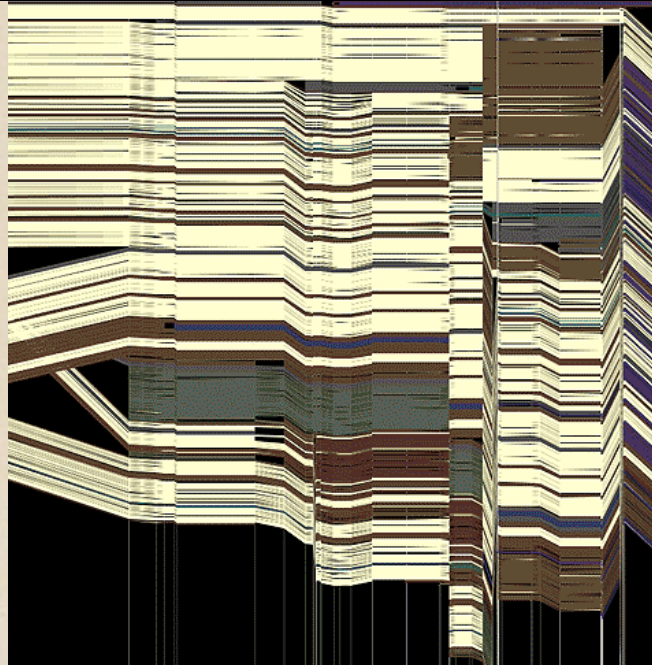
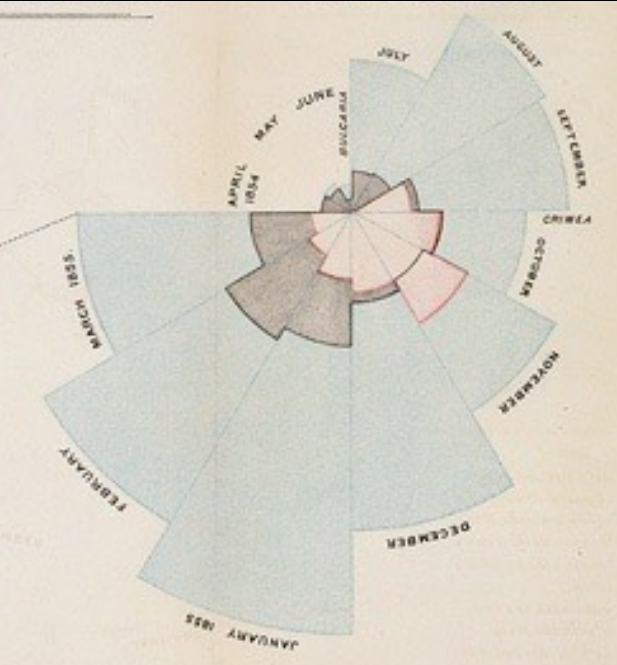


CSE 442 - Data Visualization

Data and Image Models



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



Topics

Properties of Data

Properties of Images

Mapping Data to Images

Data Models

Data Models / Conceptual Models

Data models are formal descriptions

Math: sets with operations on them

Example: integers with + and x operators

Conceptual models are mental constructions

Include semantics and support reasoning

Examples (data vs. conceptual)

1D floats vs. temperatures

3D vector of floats vs. spatial location

Taxonomy of Data Types (?)

1D (sets and sequences)

Temporal

2D (maps)

3D (shapes)

nD (relational)

Trees (hierarchies)

Networks (graphs)

Are there others?

The eyes have it: A task by data type
taxonomy for information visualization

[Shneiderman 96]

Nominal, Ordinal & Quantitative

Nominal, Ordinal & Quantitative

N - Nominal (labels or categories)

- Fruits: apples, oranges, ...

Nominal, Ordinal & Quantitative

N - Nominal (labels or categories)

- Fruits: apples, oranges, ...

O - Ordered

- Quality of meat: Grade A, AA, AAA

Nominal, Ordinal & Quantitative

N - Nominal (labels or categories)

- Fruits: apples, oranges, ...

O - Ordered

- Quality of meat: Grade A, AA, AAA

Q - Interval (location of zero arbitrary)

- Dates: Jan, 19, 2006; Location: (LAT 33.98, LONG -118.45)
- Only differences (i.e., intervals) may be compared

Nominal, Ordinal & Quantitative

N - Nominal (labels or categories)

- Fruits: apples, oranges, ...

O - Ordered

- Quality of meat: Grade A, AA, AAA

Q - Interval (location of zero arbitrary)

- Dates: Jan, 19, 2006; Location: (LAT 33.98, LONG -118.45)
- Only differences (i.e., intervals) may be compared

Q - Ratio (zero fixed)

- Physical measurement: Length, Mass, Time duration, ...
- Counts and amounts

Nominal, Ordinal & Quantitative

N - Nominal (labels or categories)

- Operations: =, ≠

O - Ordered

- Operations: =, ≠, <, >

Q - Interval (location of zero arbitrary)

- Operations: =, ≠, <, >, -
- Can measure distances or spans

Q - Ratio (zero fixed)

- Operations: =, ≠, <, >, -, %
- Can measure ratios or proportions

From Data Model to N, O, Q

Data Model

32.5, 54.0, -17.3, ...

Floating point numbers

Conceptual Model

Temperature (°C)

Data Type

Burned vs. Not-Burned (N)

Hot, Warm, Cold (O)

Temperature Value (Q-interval)

Dimensions & Measures

Dimensions (~ independent variables)

Often discrete variables describing data (N, O)

Categories, dates, binned quantities

Measures (~ dependent variables)

Data values that can be aggregated (Q)

Numbers to be analyzed

Aggregate as sum, count, avg, std. dev...

Not a strict distinction. The same variable may be treated either way depending on the task.

Example: U.S. Census Data

Example: U.S. Census Data

People Count: # of people in group

Year: 1850 - 2000 (every decade)

Age: 0 - 90+

Sex: Male, Female

Marital Status: Single, Married, Divorced, ...

Example: U.S. Census

People Count

Year

Age

Sex

Marital Status

2,348 data points

	A	B	C	D	E
1	year	age	marst	sex	people
2	1850	0	0	1	1483789
3	1850	0	0	2	1450376
4	1850	5	0	1	1411067
5	1850	5	0	2	1359668
6	1850	10	0	1	1260099
7	1850	10	0	2	1216114
8	1850	15	0	1	1077133
9	1850	15	0	2	1110619
10	1850	20	0	1	1017281
11	1850	20	0	2	1003841
12	1850	25	0	1	862547
13	1850	25	0	2	799482
14	1850	30	0	1	730638
15	1850	30	0	2	639636
16	1850	35	0	1	588487
17	1850	35	0	2	505012
18	1850	40	0	1	475911
19	1850	40	0	2	428185
20	1850	45	0	1	384211
21	1850	45	0	2	341254
22	1850	50	0	1	321343
23	1850	50	0	2	286580
24	1850	55	0	1	194080
25	1850	55	0	2	187208
26	1850	60	0	1	174976
27	1850	60	0	2	162236
28	1850	65	0	1	106827
29	1850	65	0	2	105534
30	1850	70	0	1	73677
31	1850	70	0	2	71762
32	1850	75	0	1	40834
33	1850	75	0	2	40229
34	1850	80	0	1	23449
35	1850	80	0	2	22949
36	1850	85	0	1	8186
37	1850	85	0	2	10511
38	1850	90	0	1	5259
39	1850	90	0	2	6569
40	1860	0	0	1	2120846
41	1860	0	0	2	2092162

Census: N, O, Q-Interval, Q-Ratio?

People Count

Q-Ratio

Year

Q-Interval (O)

Age

Q-Ratio (O)

Sex

N

Marital Status

N

Census: Dimension or Measure?

People Count

Measure

Year

Dimension

Age

Depends!

Sex

Dimension

Marital Status

Dimension

Census Data Demo

Data Tables & Transformations

Relational Data Model

Represent data as a **table** (or *relation*)

Each **row** (or *tuple*) represents a record

Each record is a fixed-length tuple

Each **column** (or *field*) represents a variable

Each field has a *name* and a *data type*

A table's **schema** is the set of names and types

A **database** is a collection of tables (relations)

Relational Algebra [Codd '70] / SQL

Operations on Data Tables: table(s) in, table out

Relational Algebra [Codd '70] / SQL

Operations on Data Tables: table(s) in, table out

Project (select): select a set of columns

Filter (where): remove unwanted rows

Sort (order by): order records

Aggregate (group by, sum, min, max, ...):

partition rows into groups + summarize

Combine (join, union, ...):

integrate data from multiple tables

Relational Algebra [Codd '70] / SQL

Project (select): select a set of columns
select day, stock

day	stock	price
10/3	AMZN	957.10
10/3	MSFT	74.26
10/4	AMZN	965.45
10/4	MSFT	74.69



day	stock
10/3	AMZN
10/3	MSFT
10/4	AMZN
10/4	MSFT

Relational Algebra [Codd '70] / SQL

Filter (where): remove unwanted rows

```
select * where price > 100
```

day	stock	price
10/3	AMZN	957.10
10/3	MSFT	74.26
10/4	AMZN	965.45
10/4	MSFT	74.69



day	stock	price
10/3	AMZN	957.10
10/4	AMZN	965.45

Relational Algebra [Codd '70] / SQL

Sort (order by): order records

```
select * order by stock
```

day	stock	price
10/3	AMZN	957.10
10/3	MSFT	74.26
10/4	AMZN	965.45
10/4	MSFT	74.69



day	stock	price
10/3	AMZN	957.10
10/4	AMZN	965.45
10/3	MSFT	74.26
10/4	MSFT	74.69

Relational Algebra [Codd '70] / SQL

Aggregate (group by, sum, min, max, ...):

```
select stock, min(price) group by stock
```

day	stock	price
10/3	AMZN	957.10
10/3	MSFT	74.26
10/4	AMZN	965.45
10/4	MSFT	74.69



stock	min(price)
AMZN	957.10
MSFT	74.26

Relational Algebra [Codd '70] / SQL

Join (join) multiple tables together

day	stock	price
10/3	AMZN	957.10
10/3	MSFT	74.26
10/4	AMZN	965.45
10/4	MSFT	74.69



day	stock	price	min
10/3	AMZN	957.10	957.10
10/3	MSFT	74.26	74.26
10/4	AMZN	965.45	957.10
10/4	MSFT	74.69	74.26

stock	min
AMZN	957.10
MSFT	74.26

```
select t.day, t.stock, t.price, a.min  
from table as t, aggregate as a  
where t.stock = a.stock
```

Roll-Up and Drill-Down

Want to examine population by year and age?

