Visualizing Uncertainty

Alex Kale

Visualizing uncertainty

"Uncertainty must be displayed if it is to be reasoned with and incorporated into the visual analytics process. In existing visualizations, much of the information is displayed as if it were 'true.'"

(Thomas and Cook 2005)

Why should we show uncertainty?

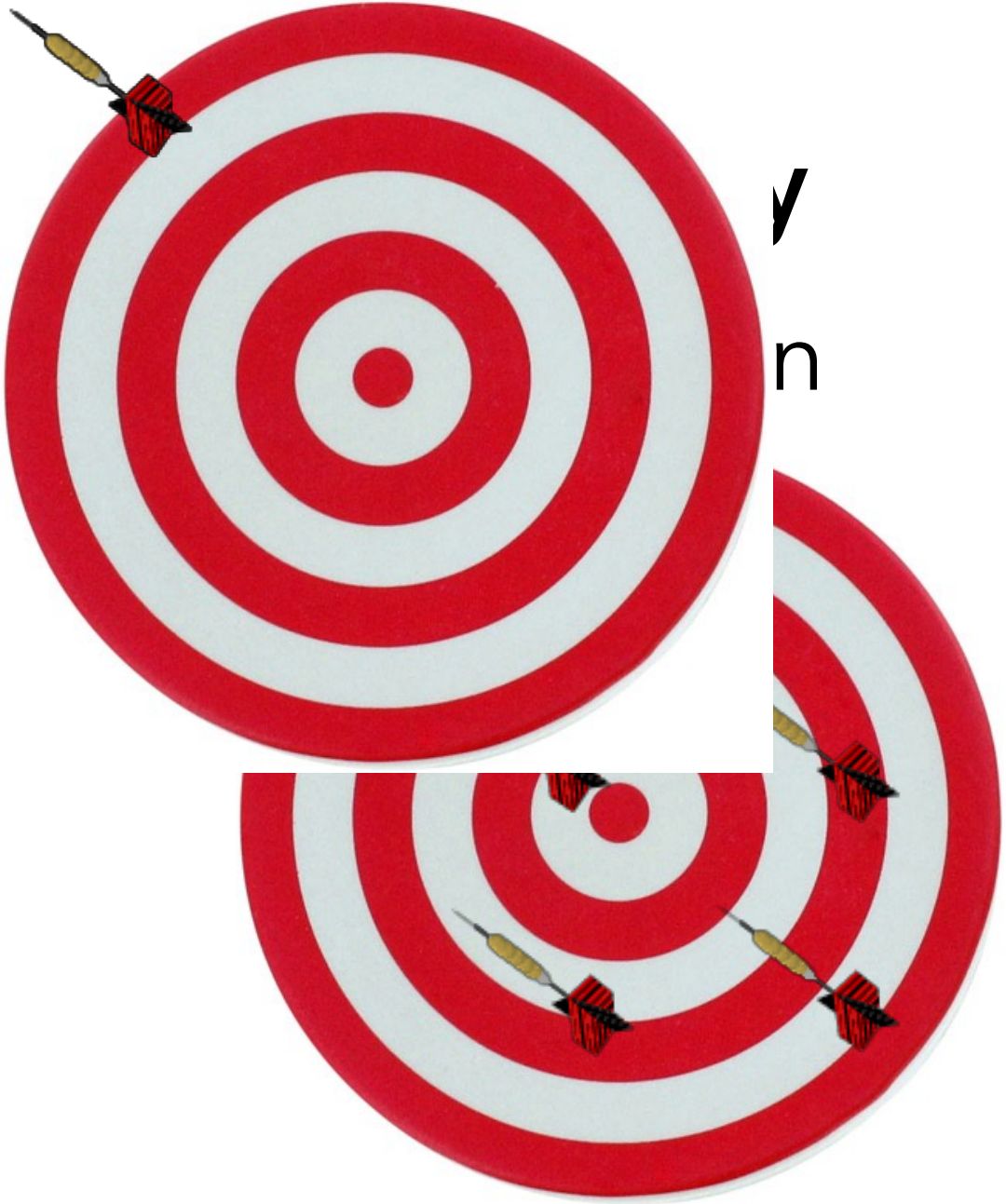
- Guard against overconfidence (i.e., ignoring uncertainty)
  - Insensitivity to sample size
  - Not acknowledging assumptions
- Visualizations often used for inferences & decisions
  - People may infer different amounts of uncertainty when omitted

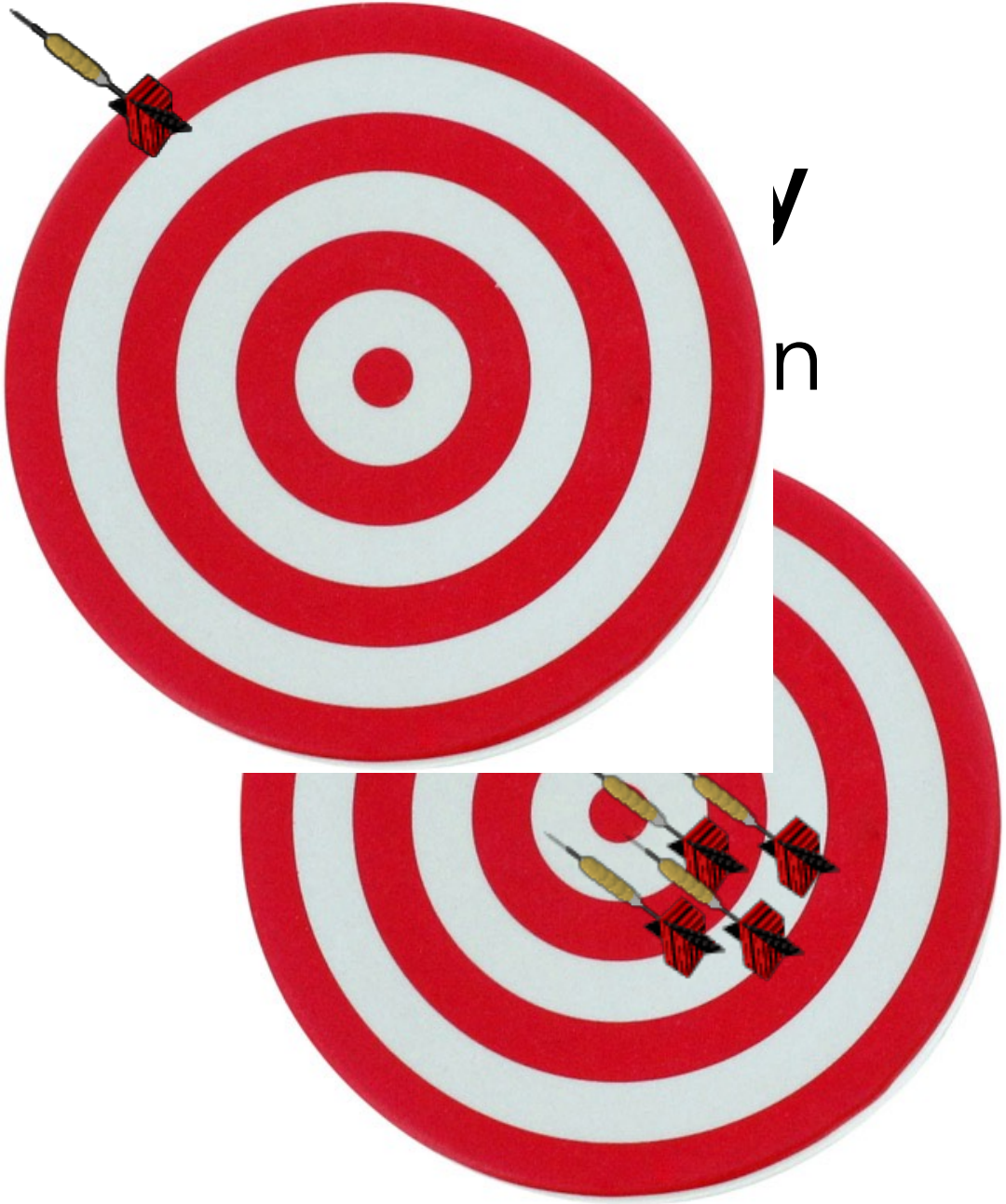
Uncertainty:

"the possibility of multiple outcomes"

