

Tracking in a Spaghetti Bowl: Monitoring Transactions Using Footprints

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Dakshi Agrawal²

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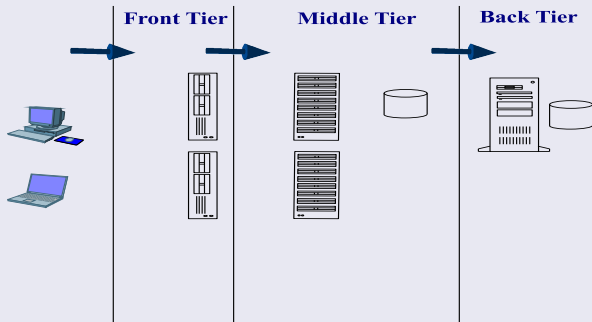
²Networking Tech., IBM Watson Research, Hawthorne, NY 10532.

ACM SIGMETRICS 2008

3 June 2008, Annapolis, MD, USA

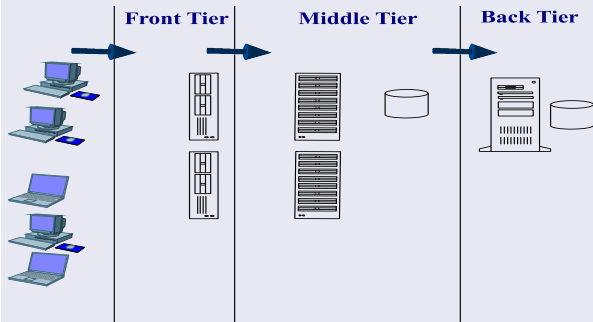
Problem Motivation

End-to-End Service Level Transactions



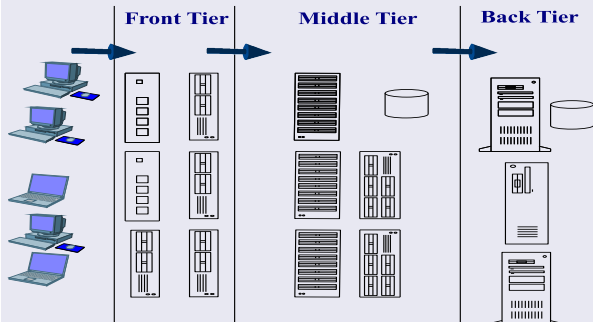
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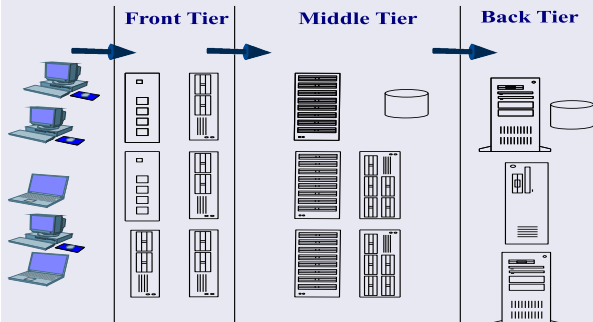
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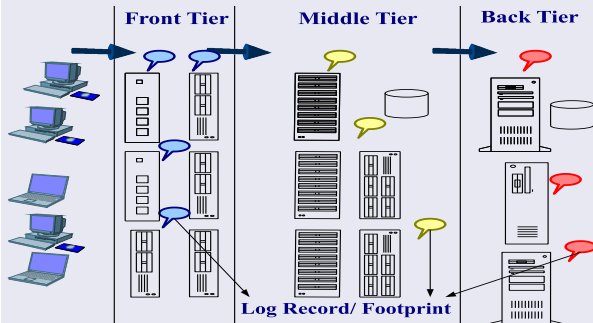
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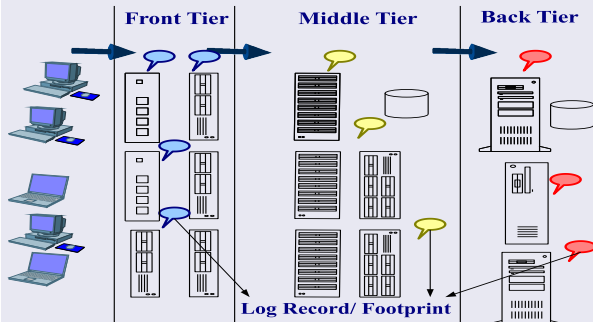
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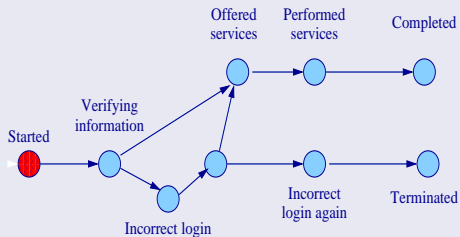


Goals

- Consider systems in absence of monitoring instrumentation
- Limited information available as **footprints**

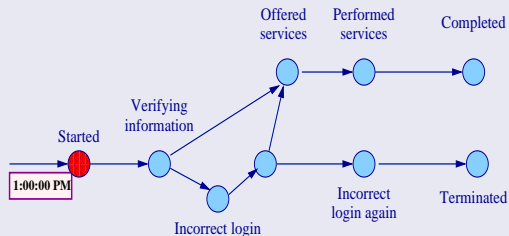
State-based Transaction Model

ATM transaction Application



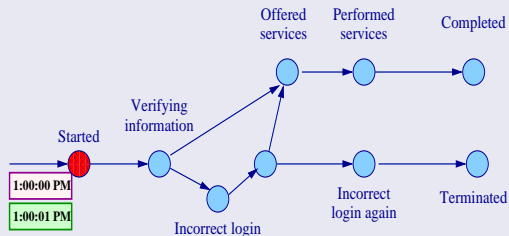
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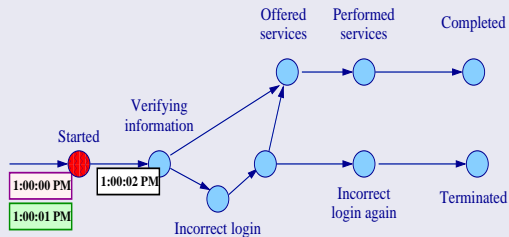
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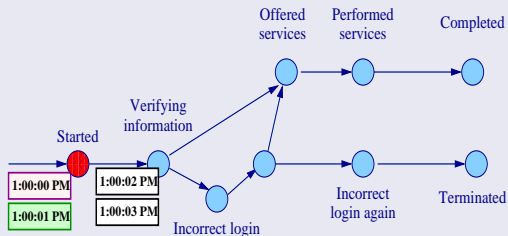
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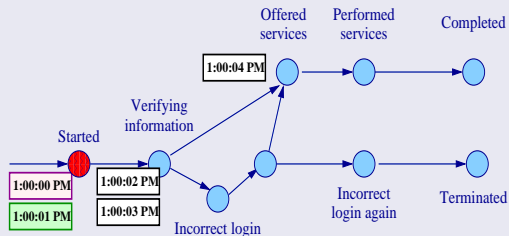
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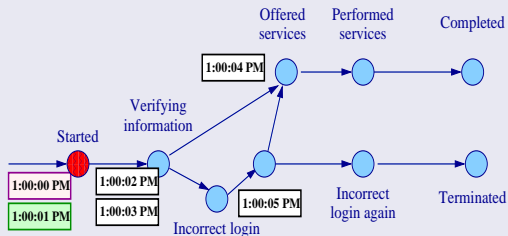
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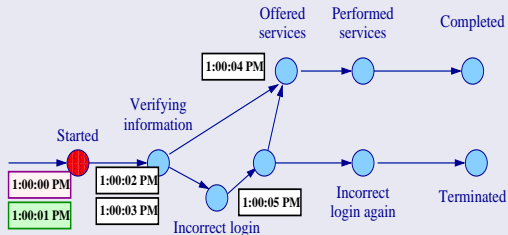
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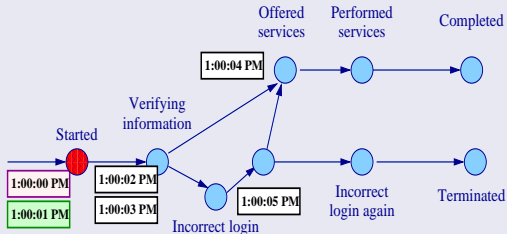


