Modeling, Estimation and Control of Complex Interactive Systems: Toward Self-healing National Infrastructures

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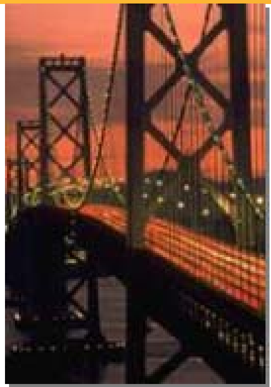
New Directions for Understanding Systemic Risk: Models of Systemic Phenomena in Other Complex Interactive Situations

Federal Reserve Bank of New York and the NAS, May 18-19, 2006

Some of the material and findings for this presentation were developed while the author was at the Electric Power Research Institute (EPRI) in Palo Alto, CA. EPRI's support and feedback is gratefully acknowledged.

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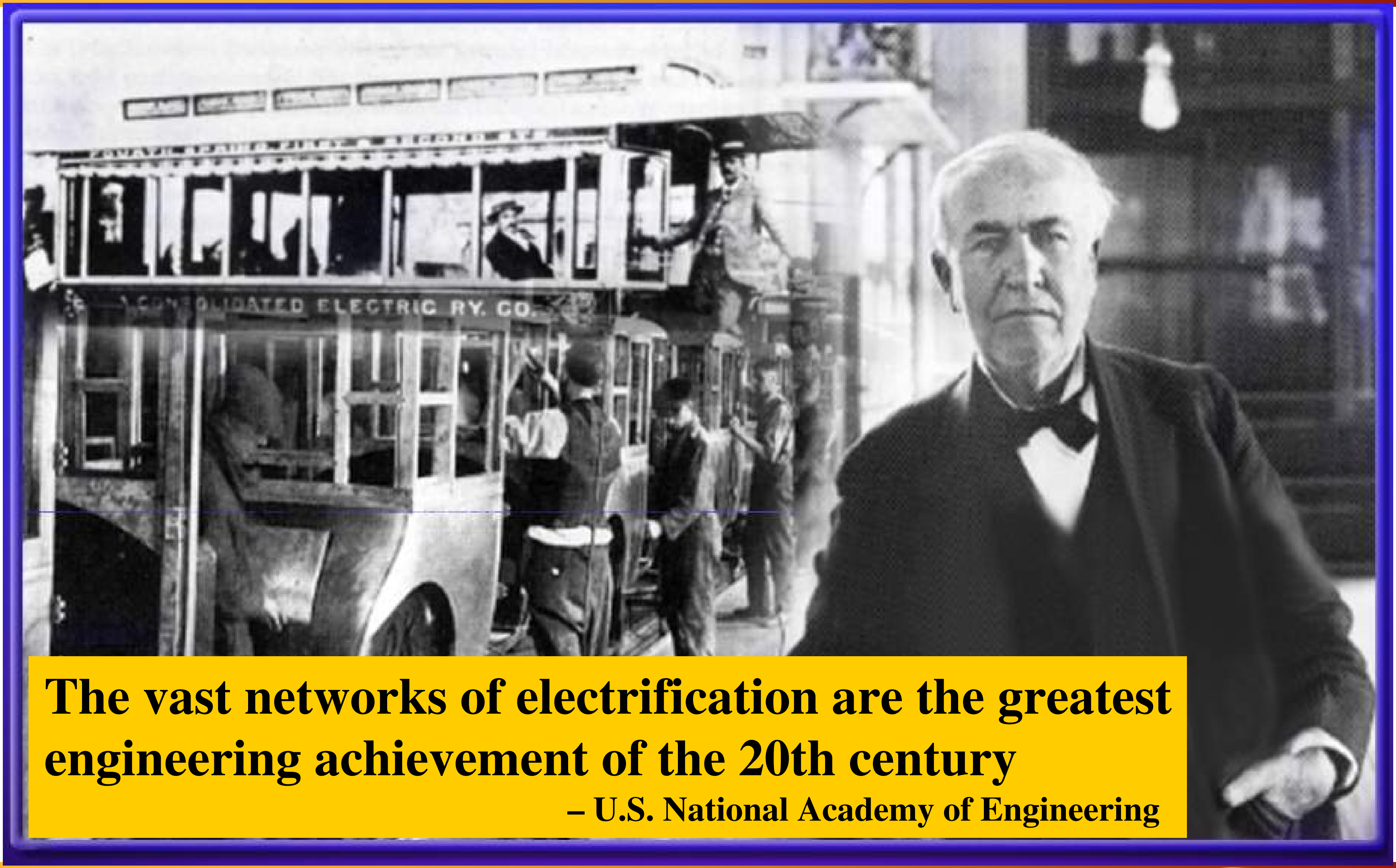
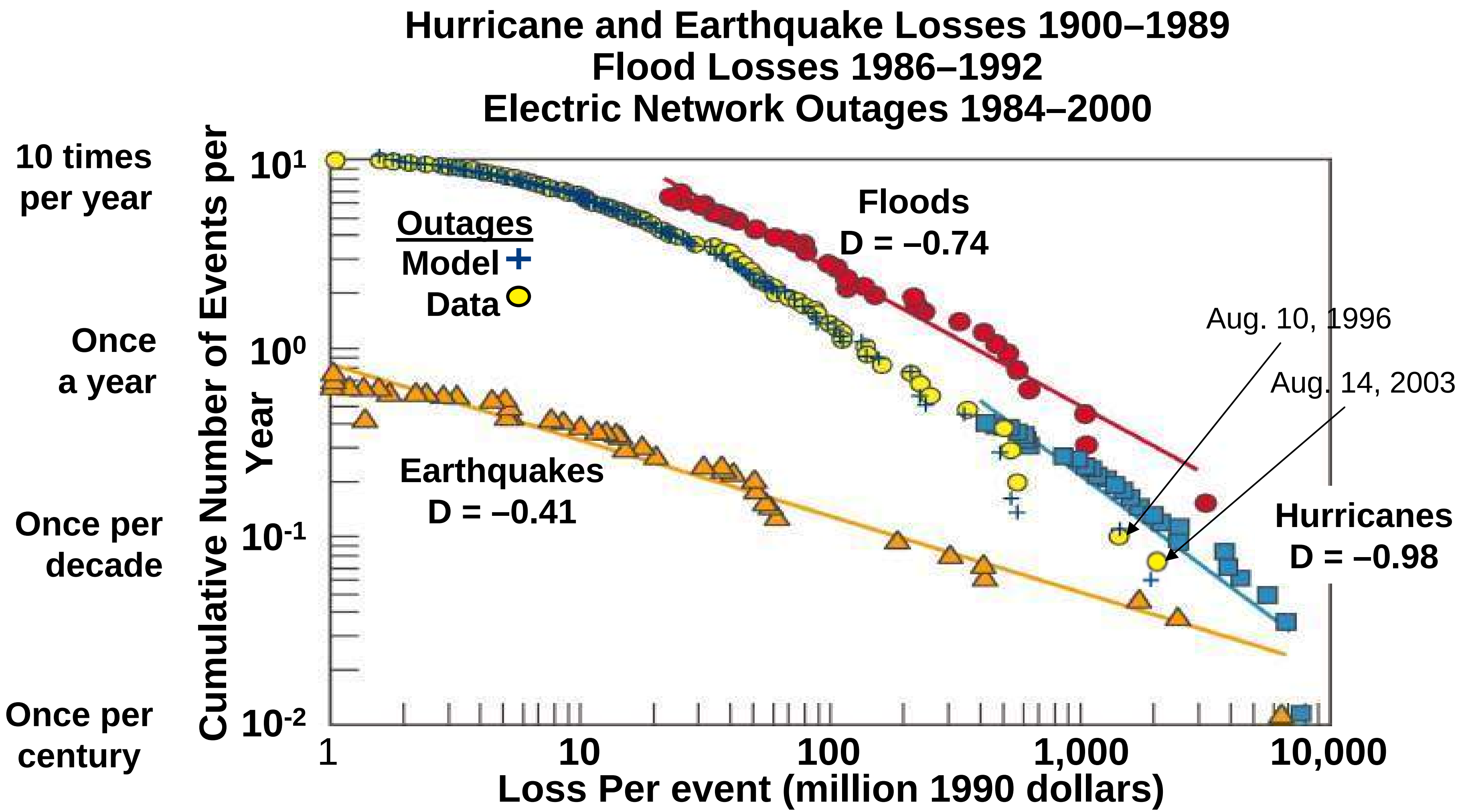
Transforming Society



The vast networks of electrification are the greatest engineering achievement of the 20th century

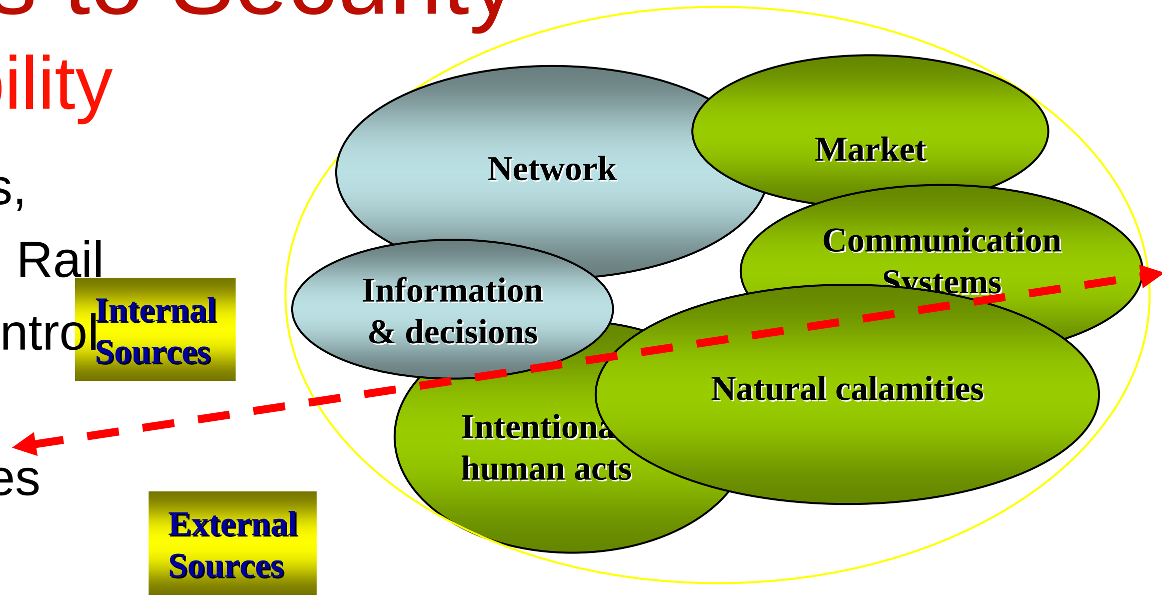
– U.S. National Academy of Engineering

Power Law Distributions: Frequency & impacts of major disasters



Context: Threats to Security

Sources of Vulnerability



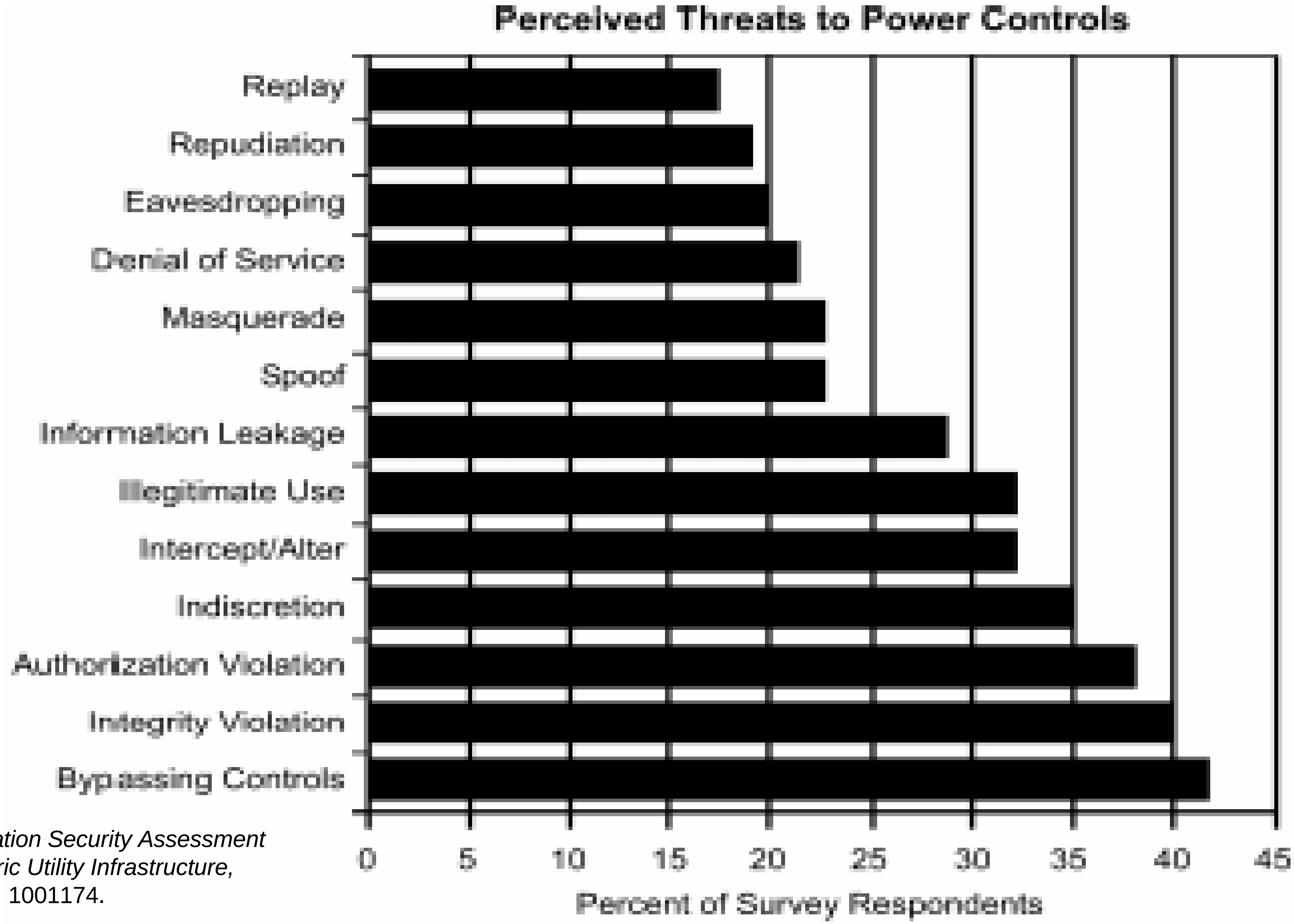
- Interdependence: Gas pipelines, compressor stations, etc.; Dams; Rail lines; Telecom – monitoring & control of system
- Transformer, line reactors, series capacitors, transmission lines...
- Protection of ALL the widely diverse and dispersed assets is impractical

Control Centers

- Combinations of the above and more using a variety of weapons:
- Truck bombs; Small airplanes; Gun shots – line insulators, transformers; more sophisticated modes of attack…

- Hijacking of control
- EMP
- Biological contamination (real or threat)
- Over-reaction to isolated incidents or threats
- Internet Attacks – over 50,000 hits a day at an ISO
- Storms, Earthquakes, Forest fires & grass land fires
- Loss of major equipment…

Cyber Threats to Controls



Source: *EPRI, Communication Security Assessment for the United States Electric Utility Infrastructure,* EPRI, Palo Alto, CA: 2000. 1001174.

Prioritization: Security Index

General

1. Corporate culture (adherence to procedures, visible promotion of better security, management security knowledge)
2. Security program (up-to-date, complete, managed, and includes vulnerability and risk assessments)
3. Employees (compliance with policies and procedures, background checks, training)
4. Emergency and threat-response capability (organized, trained, manned, drilled)

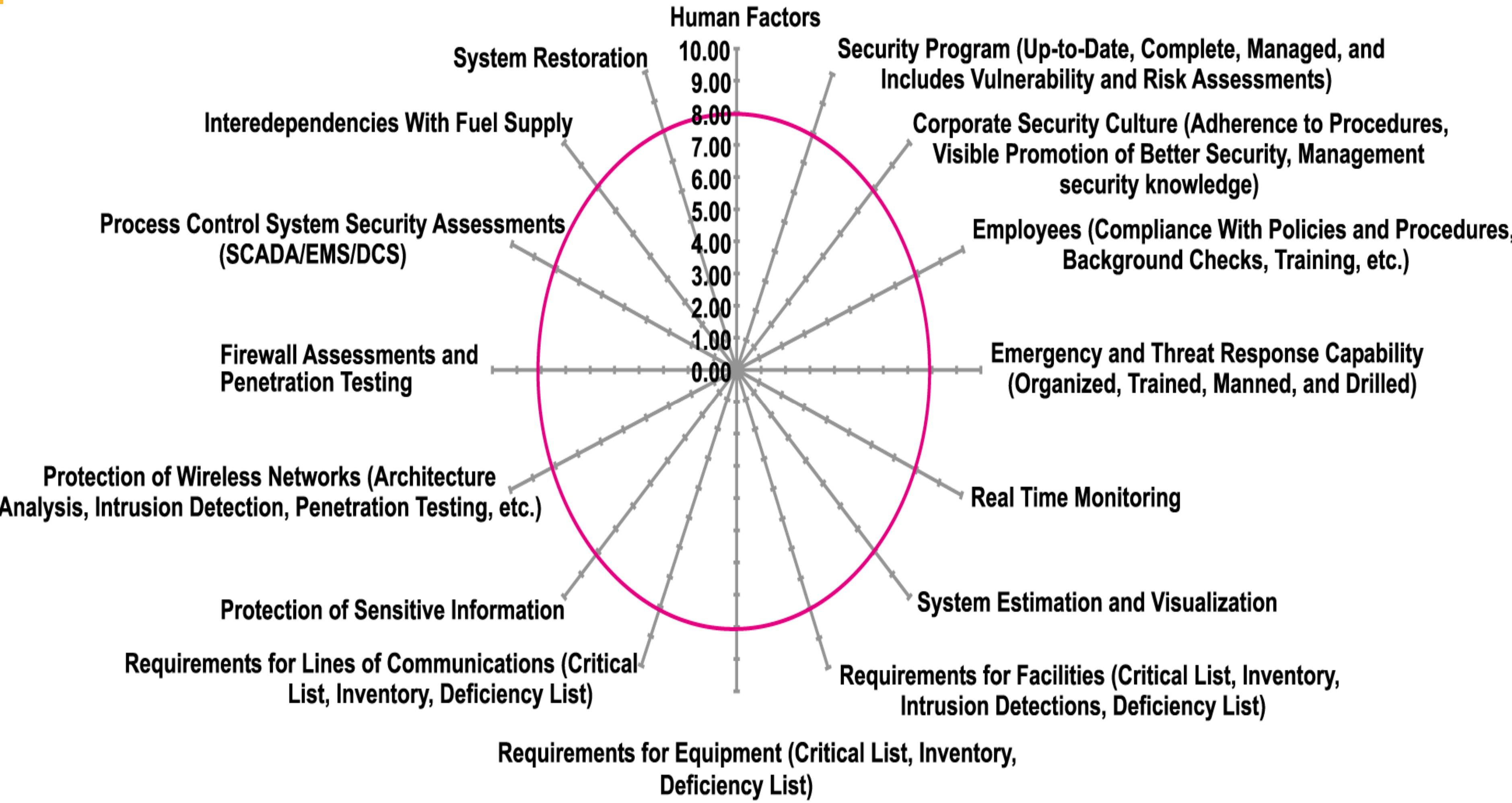
Physical

1. Requirements for facilities (critical list, inventory, intrusion detections, deficiency list)
2. Requirements for equipment (critical list, inventory, deficiency list)
3. Requirements for lines of communications (critical list, inventory, deficiency list)
4. Protection of sensitive information

Cyber and IT

1. Protection of wired networks (architecture analysis, intrusion detection)
2. Protection of wireless networks (architecture analysis, intrusion detection, penetration testing)
3. Firewall assessments
4. Process control system security assessments (SCADA, EMS, DCS)

Assessment & Prioritization: A Composite Spider Diagram to Display Security Indices



Example: Threats to the Transmission Grid

September 2002 fires

Biscuit Fire - Cascade Fire (Oregon)

Iron Mountain fire

Hickok fire - 776 acres

Freeway Fire - no threat to SCE facilities

Curve Fire: San Gabriel Canyon Road. 30-Miles N/O Azusa, 10,000 acres

Curb Fire: 19,500 acres

Leona Fire: Midway-Vincent area

Whitmore fire: Kilarc-Deschultes 60kV lost

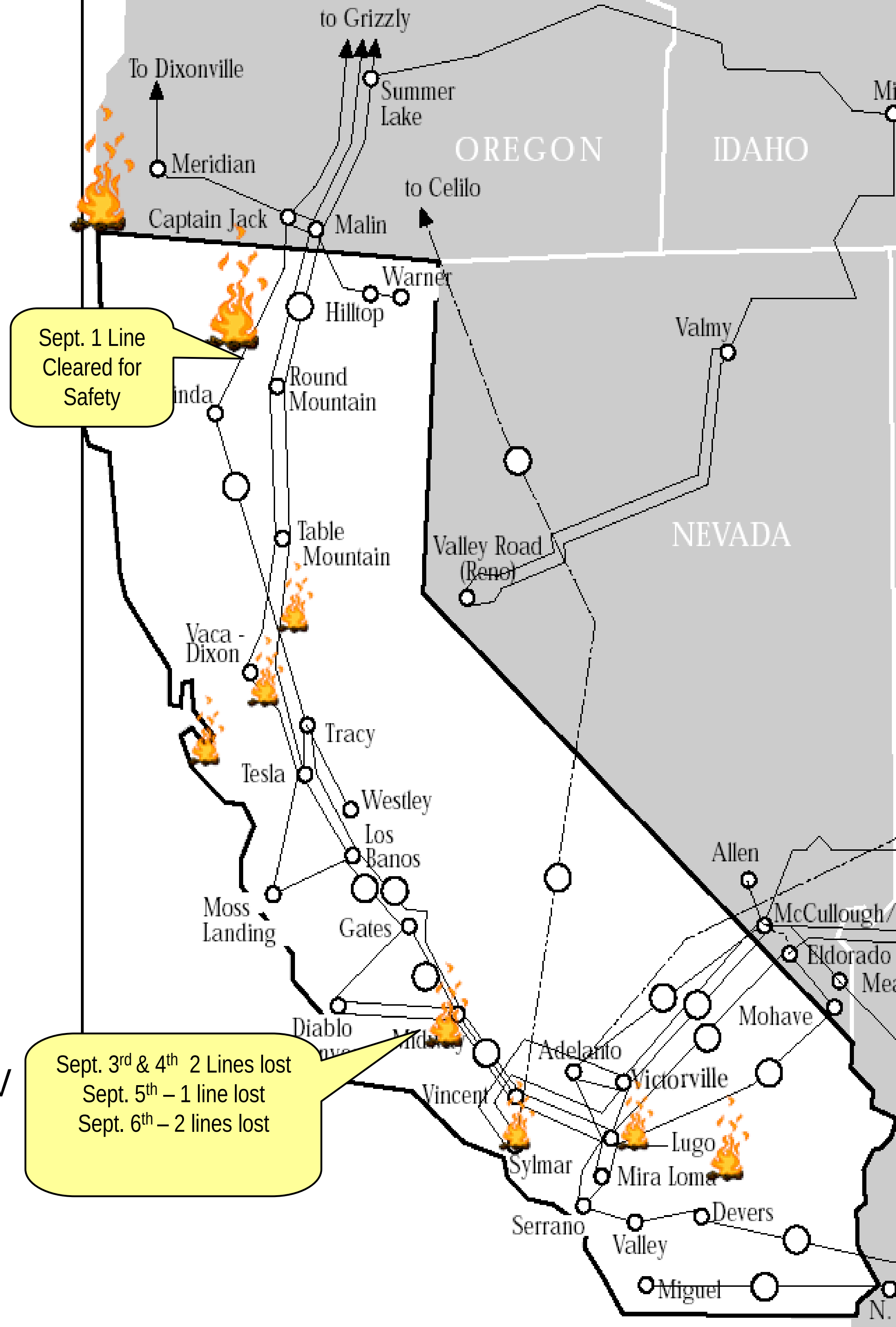
Glendale - Eagle Rock fire: Near Gould-Sylmar 220kV line

