ECEN 615
Methods of Electric Power Systems Analysis

Lecture 25: Inertia Power Flow, Black Start, Electric Grid Visualization

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Announcements

- Homework 7 is due on Nov 24
- Associated with Homework 7 there can be optional student presentations on Nov 24
  - Let me know if you would like to present

Inertia and Governor Power Flows

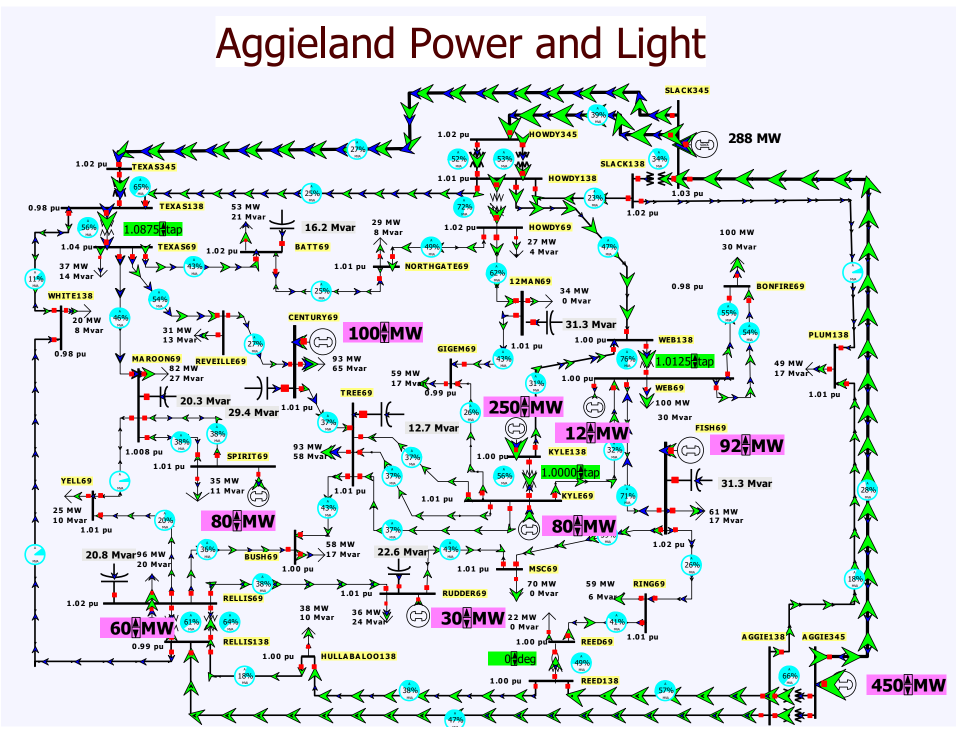
- In the regular power flow a single slack bus is used so total load + losses = total generation
- The slack bus is characterized by having a fixed voltage magnitude and angle
  - A slack bus is needed for each island though nothing precludes having multiple slack buses in an island
- If an area is on AGC then the outputs for the other generators can be changed either before or during the power flow solution
- This does not match the initial change in the generator output following a contingency

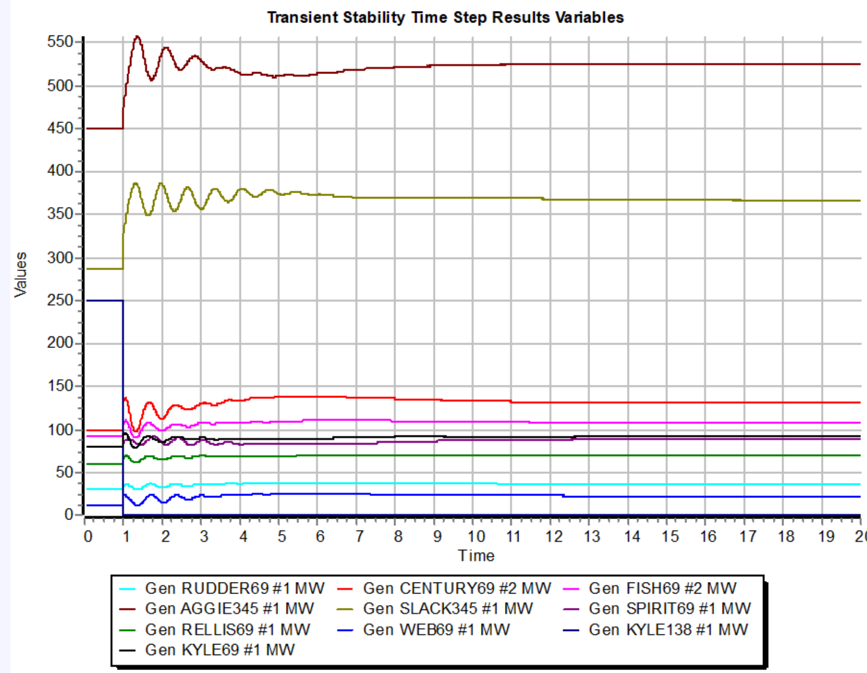
Inertia and Governor Power Flows

- Following a generation and/or load contingency the changes in the generator outputs will be
  - Initially determined by the generator's inertia
  - After several seconds the output will be determined by the generator's governor response, which takes into account limits
  - After dozens of seconds to minutes the AGC will respond
- A governor or an inertia power flow seeks to match this initial response
  - A useful reference is M. Lotfalian, R. Schlueter, et. al., "Inertial, Governor and AGC/Economic Dispatch Load Flow Simulations of Loss of Generation Contingencies," IEEE Trans. Power Apparatus and Systems, Nov. 1985

Generator Output Example

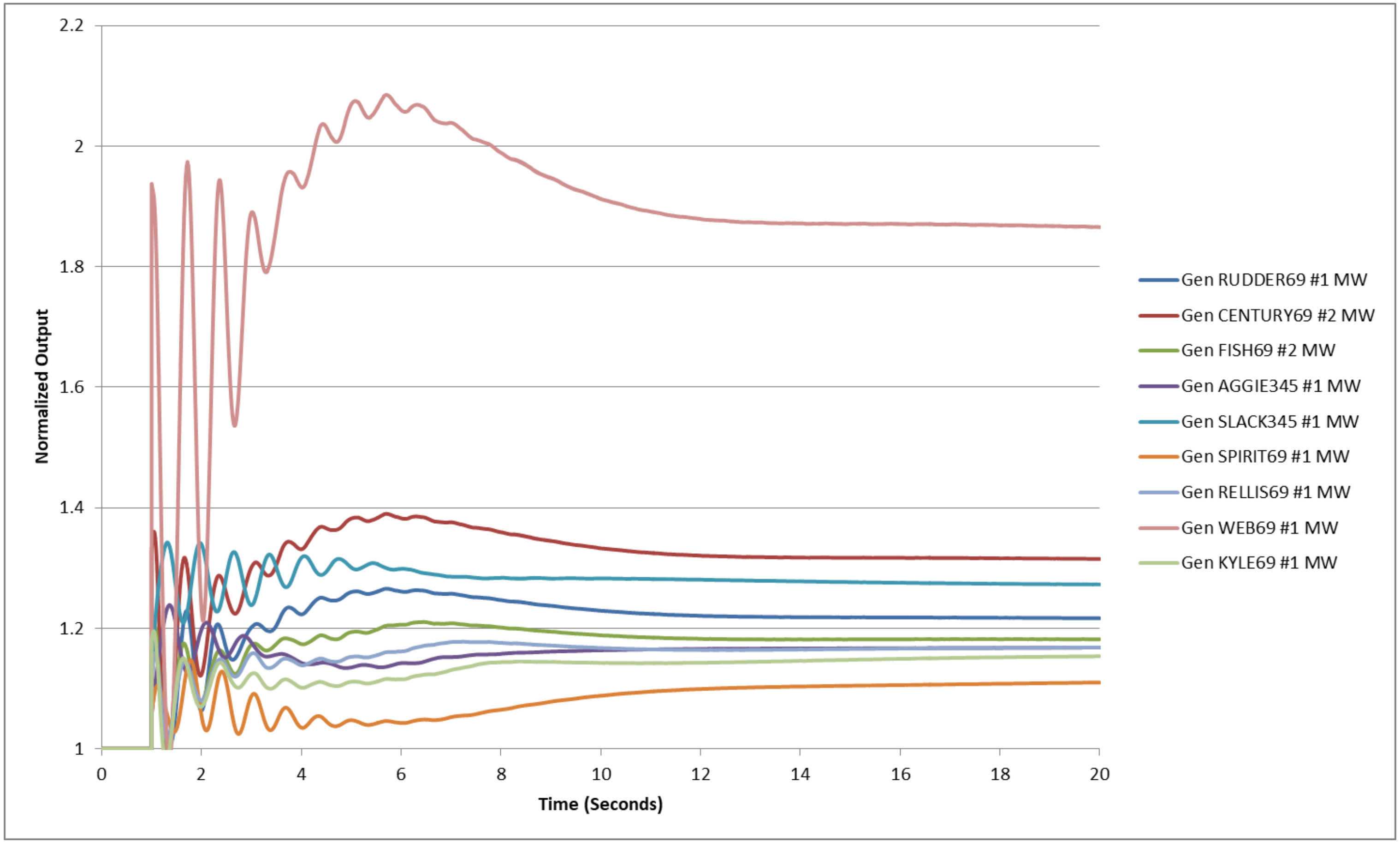
- Example shows the generator outputs following the loss of a 250 MW generator (at Kyle138)





Generator Output Example, cont.

- Graph shows the normalized change in output, with the initial value based on the inertia then on the governor



Inertia and Governor Power Flows

- The inertia and governor power flows seek to match this response by including in each real power balance equation an additional term that the allocates this power mismatch to each generator in proportion to its relative percentage inertia or relative percentage governor response
- This is a distributed slack approach since the allocation occurs inside the power flow iteration
- There is still a slack bus to provide an angle reference

Inertia Power Flow

- In an inertia power flow let α be the accelerating power. Then at each generator bus i the generator output is

$$P_{Gi} = P_{0,Gi} + \frac{H_i}{H_T}\alpha$$

where $P_{0,Gi}$ is the initial power output for the bus i generators,

H_i is the inertia constant for all the generators at bus i and

H_T is the total inertia constant for all the generators

(both values are per unit on the system MVA base)

- The accelerating power can just be included as a solution variable
- Real power flow equations are then written for all the buses, but the slack angle is not a solution variable

Two Bus DC Power Flow Example

- Assume a two bus system with the buses connected with a lossless line with X=0.1. Let bus 2 be the slack with θ_2=0, generators at both buses with P_{G1} =1 and a single load (at bus 1) with P_{L1}=3. Assume equal inertia for the generators
- In a traditional dc power flow there is one equation

$$P_{G1} - P_{L1} = 1 - 3 = 10\theta_1$$

Two Bus DC Power Flow Example

- With the inertia approach there would be two equations and the power is specified at both buses (say P_{G2}=1.5)

$$P_{G1} - P_{L1} + 0.5\alpha = 10\theta_1$$
$$P_{G2} + 0.5\alpha = 10\theta_1$$

- Solving gives

$$\begin{bmatrix} 10 & -0.5 \\ -10 & -0.5 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \alpha \end{bmatrix} = \begin{bmatrix} -2 \\ 1.5 \end{bmatrix} \rightarrow \begin{bmatrix} \theta_1 \\ \alpha \end{bmatrix} = \begin{bmatrix} -0.175 \\ 0.5 \end{bmatrix}$$

Power System Restoration

- Power system restoration or black start (or blackstart)
  - A procedure to restore power in the event of a partial or total shutdown of the power system
  - A highly complex decision problem
- Object is to serve the load as soon as possible without violating operating constraints
  - Actions are time critical
- Primarily manual work by operators
- Offline restoration planning usually based on simulations

