

Applications of Time Synchronized Measurements in the Electric Grid

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The Electric Grid

NASPI Talk

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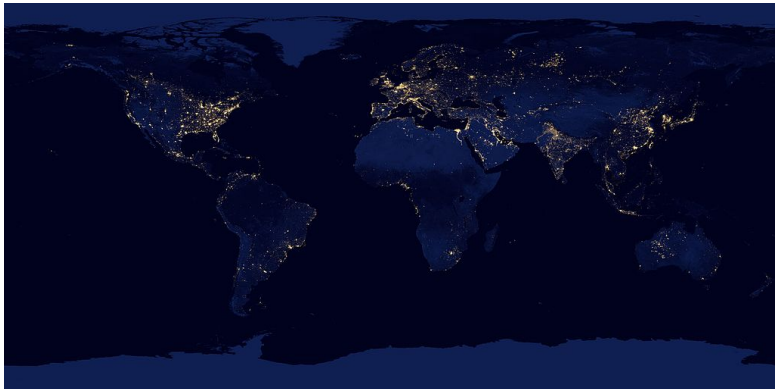
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Principles for
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Electric grids light the earth at night

New Challenges

Electric grids face looming challenges in a changing world.

Generation



Rooftop solar [9]

Demand



Demand growth [4]

Threats



Cyberattacks [2]



Wind power [6]



Novel loads [5]



Extreme weather [11]

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System Awareness

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To face these challenges, grid operators & engineers need real-time system awareness, which is traditionally lacking.



Control Room calls [10]



Truck roll [8]

"information and decision processes are becoming more interdependent and less compartmentalized" [7]

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System awareness is created from several building blocks:

- 1 Increased sensing
- 2 Data platforms
- 3 Algorithmic Tools

Phasor Measurement Units (PMUs)

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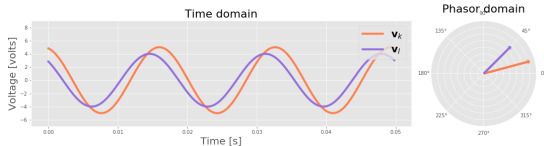
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PMUs report high resolution, time synchronized estimates of the magnitude & angle of phasor quantities.



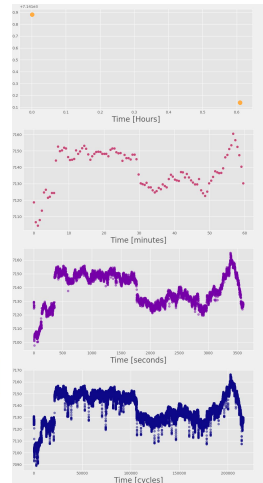
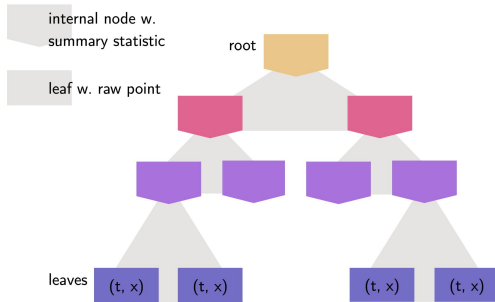
A distribution PMU



Ideal phasor voltages

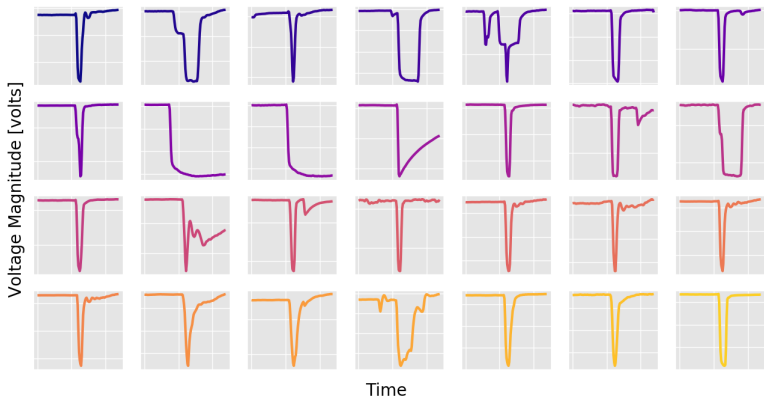
Measurement Data Platform

The Berkeley Tree Database (BTrDB) supports high performance writing and querying of time series data.



