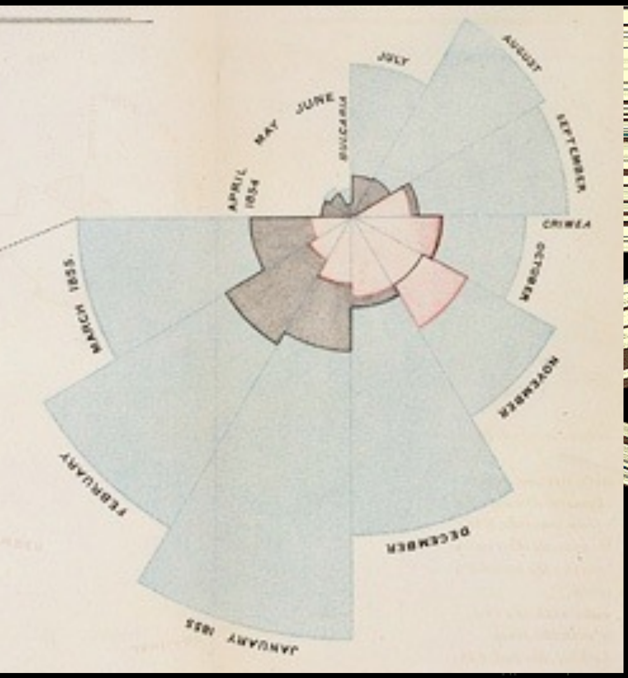
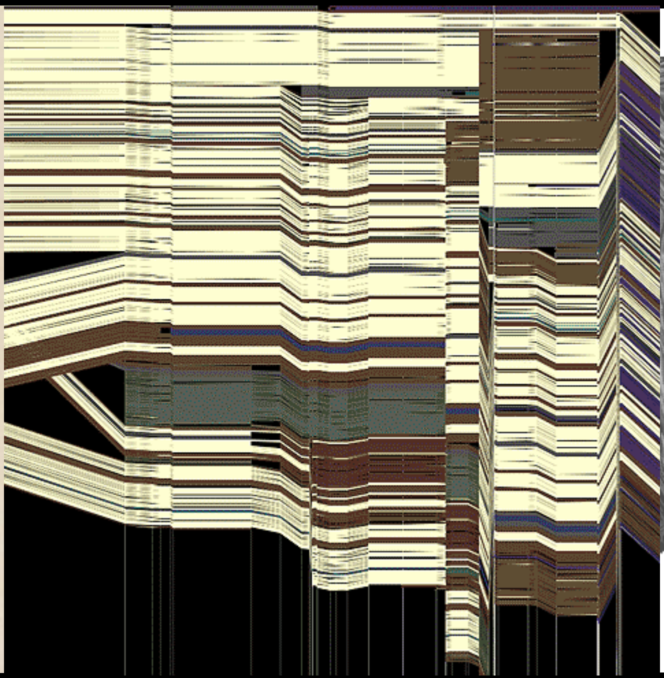
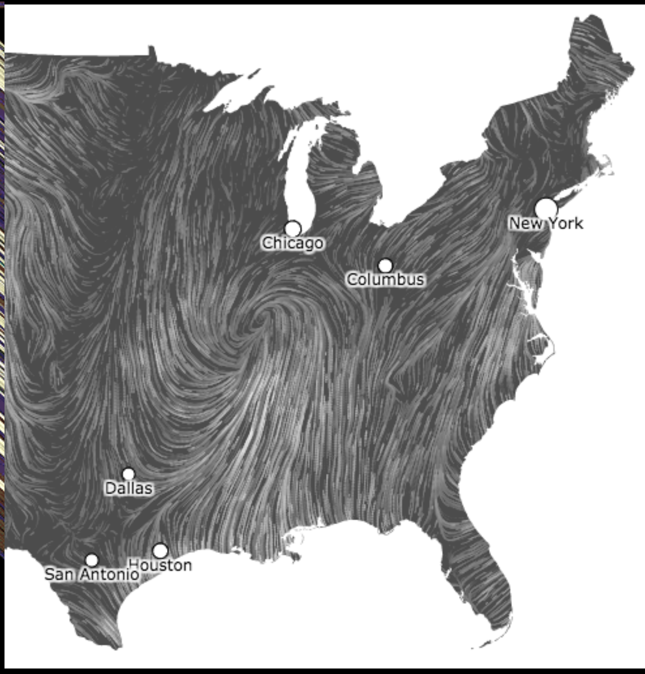
CSE 442 - Data Visualization

Data and Image Models







Leilani Battle 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

Learning Goals

We should be able to answer these questions:

How can we encode abstract data within an image?

What are the foundational principles that guide the encoding process?

Topics

Properties of Data

Properties of Images

Mapping Data to Images

Data Models

Data Models vs 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
```

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

stock	min
AMZN	957.10
MSFT	74.26

→

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

```
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 (year, age) **Measure** (sum(people))

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

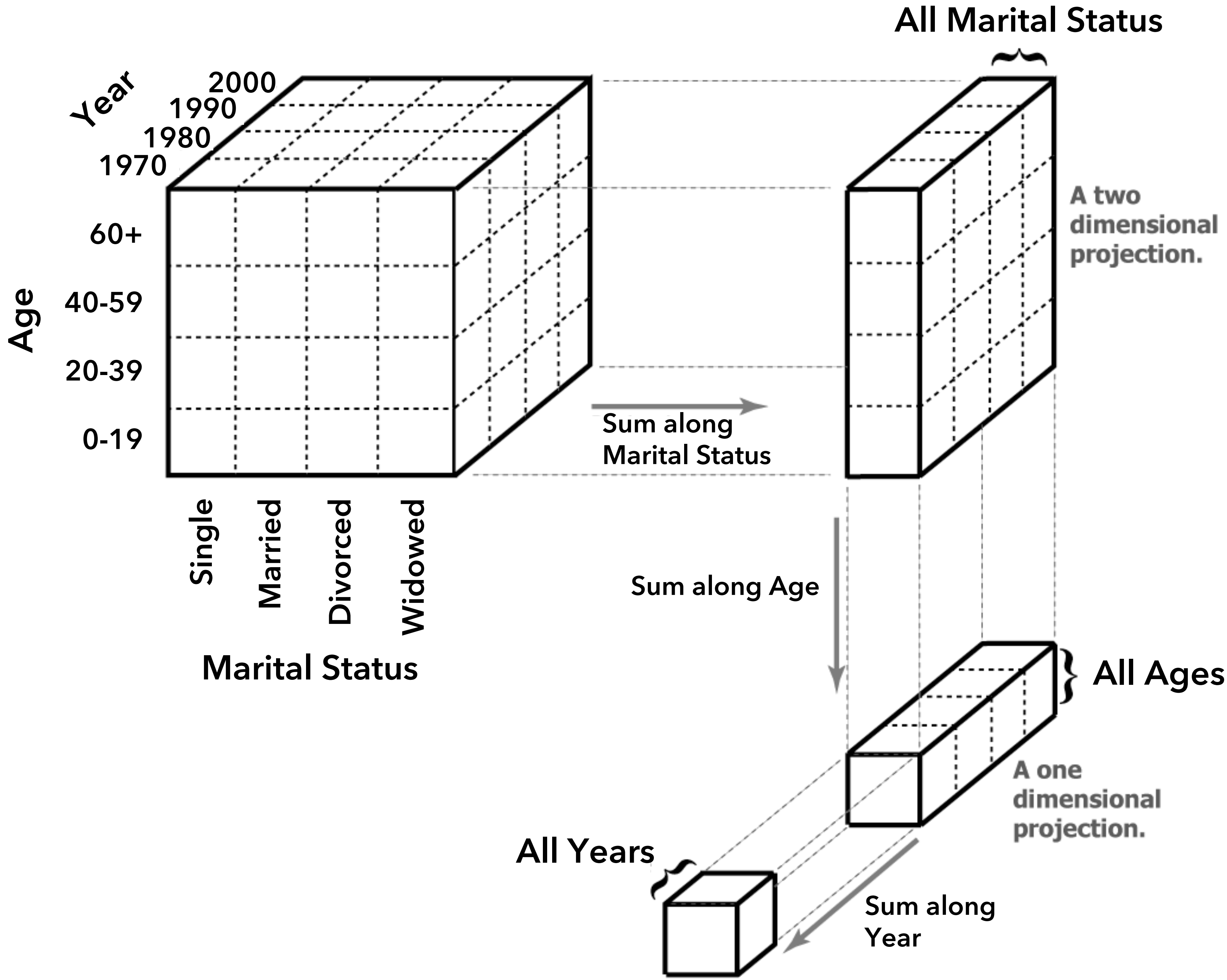
Dimensions (year, age)