Terminology

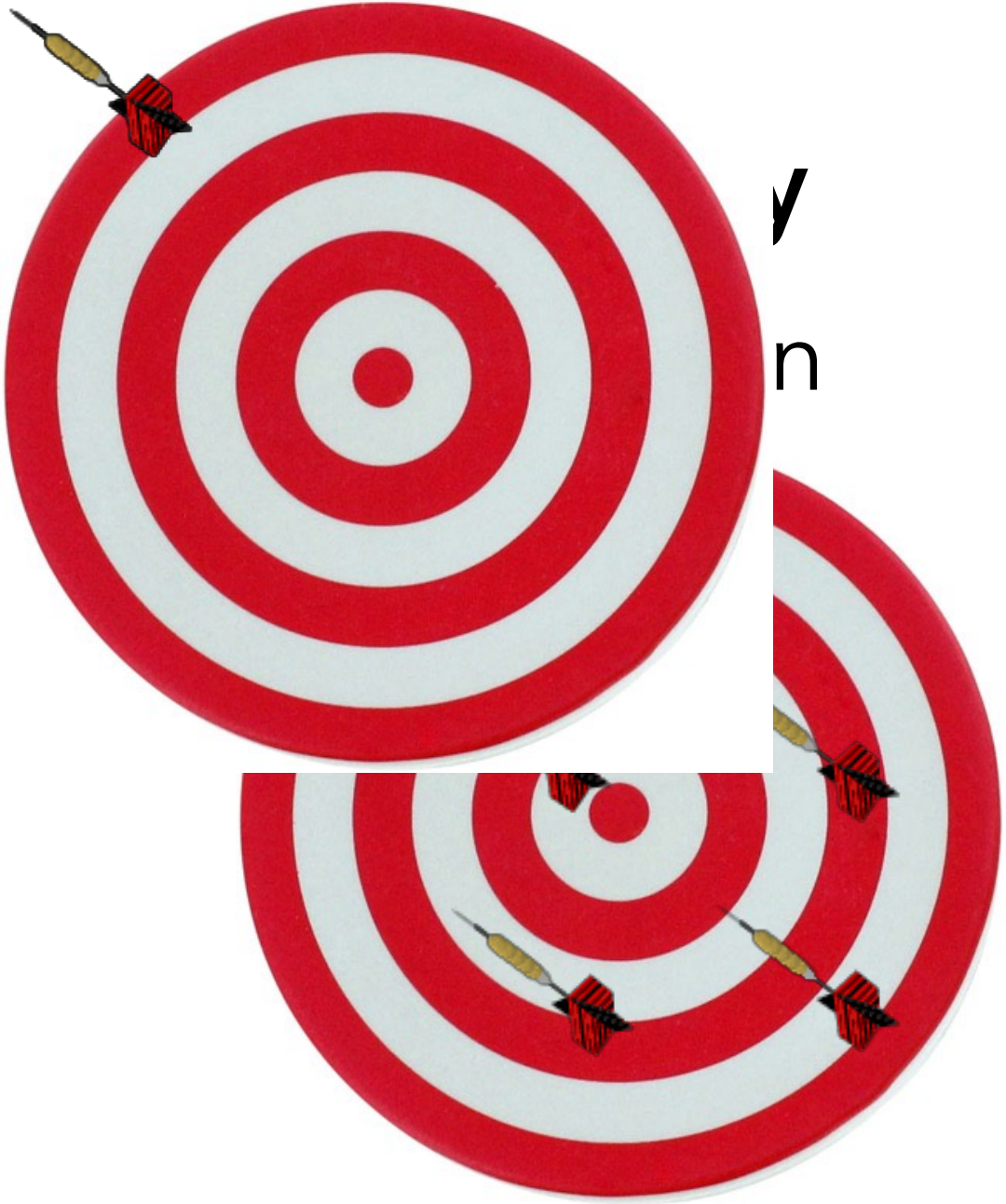
Precision





y

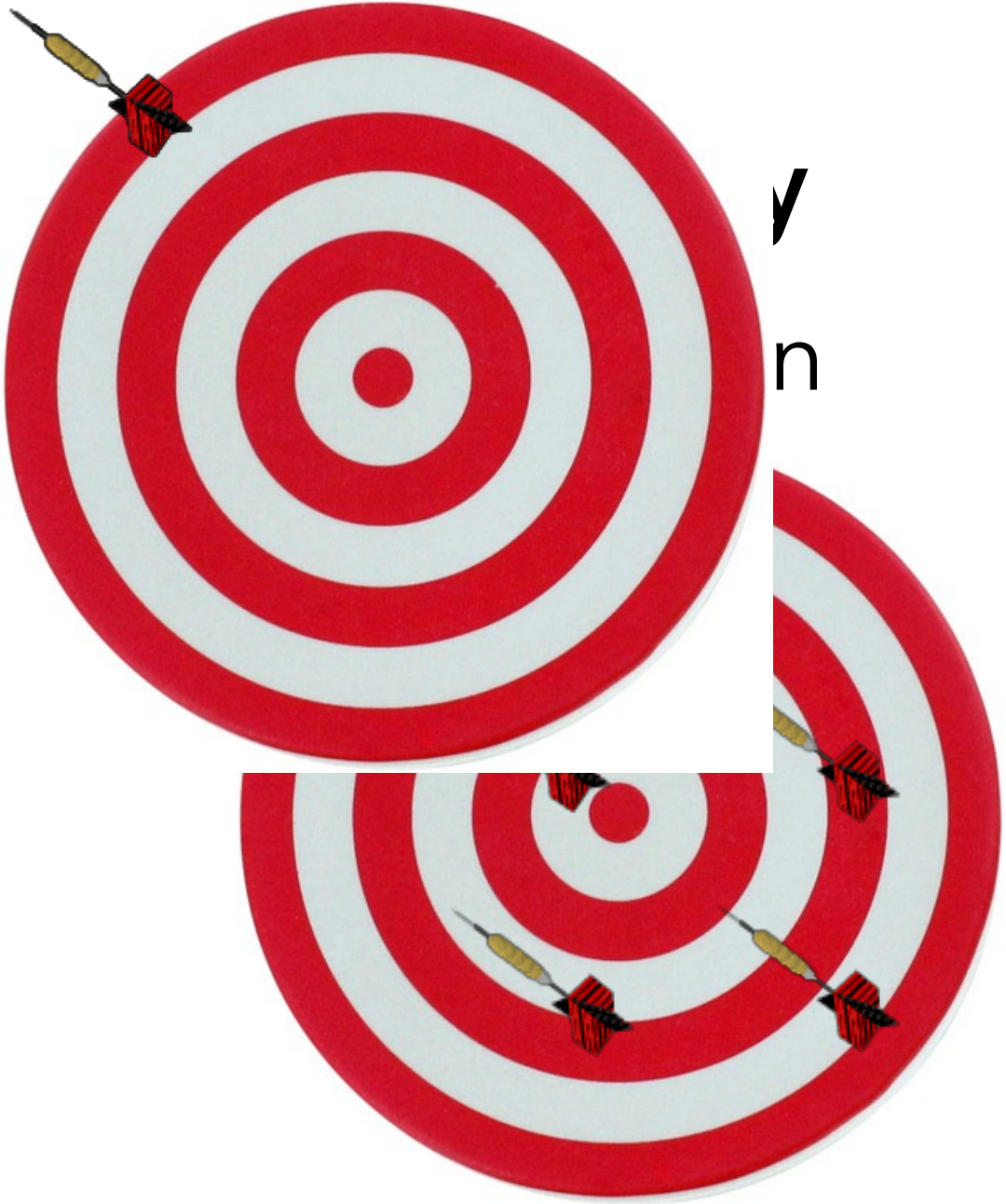
n



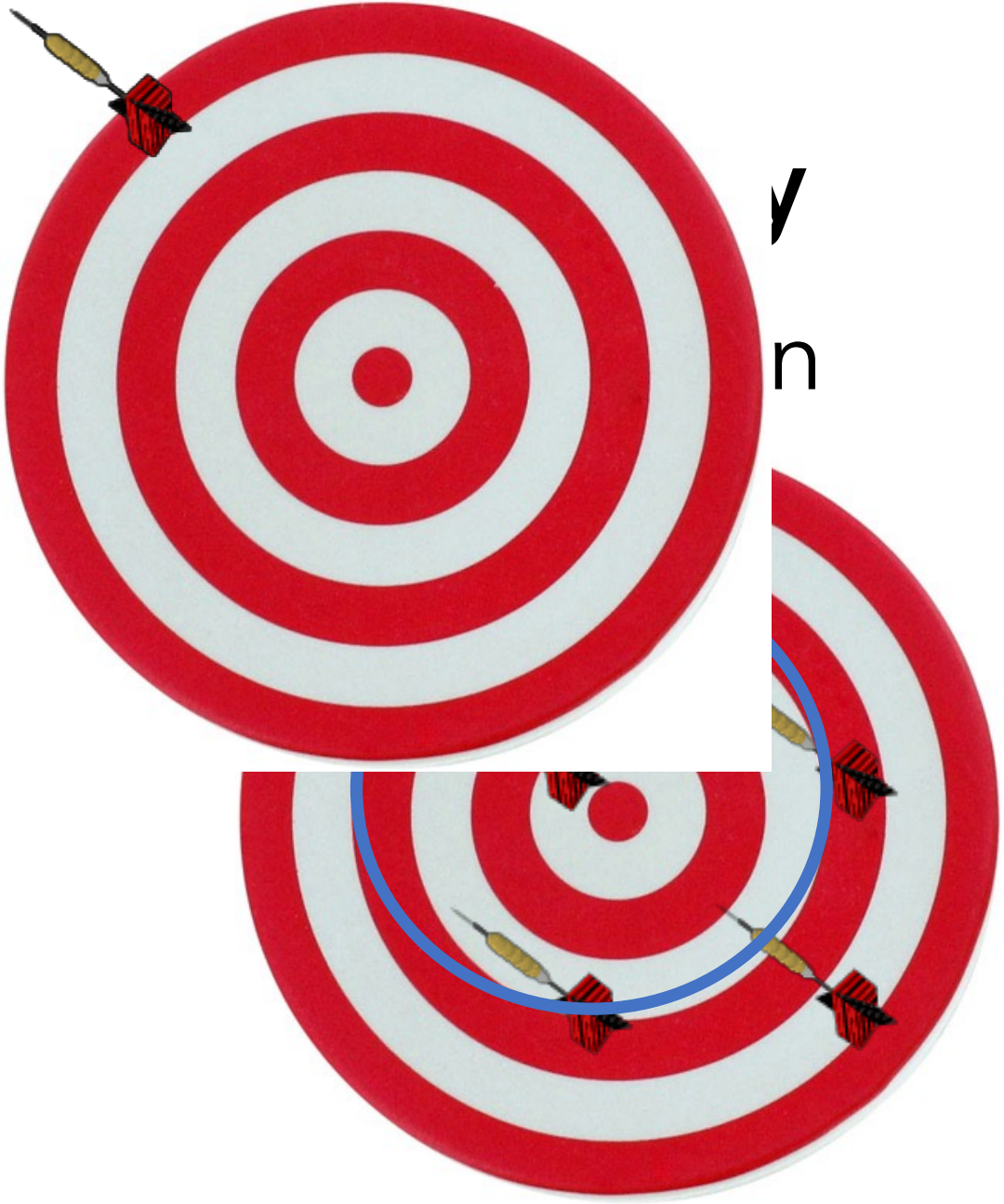
Accuracy

y

n



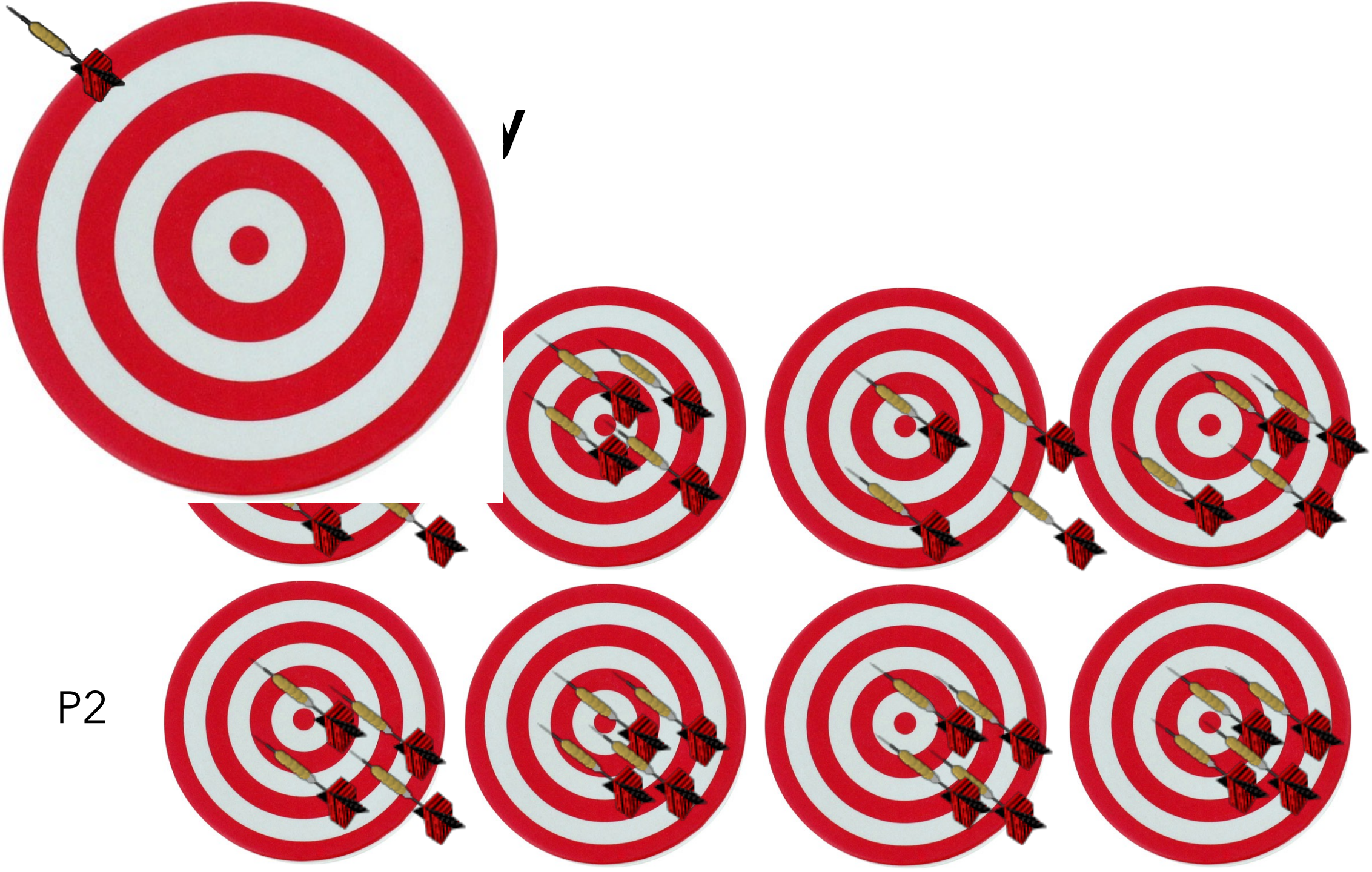
Accuracy



n

Accuracy

Bias



P2

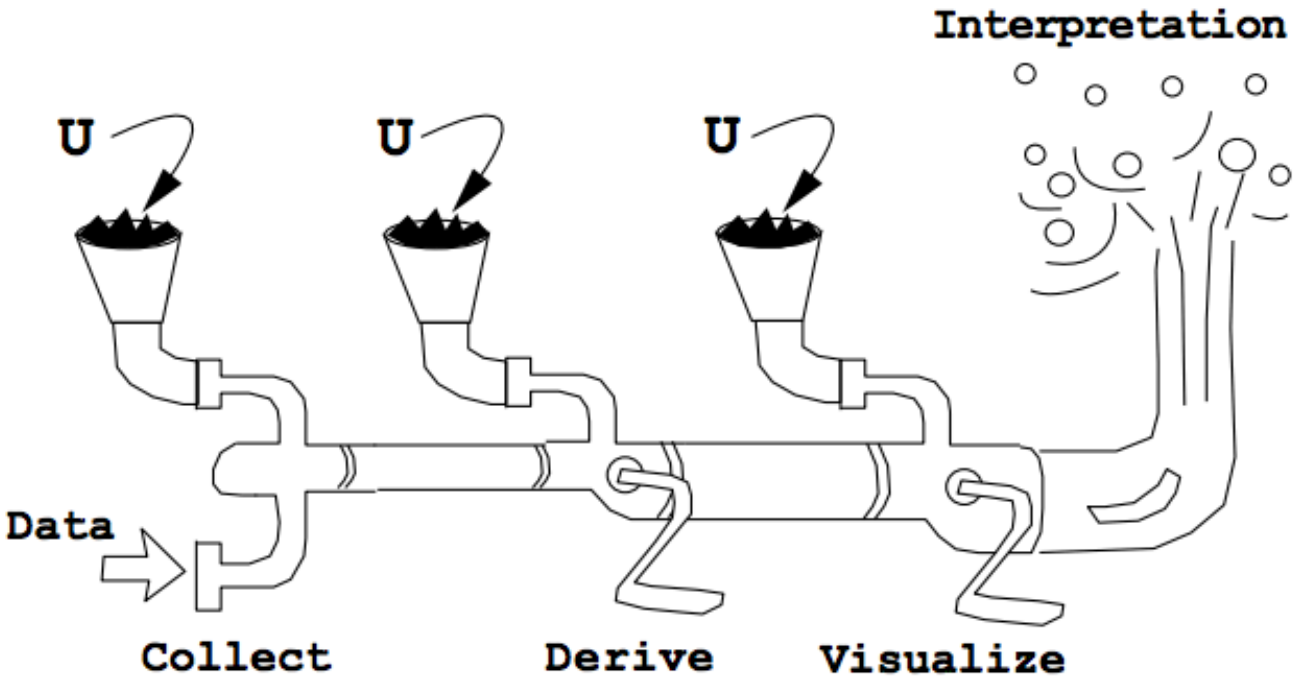


Figure 1: This visualization pipeline shows the introduction of uncertainty (U) from models and measurements, uncertainty from transformation processes, and uncertainty from the visualization process itself.

Pang, Wittenbrink, Lodha. Approaches to Uncertainty Visualization.

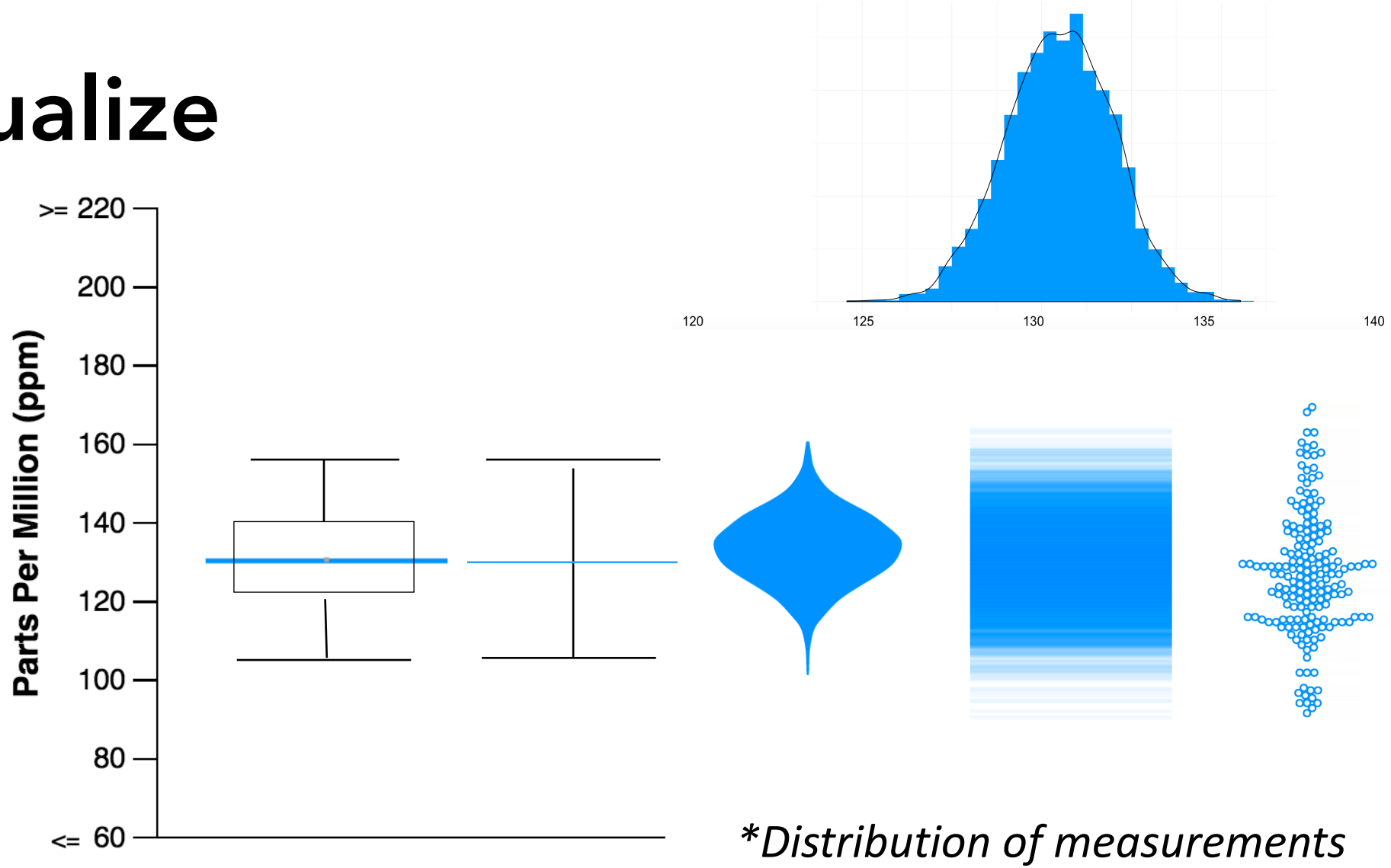
Example: Quantifying Uncertainty

Imagine that we took many measurements of the concentration of a solute in seawater.

Data (in *parts per billion*): [132.24, 131.72, 129.93, 128.60, 129.16, 127.76, 134.45, 127.03, 133.20, 133.64, 129.34, 131.96, 131.55, 131.76, 120.39, 127.49, ...]

Q: How much do these readings vary?