Power System Restoration

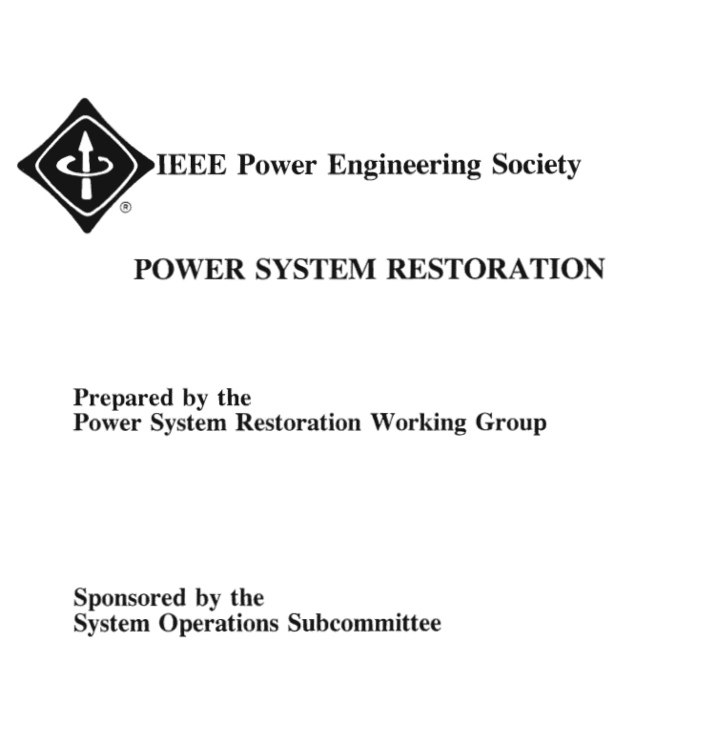
- Common characteristics of restoration (even though strategies are different)
  - Immediate resupply of station service
  - Time consuming nature of switching operation
  - Start-up timings of thermal units
  - Voltage rise problems of energizing unloaded transmission lines
  - Frequency response of prime movers to a sudden load pickup
  - Cold load inrush, power factors and coincident demand factors

System Restoration Efforts - IEEE

- After 1977 New York City blackout, DOE required operating companies to develop a power system restoration plan, train personnel, regularly update and maintain the plan.
- In response to this requirement in 1978, the Power System Operation Committee established the Power System Restoration (PSR) Task Force (TF) within the System Operation Subcommittee of the Power System Engineering Committee.
- A few years later, the PSR TF was upgraded to PSR working group (WG)

System Restoration Efforts - IEEE

- In 1993 a 110 page brochure was prepared by PSR WG and published by the IEEE PES
- Includes:
  - 14 IEEE Committee Reports
  - 5 SRWG member papers in IEEE publication
  - 13 related IEEE transaction papers



IEEE Power Engineering Society

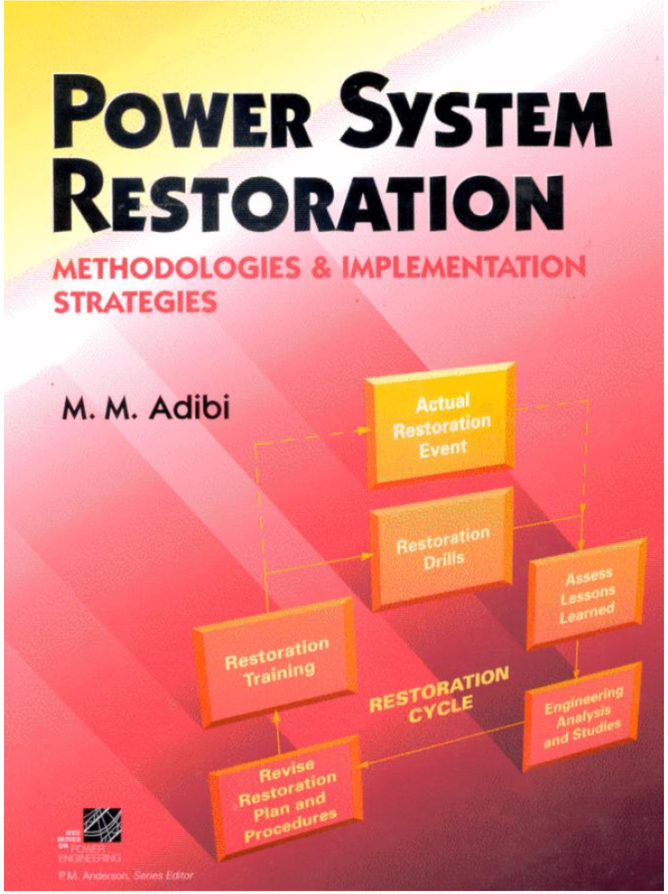
POWER SYSTEM RESTORATION

Prepared by the
Power System Restoration Working Group

Sponsored by the
System Operations Subcommittee

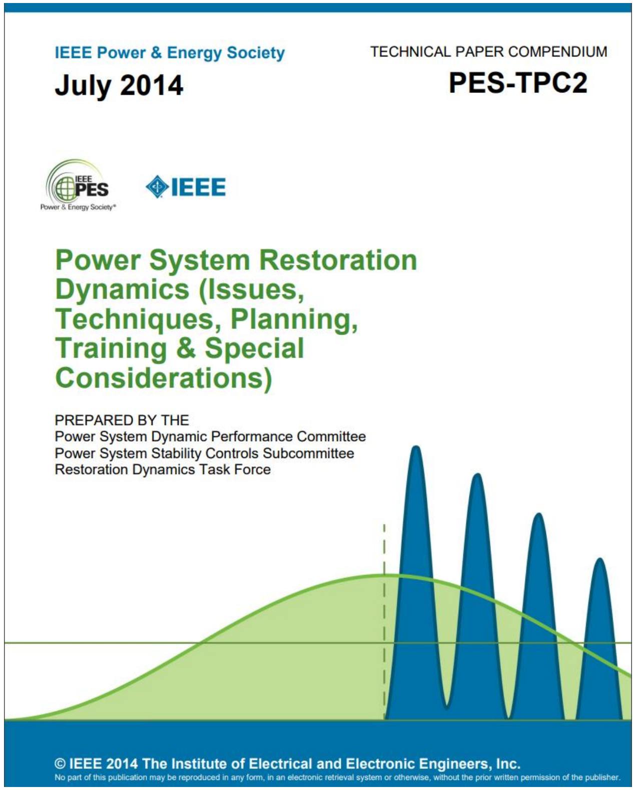
System Restoration Efforts - IEEE

- In 2000 a 700 page book was prepared by PSRWG and published by Wiley-IEEE Press
- Includes 87 papers including 14 papers in the original 1993 collection



System Restoration Efforts - IEEE

- In 2014 40 IEEE papers by 110 authors including 42 panelists of Restoration Dynamics Task Force
- Covers:
  - Real power balance and control of frequency
  - Reactive power balance and control of voltages
  - Critical tasks (time sensitive functions)
  - Analyses and simulations



Mahmood Mike Adibi (1924 – 2018)

- The godfather of power system restoration
- B.S.E. in 1950 from University of Birmingham, U.K.
- M.S.E in 1960 from Polytech Institute of Brooklyn, NY
- IEEE Life Fellow
- Founder and chairman of the IEEE System Restoration Working Group in 1979
- Author of the book, “Power System Restoration – Methodologies and Implementation Strategies”
  - A great review book of IEEE papers between 1987 and 1999
- Developed restoration plans for over a dozen utilities

Other Good References

- PJM Manual 36: System Restoration
- EPRI, “Development of Power System Restoration Tool Based on Generic Restoration Milestones,” 2010.
- PSERC, “Development and Evaluation of System Restoration Strategies from a Blackout,” 2009.
- IESO, “Part 7.8: Ontario Power System Restoration Plan,” 2017.
- K. Sun et al., “Power System Control Under Cascading Failures: Understanding, Mitigation, and System Restoration,” Wiley-IEEE Press. 2019.
- Yutian Liu, Rui Fan, and Vladimir Terzija, “Power system restoration: a literature review from 2006 to 2016,” *J. Mod. Power Syst. Clean Energy*, 2016, 4(3), pp. 332-341

NERC Standards on Restoration

- NERC System Restoration and Black Start standards
  - EOP-005-2 & EOP-005-3
    - System Restoration from Black Start Resources
    - Ensure plans, Facilities, and personnel are prepared to enable System restoration from Black Start Resources to assure reliability is maintained during restoration and priority is placed on restoring the Interconnection
  - EOP-006-2 & EOP-006-3
    - System Restoration Coordination
    - Ensure plans are established and personnel are prepared to enable effective coordination of the System restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection.

Common Issues during Restoration

- Active power balance and frequency control
  - Need to maintain system frequency within limits by system stability and protection settings
  - Can be accomplished by picking up loads in increments
- Reactive power balance and overvoltage control
  - Energizing few high voltage lines
  - Operating generators at minimum voltage levels
  - Deactivating switched shunt capacitors
  - Connecting shunt reactors
  - Adjusting transformer taps
  - Picking up reactive loads

Common Issues during Restoration

- Transient switching voltages
  - Switching surges occur when energizing equipment
- Self-excitation
  - When the charging current is high relative to the size of generators
  - When opening a line at the sending end but leaving the line connected to a large motor
  - This causes overvoltage and damages equipment
- Cold load pickup
  - When load has been de-energized for several hours or more
  - Inrush current can be as high as 8 – 10 times of the normal value

Common Issues during Restoration

- System stability
  - Voltage should be within limits
  - Angle stability have to be maintained
  - Frequency is the main issue in stability assessment
- Protective systems and load control
  - Continuous change in system configuration and in operating conditions may trigger undesirable operation of relays
  - Load shedding can be useful in case of low frequency conditions

Common Issues during Restoration

- Partitioning system into islands
  - Necessary to speed up the process, especially for large systems
  - NERC standards
    - Each islands must have sufficient black start capability
    - Each islands should have enough cranking paths to gens and loads
    - Each islands should be able to match generation and load within prescribed frequency limits
    - Each islands should have adequate voltage controls
    - All tie points must be capable of synchronization with adjacent subsystems
    - All islands should share information with other islands

Generic Restoration Steps

- Preparation stage (1 – 2 hours)
  - Evaluate pre- and post-disturbance conditions
  - Define the target system
  - Restart generators and rebuild transmission network
- System restoration stage (3 – 4 hours)
  - Energize transmission paths
  - Restore load to stabilize generation and voltage
  - Synchronize islands and reintegrate bulk power system
- Load restoration stage (8 – 10 hours)
  - Load restoration is the governing control objective
  - Load pickup is scheduled based on generation availability
  - Load restoration is effected in increasingly larger steps

System Restoration Tasks

- Know the status of the grid
- List and rank critical loads by priority
- List and rank initial sources of power by availability
  - Maximize generation capabilities with the available black start resources
- Determine the most effective ways of brining the two together
  - Schedule tasks and resources during restoration
  - Establish transmission capability and paths while meeting operating constraints

Initial Power and Load

- Initial source of power

Type	Time (min)	Success probability
Run-of-the-River Hydro	5-10	High
Pump-Storage Hydro	5-10	High
Combustion Turbine	5-15	Medium
Tie-line with Adjacent Systems	Short	

- Initial critical loads

Type	Priorities
Cranking drum-type units	High
Pipe-type cables pumping plants	High
Transmission stations	High to Medium depending on location
Distribution stations	High to Medium depending on location
Industrial loads	Medium to low

Electric Grid Visualization

- Electric grid models can be quite complex and large
  - There are commonly many assumptions and automatic control actions embedded in these models.
- Oftentimes engineers do studies associated with these grids, not always fully understanding these embedded assumptions or how the models can fail
- Electric grid visualization is focused on helping people understand what occurred when the engineer “pushed the button.”

