Cyber-Physical Systems, Smart Grids and Why Should You Care

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Speaker Bio: Background & Interests

- Born and raised in Beirut, Lebanon
- Undergrad education: American University of Beirut '2011, B.E., ECE
- Interned @ Argonne National Lab, UofT, MIT
- Finished my Ph.D. in ECE from Purdue University in August 2015
- Assistant Professor, ECE Department @ UTSA
- Research interests: Uncertain CPSs

How Can We Make 'Em More Secure?

My Ultimate Objective

Understand how complex systems operate and utilize this knowledge to create tools & algorithms that can be leveraged to social challenges

Essentially, this should improve the quality of our lives...Hopefully!

Seminar Outline

1. CPSs: past, present, & future
2. CPS application: dynamic state estimation in smart power grids
3. Future of research in CPSs
4. Open research problems

Part I — Cyber-Physical Systems: History and Introduction

...And why should I care?

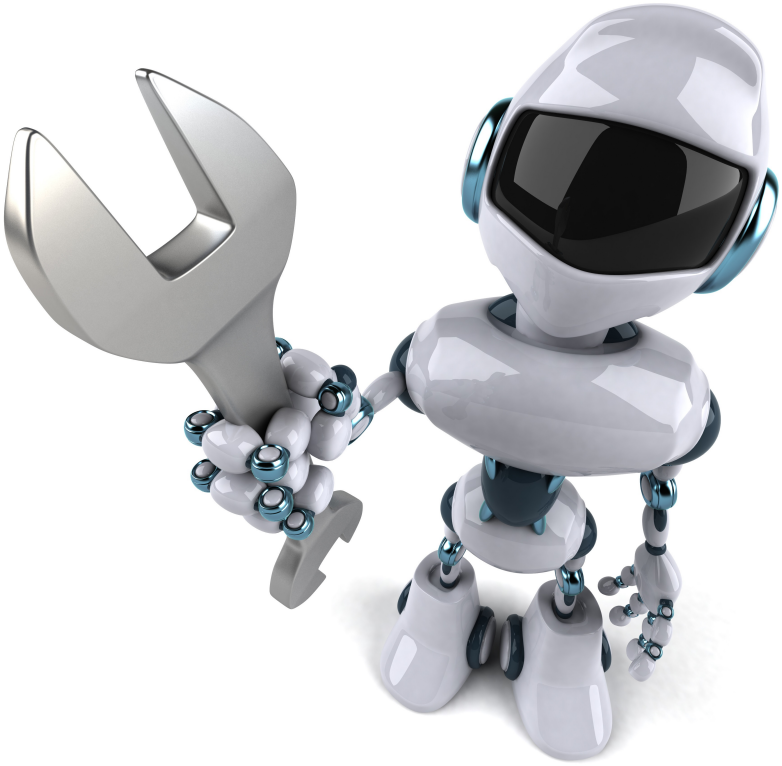
Cyber-Physical Systems — The *Ubiquity is Real!*

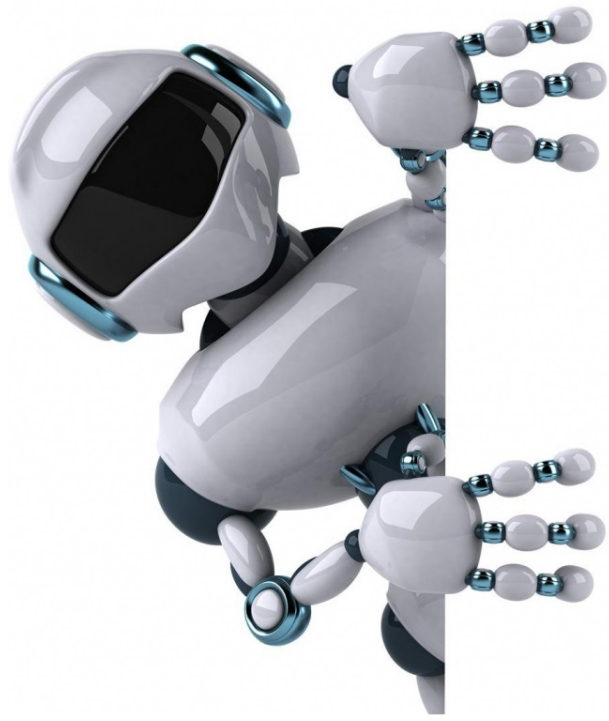
- CPSs: integrating computing, data analysis, communication, & control with physical processes
- Infrastructures are reliant on CPS-techs & communication networks
  - The Physics and The Cyber: Intertwined Responsibilities

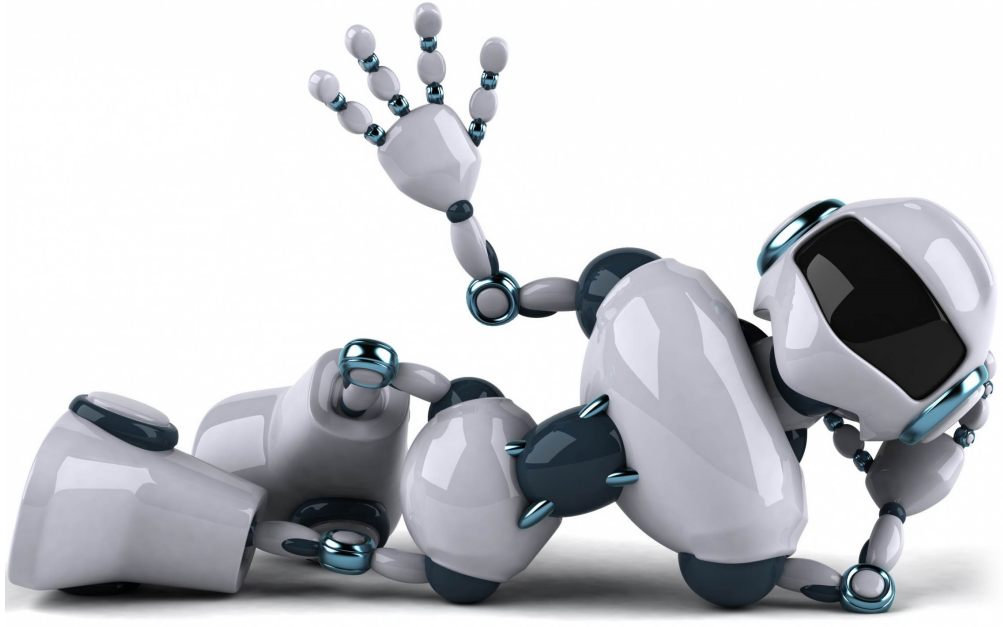
- CPSs are *inherently uncertain*; *vulnerable* to hackers & natural adversities

#TrustIssues

Can we trust computers to manage, control, and optimize physics?





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12

CPS History [Jeschke, 2013]

1898: Nikola Tesla's Radio-Controlled Boat — *Teleautomaton*

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1999: Kevin Ashton's Internet of Things

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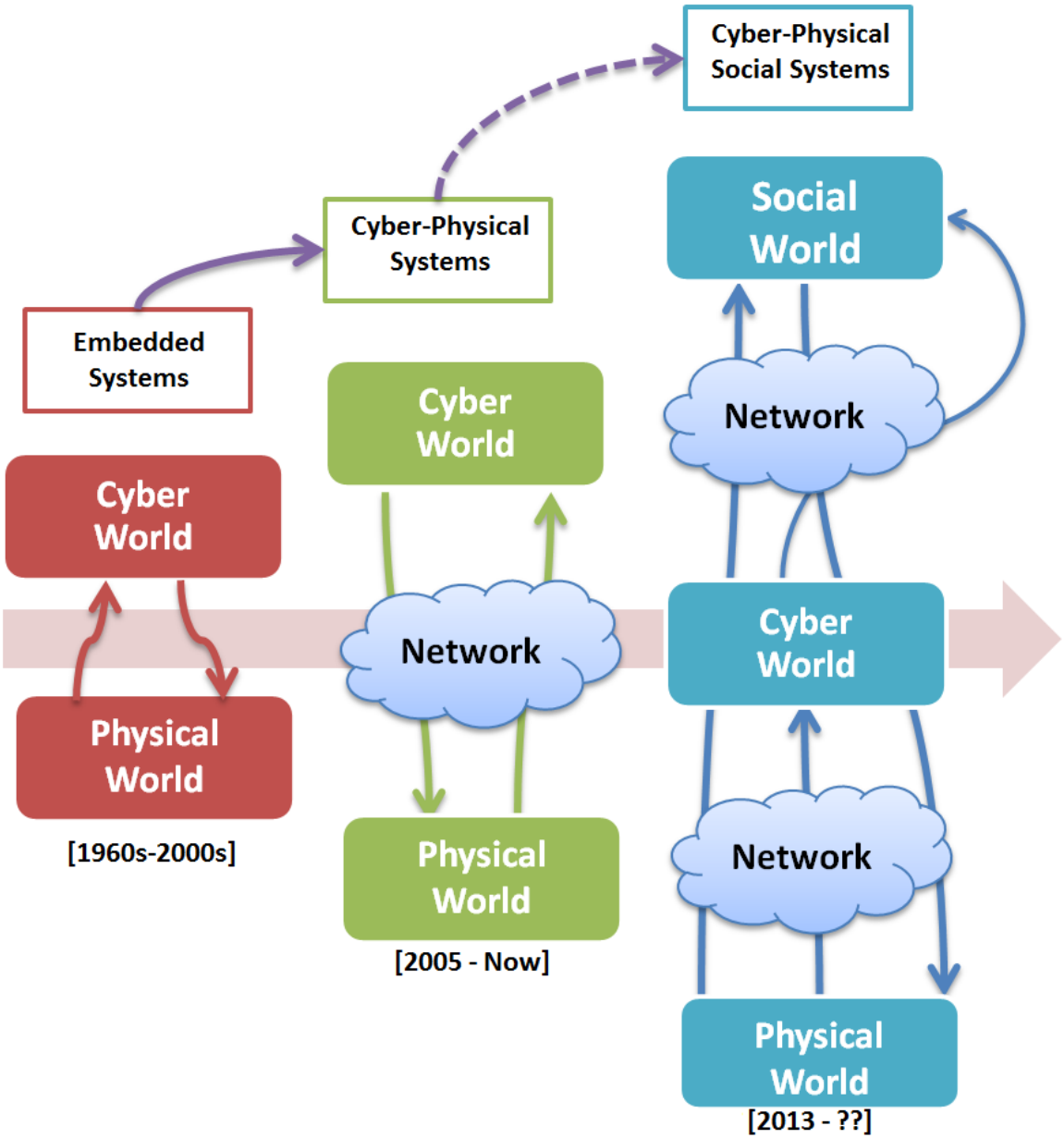
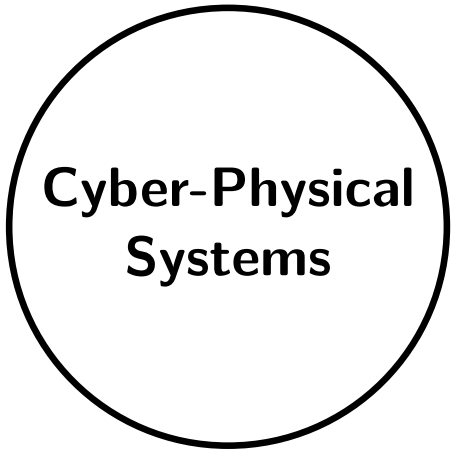
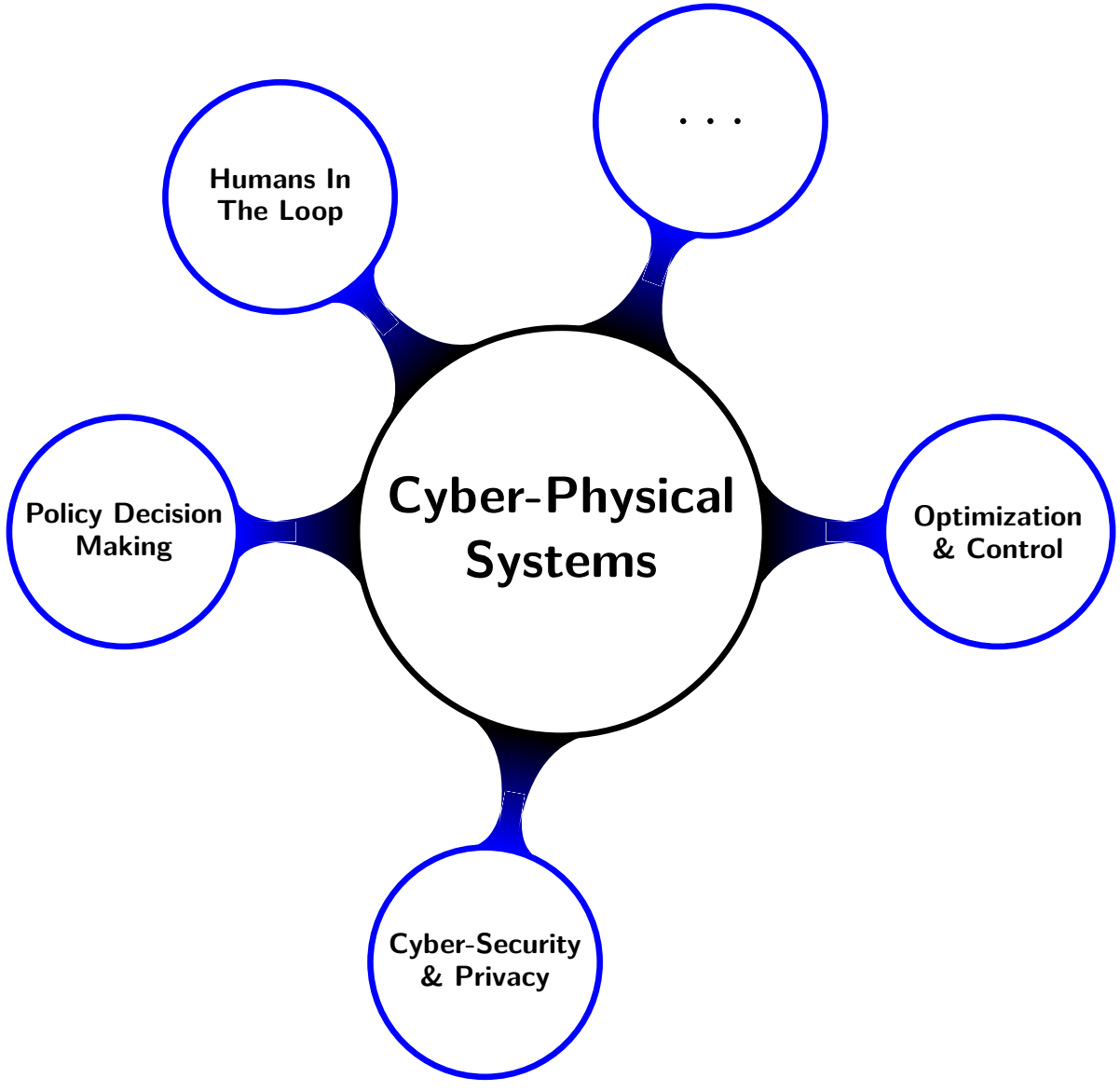
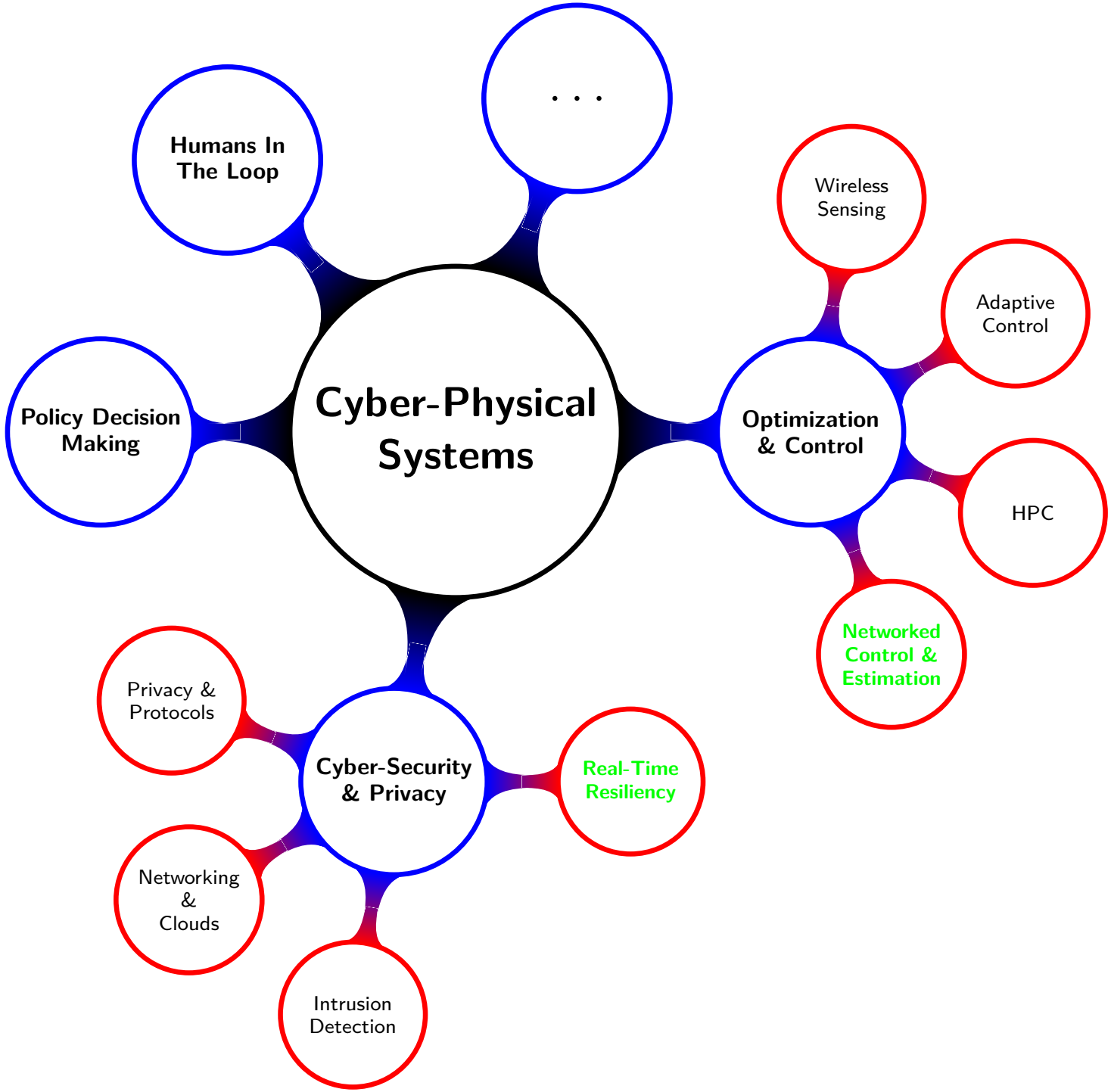
2006: Helen Gill's CPS Definition

