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# ENG 505 - ENERGY SURETY AND SYSTEMS

## ENERGY INTERDEPENDENCIES

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**SANDIA REVIEW & APPROVAL NUMBER**

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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**Outline of Presentation**

- Brief Biographical Note
- Complex Systems Construct Application to Energy Type
- Axioms of Interdependencies
- Axiom Examples
- Sandia Capabilities regarding Energy Interdependencies
- How Sandia Performs Energy Interdependencies Analyses
- Summary Overview
- Question & Answer Session

## Brief Biographical Note

- BSIE University of Pittsburgh
- MSIE, Ph. D. Purdue University
  - Staff, State Utility Forecasting Group
- Sandia National Laboratories, 1998-present
  - Critical Infrastructure Modeling, Simulation & Analysis
  - DOE Power Outage Study Team (1998-99)
  - National Infrastructure Simulation and Analysis Center (NISAC)
    - Analysis Lead
    - Chemical Supply Chain Modeling
    - Prioritization of Resources for Infrastructure Systems Mitigation (PRISM)

# Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

# Recall: Approaches* to Complex Systems

*Focus of this session*

- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Systems Engineering
- Sandia Software Tools
- Sandia Disciplines



These represent approaches or resources that an analyst or engineer may apply to a systems engineering challenge.  They are not intended to be a complete set, just one chosen to add structure to this course.

*Note: These approaches represent a simplified set  of complex systems concepts chosen for the ENG505 systems lectures. Please see the initial two systems lectures for additional detail and expanded references.

# Complex Systems Engineering*

- This approach represents a number of methodologies all which usually have four simple steps to solve systems issues!
  1. Describe the system
     - Identify the elements of your system
     - Identify the interactions between the elements
       - Identify what flows over the interactions
  2. Describe system requirements
     - Safety, reliability, security, scalability, extensibility, manageability, maintainability, interoperability, sustainability, composability, adaptability, survivability, affordability, understandability, and, agility.
  3. Identify aspects for complex systems
     - Emergence, Complexity and Information, Dynamics and Self-Organization, Networks
  4. Apply one or more methodologies
     - Theory, Tools, and Approaches
     - Example: CASoS

*Note: Additional detail and expansion around other approaches are included in the initial two ENG505 systems lectures. This is only a simplified template summary for use in ENG505 energy-focused classes.

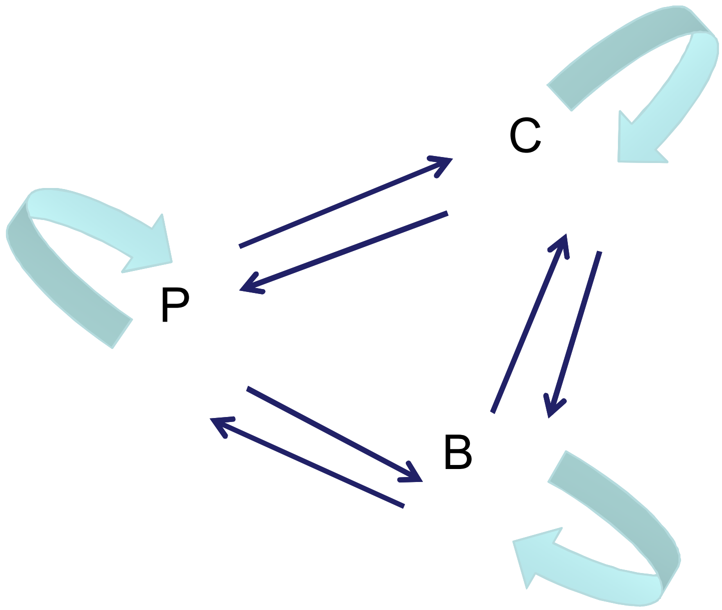
# Threat and Risks*

- This approach considers how to make the system fail with malevolent effects
  - Red teaming
    - (Adversarial-based assessment): How to make the system fail
  - Normal - Abnormal - Malevolent
    - Operational environments (from Sandia NW)
  - Threat timeline:
    - Deter-Protect-Detect-Delay-Respond-Recover
  - Lifecycle security
    - design-prototype-produce-operate-repair-retire
  - Cyber
    - integrity, availability, confidentiality, non-repudiation

*Note: Additional detail and expansion around other approaches are included in the initial two ENG505 systems lectures. This is only a simplified template summary for use in ENG505 energy-focused classes.

# Physical - Cyber – Behavior*

- This approach considers deceptively simple dependencies between physical objects, cyber or information, and the people that interact with the system.
  - Physical
    - Physical Components and Interactions
    - Physical influence on Cyber
    - Physical influence on Behavior
  - Cyber
    - Cyber Components and Interactions
    - Cyber influence on Physical
    - Cyber influence on Behavior
  - Behavior
    - Human Behaviors and Interactions
    - Behavior influence on Physical
    - Behavior influence on Cyber




*Note: Additional detail and expansion around other approaches are included in the initial two ENG505 systems lectures. This is only a simplified template summary for use in ENG505 energy-focused classes.

## Relevance of Complex Systems to Energy Interdependencies

- As you'll see, characteristics of a complex system are the characteristics of interdependencies whether or not specifically associated with the energy sector
  - system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

# Energy Interdependencies

*Axioms of Interdependencies*

- Infrastructure systems are interconnected
- Major (non-binary) heuristic control of infrastructure systems is
  - human
  - functionally specific
  - local
- Binary heuristic control of infrastructure systems is
  - component-specific by design
  - myopically local

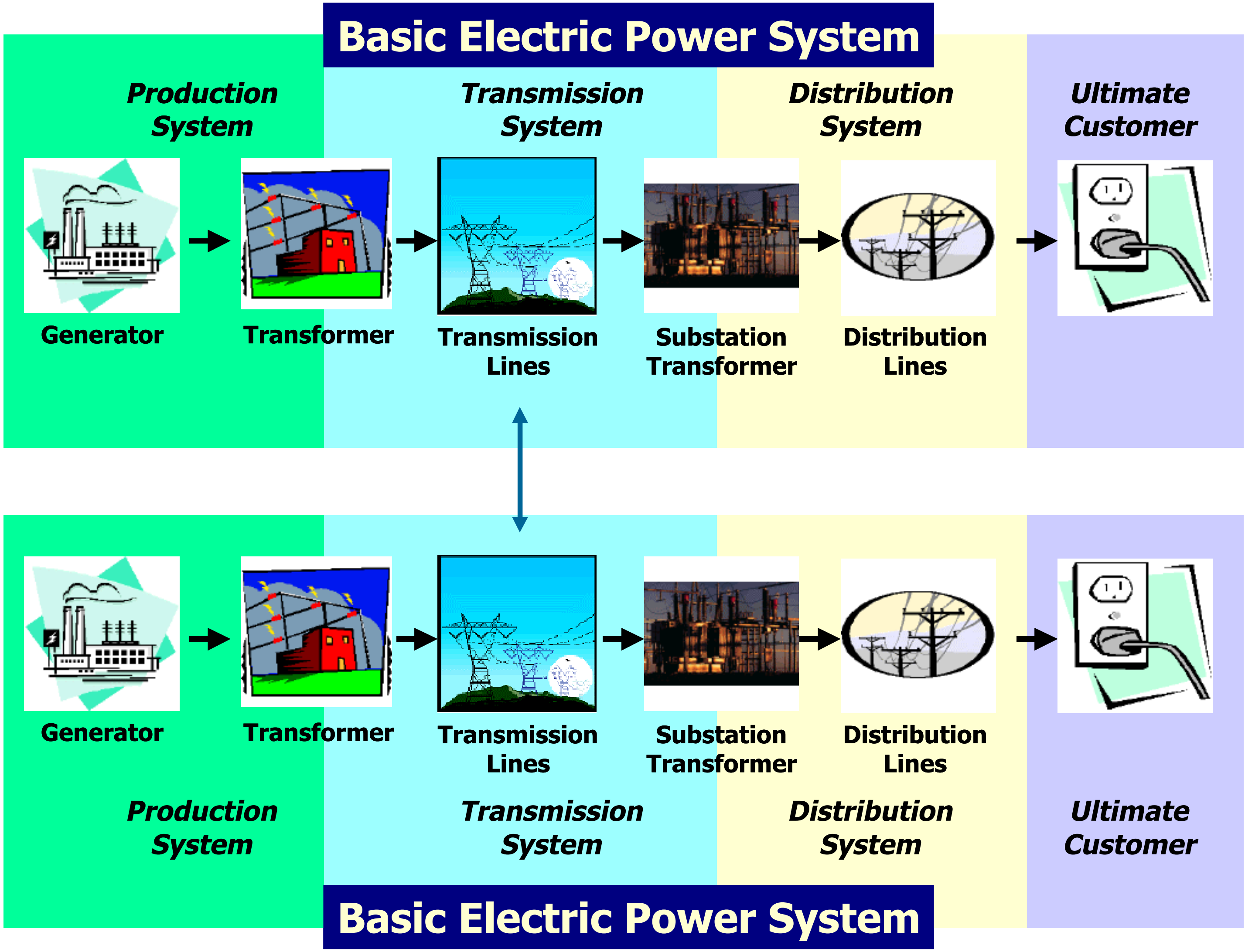
# Energy Interdependencies

*Axioms of Interdependencies*

- Time scales of events are important in determining what actions can be taken
- Infrastructure dependencies can and do occur even where there is no physical connection between the infrastructure elements other than a common location
- Interdependencies go far beyond the physical relationships, to include operating rules, regulations, and business decision-making criteria