Roll-Up and Drill-Down

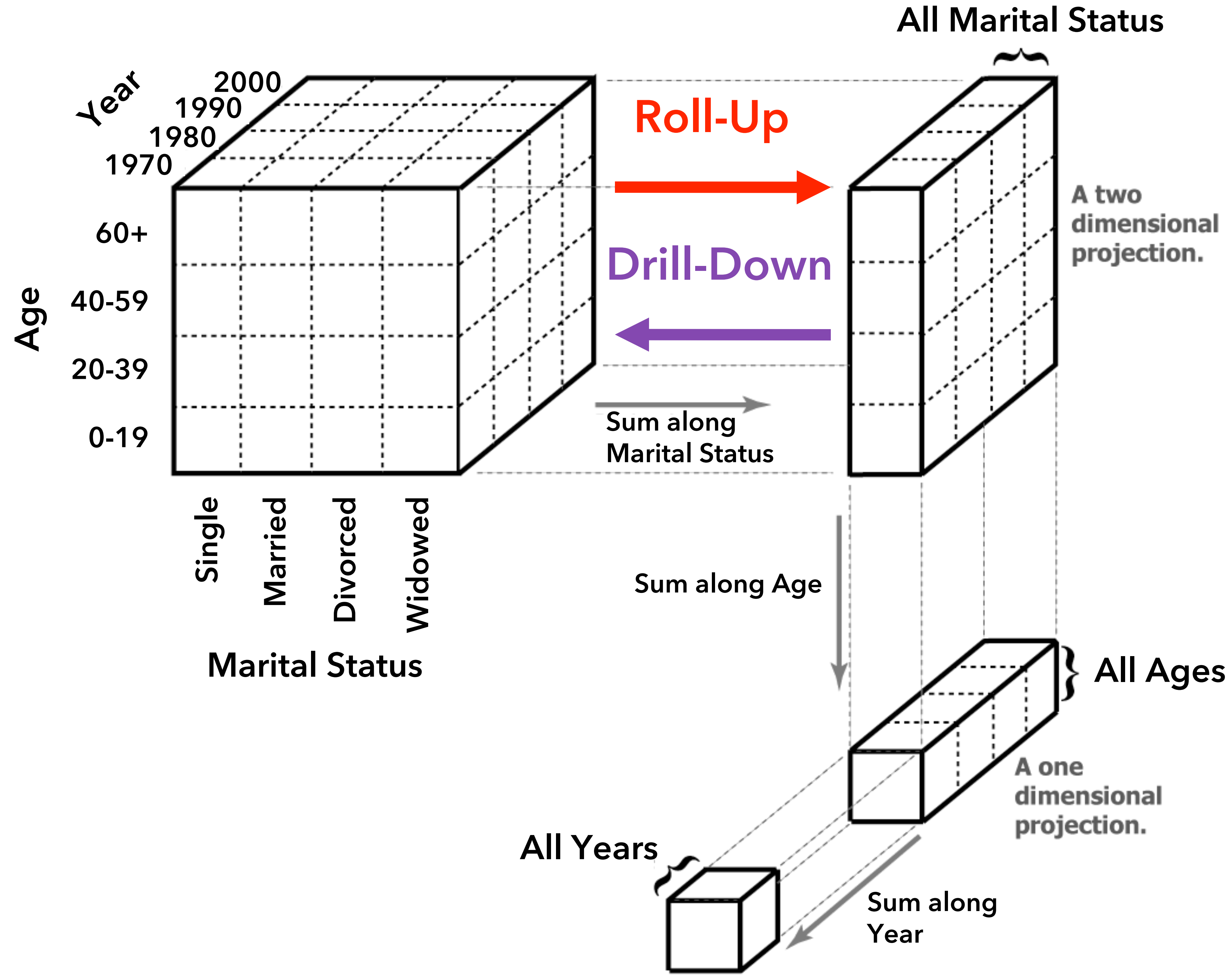
Want to see the breakdown by marital status?

Drill-down into additional dimensions

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



All Marital Status
Year
2000
1990
1980
1970
60+
40-59
20-39
0-19
Age
Single
Married
Divorced
Widowed
Marital Status
Sum along Marital Status
A two dimensional projection.
Sum along Age
All Ages
A one dimensional projection.
All Years
Sum along Year



All Marital Status
Year
2000
1990
1980
1970
Roll-Up
Drill-Down
A two dimensional projection.
Age
60+
40-59
20-39
0-19
Sum along Marital Status
Single
Married
Divorced
Widowed
Sum along Age
Marital Status
All Ages
A one dimensional projection.
All Years
Sum along Year

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
. . .				

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?

PIVOTED (or CROSS-TABULATION)

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

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


...
```

Common Data Formats

CSV: Comma-Separated Values

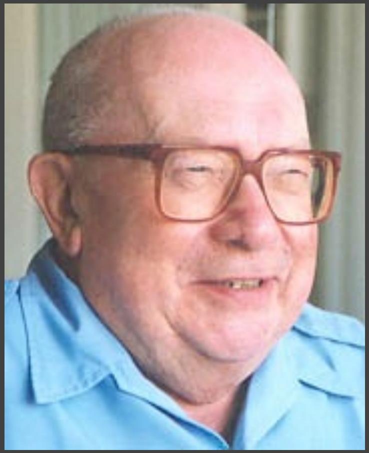
```
year,age,marst,sex,people
1850,0,0,1,1483789
1850,5,0,1,1411067


