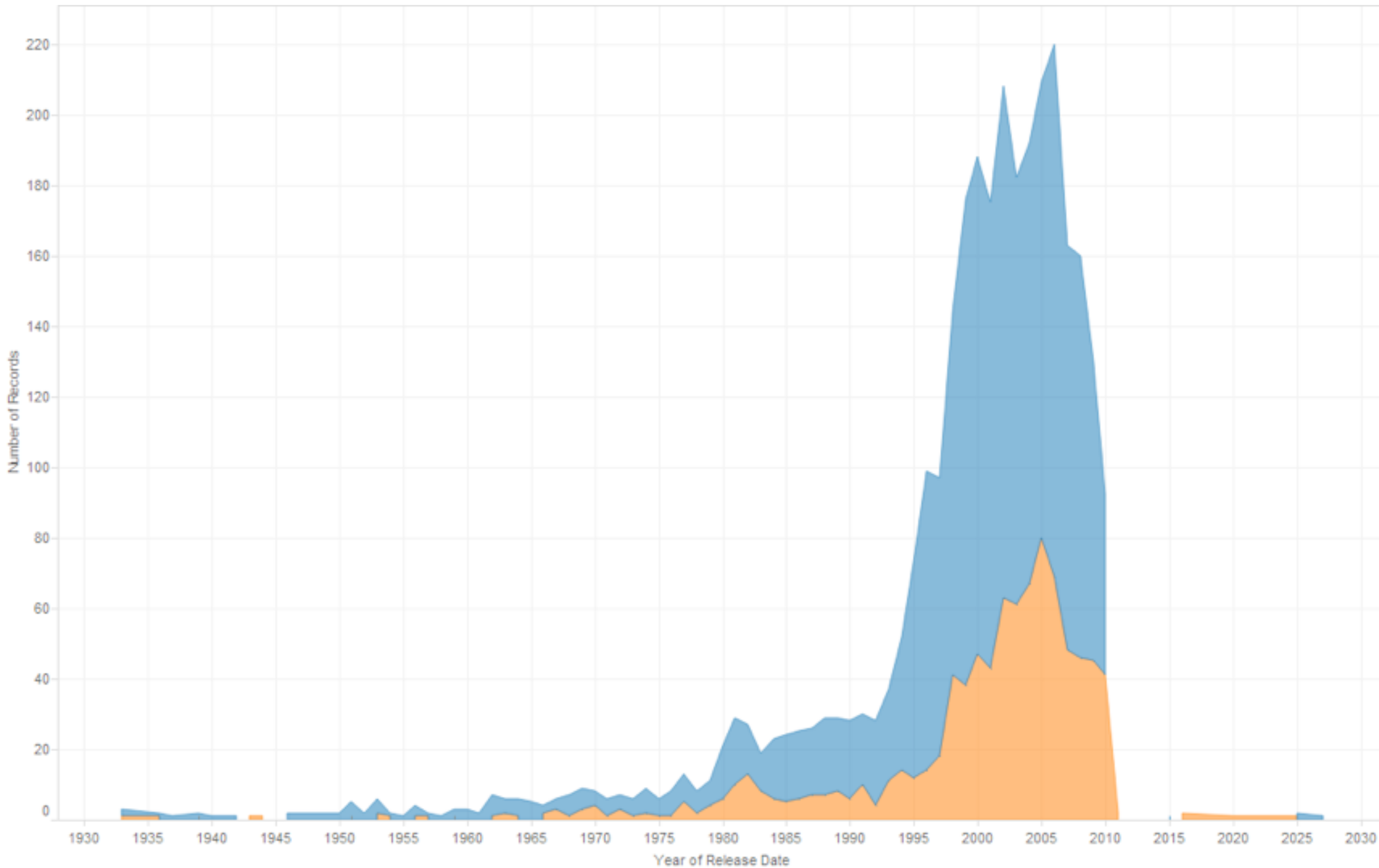
IMDB Rating
Rotten Tomatoes Rating
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100



IMDB Rating
Rotten Tomatoes Rating
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
The Shawshank Redemption
The Godfather
Inception
Pulp Fiction
Fight Club
Forrest Gump
Blood Diamond
Aeon Flux
Equilibrium
The Boondock Saints
I Am Sam
Double Take
Fair Game
Krrish
Iris
School Daze
Beloved
Drumline
Cinderella
Popeye
Superman
Air Bud
ATL
Day of the Dead
Volver
Black Rain
Hardball
Pokemon 3: The Movie
The Fog
Milk
Heist
Alive
Hud
Beauty and the Beast
Steel
Madea Goes To Jail
Closer
Scream
Panic
Shanghai Surprise
The Ten Commandments
Gigli
Chairman of the Board
From Justin to Kelly



The Godfather
Inception
The Godfather: Part II
Fight Club
Forrest Gump
Aeon Flux
Blood Diamond
Casino Royale
Saw
I Am Sam
Double Take
Fair Game
Krrish
Iris
Beloved
Drumline
Cinderella
Popeye
Superman
ATL
Air Bud
Day of the Dead
Black Rain
Volver
Hardball
Milk
Pokemon 3: The Movie
The Fog
Heist
Alive
Hud
Beauty and the Beast
Steel
Madea Goes To Jail
Closer
Scream
Panic
The Ten Commandments
Chairman of the Board
From Justin to Kelly
Premonition
Dude, Where's My Car?
Bad Lieutenant: Port of Call New Orleans
IMDB Rating
Rotten Tomatoes Rating



220
200
180
160
140
120
100
80
60
40
20
0
Number of Records
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year of Release Date

Lesson: Exercise Skepticism

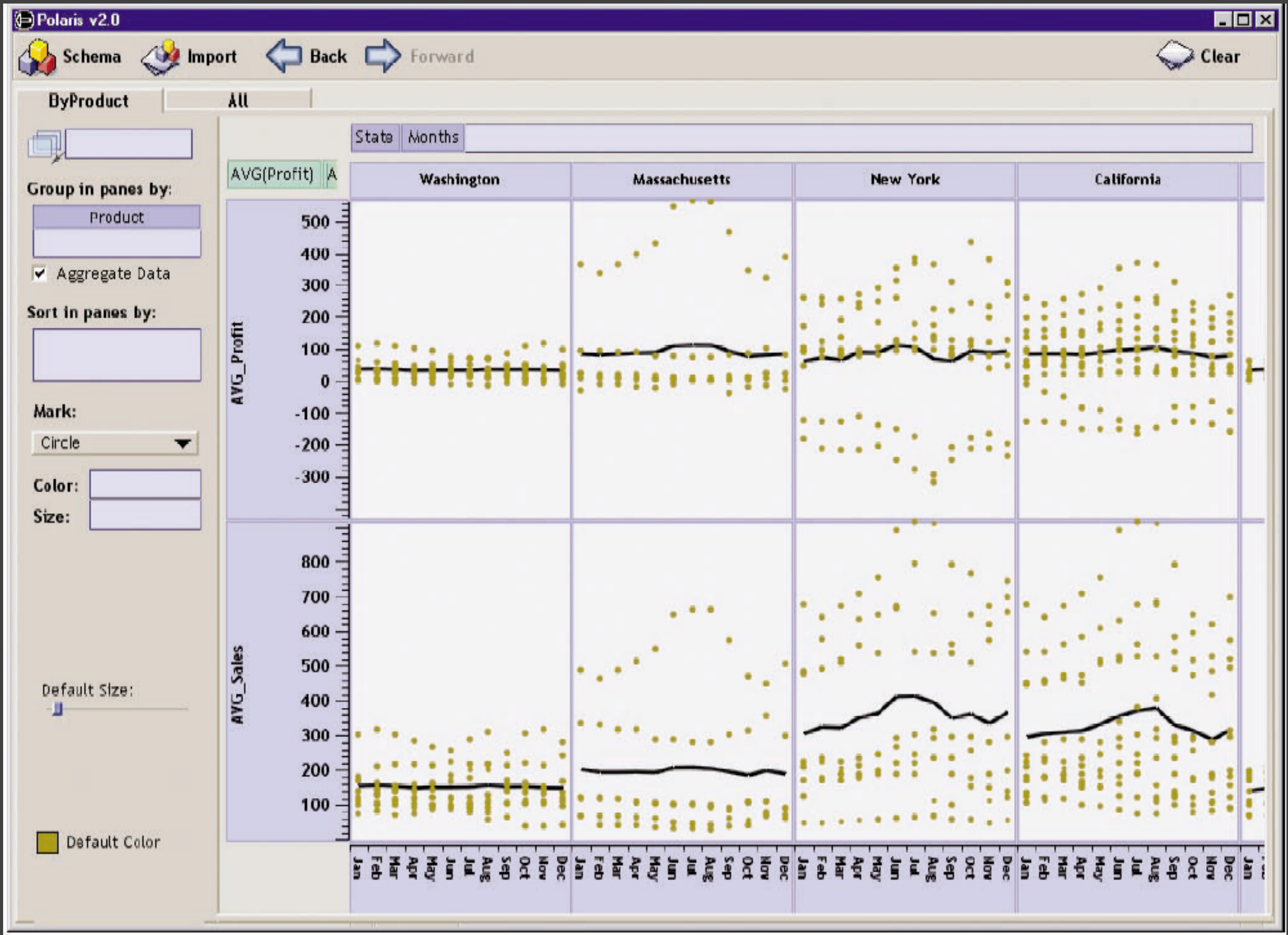
Check **data quality** and your **assumptions**.

Start with **univariate summaries**, then start to consider **relationships among variables**.

Avoid premature fixation!

Tableau / Polaris

Polaris [Stolte et al.]



