

Multi-Hop Knowledge Graph Reasoning with Reward Shaping

Victoria Lin, Richard Socher, Caiming Xiong
[{xilin, rsocher, cxiong}@salesforce.com](mailto:{xilin,rsocher,cxiong}@salesforce.com)

EMNLP 2018

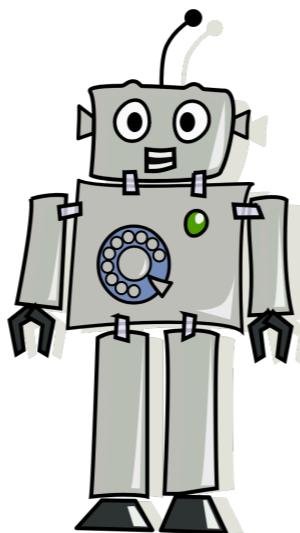


Question Answering System

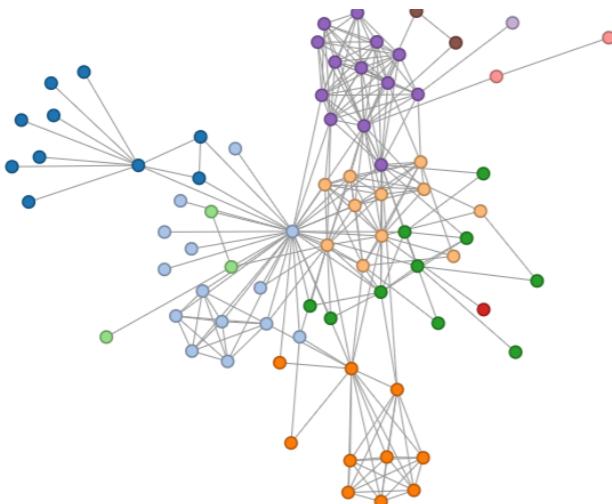
Text



Images



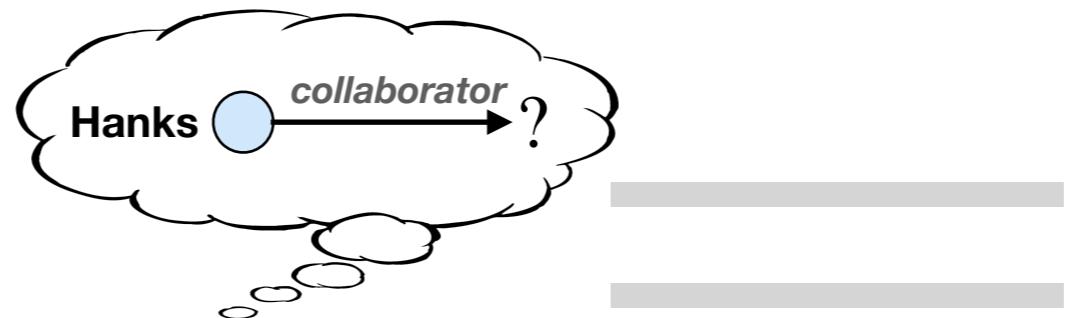
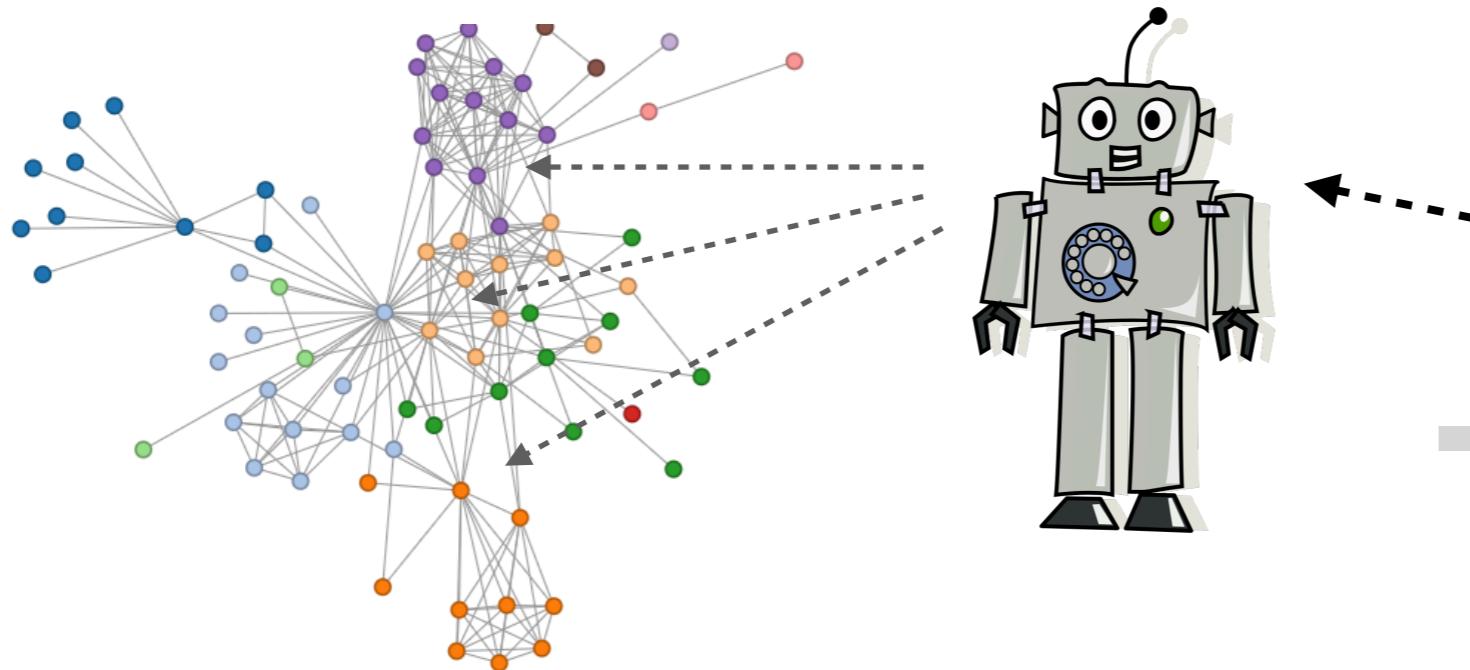
Knowledge Graph



Which directors
has Tom Hanks
collaborated with?

