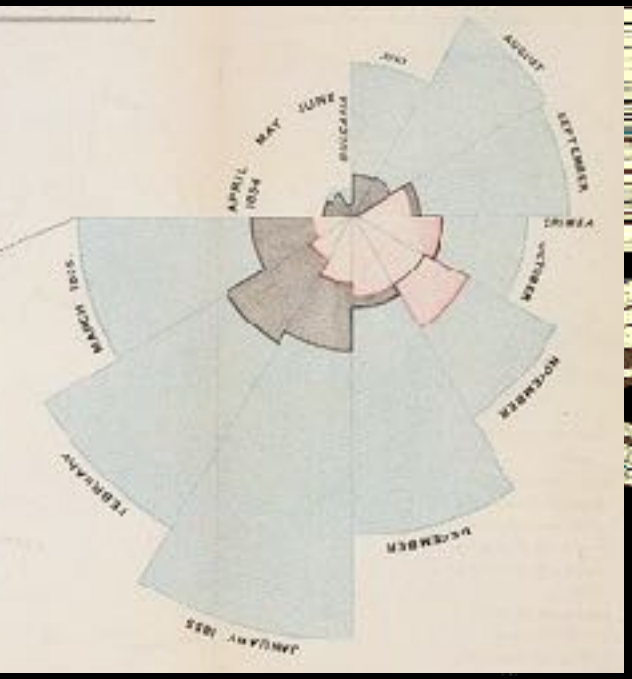
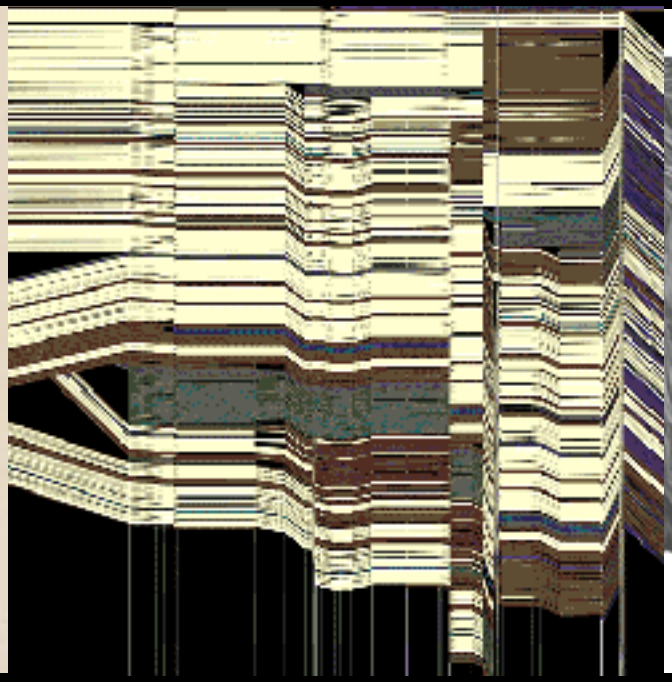
CSE 512 - Data Visualization

Interaction





Leilani Battle University of Washington

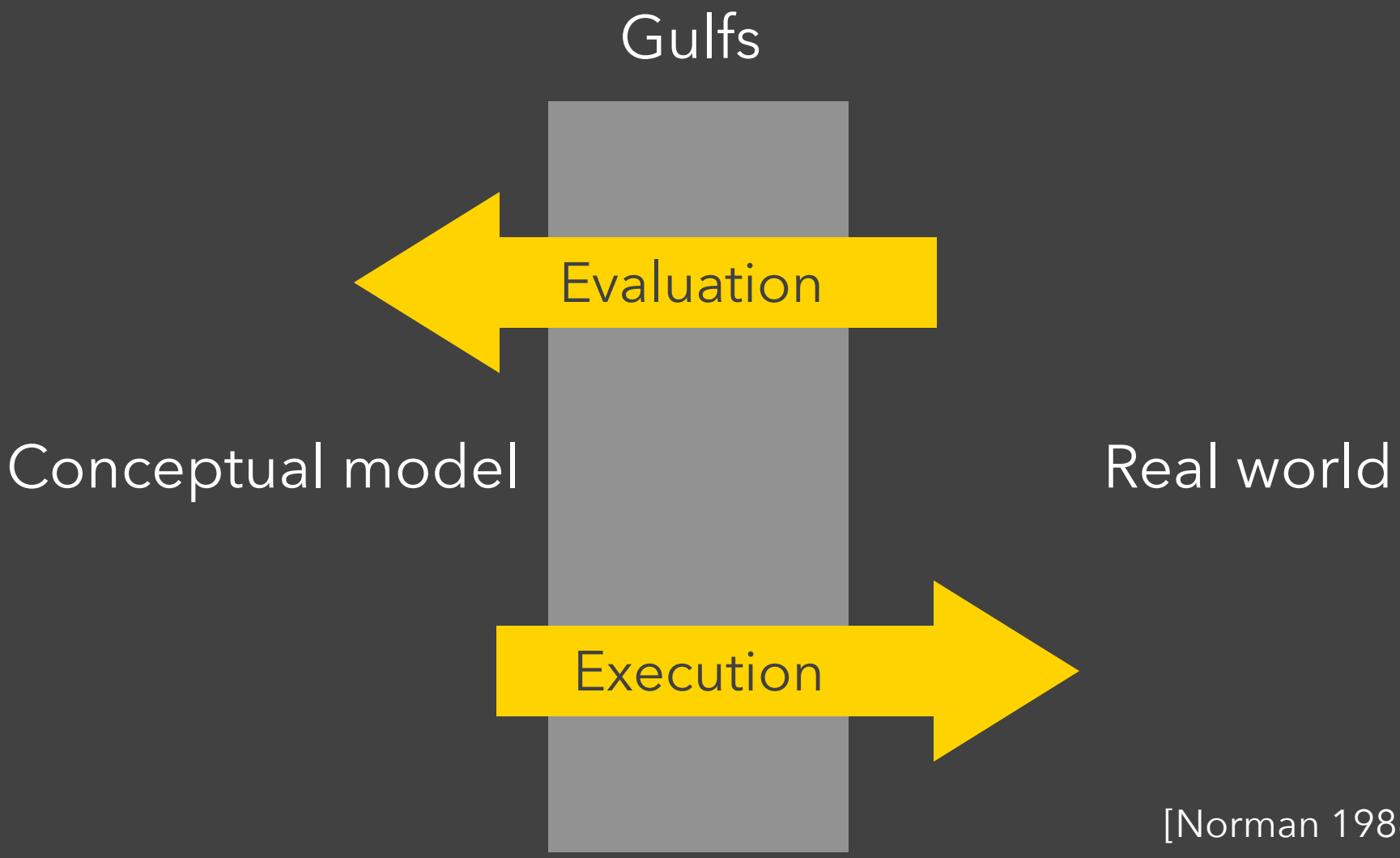
[There is an] apparent challenge that computational artifacts pose to the longstanding distinction between the physical and the social, in the special sense of those things that one designs, builds, and uses, on the one hand, and those things with which one communicates, on the other.

“Interaction”– in a sense previously reserved for describing a uniquely interpersonal activity – seems appropriately to characterize what goes on between people and certain machines as well.

Lucy Suchman, *Plans and Situated Actions*

Interaction between people and machines requires *mutual intelligibility* or *shared understanding*.

Gulfs of Execution & Evaluation



[Norman 1986]

Gulf of Execution

The difference between the user's intentions and the allowable actions.

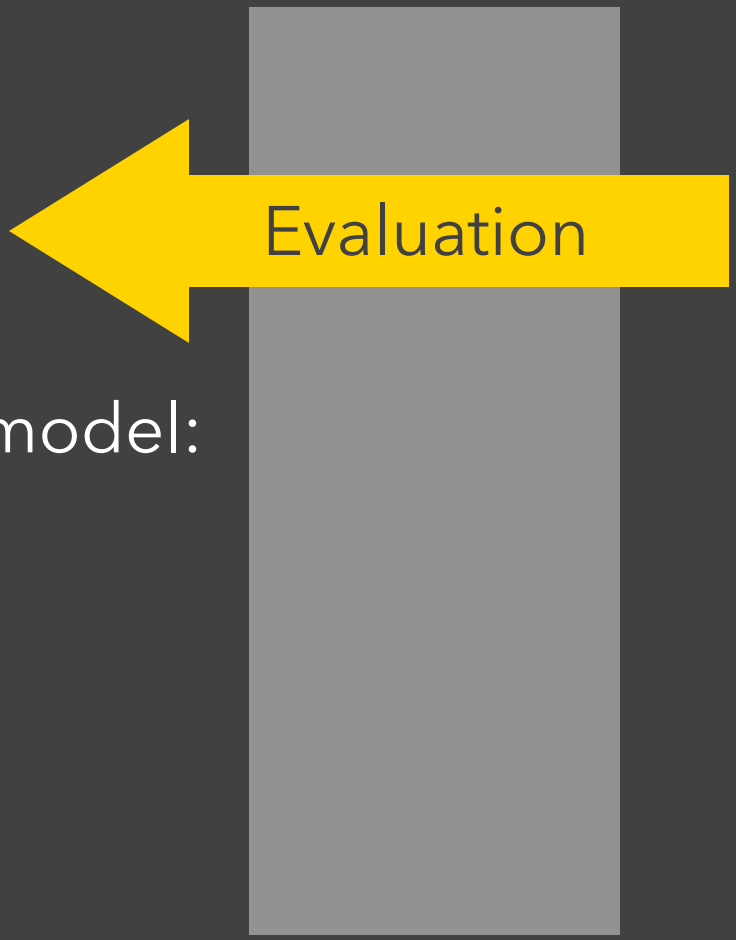
Gulf of Evaluation

The amount of effort that the person must exert to interpret the state of the system and to determine how well the expectations and intentions have been met.

[Norman 1986]

Gulf of Evaluation

Gulf



Conceptual model:
x, y related?

Real world:

X	Y
0.67	0.79
0.32	0.63
0.39	0.72
0.27	0.85
0.71	0.43
0.63	0.09
0.03	0.03
0.20	0.54
0.51	0.38
0.11	0.33
0.46	0.46

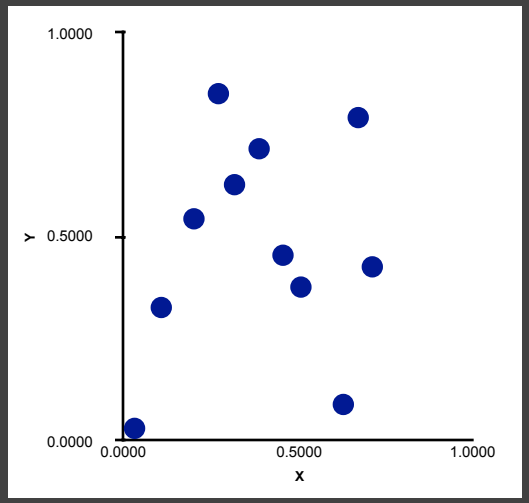
Gulf of Evaluation

Gulf

Evaluation

Conceptual model:
x, y related?

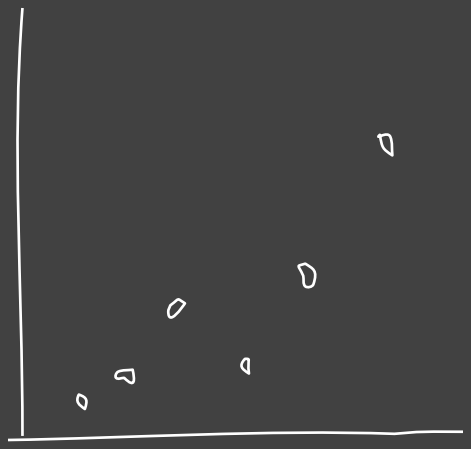
Real world:



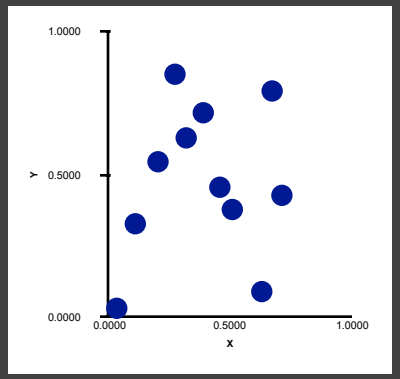
Gulf of Execution

Gulf

Conceptual model:
Draw a scatterplot



Execution



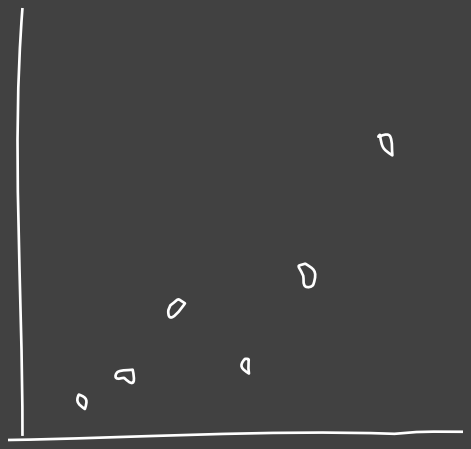
Real world

Move 90 30
Rotate 35
Pen down
…

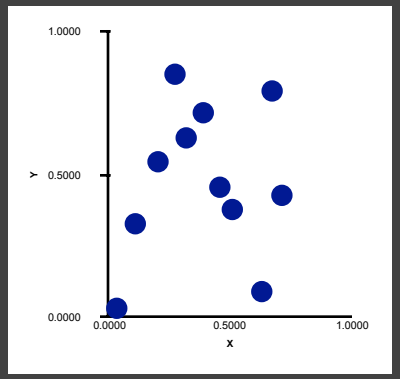
Gulf of Execution

Gulf

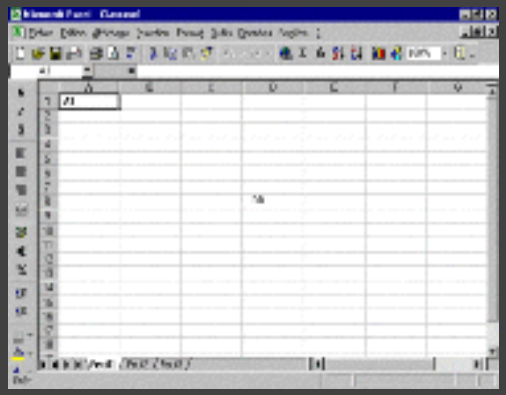
Conceptual model:
Draw a scatterplot



Execution



Real world



Gulf of Execution

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Gulf of Evaluation

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[Norman 1986]

Interactive Visualization

Interaction Techniques

Are there “essential” interactive operations for exploratory data visualization?

Taxonomy of Interactions

Taxonomy of Interactions

Data and View Specification

Visualize, Filter, Sort, Derive

[Heer & Shneiderman 2012]

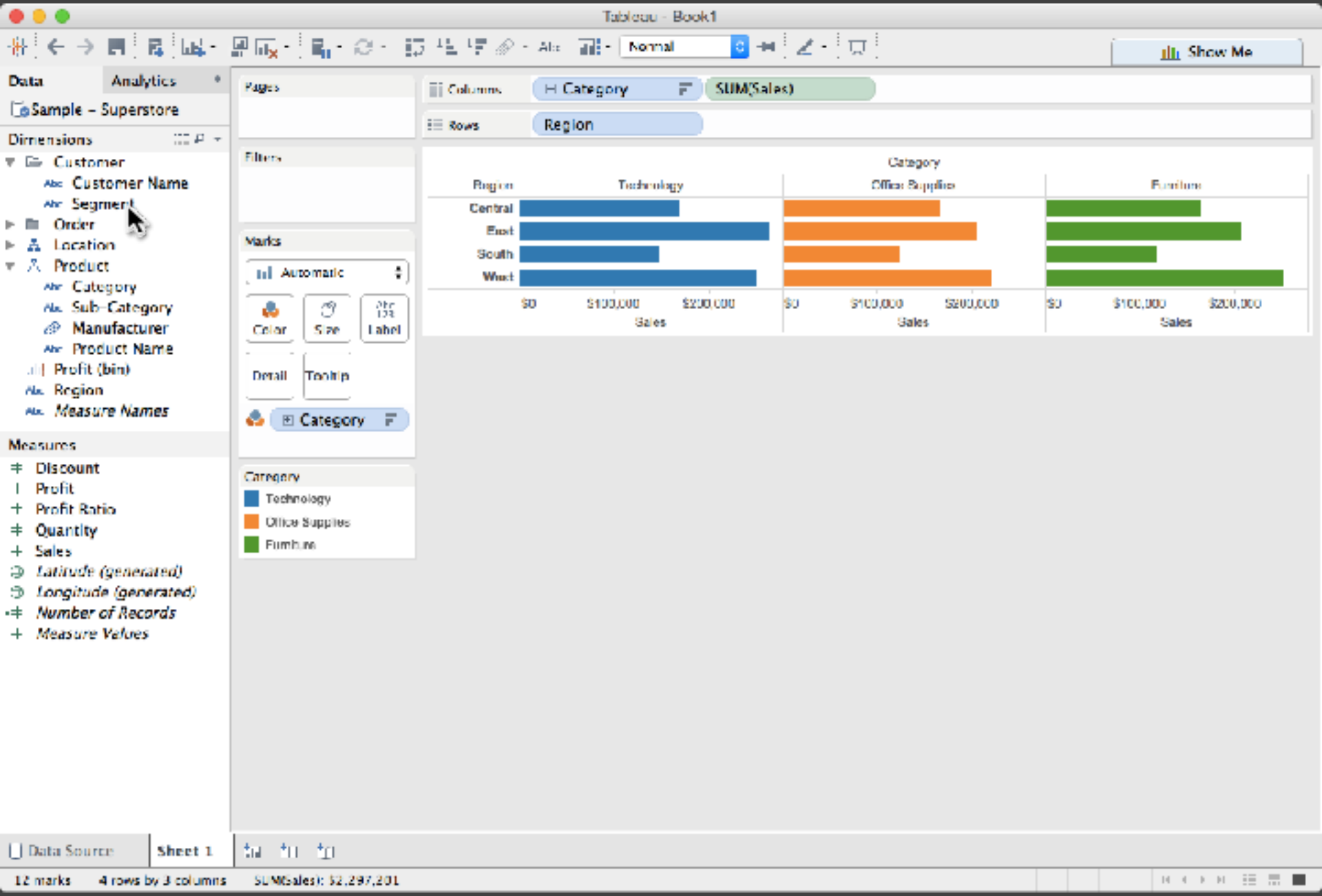


Tableau - Book1
Normal
Show Me
Data
Analytics
Sample – Superstore
Dimensions
Customer
Customer Name
Segment
Order
Location
Product
Category
Sub-Category
Manufacturer
Product Name
Profit (bin)
Region
Measure Names
Measures
Discount
Profit
Profit Ratio
Quantity
Sales
Latitude (generated)
Longitude (generated)
Number of Records
Measure Values
Pages
Filters
Marks
Automatic
Color
Size
Label
Detail
Tooltip
Category
Columns
Category
SUM(Sales)
Rows
Region
Category
Region
Technology
Office Supplies
Furniture
Central
East
South
West
$0
$100,000
$200,000
Sales
Category
Technology
Office Supplies
Furniture
Data Source
Sheet 1
12 marks
4 rows by 3 columns
SUM(Sales): $2,297,201

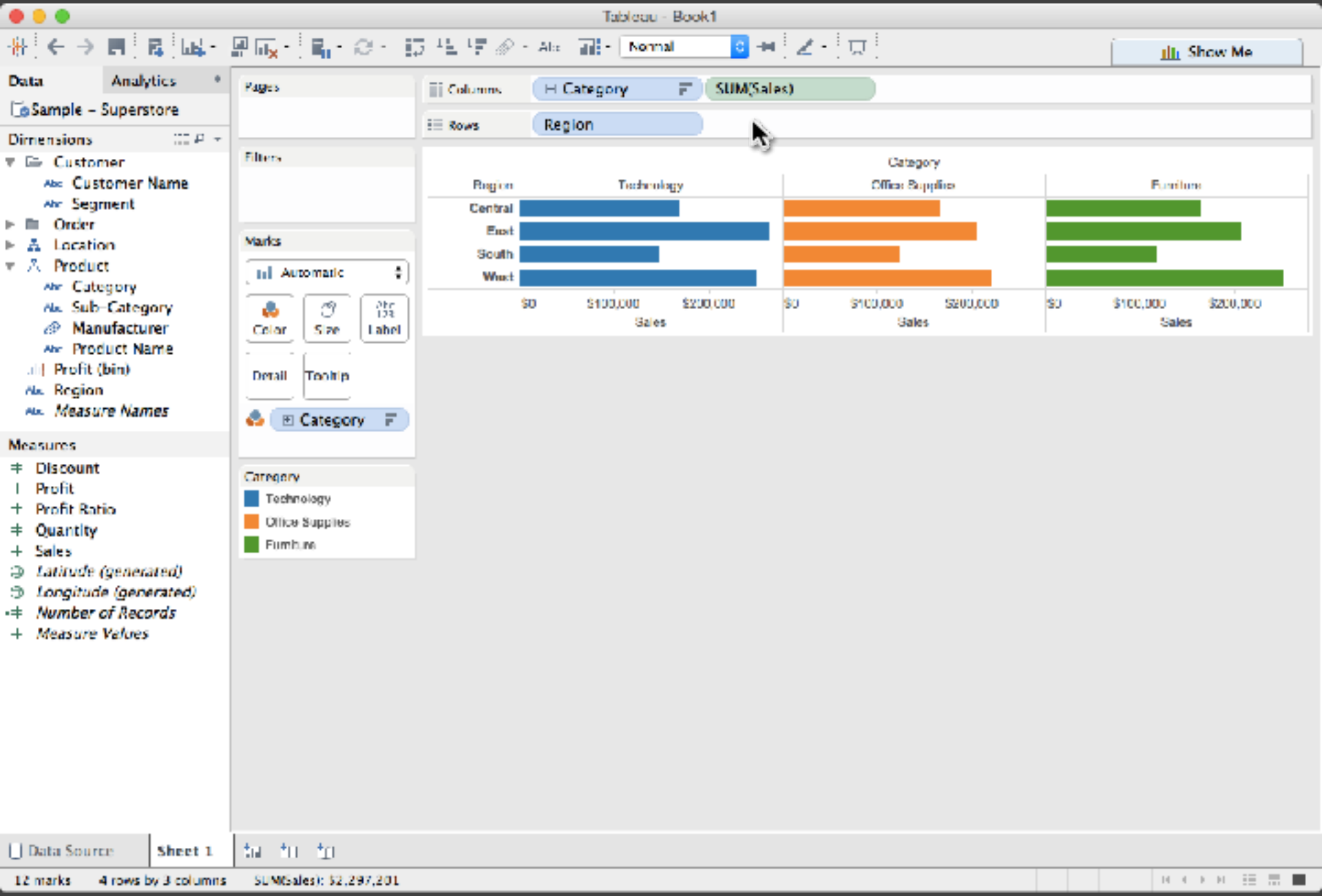


Tableau - Book1
Normal
Show Me
Data
Analytics
Sample – Superstore
Dimensions
Customer
Customer Name
Segment
Order
Location
Product
Category
Sub-Category
Manufacturer
Product Name
Profit (bin)
Region
Measure Names
Measures
Discount
Profit
Profit Ratio
Quantity
Sales
Latitude (generated)
Longitude (generated)
Number of Records
Measure Values
Pages
Filters
Marks
Automatic
Color
Size
Label
Detail
Tooltip
Category
Columns
Category
SUM(Sales)
Rows
Region
Category
Region
Technology
Office Supplies
Furniture
Central
East
South
West
$0
$100,000
$200,000
Sales
Category
Technology
Office Supplies
Furniture
Data Source
Sheet 1
12 marks
4 rows by 3 columns
SUM(Sales): $2,297,201

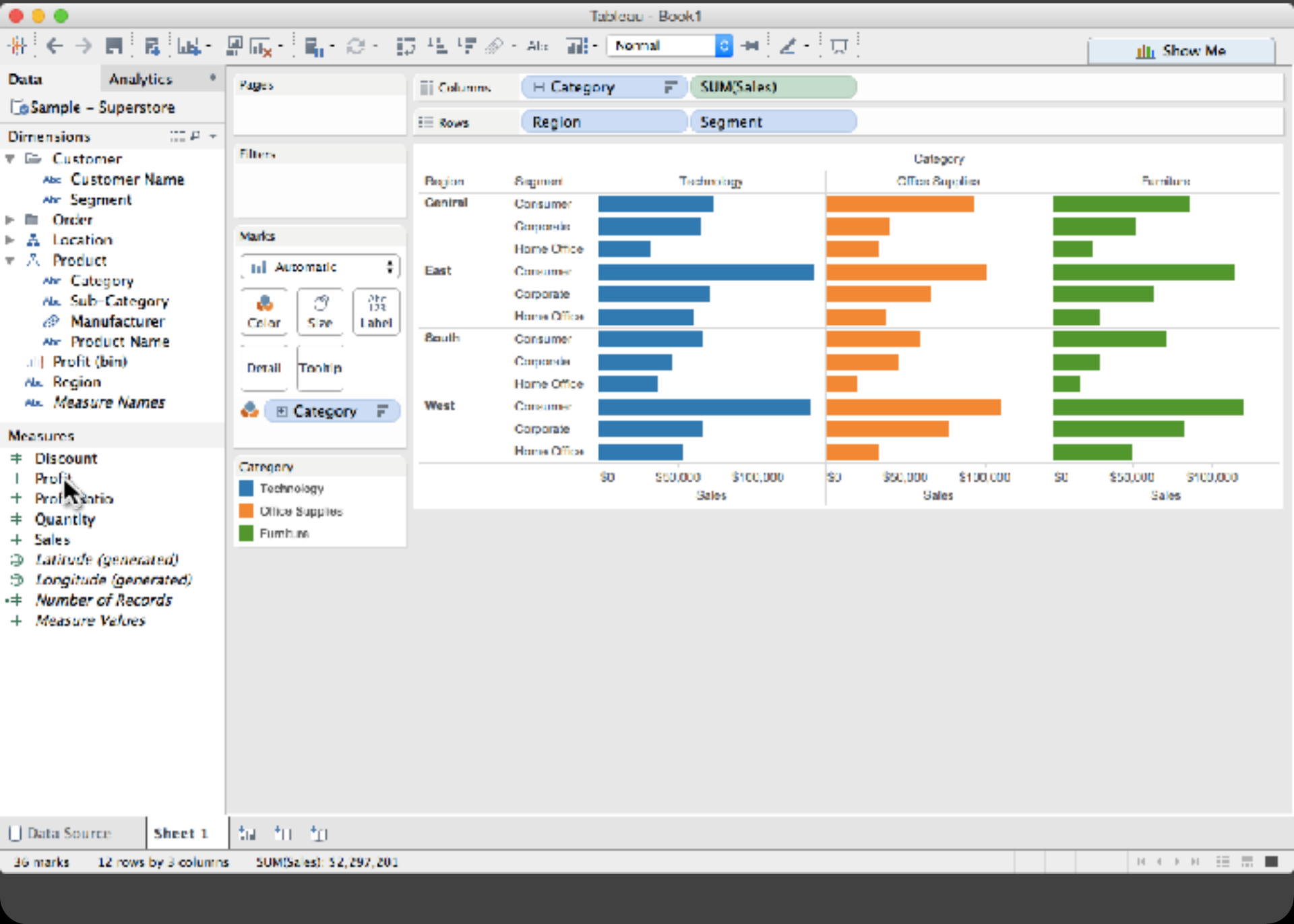


Tableau - Book1
Normal
Show Me
Data
Analytics
Sample – Superstore
Dimensions
Customer
Customer Name
Segment
Order
Location
Product
Category
Sub-Category
Manufacturer
Product Name
Profit (bin)
Region
Measure Names
Measures
Discount
Profit
Profit Ratio
Quantity
Sales
Latitude (generated)
Longitude (generated)
Number of Records
Measure Values
Pages
Filters
Marks
Automatic
Color
Size
Label
Detail
Tooltip
Category
Technology
Office Supplies
Furniture
Columns
Category
SUM(Sales)
Rows
Region
Segment
Category
Region
Segment
Technology
Office Supplies
Furniture
Central
East
South
West
Consumer
Corporate
Home Office
$0
$50,000
$100,000
Sales
Data Source
Sheet 1
46 marks
12 rows by 3 columns
SUM(Sales): $2,297,201

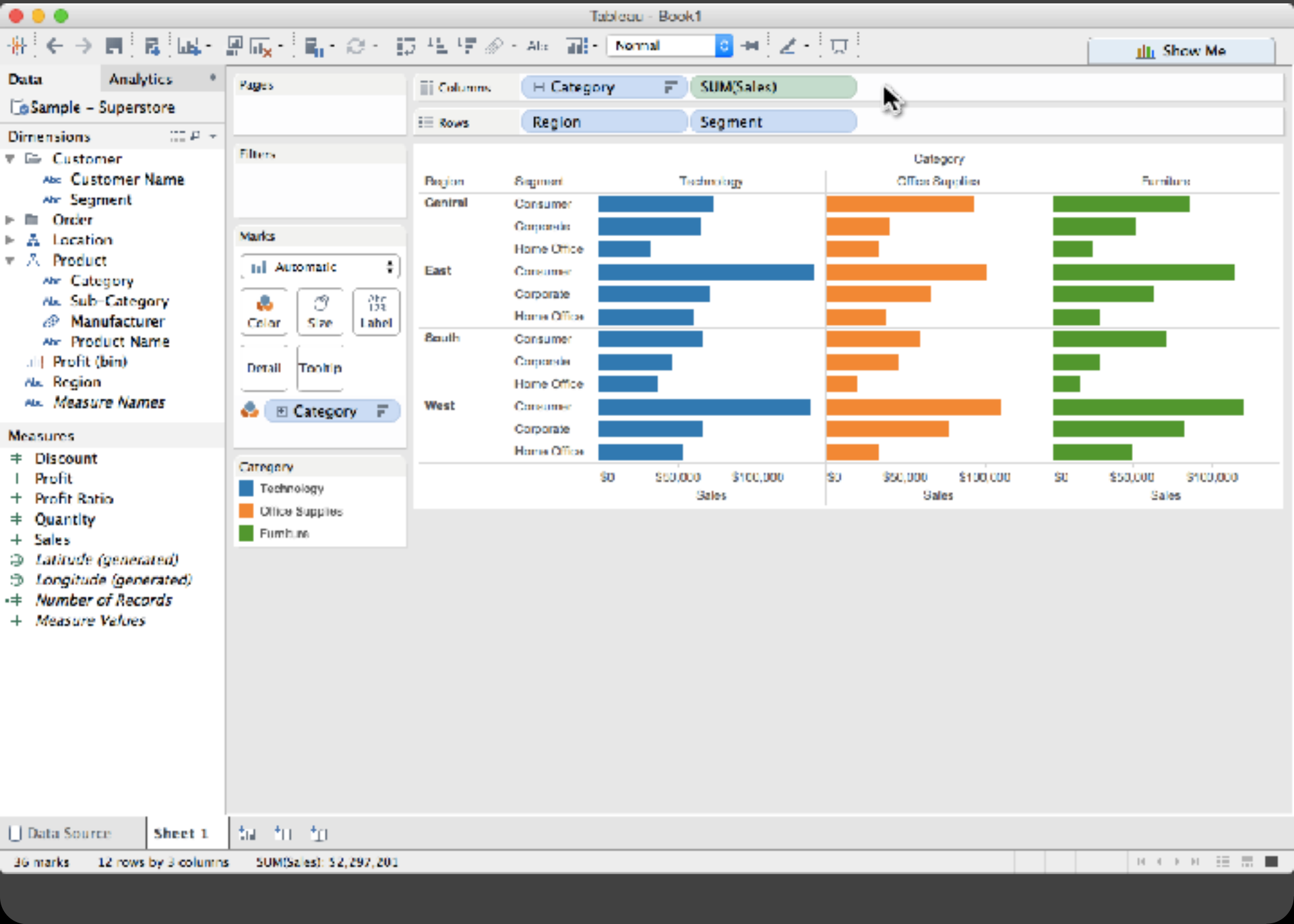


Tableau - Book1
Normal
Show Me
Data
Analytics
Sample – Superstore
Dimensions
Customer
Customer Name
Segment
Order
Location
Product
Category
Sub-Category
Manufacturer
Product Name
Profit (bin)
Region
Measure Names
Measures
Discount
Profit
Profit Ratio
Quantity
Sales
Latitude (generated)
Longitude (generated)
Number of Records
Measure Values
Pages
Filters
Marks
Automatic
Color
Size
Label
Detail
Tooltip
Category
Columns
Category
SUM(Sales)
Rows
Region
Segment
Category
Technology
Office Supplies
Furniture
Region
Segment
Central
East
South
West
Consumer
Corporate
Home Office
$0
$50,000
$100,000
Sales
Data Source
Sheet 1
36 marks
12 rows by 3 columns
SUM(Sales): $2,297,201