CPS & CPSS Evolution




Cyber-Physical
Systems


Humans In
The Loop
. . .
Policy Decision
Making
Cyber-Physical
Systems
Optimization
& Control
Cyber-Security
& Privacy


Cyber-Physical Systems
Humans In The Loop
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Policy Decision Making
Optimization & Control
Wireless Sensing
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Networked Control & Estimation
Cyber-Security & Privacy
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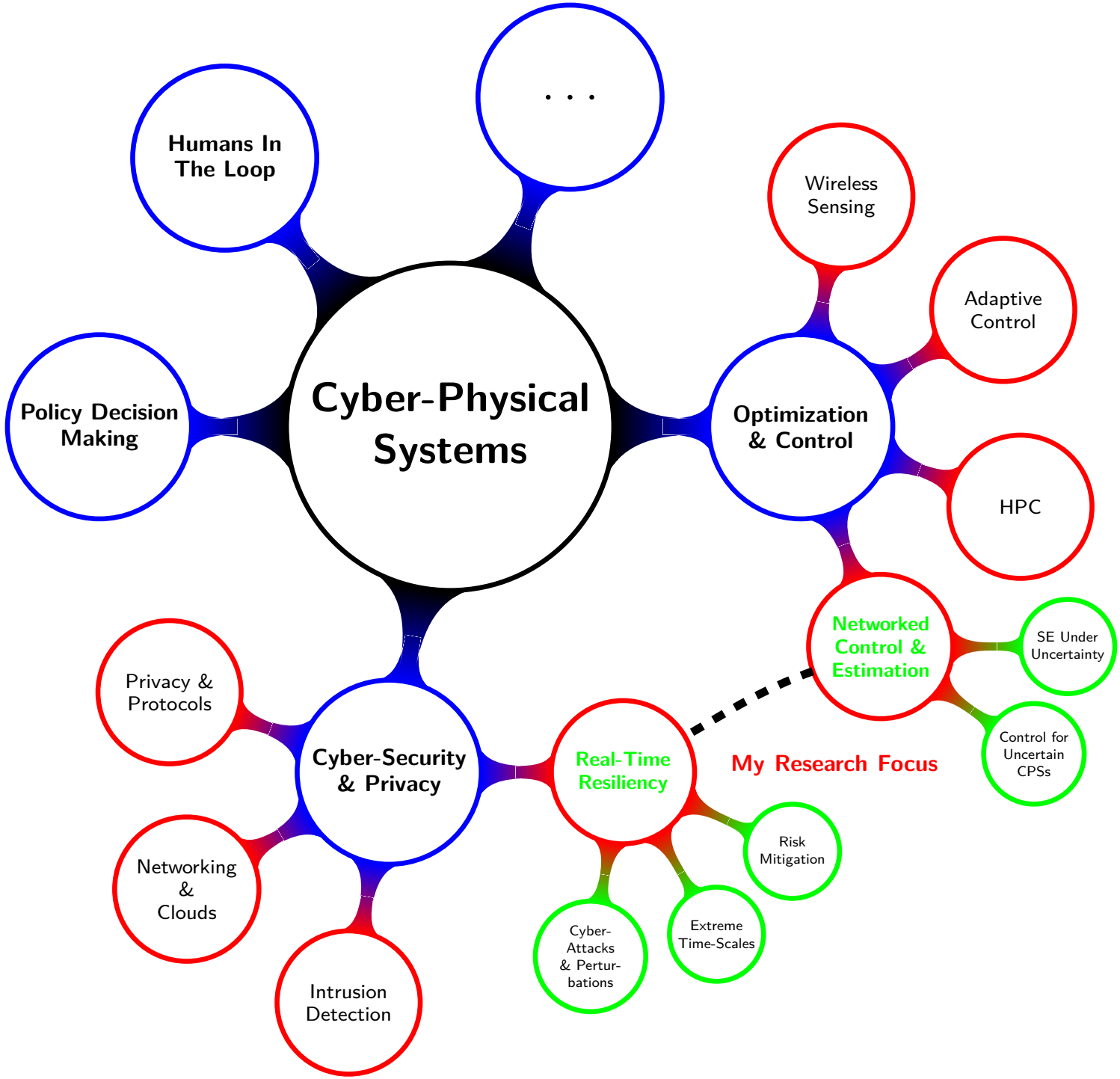
Real-Time Resiliency
Networking & Clouds
Intrusion Detection


Cyber-Physical Systems
Humans In The Loop
. . .
Policy Decision Making
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Networked Control & Estimation
SE Under Uncertainty
Control for Uncertain CPSs
My Research Focus
Real-Time Resiliency
Risk Mitigation
Extreme Time-Scales
Cyber-Attacks & Perturbations
Cyber-Security & Privacy
Privacy & Protocols
Networking & Clouds
Intrusion Detection

CPS Vision & Mission

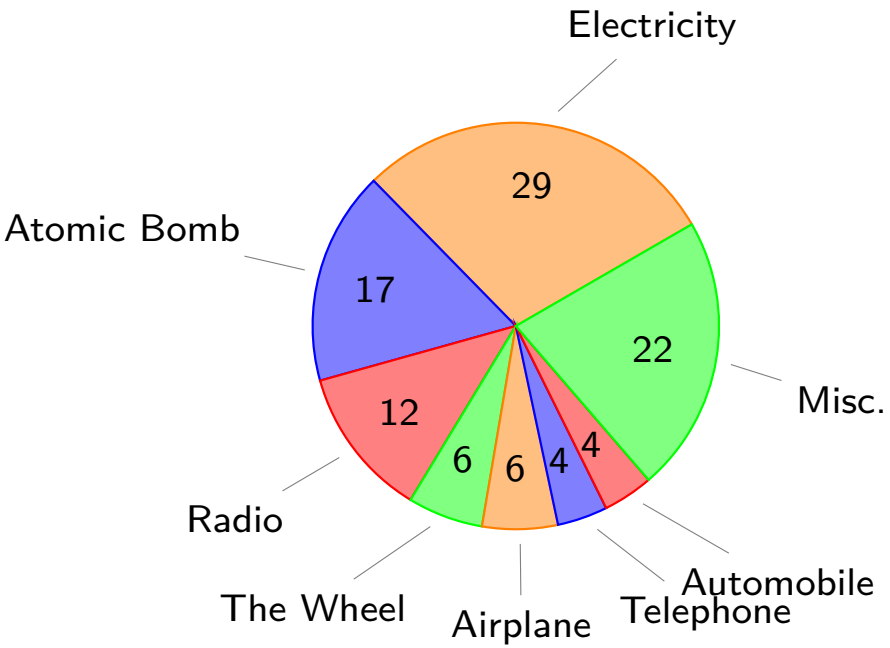
- **Vision**: *building* ***secure & resilient critical infrastructures***
- ***Mission***: *leading efforts to secure infrastructure by* ***managing risk & enhancing resilience*** *through open collaborations* — a DHS mission [DHS, 2015]

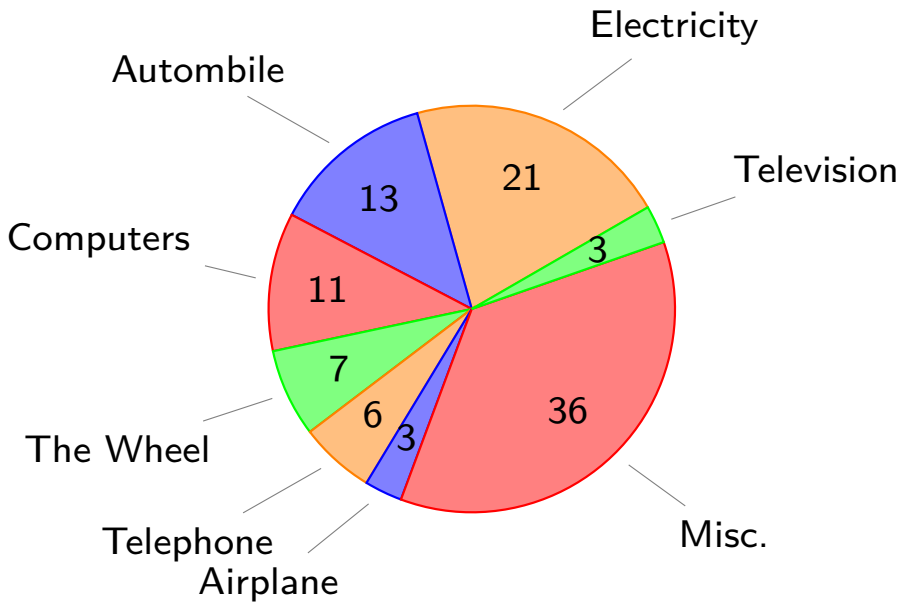
Research **Focus**

Developing secure computational methods for uncertain CPSs with applications to dominant CPS applications