Visualize



*Distribution of measurements

Q: How much do these readings vary?

Example: Quantifying Uncertainty

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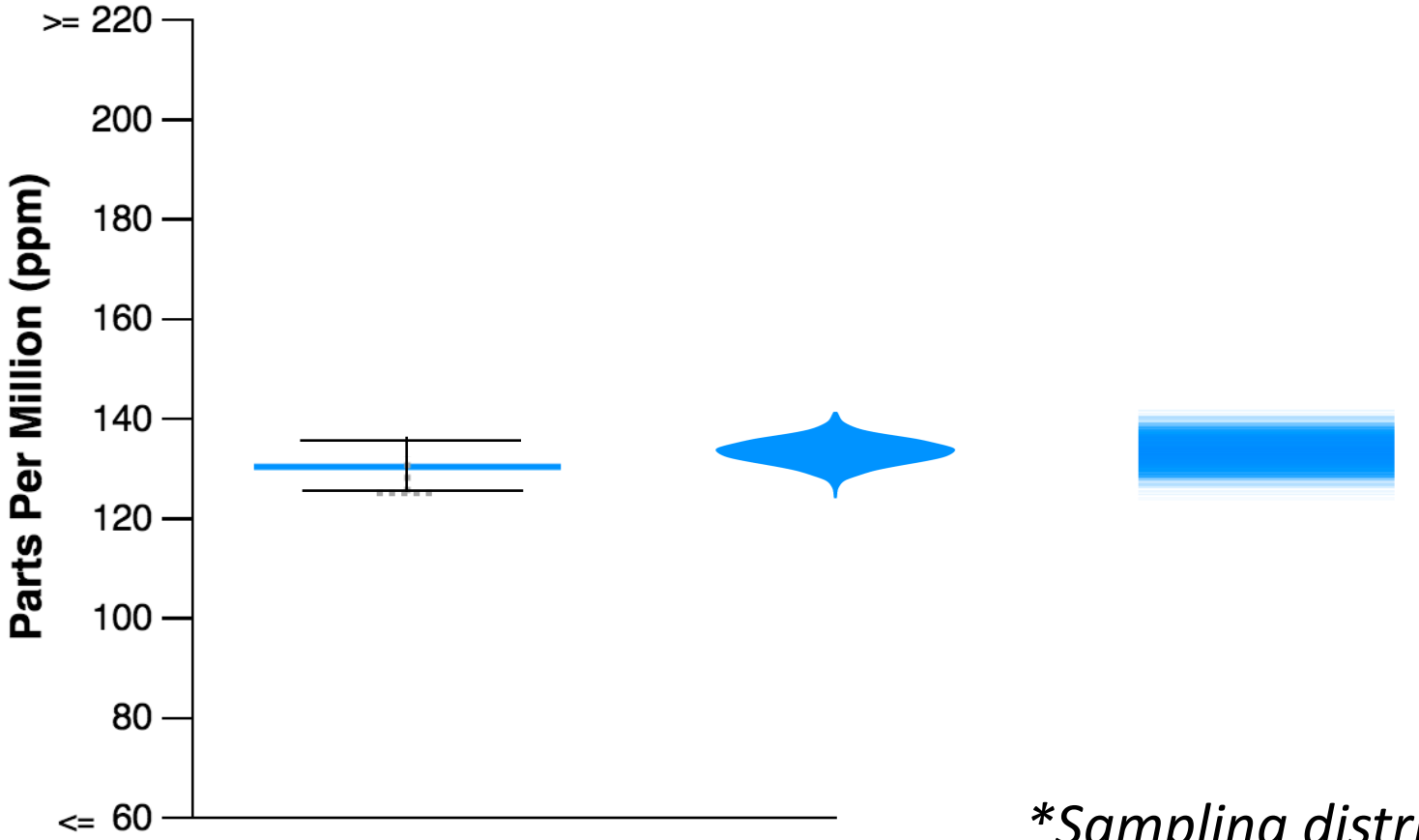
Q: How do our predictions of the level in the entire ocean vary?

Visualize



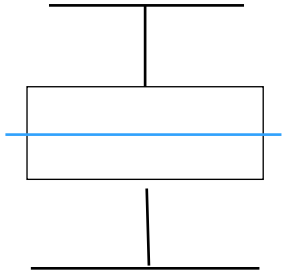
*Sampling distribution

Q: How do our predictions of the level in the entire ocean vary?

Visualization Approaches

Glyphs and summary plots

- Error bars
- Boxplots

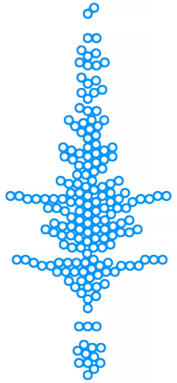


Visual variables

- Lightness/value, area
- Blur/focus, “sketchiness”

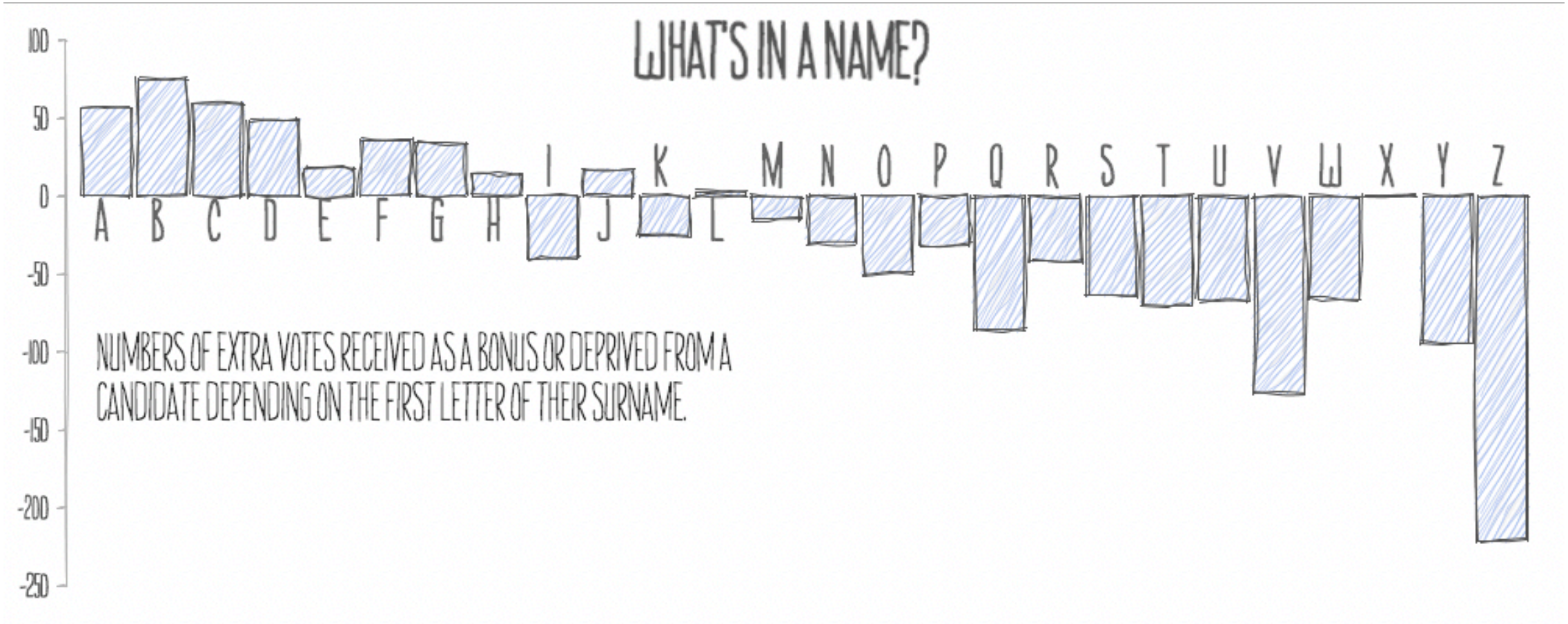
Set of discrete outcomes

- Beeswarm plot, dotplot
- Hypothetical outcome plots



Visualization Approaches

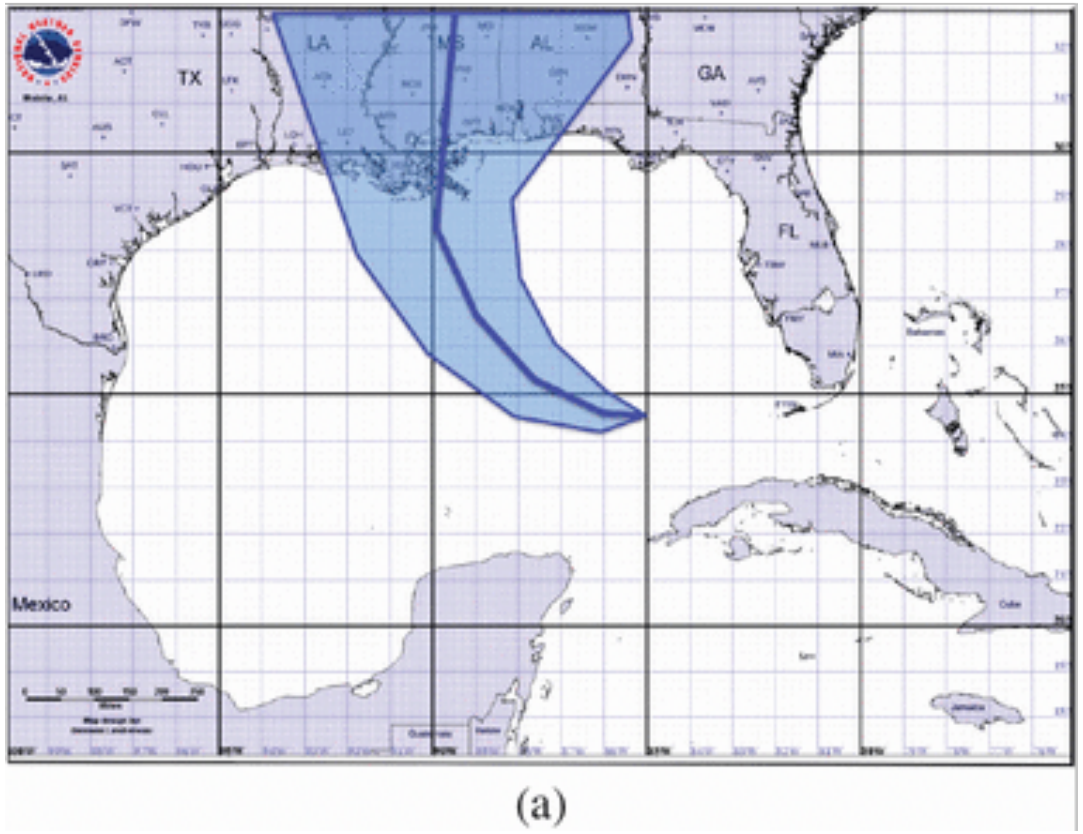
What is “sketchiness”?

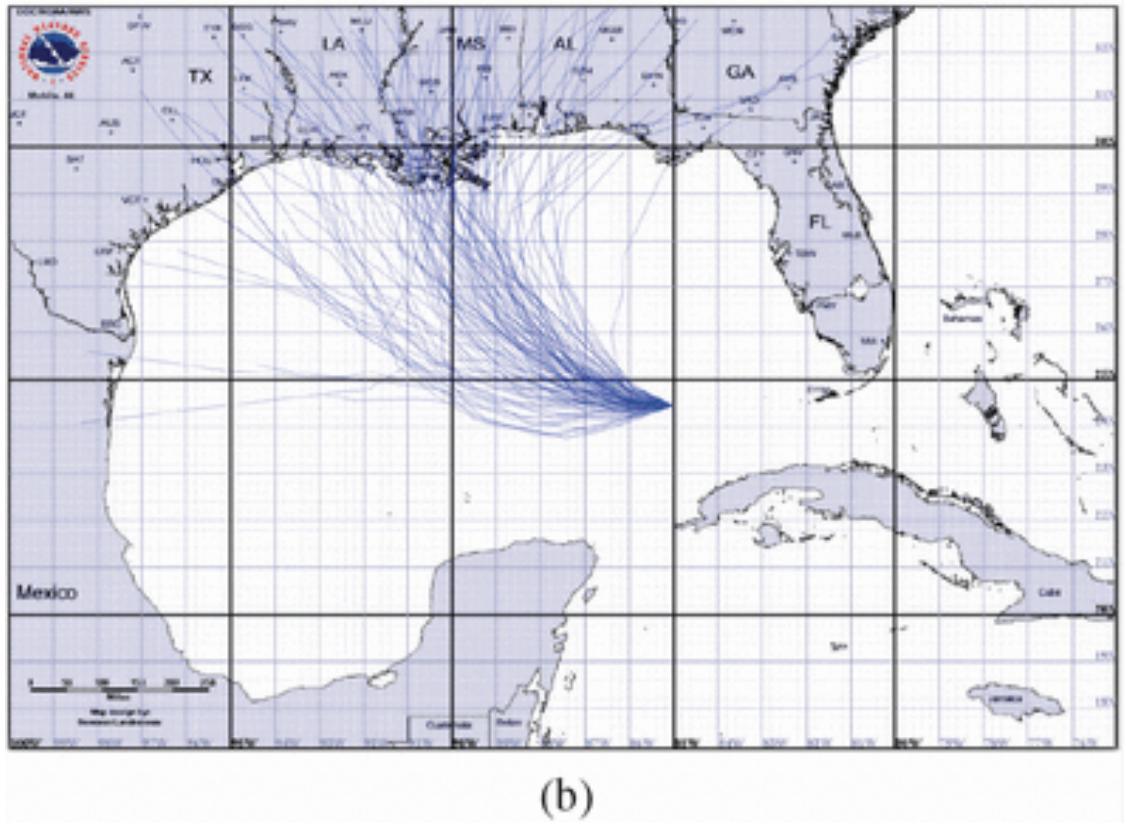


Boukhelifa et al. (2012), Wood, Jo et al. (2012)

Visualization Approaches

Summaries vs discrete outcomes

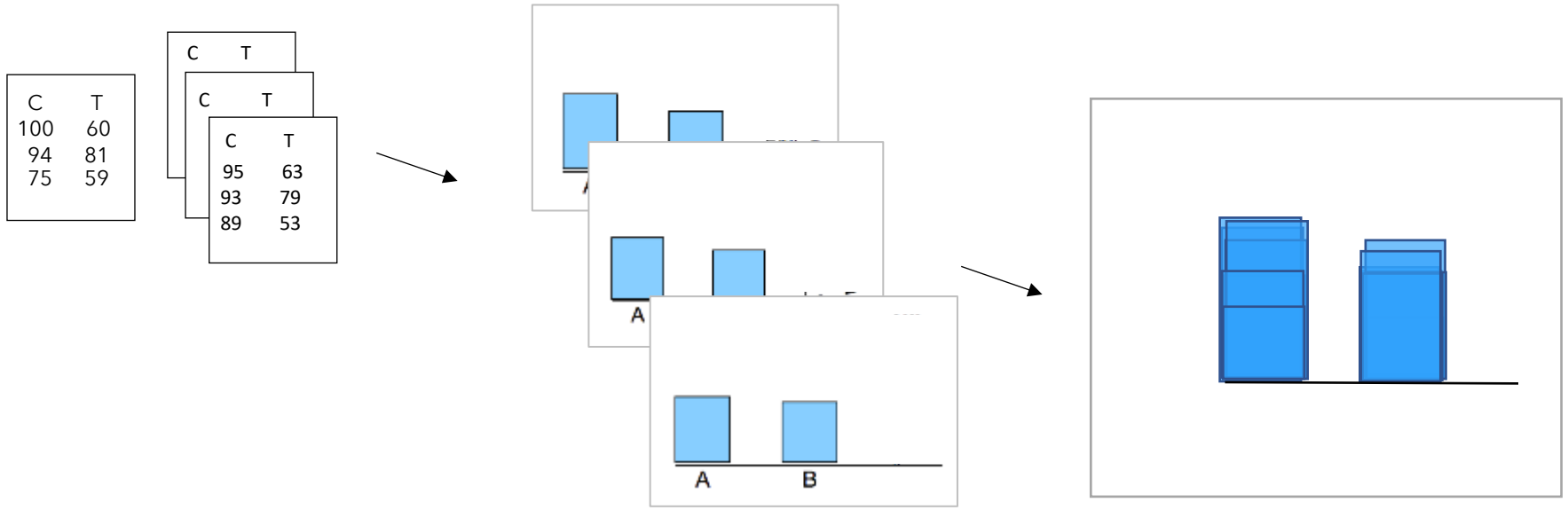




Cox et al. (2013)

