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

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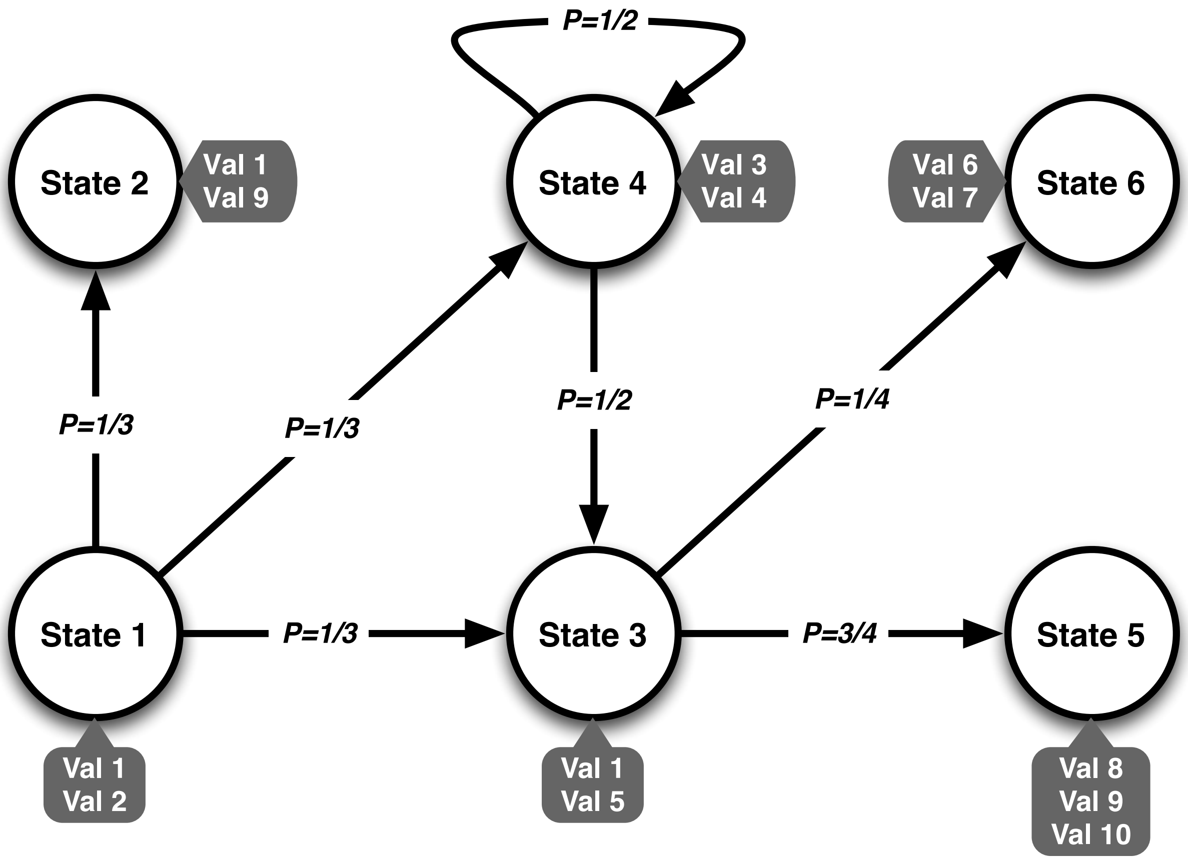
ENEMY SITUATION