Question Answering System

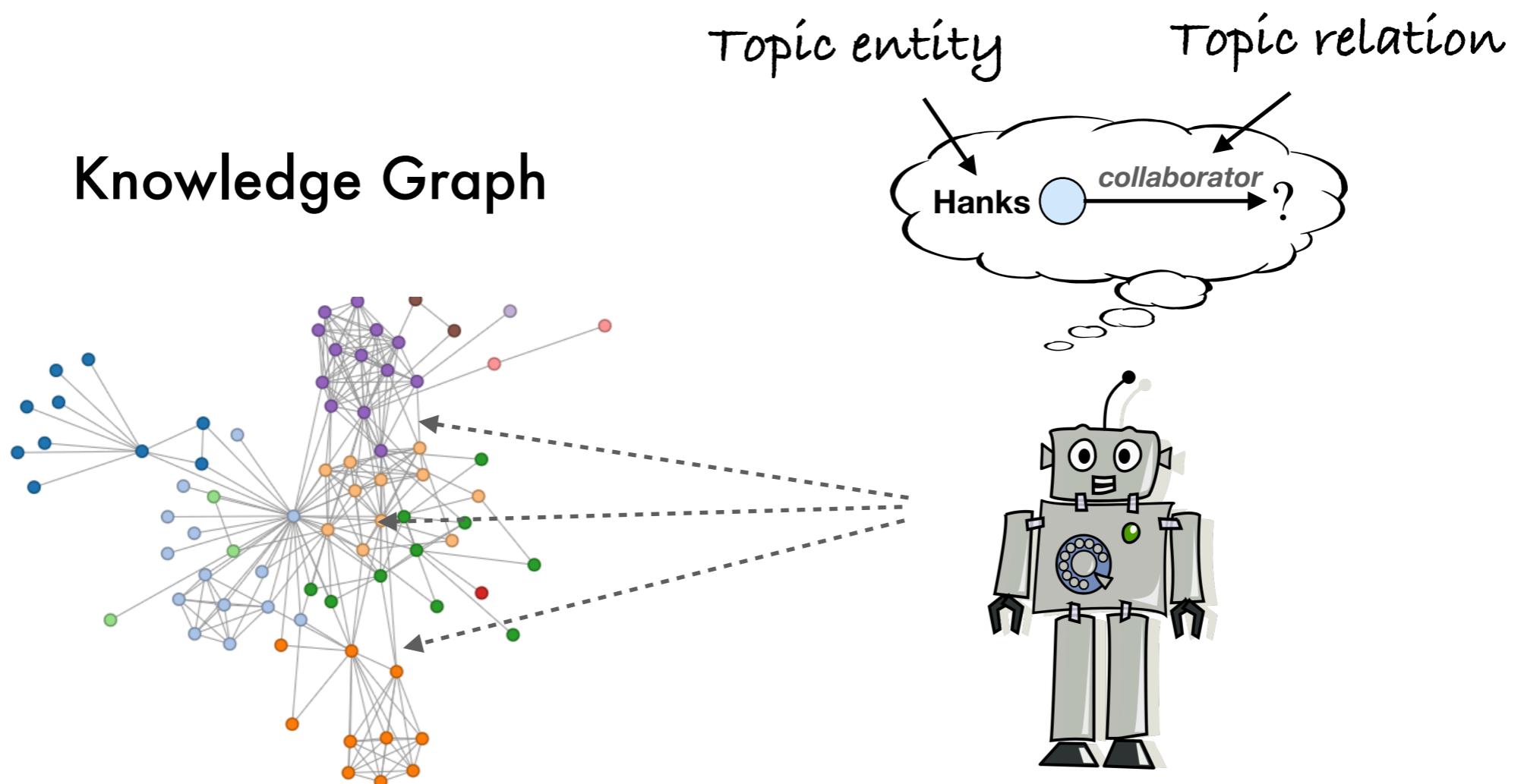
Knowledge Graph



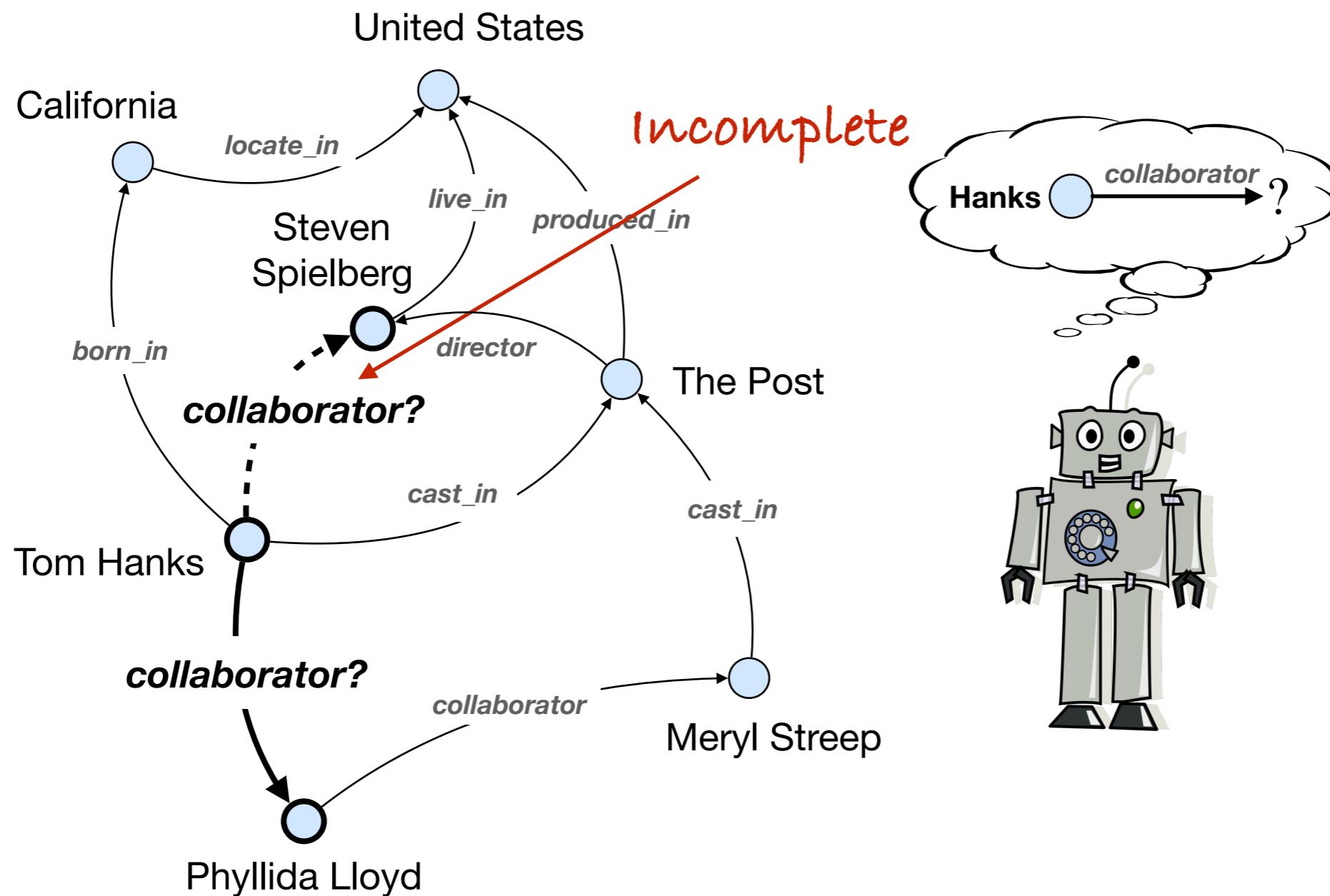
Which directors
has **Tom Hanks**
collaborated with?



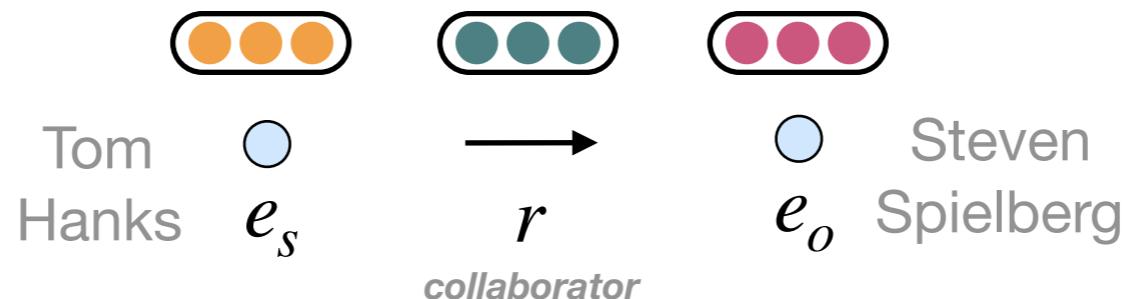
Structured Query Answering



Structured Query Answering



Knowledge Graph Embeddings



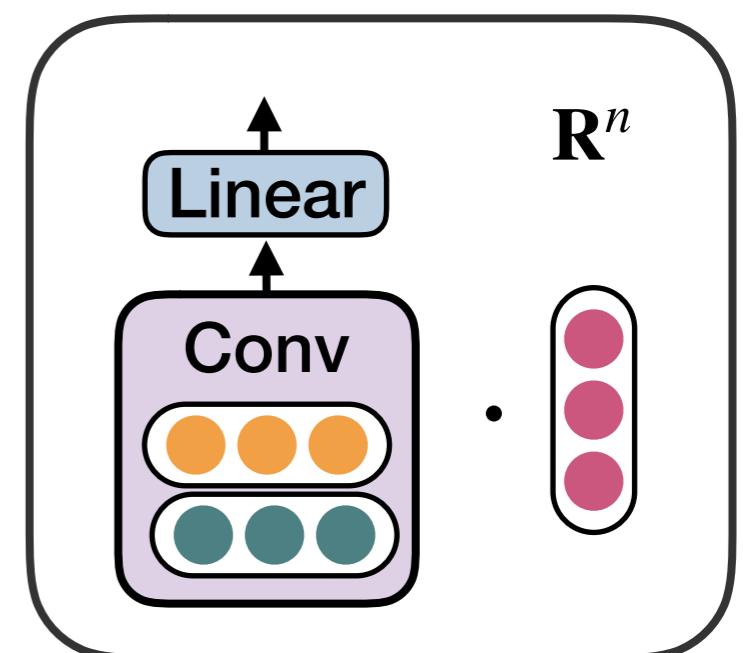
Highly accurate &
Efficient

	MRR
ConvE	0.957 (max = 1)

Tab 1. ConvE query answering performance on the UMLS benchmark dataset (Kok and Domingos 2007)