Visualization Software Design

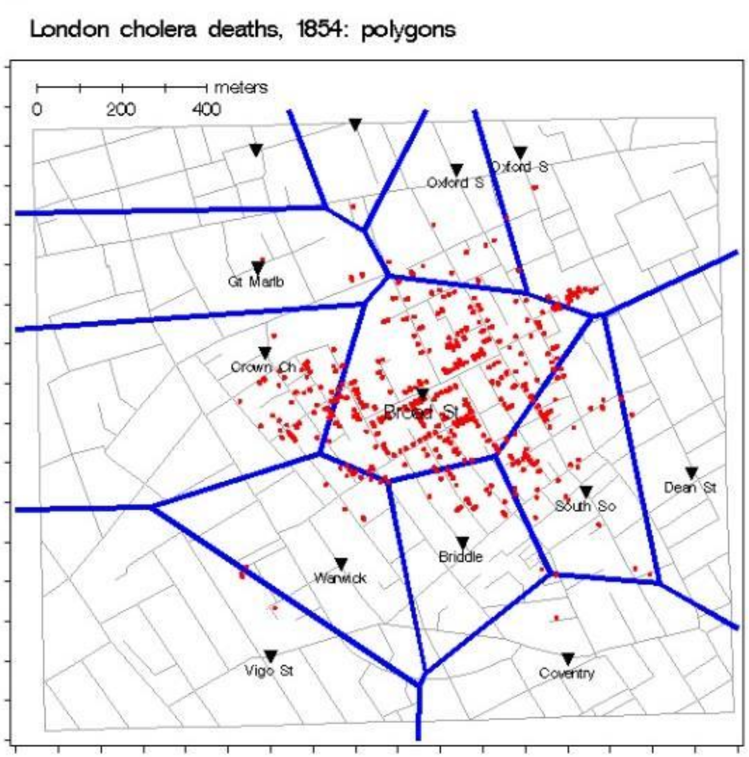
- Key question: what are the desired tasks that need to be accomplished?
  - Needs for real-time operations might be quite different than what is needed in planning
- Understanding the entire processes in which the visualizations are embedded is key
- Software should help humans make the more complex decisions, i.e., those requiring information and knowledge
  - Enhance human capabilities
  - Alleviate their limitations (adding up flows into a bus)

Some Useful General References

- Colin Ware, *Information Visualization: Perception for Design*, Fourth Edition, 2021
- Edward Tufte, *Envisioning Information*, 1990
- Edward Tufte, *Visual Explanations: Images and Quantities*, 1997
- Edward Tufte, *The Visual Display of Quantitative Information*, 2001
- Edward Tufte, *Beautiful Evidence*, 2006
- Claus Wilke, *Fundamentals of Data Visualization*, 2019

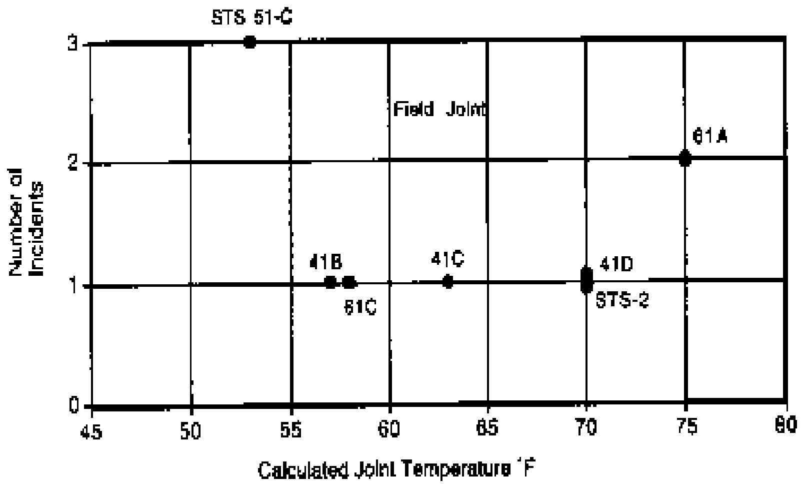
Example: Visualization and Cholera in Central London, 1854

Dr. John Snow helped to end an epidemic by noting that the deaths were clustered about the Broad Street Water pump

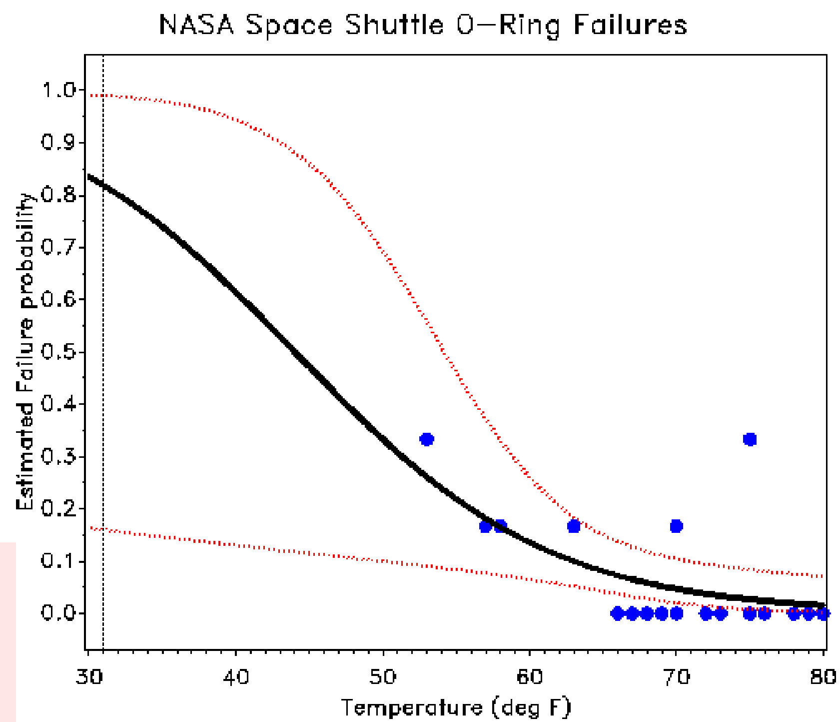


Images source: http://www.datavis.ca/gallery/historical.php

Example: Visualization and Challenger, 1986



Graph used to determine whether to launch Challenger in 1986; shows O-ring failure vs. temperature but neglects launches with no failures



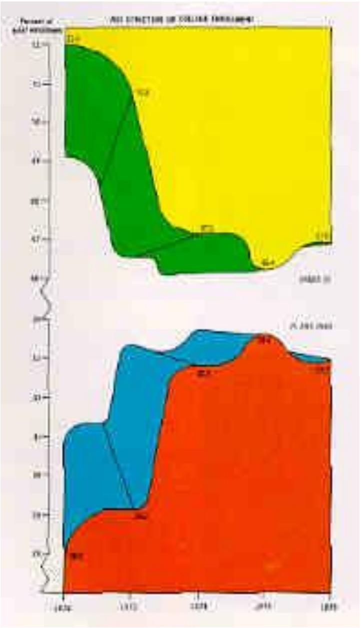
A better graphic including all data. Would you launch at 32ºF?

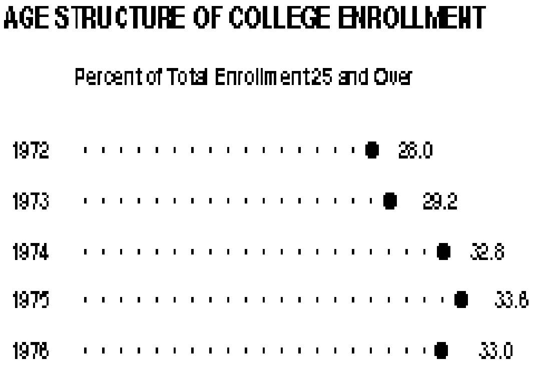
http://www.datavis.ca/gallery/missed.php

Visualization Cautions!

- Just because information can be shown graphically, doesn’t mean it should be shown
- Three useful design criteria from 1994 EPRI visualization report:

  1. Natural encoding of information
  2. Task specific graphics
  3. No gratuitous graphics





Tufte: “may well be worst graphic ever”

Source: E. Tufte, The Visual Display of Quantitative Information, Graphics Press, Cheshire, CT, 1983.

Visualization and User Familiarity

- Visualizations do not exist in a vacuum; the prior experience of the users is a key consideration
  - QWERTY keyboard arrangement is a classic example, in which a design that was originally setup in the 1870's to prevent mechanical problems is still used today
- Using existing visual metaphors in new designs help them seem more familiar (like a folder)
  - A skeuomorphic design retains no longer needed structures that were inherent in the original, usually to make them more familiar (using gauges, sliders, buttons and analog clocks in visualizations are examples)

Decision Making, Data, Information, Knowledge

- Ultimate goal is to help humans make better decisions
- Competing definitions for the process of taking raw "data" and producing something useful
  - Understanding, decisions, wisdom
- Data: symbols, raw, it simply exists
- Information: Data that is given meaning, often in a relational context; some how processed
- Knowledge: Application of information to answer "how." Connecting patterns.
- Understanding, and/or wisdom at top

The Visualization Process

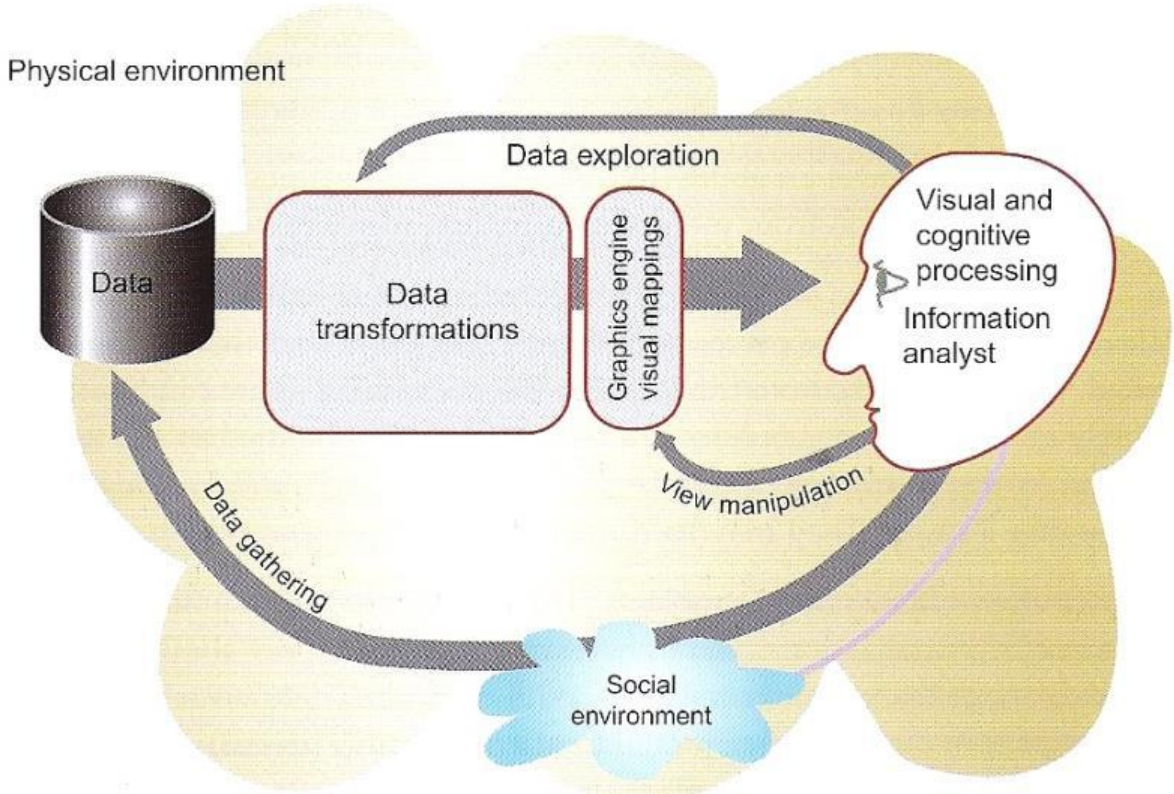


Figure 1.2 The visualization process.

Image source: Colin Ware, *Information Visualization*, Fourth Edition, 2021

Understanding the Entire Process is Key

- Understanding the entire processes in which the visualizations are embedded is key.
  - What is the "information access" cost?
  - How will the information be used and shared?
  - Is it raw data, or derived values?
  - Should the visualizations sit on top of a model, or is a standalone process sufficient?
  - Ultimately, what are the desired tasks that need to be accomplished?
- We'll start with a brief coverage of some traditional approaches (tabular, graphs and onelines, then go into some newer ones)

Example: Tabular Displays

- In many contexts, tabular displays (particularly with interactive features such as sorting, filtering, drill-down, and the ability to enter data) can be a great way to show data