Goal

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

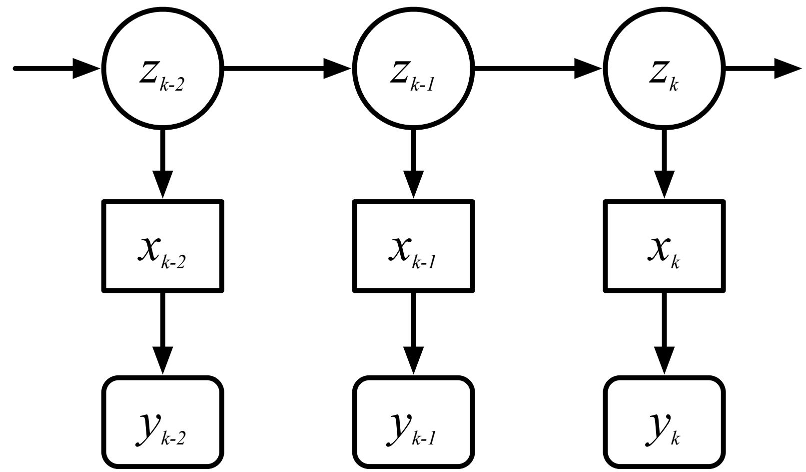
Problem Model



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

Analytic Formulation

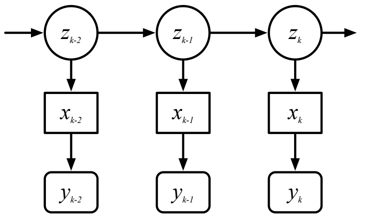
- State transition sequence:
  $$\mathbf{z} = (z_1, ..., z_T)$$
- True value sequence:
  $$\mathbf{x} = (x_1, ..., x_T)$$
- Measurement sequence:
  $$\mathbf{y} = (y_1, ..., y_T)$$



Augmented HMM

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

Analytic Formulation

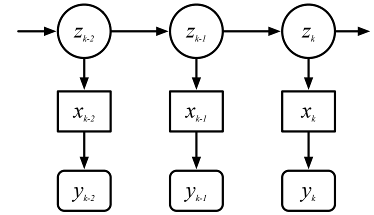


$$p(\mathbf{zx}|\mathbf{y}) = \frac{p(\mathbf{zxy})}{p(\mathbf{y})}$$

$$= \frac{p(\mathbf{y}|\mathbf{xz})p(\mathbf{zx})}{p(\mathbf{y})}$$

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

Analytic Formulation



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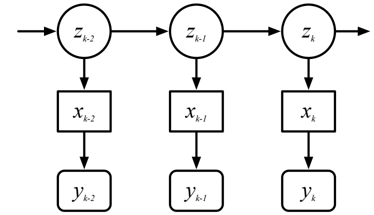
$$p(z_0)\prod_{i=1}^{T} p(z_i|z_{i-1})$$

Markov property

Analytic Formulation



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Markov property

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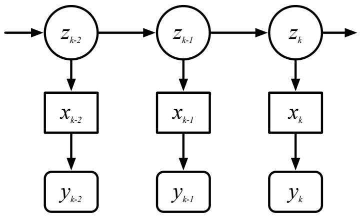
$$= \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x}|\mathbf{z})p(\mathbf{z})}{p(\mathbf{y})}$$

emission probabilities

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

Analytic Formulation



$$p(\mathbf{zx}|\mathbf{y}) = \frac{p(\mathbf{zxy})}{p(\mathbf{y})}$$

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

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

value confusion probability

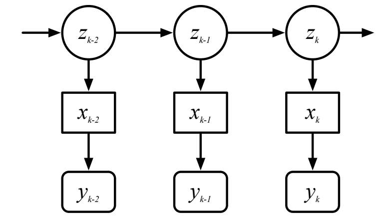
$$p(z_0)\prod_{i=1}^{T} p(z_i|z_{i-1})$$

Markov property

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

emission probabilities

Analytic Formulation



- Rewritten objective:

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

DP Solution Sketch

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

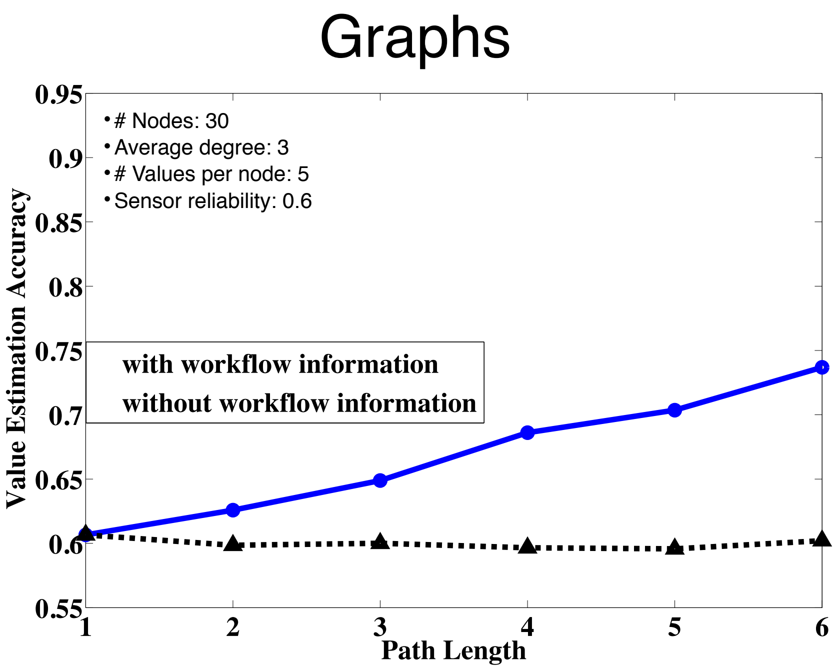
$$\mu_T(z_T, x_T) = \arg\max_{z_{1:T}, x_{1:T}} [\mu_{T-1}(z_{T-1}, x_{T-1}) p(x_T|z_T) \\ p(z_T|z_{T-1})\, p(y_T|x_T)]$$

