



Exploiting Structured Human Interactions to Enhance Estimation Accuracy in Cyber-physical Systems

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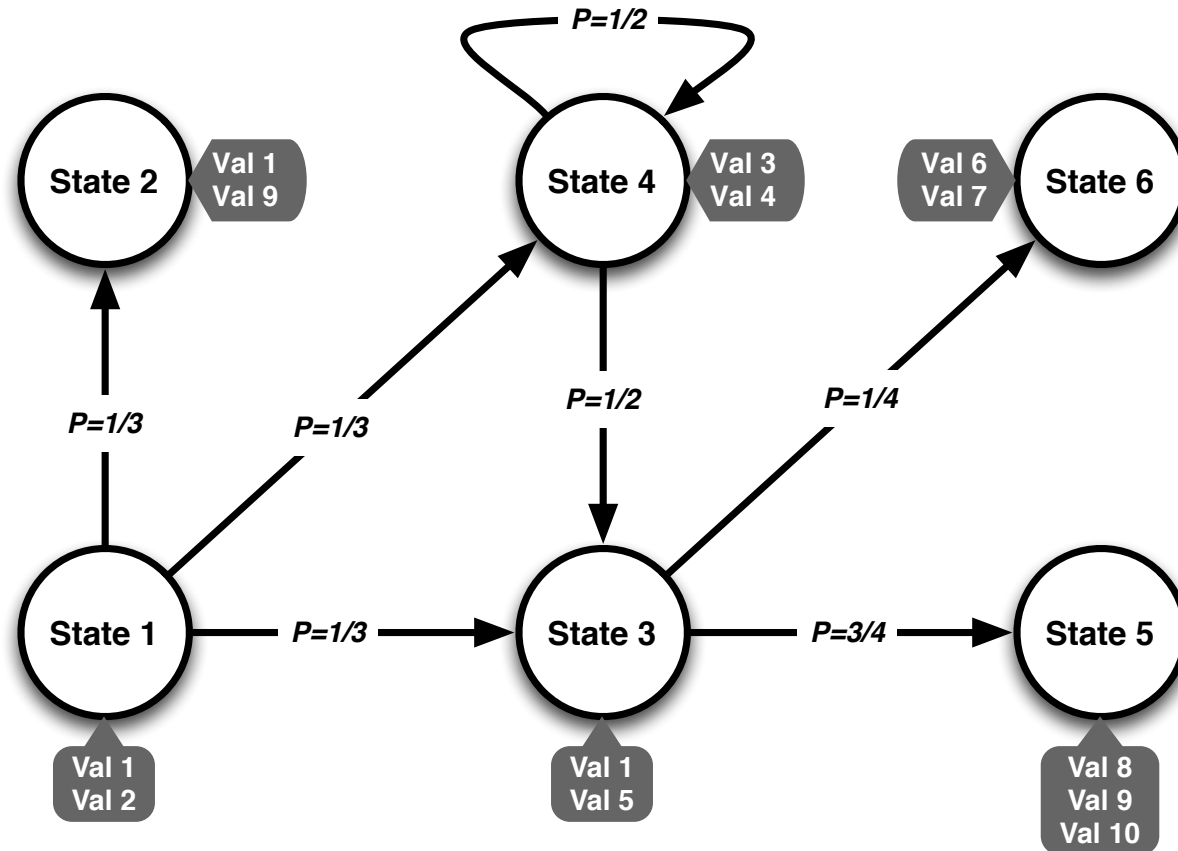




Goal

Exploit knowledge on underlying *workflows* information to *improve* estimation accuracies from *unreliable* sensors in cyber-physical systems.

Problem Model



- Given: workflow (state transition model) and (noisy) measurements
- Seek: state sequence and value estimations

Analytic Formulation

- State transition sequence:

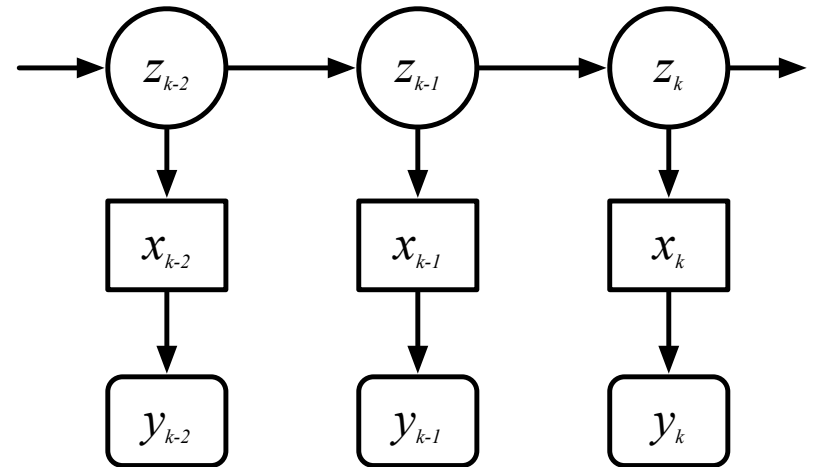
$$\mathbf{z} = (z_1, \dots, z_T)$$

- True value sequence:

$$\mathbf{x} = (x_1, \dots, x_T)$$

- Measurement sequence:

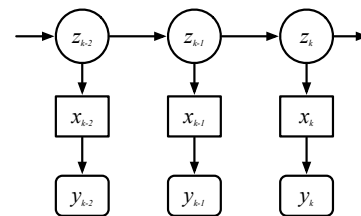
$$\mathbf{y} = (y_1, \dots, y_T)$$



Augmented HMM

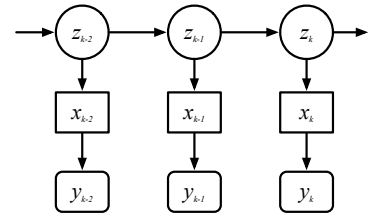
Objective:
$$\widehat{\mathbf{z}\mathbf{x}} = \underset{\mathbf{z}\mathbf{x}}{\operatorname{argmax}} p(\mathbf{z}\mathbf{x} | \mathbf{y})$$

Analytic Formulation



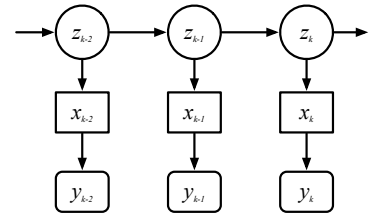
$$\begin{aligned} p(\mathbf{z}\mathbf{x}|\mathbf{y}) &= \frac{p(\mathbf{z}\mathbf{x}\mathbf{y})}{p(\mathbf{y})} \\ &= \frac{p(\mathbf{y}|\mathbf{x}\mathbf{z})p(\mathbf{z}\mathbf{x})}{p(\mathbf{y})} \\ &= \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x}|\mathbf{z})p(\mathbf{z})}{p(\mathbf{y})} \end{aligned}$$

Analytic Formulation



$$\begin{aligned} p(\mathbf{z}\mathbf{x}|\mathbf{y}) &= \frac{p(\mathbf{z}\mathbf{x}\mathbf{y})}{p(\mathbf{y})} p(z_0) \prod_{i=1}^T p(z_i|z_{i-1}) \\ &= \frac{p(\mathbf{y}|\mathbf{x}\mathbf{z})p(\mathbf{z}\mathbf{x})}{p(\mathbf{y})} \uparrow \text{Markov property} \\ &= \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x}|\mathbf{z})p(\mathbf{z})}{p(\mathbf{y})} \end{aligned}$$

Analytic Formulation



$$p(\mathbf{z}\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{z}\mathbf{x}\mathbf{y})}{p(\mathbf{y})} p(z_0) \prod_{i=1}^T p(z_i|z_{i-1})$$

$$= \frac{p(\mathbf{y}|\mathbf{x}\mathbf{z})p(\mathbf{z}\mathbf{x})}{p(\mathbf{y})}$$

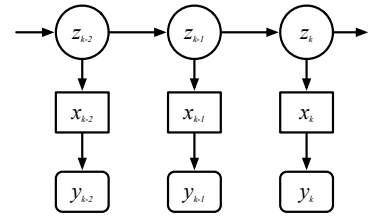
Markov property

$$= \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x}|\mathbf{z})p(\mathbf{z})}{p(\mathbf{y})}$$

emission probabilities

$$\prod_{i=1}^T p(x_i|z_i)$$

Analytic Formulation



$$\begin{aligned}
 \prod_{i=1}^T p(y_i | x_i) &= \frac{p(\mathbf{z} \mathbf{x} | \mathbf{y})}{p(\mathbf{y})} p(z_0) \prod_{i=1}^T p(z_i | z_{i-1}) \\
 &= \frac{p(\mathbf{y} | \mathbf{x} \mathbf{z}) p(\mathbf{z} \mathbf{x})}{p(\mathbf{y})} \\
 &= \frac{p(\mathbf{y} | \mathbf{x}) p(\mathbf{x} | \mathbf{z}) p(\mathbf{z})}{p(\mathbf{y})}
 \end{aligned}$$

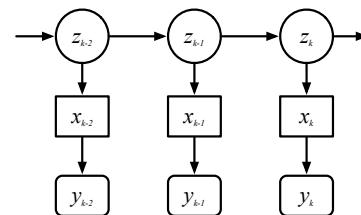
value confusion probability (points to $\prod_{i=1}^T p(y_i | x_i)$)

Markov property (points to $\prod_{i=1}^T p(z_i | z_{i-1})$)

emission probabilities (points to $p(\mathbf{y} | \mathbf{x})$)

$$\prod_{i=1}^T p(x_i | z_i)$$

Analytic Formulation



- Rewritten objective:

$$\widehat{\mathbf{zX}} = \arg \max_{\mathbf{zX}} \left[\prod_{i=1}^T p(x_i | z_i) \right. \\ \prod_{i=1}^T p(z_i | z_{i-1}) \\ \prod_{i=1}^T p(y_i | x_i) \\ \left. p(z_0) \right]$$