Visualization Approaches

Hypothetical Outcome Plots

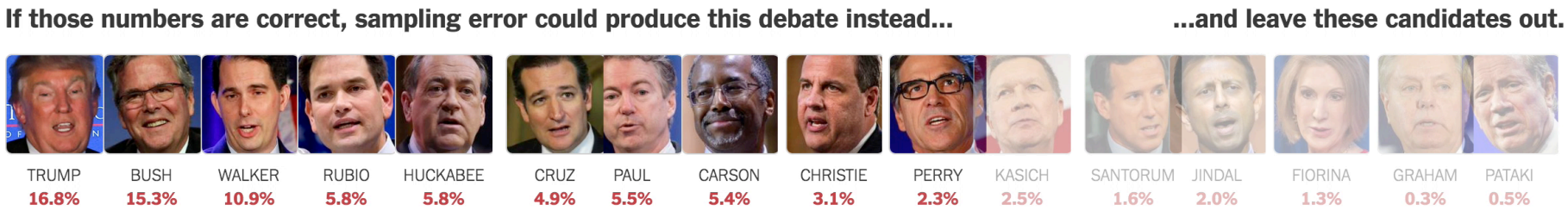


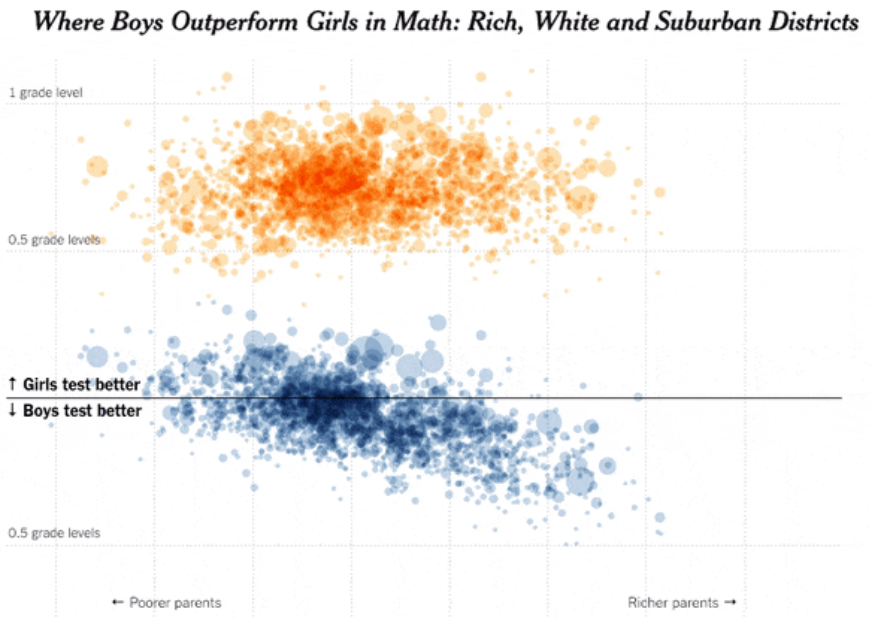
Present uncertainty as samples *over time*, where each sample is a new frame in an animated visualization

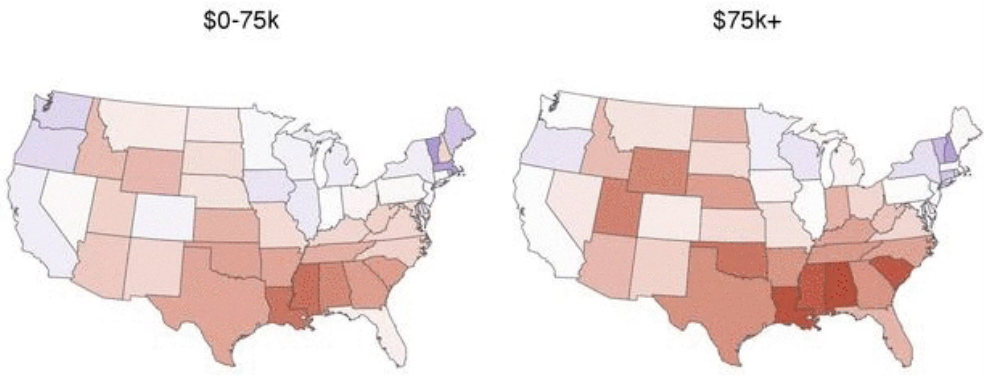
Hullman et al. (2015)

Visualization Approaches

Hypothetical Outcome Plots

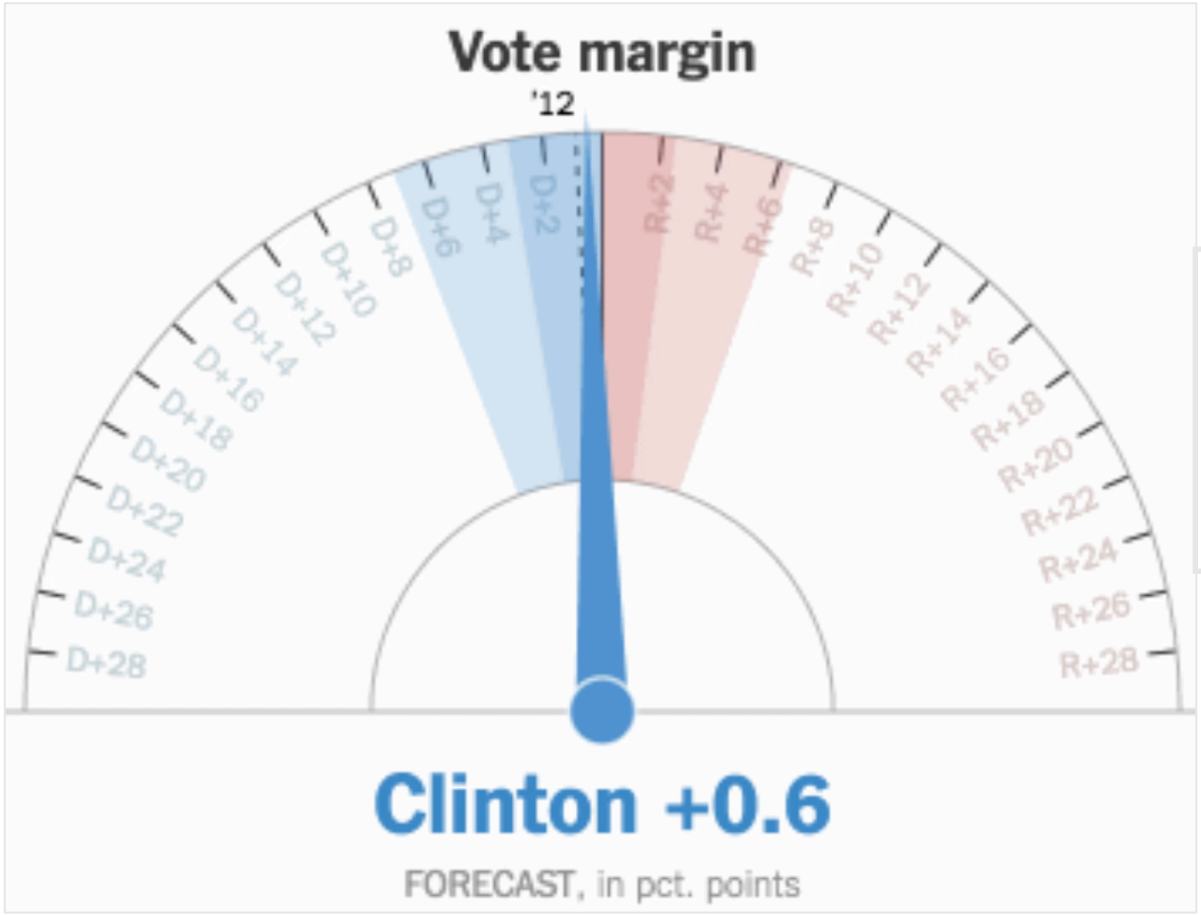




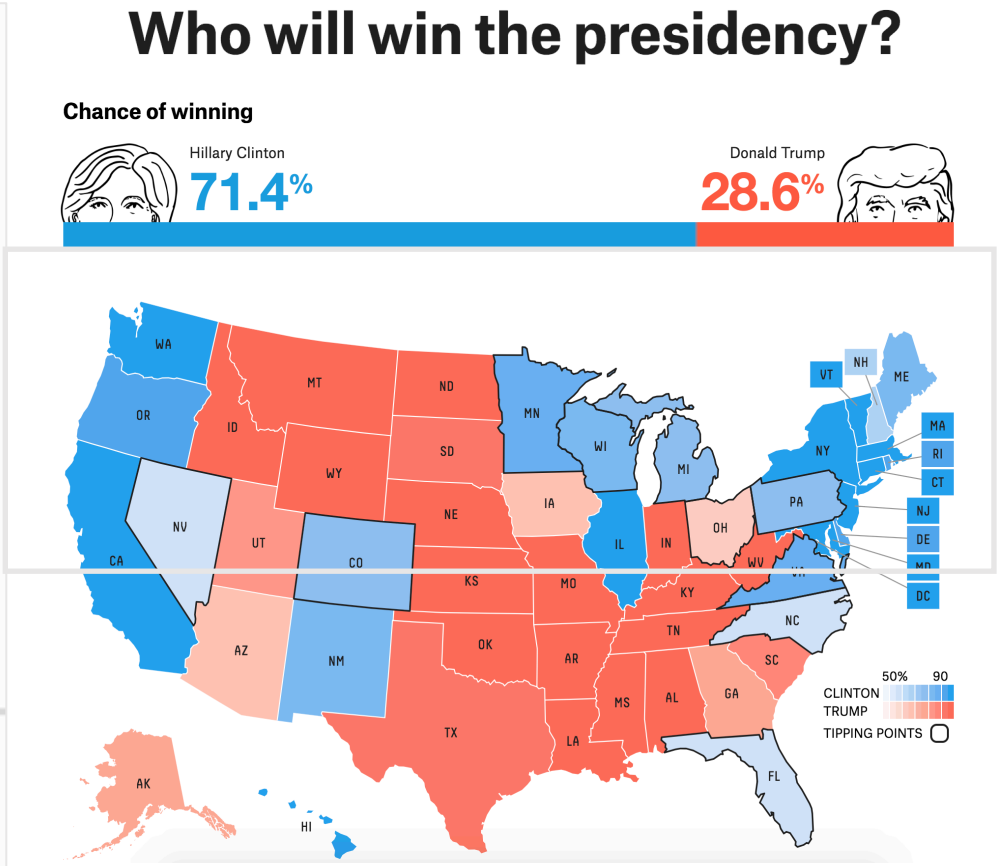


Applicable to arbitrary encodings

Animating Uncertainty is Controversial

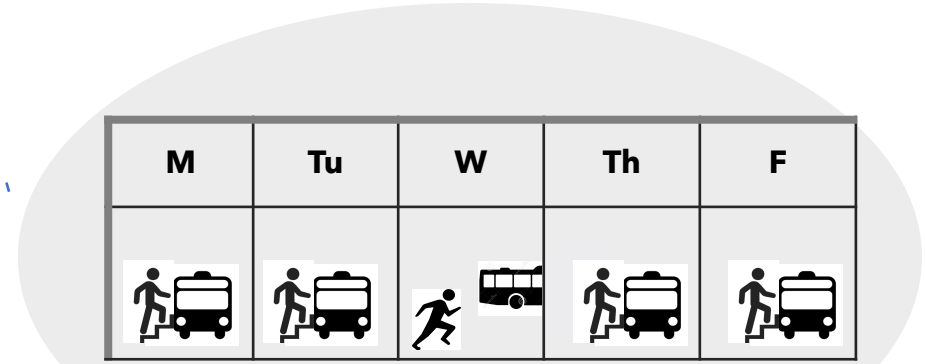


Bad?



Better?