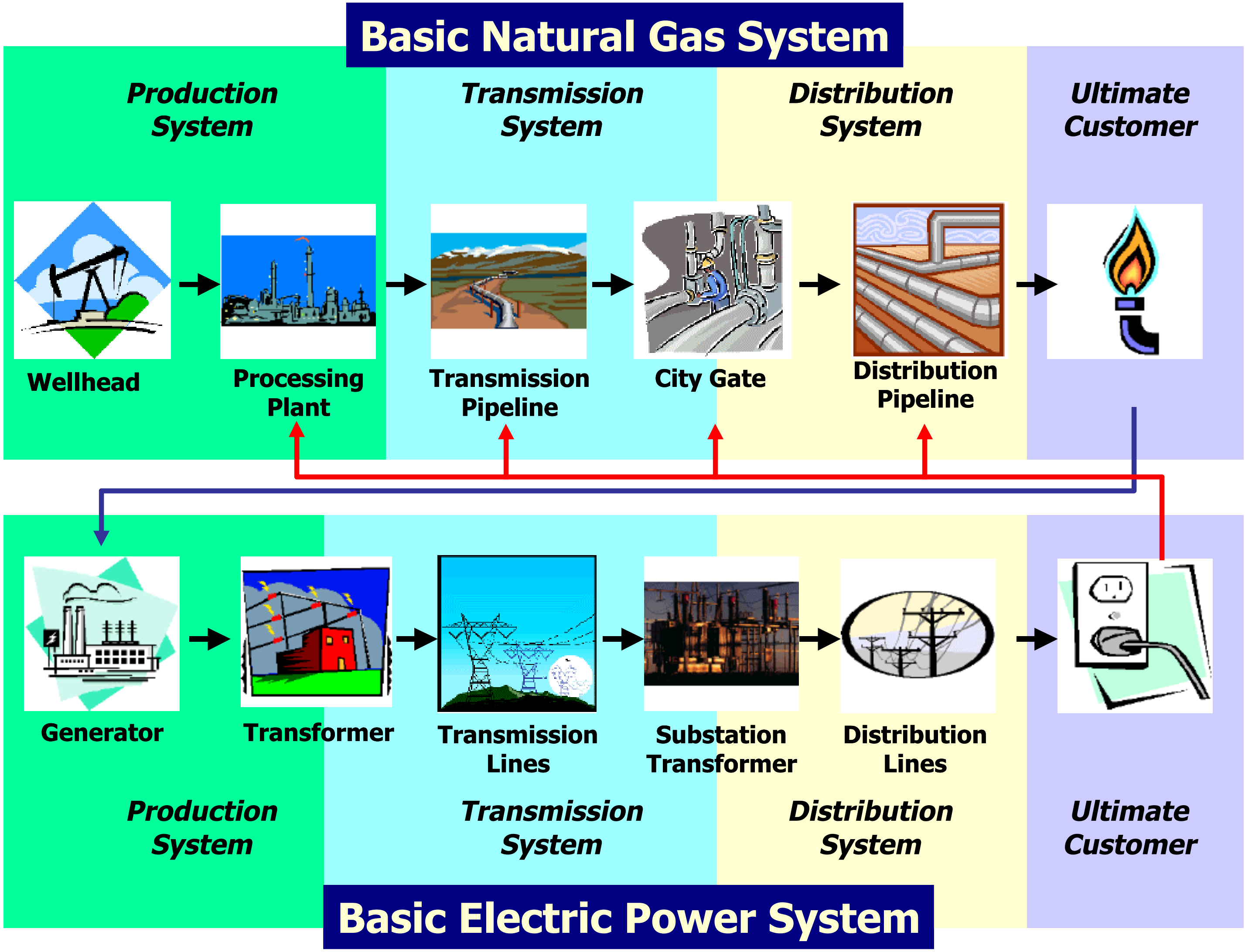
# Energy Interdependencies

*Axioms: Infrastructure Systems are Interconnected*



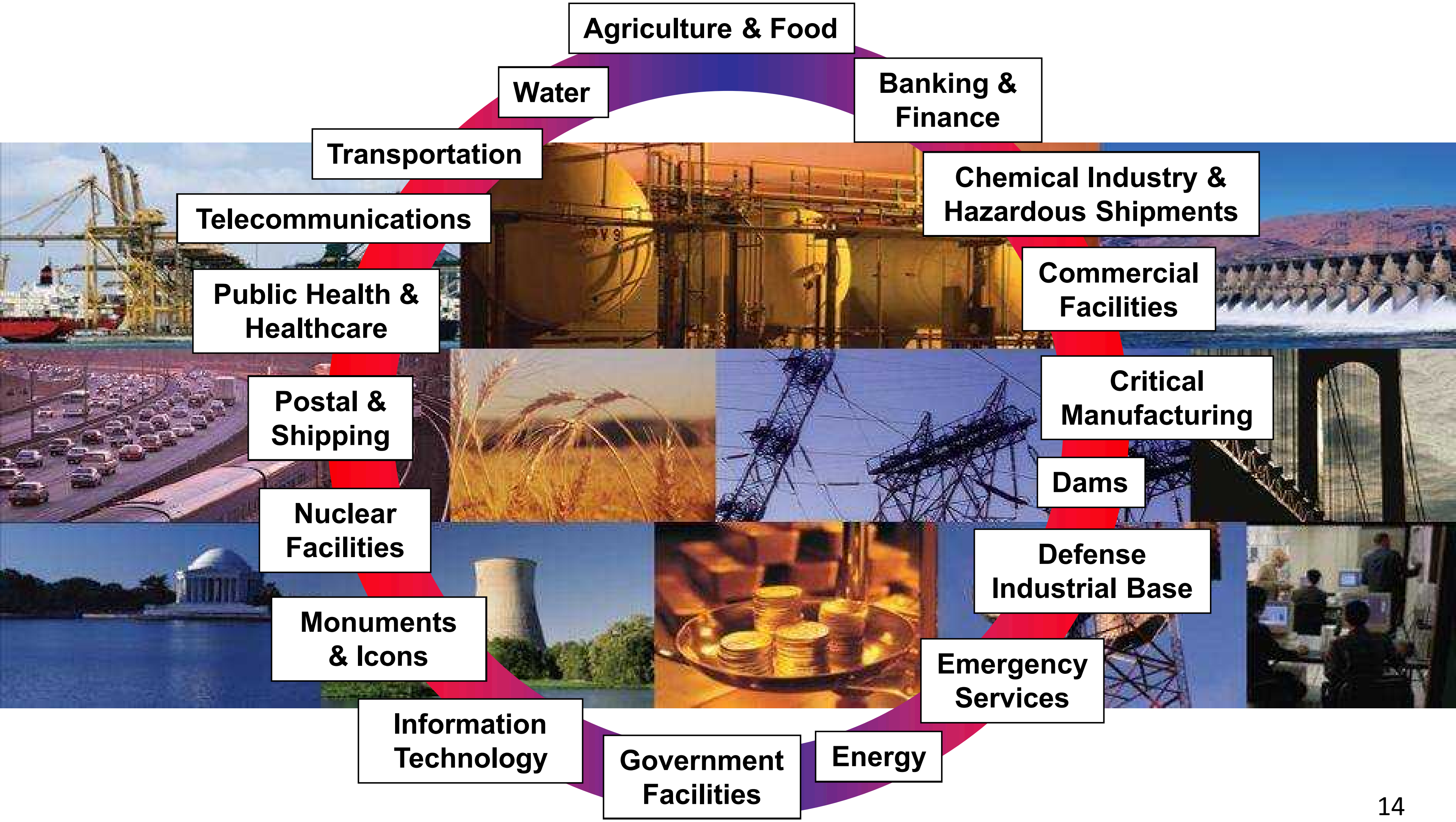
# Energy Interdependencies

*Axioms: Infrastructure Systems are Interconnected*



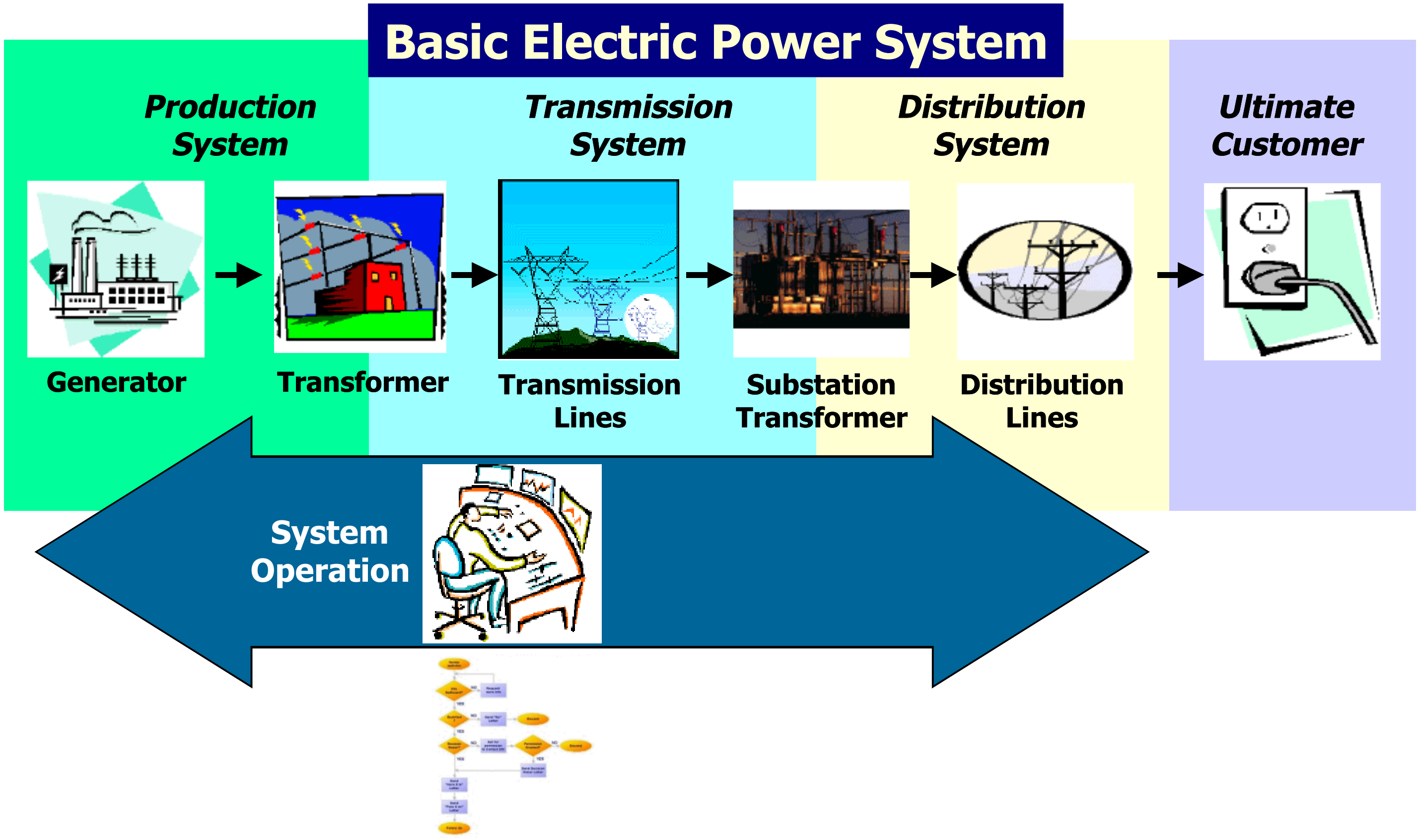
# Energy Interdependencies

*Axioms: Infrastructure Systems are Interconnected*



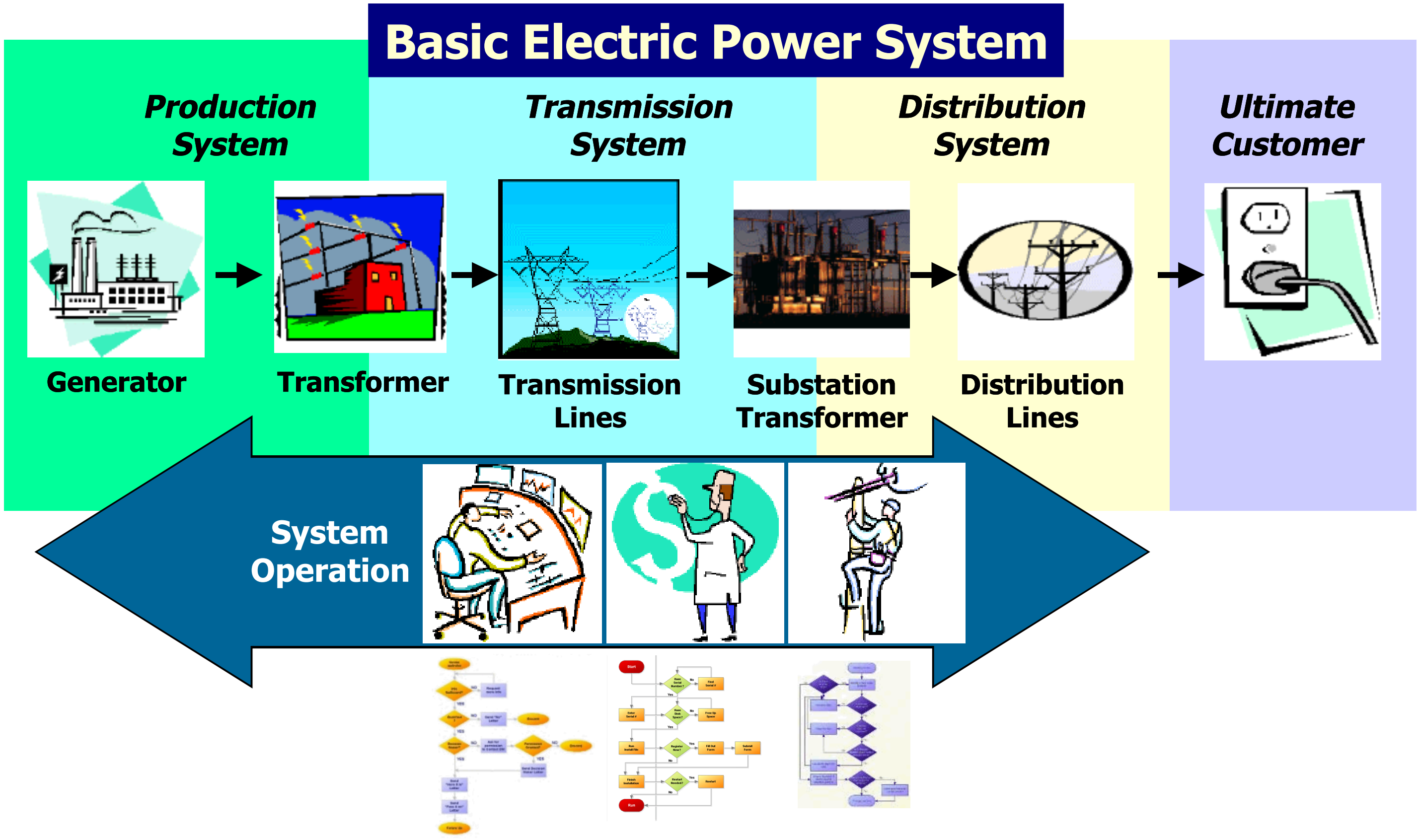
# Energy Interdependencies

*Axioms: Non-Binary Control of Infrastructure Systems is Human*



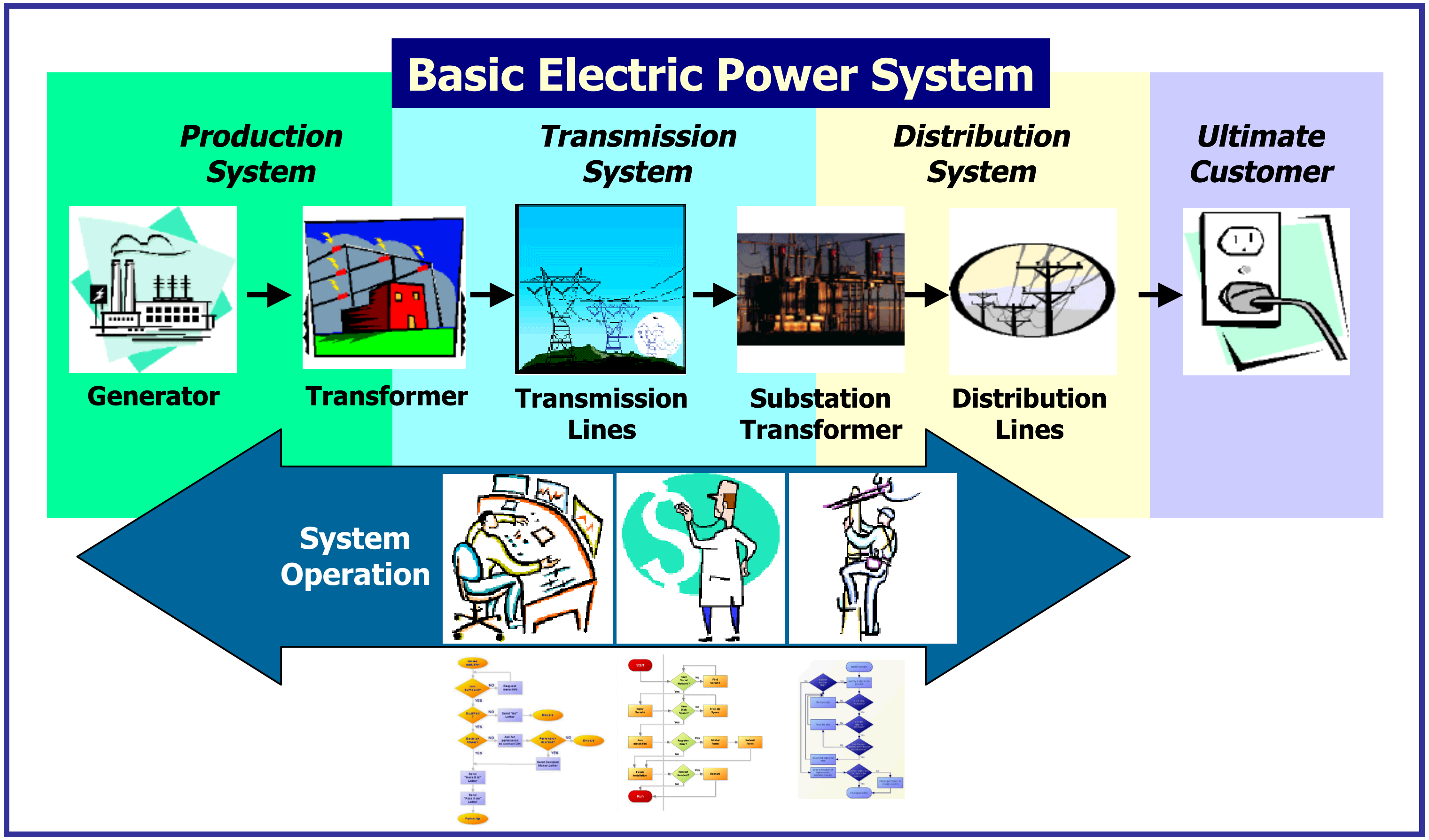
# Energy Interdependencies

*Axioms: Non-Binary Control of Infrastructure Systems is Functionally Specific*



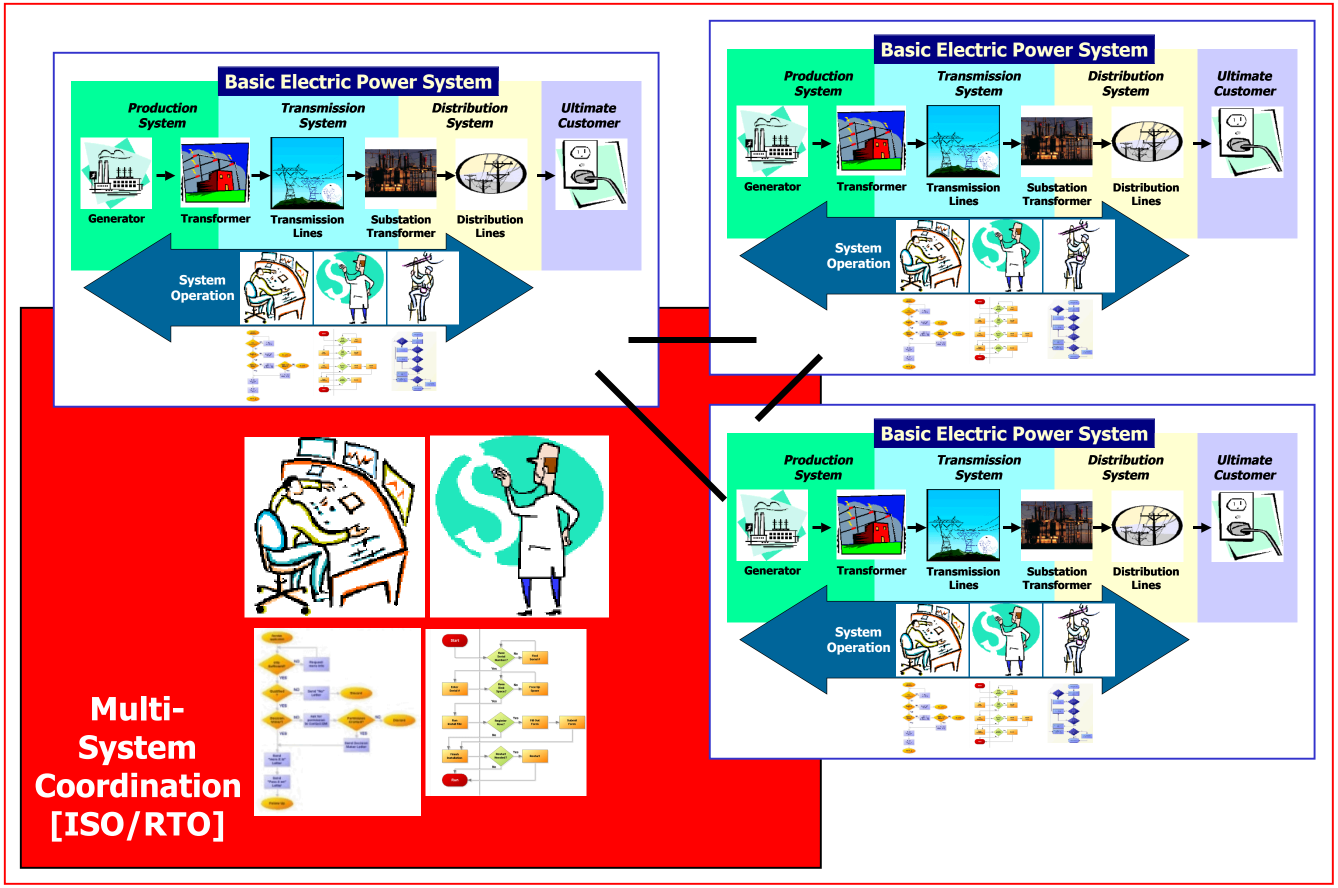