DP Solution Sketch

- Denote the solution at T as $\mu_T(z_T, x_T)$, then we have the recurrence:

$$\mu_T(z_T, x_T) = \arg \max_{z_{1:T}, x_{1:T}} [\mu_{T-1}(z_{T-1}, x_{T-1}) p(x_T | z_T) p(z_T | z_{T-1}) p(y_T | x_T)]$$

- DP complexity: $O(TVN^2)$, where T - workflow path length, V - value space size, N - state space size
 - exhaustive search: $O((VN)^T)$

Evaluation: Simulation

- Topologies

- Directed graphs:

- # Nodes: 30
 - Average degree: 3
 - # Values per node: 5
 - Path length: 6
 - Sensor reliability: 0.6

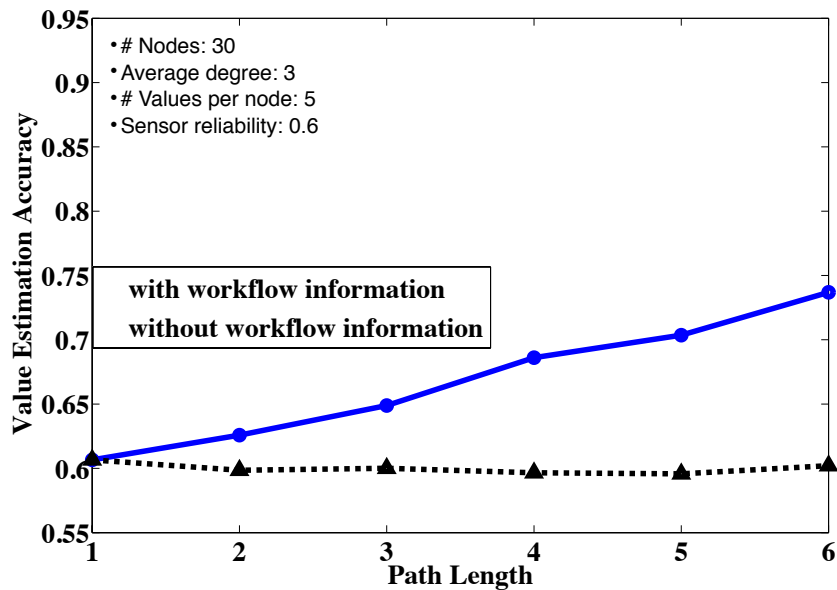
- Directed tree:

- Height: 5
 - Order: 3
 - # Values per node: 5
 - Path length: 6
 - Sensor reliability: 0.6

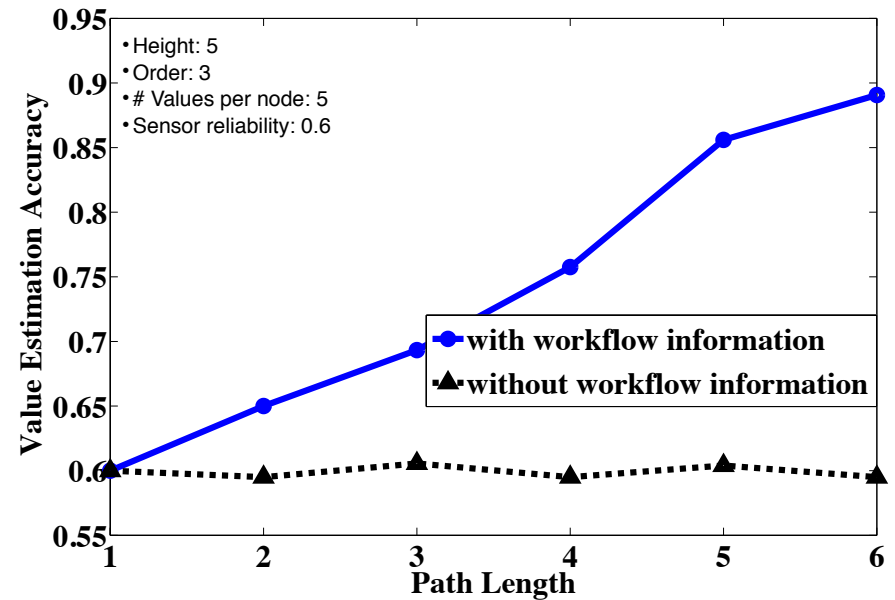
- Randomly generated workflow topologies
- Randomly selected groundtruth workflow paths
- Metric: estimation accuracy