Olita Fire: El Dorado County –Gold Hill SS

Mountain Fire: Rutledge - Hardie area

Croy Fire: Morgan Hill area -Metcalf-Green Valley 115kV line impacted

Williams Fire: 35,000 acres



Source CA-ISO

Example: Fire under the 500 kV Lines – Sept 2002

Example: Midway – Vincent 500 kV line tower damage

Midway – Vincent 500 kV line damage

Vincent Substation before Transformer Explosion & Fire

Source CA-ISO

500 / 230 kV Transformer Explosion & Fire March 21, 2003
Vincent Substation

Lessons learned, e.g.: Redundancy Lowers Impact of Threats

- Two Separate Control Rooms – 500 miles apart
- Dual EMS systems at each location + Training/testing EMS
- Diversified communications networks

Overview of my research areas (1998-2003):

Initiatives and Programs I developed and/or led at EPRI

1999-2001	**Y2K**→2000-present	2002-present	2001-present
EPRI/DoD Complex Interactive Networks (CIN/SI)	Enterprise Information Security (EIS)	Infrastructure Security Initiative (ISI)	Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)
Underpinnings of Interdependent Critical National Infrastructures Tools that enable secure, robust & reliable operation of interdependent infrastructures with distributed intel. & self-healing	▪ Information Sharing ▪ Intrusion/Tamper Detection ▪ Comm. Protocol Security ▪ Risk Mgmt. ▪ Enhancement ▪ High Speed Encryption	**Response to 9/11 Tragedies** ▪ Strategic Spare Parts Inventory ▪ Vulnerability Assessments ▪ Red Teaming ▪ Secure Communications	▪ Self Healing Grid ▪ IntelliGrid™ ▪ Integrated Electric Communications System Architecture ▪ Fast Simulation and Modeling

Recent Directions: EPRI/DOD Complex Interactive Network/Systems Initiative

"We are sick and tired of them and they had better change!"
Chicago Mayor Richard Daley on the August 1999 Blackout

Complex interactive networks:

- *Energy infrastructure*: Electric power grids, water, oil and gas pipelines
- *Telecommunication:* Information, communications and satellite networks; sensor and measurement systems and other continuous information flow systems
- *Transportation and distribution networks*
- *Energy markets, banking and finance*

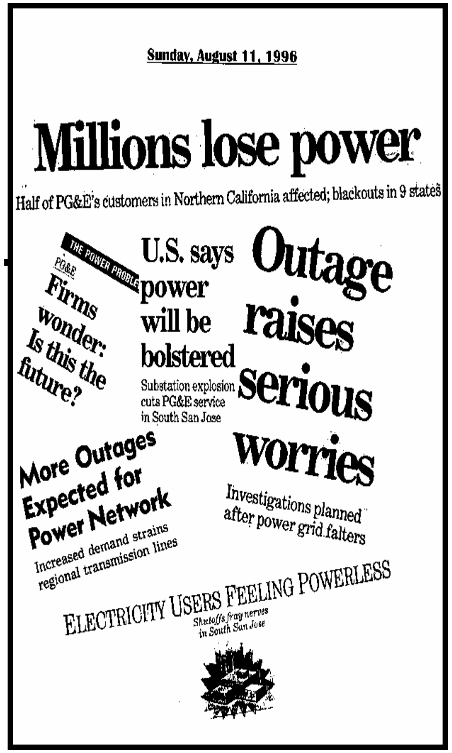
1999-2001: $5.2M / year —
Equally Funded by DoD/EPRI

Develop tools that enable secure, robust and reliable operation of interdependent infrastructures with distributed intelligence and self-healing abilities

Background: EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

The Reason for this Initiative: "Those who do not remember the past are condemned to repeat it."
George Santayana

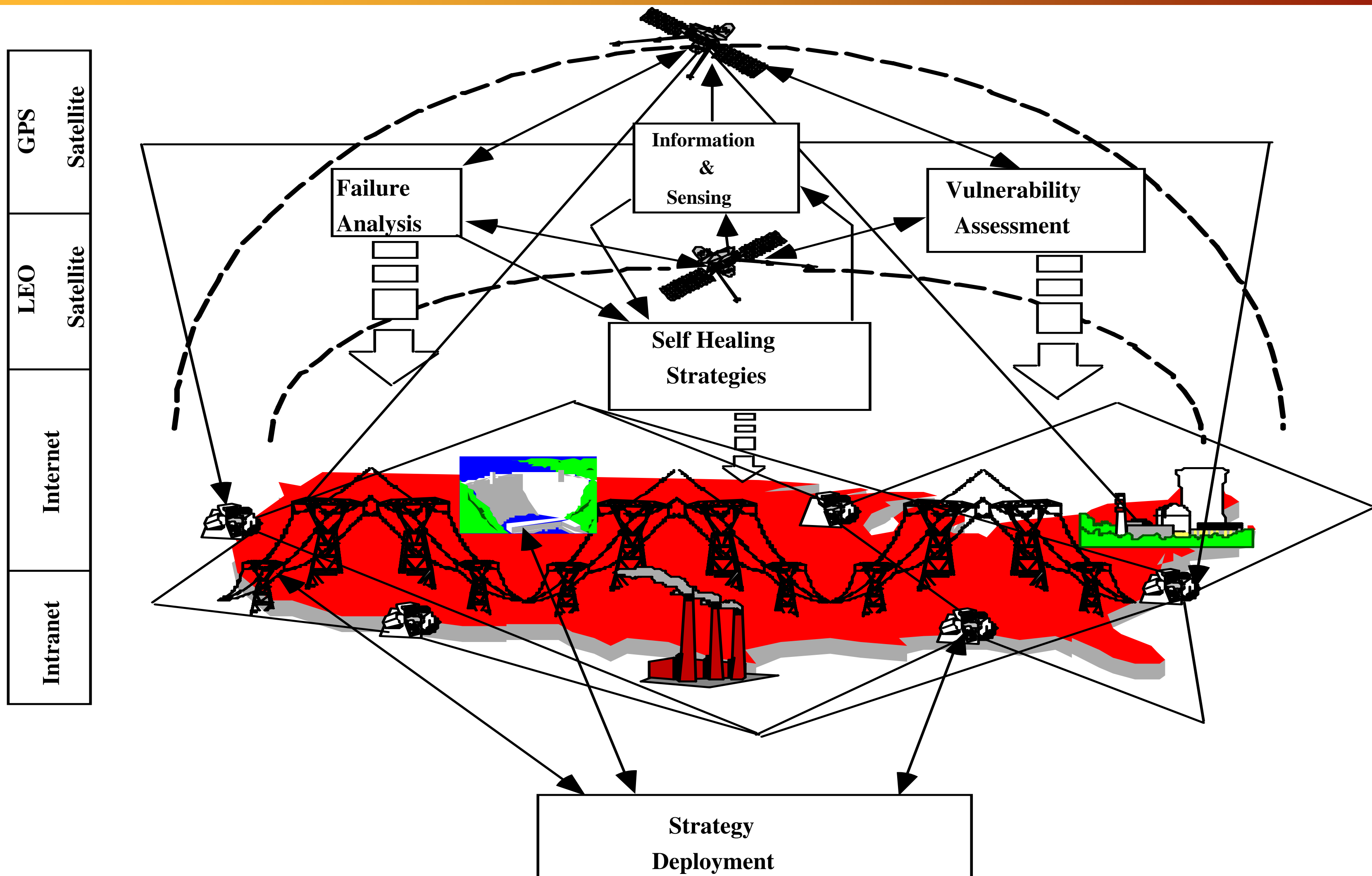
- Two faults in Oregon (500 kV & 230 kV) led to…
  - …tripping of generators at McNary dam
  - …500 MW oscillations
  - …separation of the Pacific Intertie at the California-Oregon border
  - …blackouts in 13 states/provinces
- Some studies show with proper "intelligent controls," all would have been prevented by shedding 0.4% of load for 30 minutes!



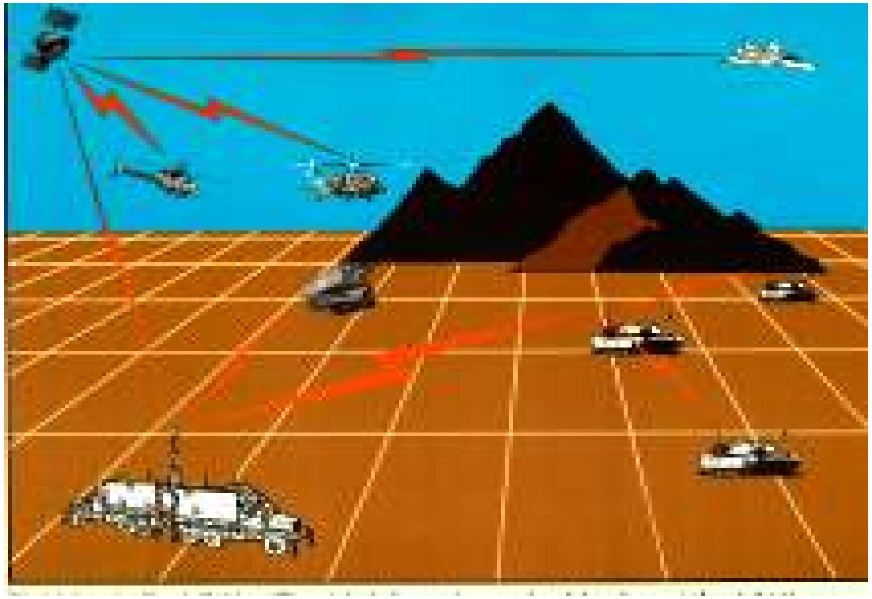
August 10, 1996

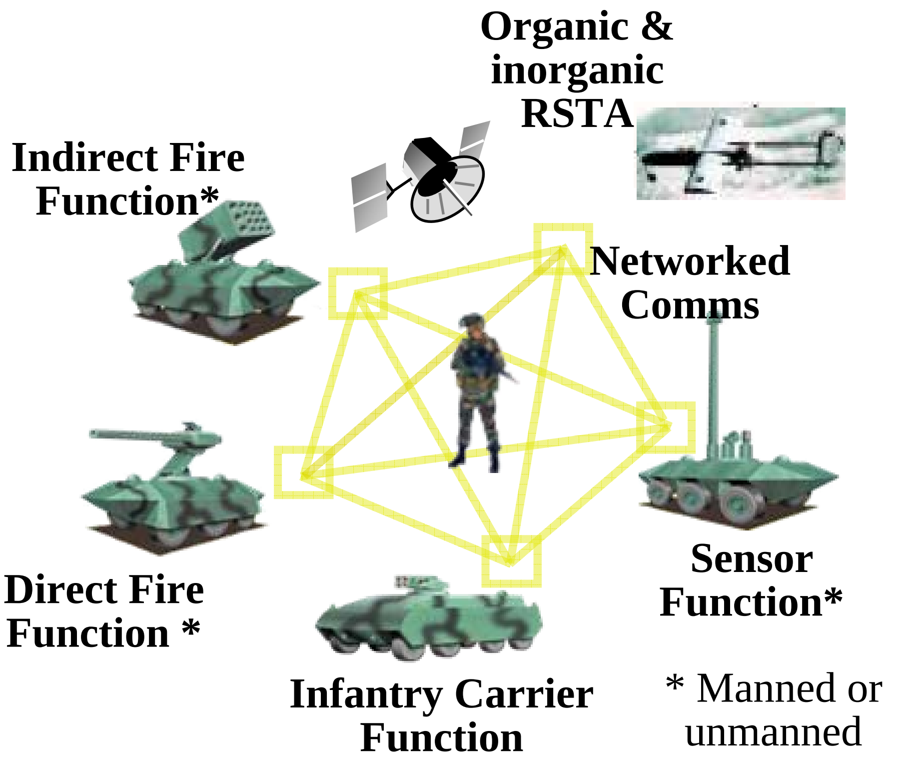
Everyone wants to operate the power system closer to the edge. A good idea! but *where is the edge* and *how close are we to it*.

Complex Interactive Networks



Network Centric Objective Force





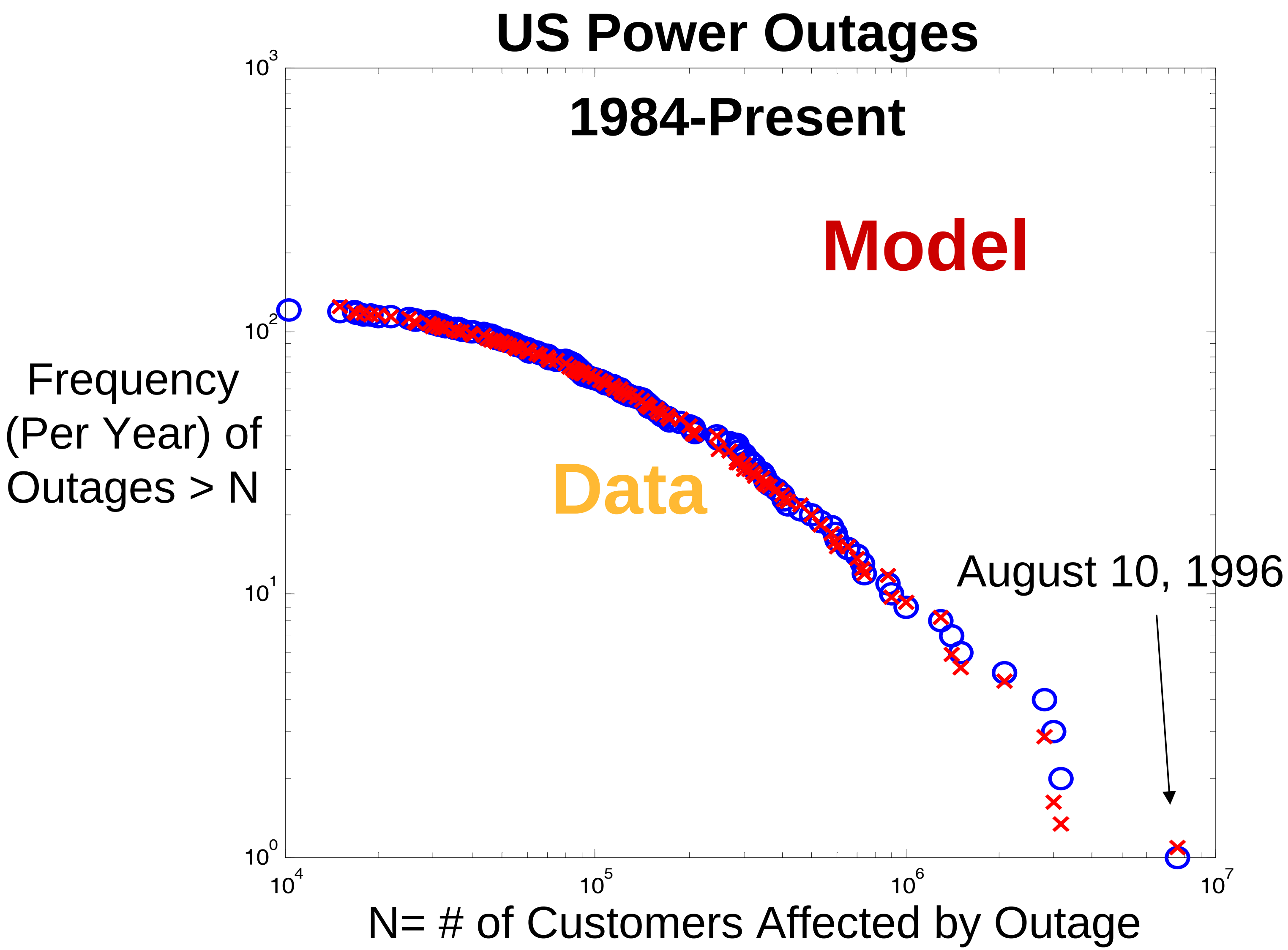
CIN/SI Funded Consortia

107 professors in 28 U.S. universities are funded: Over 360 publications, and 19 technologies extracted, in the 3-year initiative

- U Washington, Arizona St., Iowa St., VPI
- Purdue, U Tennessee, Fisk U, TVA, ComEd
- Harvard, UMass, Boston, MIT, Washington U.
- Cornell, UC-Berkeley, GWU, Illinois, Washington St., Wisconsin
- CMU, RPI, UTAM, Minnesota, Illinois
- Cal Tech, MIT, Illinois, UC-SB, UCLA, Stanford

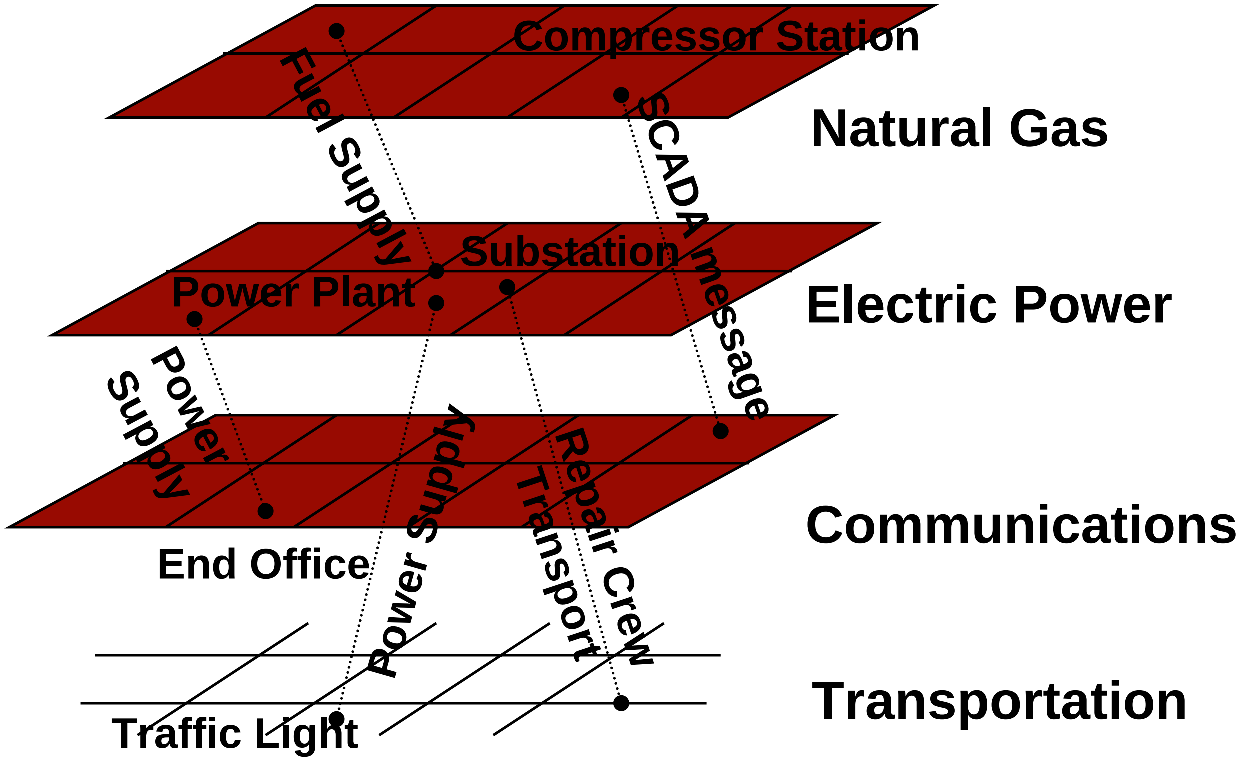
- Defense Against Catastrophic Failures, Vulnerability Assessment
- Intelligent Management of the Power Grid
- Modeling and Diagnosis Methods
- Minimizing Failures While Maintaining Efficiency / Stochastic Analysis of Network Performance
- Context Dependent Network Agents
- Mathematical Foundations: Efficiency & Robustness of Distributed Systems

Background: Power Laws



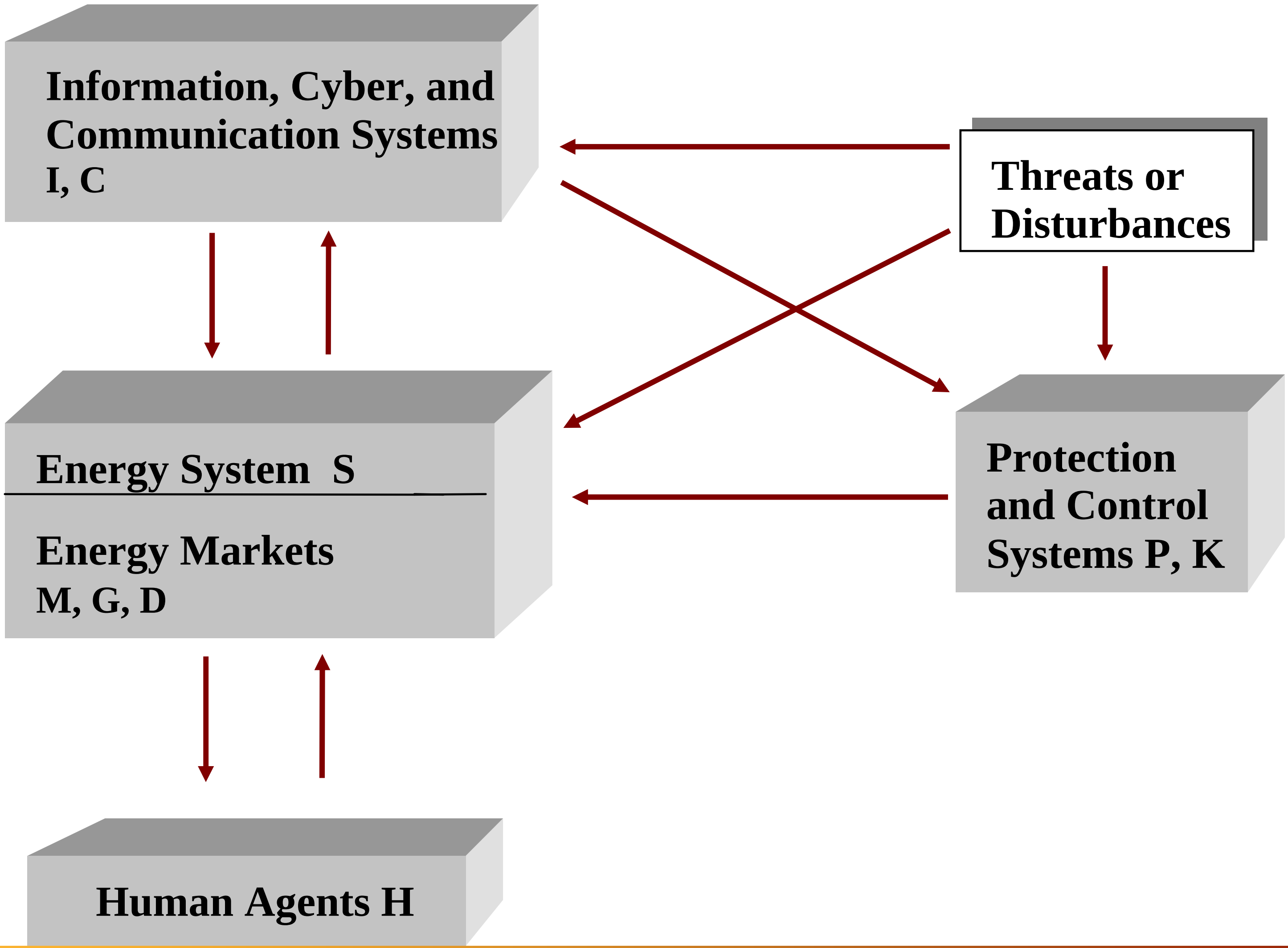
EPRI/DoD CIN/S Initiative

Infrastructure Interdependencies



- Critical system components
- Interdependent propagation pathways and degrees of coupling
- Benefits of mitigation plans