Roll-up the data along the desired dimensions

Dimensions Measure

```
SELECT year, age, sum(people)
FROM census
GROUP BY year, age
```

Dimensions

Roll-Up and Drill-Down

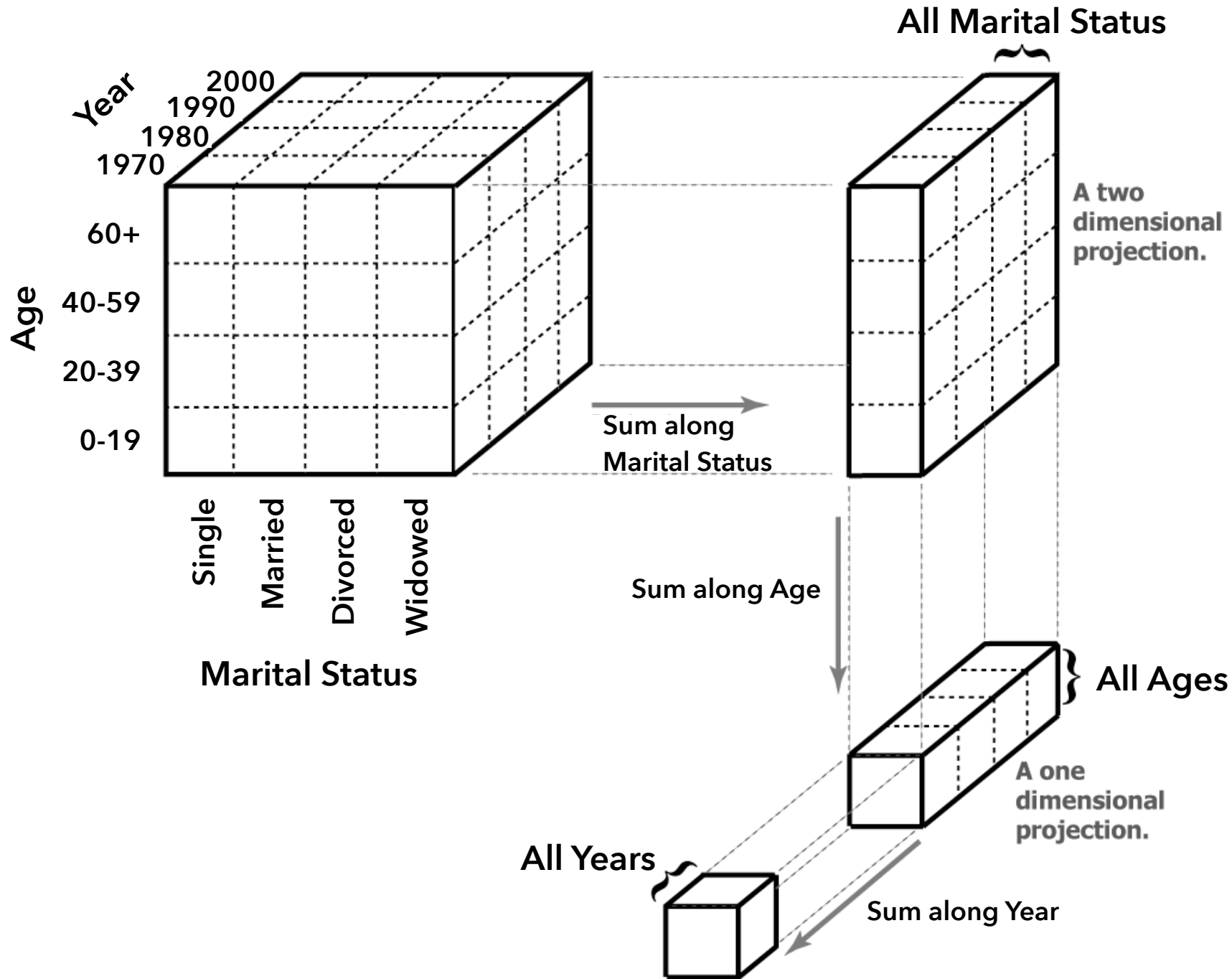
Want to see the breakdown by marital status?

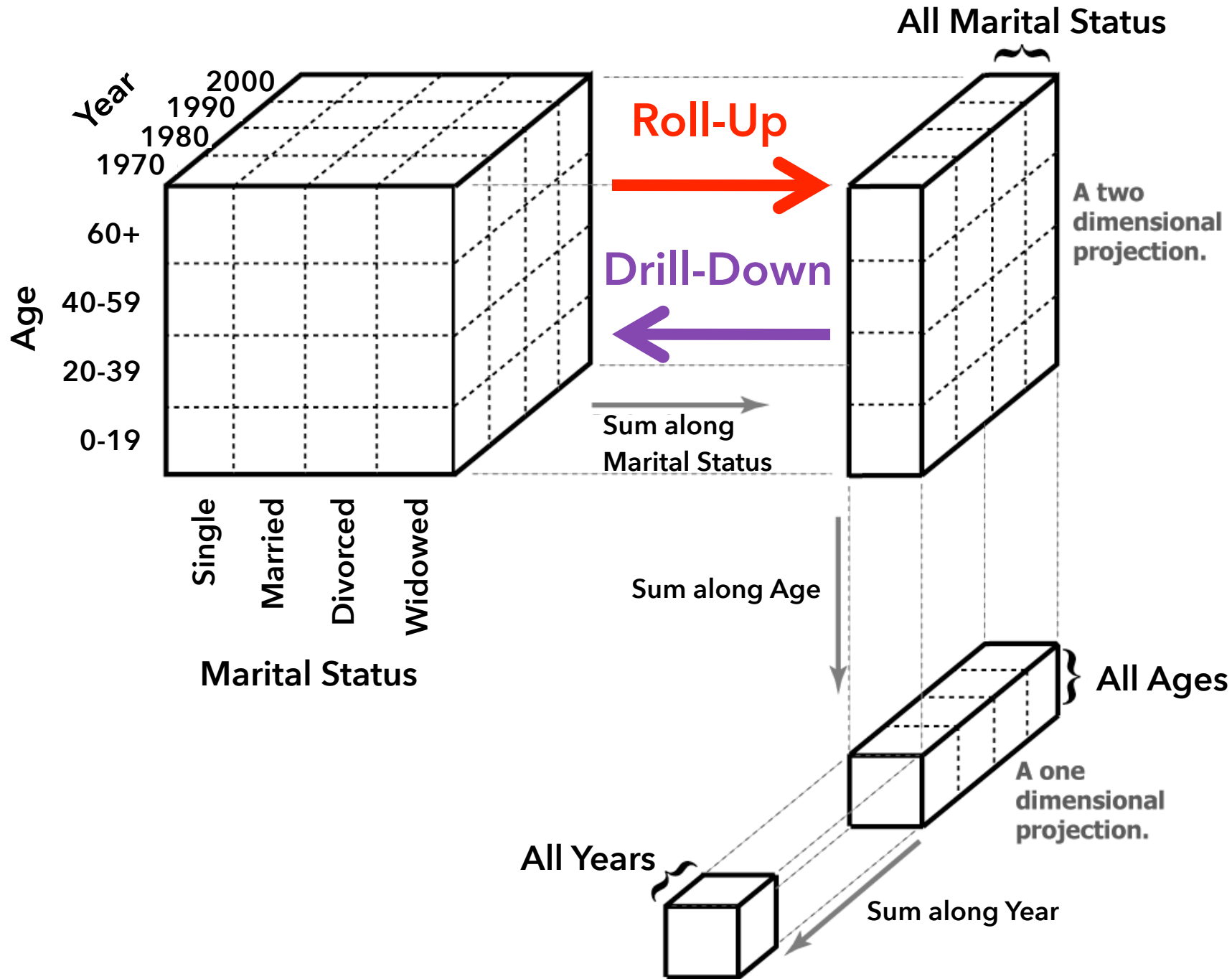
Drill-down into additional dimensions

```
SELECT year, age, marst, sum(people)
```

```
FROM census
```

```
GROUP BY year, age, marst
```





ORIGINAL

YEAR	AGE	MARST	SEX	PEOPLE
1850	0	0	1	1,483,789
1850	5	0	1	1,411,067
1860	0	0	1	2,120,846
1860	5	0	1	1,804,467
...				