# Energy Interdependencies

*Axioms: Non-Binary Control of Infrastructure Systems is Local*



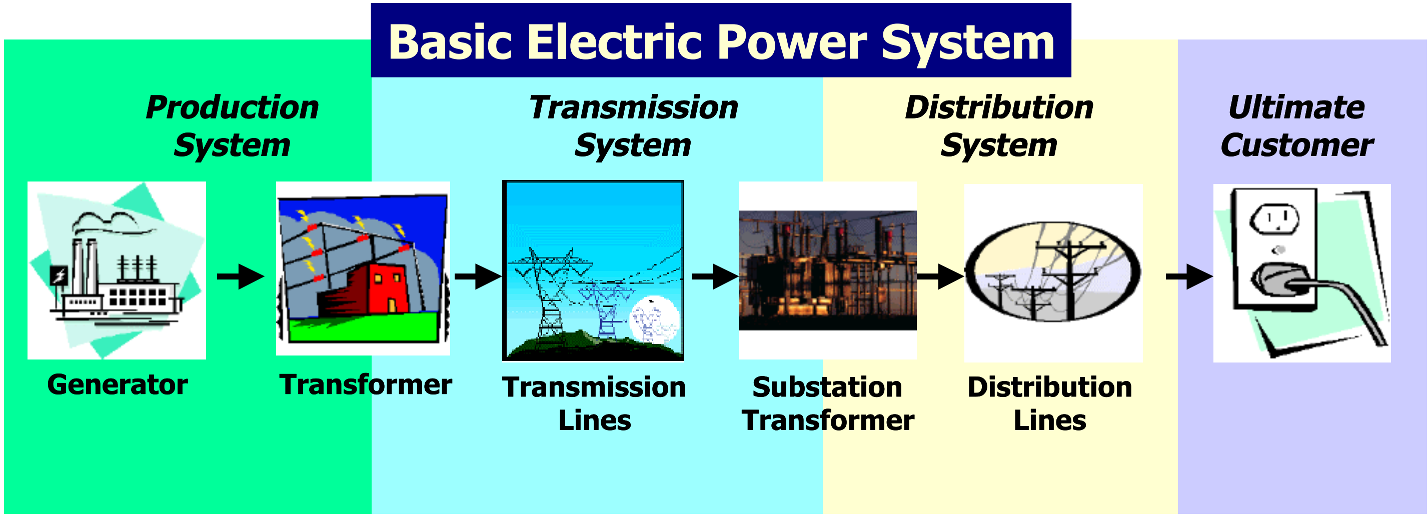
# Energy Interdependencies

*Axioms: Non-Binary Control of Infrastructure Systems is Local*



# Energy Interdependencies

*Axioms: Binary Control*




- Binary Heuristic control of infrastructure systems is component-specific and myopically local
  - Each element composed of physical components
  - Physical components include limitations on the physical performance of the component
  - These rules exist for the physical protection of the components (primarily) and the system as a whole (hopefully)

# Energy Interdependencies

*Axioms: The Importance of Timing*

- Timing of events is important
  - When the event occurs
  - What preceded/follows
- Delays in consequences vary widely
  - Storage a key factor

# Energy Interdependencies

*Axioms: The Importance of Timing*

- Timing and Information
  - The "Just In Time" (JIT) Nature of the Infrastructure
    - Traditionally, Electric Power (along with telecommunications) has been the most JIT of the infrastructures (production to consumption)
    - Layering of a market structure has increased the number of JIT layers involved in day-to-day operations
      - This increases the potential for disruption
  - Information from other infrastructures
    - Is critical to reducing the potential for disruption
    - Is a dual-edged sword
      - Information can help you mitigate
      - Information could be used to litigate against you