Searching with BTrDB

BTrDB's summary statistics enable rapid localization of extreme values across years of high resolution data.



A collection of voltage sags extracted from months of voltage magnitude data.

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Data but no insights

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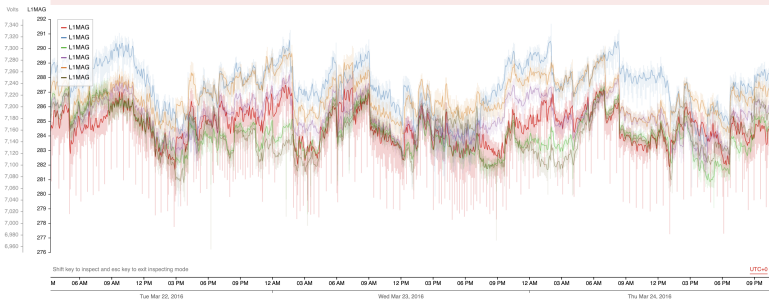
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Tools for Insight

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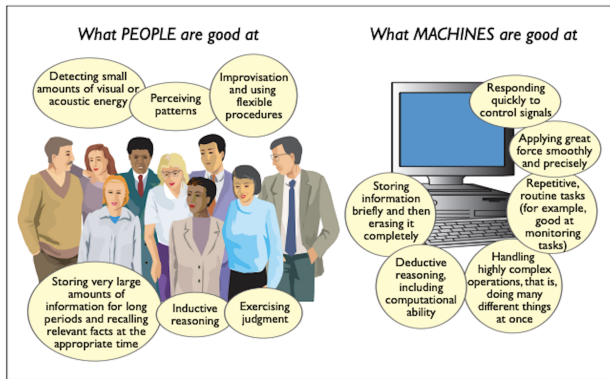
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We need algorithmic tools that transform data to insights for
human users.

Why humans?

"Operator experience—the accumulation of observational evidence, studied with awareness—has always been vitally important in this industry"



Taken from *Human-computer interaction: the human and computer as a team in emergency management information systems* [3]

Tools in Industry

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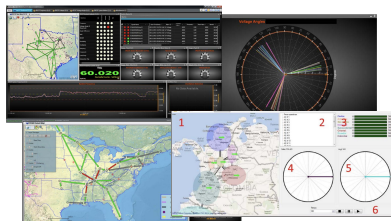
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Industry tools tend to have:

- 1 Low / flexible input information requirements.
- 2 Highly transparent results.



Oscillation monitoring tools

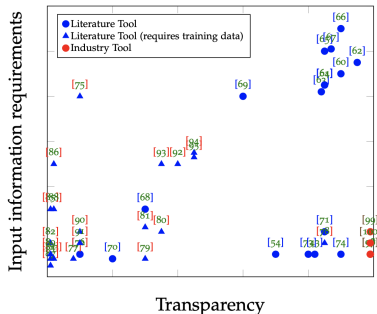


Angle difference monitoring tools

Tools in the Literature

The research literature is replete with tools for grid monitoring. They tend to have:

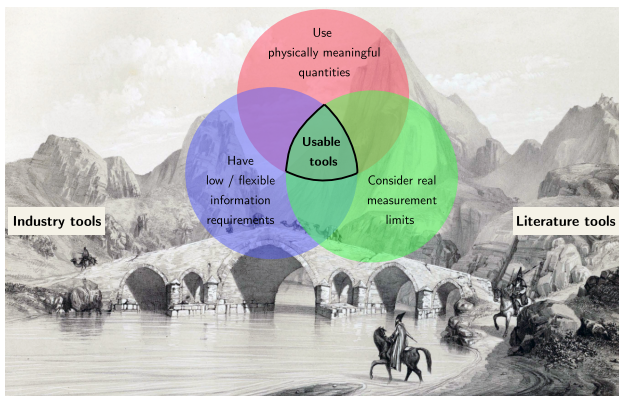
- High input information requirements.
- Low algorithmic or output transparency.