PIVOTED (or CROSS-TABULATION)

AGE	MARST	SEX	1850	1860	...
0	0	1	1,483,789	2,120,846	...
5	0	1	1,411,067	1,804,467	...
...					

Which format might we prefer? Why?

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 normalized forms in DB theory)

Common Data Formats

CSV: Comma-Separated Values (d3.csv)

```
year,age,marst,sex,people
```

```
1850,0,0,1,1483789
```

```
1850,5,0,1,1411067
```

```
...
```

Common Data Formats

CSV: Comma-Separated Values (d3.csv)

```
year,age,marst,sex,people  
1850,0,0,1,1483789  
1850,5,0,1,1411067  
...
```

JSON: JavaScript Object Notation (d3.json)

```
[  
  {"year":1850,"age":0,"marst":0,"sex":1,"people":1483789},  
  {"year":1850,"age":5,"marst":0,"sex":1,"people":1411067},  
  ...  
]
```

Administrivia

A1: Expository Visualization

Design a static visualization for a data set.

The climate of a place can have a tremendous impact on people's lived experience. You will examine average monthly climate measurements for six major U.S. cities, roughly covering the edges of the continental United States.

You must choose the message you want to convey. What question(s) do you want to answer? What insight do you want to communicate?

A1: Expository Visualization

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

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

You are free to **use any tools** (inc. pen & paper).

Deliverables (upload via Canvas; see A1 page)

Image of your visualization (PNG or JPG format)

Short description + design rationale (≤ 4 paragraphs)

Due by **11:59 pm, Monday October 11.**

Course Participation

Discussion comment on class forum (Ed).

Quiz - not graded, but required - on Canvas.

Both are due by Friday, 11:59pm.

One comment per week, except in later weeks where we have assigned peer reviews.

You have 1 discussion "pass" for the quarter.

Observable + Data Tutorial

~~Friday Oct. 1, 4:30-6pm on Zoom~~

Introduction to Observable notebooks, JavaScript basics, and data management and transformation, led by Firn & Yueqian.

Recording is available on Canvas, under

Zoom > Cloud Recordings:

[https://canvas.uw.edu/courses/1477514/
external_tools/95443](https://canvas.uw.edu/courses/1477514/external_tools/95443)

Tableau Tutorial

Friday Oct. 8, 4:30-6pm on Zoom

Introduction to Tableau: a graphical tool for visualization construction, helpful for both exploration and prototyping. Tutorial led by Naveena & Xia.

Zoom link is available on Canvas.

The tutorial will be recorded.

Download Tableau and sign up for a student license prior to tutorial!

Image Models



Visual Language is a Sign System



Jacques Bertin

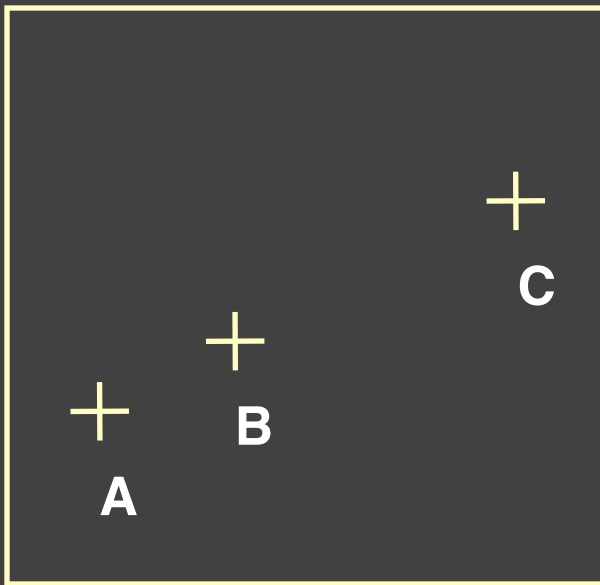
Images perceived as a set of signs

Sender encodes information in signs

Receiver decodes information from signs

Sémiologie Graphique, 1967

Bertin's Semiology of Graphics



1. A, B, C are distinguishable
2. B is between A and C.
3. BC is twice as long as AB.

∴ Encode quantitative variables

"Resemblance, order and proportional are the three signfields in graphics." - Bertin

LES VARIABLES DE L'IMAGE

	POINTS			LIGNES			ZONES	
XY 2 DIMENSIONS DU PLAN								
Z TAILLE								
VALEUR								

LES VARIABLES DE SÉPARATION DES IMAGES

GRAIN								
COULEUR								
ORIENTATION								
FORME								

Visual Encoding Variables

Position (x 2)