Polls of Greatest Inventions

- Polls of greatest inventions ever made — in 1947 & 2005 [Gallup, 2005]
- Most are CPSs: varying in complexity and size





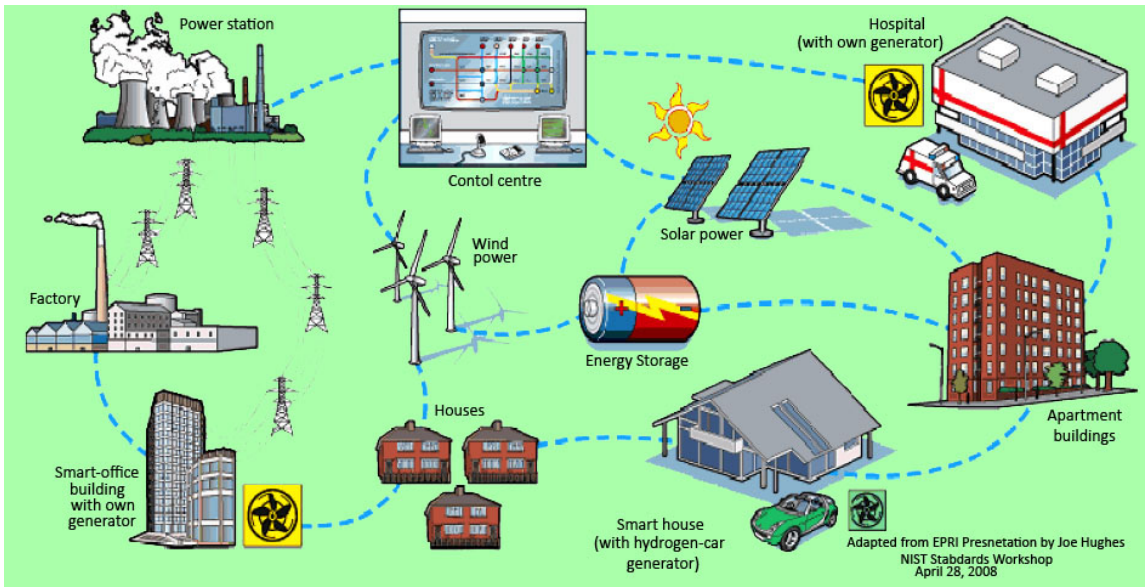
- Electricity remains on top
- With increasing role of **networks**, security has been identified as one of the main issues [Sridhar et al., 2012]

Part II — CPS Application: Smart Grids

Smart Grids: The Most Complex CPS?

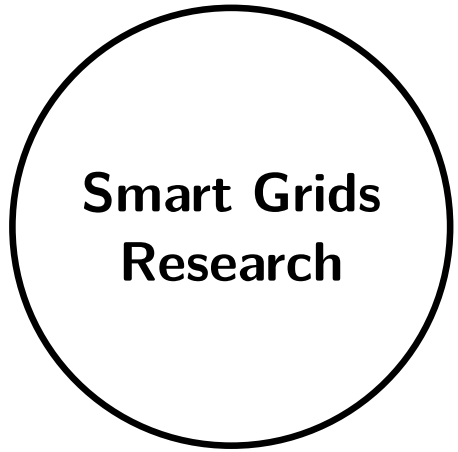
What is a Smart Grid?

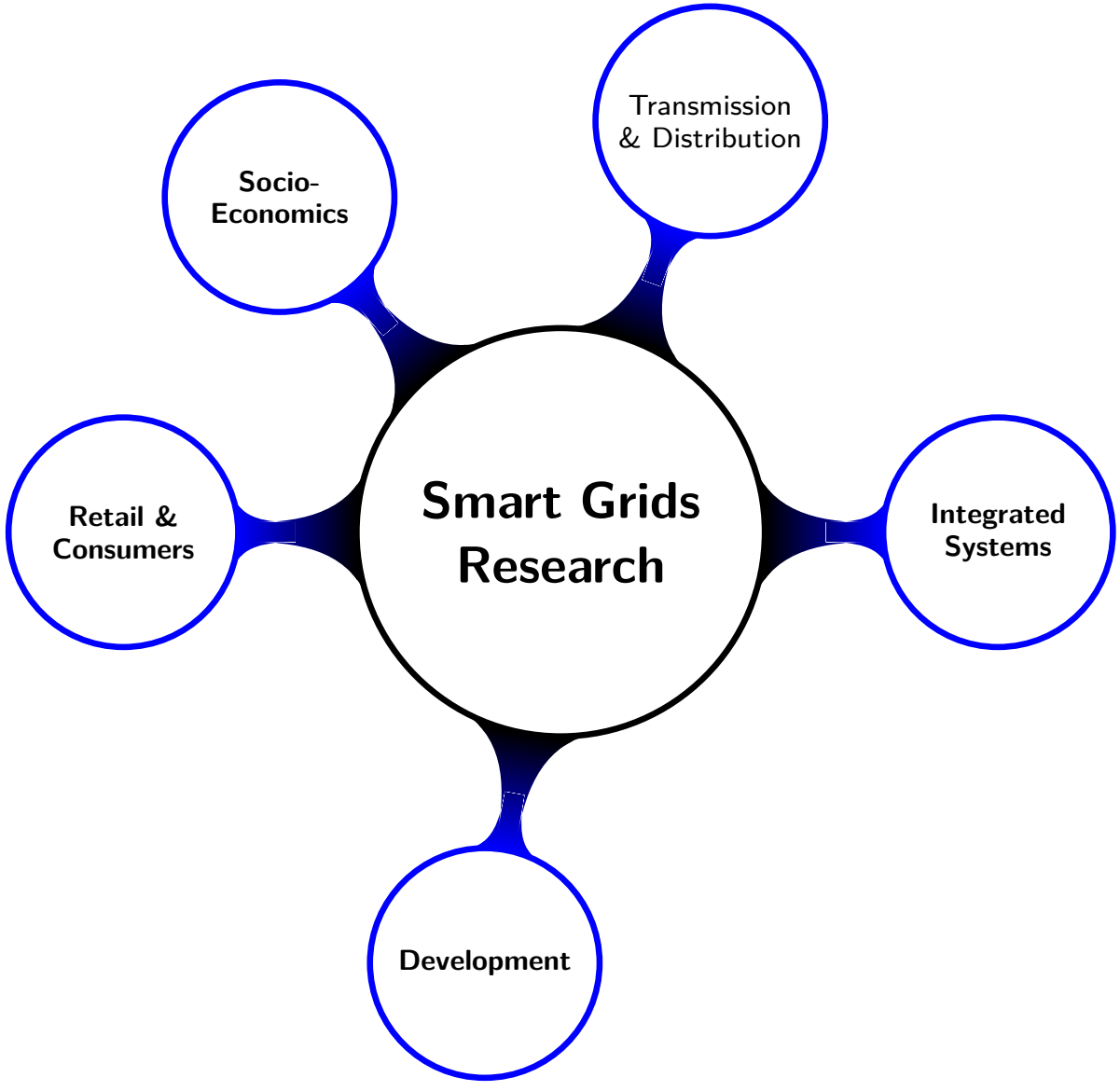
- Modernized electrical grid, uses communications to gather & act on data such as:
  - Consumers' & suppliers' behaviors and preference, market competition, pricing

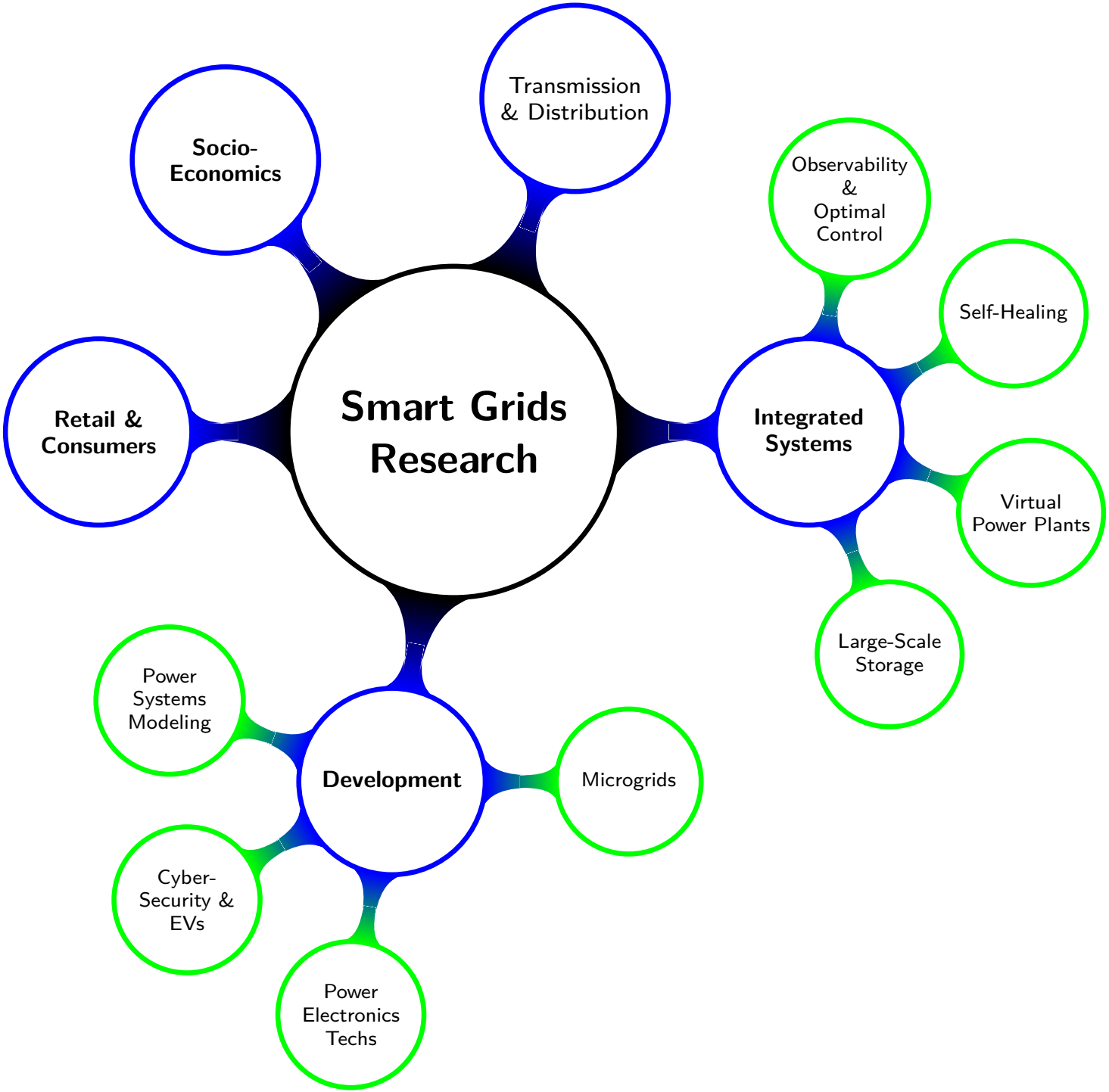


SMART-GRIDS SHOULD **coordinate** NEEDS & CAPABILITIES OF **all market stakeholders** TO OPERATE PARTS OF THE SYSTEM AS **efficiently** AS POSSIBLE, MINIMIZING COSTS & ENVIRONMENTAL IMPACTS WHILE MAXIMIZING SYSTEM RELIABILITY, **resilience & stability**.[1]

[1] Technology Road-map, International Energy Agency, 2011.


Smart Grids
Research


Smart Grids Research
Transmission & Distribution
Socio-Economics
Retail & Consumers
Integrated Systems
Development


Smart Grids Research
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Observability & Optimal Control
Self-Healing
Virtual Power Plants
Large-Scale Storage
Development
Power Systems Modeling
Microgrids
Cyber-Security & EVs
Power Electronics Techs

CPS & Smart-Grid Research: Dynamic State Estimation

- What is *dynamic state estimation* (DSE)?
  - Accurately depicting what's happening inside a system
- Precisely: estimating internal system states
  - In circuits: *voltages and currents*
  - Water networks: *amount of water flowing*
  - Chemical plants: *concentrations*
  - Robots and UAVs: *location & speed*
  - Humans: *temperature, blood pressure, glucose level*
- *So how does having estimates help me?*
  - Well, if you have estimates, you can do control
  - And if you do good control, you become better off!
- In power systems: DSE can tell me what's happening to generators & lines

$$\Rightarrow \textsc{Preventing/Predicting Blackouts!}$$

Research Question

What is a secure DSE method for power systems under attacks & unknown inputs?

- Research @ Argonne National Lab, supported by DoE

Why Dynamic State Estimation?

- Because static state estimators may not detect *anomalies*
- Availability of real-time data from PMUs $\Rightarrow$ utilize DSE methods...