Visualizing tools from literature and industry in the two dimensional space of transparency and input information requirements.

Bridging the gap

I propose the creation of *usable tools* with three broad features.



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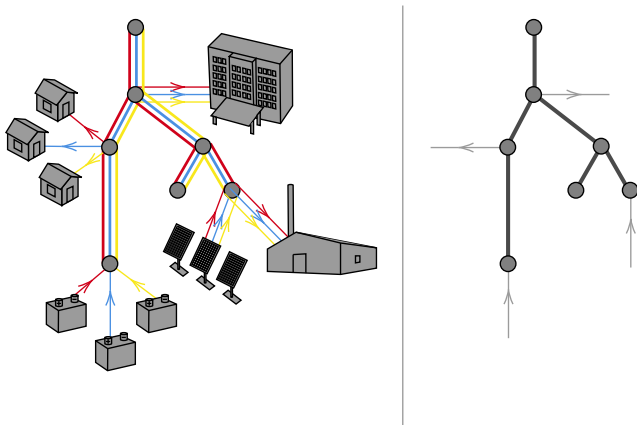
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Toward Usable Tools for Topology

Topology is the fundamental property of all electric networks, encompassing the network structure, line impedances, and line phases.



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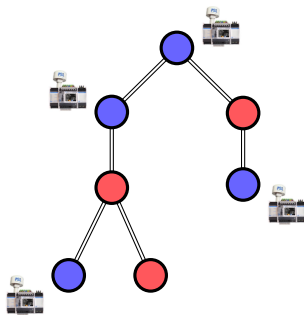
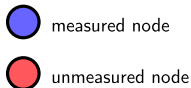
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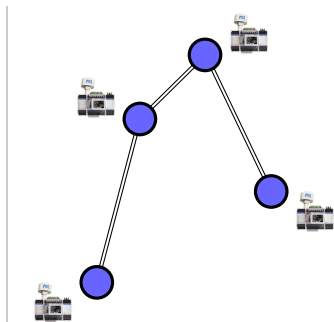
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corr-top : A correlation based approach

Estimates the relative connectivity of measured nodes in a radial network from voltage magnitude measurements.