Monitoring

- Footprints may not have identifiers or tokens

State-based Transaction Model

ATM transaction Application

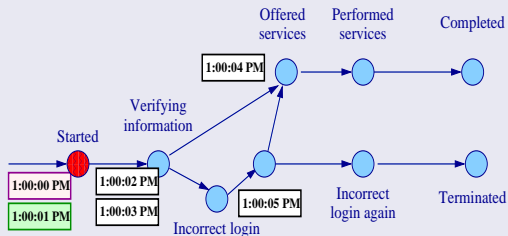


Monitoring

- Footprints may not have identifiers or tokens
- Which transaction had the wrong login?

State-based Transaction Model

ATM transaction Application



Monitoring

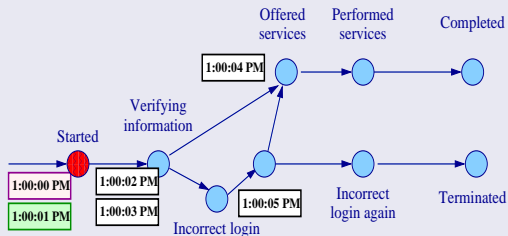
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Probabilistic Monitoring Using Footprints Without Tokens

Maximum likelihood rule: best probabilistic guarantee

State-based Transaction Model

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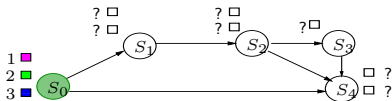
Probabilistic Monitoring Using Footprints Without Tokens

Maximum likelihood rule: best probabilistic guarantee

Maximum Likelihood Rule

Maximize probability that **each** footprint is matched correctly to the **unique** transaction that generated it

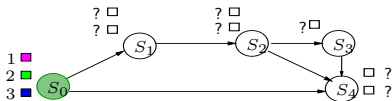
Problem Formulation



Information in Footprint

- State & time stamp, optionally tokens (identifiers)

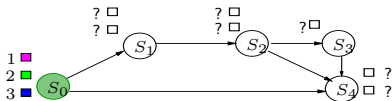
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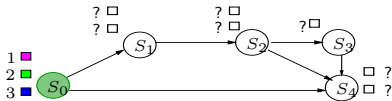
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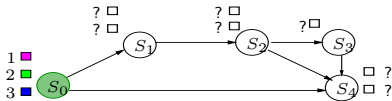
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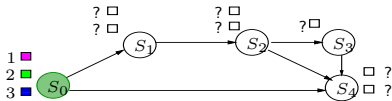
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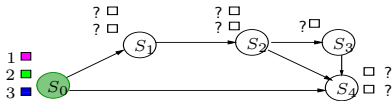
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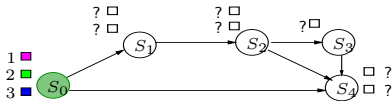
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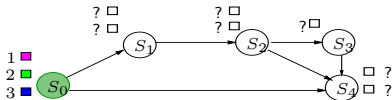
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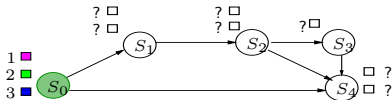
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- IID transitions of transactions

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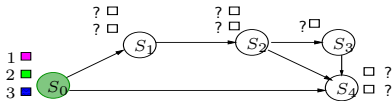
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- IID transitions of transactions
- Acyclic semi-Markov process

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Summary of Results

Problem Statement

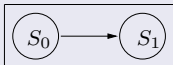
Maximum likelihood match between footprints & transactions

Summary of Results

Problem Statement

Maximum likelihood match between footprints & transactions

Maximum Likelihood for Two-state Systems

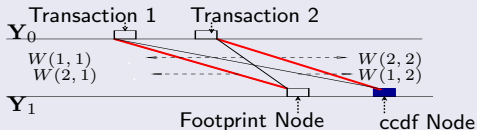
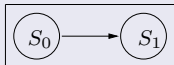


Summary of Results

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Maximum Likelihood for Two-state Systems



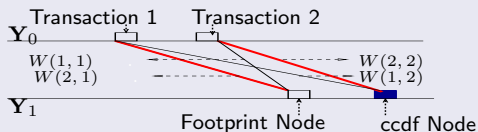
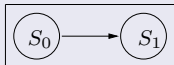
- Reduction to bipartite minimum weight perfect matching

Summary of Results

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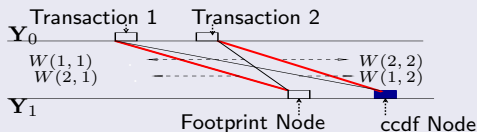
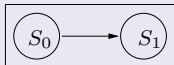
- Reduction to bipartite minimum weight perfect matching
- Reduction to FIFO for a class of transition-time pdfs

Summary of Results

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Maximum Likelihood for Two-state Systems



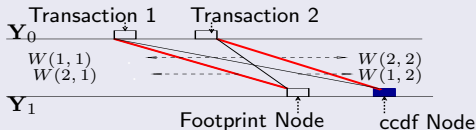
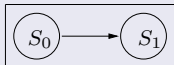
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Worst Case Analysis of Maximum Likelihood Performance

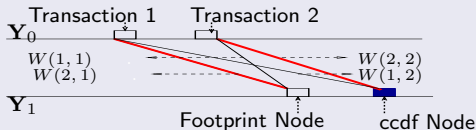
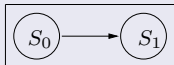
- Uniform and exponential transition times are worst-case distributions

Summary of Results

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Maximum Likelihood for Two-state Systems



- Reduction to bipartite minimum weight perfect matching
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Worst Case Analysis of Maximum Likelihood Performance

- Uniform and exponential transition times are worst-case distributions
- Equal to reciprocal of number of unique perfect matchings

Summary of Results (cont.)

Maximum Likelihood for Multi-state Systems

- Series of bipartite matchings in high-level two-state systems

Summary of Results (cont.)

Maximum Likelihood for Multi-state Systems

- Series of bipartite matchings in high-level two-state systems
- Constructive proof of optimality: Decentralized rules

Summary of Results (cont.)