...
```

JSON: JavaScript Object Notation

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

Image Models

Visual Language is a Sign System



Jacques Bertin

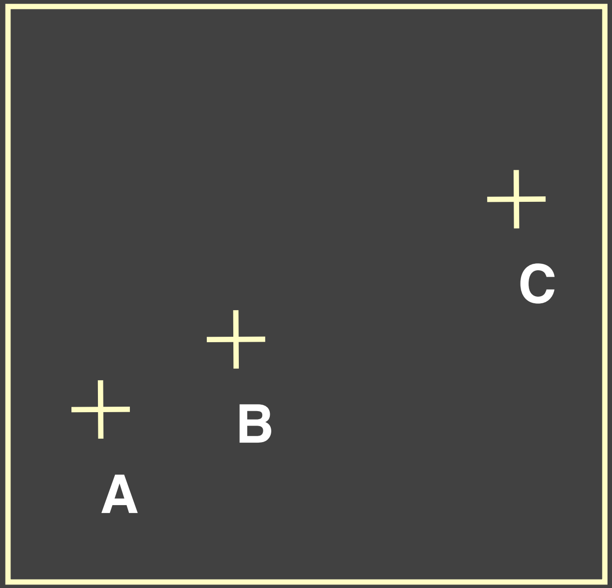
Images perceived as a set of signs

Sender encodes information in signs

Receiver decodes information from signs

Sémiologie Graphique, 1967

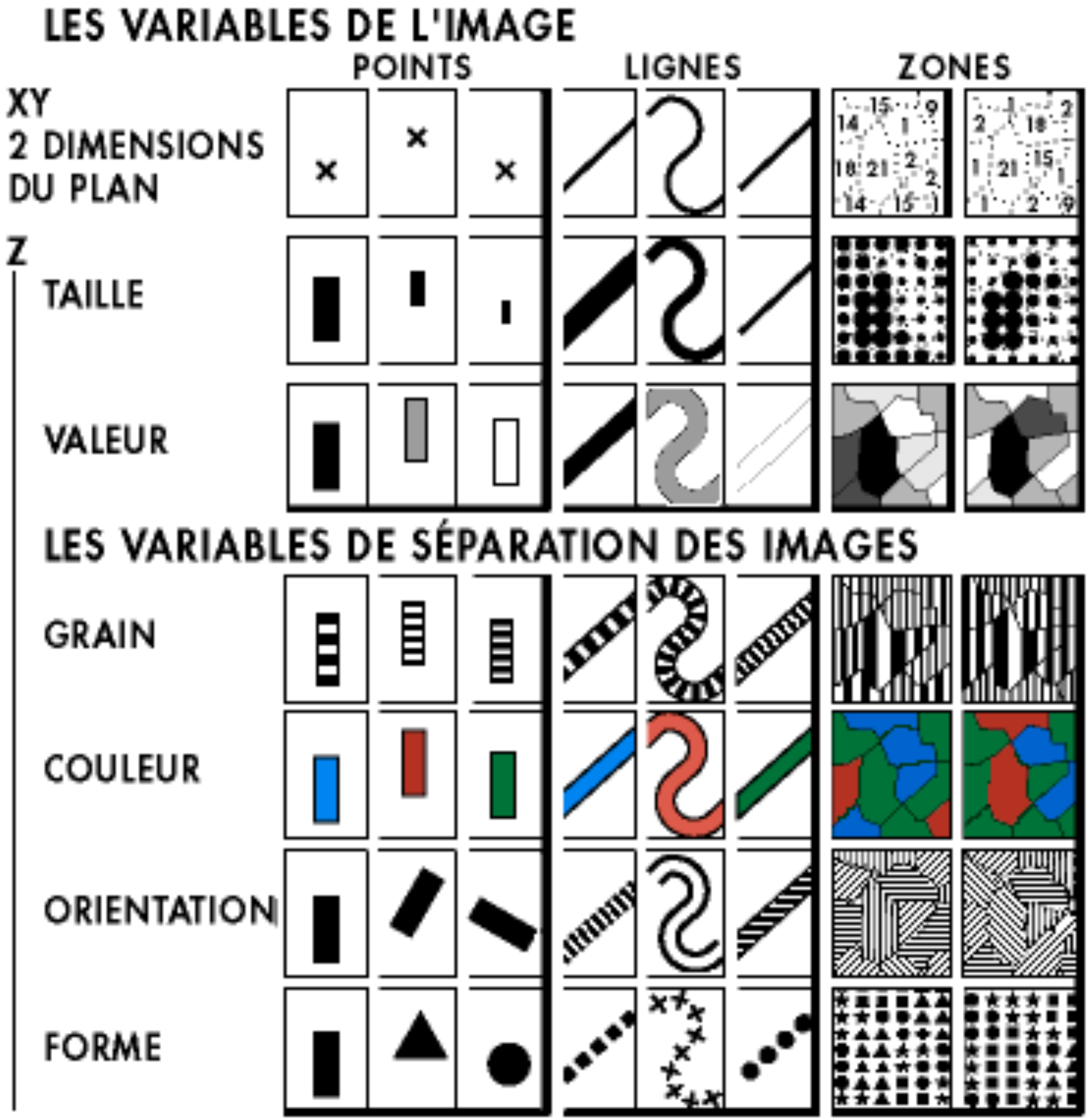
Bertin's Semiology of Graphics



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

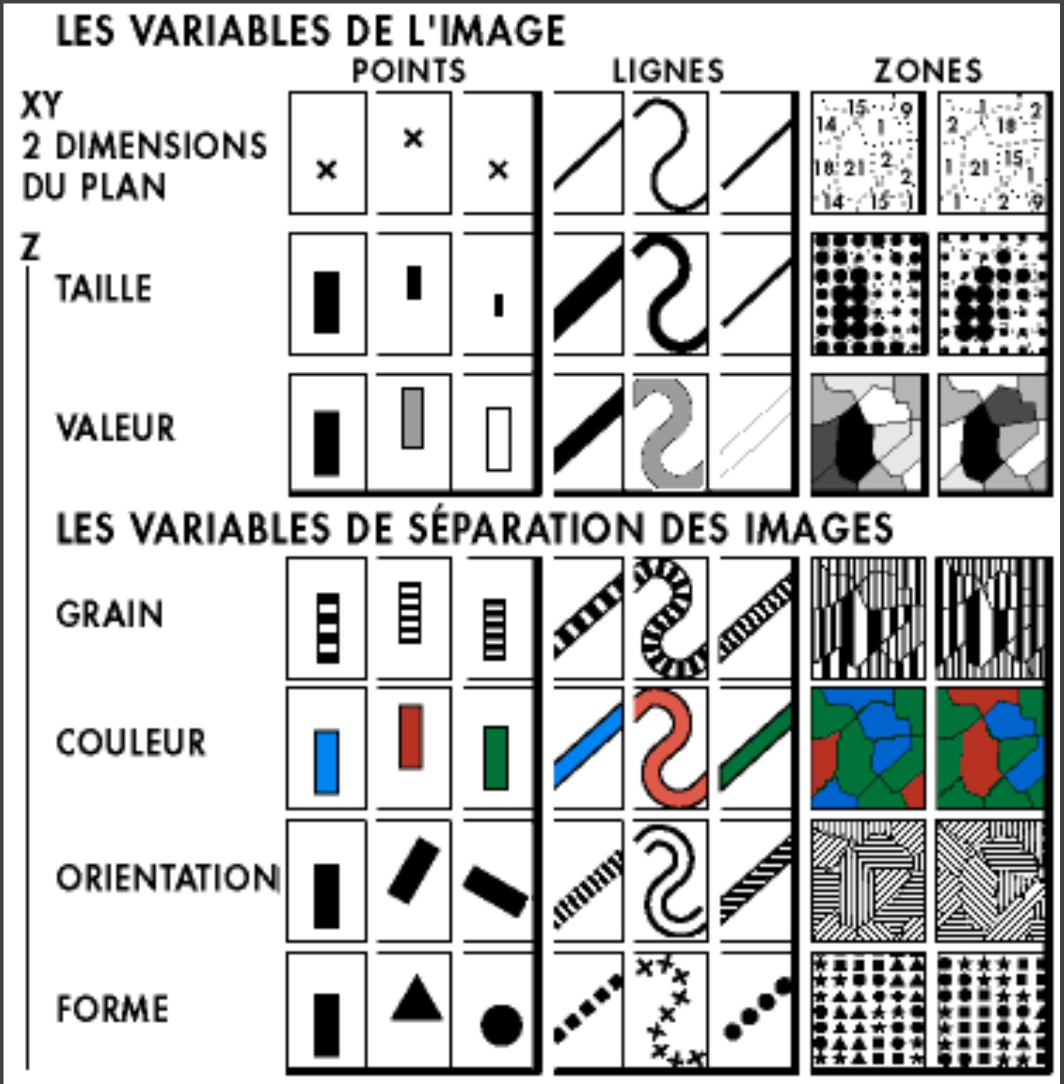
∴ Encode quantitative variables

"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

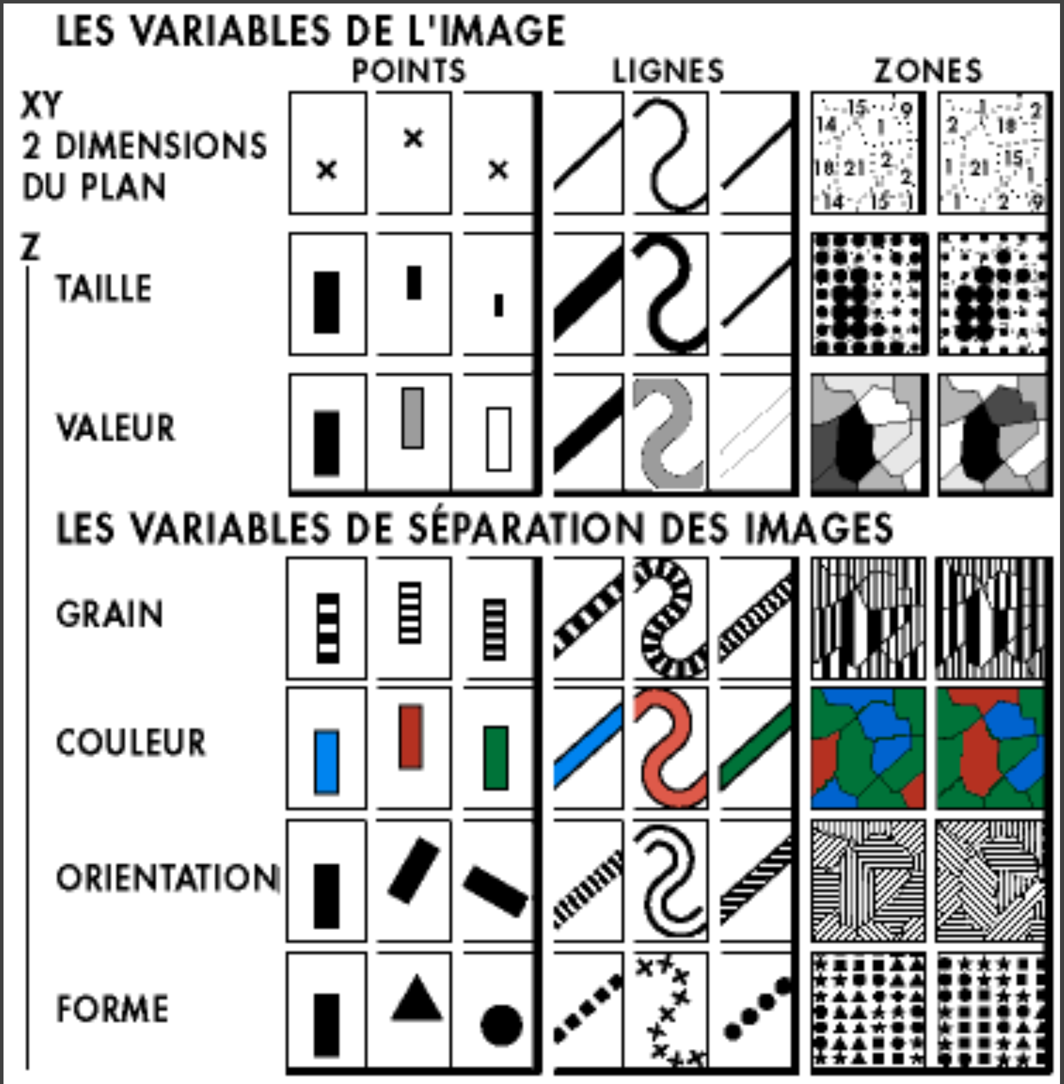
Visual Encoding Variables

Position (x 2)
Size
Value
Texture
Color
Orientation
Shape



Visual Encoding Variables

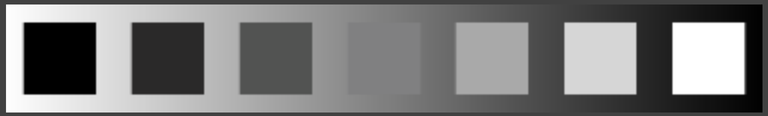
Position
Length
Area
Volume
Value
Texture
Color
Orientation
Shape
Transparency