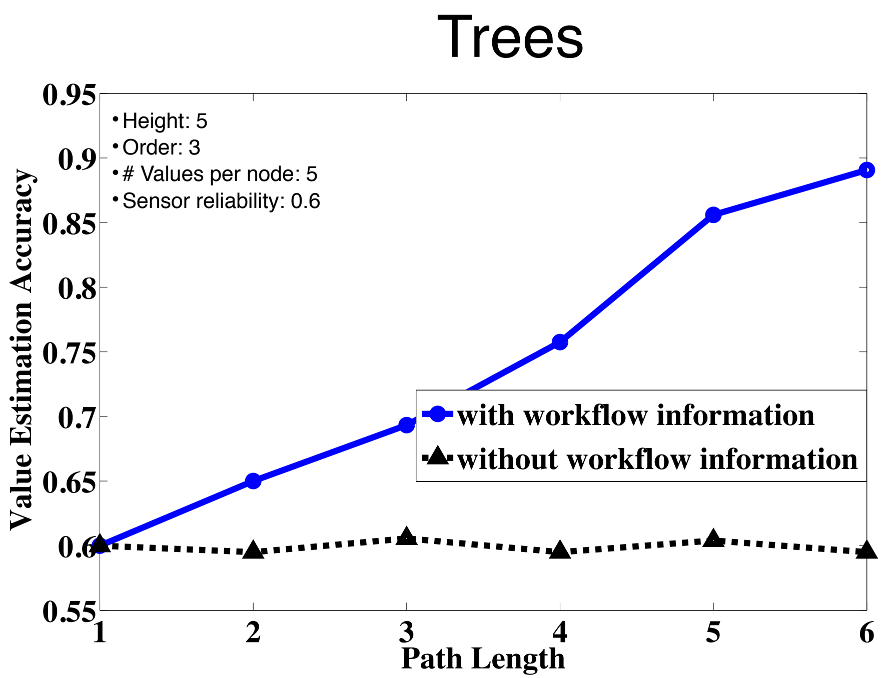
- DP complexity: $O(TVN^2)$, where T - workflow path length, V - value space size, N - state space size
  - exhaustive search: $O((VN)^T)$