Tableau

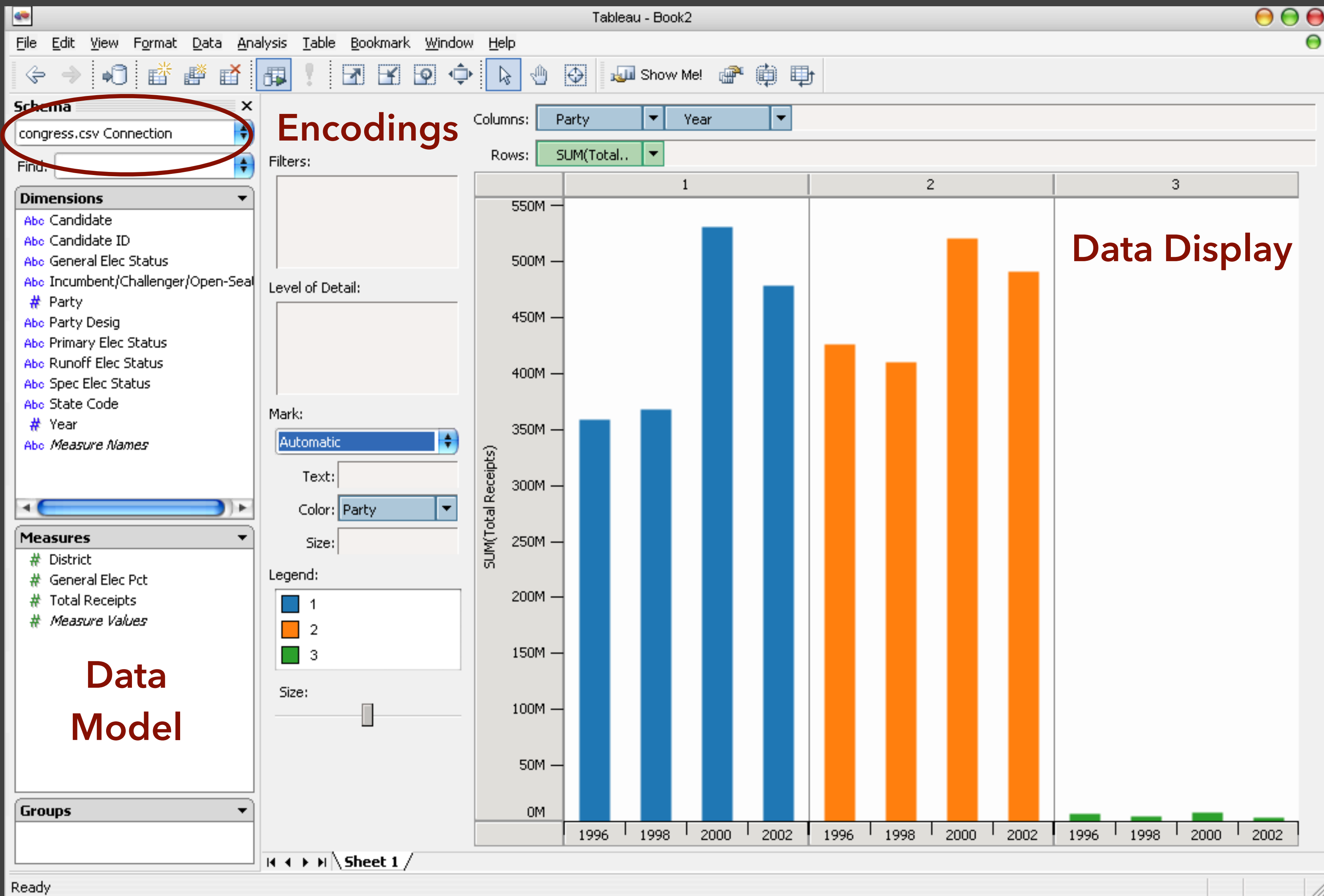


Tableau - Book2
File Edit View Format Data Analysis Table Bookmark Window Help
Show Me!
Schema
congress.csv Connection
Find:
Dimensions
Candidate
Candidate ID
General Elec Status
Incumbent/Challenger/Open-Seat
Party
Party Desig
Primary Elec Status
Runoff Elec Status
Spec Elec Status
State Code
Year
Measure Names
Measures
District
General Elec Pct
Total Receipts
Measure Values
Data Model
Groups
Encodings
Filters:
Level of Detail:
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Automatic
Text:
Color: Party
Size:
Legend:
1
2
3
Size:
Columns: Party Year
Rows: SUM(Total..
1
2
3
Data Display
SUM(Total Receipts)
550M
500M
450M
400M
350M
300M
250M
200M
150M
100M
50M
0M
1996 1998 2000 2002 1996 1998 2000 2002 1996 1998 2000 2002
Sheet 1
Ready

Tableau / Polaris Approach

Insight: can simultaneously specify both database queries and visualization

Choose data, then visualization, not vice versa

Use smart defaults for visual encodings

Can also suggest encodings upon request

Tableau Demo

The dataset:

Federal Elections Commission Receipts

Every Congressional Candidate from 1996 to 2002

4 Election Cycles

9216 Candidacies

Dataset Schema

Year (Qi)
Candidate Code (N)
Candidate Name (N)
Incumbent / Challenger / Open-Seat (N)
Party Code (N) [1=Dem,2=Rep,3=Other]
Party Name (N)
Total Receipts (Qr)
State (N)
District (N)

This is a subset of the larger data set available from the FEC.

Hypotheses?

What might we learn from this data?

Hypotheses?

What might we learn from this data?

Correlation between receipts and winners?

Do receipts increase over time?

Which states spend the most?

Which party spends the most?

Margin of victory vs. amount spent?

Amount spent between competitors?

Tableau Demo

EDA Summary

Exploratory analysis combines graphical methods, data transformations, and statistics.

Use questions to uncover more questions.

Formal methods may be used to confirm, sometimes on held-out or unseen data.

Visualization can further aid assessment of fitted statistical models.

More to come in the *Uncertainty* lecture!

Dimensionality Reduction

Dimensionality Reduction (DR)

Project nD data to 2D or 3D for viewing. Often used to interpret and sanity check high-dimensional representations fit by machine learning methods.

Different DR methods make different trade-offs: for example to **preserve global structure** (e.g., PCA) or **emphasize local structure** (e.g., nearest-neighbor approaches, including t-SNE and UMAP).

In contrast, multidimensional scaling (MDS) attempts to preserve pairwise distances.

Reduction Techniques

LINEAR - PRESERVE GLOBAL STRUCTURE

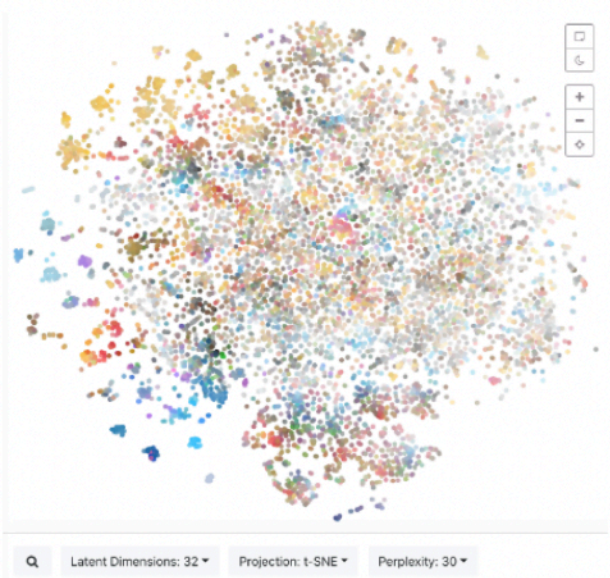
Principal Components Analysis (PCA)
Linear transformation of basis vectors, ordered by amount of data variance they explain.

NON-LINEAR - PRESERVE LOCAL TOPOLOGY

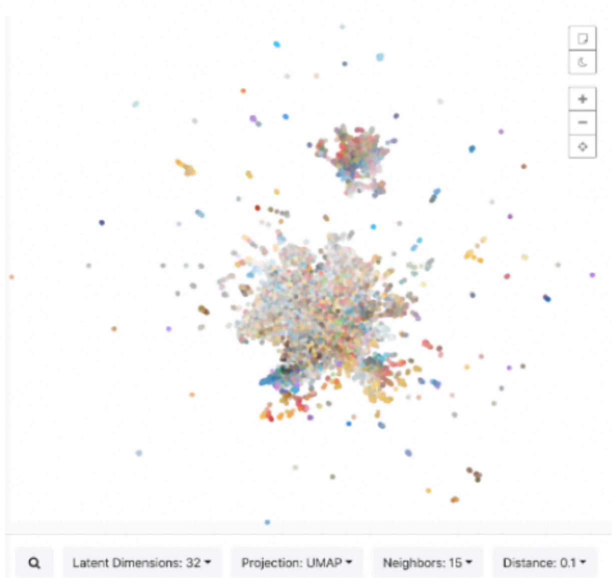
t-Dist. Stochastic Neighbor Embedding (t-SNE)
Probabilistically model distance, optimize positions.

Uniform Manifold Approx. & Projection (UMAP)
Identify local manifolds, then stitch them together.