	Number	Area Name	Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Act G Shunt MW	Act B Shunt Mvar	Area Num	Zone Name	Zone Num
1	1001	Far West	ODESSA 2 0	115.00	0.98089	112.802	-30.18	20.78	5.89				0.00	0.00	1	Far West T	9
2	1002	Far West	PRESIDIO 2 0	115.00	1.01218	116.400	-24.75	15.41	4.37				0.00	0.00	1	Far West T	9
3	1003	Far West	O DONNELL 1	115.00	1.00832	115.956	-25.02						0.00	0.00	1	Far West T	9
4	1004	Far West	O DONNELL 1	230.00	1.01000	232.301	-26.84			158.25	-29.07		0.00	0.00	1	Far West T	9
5	1005	Far West	BIG SPRING 5	115.00	1.00790	115.908	-22.77						0.00	0.00	1	Far West T	9
6	1006	Far West	BIG SPRING 5	13.80	1.00147	13.820	-20.60			25.73	-4.94		0.00	0.00	1	Far West T	9
7	1007	Far West	VAN HORN 0	115.00	1.01973	117.268	-25.10	7.01	1.99			0.00	0.00	0.00	1	Far West T	9
8	1008	Far West	IRAAN 2 0	115.00	1.00133	115.153	-13.78						0.00	0.00	1	Far West T	9
9	1009	Far West	IRAAN 2 1	13.80	1.00000	13.800	-10.41			61.87	-2.55		0.00	0.00	1	Far West T	9
10	1010	Far West	PRESIDIO 1 0	115.00	1.01933	117.223	-23.46					0.00	0.00	0.00	1	Far West T	9
11	1011	Far West	PRESIDIO 1 1	22.00	1.01958	22.431	-22.12			7.50	0.00		0.00	0.00	1	Far West T	9
12	1012	Far West	SANDERSON	115.00	0.98899	113.734	-29.67	2.99	0.85			9.29	0.00	0.00	1	Far West T	9
13	1013	Far West	MONAHANS 2	115.00	1.00167	115.192	-21.95	29.23	8.28				0.00	0.00	1	Far West T	9
14	1014	Far West	GRANDFALLS	115.00	1.00324	115.373	-18.04	2.22	0.63				0.00	0.00	1	Far West T	9
15	1015	Far West	MARFA 0	115.00	1.02132	117.451	-24.87	7.51	2.13				0.00	0.00	1	Far West T	9
16	1016	Far West	GARDEN CITY	115.00	1.01758	117.022	-21.94	2.89	0.82			31.06	0.00	0.00	1	Far West T	9
17	1017	Far West	ODESSA 4 0	115.00	0.98205	112.936	-28.53	18.34	5.20				0.00	0.00	1	Far West T	9
18	1018	Far West	NOTREES 0	115.00	0.99128	113.997	-27.25	0.07	0.02				0.00	0.00	1	Far West T	9
19	1019	Far West	MIDLAND 4 0	115.00	1.00078	115.090	-29.70	61.78	17.50			143.20	0.00	0.00	1	Far West T	9
20	1020	Far West	BIG SPRING 1	115.00	1.02190	117.519	-21.73					80.13	0.00	0.00	1	Far West T	9
21	1021	Far West	BIG SPRING 1	13.80	1.00000	13.800	-15.11			149.63	-25.59		0.00	0.00	1	Far West T	9
22	1022	Far West	O DONNELL 2	115.00	1.01132	116.302	-24.18						0.00	0.00	1	Far West T	9
23	1023	Far West	O DONNELL 2	13.80	1.01000	13.938	-15.27			135.00	3.21		0.00	0.00	1	Far West T	9
24	1024	Far West	ODESSA 6 0	115.00	0.99425	114.338	-26.17	63.04	17.86				0.00	0.00	1	Far West T	9
25	1025	Far West	BIG SPRINGS 0	115.00	1.01805	117.076	-20.73						0.00	0.00	1	Far West T	9
26	1026	Far West	BIG SPRINGS 1	13.80	1.00000	13.800	-11.21			93.15	-4.41		0.00	0.00	1	Far West T	9
27	1027	Far West	MIDLAND 2 0	115.00	1.01258	116.447	-32.98	101.21	28.68			76.90	0.00	0.00	1	Far West T	9
28	1028	Far West	COAHOMA 0	115.00	1.01371	116.577	-25.80	10.01	2.84				0.00	0.00	1	Far West T	9
29	1029	Far West	MIDLAND 3 0	115.00	1.00868	115.998	-31.93	83.18	23.57			40.70	0.00	0.00	1	Far West T	9

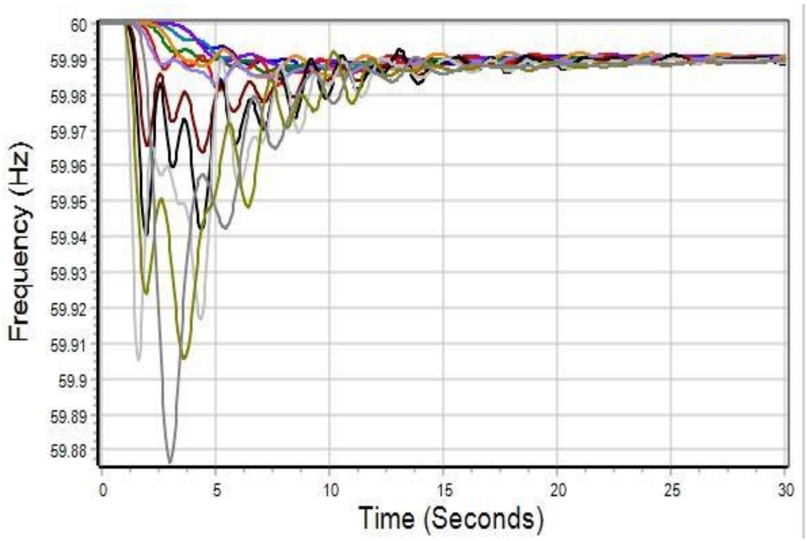
Use of Color

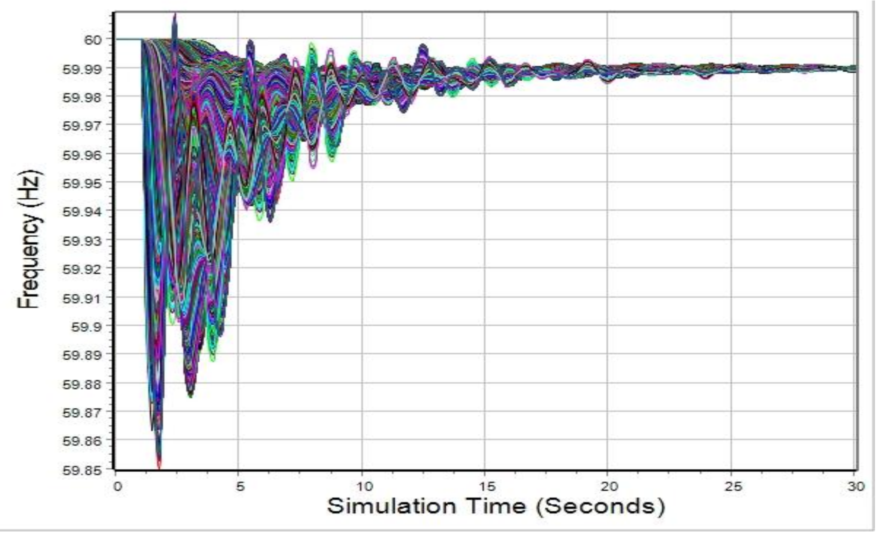
- Some use of color can be quite helpful
  - 10% of male population has some degree of color blindness (1% for females)
- Do not use more than about ten colors for coding if reliable identification is required
- Color sequences can be used effectively for data maps (like contours)
  - Grayscale is useful for showing forms but not values
  - Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

The book by Colin Ware is a great resource

Graphs

- Graphs are also a great way to show information, particularly for time-variation
- The number of curves needs to match the task



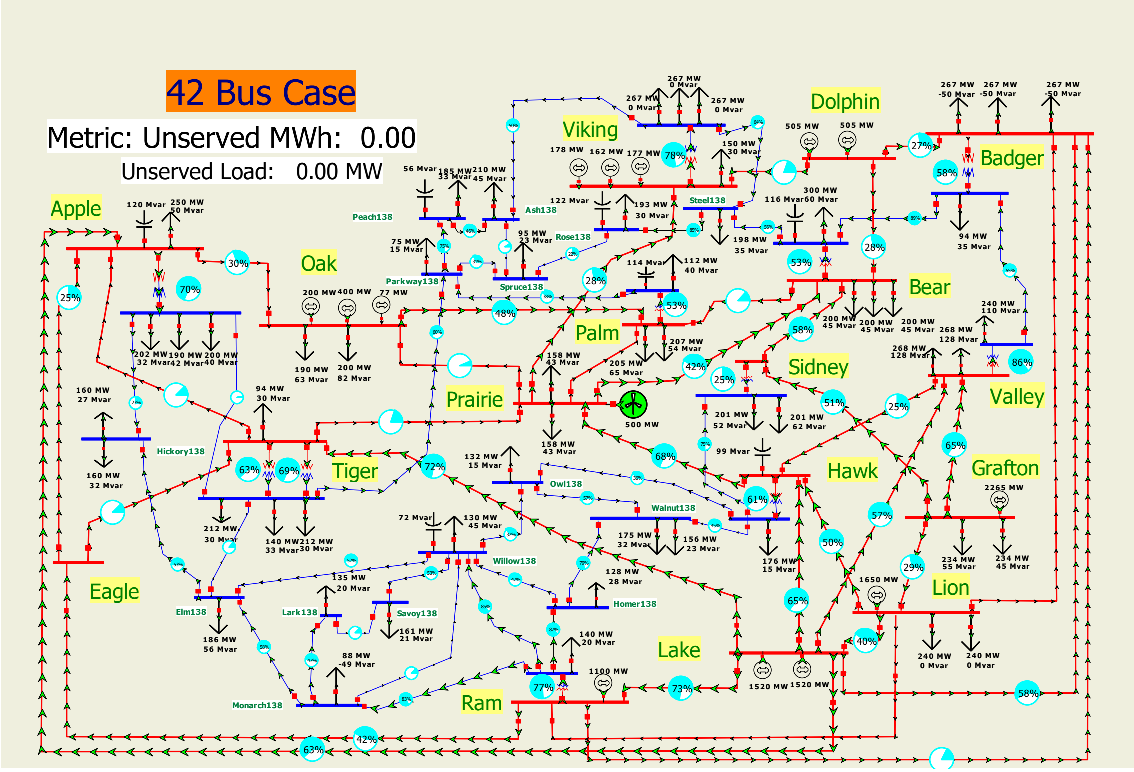


A few curves, detail of each visible, key can identify objects (several thousand values)

Envelope of response for the 80k bus, 40,000 substation frequencies (24 million values)

Onelines

- Widely used and can be quite effective for showing substations (or local regions) or smaller grids; can be slow on larger systems



Visualization Background: Preattentive Processing

- When displaying large amounts of data, take advantage of preattentive cognitive processing
  - With preattentive processing the time spent to find a “target” is independent of the number of distractors
- Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position