Lack
interpretability

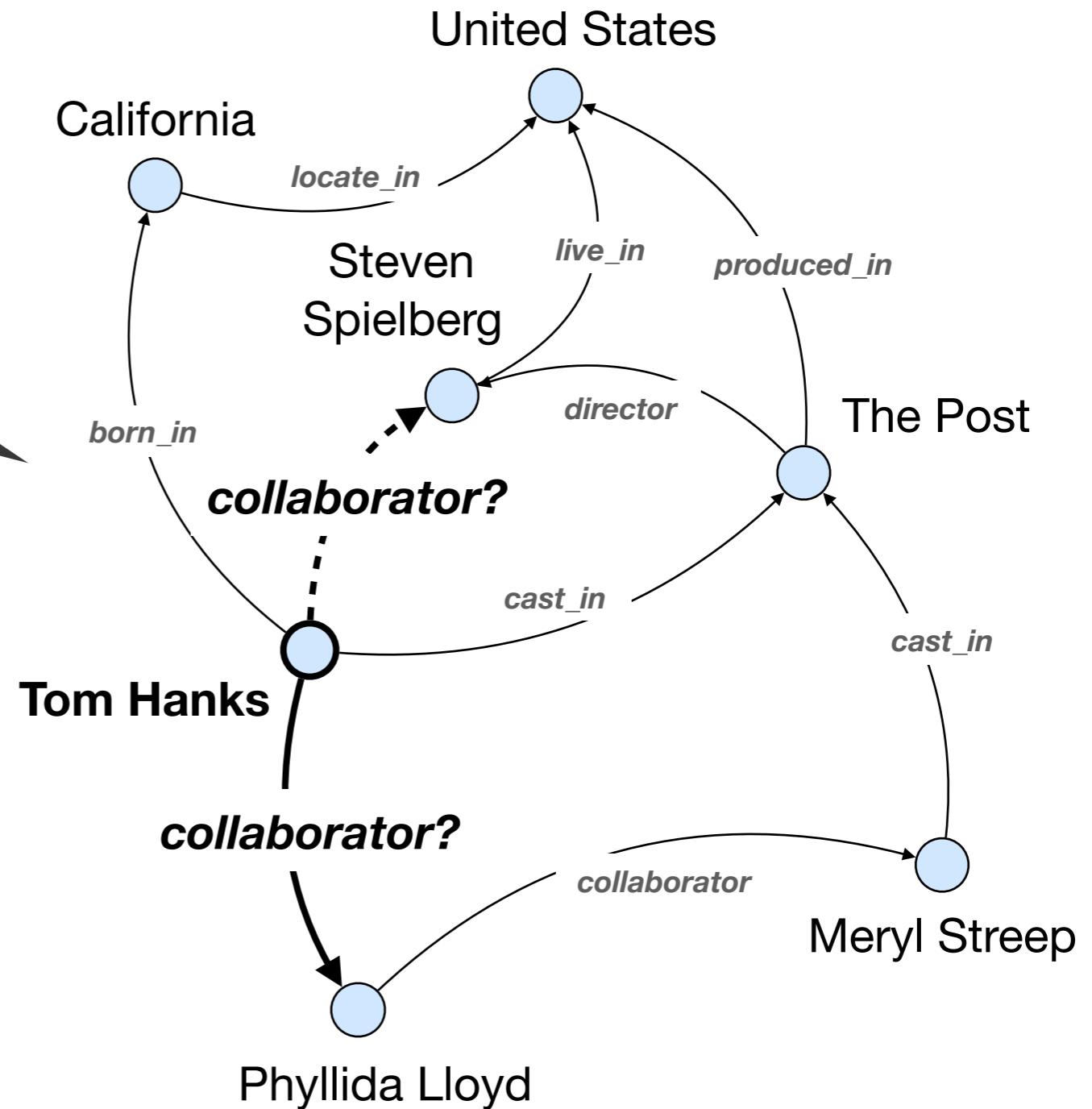
Why Spielberg
is a collaborator
of Hanks?