Simulation Results

Graphs



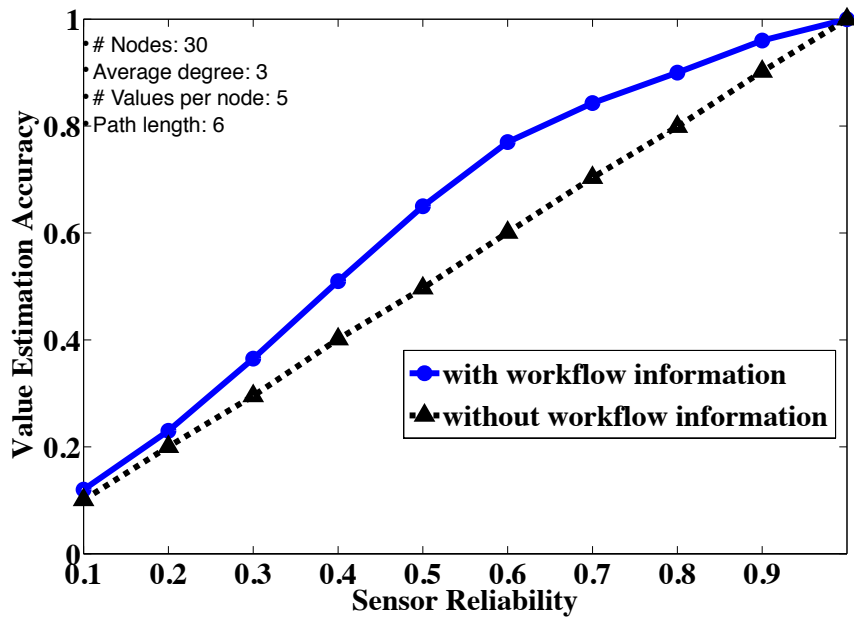
Trees



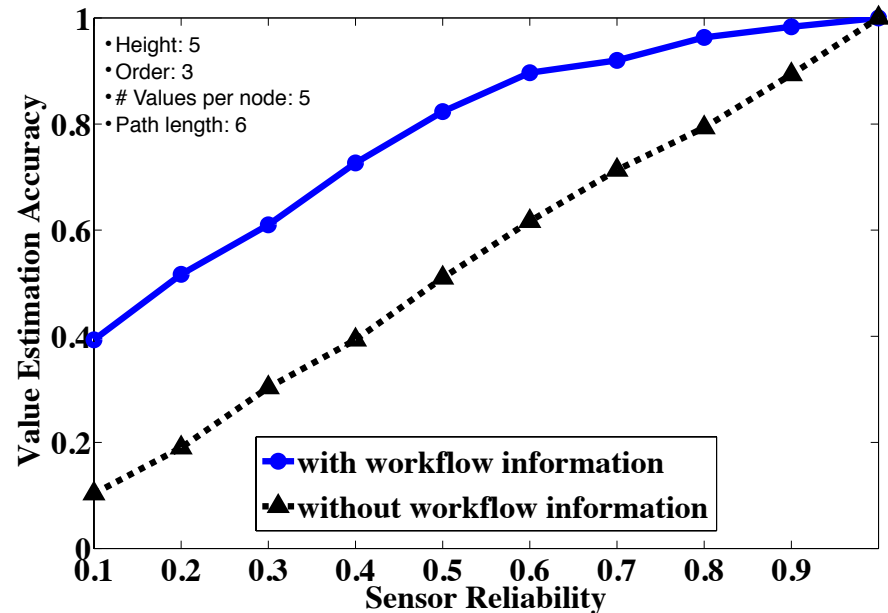
Longer workflow path => **Higher error correction power**

