Thinking About the Whole Grid:

Grid Architecture

The Word “Architecture” Is Used Many Ways

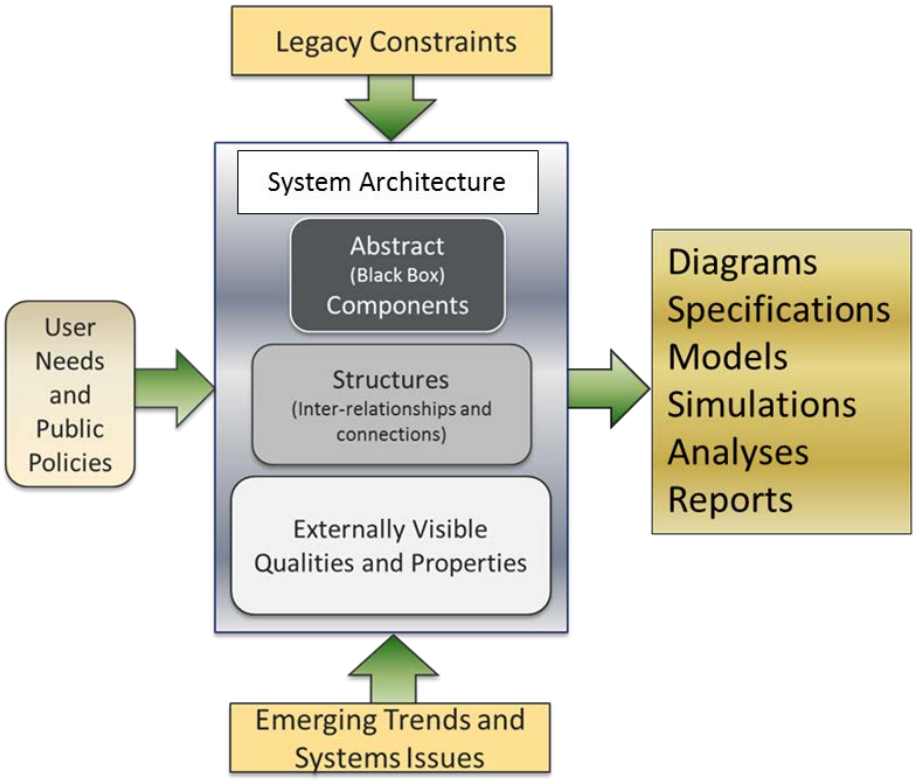
- House or building layouts
- Master plans
- Organization models
  - device like an integrated circuit chip
  - company internal arrangement
- Block diagrams
- High level (“logical”) design views of IT systems
- System designs or implementations
- Other abstractions like layer models

We need to be clear on what we mean by grid architecture.

System Architecture

Architecture

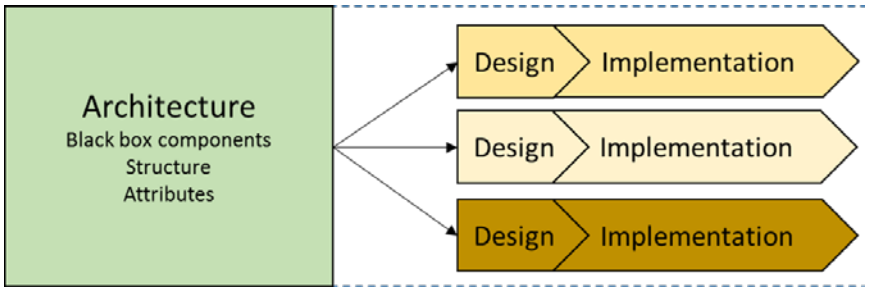
- An abstract depiction of a system, consisting of black box components, structure, and externally visible properties



Purposes:

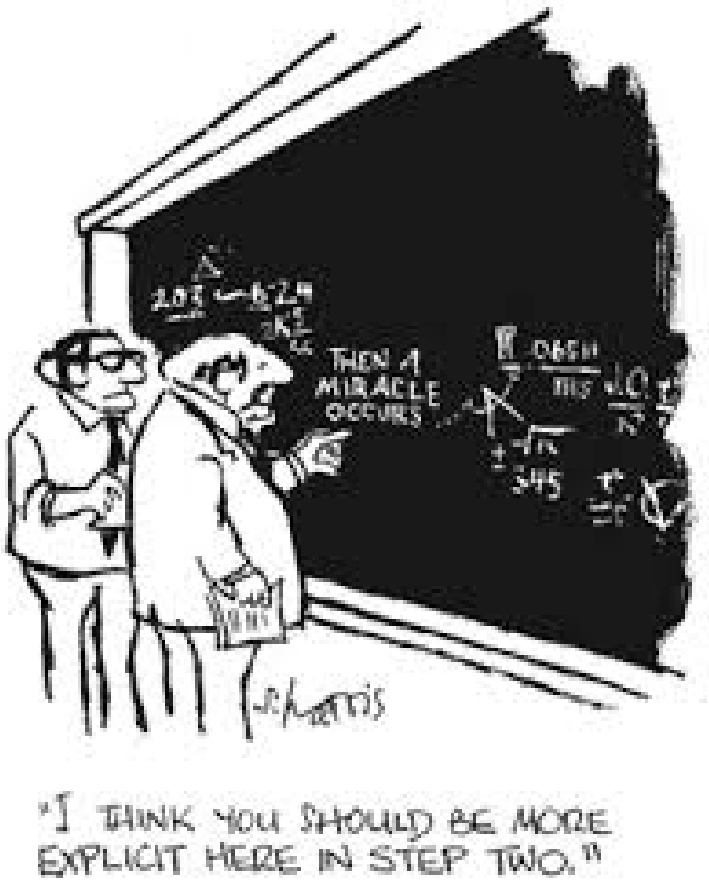
- Identify legacy constraints
- Remove barriers and refine essential limits
- Help manage complexity (and therefore risk)
- Support early stage modernization processes
- Identify gaps in structure, technology
- Assist communication among stakeholders
- Define platforms
- Inform interfaces and interoperability

Architecture is *not* design.



Elements of System Architecture: Components

- Abstract components
  - The individual parts, viewed as "black boxes"
  - Example: storage battery
    - At this level we do not specify how the battery works
    - Care about externally visible characteristics like storage capacity, max power rating
  - But thoroughly grounded in reality
    - no "magic" boxes, miracles, or anti-gravity

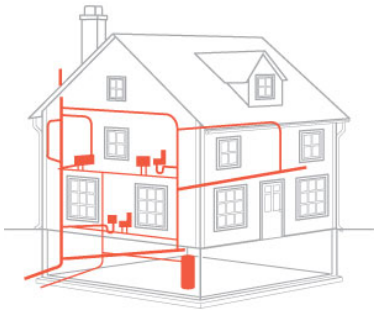


Source: Sidney Harris

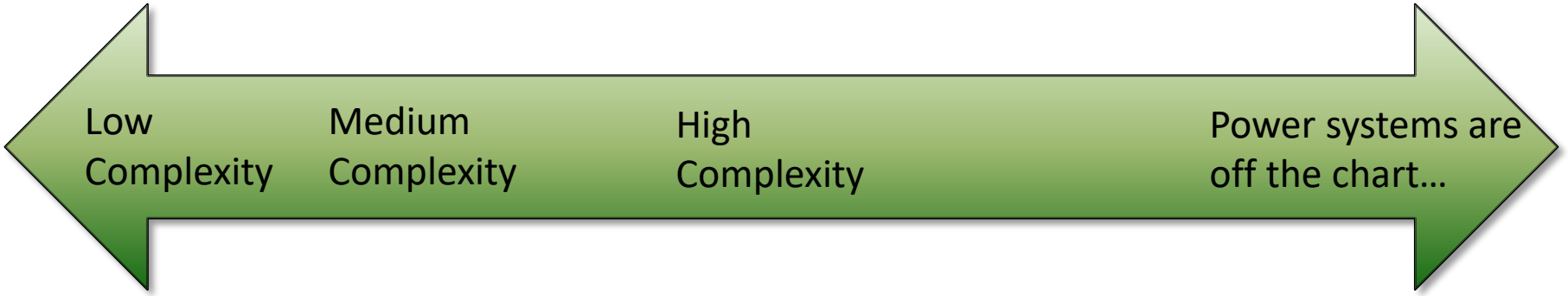
Elements of System Architecture: Structure

- Abstract components
  - The individual parts, viewed as “black boxes”
  - But thoroughly grounded in reality (no “magic” boxes)

- Structures
  - The overall shape of the system and how components interact
  - Any complex system has multiple structures, requiring multiple views
  - No real architecture can be represented in a single diagram