Blur / Focus …



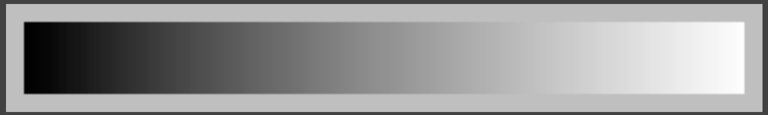
Information in Hue and Value

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

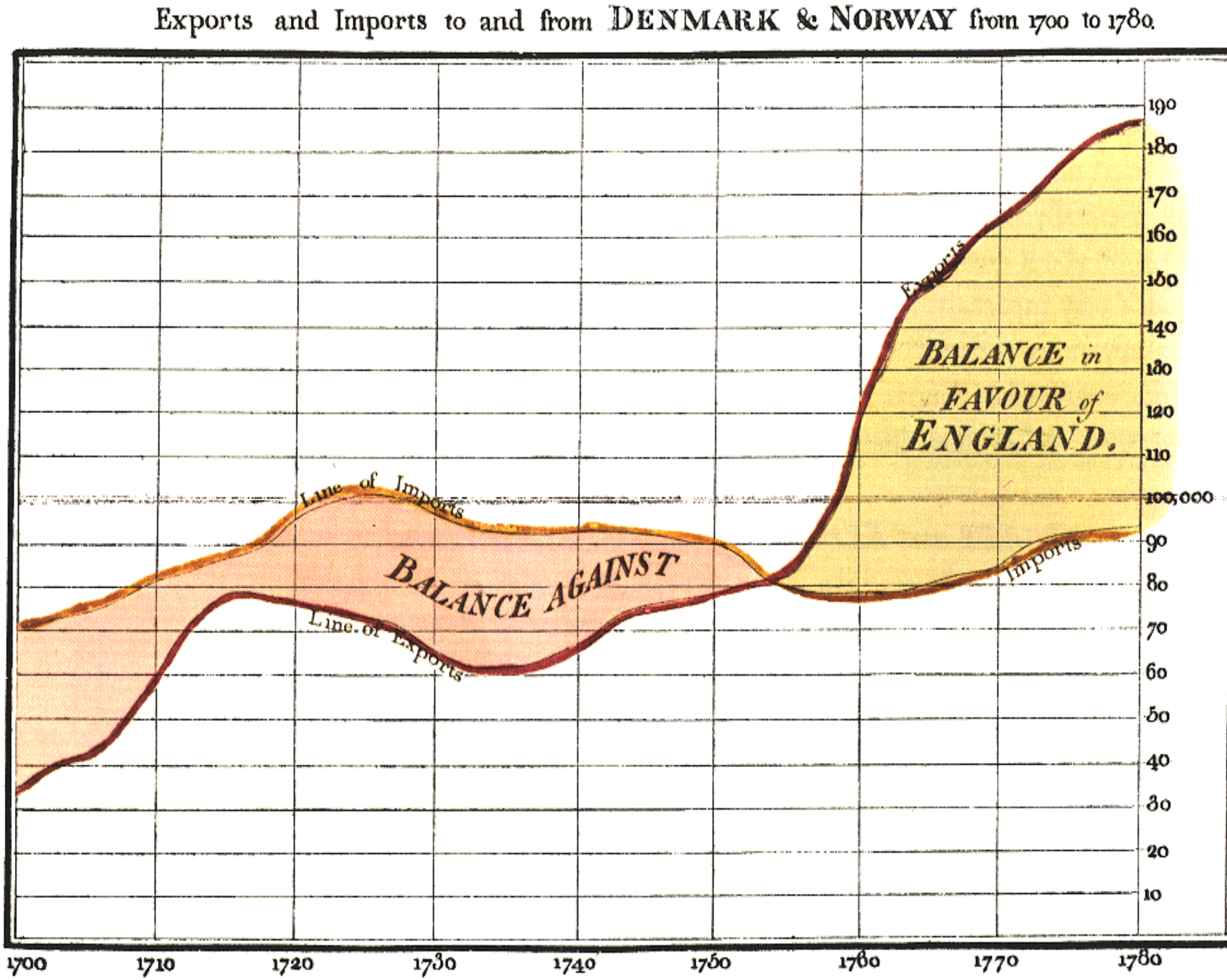
Nominal

Ordinal

Quantitative

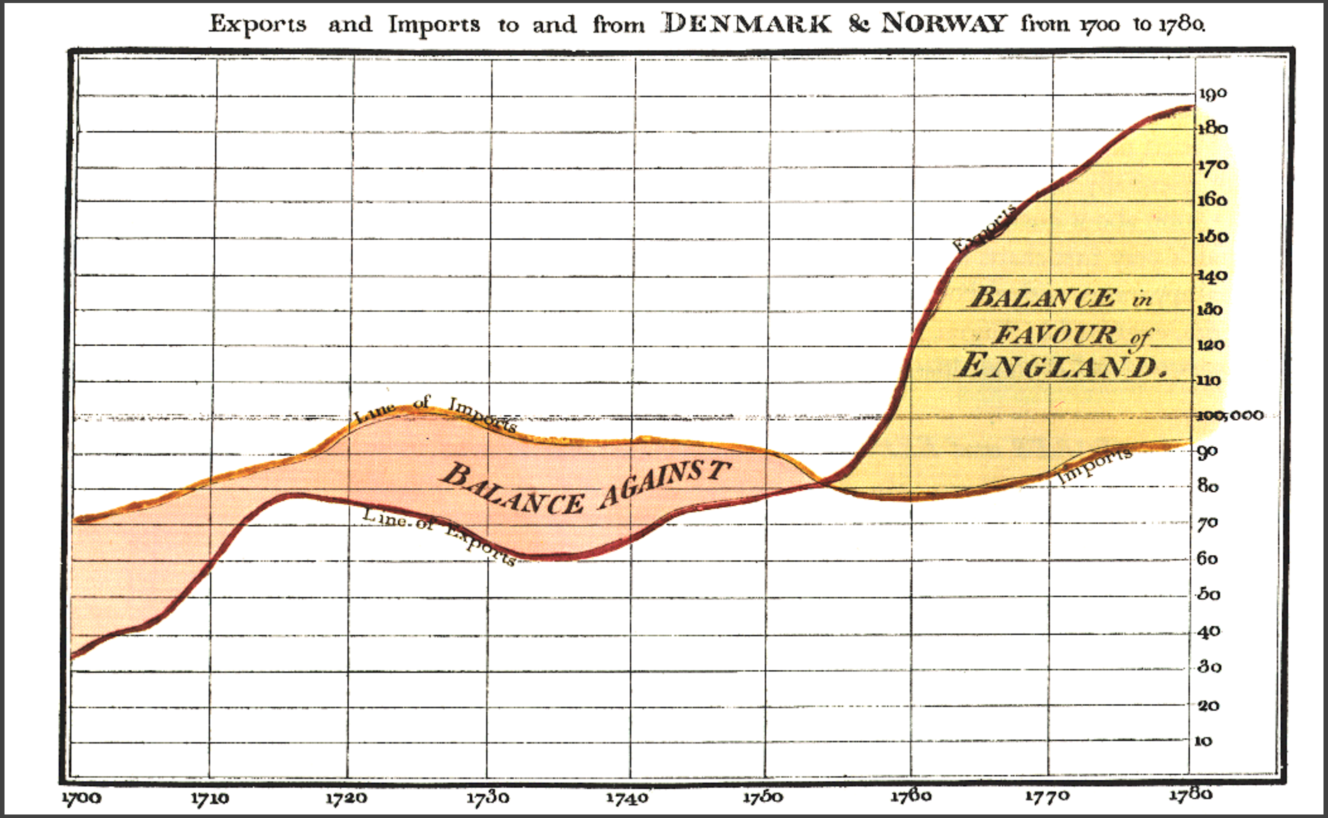
Note: $\mathbf{Q} \subset \mathbf{O} \subset \mathbf{N}$

Deconstructions

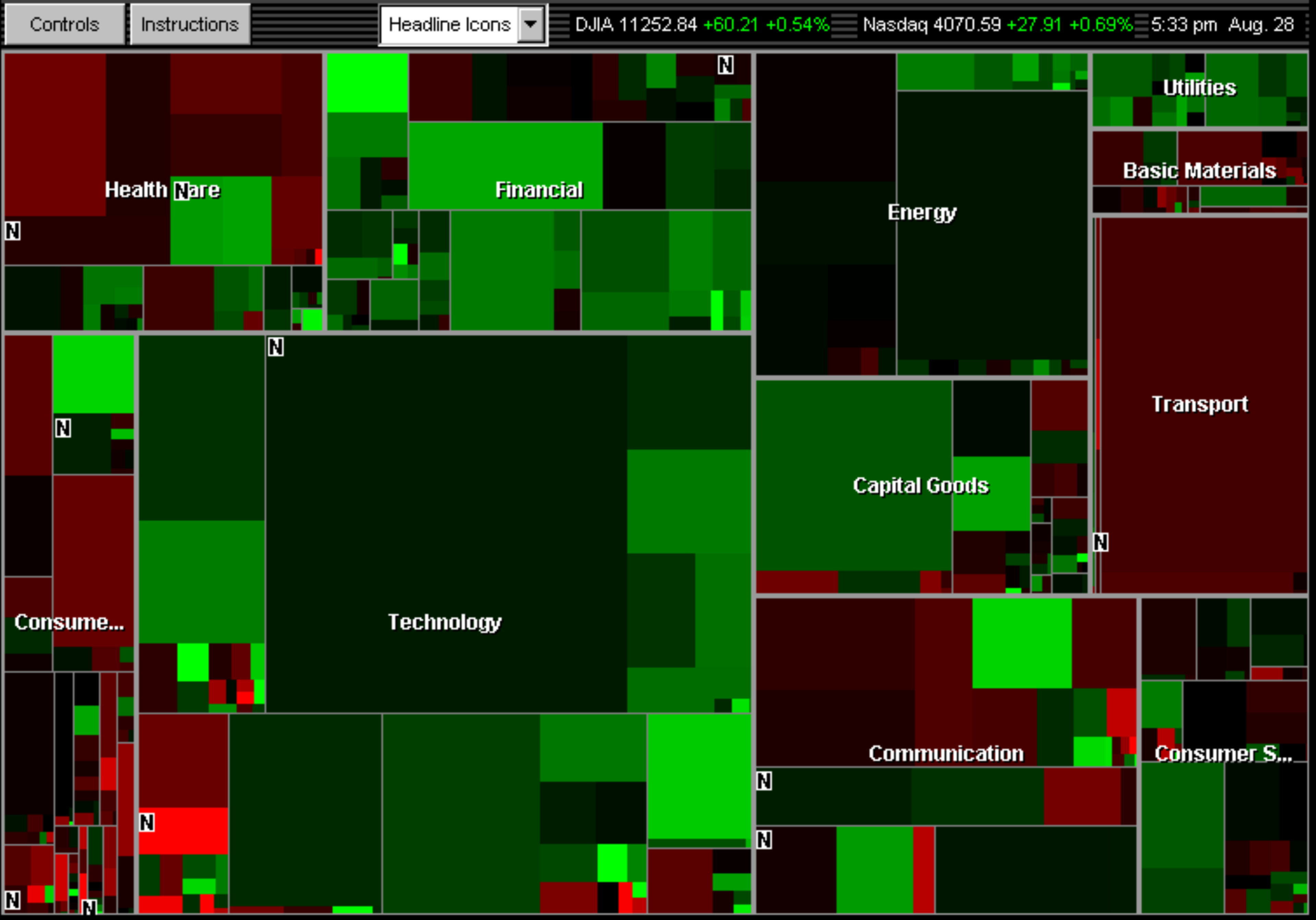


Exports and Imports to and from DENMARK & NORWAY from 1700 to 1780.
Line of Imports
Line of Exports
BALANCE AGAINST
Exports
Imports
BALANCE in FAVOUR of ENGLAND.
190
180
170
160
150
140
130
120
110
100,000
90
80
70
60
50
40
30
20
10
1700
1710
1720
1730
1740
1750
1760
1770
1780

William Playfair, 1786

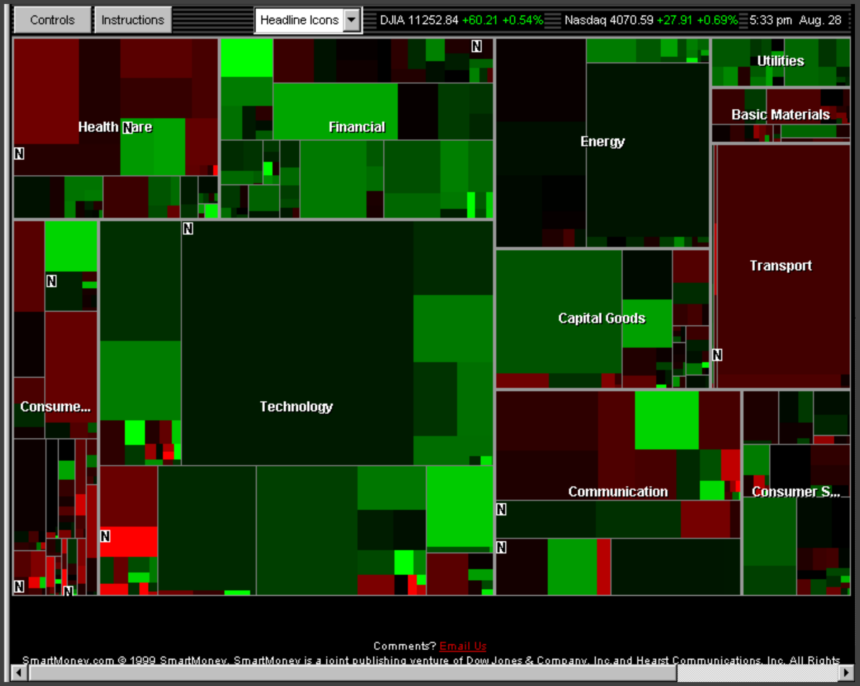


X-axis: year (Q)
Y-axis: currency (Q)
Color: imports/exports (N, O)



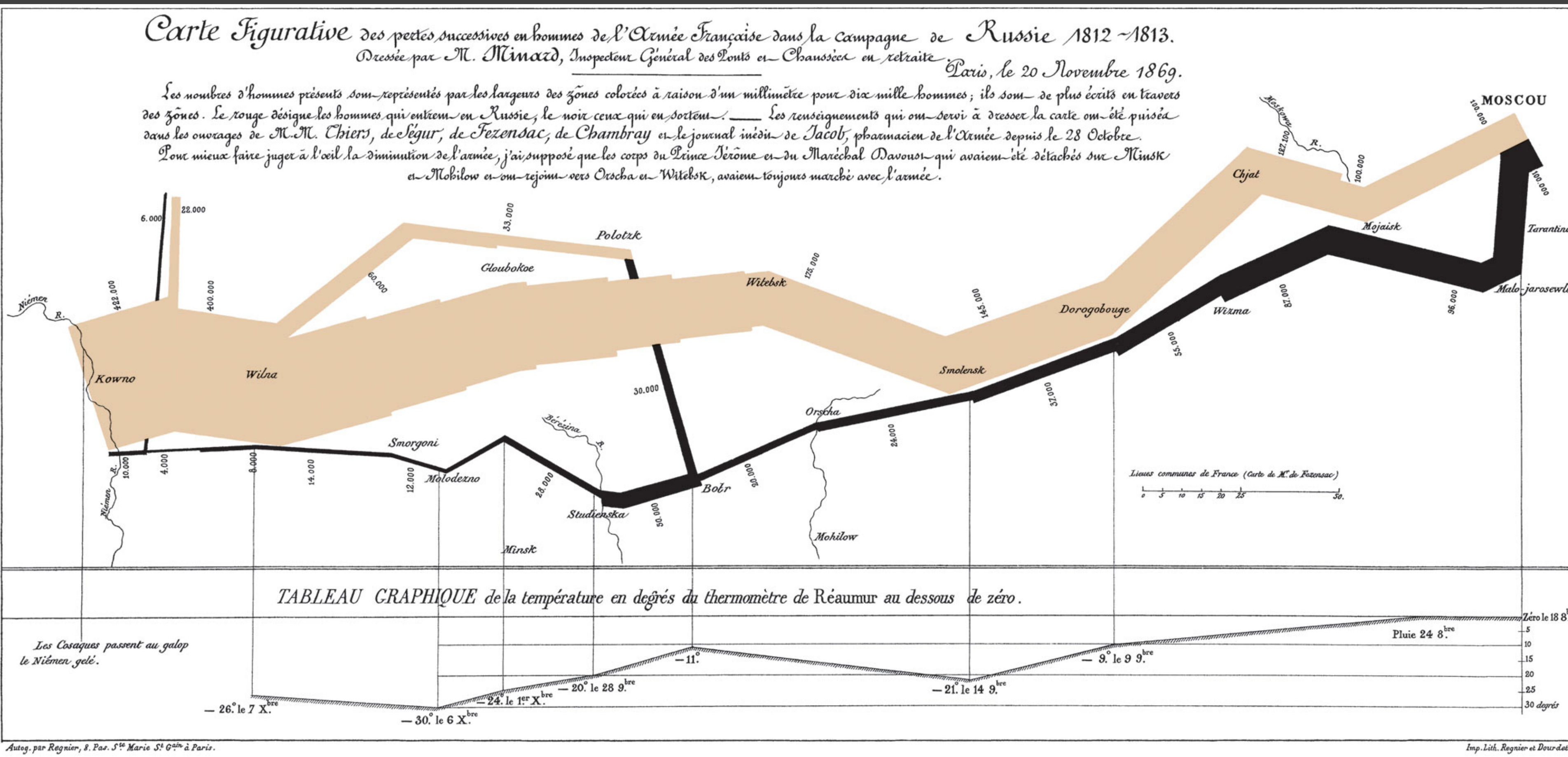
http://www.smartmoney.com/marketmap/

