Energy Security: Opportunities at the Intersection of Computer Science, Information Theory, and Decision and Control

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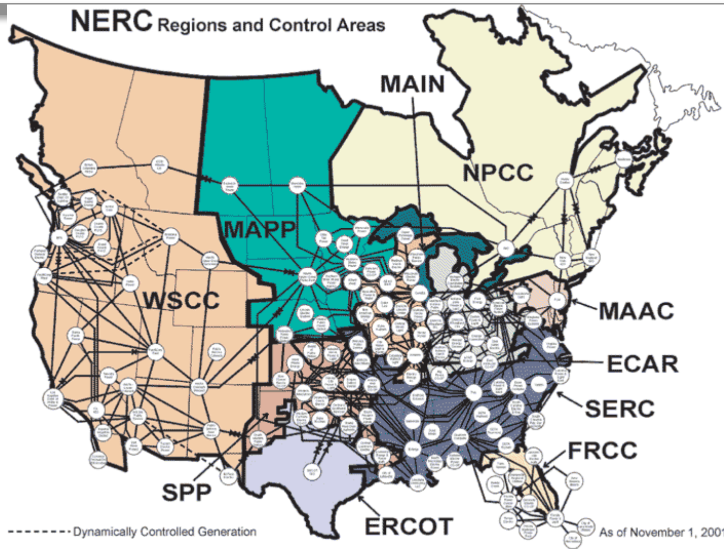
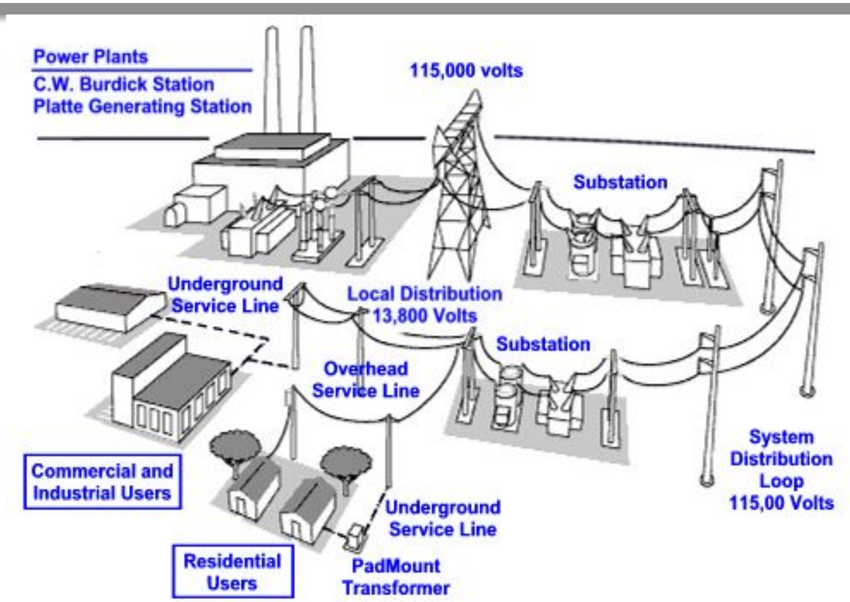
Energy Networks





Highly interconnected, prone to cascade effects

through state/structure interactions

Subject to many disturbances:

- Primary – Environmental, equipment malfunctions, loads…
- Secondary – Protection mechanisms, operator initiated controls, …

No global stability regimes, inter-area behaviors

Seasonal, weather induced, and circadian variations

Sensor poor => incomplete observability

Future Energy Systems: Improve command and control through:

- Increased sensing and sensor fusion
- Command, communications and control
- Diagnose system operating state
- Manage a highly distributed and diverse generation/load mix
- Improve operational readiness-predict cascade effects

The Energy System is Complex

- Multi-level and Hierarchical
- Dynamic System
  - Hybrid System-includes both continuous and discrete variables
- Distributed System organized into modules/subsytems
  - Tightly and loosely connected subgroups
- Probabilistic and stochastic attributes (generation, demand, availability)
- Multiple types of behaviors
  - Dynamics evolving on diverse temporal and spatial scales
  - Nonlinear with interactions between state and structure
- Decision-making at multiple levels
  - Coordination
  - Control

