High Performance Computing for Situational Awareness in Power System Grid

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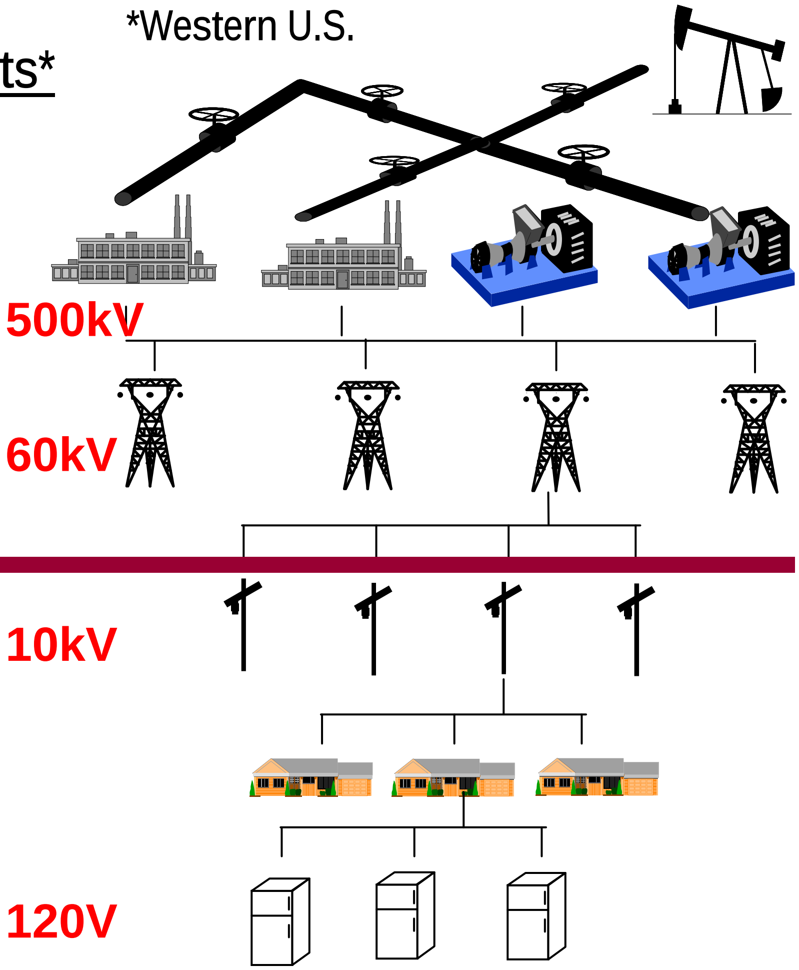
Power System Simulation Complexity

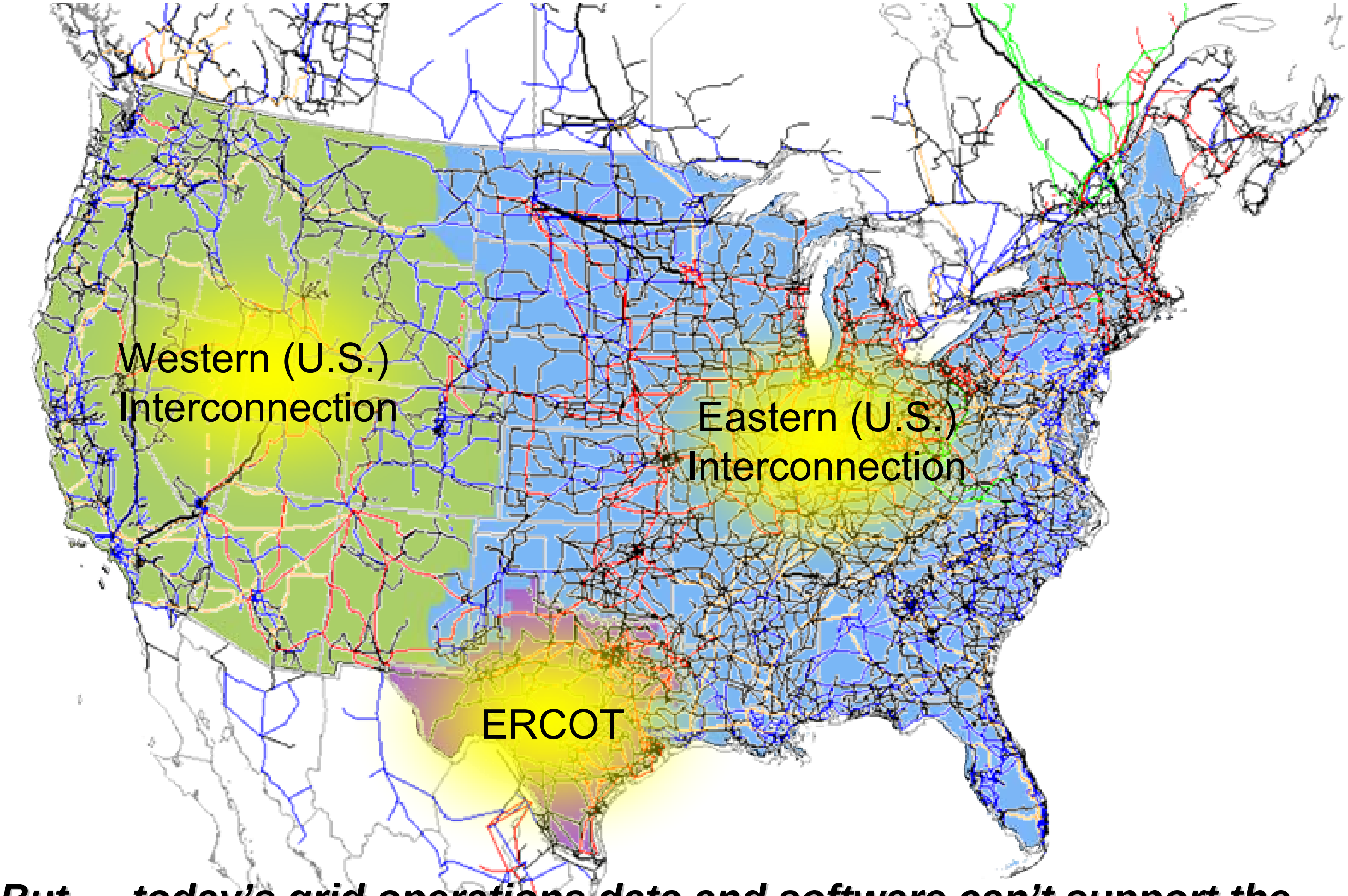
Element	Transmission-level Simulation	Components*
Generation		~10^2
Transmission	~10^4	~10^3
Substations		~10^4
Distribution Feeders		~5 x 10^4
Customer Meters	~10^4	~10^7
Appliances/Equipment		~5 x 10^8