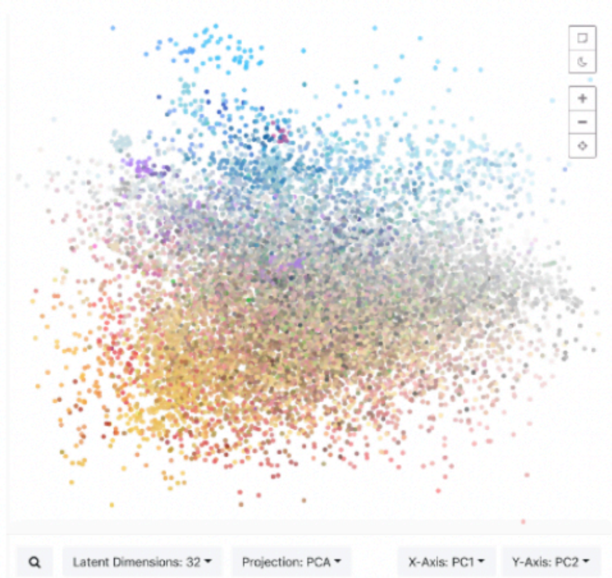
Mapping Emoji Images



t-SNE

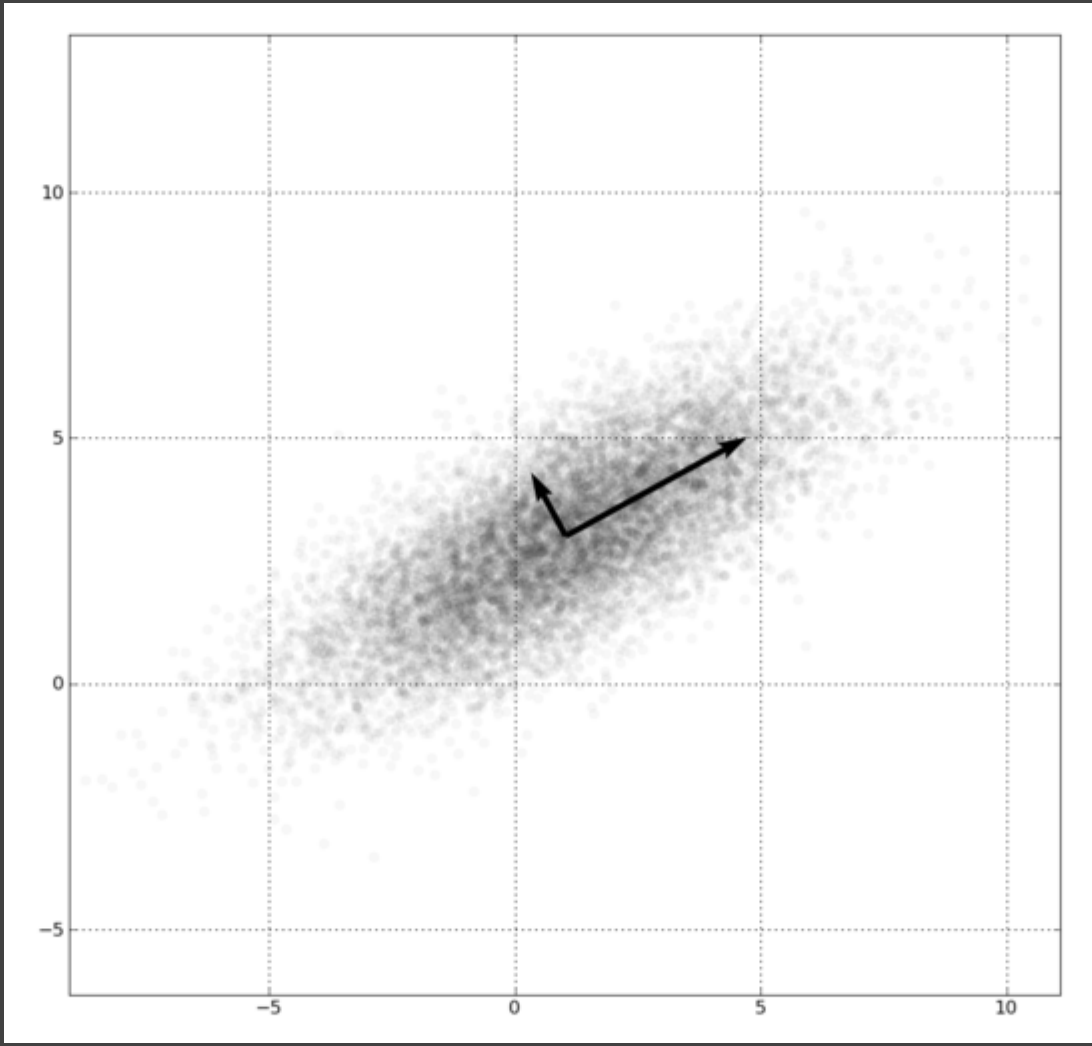


UMAP



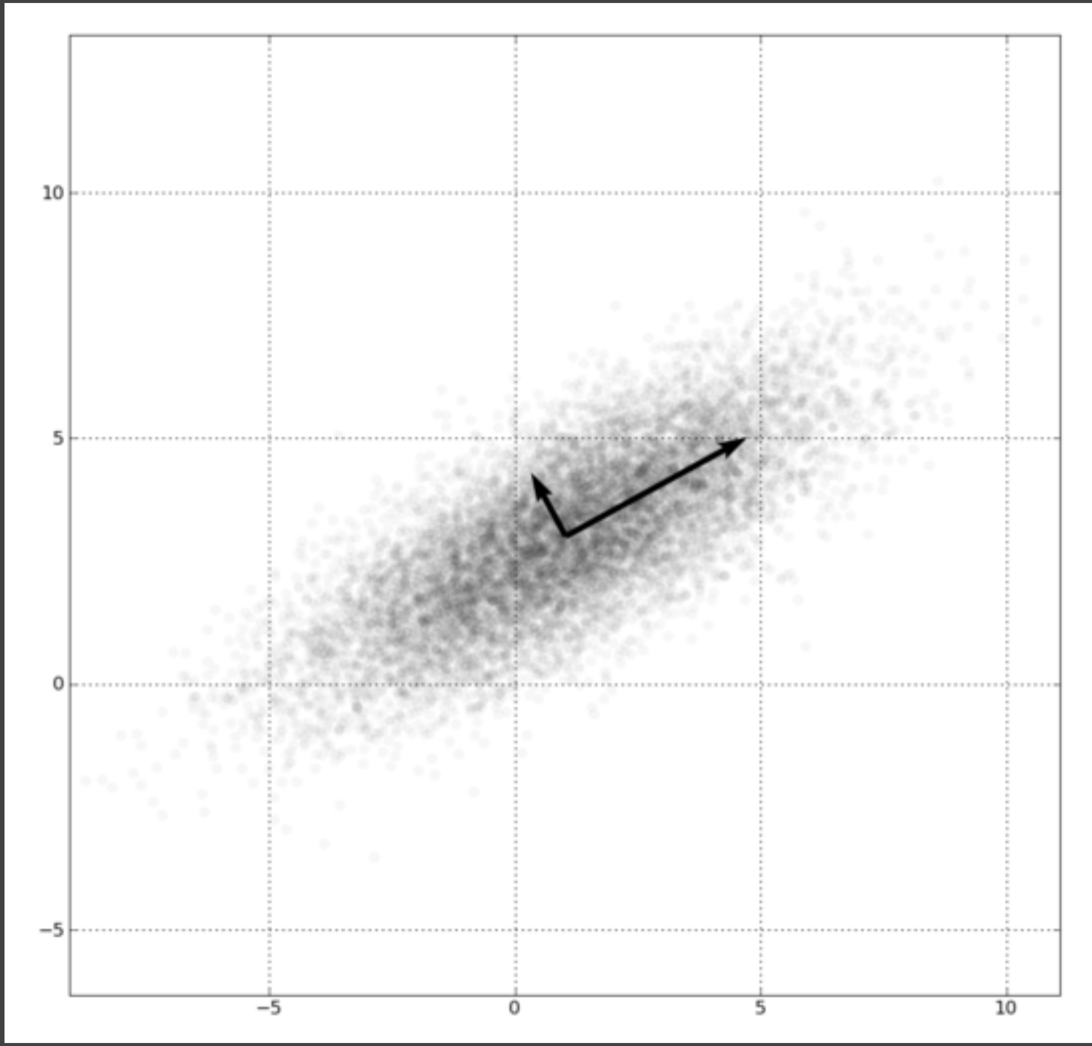
PCA

Principal Components Analysis



1. Mean-center the data.
2. Find ⊥ basis vectors that maximize the data variance.
3. Plot the data using the top vectors.

Principal Components Analysis

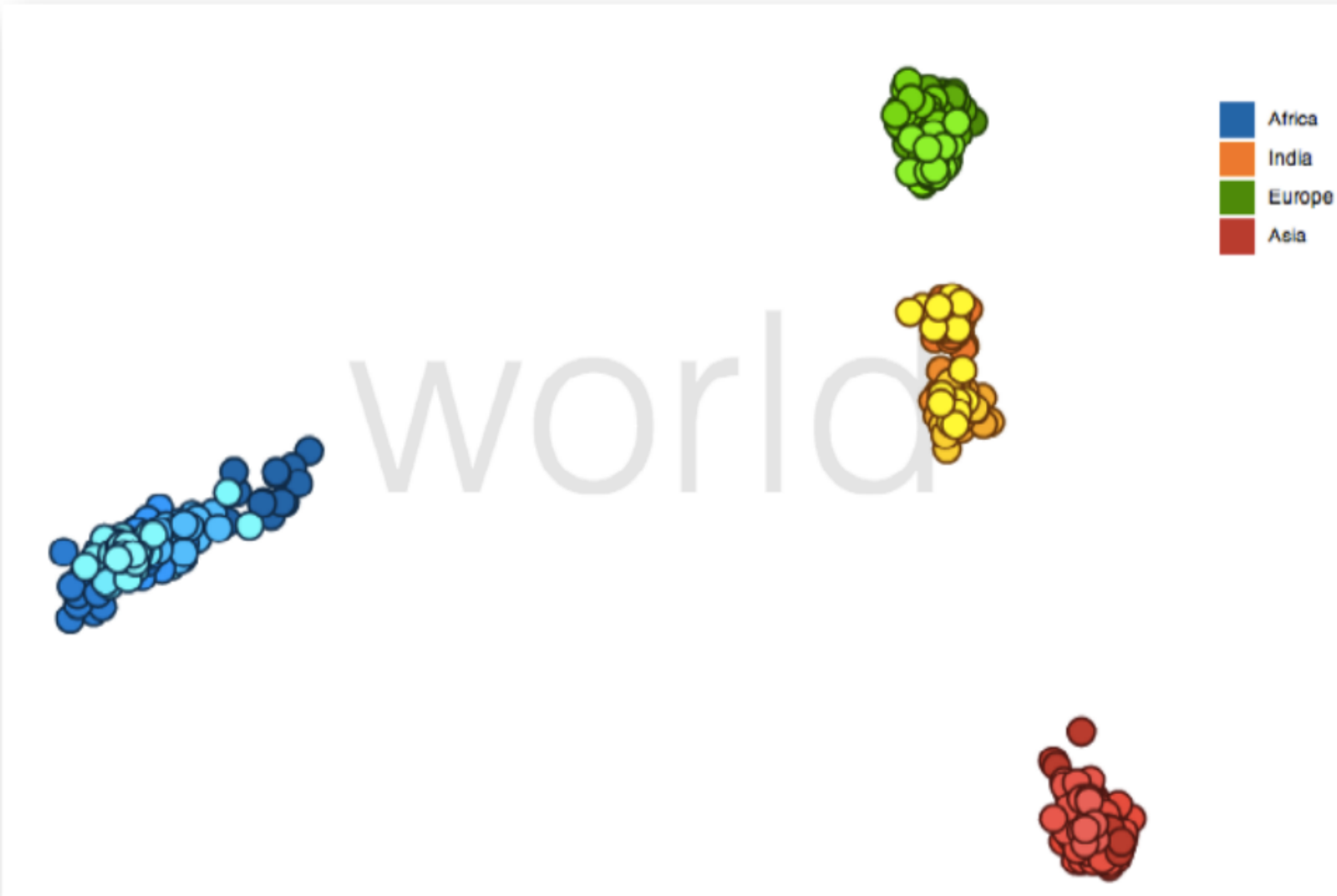


Linear transform: scale and rotate original space.

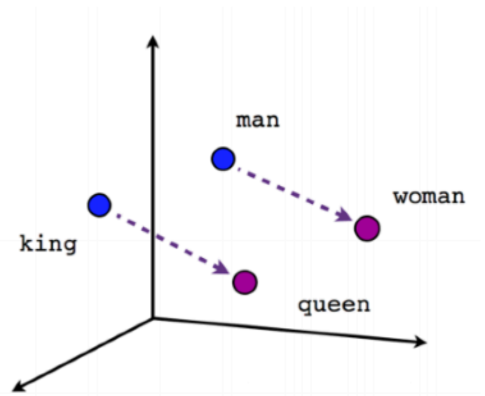
Lines (vectors) project to lines.

Preserves global distances.

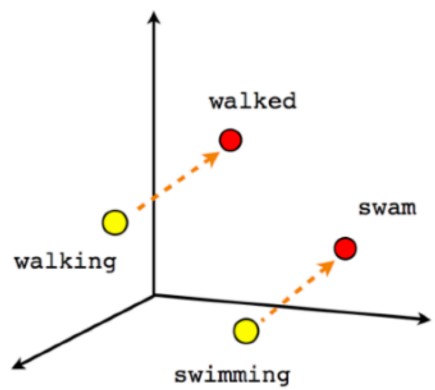
PCA of Genomes [Demiralp et al. '13]



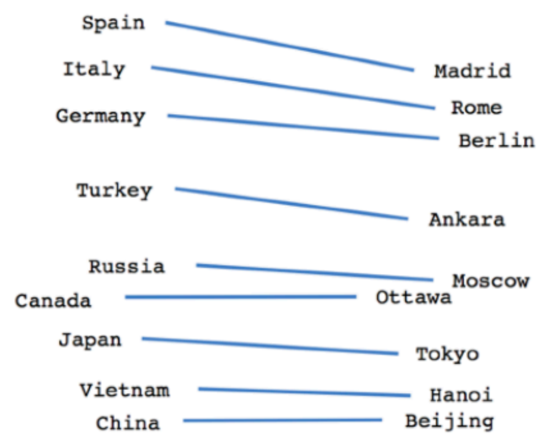
Word Embeddings (word2vec, GloVe)



Male-Female

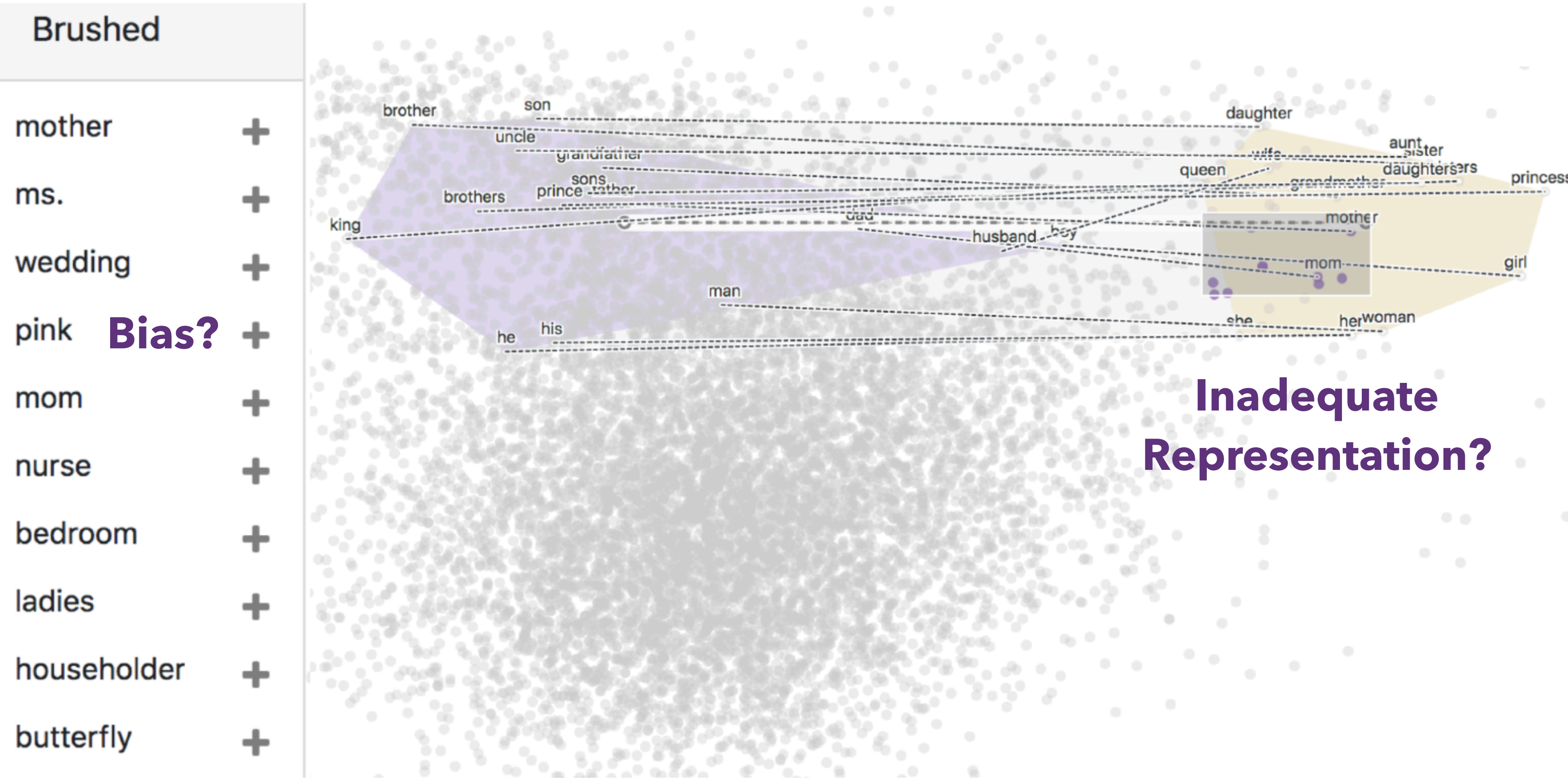


Verb tense



Country-Capital

Mapping Latent Spaces [Liu 2019]



Non-Linear Techniques

Distort the space, trade-off preservation of global structure to emphasize local neighborhoods. Use topological (nearest neighbor) analysis.