Energy System Operating Model

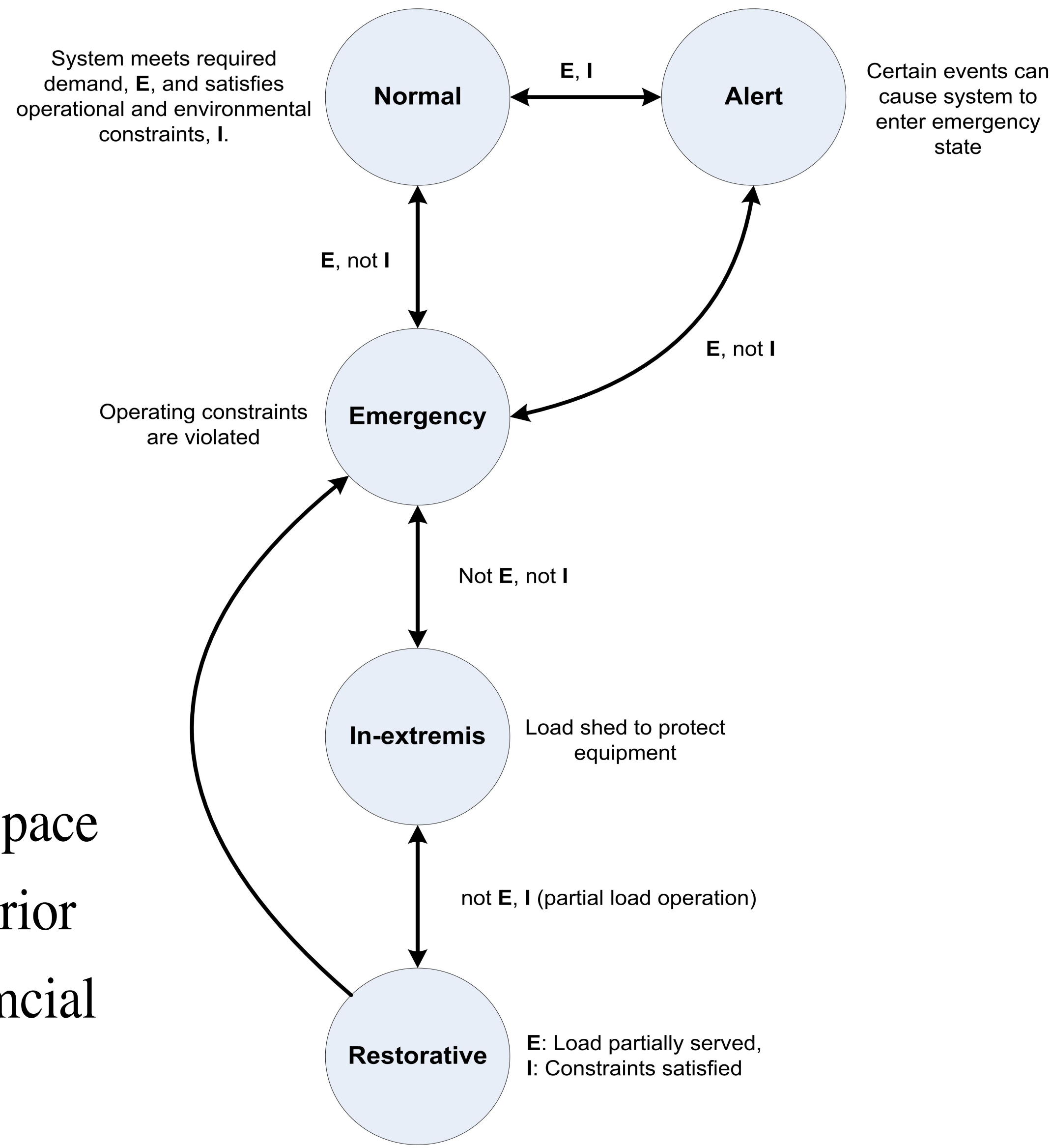
E=Equality Constraints
I=Inequality Constraints

Security is a time-varying measure of the ability of system to remain in the Normal state.