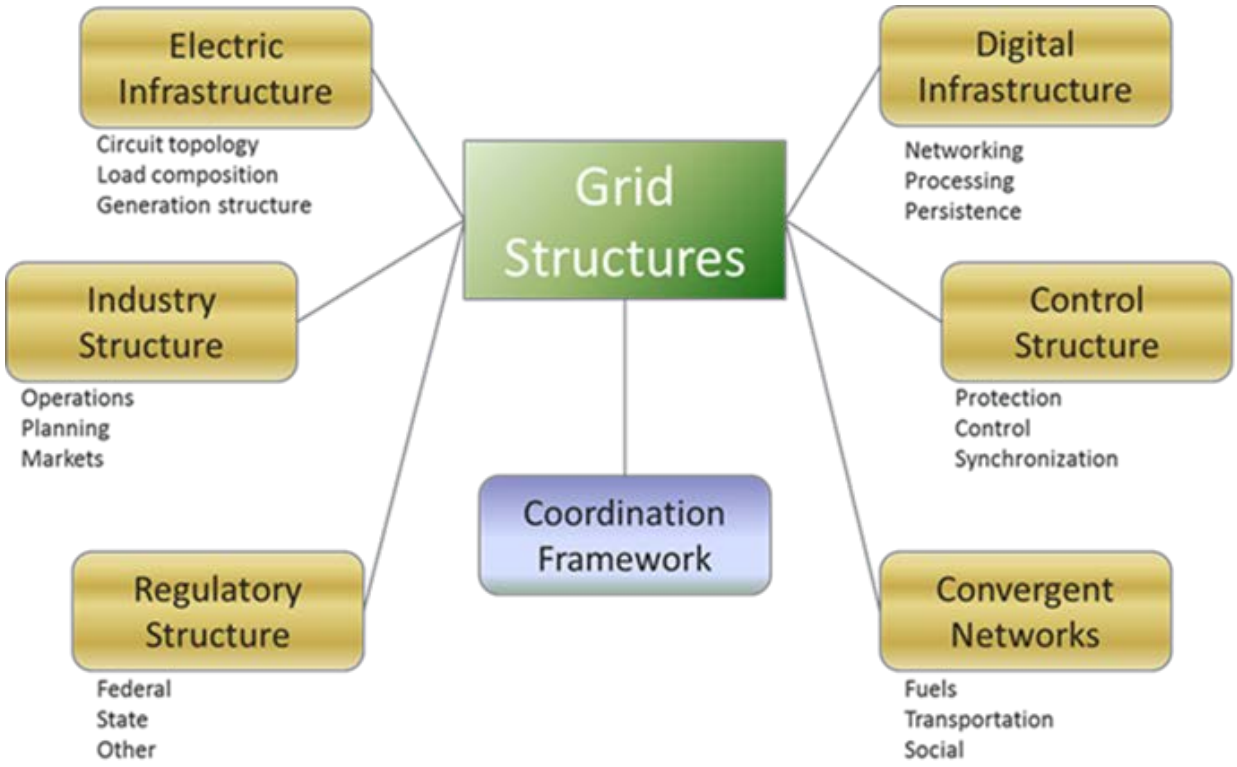
System Complexity and Electric Grids



Complexity is the hidden bear in the room when dealing with grid futures.

Why is the Grid Ultra-Large-Scale Complex?

- The grid is comprised of many already complex structures
- These structures are interconnected and interact in complex ways
- This results in an explosion of complexity.



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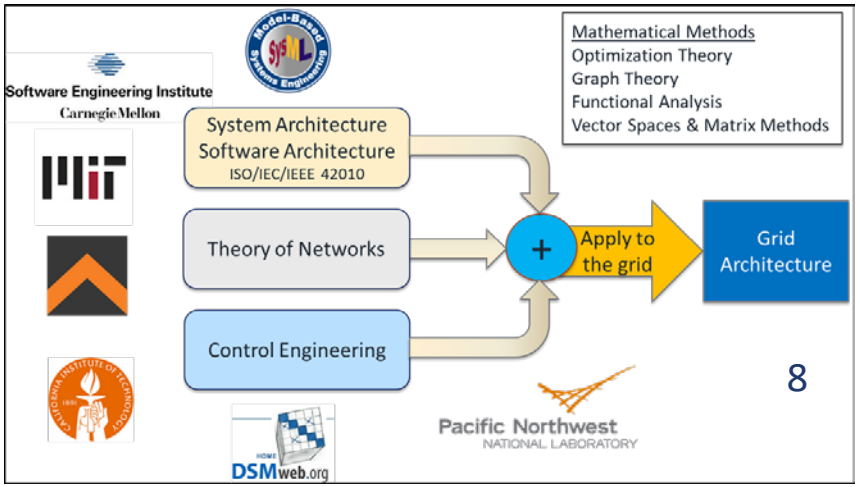
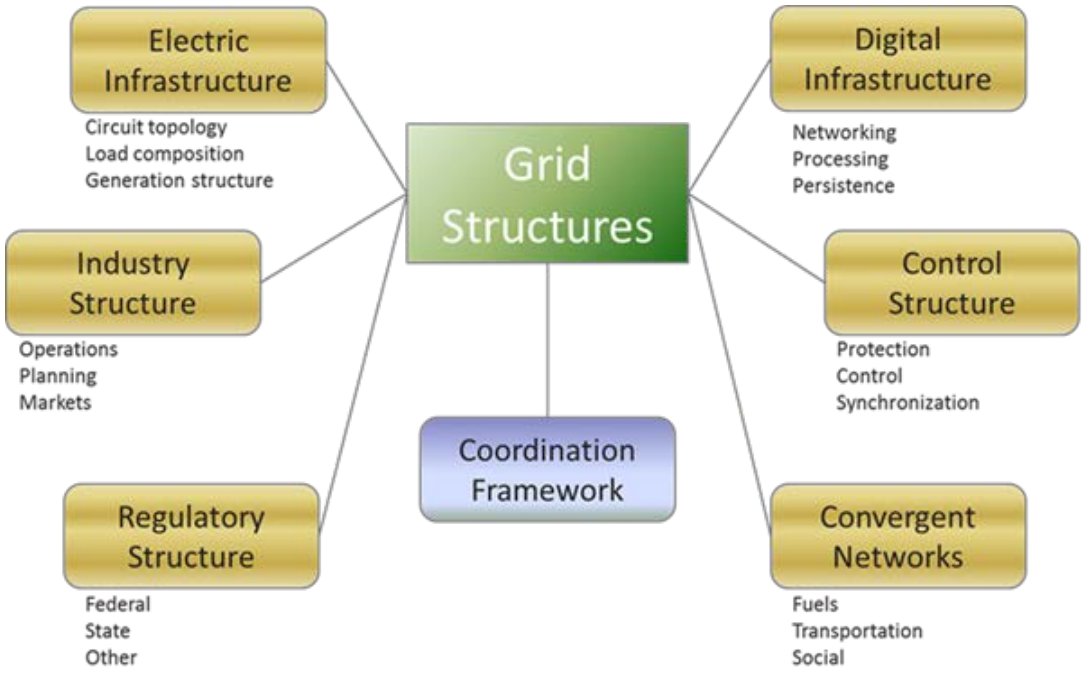
Grid Architecture is the application of system architecture, network theory, and control theory to the electric power grid.

A grid architecture is the highest level description of the complete grid, and is a key tool to help understand and define the many complex interactions that exist in present and future grids.



Grid Architecture Focuses on Structure

- Because we have inherited much legacy grid structure, new capabilities and improved characteristics can require understanding of existing grid structure and potential changes to grid structure
- Determining minimal changes to relieve structural constraints is a key grid architecture problem



- Get the structure right and all the pieces fit into place neatly, all the downstream decisions are simplified, and investments are future-proofed
- Get the structure wrong and integration is costly and inefficient, investments are stranded, and benefits realization is limited

Values of Good Structure

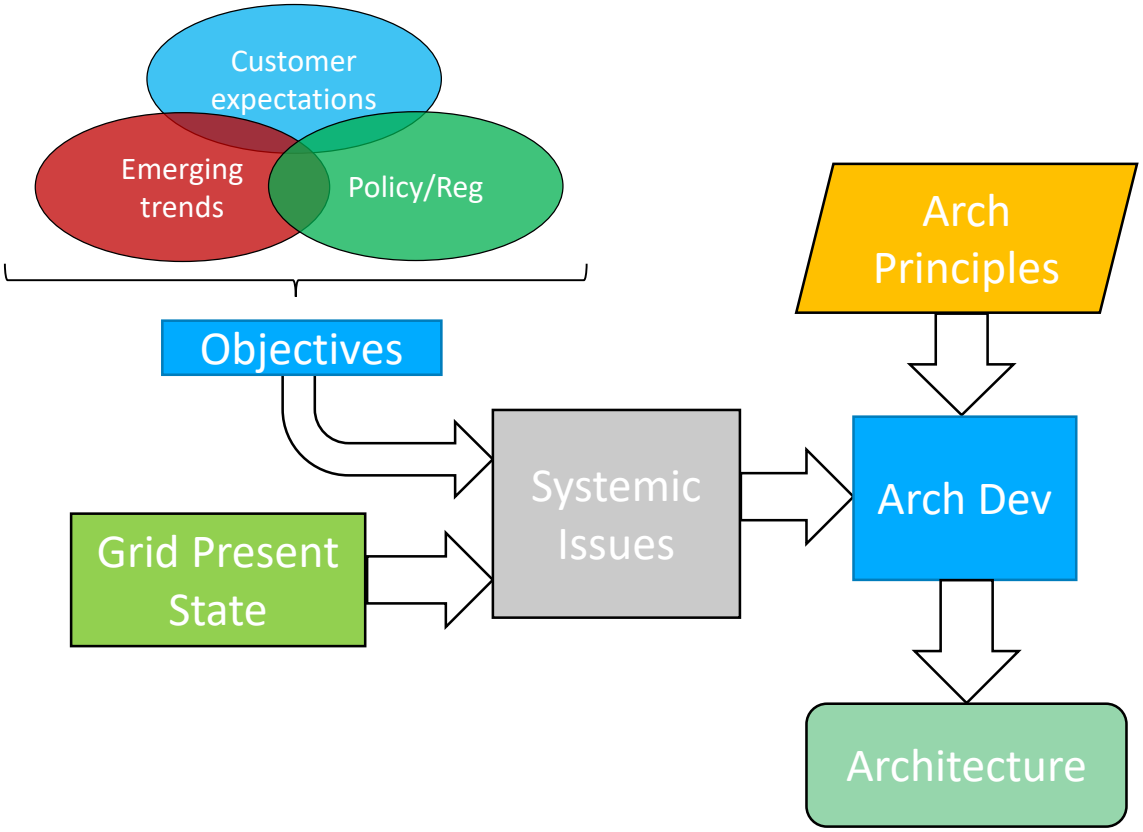
- Good structure has well-understood properties that can be relied upon for grid design.