Framing Probability as Frequency



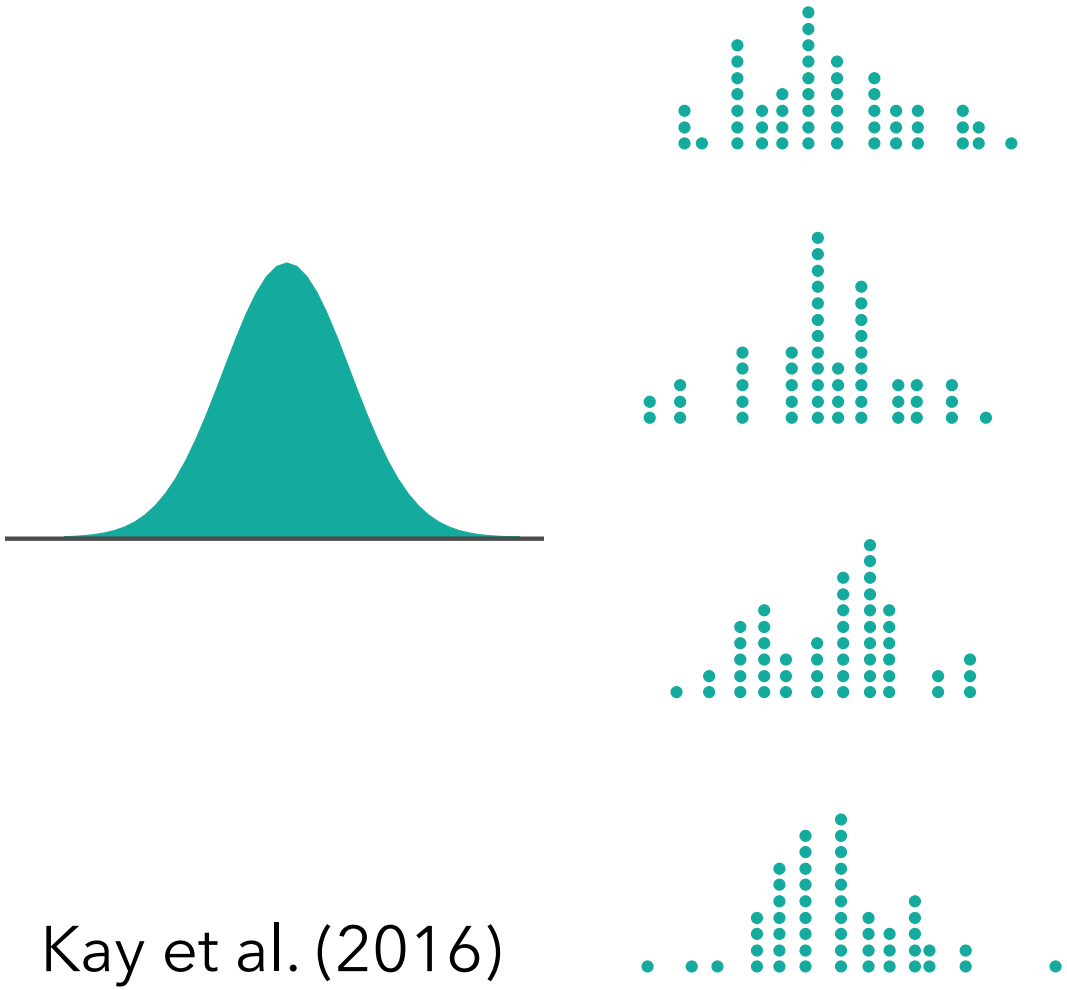
Frequency framing improves reasoning

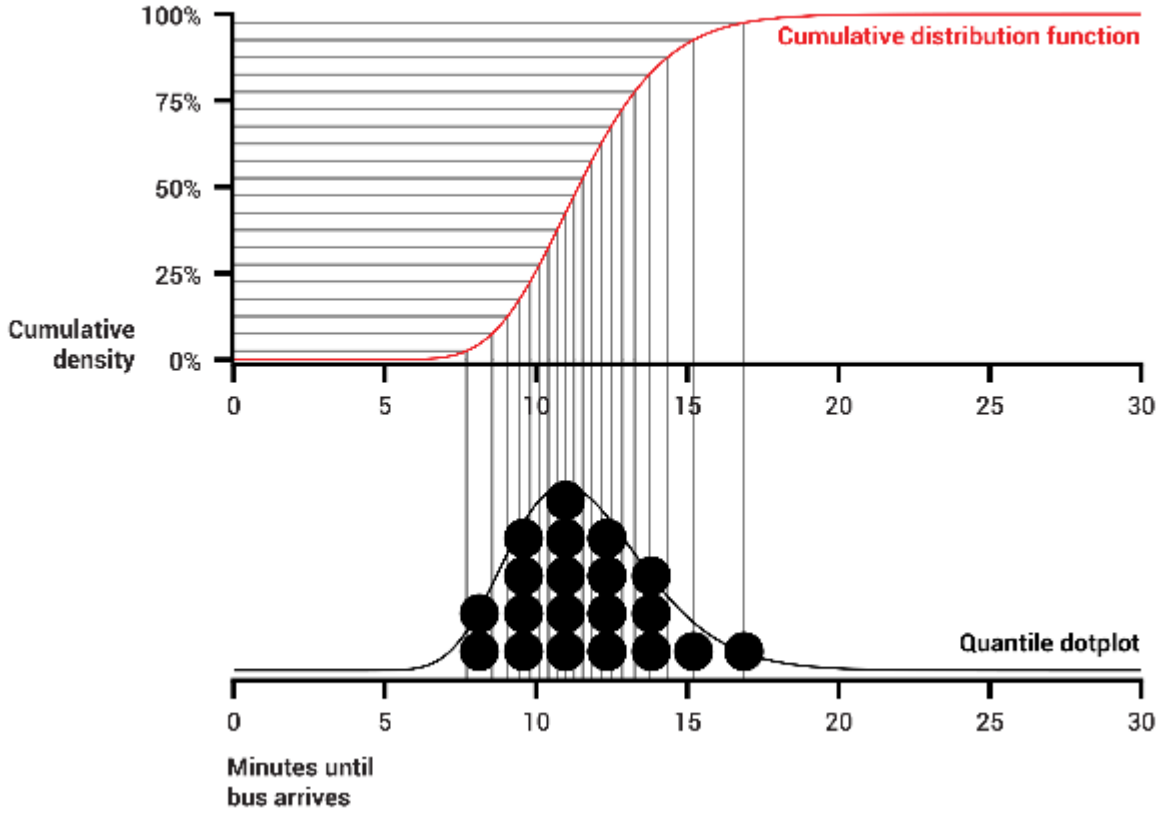
4 out of 5 times, vs 80%

(Gigerenzer & Hoffrage 1995)

Visualization Approaches

Quantile Dotplots

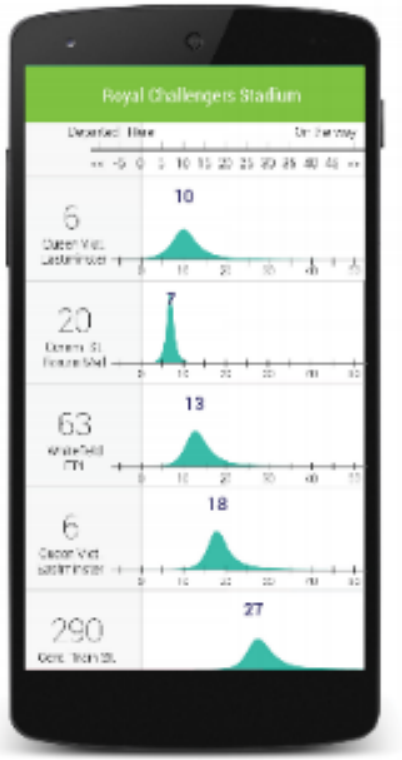




Kay et al. (2016)

Visualization Approaches

Quantile Dotplots



Bus riders made more accurate probability estimates with 20 dot QDPs than with 100 dot QDPs or densities

Better quality decisions with 50 and 20 dot QDPs vs densities, intervals, or text

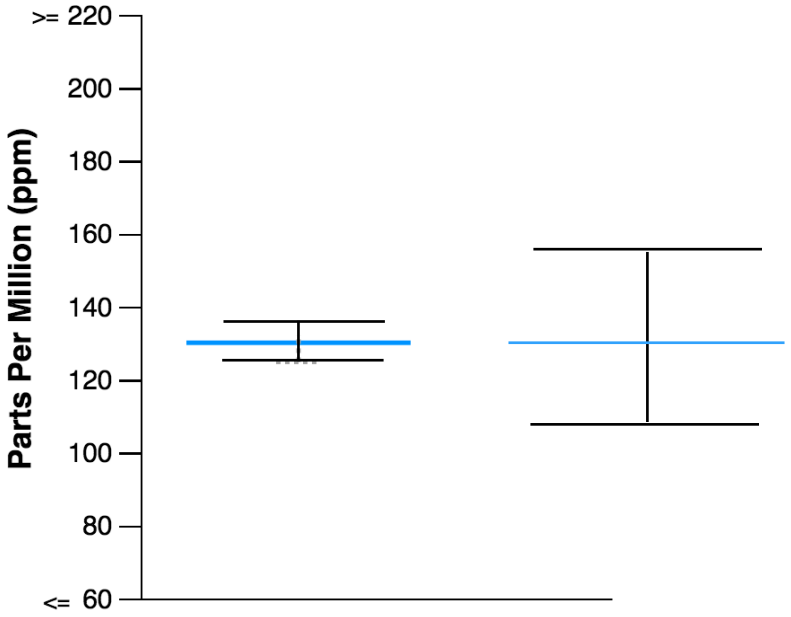
Kay et al. (2016), Fernandes et al. (2019)

Evaluating Uncertainty Visualizations

“The advantage for uncertainty estimates depends critically on how they are expressed. It is crucial that the expression is compatible with both the decision task and cognitive processes of the user.”

Joslyn & LeCleric (2013)

Does the vis support the user's task?



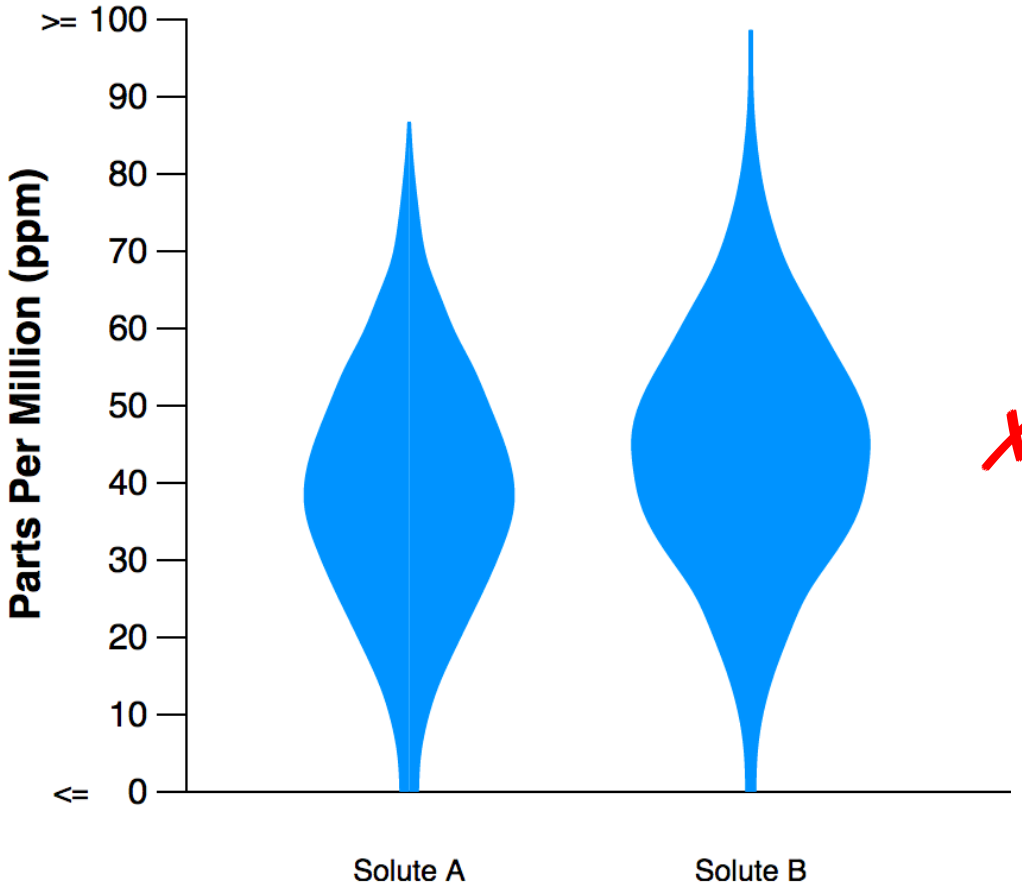
Is the model of uncertainty appropriate to answer the user's question?

What is the level in the entire ocean?

vs

How much do the readings vary?

Does the vis support the user's task?



Can the user extract the needed information from the visualization?

How confident are you that $\mu_B > \mu_A$?

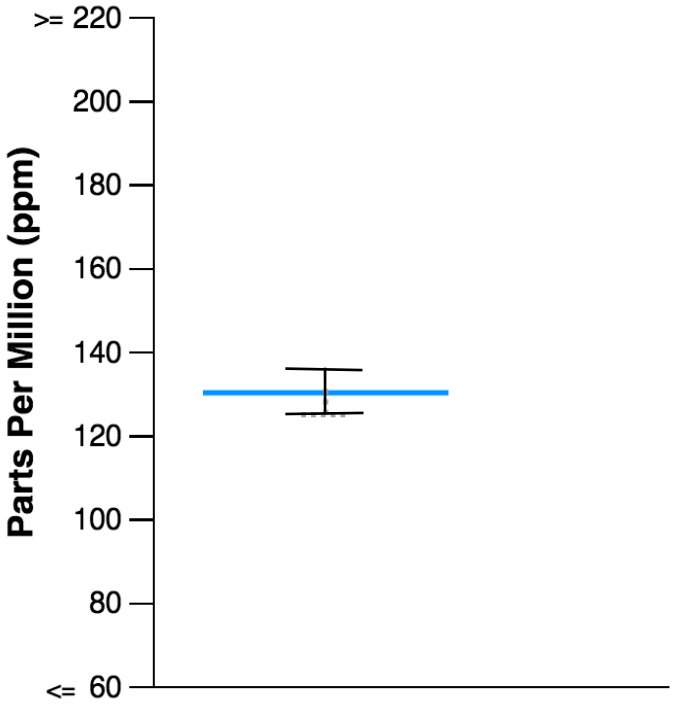
✗ *What is probability that B > A?*

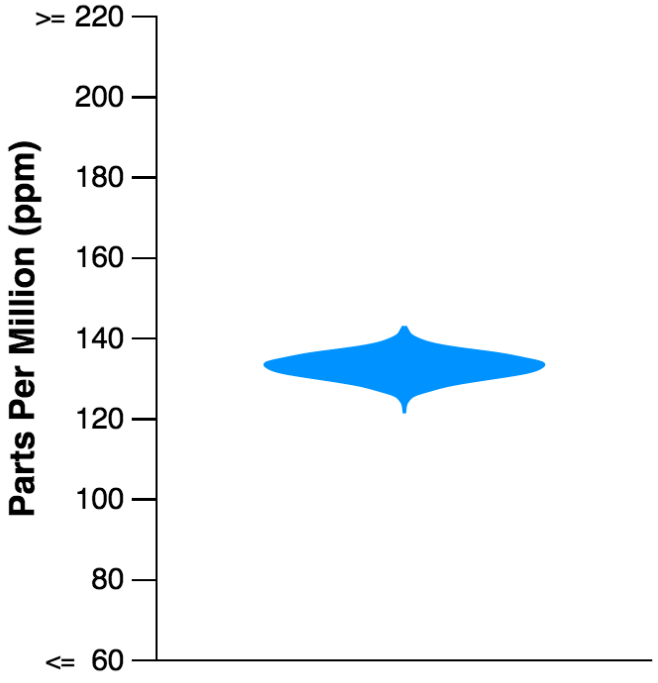
Are A and B correlated?

Is the vis expressive & can users infer meaning?

Expressiveness: How well does the visualization present all the facts (and only the facts)?

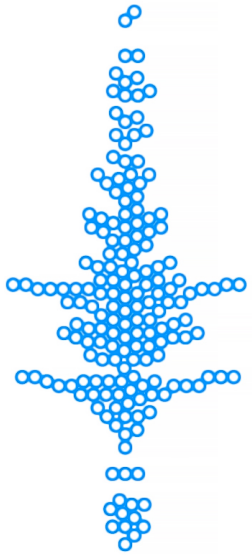
Mackinlay (1986)





What is the information format?

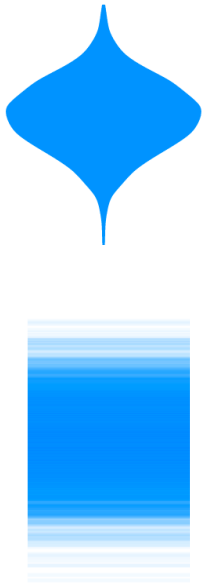
Does the visualization present data in a way that aligns with human reasoning abilities?