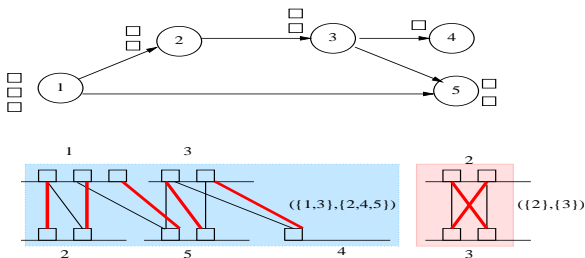
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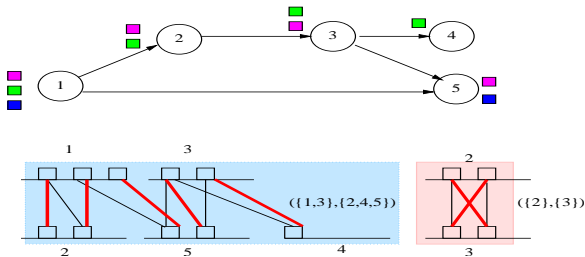
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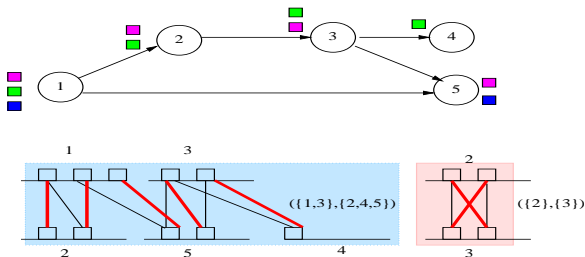
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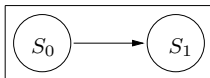
Presence of Tokens

For linear model, ML rule is still decentralized bipartite matching

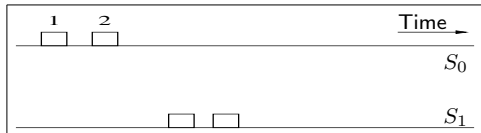
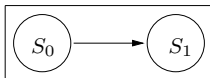
Outline

- 1 Introduction
- 2 Two-state System
- 3 Multi-state System
- 4 Conclusion

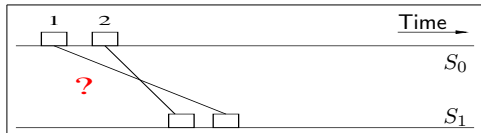
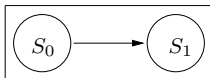
Two-state System



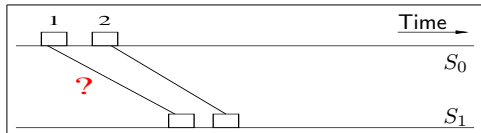
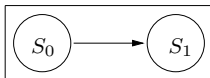
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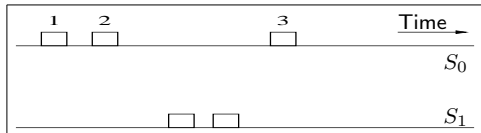
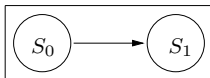
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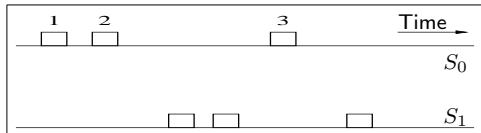
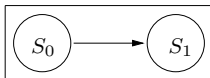
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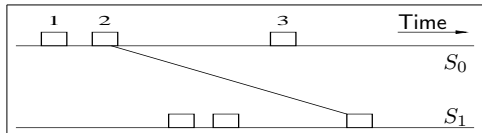
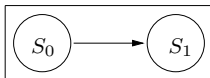
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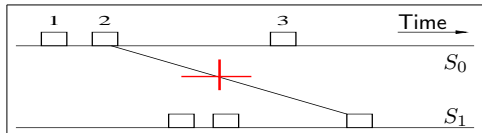
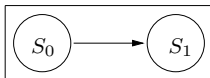
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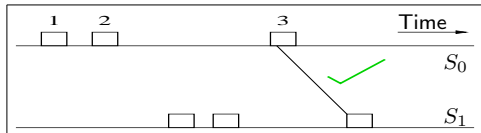
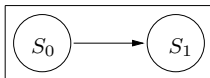
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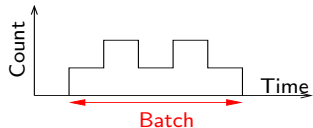
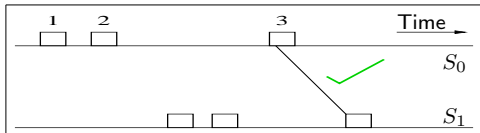
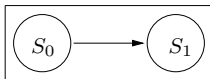
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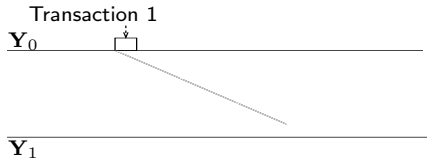
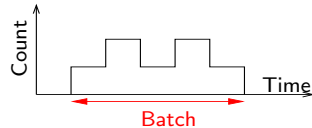
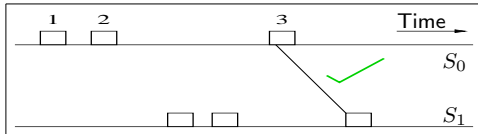
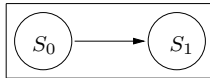
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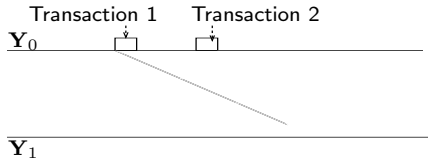
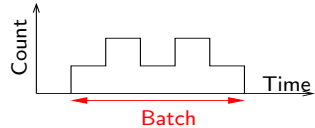
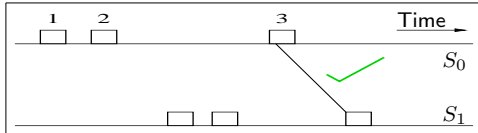
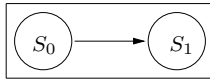
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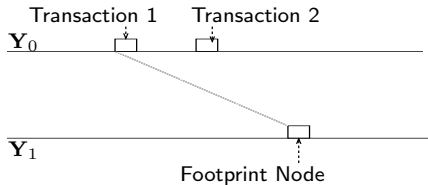
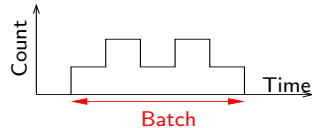
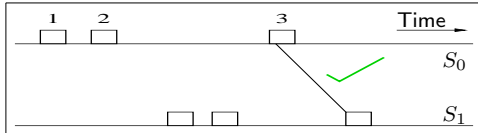
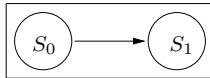
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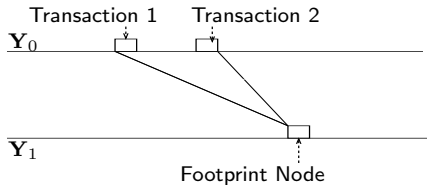
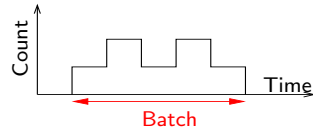
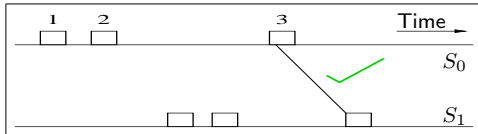
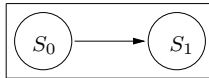
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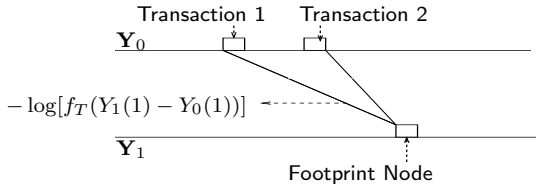
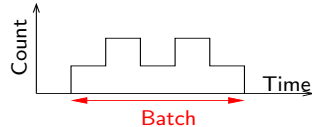
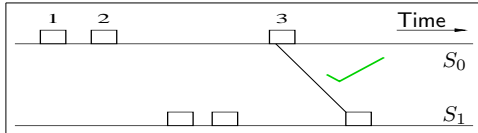
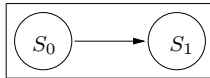
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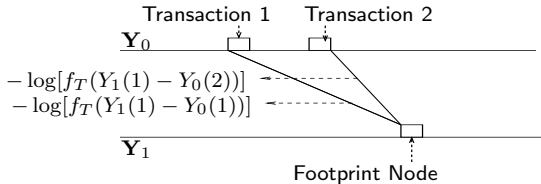
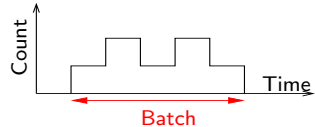
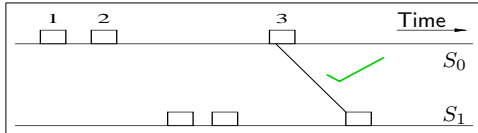
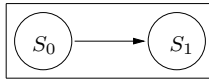
Two-state System