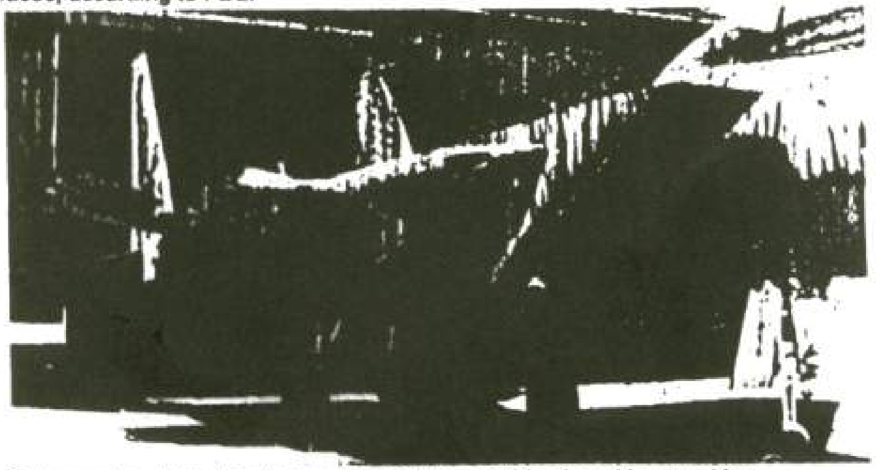
Integrated Protection and Control



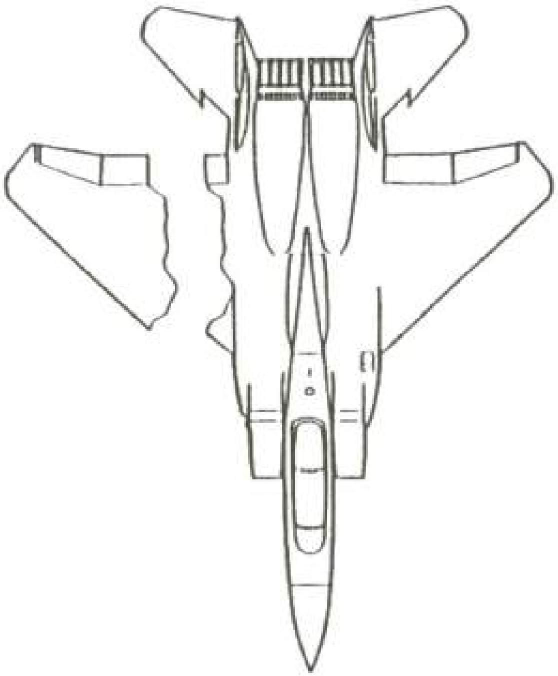
Background:
The Self Healing Grid

Background: The Case of the Missing Wing

Believe it or not, this one made it back! This F-15, with half its wing missing, is a good example of what is currently considered an "unflyable" aircraft. However, the pilot's success in bringing it home helped to inspire a new program at Aeronautical Systems Division's Flight Dynamics Laboratory aimed at enabling future fighter pilots to fly aircraft with severely damaged control surfaces. The pilot of this F-15 configured in unusual ways the control surfaces that were still working to compensate for the damaged wing. The FDL program will make this "survivors" reaction automatic to the aircraft. Therefore, flying a damaged aircraft will be much easier on the pilot. Through a self-repairing flight control system nearing development, a computerized "brain" will automatically reconfigure such surfaces as rudders, flaperons, and ailerons to compensate for grave damage to essential flying surfaces, according to FDL.

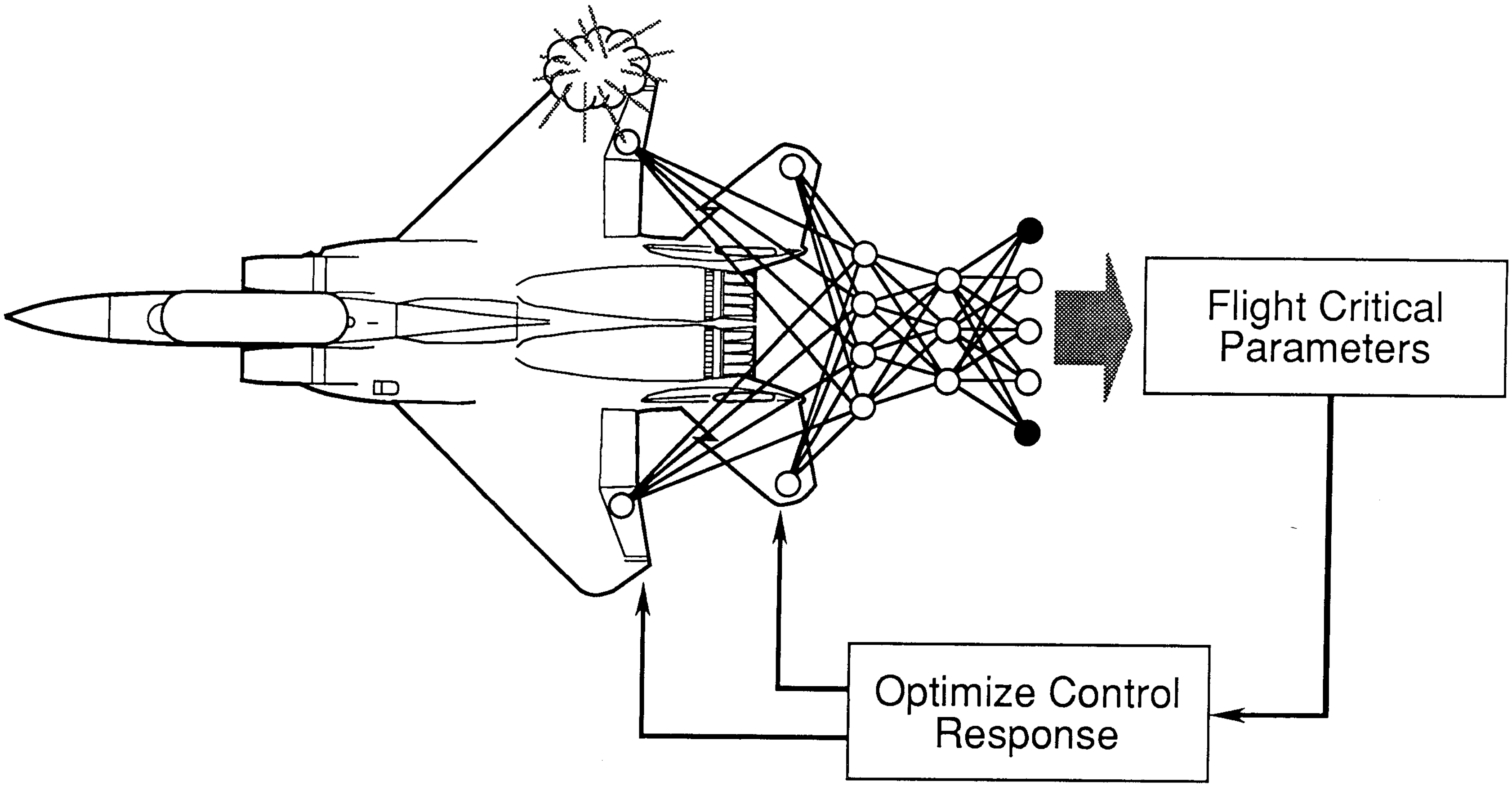


Only smart work by the pilot and the unique combination of interworking control surfaces on the F-15 brought this one back alive. With old-fashioned conventional ailerons and horizontal stabilizer, it couldn't have happened.



NASA/MDA/WU IFCS: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University in St. Louis.

Goal: Optimize controls to compensate for damage or failure conditions of the aircraft*



NASA/MDA/WU IFCS

Dynamical System Estimation: Topology of RHONN

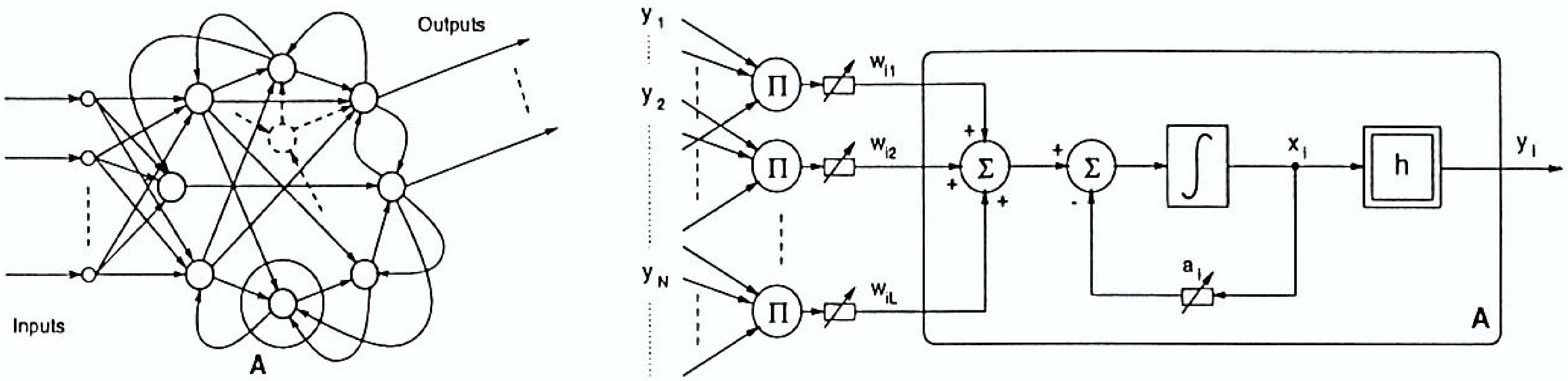


Figure 2: Network structure with higher-order unit ($d_{jk} = 1$)

– Dynamical elements in the form of feedback connections.

– Dynamical components are distributed in form of dynamical units throughout the network.

– Higher-order interactions between neurons: the input to a unit is a linear combination of the components of outputs and their products.

System Estimator: Unit Dynamics

$$
\begin{aligned}
\dot{x}_i &= -a_i x_i + \sum_{k=1}^{L} w_{ik} \prod_{j \in I_k} y_j^{d_{jk}}, \quad x_i(0) = x_{i0}, \quad i = 1, \ldots N \\
y &= [y_1, y_2, \ldots, y_M, y_{M+1}, \ldots, y_{M+N}]^T \\
&= [u_1,\ u_2,\ \ldots,\ u_M,\ h(x_1),\ h(x_2),\ \ldots,\ h(x_N)]^T
\end{aligned}
$$

where

$\{I_1, I_2, \ldots, I_L\}$	:	collection of L not-ordered subsets of $\{1, 2, \ldots, M+N\}$
M	:	number of inputs u_i
N	:	number of dynamical units (states) x_i
$a_i > 0$	:	dynamical parameter
w_{ik}	:	weight parameter
$d_{jk} > 0$	:	integer
$h(\cdot)$	:	nonlinear continuous functions

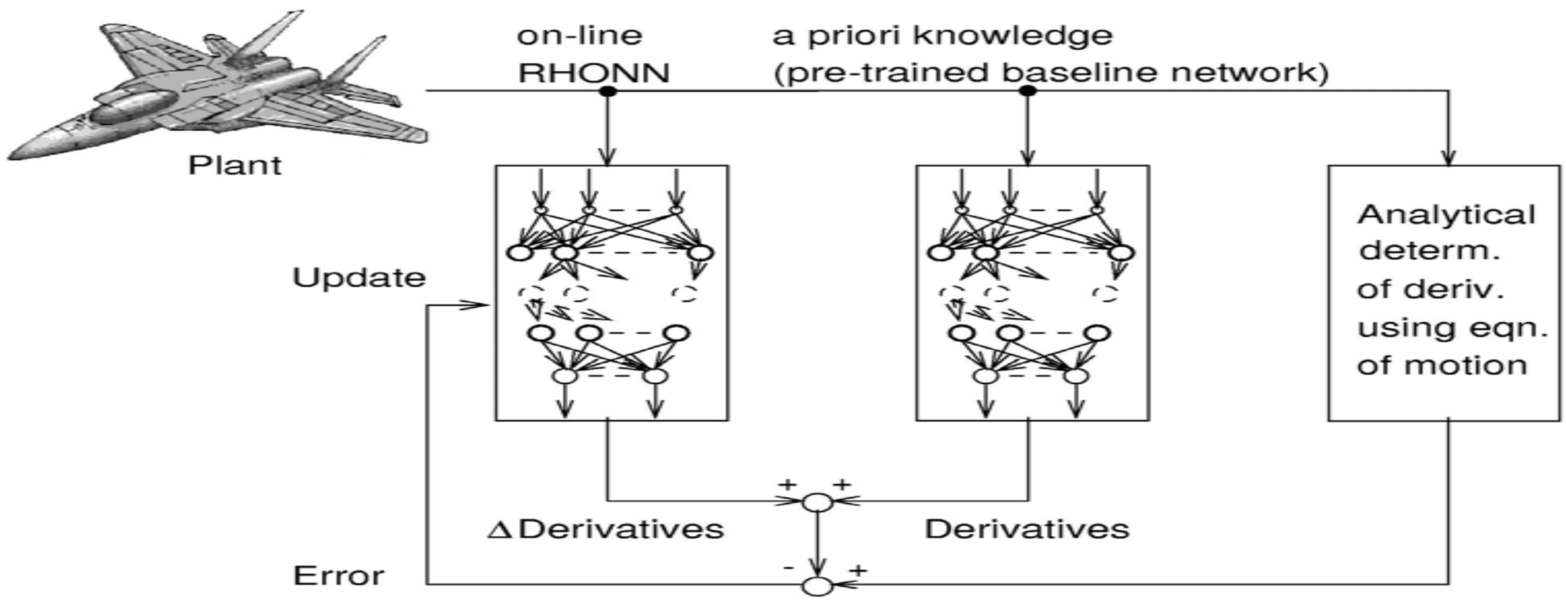
RHONN Overall System Dynamics

$$\begin{aligned} \dot{x} &= Ax + Bg(x,u), \quad x(0) = x_0 \\ y_{ext} &= Cx \end{aligned} \tag{1}$$

where

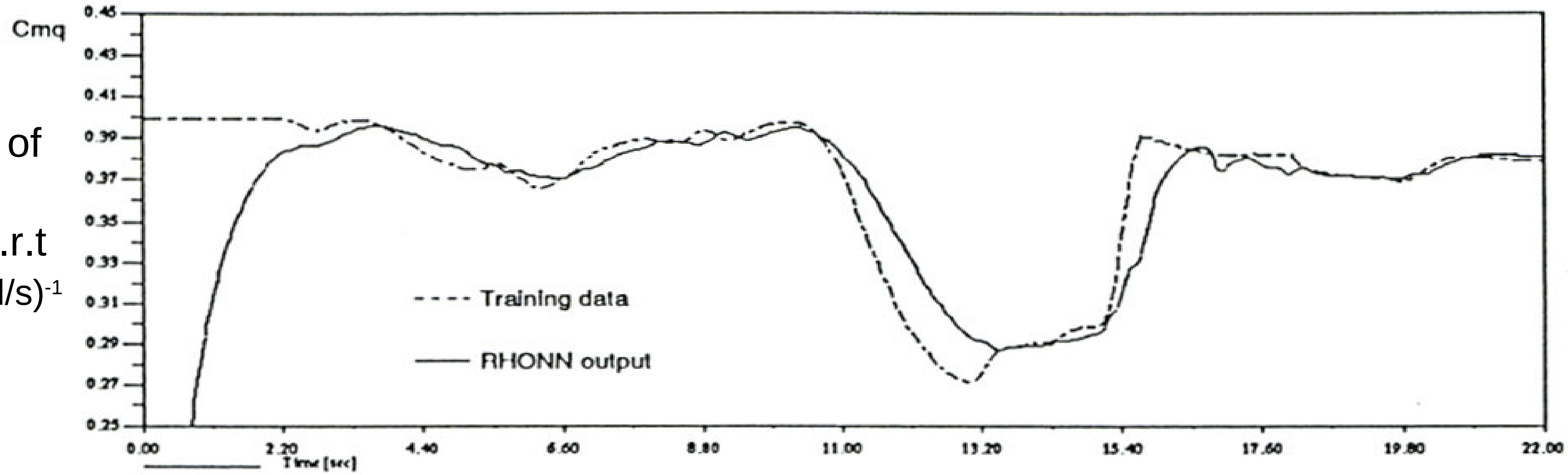
$$\begin{aligned} g &= [\prod_{j\in I_1} y_j^{d_{j1}},\ \prod_{j\in I_2} y_j^{d_{j2}},\ \ldots,\ \prod_{j\in I_L} y_j^{d_{jL}}]^T \in \mathcal{R}^L \\ x &= [x_1,\ x_2,\ \ldots,\ x_N]^T \in \mathcal{R}^N \\ A &= -diagonal\,\{a_1,\ a_2,\ \ldots,\ a_N\} \in \mathcal{R}^{N\times N} \\ b_i &= [w_{i1},\ w_{i2},\ \ldots,\ w_{iL}]^T \in \mathcal{R}^L \\ B &= [b_1,\ b_2,\ \ldots,\ b_N]^T \in \mathcal{R}^{N\times L} \end{aligned}$$