Two popular contemporary methods:

t-SNE - probabilistic interpretation of distance

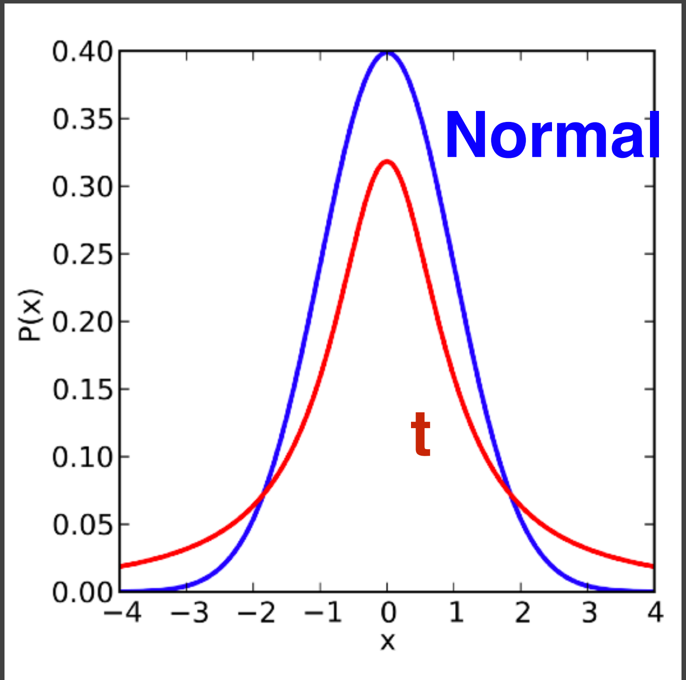
UMAP - tries to balance local/global trade-off

t-SNE [Maaten & Hinton 2008]

1. Model probability **P** of one point "choosing" another as its neighbor in the original space, using a Gaussian distribution defined using the distance between points. Nearer points have higher probability than distant ones.

t-SNE [Maaten & Hinton 2008]

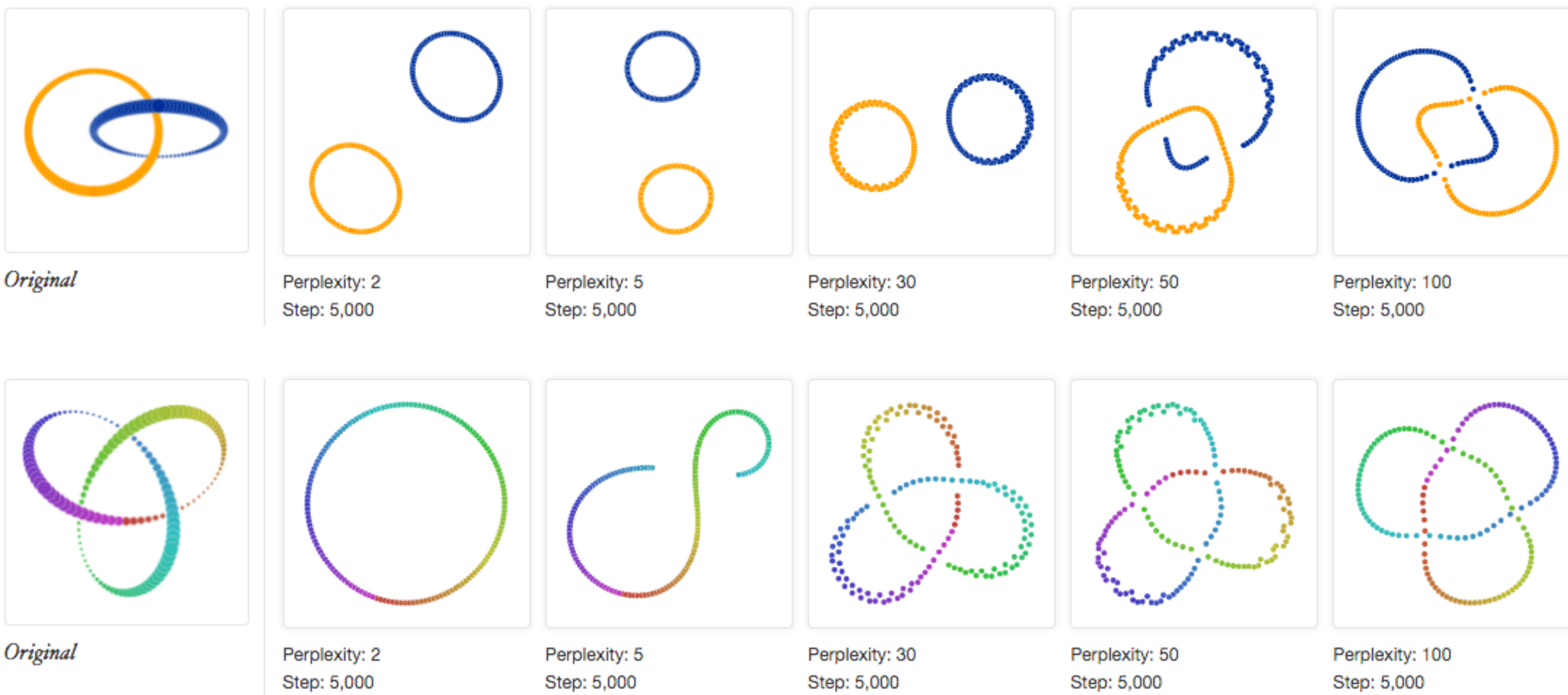
2. Define a similar probability **Q** in the low-dimensional (2D or 3D) embedding space, using a Student's *t* distribution *(hence the "t-" in "t-SNE"!)*. The *t*-distribution is heavy-tailed, allowing distant points to be even further apart.



t-SNE [Maaten & Hinton 2008]

1. Model probability **P** of one point “choosing” another as its neighbor in the original space, using a Gaussian distribution defined using the distance between points. Nearer points have higher probability than distant ones.
2. Define a similar probability **Q** in the low-dimensional (2D or 3D) embedding space, using a Student’s *t* distribution *(hence the “t-“ in “t-SNE”!)*. The *t*-distribution is heavy-tailed, allowing distant points to be even further apart.
3. Optimize to find the positions in the embedding space that minimize the Kullback-Leibler divergence between the **P** and **Q** distributions: $KL(P \,||\, Q)$

Visualizing t-SNE [Wattenberg et al. '16]



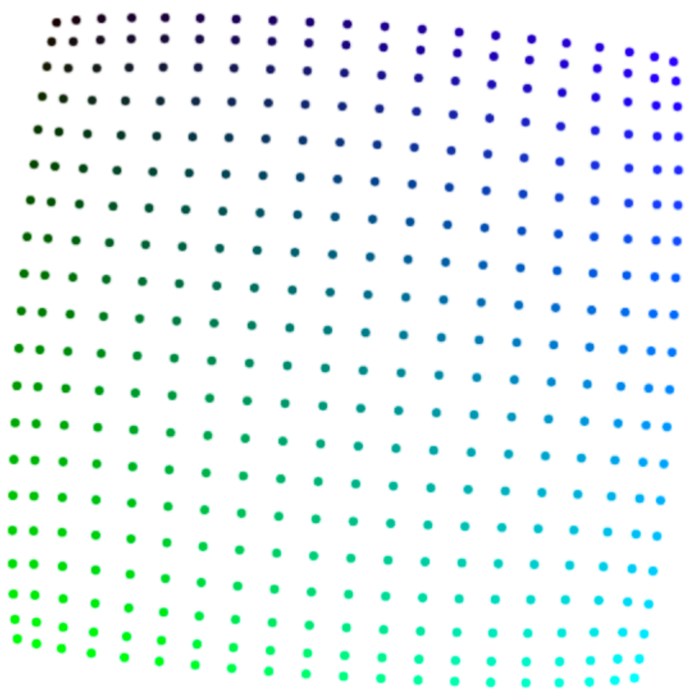
Results can be highly sensitive to the algorithm parameters!

Are you seeing real structures, or algorithmic hallucinations?

Distill ABOUT PRIZE SUBMIT

How to Use t-SNE Effectively

Although extremely useful for visualizing high-dimensional data, t-SNE plots can sometimes be mysterious or misleading. By exploring how it behaves in simple cases, we can learn to use it more effectively.



Step 1,910

A square grid with equal spacing between points. Try convergence at different sizes.

Points Per Side 20

Perplexity 10

Epsilon 5

MARTIN WATTENBERG Google Brain

FERNANDA VIÉGAS Google Brain

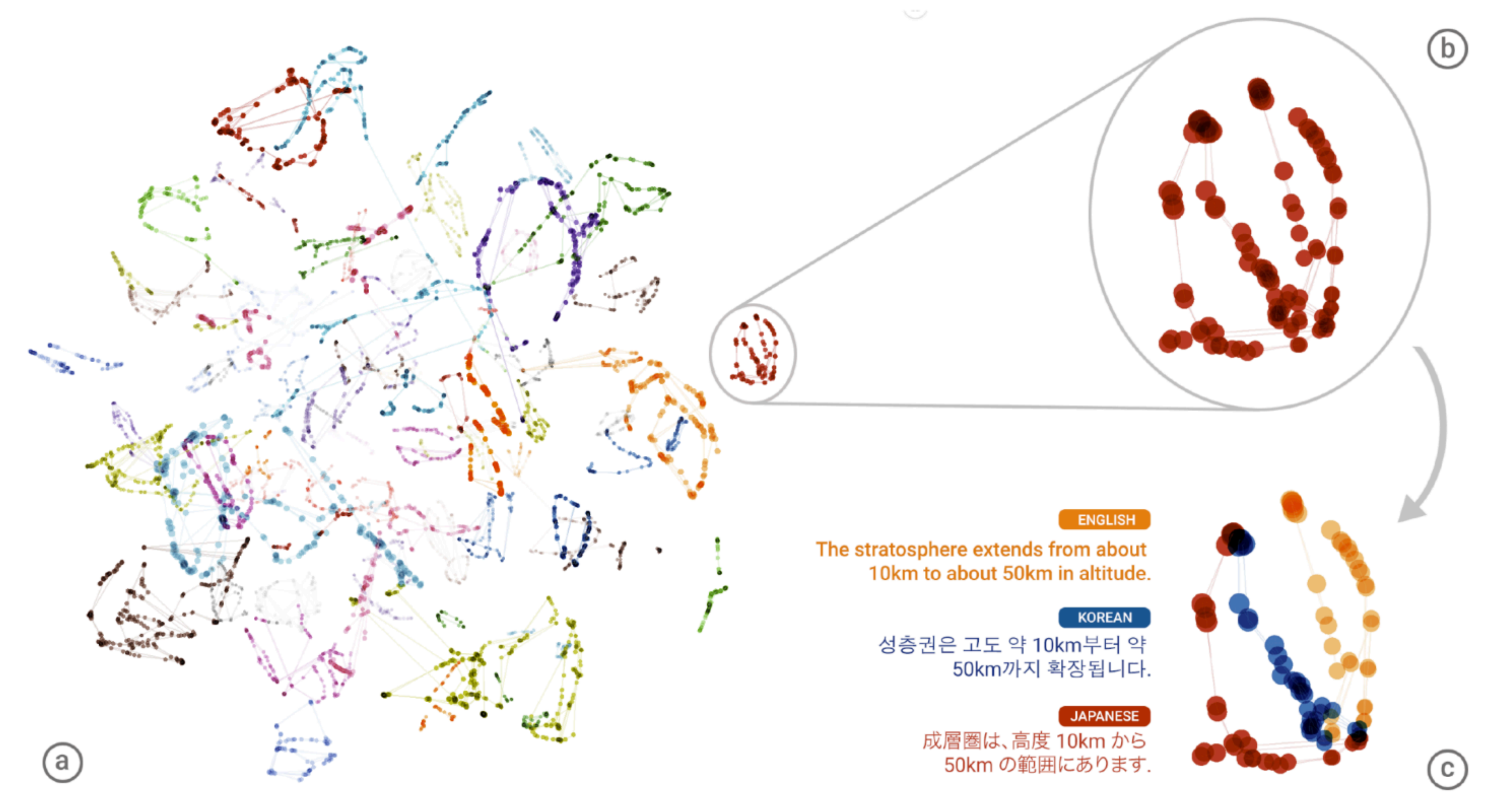
IAN JOHNSON Google Cloud

Oct. 13 2016

Citation: Wattenberg, et al., 2016

distill.pub

MT Embedding [Johnson et al. 2018]



t-SNE projection of latent space of language translation model.