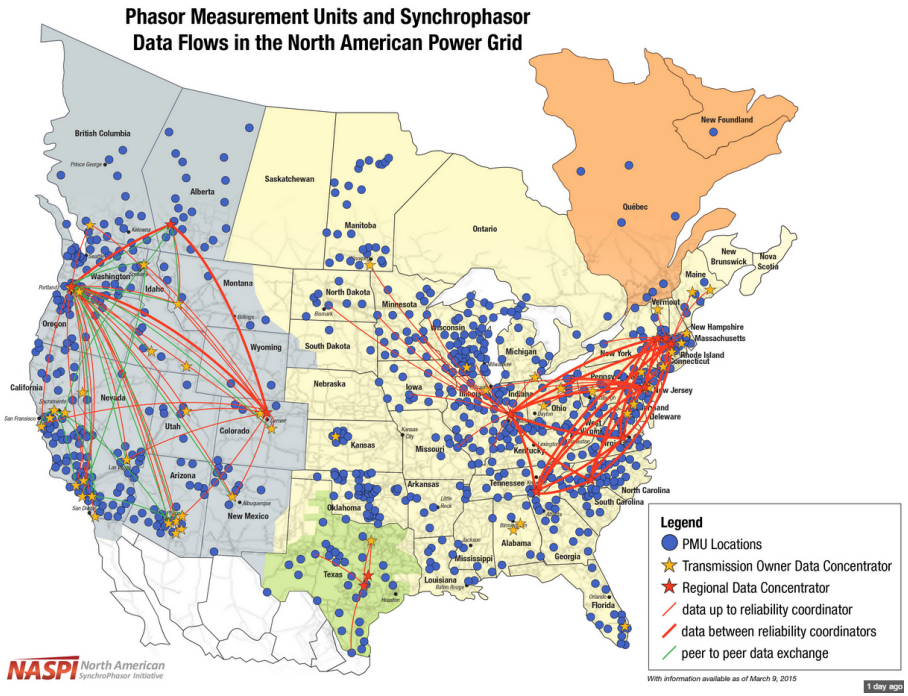


Figure from: https://www.naspi.org

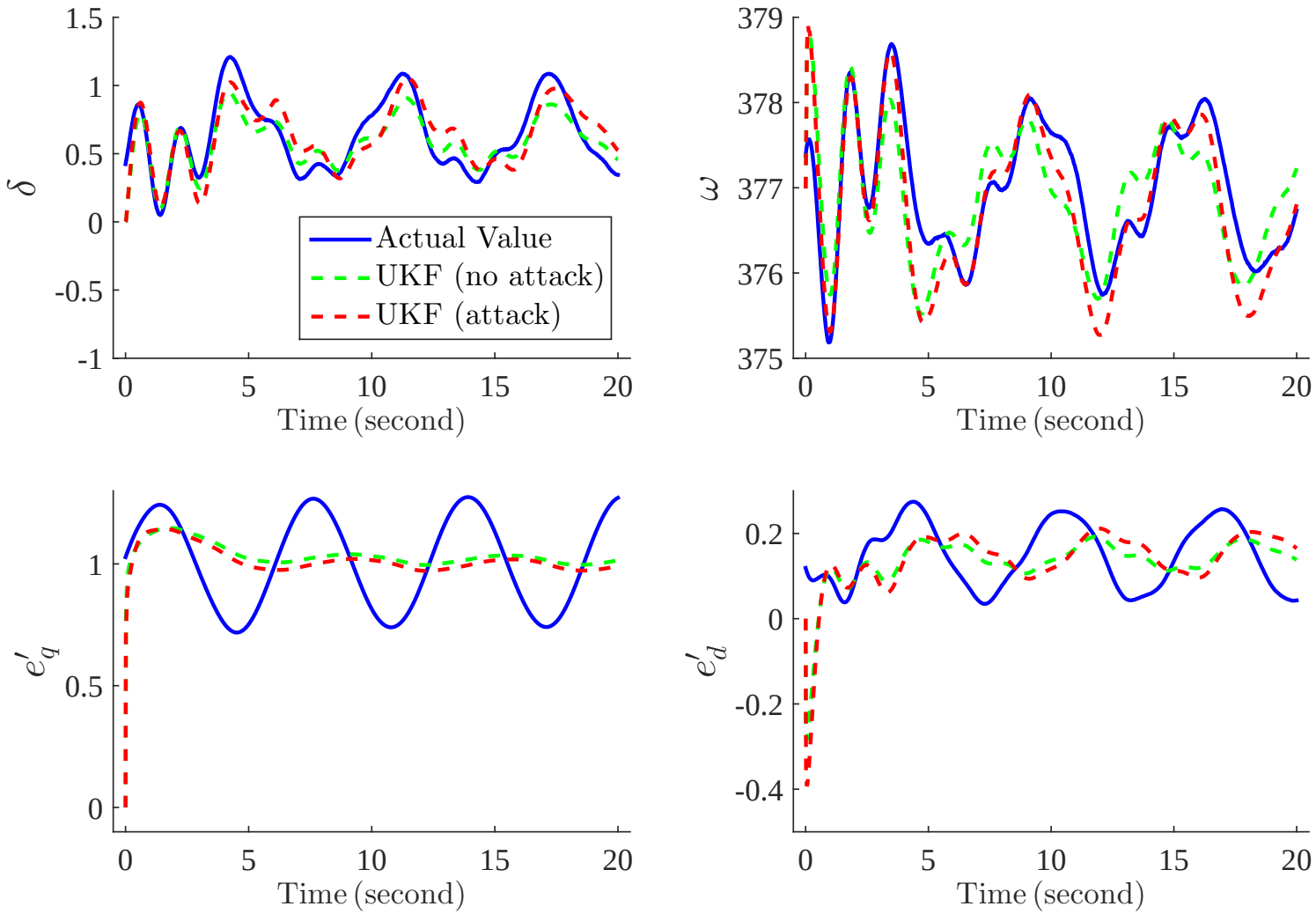
- ...But PMUs can be subject to disturbances, malfunctions
- Failure scenarios [EPRI, 2014]:
  - WAMPAC.4: *Measurement Data Compromised*
  - WAMPAC.6: *Communications Compromised between PMUs & Control Center*

Research Gap

Recent DSE studies can not deal with unknown inputs & potential attack vectors

Current Methods: Tested Under Attacks & Unknown Inputs

- Unscented Kalman Filter [Wang et al., 2012; Singh & Pal, 2014] state-estimation

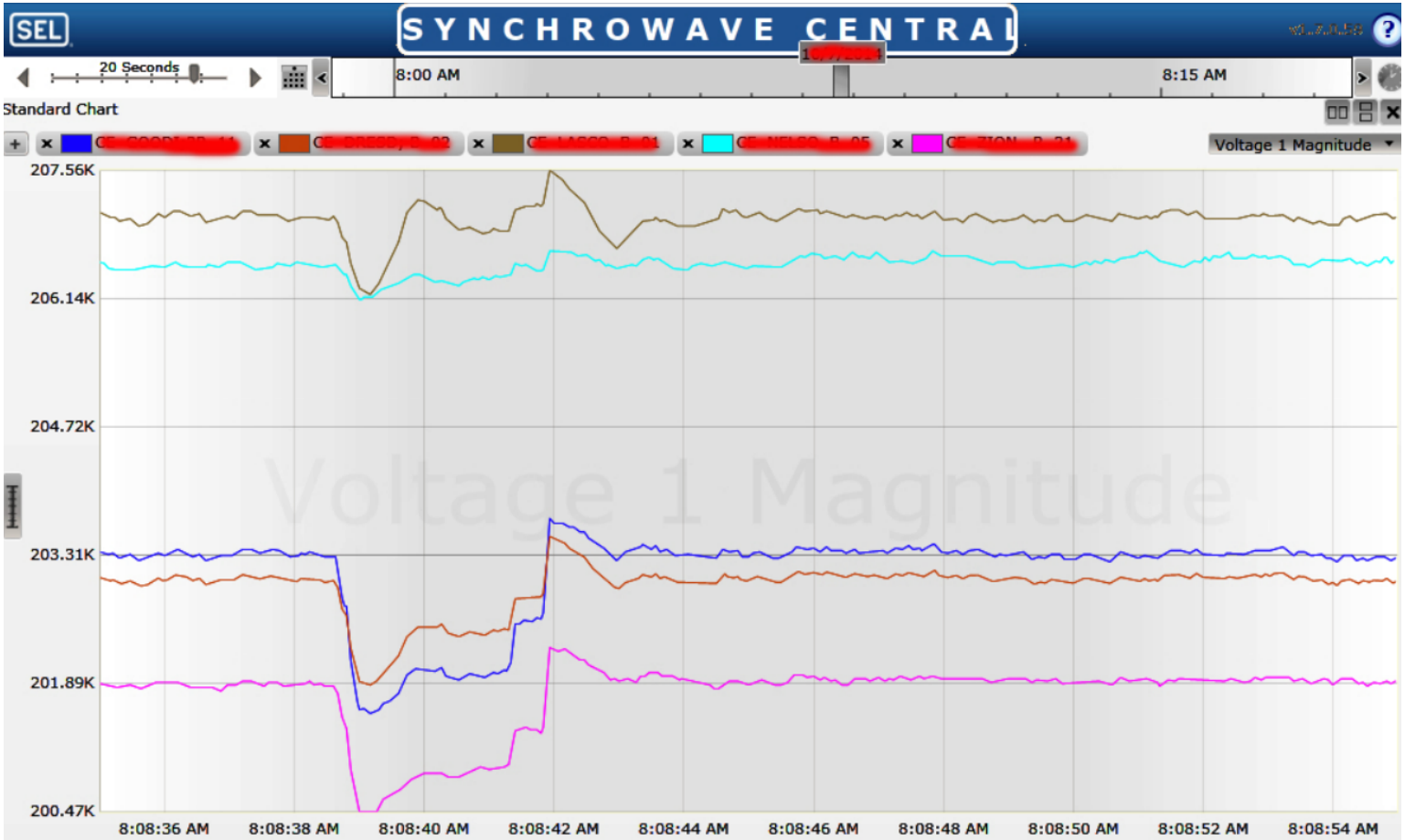


The Poor Ol' Squirrel...And the 12kV Bus[2]

- Picture is self-explanatory
- Squirrel should have been elsewhere ☹

[2] Credits to Commonwealth Edison (ComEd — largest utility in Illinois) for sharing the pictures.

PMU Measurements — Lesson Learned



- PMU detected the **significant** transients due to the squirrel *bite*
- ComEd/Argonne work: better models + **improved DSE** + event detection

Current DSE Methods

Power systems DSE has been implemented by:

- Stochastic estimators:
  - EKF, UKF, PF [Ghahremani & Kamwa, 2011; Singh & Pal, 2014; Ghahremani & Kamwa, 2015]
  - Methods perform poorly in higher dimensions & under attack vectors
- Deterministic linear observers [Pasqualetti et al., 2011; Teixeira et al., 2010]

Our DSE Objective

Objective 1

Present DSE alternatives that address major limitations of current DSE methods such as:

- Tolerance to state-disturbances & attack-vectors
- Unknown initial conditions
- Guaranteed convergence

Objective 2

Perform comparative study and **recommend** DSE methods for uncertain CPSs

Single-Machine Infinite Bus (SMIB) System Dynamics

- SMIB: simplification of a power system — benchmark in DSE studies [Tripathy et al., 2010; Singh & Pal, 2014; Ghahremani & Kamwa, 2015]
- Nominal SMIB nonlinear dynamics:

$$\dot{\boldsymbol{x}}(t) = \underbrace{\boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t)}_{\text{linear terms}} + \underbrace{\boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u})}_{\text{nonlinear interconnections}}$$

$$\boldsymbol{x} = \begin{bmatrix} \delta \\ \omega \\ e'_q \\ e'_d \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} T_m \\ E_{f_d} \end{bmatrix}, \boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{K_D}{2H} & 0 & 0 \\ 0 & 0 & -\frac{1}{T'_{do}} & 0 \\ 0 & 0 & 0 & -\frac{1}{T'_{qo}} \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ \frac{\omega_0}{2H} & 0 \\ 0 & \frac{1}{T'_{do}} \\ 0 & 0 \end{bmatrix}, \boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) = \begin{bmatrix} -\omega_0 \\ \frac{\omega_0}{2H}\left(-T_e(\boldsymbol{x}, \boldsymbol{u}) + K_D\right) \\ -\frac{x_d - x'_d}{T'_{do}} i_d(\boldsymbol{x}, \boldsymbol{u}) \\ \frac{x_q - x'_q}{T'_{qo}} i_q(\boldsymbol{x}, \boldsymbol{u}) \end{bmatrix}$$

Proposal I: Stochastic Estimation — Cubature Kalman Filter (CKF)

- EKF & UKF can suffer from the curse of dimensionality
- CKF: scalable computations of multivariate moments [Arasaratnam & Haykin, 2009]
- We utilize CKF for DSE in power systems
- SMIB nonlinear system can be written in discrete-time form:

$$\boldsymbol{x}_k = \boldsymbol{f}(\boldsymbol{x}_{k-1}, \boldsymbol{u}_{k-1}) + \boldsymbol{q}_{k-1}$$
$$\boldsymbol{y}_k = \boldsymbol{h}(\boldsymbol{x}_k, \boldsymbol{u}_k) + \boldsymbol{r}_k$$

  - $\boldsymbol{q}_{k-1} \sim N(0, \boldsymbol{Q}_{k-1})$ and $\boldsymbol{r}_k \sim N(0, \boldsymbol{R}_k)$: process & measurement noise
  - $\boldsymbol{Q}_{k-1}$ and $\boldsymbol{R}_k$: covariance of $\boldsymbol{q}_{k-1}$ & $\boldsymbol{r}_k$

Proposal II: Deterministic Estimation — Dynamic Observers

- **Question:** What if statistical distributions are unavailable or inaccurate?
- **Answer:** Use deterministic estimators
- Nonlinear term in the dynamics $\boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u})$ is:
  - One-sided Lipschitz:

$$\langle \boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) - \boldsymbol{\phi}(\boldsymbol{z}, \boldsymbol{u}), \boldsymbol{x} - \boldsymbol{z} \rangle \leq k_1 \|\boldsymbol{x} - \boldsymbol{z}\|^2$$