Wattenberg's Map of the Market

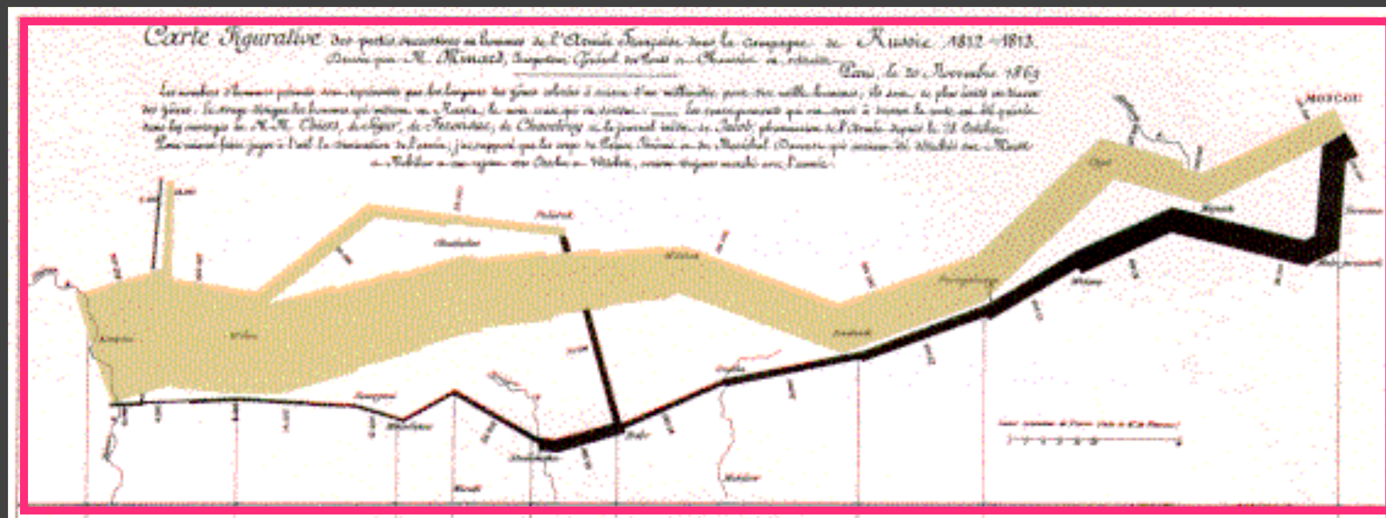


Rectangle Area: market cap (Q)
Rectangle Position: market sector (N), market cap (Q)
Color Hue: loss vs. gain (N, O)
Color Value: magnitude of loss or gain (Q)

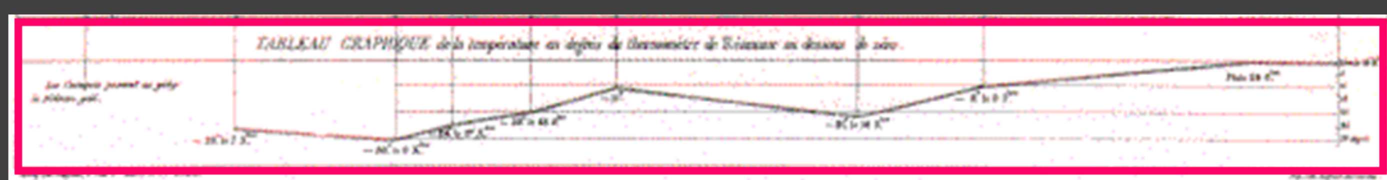
Minard 1869: Napoleon’s March



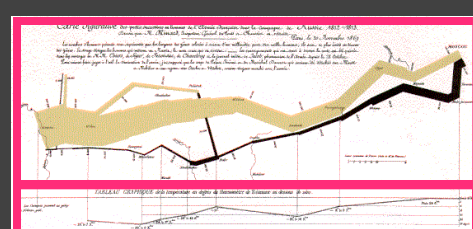
Single-Axis Composition



+



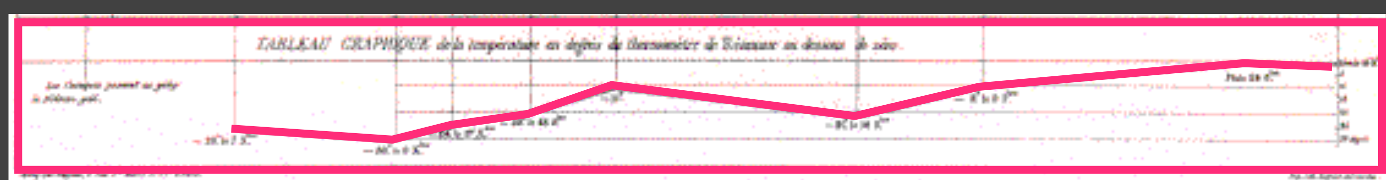
=



Mark Composition

Y-axis: temperature (Q)

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

\= 

Temp over space/time (Q x Q)

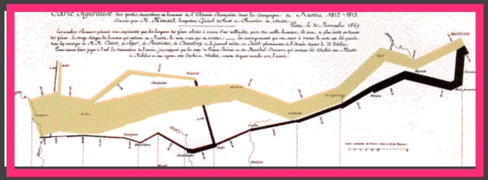
Mark Composition

Y-axis: latitude (Q)

+ X-axis: longitude (Q)

+ Width: army size (Q)

=

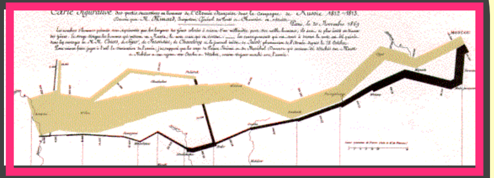


Army position (Q x Q) and army size (Q)

latitude (Q)

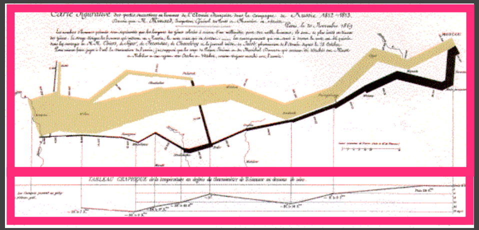
longitude (Q)

army size (Q)