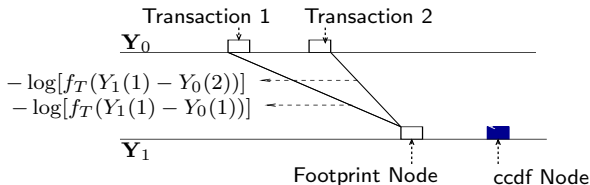
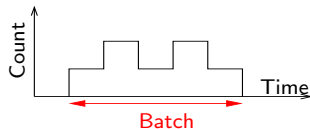
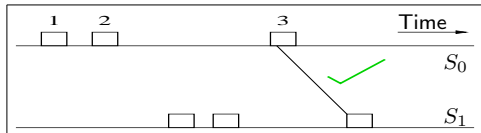
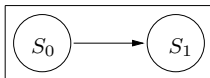
Two-state System



Two-state System



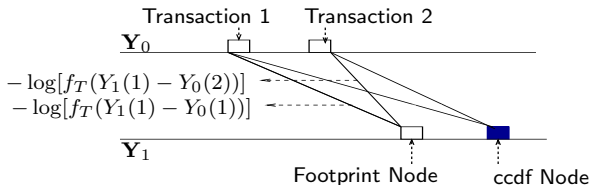
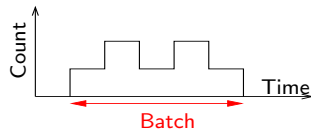
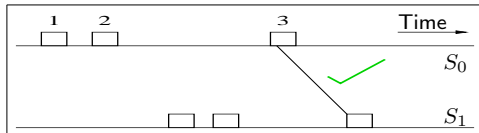
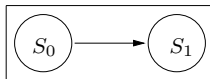
Two-state System



Real Time Matching: All Footprints Not Yet Available

Add virtual node: event that transaction is still resident at S_0

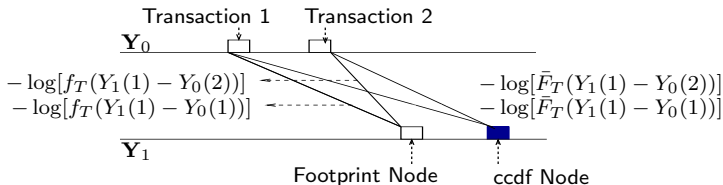
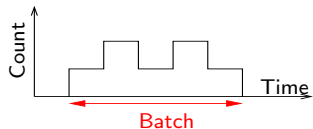
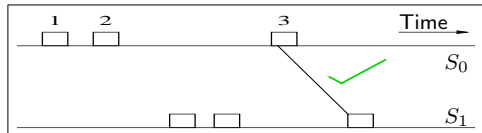
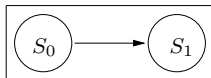
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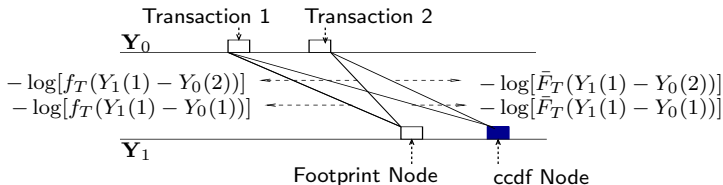
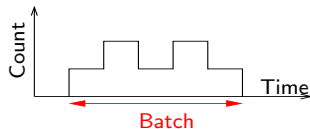
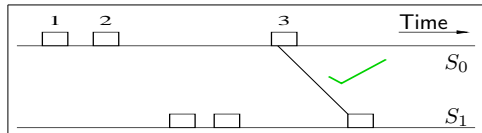
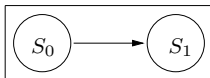
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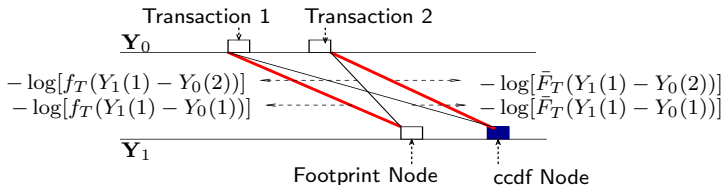
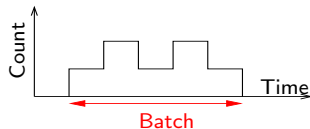
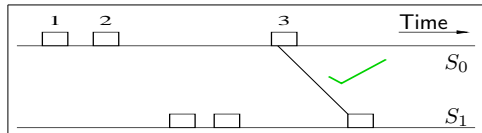
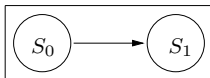
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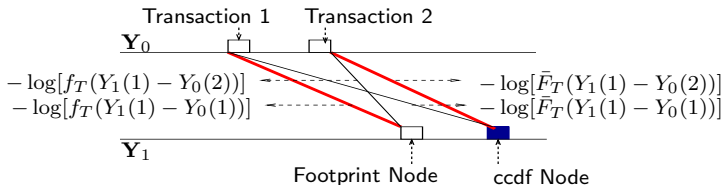
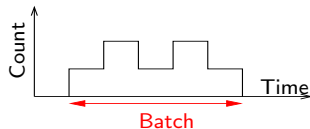
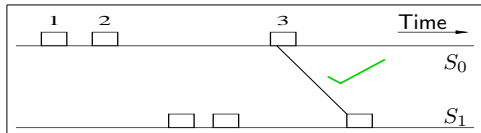
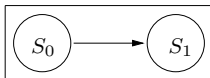
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Maximum Likelihood \equiv Minimum Weight Perfect Match

Worst Case Maximum Likelihood Performance

Definition

Minimum probability of correct match over transition time pdfs

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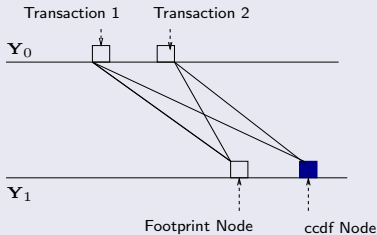
$$\text{Worst Case ML Performance} = \frac{1}{\text{No. of Unique Matches}}$$