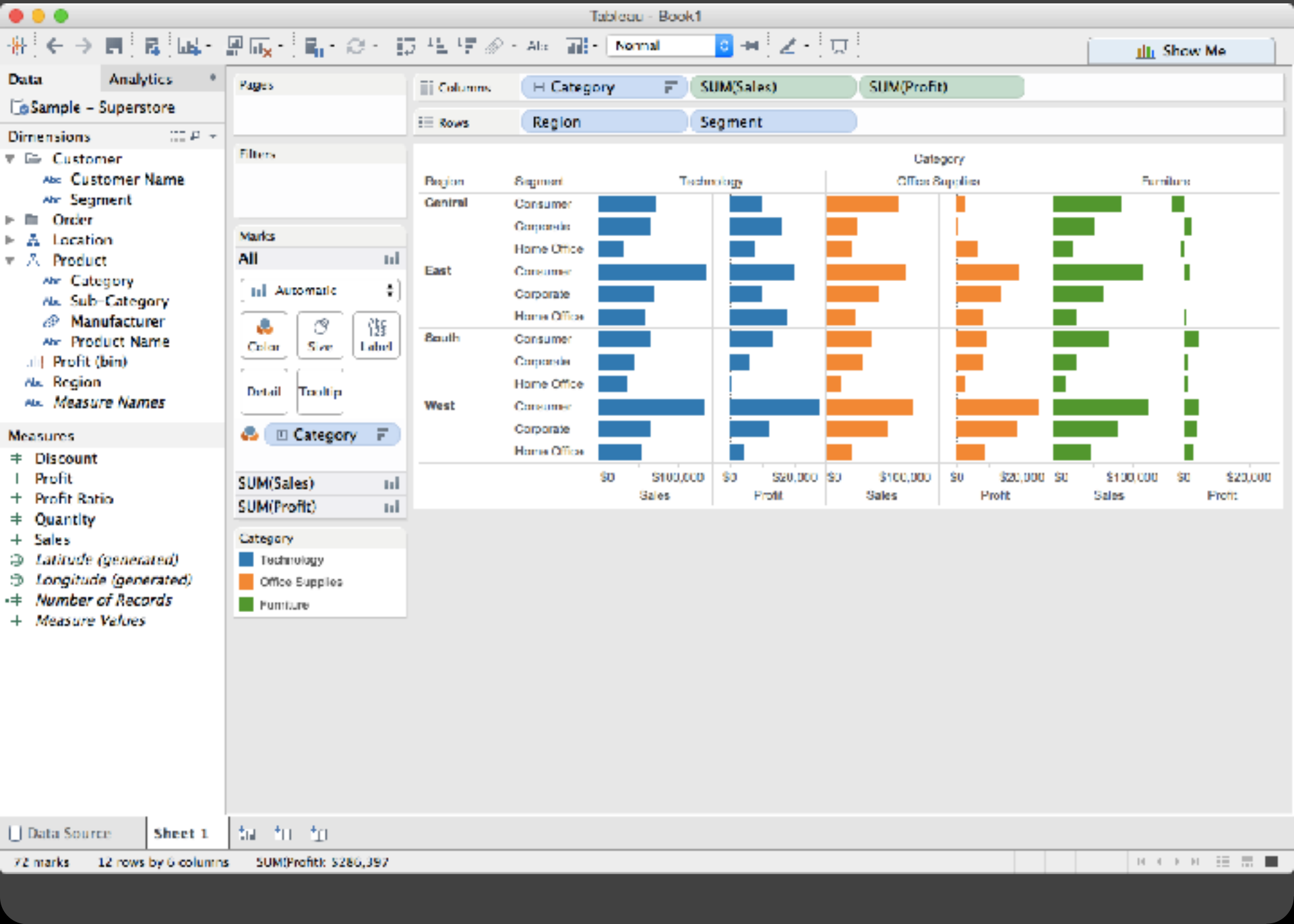


Tableau - Book1
Normal
Show Me
Data
Analytics
Sample – Superstore
Dimensions
Customer
Customer Name
Segment
Order
Location
Product
Category
Sub-Category
Manufacturer
Product Name
Profit (bin)
Region
Measure Names
Measures
Discount
Profit
Profit Ratio
Quantity
Sales
Latitude (generated)
Longitude (generated)
Number of Records
Measure Values
Pages
Filters
Marks
All
Automatic
Color
Size
Label
Detail
Tooltip
Category
SUM(Sales)
SUM(Profit)
Category
Technology
Office Supplies
Furniture
Columns
Category
SUM(Sales)
SUM(Profit)
Rows
Region
Segment
Category
Region
Segment
Technology
Office Supplies
Furniture
Central
East
South
West
Consumer
Corporate
Home Office
$0
$100,000
$20,000
Sales
Profit
Data Source
Sheet 1
72 marks
12 rows by 6 columns
SUM(Profit): $286,397

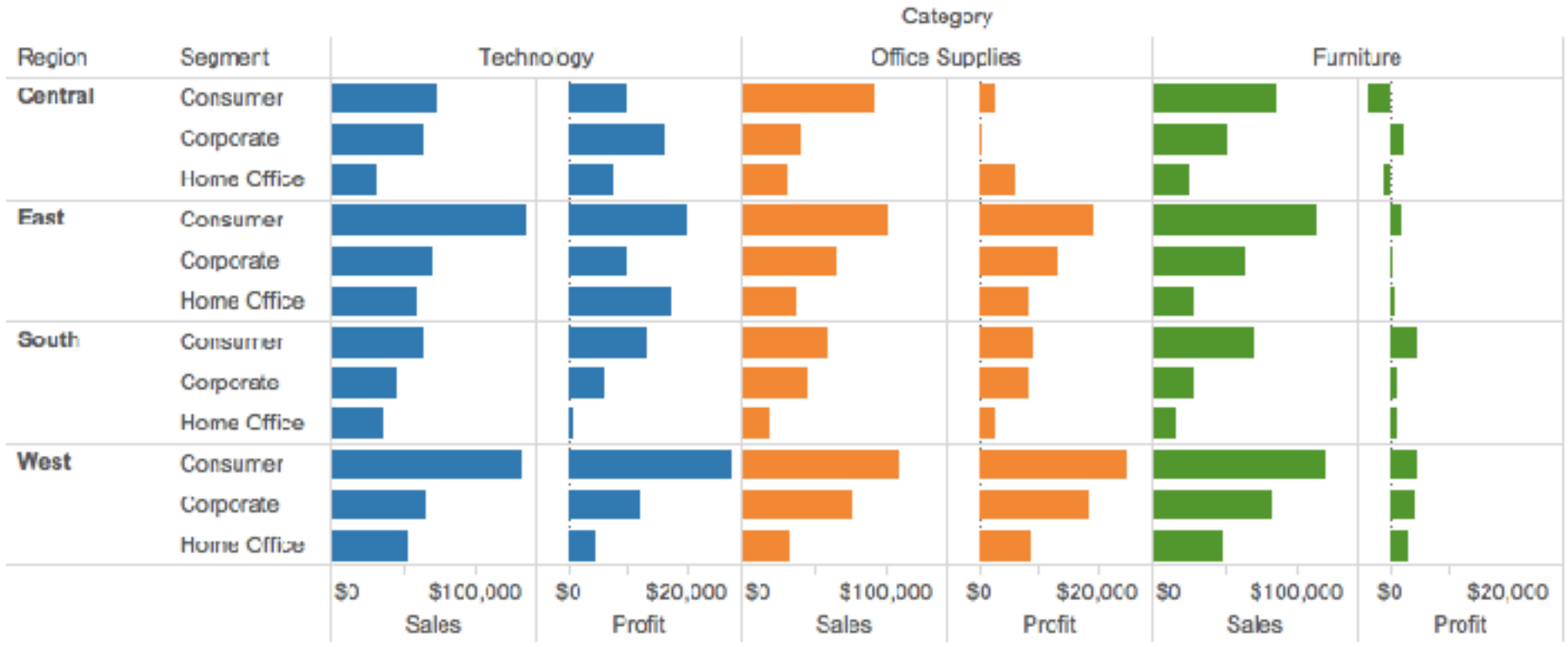
Tableau - Book1

Normal

Show Me

Columns: Category, SUM(Sales), SUM(Profit)

Rows: Region, Segment



Taxonomy of Interactions

Data and View Specification

Visualize, Filter, Sort, Derive

Taxonomy of Interactions

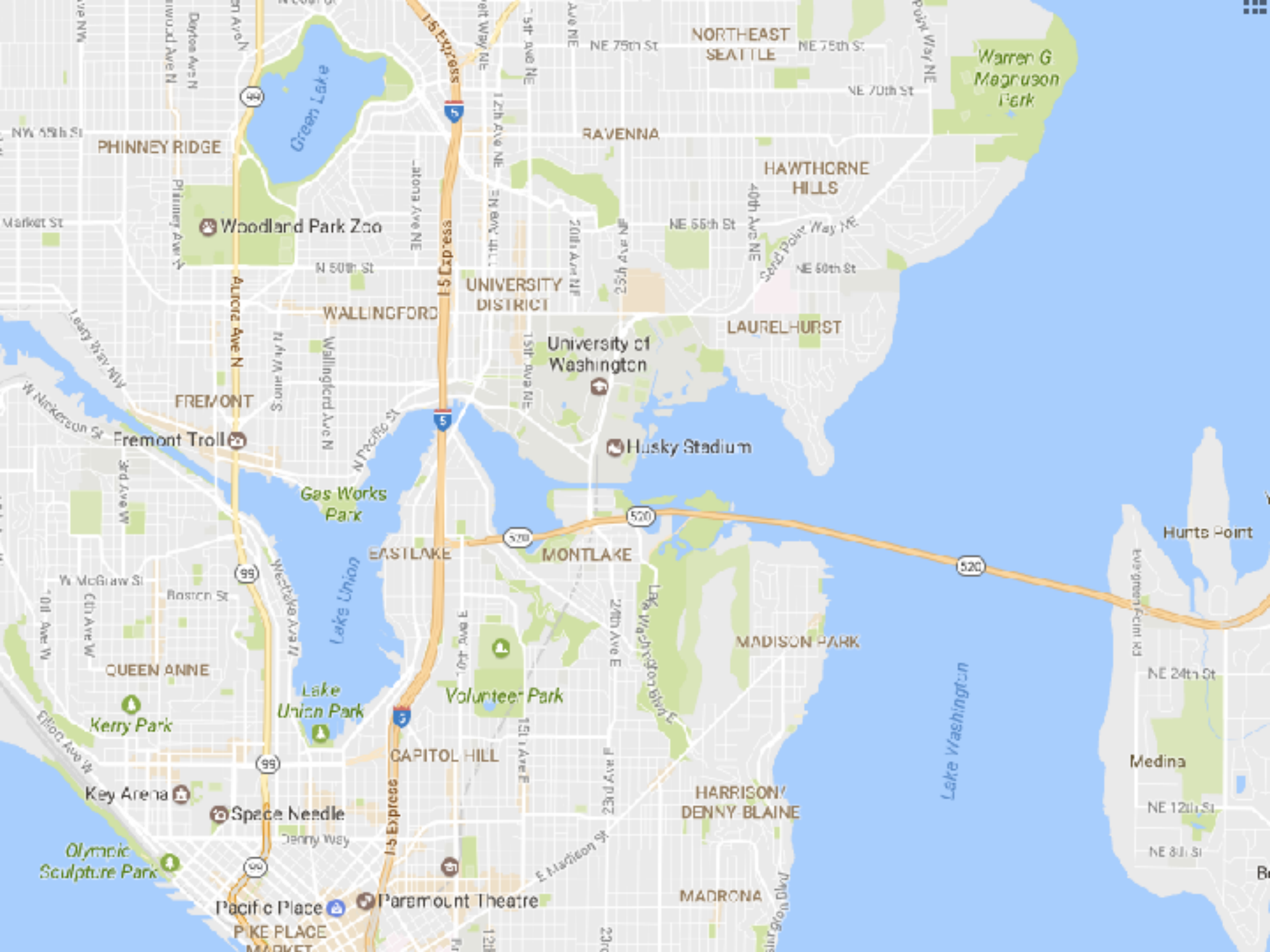
Data and View Specification

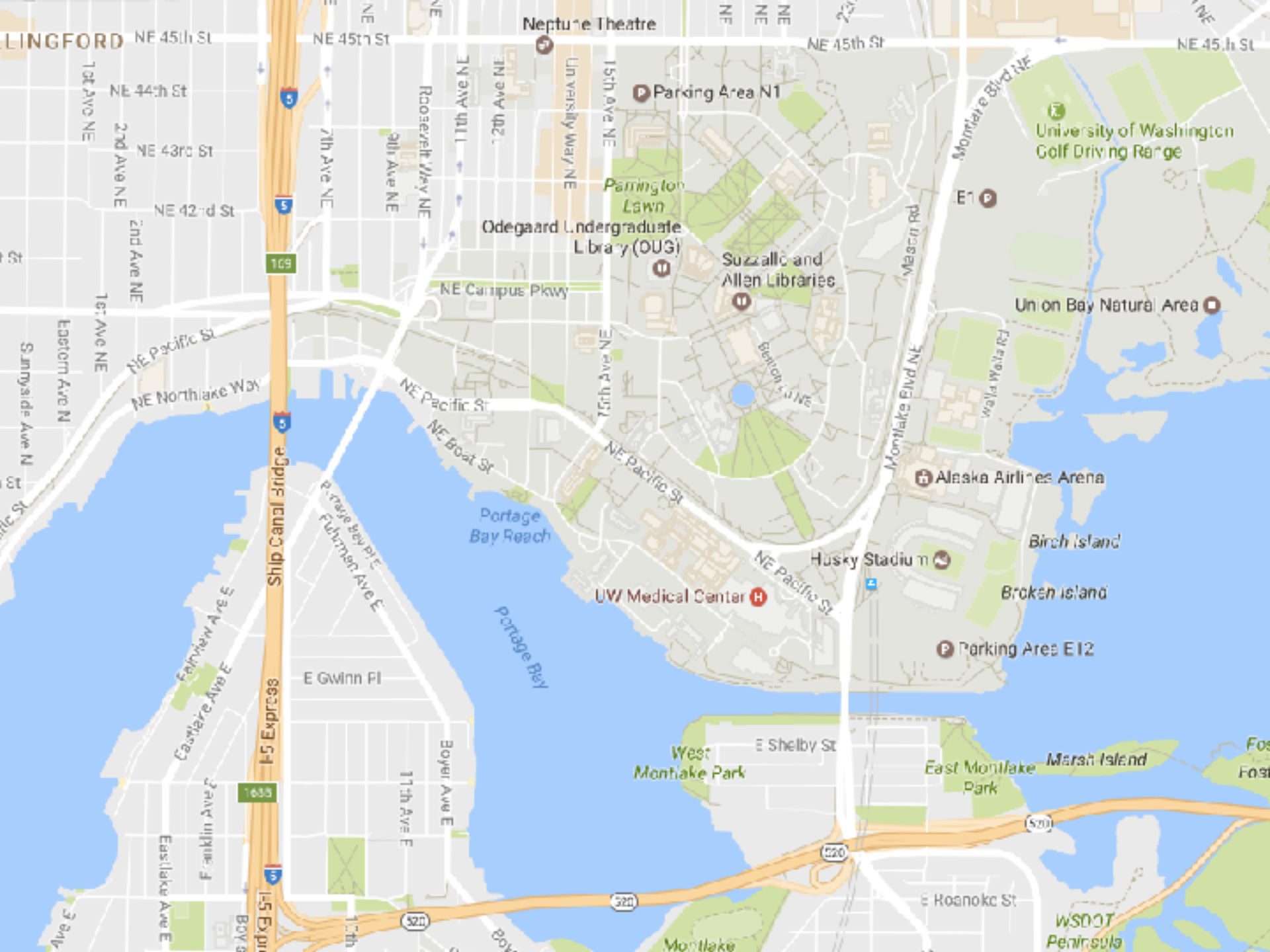
Visualize, Filter, Sort, Derive

View Manipulation

Select, Navigate, Coordinate, Organize

[Heer & Shneiderman 2012]


NORTHEAST SEATTLE
NE 75th St
Warren G Magnuson Park
NE 70th St
Green Lake
PHINNEY RIDGE
RAVENNA
HAWTHORNE HILLS
Woodland Park Zoo
NE 65th St
N 50th St
NE 50th St
I-5 Express
UNIVERSITY DISTRICT
WALLINGFORD
LAURELHURST
University of Washington
FREMONT
Fremont Troll
Husky Stadium
Gas Works Park
EASTLAKE
MONTLAKE
Hunts Point
Lake Union
MADISON PARK
QUEEN ANNE
Lake Union Park
Volunteer Park
Kerry Park
CAPITOL HILL
Key Arena
Space Needle
HARRISON/ DENNY-BLAINE
Lake Washington
Medina
Olympic Sculpture Park
Pacific Place
Paramount Theatre
PIKE PLACE
MADRONA
520
99
5


NE 45th St
Neptune Theatre
Parking Area N1
University of Washington Golf Driving Range
Parrington Lawn
Odegaard Undergraduate Library (OUGL)
Suzzallo and Allen Libraries
NE Campus Pkwy
Union Bay Natural Area
E1
NE 43rd St
NE 42nd St
NE Pacific St
NE Northlake Way
NE Boat St
Ship Canal Bridge
I-5 Express
Portage Bay Reach
Portage Bay
Alaska Airlines Arena
Husky Stadium
Birch Island
Broken Island
UW Medical Center
Parking Area E12
E Gwinn Pl
E Shelby St
West Montlake Park
East Montlake Park
Marsh Island
E Roanoke St
WSDOT Peninsula
Montlake
Montlake Blvd NE
Mason Rd
Walla Walla Rd
Boyer Ave E
Fuhrman Ave E
Eastlake Ave E
Fairview Ave E
Roosevelt Way NE
University Way NE
15th Ave NE
12th Ave NE
7th Ave NE
2nd Ave NE
1st Ave NE
Eastern Ave N
Sunnyside Ave N
520
5
99
1635

Taxonomy of Interactions

Data and View Specification

Visualize, Filter, Sort, Derive

View Manipulation

Select, Navigate, Coordinate, Organize

[Heer & Shneiderman 2012]

Taxonomy of Interactions

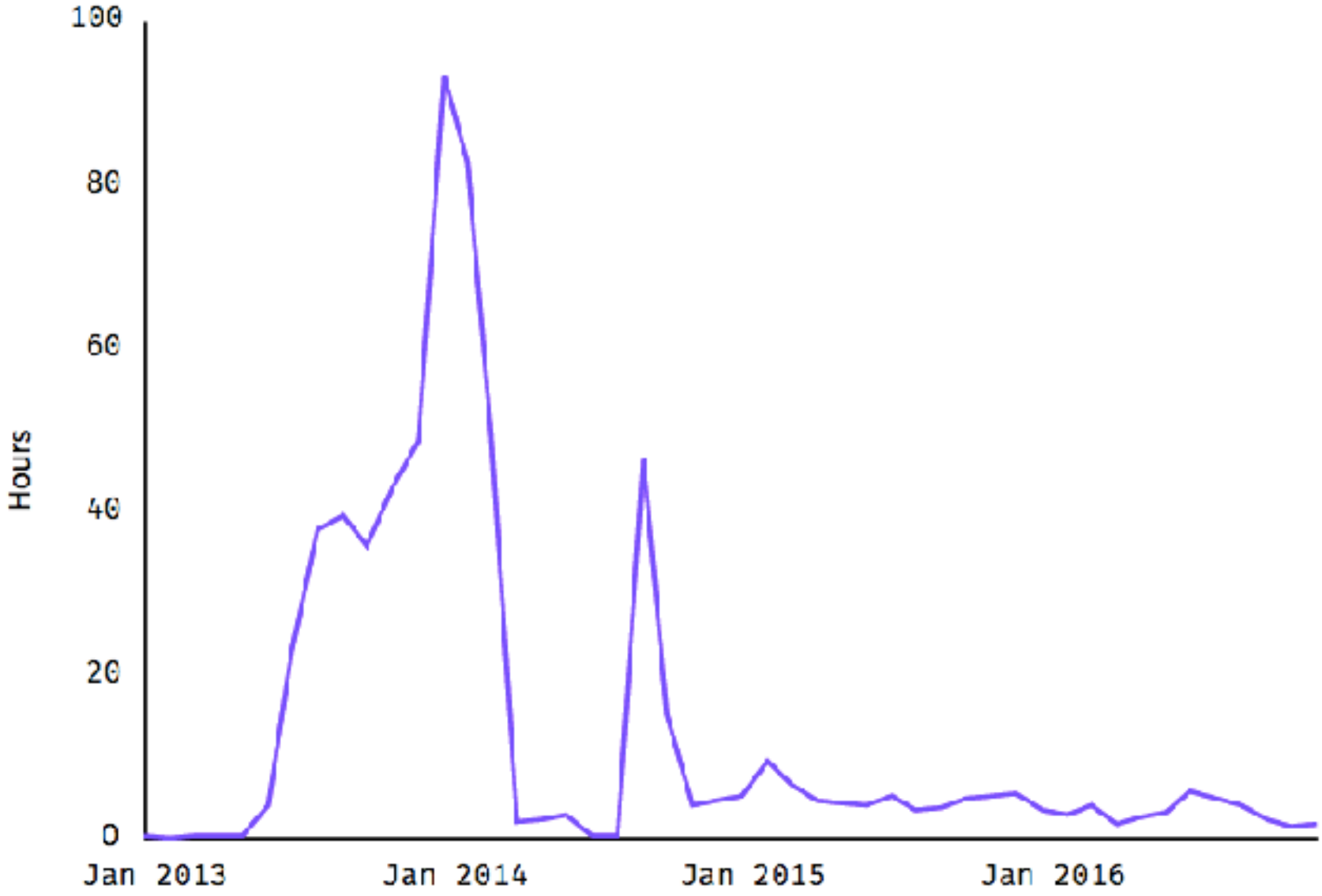
Data and View Specification
Visualize, Filter, Sort, Derive

View Manipulation
Select, Navigate, Coordinate, Organize

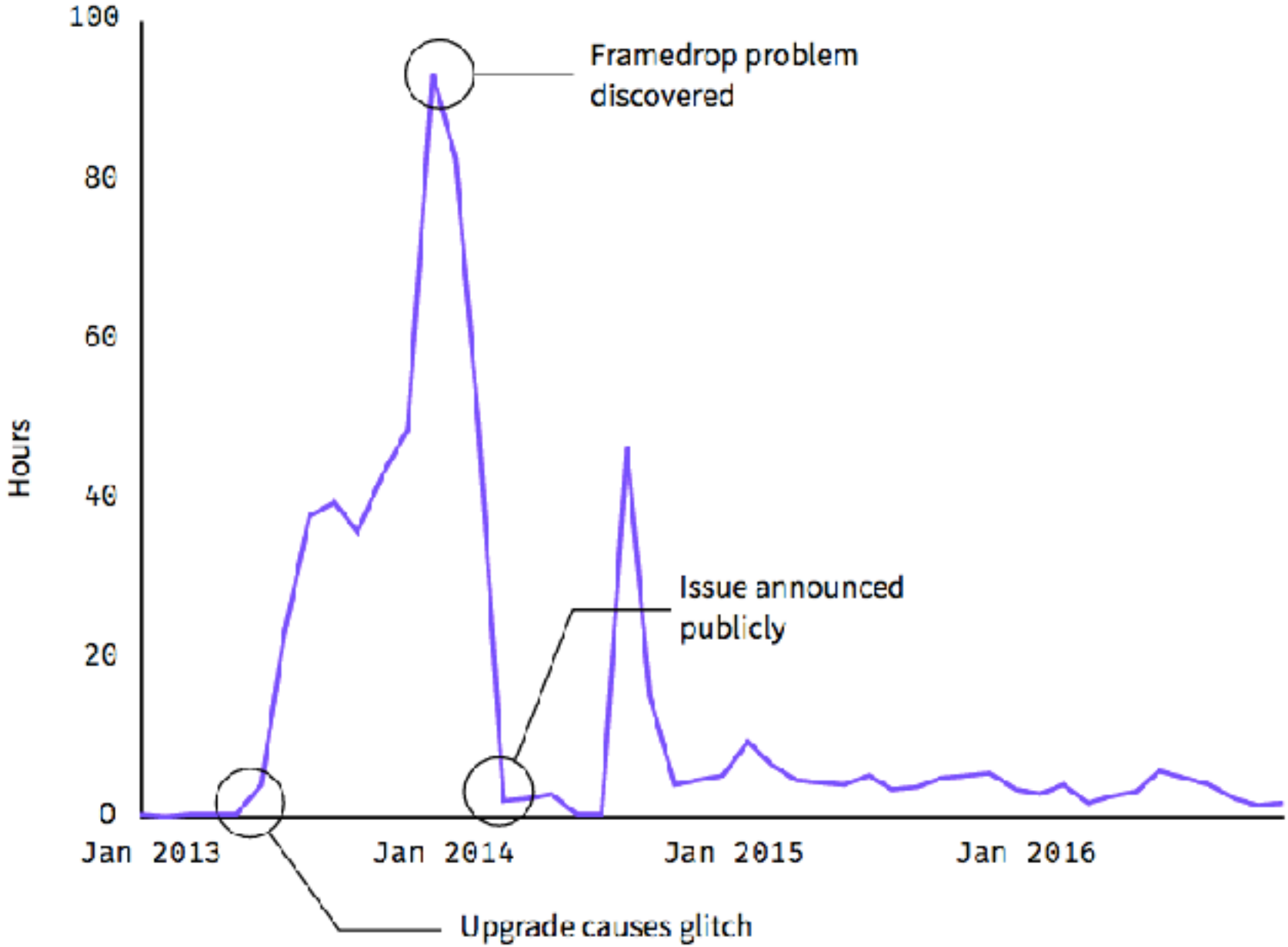
Process and Provenance
Record, Annotate, Share, Guide

[Heer & Shneiderman 2012]

Hours of footage lost each month due to dropped frames



Hours of footage lost each month due to dropped frames



Taxonomy of Interactions

Data and View Specification
Visualize, Filter, Sort, Derive

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Select, Navigate, Coordinate, Organize

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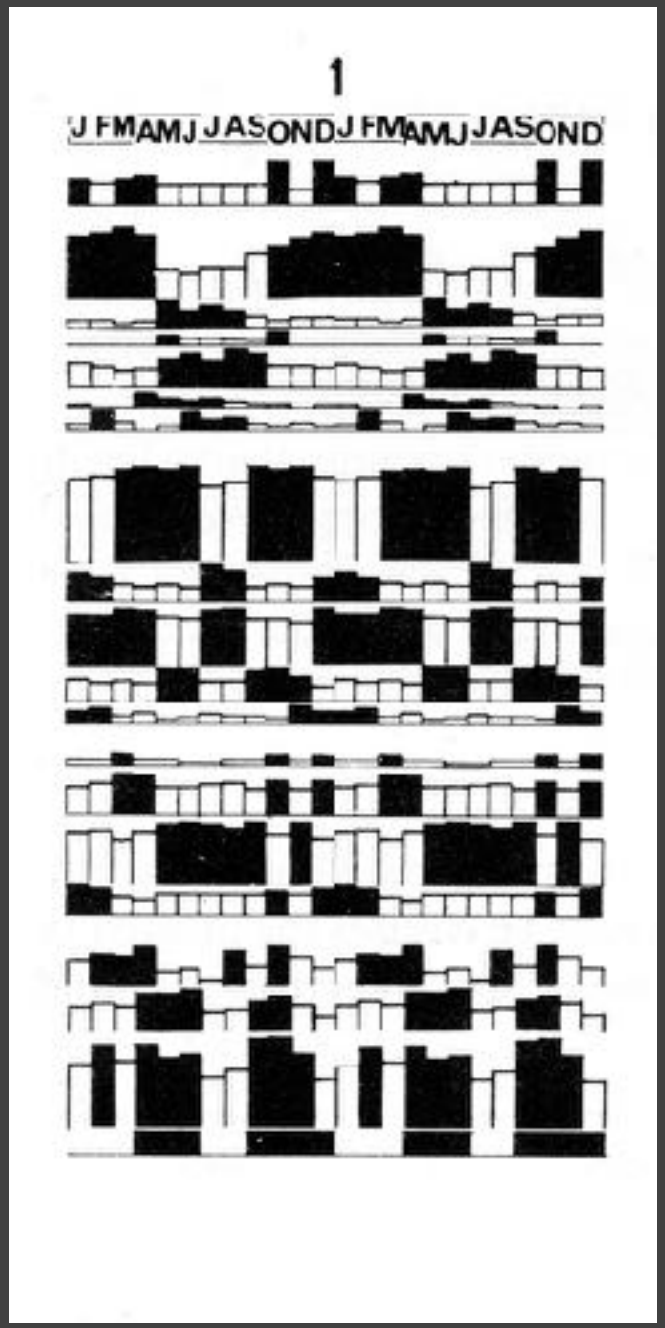
Record, Annotate, Share, Guide