Size

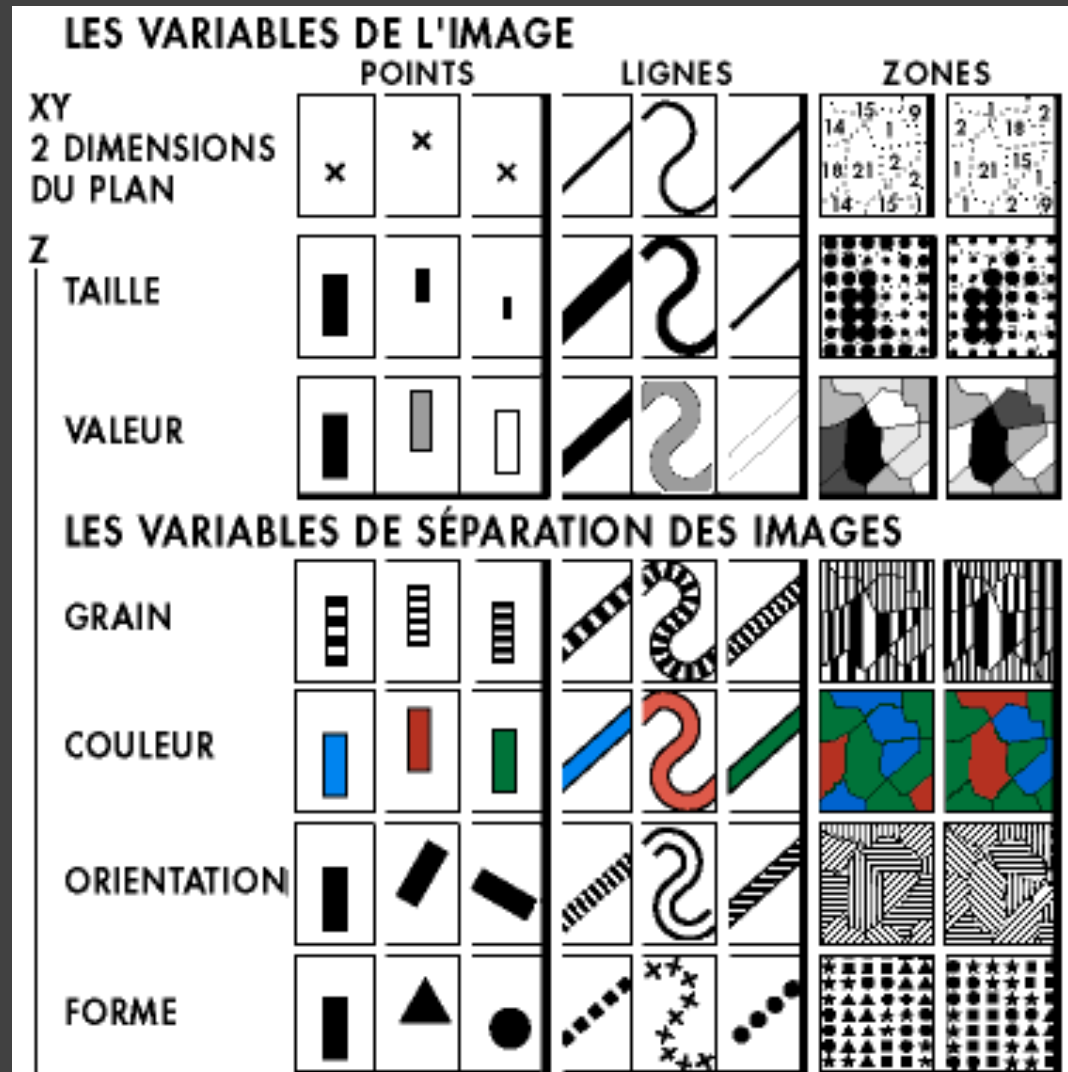
Value

Texture

Color

Orientation

Shape



Visual Encoding Variables

Position

Length

Area

Volume

Value

Texture

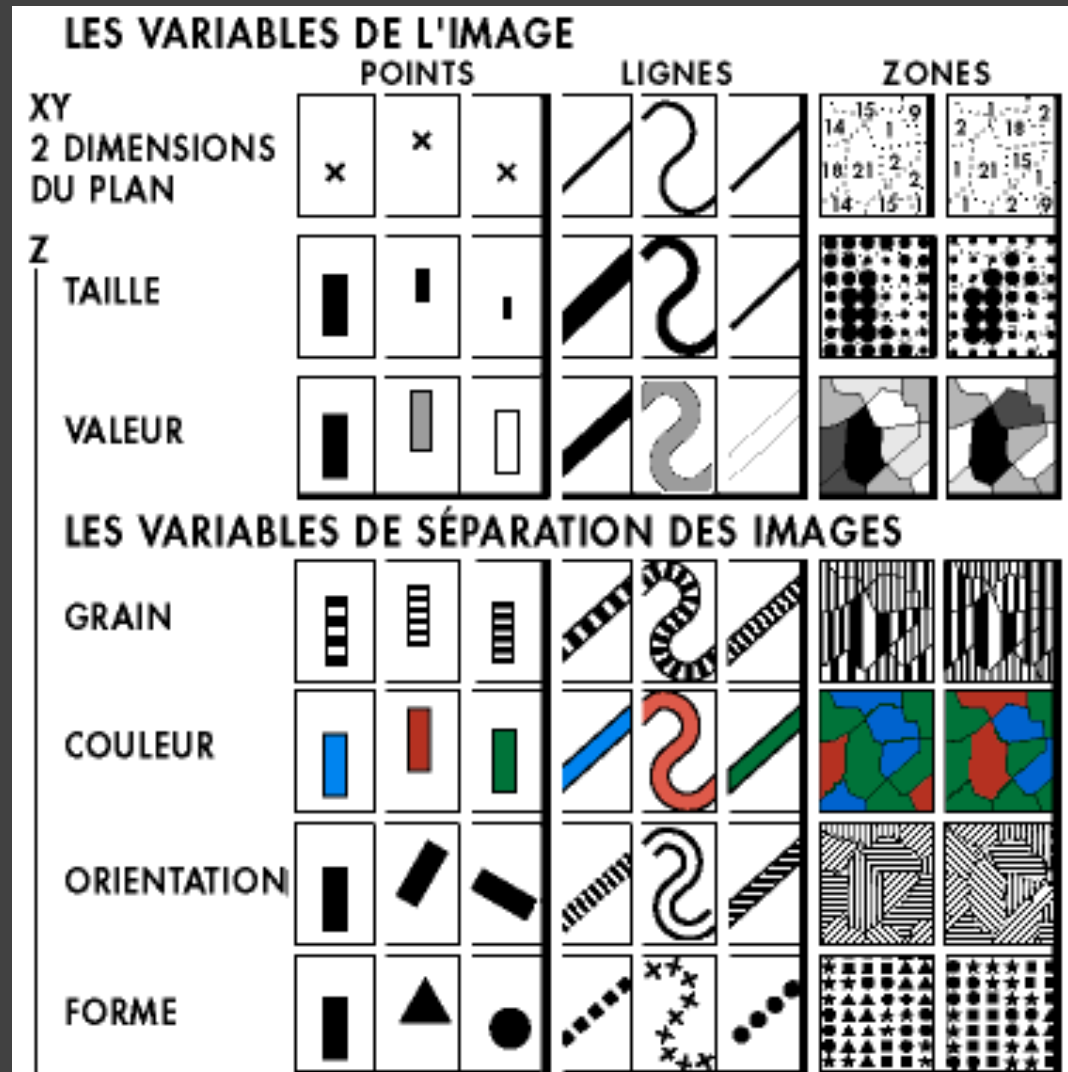
Color

Orientation

Shape

Transparency

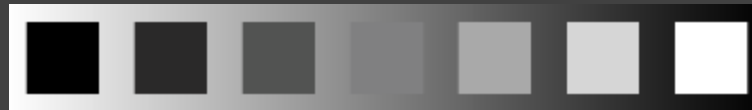
Blur / Focus ...