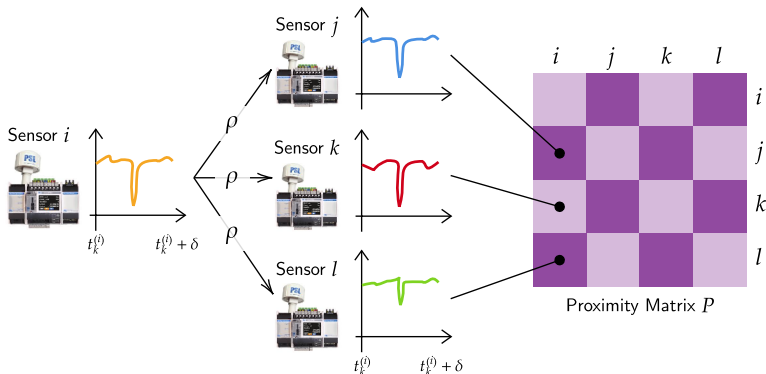
Original network



Recovered Topology

[corr-top] Algorithm

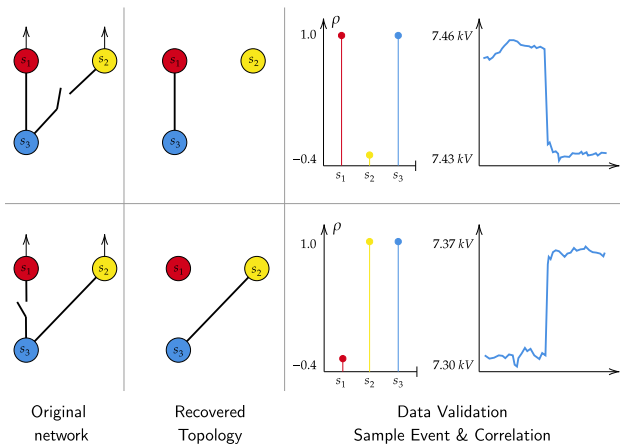
The algorithm uses averaged voltage magnitude correlations as an indicator of electrical distance.



Visualizing the corr-top algorithm.

[corr-top] Data Validation

The algorithm has transparent structure and outputs, bolstered by a returned data validation.



[corr-top] Usability

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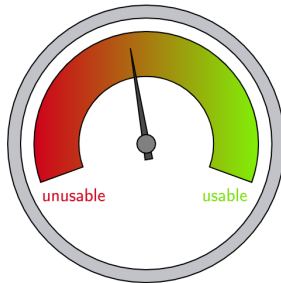
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consider real
measurement
limits

use physically
meaningful
quantities /
physics model

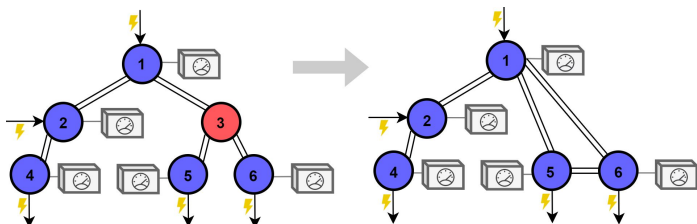


low / flexible
information
requirements

kron-top: A physics based approach¹

Estimates the Kron reduced network model from voltage and current phasor measurements at *active nodes*.

$$\mathbf{V}_A = \mathbf{Z}_K \mathbf{I}_A$$



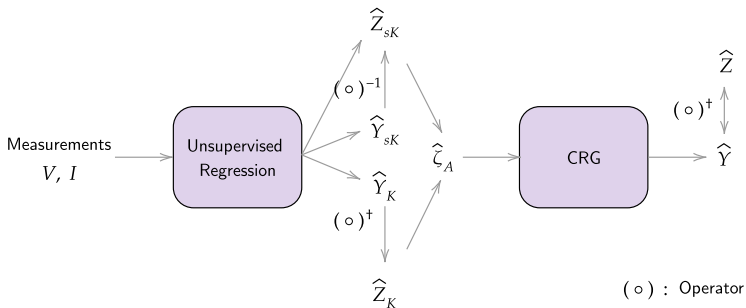
Kron reduction applied to a 6 node toy network with 5 active nodes and 1 passive node.

¹with Keith Moffat, UC Berkeley

[kron-top] Algorithm

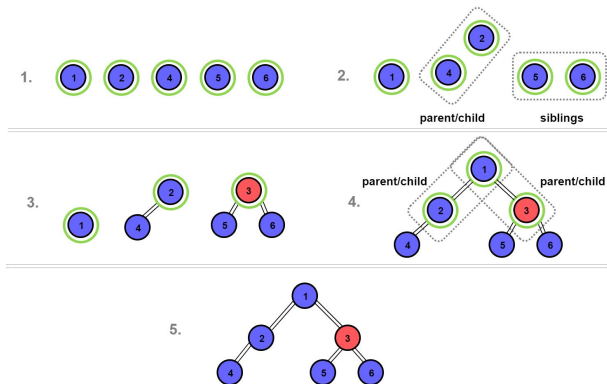
The algorithm proceeds in two steps:

- 1 Unsupervised Regression estimates Kron model from measurements.
- 2 Complex Recursive Grouping recovers full radial topology from Kron model.