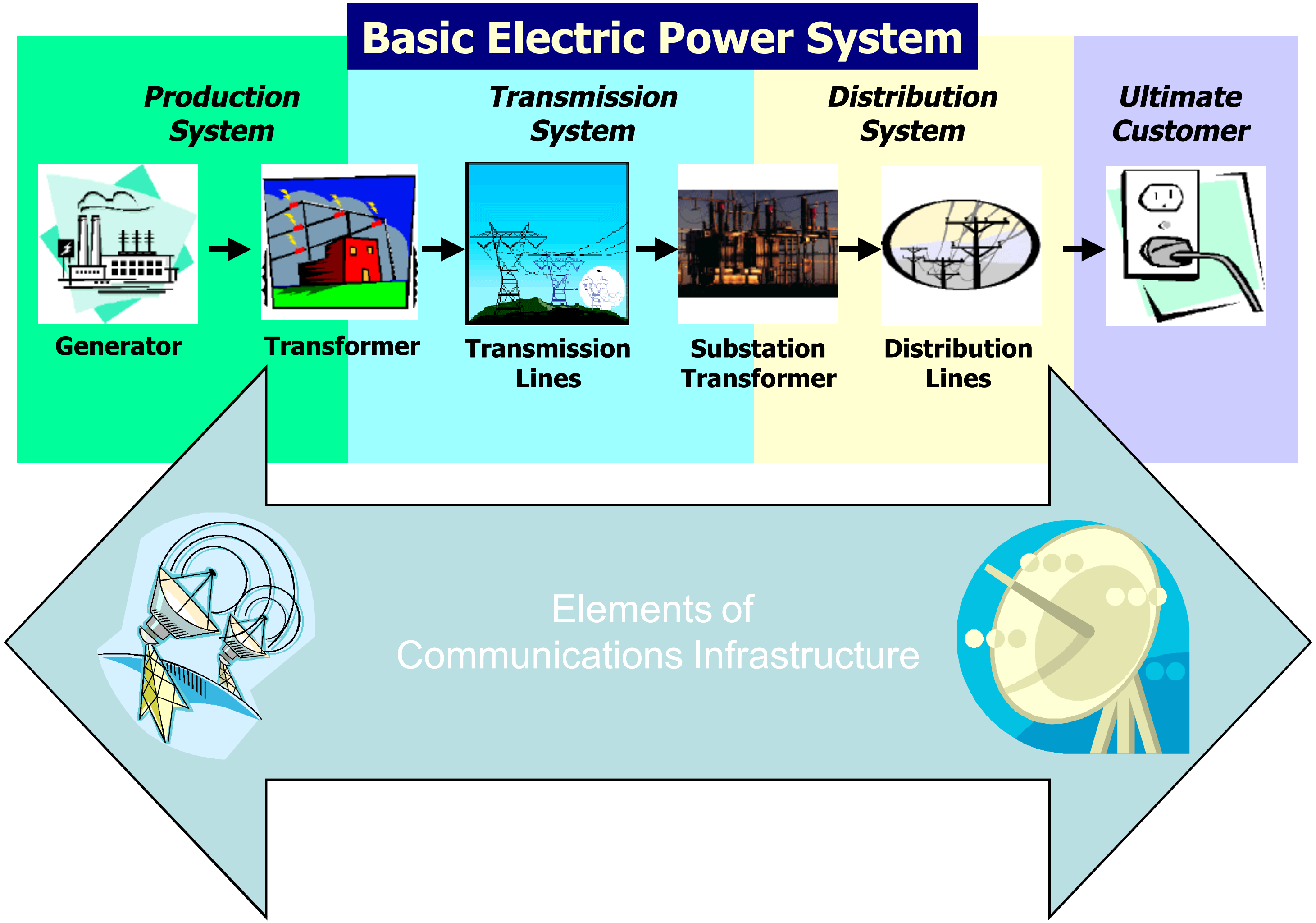
# Energy Interdependencies

*Axioms: Dependencies of the Energy Infrastructure*

- On other segments of the same sector of the energy infrastructure
- On other sectors of the energy infrastructure
- On other infrastructures
  - Water
  - Telecommunications
  - Transportation

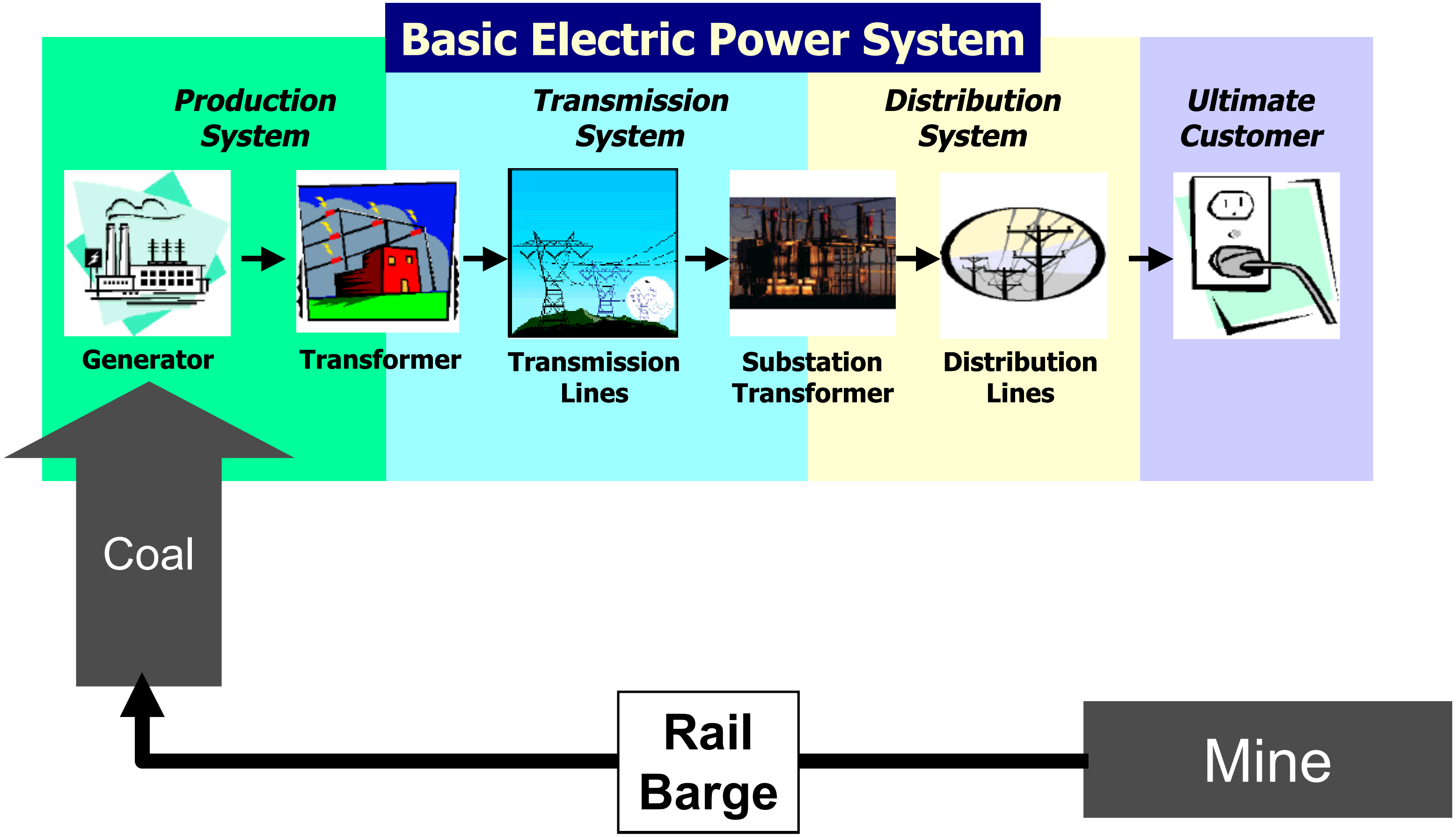
# Energy Interdependencies

*Axioms: Dependencies of the Energy Infrastructure*



# Energy Interdependencies

*Axioms: Dependencies of the Energy Infrastructure*



# Energy Interdependencies

*Axioms: Co-location of Infrastructure Systems*

- The location of infrastructure elements along a common corridor
  - Examples include pipelines, electric power transmission lines, rail lines, highways, telecommunications trunks
- Often chosen to utilize existing rights-of-way
  - Rail rights of way most common
- Within an infrastructure sector, occasionally used as a marketplace (or market reference point)
  - Henry Hub

# Energy Interdependencies



*Axioms: Co-location of Infrastructure Systems*


**NW Airlines Loses Communication**

EAGAN, Minn. (AP) -- Northwest Airlines lost most of its communications lines systemwide for about 2 1/2 hours Tuesday when an independent contractor hit a fiber-optic cable, leading to cancellations and delays around the country.

Passengers aboard planes were not in danger, but Northwest temporarily suspended boarding additional flights until the problem was fixed, said spokeswoman Mary Beth Schubert.

About **130 of the airline's 1,700 daily flights were canceled** systemwide, and an undetermined number were delayed. Schubert said communications lines went down just after 2 p.m. CST, affecting reservations and baggage information and the airline's electronic ticketing system.

Major delays were reported in Detroit, where about 30 flights were canceled, according to Northwest spokesman Doug Killian.

Another 19 were canceled in Minneapolis, with the remainder scattered around the system. **Some delays also were experienced in Singapore and Bangkok**, he said.

Northwest's Web site also was out of service because of the severed cable.

Kim Bothun, a spokesman for U S West, the telecom that owns the fiber-optic cable, said the **line was cut by a competitor McLeod USA, a local and long-distance telecommunications company based in Cedar Rapids, Iowa**. She said it is not uncommon for telecommunications companies' cables to be very close to each other.

Calls to McLeod USA were met with a busy signal Tuesday night.