- Proper structure creates intrinsic grid characteristics that bolster resilience, capability, and affordability and help safeguard investments by limiting change effects.

- Well-planned grid structure simplifies downstream decisions and frees up architects and engineers working on individual components or systems to employ creativity with assurance that unintended consequences will not crop up to hamper or even invalidate their work.

Grid Architecture Methods

- Clarity of definitions
- Focus on structure
- Uses foundational principles
- Driven by:
  - User requirements
  - Emerging trends
  - Public policy/regulation
- Agnostic to:
  - Products and services
  - Business models
  - Hype cycles
- Reference architectures are instructive, not prescriptive

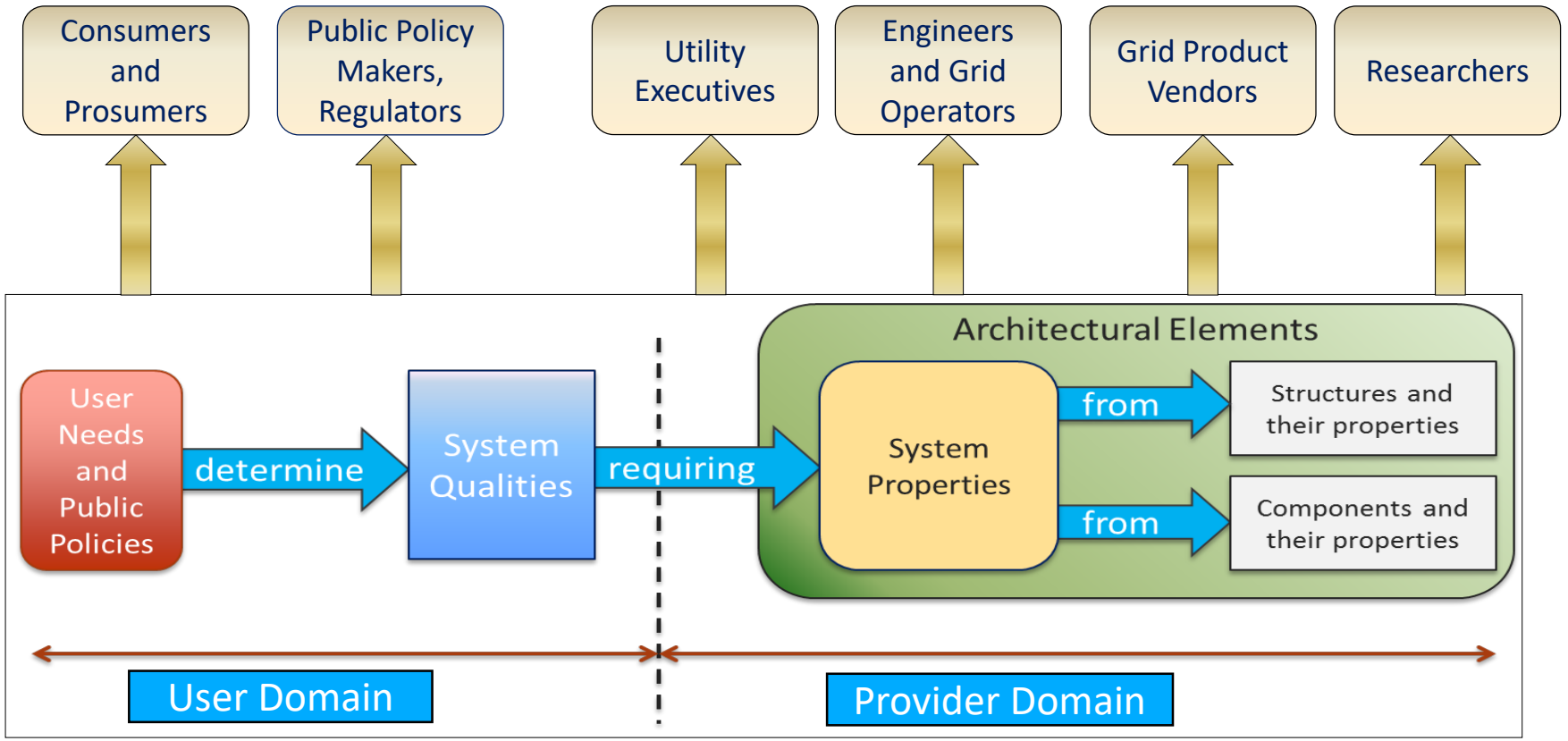


Manage Complexity

Produce Insight

You Do Not Have to be an Architect to Use the Results of Grid Architecture

Grid Architecture supports a wide range of stakeholders, including:



Applying Grid Architecture

A Few Core Grid Architecture Principles

- Understanding structure and structural context
- Structure Problems:
  - Bypass
  - Hidden coupling
  - Gapping
- Modularity and Decoupling
- Layering and Platforms
- Buffering
- Layered Decomposition