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

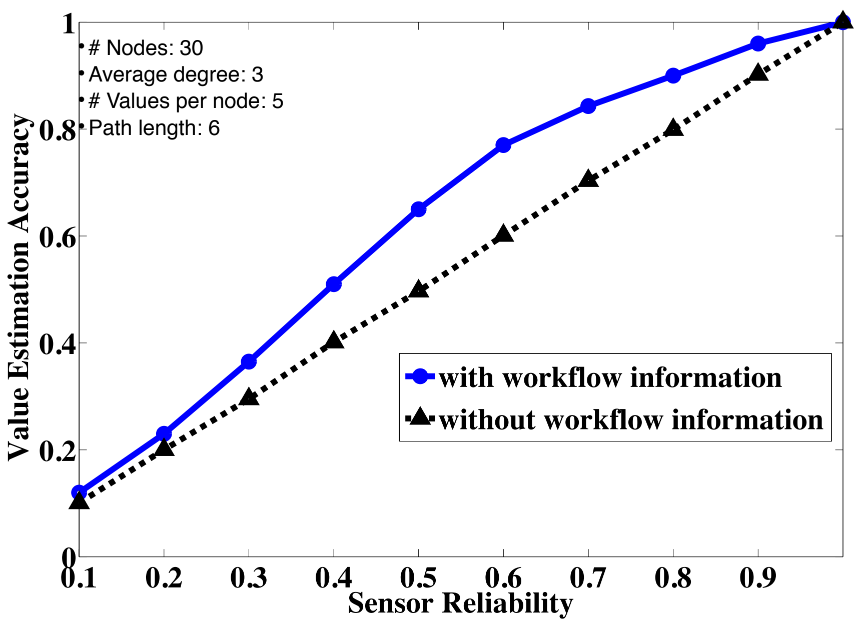




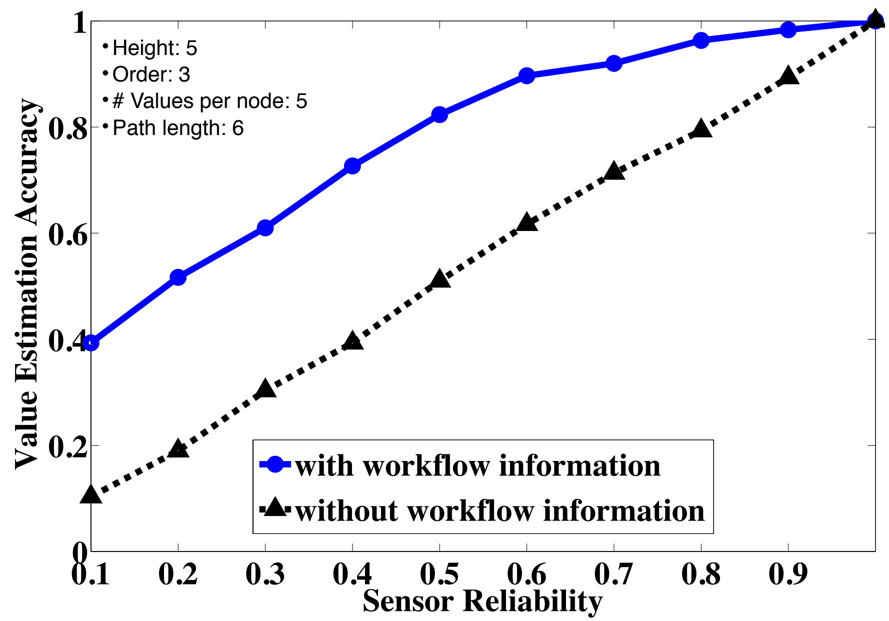
Longer workflow path => Higher error correction power