UMAP [McInnes et al. 2018]

Form weighted nearest neighbor graph, then layout the graph in a manner that balances embedding of local and global structure.

"Our algorithm is competitive with t-SNE for visualization quality and arguably preserves more of the global structure with superior run time performance." - McInnes et al. 2018

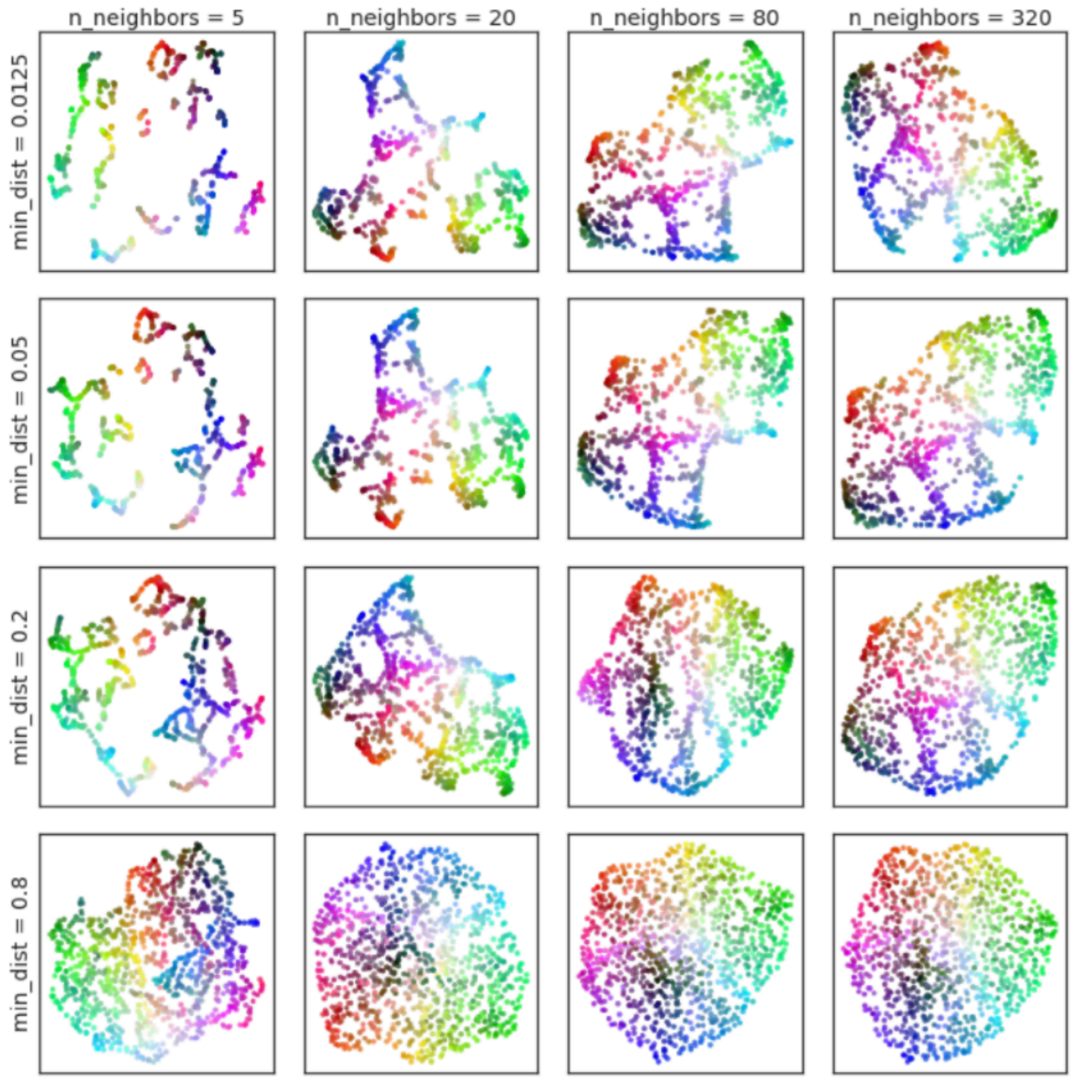


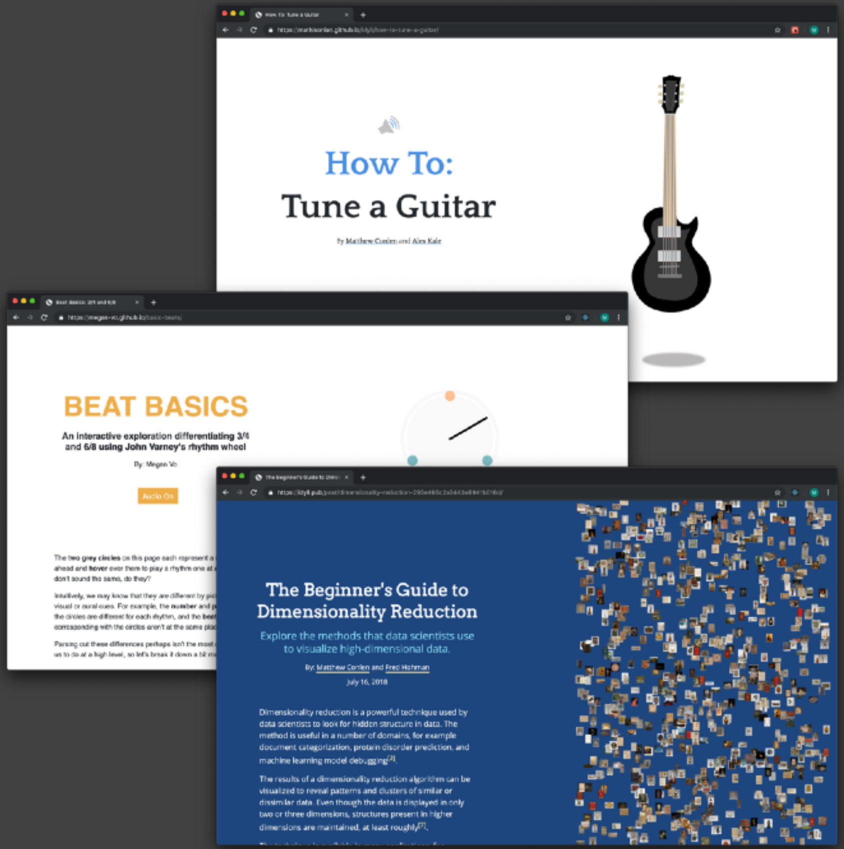
Figure 1: Variation of UMAP hyperparameters n and min-dist result in different embeddings. The data is uniform random samples from a 3-dimensional color-cube, allowing for easy visualization of the original 3-dimensional coordinates in the embedding space by using the corresponding RGB colour. Low values of n spuriously interpret structure from the random sampling noise – see Section 6 for further discussion of this phenomena.

User Activity in Interactive Articles

Represent reader sessions as a feature vector with:
- time spent in each section
- count of variable changes

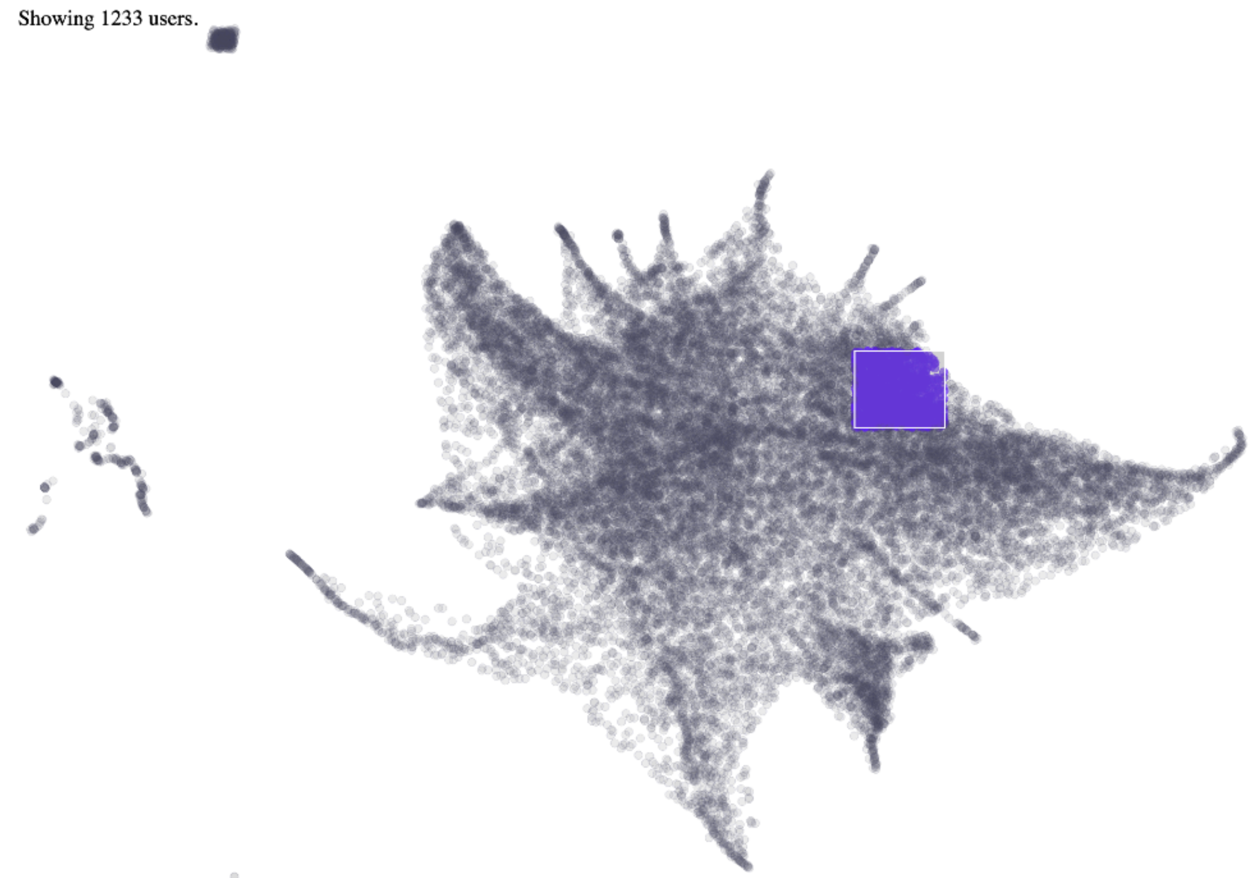
Provide an overview of usage patterns of interactive features.

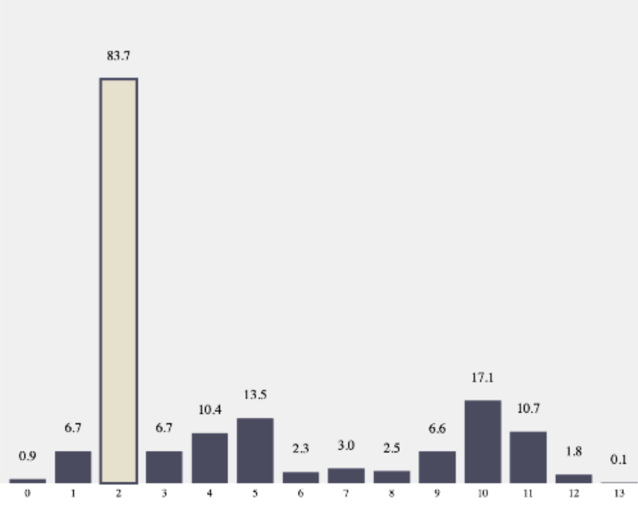
Identify variations in usage.