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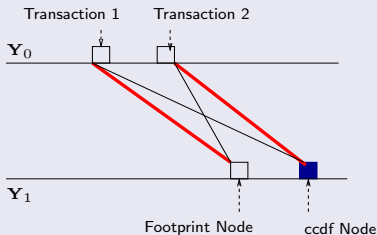


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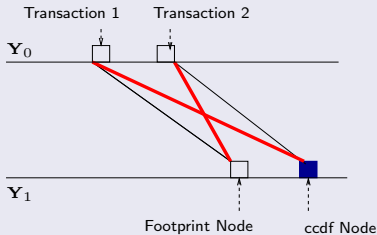


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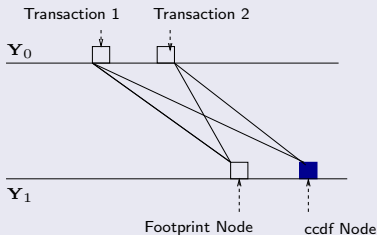


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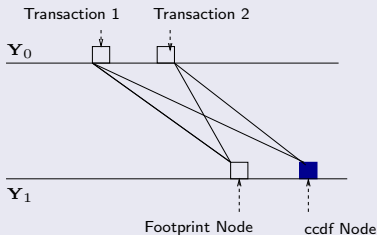
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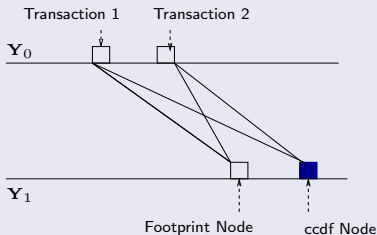
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Partial Batch

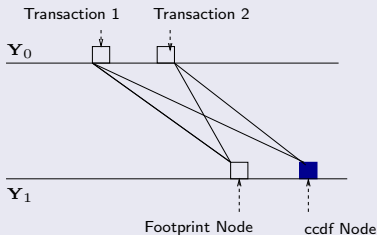
Exponential = Worst Case

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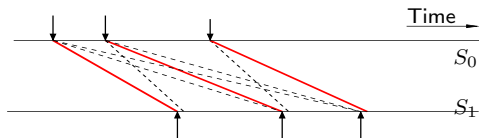
Partial Batch

Exponential = Worst Case

Complete Batch

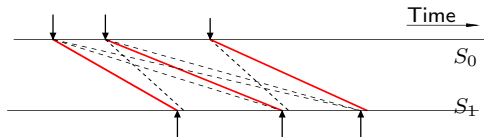
Uniform, Exponential = Worst Case

Comparison of Maximum Likelihood with FIFO



FIFO = Match footprint with earliest unmatched transaction

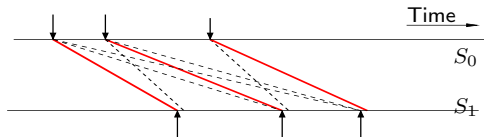
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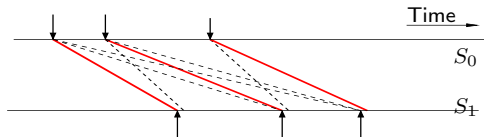


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Can FIFO and maximum likelihood coincide?

Comparison of Maximum Likelihood with FIFO



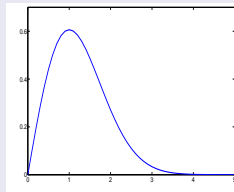
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Yes: Quadrangle Inequality

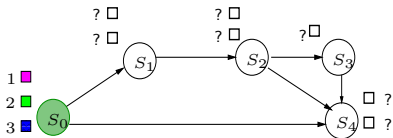
$$f_T(t_1)f_T(t_2) \geq f_T(t_1 - \tau)f_T(t_2 - \tau)$$



Outline

- 1 Introduction
- 2 Two-state System
- 3 Multi-state System**
- 4 Conclusion

Recap of Transaction Model

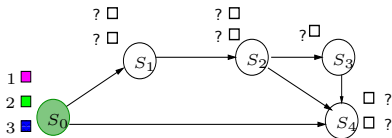


Transaction Model

- Acyclic semi-Markov process

Definition of Semi-Markov Process

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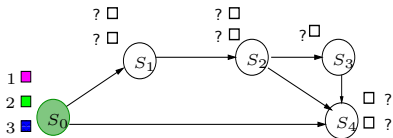


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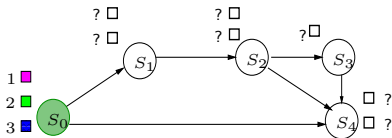
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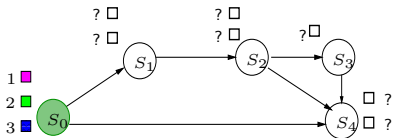
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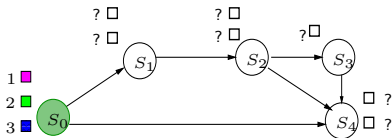
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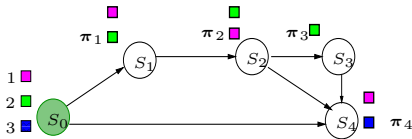
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Maximum Likelihood Rule

Maximize probability that **each** footprint is matched correctly to the **unique** transaction that generated it

$$[\hat{\pi}_1^{\text{ML}}, \dots, \hat{\pi}_{N_s}^{\text{ML}}] := \arg \max_{\pi_1, \dots, \pi_{N_s}} \mathbb{P}(\mathbf{Y}_1^{\pi_1}, \dots, \mathbf{Y}_{N_s}^{\pi_{N_s}} | \mathbf{Y}_0).$$

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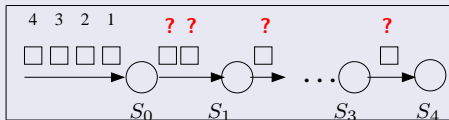
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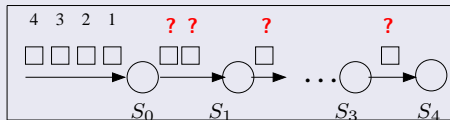
Special Cases: Linear & Tree Models

Linear Model With Snapshot of Footprints



Special Cases: Linear & Tree Models

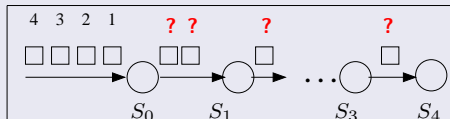
Linear Model With Snapshot of Footprints



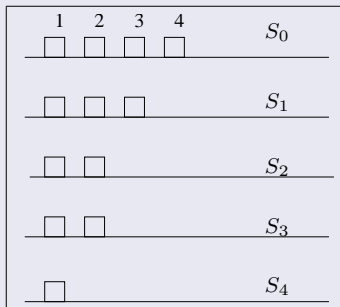
Maximum Likelihood in Linear Model

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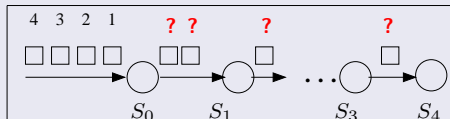