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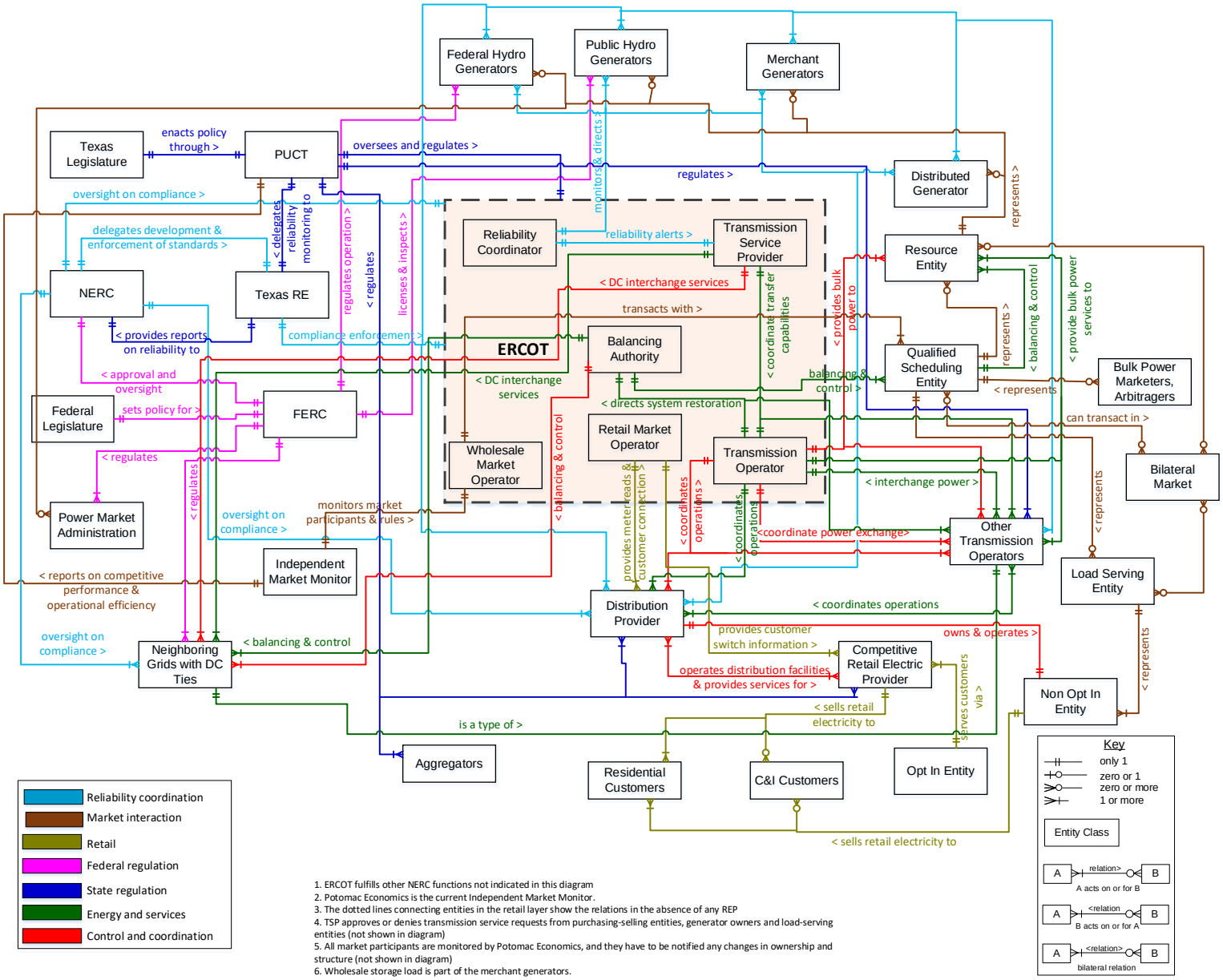
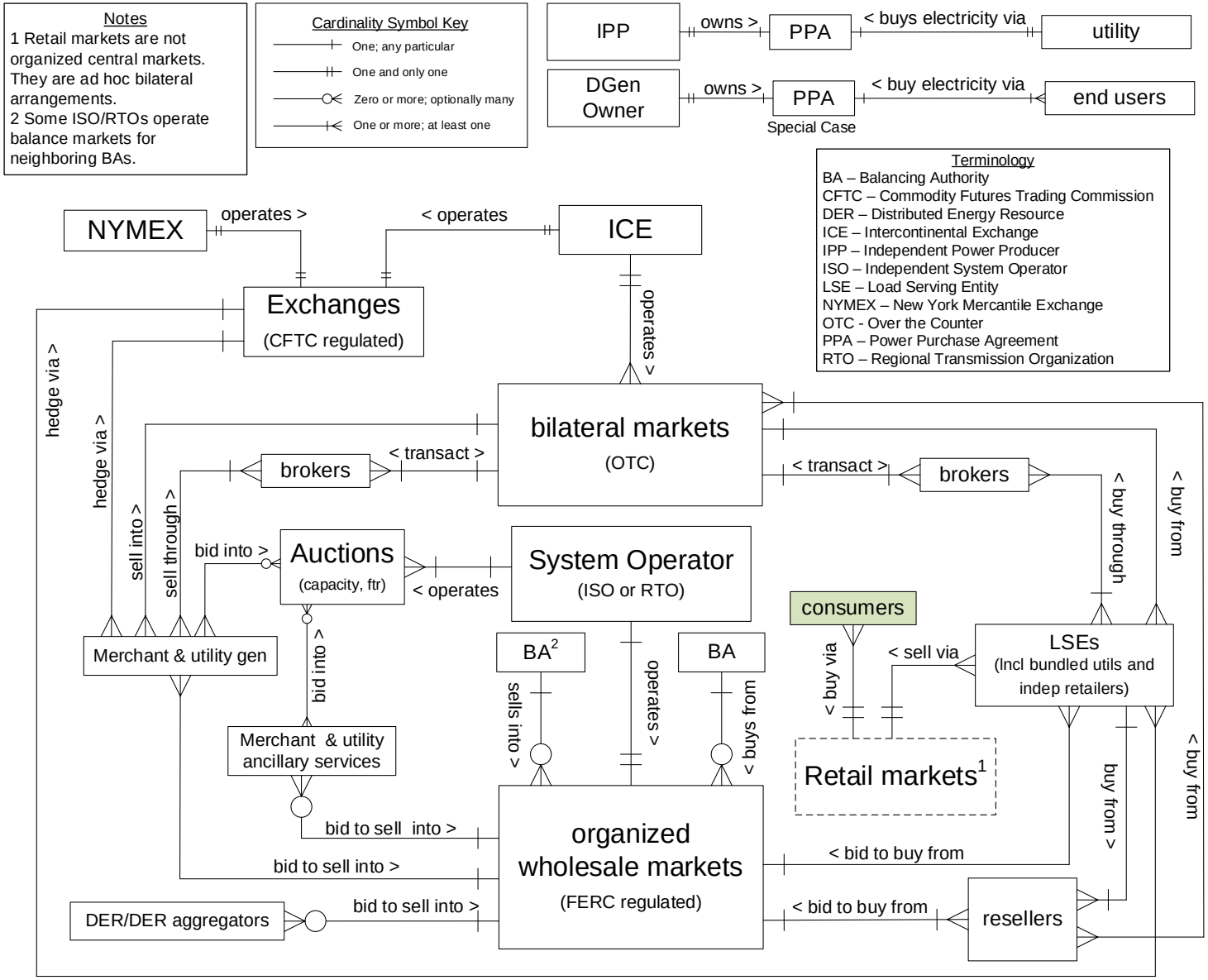
Structure Models: ERCOT

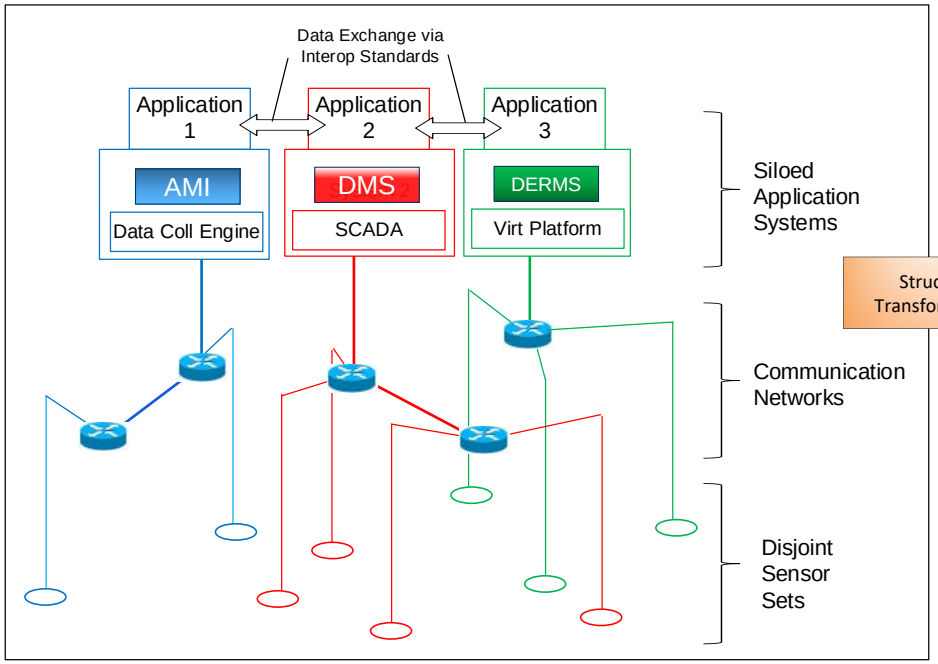


1. ERCOT fulfills other NERC functions not indicated in this diagram
2. Potomac Economics is the current Independent Market Monitor.
3. The dotted lines connecting entities in the retail layer show the relations in the absence of any REP
4. TSP approves or denies transmission service requests from purchasing-selling entities, generator owners and load-serving entities (not shown in diagram)
5. All market participants are monitored by Potomac Economics, and they have to be notified any changes in ownership and structure (not shown in diagram)
6. Wholesale storage load is part of the merchant generators.

