Distributed In-Network Decision Making in Sensor Networks

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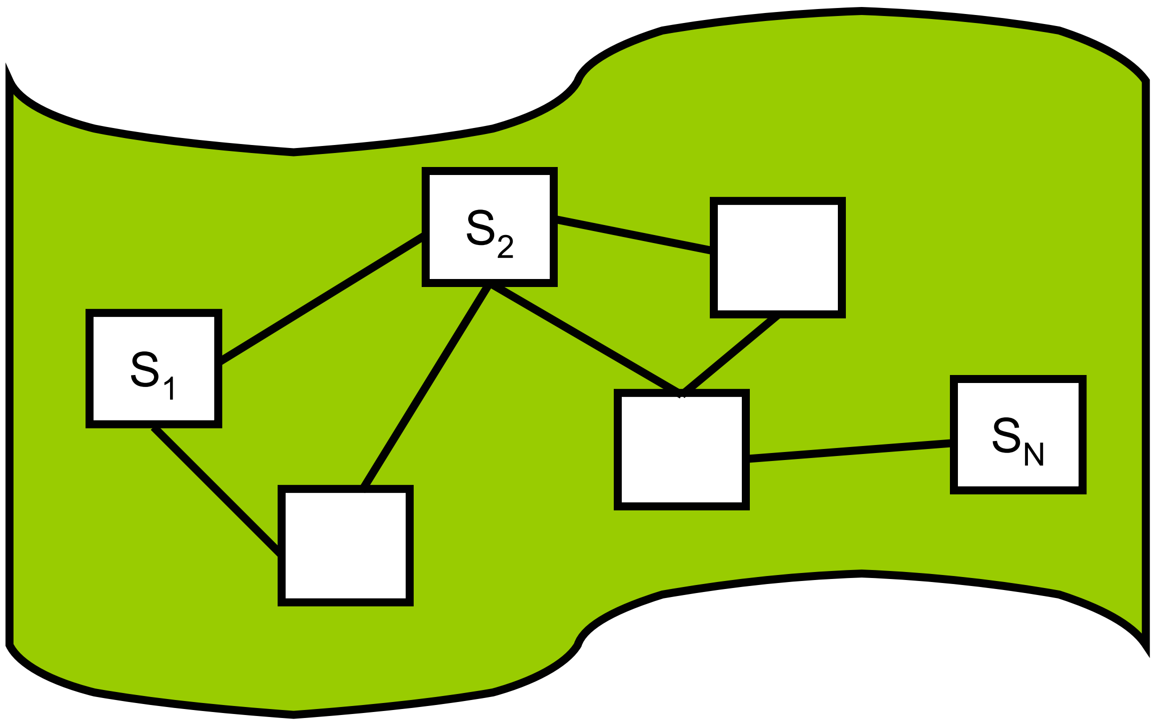
Applications

Moisture sensors on trees
BU Sargent Camp

- Habitat monitoring
- Inventory control
- Military applications
- …

Salient Features



- Spatial and temporal variability of sensed data
- Low-resolution / inexpensive sensors
- Multiple sensing modalities (e.g. moisture,light,…)
- Wireless communication links (topology depends on geographical proximities)

Features Contd

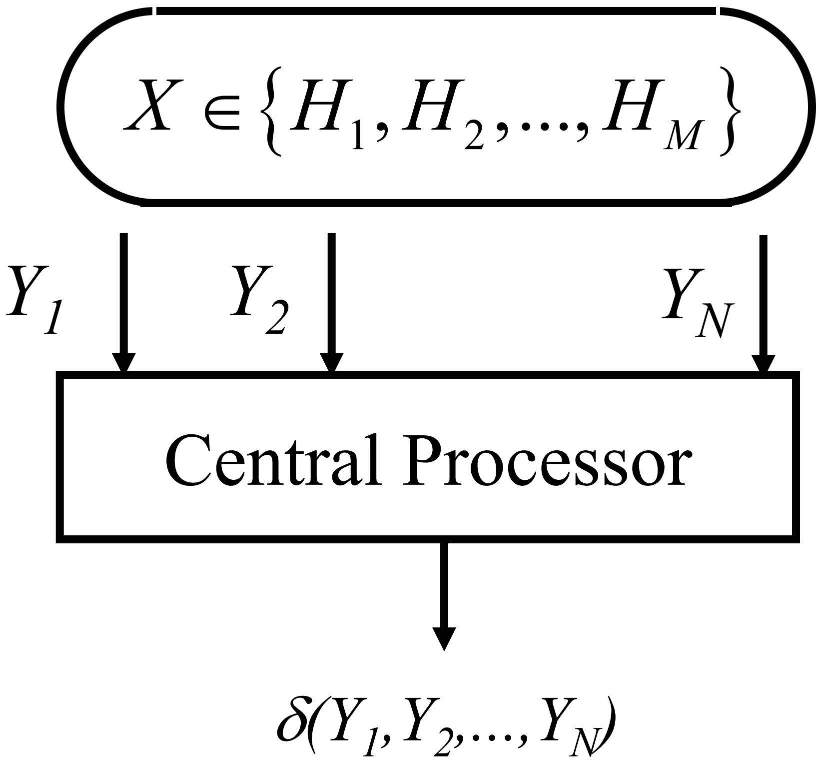
Sensing Tasks:

- Classification
- Parameter Estimation
- Localization
- Tracking

Requirements:

- Scalable architecture
- Power efficiency
- Robustness to failures
- Ad-hoc operation
- Graceful response to quantization & errors

Centralized Detection



Y_i : Measurement of sensor i

δ : Decision rule

- Model:

  $P(Y_1, Y_2, \ldots, Y_N \mid X)$

- Formulation:

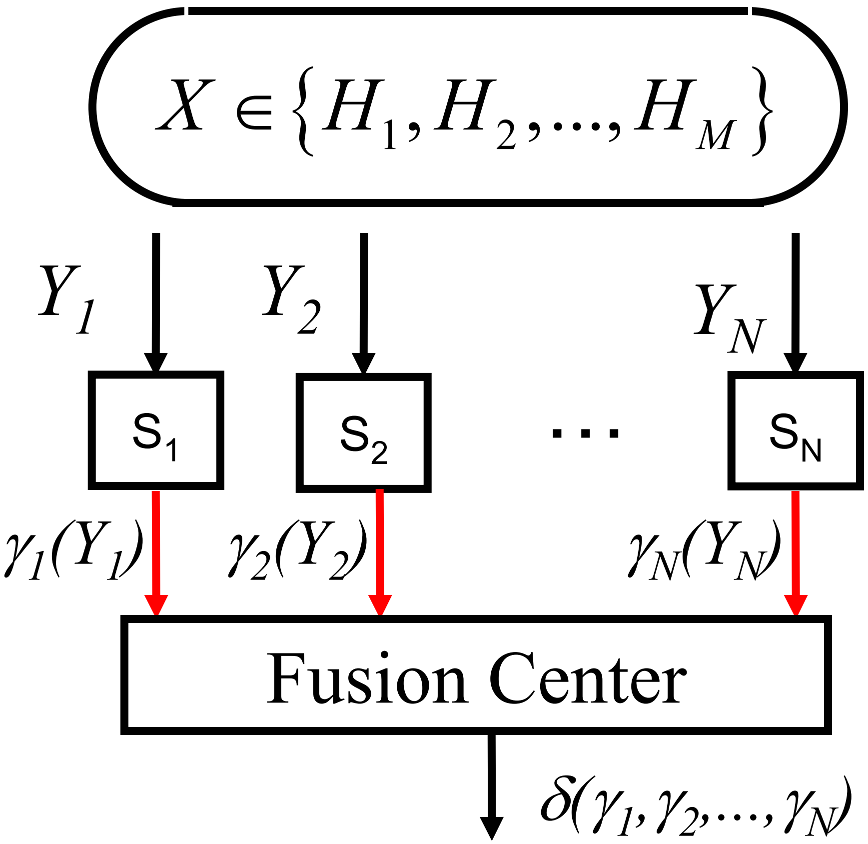
  Bayesian, Minimax, Neyman-Pearson, …

  (Van Trees 1968)

- Maximum Likelihood (ML) estimator:

  $max_m\, P(Y_1 = y_1, \ldots, Y_N = y_N \mid H_m)$

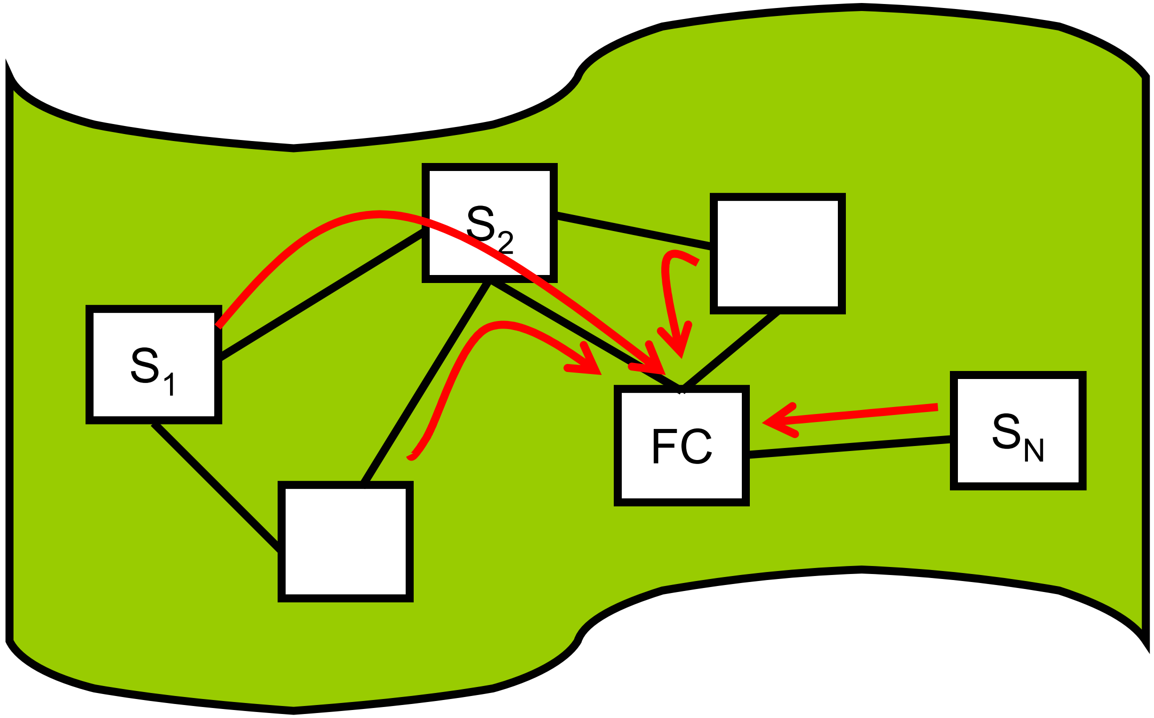
Decentralized Detection



$\gamma_i \in Finite\ Alphabet$

- Finding optimal rules is hard (Papadimitriou & Tsitsiklis 1986)
- Special cases:
  Forms of optimal γ_i , δ are known but depend on other sensors' measurement models. (Tsitsiklis 1993)
- The CEO problem:
  Minimize distortion between X and δ subject to rate constraint on channels (Berger et al., 1996)

Accounting for the Network

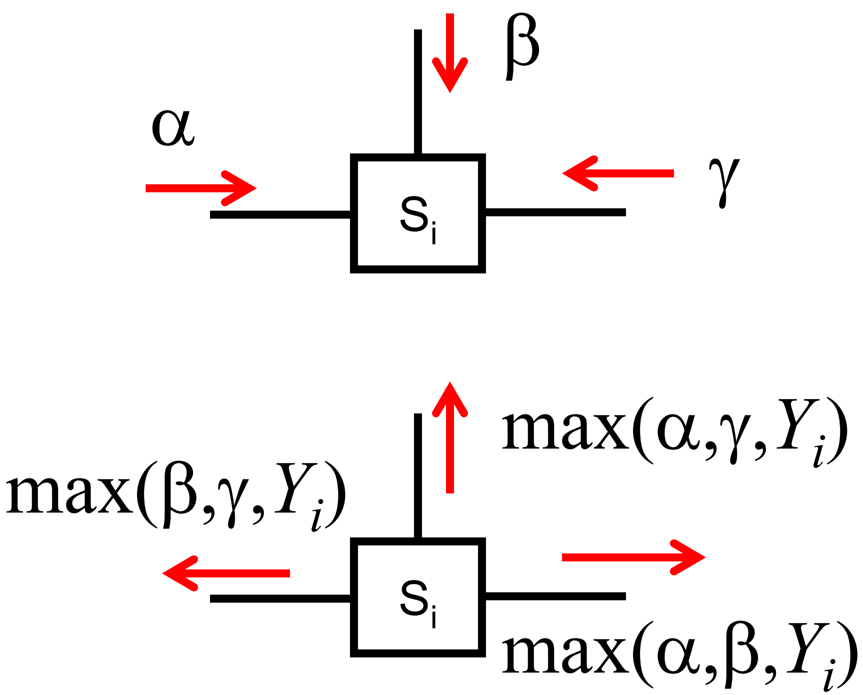


Issues:

- Limitations due to network transport capacity (Gupta & Kumar 2000)
- Is out-of-network processing efficient?