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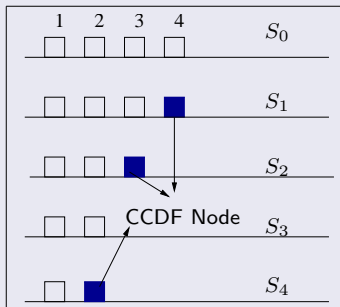


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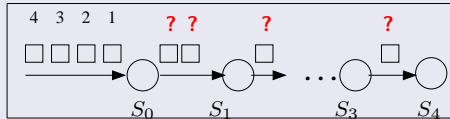


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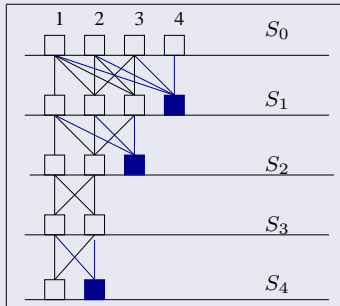


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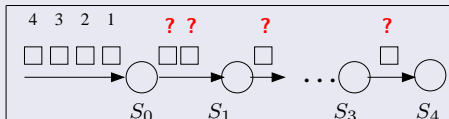


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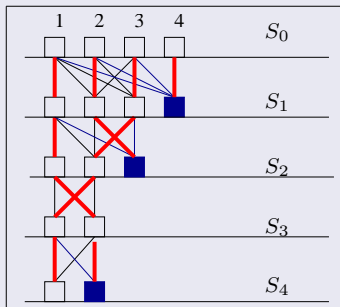


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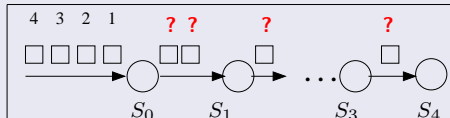


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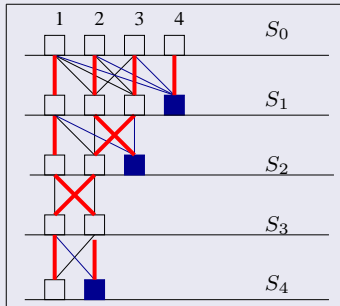


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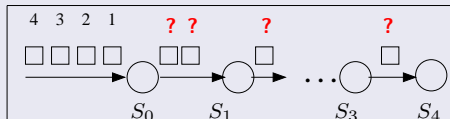
Maximum Likelihood in Linear Model



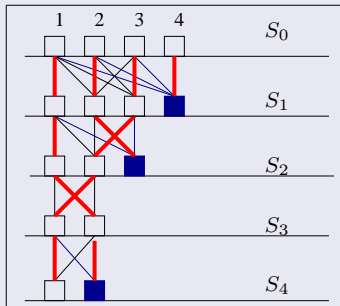
Tree Model

Special Cases: Linear & Tree Models

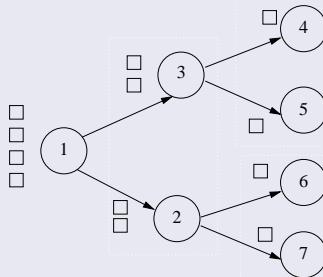
Linear Model With Snapshot of Footprints



Maximum Likelihood in Linear Model

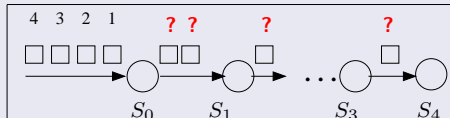


Tree Model

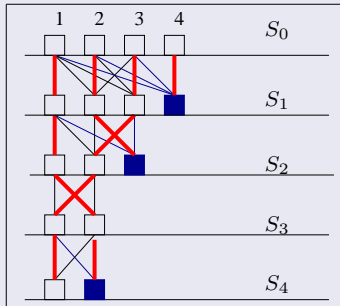


Special Cases: Linear & Tree Models

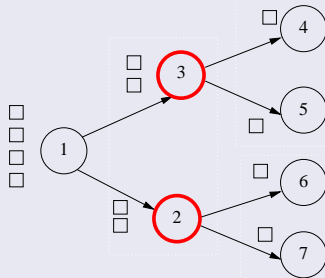
Linear Model With Snapshot of Footprints



Maximum Likelihood in Linear Model

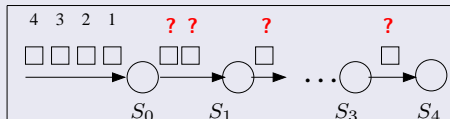


Tree Model

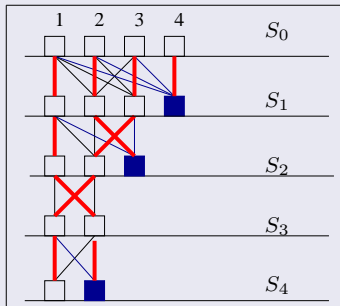


Special Cases: Linear & Tree Models

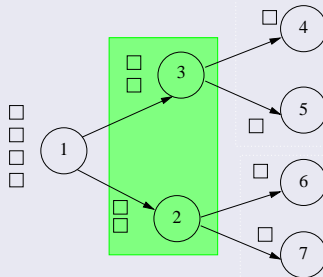
Linear Model With Snapshot of Footprints



Maximum Likelihood in Linear Model

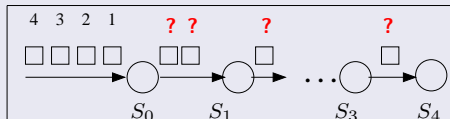


Tree Model

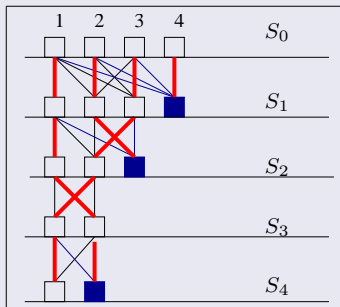


Special Cases: Linear & Tree Models

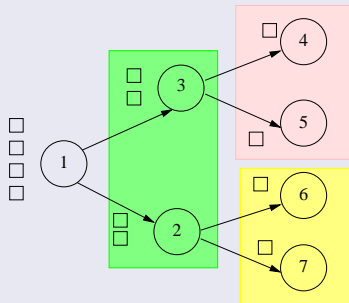
Linear Model With Snapshot of Footprints



Maximum Likelihood in Linear Model

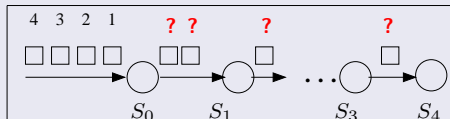


Tree Model

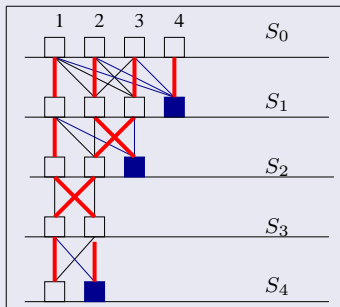


Special Cases: Linear & Tree Models

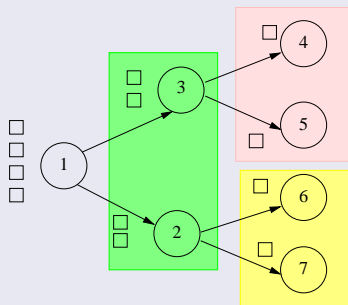
Linear Model With Snapshot of Footprints