Structural Models

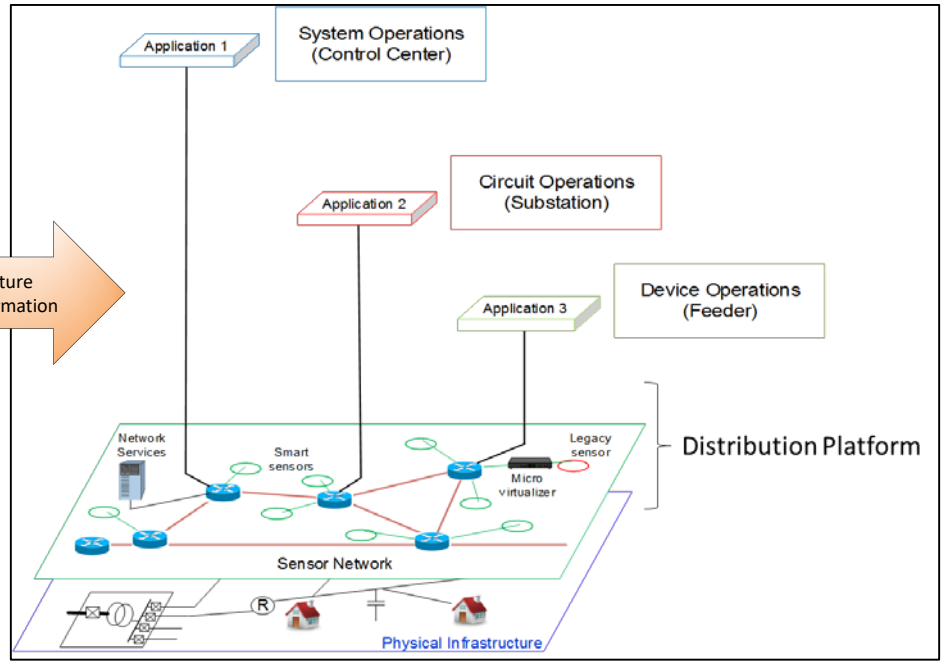


Sensor-Communications Network Layers: Reduce Dependency & Brittleness



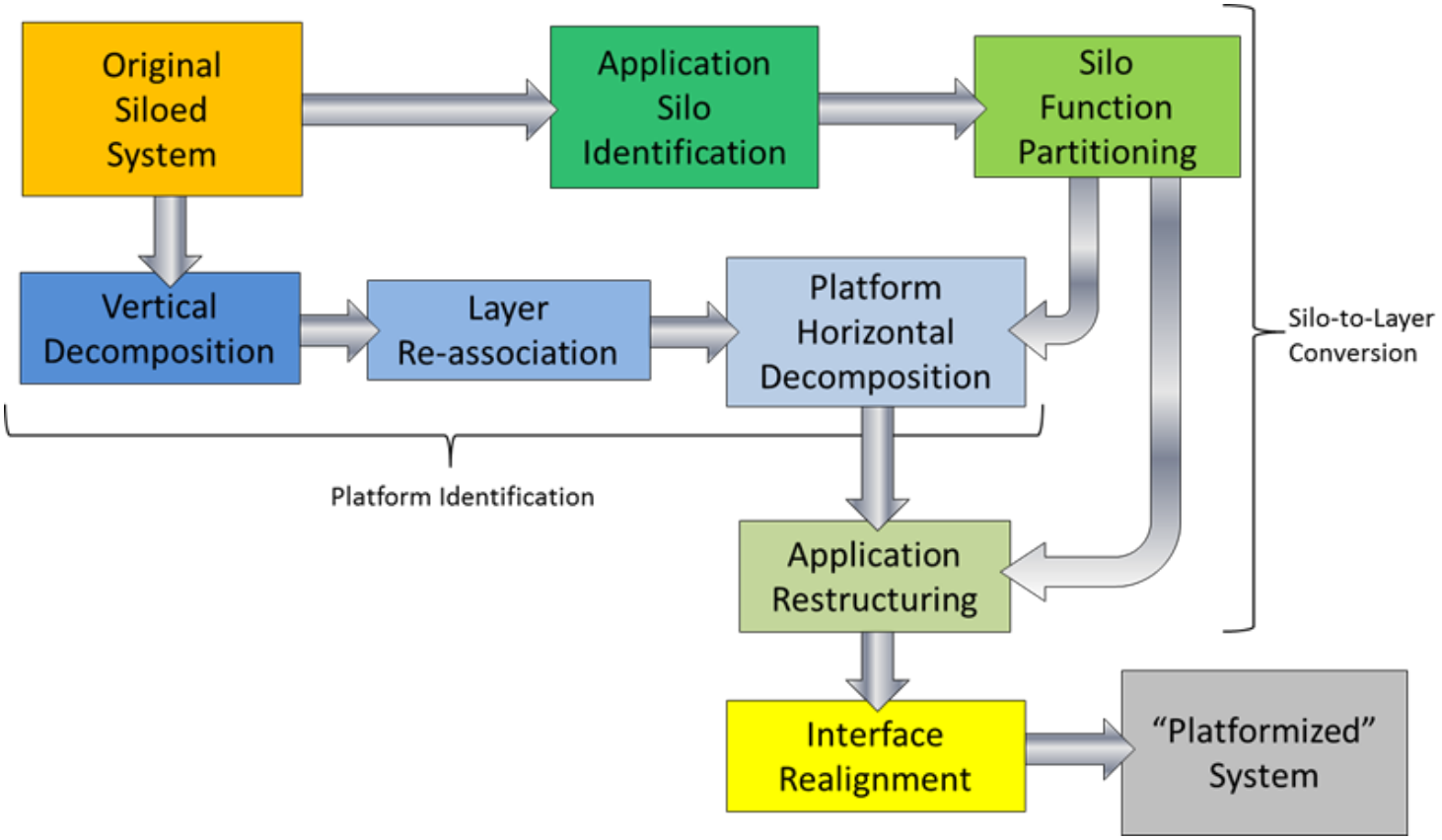
Brittle & Expensive

Structure Transformation



Resilient & Future-proofed

An Example Grid Architecture Method



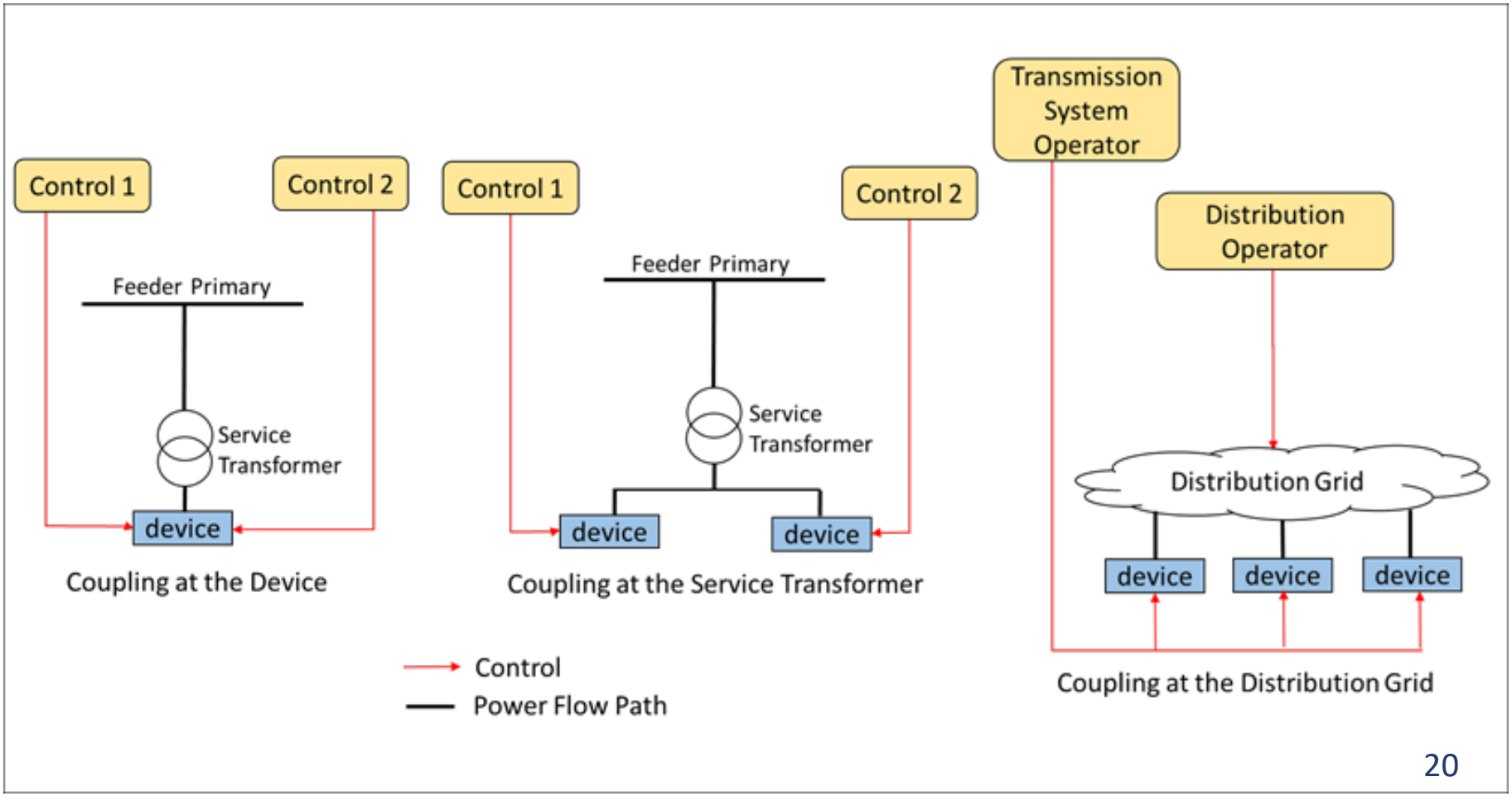
Definition: The Grid Coordination Problem

- Grid coordination is the systematic operational alignment of utility and non-utility assets to provide electricity delivery
- Coordination was not a well recognized issue for electric distribution until fairly recently
  - Some forms have been around a long time
    - C&I DR
    - Bulk gen in deregulated industry segments
- The motivation for the present level of interest is the rise of three things:
  - Distribution connected DG and DS
  - Flexibly controllable loads
  - Ubiquitous connectivity

Coordination is an issue because many of these resources are not owned by the utility and often may not be controlled directly.