[Heer & Shneiderman 2012]

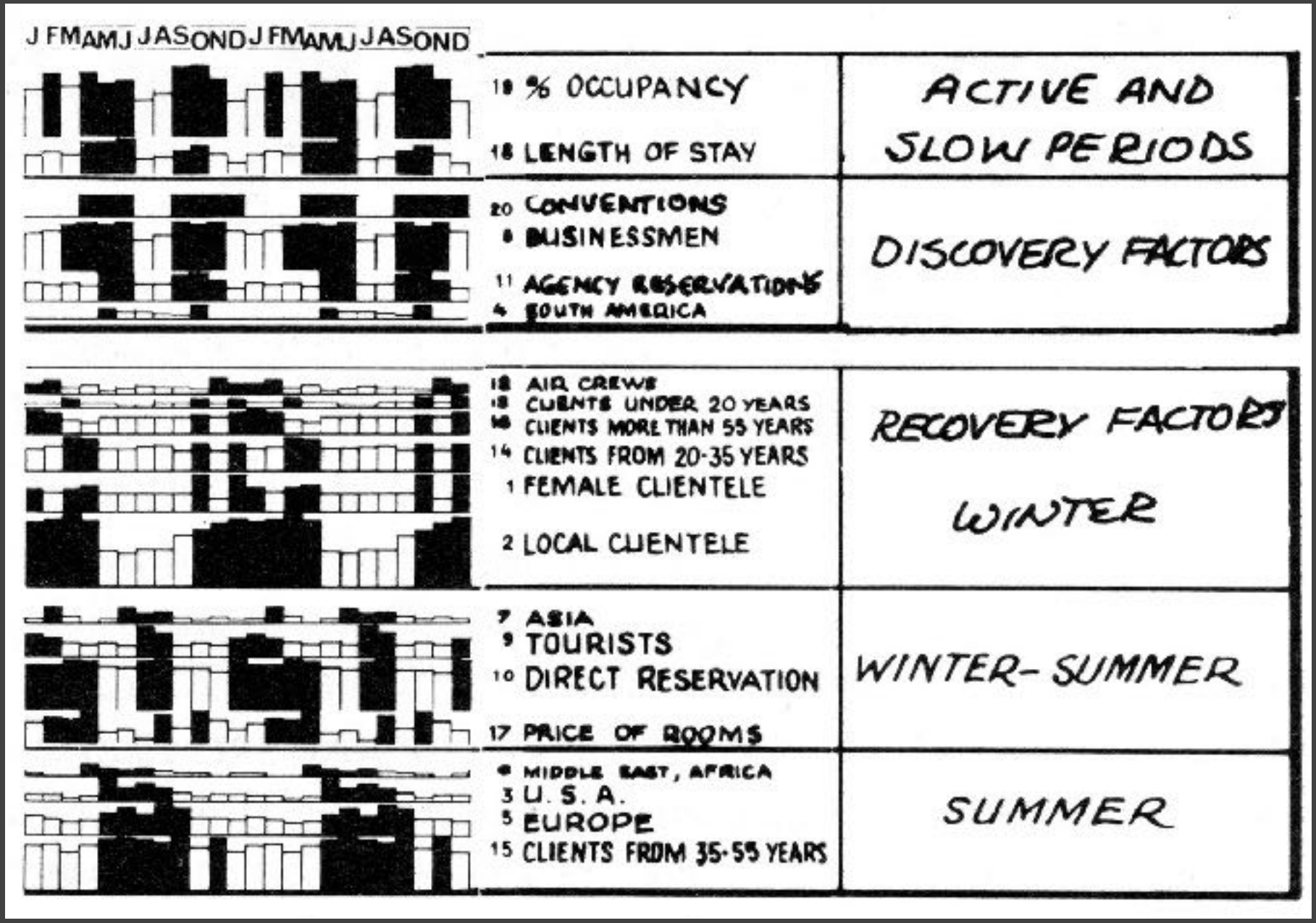
E X A M P L E :
Bertin’s Hotel Data

J	F	M	A	M	J	J	A	S	O	N	D		
26	21	26	28	20	20	20	20	20	40	15	40	1	% CLIENTELE FEMALE
69	70	77	71	37	36	39	39	55	60	68	72	2	% —〃— LOCAL
7	6	3	6	23	14	19	14	9	6	8	8	3	% —〃— U.S.A.
0	0	0	0	8	6	6	4	2	12	0	0	4	% —〃— SOUTH AMERICA
20	15	14	15	23	27	22	30	27	19	19	17	5	% —〃— EUROPE
1	0	0	8	6	4	6	4	2	1	0	1	6	% —〃— M.EAST, AFRICA
3	10	6	0	3	13	8	9	5	2	5	2	7	% —〃— ASIA
78	80	85	86	85	87	70	76	87	85	87	80	8	% BUSINESSMEN
22	20	15	14	15	13	30	24	13	15	13	20	9	% TOURISTS
70	70	75	74	69	68	74	75	68	68	64	75	10	% DIRECT RESERVATIONS
20	18	19	17	27	27	19	19	26	27	21	15	11	% AGENCY ———〃———
10	12	6	9	4	5	7	6	6	5	15	10	12	% AIR CREWS
2	2	4	2	2	1	1	2	2	4	2	5	13	% CLIENTS UNDER 20 YEARS
25	27	37	35	25	25	27	28	24	30	24	30	14	% —〃— 20-35 —〃—
48	49	42	48	54	55	53	51	55	46	55	43	15	% —〃— 35-55 —〃—
25	22	17	15	19	19	19	19	19	20	19	22	16	% —〃— MORE THAN 55 —〃—
163	167	166	174	152	155	145	170	157	174	165	156	17	PRICE OF ROOMS
1.65	1.71	1.65	1.91	1.90	2.	1.54	1.60	1.73	1.82	1.66	1.44	18	LENGTH OF STAY
67	82	70	83	74	77	56	62	90	92	78	55	19	% OCCUPANCY
			X	X	X			X	X	X	X	20	CONVENTIONS

[Graphics and Graphic Information Processing, Bertin 81]

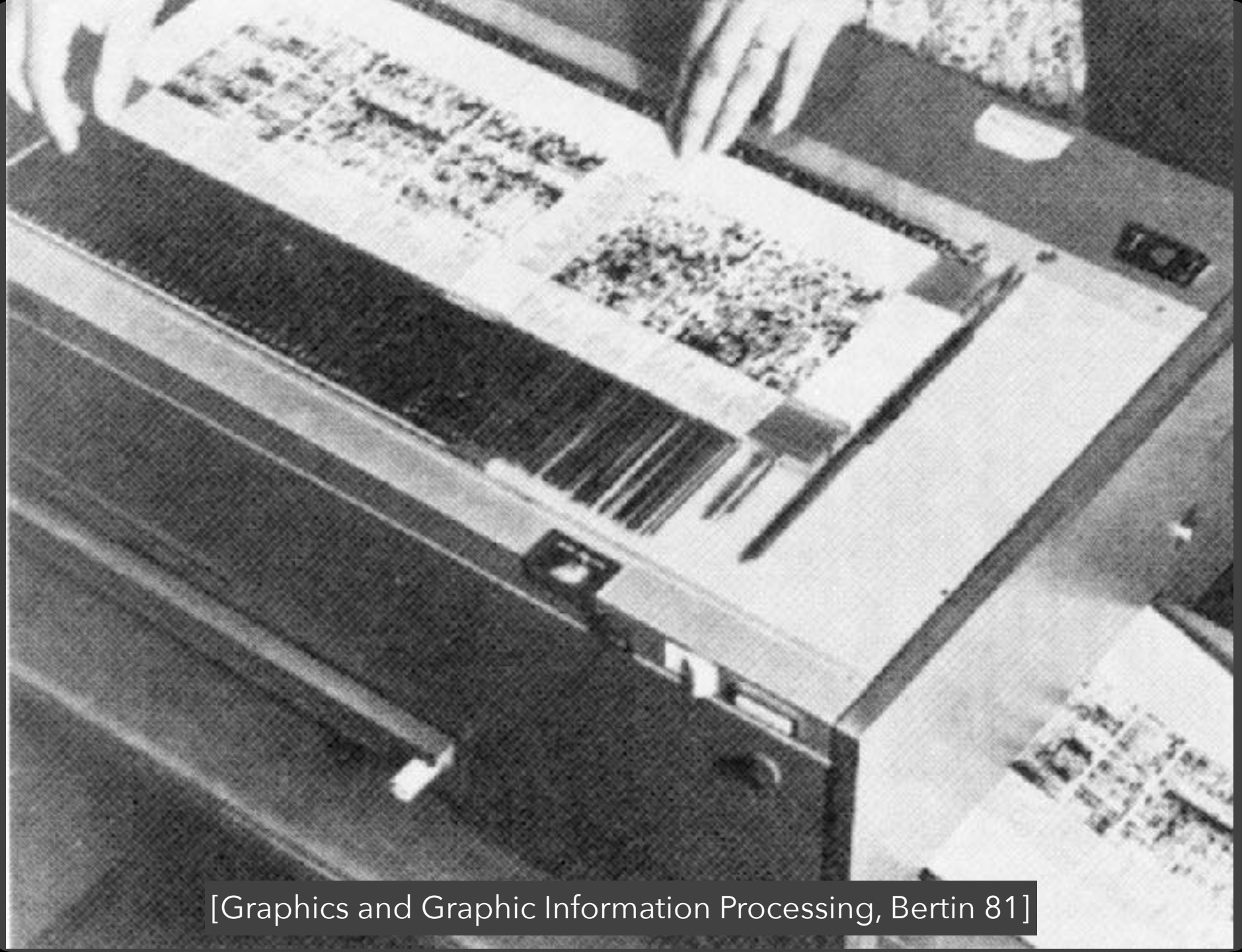


[Graphics and Graphic Information Processing, Bertin 81]



[Graphics and Graphic Information Processing, Bertin 81]

[Graphics and Graphic Information Processing, Bertin 81]



[Graphics and Graphic Information Processing, Bertin 81]

[Graphics and Graphic Information Processing, Bertin 81]

E X A M P L E :
Tukey et al.’s PRIM-9

PRIM-9, Tukey, Fisherkeller, Friedman 1972

Selection

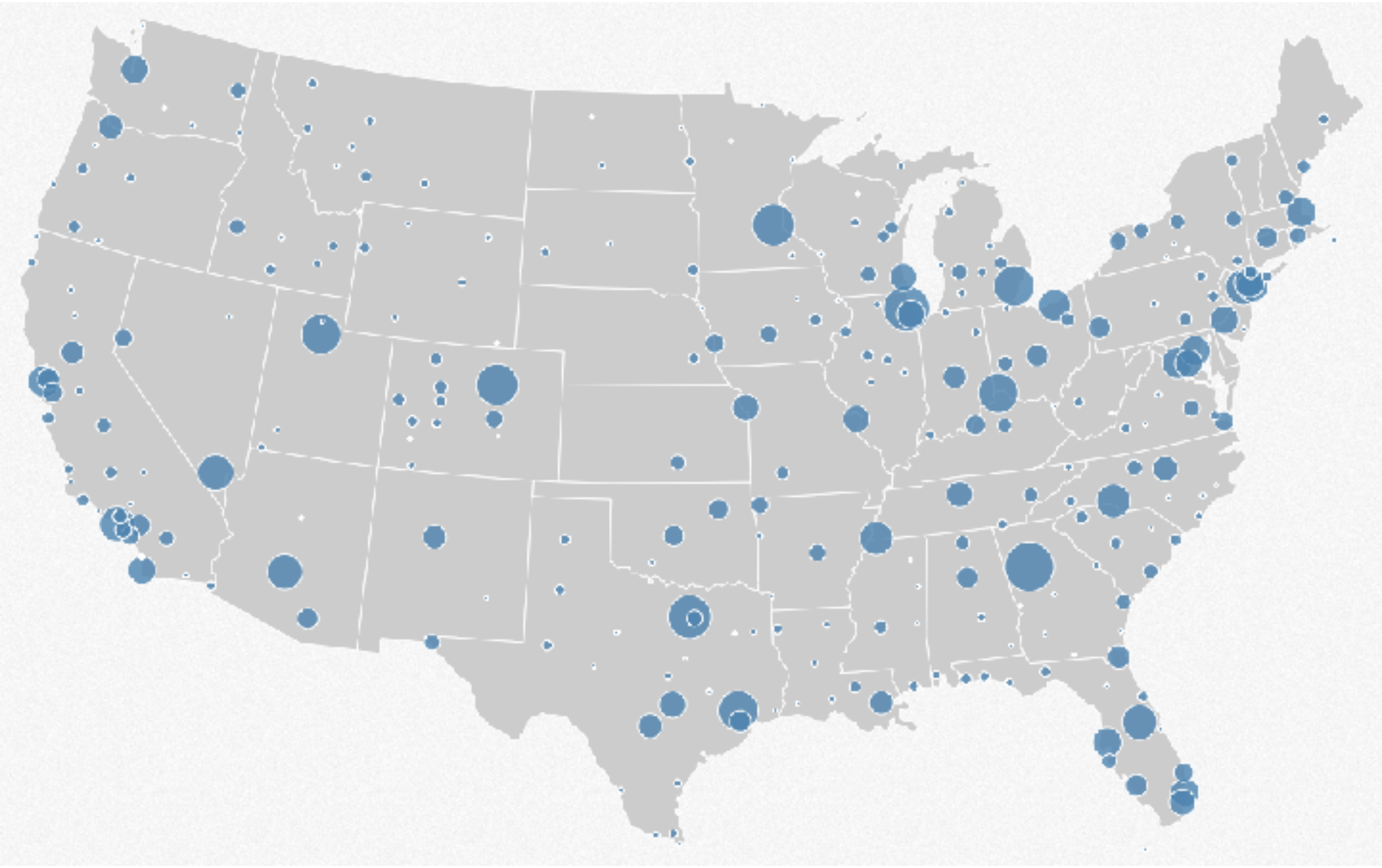
Basic Selection Methods

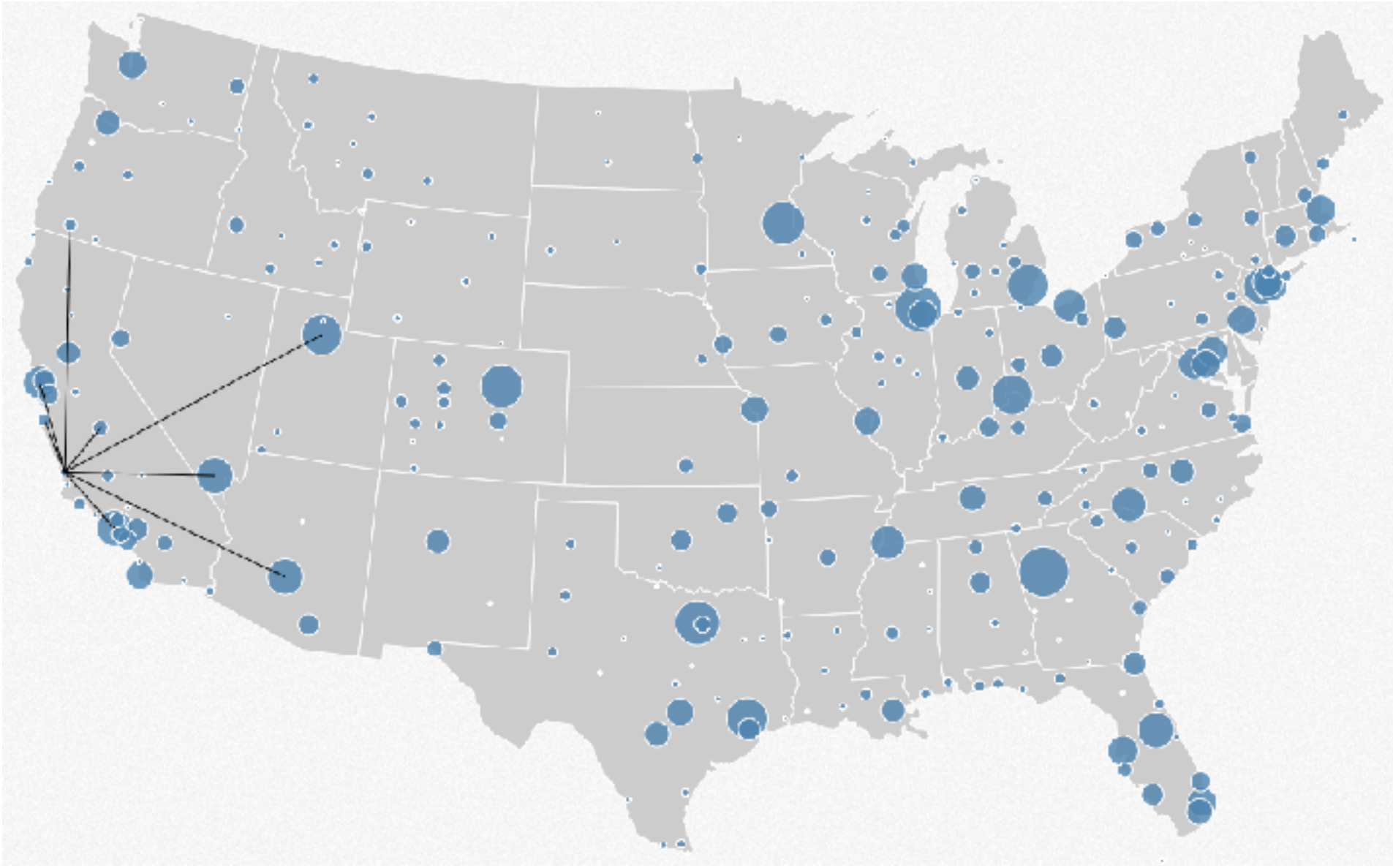
Point Selection

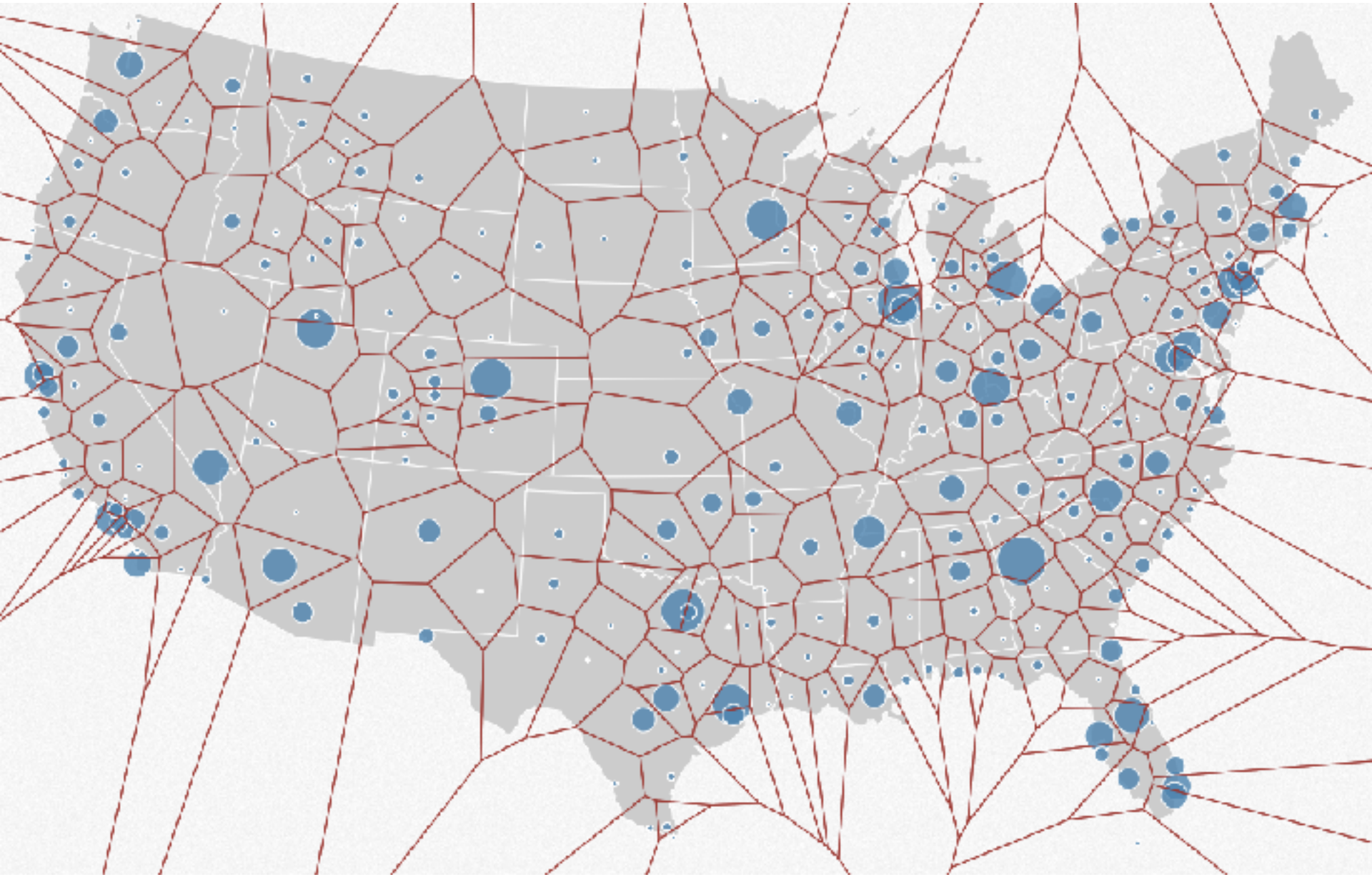
Mouse Hover / Click

Touch / Tap

Select Nearby Element (e.g., Bubble Cursor)







Basic Selection Methods

Point Selection

Mouse Hover / Click

Touch / Tap

Select Nearby Element (e.g., Bubble Cursor)

Region Selection

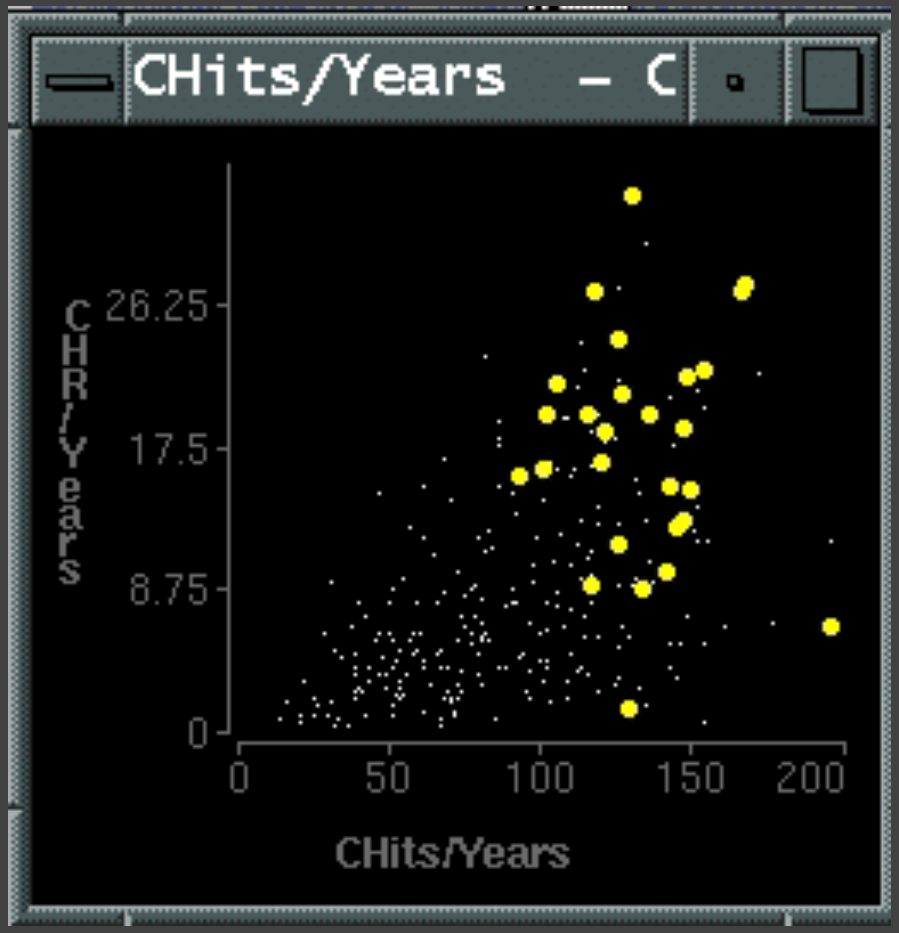
Rubber-band (rectangular) or Lasso (freehand)

Area cursors (“brushes”)

Brushing & Linking

Brushing

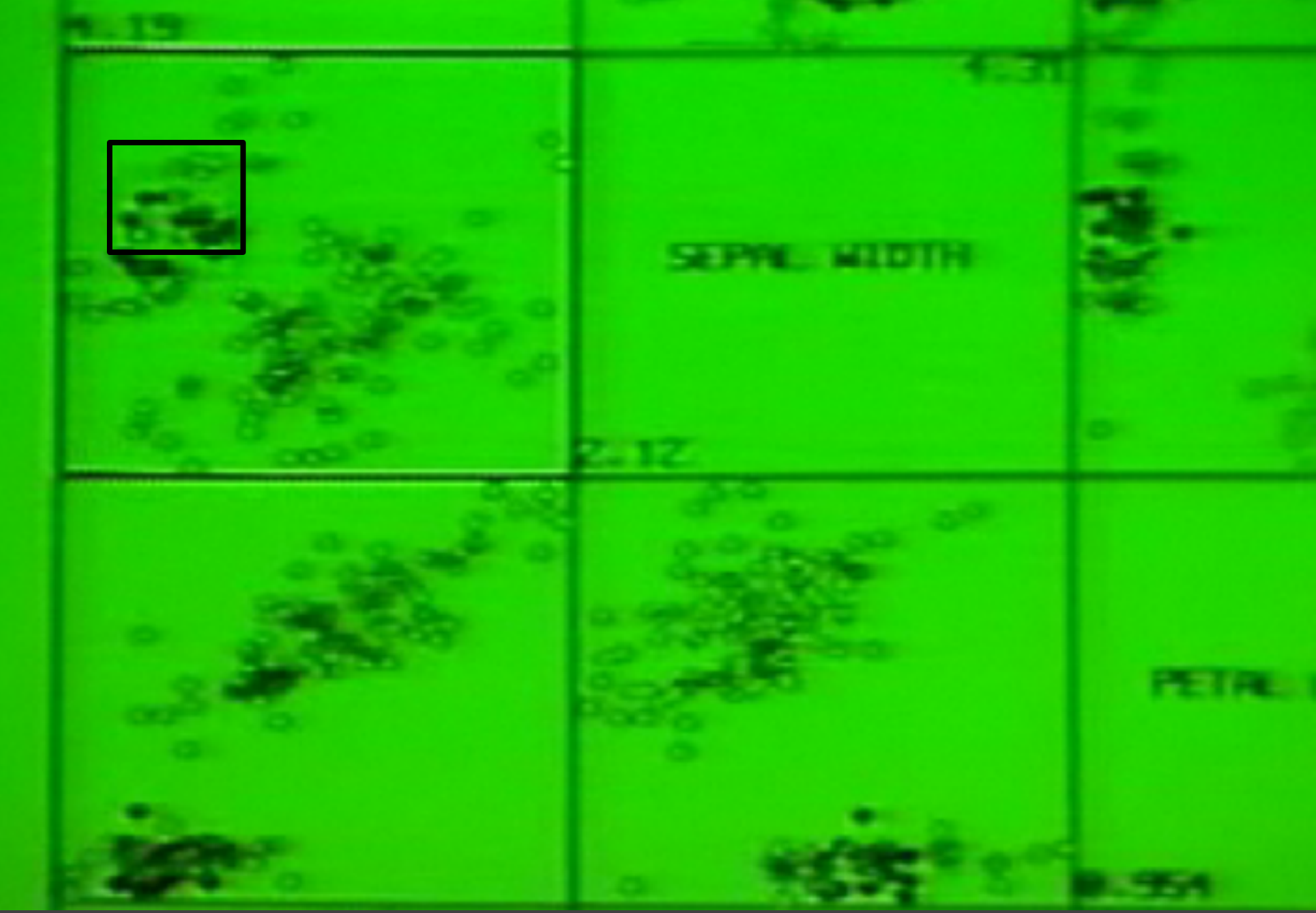
Direct attention to a subset of data [Wills 95]



Brushing & Linking

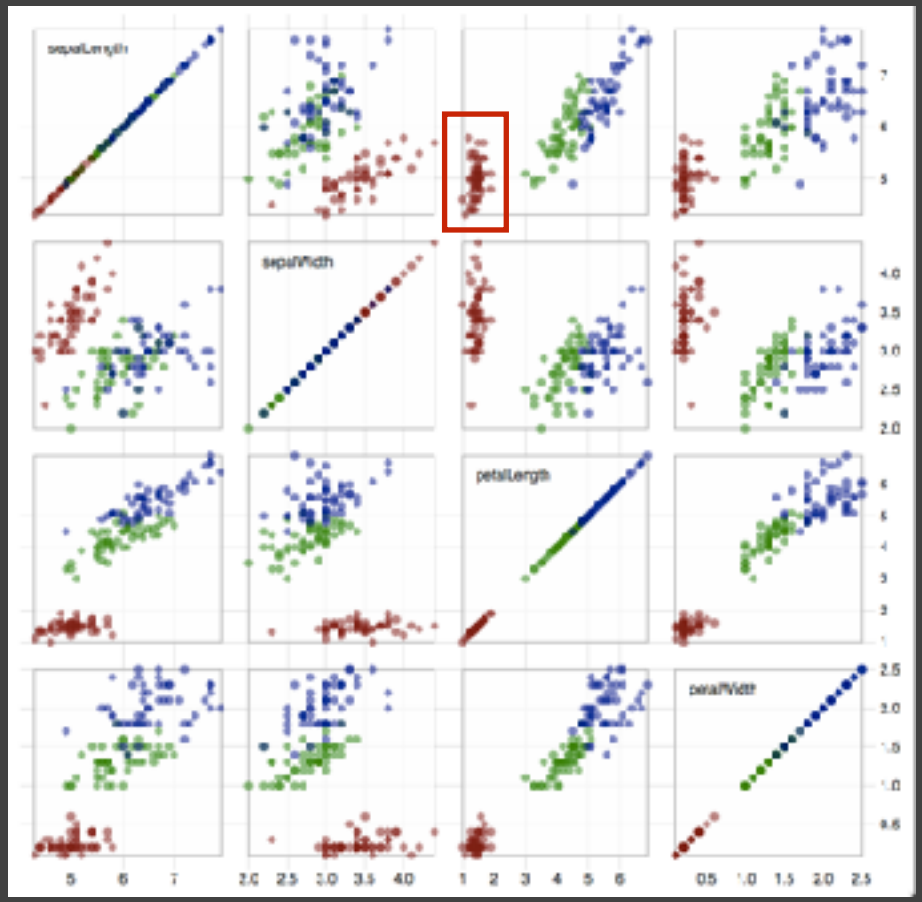
Select ("***brush***") a subset of data
See selected data in other views