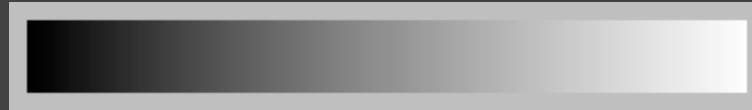
Information in Hue and Value

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



Bertin's Levels of Organization

Position

N	O	Q
---	---	---

Nominal

Size

N	O	Q
---	---	---

Ordinal

Value

N	O	Q
---	---	---

Quantitative

Note: **Q** \subset **O** \subset **N**

Texture

N	o	
---	---	--

Color

N		
---	--	--

Orientation

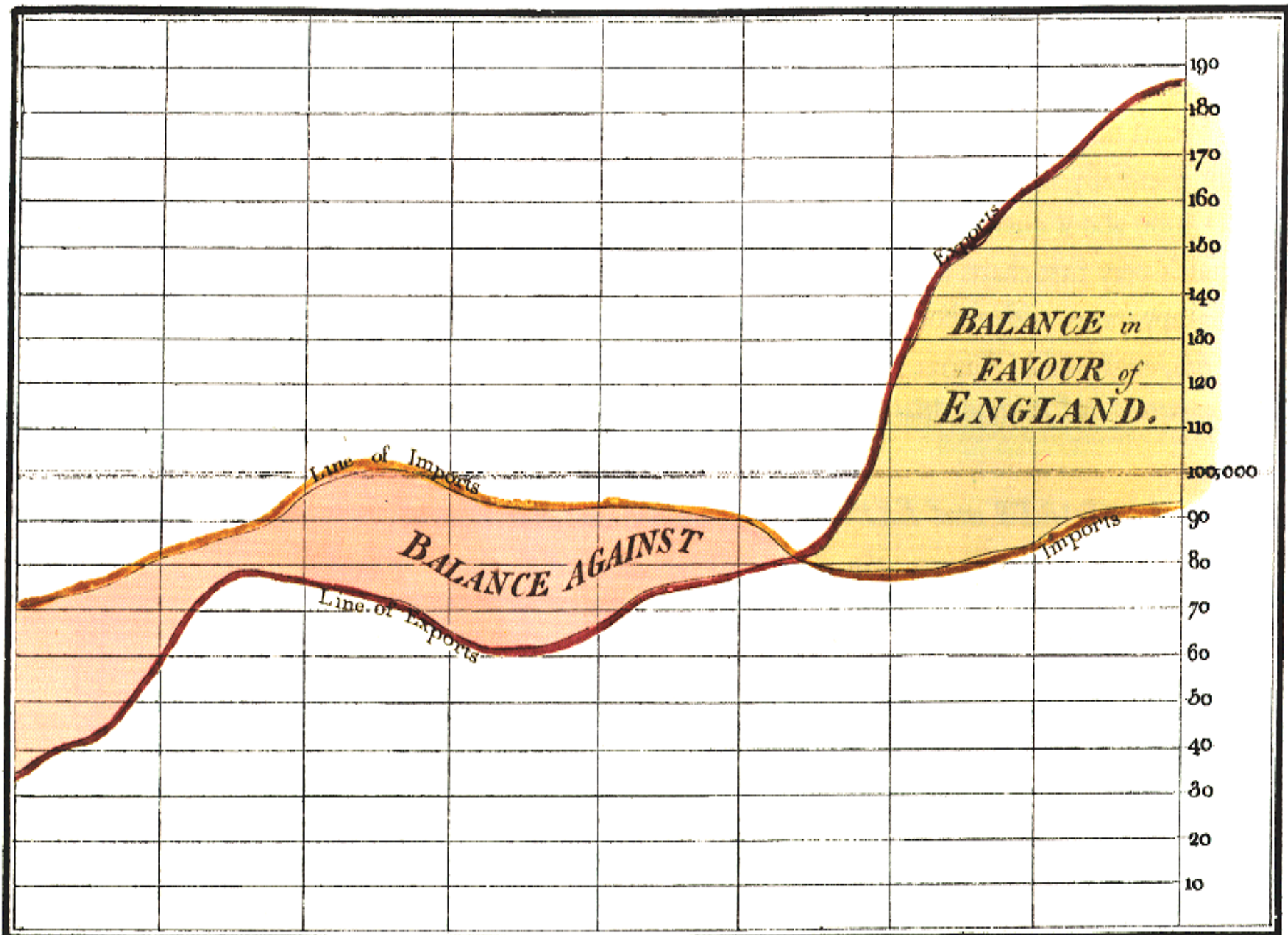
N		
---	--	--

Shape

N		
---	--	--

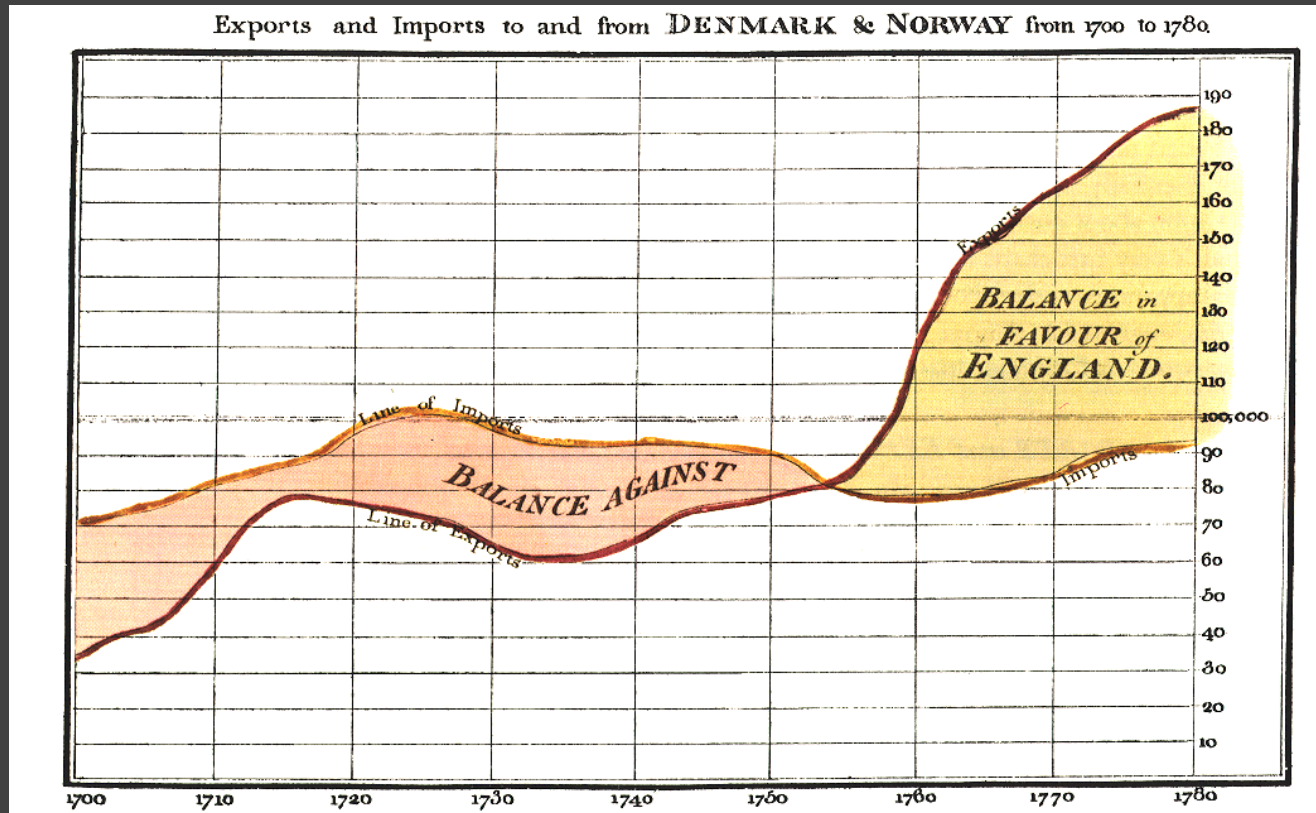
Deconstructions

Exports and Imports to and from DENMARK & NORWAY from 1700 to 1780.



1700 1710 1720 1730 1740 1750 1760 1770 1780

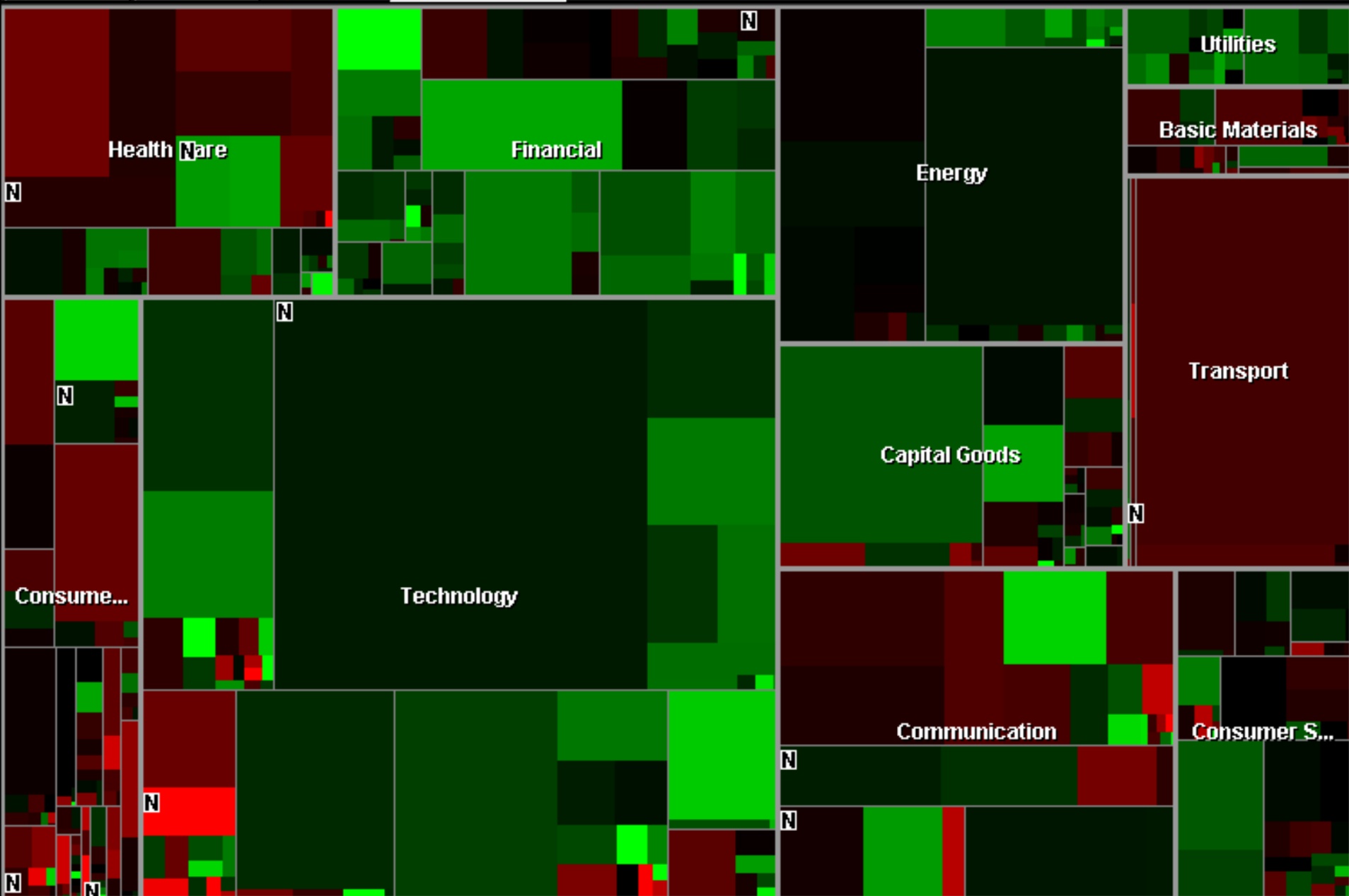
William Playfair, 1786



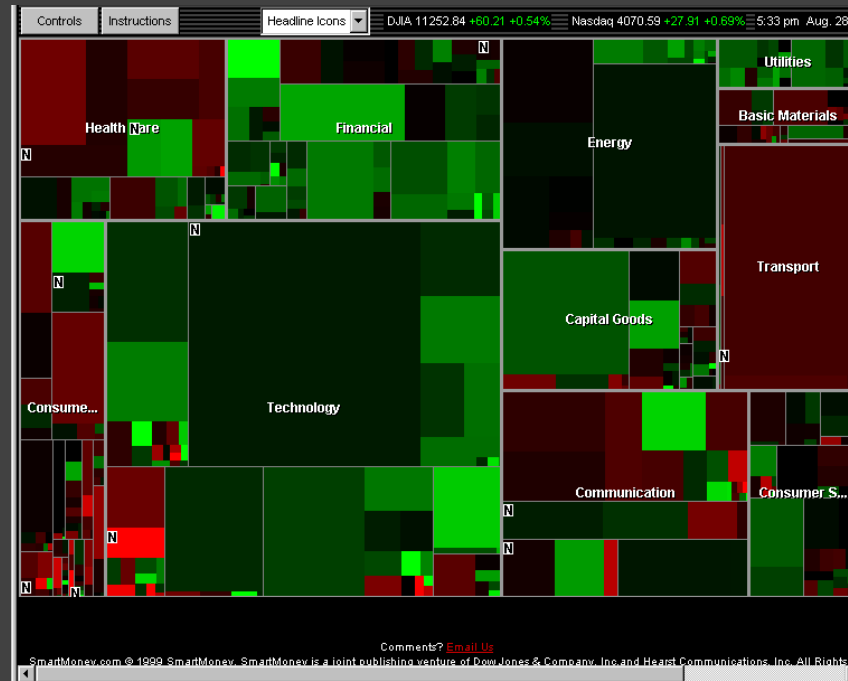
X-axis: year (Q)

Y-axis: currency (Q)

Color: imports/exports (N, O)



Wattenberg's Map of the Market



Rectangle Area: market cap (Q)

Rectangle Position: market sector (N), market cap (Q)