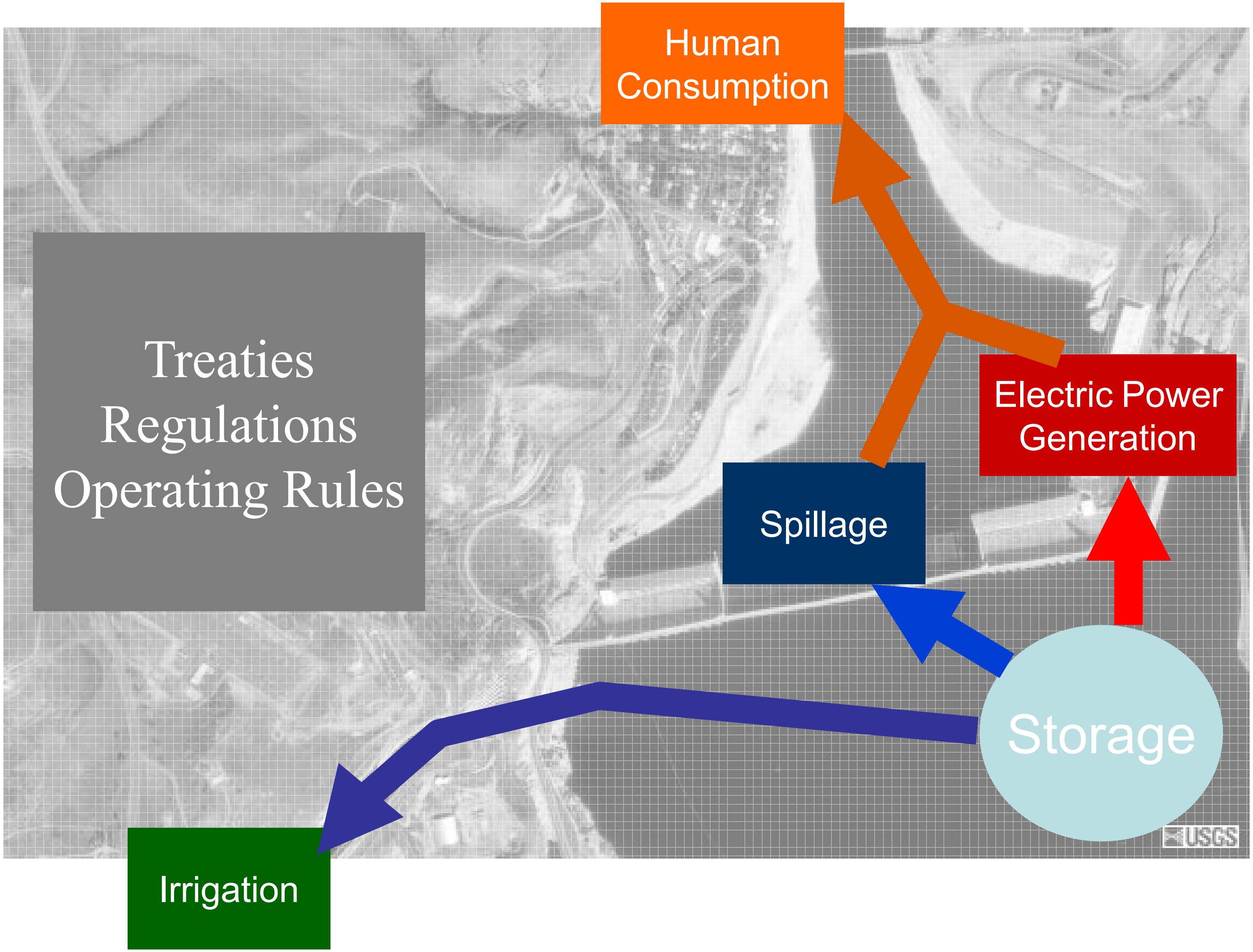
Northwest officials said the airline expected to be back to normal operations by Wednesday morning.

Passengers scheduled to fly on Northwest Tuesday evening were given the option of rescheduling their flights.

Associated Press Archive - March 22, 2000, at http://newslibrary.com

# Energy Interdependencies

*Axioms: Co-dependence of Infrastructure Systems*

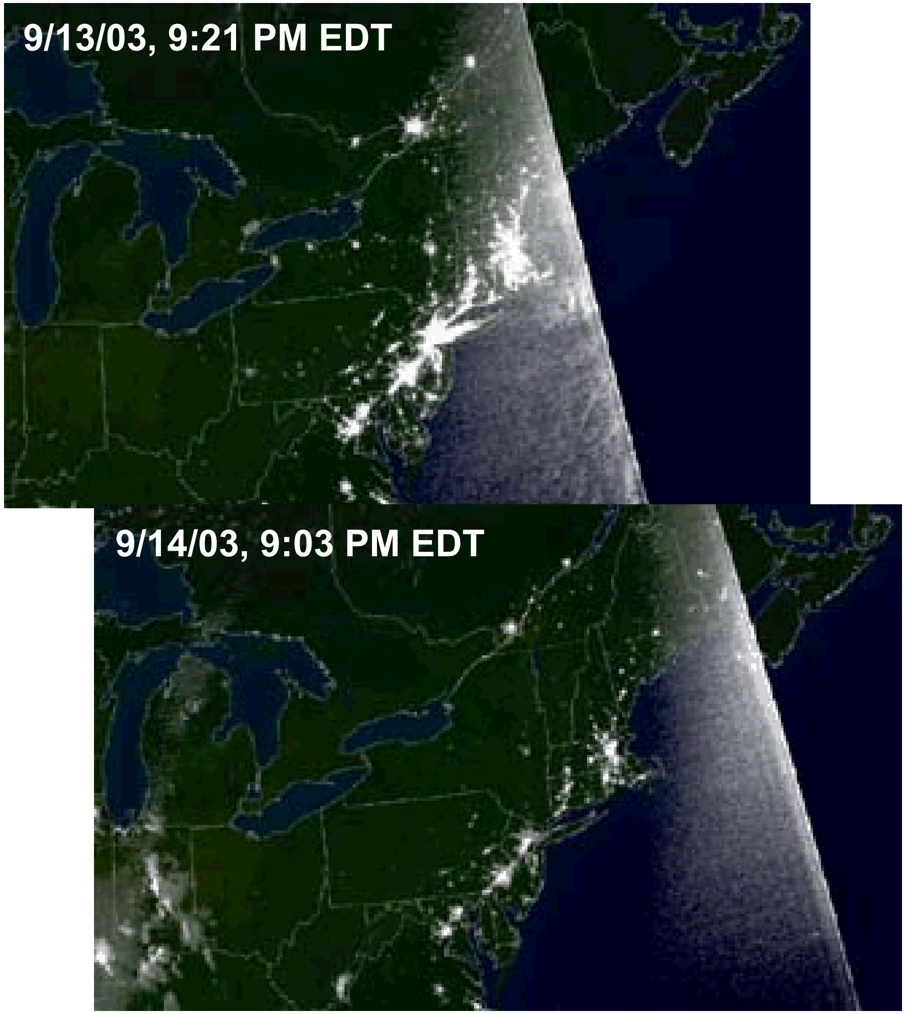


# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

- 61,800 MW load lost
  - Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey, and Ontario
  - Estimated 50 million people affected
- $4 to $10 billion impact in the US

Reference: "The Economic Impacts of the August 2003 Blackout," Electric Consumer Research Council (ELCON), February 2, 2004.