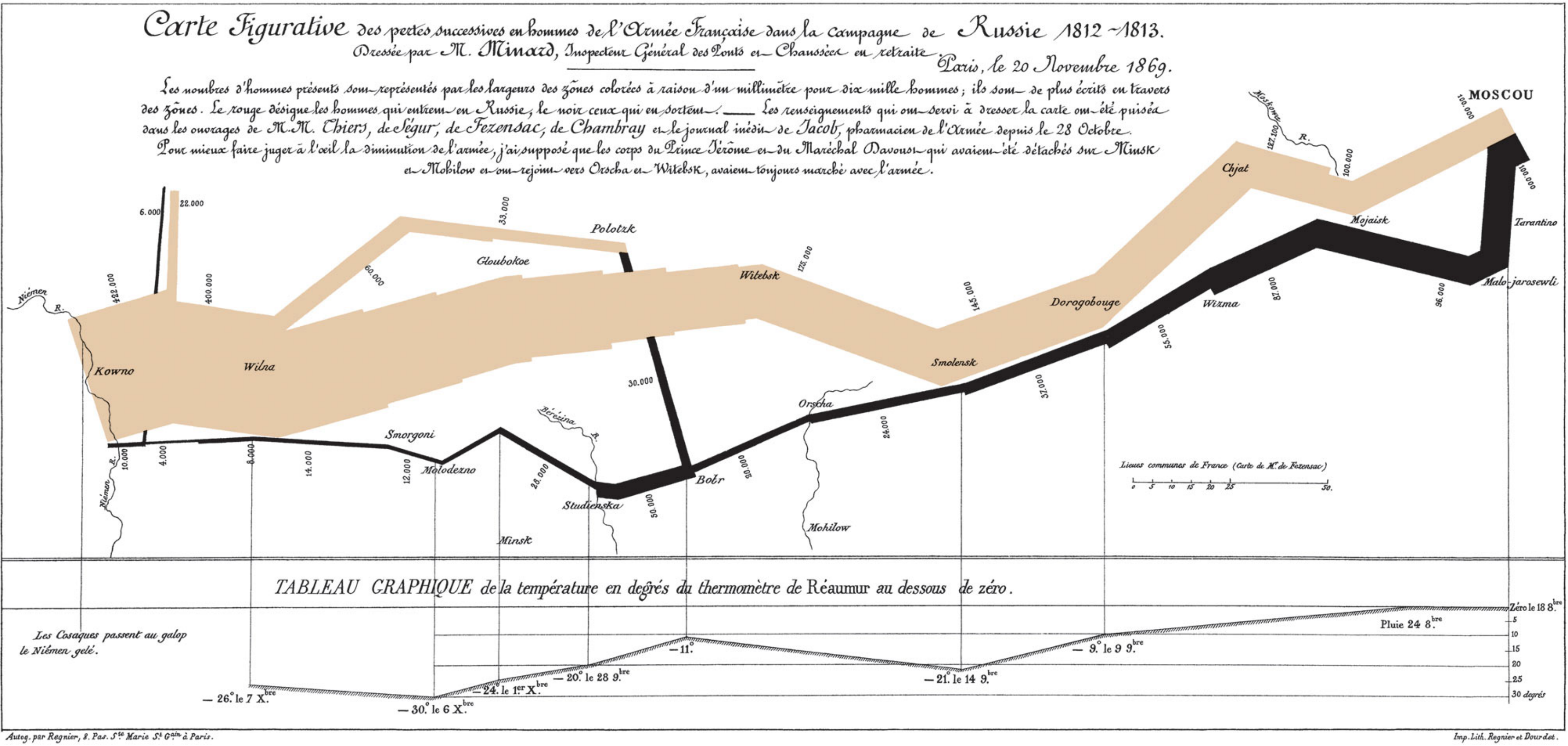


temperature (Q)

longitude (Q) / time (O)



Minard 1869: Napoleon's March



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.

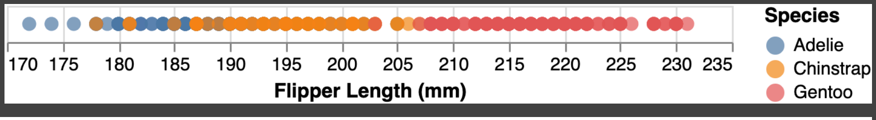
Design Criteria [Mackinlay 86]

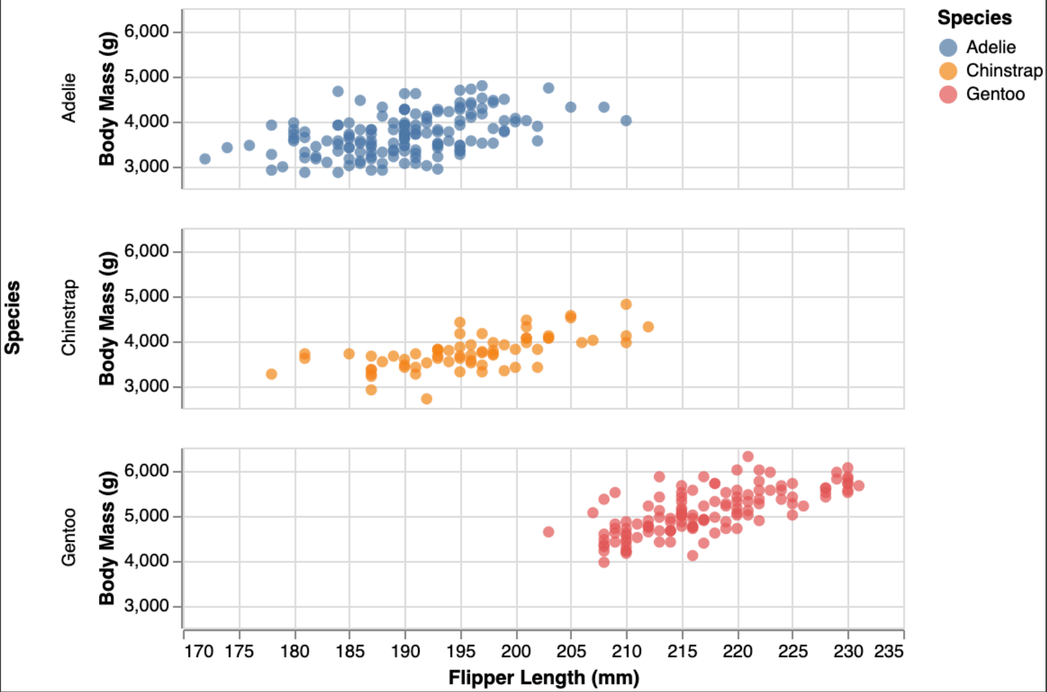
Expressiveness
A set of facts is *expressible* in a visual language if the sentences (i.e. the visualizations) in the language express all the facts in the set of data, and only the facts in the data.

Effectiveness
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.

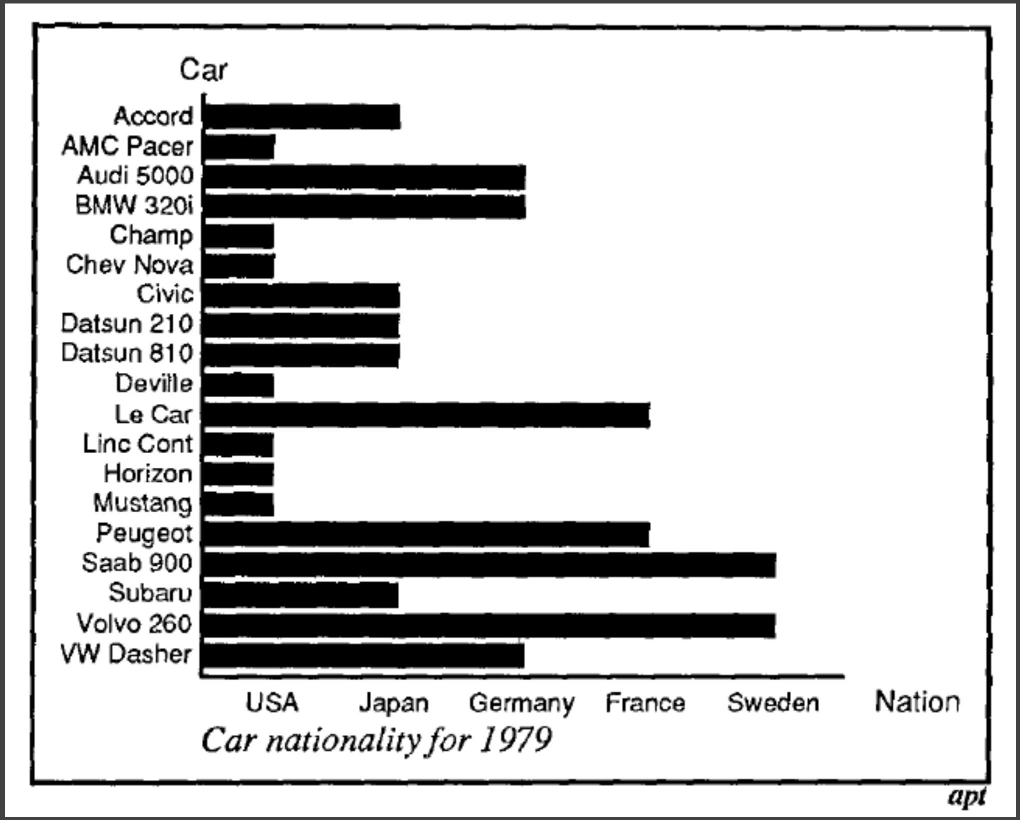
Cannot express the facts

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
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.

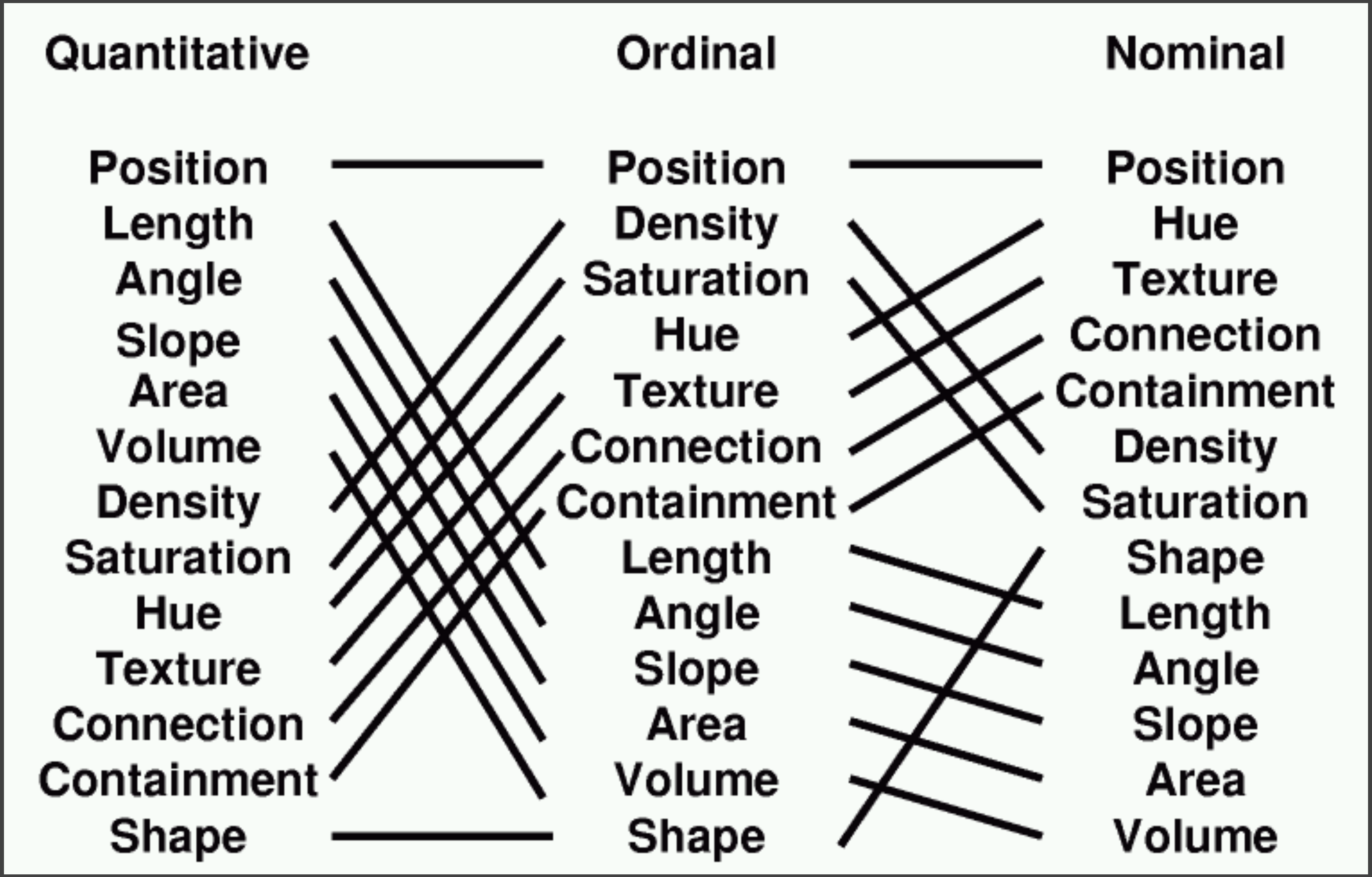
Effectiveness
A visualization is more *effective* than another visualization if the information conveyed by one visualization is more readily perceived than the information in the other visualization.