Distribution-level Simulation

*Western U.S.

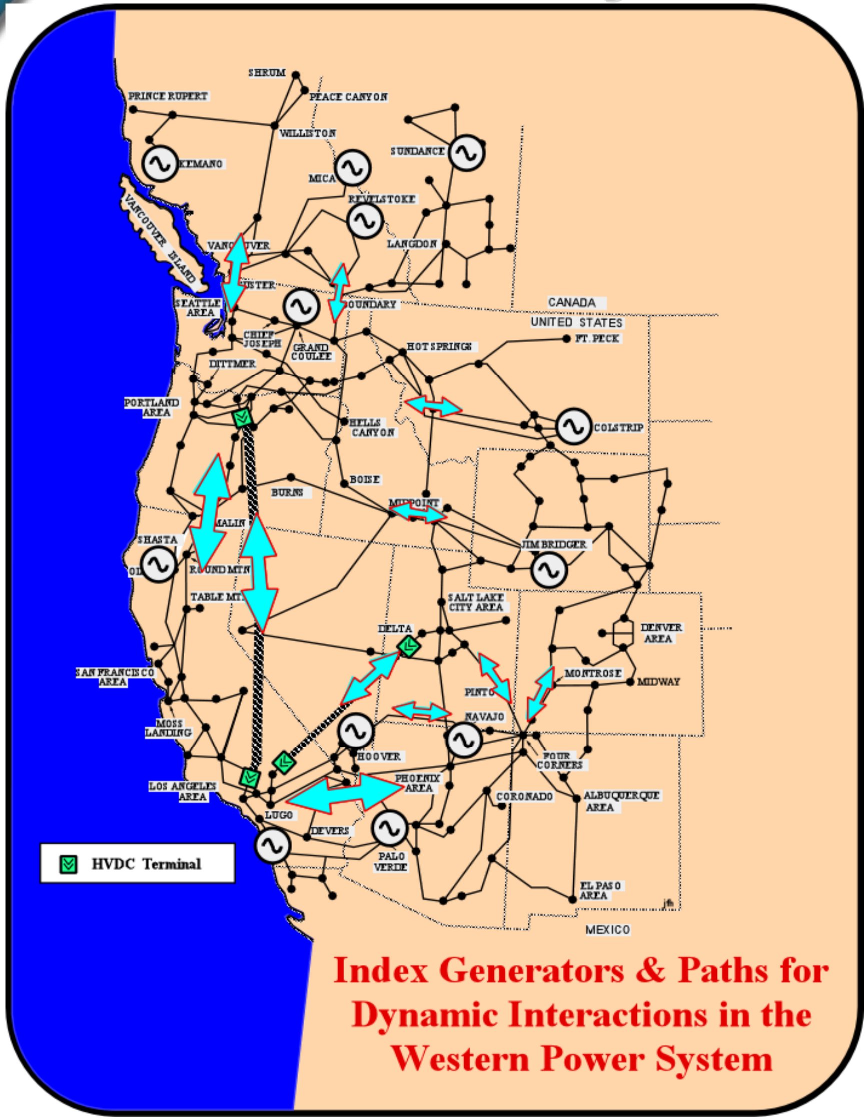


Situational Awareness in Power Grid Is An Interconnection-Scale Issue



But … today's grid operations data and software can't support the real-time analysis required for dynamic situational awareness of such large and complex systems

Power System Dynamic Model



Index Generators & Paths for Dynamic Interactions in the Western Power System

Source: J. Hauer. 2004

Differential Algebraic Equations

$$\begin{cases} \dfrac{dx}{dt} = f(x, y) & \text{Dynamic models} \\ 0 = g(x, y) & \text{Power flow model} \end{cases}$$