Preattentive Processing Examples

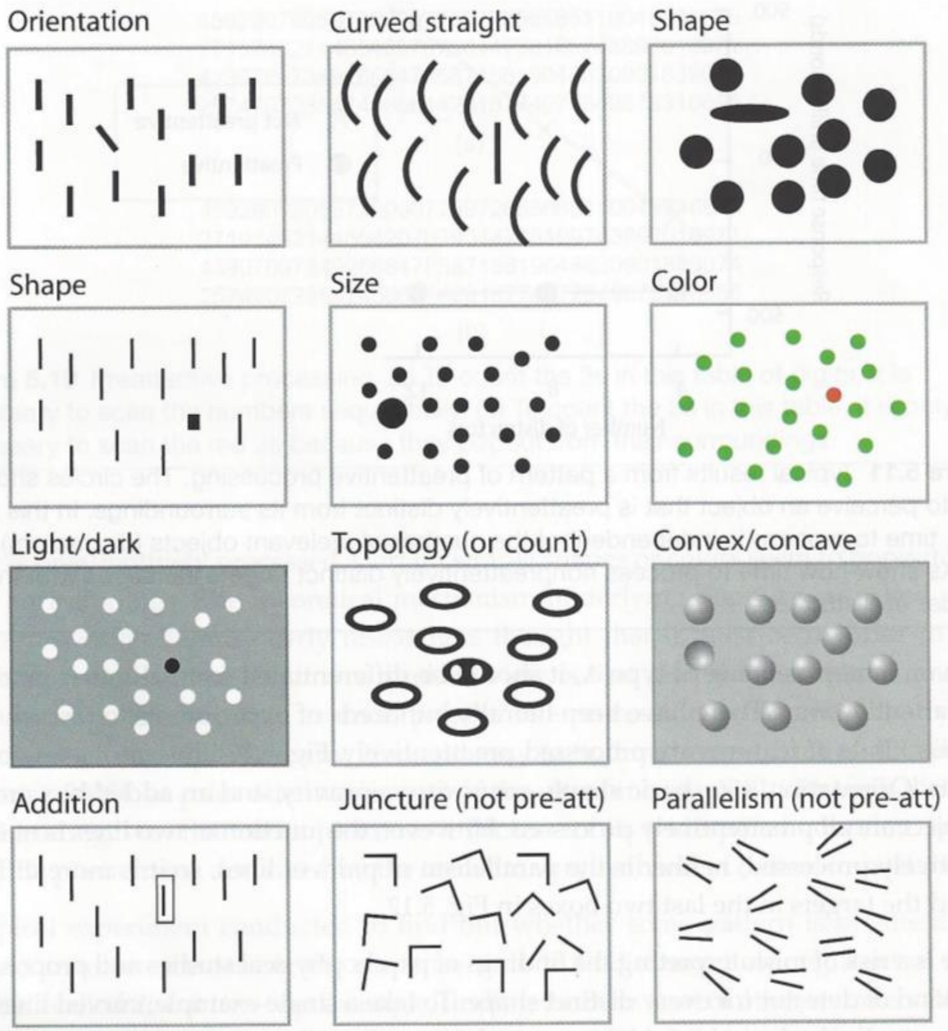
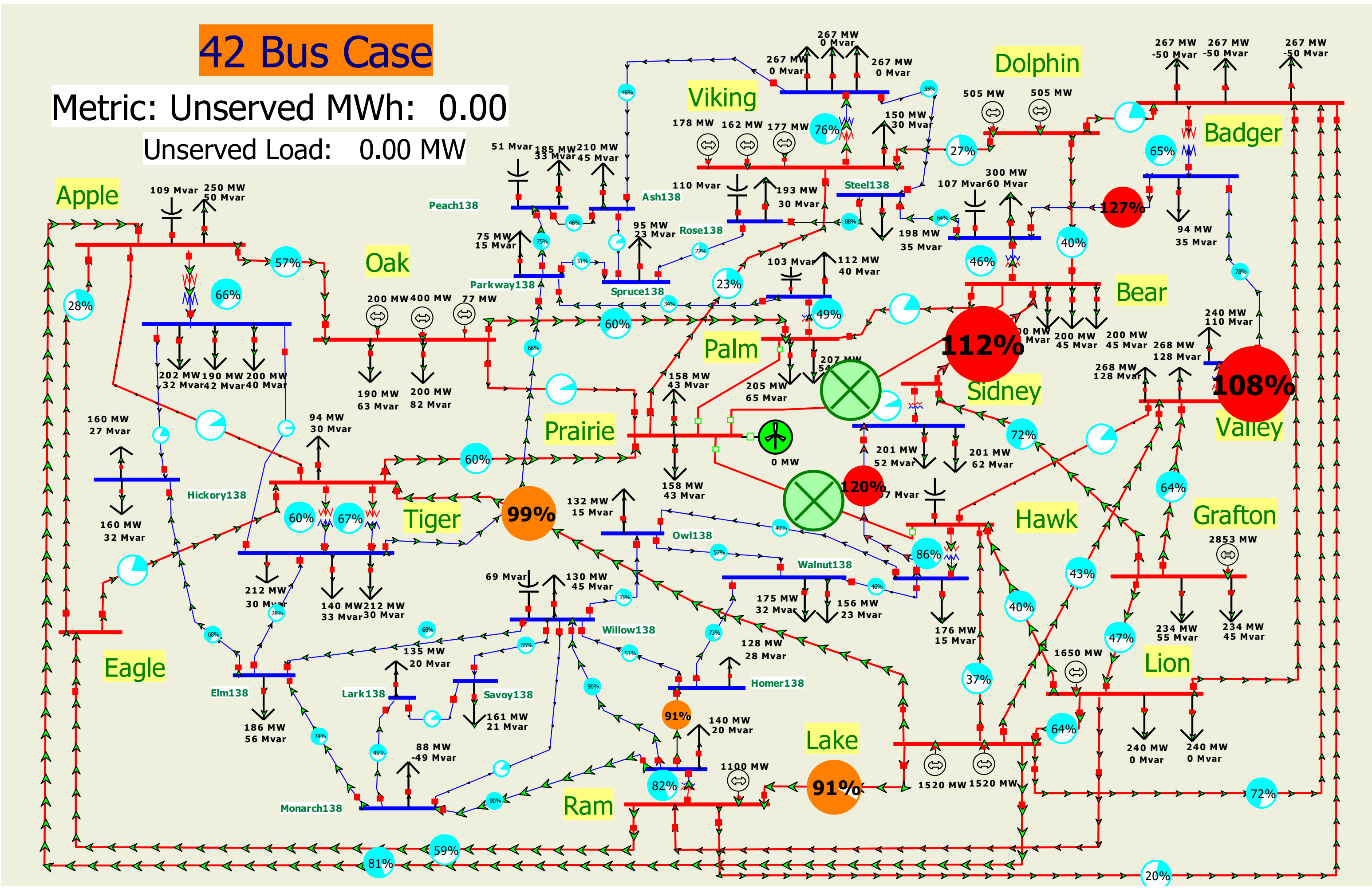


Figure 5.12 Most of the preattentive examples given here can be accounted for by the processing characteristics of neurons in the primary visual cortex.

All are preattentively processed except for juncture and parallelism; however too many can defeat their purpose

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Fig 5.12

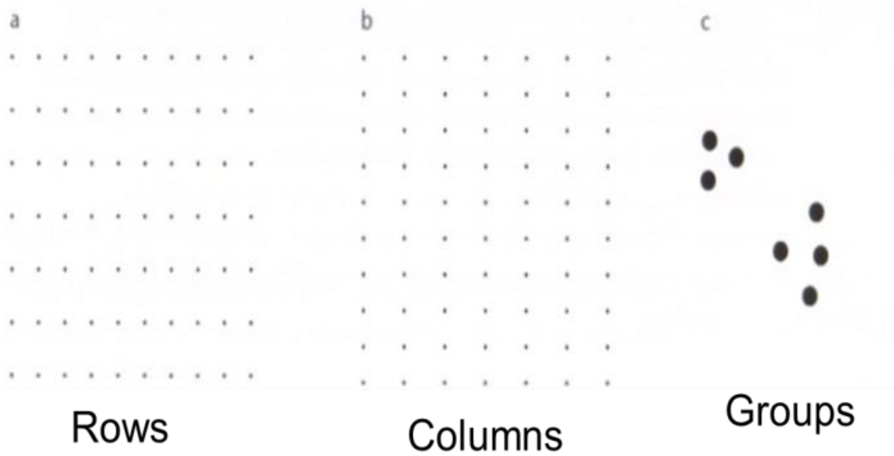
Preattentive Processing with Color & Size

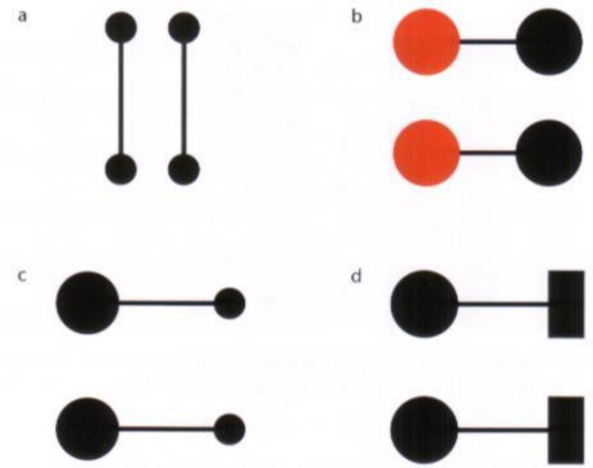


Detecting Patterns

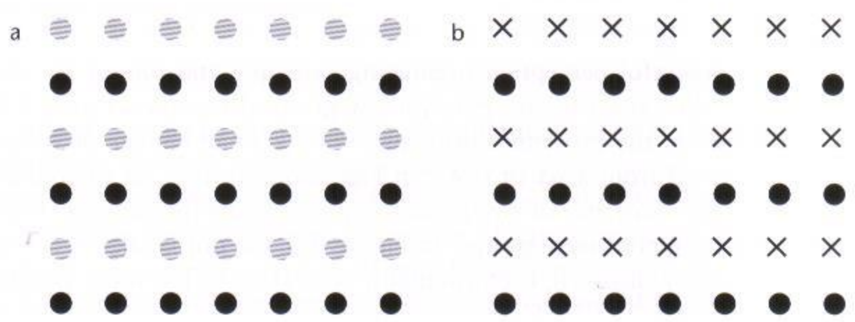
- A large portion of information visualization is associated with detecting patterns
- Gestalt (German for “pattern”) Laws
  - Proximity
  - Similarity (we didn’t discuss color)
  - Connectedness
  - Common Fate (flows)

Proximity, Similarity, Connectedness,





Connectedness is stronger than proximity, color, shape

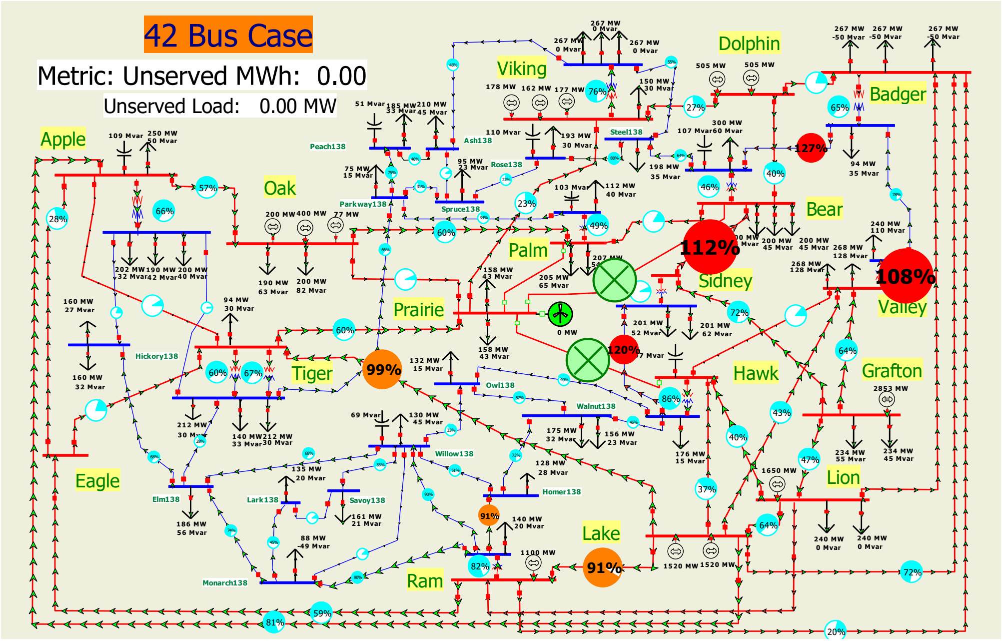


Similarity makes all perceived as rows

Source: *Information Visualization* (Fourth Edition) by Colin Ware, Chapter 6 Images

Common Fate: Patterns in Motion

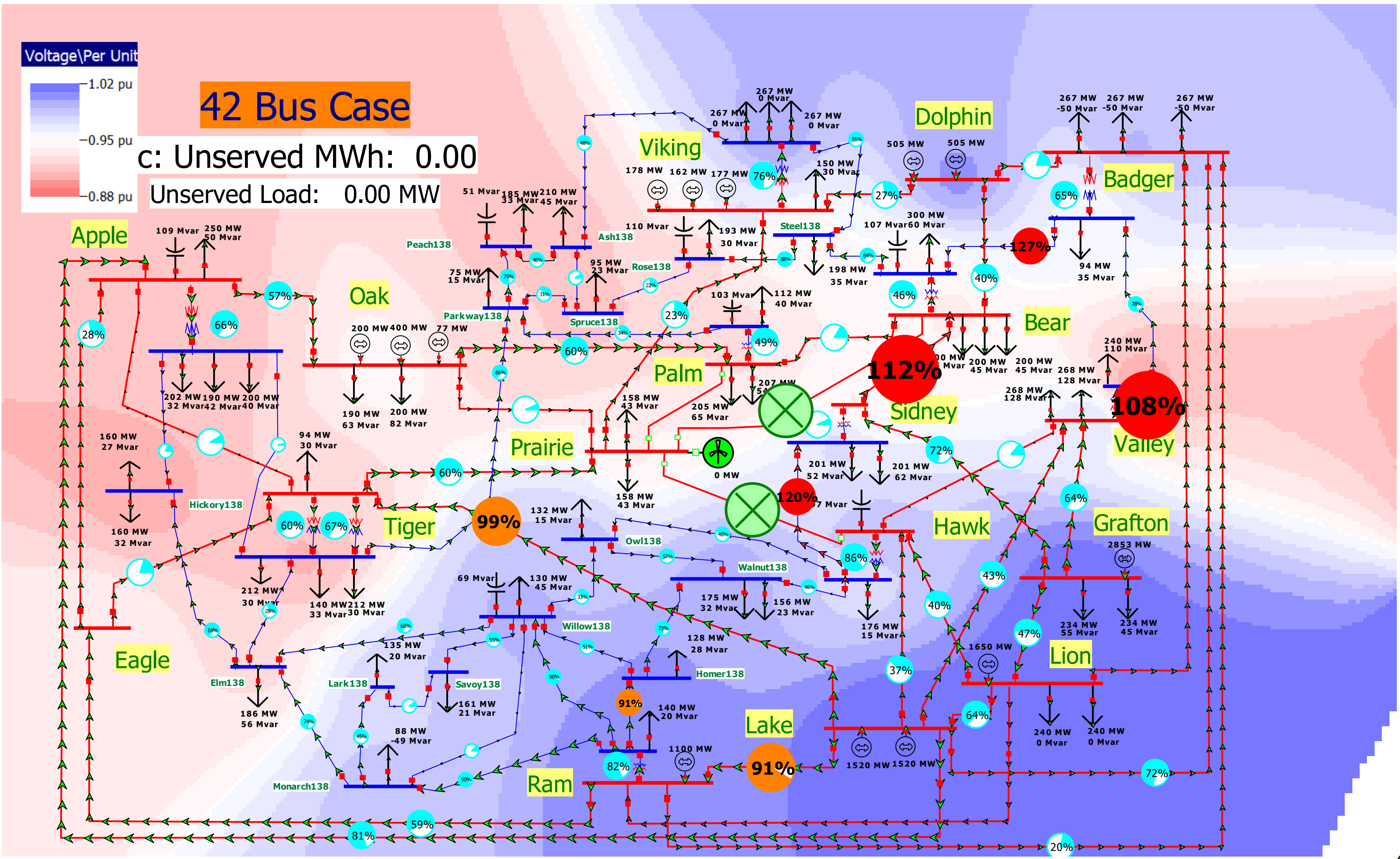
- Motion can be a very effective means for showing relationships between data
- People perceive motion with great sensitivity
- Motion can also be used to convey causality (one event causing another)
- However, too much motion can be a distractor