Design Criteria ***Translated***

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

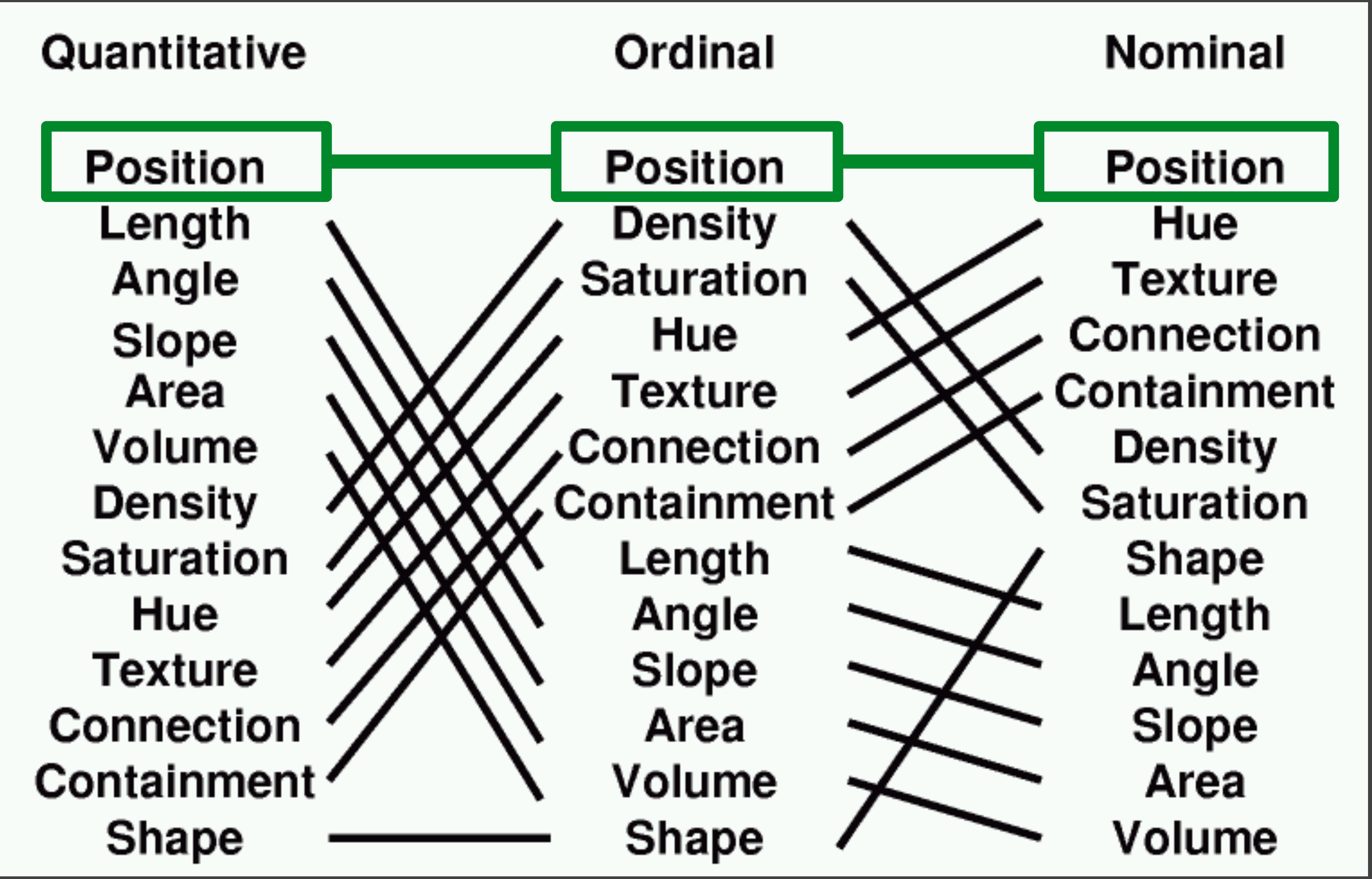
Use encodings that people decode better
(where better ≈ faster and/or more accurate)

Mackinlay's Ranking



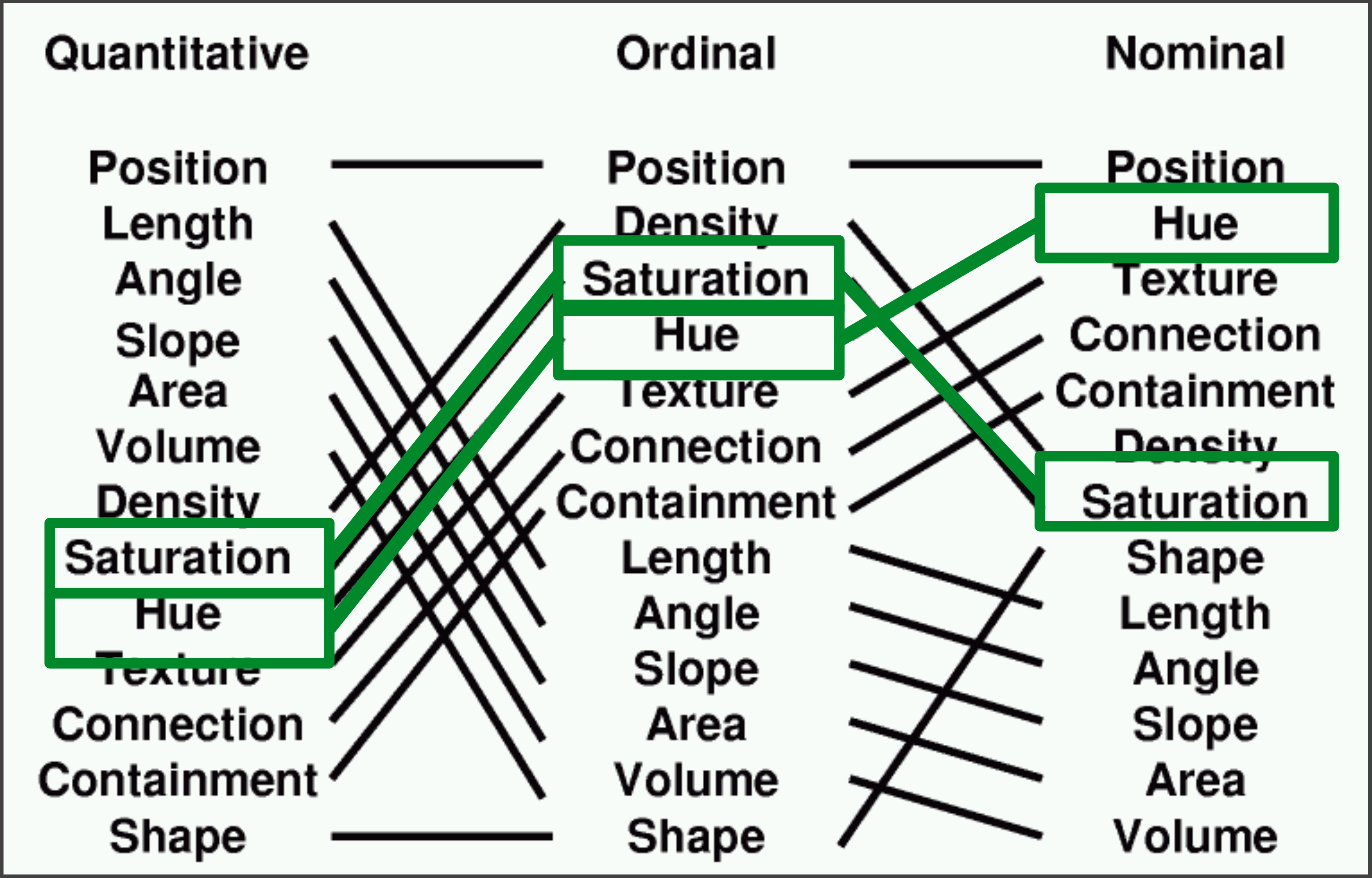
Conjectured *effectiveness* of encodings by data type

Mackinlay’s Ranking



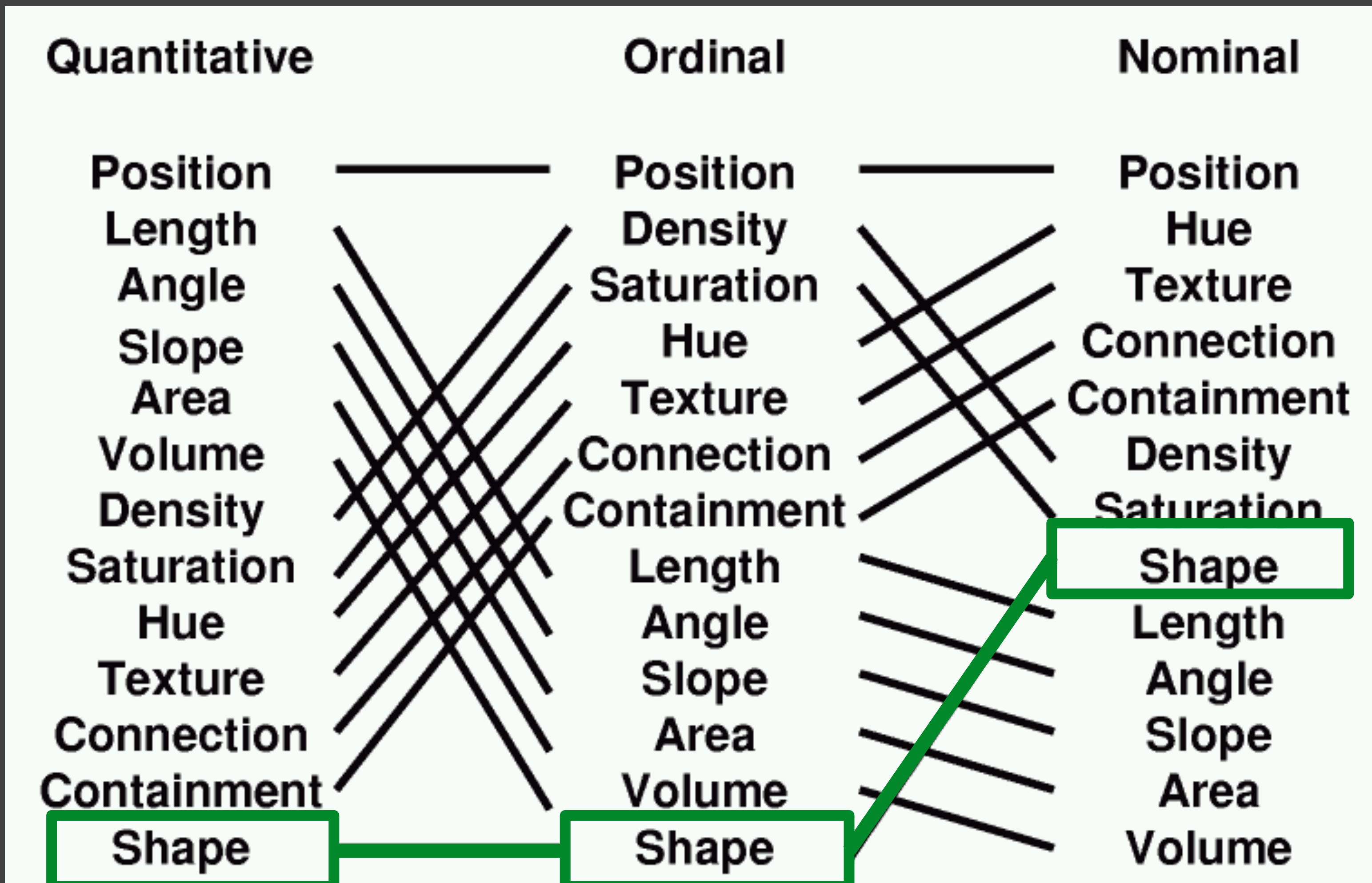
Conjectured *effectiveness* of encodings by data type

Mackinlay's Ranking



Conjectured *effectiveness* of encodings by data type

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

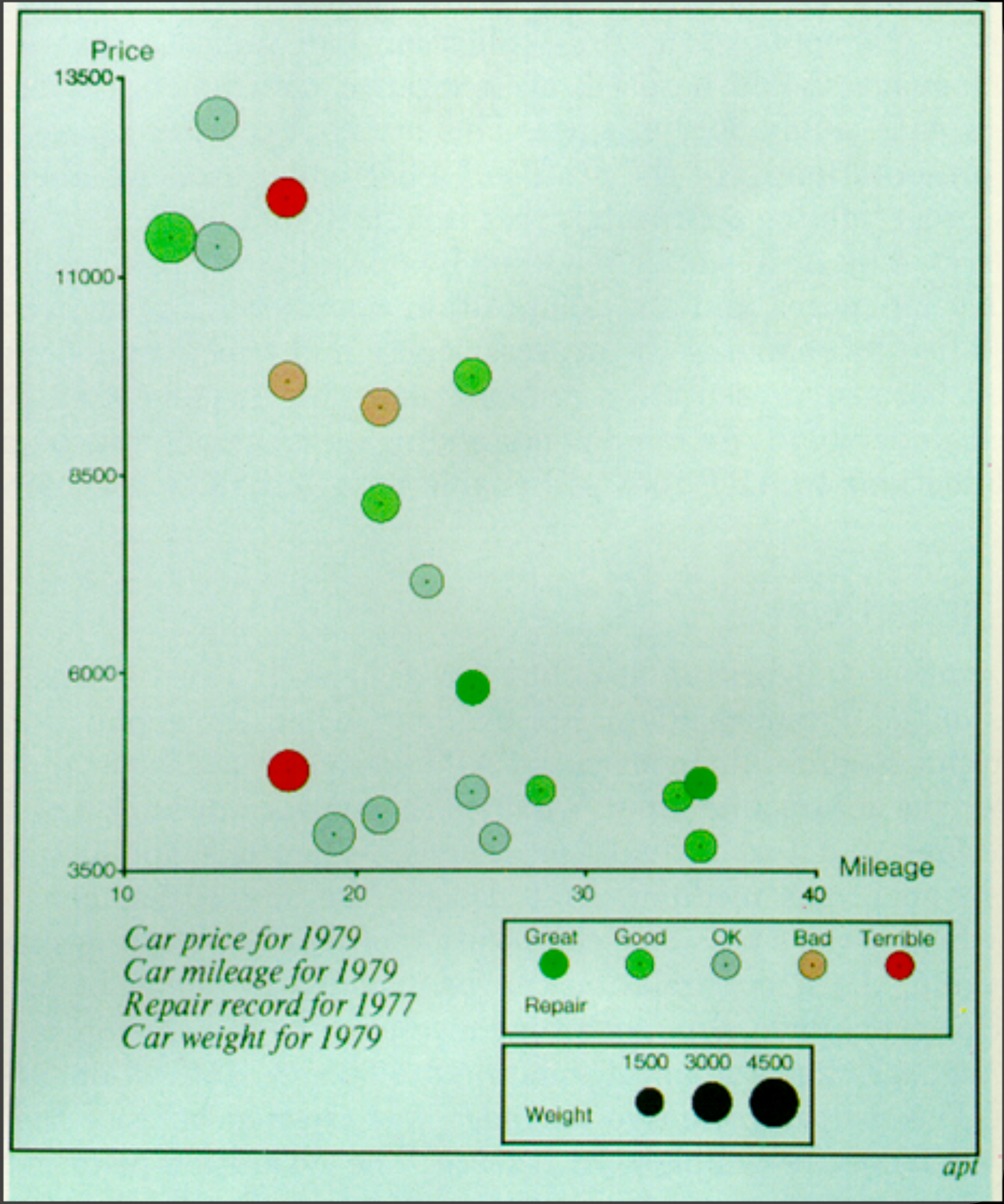
APT searches over design space
Test expressiveness of each visual encoding
Generate encodings that pass test
Rank by perceptual effectiveness criteria

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…*

Administrivia

Observable + Data Tutorial

Friday Jan. 6, 4:30-6pm

Introduction to Observable notebooks, JavaScript basics, and data management and transformation, led by Katherine.

Zoom link is available on Canvas.
The tutorial will be recorded.

Tutorial 2: Tableau

Led by Ian and Vineet

This Friday Oct 7 at 4:30 PM

The tutorial will be recorded via Zoom/Canvas.

Introduction to Tableau: a graphical tool for visualization construction, helpful for both exploration and prototyping.

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

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 on Gradescope; see A1 page)

Image of your visualization (PNG or JPG format)

Short description + design rationale (≤ 4 paragraphs)

Due by **11:59 pm, Wed Jan11**.

Quick poll!

Respond here: pollev.com/leibatt

Break Time!