Architecture

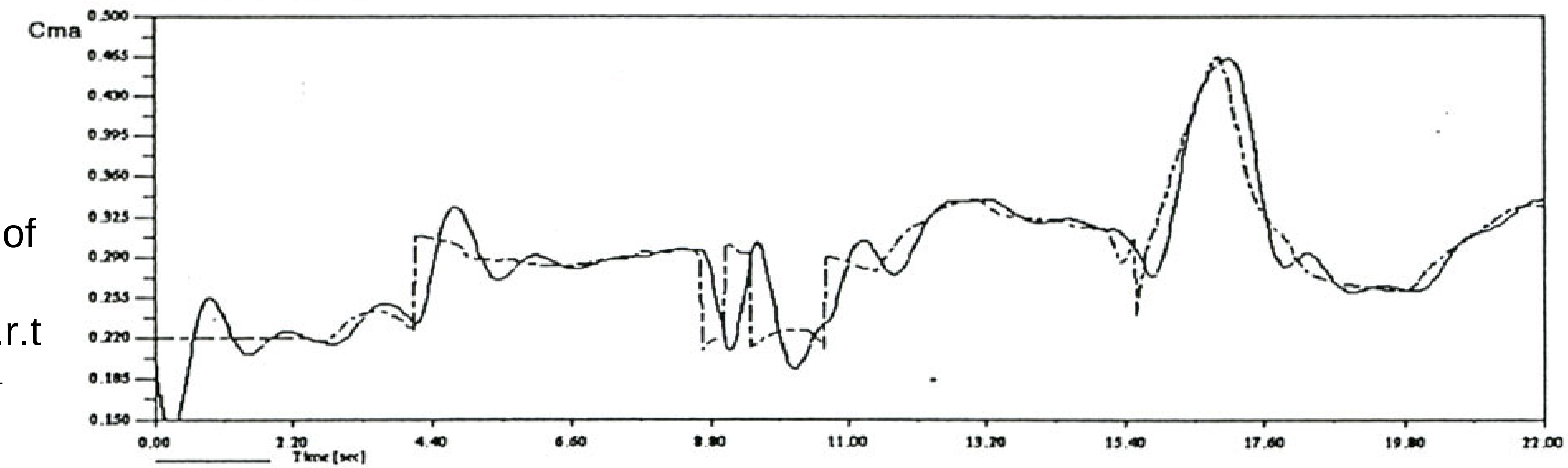


On-Line Learning Without Baseline Network

Partial Derivative of Pitching moment w.r.t pitch rate (d/s)$^{-1}$

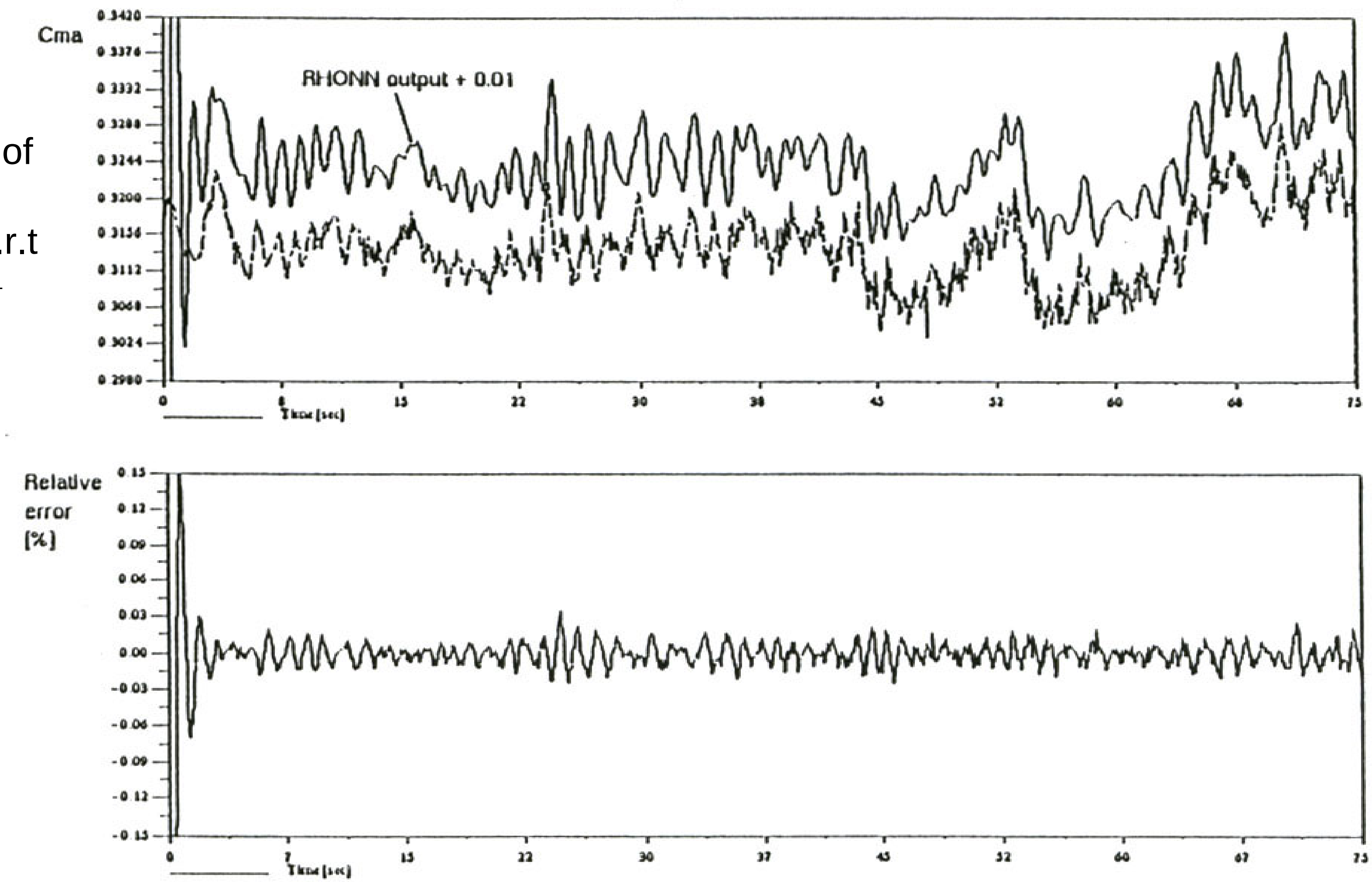


Partial Derivative of Pitching moment w.r.t AoA (d)$^{-1}$

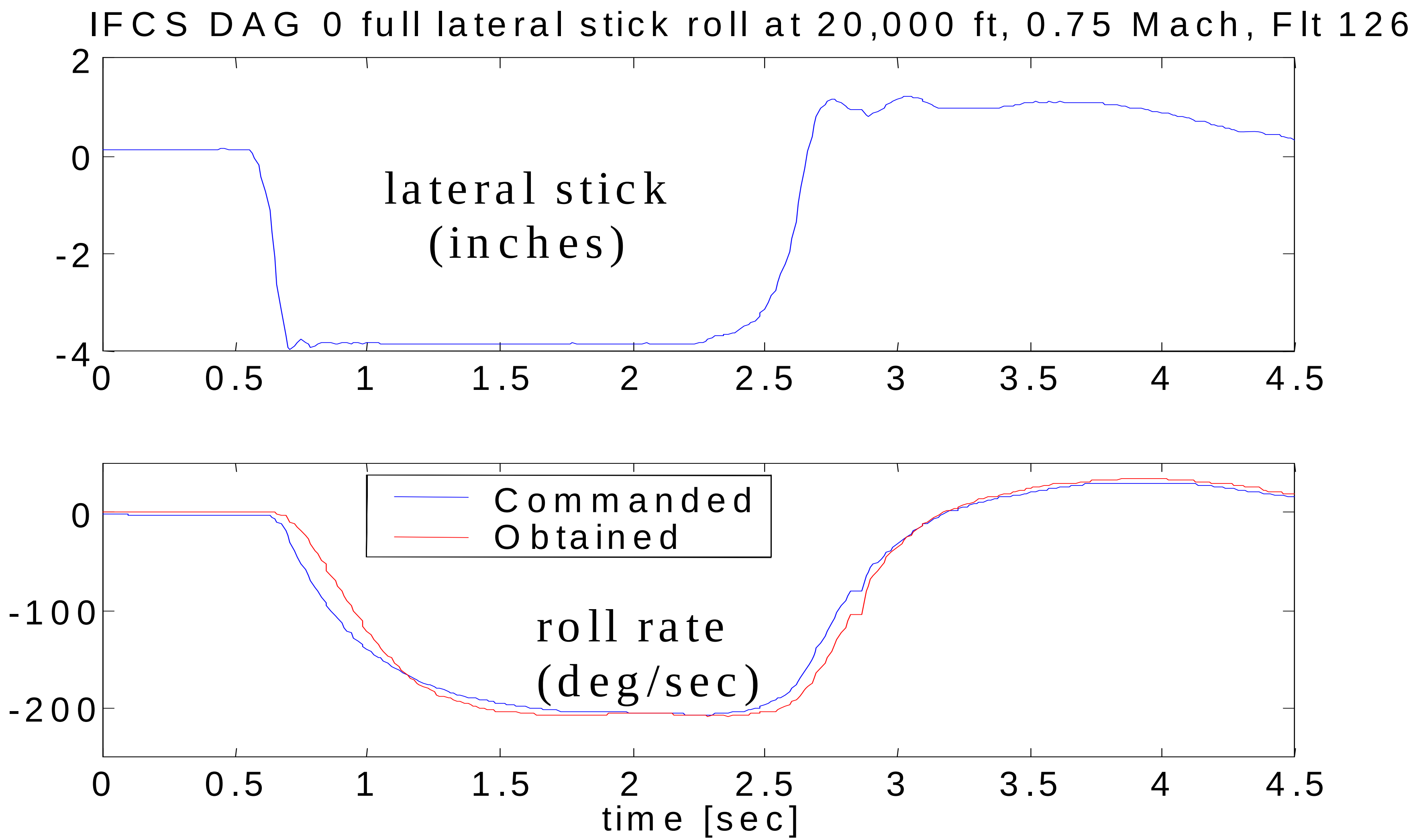


On-Line Learning Without Baseline Network

Partial Derivative of Pitching moment w.r.t AoA $(d)^{-1}$



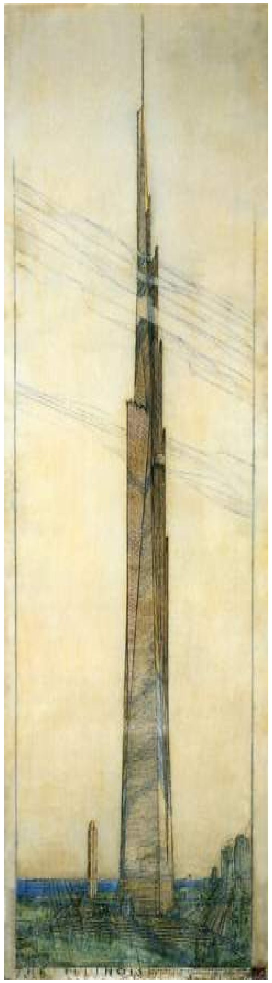
Roll Axis Response of the Intelligent Flight Control System



Accomplishments in the IFCS program

- The system was successfully test flown on a test F-15 at the NASA Dryden Flight Research Center:
  - Fifteen test flights were accomplished, including flight path control in a test flight envelope with supersonic flight conditions.
  - Maneuvers included 4g turns, split S, tracking, formation flight, and maximum afterburner acceleration to supersonic flight.
- Stochastic Optimal Feedforward and Feedback Technique (SOFFT) continuously optimizes controls to compensate for damage or failure conditions of the aircraft.
- Flight controller uses an on-line solution of the Riccati equation containing the neural network stability derivative data to continuously optimize feedback gains.
- Development team: NASA Ames Research Center, NASA Dryden Flight Research Center, Boeing Phantom Works, and Washington University.

Self-healing Grid



Building on the Foundation:

- Anticipation of disruptive events
- Look-ahead simulation capability
- Fast isolation and sectionalization
- Adaptive islanding

Tools: EPRI/DOD Complex Interactive Network/Systems Initiative (CIN/SI)

Tools:

- Dynamical systems
- Statistical physics
- Information & communication science
- Computational complexity

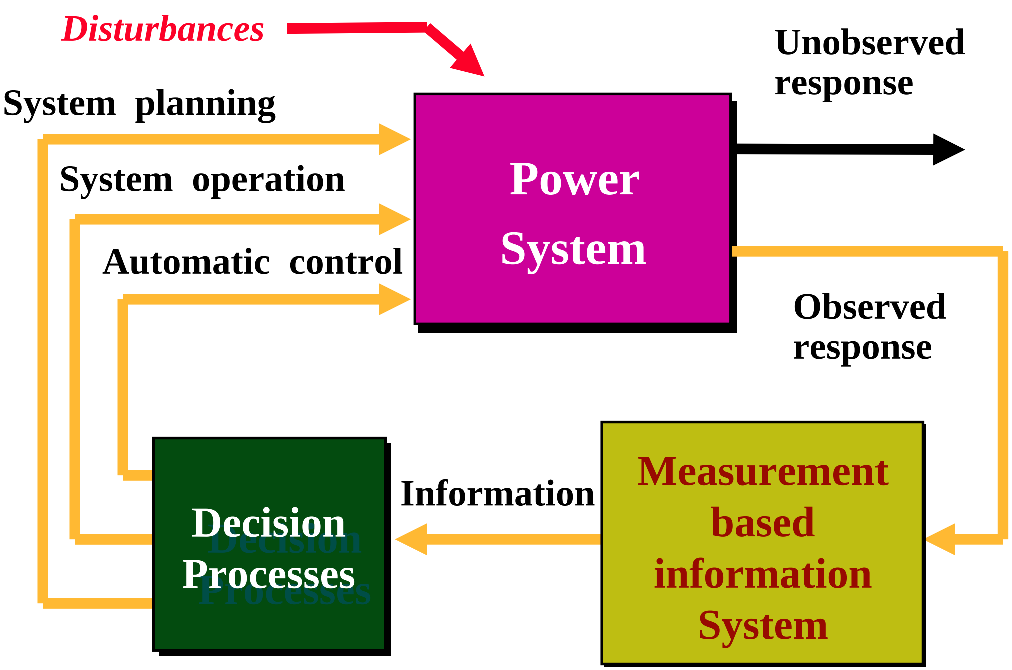
To measure and model coupled large-scale systems including:

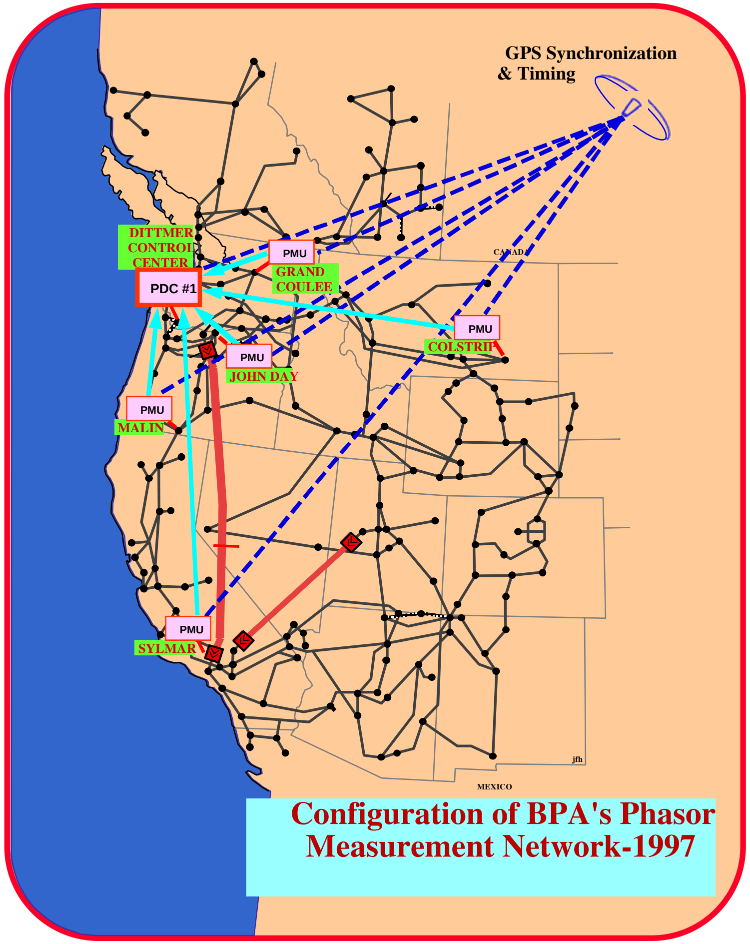
- Electricity Infrastructure
- Telecommunication networks
- Economic markets
- Cell phone networks and the Internet
- Other complex systems

Wide-Area Measurement System (WAMS)

Integrated measurements facilitate system management

"Better information supports better - and faster - decisions."

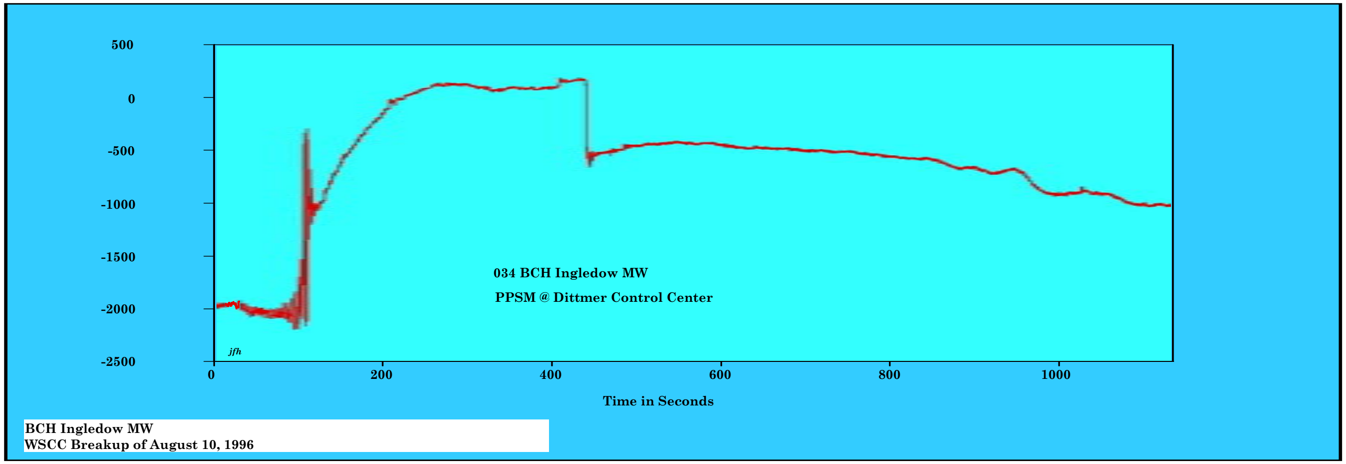


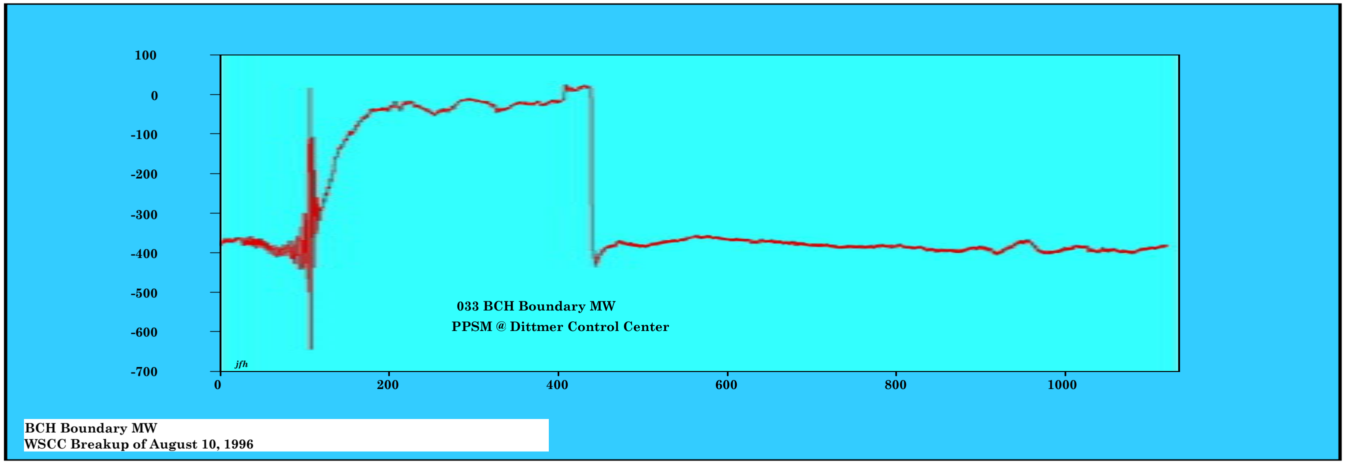


Configuration of BPA's Phasor Measurement Network-1997

Source: DOE/EPRI WAMS project-- BPA & PNNL

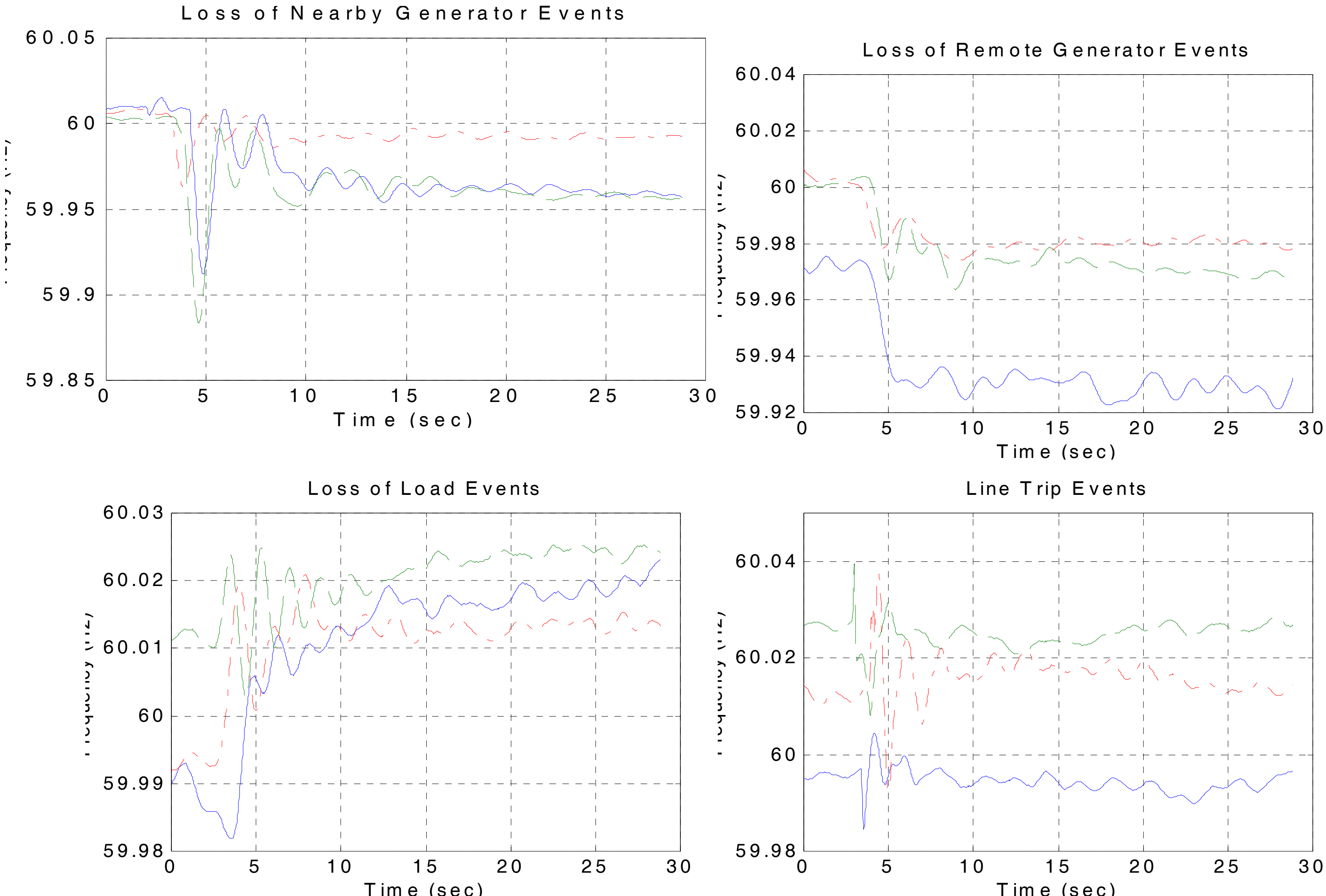
Detecting Precursors:
Disturbance records the August 10, 1996





Source: DOE/EPRI WAMS project

Detecting Precursors: Classification of fault signatures



Disturbance Feature Extraction

Disturbance	Frequency change	Frequency derivative	Line flow change
Loss of nearby generation	Negative	Steep	Large
Loss of remote generation	Negative	Moderate	Negligible
Loss of load	Positive	Moderate	Detectable
Line trip close to DRD	Negligible	Steep	Large
Oscillations	Negligible	Small	oscillations

Time-Scale of Actions & Operations Within the Power Grid

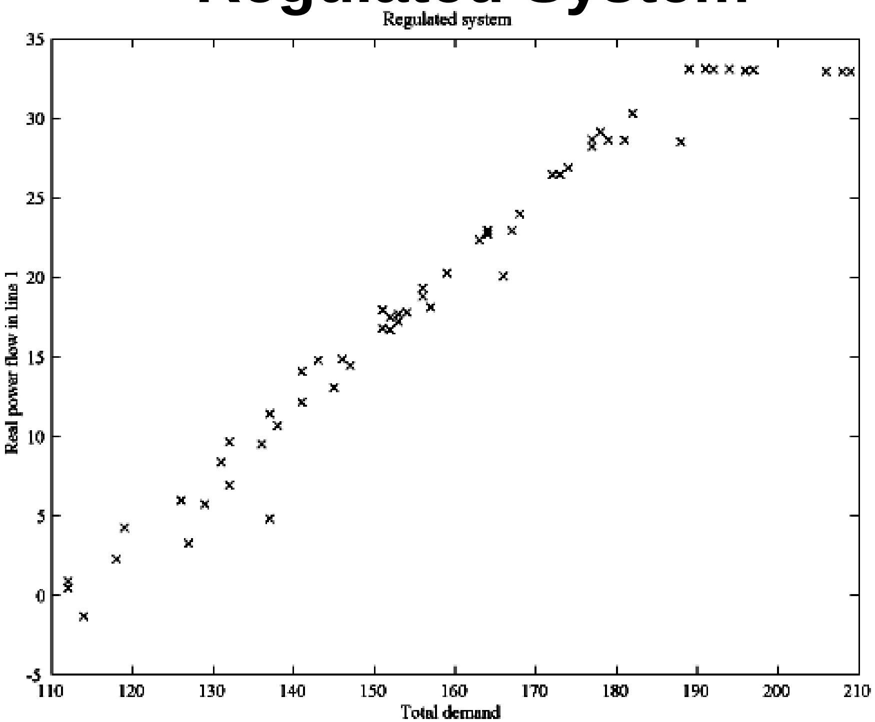
Action or Operation	Timeframe
Wave effects (fast dynamics such as lightning)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Tie-line load frequency control	1 to 10 seconds
Economic load dispatch	10 seconds to 1 hour
Load management, load forecasting, generation scheduling	1 hour to 1 day or more

Transmission Limits

- High dimensional problem
  - Large interconnection models require ~40,000 buses & ~50,000 lines, and ~3,000 generators with ~120 control areas
  - Each line has a capacity limit
  - The system must withstand of loss of any one line or generator (~53,000 contingencies)
  - 53,000 x 50,000 = 2,650,000,000 possible constraints
- Reliable operation requires an operating point that satisfy these 2.65 billion constraints!