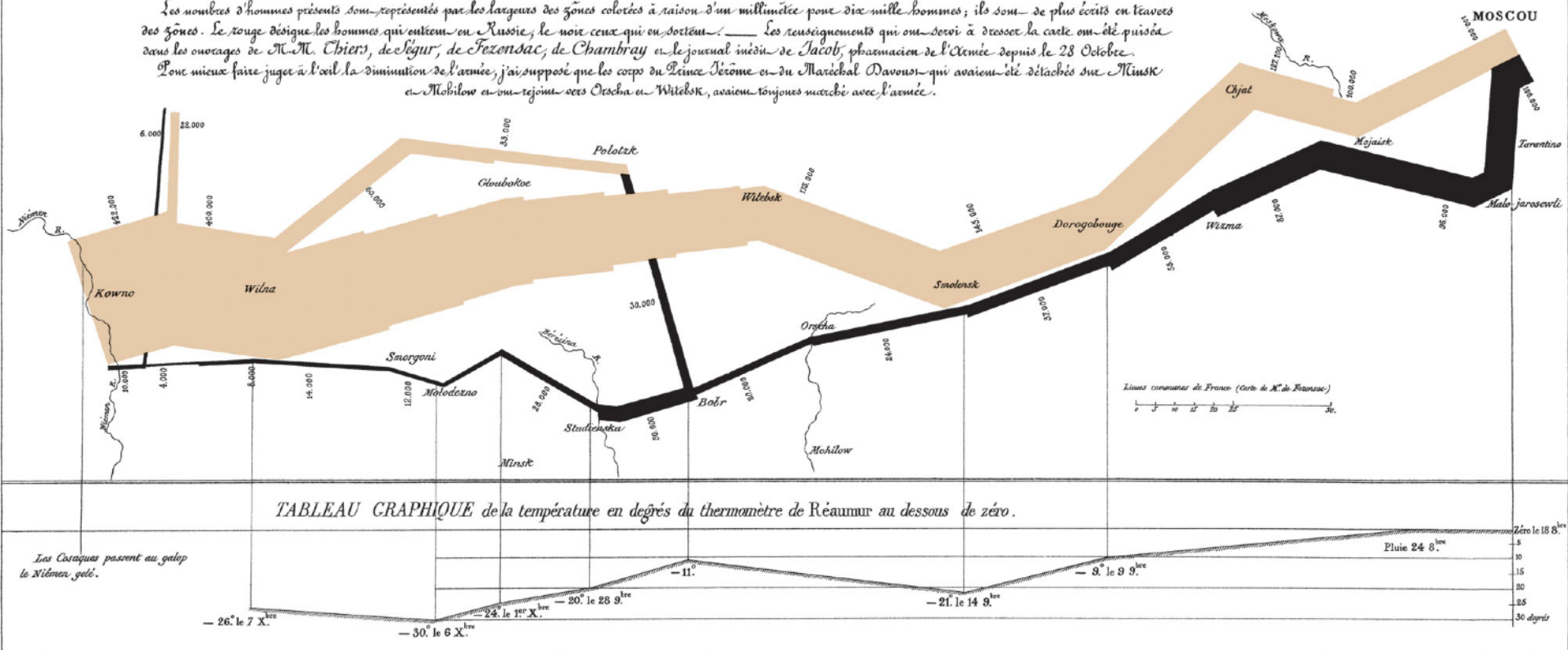
Color Hue: loss vs. gain (N, O)

Color Value: magnitude of loss or gain (Q)

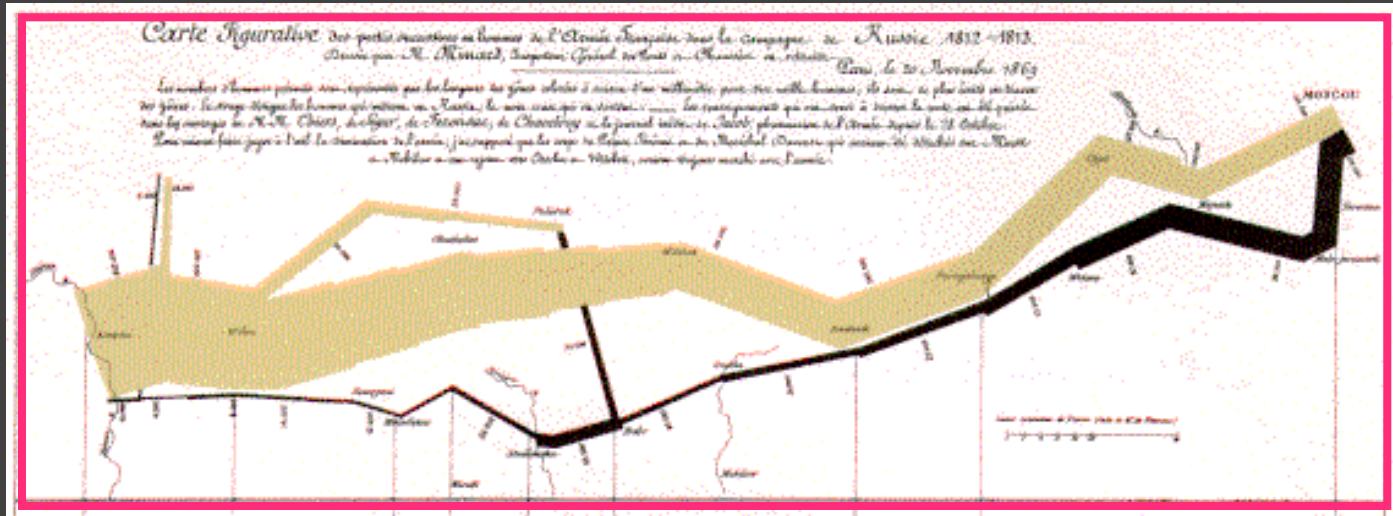
Minard 1869: Napoleon's March

Carte Figurative des pertes successives en hommes de l'Armée Française dans la campagne de Russie 1812-1813.
 Dressée par M. Minard, Inspection Générale des Ponts et Chaussées en retraite Paris, le 20 Novembre 1869.

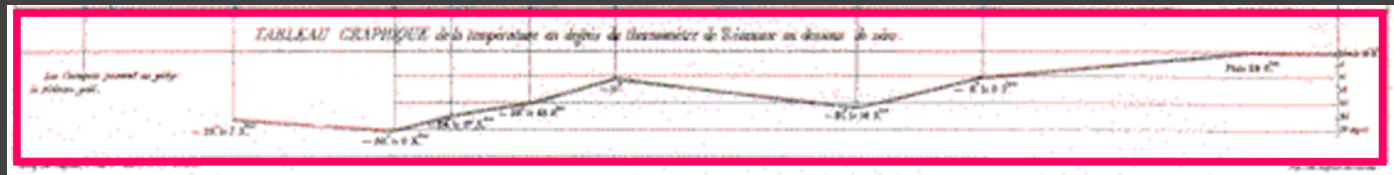
Les nombres d'hommes présents sont représentés par les largeurs des zones colorées à raison d'un millimètre pour dix mille hommes; ils sont de plus écrits en travers des zones. Le rouge désigne les hommes qui entrent en Russie, le noir ceux qui en sortent. Les renseignements qui ont servi à dresser la carte ont été puisés dans les ouvrages de M. M. Chiers, de Légar, de Fezensac, de Chambray et le journal inédit de Jacob, pharmacien de l'Armée depuis le 28 Octobre. Pour mieux faire juger à l'œil la diminution de l'armée, j'ai supposé que les corps du Prince Jérôme et du Maréchal Davout qui avoient été détachés sur Minsk et Mohilow et qui rejoindrent vers Orscha et Witebsk, avoient toujours marché avec l'armée.



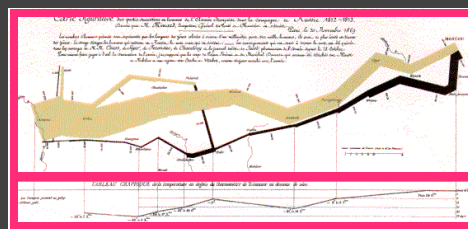
Single-Axis Composition



+



=



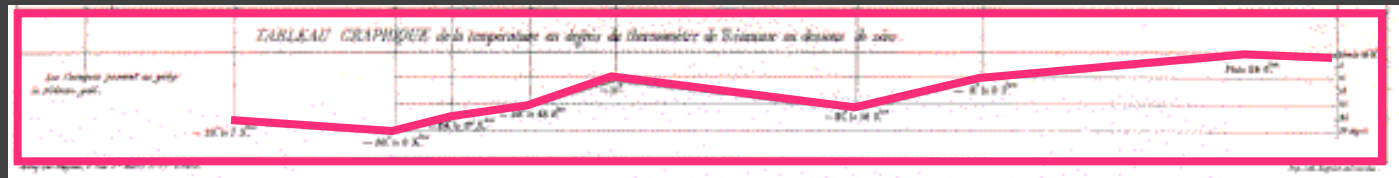
Mark Composition

Y-axis: temperature (Q)

+

X-axis: longitude (Q) / time (O)

=



Temp over space/time (Q x Q)

Mark Composition

Y-axis: latitude (Q)

+

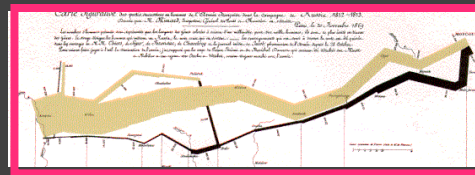
X-axis: longitude (Q)

+

Width: army size (Q)



=

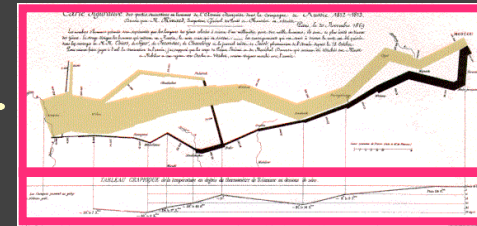
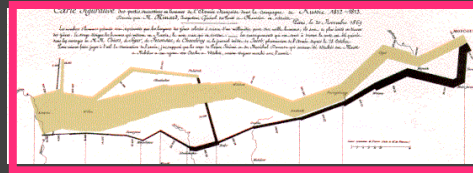