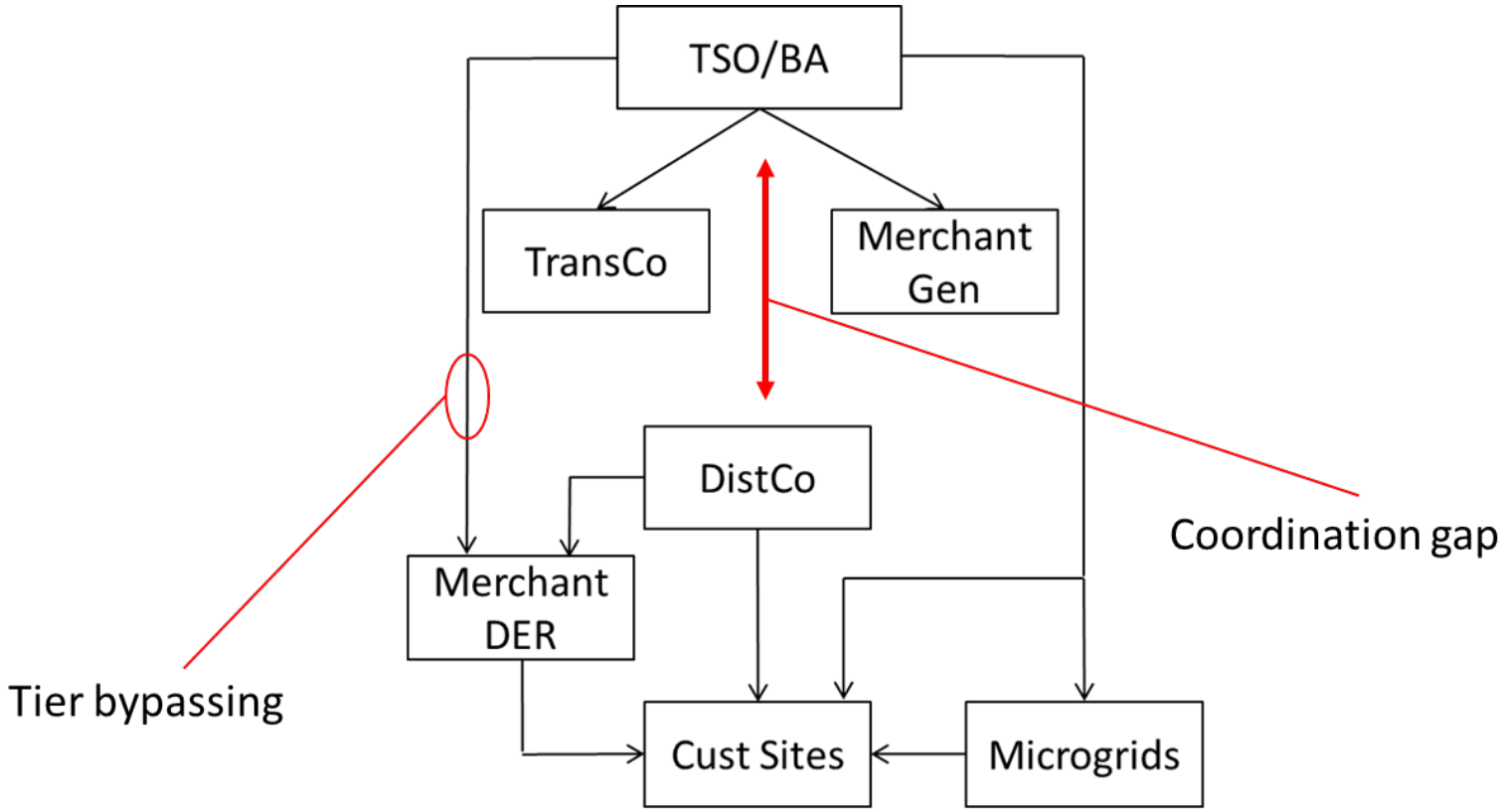
Structural Problems to Avoid-1

- Hidden Coupling

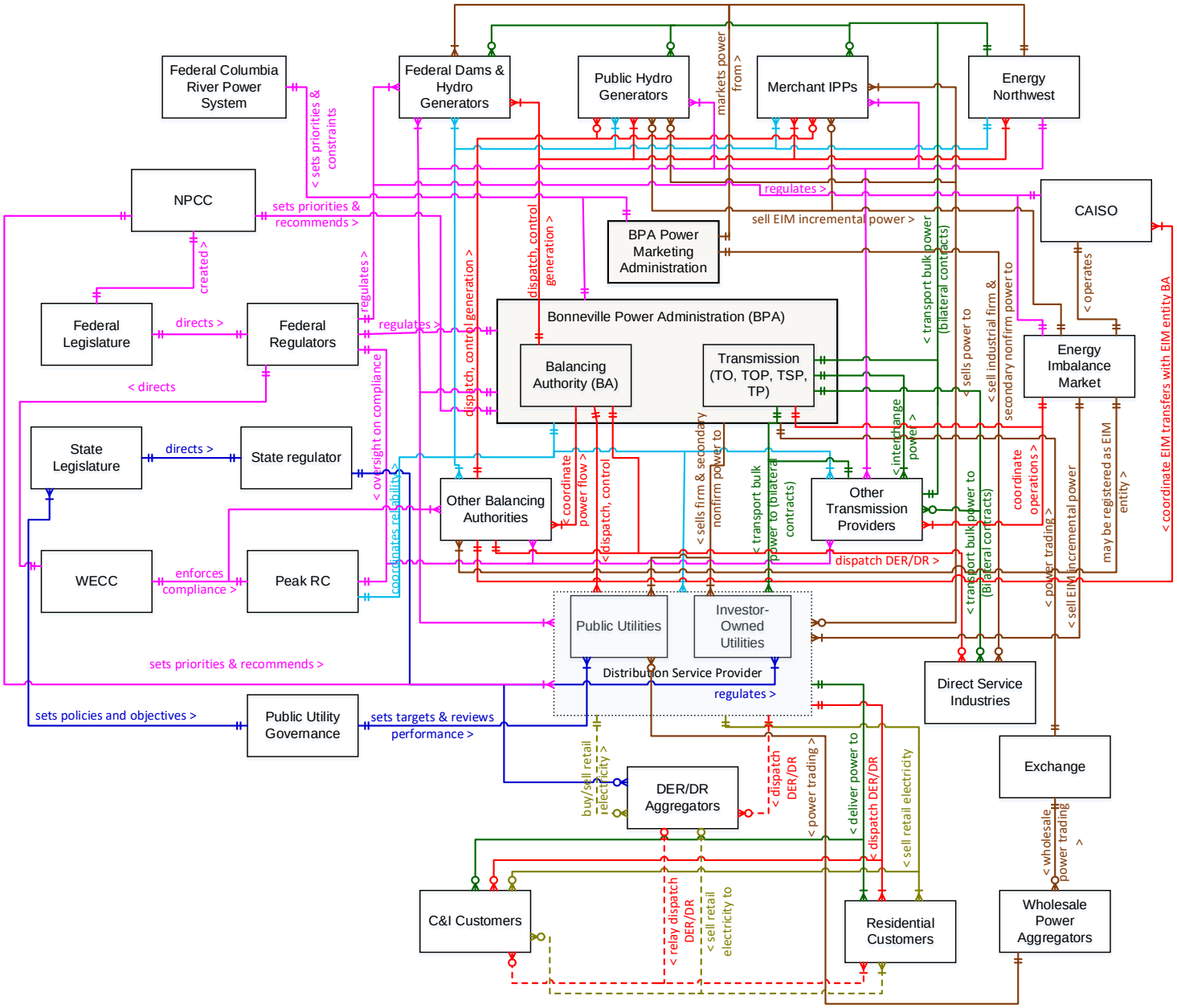


Structural Problems to Avoid-2

- Tier Bypassing
- Coordination Gapping



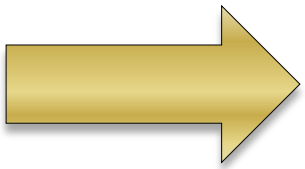
Not So Simple in Real Situations



Structural Basis for System Coordination

- Want structure to be derived rigorously
- Need a distributed form with knowable properties
- Here we are not interested in a specific solution but rather a class of solutions
- We wish to extract essential *structure* by understanding the problem class