x: State Variables

y: Algebraic Variables

WECC Power System

2,700 generators

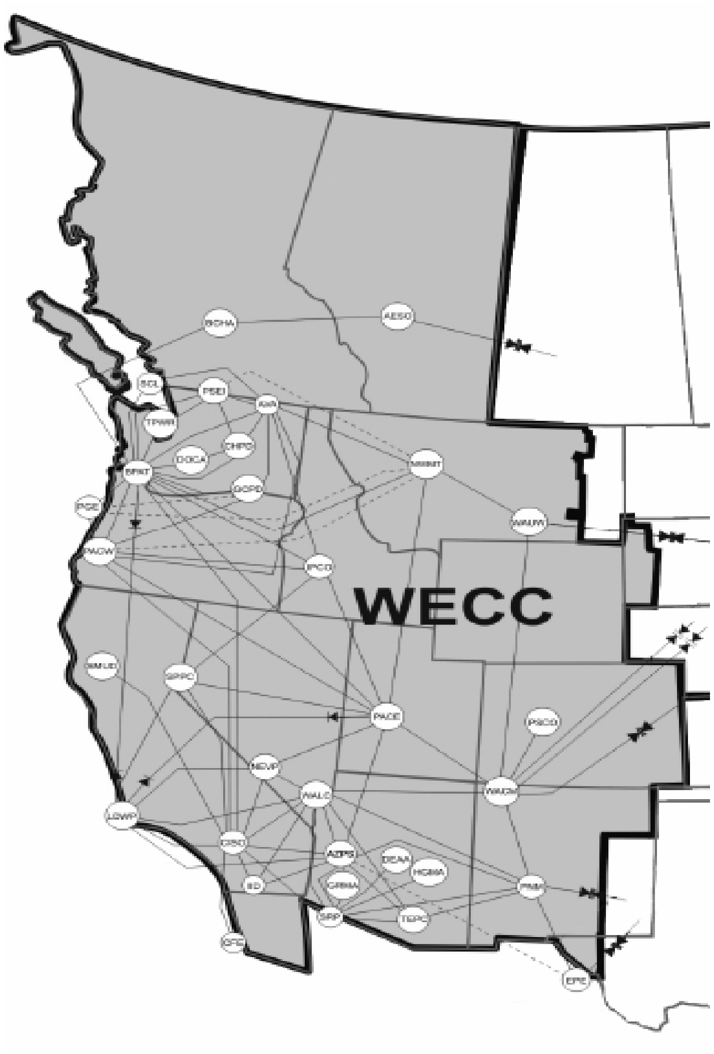
3^{rd}-order model

8,100 state variables

Plus other dynamic models

State Variables: an order of 10^4

Steady-State Model



Power Flow Equation

$$0 = g(V, \theta, P, Q)$$

Breaker-Oriented Model (EMS)
WECC Power System

10,000 buses
16,000 lines
2,700 generators
20,000 unknowns in power flow model
40,000 analog measurements
100,000 digital measurements

State Variables:

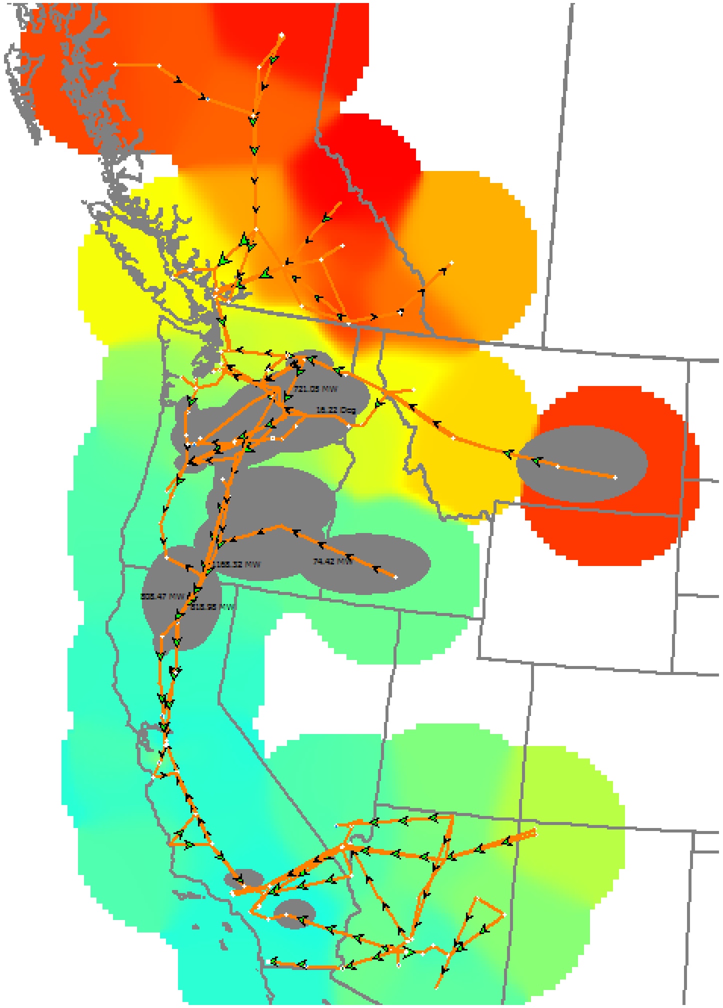
An order of 10^4 (PF) & 10^5 (EMS)

Does not seem that bad but…

For effective decision support we need to run analysis in seconds!!