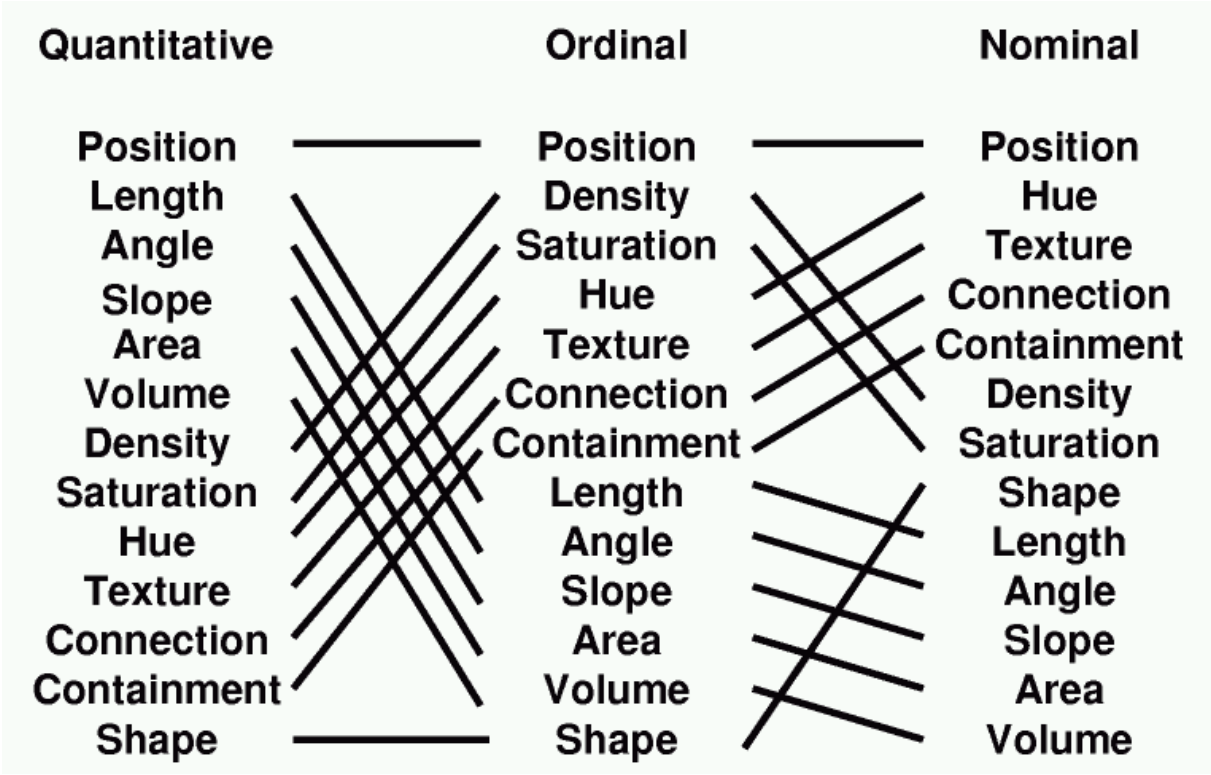


Can users decode the data from the chart?

Effectiveness: How easily can a human estimate the values from the visualization?

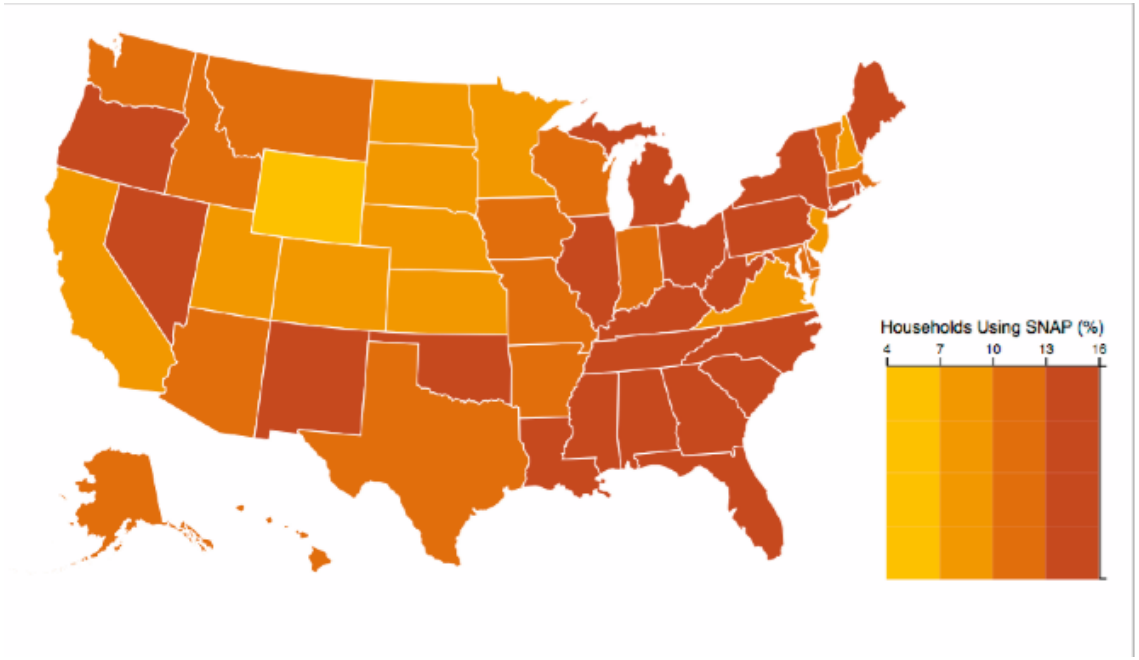
Mackinlay (1986)