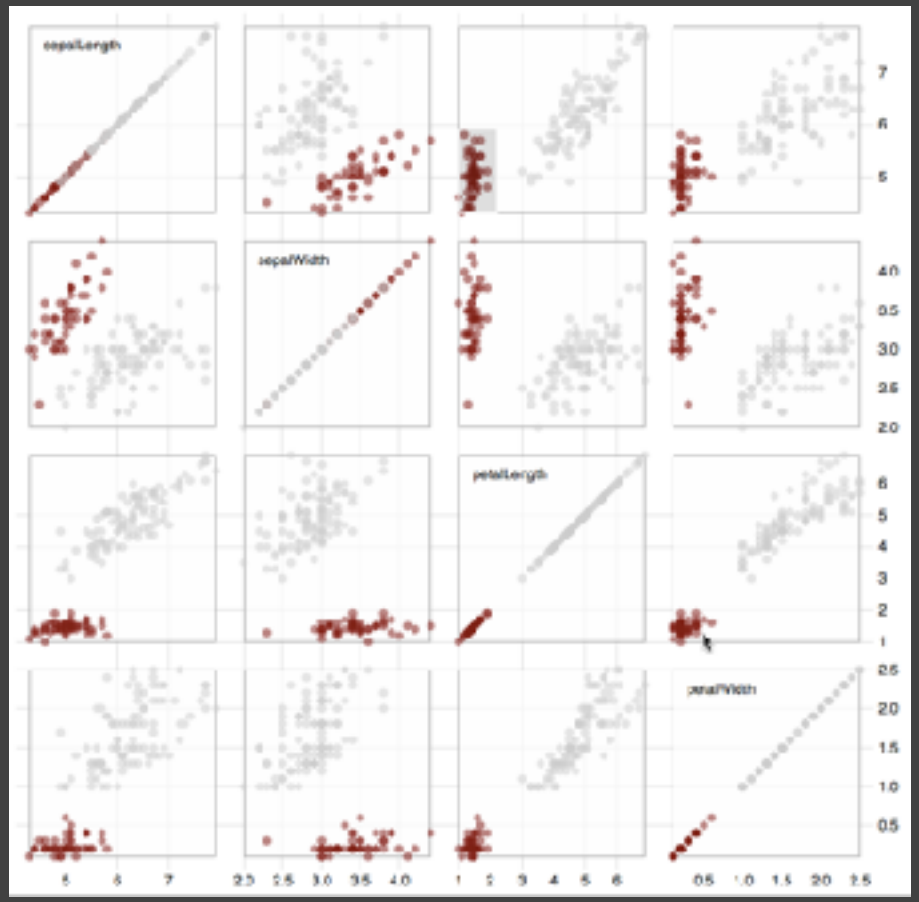
The components must be ***linked***
by *tuple* (matching data points), or
by *query* (matching range or values)



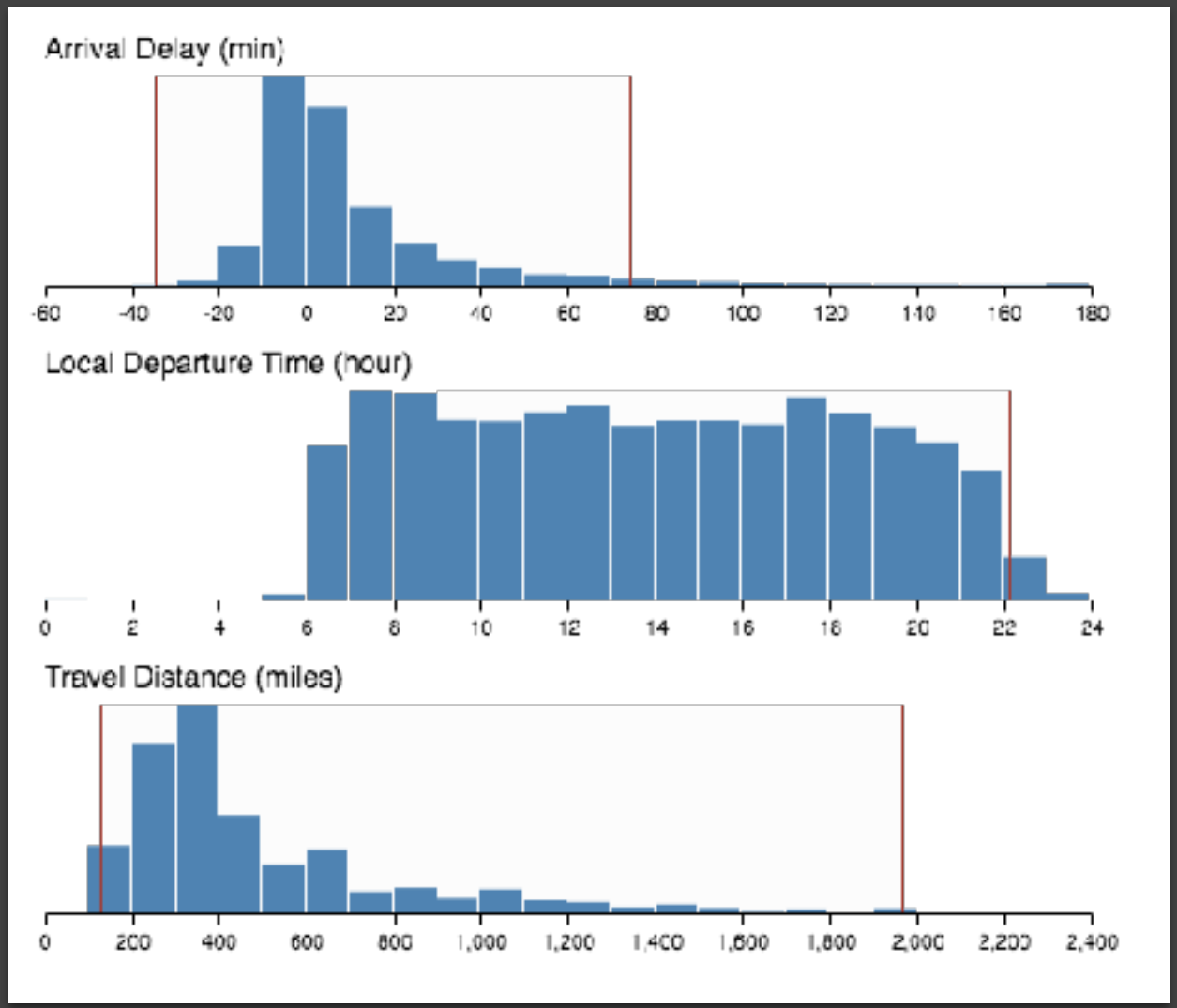
Brushing Scatterplots, Becker & Cleveland 1982

Brushing Scatterplots

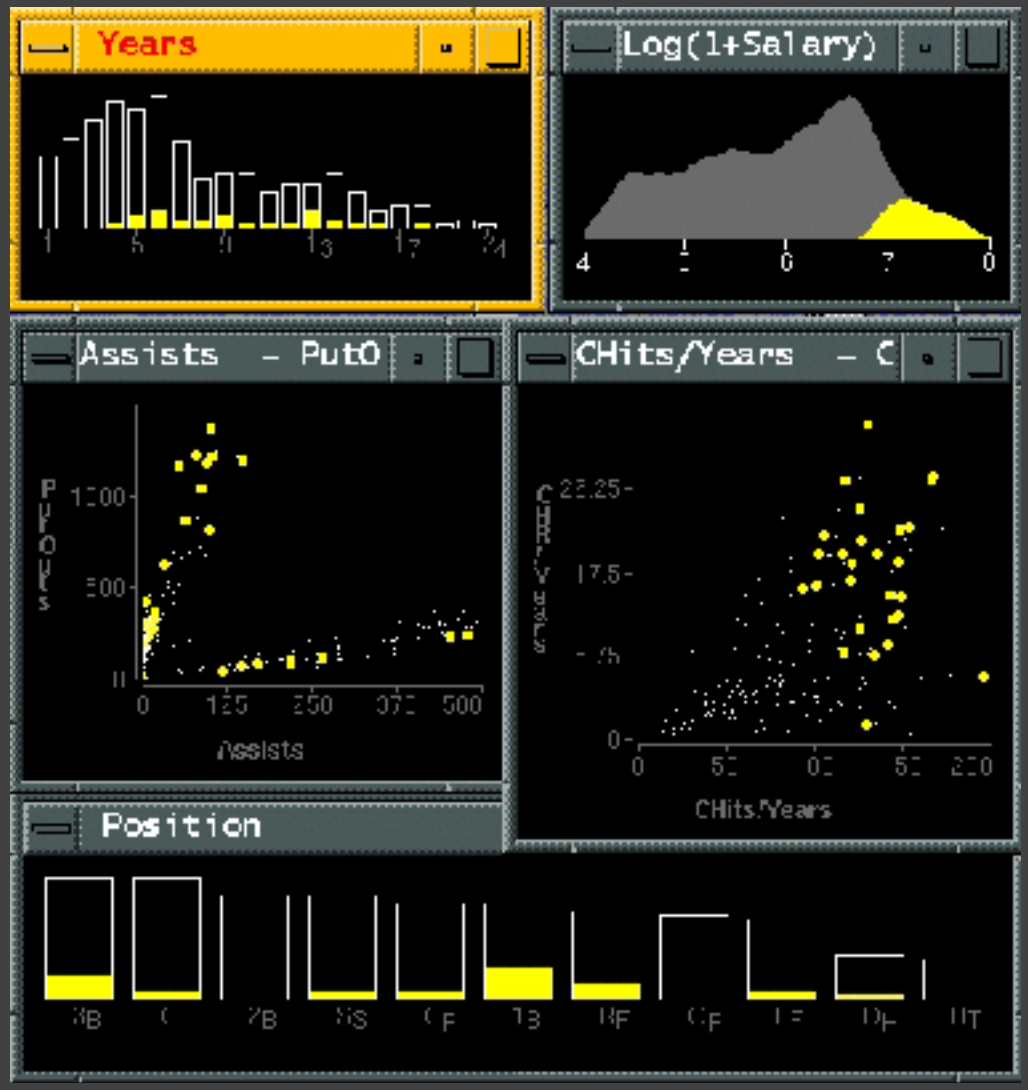




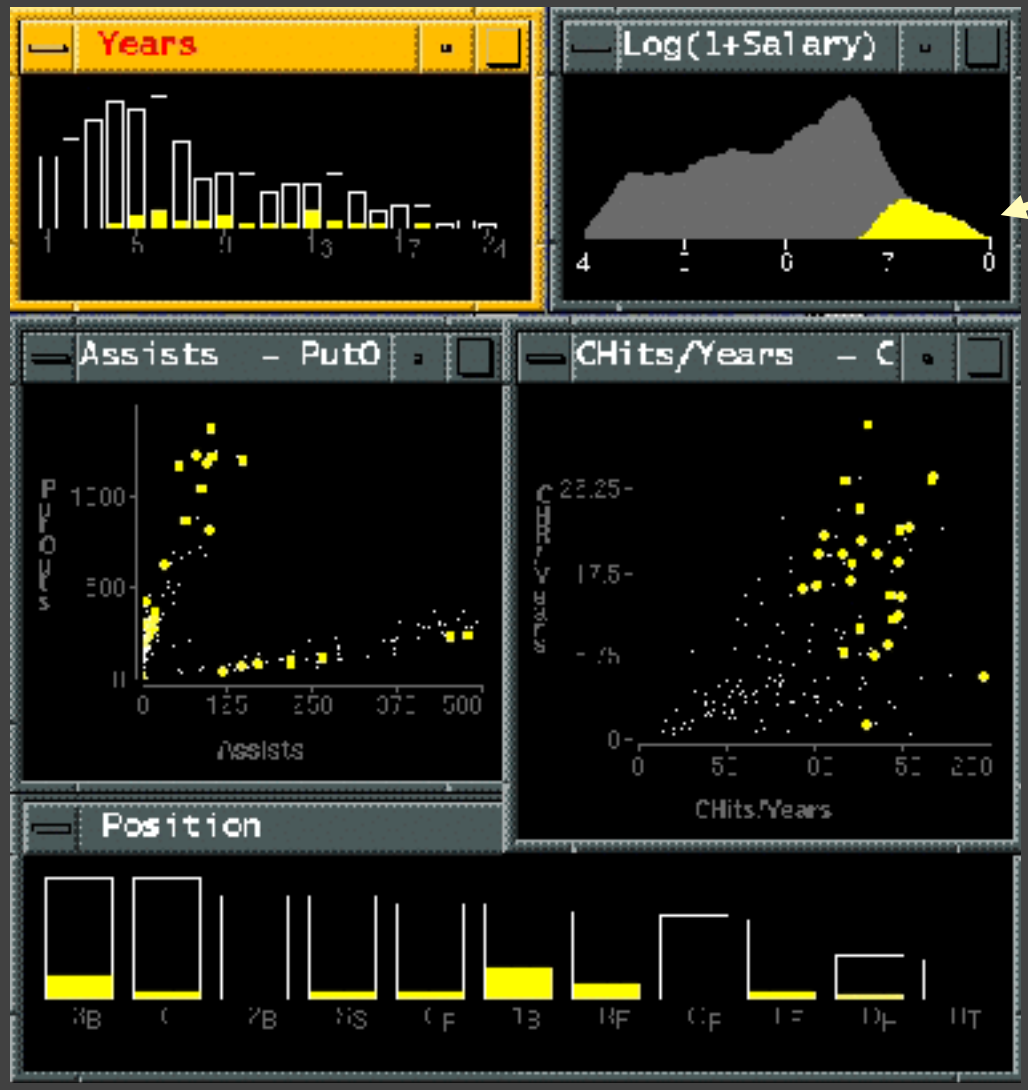
Cross-Filtering



Baseball Statistics [Wills 95]

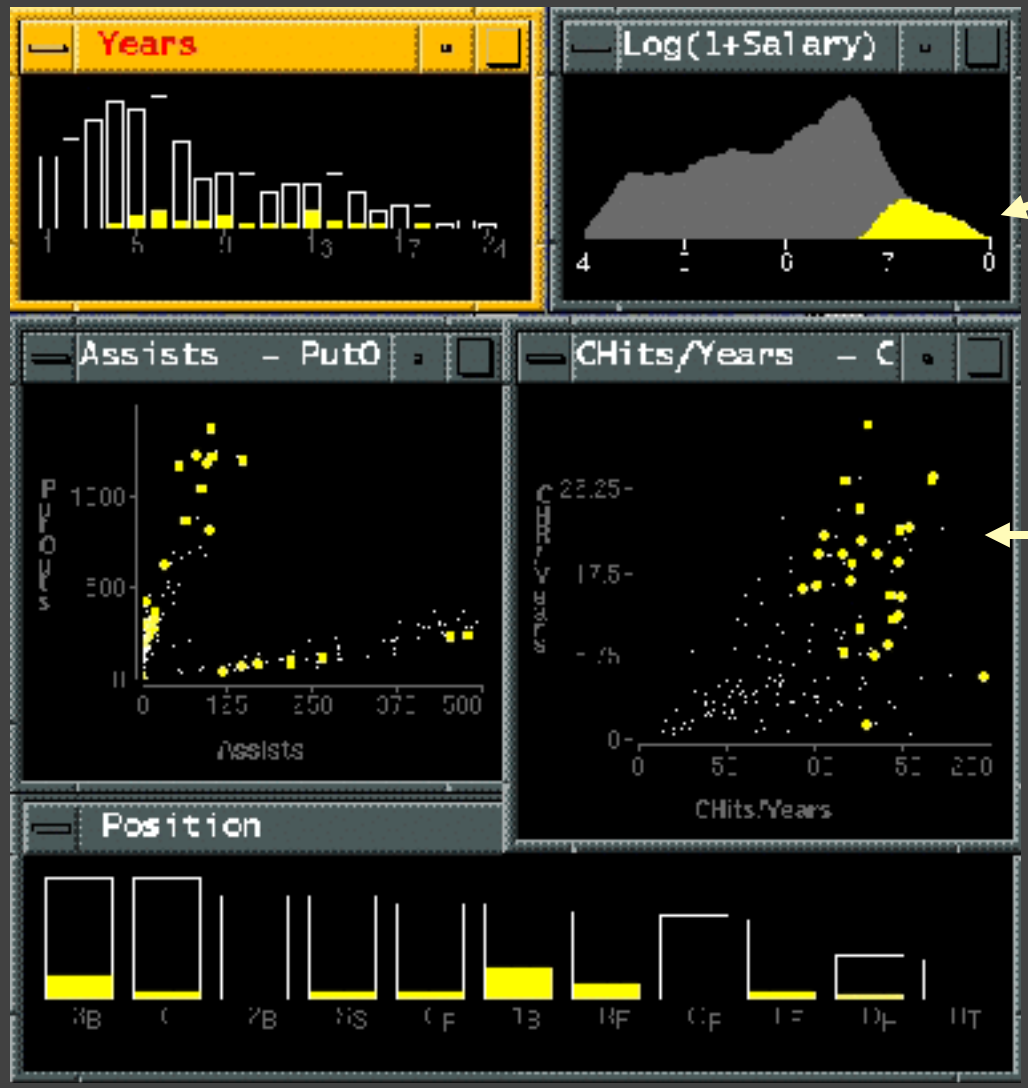


Baseball Statistics [Wills 95]



select high salaries

Baseball Statistics [Wills 95]

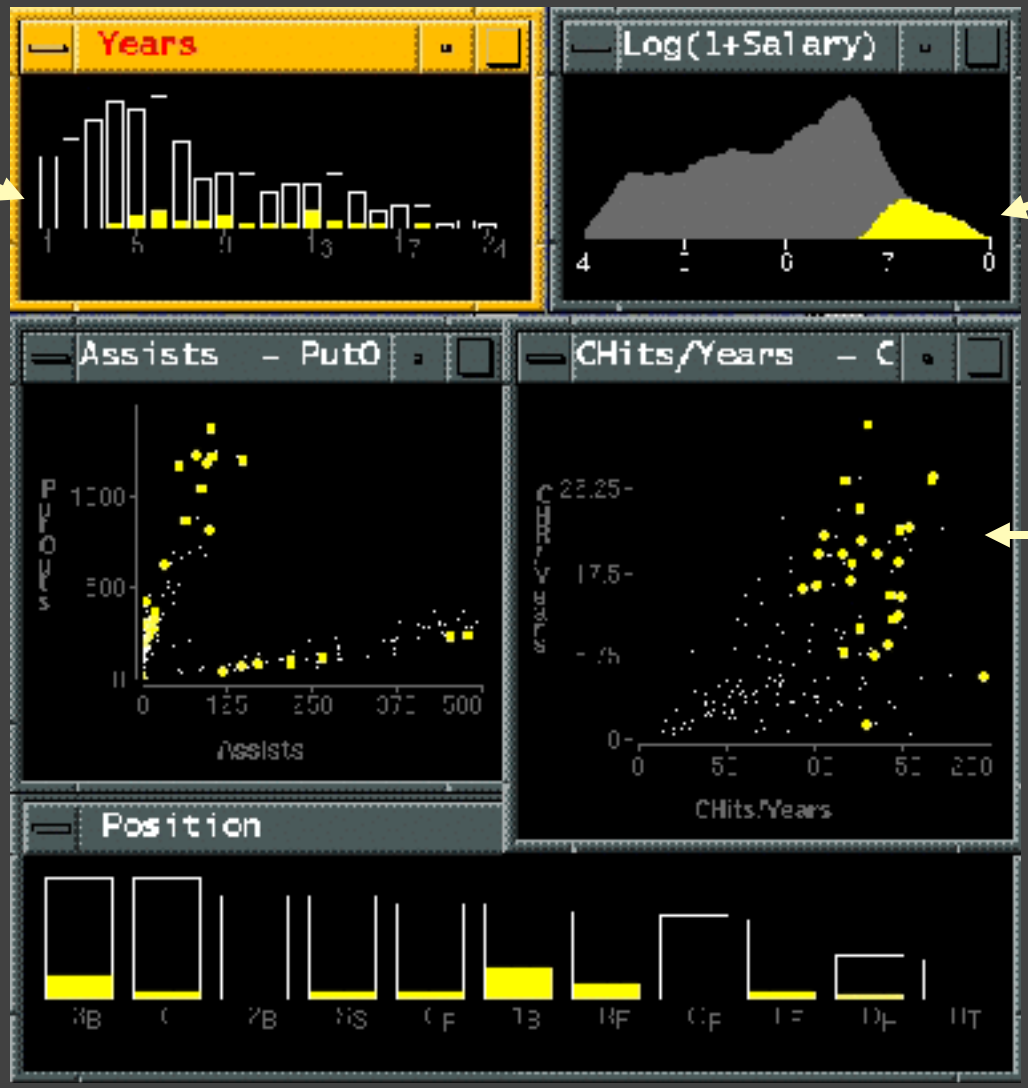


select high salaries

avg career HRs vs avg career hits (batting ability)

Baseball Statistics [Wills 95]

how long in majors

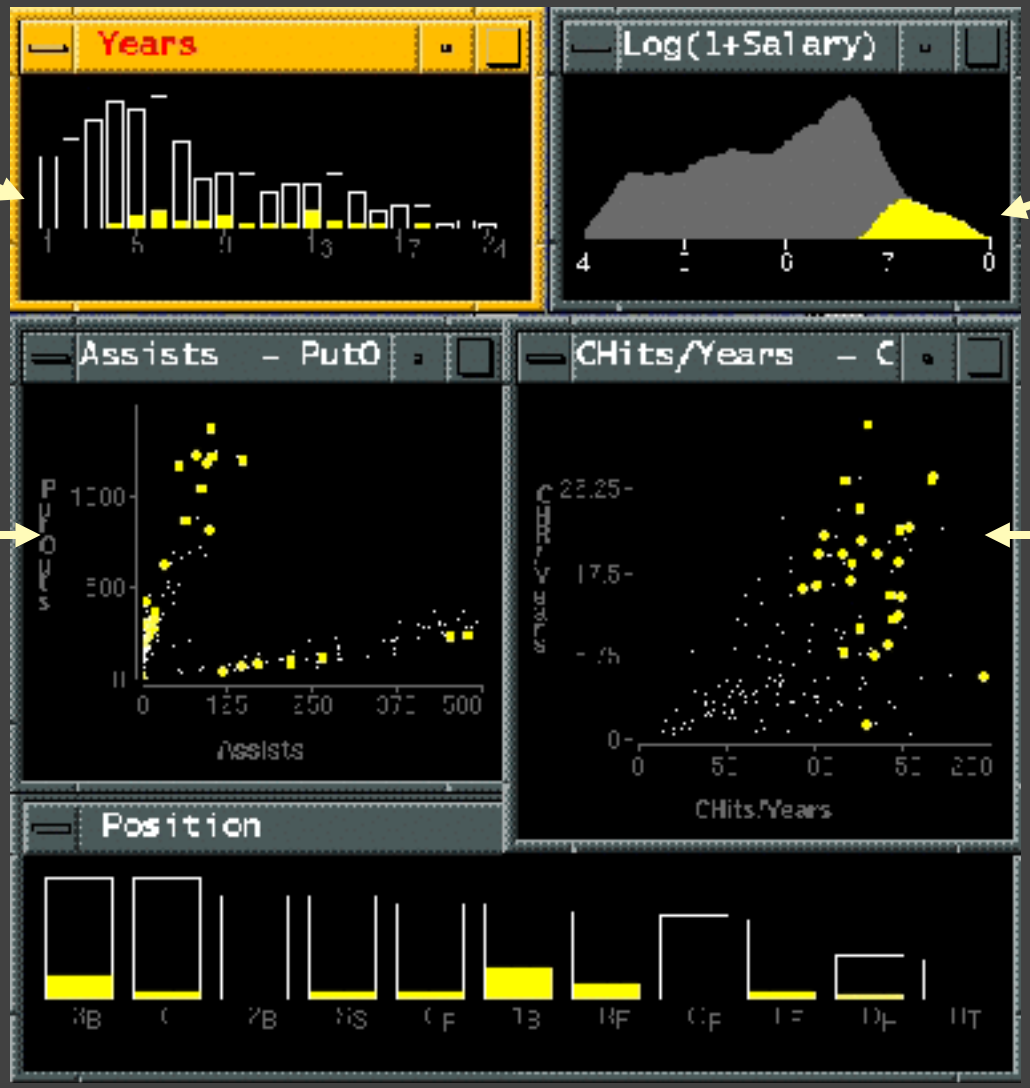


select high salaries

avg career HRs vs avg career hits (batting ability)

Baseball Statistics [Wills 95]

how long in majors



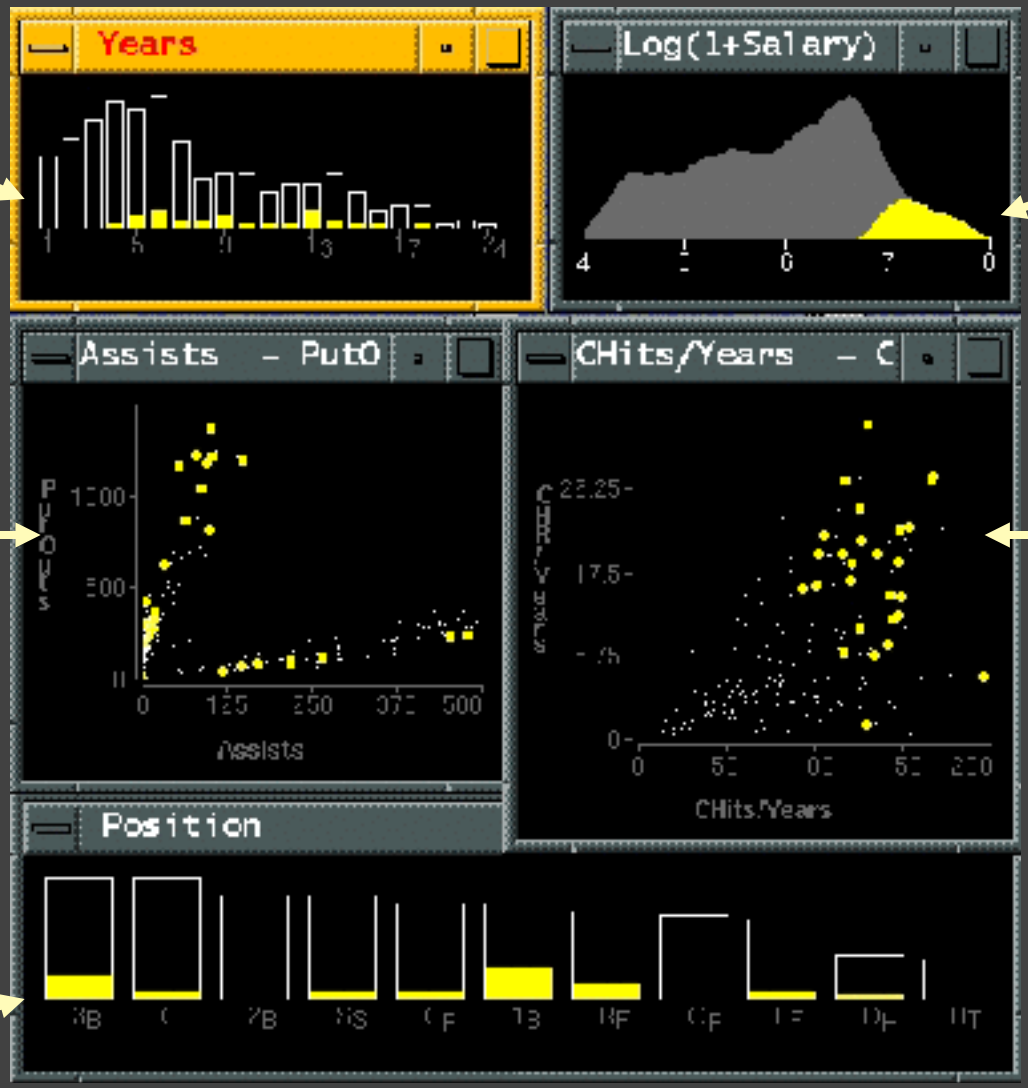
select high salaries

avg assists vs avg putouts (fielding ability)

avg career HRs vs avg career hits (batting ability)