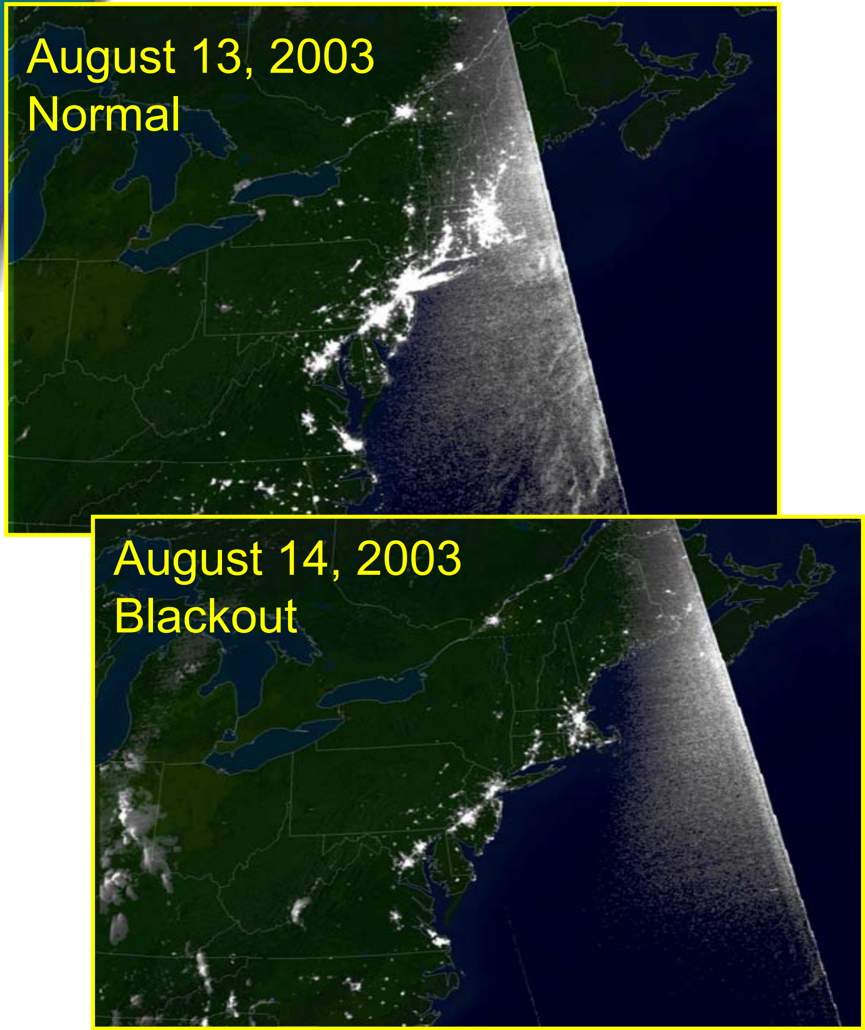
Telemetry Data

- High-Level Real-Time View of WECC System
  - 500 kV AC
  - 367 lines
  - 167 buses
  - ~70 PMUs
- **Data Volume and Rates**
  - SCADA system: ~4 seconds
    6 GB/day
  - Phasor system: 1/30 second
    5 GB/day ➔ 3 TB/day



Electricity Infrastructure Operations Center

Blackout of 2003



Source: NOAA/DMSP

Source: Blackout Final Report

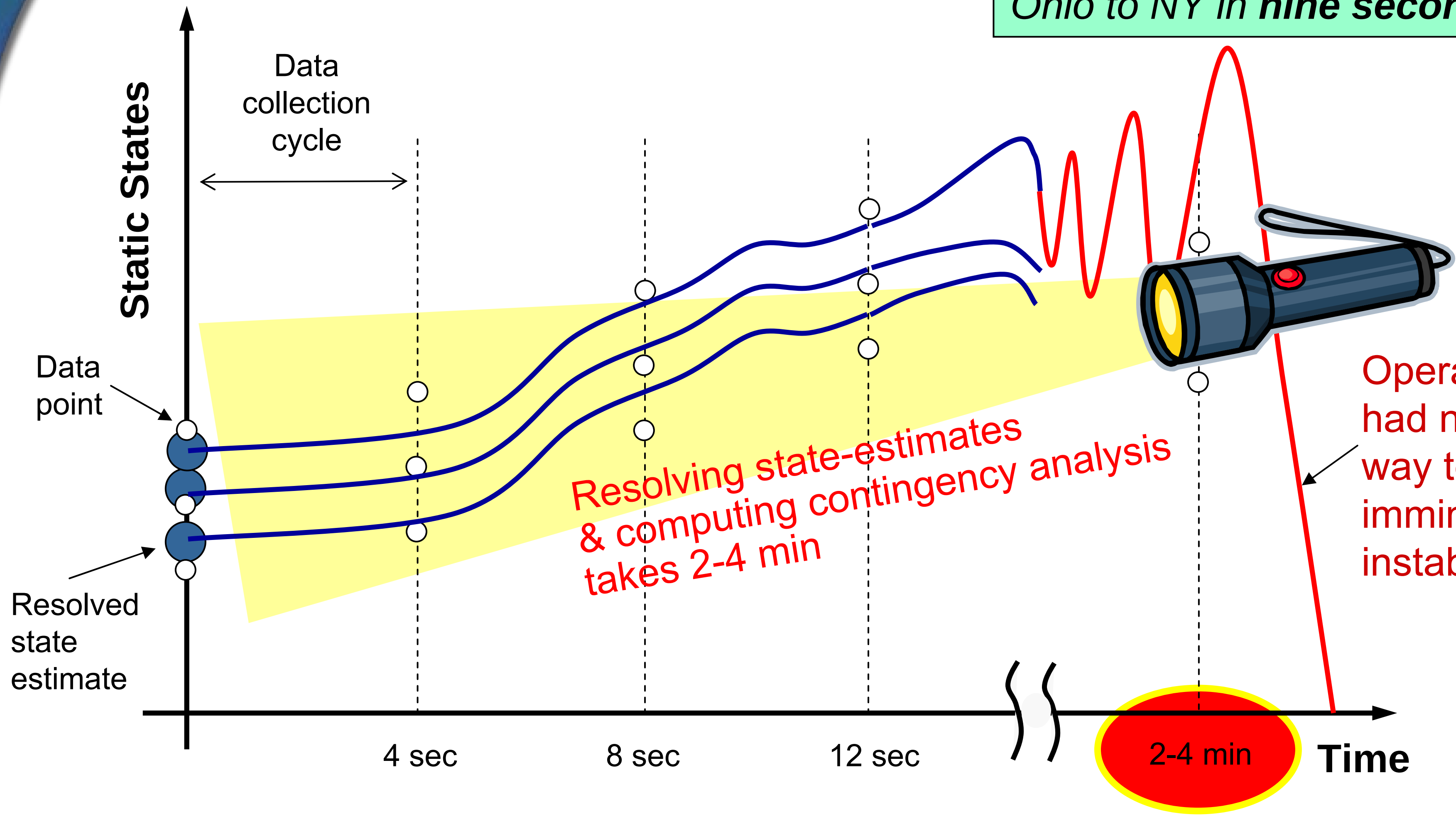
> > **Lack of situational awareness!**

> > **How to improve situational awareness?**

Computational Problem

Point-of-departure: Static State Estimation

*Once the cascade began, the 2003 blackout swept from Ohio to NY in **nine seconds!***