Simulation Results

Graphs



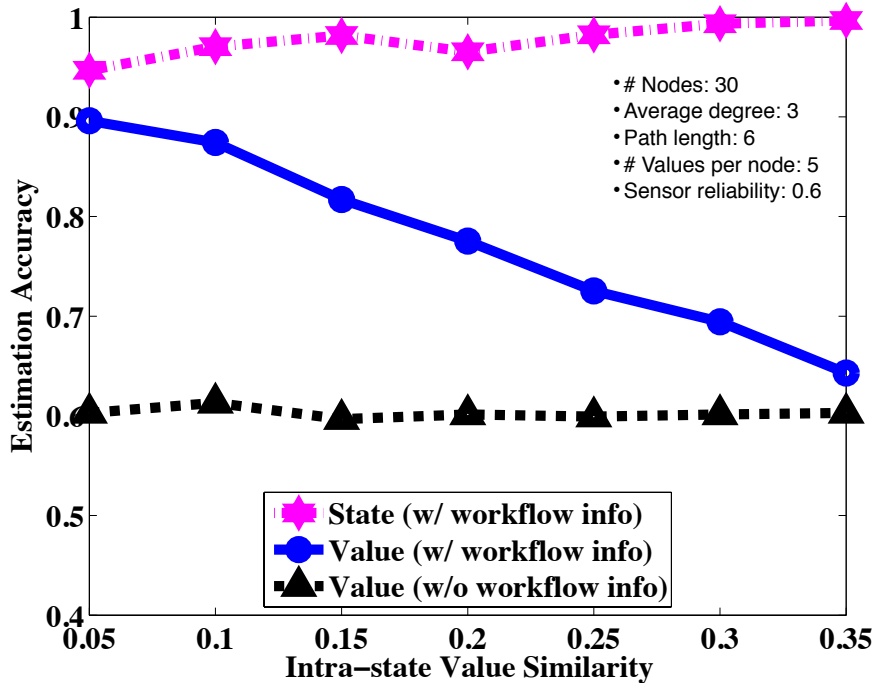
Trees



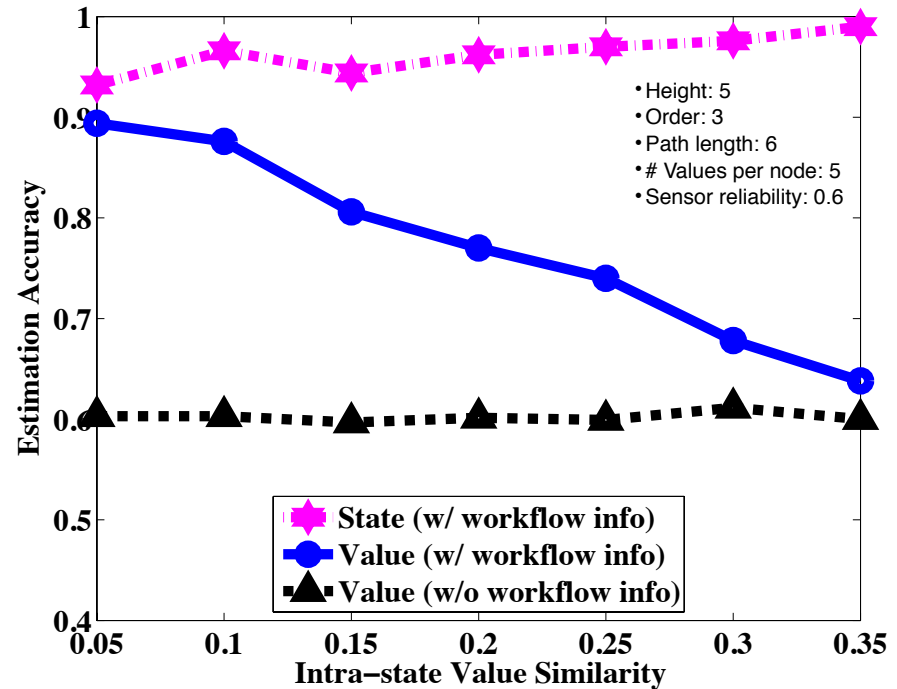
Higher sensor reliability => **Higher classification & tracking accuracy**

Simulation Results

Graphs



Trees



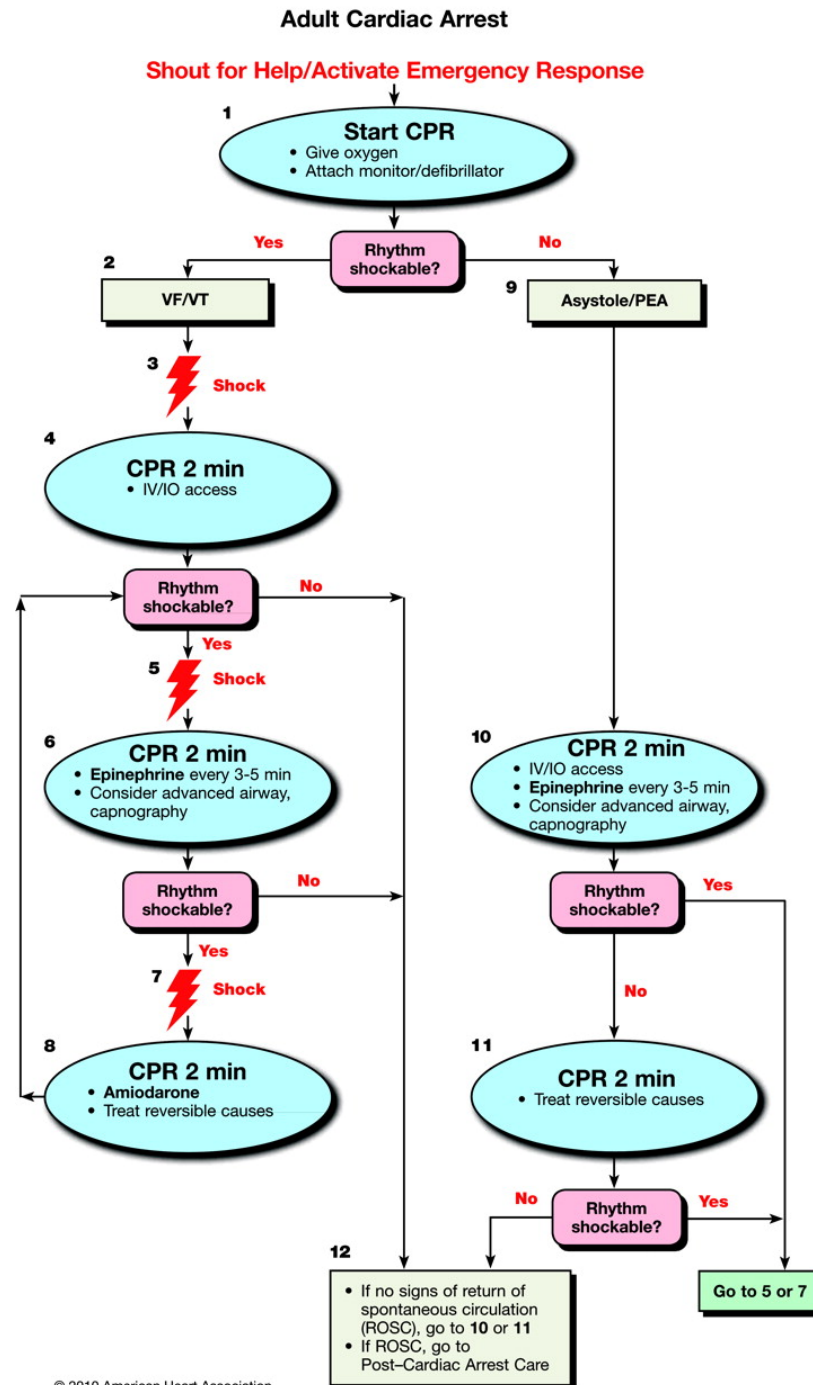
Higher intra-state value similarity => **Higher state tracking accuracy,**
Lower value estimation accuracy