[kron-top] Complex Recursive Grouping

CRG reconstructs topology through triplet tests on node distances.



Recovering parent & child relationships with CRG.

[kron-top] Performance

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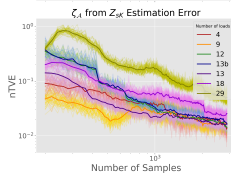
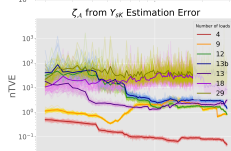
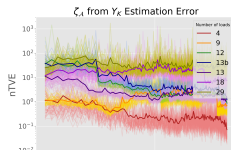
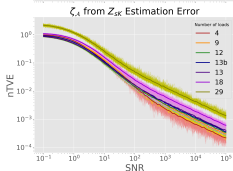
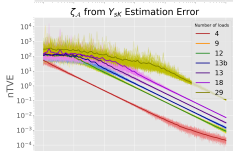
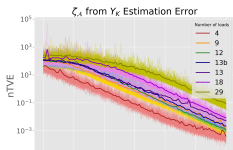
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[kron-top] Performance

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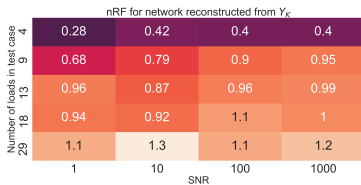
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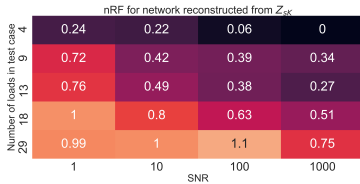
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kron-top outperforms the prior work on noisy data.



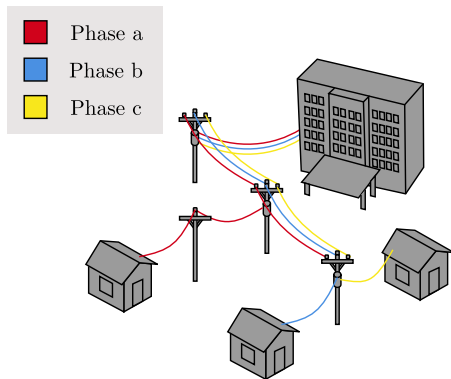
Prior Work



kron-top

gpt: greedy phase & topology recovery²

gpt is a provable algorithm for jointly recovering phase and connectivity in unbalanced three phase networks from voltage measurements.



A three phase distribution grid

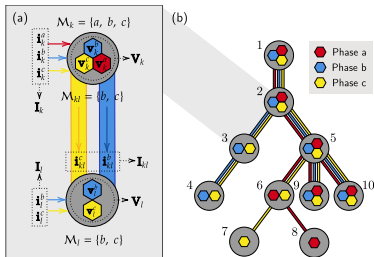
²with Deep Deka, LANL

[gpt] A three phase model

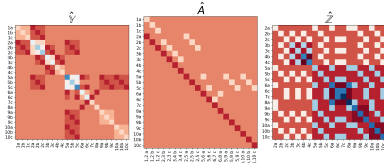
gpt is built on two critical elements:

- 1 a carefully defined linear model of an unbalanced three phase network.
- 2 statistical assumptions on load.

These enable the derivation of trends in voltage covariances from which topology can be recovered.



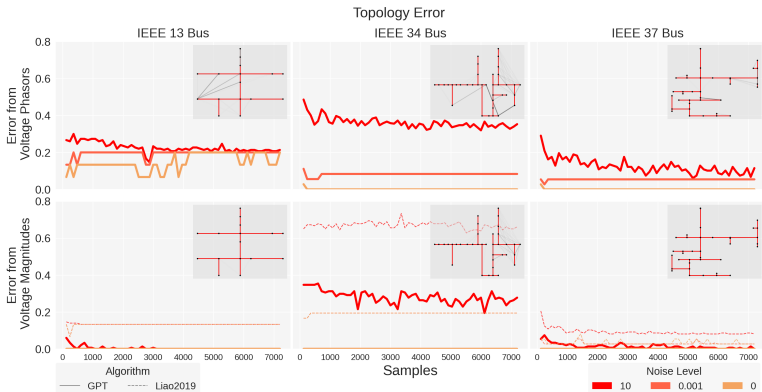
ToyNet



ToyNet system matrices

[gpt] Performance

We evaluate gpt in simulation on 3 IEEE test networks.