Static States

Data collection cycle

Data point

Resolved state estimate

Resolving state-estimates & computing contingency analysis takes 2-4 min

Operators had no way to see imminent instability!

4 sec

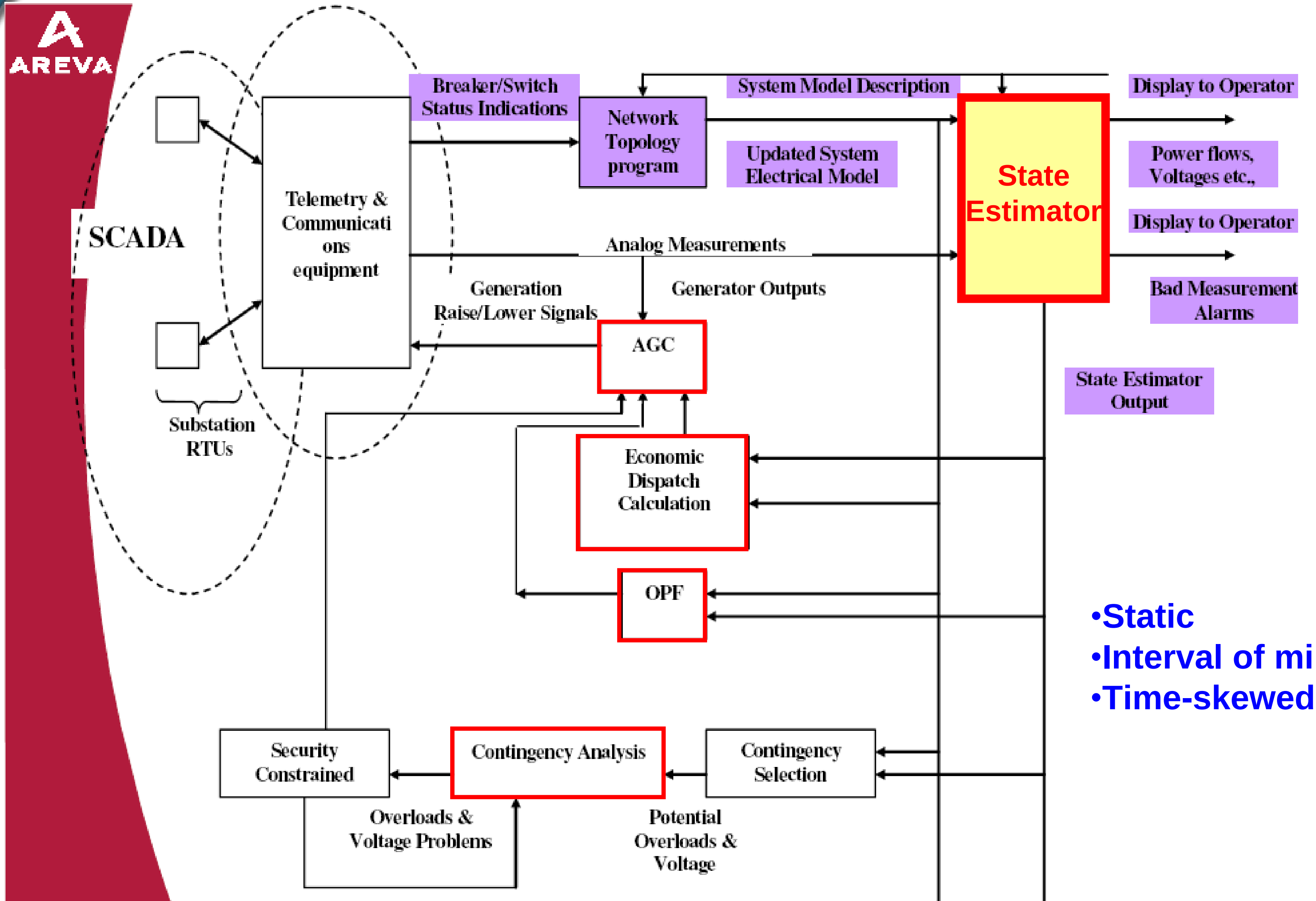
8 sec

12 sec

2-4 min

Time

State Estimation
Core of Power System Monitoring and Operations



- Static
- Interval of minutes
- Time-skewed data

Source: L. Jones, AREVA

Weighted Least Square State Estimation

- Nonlinear Optimization Problem
  - Maximum Likelihood Weighted Least Squares (WLS) method
  - Weighted Least Absolute Value (WLAV)
    - LP problem (Simplex, Karmarkar)
- Our focus is on the WLS method
  - Iterative procedure requires a solution of a large sparse set of linear equations $A\Delta x = b$ obtained through linearization in each iterative step of Newton-Raphson
- The main computational effort is the solver of linear equations – highly irregular sparsity patterns
  - *Direct Methods give fast solution on a serial processor but offer limited coarse-grain parallelism*
  - *Iterative Methods are slower on serial processor but offer higher coarse-grain parallelism*