Baseball Statistics [Wills 95]

how long in majors



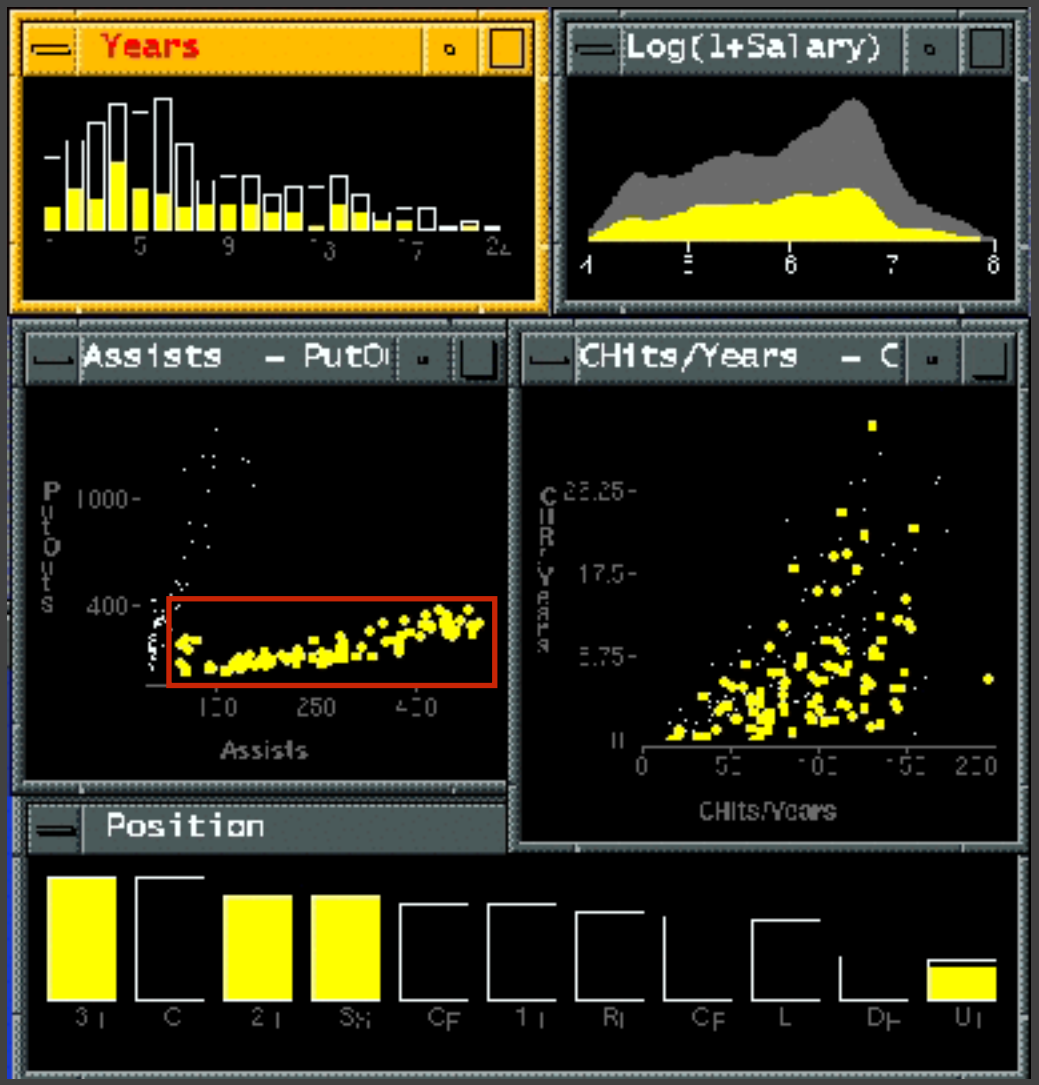
select high salaries

avg assists vs avg putouts (fielding ability)

avg career HRs vs avg career hits (batting ability)

distribution of positions played

Linking Assists to Positions



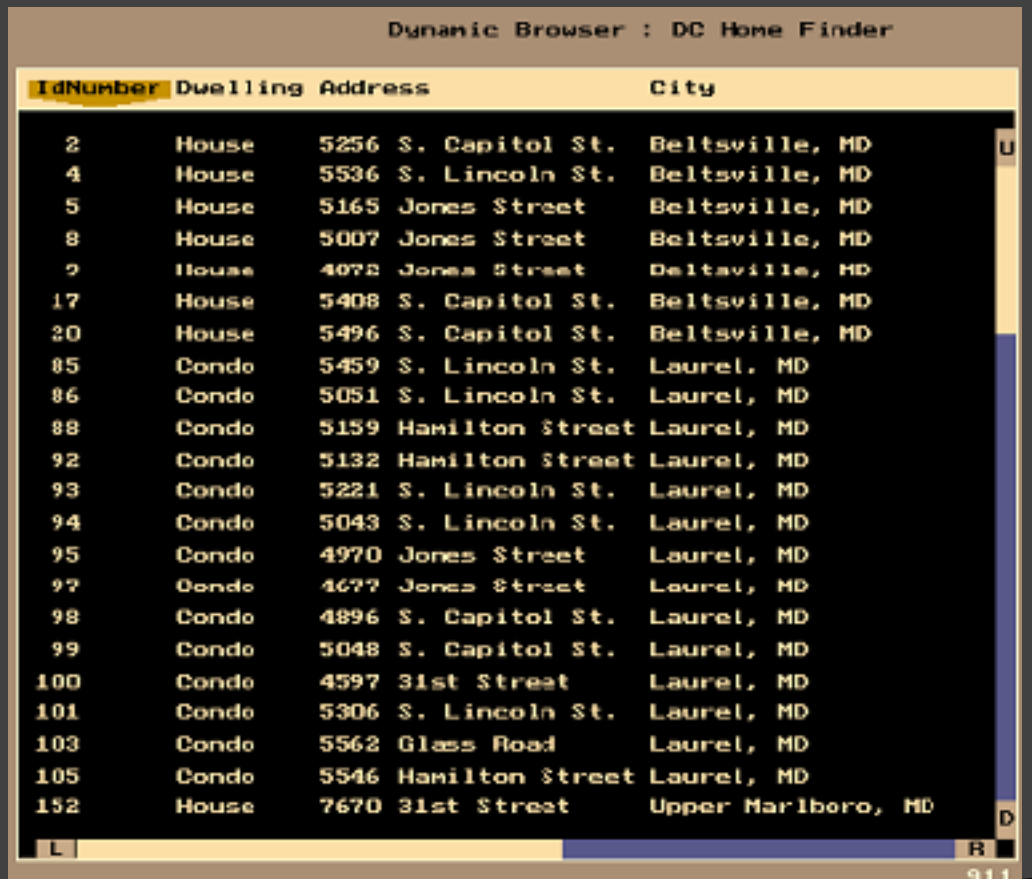
Dynamic Queries

Query & Results

SELECT house FROM seattle_homes

WHERE price < 1,000,000 AND bedrooms > 2

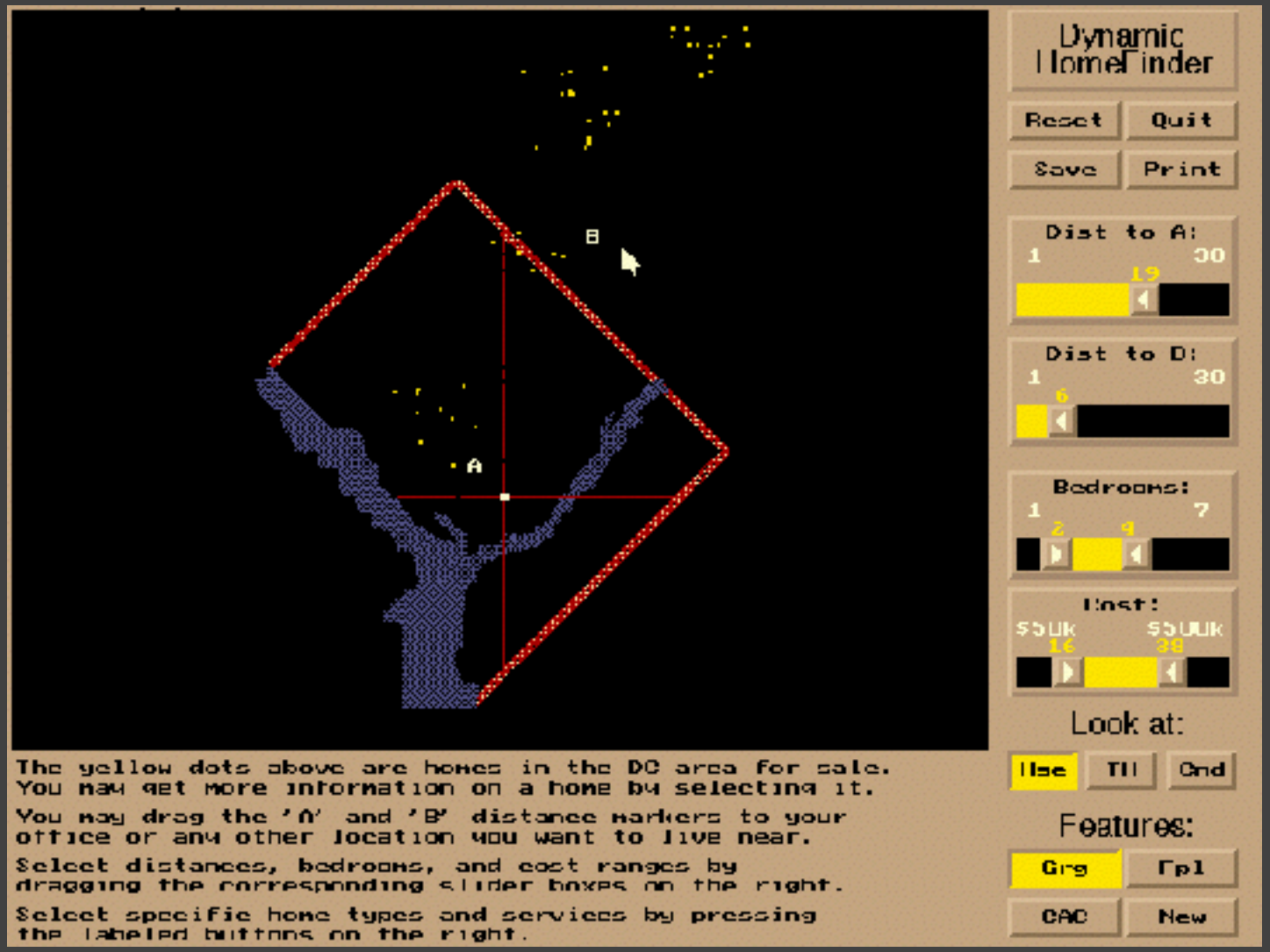
ORDER BY price



Issues with Textual Queries

1. For programmers
2. Rigid syntax
3. Only shows exact matches
4. Too few or too many hits
5. No hint on how to reformulate the query
6. Slow question-answer loop
7. Results returned as table

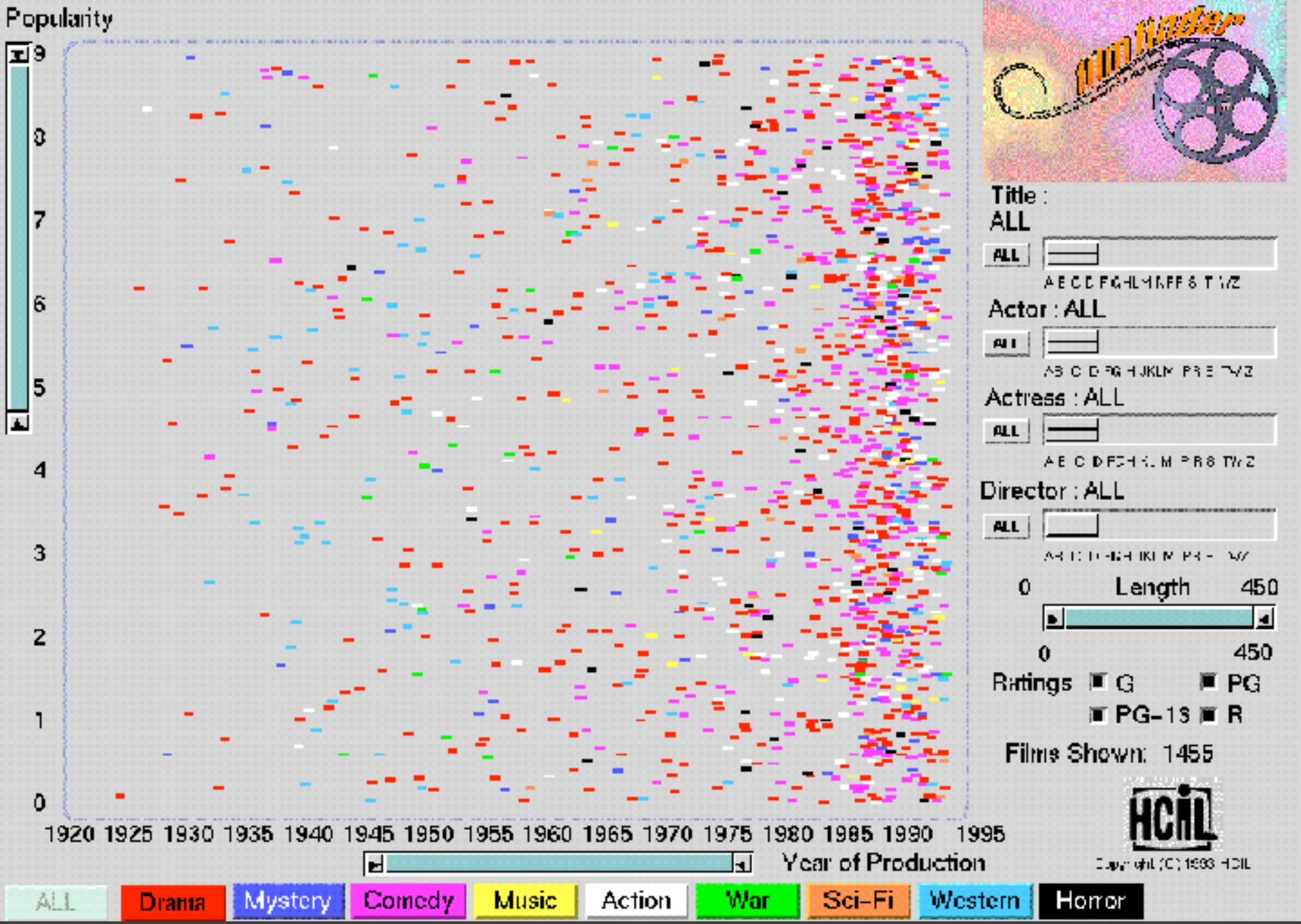
HomeFinder



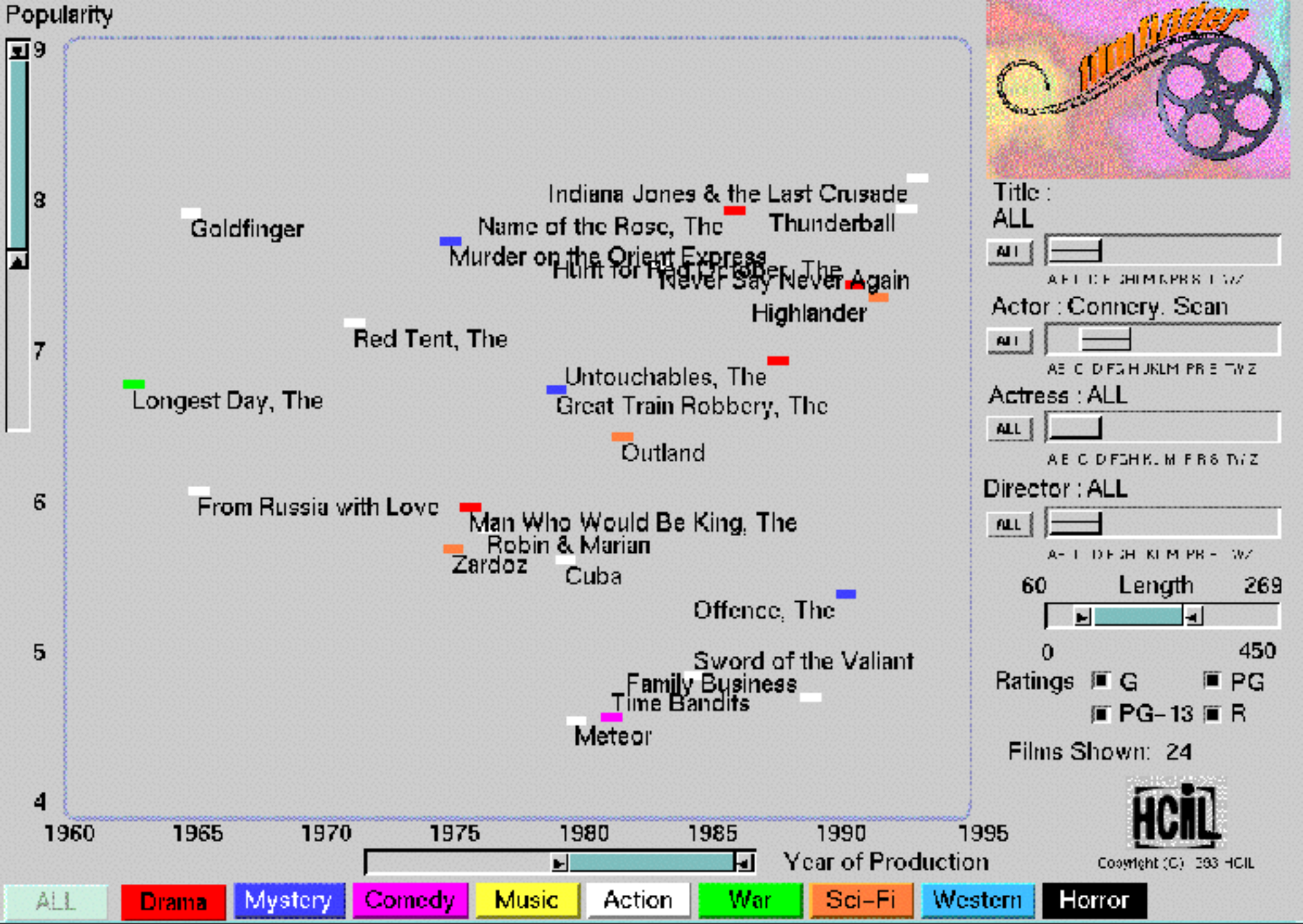
[Williamson and Shneiderman 92]

Direct Manipulation

1. Visual representation of objects and actions
2. Rapid, incremental and reversible actions
3. Selection by pointing (not typing)
4. Immediate and continuous display of results

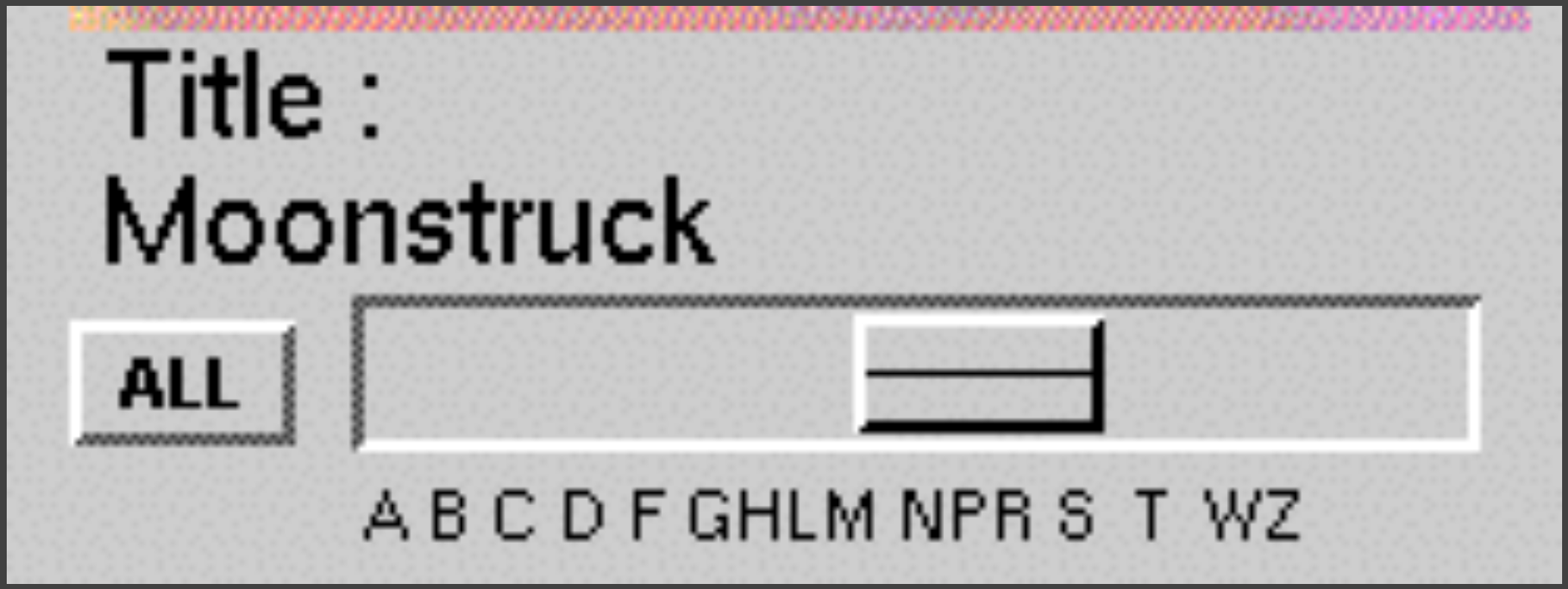


[Ahlberg and Shneiderman 94]



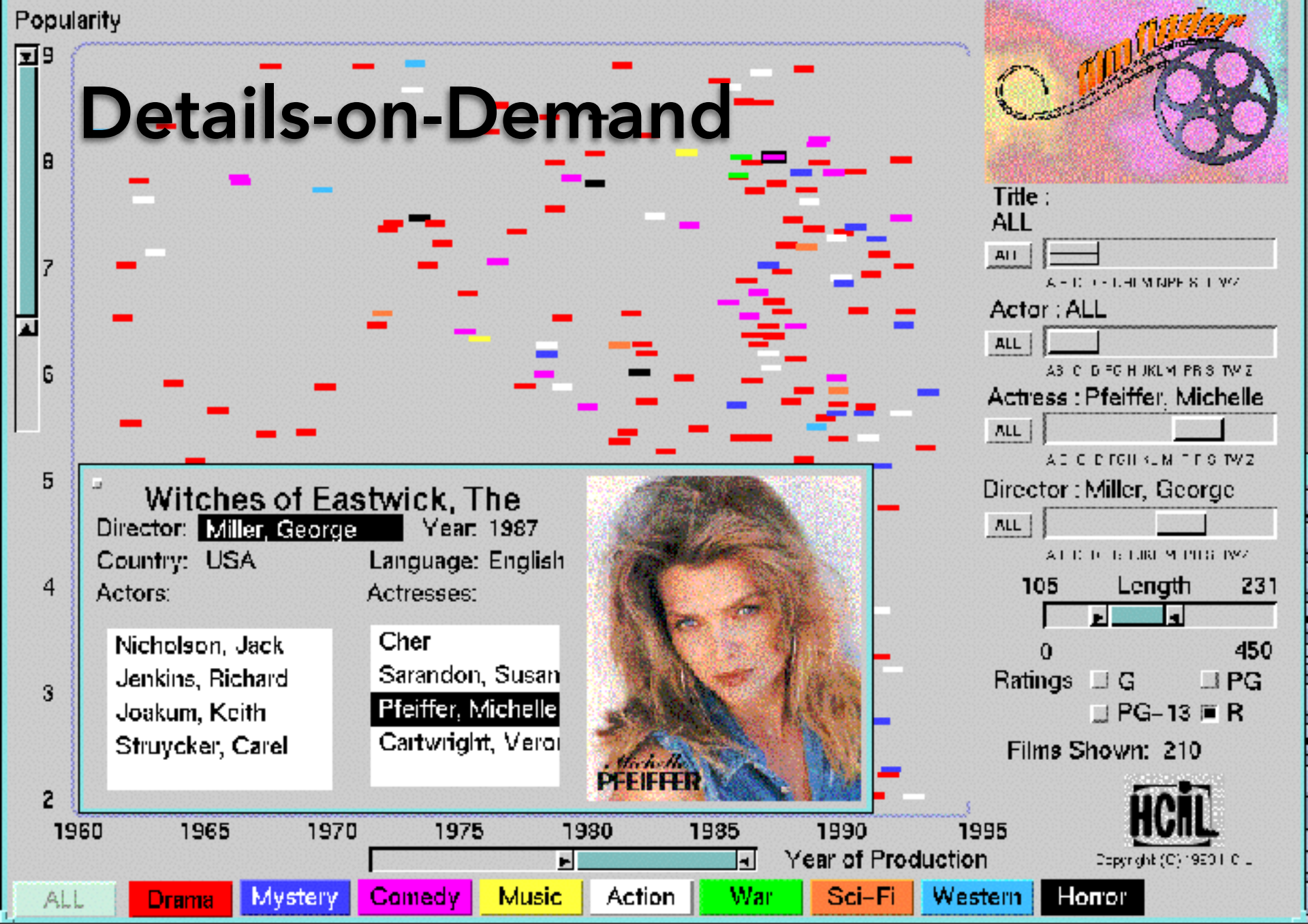
[Ahlberg and Shneiderman 94]

Alphaslider (?)



[Ahlberg and Shneiderman 94]

Details-on-Demand

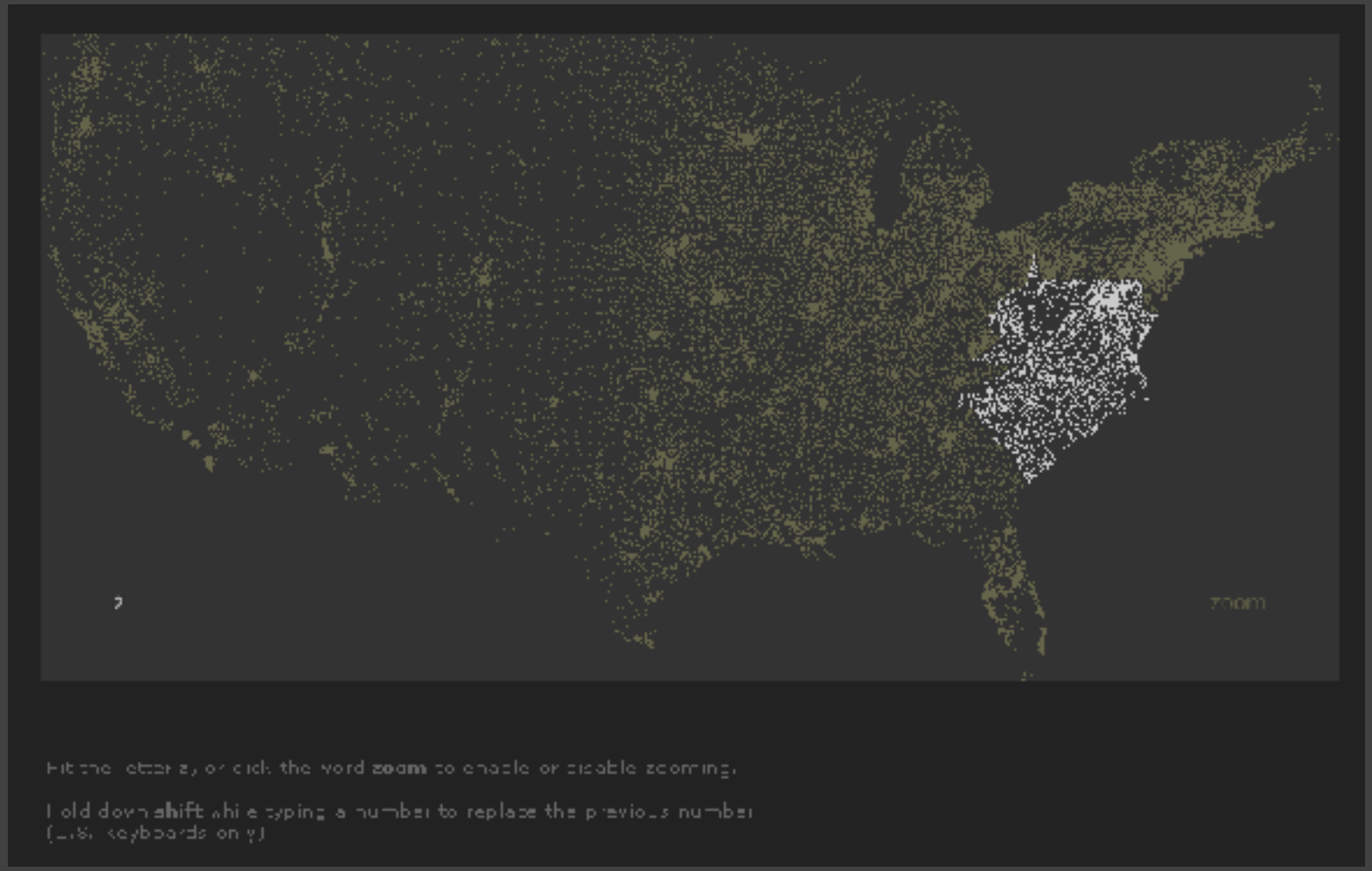


[Ahlberg and Shneiderman 94]

Attribute Explorer [Spence & Tweedie 96]

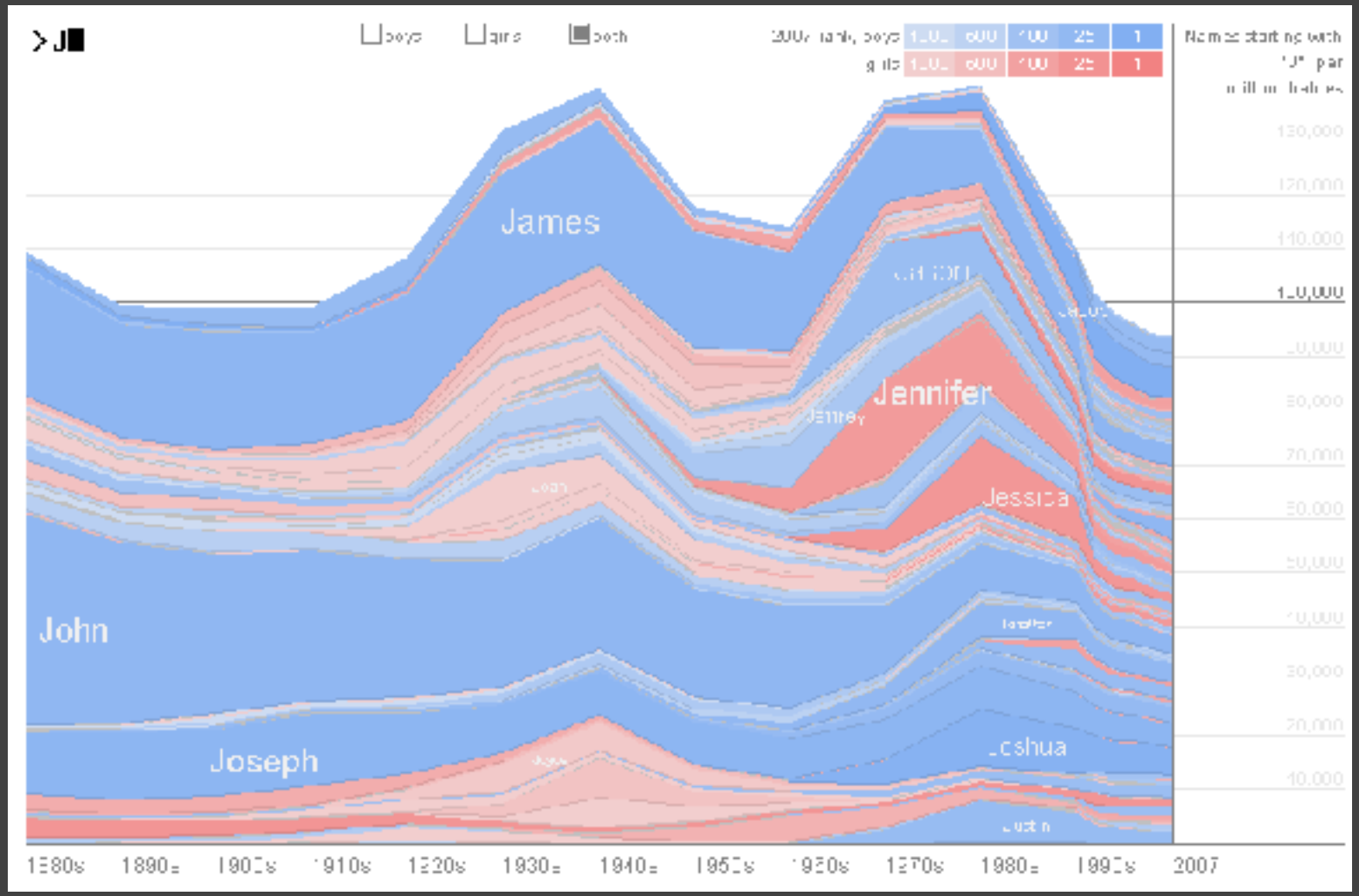
- The Attribute Explorer

Zipdecode [Fry 04]