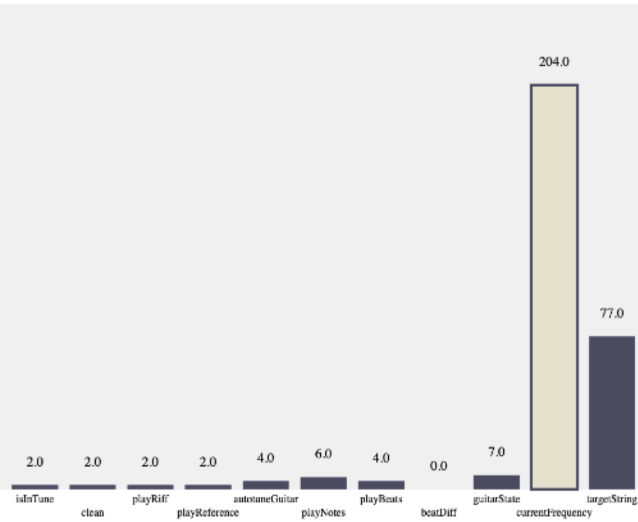


[Conlen '19]

User Activity in Interactive Articles



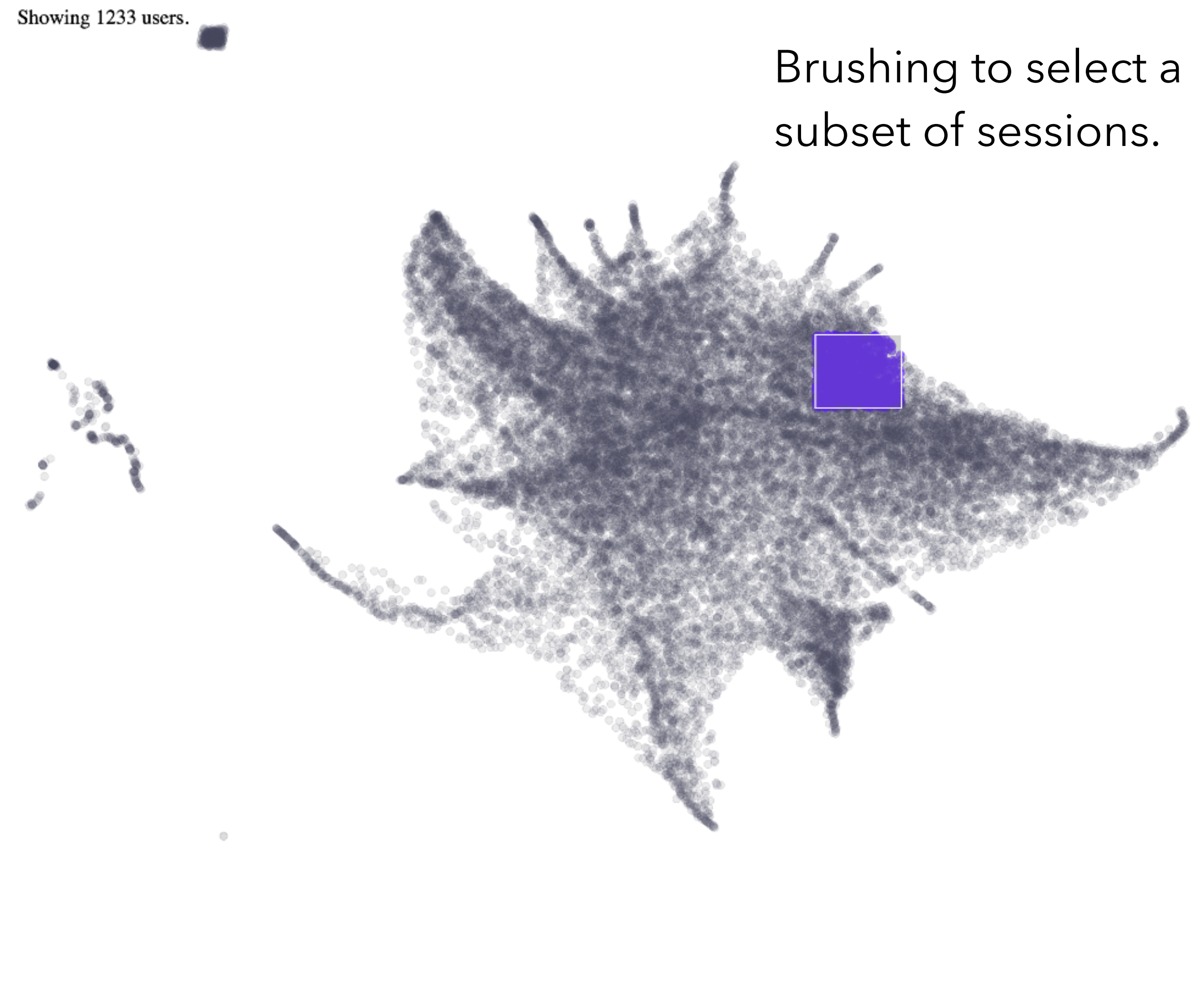


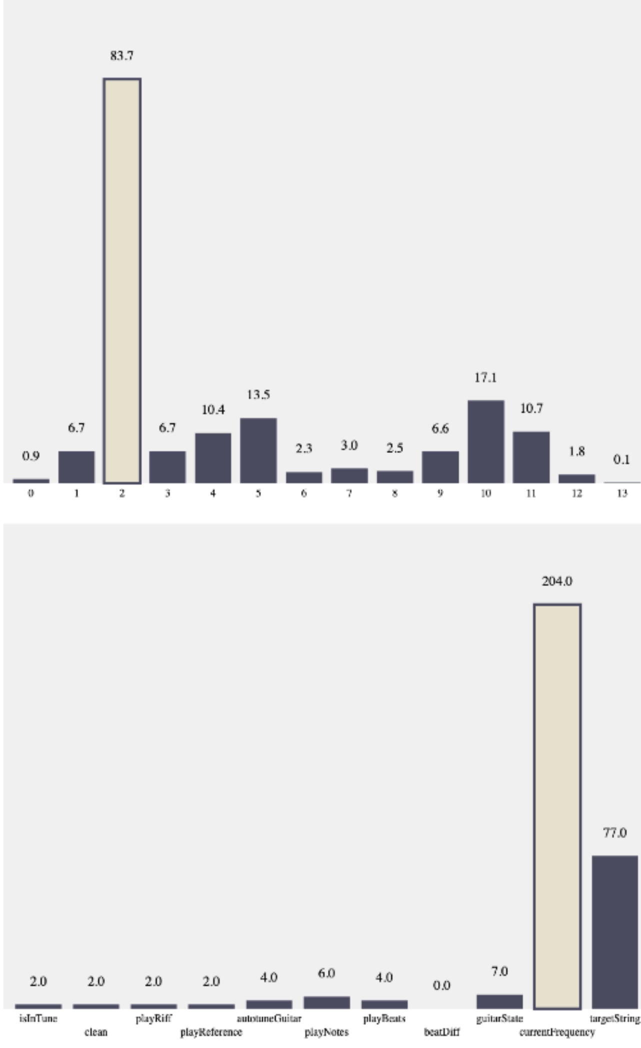


Each point represents a readers session, projected via UMAP.

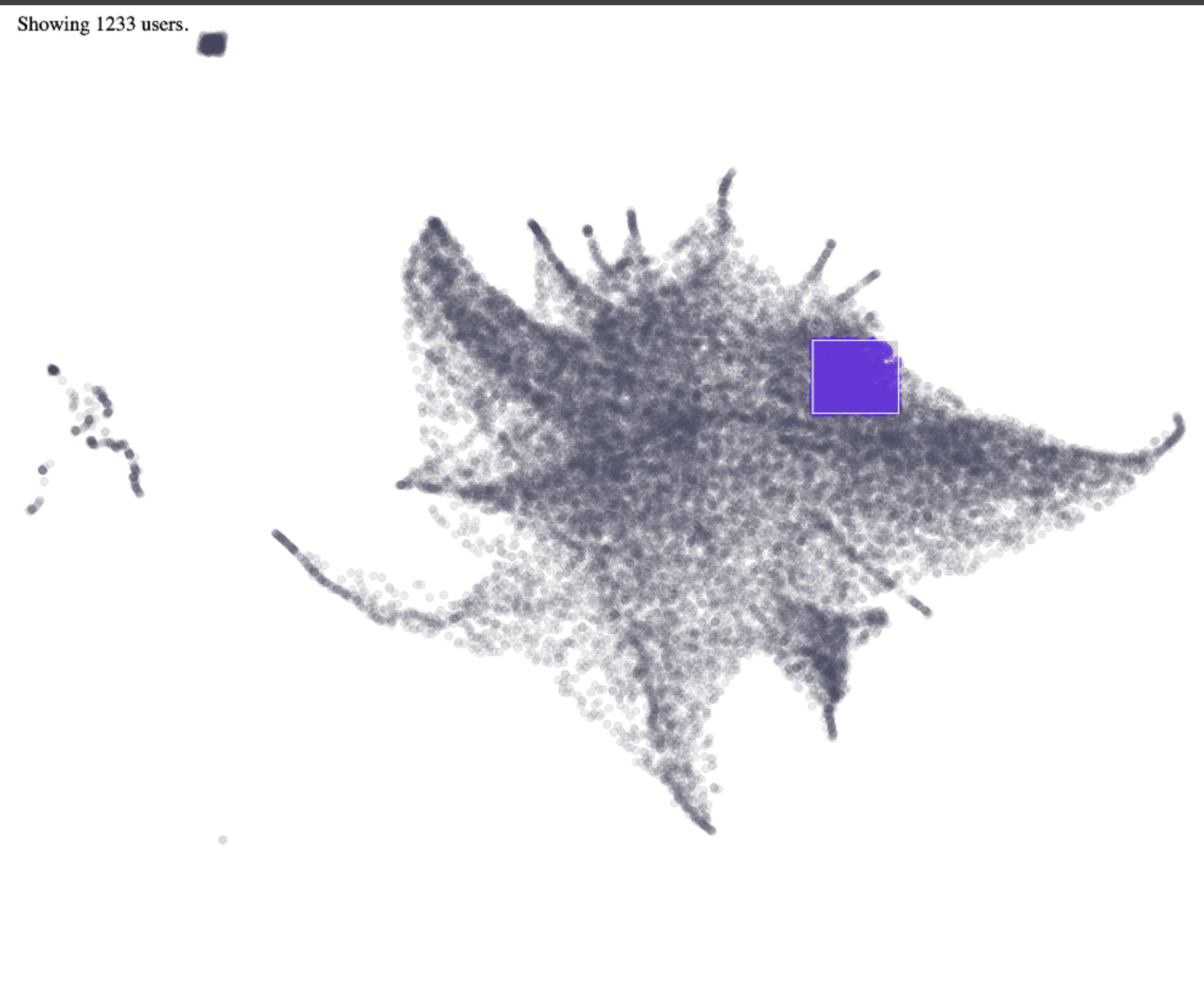
User Activity in Interactive Articles

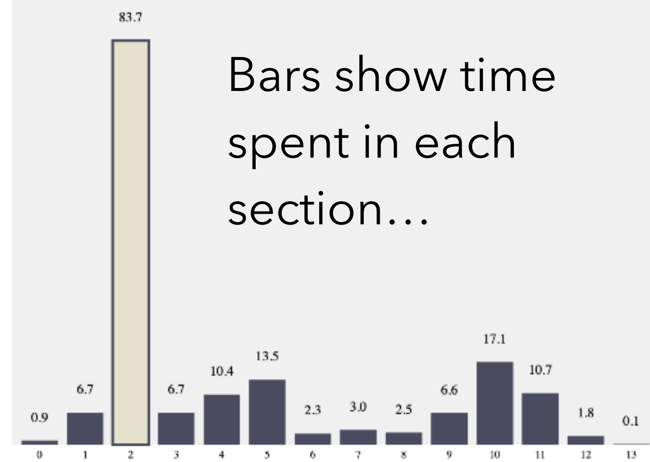
Brushing to select a subset of sessions.