Maximum Likelihood in Linear Model



Tree Model



ML \equiv Series of Bipartite Matchings

Acyclic Semi-Markov Process

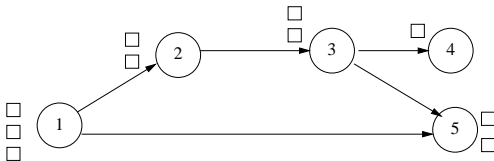
Acyclic Semi Markov Process: Two-Stage Systems

No common imm. predecessor: States in end stage of different systems

Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

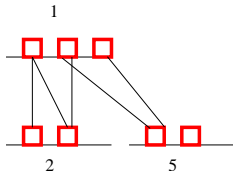
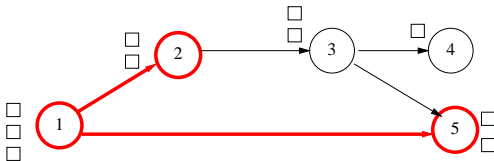
No common imm. predecessor: States in end stage of different systems



Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

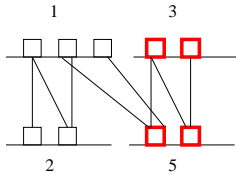
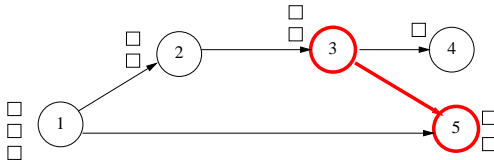
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

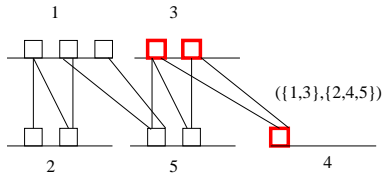
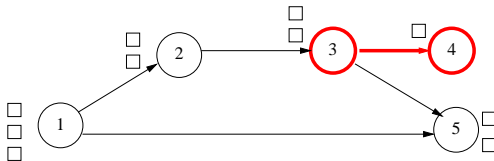
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

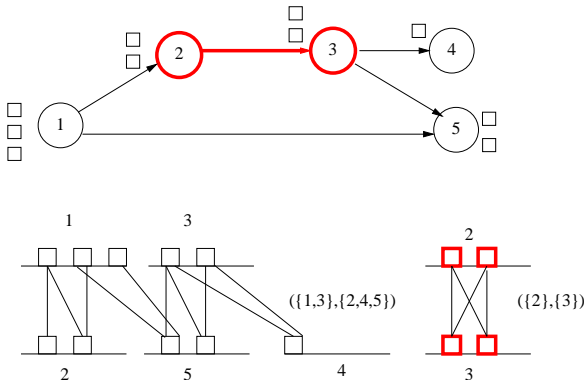
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

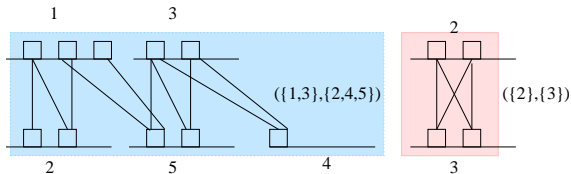
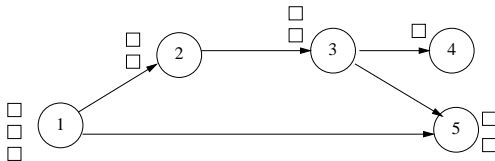
No common imm. predecessor: States in end stage of different systems



Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

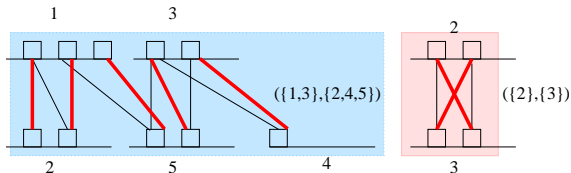
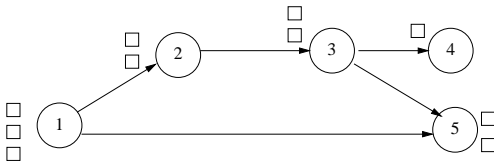
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

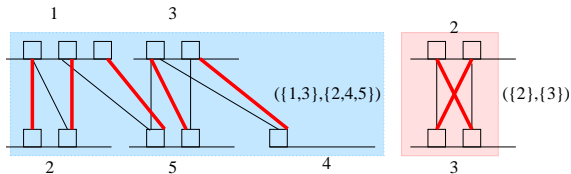
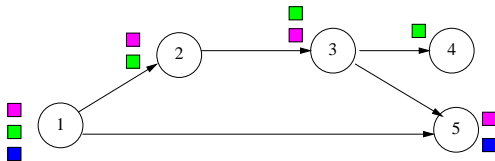
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

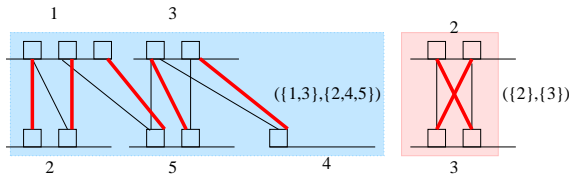
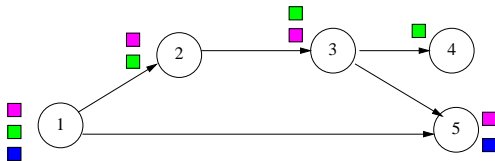
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Acyclic Semi-Markov Process

Acyclic Semi Markov Process: Two-Stage Systems

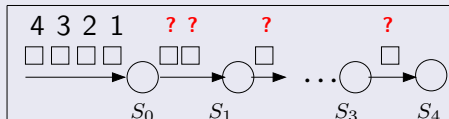
No common imm. predecessor: States in end stage of different systems



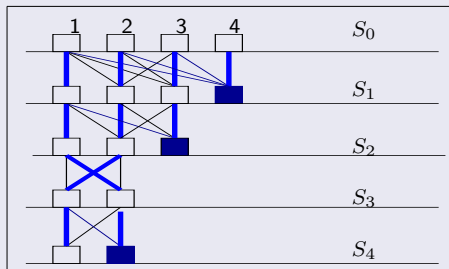
ML Rule \equiv Series of Bipartite Matchings in 2-State Systems