Simulation Results

Graphs



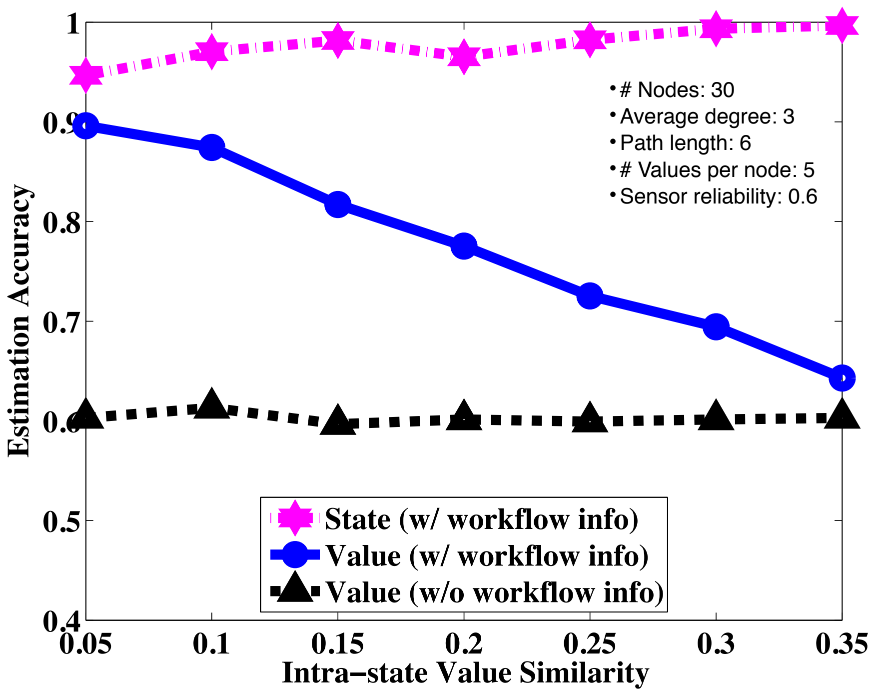
Trees



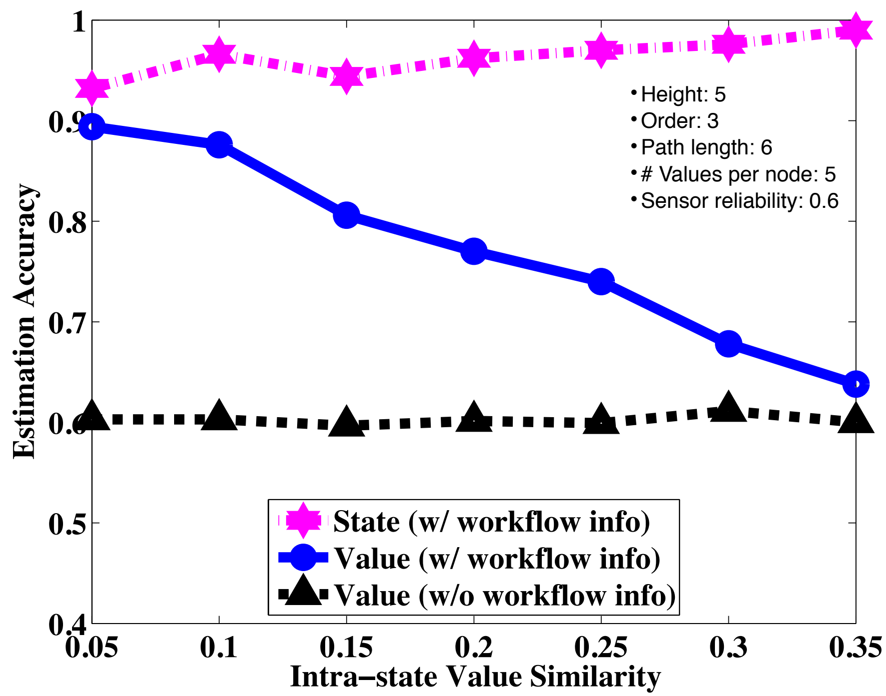
Higher sensor reliability => Higher classification & tracking accuracy