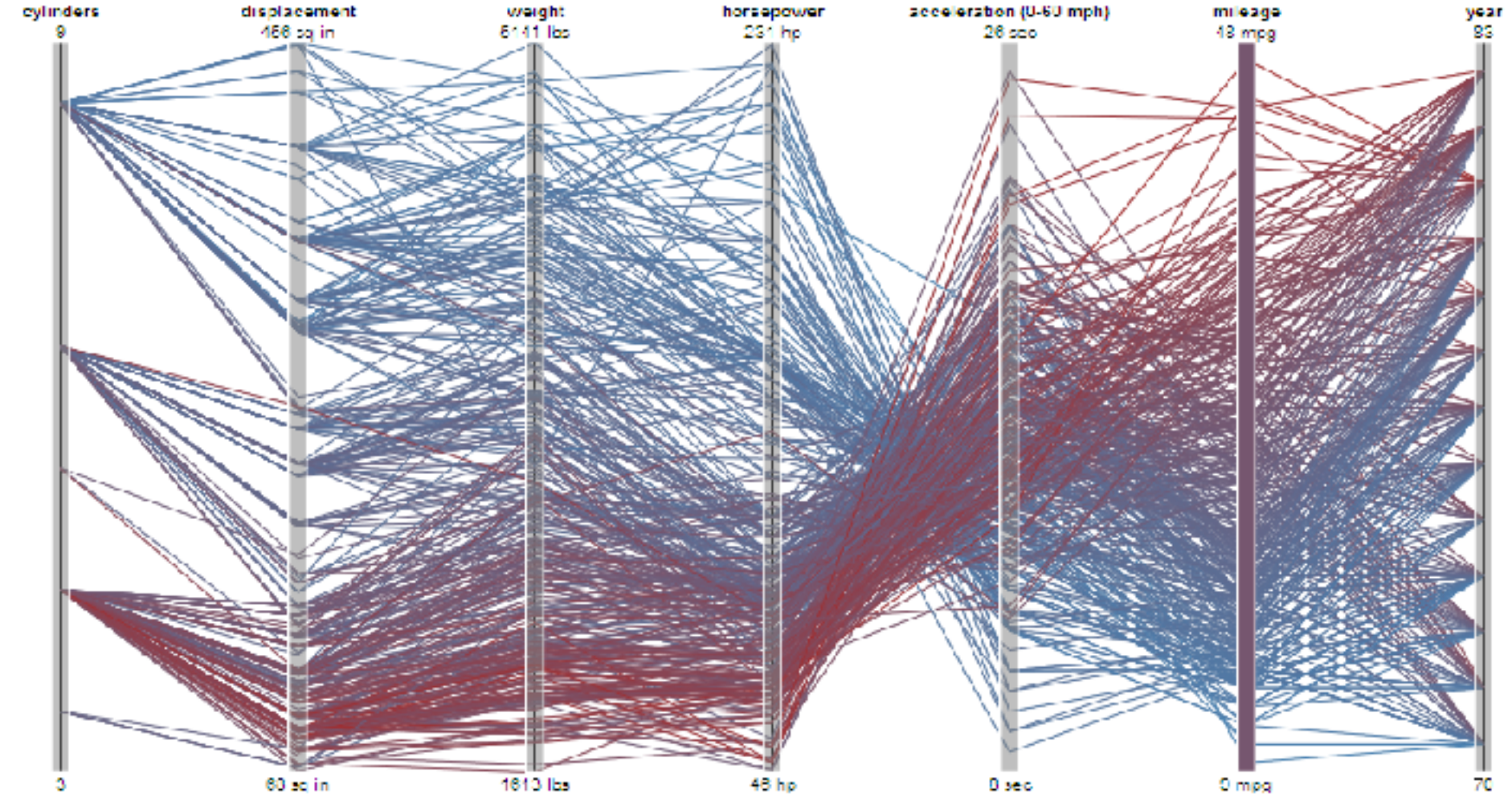
http://benfry.com/zipdecode/

NameVoyager [Wattenberg 06]

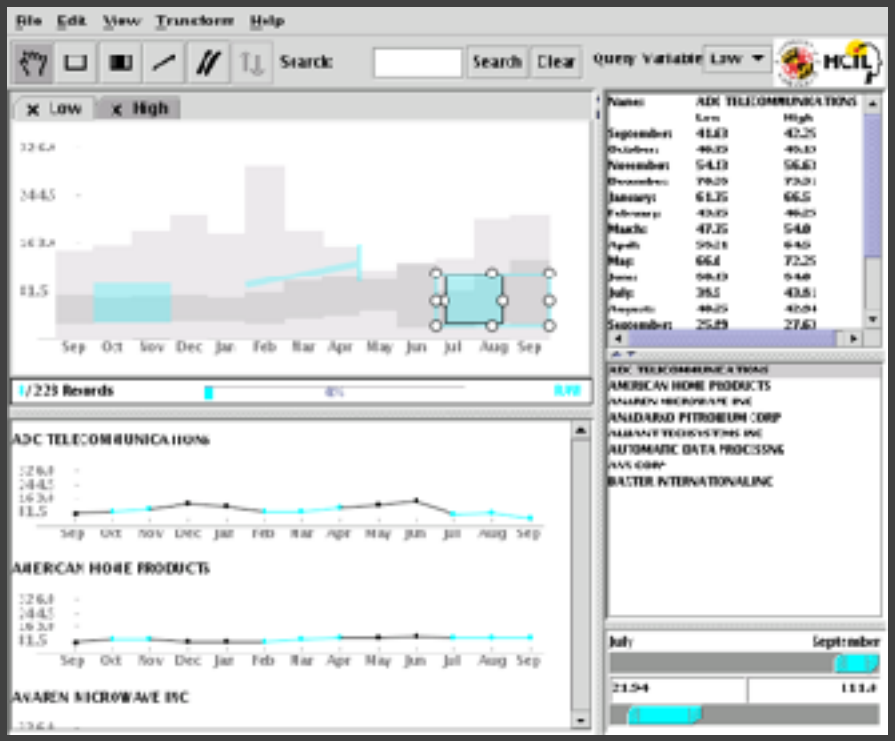


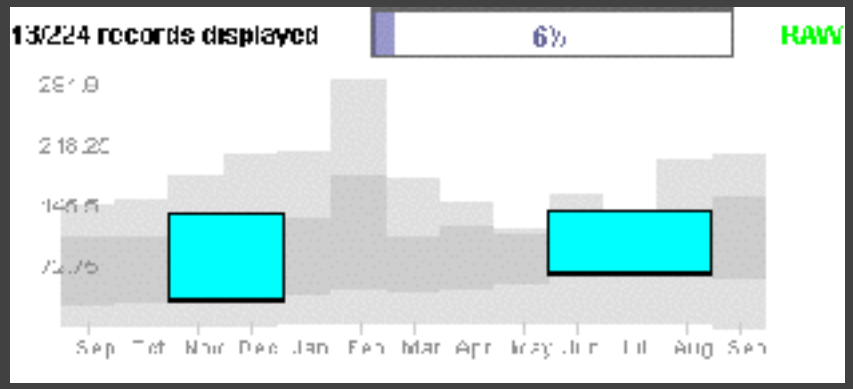
http://www.babynamewizard.com/voyager

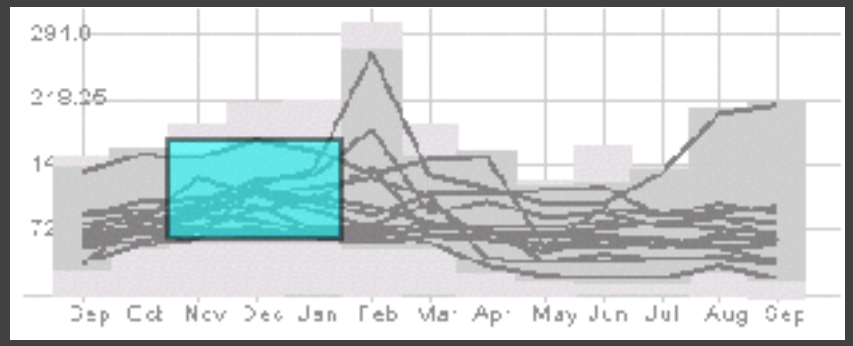
Parallel Coordinates [Inselberg]



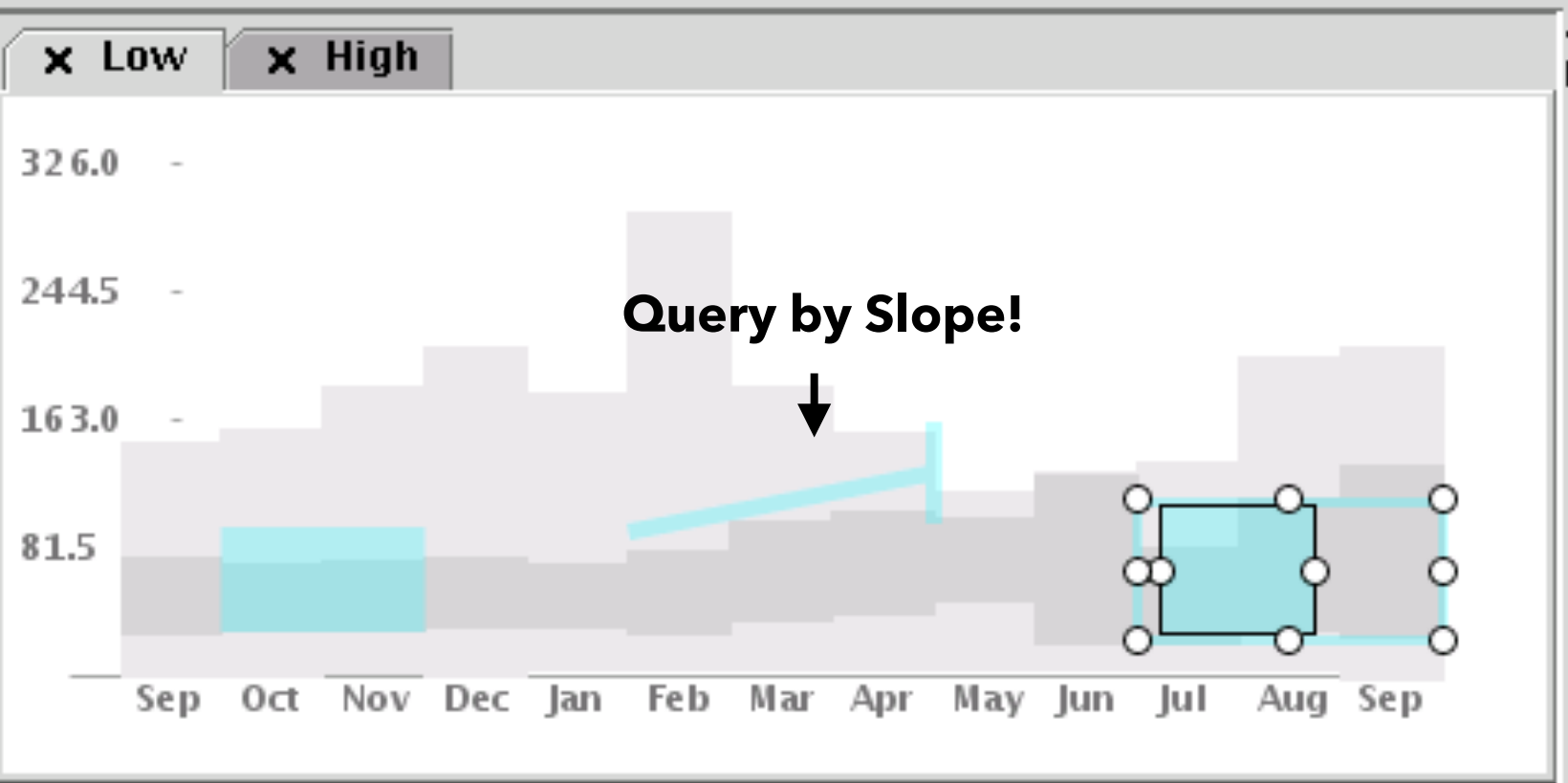
TimeSearcher [Hocheiser 02]

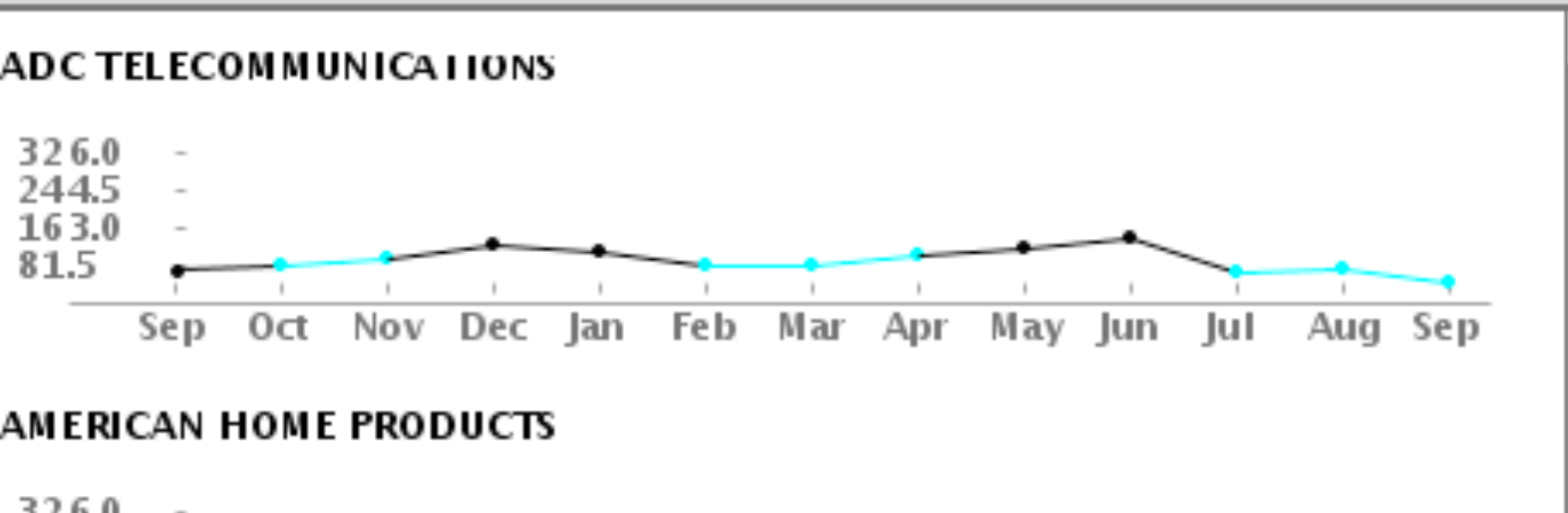






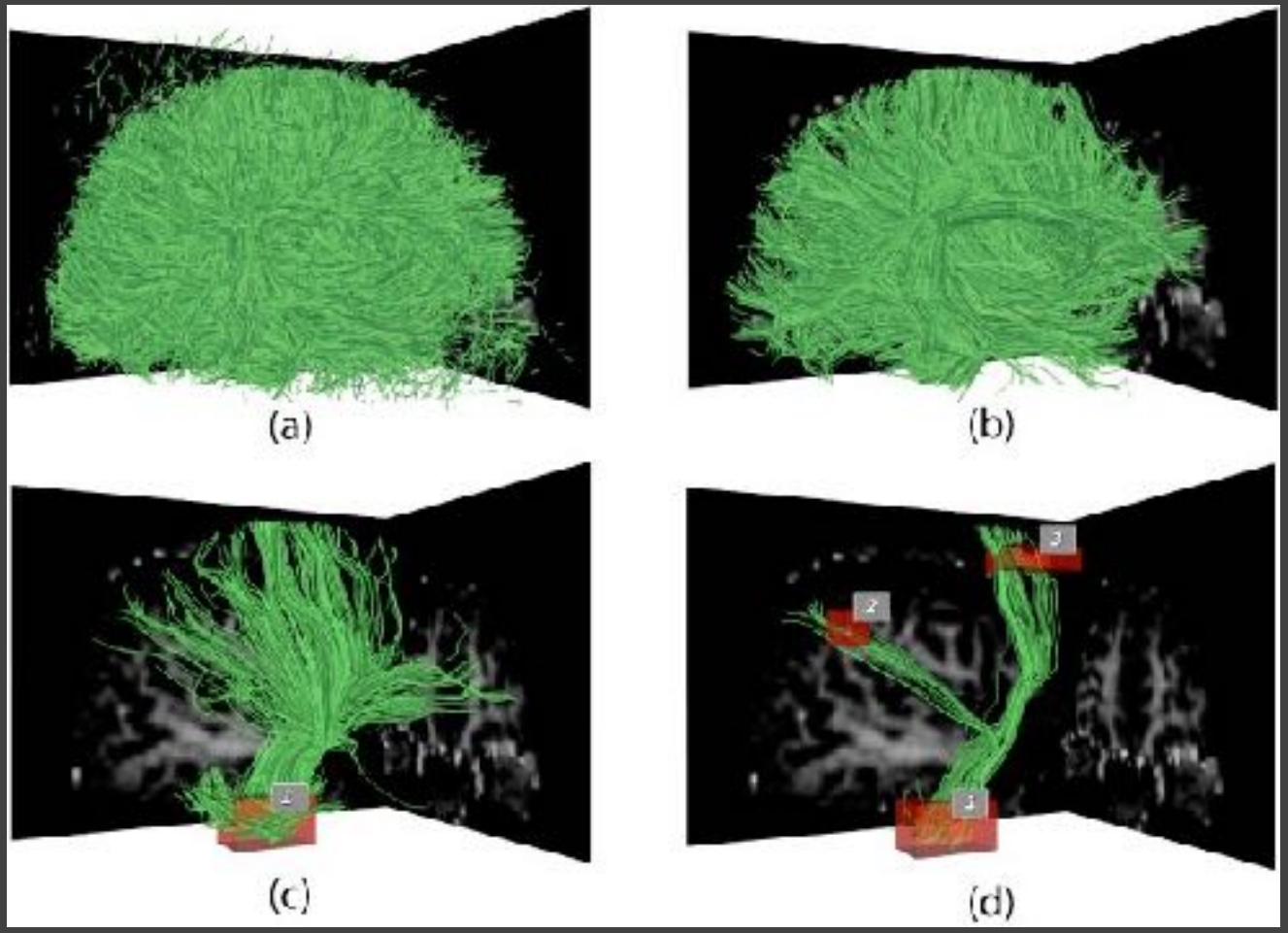
Builds on Wattenberg's [2001] idea for sketch-based queries of time-series data.


Low
High
326.0
244.5
163.0
81.5
Query by Slope!
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
8/223 Records
4%
RAW

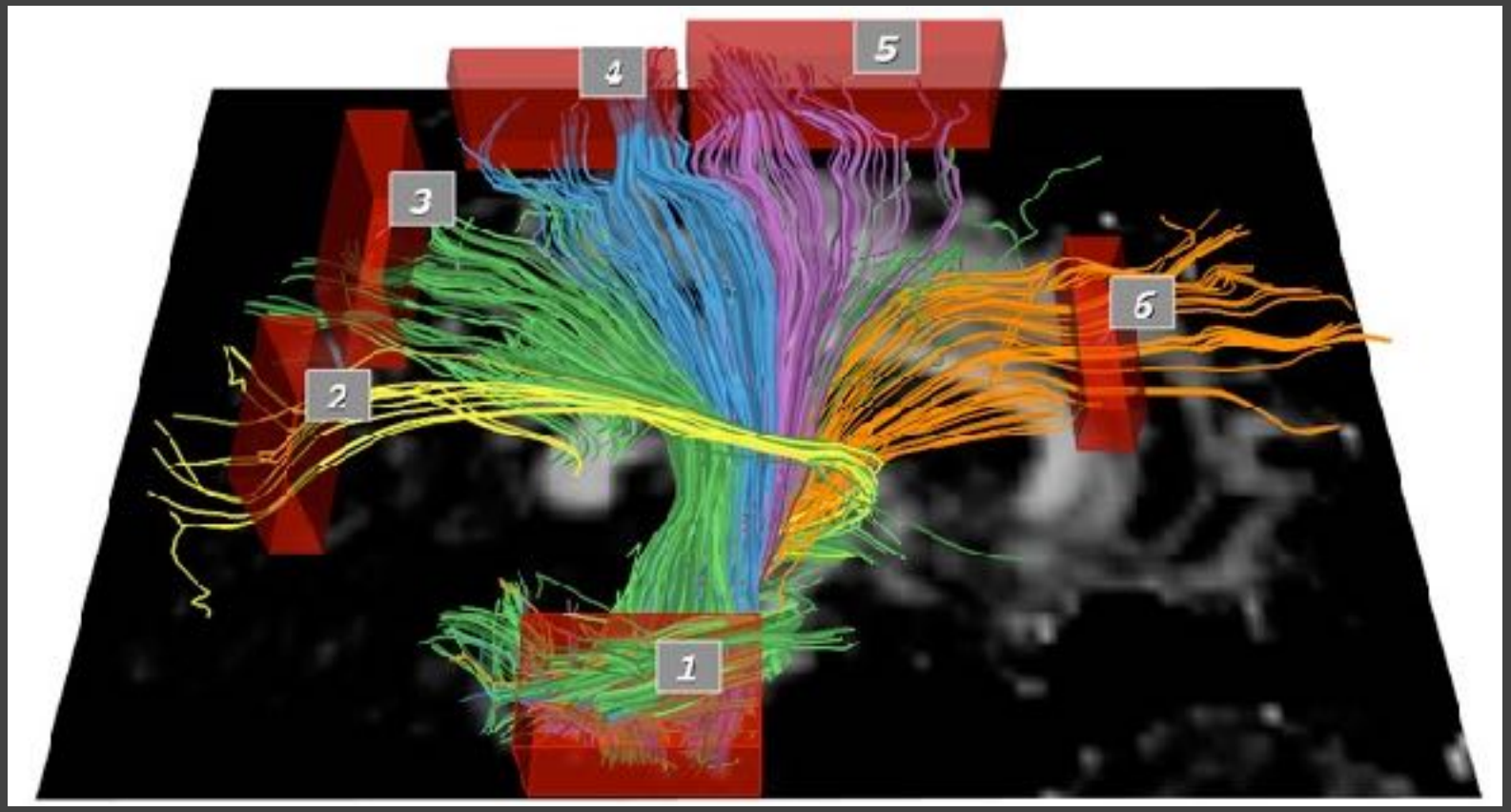

ADC TELECOMMUNICATIONS
326.0
244.5
163.0
81.5
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
AMERICAN HOME PRODUCTS


Name:
September:
October:
November:
December:
January:
February:
March:
April:
May:
June:
July:
August:
September:
ADC TELECOMM
AMERICAN HOM
ANAREN MICRO
ANADARKO PE
ALLIANT TECHS
AUTOMATIC DA
AVX CORP
BAXTER INTERN

3D Dynamic Queries [Akers 04]



3D Dynamic Queries [Akers 04]



Pros & Cons

Pros

Controls useful for both novices and experts

Quick way to explore data

Pros & Cons

Pros

Controls useful for both novices and experts

Quick way to explore data

Cons

Simple queries

Lots of controls

Amount of data shown limited by screen space

Who would use these kinds of tools?

Summary

Most visualizations are interactive
Even passive media elicit interactions

Good visualizations are task dependent
Pick the right interaction technique
Consider the semantics of the data domain

Fundamental interaction techniques
Selection / Annotation, Sorting, Navigation,
Brushing & Linking, Dynamic Queries

Administrivia

Tutorials

Introduction to D3.js

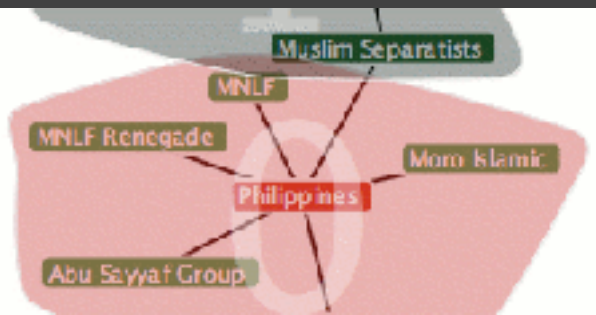
Thursday, Apr. 19 - 4:30-6:30pm - Sieg 134

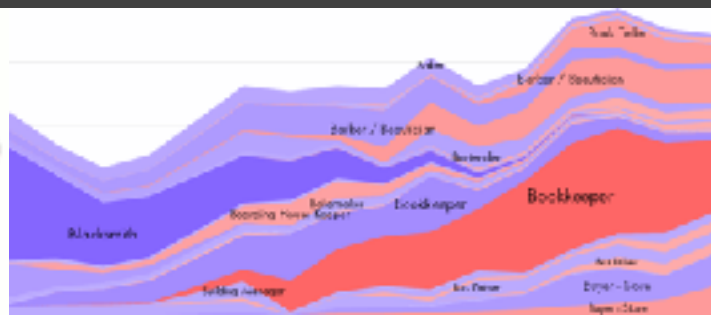
A3: Interactive Prototype

Create an interactive visualization. Choose a driving question for a dataset and develop an appropriate visualization + interaction techniques, then deploy your visualization on the web.

Due by *11:59pm* on **Monday, April 30**.

Work in project teams of 3-4 people.

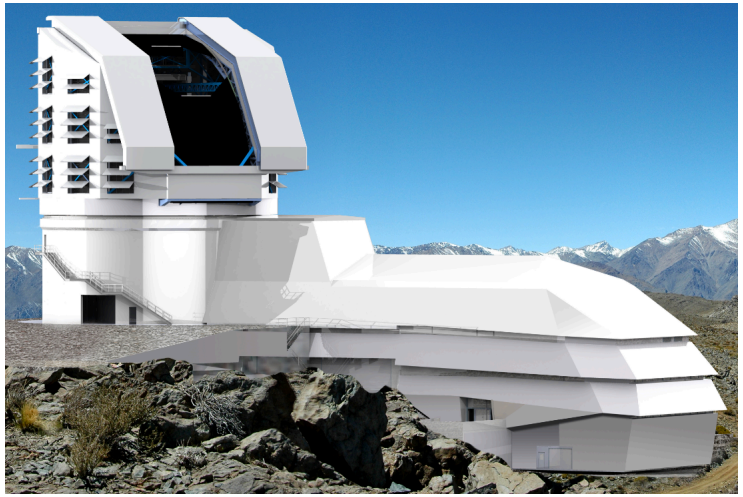


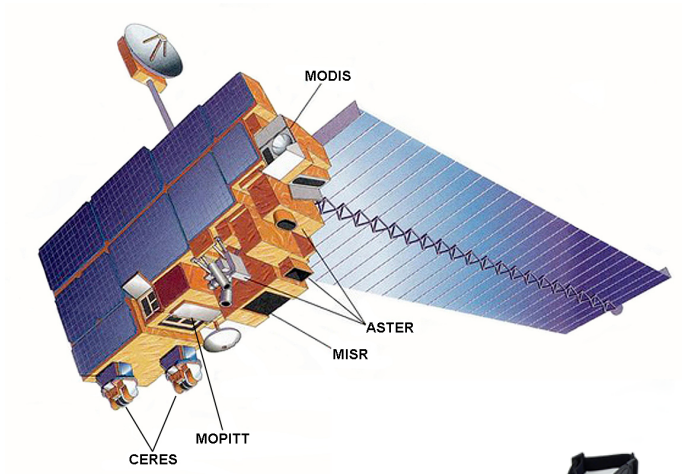


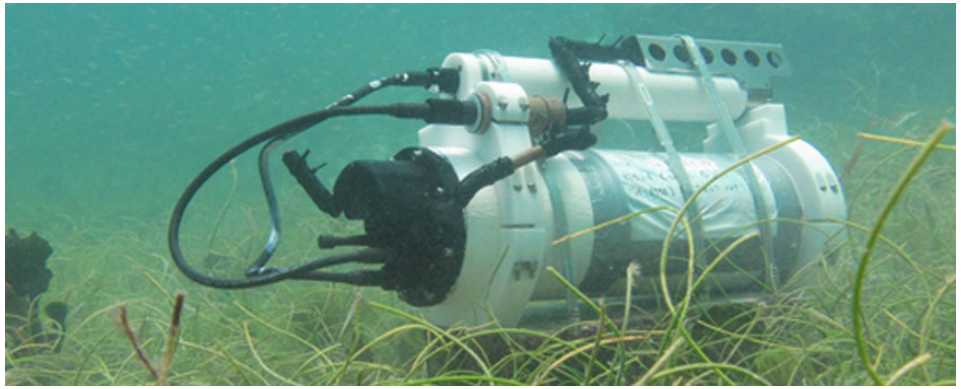
Behavior-Driven Optimizations for Big Data Exploration

Leilani Battle

More sciences are becoming data driven



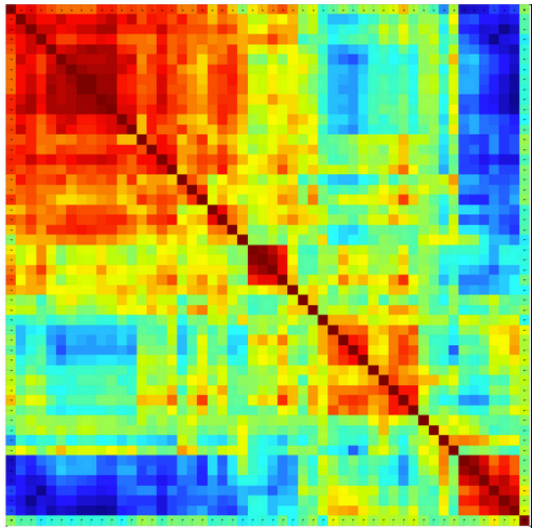




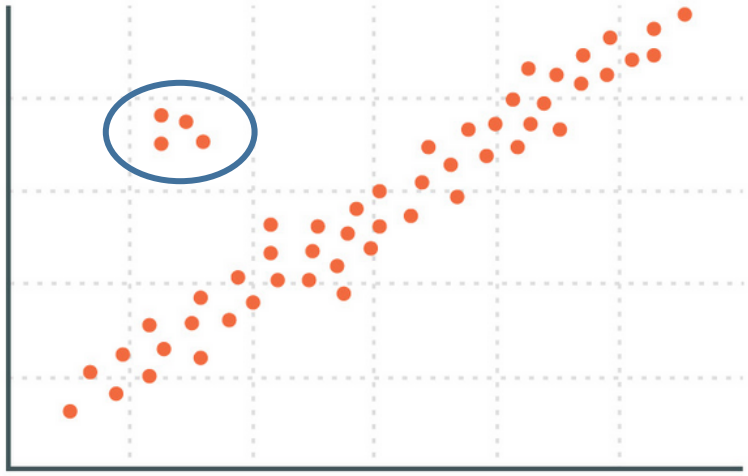
Scientists need ways to explore large datasets efficiently