[gpt] Usability

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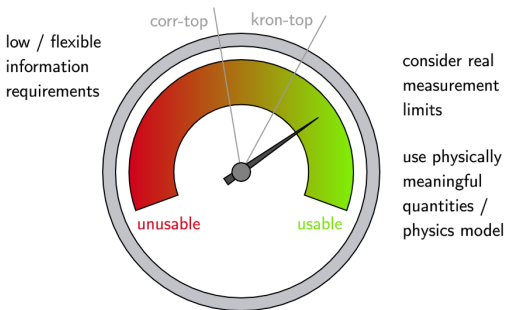
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Justified Heuristics for topology monitoring

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Starting with linear physics models and well-defined assumptions, we can derive simple, highly usable approaches to topology monitoring.

graph theory + statistical assumptions \longrightarrow usable tools

[Justified Heuristics] Four techniques

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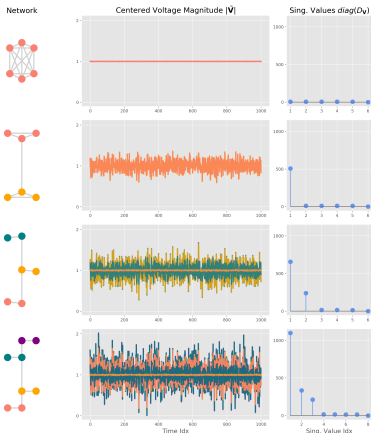
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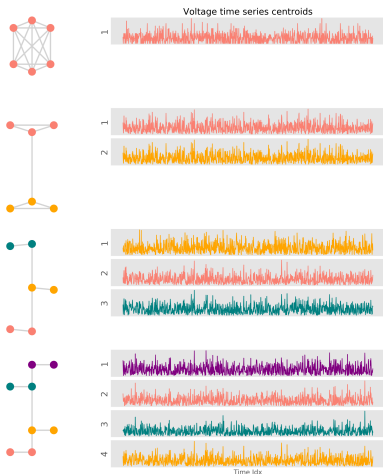
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Voltage singular values



Voltage clustering

[Justified Heuristics] Four techniques

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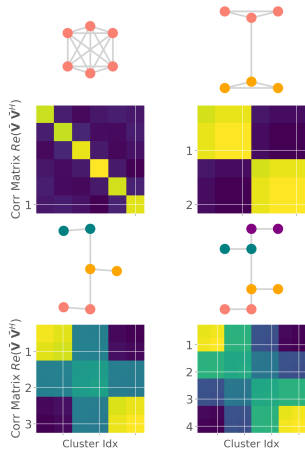
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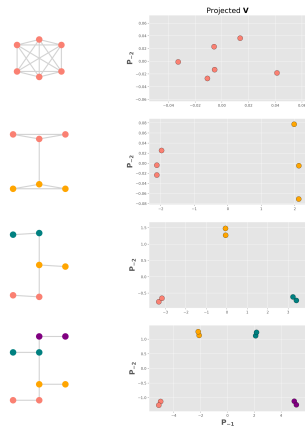
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Voltage correlation clustering



Voltage PCA

[Justified Heuristics] Defined Failures

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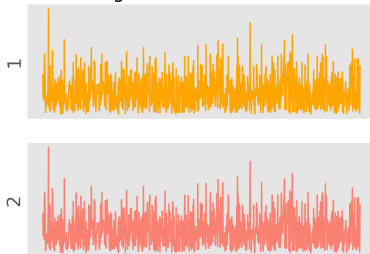
References

Well-defined assumptions \rightarrow well-defined failure modes

Injection Corr Mat



Voltage time series centroids



Voltage clustering fails with highly correlated current injections.