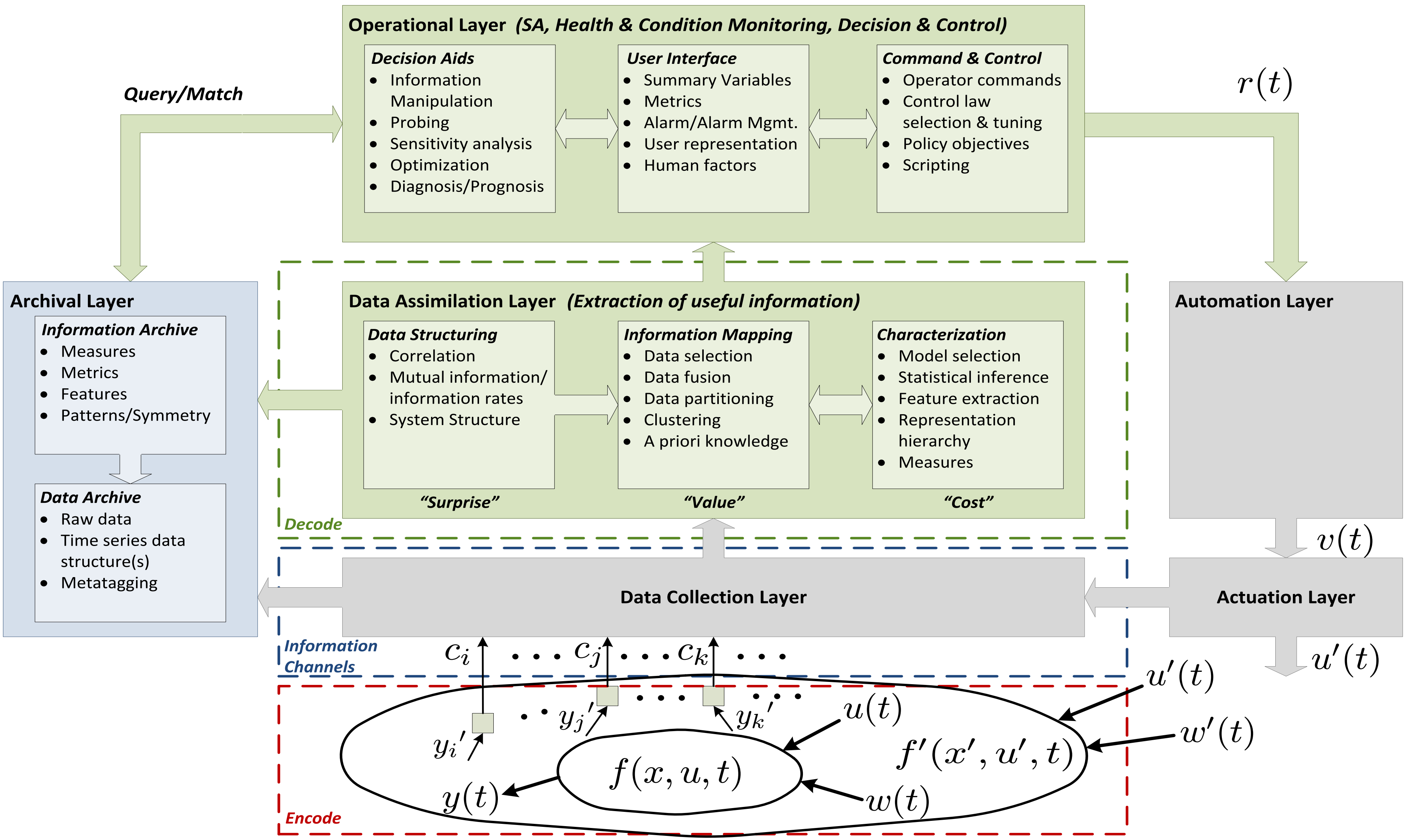
$$\text{Security Measure } = \int_S p_\tau(x \mid Y_t)dx$$

S = set of secure states in the state space

$p_\tau(x \mid Y_t)$ = the conditional a posterior density of the random hybrid dynamcial system and $\tau \geq$ t



An Information-theoretic Architecture for Situational Awareness



Random Dynamical Systems

- Stochastic system-ODE model: $dx_t = f(x_t)dt$

Initial value problem: $x_t = \phi_t(x_0);\ x_{t_0} = x_0 \sim p_0(x); t \geq t_0$