Evaluation: Case Study

- Emergency Transcriber
 - Scenario: cardiac arrest, with multiple physicians and nurses operating at the same time, **vocally** communicating medical orders under **noisy** environment.
 - Goal: track/record the progress of the medical procedure

Case Study

- Realistic cardiac arrest workflow



- CPR Quality**
- Push hard (≥ 2 inches [5 cm]) and fast (≥ 100 /min) and allow complete chest recoil
 - Minimize interruptions in compressions
 - Avoid excessive ventilation
 - Rotate compressor every 2 minutes
 - If no advanced airway, 30:2 compression-ventilation ratio
 - Quantitative waveform capnography
 - If $PETCO_2 < 10$ mm Hg, attempt to improve CPR quality
 - Intra-arterial pressure
 - If relaxation phase (diastolic) pressure < 20 mm Hg, attempt to improve CPR quality

- Return of Spontaneous Circulation (ROSC)**
- Pulse and blood pressure
 - Abrupt sustained increase in $PETCO_2$ (typically ≥ 40 mm Hg)
 - Spontaneous arterial pressure waves with intra-arterial monitoring

- Shock Energy**
- **Biphasic:** Manufacturer recommendation (eg, initial dose of 120-200 J); if unknown, use maximum available. Second and subsequent doses should be equivalent, and higher doses may be considered.
 - **Monophasic:** 360 J

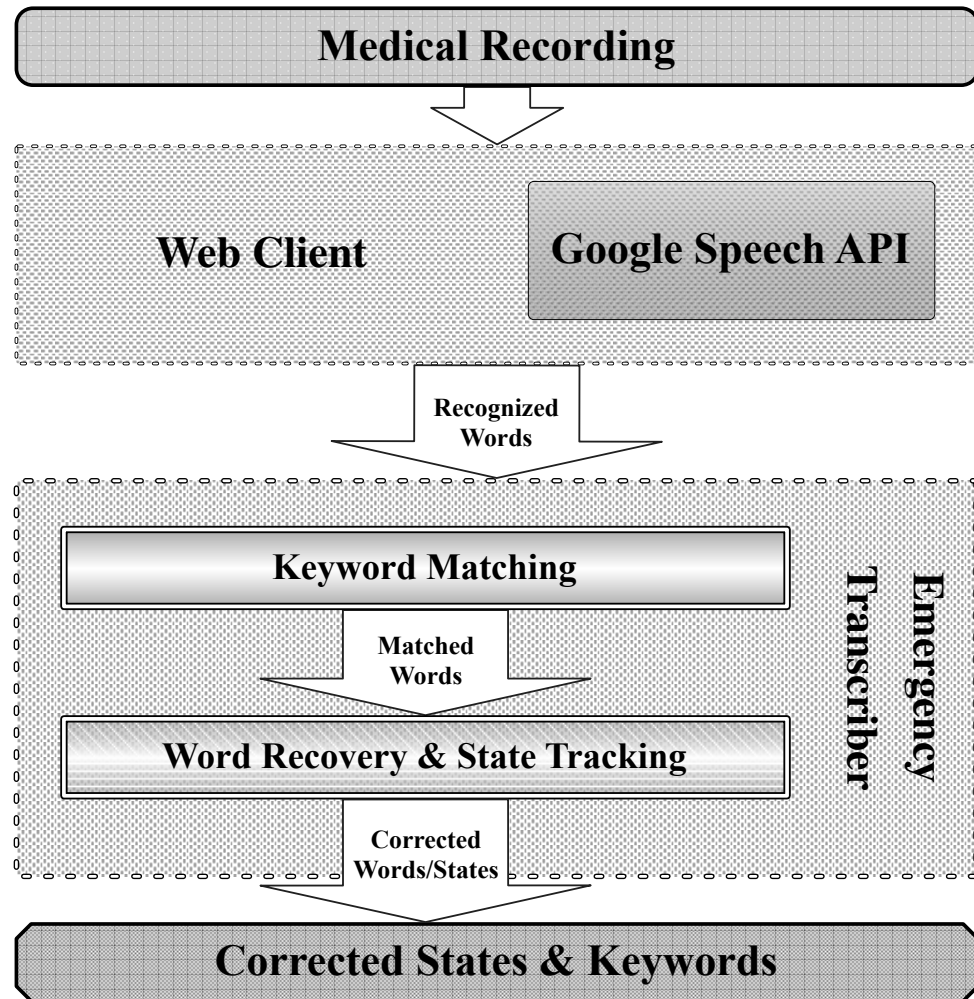
- Drug Therapy**
- **Epinephrine IV/IO Dose:** 1 mg every 3-5 minutes
 - **Vasopressin IV/IO Dose:** 40 units can replace first or second dose of epinephrine
 - **Amiodarone IV/IO Dose:** First dose: 300 mg bolus. Second dose: 150 mg.