WLS Method

$z = h(x) + e$

Truncated Taylor series expansion:

$z = h(x^*) + H(x^*)\Delta x + e$

$H = \partial h(x)/\partial x \big|_{x=x^*}$

$\text{Min } (z-h(x))^{\dagger} R^{-1} (z-h(x))$

$x^{k+1} = x^k + A\,(z-h(x^k))$

$A = [H^{\dagger} R^{-1} H]^{-1} H^{\dagger} R\text{-}1$

R – noise covariance matrix
z – measurement vector
H – Jacobian matrix of h
x – state vector (voltage&angle)
h –nonlinear function

Architectural Considerations

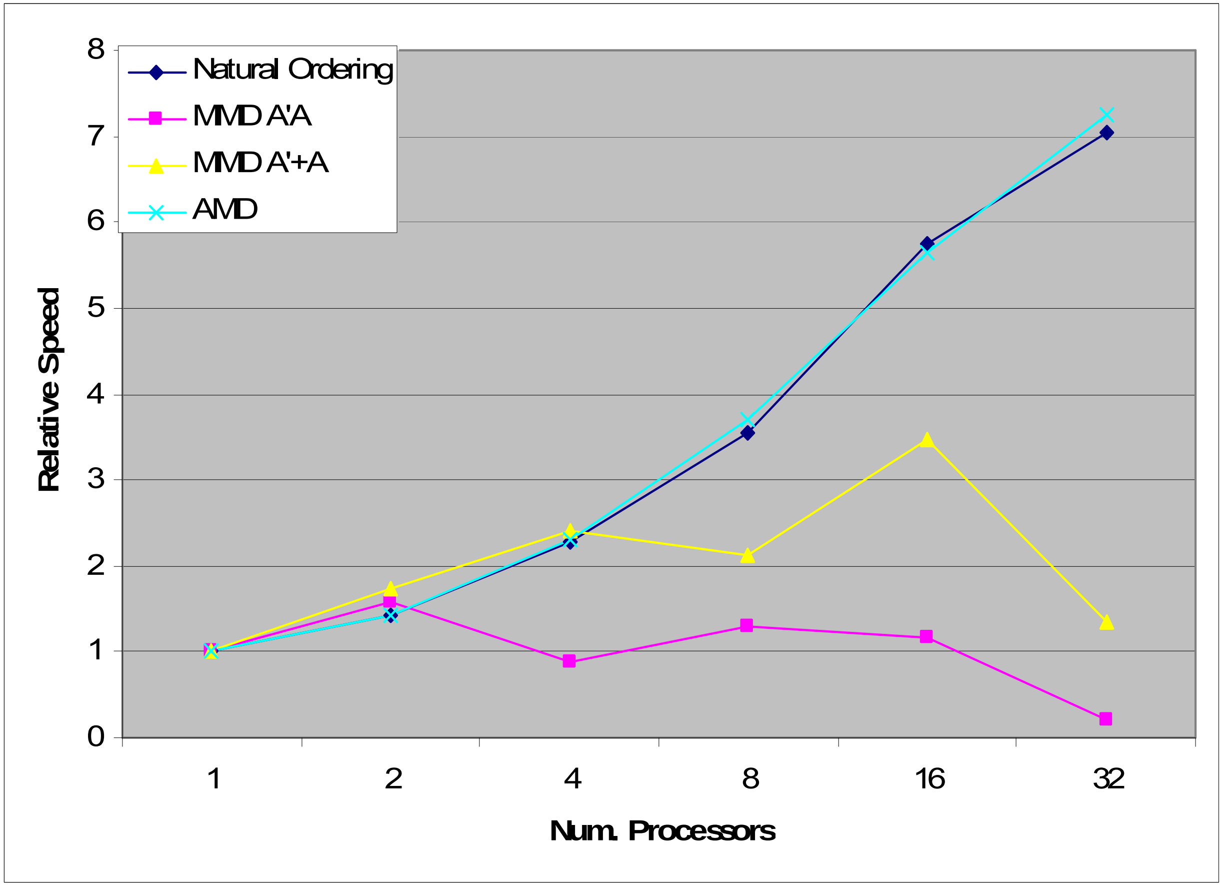
- Characteristic of the problem
  - need for near real-time operation
  - Problem sizes not very big + fine grain computations
  - Irregular communication
- Focus on shared-memory multiprocessor systems rather than on clusters
- SGI Altix with 128 1.5 GHz Itanium-2 CPUs
  - Shared memory programming models
    - Pthreads, OpenMPI, System V shared memory
  - Standard MPI distributed memory programming model
- Cray MTA-2 multithreaded system

Parallel WLS State Estimation

- Critical to accelerate solution of the Weighted Least Square Algorithm
  - Solve very large problems >10,000-100,000 bus systems
  - Exploit emerging systems with multi-core processors
    - Rely of efficiency of shared memory communication
    - Such systems will be broadly available and affordable to industry
- Solution of Sparse Linear System of Equations is the core computational kernel in the WLS algorithm
- Deployed State-of-the-art Direct Solvers
  - SuperLU is frequently used for solving PDEs
- SGI Altix shared memory system
  - Multithreaded version of SuperLU
  - MPI version slower
    - SGI MPI (shared memory)