Given the a priori density $p_0(x)$ determine the a posteriori density $p_t(x)$

Given that $f(x)$ is a smooth vector field:

$$\frac{\partial p_t(x)}{\partial t} = -\sum_{i=1}^{n} \frac{\partial}{\partial x_i}(f_i(x)p_t(x))$$

Stability must now be analyzed probabilistically, e.g, almost sure stability: $\Pr\{\lim_{t\to\infty} x_t = 0\} = 1$

Random Hybrid Dynamical Systems

- Dynamical Systems that include both continuous and discrete state elements, i.e.

$$dx_t = f_{\lambda_t}(x_t)dt$$

$$x_t \in R^n, \lambda_t \in \{1,2,...,N\}$$

Examples:

$$dx_t = f_{\lambda_t}(x_t)dt$$

λ_t is a FSCT Markov Process

$\begin{pmatrix} x_t \\ \lambda_t \end{pmatrix}$ is a Markov Process

Joint density $p_t(x,i),\ i = 1,2,...,N$

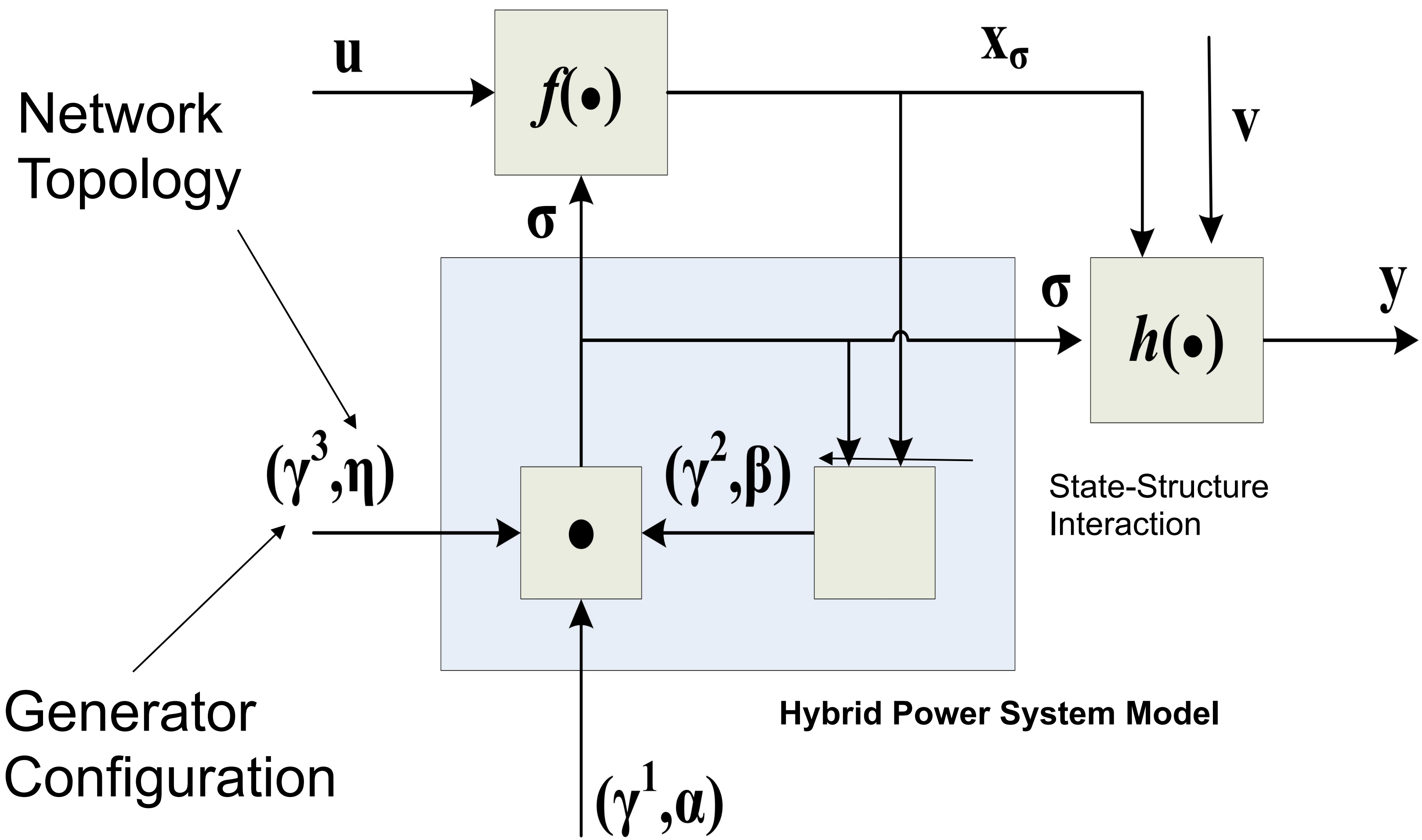
$$dx_t = f_{\lambda_t}(x_t)dt$$

$$R^n = A \cup B \cup \partial_{AB},\ \lambda_t(x) = \begin{cases} 1,\ x_t \in A \\ 2,\ x_t \in B \end{cases}$$

x_t is a Markov Process

$f_\lambda(x)$ is a discontinuous vector field

Hybrid Power System Model



Random Hybrid Dynamical Systems

- Because the vector field is discontinuous, Liouville's Theorem is not applicable for determining the a posteriori density

$$dx_t = f_{\lambda_t}(x_t)dt$$

$$R^n = A \cup B \cup \partial_{AB},\ \lambda_t(x) = \begin{cases} 1, & x_t \in A \\ 2, & x_t \in B \end{cases}$$