ConvE

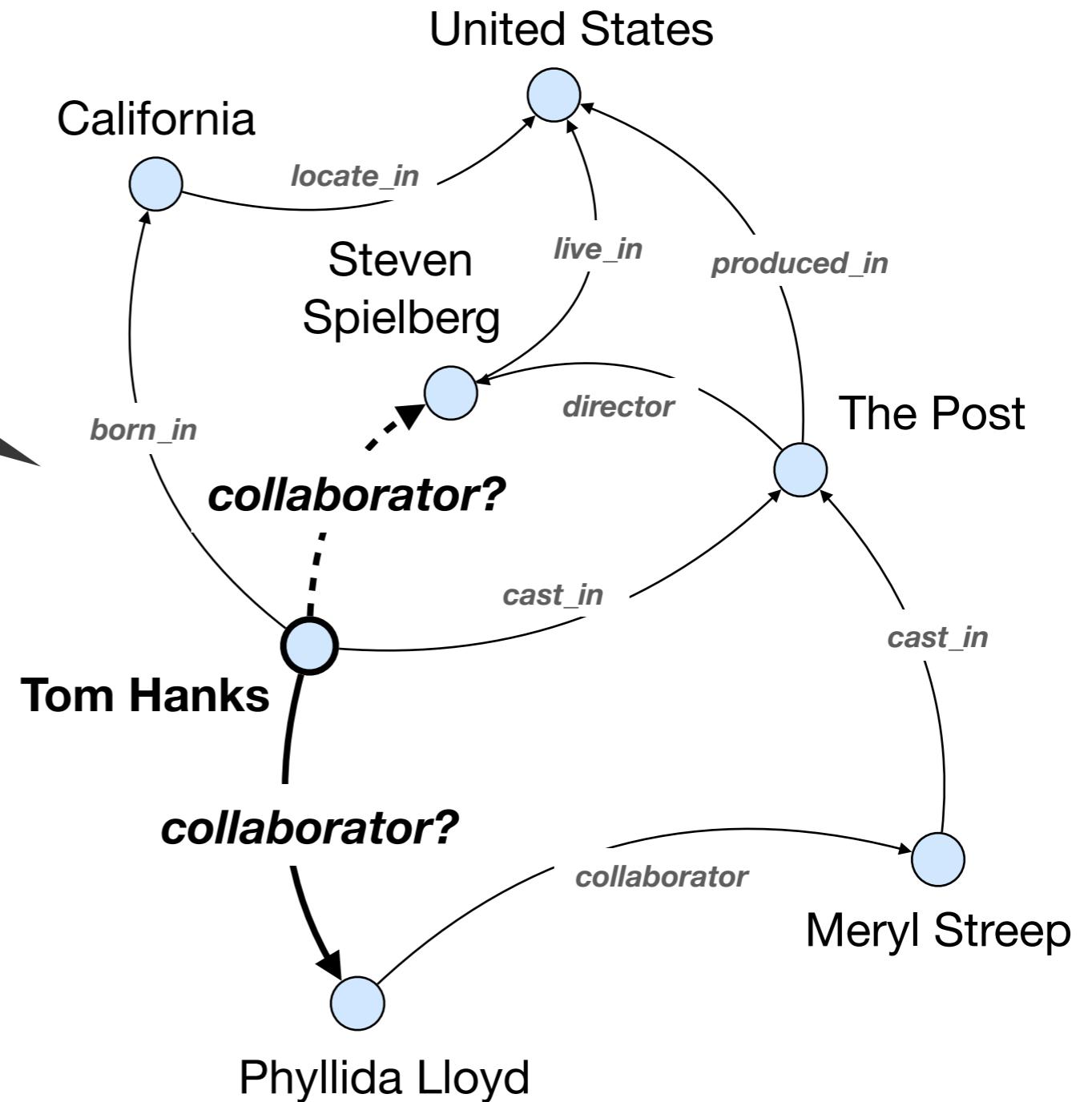
Multi-Hop Reasoning Models

Reasoning
over discrete
structures

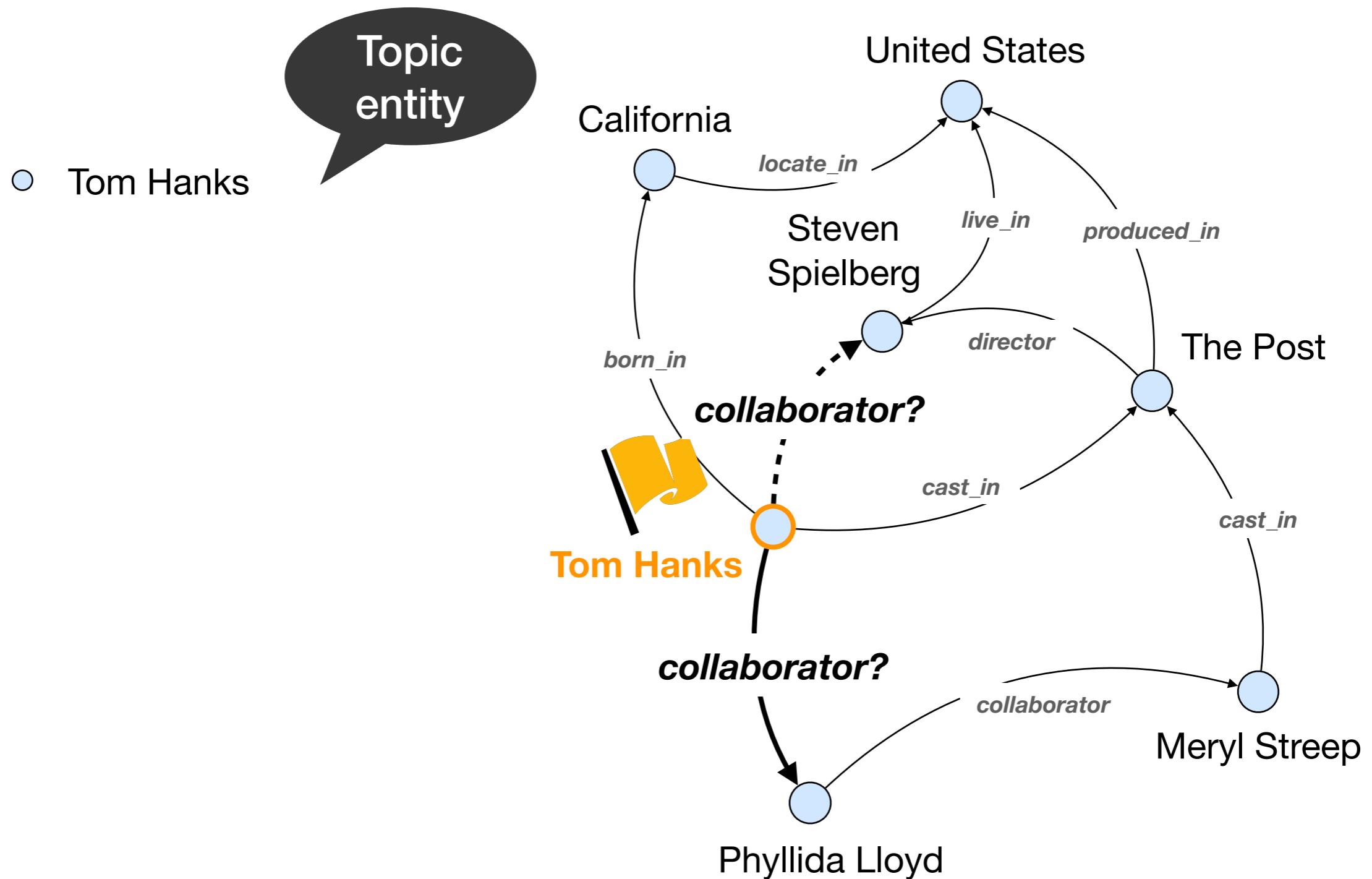


Multi-Hop Reasoning Models

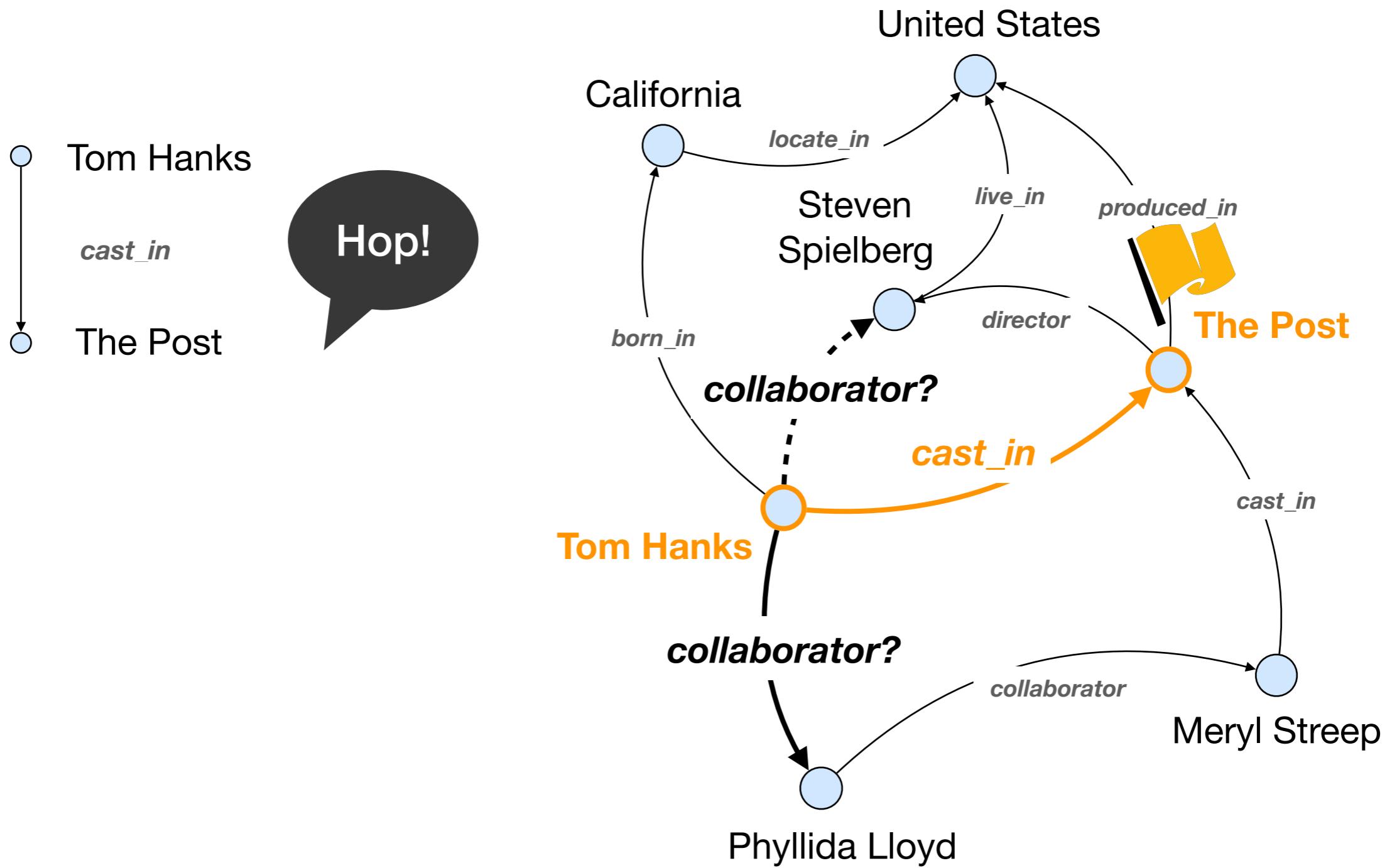
Sequential
decision making



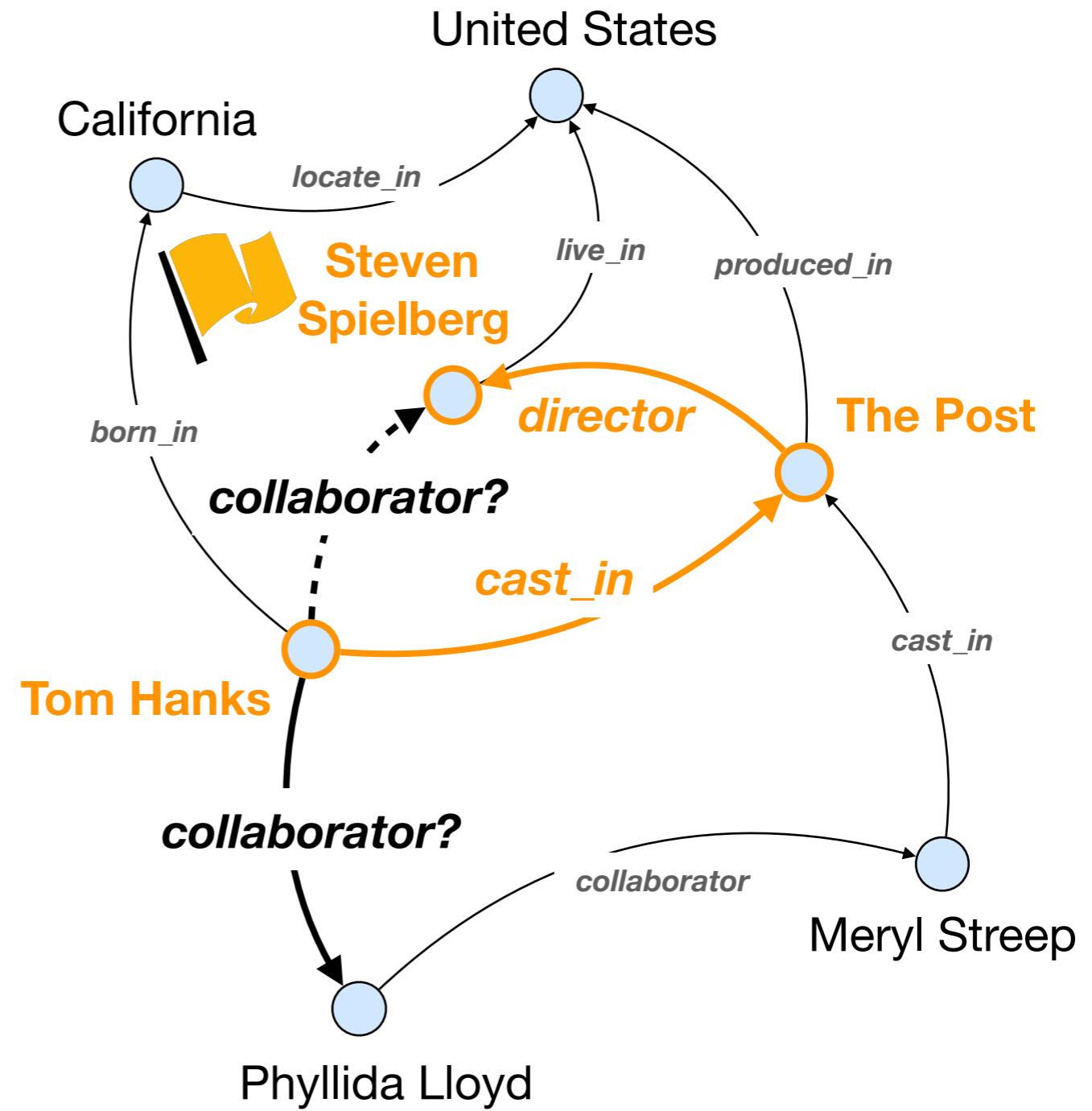
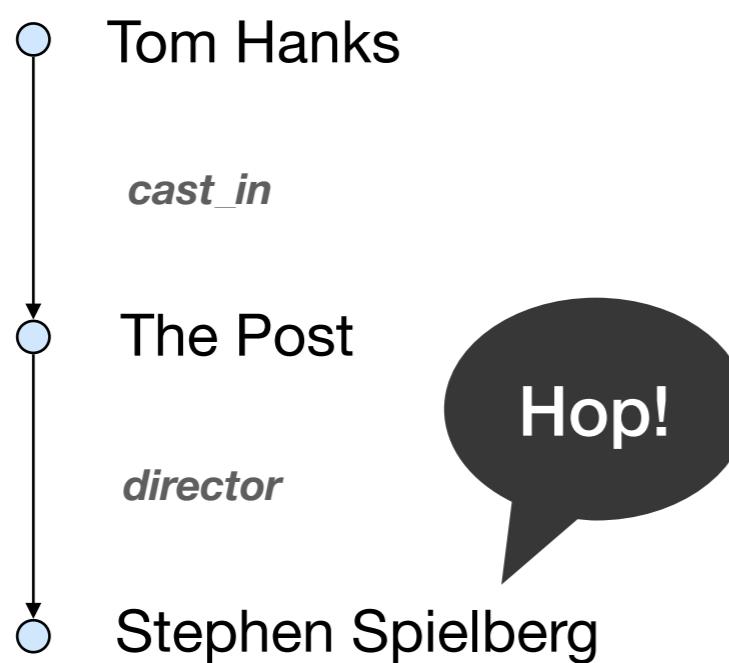
Multi-Hop Reasoning Models