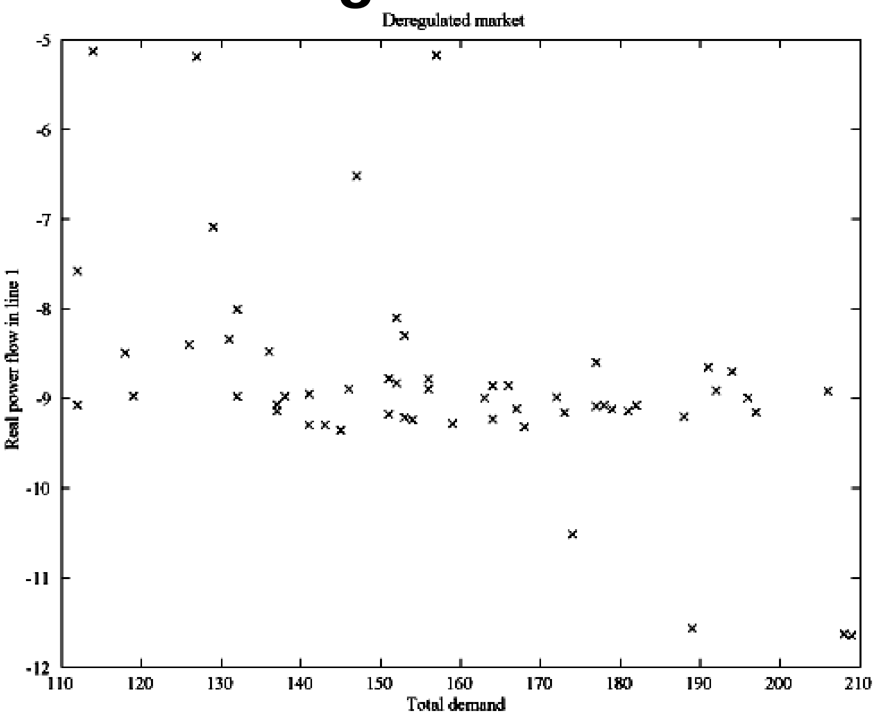
New Challenges:
Can Operators Predict Market Behavior?

Regulated System



- Economic dispatch
- Strong correlation between power flow and demand

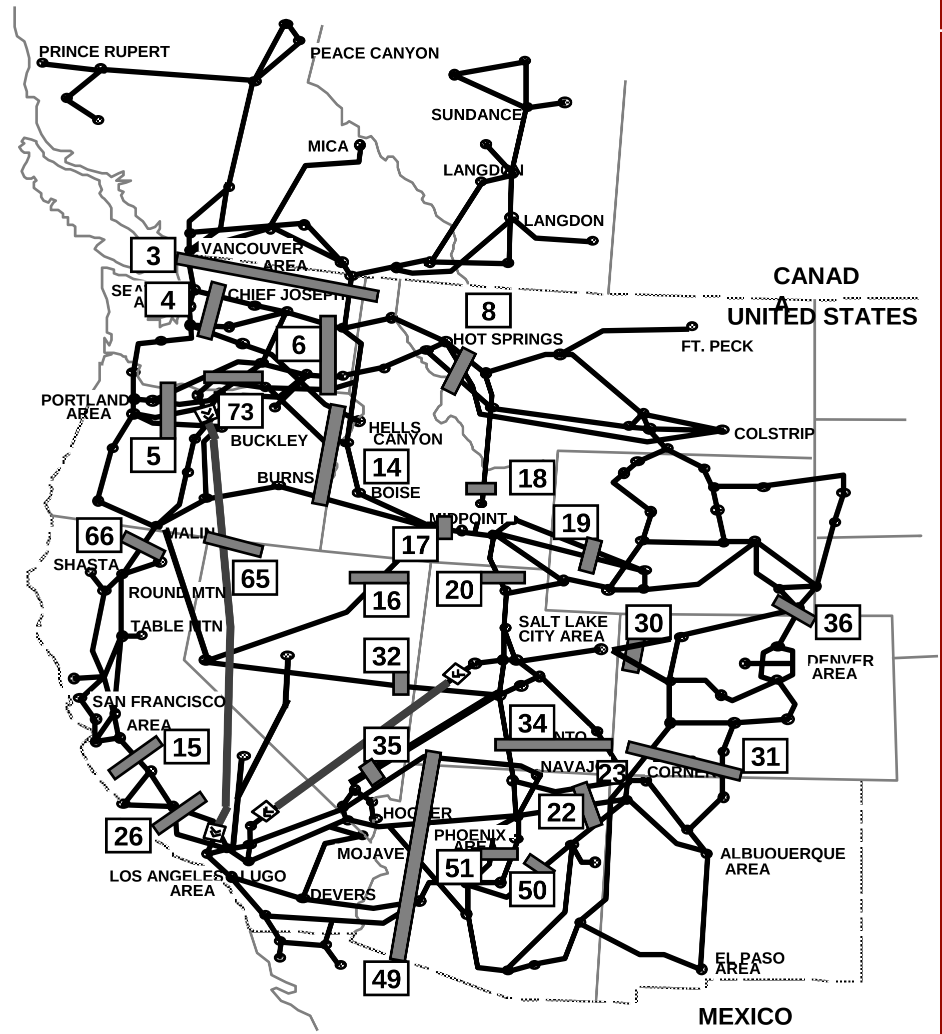
Deregulated Market



- Market-based dispatch
- Poor correlation between power flow and demand

Example: WECC Network Model & Tools

- One single model for Regional studies
- 13,000 buses
- Need Real-time State Estimator and Security Assessment Applications
- Need System Restoration analysis tools



Source: CA-ISO

Communication Requirements

Power System Tasks	Bandwidth Requirement	Current Response Time
Load Shedding (Local Decision)	Low	Seconds
Adaptive Relaying (e.g., Blocking relay)	Low	Not Available
Hierarchical Data Acquisition and Transfer	High	Seconds (e.g., 2-12 seconds / scan for RTUs)
Line / Bus Reconfiguration	Low	Minutes (manual)
Control Devices (e.g., FACTS, Transformer,…)	Medium	Seconds (manual)
Fault Event Recorder Information	Medium	Minutes
Generator Control	Low	Seconds
Strategic Power Infrastructure Defense & Coordination with Control Centers (EPRI/DoD CINSI)	High	Not Applicable

State Estimation:

$$Z = h(X) + V$$

where:

Z = The measurement vector

X = The state vector

V = The measurement error vector

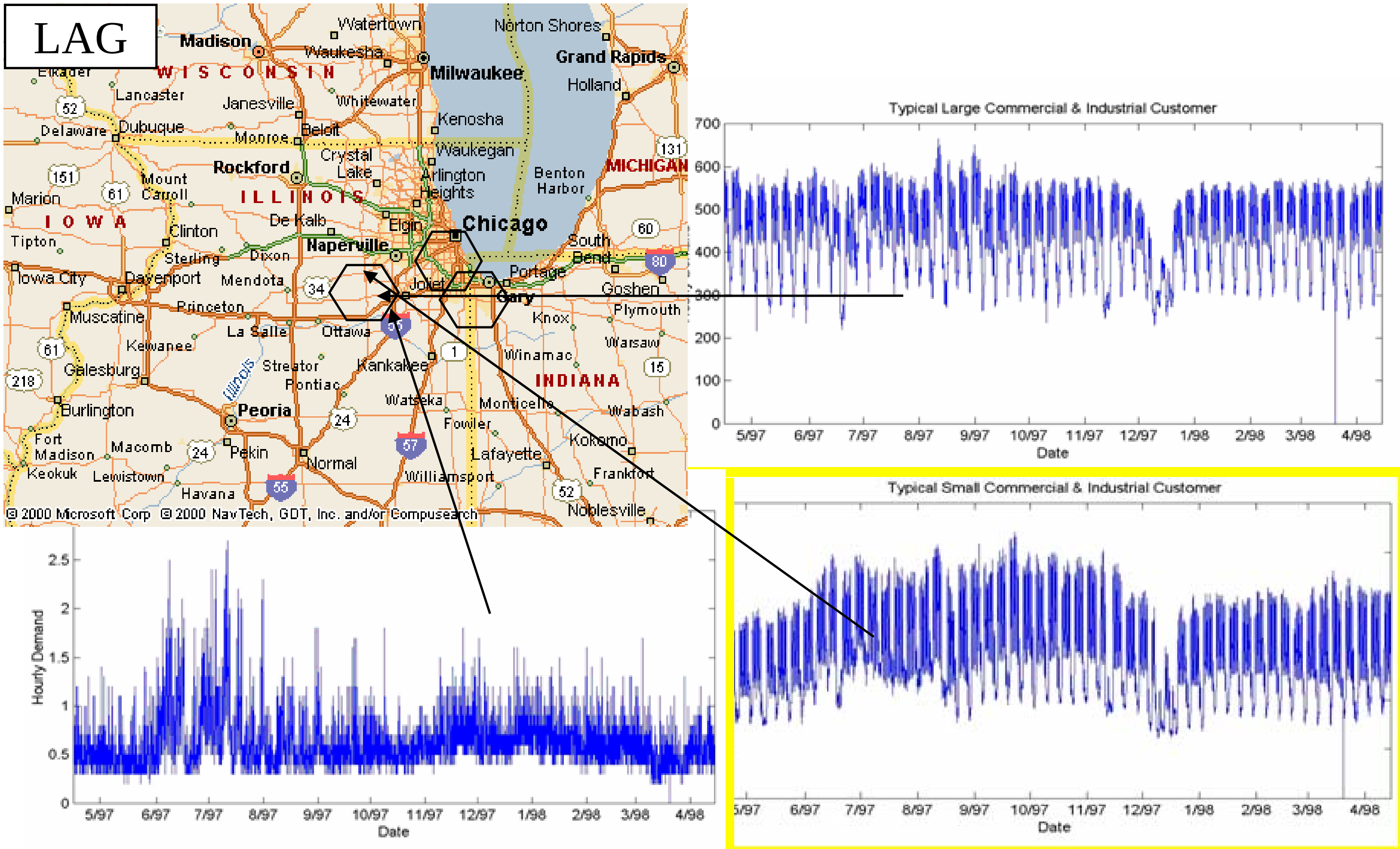
$h(X)$ = Non-linear observation function, the set of electrical equations relating MW and MVAR values to bus voltages and angles

$$Min.\ J(X) = [\,Z - h(X)\,]^{T} R^{-1} [\,Z - h(X)\,]$$

R = The measurement error covariance matrix

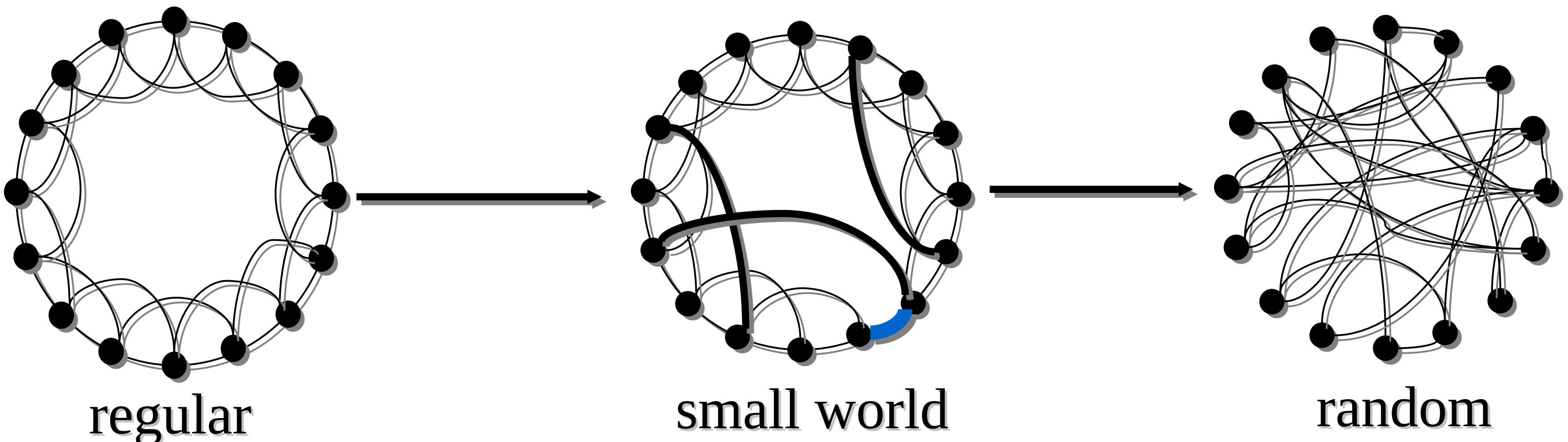
Extended to Advanced Topology Estimator: Determine unknown substation switch settings from voltages, power flows, and current measurements

Local area grids (LAG)



Efficient and designed networks
… relations to Topology &Dynamics?

- Topology affects dynamics (Watts/Strogatz ‘98; Watts’99).
  - “small world” topology enhances signal propagation.
  - Dynamics of cascading failures is related to the topology of the telecommunication network or power grid.
  - The Transmission network of Western U.S. has a small world topology (Watts & Strogatz, ‘98; Watts, ‘99)



Small-World Models: Objectives

- Develop protection strategies that are:
  - self-optimizing
    - minimize the load lost due to disturbances
  - self-healing
    - Resilient and Robust providing efficient restoration

- First step: understand collapse phenomena.

Source: EPRI/DOD CIN/SI

Crude Propagation Model

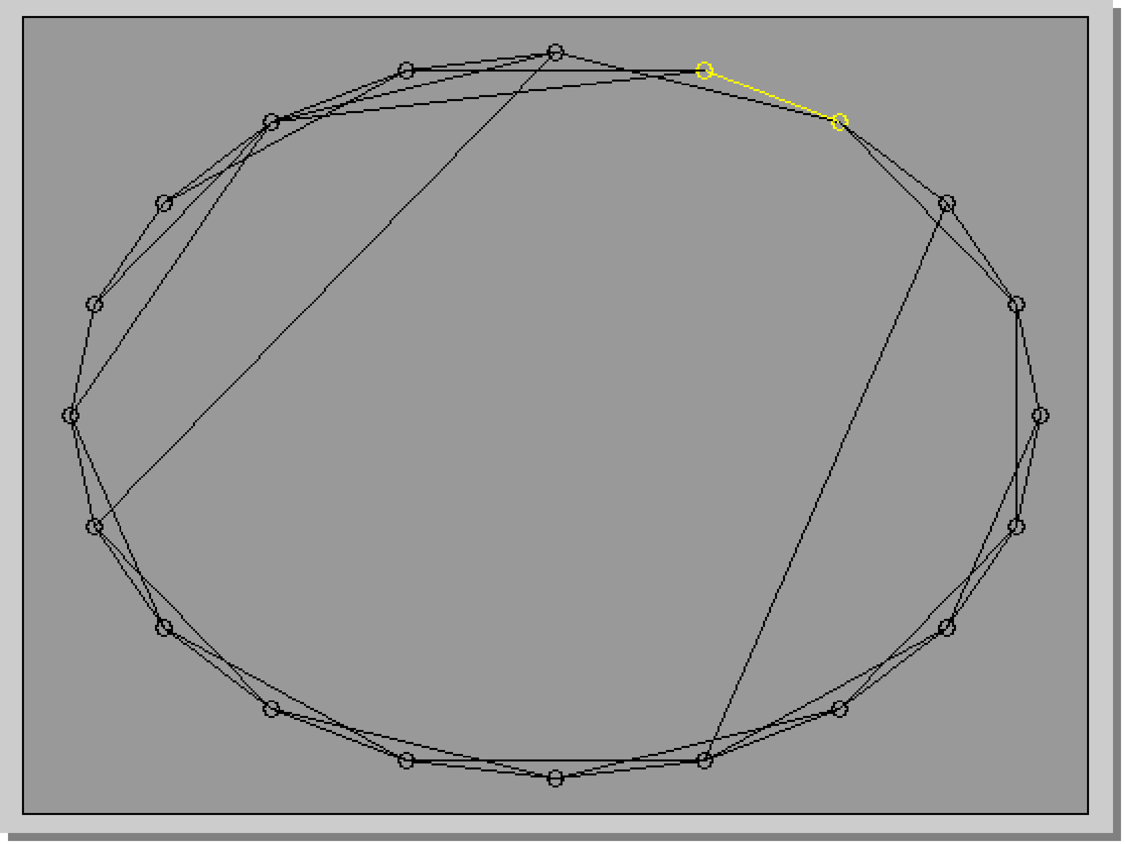
Circuit Breaker Action $\Leftrightarrow$ virus spreading

1) Lightening strikes a line.

2) Induced transient trips breakers at neighboring busses with probability $0 \leq q \leq 1$.

3) Continue until cascade stops.

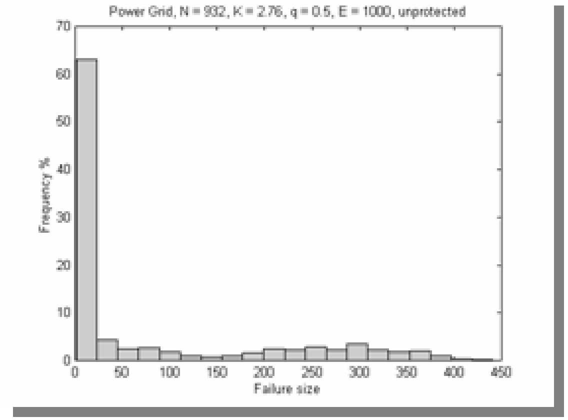
4) Blackout size $\propto$ number of busses affected.



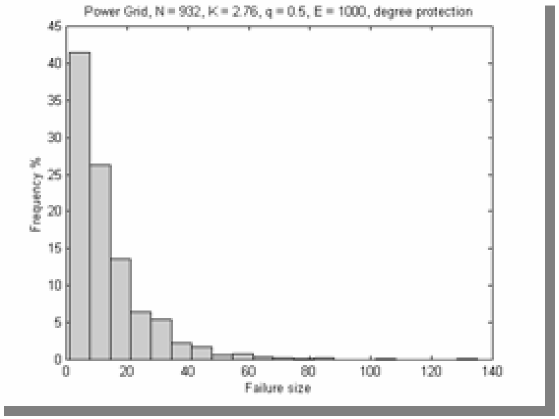
Fortification: Illustration (real topology data)

Experiments conducted using topology data for a portion of the Western U.S. power grid.

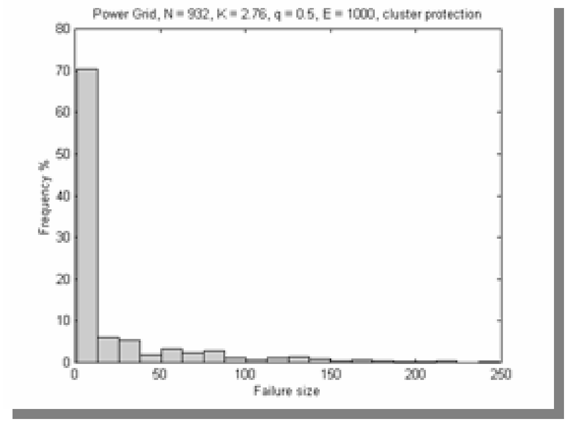
- 932 busses
- 1288 lines



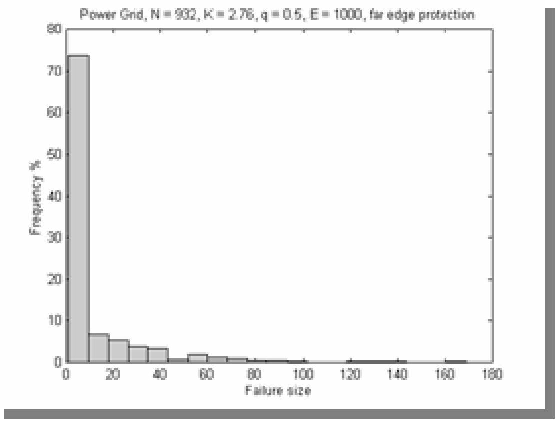
No short cut fortification
mean = 78.96



Heuristic 1: Degree fortification
mean = 13.36



Heuristic 2: Cluster fortification
mean = 22.90



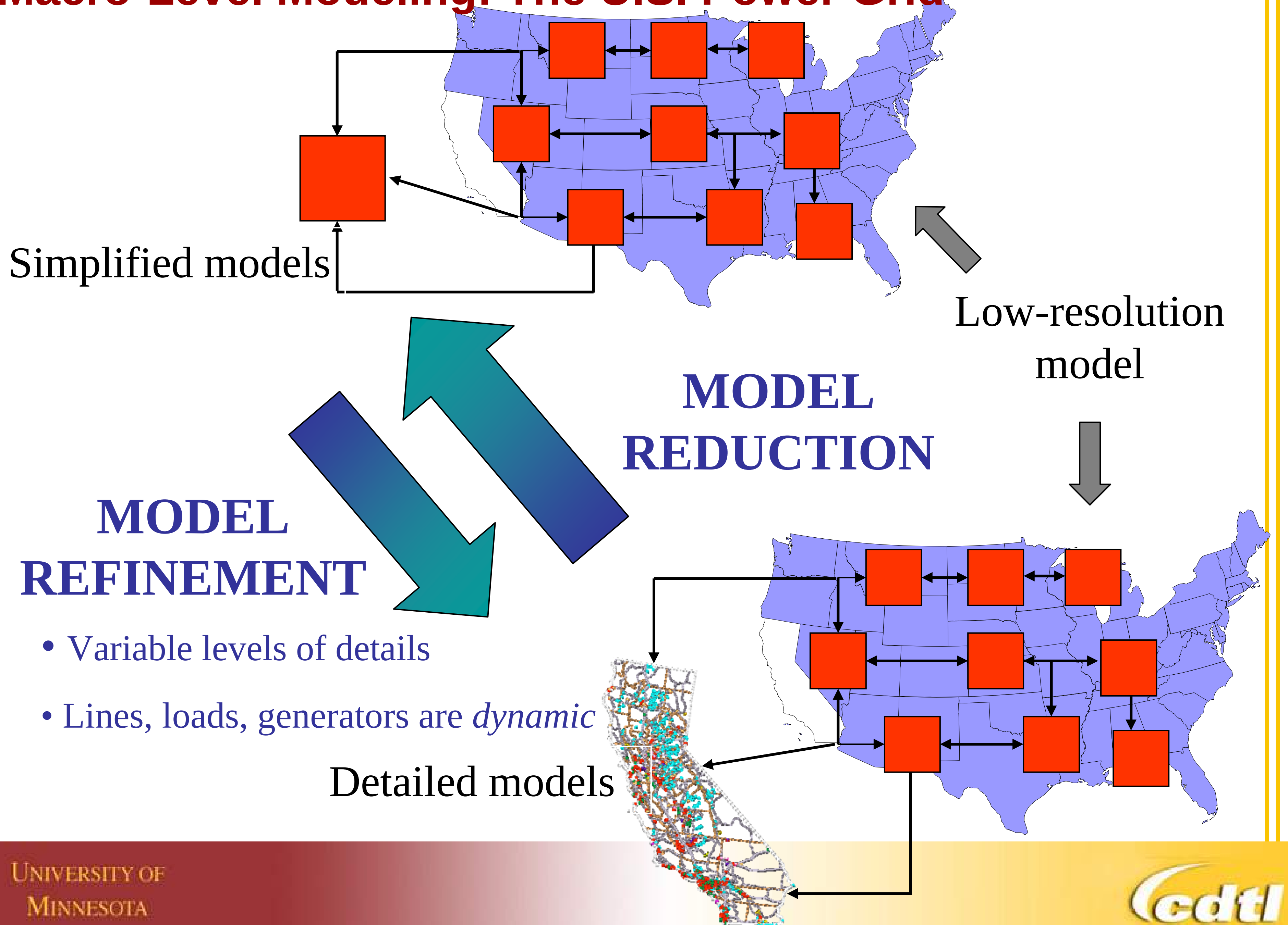
Heuristic 3: Far Edge fortification
mean = 11.62

Look-Ahead Simulation Applied to Multi-Resolution Models

- Provides faster-than-real-time simulation
  - By drawing on approximate rules for system behavior, such as power law distribution
  - By using simplified models of a particular system

