



# A Knowledge Representation and Information Fusion Framework for Decision Making in Complex Cyber-Physical Systems

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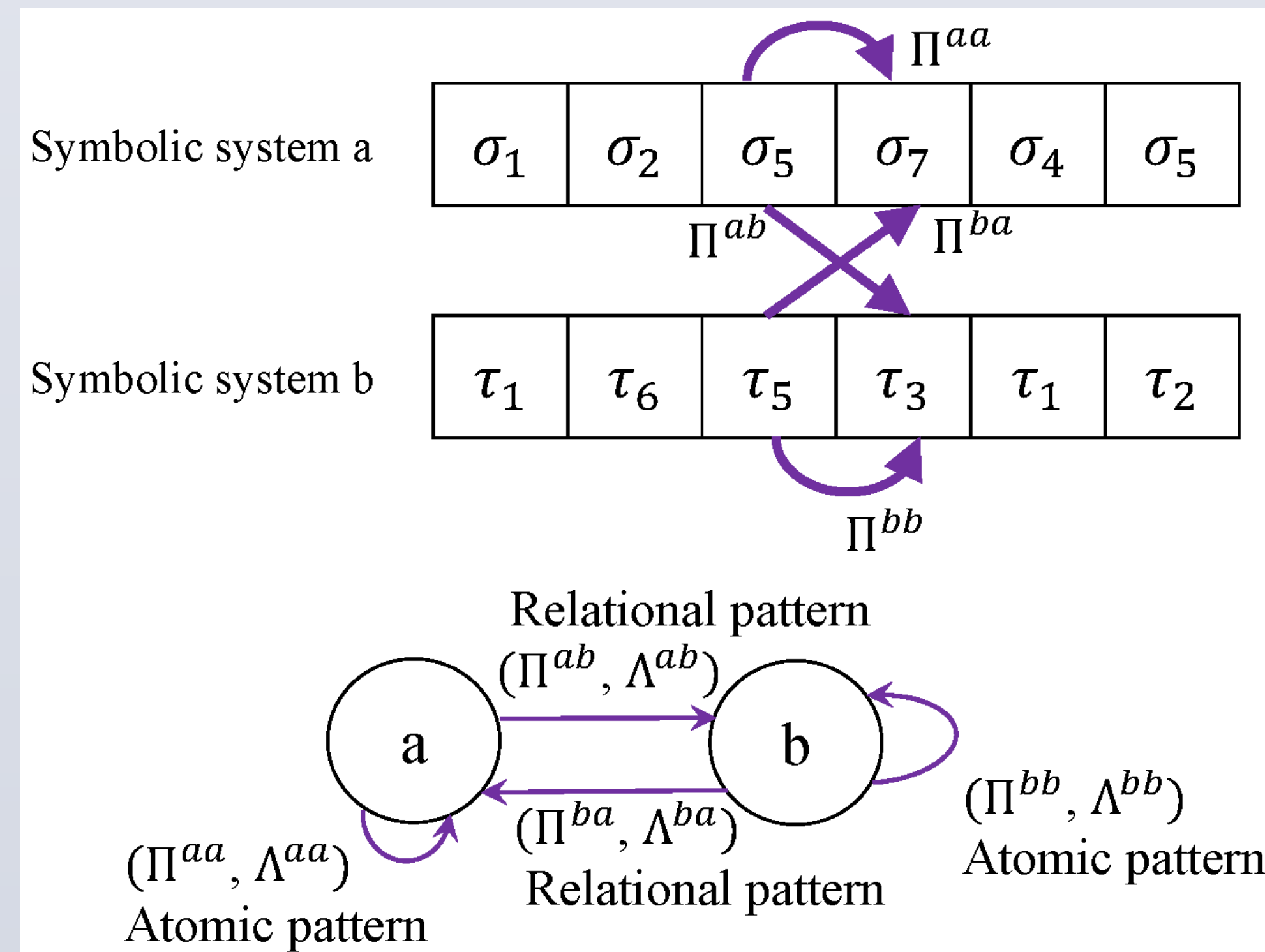
## Project Objectives

- Develop a **data-driven modeling framework** for CPSs that reliably captures cyber and physical sub-system behaviors as well as their interaction characteristics.
- To address the need of **performance monitoring and fault detection & diagnostics (FDD)** in distributed CPSs (e.g., integrated building), with **cyber attacks and physical anomalies**.
- Challenge: **Inference and root cause analysis** in complex CPSs with **multiple (possibly unforeseen) anomalies** at the same time, **system wide impact estimation** in a large interconnected system.