  - Quadratically inner-bounded:

$$(\boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) - \boldsymbol{\phi}(\boldsymbol{z}, \boldsymbol{u}))^\top (\boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) - \boldsymbol{\phi}(\boldsymbol{z}, \boldsymbol{u})) \leq k_2 \|\boldsymbol{x}-\boldsymbol{z}\|^2 + k_3 \langle \boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) - \boldsymbol{\phi}(\boldsymbol{z}, \boldsymbol{u}), \boldsymbol{x}-\boldsymbol{z} \rangle$$

  - Legitimate assumptions for power systems [Siljak et al., 2002; Kalsi, 2010]
  - Example: if $\boldsymbol{\phi}(\boldsymbol{x}) = \sin(\boldsymbol{x})$, then $\rho = 1$

Observer Design

- Plant dynamics under unknown inputs & attack-vectors:

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &= \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u}) + \boldsymbol{D}\boldsymbol{d}(t) \\ \boldsymbol{y}(t) &= \boldsymbol{C}\boldsymbol{x}(t) + \boldsymbol{v}(t) \end{aligned}$$

- Observer dynamics [Zhang et al., 2012]:

$$\dot{\hat{\boldsymbol{x}}}(t) = \boldsymbol{A}\hat{\boldsymbol{x}}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{\phi}(\hat{\boldsymbol{x}}, \boldsymbol{u}) + \boldsymbol{L}(\boldsymbol{y}(t) - \boldsymbol{C}\hat{\boldsymbol{x}}(t))$$

- Matrix-gain $\boldsymbol{L}$ determined as follows:
  1. Given k_1, k_2, k_3, solve this LMI for $\epsilon_1, \epsilon_2, \sigma$ and $\boldsymbol{P} = \boldsymbol{P}^\top \succ \boldsymbol{O}$:

$$\begin{bmatrix} \boldsymbol{A}^\top \boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} + (\epsilon_1 k_1 + \epsilon_2 k_2)\boldsymbol{I}_n - \sigma \boldsymbol{C}^\top \boldsymbol{C} & \boldsymbol{P} + \dfrac{k_3\epsilon_2 - \epsilon_1}{2}\boldsymbol{I}_n \\ \left(\boldsymbol{P} + \dfrac{k_3\epsilon_2 - \epsilon_1}{2}\boldsymbol{I}_n\right)^\top & -\epsilon_2 \boldsymbol{I}_n \end{bmatrix} < 0$$

  2. Compute observer gain $\boldsymbol{L}$:

$$\boldsymbol{L} = \frac{\sigma}{2}\boldsymbol{P}^{-1}\boldsymbol{C}^\top$$

- **Extension**: reduced-order DSE

Numerical Results – A Comparative Study

- SMIB parameters from PST toolbox [Chow & Cheung, 1992]
- Initial conditions:

$$\begin{aligned} \boldsymbol{x}(0) &= \begin{bmatrix} 0.4233 & 377.3780 & 1.0277 & 0.1190 \end{bmatrix}^\top \\ \hat{\boldsymbol{x}}(0) &= \begin{bmatrix} 0 & \omega_0 & 0 & 0 \end{bmatrix}^\top \end{aligned}$$

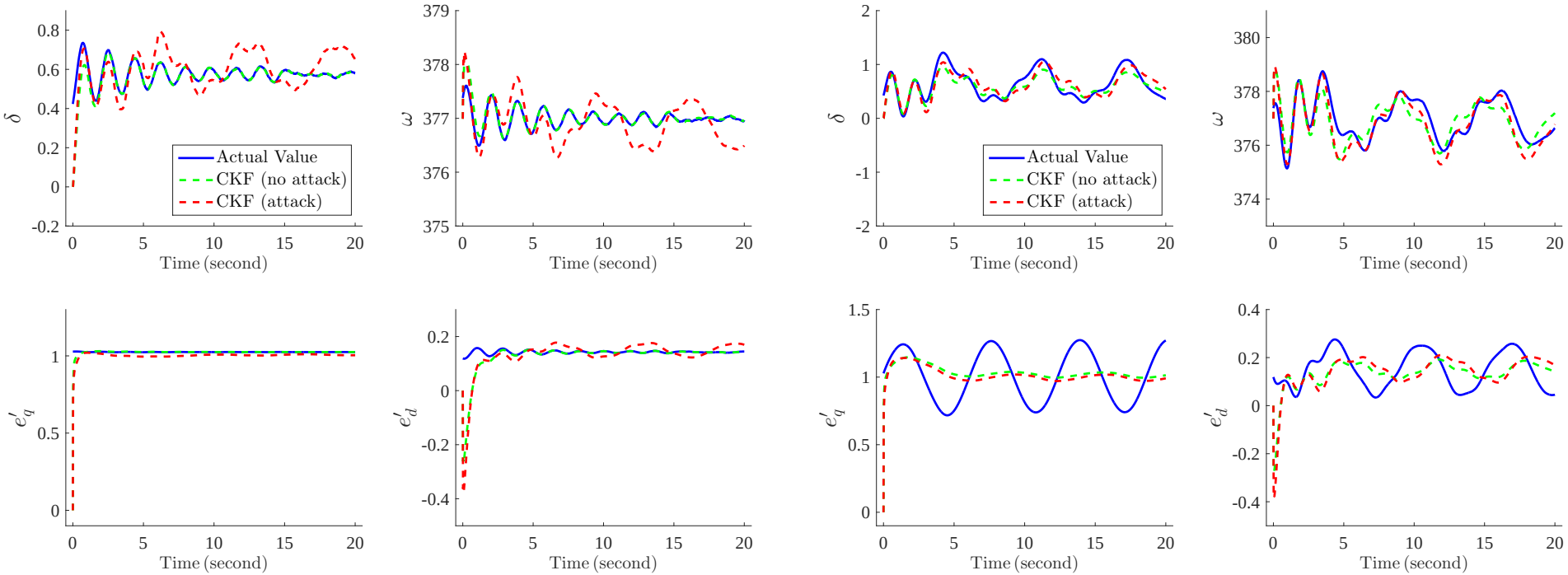
- $\boldsymbol{D}$ is randomly chosen (2 UIs); unknown input vector: $\boldsymbol{d}(t) = 0.01\cos(t)$
- Attack vector, $\boldsymbol{v}(t)$:

$$\begin{aligned} v_1(t) &= 0.2\sin(t) \\ v_2(t) &= \begin{cases} 0.5\sin(2t) + \frac{5}{t^2} & 5 < t < 6 \\ 0 & \text{otherwise} \end{cases} \\ v_3(t) &= 0.3\cos(t) \\ v_4(t) &= 0.2 \end{aligned}$$

- Gaussian process & measurement noise are added

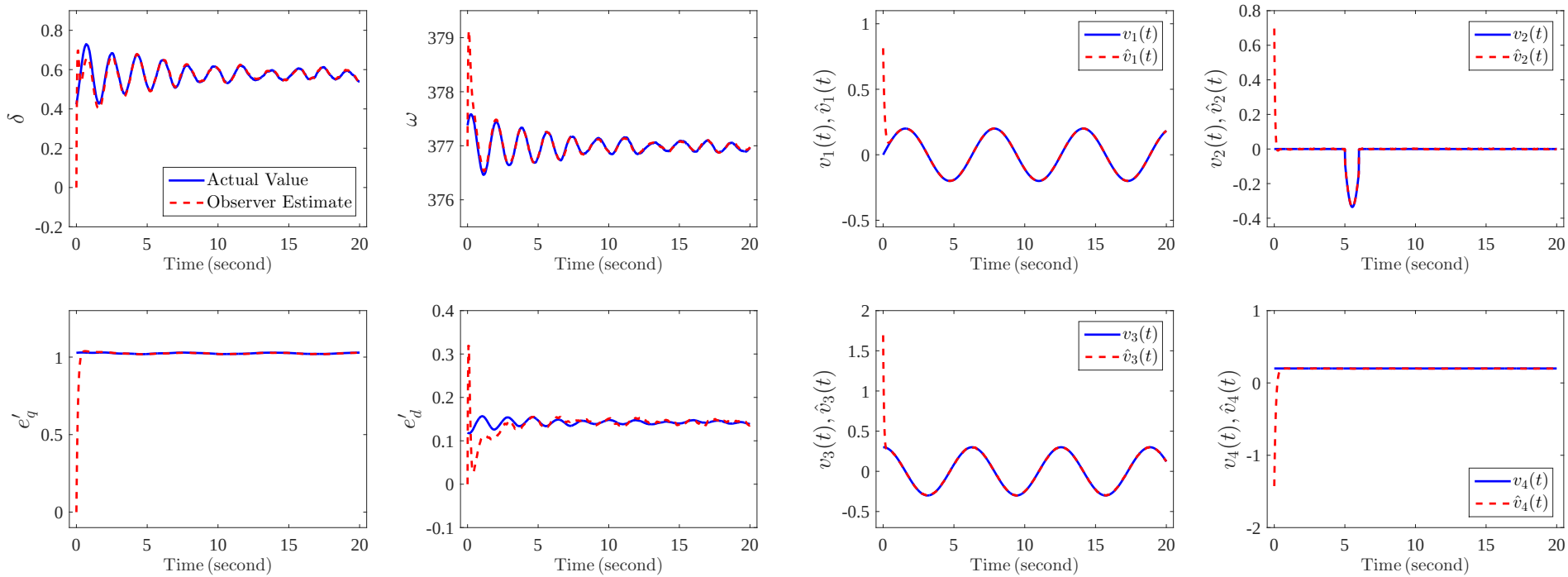
DSE Results: Stochastic Estimation — CKF

- CKF estimates converge in the absence of attack-vectors & unknown inputs (left figure)
- Under noise, unknown inputs & attacks, CKF estimates fail to converge (right figure)



DSE Results: Determinstic Estimation — Dynamic Observer

- Under noise, unknown inputs & attacks, observer estimates rapidly converge (left figure)
- Attack-vector estimator accomplishes near-perfect disturbance estimation (right figure)



DSE for Power Systems: *The Good, the Bad & the Ugly*

#TeamObservers

Functionality/Characteristic	**Kalman Filter Derivatives**			
	EKF	UKF	CKF	Observer
System's Nonlinearities	✗	✓	✓	✓
Tolerance to Different Initial Conditions	✗	✗	✗	✓
Tolerance to Unknown Inputs	✗	✗	✗	✓
Tolerance to Cyber-Attacks	✗	✗	✗	✓
Tolerance to Process & Measurement Noise	✓	✓	✓	✓
Guaranteed Convergence	—	—	—	✓
Computational Complexity	$\mathcal{O}(n^3)$	$\mathcal{O}(n^3)$	$\mathcal{O}(n^3)$	$\mathcal{O}(n^3)$

- Running time:

Initial Conditions	Running Time (seconds)		
	CKF	UKF	Observer
$\hat{\boldsymbol{x}}(0) = [0\ \omega_0\ 0\ 0]^\top$	3.28	6.30	0.76
$\hat{\boldsymbol{x}}'(0) = [3\ \omega_0\ 0\ 0]^\top$	3.27	6.27	0.76

Contributions

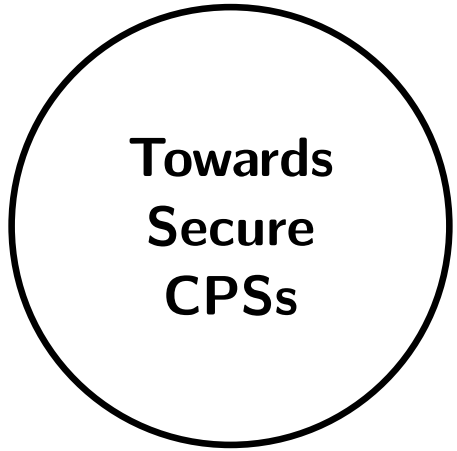
- Current DSE methods: intolerant to attack-vectors & unknown inputs

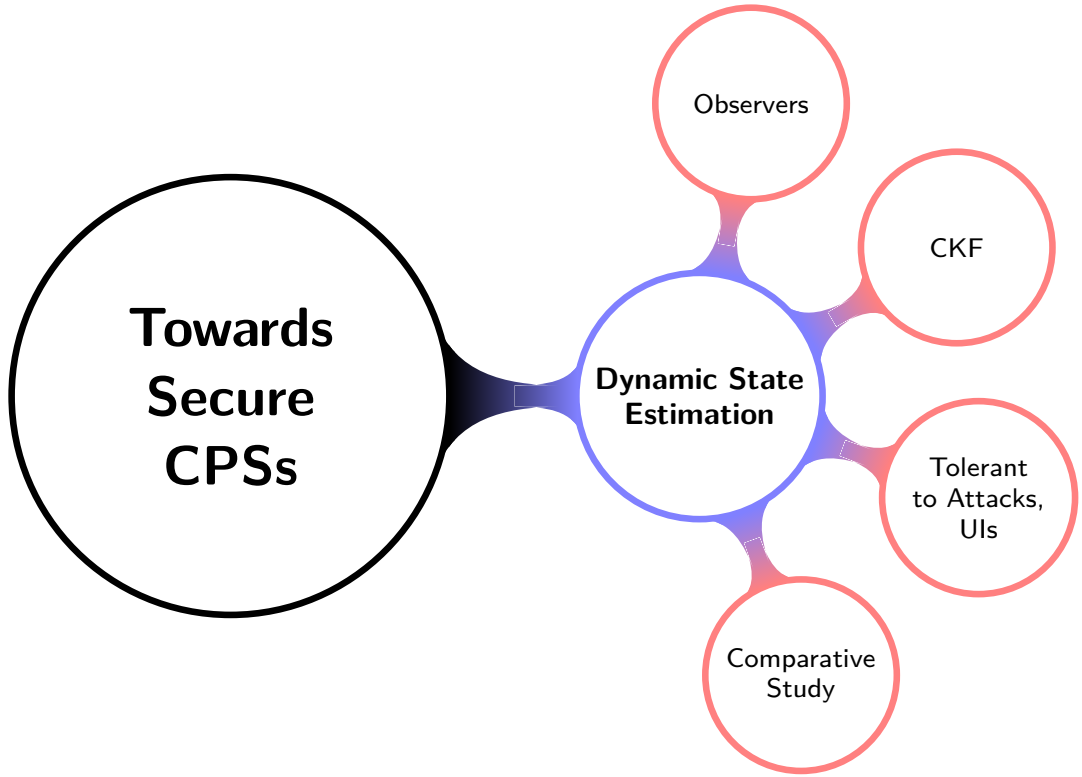
Contributions:

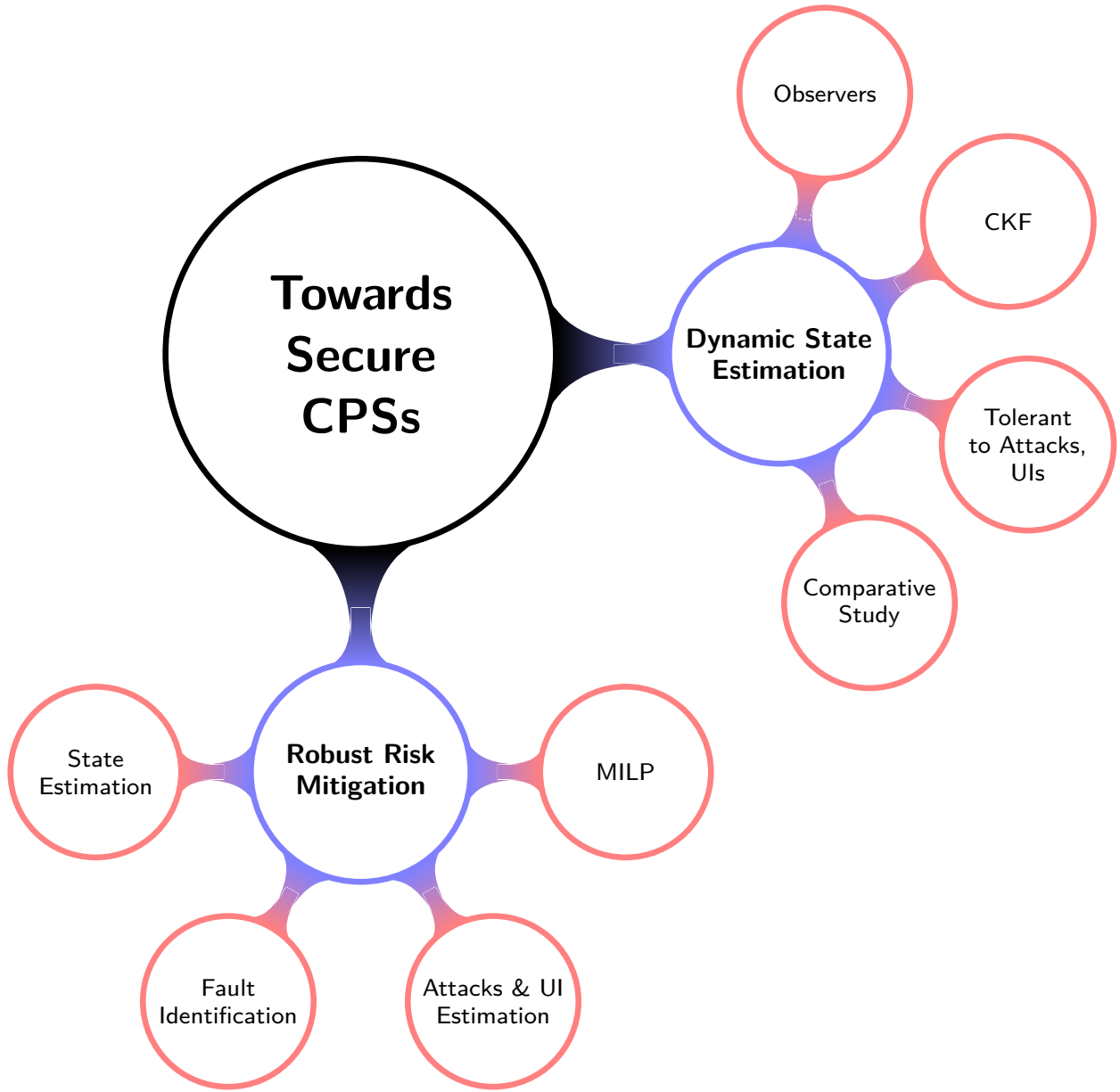
1. Introduce deterministic estimators for nonlinear, uncertain power systems
2. Perform a comparative study of DSE methods for uncertain CPSs & provide recommendations

- **Generalization:** under one-sided Lipschitz assumption of $\boldsymbol{\phi}(\boldsymbol{x}, \boldsymbol{u})$, results can be extended to various uncertain CPSs

Part III — Future of Research in CPSs, My Interests


Towards
Secure
CPSs


Towards Secure CPSs
Dynamic State Estimation
Observers
CKF
Tolerant to Attacks, UIs
Comparative Study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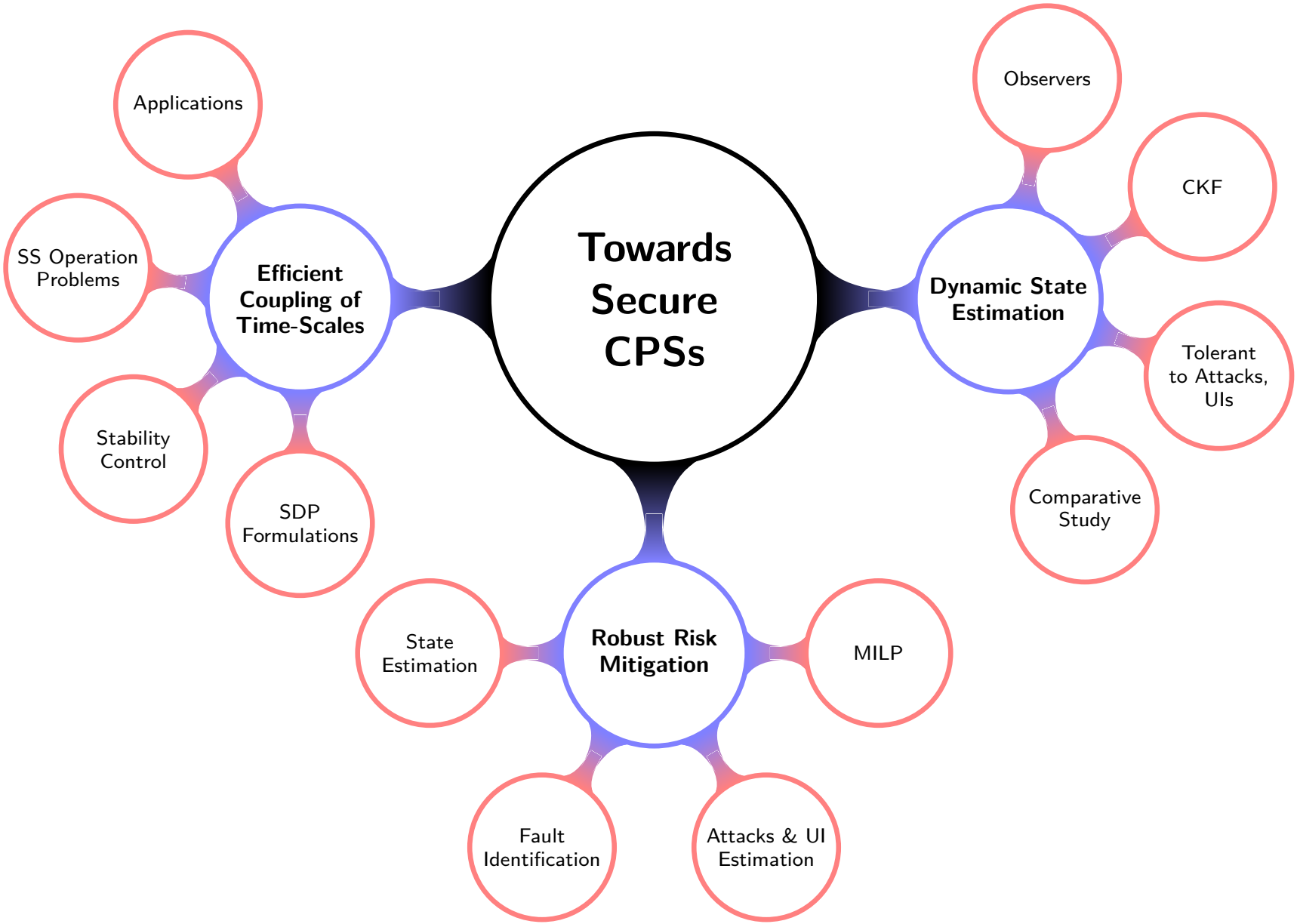
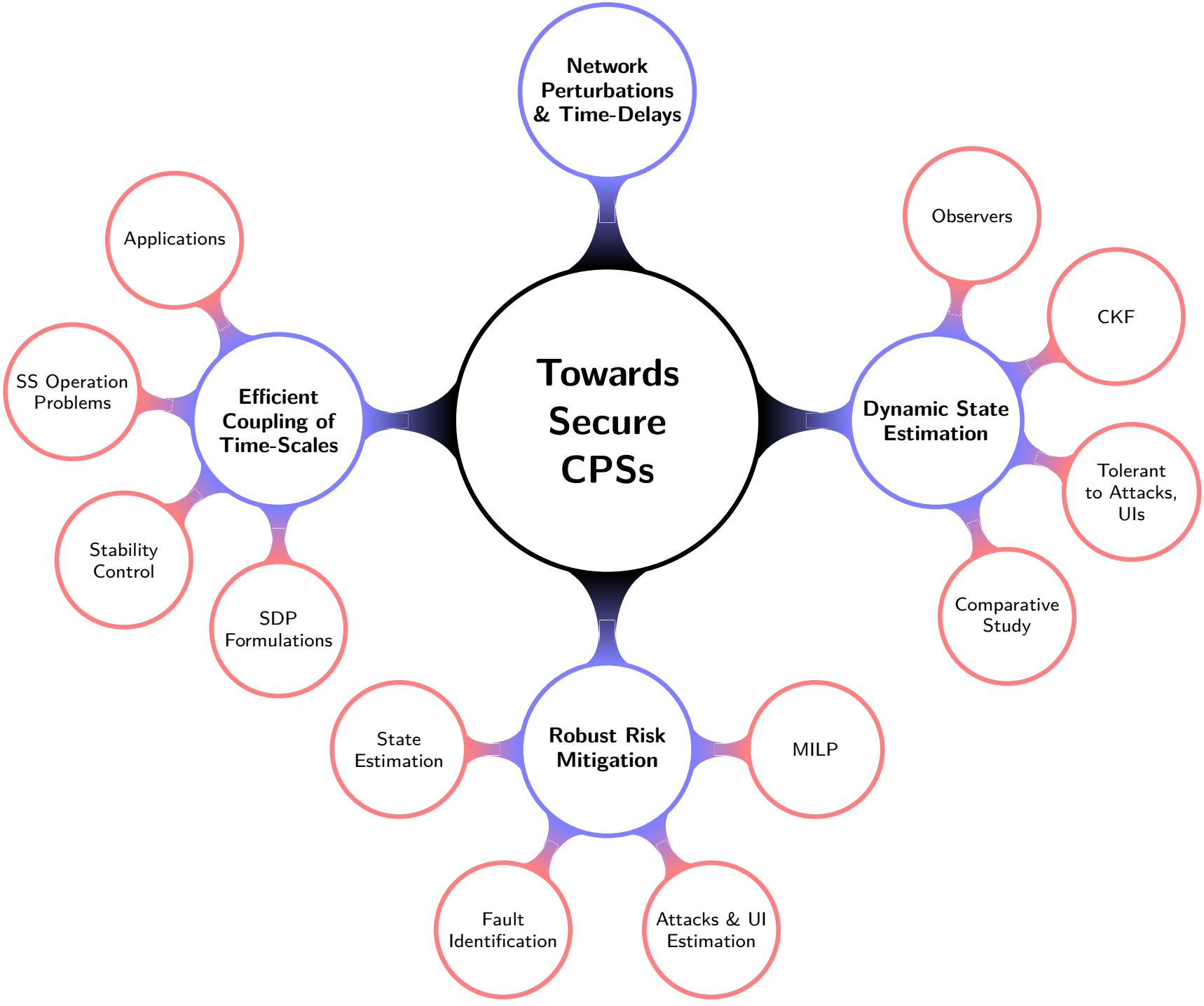
Comparative Study
Robust Risk Mitigation
State Estimation
MILP
Fault Identification
Attacks & UI Estimation


Towards Secure CPSs
Efficient Coupling of Time-Scales
Applications
SS Operation Problems
Stability Control
SDP Formulations
Dynamic State Estimation
Observers
CKF
Tolerant to Attacks, UIs
Comparative Study
Robust Risk Mitigation
State Estimation
MILP
Fault Identification
Attacks & UI Estimation