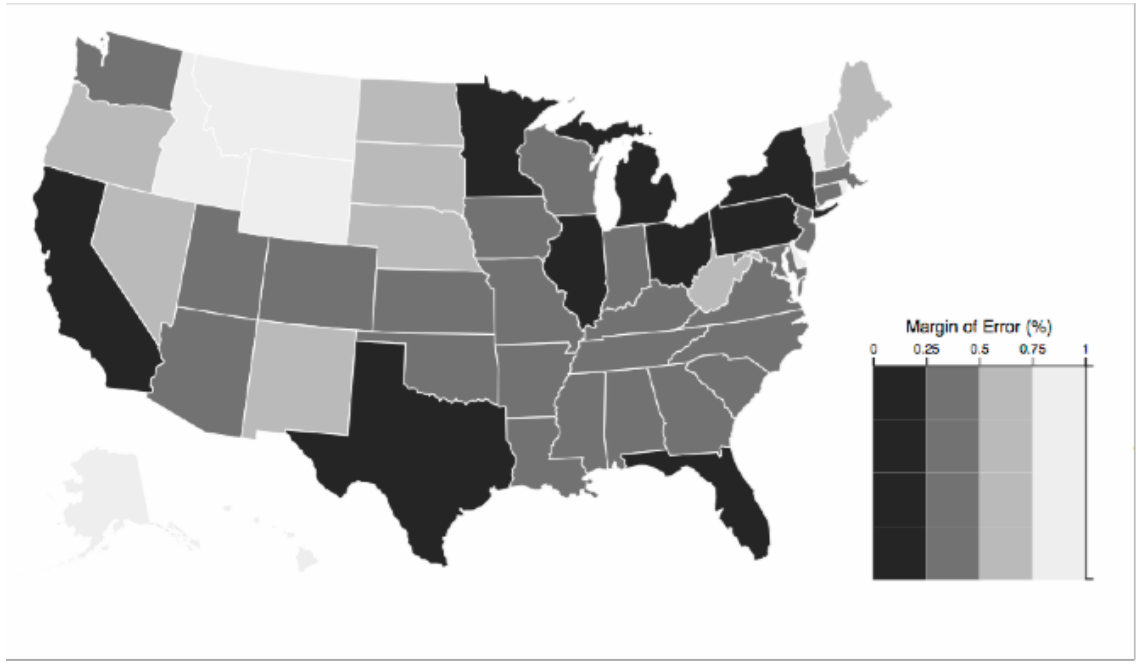


Presenting Uncertainty When Position Encoding is Occupied

Juxtaposition

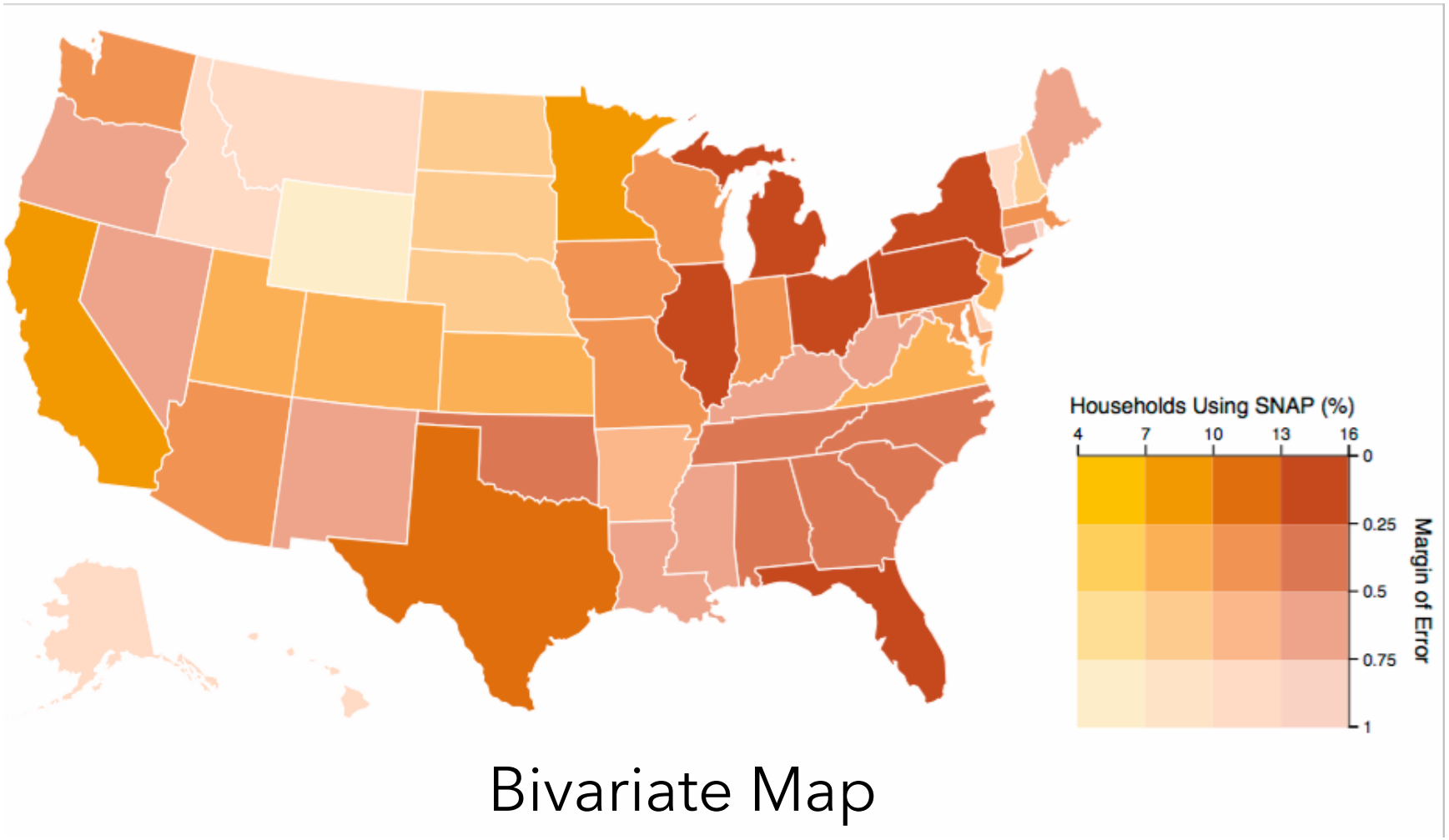


Data Map



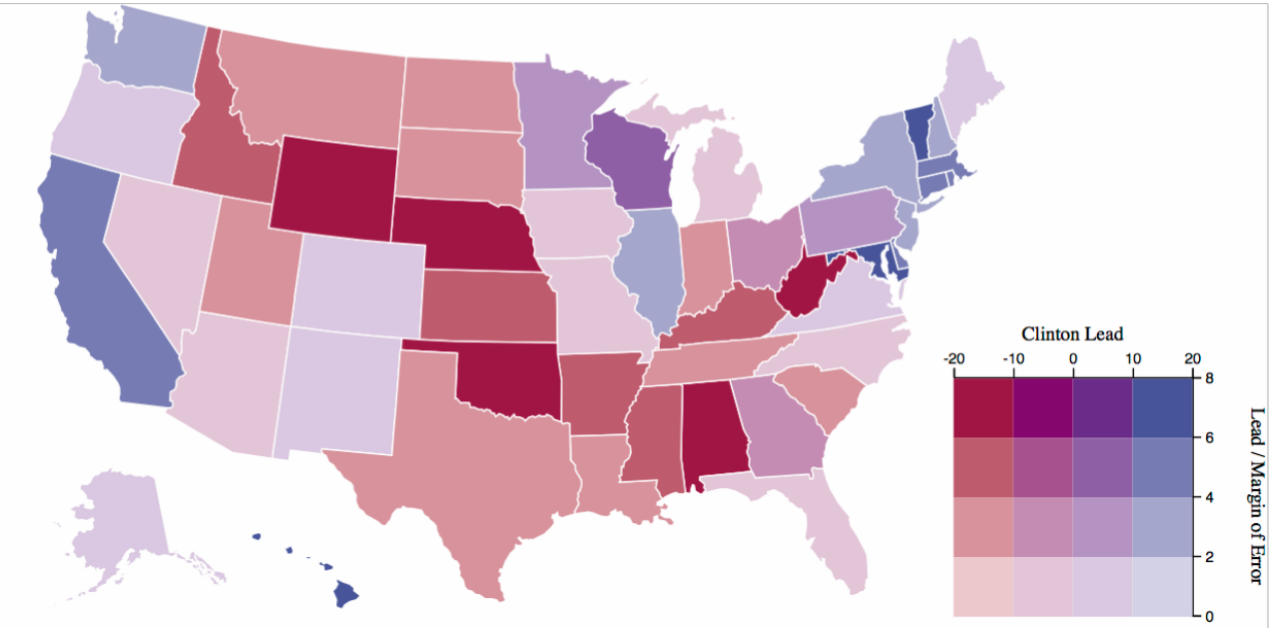
Uncertainty Map

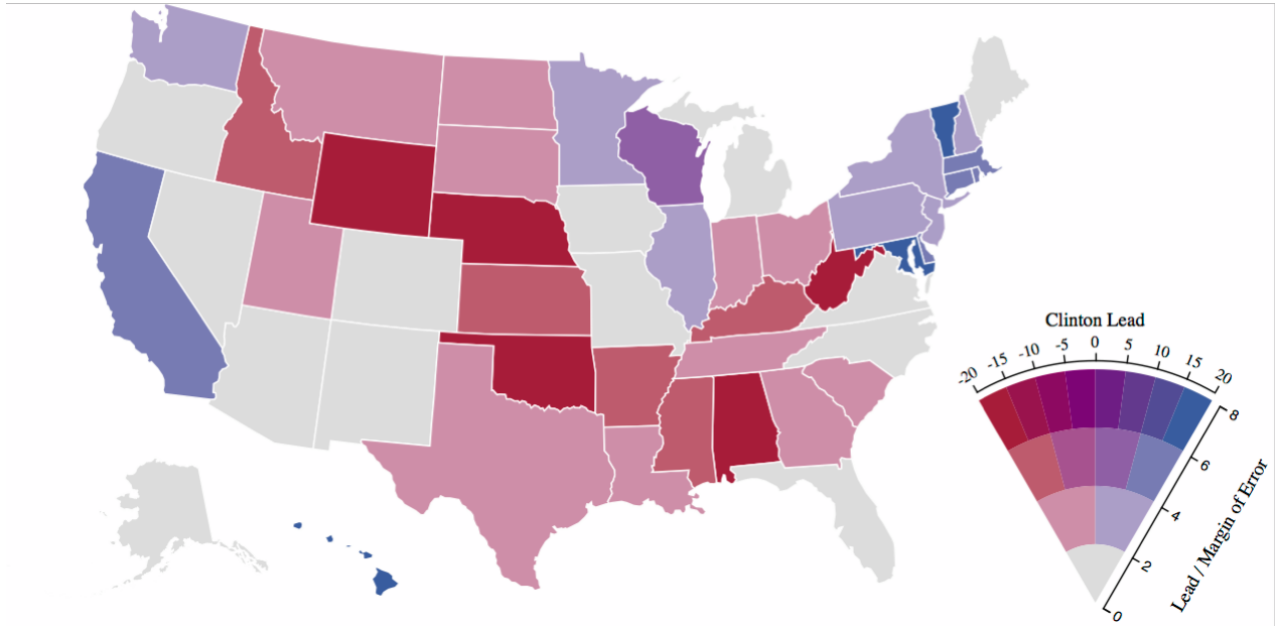
Superposition



Bivariate Map

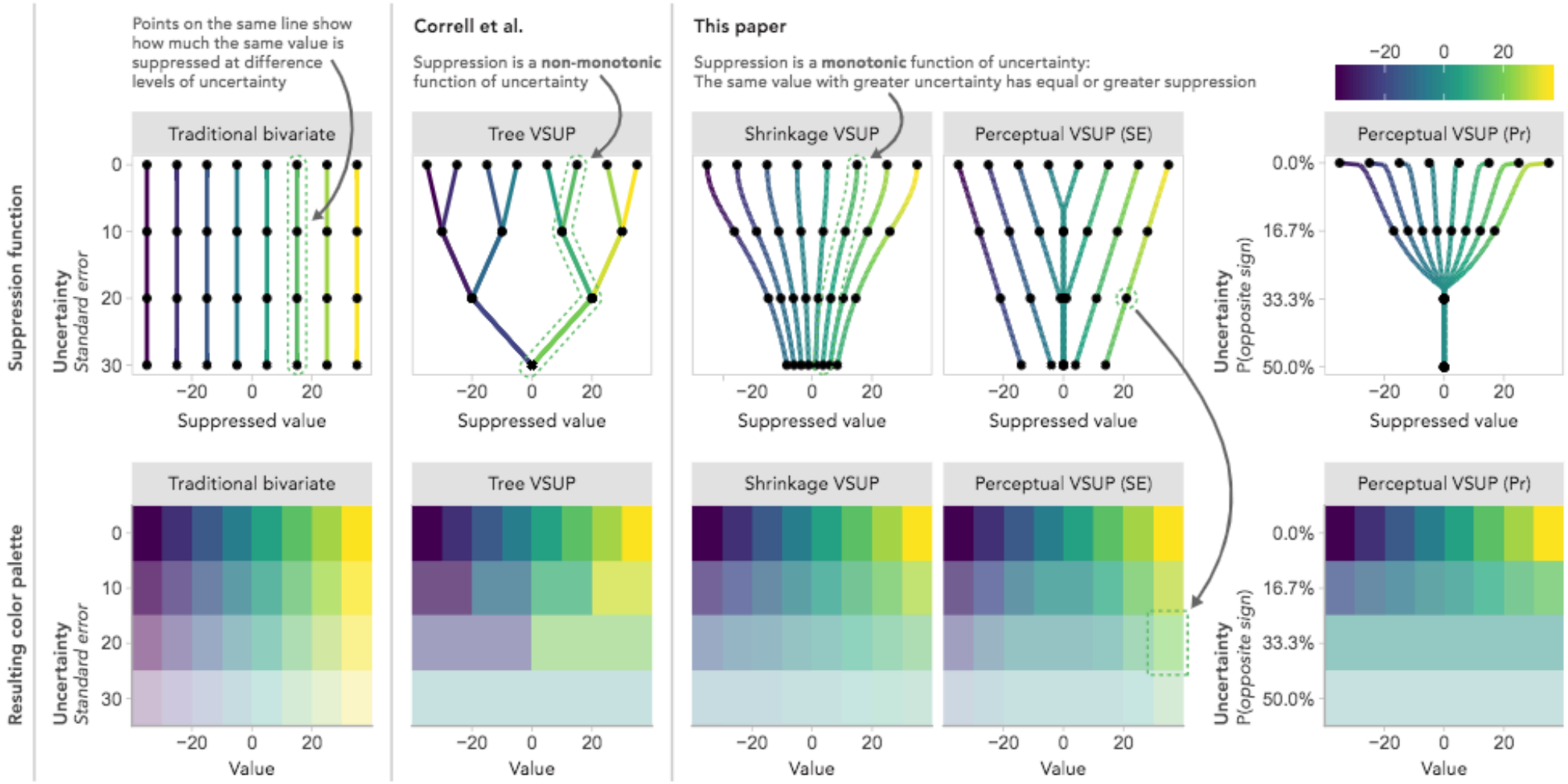
Value-Suppressing Uncertainty Palettes





Correl et al. (2018)

Value-Suppressing Uncertainty Palettes



Kay (in press)

Presenting Uncertainty for Multivariate Data

Multivariate Data

Example: MR spectroscopy

Measure the resonance frequencies of molecules in the brain.

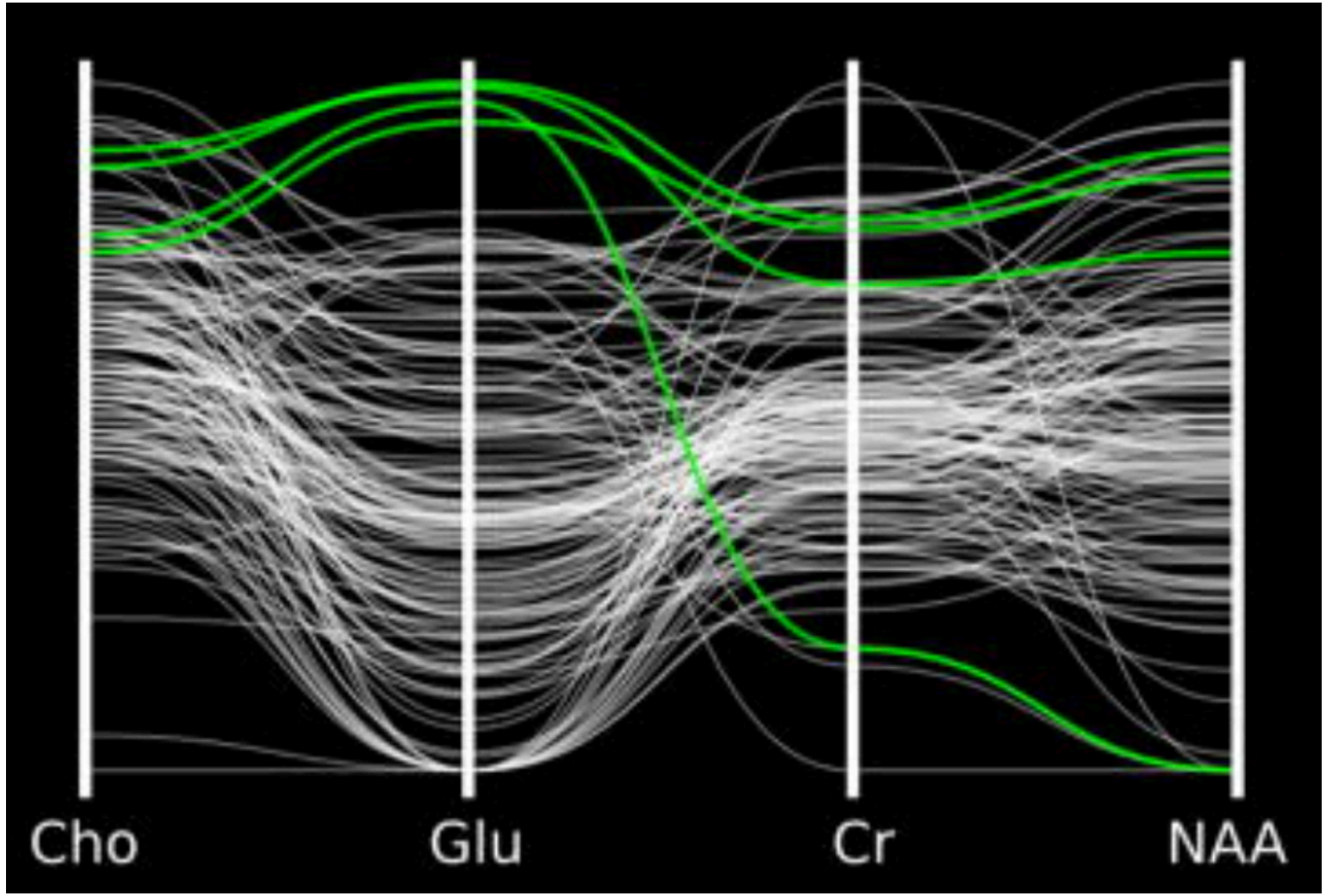
Voxels: spatial resolution of about a cubic centimeter

Model concentrations of different molecules.

Data format: One row per voxel; One column per molecule.

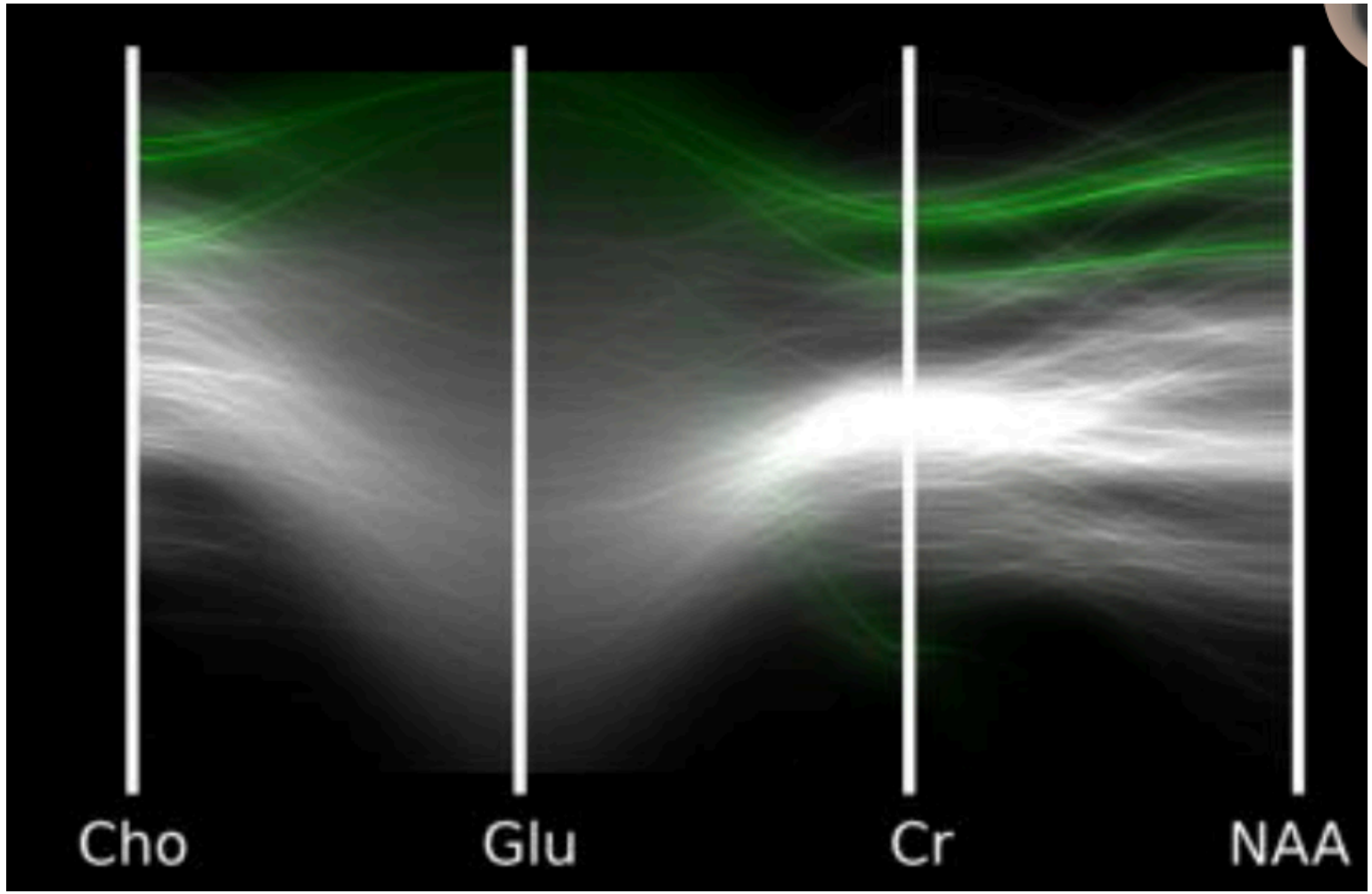
Parallel Coordinates

One line per voxel
(spatial unit)