Simulation Results

Graphs



Trees



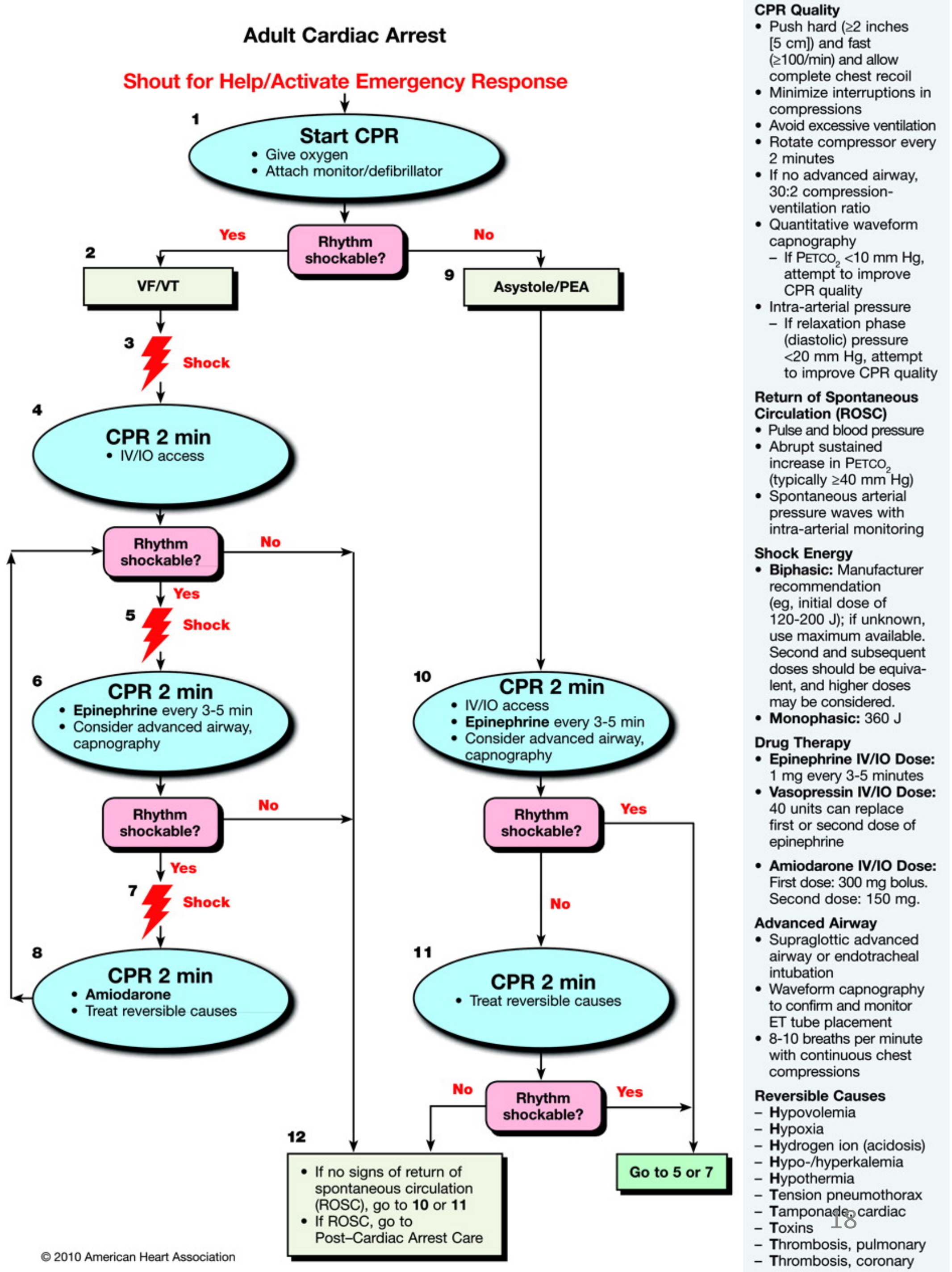
Higher intra-state value similarity => Higher state tracking accuracy,
Lower value estimation accuracy