In-Network Processing

- Ex: Find max$\{Y_1, \ldots, Y_N\}$



Related work:

In-network data aggregation (TinyDB, Cougar, TiNa, Galore):

- Distributed Query processing
- Hierarchical topologies

Our Goal

General approach to distributed in-network
{detection, estimation, tracking,…}

Essential Components:

1. Modeling spatial correlations in data
2. *Local* message passing techniques

1. Modeling Sensed Medium

- Markov Random Fields:

  $X=(X_1, X_2, \ldots, X_N)$ is a MRF wrt graph (N,E) if

$$P(\underline{x}) \propto \prod_{i \in N} \phi_i(x_i) \prod_{(i,j) \in E} \mu_{i,j}(x_i, x_j)$$

$\phi_i(x_i)$ Self potential

$\mu_{i,j}(x_i, x_j)$ Pair potential

Models in image processing, coding, statistical mechanics,…

- Example:

$$X_i \in \{H_1, H_2, \ldots, H_M\}$$

$$\phi_i(H_m) = P(Y_i = y_i \mid H_m)$$

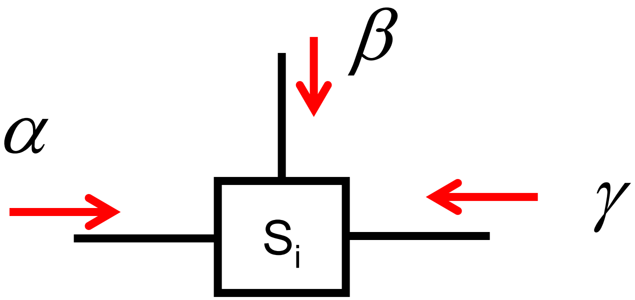
$$\mu_{i,j}(H_i, H_j) = 1\{H_i = H_j\}$$

$$P(\underline{x}) \propto \prod_i P(Y_i = y_i \mid H_m)$$

If $x_1 = \ldots = x_N = H_m$

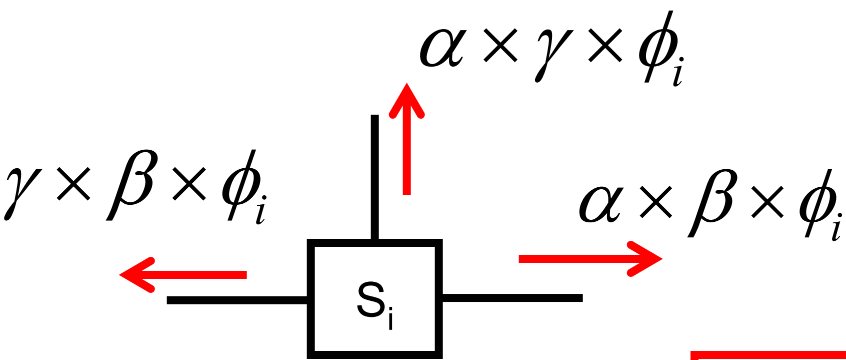
2. Local Message Passing

- Belief propagation (Pearl 1988)
- Example continued: Pearl's sum-product algorithm



"Belief" of sensor i:

$$\pi_i(H_m) \propto \alpha \times \beta \times \gamma \times \phi_i(H_m)$$



If network topology is a tree, then eventually

$$\pi_i(H_m) \propto \prod_j P(Y_j = y_j \mid H_m)$$

Cond. Independent observations:
ML estimate = $\arg\max_m \pi_i(H_m)$

Robustness: Loopy Graphs

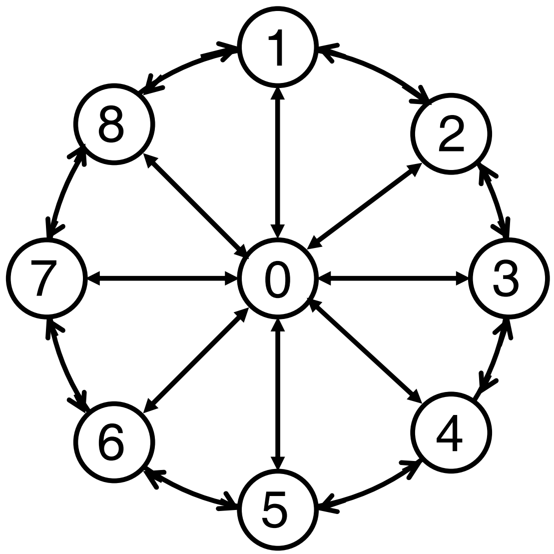
$$\pi_i(H_m) \to 0 \Leftrightarrow m \notin \arg\max_{\hat{m}} \prod_j P(Y_j = y_j \mid H_{\hat{m}})^{\lambda(j)}$$

- $\lambda(j)$ depends on how well-connected sensor j is.
- If $\lambda(j)$ = constant and m^* is the unique ML estimate, then

$$\pi_i(H_{m^*}) \to 1$$

- Final configuration is a consensus: All sensors share the same belief.

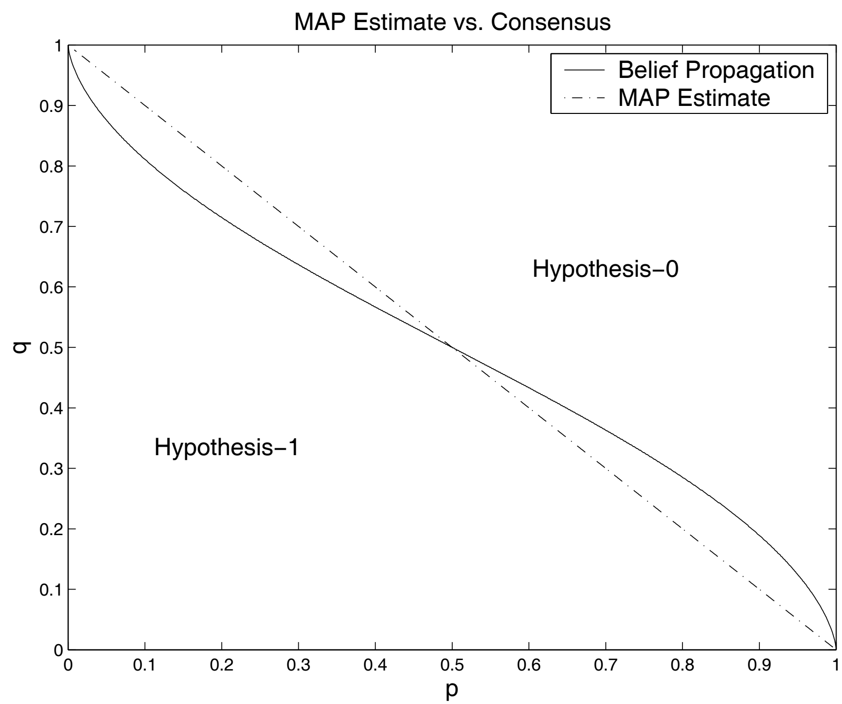
Example: Star topology



Initial Beliefs

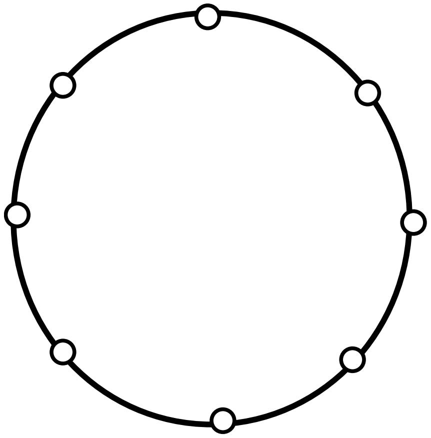
	H_0	H_1
S_0	q	$1-q$
S_1	p	$1-p$
$S_2 - S_8$	0.5	0.5