Towards Secure CPSs
Network Perturbations & Time-Delays
Efficient Coupling of Time-Scales
Applications
SS Operation Problems
Stability Control
SDP Formulations
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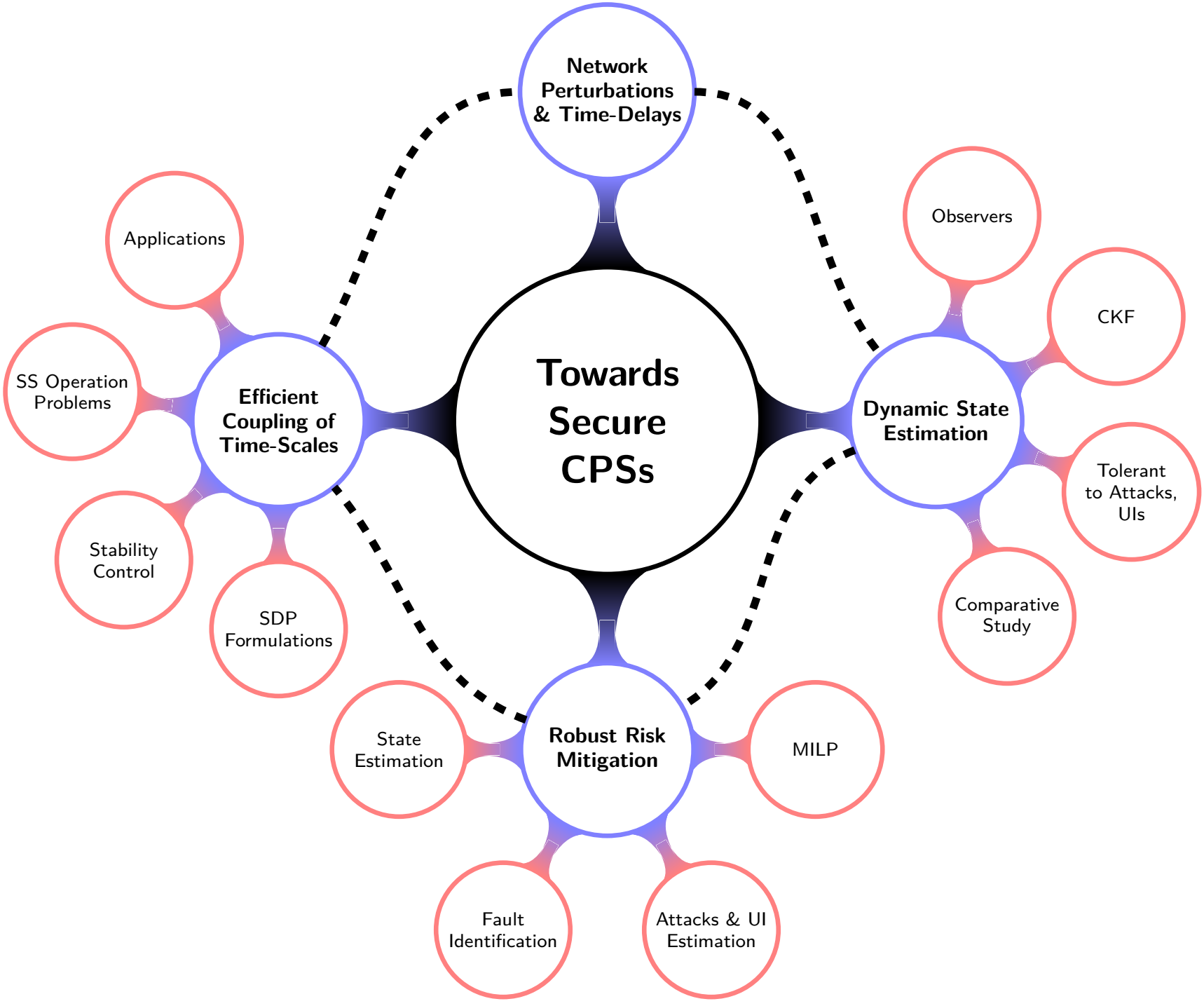
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Open Research Questions & Future Work

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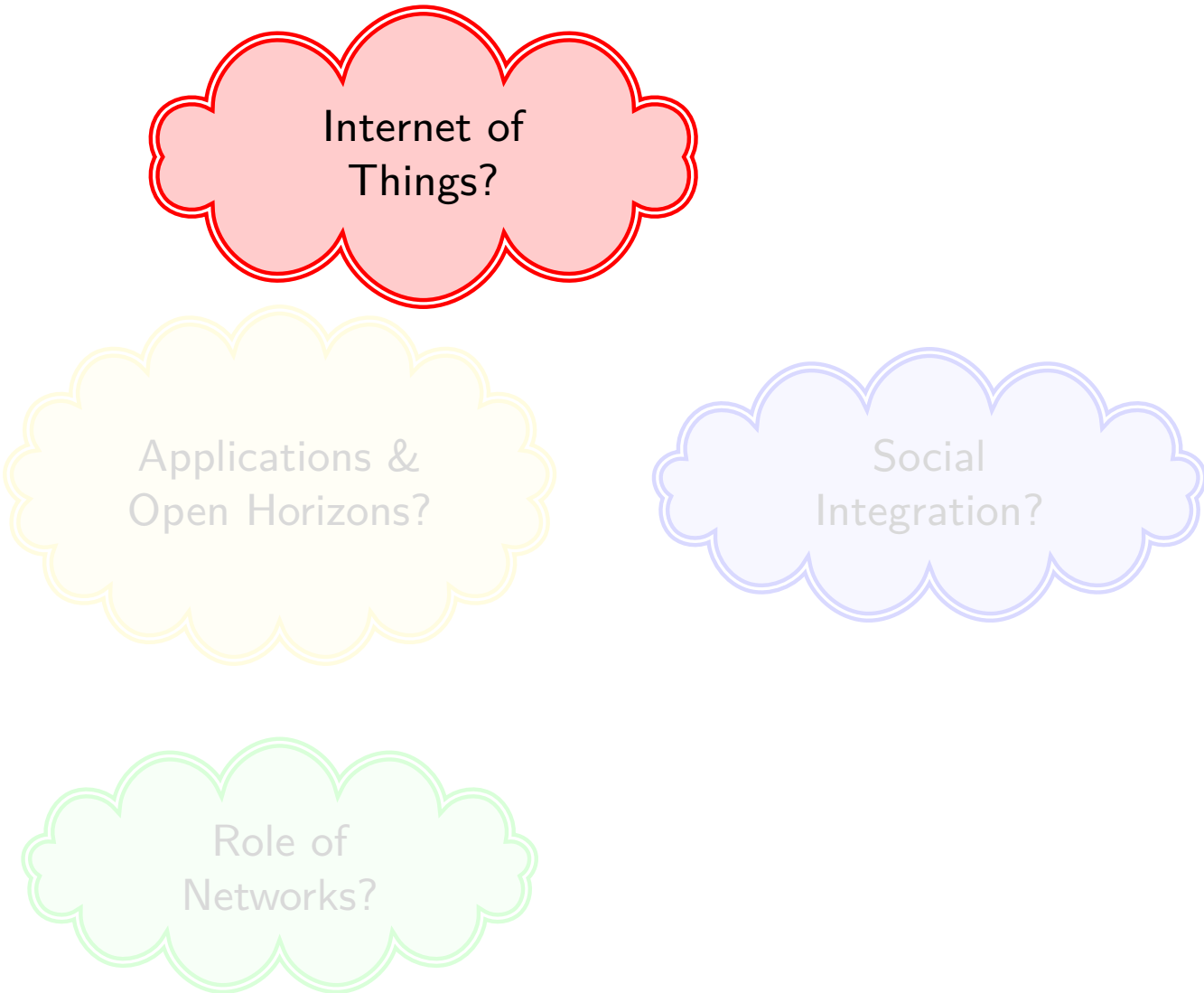

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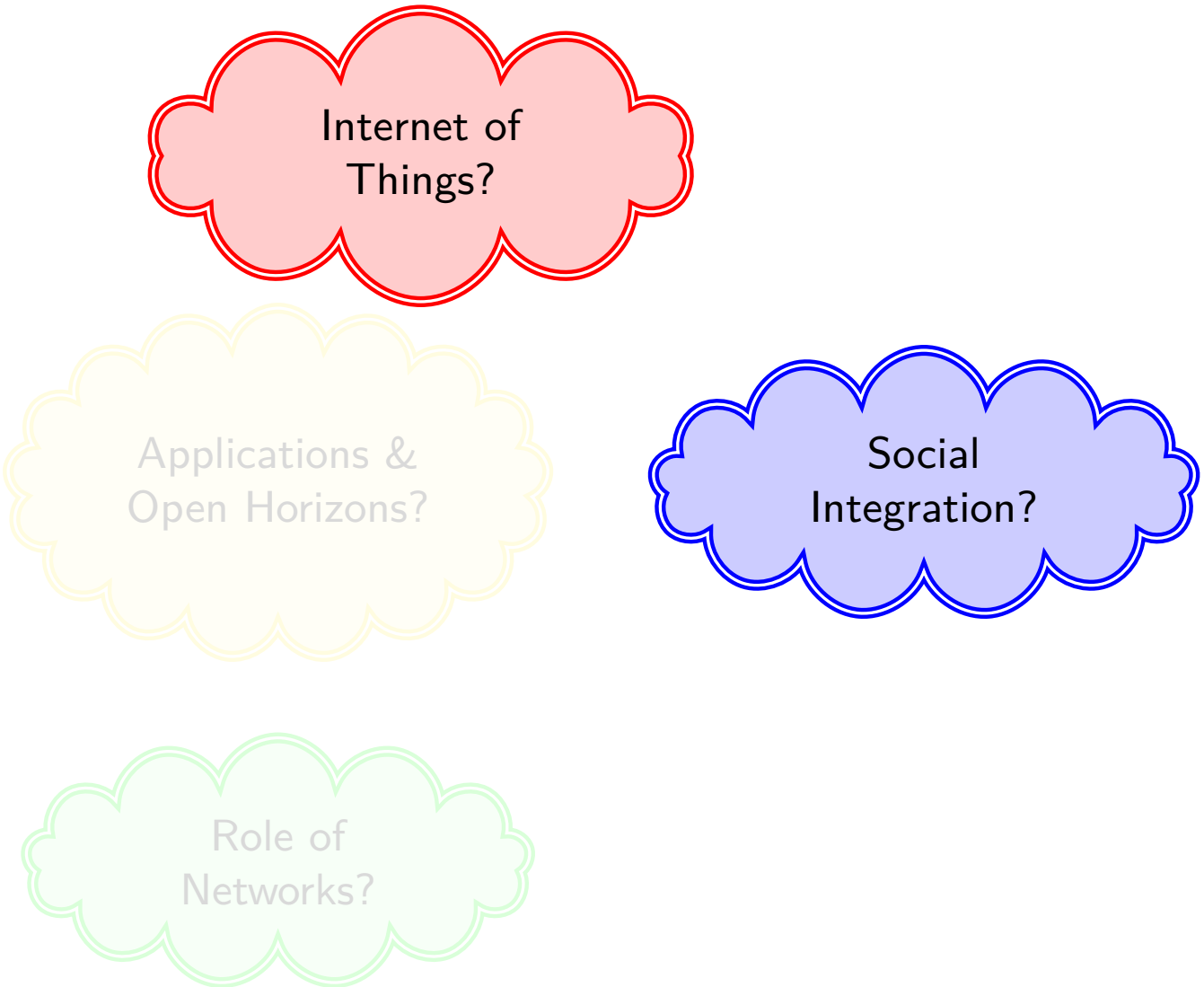

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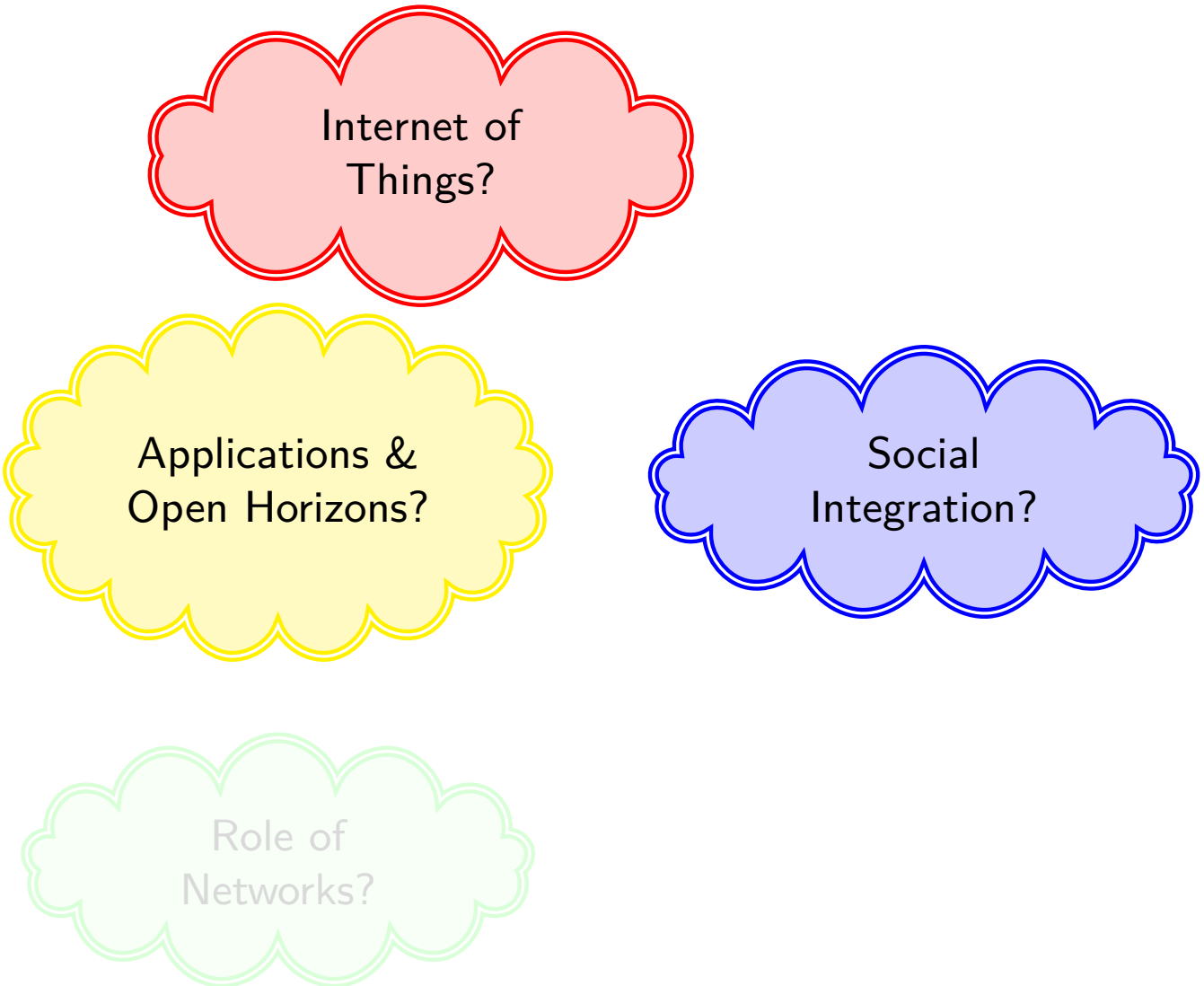