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

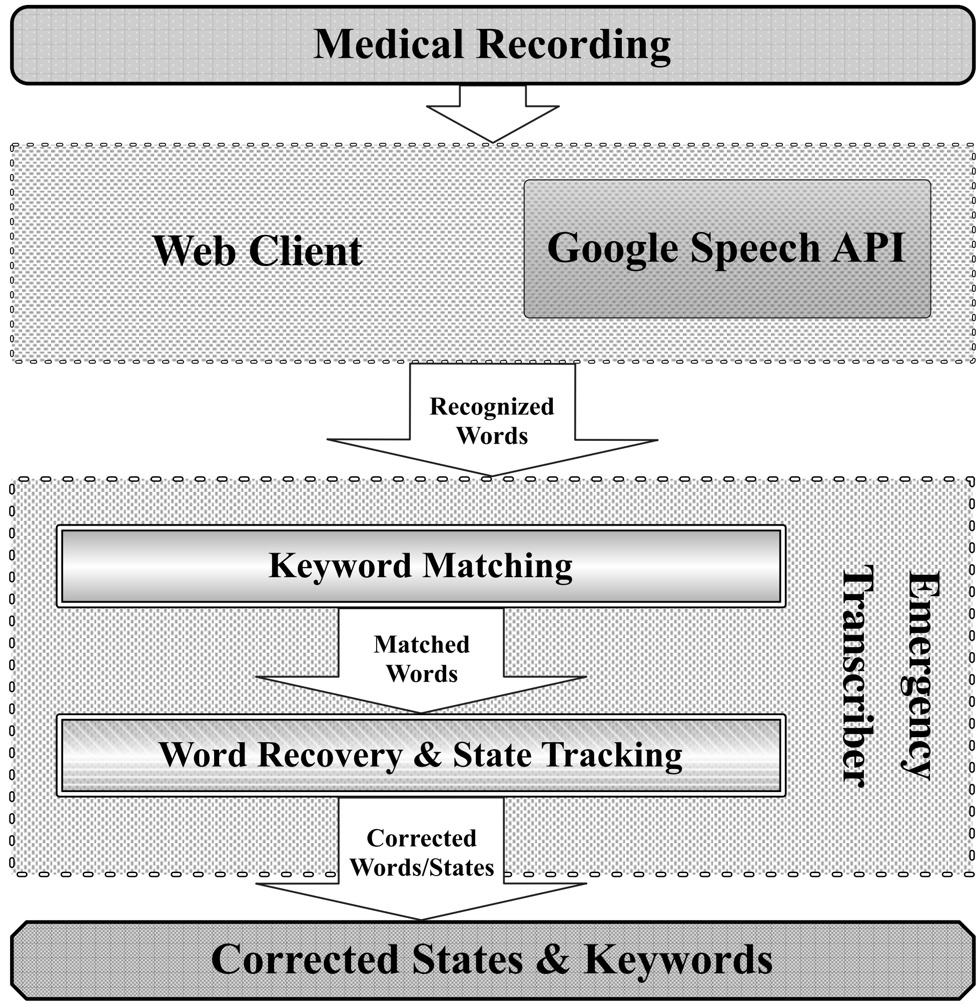
- Realistic cardiac arrest workflow



[http://www.uwhealth.org/files/uwhealth/docs/pdf4/EEC/acls_algorithms.pdf]