Presence of Tokens

Linear Semi Markov Process

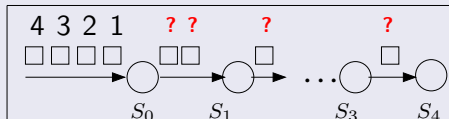


Maximum Likelihood in Presence of Tokens

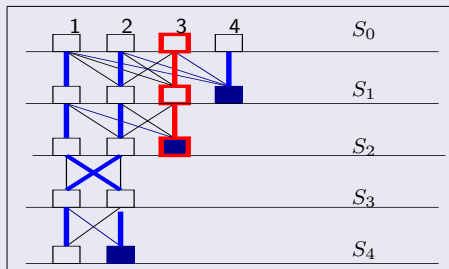


Presence of Tokens

Linear Semi Markov Process

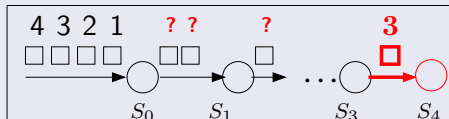


Maximum Likelihood in Presence of Tokens

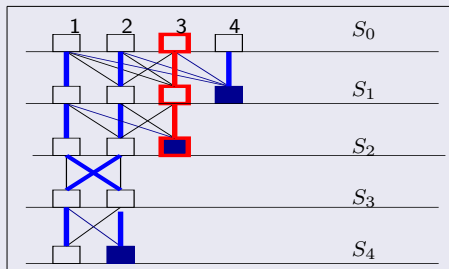


Presence of Tokens

Linear Semi Markov Process

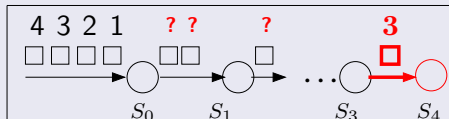


Maximum Likelihood in Presence of Tokens

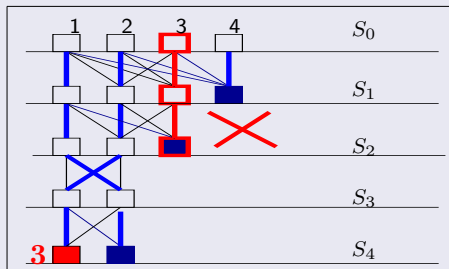


Presence of Tokens

Linear Semi Markov Process

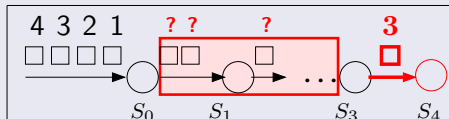


Maximum Likelihood in Presence of Tokens

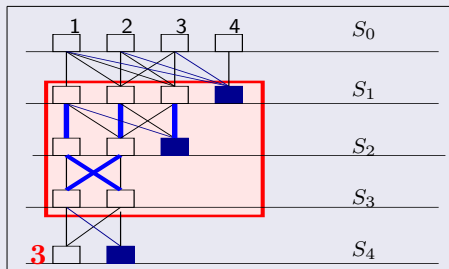


Presence of Tokens

Linear Semi Markov Process

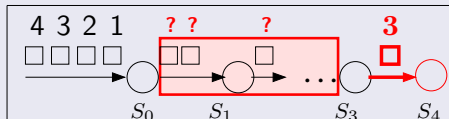


Maximum Likelihood in Presence of Tokens

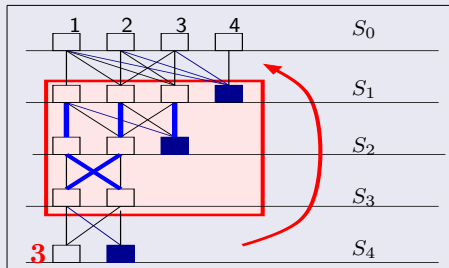


Presence of Tokens

Linear Semi Markov Process

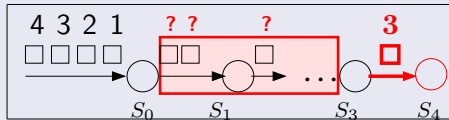


Maximum Likelihood in Presence of Tokens

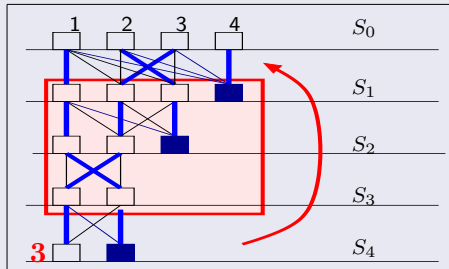


Presence of Tokens

Linear Semi Markov Process

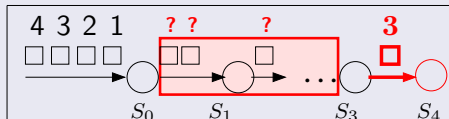


Maximum Likelihood in Presence of Tokens

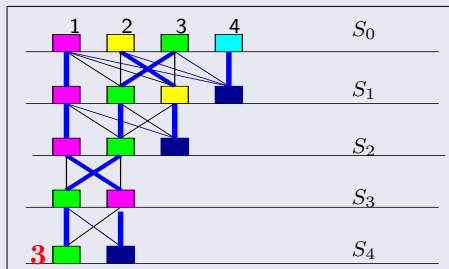


Presence of Tokens

Linear Semi Markov Process

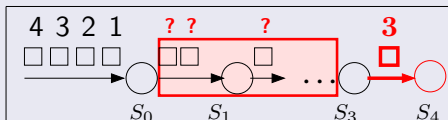


Maximum Likelihood in Presence of Tokens

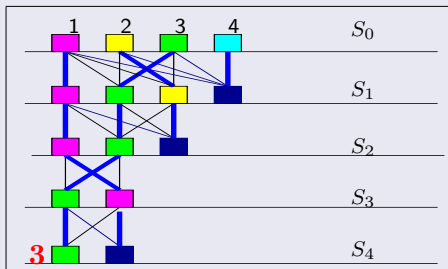


Presence of Tokens

Linear Semi Markov Process



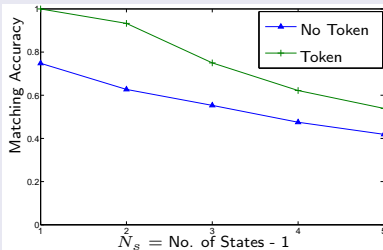
Maximum Likelihood in Presence of Tokens



ML \equiv Series of Bipartite Matchings for Tokenized Linear Model

Simulation Results

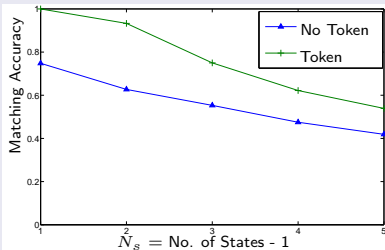
Effect of Tokens in Linear Model



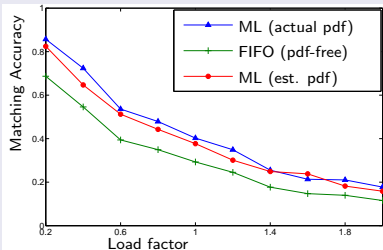
ML vs. FIFO for 2-state System

Simulation Results

Effect of Tokens in Linear Model



ML vs. FIFO for 2-state System



Outline

- 1 Introduction
- 2 Two-state System
- 3 Multi-state System
- 4 Conclusion**

Conclusion

Summary

- End-to-end monitoring of transactions using footprints
- Optimal maximum likelihood rule for matching footprints to transactions
- Reduction of ML rule to bipartite matching for two-state systems
- Reduction of ML rule to a series of bipartite matching for multi-state systems

Outlook

- General transaction models e.g., higher order Markov, petri-nets
- Relaxation of assumptions
 - ▶ Perfect knowledge of transaction model
 - ▶ Missing footprints, lack of synchronization

Related Work

Identification of Global System States

- Classical work by Chandy & Lamport (85)
- Do not deal with monitoring individual transaction instances

Whitebox/Tokenized Methods (Chen et al. 04, Schmid et al. 07)

- Require industry standards like Open Group ARM instrumentation
- Not applicable if such instrumentation is not available

Blackbox Methods (Aguilera et al. 03, Liu et al. 07)

- Do not require token generating instrumentation
- Do not deal with monitoring individual transaction instances

Discovery of Transaction Model

- Extensive work in this area (Agrawal, Gunopulos, Leymann 98)

Related Publication (Sengupta, Banerjee, Anandkumar, Bisdikian NOMS 08)

- Implementation of monitoring system, experimental results on response times
- Bounds on aggregate number of transactions in any state of the model

Thank You !