Parallel Coordinates for Distributions

Show multivariate distribution for each voxel



Step 1: Interpolation

Input: Two distributions

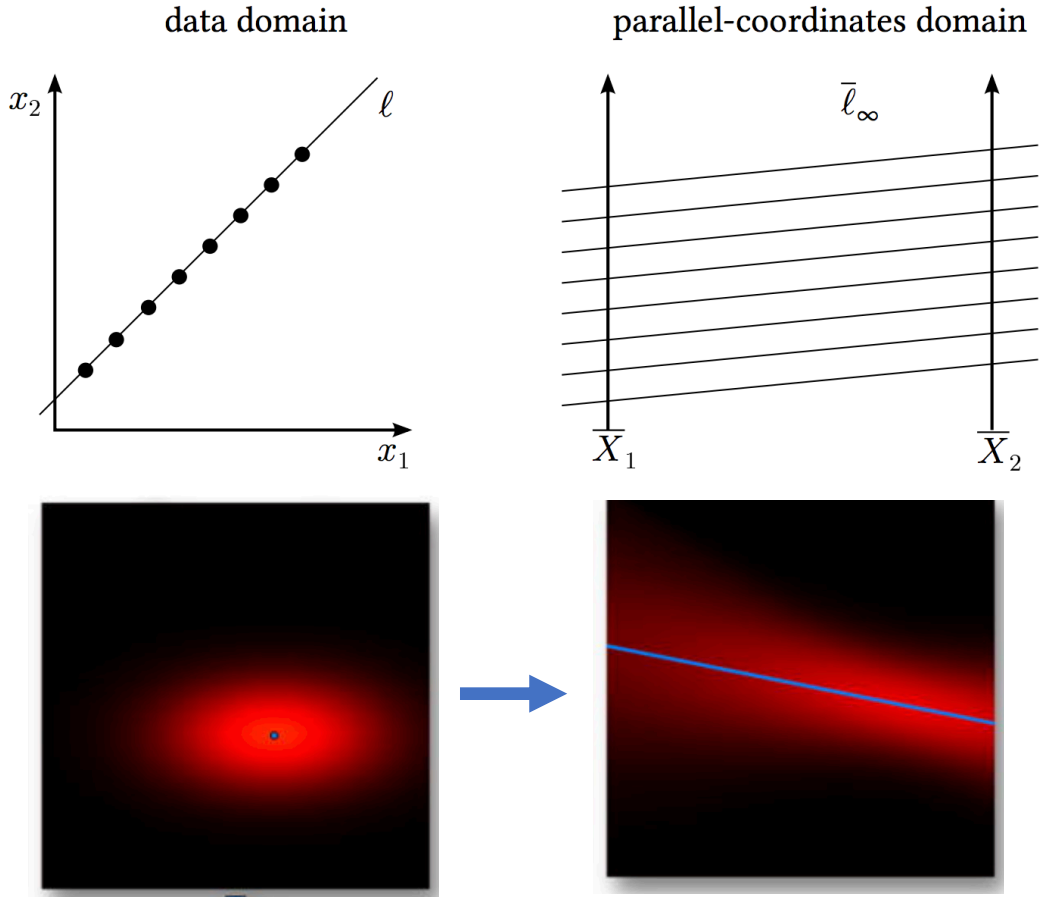
$x_1 = \mathrm{N}(\mu_1, \sigma_1^2)$

$x_2 = \mathrm{N}(\mu_2, \sigma_2^2)$

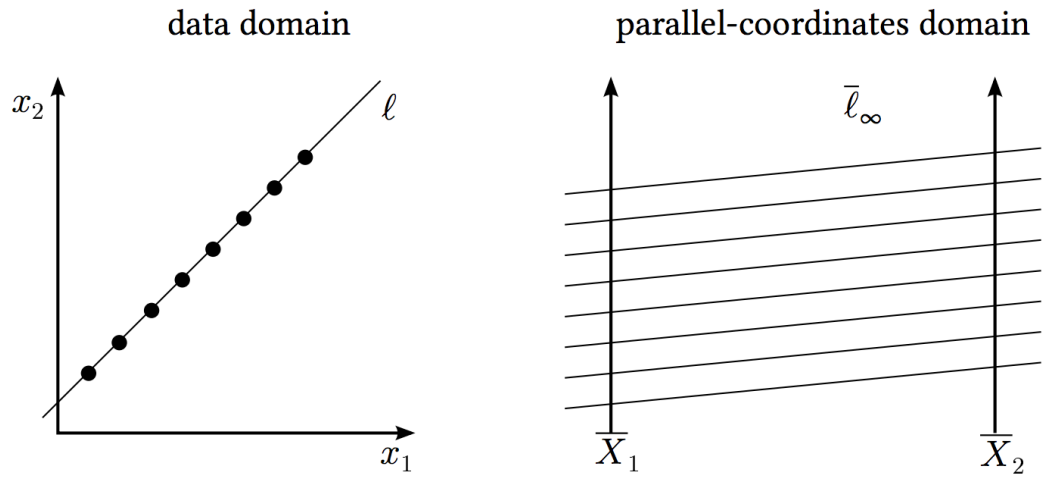
Output: μ and σ^2 across horizontal axis $a \in [0,1]$

$\mu_a = (1-a)\mu_1 + a\mu_2$

$\sigma_a^2 = (1-a)^2\sigma_1^2 + a^2\sigma_2^2$



Step 2: Calculate Probability Density



Input: μ_a and $\sigma_a{}^2$

Output: Probability density over horizontal span a and vertical span b

$\mathrm{PC}(a, b) = (1/\sqrt{2\boldsymbol{n}\sigma_a{}^2})\exp[-(b-\mu_a)2/2\sigma_a{}^2]$

Emphasizing Means

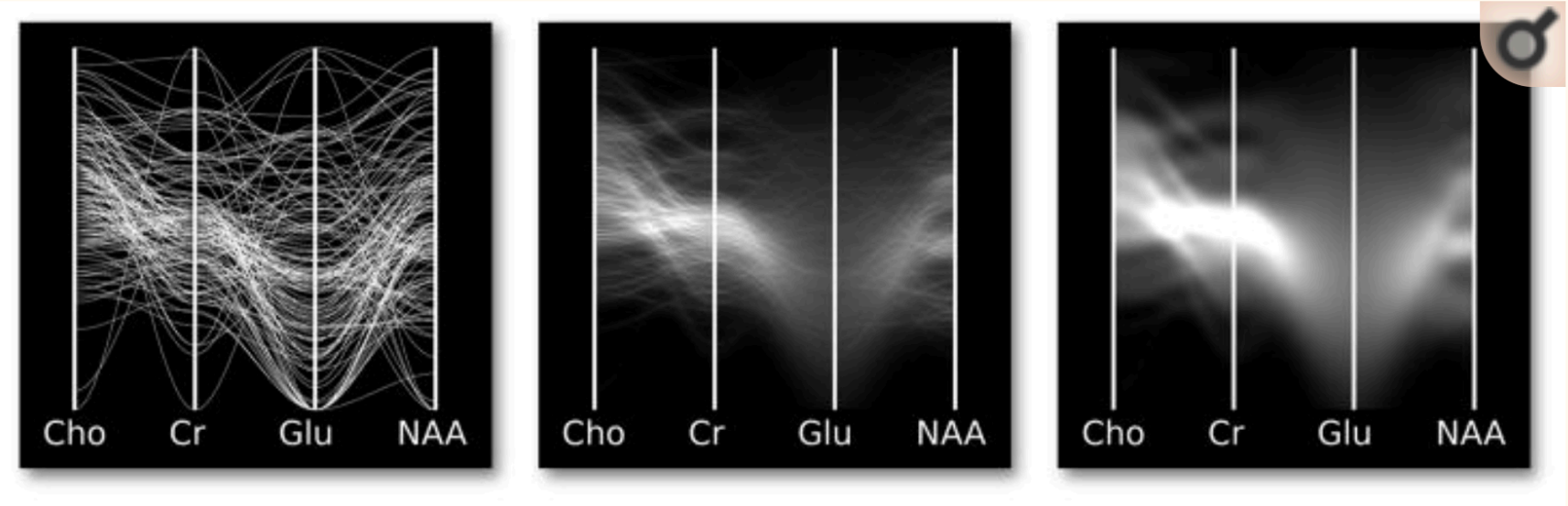
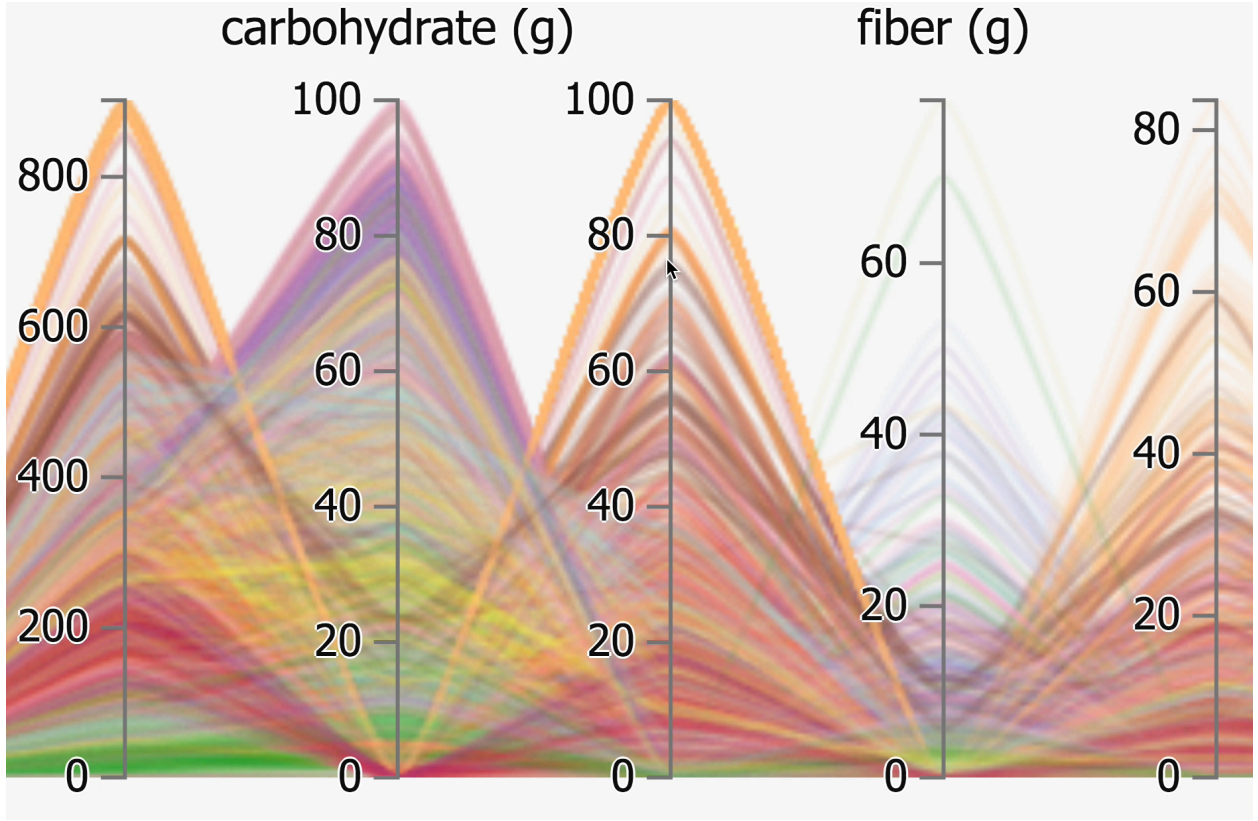
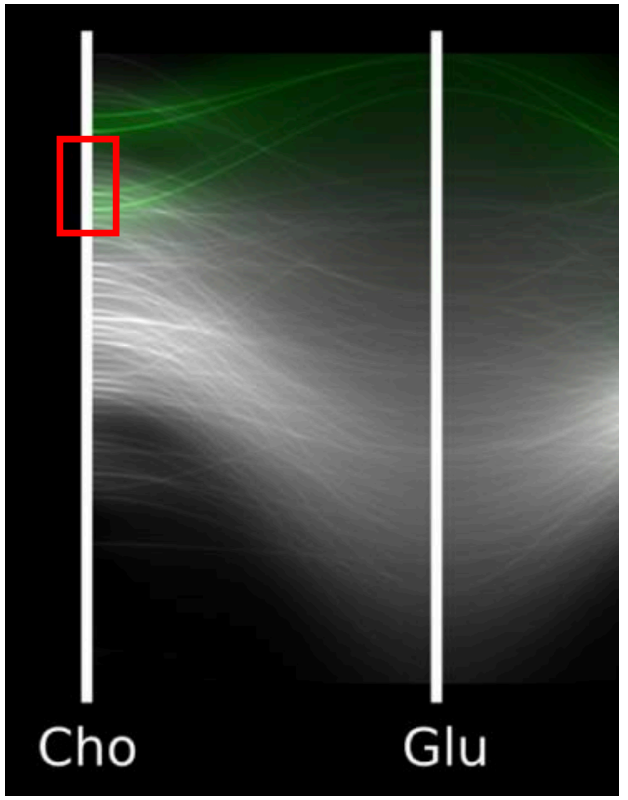


Fig. 6

Parallel coordinates plots of four MR spectroscopy metabolites. From left to right, means are decreasingly emphasized. Left: a sigmoidal PC plot of the same data shown in Figure 4 with two additional variables (glutamate and n-acetylaspartate). Center: the estimated PDF mapped into PC space, with means emphasized according to their uncertainty. Right: direct visualization of the PDF.

Implications for Brush Selection

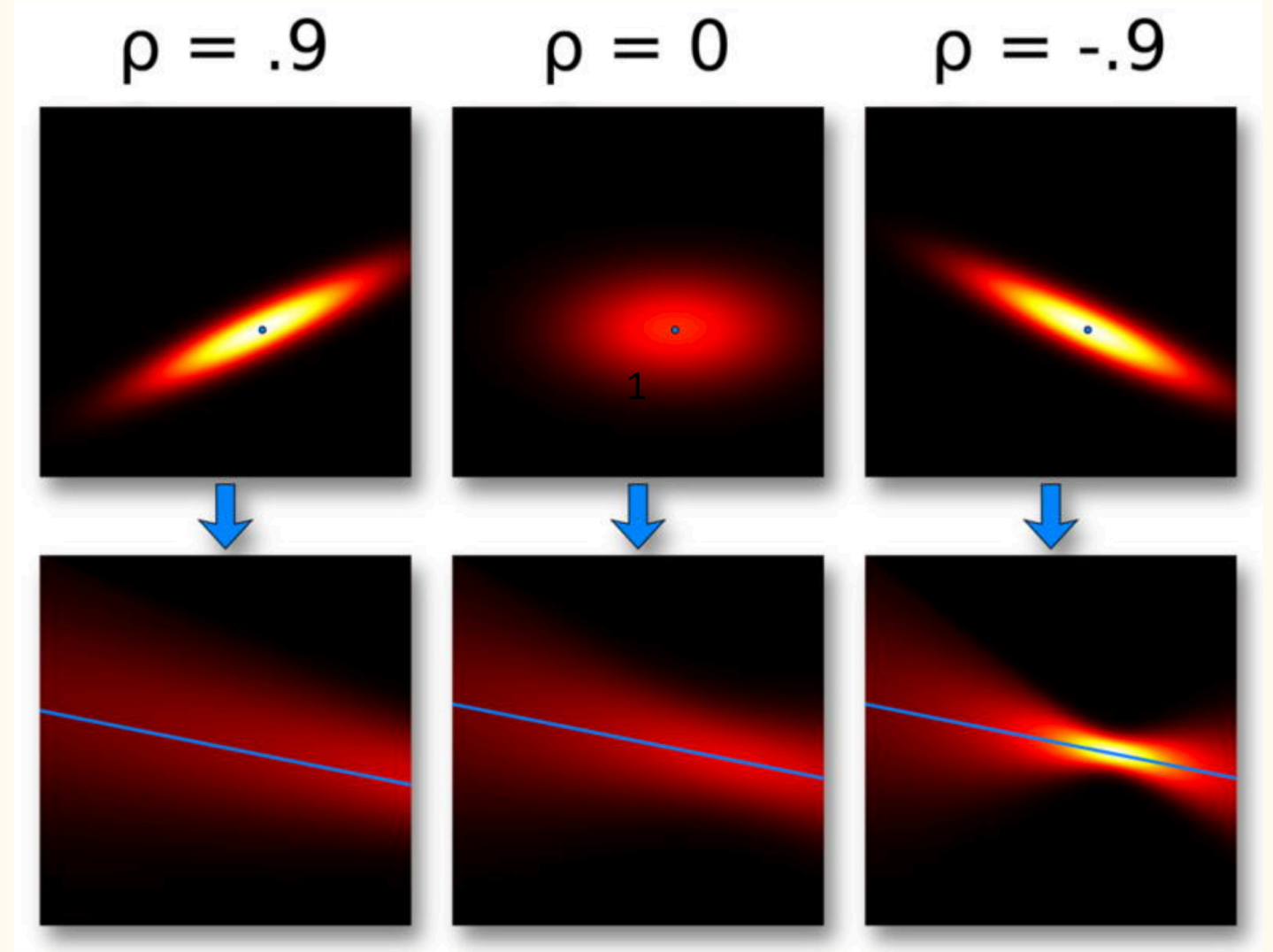




Compute integral within range of selection

Define threshold (e.g., 95%) to determine what lines are selected

Limited for Correlated Variables



Thanks!

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Slides adapted from Jessica Hullman & Michael Correl