- Allows system operators to change the resolution of modeling at will
  - Macro-level (regional power systems)
  - Meso-level (individual utility)
  - Micro-level (distribution feeders/substations)

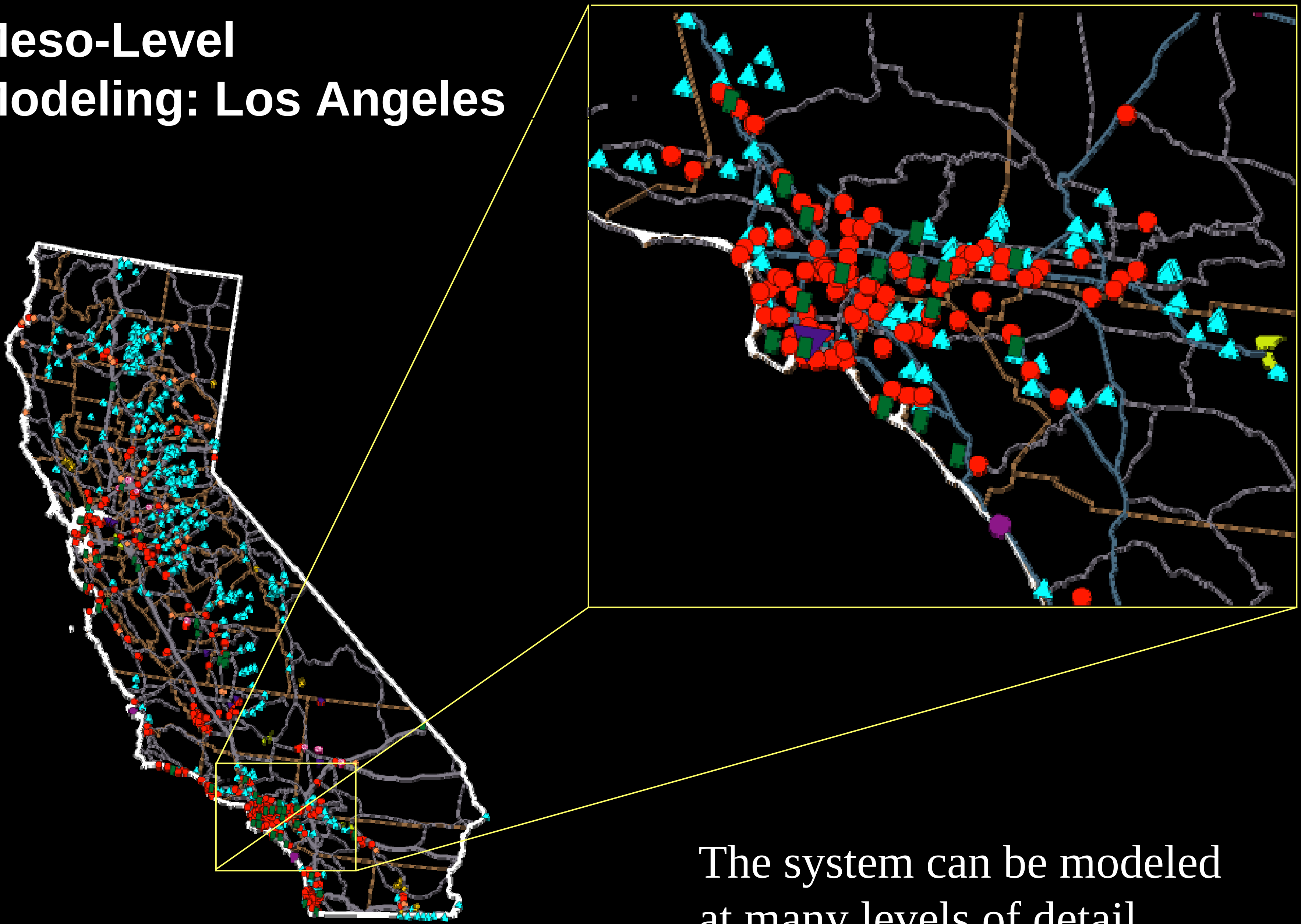
Macro-Level Modeling: The U.S. Power Grid



• Variable levels of details

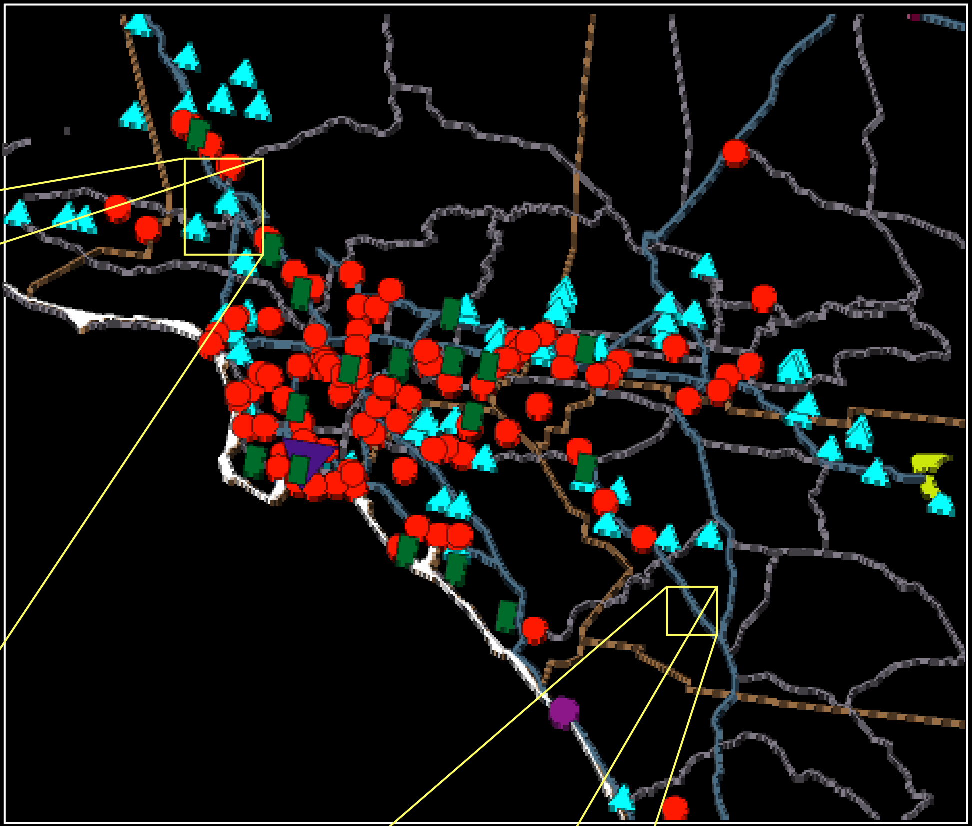
• Lines, loads, generators are *dynamic*

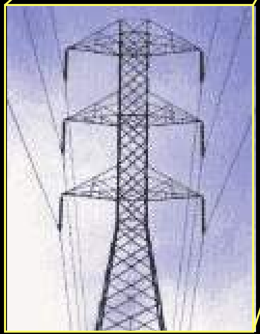
Meso-Level Modeling: Los Angeles



The system can be modeled at many levels of detail

Micro-Level Modeling: System Components



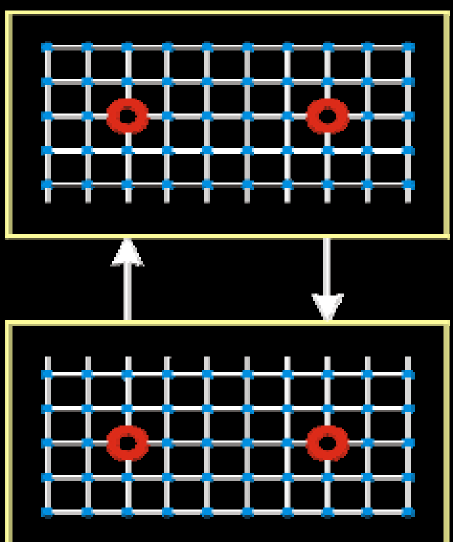


At this level, dynamic models include the *swing equations*

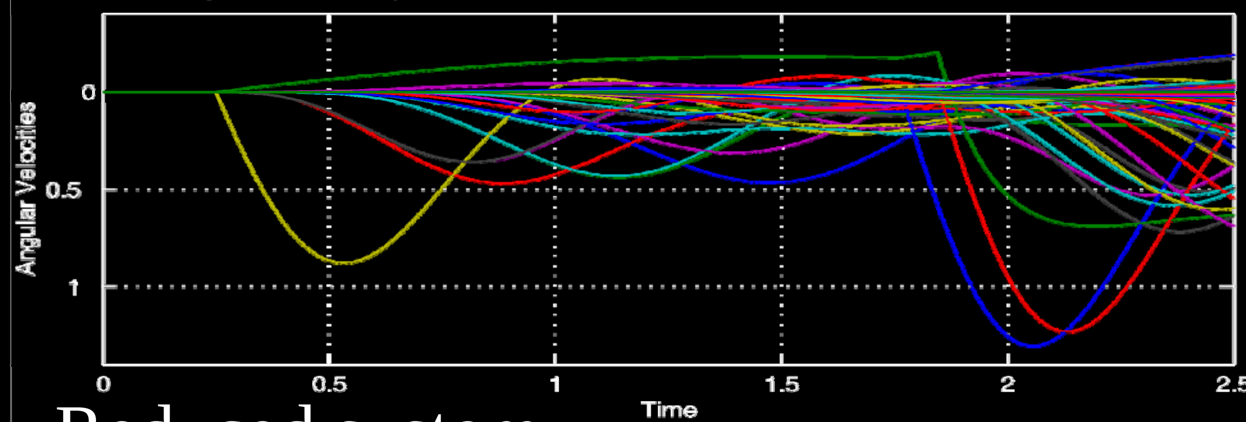
$$m_i \ddot{\delta}_i + D_i \dot{\delta}_i = P_i + \sum_j b_{ij} \sin(\delta_i - \delta_j)$$

Fast Simulation

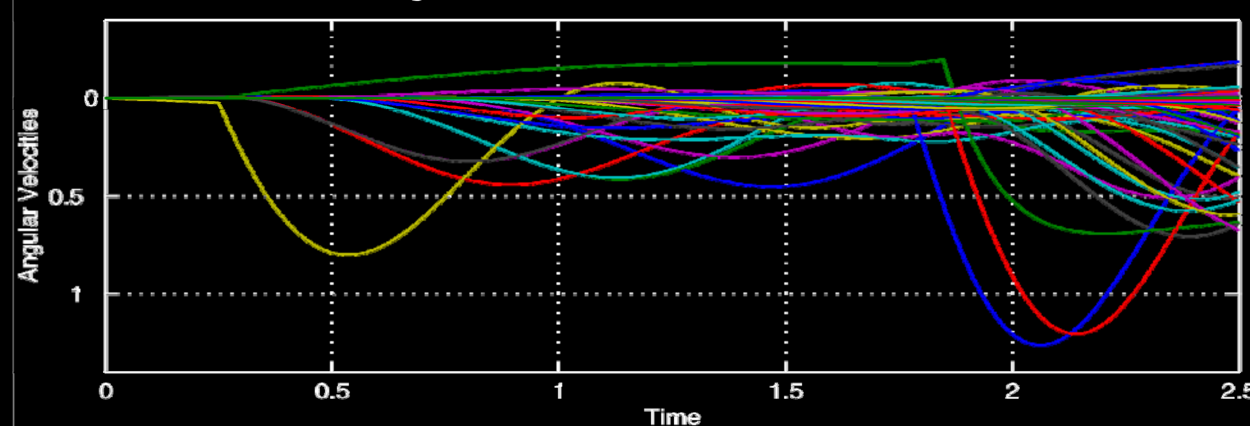
Capturing System Dynamics and Accelerating Computations Using Novel Model Reduction



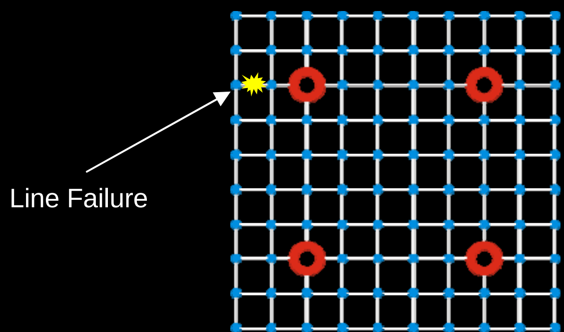
Original system



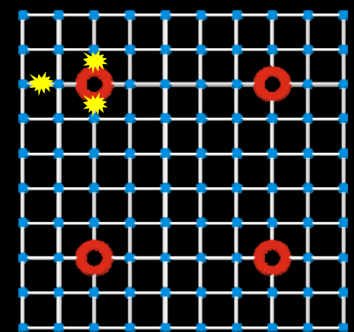
Reduced system



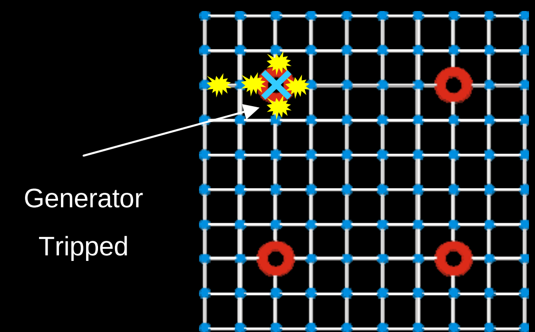
Fast Look-Ahead Simulation Of Cascading Failures



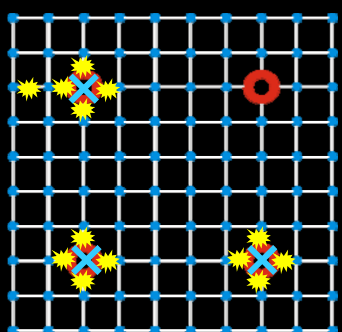
0.25
0.25



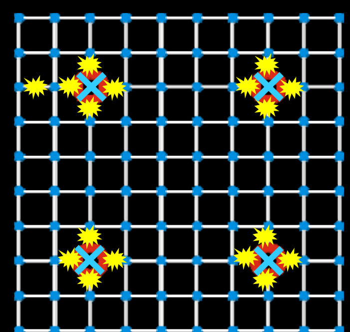
1.764
1.773



1.845
1.848



2.570
2.574



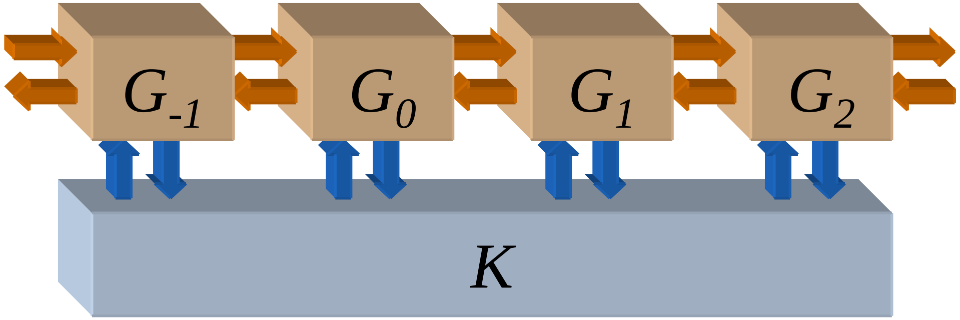
2.582
2.594

Failure time:
Original system
Reduced system
(Predicted up to 12-times faster)

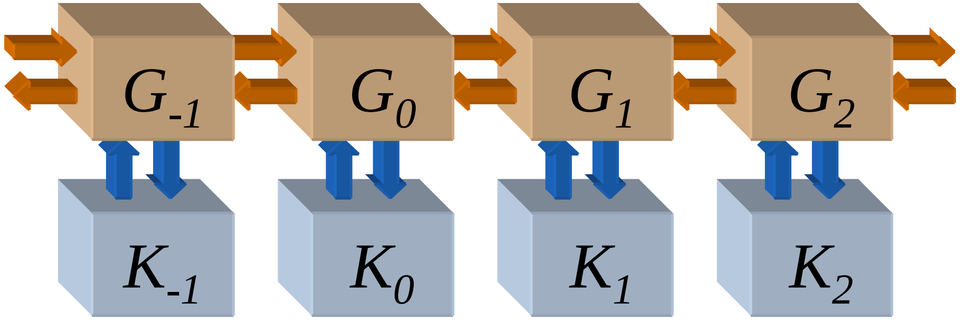
(EPRI/DOD CINSI)