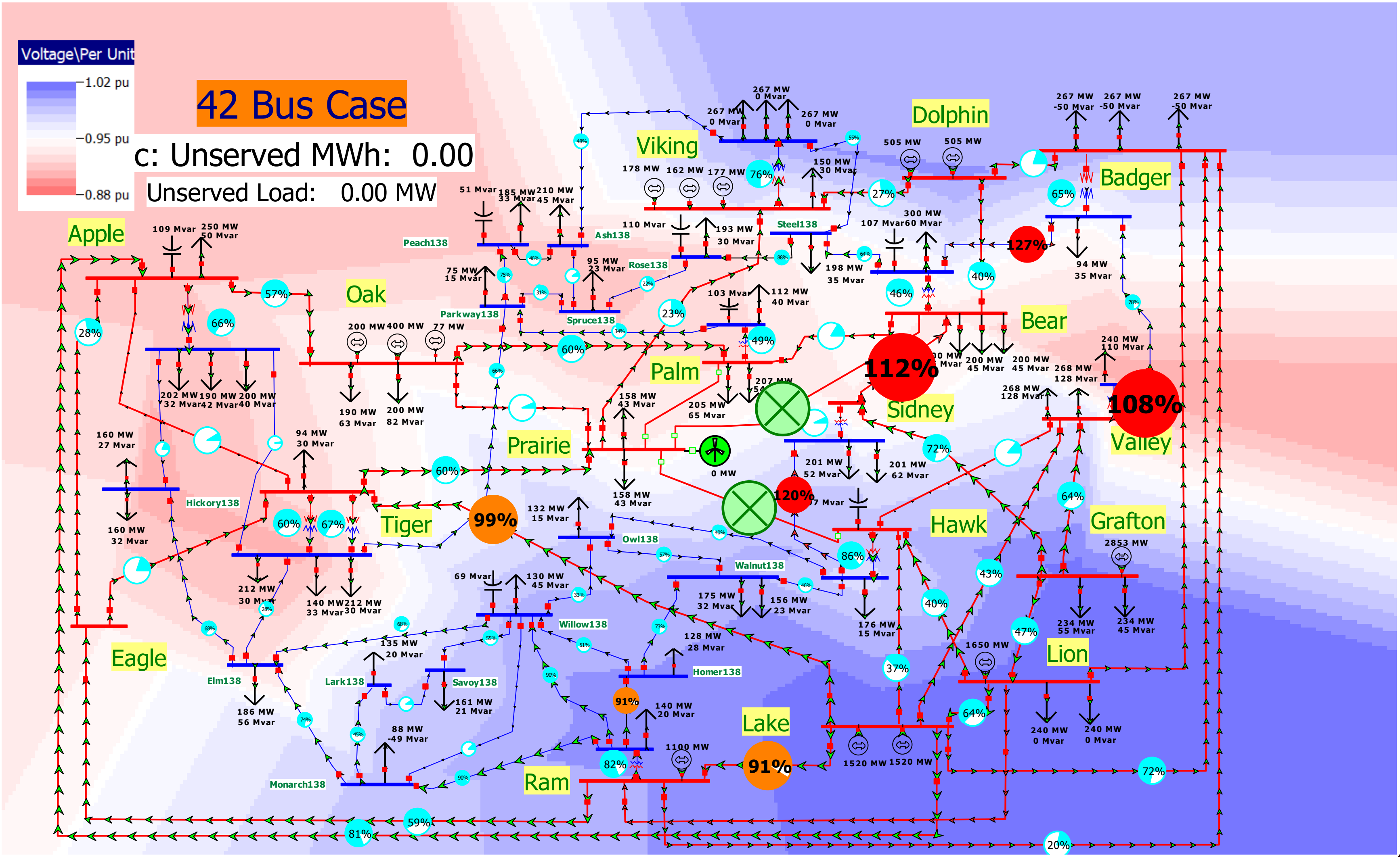
Scattered Data Interpolation (Colored Contouring)

- For wide-area visualization, contours can be effective for showing large amounts of spatial data
  - Takes advantage that as humans we perceive the world in patterns (sometimes even when none exist!)
  - Now widely used
- Scattered data interpolation algorithms are needed to take the discrete power system data and make it spatially continuous
  - Various algorithms can be used include a modified Shephard's and Delaunay triangulation
- A color mapping is needed

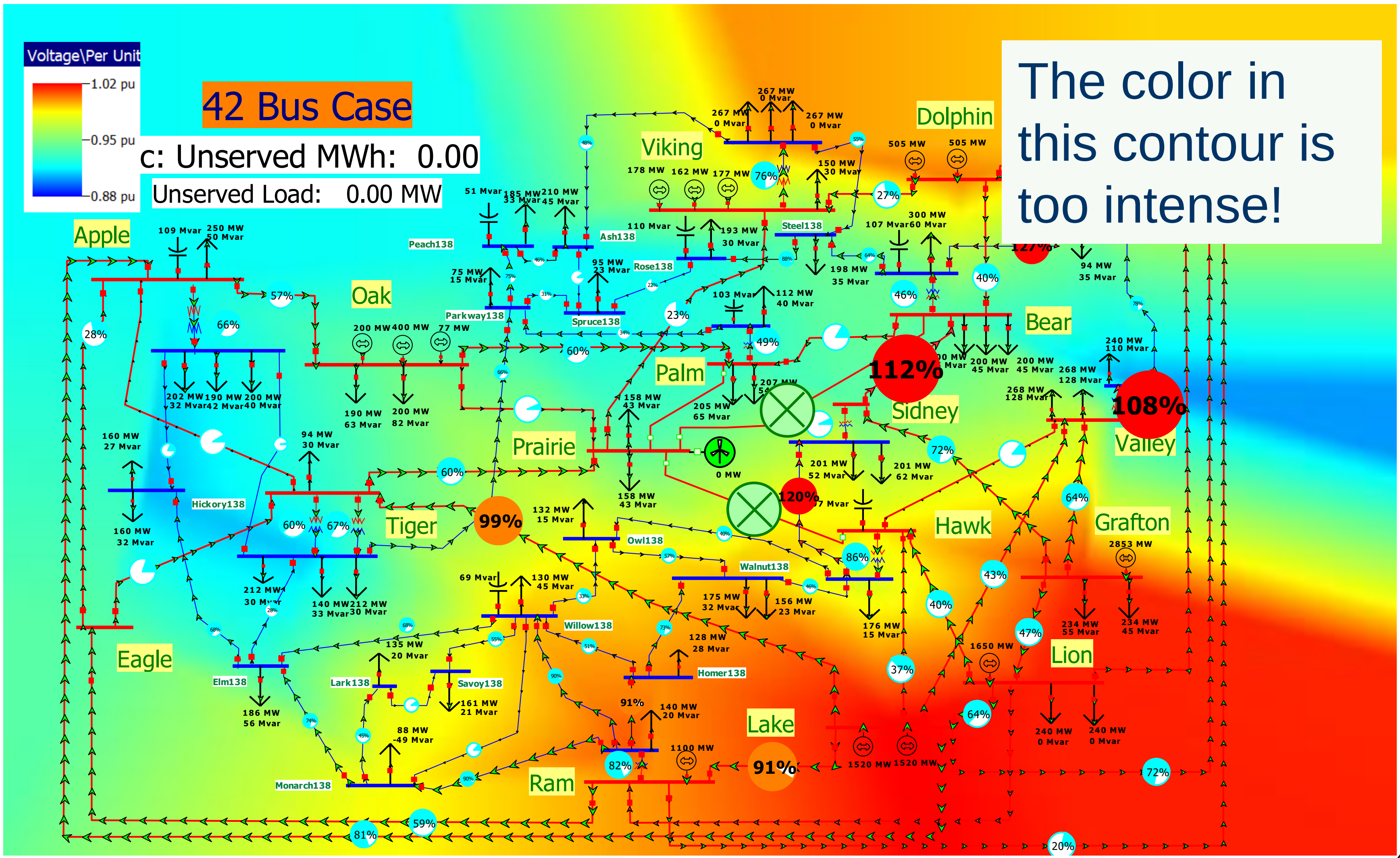
Shepard's Algorithm, Blue/Red Discrete Color mapping



Delaunay Algorithm, Blue/Red Discrete Color mapping



Delaunay Algorithm, Spectrum Continuous Color mapping



Some General Thoughts on Power System Visualizations

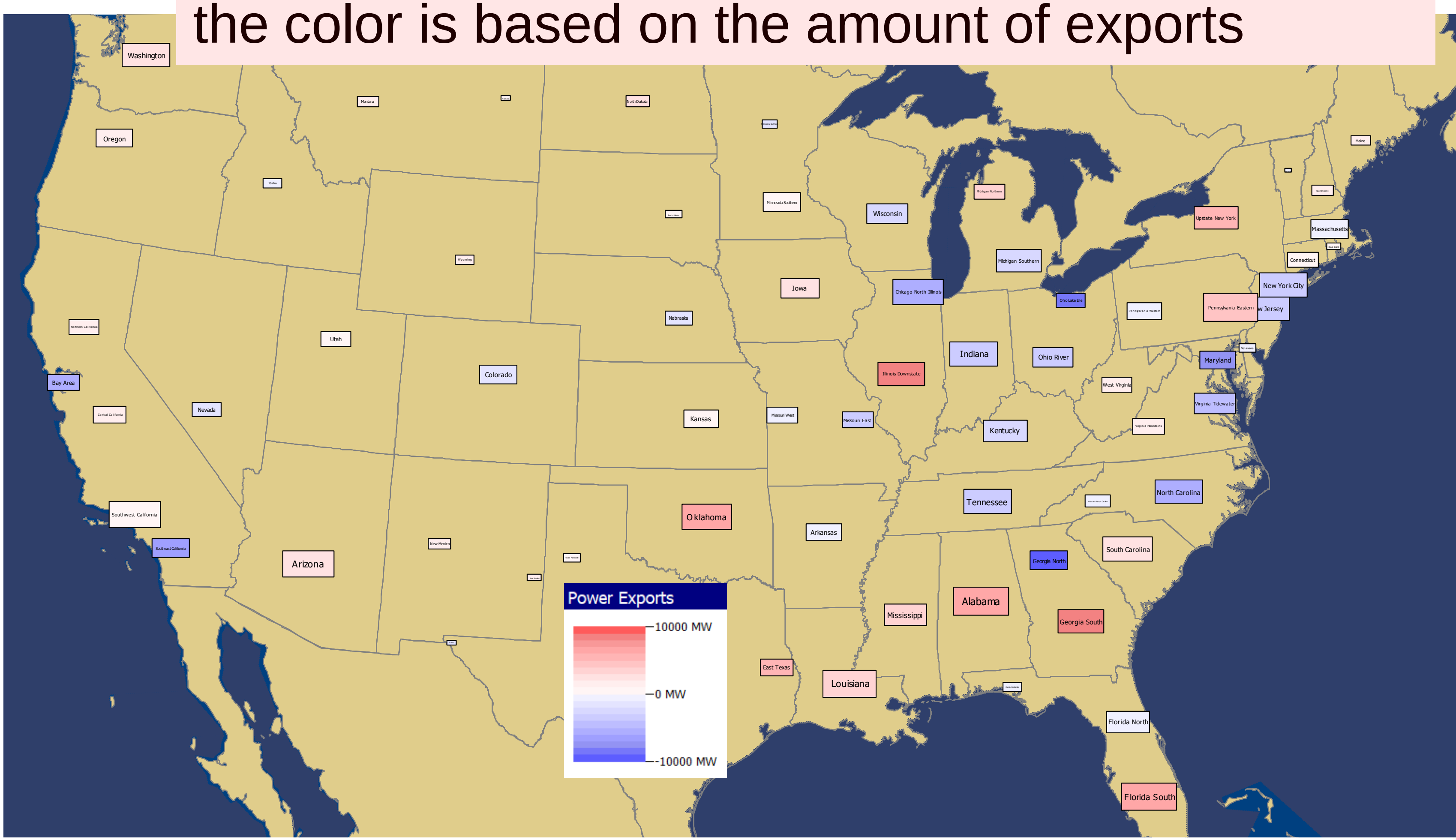
- While the previous techniques can be quite helpful, there is often just too much data to display
- Interactive visualizations, taking advantage of the underlying geographic information, can be quite effective, particularly if the displays can be rapidly customized to show different sets of information
- Also, much of the data should first be pre-processed using potentially quite sophisticated algorithms