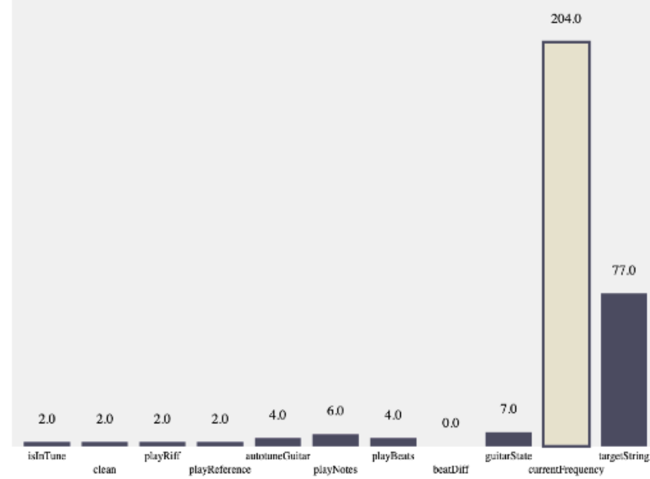


User Activity in Interactive Articles

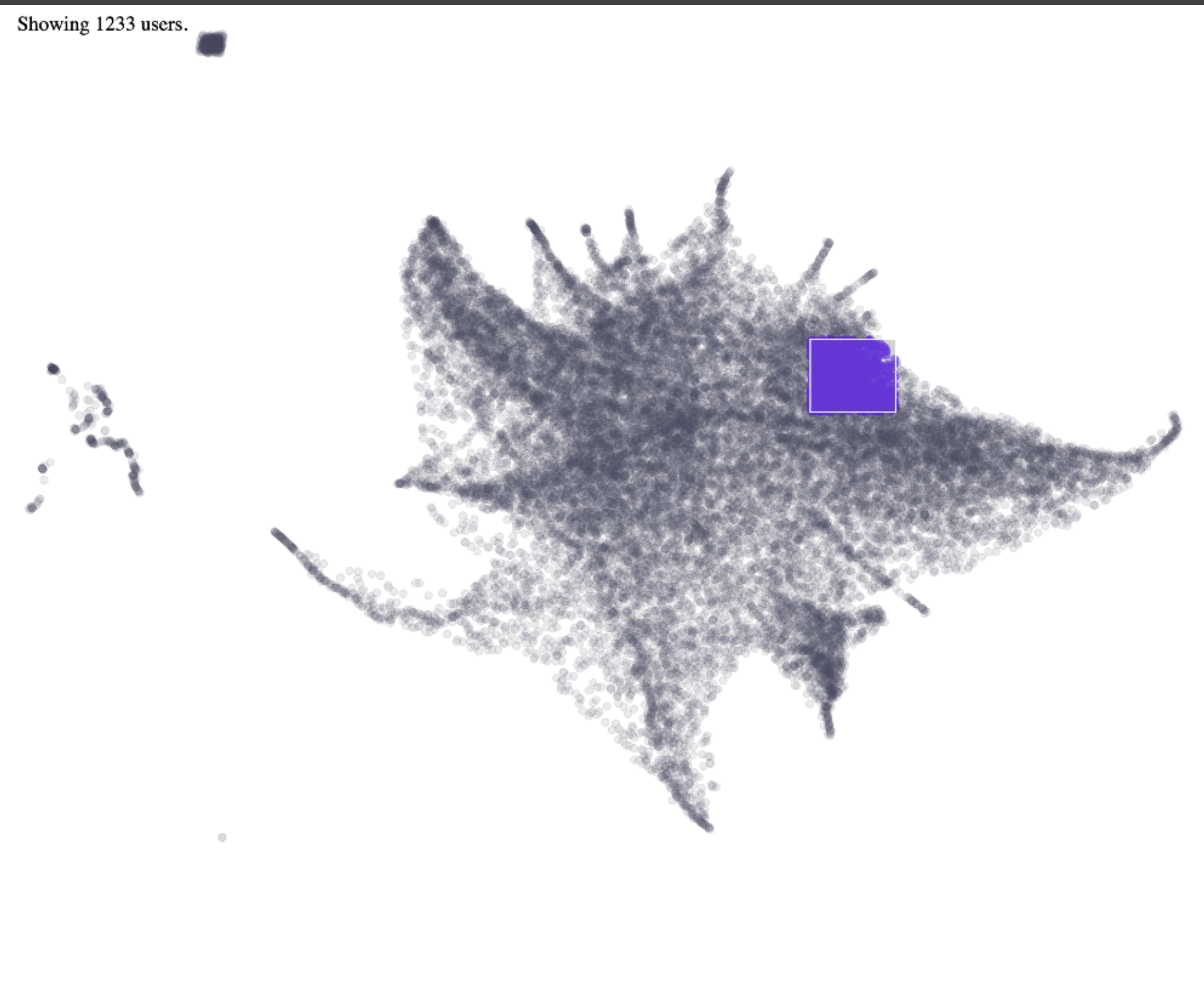


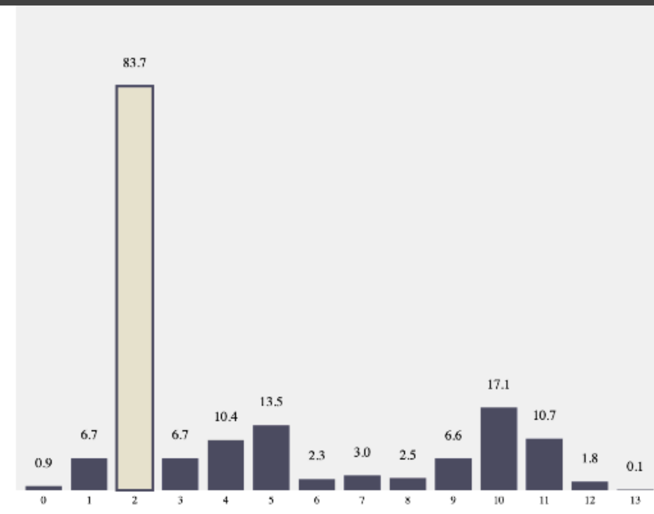


Bars show time spent in each section…

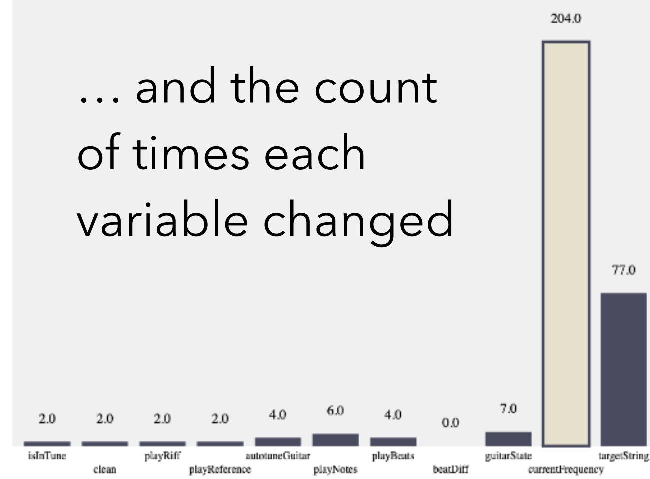


User Activity in Interactive Articles

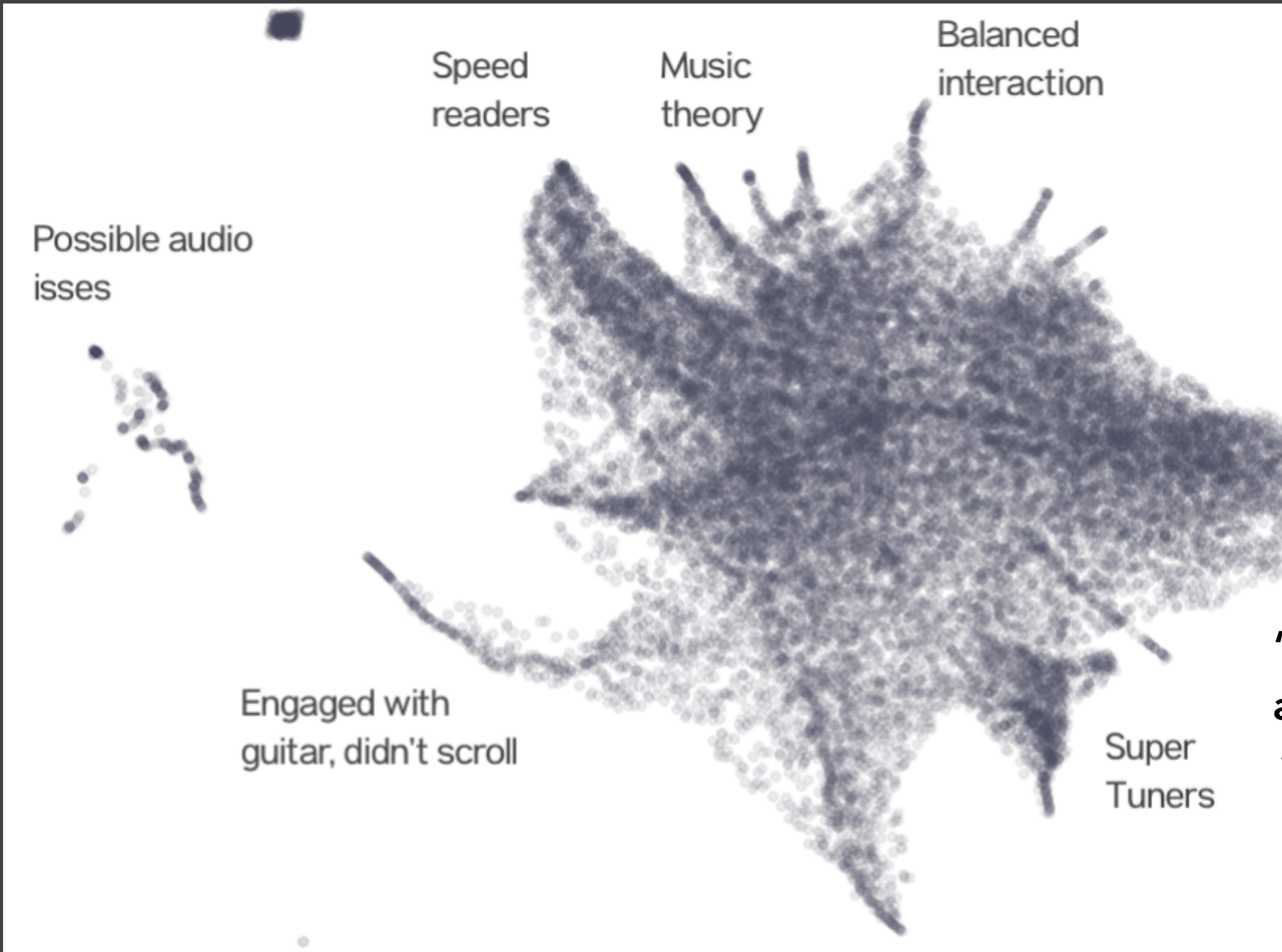




… and the count of times each variable changed



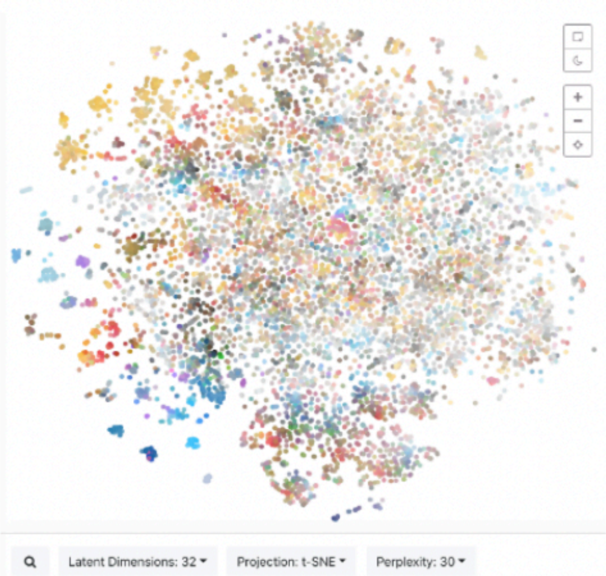
Reader Behavior [Conlen et al. 2019]



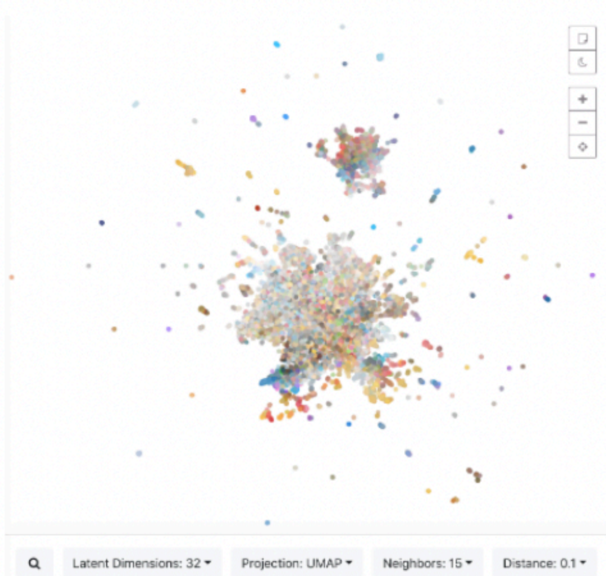
"Tentacles" map to activity archetypes, "blob" body maps to sessions that blend behaviors.