x_t is a Markov Process

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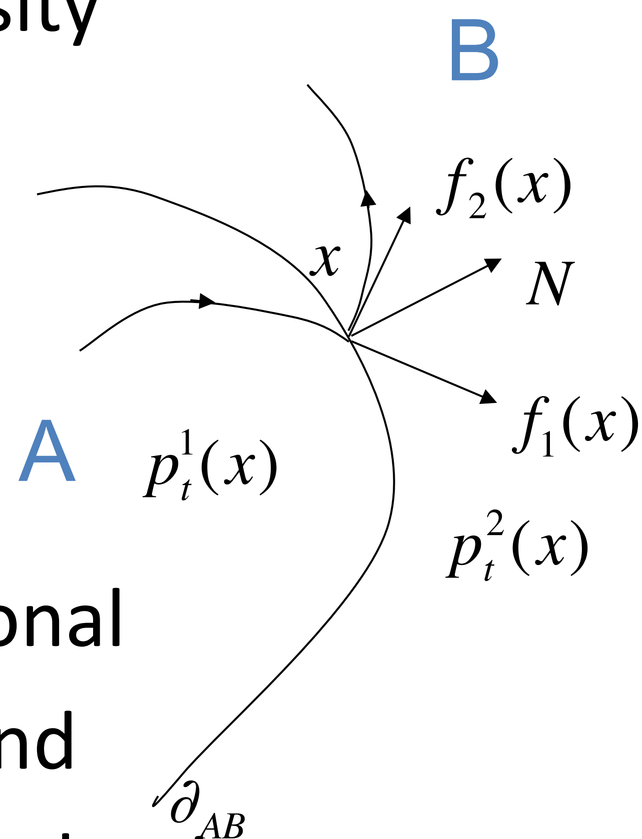
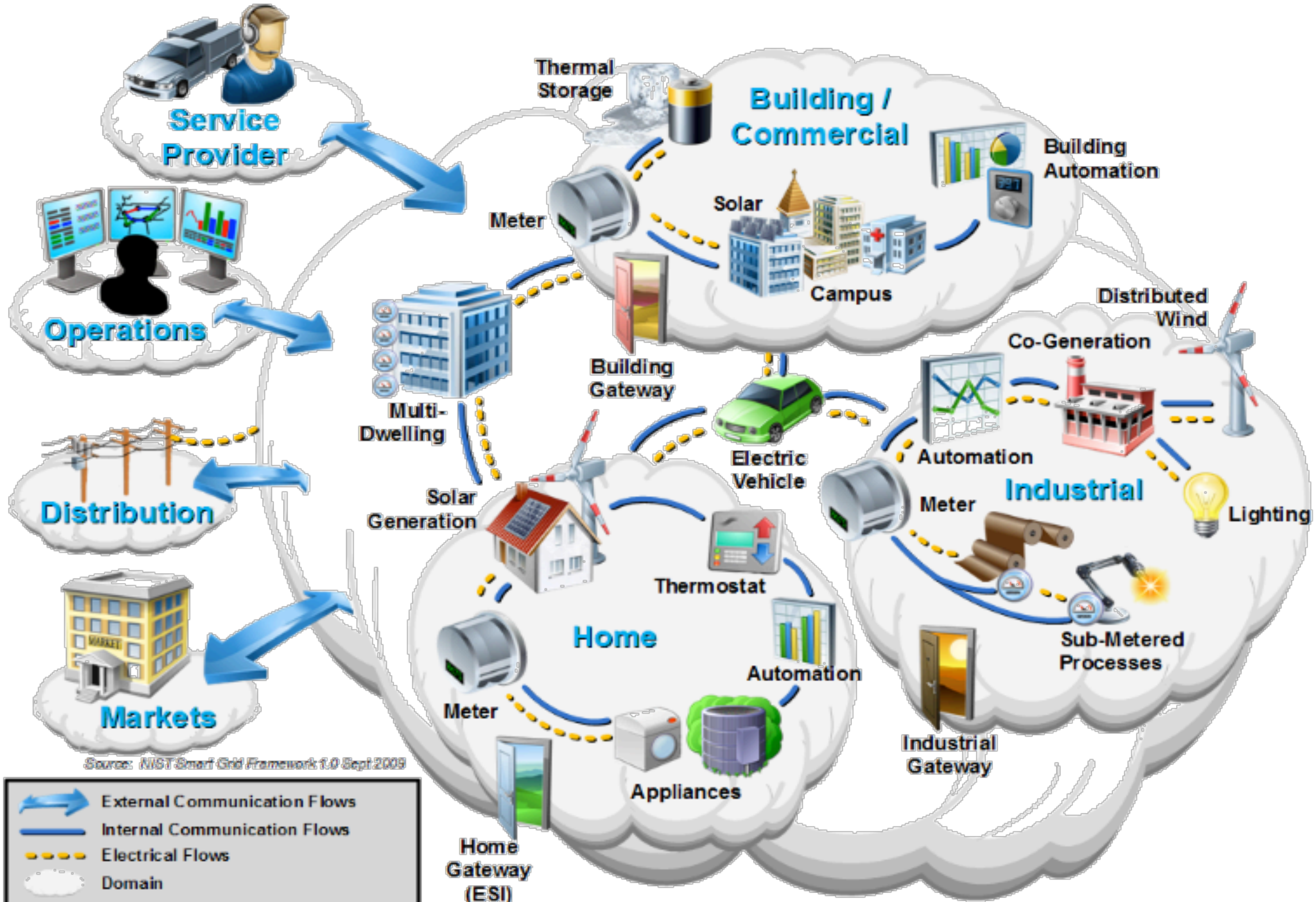


- We have developed a computational method that solves this problem, and provides an approach to security evaluation

Energy Security

- Mathematical modeling of the power system-stochastic hybrid system with state/structure interaction
  - State: Voltages, Angles
  - Structure: Network Topology
- Security Evaluation
  - Estimation Problem: $\int_S p_t(x \mid Y_t)dx$
- Security Assessment
  - Forecasting Problem: $\min_C \int_S p_\tau(x \mid Y_t)dx,\ \tau > \mathrm{t}$
- Security Enhancement
  - Stochastic Control Problem: $\max_u \int_S p_\tau(x \mid Y_t)dx,\ \tau > \mathrm{t}$

Future Distribution System



Desired System Capabilities

- Enable customer participation in electricity markets
- Enable the integration of storage devices
- Enable distributed generation to enhance grid stability/load serving capability

Distributed Architecture

- Device-level software agents:
  - supply agents, load agents, storage agents, network agents
- Agent connectivity through a real-time communication network
  - Adaptation of direct-level reactive controls
  - Coordination to achieve system-level objectives
- System-level agents enable coordination and functionality such as contingency analysis, interchange scheduling, …