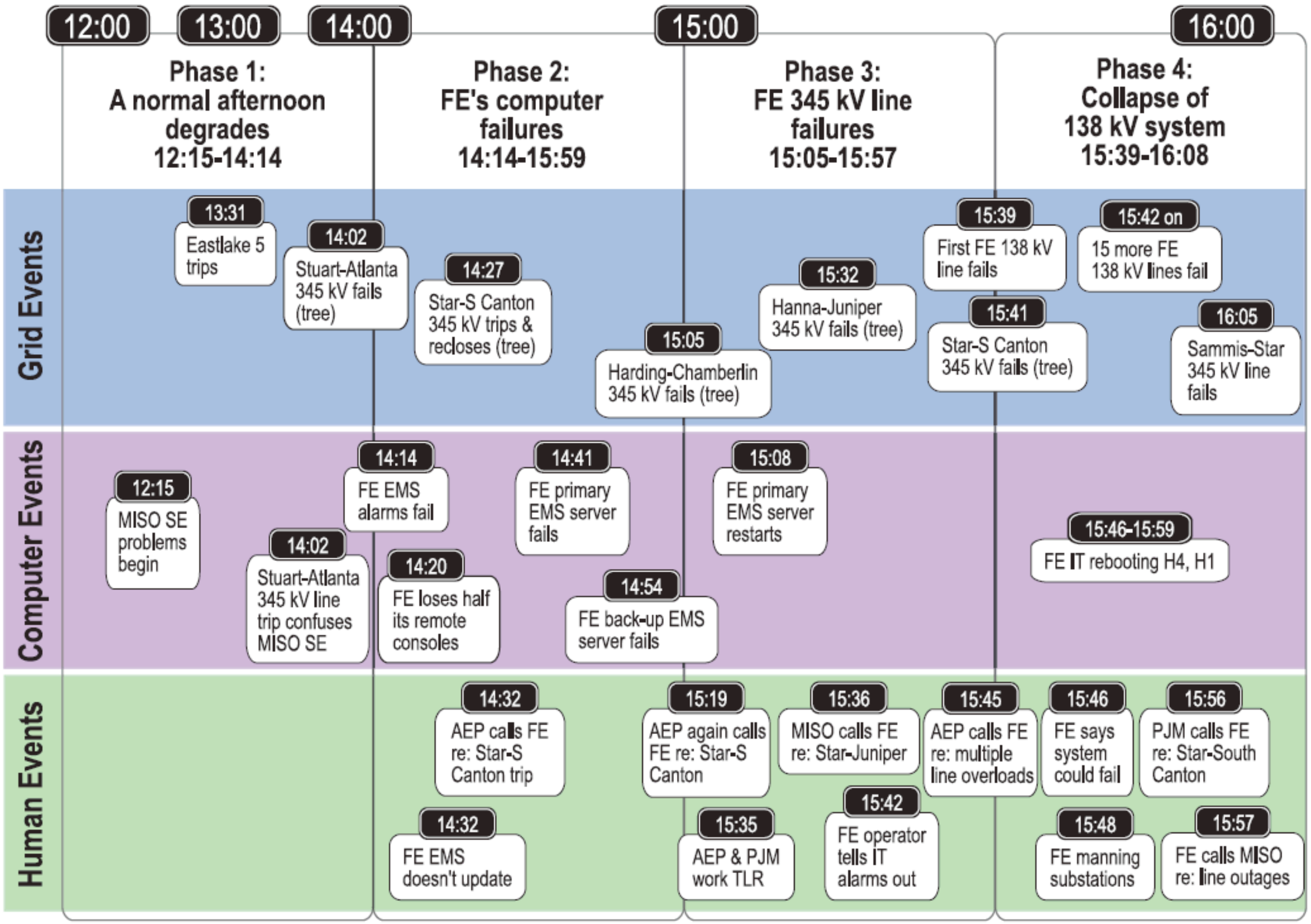



Images: NOAA

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

**Figure 5.1. Timeline: Start of the Blackout in Ohio**

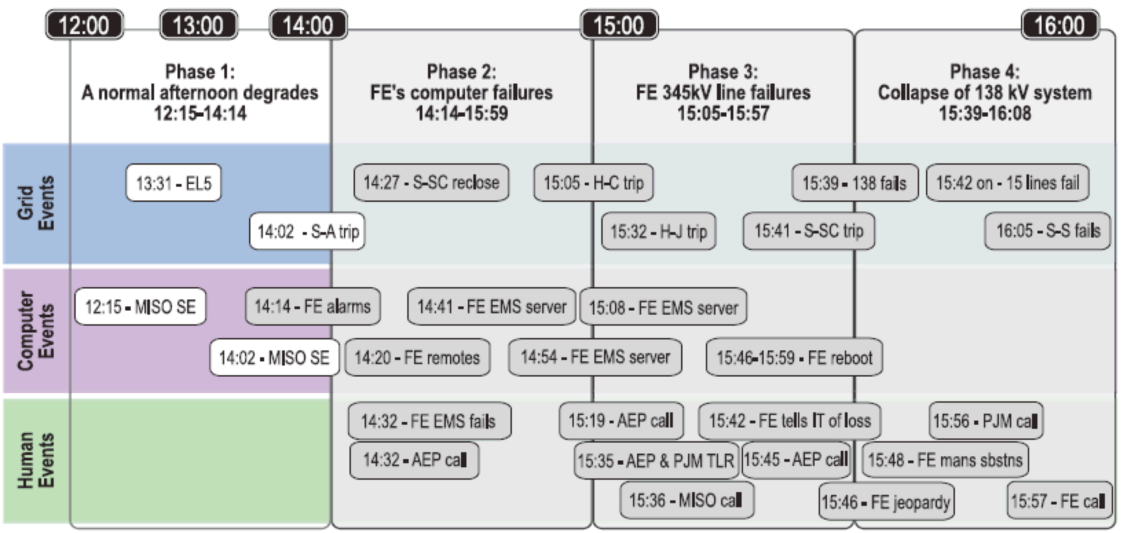



Reference: *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations.* U.S.–Canada Power System Task Force. April 2004.

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

Figure 5.2. Timeline Phase 1

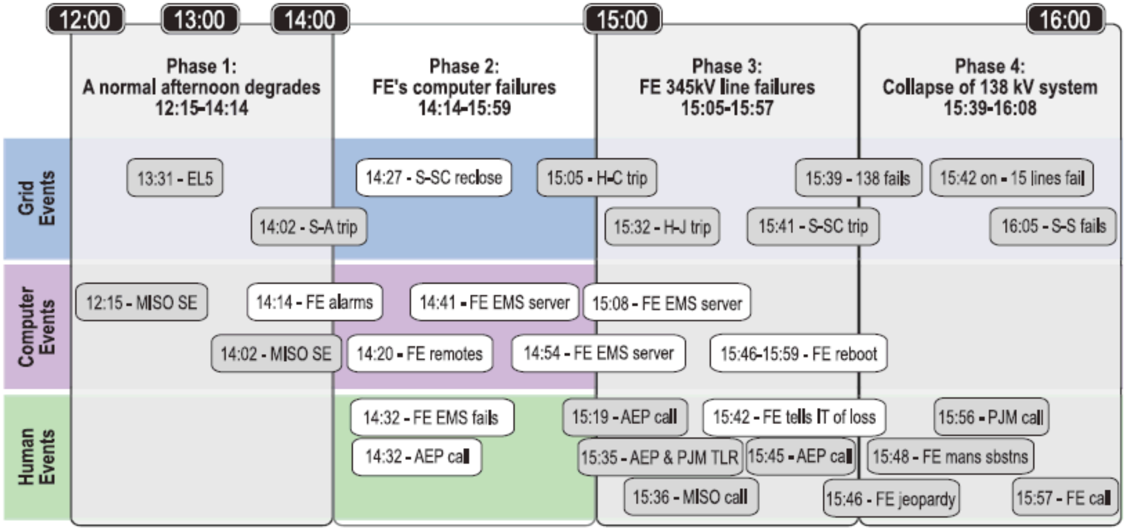



- Phase 1 Events
  - 1215: MISO State Estimator compromised
    - program used to calculate state of the system based on measurements and a model
    - 230kV Bloomington-Denois line trips
      - In Cinergy's territory
      - No electrical effect with the blackout
      - Trip data was not effectively communicated to MISO
      - As a result, MISO's SE showed high mismatch (unacceptable error)
  - about 1300: Line inaccuracy in the model discovered and fixed
    - Automatic trigger disabled
    - SE solves once at 1307
  - about 1440: Trigger error discovered
    - Trigger was re-enabled

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

**Figure 5.4. Timeline Phase 2**

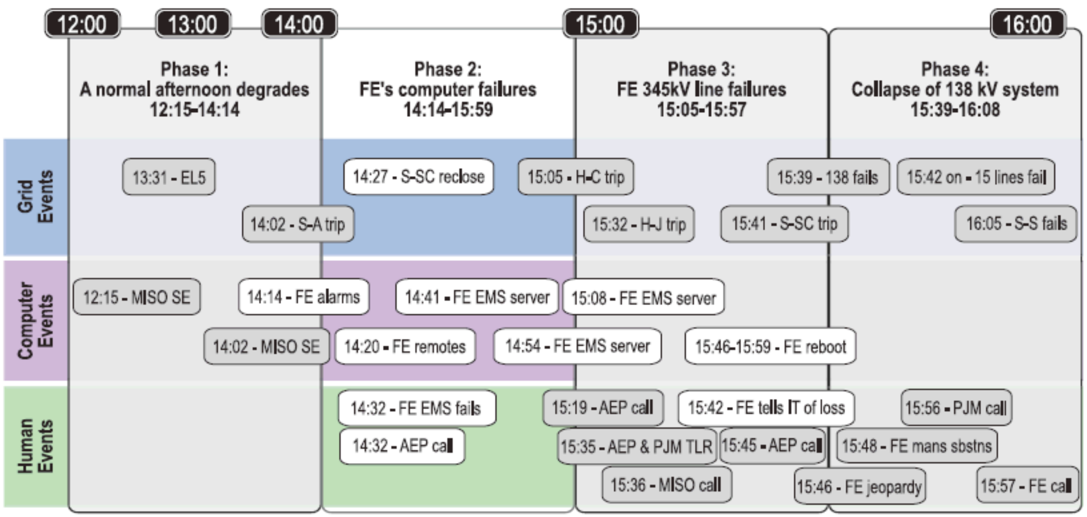



- Phase 2 Events
  - 1414: FE Alarm/Logging system Failure
  - 1420: FE Remote EMS console failure (overload)
    - Last time a valid alarm recorded
    - System lack alarms on Human-Machine Interfaces (HMIs), recorded/printed record, map board for quick diagnosis
    - FirstEnergy (FE) relies on alarms for updates about changing grid conditions
    - Operators were unaware that alarms had failed
    - Processing of an alarms stalled
    - New data fills and overfills input buffers

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

Figure 5.4. Timeline Phase 2




- Phase 2 Events
  - 1427: Star – S. Canton 345 kV line trips and closes
    - Tree contact
  - 1432: AEP calls FE re: Star – S. Canton
    - Not seen in FE because of alarm failure
  - 1441: Primary FE Control Server Fails
    - Alarm stall also transfers
  - 1454: Back-up FE Control Server Fails
    - HMI refresh rate, normally 1-3 seconds, now 59 seconds
    - Warm reboot of primary alarm server at 1508 resolves refresh rate issue *but not* alarm stall