Control Strategies

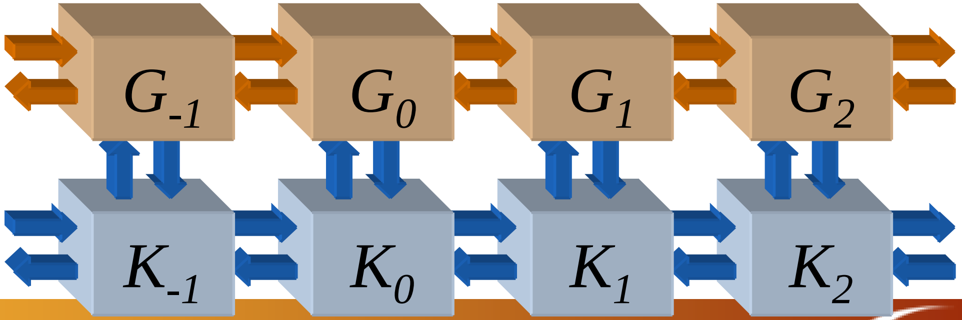
- Centralized



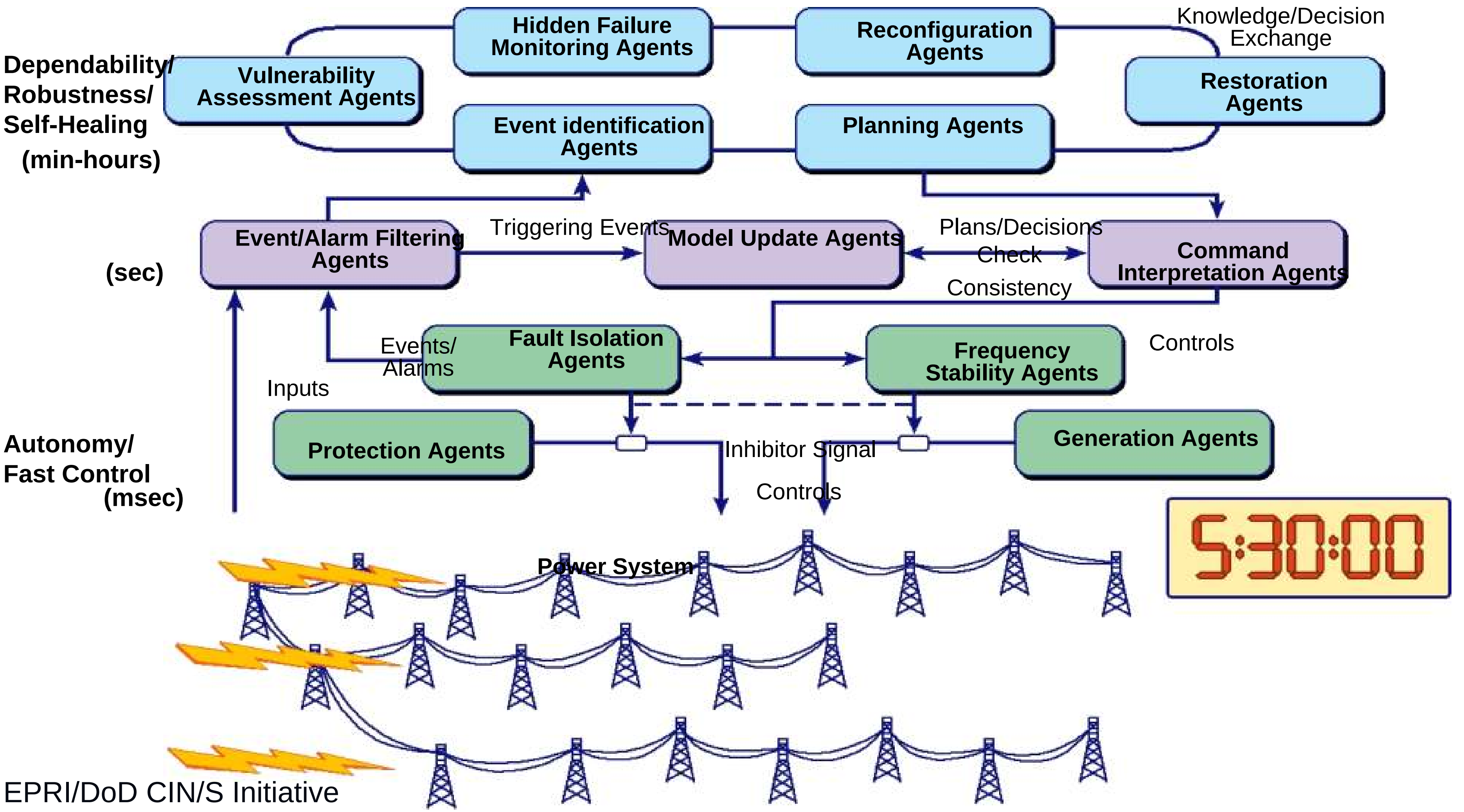
- Perfectly decentralized



- Distributed

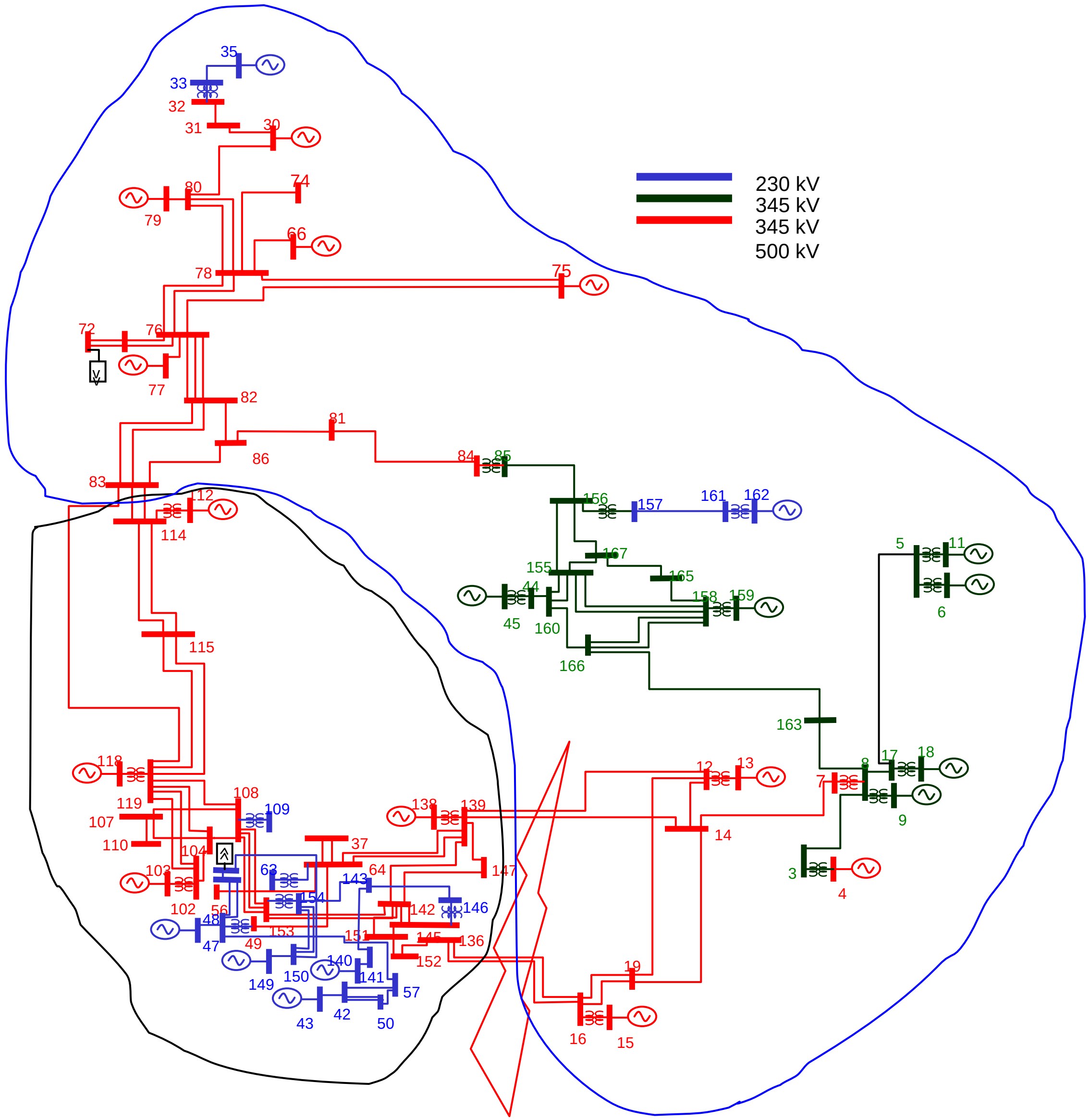


Background: The Self-Healing Grid

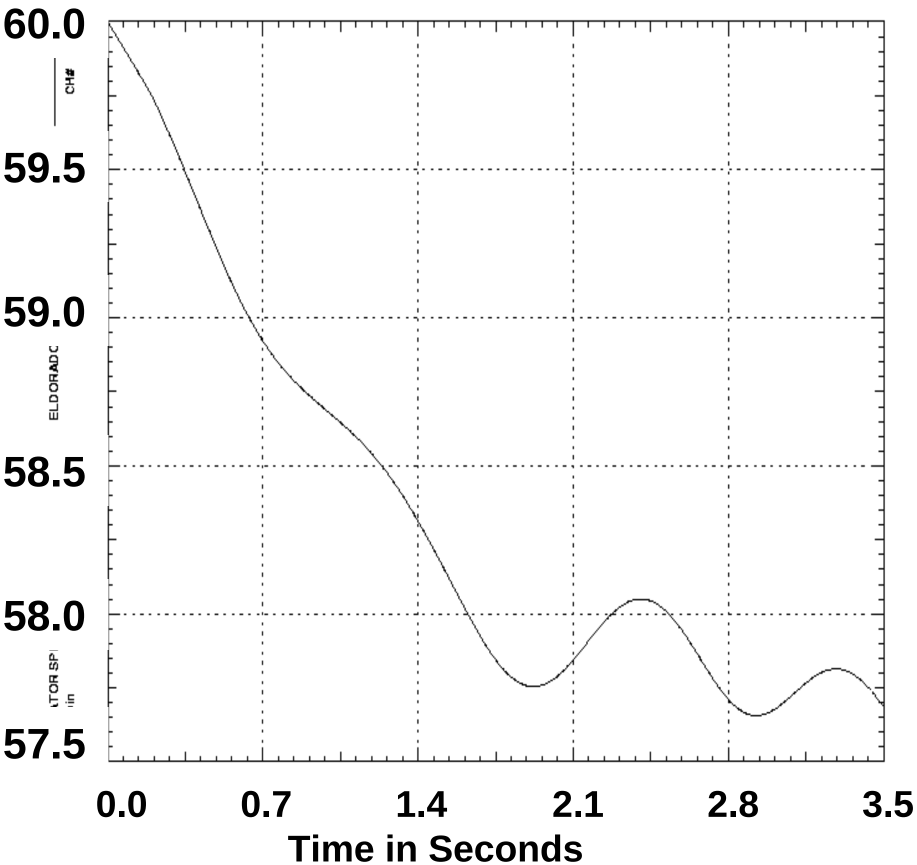


EPRI/DoD CIN/S Initiative

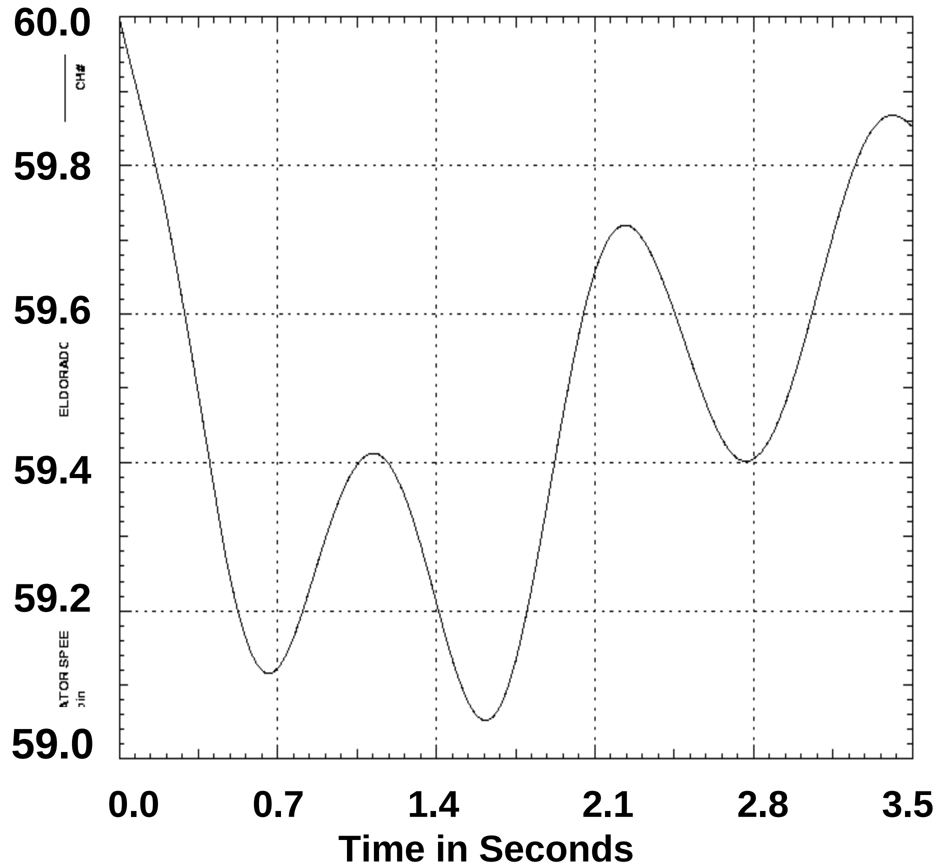
Background: Intelligent Adaptive Islanding



Background: Simulation Result

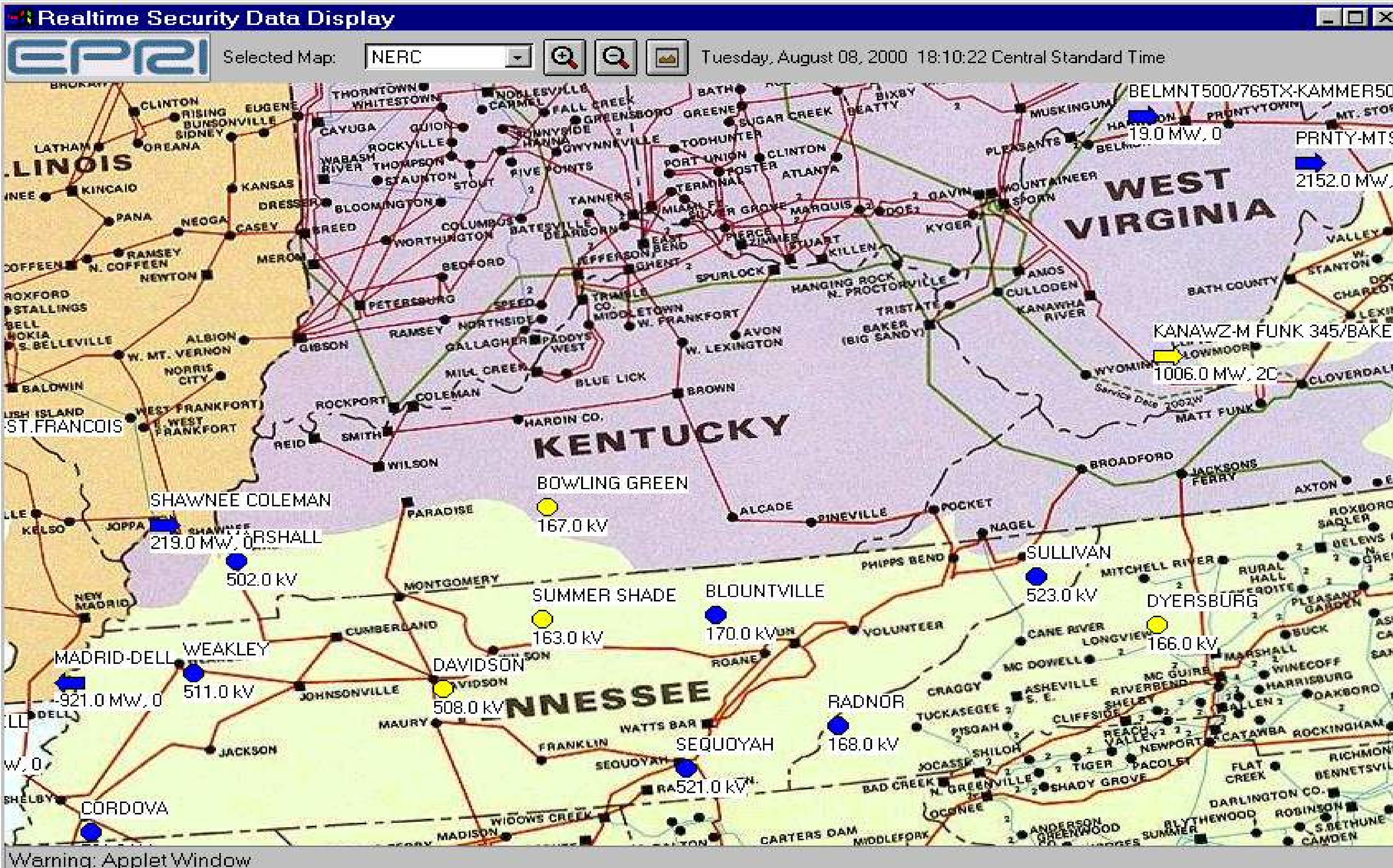


No Load Shedding Scheme



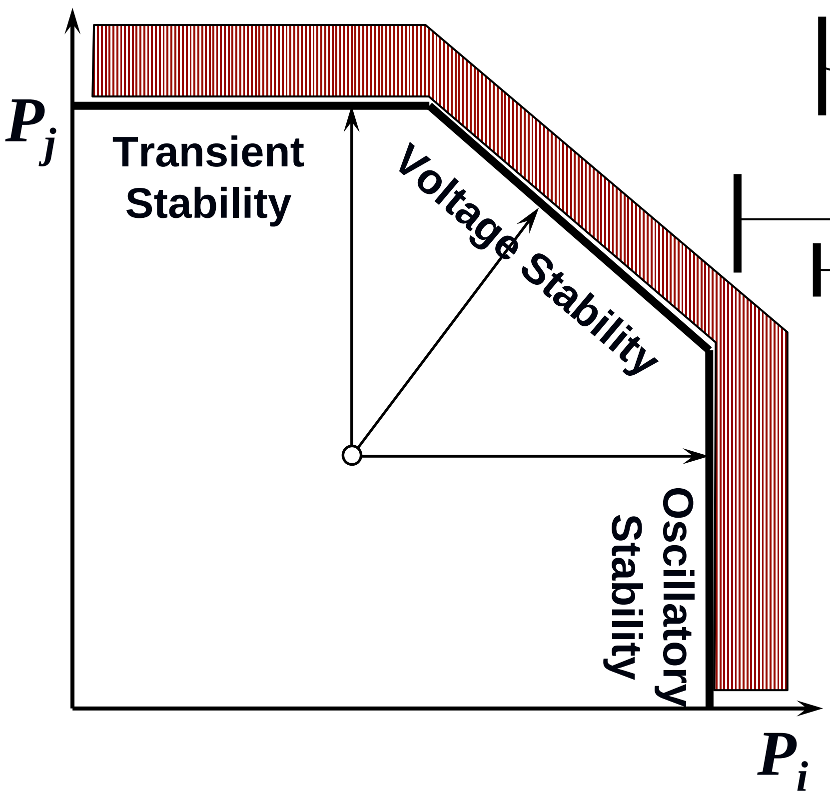
New Scheme

EPRI's Reliability Initiative-- Sample Screen of Real-time Security Data Display (RSDD)

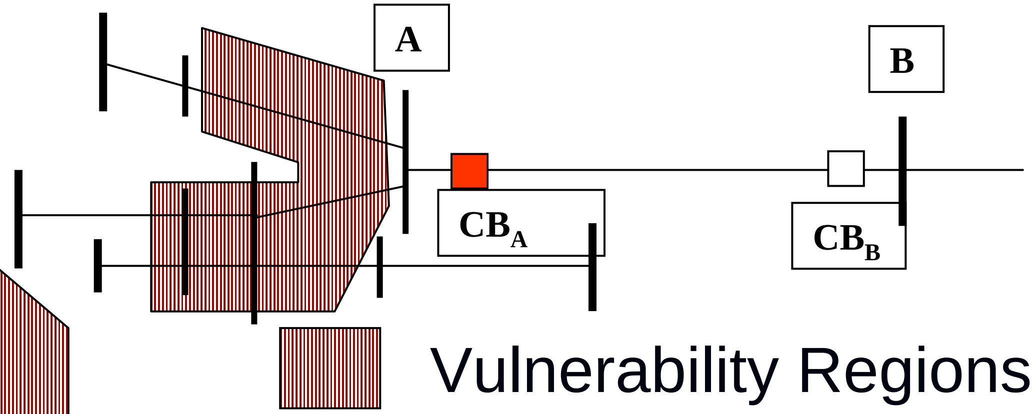


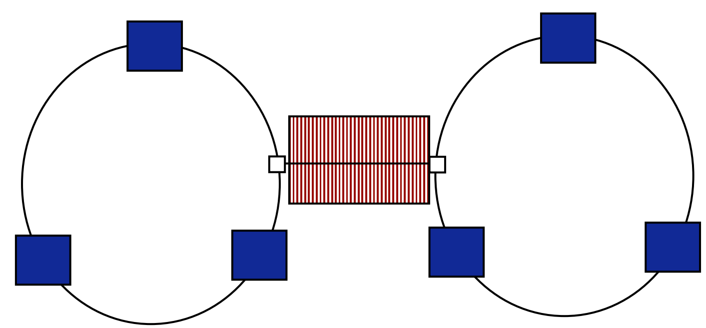
Vulnerability Indices

Dynamics and Control



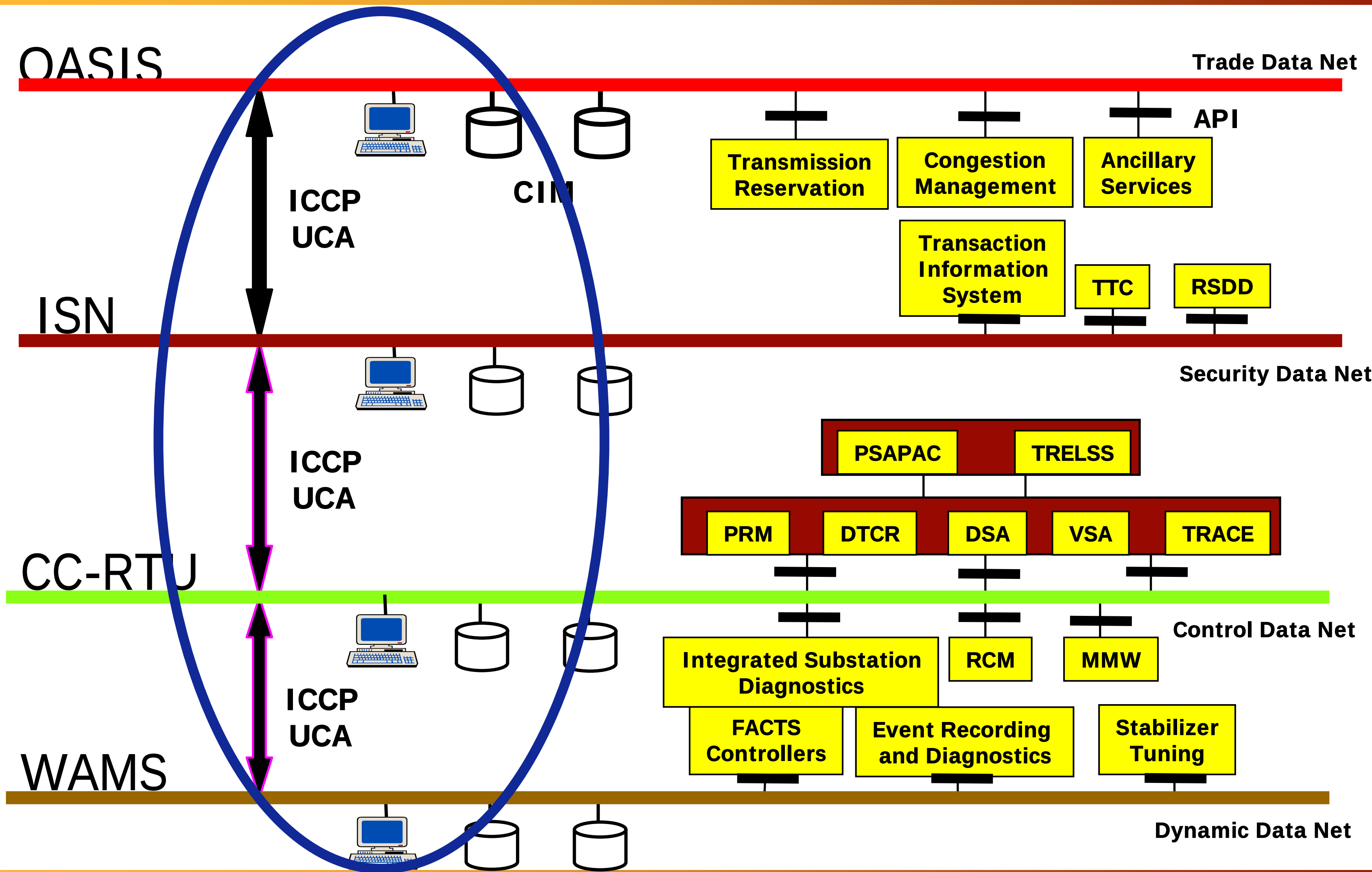
Protection



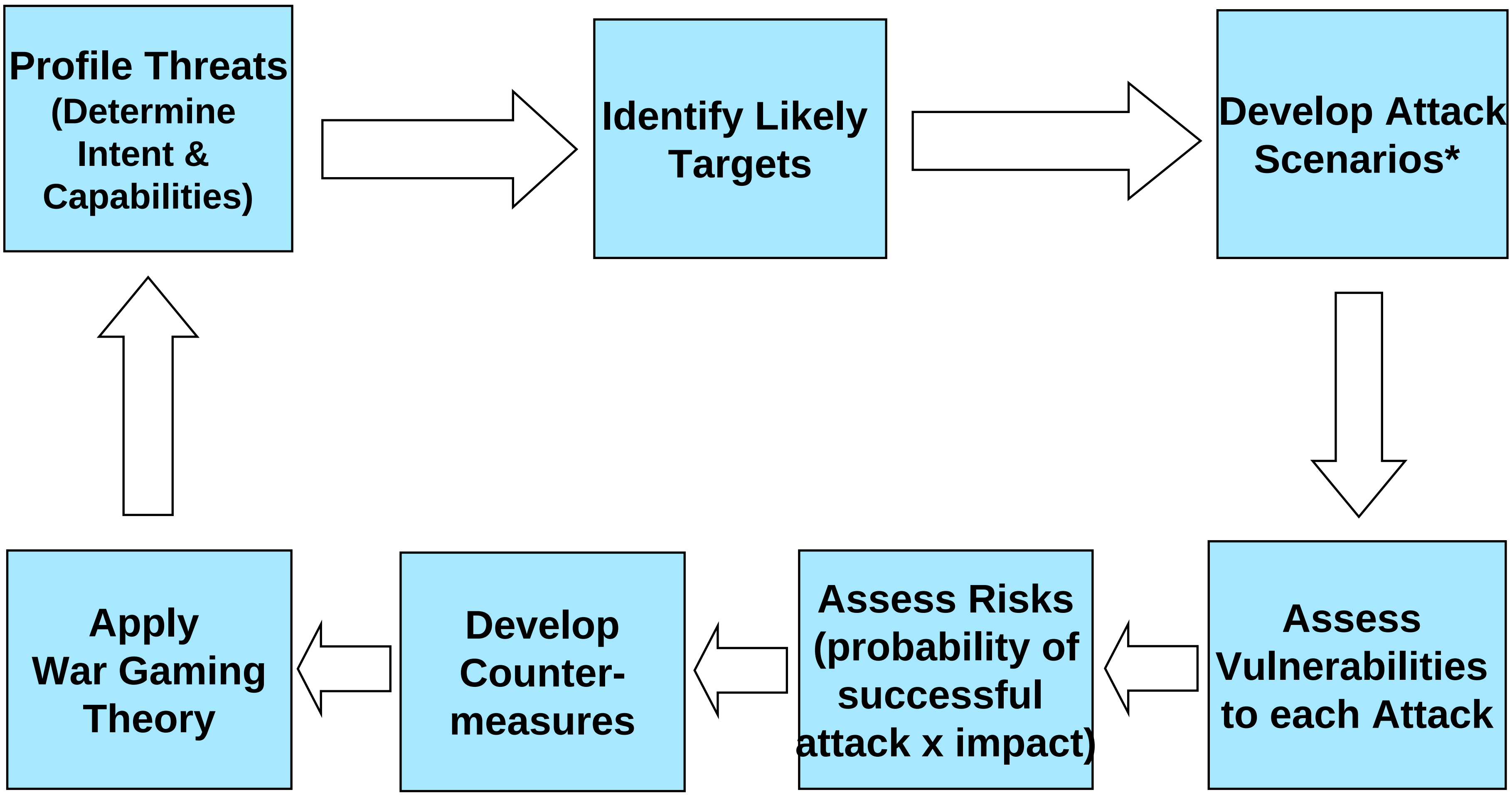


A new method to measure the vulnerability of the communication system and its impact on the performance of the power grid; will be extended to use dynamical PRA and sensor data