- Interactivity is critical
- Big datasets don't fit on laptops
- Need scalability *and* interactive performance

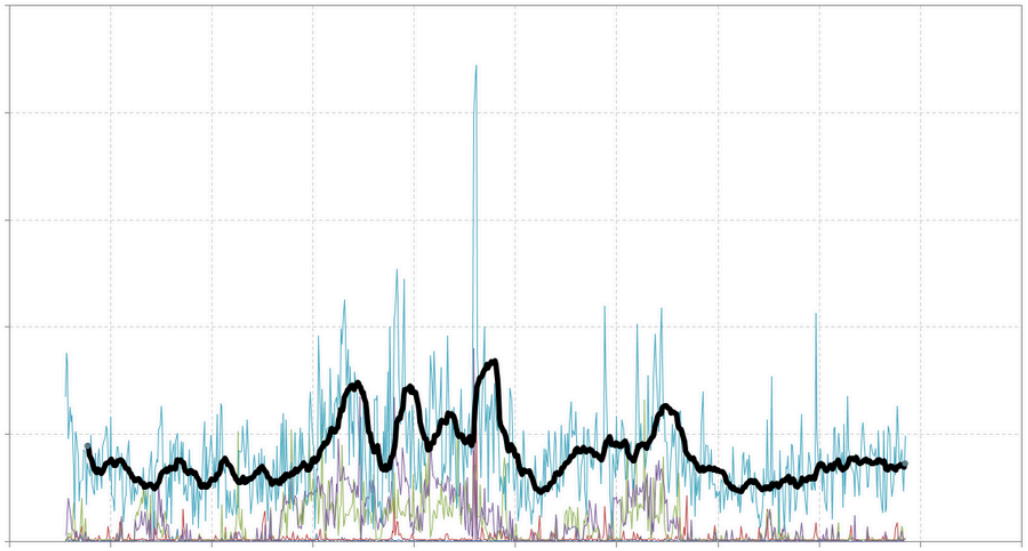
Extract patterns



Identify anomalies



Debug workflows



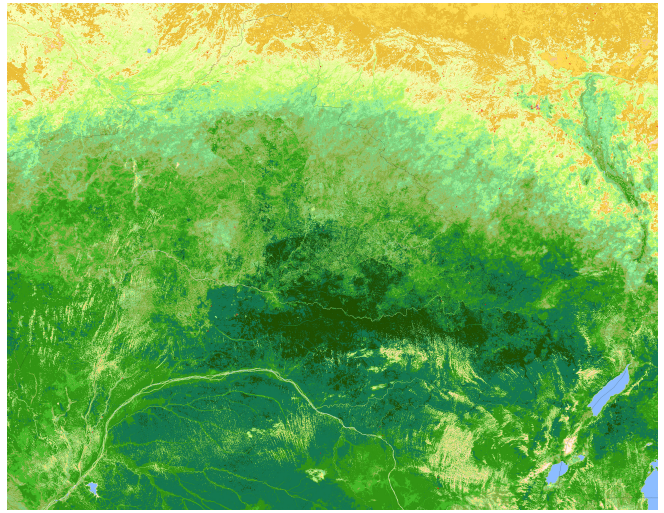
Example use case: satellite sensor data from NASA MODIS

longitude_e4	latitude_e4	start_time	b6	b26rad	b1	b4	land_sea_mask	b2
-1621001	341579	201412142045	0.262546	1.93486	0.302514	0.306774	7	0.331859
-1620992	341760	201412142045	0.262305	1.81157	0.301294	0.305743	7	0.328281
-1620982	341941	201412142045	0.268503	1.89693	0.302991	0.305485	7	0.327451
-1620974	342122	201412142045	0.266816	1.9728	0.30649	0.307676	7	0.329815
-1620965	342303	201412142045	0.269743	2.35849	0.312587	0.311543	7	0.337225
-1620956	342485	201412142045	0.256416	2.67147	0.309618	0.309395	7	0.333456
-1620948	342666	201412142045	0.249322	3.02871	0.30368	0.305313	7	0.326109
-1620939	342847	20					7	0.320328
-1620931	343028	20					7	0.317358
-1620923	343209	20					7	0.307967
-1620877	342461	20					7	0.338566
-1620868	342642	20					7	0.331507
-1620859	342823	20					7	0.32068
-1620850	343004	20					7	0.317454
-1620841	343185	20					7	0.303719
-1620833	343366	20					7	0.29369
-1620824	343547	20					7	0.295415
-1620816	343729	20					7	0.298098
-1620808	343910	20					7	0.309277
-1620800	344091	20					7	0.305221
-1620780	343348	201412142045	0.228006	3.02871	0.276111	0.280479	7	0.298769
-1620771	343529	201412142045	0.229487	2.64618	0.27696	0.281424	7	0.298162
-1620762	343710	201412142045	0.227902	2.74418	0.279398	0.284088	7	0.297427
-1620753	343891	201412142045	0.229831	2.64618	0.288358	0.291994	7	0.306211
-1620744	344072	201412142045	0.227214	2.65566	0.283375	0.287697	7	0.299503
-1620736	344253	201412142045	0.231553	2.60824	0.295621	0.297365	7	0.315186
-1620727	344435	201412142045	0.232035	2.59876	0.293024	0.298095	7	0.312343
-1620719	344616	201412142045	0.23968	2.62405	0.295303	0.299513	7	0.316272
-1620711	344797	201412142045	0.243743	2.71889	0.290691	0.297794	7	0.313621

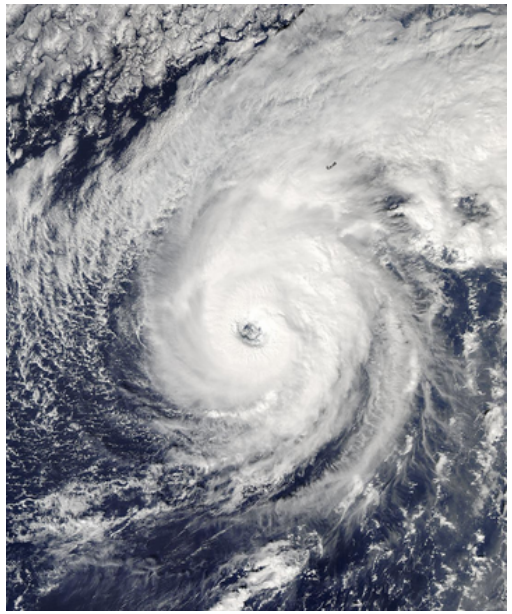
2 weeks = 10 TB!
Conserving disk space is important

Exploring NASA MODIS data

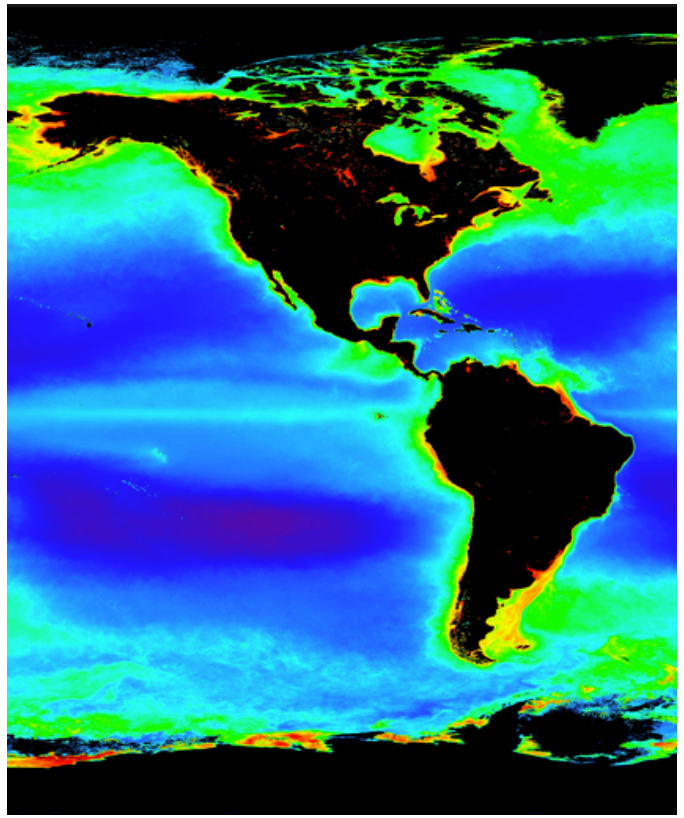
Measure vegetation density



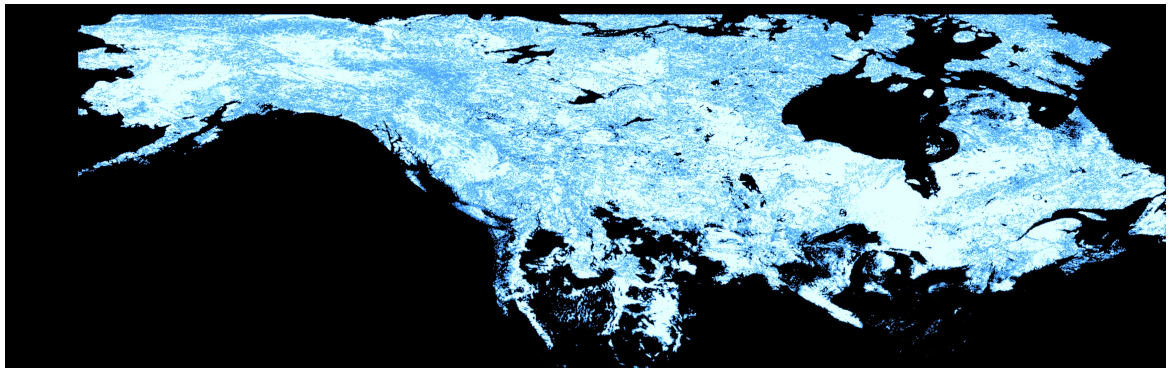
Track hurricanes



Track phytoplankton populations

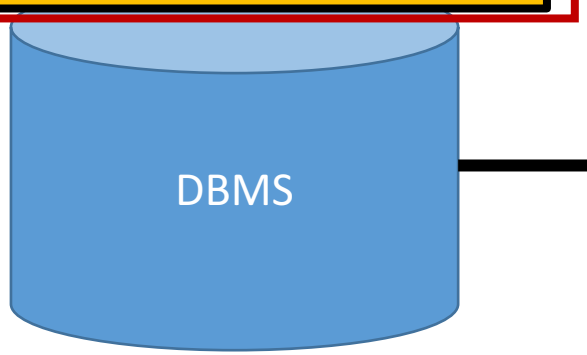


Measure snow melt



Supporting scalability and interactivity

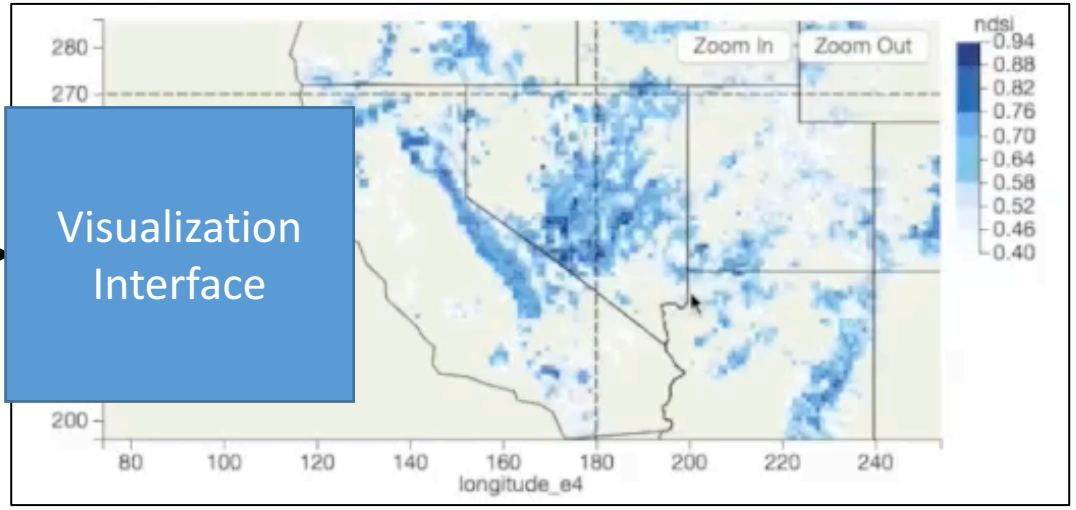

```
SELECT lat, lng,
   (b4-b6)/(b4+b6) as ndsi
FROM modis_data
WHERE ndsi >0.7
```



My Work

Optimization Layer

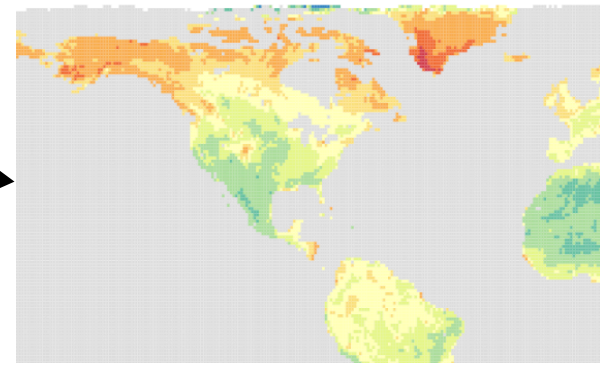
Visualization Interface



Exploratory browsing systems design

Exploratory Browsing

```
SELECT lat, lng, (b4-b6)/(b4+b6) as ndsi
FROM modis_data
WHERE ndsi >0.7
```



query

Client

Server

result

DBMS

PostgreSQL

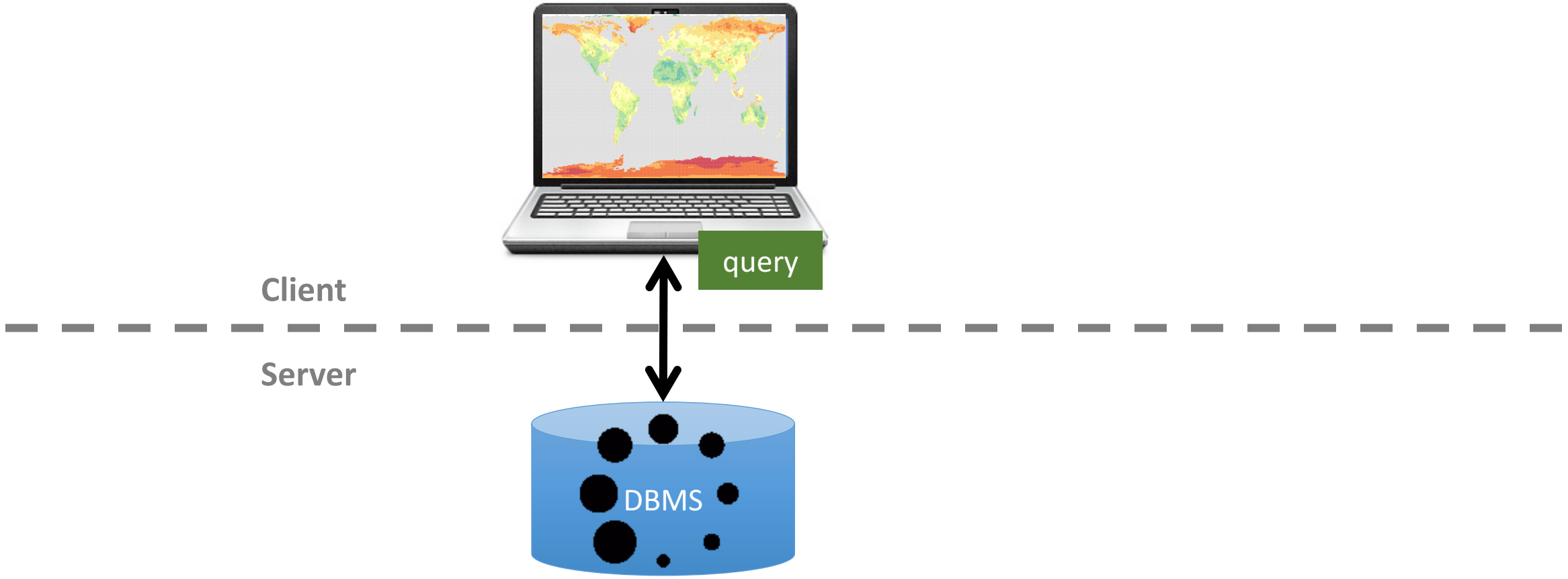
MySQL

VERTICA An HP Company

SciDB

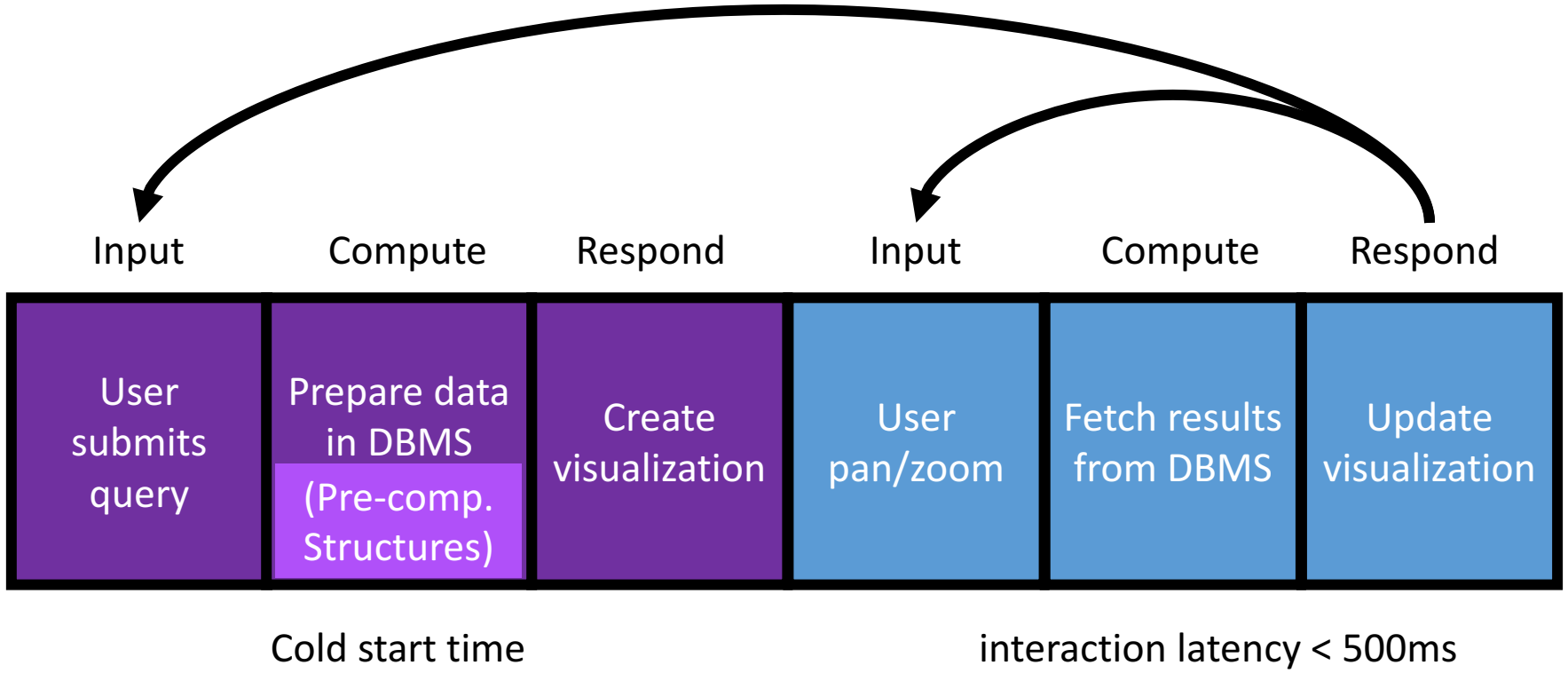
Challenge: Databases can be slow

Exploratory Browsing



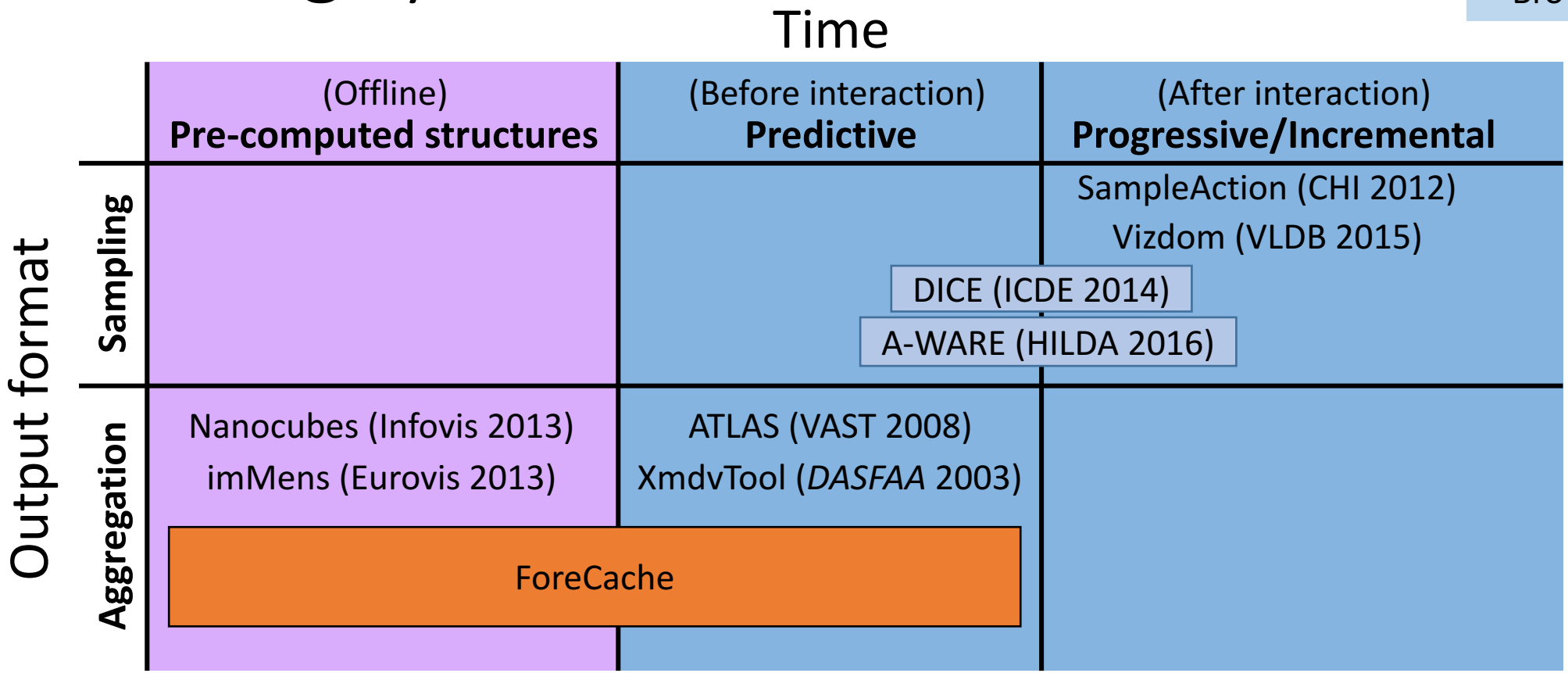
Target metric: responsiveness

Exploratory Browsing



Comparing with existing exploratory browsing systems

Exploratory Browsing



ForeCache[1]

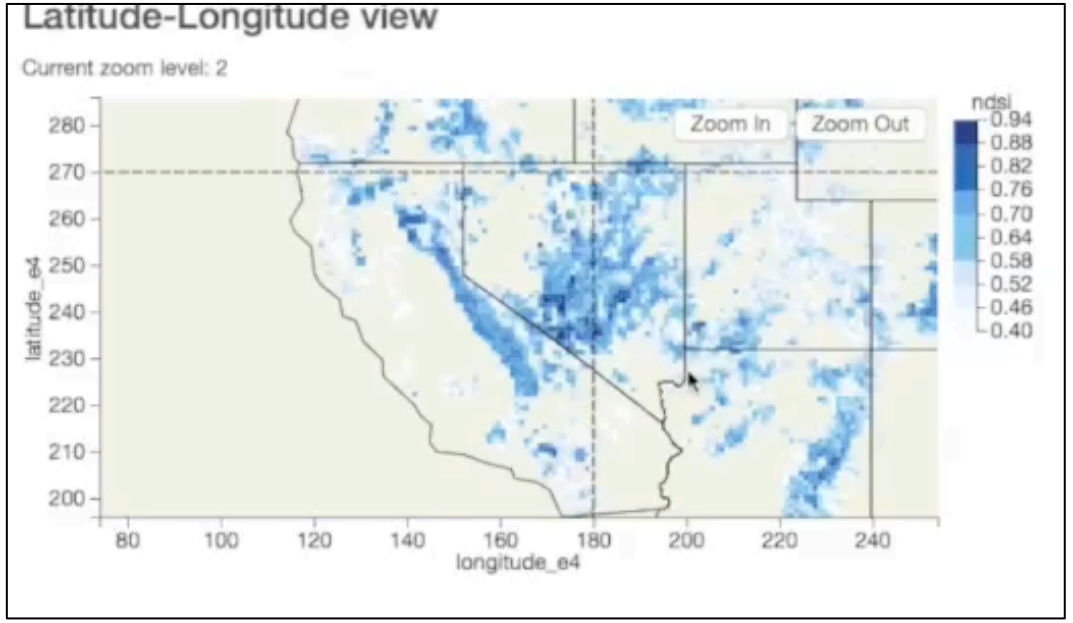
- Supports detail-on-demand (i.e., pan-zoom) browsing of arrays
- Predict user interactions, pre-fetch corresponding data
- Server-side middleware layer

[1]Leilani Battle, Remco Chang, and Michael Stonebraker. Dynamic Prefetching of Data Tiles for Interactive Visualization. *SIGMOD 2016*