UMAP projection of reader activity for an interactive article.

Mapping Emoji Images



t-SNE

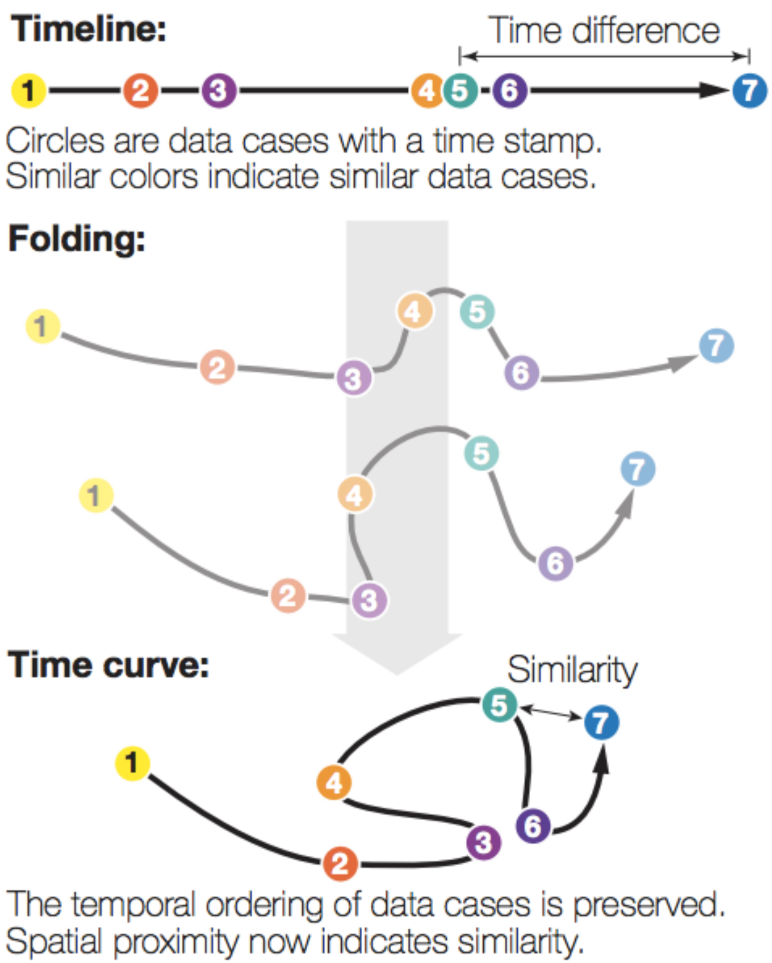


UMAP

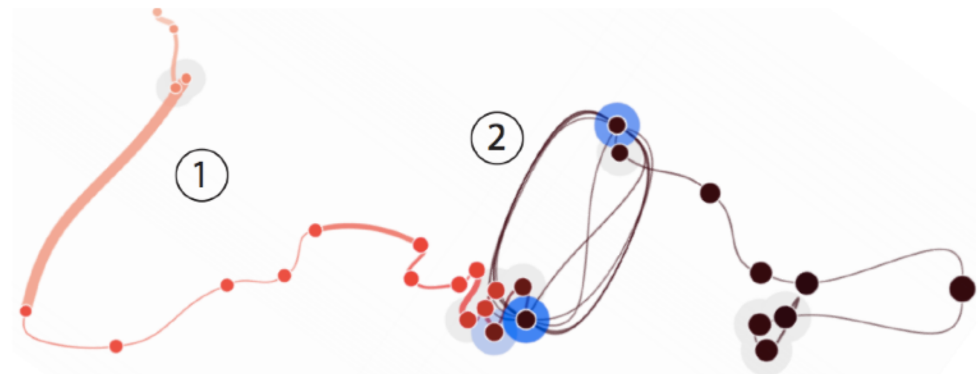
PCA

Each has strengths and weaknesses – and they can be used in tandem!

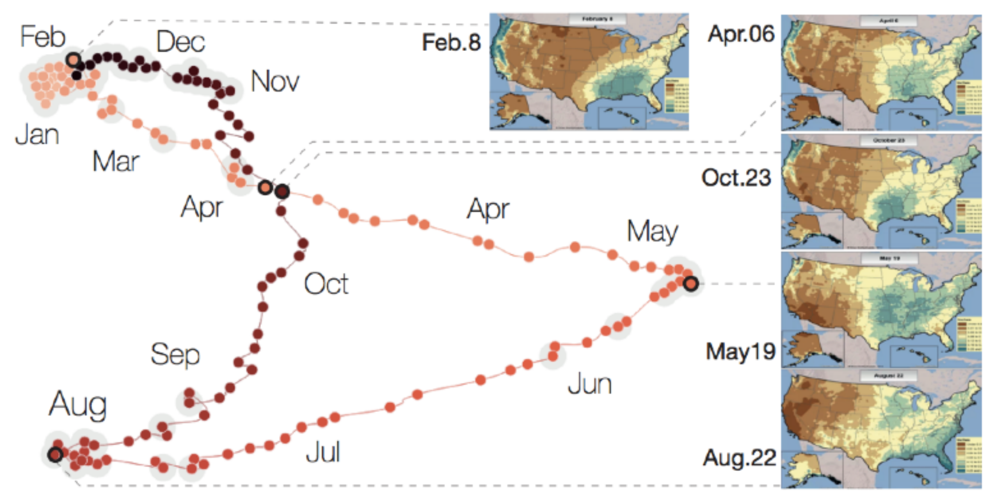
Time Curves [Bach et al. '16]



(a) Folding time



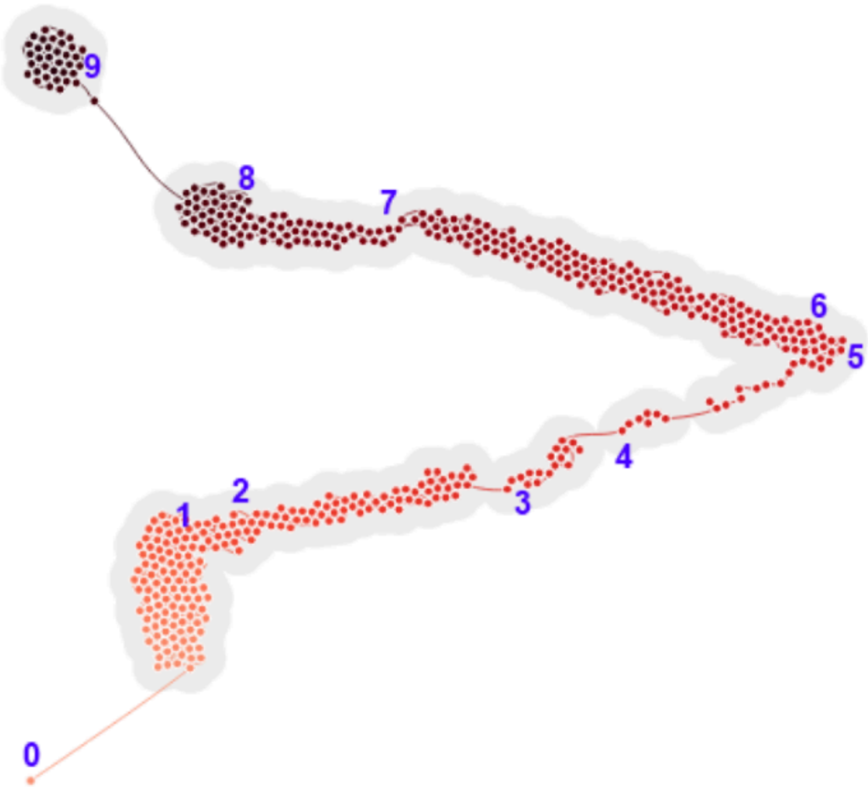
Wikipedia "Chocolate" Article



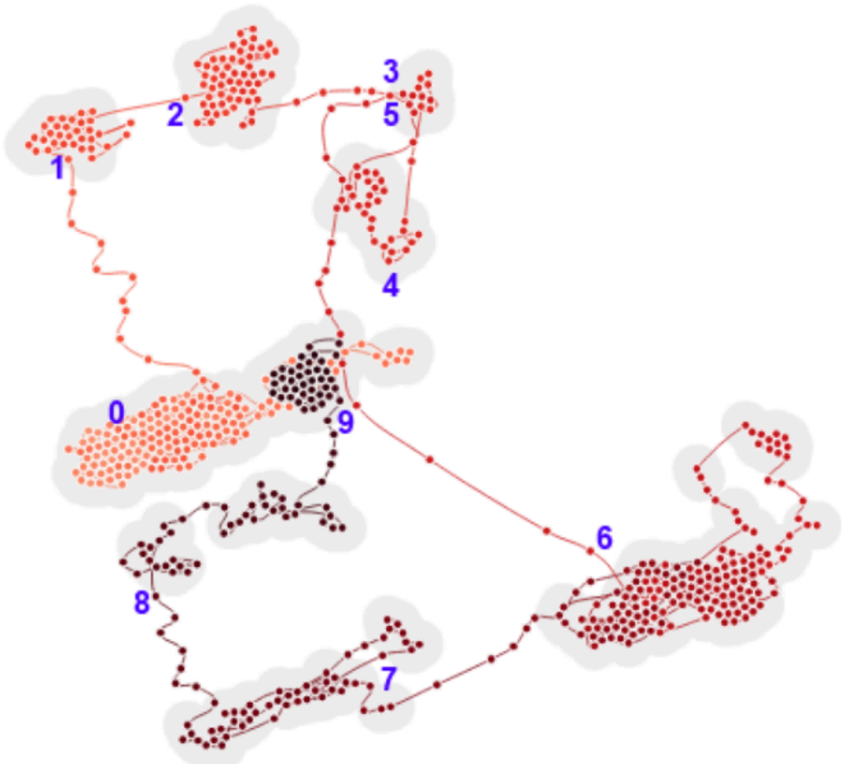
U.S. Precipitation over 1 Year

Rover Telemetry [Guy '16]

How to track high-dimensional state?



Using Raw Multi-D Data



Using Pearson Correlation Matrix

Dimensionality Reduction Issues

Dimensionality Reduction Issues

Reproducible?

Projections are *data-dependent*. Fitting a new projection with different data can give rise to different results.

Dimensionality Reduction Issues

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Projections are *data-dependent*. Fitting a new projection with different data can give rise to different results.

Reusable?
PCA and UMAP provide reusable projection functions that can map new points from high-D to low-D. t-SNE (and others, like MDS) do not provide this.

Dimensionality Reduction Issues

Reproducible?
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PCA and UMAP provide reusable projection functions that can map new points from high-D to low-D. t-SNE (and others, like MDS) do not provide this.

Interpretable?
DR plots are hard to interpret! Try multiple methods and hyperparameter settings. Inspect via interaction!