Case Study

- System architecture

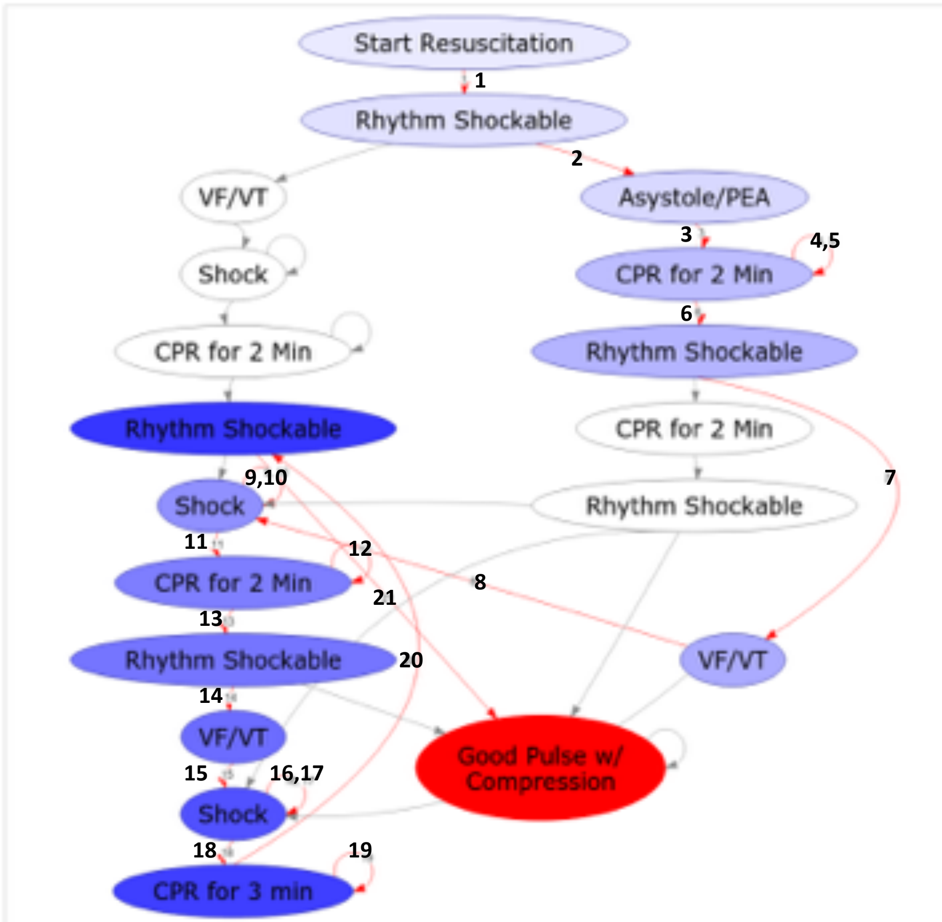


Running Instance

Emergency Transcriber - Resuscitation

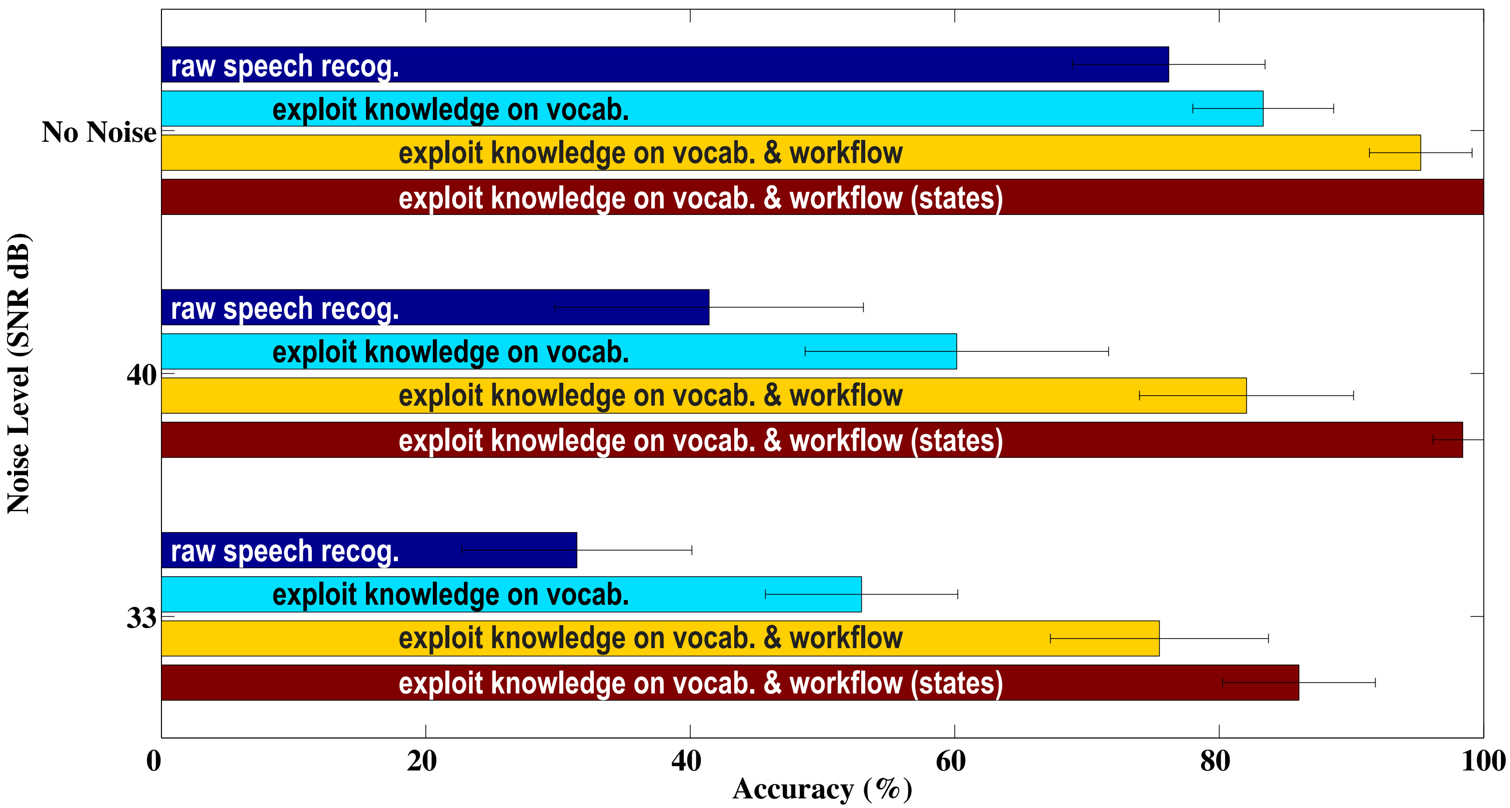
Assassination
what's the rhythm
the patient has a systole
start CPR for 2 minutes
give epinephrine for 3
minutes interval
what's the rhythm
the patient has V fib
charge the defibrillator
the patient
start CPR for 2 minutes
interval
what's the
the patient has me fit
defibrillator
clear the bed
shock the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