Information Networks for On-Line Trade, Security and Control



What can be Done? Vulnerability Assessment

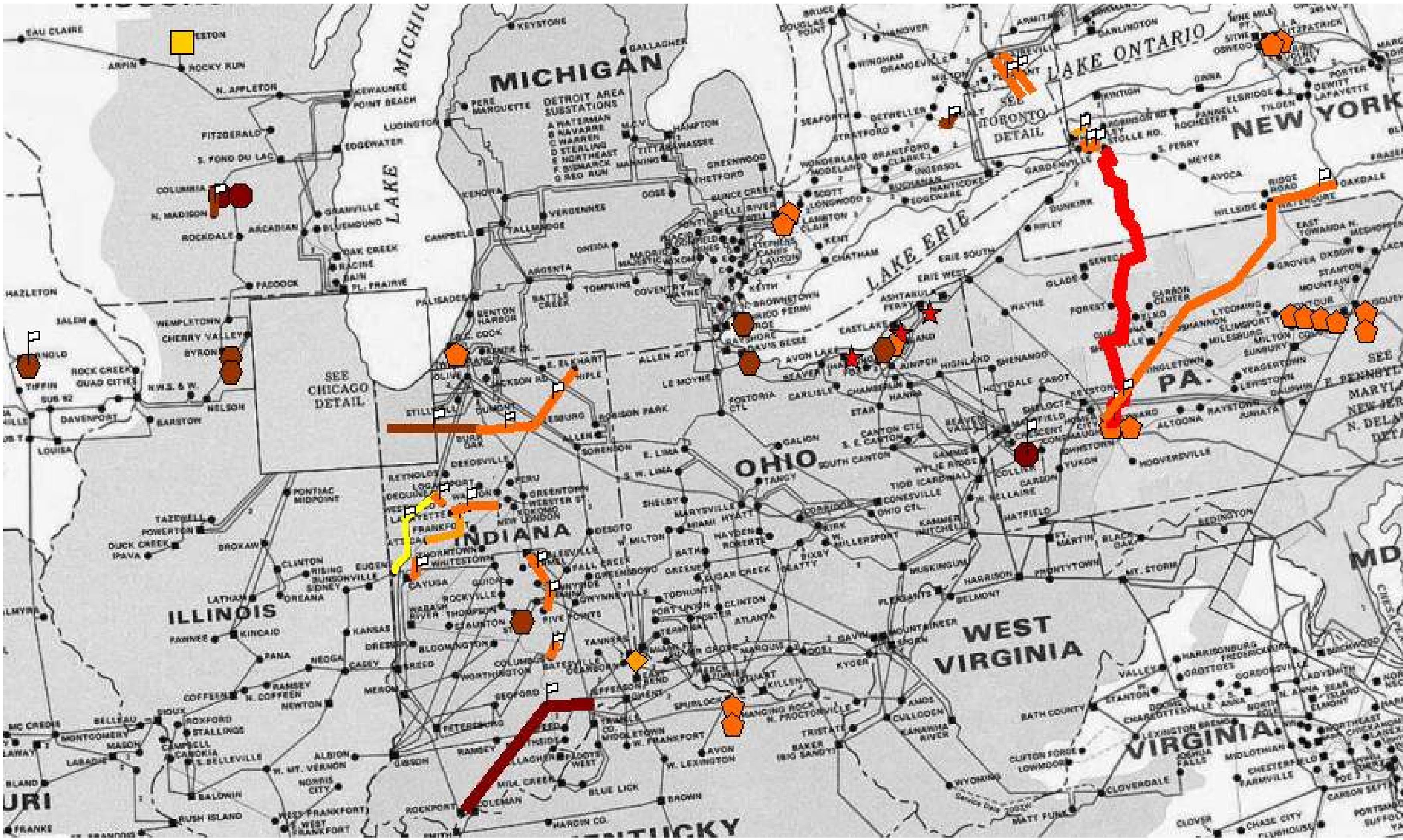


*Evolving spectra of targets and modes of attack

PRA - In Depth

Sensitive

Voltage Root Causes



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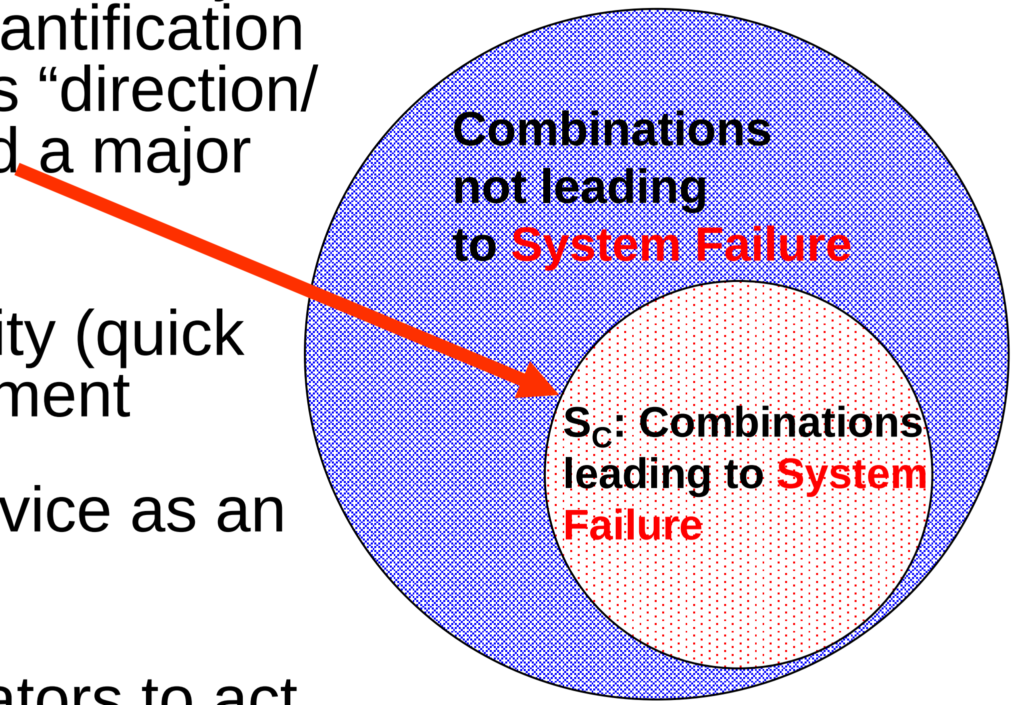
INSTITUTE OF TECHNOLOGY

cdtl
Center for the Development of Technological Leadership

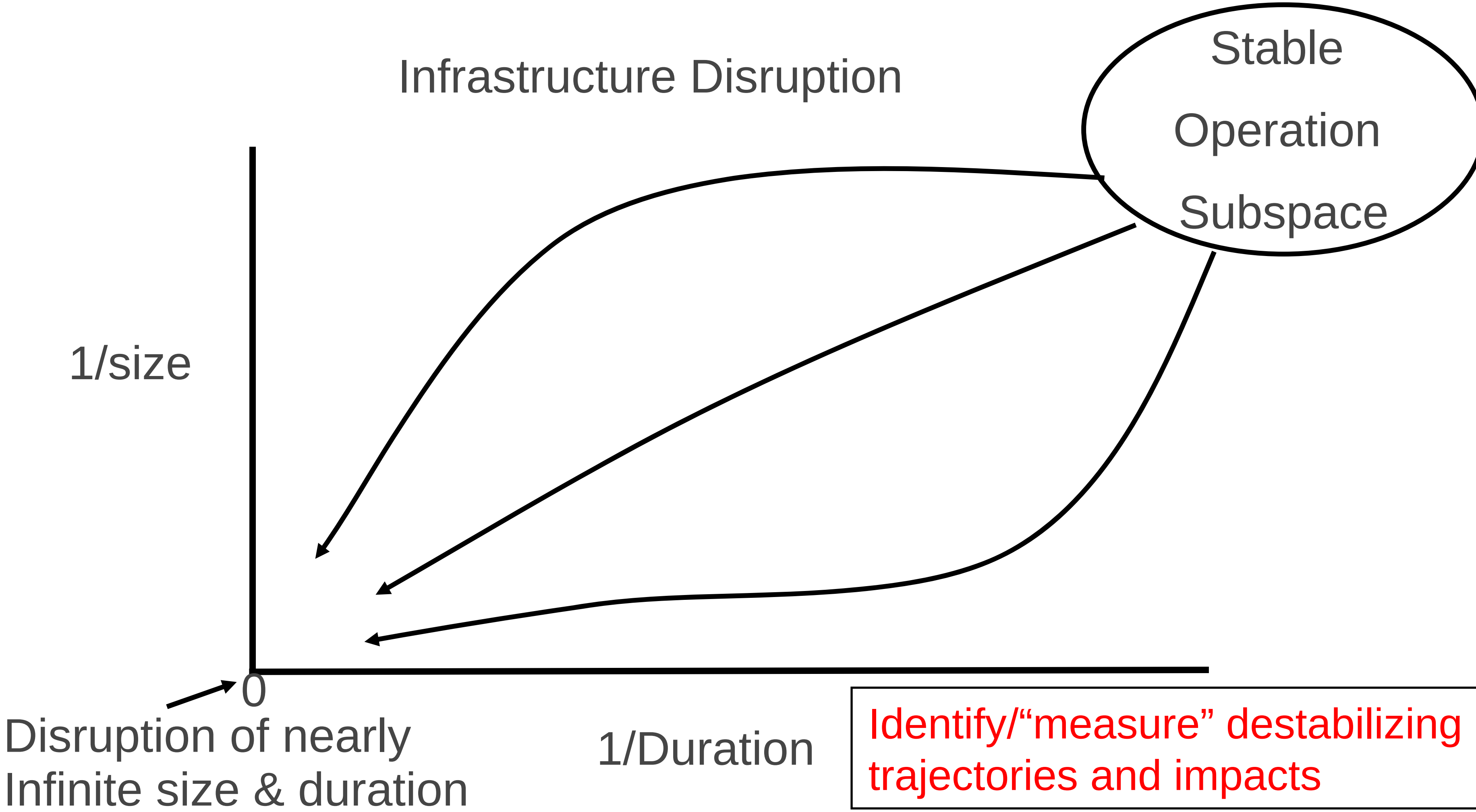
Systems Control Challenge

- Enhancing Reliability and Security of Network Operation via quantification of the system state and its “direction/ speed/momentum” toward a major failure
- Making Network Availability (quick restoration) a key requirement
- Introducing Quality of Service as an additional constraint
- Ultimately, enabling operators to act more efficiently and with greater confidence in difficult (sometimes unclear, unexpected or even conflicting) circumstances



Which trajectories lead to catastrophic failures?

An Assessment Methodology

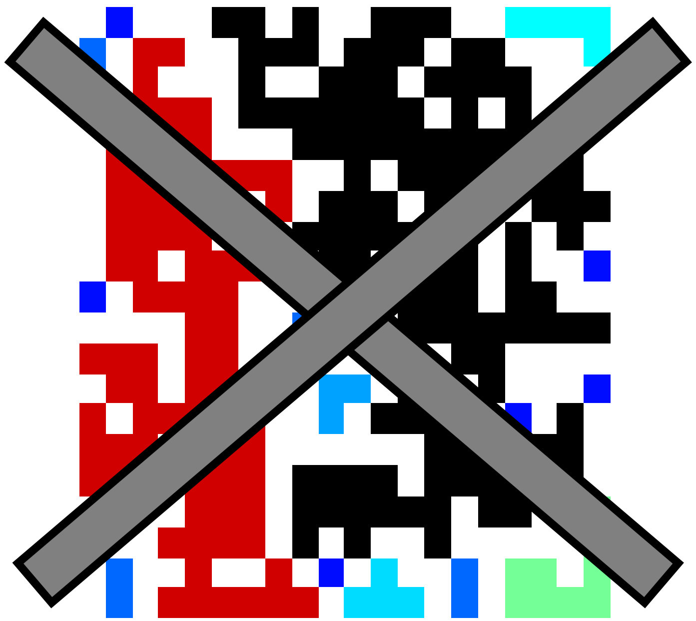


Identify/“measure” destabilizing trajectories and impacts

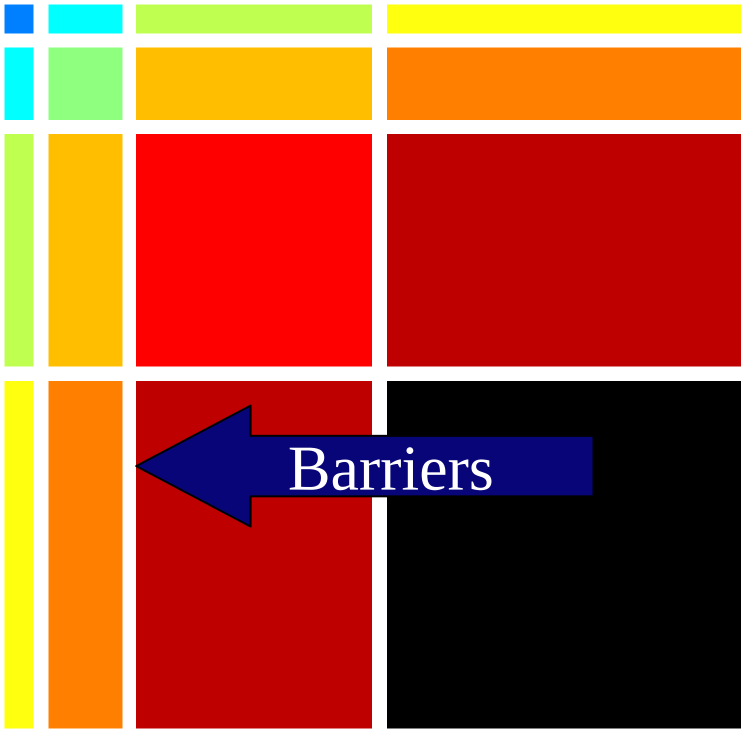
Complex Interactive Networks/Systems

Failure Propagation on Grid

Percolation

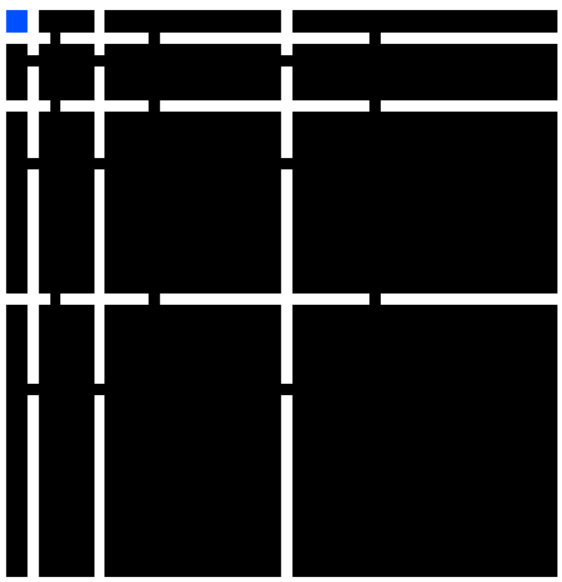


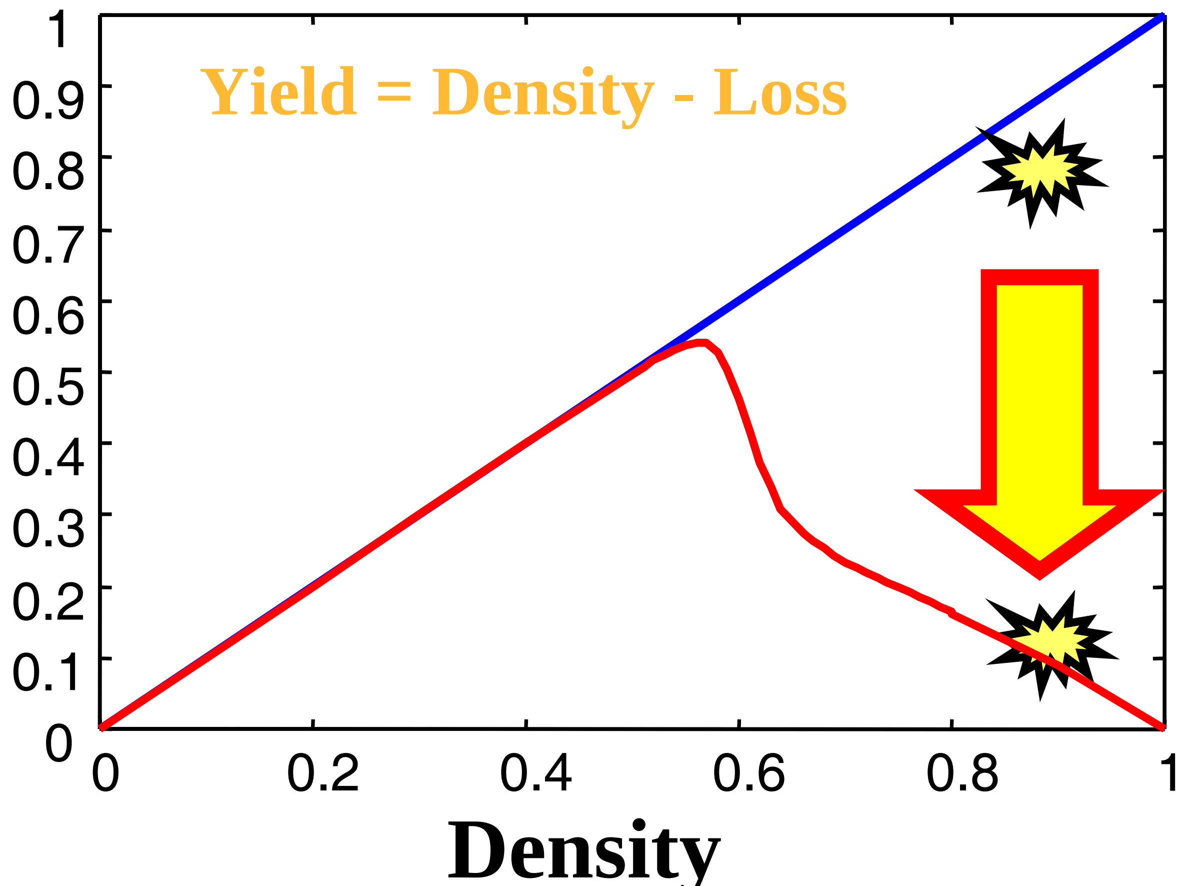
Designed System



Complex Interactive Networks/Systems

Failure Propagation on Grid – Topology & Probability

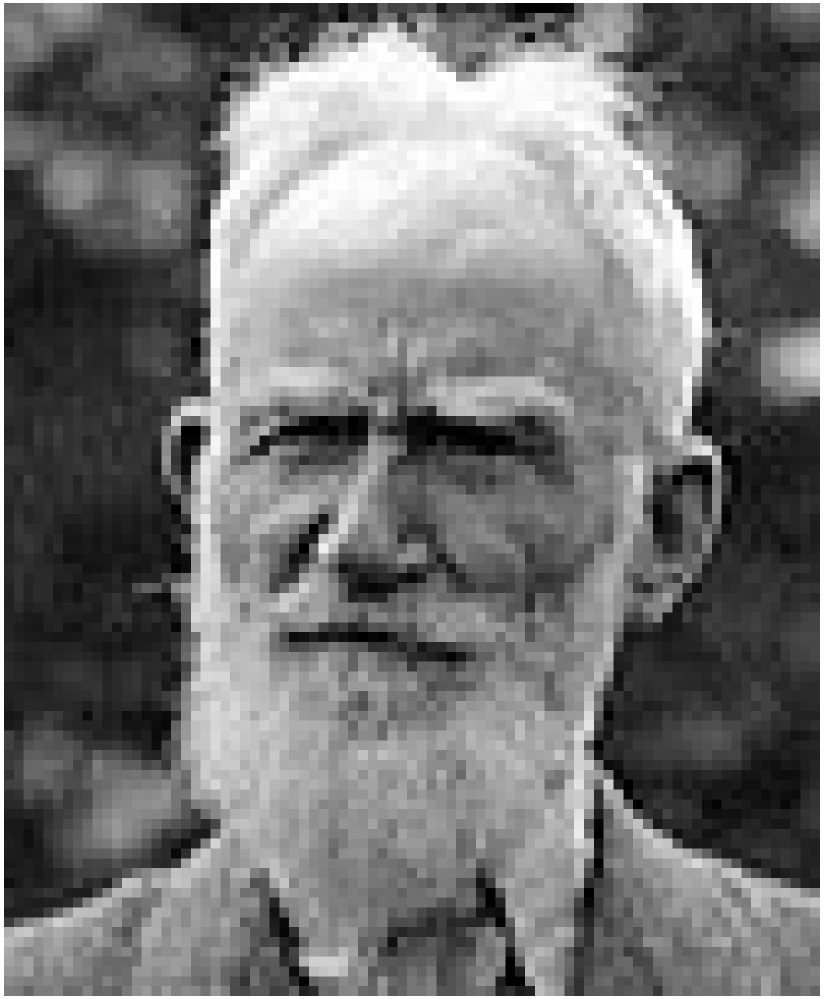




Progress...

"The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man."

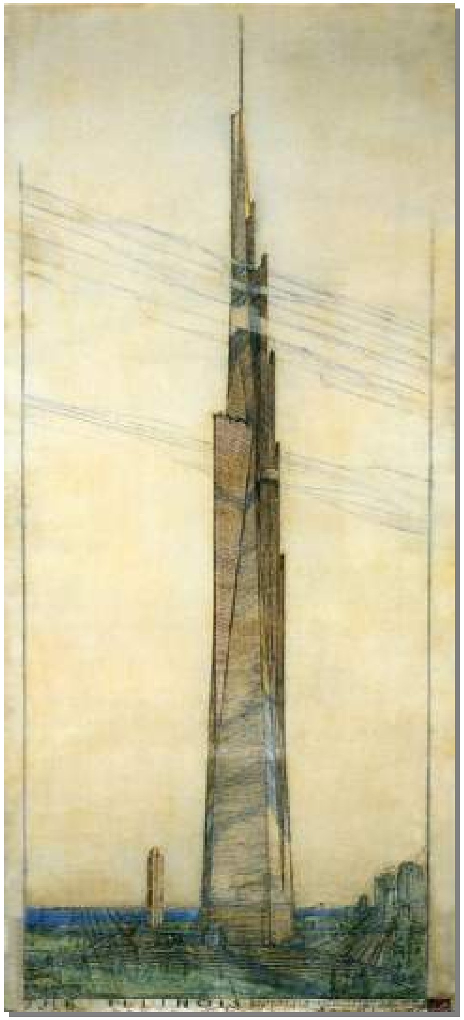
George Bernard Shaw *(1856 - 1950)*



One of my research areas: S&T Assessment, Scan and Map (April 2005-Feb 2006; Galvin Electricity Initiative)

Objectives:

- Identify the most significant Science & Technology innovations which would meet energy service needs over the next 10 or 20 years;
- Determine Science & Technologies areas and concepts which address customer aspirations and hopes; when conceived, they will lead to:
  - Technologies that encourage job creation and address the needs of the society;
  - An energy system so robust and resilient that it will not fail;
  - A totally reliable, secure communication system that will not fail.



Source: Galvin Electricity Initiative www.galvinelectricity.org

Toward High Reliability Infrastructures

- Realistic and scalable models, estimation and control
- Coupling to state estimation, dynamic monitoring, simulation, identification, disturbance analysis
- Multiresolution models for wide-area data, distributed control
- Real-time wide-area sensing, communications, analysis and control for contingency planning
- Sensor mix and placement; new sensors
- Communication, intelligent data management
- Integrated System Assessment, Security, Planning & Interoperability
- Wide-area control for operation near margins; control with uncertain delays; layered fail-safe control; control mix/placement.

Research Challenges

- Intelligent sensors as elements in real-time data base; seek appropriate high level query tools for such a database? Sensor interface to models? Metrics?
- Dependability/security/robustness is the key… V&V remains a big challenge
- Restructuring "trilemma": Unresolved Issues Cloud Planning for the Future-- Regulatory issues
- Increased dependence on information systems and software
- Effect of market structures, distributed generation, other new features on above issues; economic evaluations


Thank you