# Processors vs. Programming Model	1	2	4
MT-SuperLU	0.209s	0.147s	0.169s
MPI-SuperLU	1.106s	1.102s	1.102s

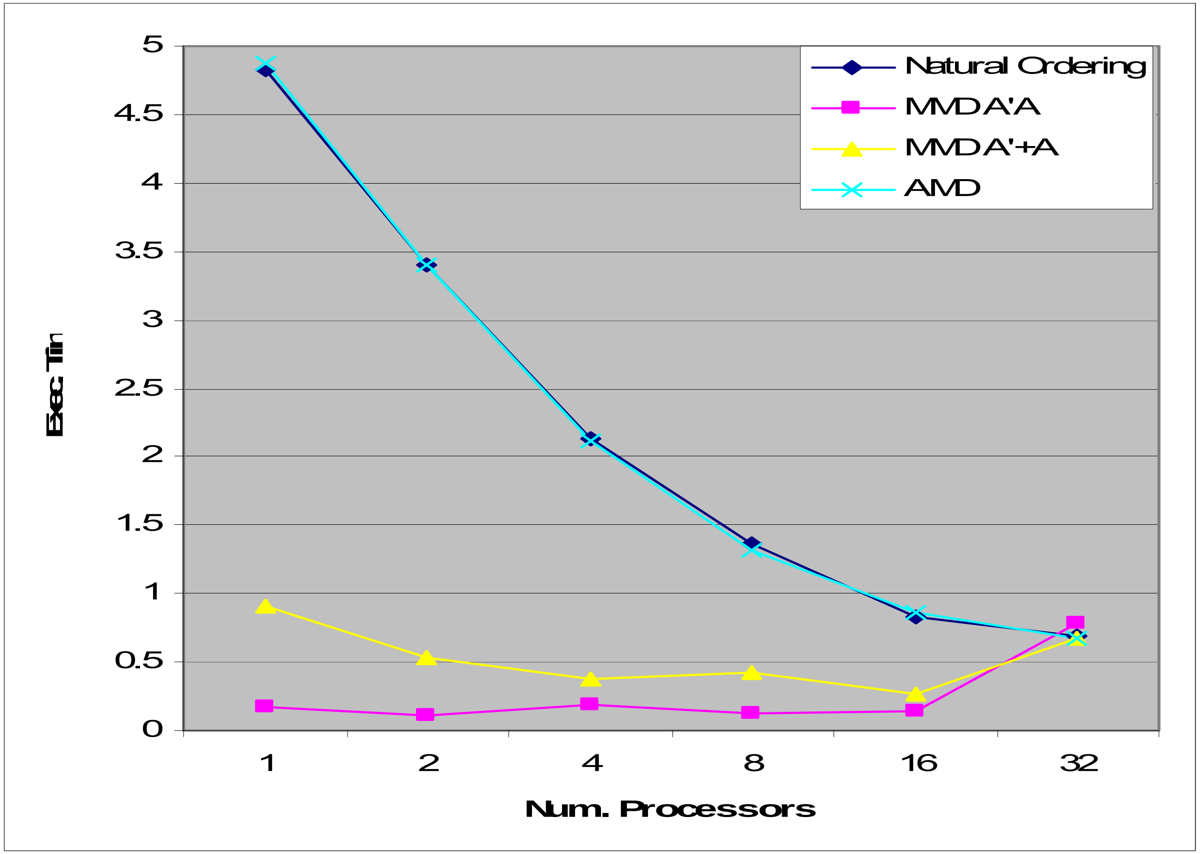
Ordering Scheme and Speedup



Approximate Minimum Degree Produces Best Speedups !