## Spatiotemporal pattern network (STPN)

- Based on symbolic dynamic filtering (SDF), uses concepts of probabilistic finite state automaton (PFSA),  $D$ -Markov machine, and  $xD$ -Markov machine, STPN is defined as a 4-tuple

$$W_D \equiv (Q^a, \Sigma^b, \Pi^{ab}, \Lambda^{ab})$$



## Restricted Boltzmann machine (RBM)

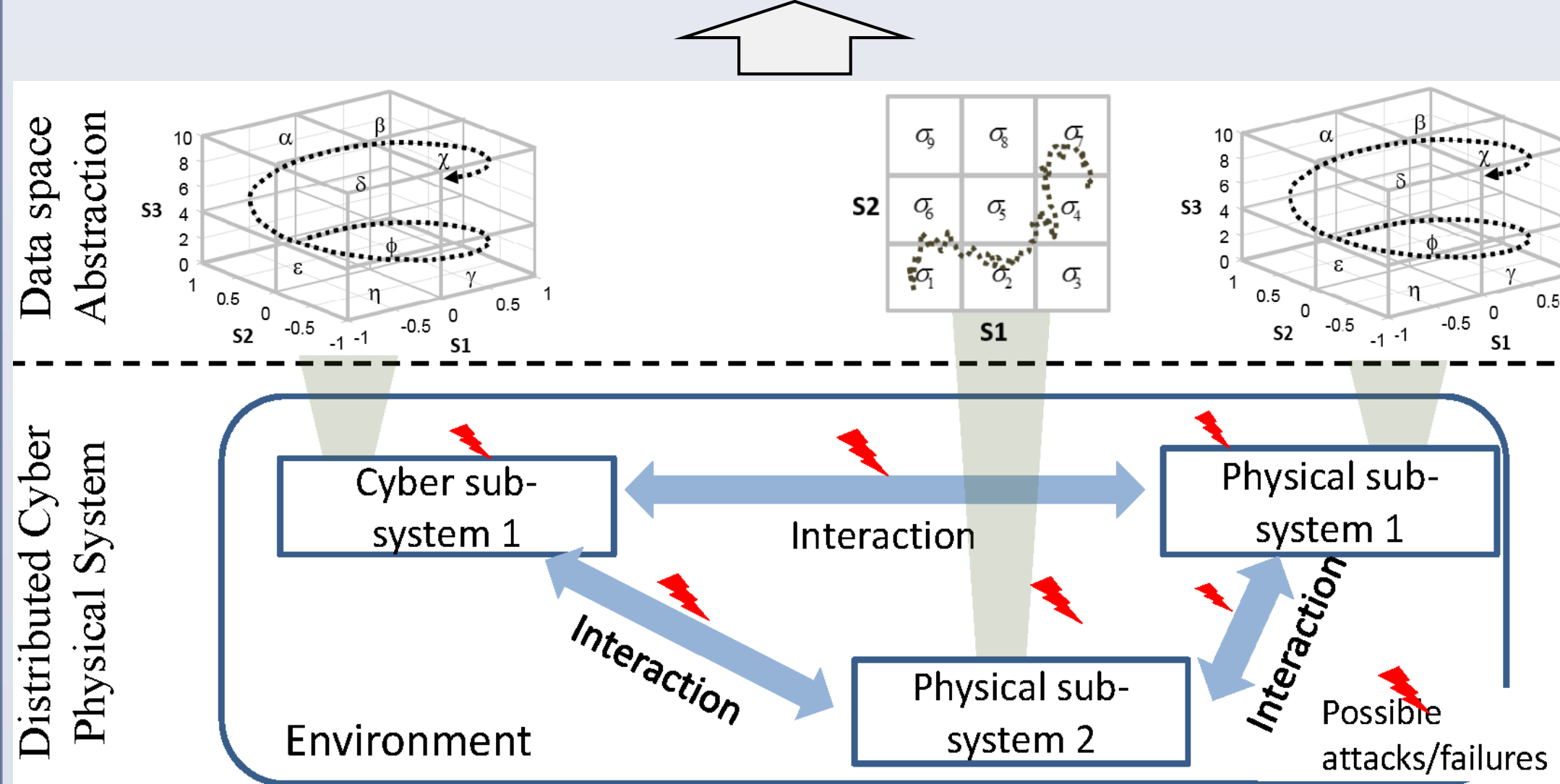