Army position (Q x Q) and army size (Q)

latitude (Q)

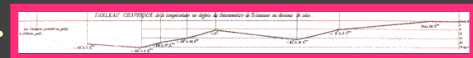
longitude (Q)

army size (Q)



temperature (Q)

longitude (Q) / time (O)



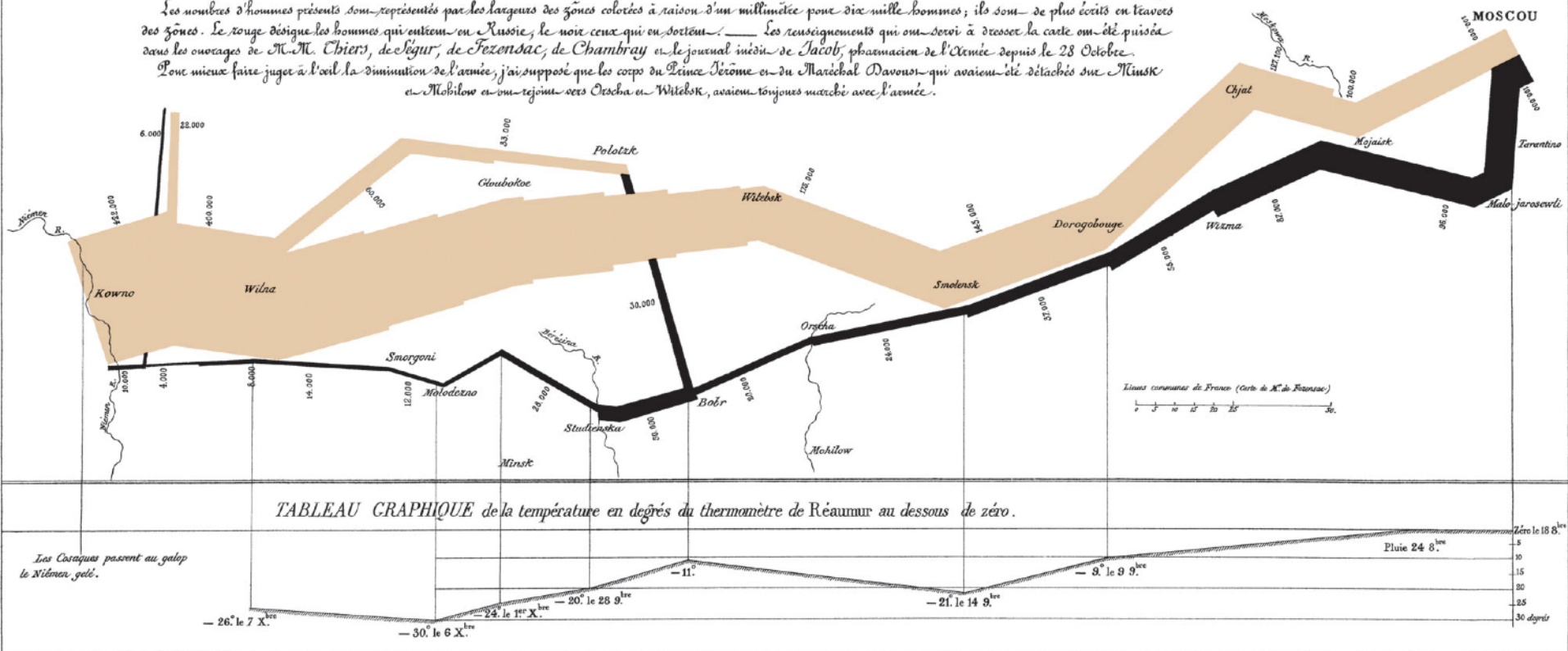
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Dressée par M. Minard, Inspection Générale des Ponts et Chaussées en retraite Paris, le 20 Novembre 1869.

Les nombres d'hommes présents sont représentés par les largeurs des zones colorées à raison d'un millimètre pour dix mille hommes; ils sont de plus écrits en travers des zones. Le rouge désigne les hommes qui entrent en Russie, le noir ceux qui en sortent. Les renseignements qui ont servi à dresser la carte ont été puisés dans les ouvrages de M. M. Chiers, de Légué, de Fezensac, de Chambray et le journal inédit de Jacob, pharmacien de l'Armée depuis le 28 Octobre.

Pour mieux faire juger à l'œil la diminution de l'armée, j'ai supposé que les corps du Prince Jérôme et du Maréchal Davout qui avoient été détachés sur Minsk et Mohilow et qui rejoindrent Orscha et Witebsk, avoient toujours marché avec l'armée.



Autog. par Regnier, 8. Par. S^{te} Marie S^{te} O^{de} à Paris.

Imp. Lit. Regnier et Dourdet.

Depicts at least 5 quantitative variables. Any others?

Formalizing Design

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.

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.

Design Criteria [Mackinlay 86]

Expressiveness

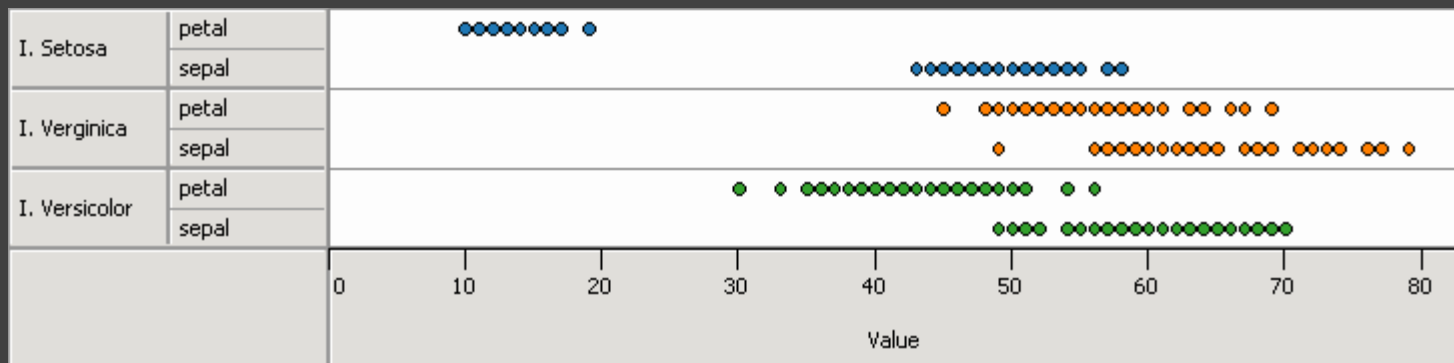
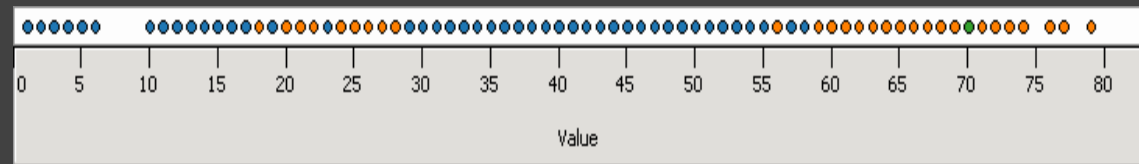
A set of facts is *expressible* in a visual language if the sentences (i.e. the visualizations) in the language express all the facts in the set of data, and only the facts in the data.

Effectiveness

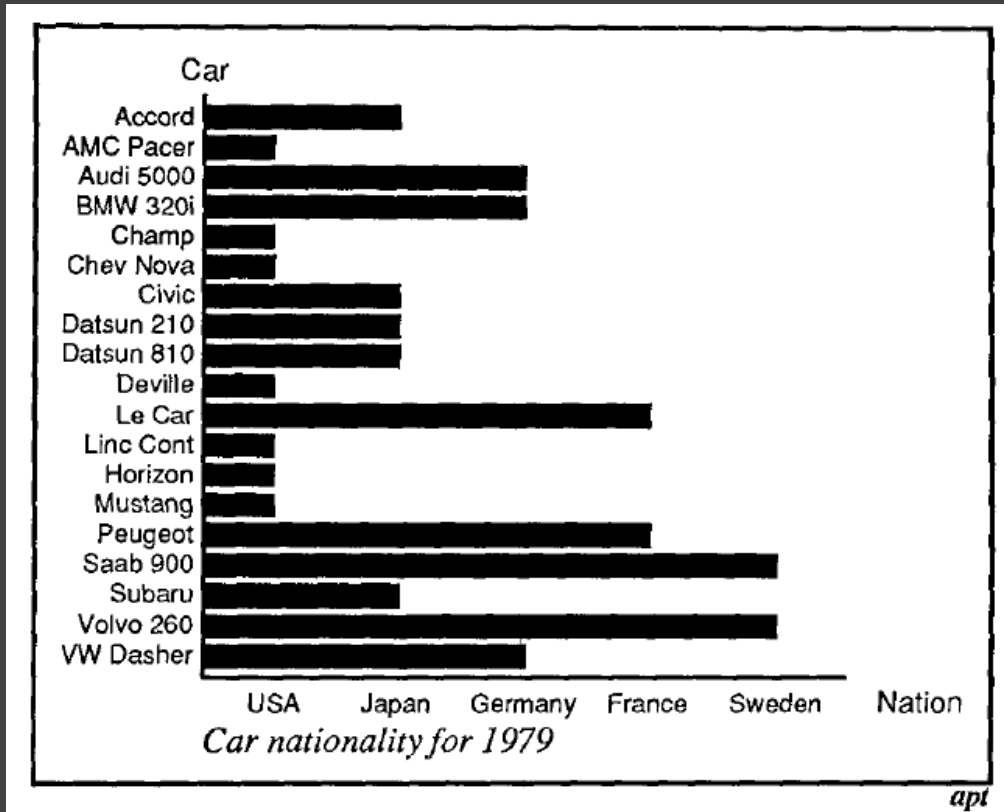
One visualization is more effective than another if the information conveyed by one is perceived to be more useful than the other visualization.