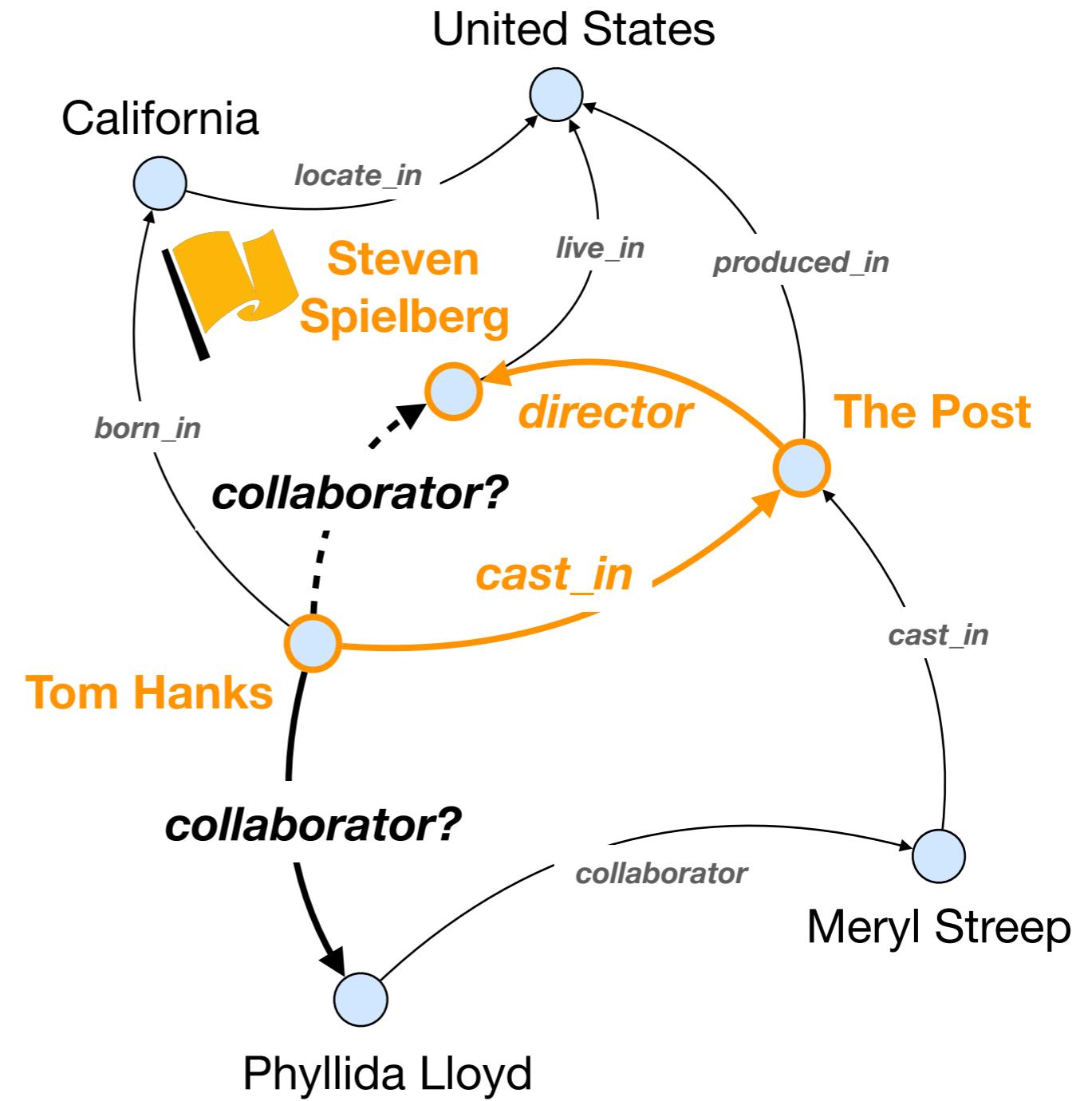
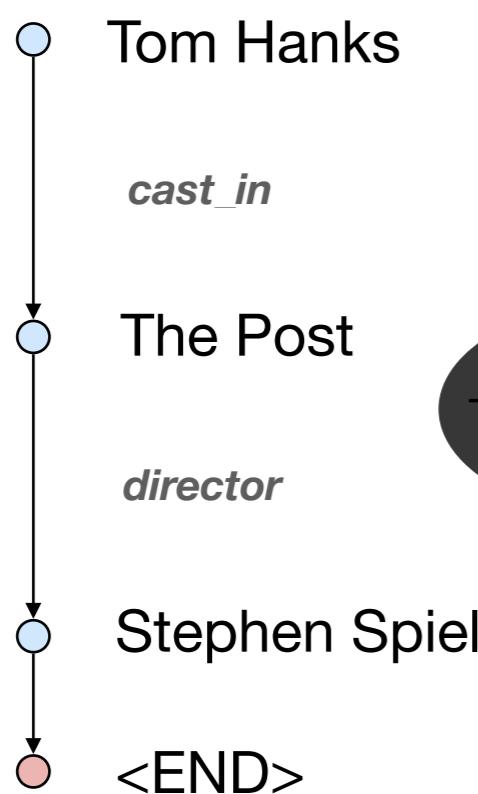
Multi-Hop Reasoning Models