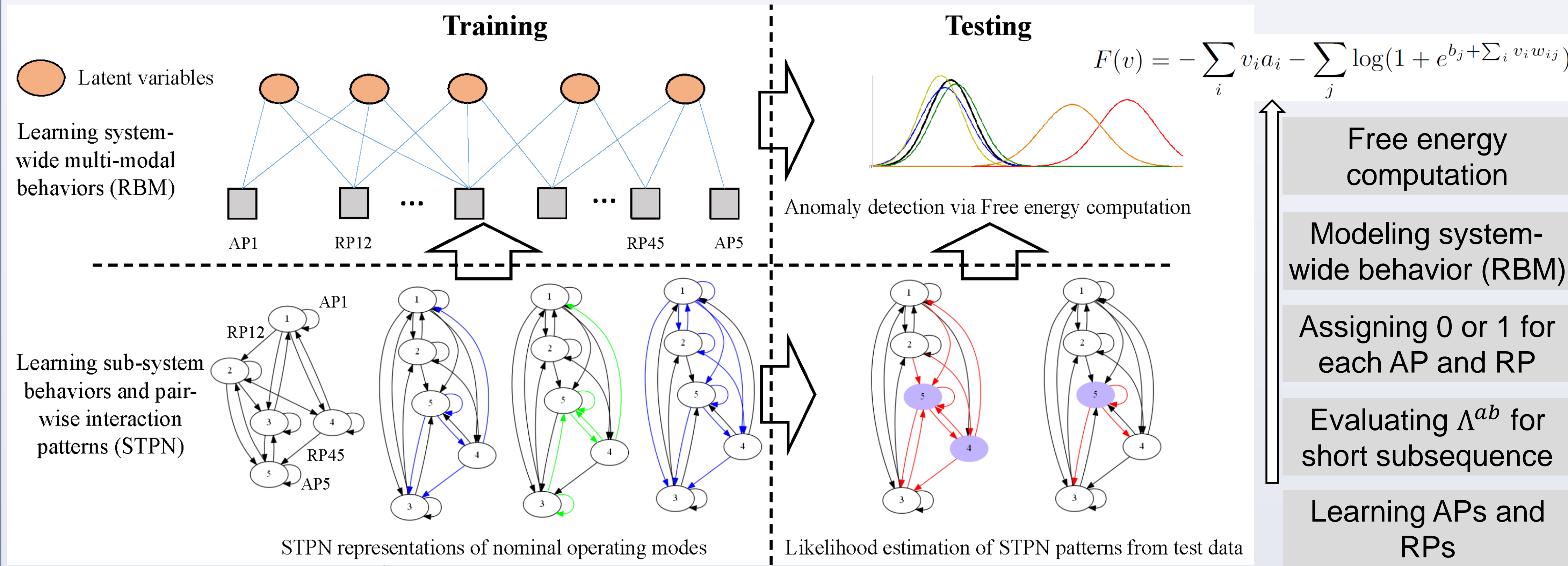
- Stochastic energy based graphical model using Boltzmann distribution to represent joint distribution visible ( $v$ ) and hidden ( $h$ ) variables

$$P(v, h) = \frac{e^{-E(v, h)}}{\sum_{v, h} e^{-E(v, h)}}$$

- Fully connected bipartite structure between visible and hidden layers, no connection within a layer