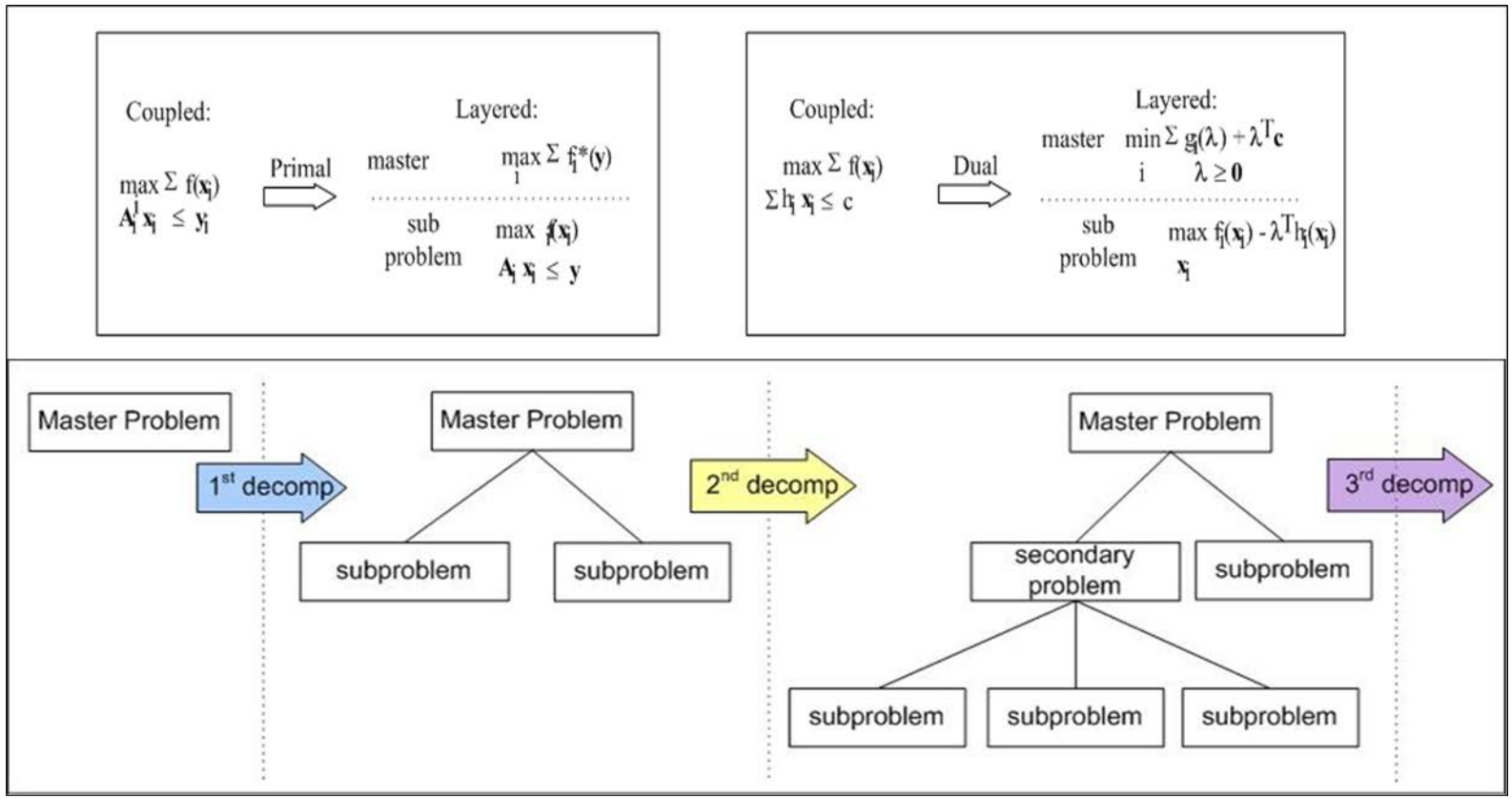
Mathematical Basis from Optimization Theory



Laminar Coordination Framework

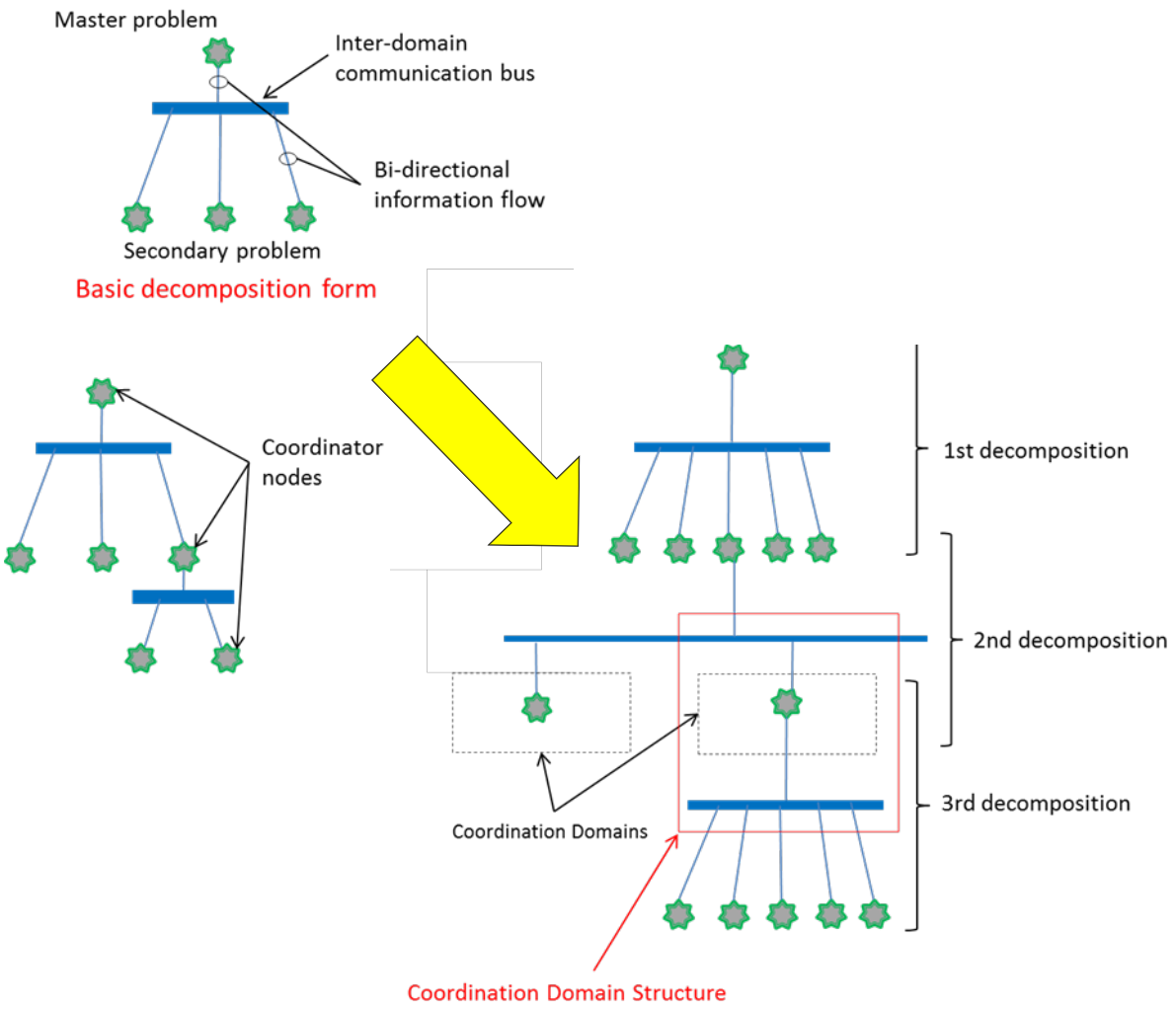
Network Utility Maximization via Layering for Optimization Decomposition

- Well-known in optimization theory for solving problems with highly coupled constraints
- We will use the math to *induce* a coordination structure



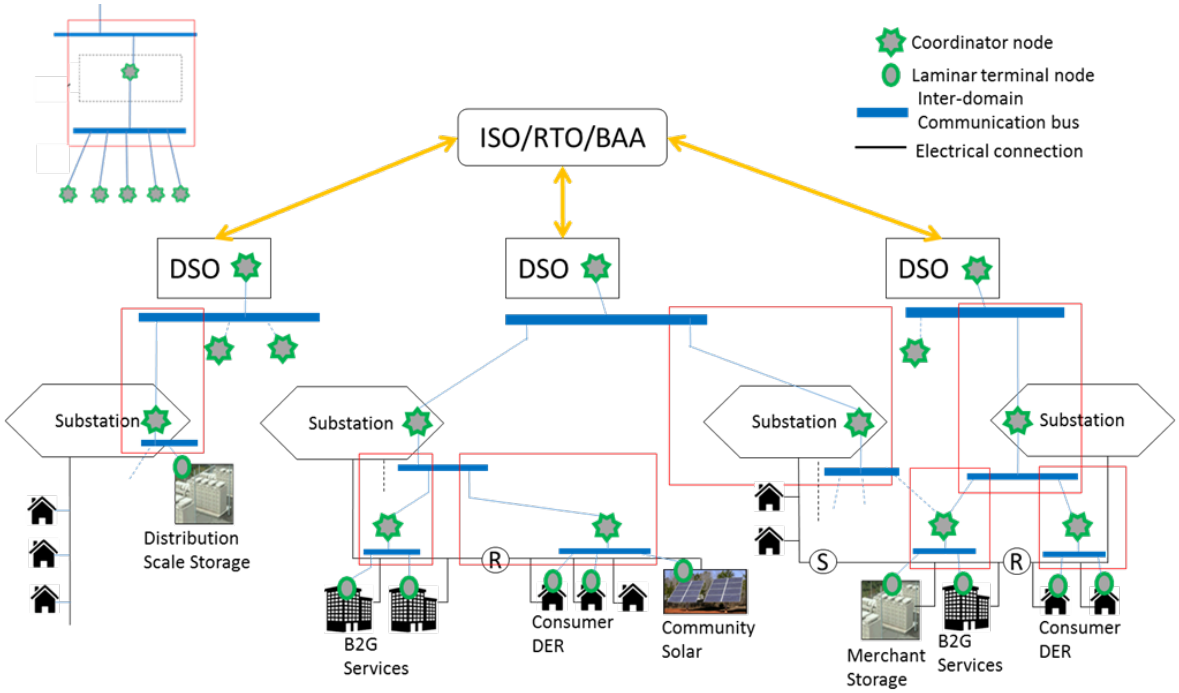
Essential Laminar Coordination Structure