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Grid Events

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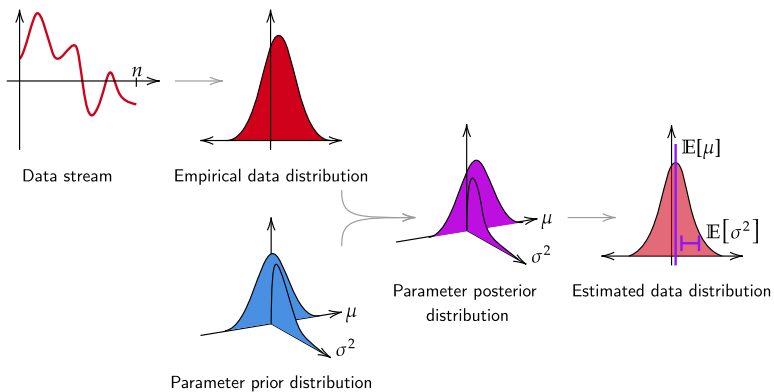
Continually, *events* occur in the electric grid.



Together, event detection & classification find and label events, reducing data to a human scale.

bay-detect: Bayesian Event Detection

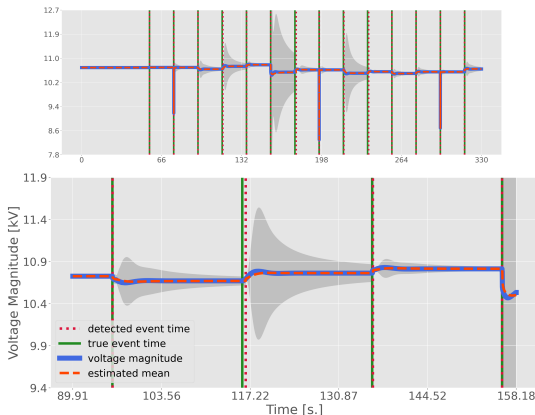
bay-detect estimates data distribution parameters in streaming fashion, flagging outliers as events.



Visualizing the distributions involved in bay-detect

[bay-detect] Demonstration

Statistical methods are interpretable, visualizable, and easily tuned.



bay-detect applied to a simulated voltage magnitude time series containing 14 events.

kShapeStream: Streaming Event Clustering³

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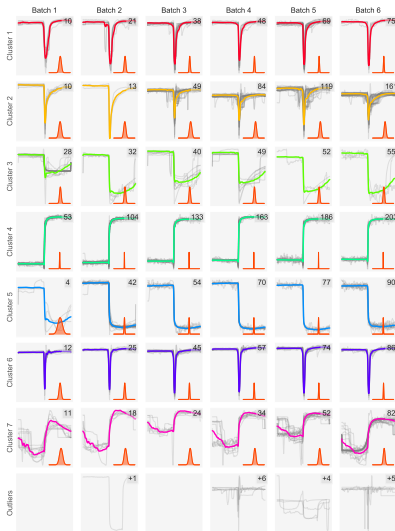
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³with John Paparrizos, U. Chicago

[kShapeStream]: Demonstration

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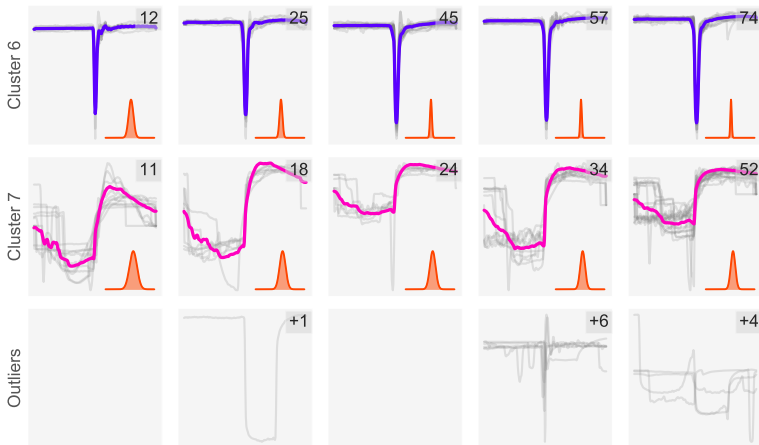
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[kShapeStream] Use Case