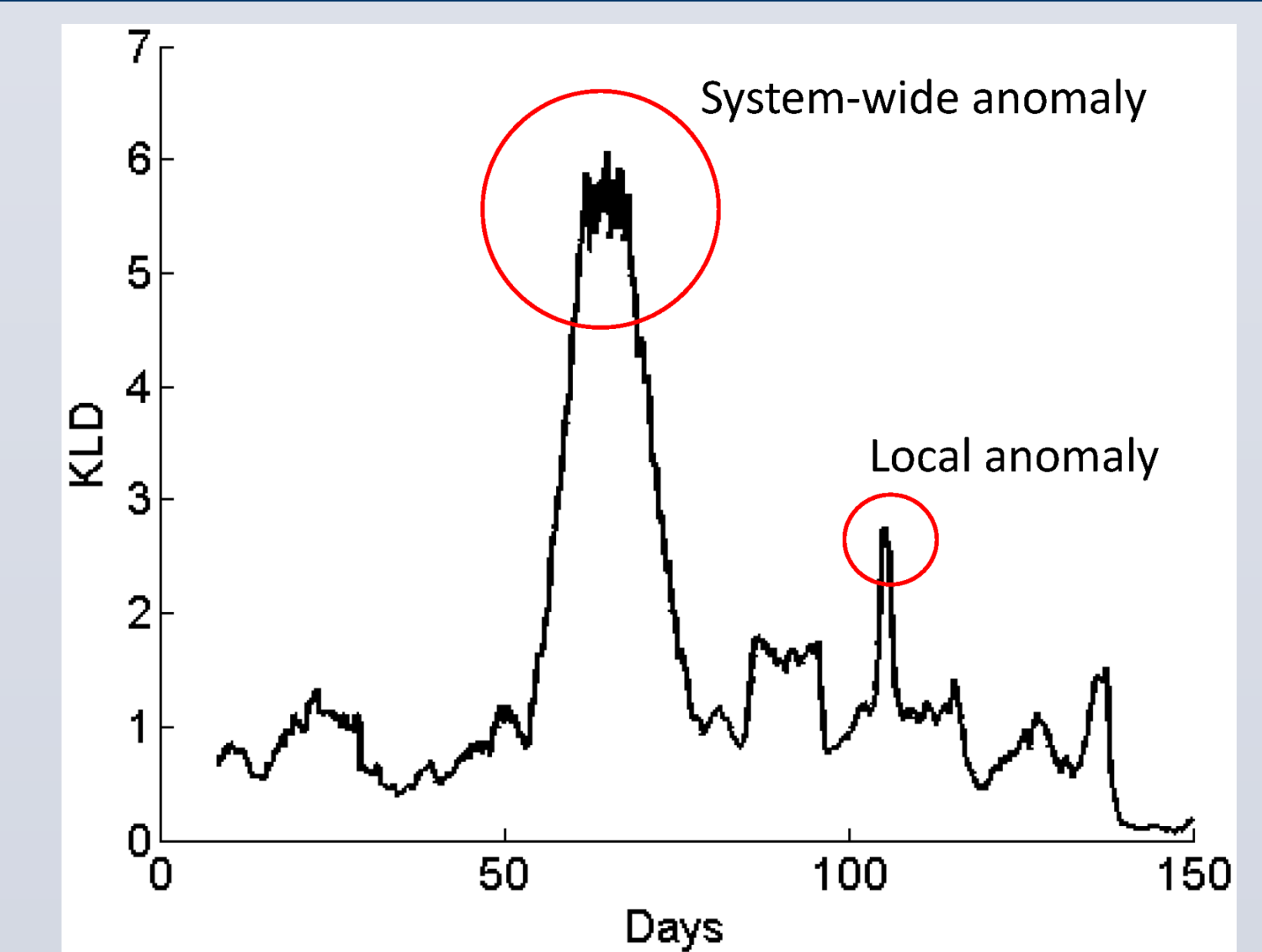
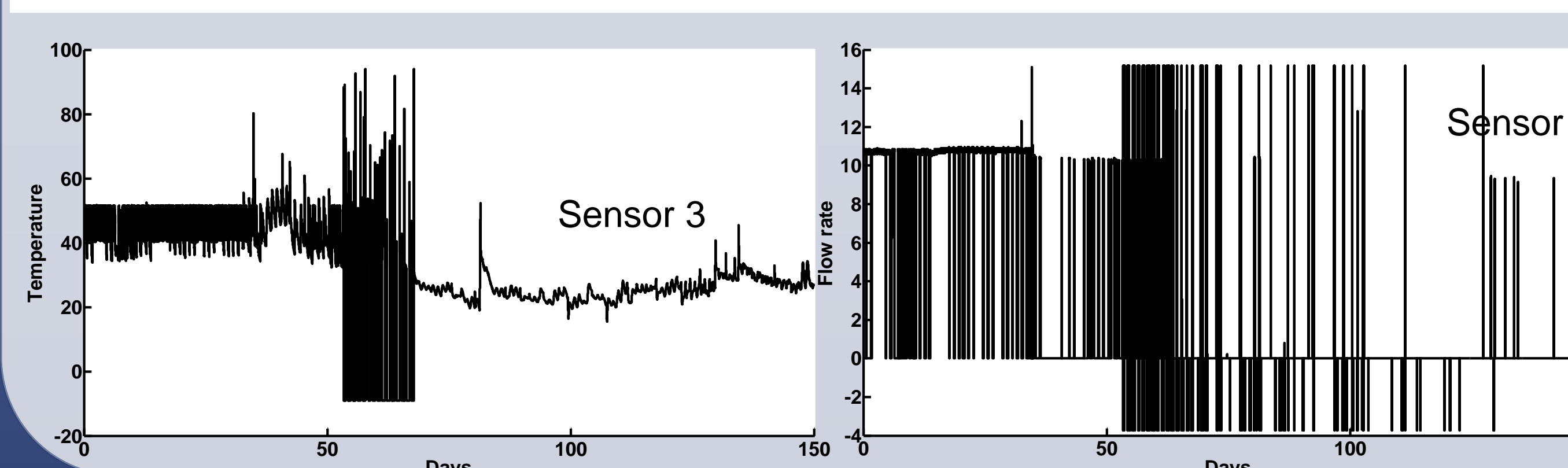