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.

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

One visualization is more effective than another if the information conveyed by one is perceived to be more effective than the other visualization.

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

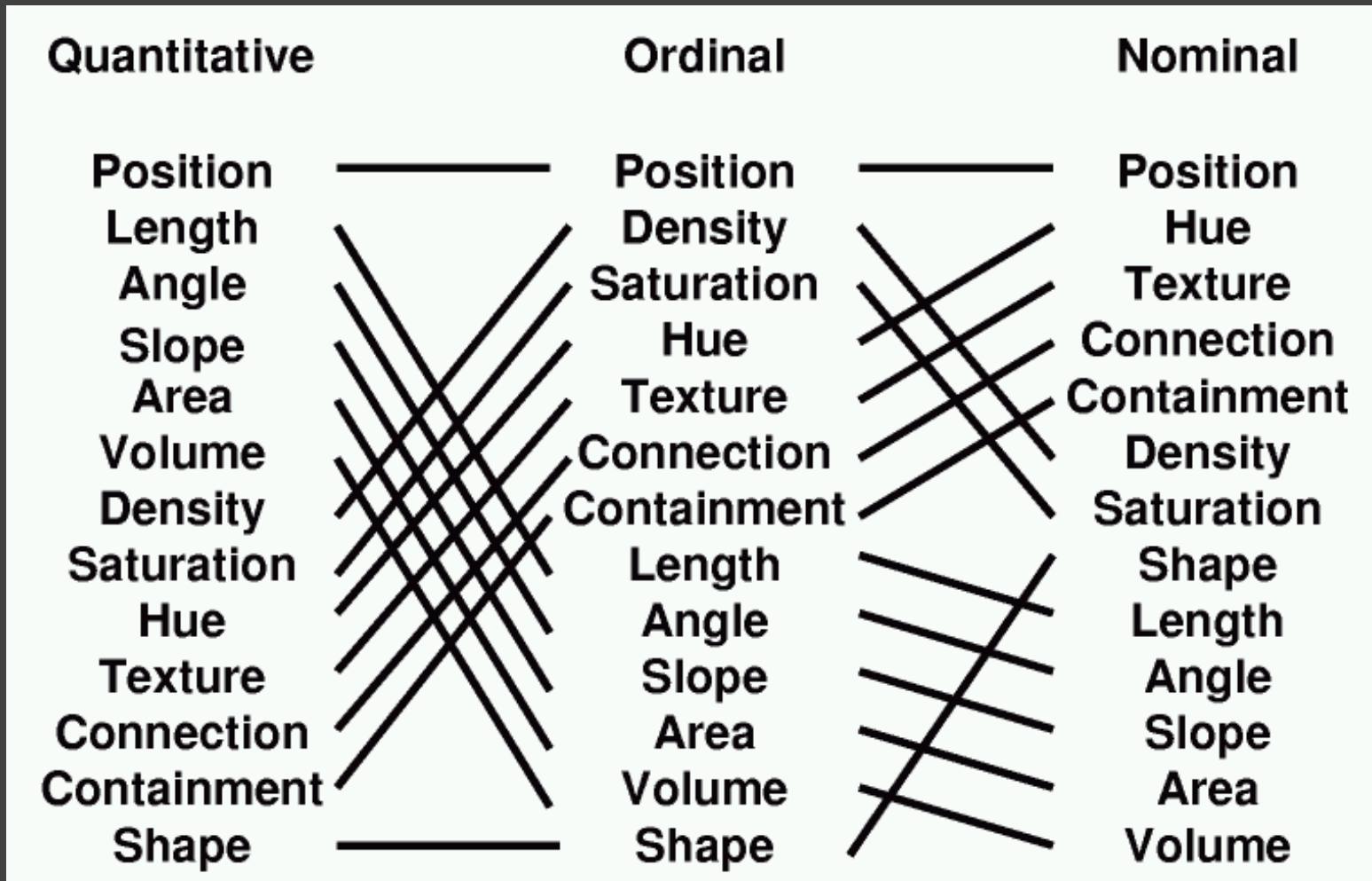
A visualization is more *effective* than another visualization if the information conveyed by one visualization is more readily perceived than the information in the other visualization.

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)

Mackinlay's Ranking



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

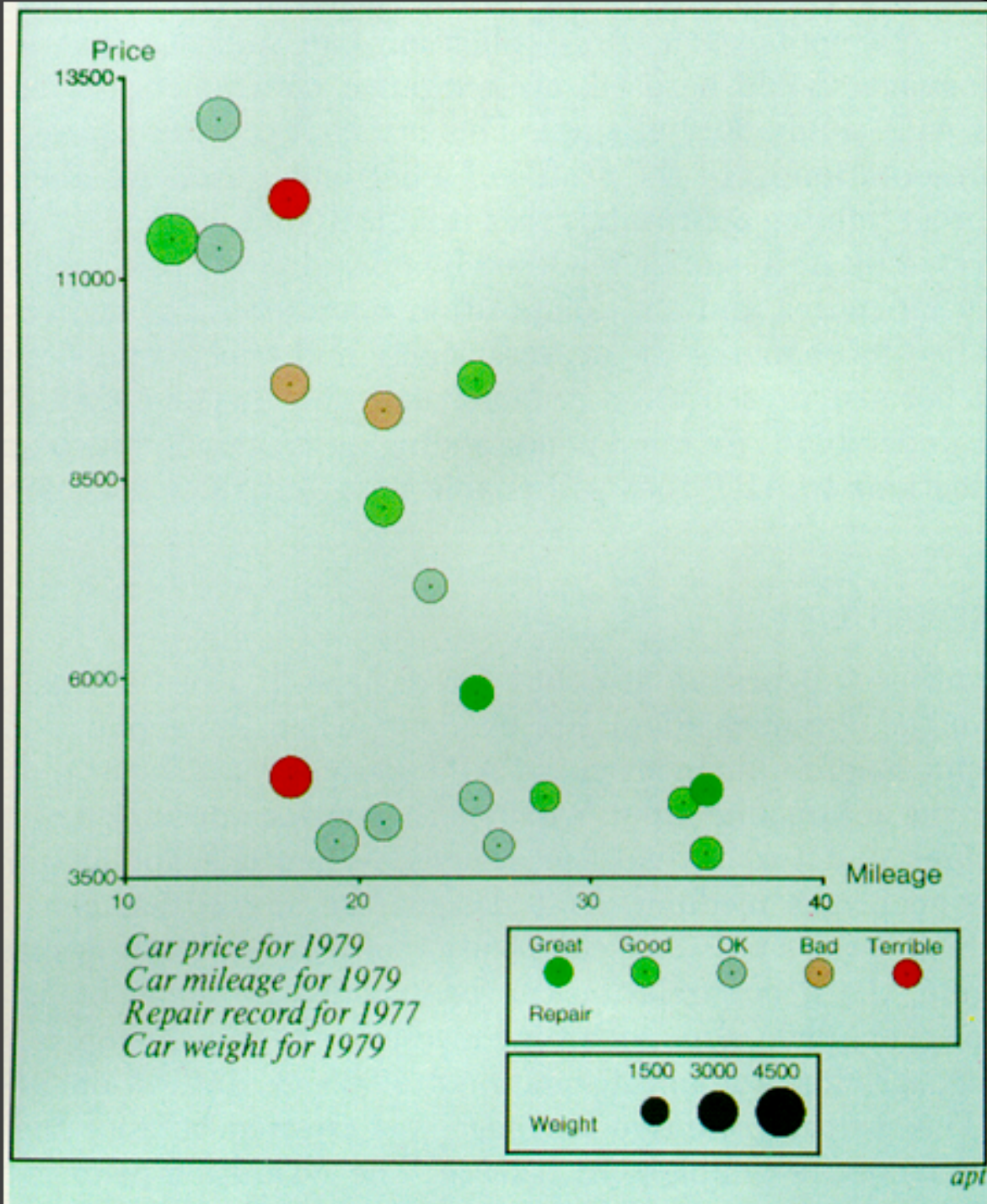
Output the "most effective" visualization

APT

Automatically
generate chart
for car data

Input variables:

1. Price
2. Mileage
3. Repair
4. Weight



Limitations of APT?

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

Summary: Data & Image Models

Formal specification

Data model: relational data; N,O,Q types

Image model: visual encoding channels

Encodings map data to visual variables

Choose expressive and effective encodings

Rule-based tests of expressiveness

Perceptual effectiveness rankings

Question: how do we establish effectiveness criteria? *Subject of perception lectures...*