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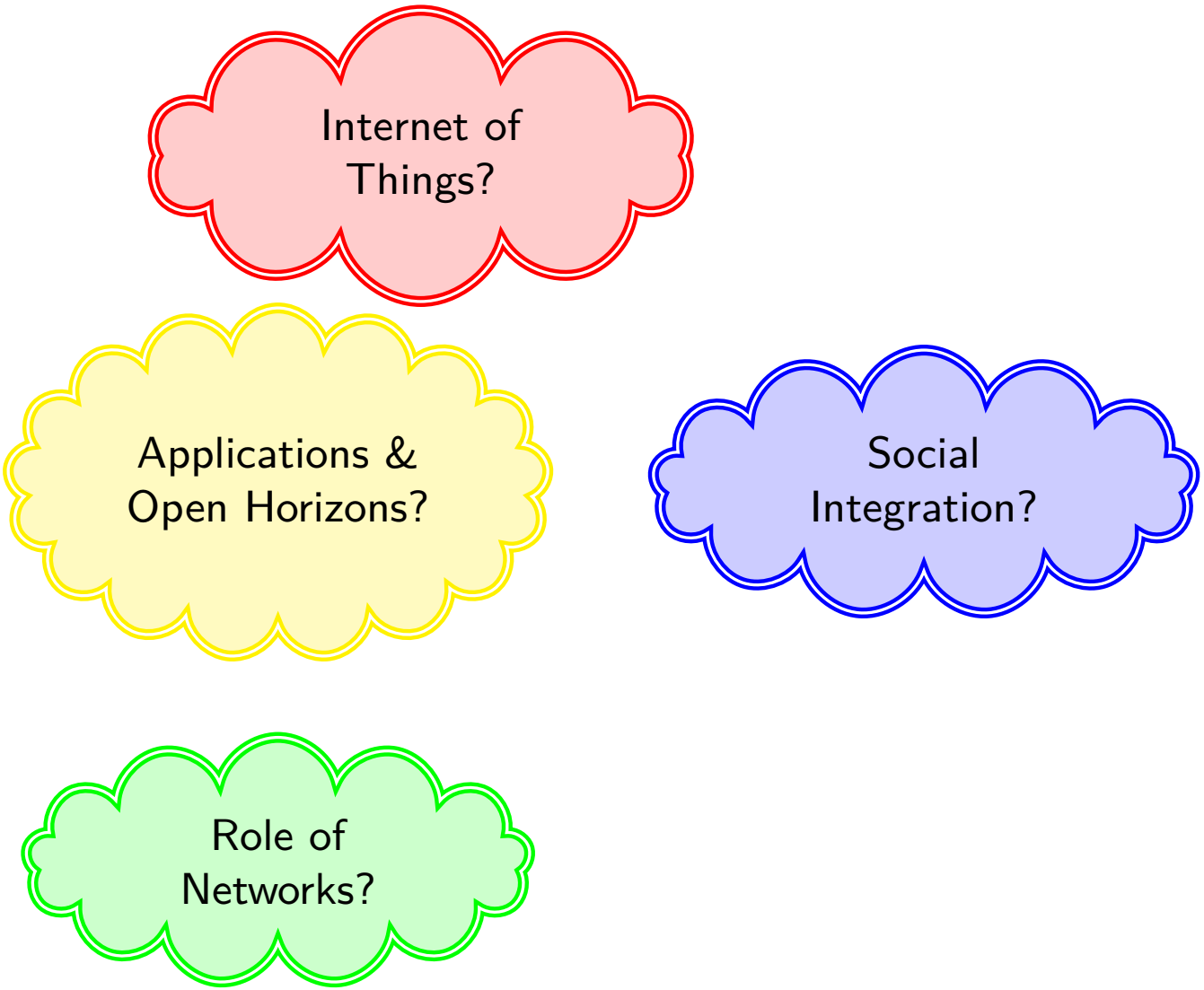
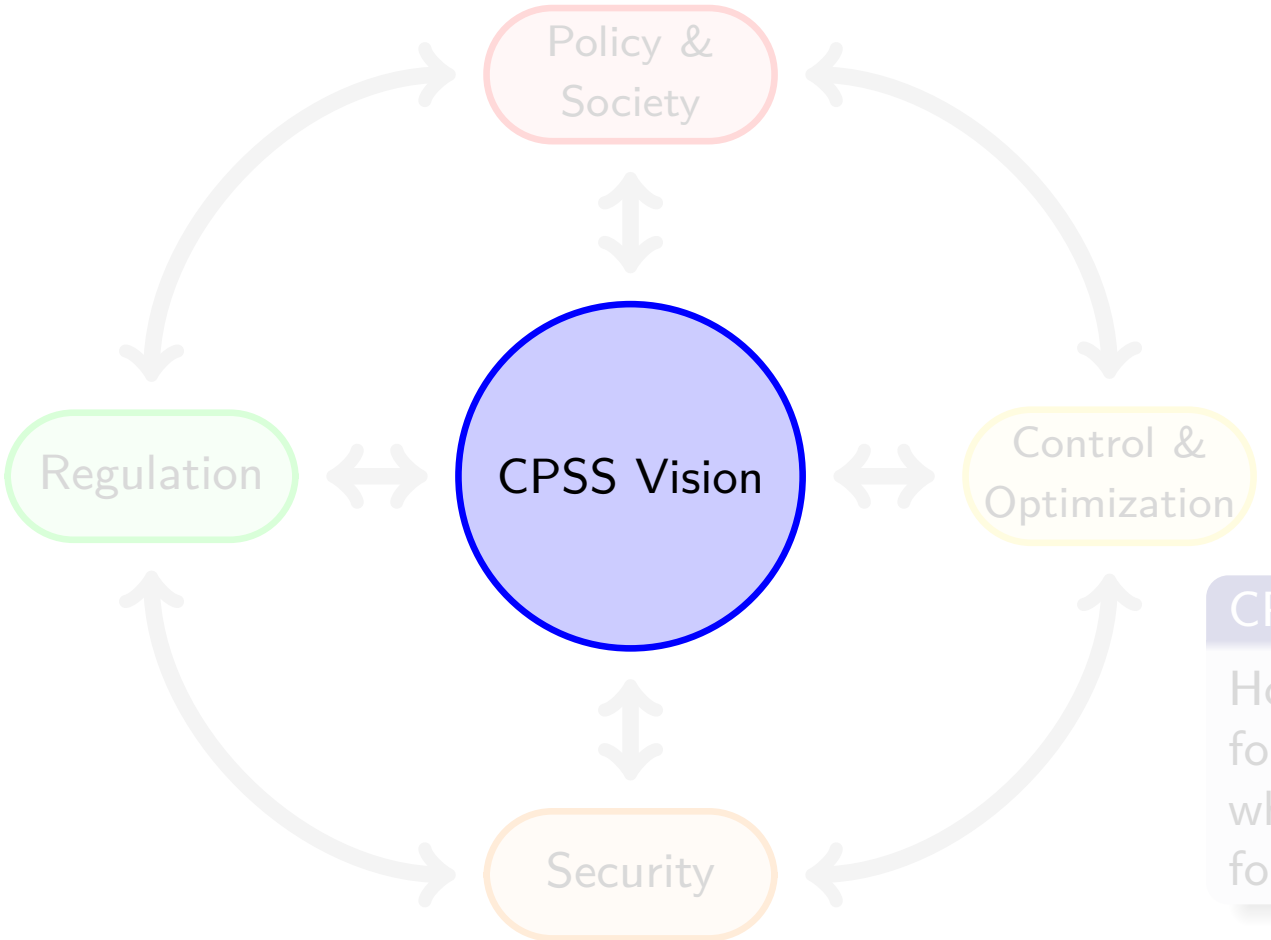


Open Research Questions (2)

Cyber-Physical Social Systems (CPSS):

- Social & policy-decision making components in CPSs are often ignored
- $\Rightarrow$ Need to link physical, technology, & societal objectives [IEA, 2011]



CPSS Research Question

How can we establish foundations for resilient CPSS while supporting policy design for economic incentives?

Open Research Questions (2)

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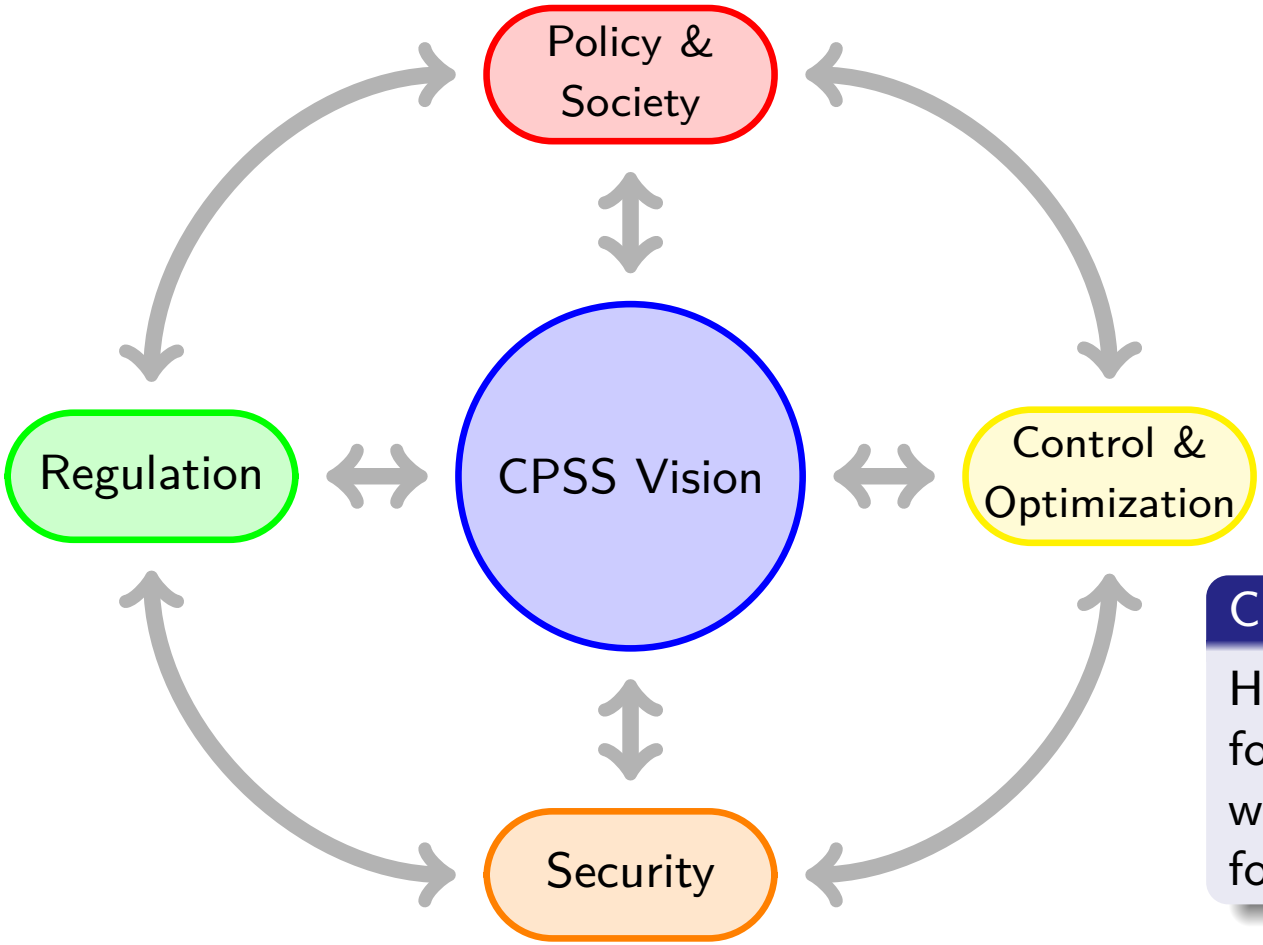

CPSS Research Question

How can we establish foundations for resilient CPSS while supporting policy design for economic incentives?

Questions And Suggestions?

Thank You!

Please visit

engineering.utsa.edu/~taha

IFF you want to know more ☺

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