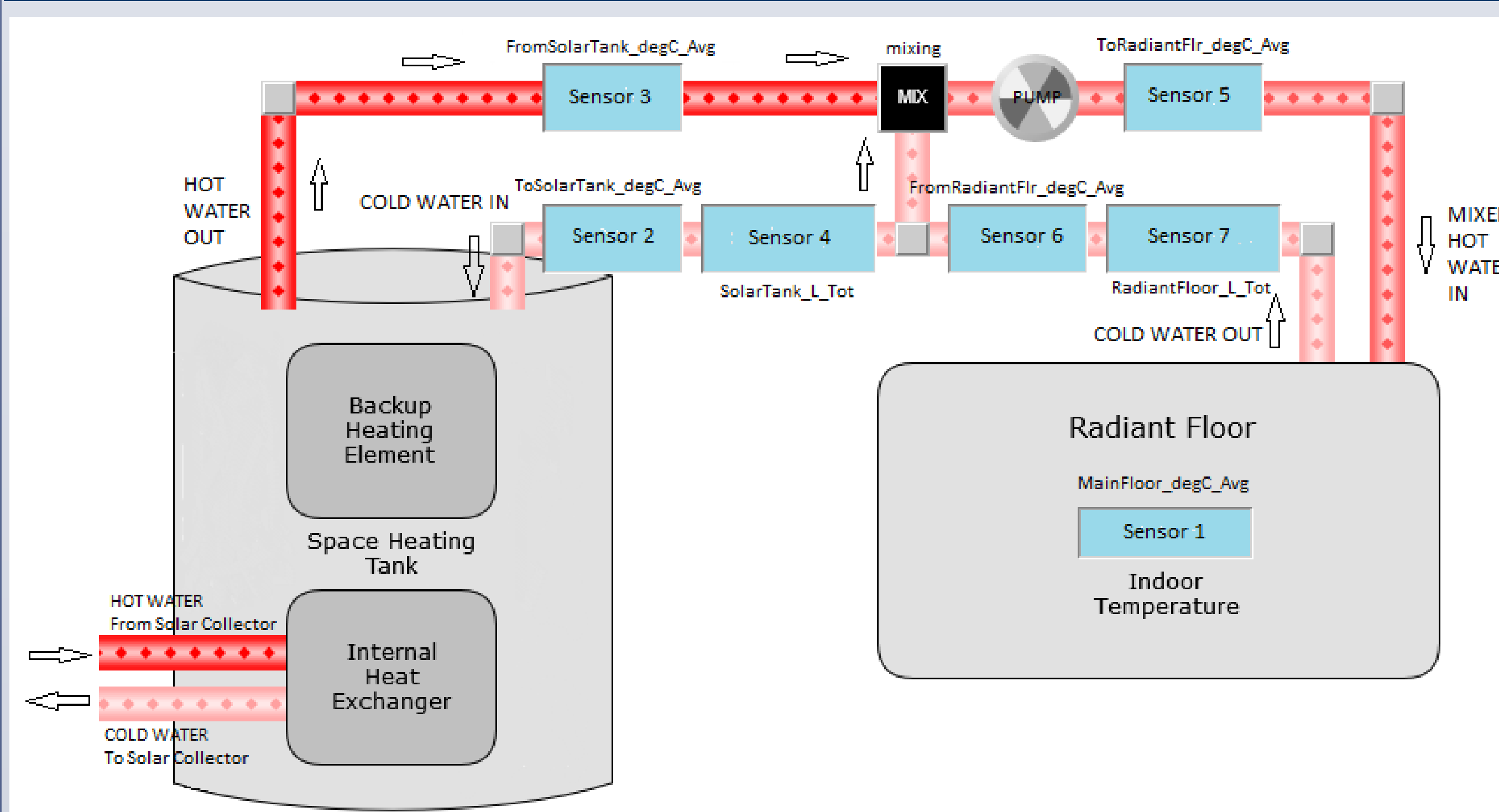
## Unsupervised spatiotemporal graphical modeling approach to anomaly detection