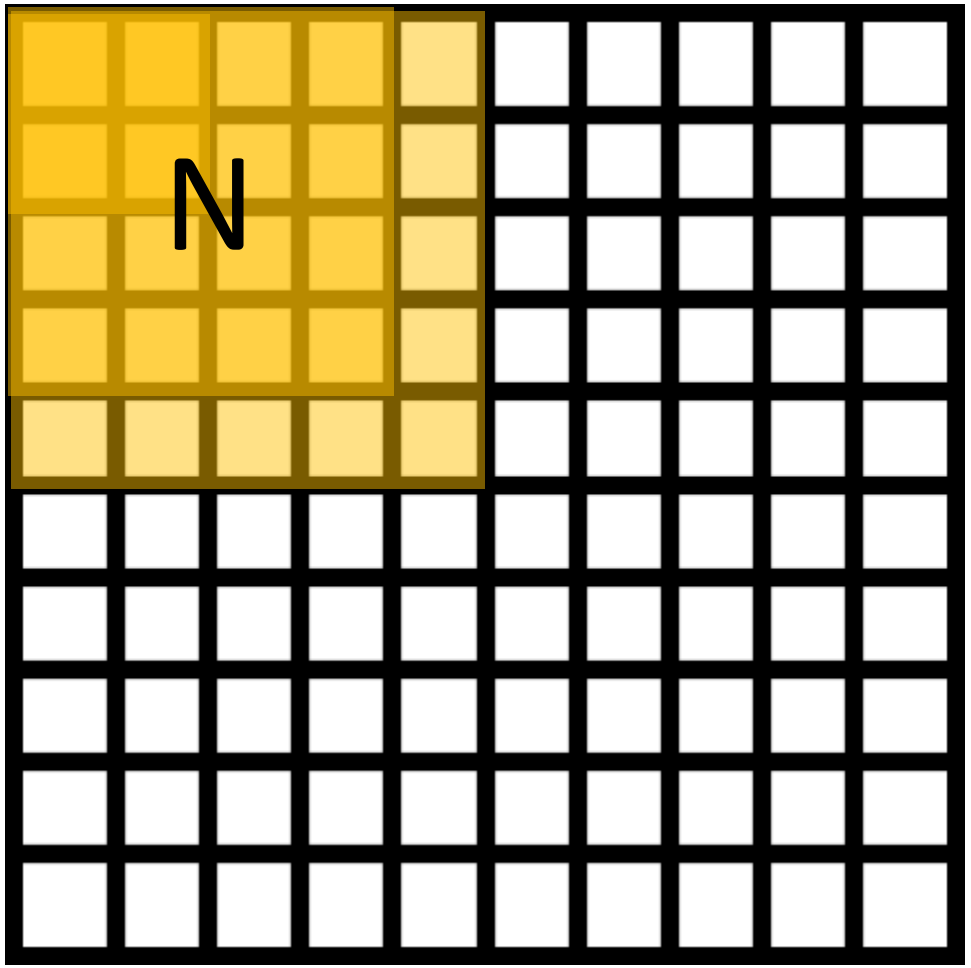
Example: exploring snow cover

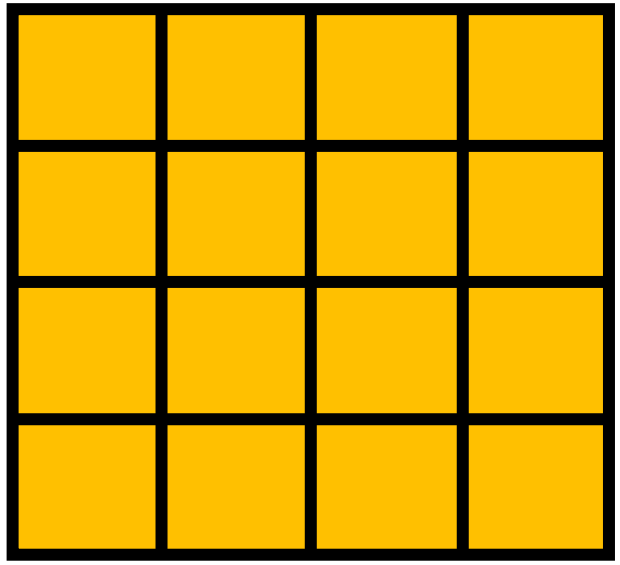
ForeCache

Exploring
Latitude/Longitude



Tile data model





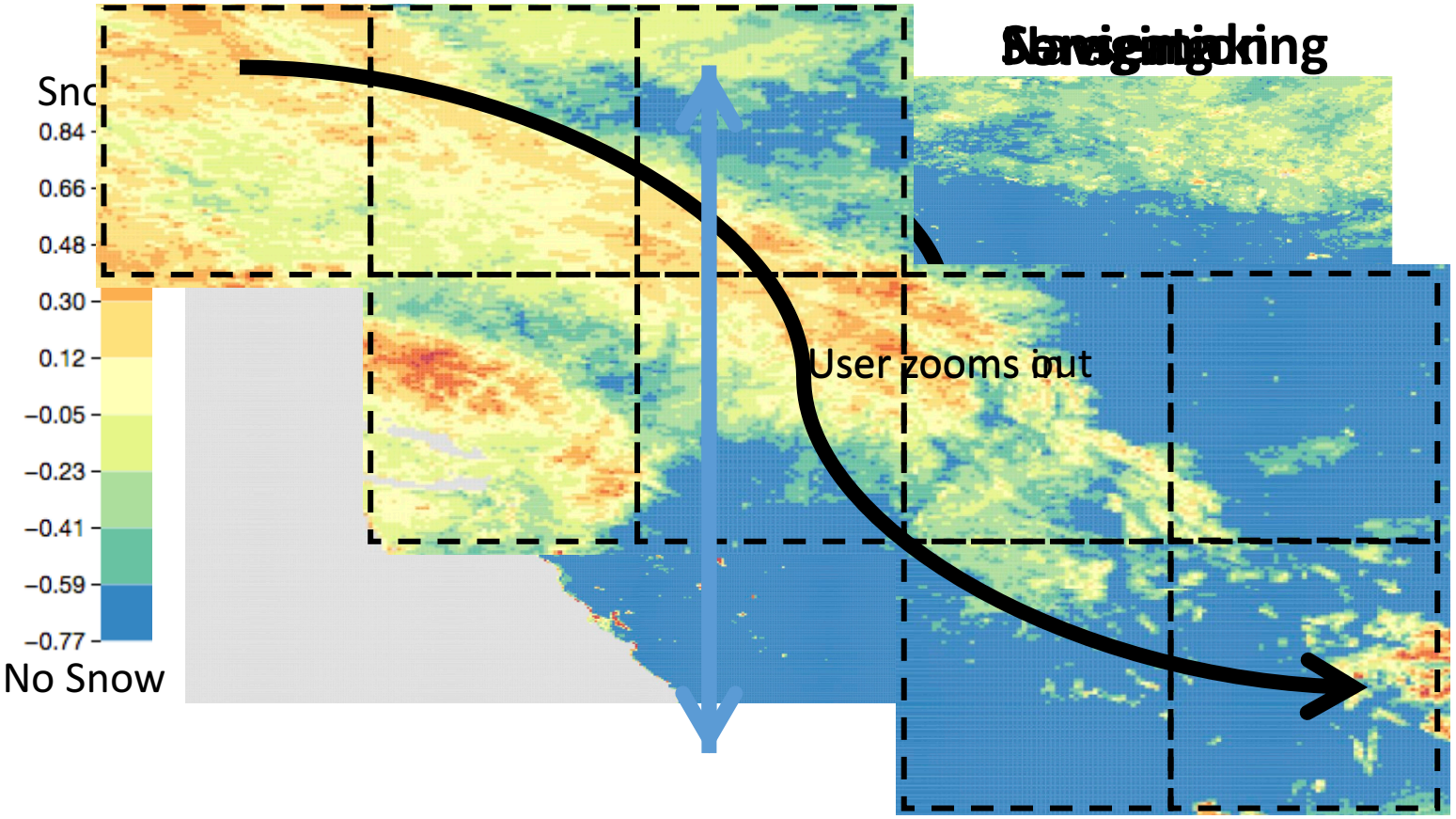
3-phase analysis model

ForeCache

- Foraging
- Sensemaking
- Navigation

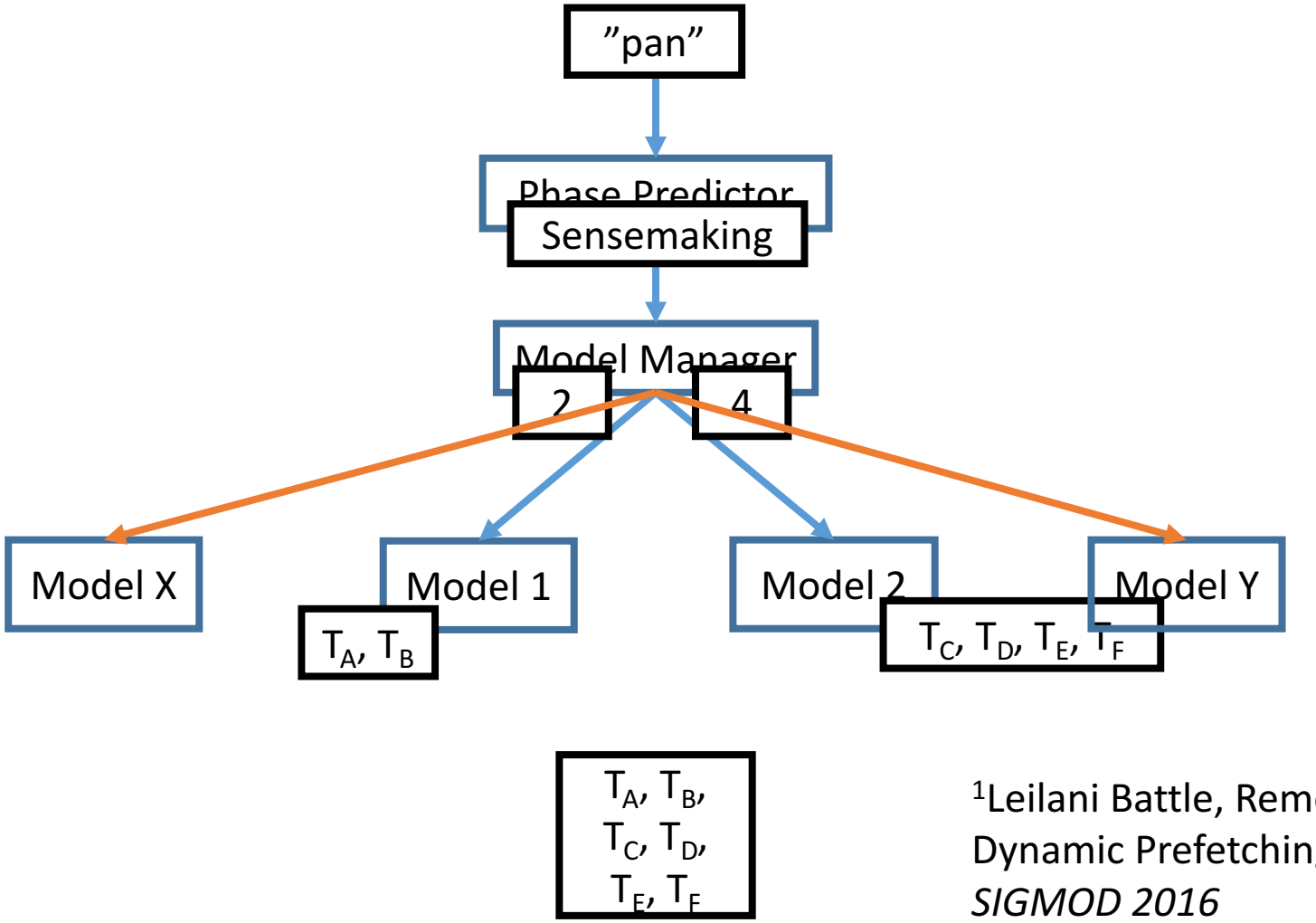
Example

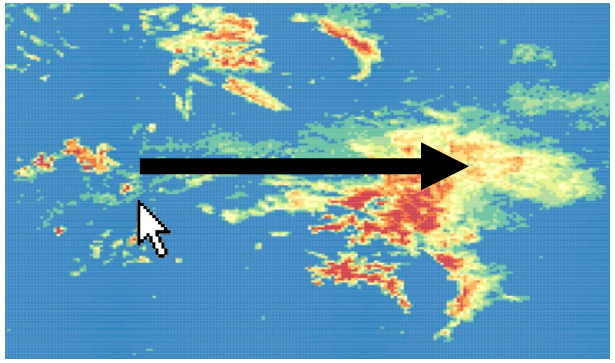
ForeCache



2D predictor[1]

ForeCache





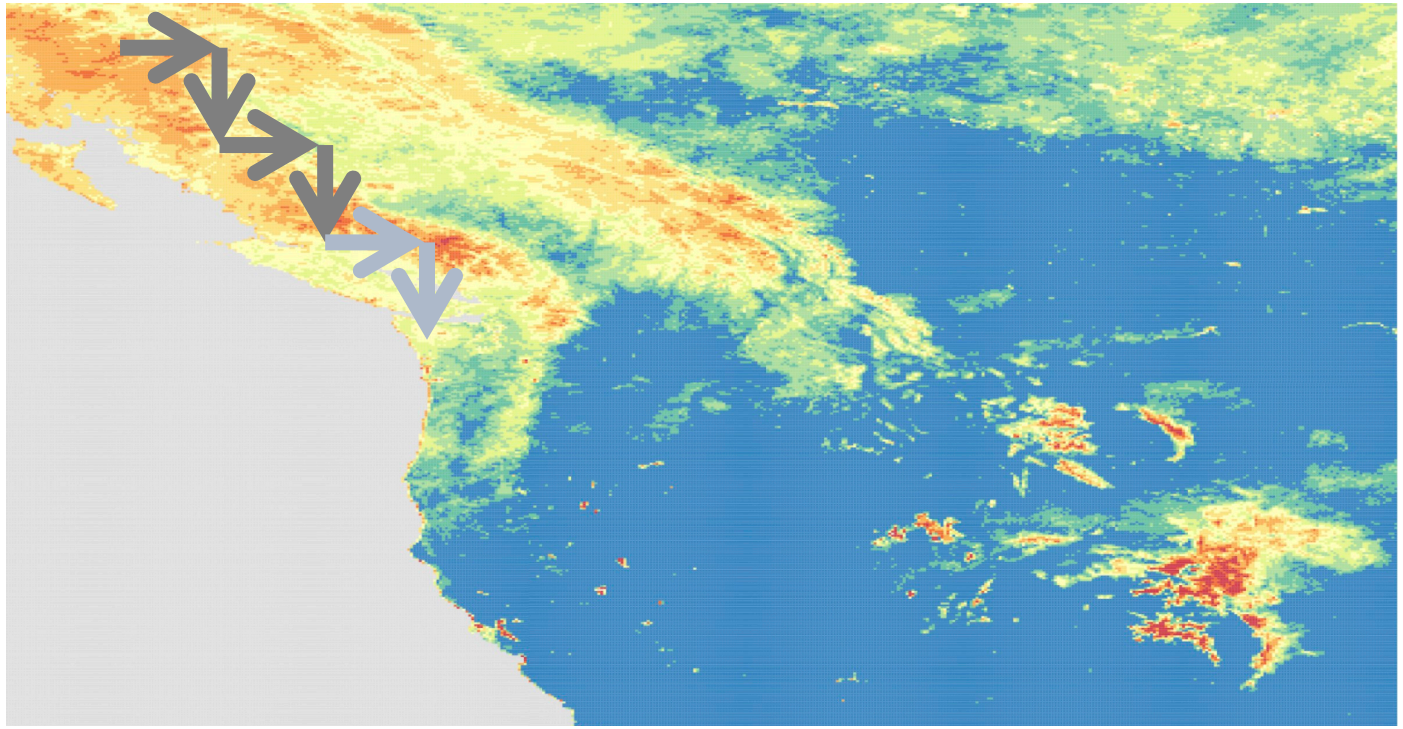
T_A, T_B, T_C, T_D, T_E, T_F

[1]Leilani Battle, Remco Chang, and Michael Stonebraker. Dynamic Prefetching of Data Tiles for Interactive Visualization. *SIGMOD 2016*

Action-based recommendation

ForeCache

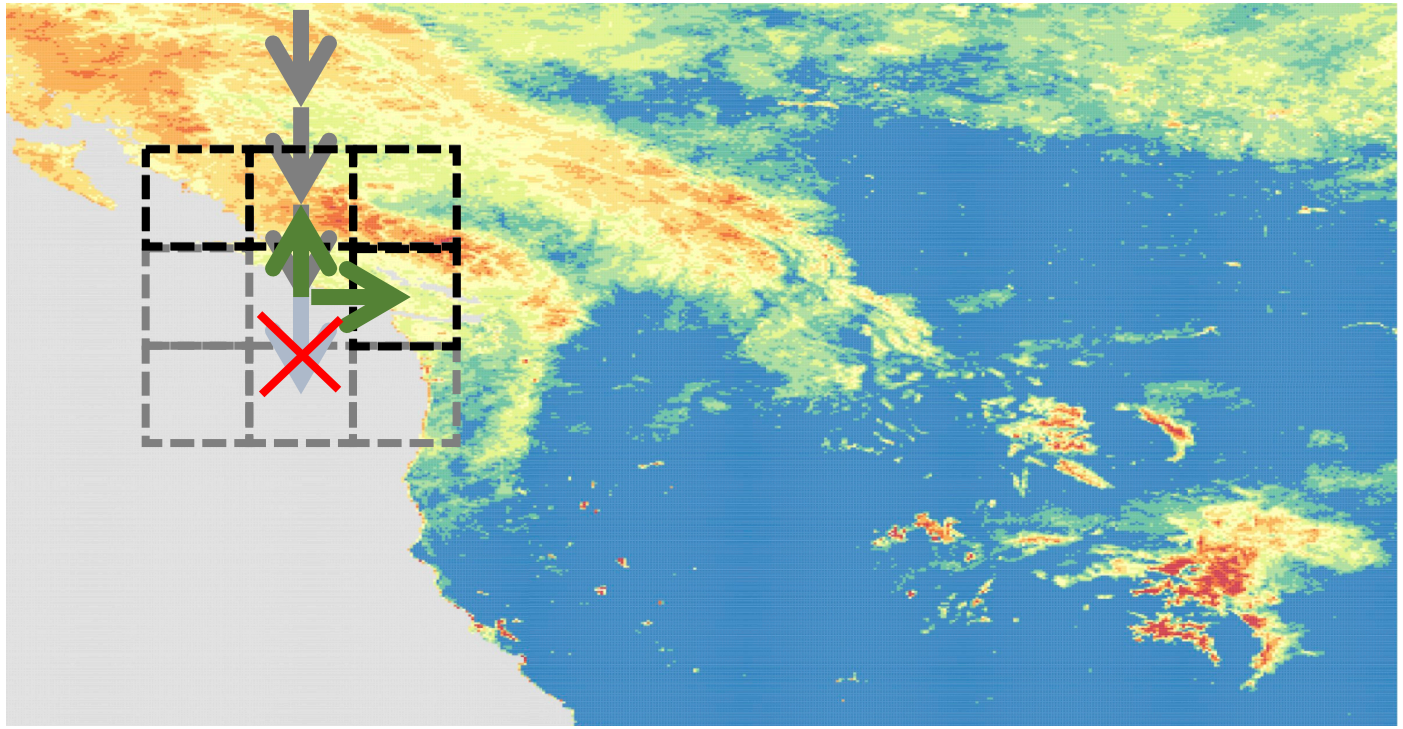
- Idea: user consistently moves in predictable directions
- Applied Markov model



Signature-based recommendation

ForeCache

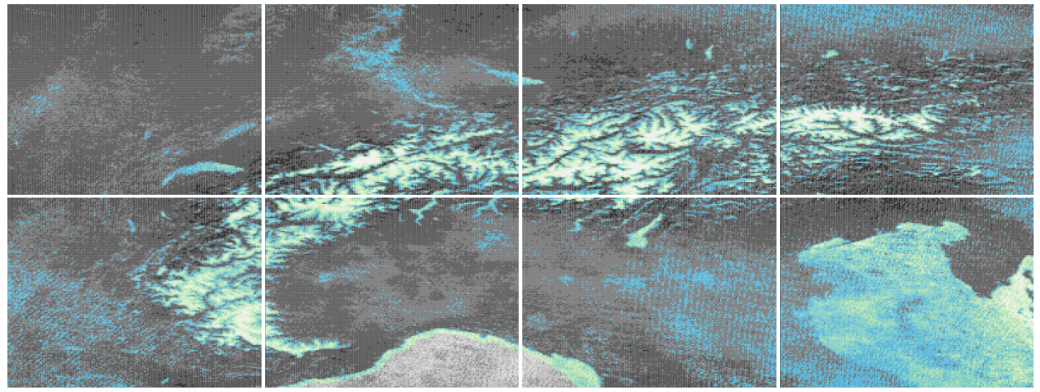
- Idea: user wants to see more of the same thing
- Identify neighboring tiles that are visually similar

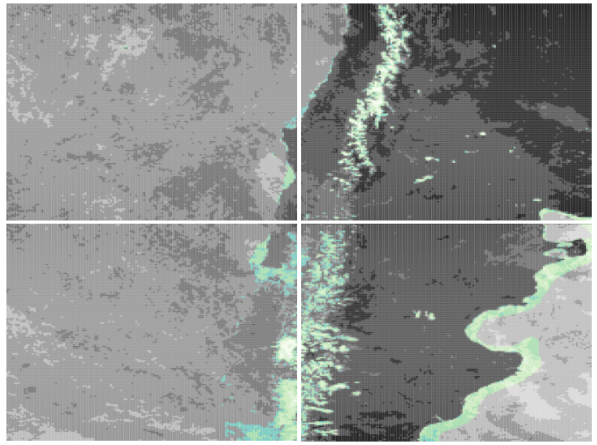


User study

ForeCache

- Participants: 18 earth science researchers
  - Explored snow cover measurements computed from satellite sensor data
- 16 users closely matched our 3-phase model





Performance experiments

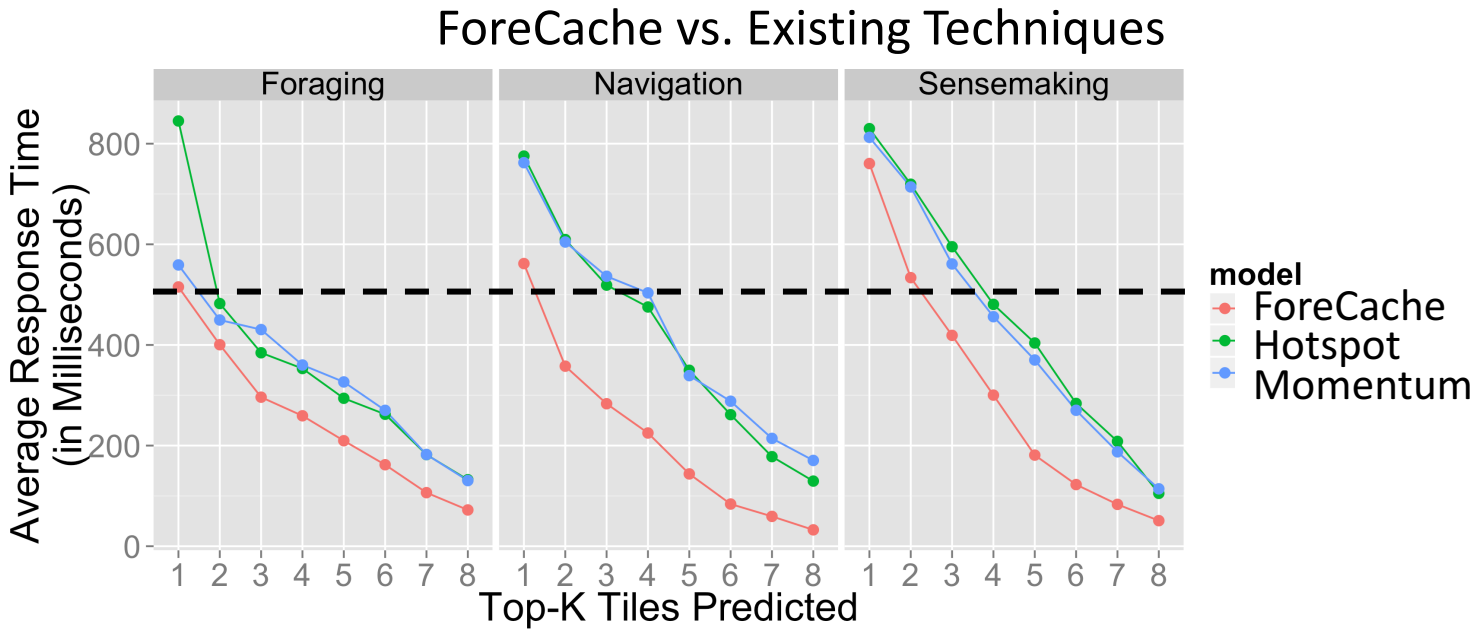
ForeCache

- Retroactively measured response times and prediction accuracy
- Single-threaded SciDB setup
- Compared with:
  - Non-prefetching baseline
  - 2 existing prefetching approaches:
    - Momentum[1]
    - Hotspot[1]

[1]P. Doshi, E. Rundensteiner, and M. Ward. Prefetching for visual data exploration. In *Proc. DASFAA*, 2003.

2D study results

- Ran experiments on the user study data
- ~20% improvement in accuracy
- Correct prediction = ~20ms latency, incorrect = ~1s
- 88+% faster for k >= 5 (400% over non-prefetching baseline)



Summary

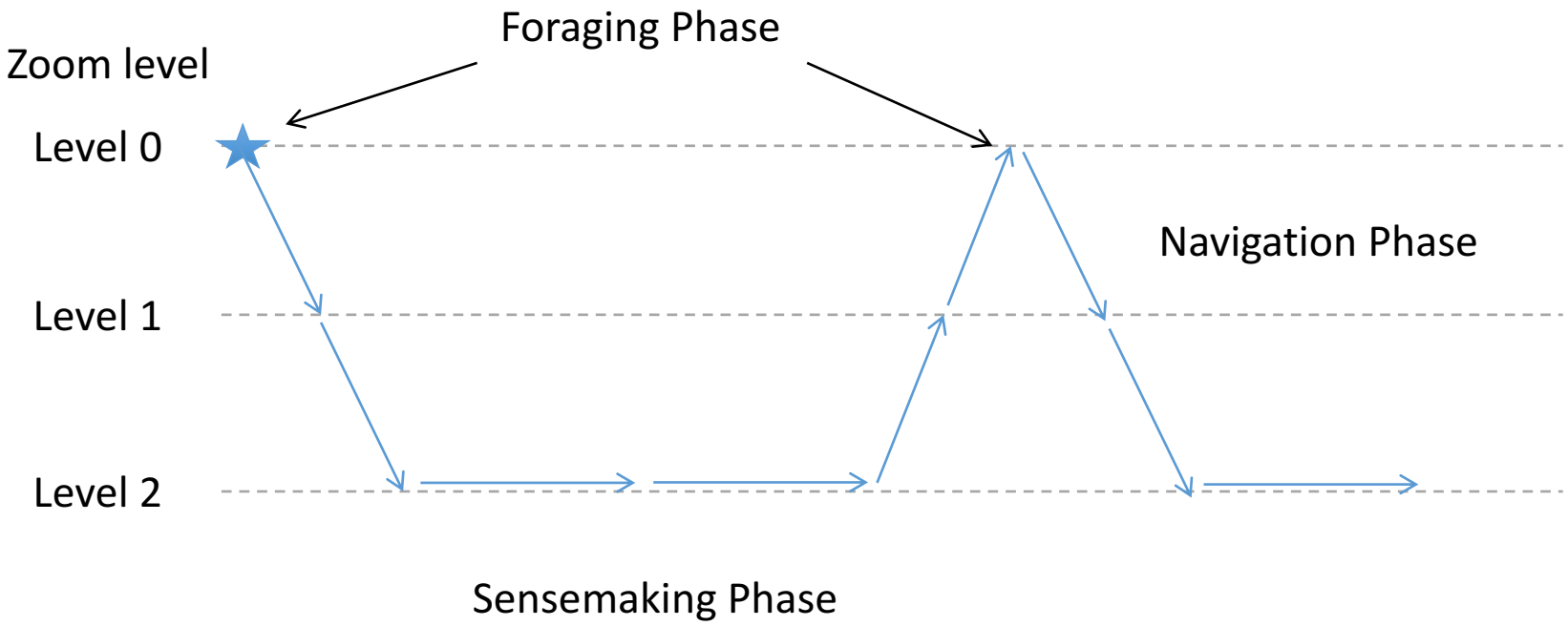
ForeCache

- Presented ForeCache
- Contributions:
  - Analysis model for visual exploration
  - Predictive data prefetching based on interaction histories
  - User study with scientists exploring real-world data
- Enables scientists to interactively explore large datasets

Questions?

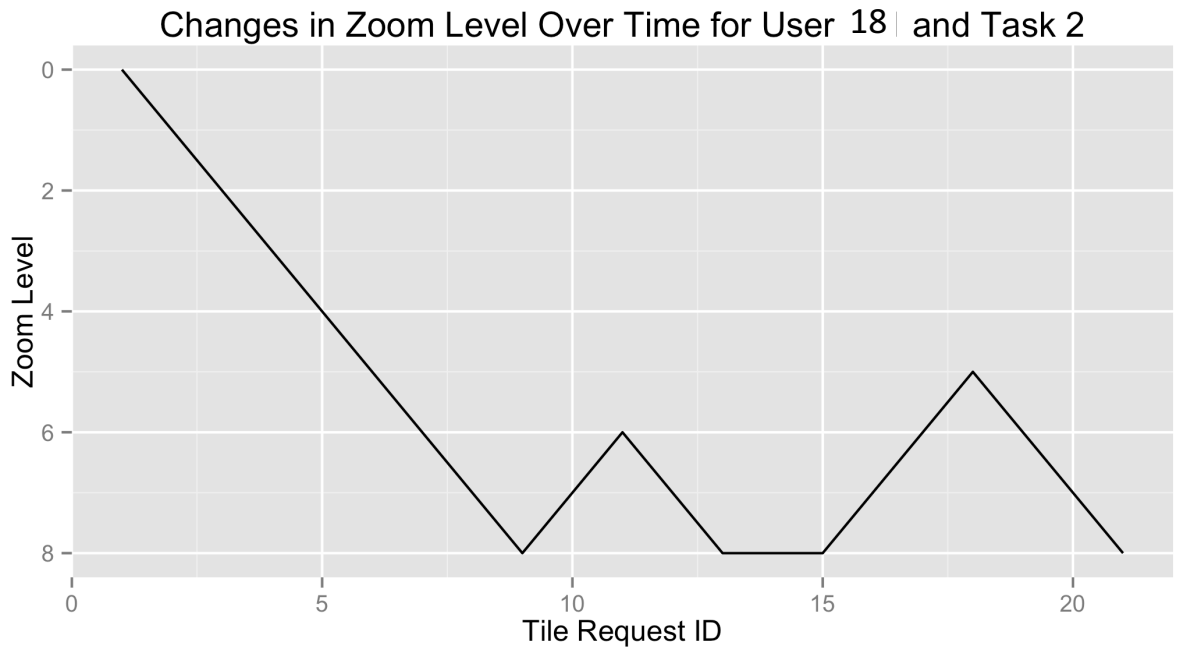
- My goal is to develop easy-to-use systems for complex analytics
- My work spans databases, HCI and visualization
- I model user behavior, and leverage it to improve system performance
- I evaluate systems with real users and real-world data

Testing our analysis model: assumptions



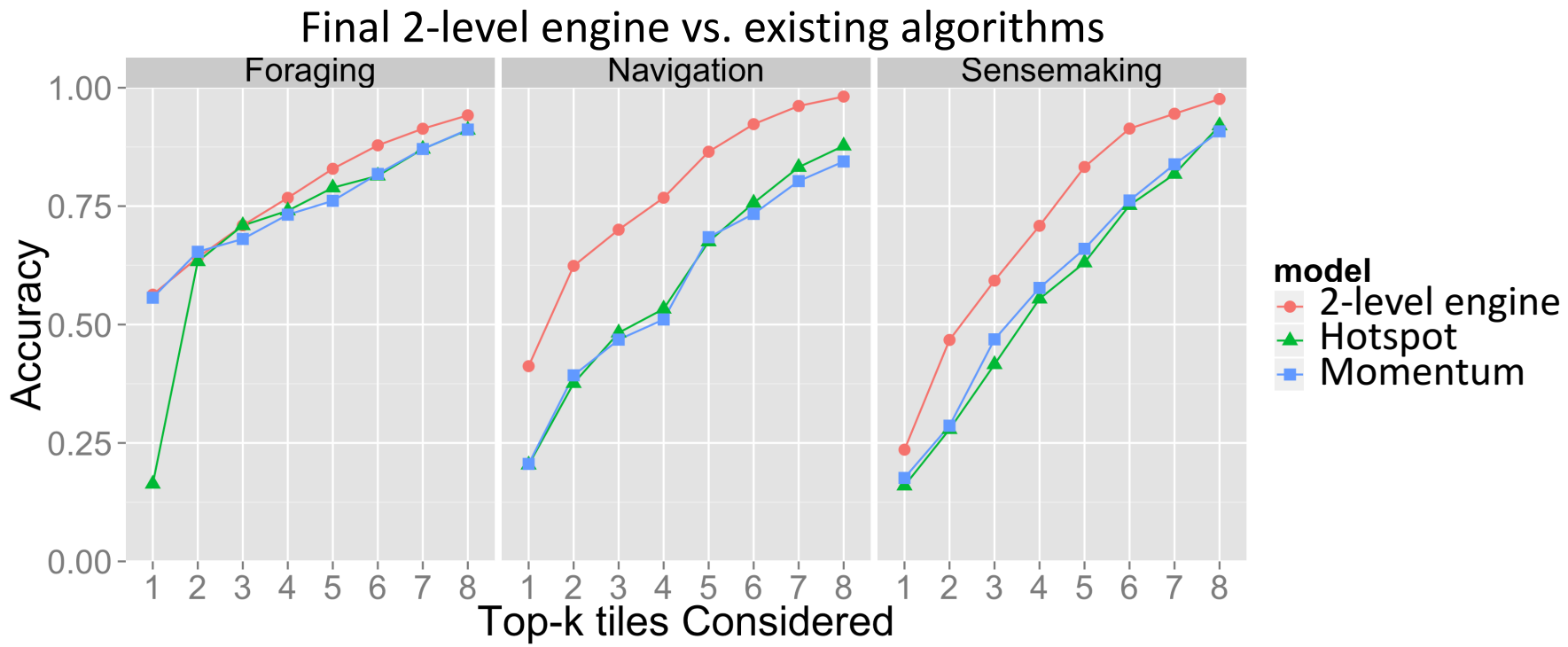
Evaluating the analysis model

- Plotted change in zoom levels over time



Prediction accuracy per phase

- ~20% improvement in accuracy
- 25% improvement for Navigation phase



Prediction accuracy per phase

- X-axis = # tiles predicted before each request (k)
- Accuracy = fraction of prediction attempts that contained the correct tile (averaged across all users)