$$\frac{\lambda(0)}{\lambda(1)} = 1.5091$$

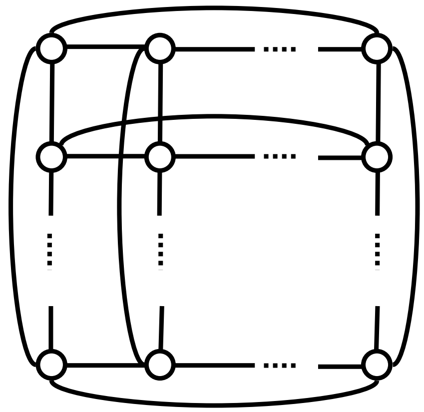


Balanced Topologies

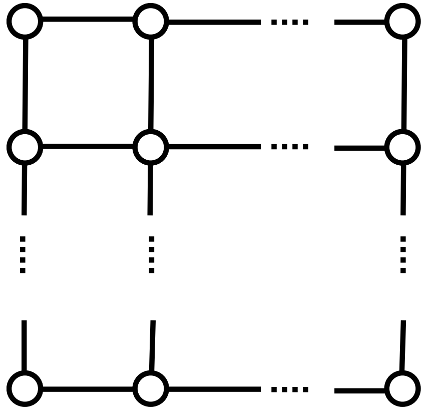
Ring



Torus



Grid

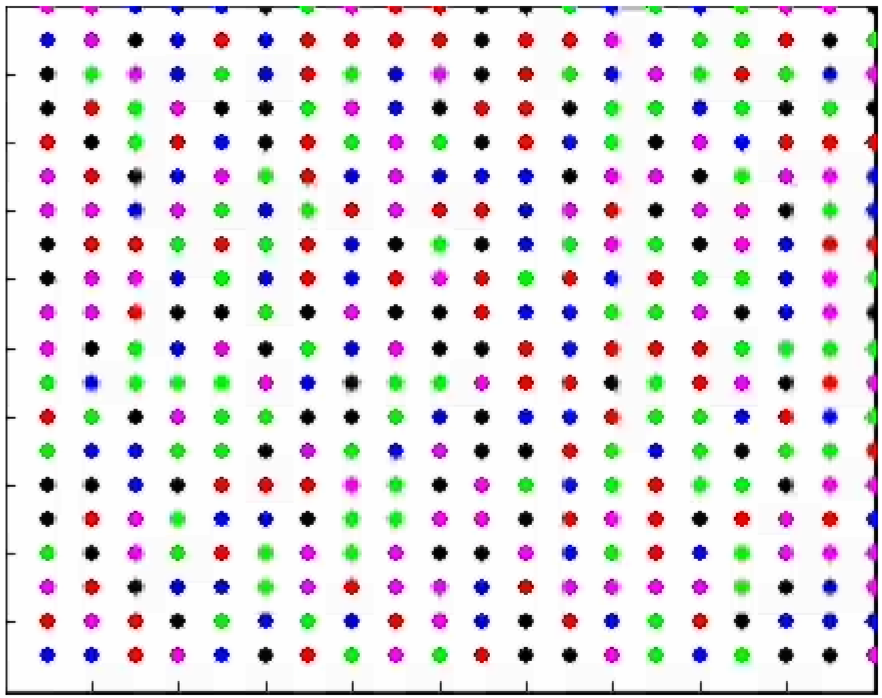


$$\frac{\lambda(i)}{\lambda(j)} \approx 1 \text{ for most nodes}$$

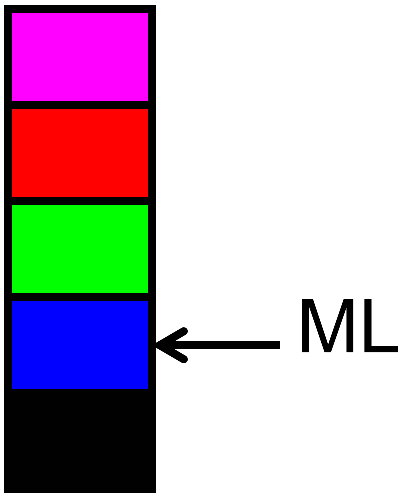
Regular Graphs:

$$\frac{\lambda(i)}{\lambda(j)} = 1 \text{ for all nodes}$$

Example: 20x20 Grid



5 Hypotheses



Most likely hypothesis by sensor

Summary

- In-network inference via local messages
- Network-wide consensus that reflects centralized solution
- Ongoing work: continuous parameter estimation & tracking
- Energy efficiency and sensor actuation strategies
- Testbed: BU Sargent Camp test field for ecological applications