Geographic Data Views

- One way to make visualizations more interactive is to use underlying geographic information to quickly auto-create displays
  - Known as geographic data views (GDVs)
- GDVs can be used either on individual objects (like generators, buses, or substations), or on aggregate objects (like areas and zones)
- The GDV display attributes (e.g., size, color) can be used to show object data
- The GDV displays can be saved for later use and links to the underlying objects allow for drilldown

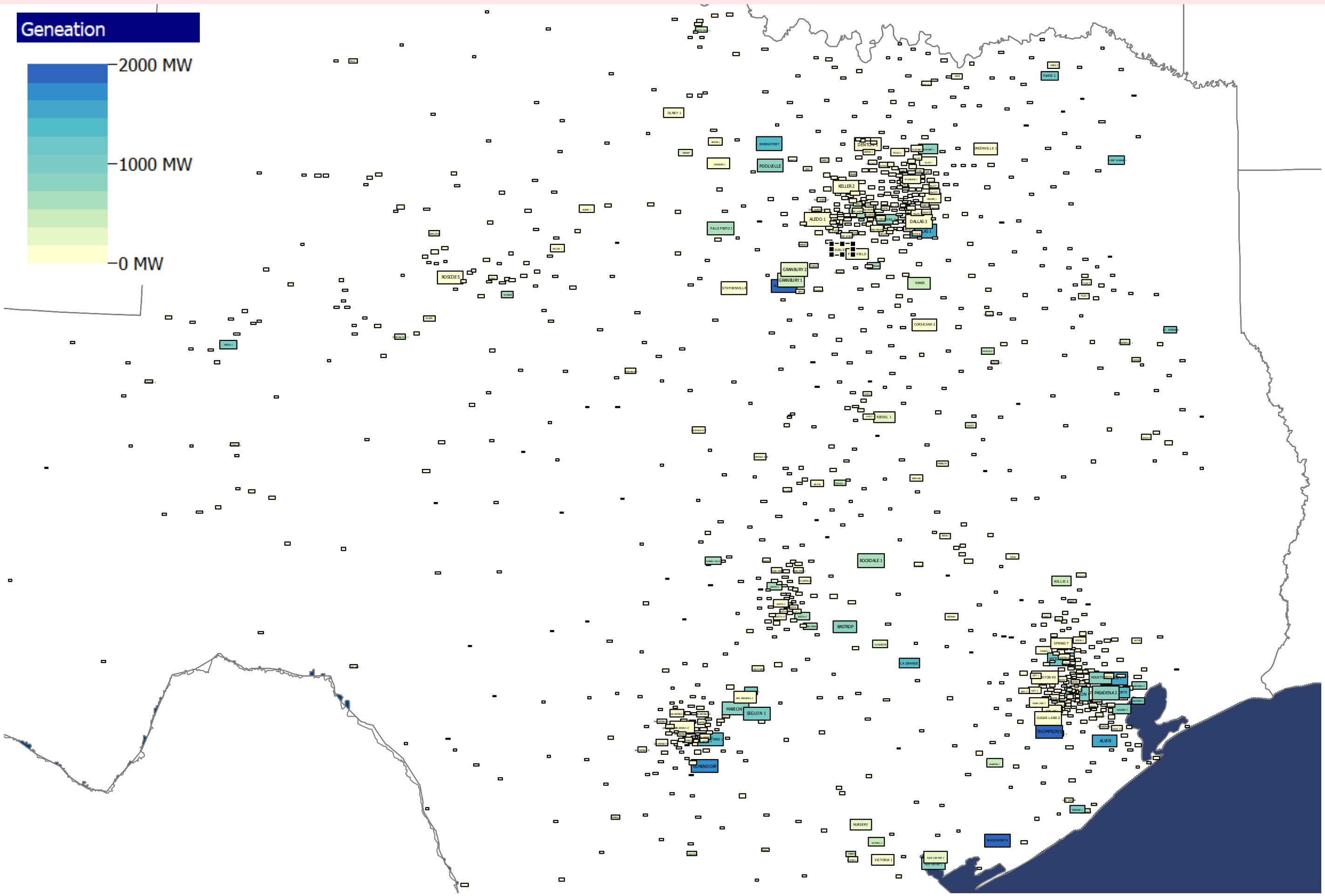
80,000 Bus System Area GDV Example

Size is proportional to the area's generation, while the color is based on the amount of exports



Texas 2000 Substation GDV

Size is proportional to the substation MW throughput, while the color is based on the amount of substation generation



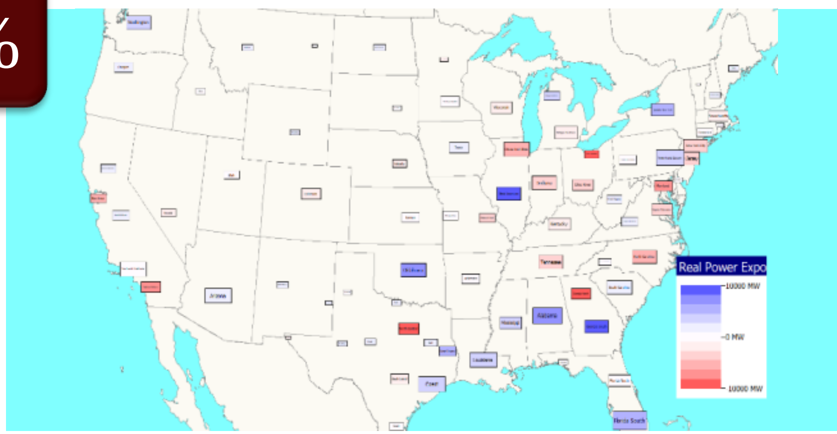
Pseudo-Geographic Mosaic Displays

- GDVs can be quite useful, but there is a tradeoff between geographic accuracy and maximum display space usage
  - Much of the electric grid is concentrated in small (primarily urban) areas
- Pseudo-Geographic Mosaic Displays (PGMDs) utilize a tradeoff of geographic accuracy to maximize display space

80,000 Bus System Area PGMD

GDVs are as before (size = area gen MW, color = interchange); the percentages show the amount of transition

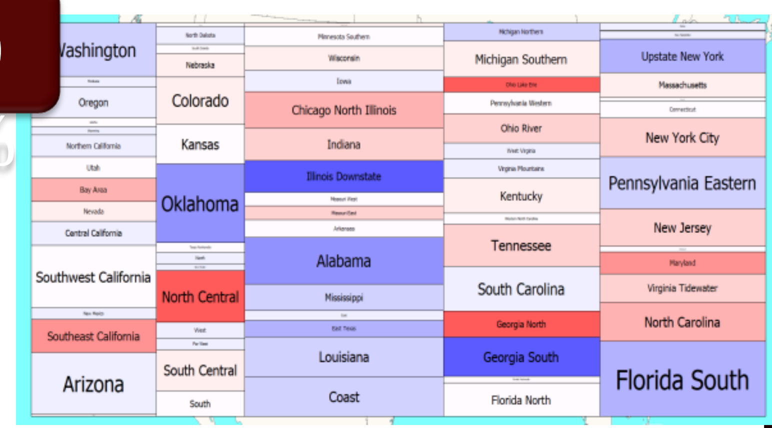
0%



25%

60%

100%



Some Techniques for Dealing with Time-Varying Data

- Need to keep in mind the desired task!
- Tabular displays
- Time-based graphs (strip-charts for real-time)
- Animation loops
  - Can be quite effective with contours, but can be used with other types of data as well
- Data analysis algorithms, such as clustering, to detect unknown properties in the data
  - There is often too much data to make sense without some pre-processing analysis!

Animation loops

- Animation loops trade-off the advantages of snapshot visualizations with the time needed to play the animation loop
  - A common use is in weather forecasting
- In power systems applications the length/speed of the animation loops would depend on application
  - In real-time displays could update at either SCADA or PMU rates
  - Could be played substantially faster than real-time to show historical or perhaps anticipated future conditions