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

**Figure 5.10. Cause of the Hanna-Juniper Line Loss**

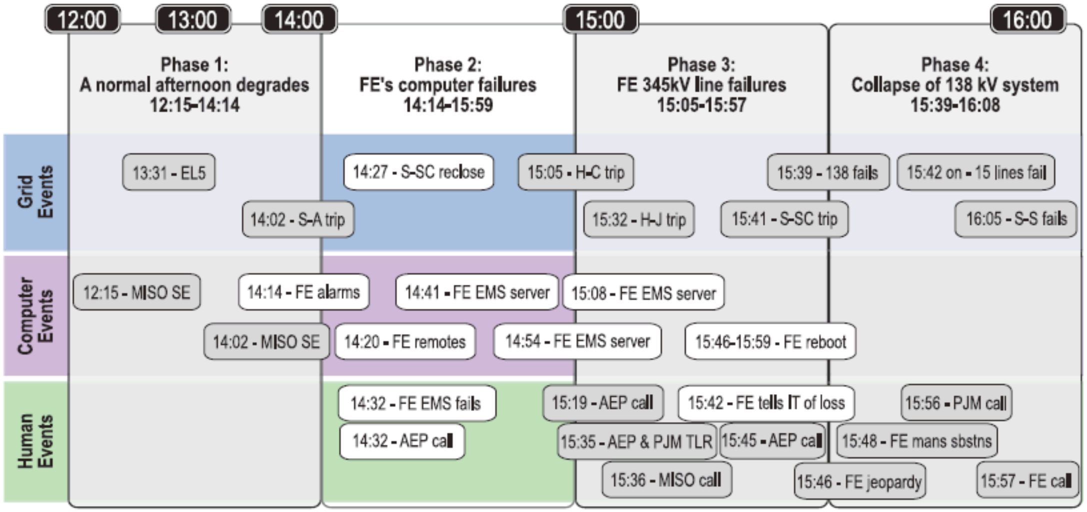

This August 14 photo shows the tree that caused the loss of the Hanna-Juniper line (tallest tree in photo). Other 345-kV conductors and shield wires can be seen in the background. Photo by Nelson Tree.

- More Phase 2 Events
  - 1542: FE's western transmission operator calls to describe their compromised EMS
    - Control center operators mention their EMS problems to the IT staff
    - More calls to FE control center
  - 1545: A tree-trimming crew reported a tree fault on the Eastlake – Juniper (345kV) line
    - The actual fault was to the nearby Hanna – Juniper line
    - This confused FE more, since the balky EMS accurately showed flow on Eastlake – Juniper
  - 1545: AEP called about the third and last trip of the Star – S. Canton line
    - FE believes them
  - 1546: Perry operator calls back to report imminent trip

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

Figure 5.4. Timeline Phase 2

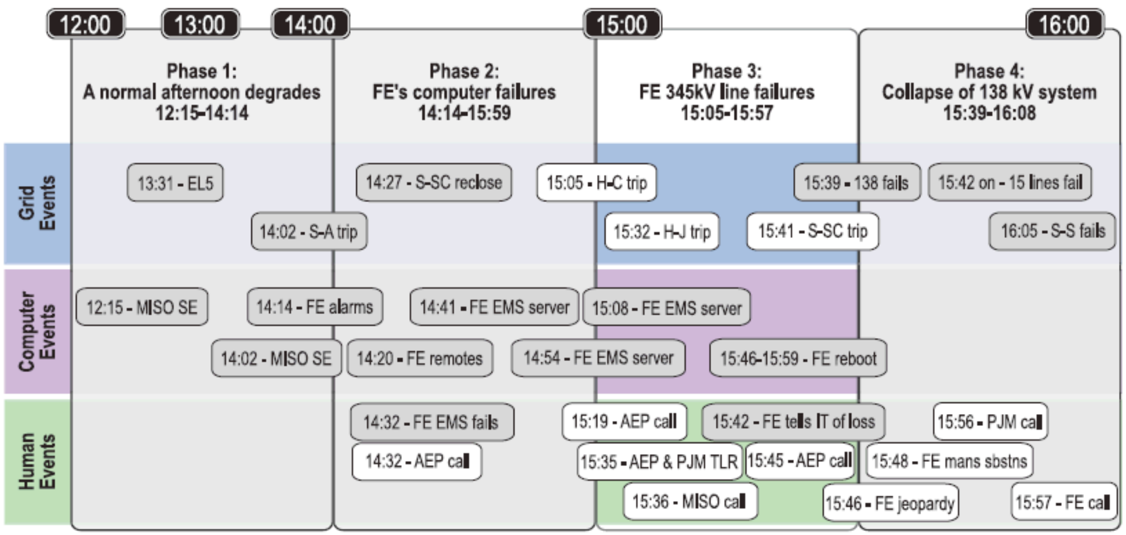



- Still More Phase 2 Events
  - 1546-1559: FE IT personnel try rebooting the primary and backup servers
    - A “cold” reboot was discussed and rejected because of the ongoing grid problems
    - A cold reboot probably the only thing that would have worked
    - EMS HMI refresh again crawls

# Energy Interdependencies

*Axiom Example: August 14, 2003 Blackout*

Figure 5.7. Timeline Phase 3




- Phase 3 Events
  - 1535: AEP and PJM Begin Arranging for TLR for Star – S. Canton
  - 1536: MISO calls PJM to confirm Stuart-Atlanta trip
  - 1541: Star – S. Canton 345 kV line trips again, locks out
    - Load shift from other outages pushed it to 93%
    - Again, outage was tree-related

Loss of the three 345 kV paths (Star – S. Canton, Hanna – Juniper, Harding – Chamberlain) shift the grid load to the 138kV network, which *cannot carry it.*

# Energy Interdependencies

*Axiom Examples: July 23, 1999 South-Central States Rolling Outages*

At 1:59 p.m., Western Resources (WR) lost Jeffrey Unit 3 and entered a 700-MW derating contingency, creating a reserve deficiency for SPP. SPP's operating reserve-sharing software — SCCSWin — was unable to develop a feasible schedule. Therefore, SCCSWin output its most recent, infeasible solution and distributed this fictitious schedule to all reserve-sharing participants. Pool members then began to call SPP, asking it to check the validity of the schedule. The SPP found that the schedule was invalid and asked members seeking reserves to speak directly with WR. Although the reserve-sharing program malfunctioned at 1:59 p.m. and issued fictitious schedule notifications to participants, KCPL and Entergy continued to receive assistance, as scheduled. At this time, SPP had a reserve deficiency of 396 MW because five contingencies totaling 2,177 MW had been entered in the last hour.

During the 2 p.m. hour, Entergy continued to inquire about purchasing power from several parties. While none of these parties had power available, some agreed to assist Entergy in looking for power. SPP contingency events continued. At 2:09 p.m., Sunflower Electric Corporation lost its Garden City unit and entered a 50-MW derating contingency. At 2:18 p.m., WR lost Lawrence Energy Center Unit 5 and entered a 340-MW derating contingency. The SCCSWin software produced fictitious schedules for each of these contingencies.

**Reference:** ***Interim Report of the U.S. Department of Energy's Power Outage Study Team: Findings From the Summer of 1999*. January 2000, pp. 1-33, 1-34.**

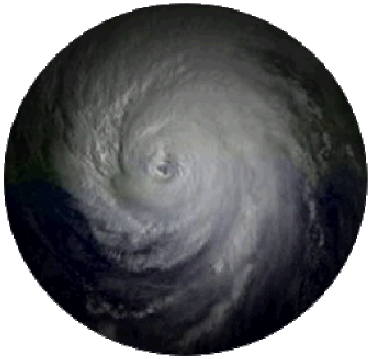
## Sandia Capabilities regarding Energy Interdependencies

- Modeling, Simulation and Analysis
  - Dynamic Simulation Models
  - Agent-Based Simulation
    - Supply chain modeling
  - GIS Awareness tools
  - Economic analysis
- Models extend beyond the energy sector
  - Consequence analysis
    - Natural disasters
    - Business decision making
  - Policy modeling
  - Interdependencies with other sectors
    - Water

**How Sandia Performs Energy Interdependencies Analyses**

- Find data
- Build the system model
  - Know the system with the bare minimum of interdependencies
  - Add interdependencies to reflect conditional and temporal concerns
- Execute the system model to establish baseline
  - Does this look like normal?
  - Iterative loop
- Define the perturbation
  - Refine the system model or data as needed to reflect perturbation conditions
- Execute the system under perturbation
- Compare and contrast results
  - Looking for the unexpected in real eventsto revise modeling

## How Sandia Performs Energy Interdependencies Analyses



Katrina
2005

Ike
2008

- Pipeline disruptions
  - Loss of pump stations
- Flooding vs wind damage

- Refinery startup issues
  - Lack of industrial gas

## Summary Overview

- Characteristics of a complex system are the characteristics of interdependencies whether or not specifically associated with the energy sector
- Infrastructure systems are interconnected
- Infrastructure systems have a range of different means by which they are controlled
  - These controls have inherent conflicts
- The timing of events affecting infrastructure can play a large part in determining whether an event is isolated or leads to a cascade
- Interdependencies exist where no physical connection is present
- Sandia is doing much to better understand interdependencies of the energy infrastructure to identify potential consequences resulting from interdependencies before they happen

# QUESTIONS & ANSWERS

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