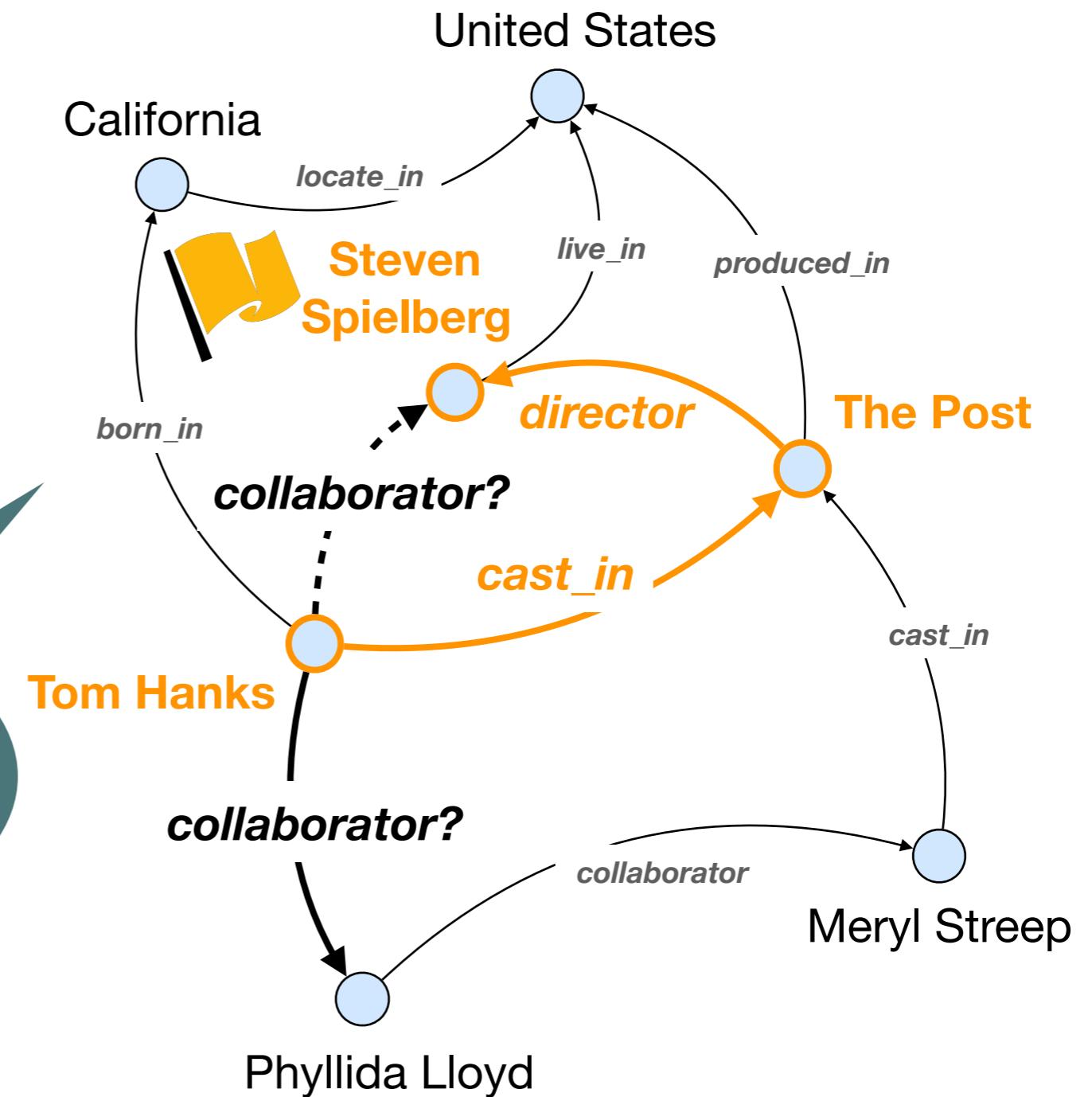
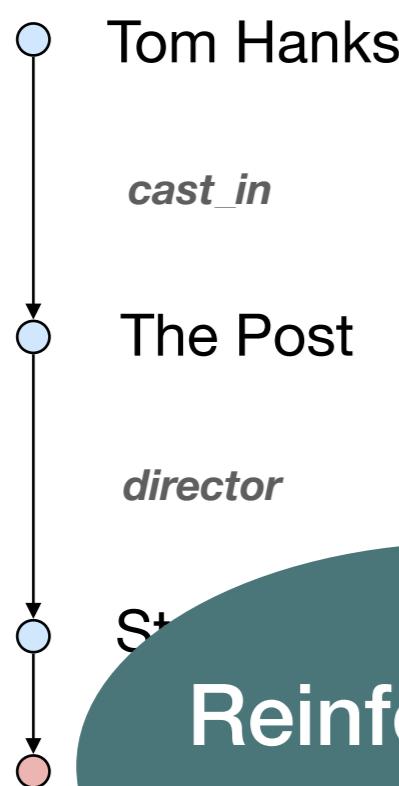
Multi-Hop Reasoning Models