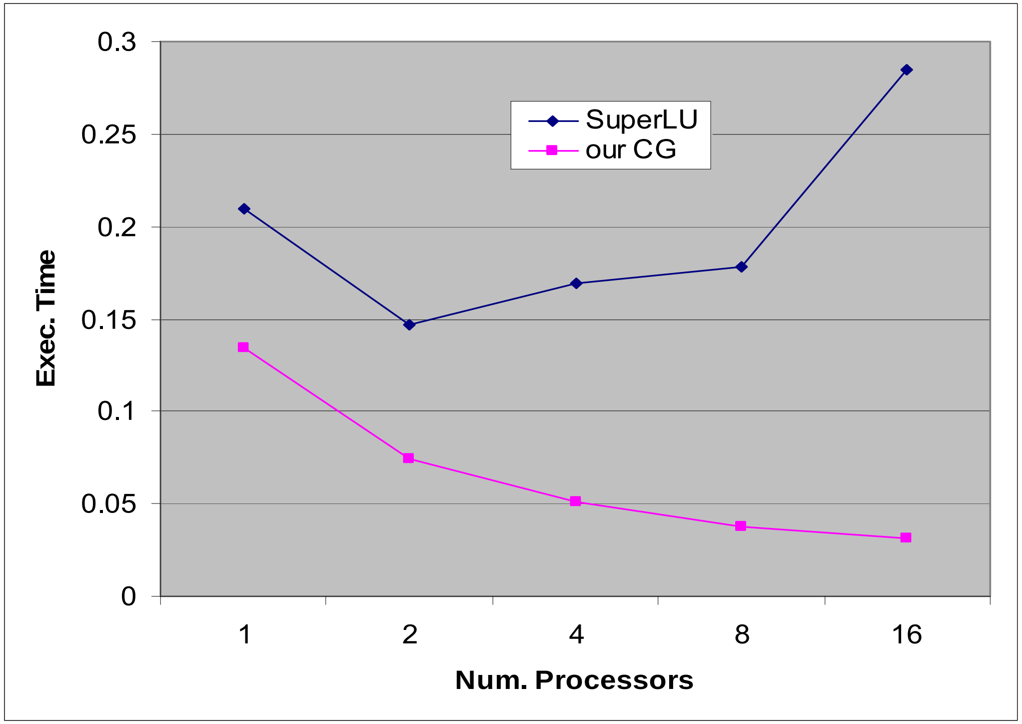
Ordering Scheme and Time to Solution

Multiple Minimum Degree
Is FASTEST
BUT
Not Much Faster Than
Serial Algorithm



Conjugate Gradient in State Estimation

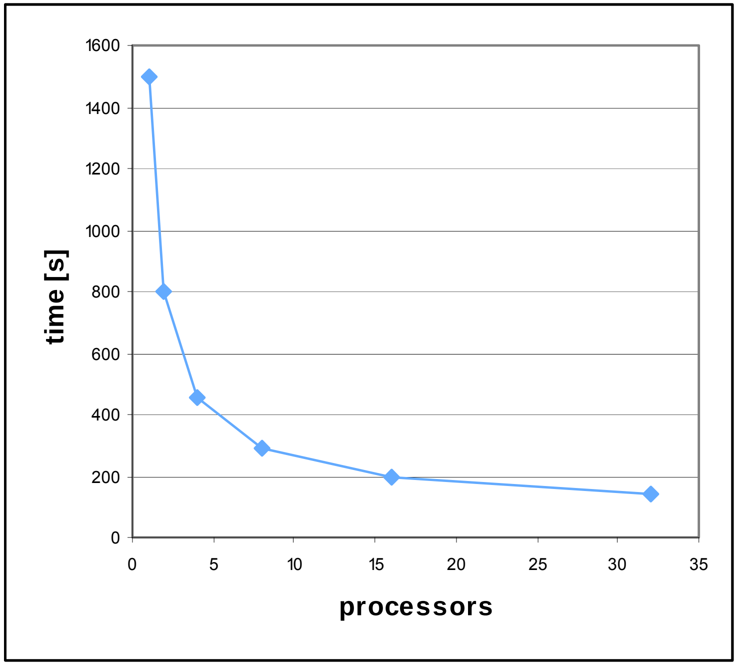
- Shared memory version of Conjugate Gradient
  - Load balancing in the sparse matrix-vector product
  - Experimental evaluation on the SGI Altix shared memory system
  - Better performance and scalability compared to SuperLU package (both multithreaded and MPI versions)

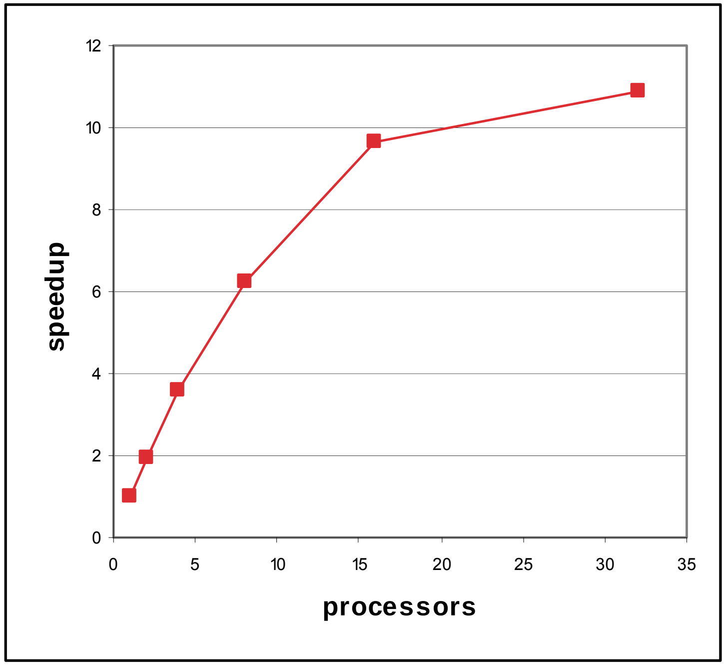


Paper at 2006 IEEE PES General Meeting. Montreal, June 2006: Nieplocha J, A Marquez, V Tipparaju, D Chavarría-Miranda, RT Guttromson, and Z Huang. "*Towards Efficient Parallel State Estimation Solvers on Shared Memory Computers*"

Full State Estimation on Cray MTA-2

- Cray MTA-2 parallel multithreaded architecture
- Parallelization of the full WLS State Estimation Code done based on Cray language directives
- WECC model simplified: ~14000 buses





Challenges in Dynamic State Estimation

- **Non-linearity of the model**
- **Large set of ODEs and Algebraic Equations**
- **Sparsity**
- **Real-time operation requirements**
- **Need solvers effective for the power system area**
- **Data management for telemetry data**
- **We are developing Extended Kalman Filter**

Added Complexity of Problem Scales

- **Data Volume/Rate and State Estimation Requirements**
  - SCADA: ~4 seconds ➔ 100 time speedup
    6 GB/day
  - Phasor data: 1/30 second ➔ 10^4 time speedup
    5 GB/day ➔ 3 TB/day
- **Problem Size**
  - Currently contingency analysis: N-1 only = ~20000 cases, BPA runs only 500 select cases every 5 minutes.
  - N-2 = ~10^8; N-3 = ~10^{12}; N-4 = ~10^{17} ➔ **a Peta-scale problem**
- **Other Factors**
  - Weather – load, wind power
  - Environment
  - …

Dozens of components went out of service during 2003 blackout!!!

- It can not be solved with hardware and software currently used. We must explore advanced computing

Outlook into the Future with HPC Power System Computation

- **Better Models and Simulation**
  - Model identification/validation/enhancement
  - Topology/parameter estimation and identification
  - Faster dynamic simulation
- **Better Monitoring**
  - Dynamic stability monitoring
  - Response adequacy measurement and monitoring
  - Power quality monitoring/enhancement
- **Better Control**
  - SPS/RAS design and operation
  - Reactive power coordination
  - Resource adequacy, commitment & scheduling
  - Fault/outage management

Questions?