- Multi-layer structure
- “Vertical” chain of coordination nodes: scalable message flow
- Core repeating building block: coordination domain
- Scalable
- Distributed

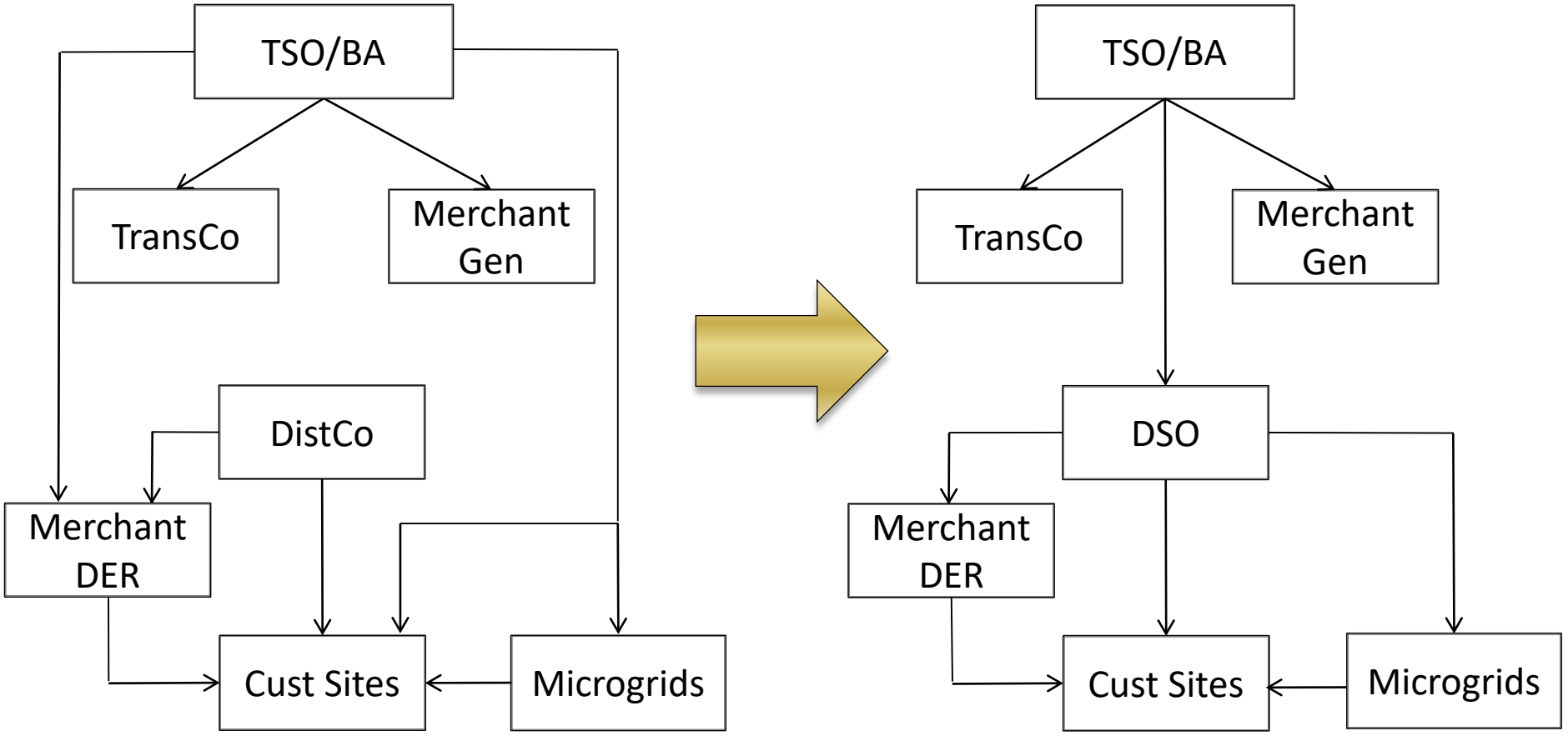


Mapping to the Grid

- Decomposition can be applied to as many levels as needed
- Known structural properties
- Accommodates multiple coordination approaches
- Boundary deference
- Multi-level objectives & constraint fusion
  - Local objectives & constraints
  - Global coordination
- Proportional buildability



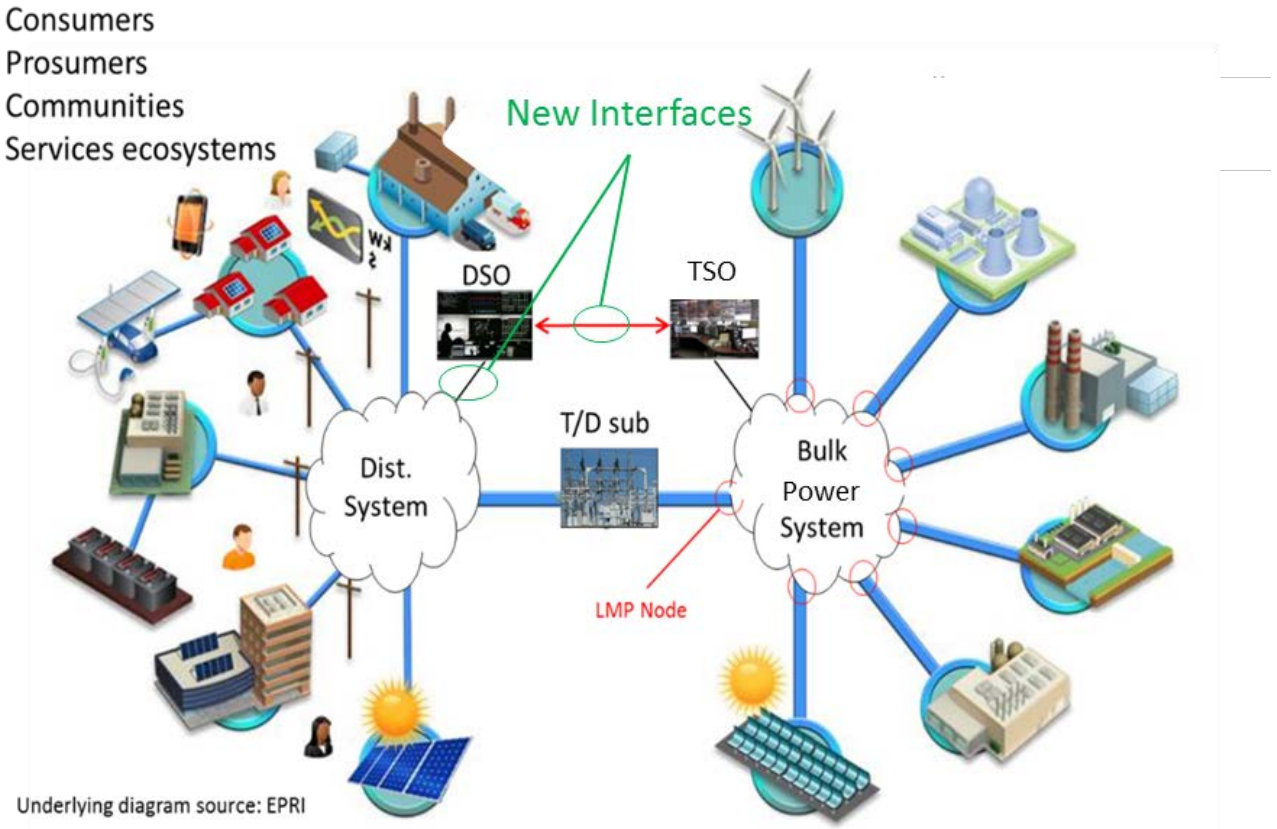
Adjusting Coordination Structure



This Approach Leads to General Principles

- Scalable multi-layer form
- Local selfish optimization inside global coordination
- Allows mixed coordination signal models:
  - Allocations (control)
  - Prices (market-like methods)
- Proportional buildability

Grid Architecture Informs the TDC Coordination Problem in Useful Ways



- Roles and Responsibilities
- Grid observability
- Distributed control
- Coordination structure

- Scalability, granularity
- Functional flexibility
- Distribution platforms
- Cyber security

Thank you

See Grid Architecture website at:
https://gridarchitecture.pnnl.gov/