Multi-Hop Reasoning Models



Multi-Hop Reasoning Models



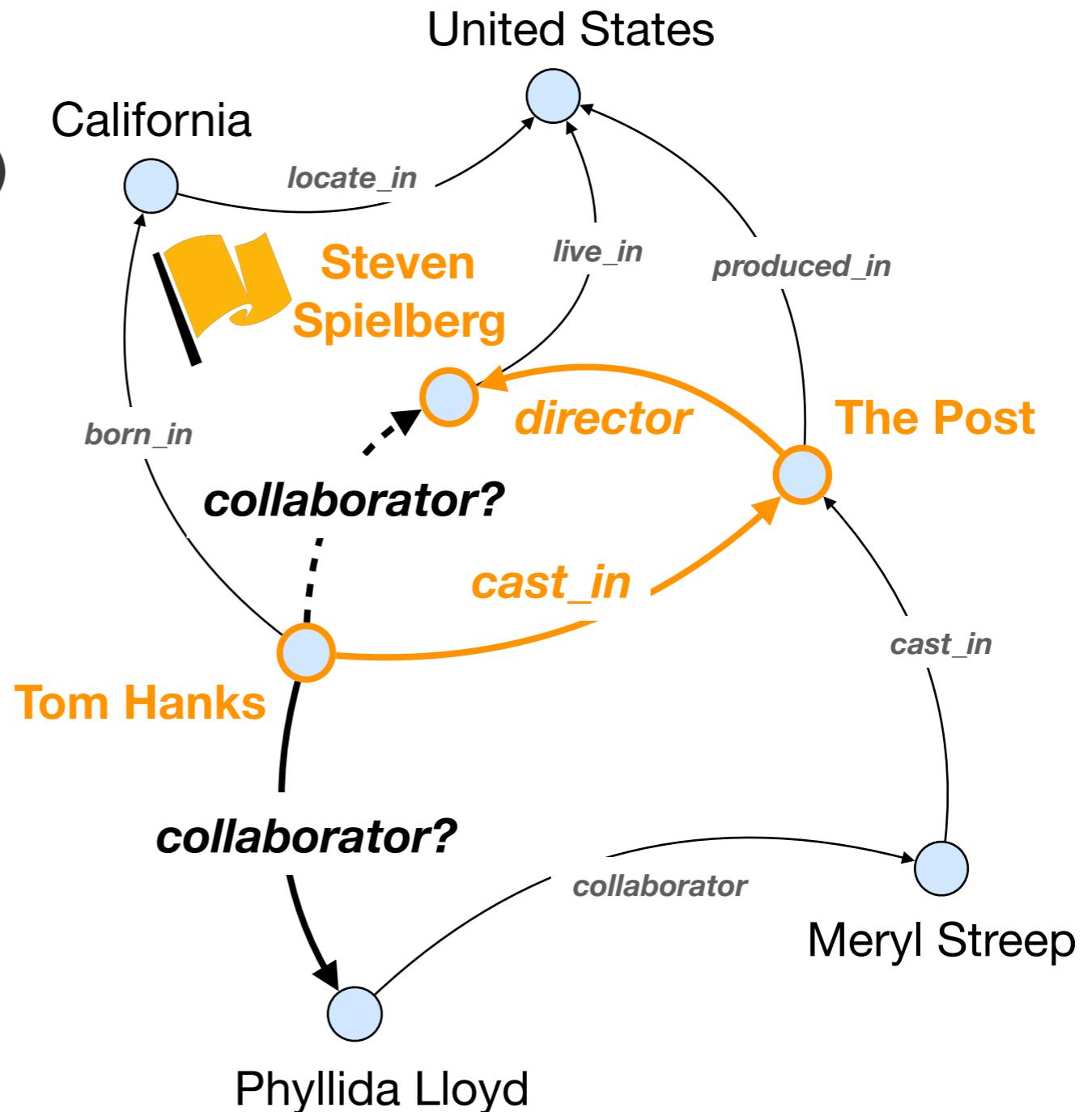
Multi-Hop Reasoning Models



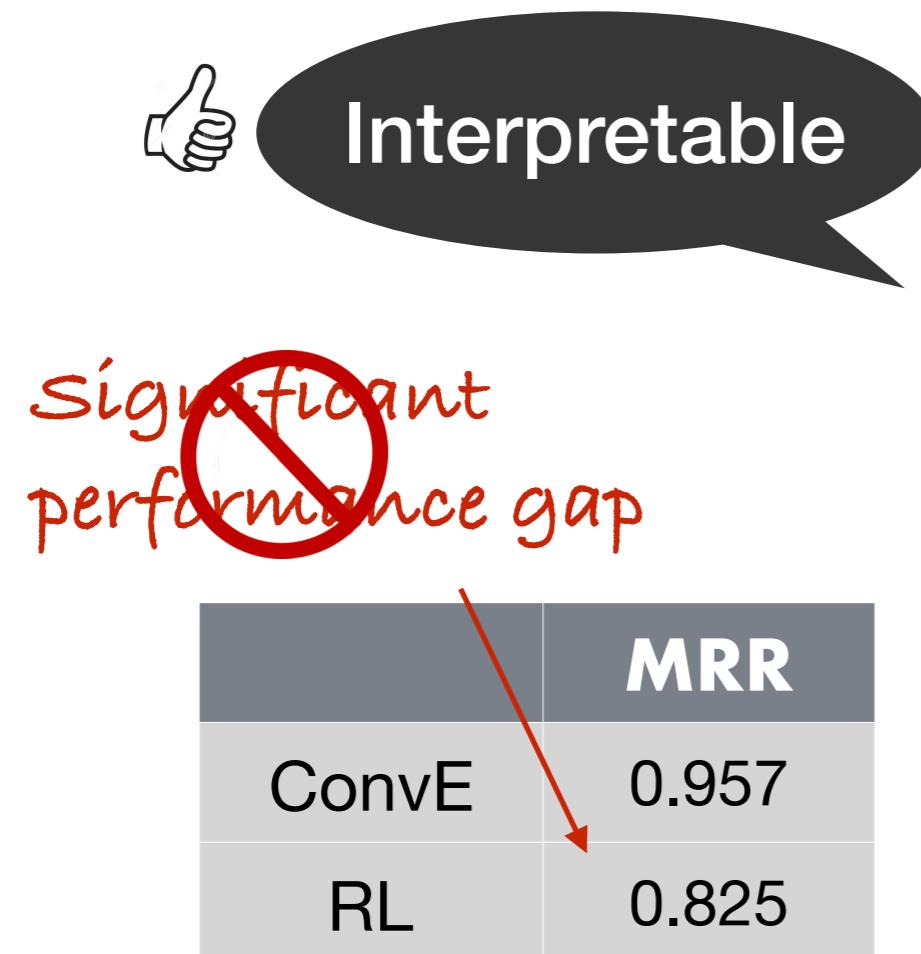
significant
performance gap

MRR	
ConvE	0.957
RL	0.825

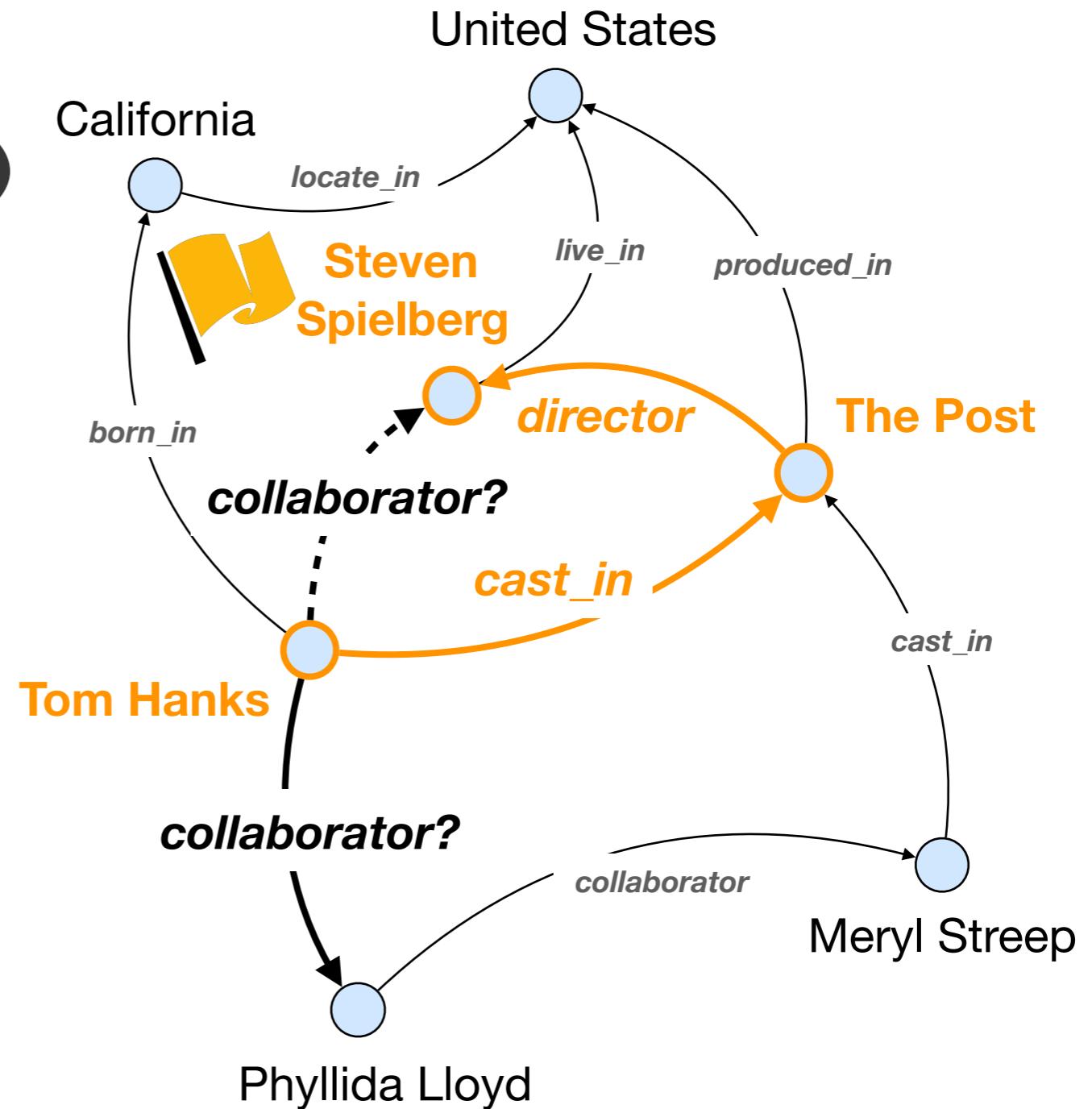
Tab 2. ConvE and RL (MINERVA) query answering performance on the UMLS benchmark dataset (Kok and Domingos 2007)



Multi-Hop Reasoning Models: Ideal Case

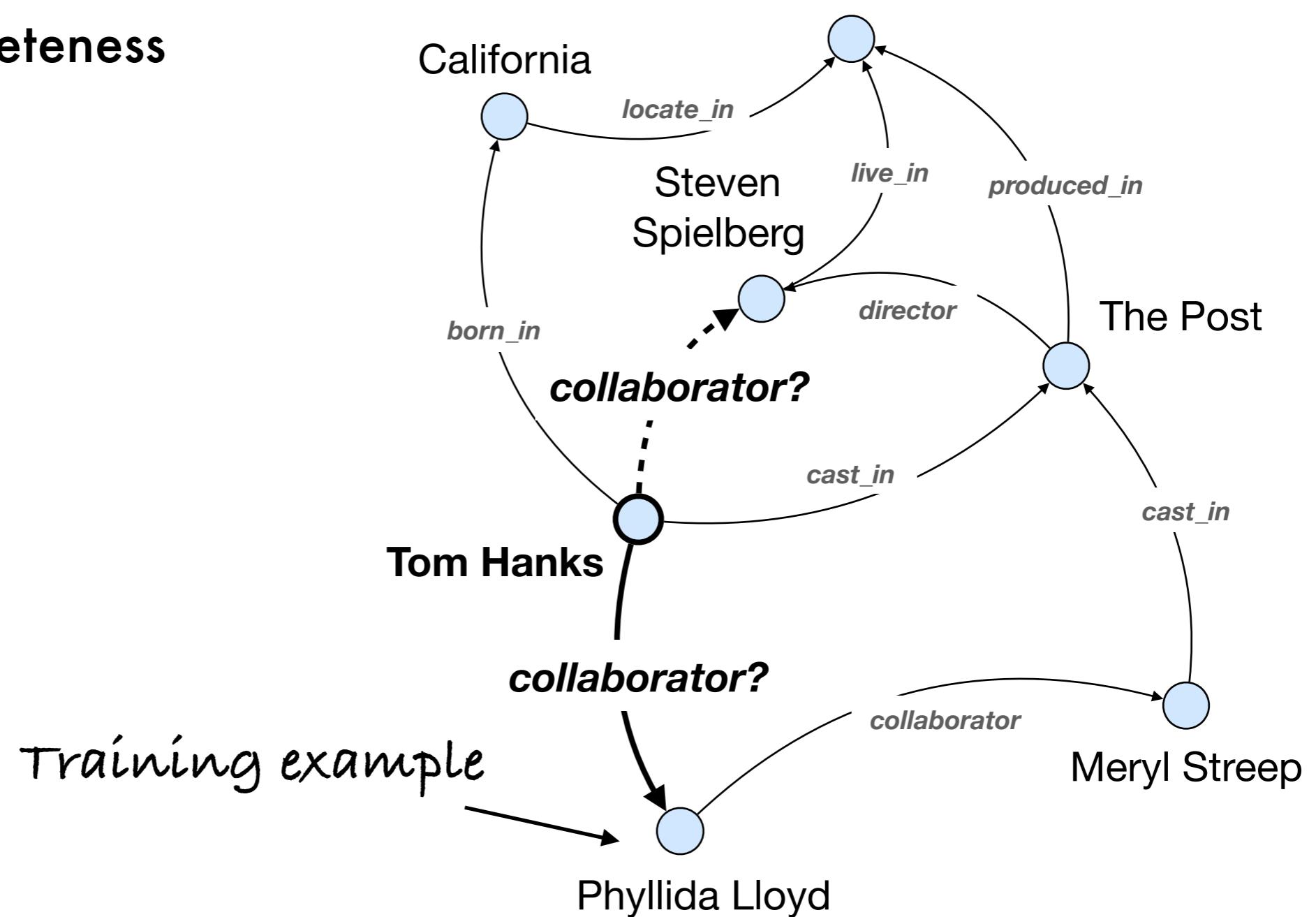


Tab 2. ConvE and RL (MINERVA) query answering performance on the UMLS benchmark dataset (Kok and Domingos 2007)