### Data-driven framework for system-wide anomaly detection



- Symbolic analysis can process **mixed data types**: (1) continuous temporal information from physical space, (2) discrete event-driven data from cyber space
- **STPN models sub-systems** (by atomic pattern, AP) and their interactions (by relational pattern, RP)
- **Multiple nominal modes**: each STPN represents an operational mode and multiple modes are captured by RBM via minimizing energy of all nominal STPN configurations

## Validation on a Real System – Net Zero energy Building test bed (Interlock House, Iowa)



- Detect **global anomaly** that appears as a large peak, and **local anomaly** which is intermittent and not much pronounced.
- Handle nominal data for all such modes without false detection, including different sets of test data for **different operational modes** (summer and winter).

## Discussions

- Case study shows: technique can process **mixed data types** and capture **multiple nominal modes**.
- Can detect both **local and global anomalies**.
- **Robust** to spurious disturbances as it is designed to identify only persistent anomalies.
- Potential for monitoring ranging from small physical degradation to severe faults/cyber-attacks.

## Conclusions & Future Work

- A new **data-driven framework** for CPSs to address a wide-range of nominal operating modes and unforeseen anomalous situations.
- A **spatiotemporal feature extraction** scheme for discovering the causal interactions and a free energy estimation of system-wide patterns.

### Further works will pursue the following:

- **Root-cause analysis** with graphical model,
- **Stacked RBM approach** to capture more complex nominal patterns,
- Detection of **simultaneous multiple faults** in distributed CPSs, and
- **System-wide event propagation and impact analysis** in both off-line and on-line fashion.

## Team & Acknowledgments

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