- Advanced Airway**
- Supraglottic advanced airway or endotracheal intubation
 - Waveform capnography to confirm and monitor ET tube placement
 - 8-10 breaths per minute with continuous chest compressions

- Reversible Causes**
- Hypovolemia
 - Hypoxia
 - Hydrogen ion (acidosis)
 - Hypo-/hyperkalemia
 - Hypothermia
 - Tension pneumothorax
 - Tamponade, cardiac
 - Toxins
 - Thrombosis, pulmonary
 - Thrombosis, coronary

Case Study

- System architecture

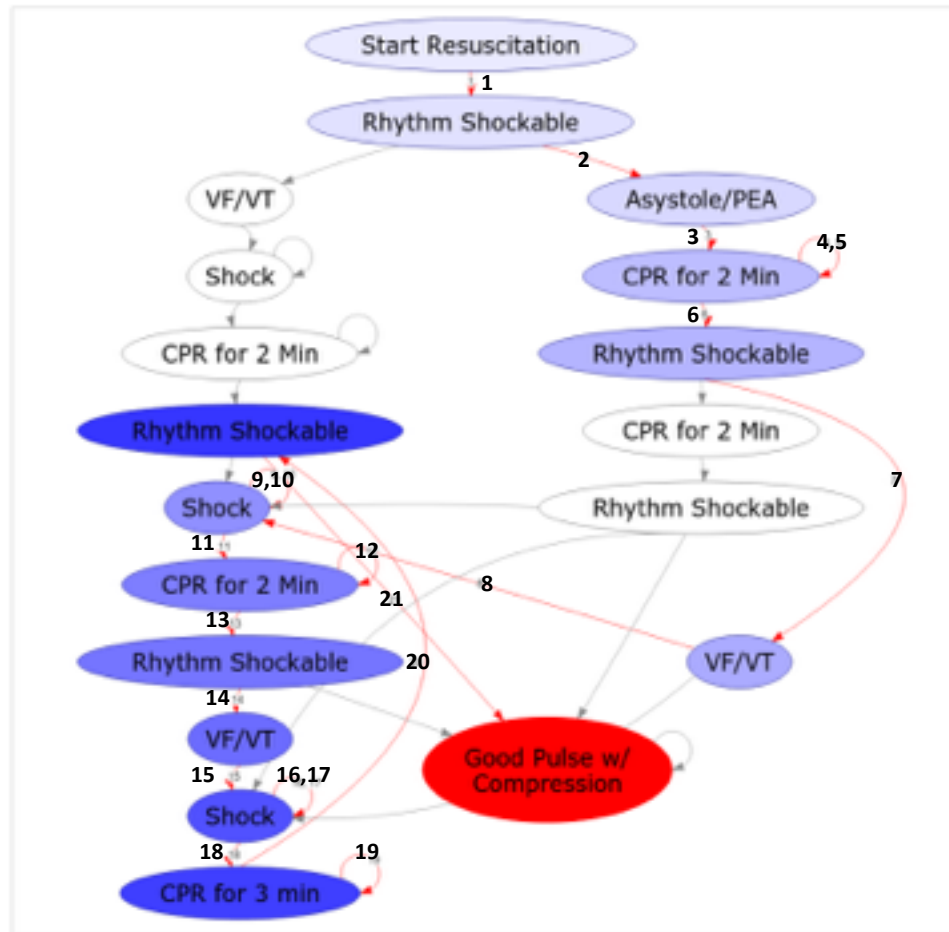


Running Instance

Emergency Transcriber - Resuscitation

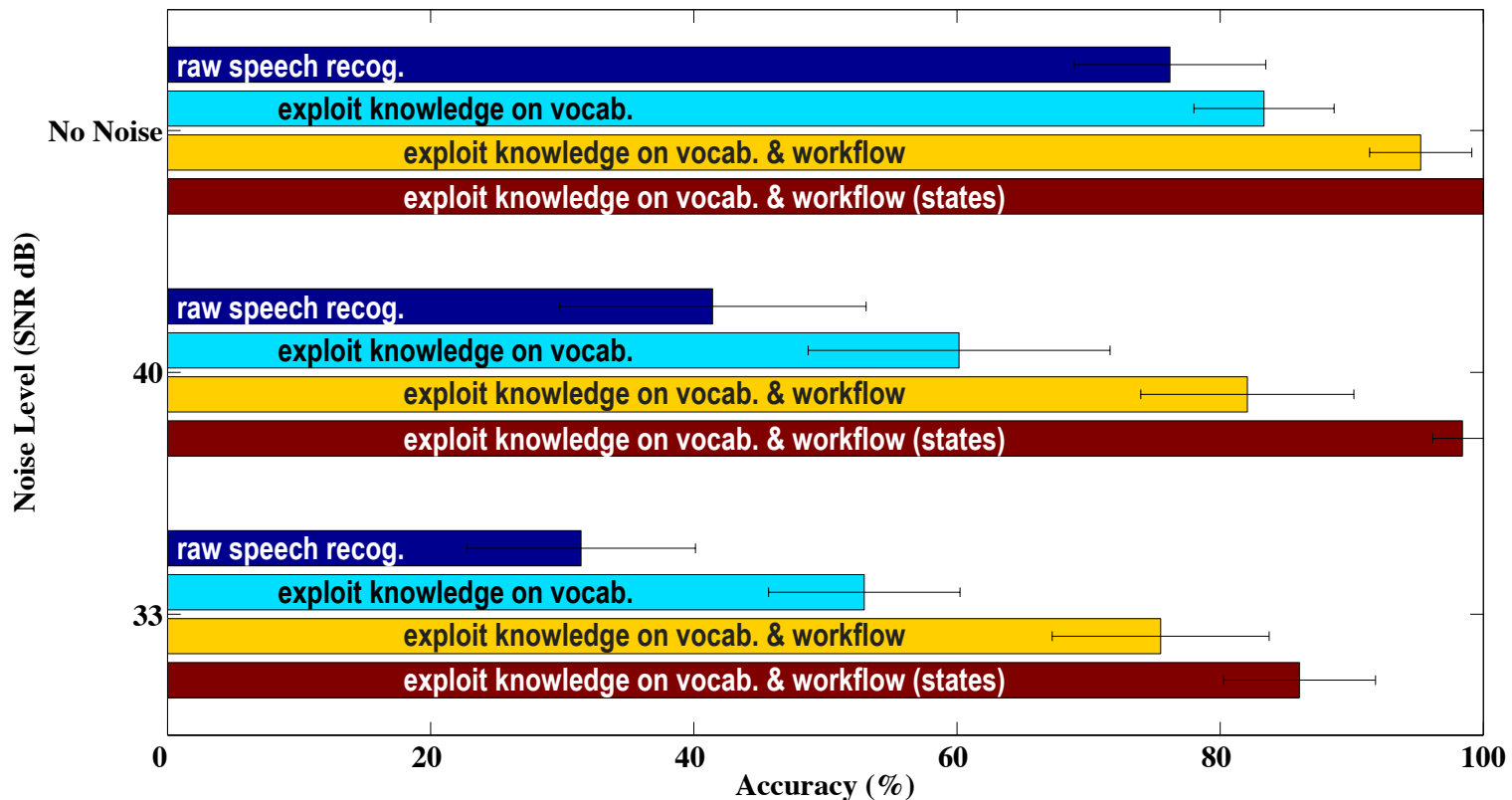
Assassination
 what's the rhythm
 the patient has a systole
 start CPR for 2 minutes
 give epinephrine for 3
 minutes interval
 what's the rhythm
 the patient has V fib
 charge the defibrillator
 the patient
 start CPR for 2 minutes
 interval
 what's the
 the patient has me fit
 defibrillator
 clear the bed
 shock the patient
 start CPR for 2 minutes
 3 minute interval
 what's the rhythm
 good pulse with compression

Send to UDP



Step	Word
0.	resuscitation
1.	rhythm
2.	asystole
3.	CPR
4.	CPR
5.	epinephrine
6.	rhythm
7.	VFib
8.	defibrillator
9.	clear
10.	shock
11.	CPR
12.	epinephrine
13.	rhythm
14.	VFib
15.	defibrillator
16.	clear
17.	shock
18.	CPR
19.	amioderone
20.	rhythm
21.	compression

Emergency Transcriber Results



- **Noise negatively affects the overall accuracy**
- **Our method takes advantage of workflow information and greatly improves estimation accuracy**

Conclusion

- We design algorithm that **improves estimation accuracies in CPS by exploiting workflow** information.
- Simulation results confirm the benefits.
- We design and implement Emergency Transcriber, and show performance in realistic settings.

THANKS