Wide-Area Contours Can be Quickly Created Using GDVs

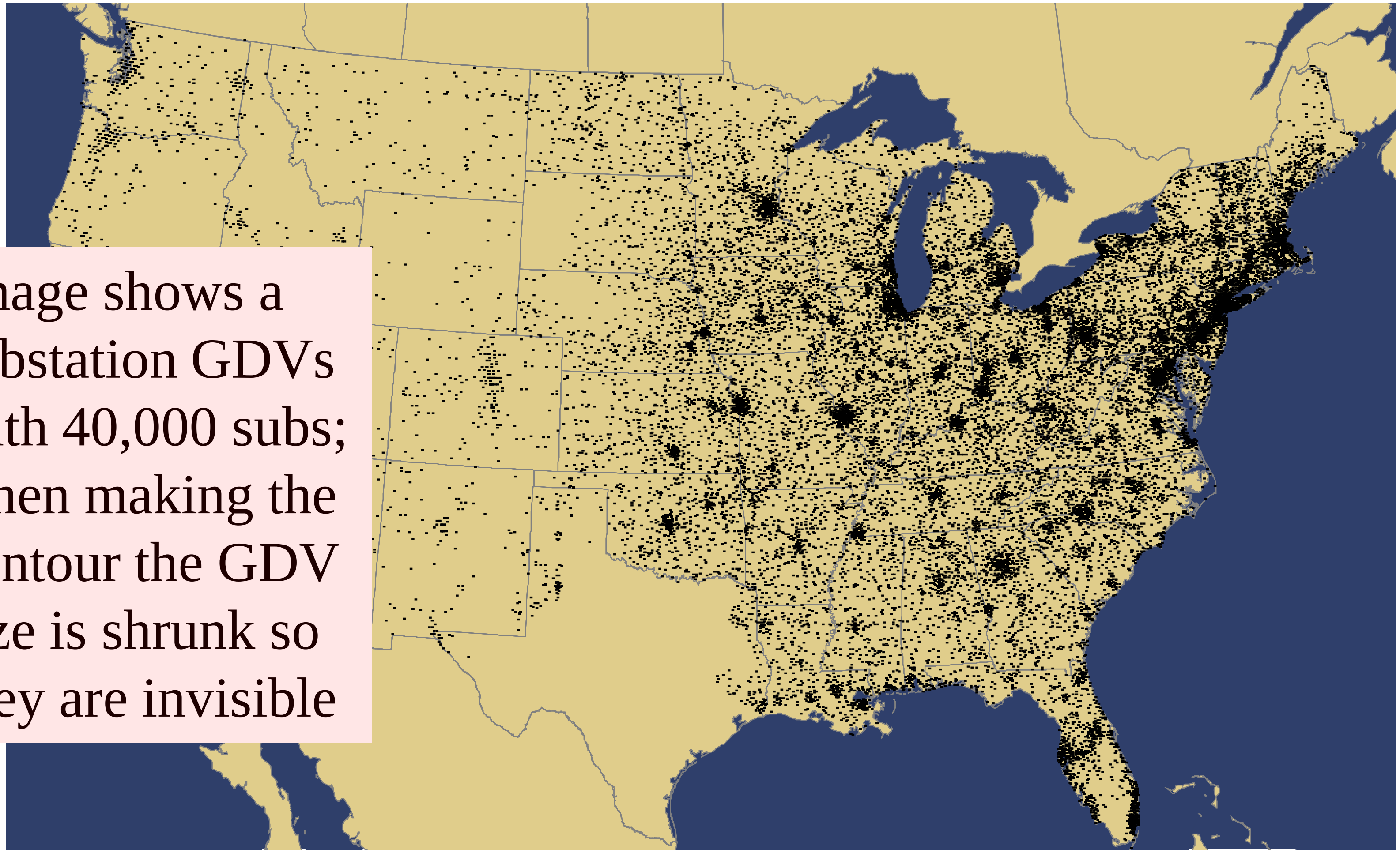
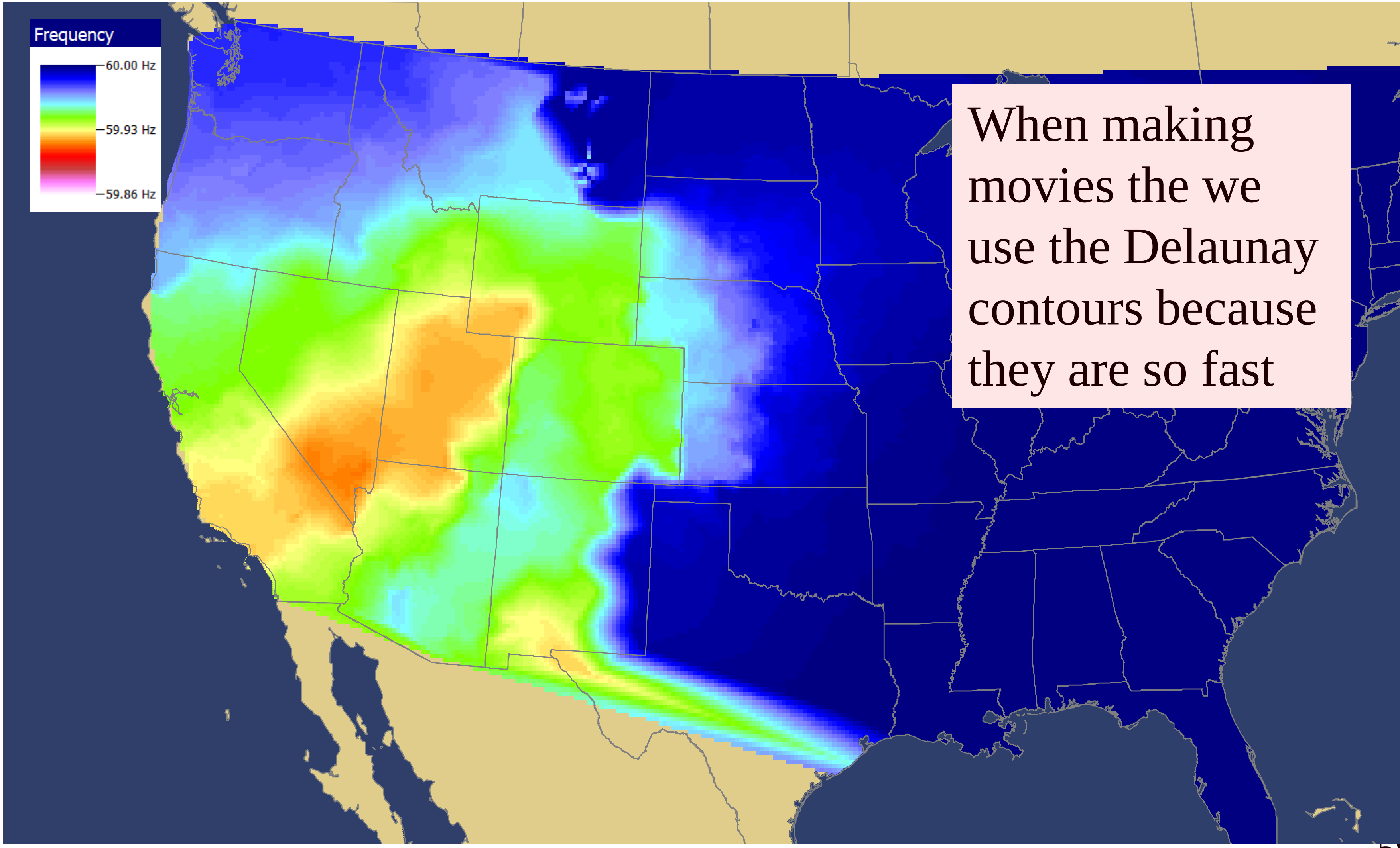


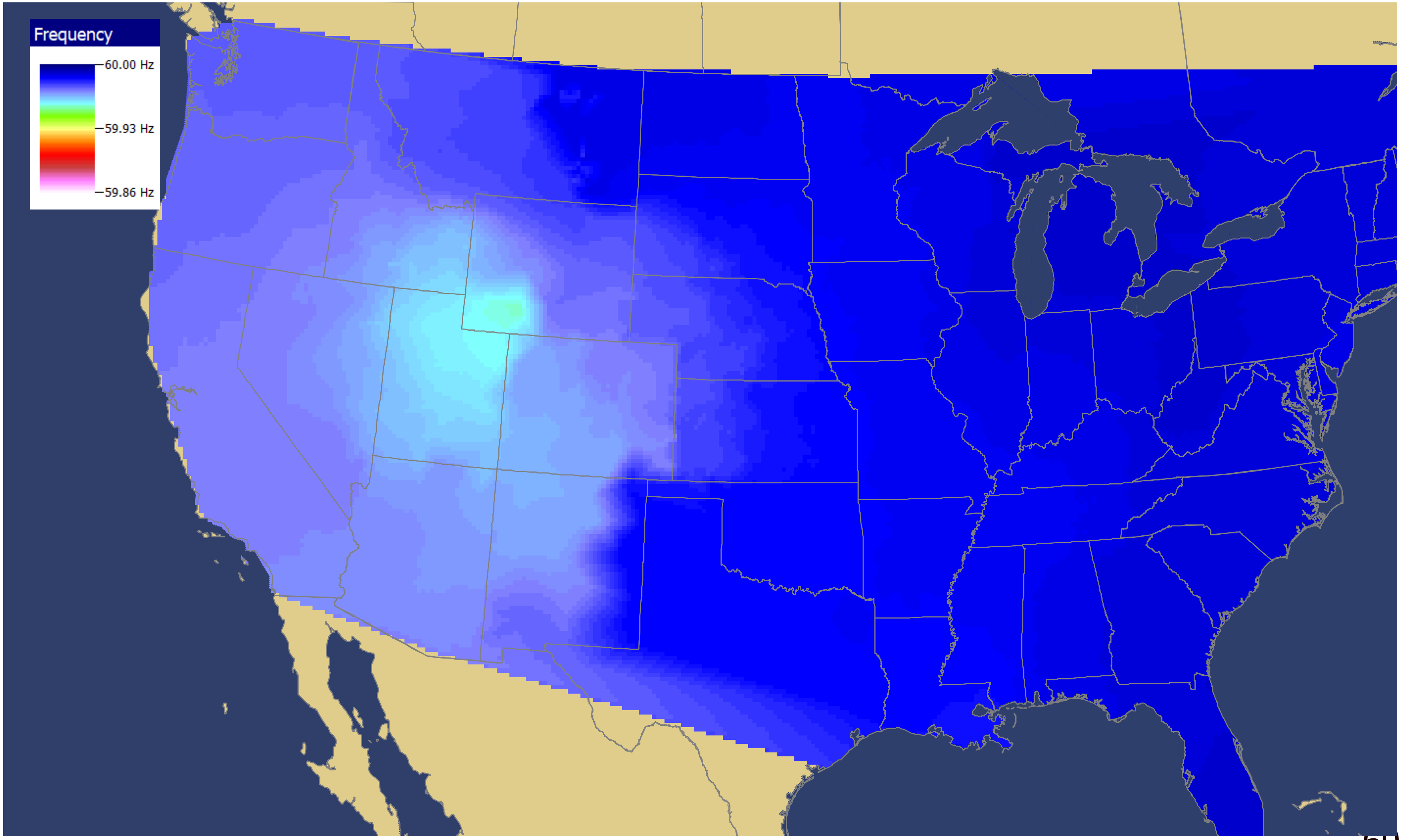
Image shows a substation GDVs with 40,000 subs; when making the contour the GDV size is shrunk so they are invisible

80K-Bus Frequency Variation (Substation Contour; Time = 2.0 Seconds)

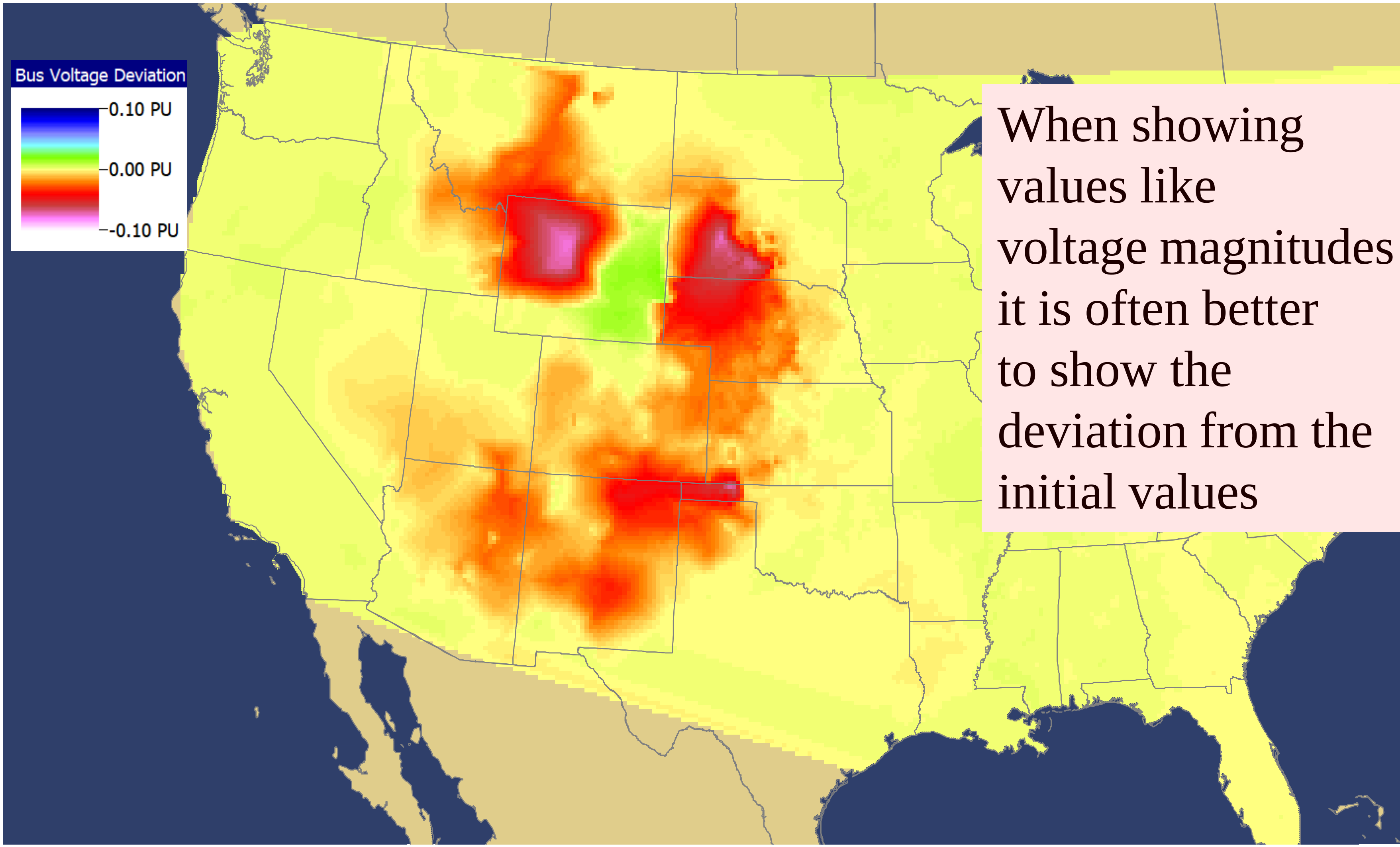


When making movies the we use the Delaunay contours because they are so fast

80K-Bus Frequency Variation (Substation Contour; Time = 8.0 Seconds)



80K-Bus Voltage Magnitude Variation (Substation Contour; Time = 5.0 Seconds)



When showing values like voltage magnitudes it is often better to show the deviation from the initial values