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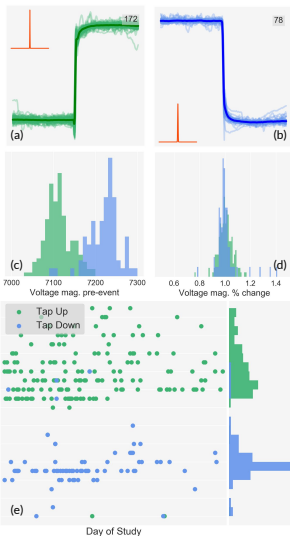
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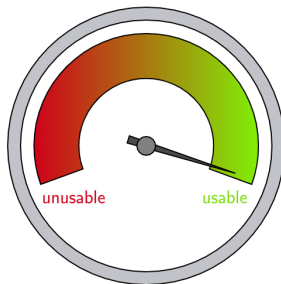
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consider real
measurement
limits

use physically
meaningful
quantities /
physics model

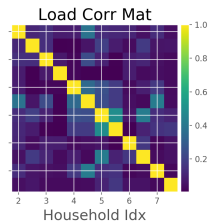
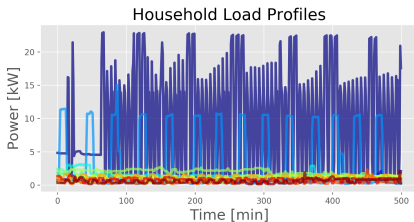
low / flexible
information
requirements

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Principles for Tool Design

The following are effective building blocks for creating usable tools.

- 1 Linear Models
- 2 Statistical Assumptions
- 3 Statistical Baselines



Visualizing the uncorrelated load assumption on Pecan Street Data.

Avoiding bad tools

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Key attributes of poor tooling [3]:

- Strong - Behaves autonomously
- Silent - Inadequate feedback & transparency
- Clumsy - Adds cognitive load, impedes
- Obstructive - Inflexible so not used as intended

The irony: *"the more advanced a control system is, so the more crucial may be the contribution of the human operator."*[1]

A vision for tools

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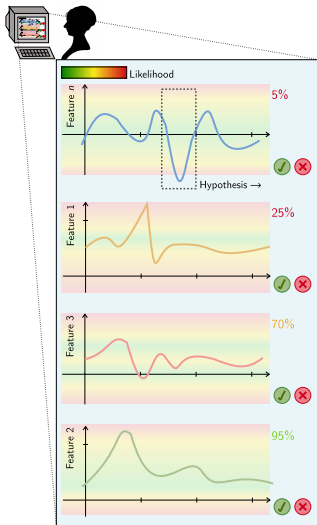
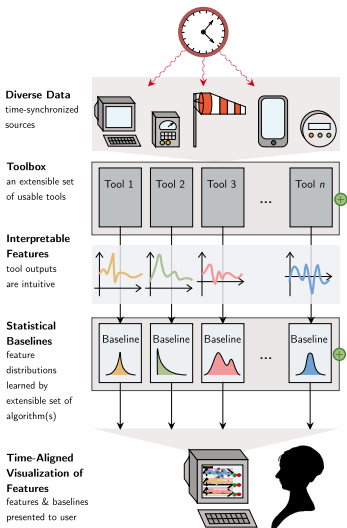
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Thank You...

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Questions?

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Please contact me with questions, comments, critiques, paper requests at *mohini@berkeley.edu*.



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