Challenges

Incompleteness



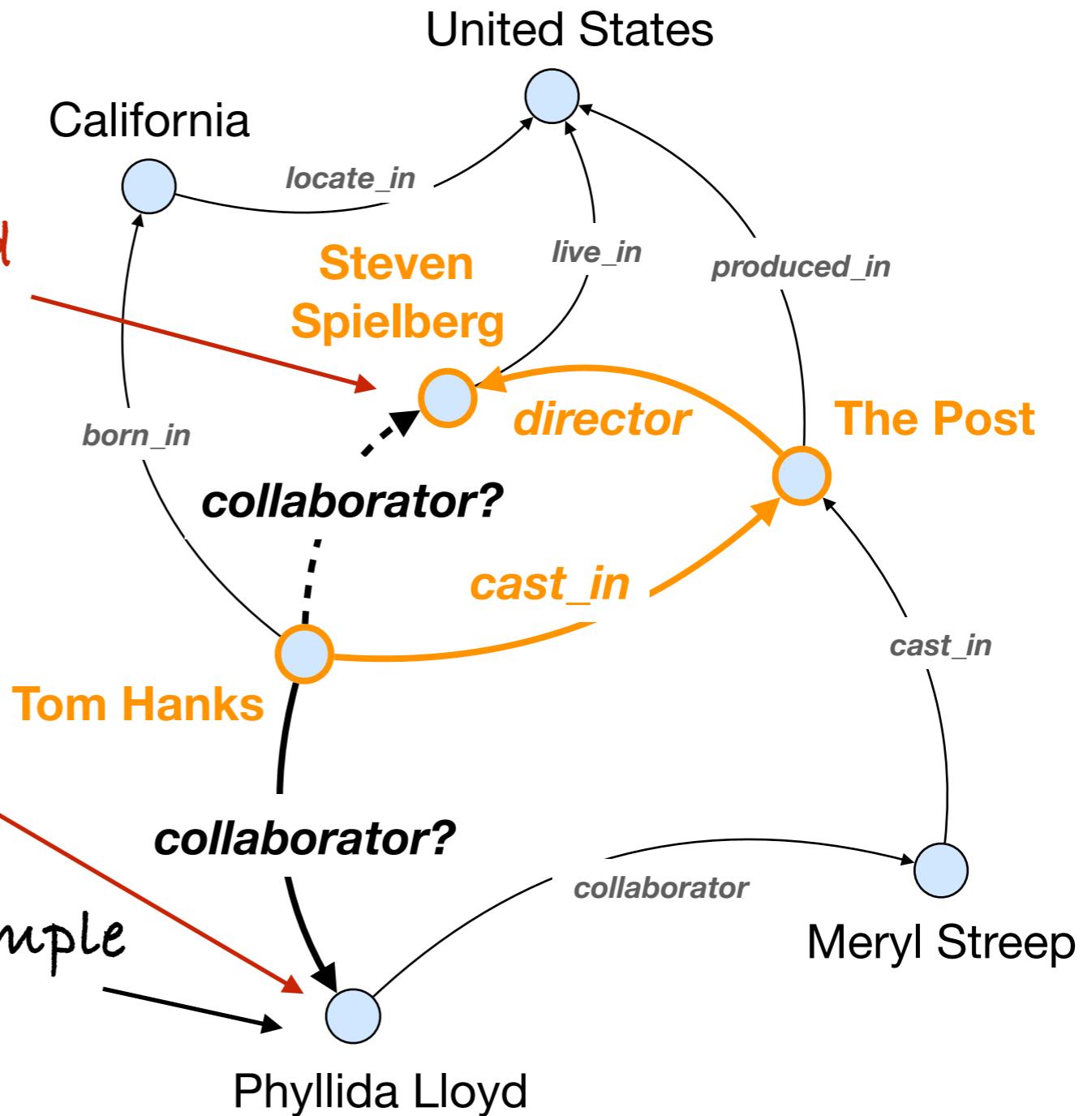
Challenges

Incompleteness

No reward

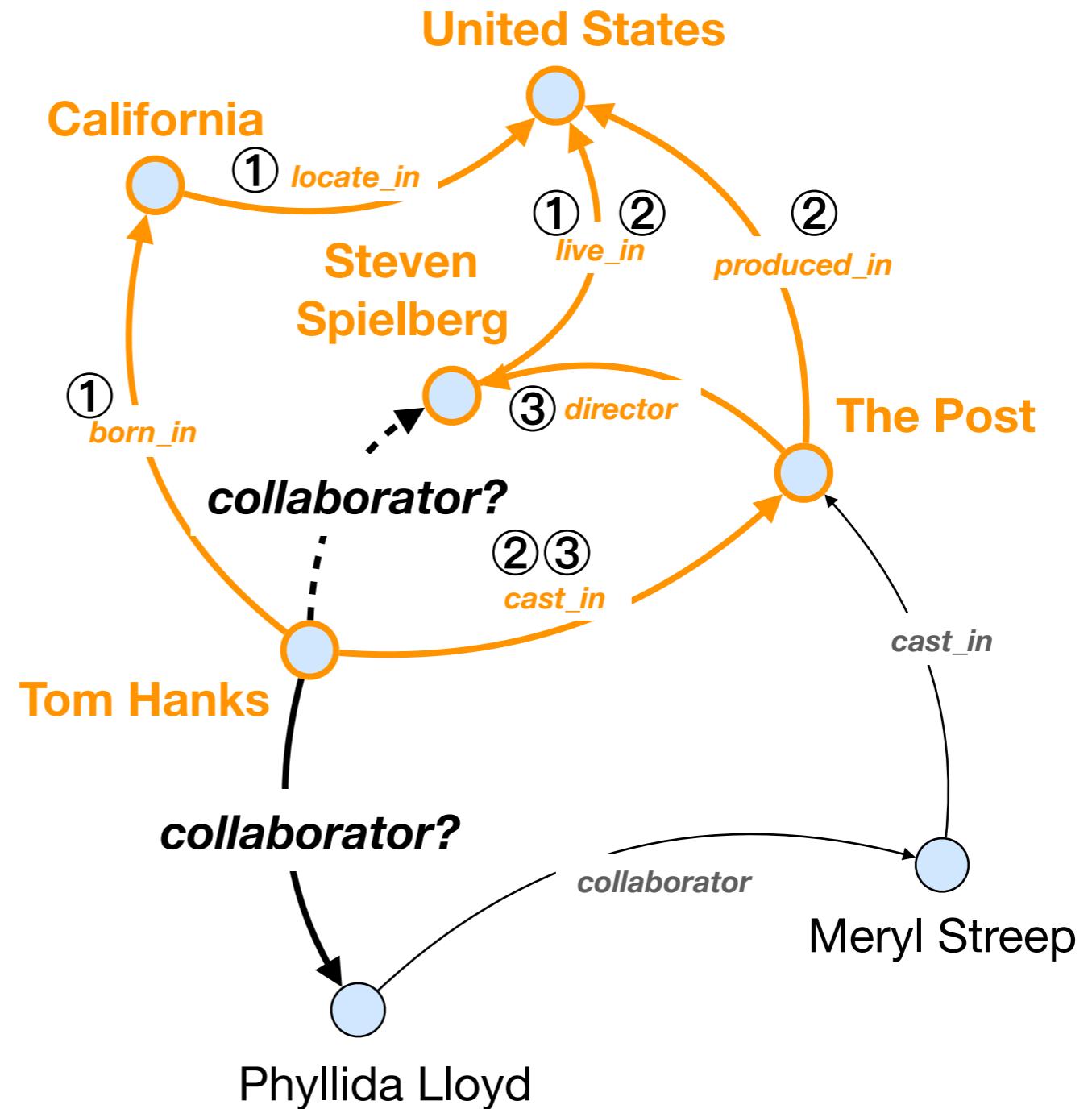
Overfit to the
observed answers

Training example



Challenges

Path Diversity

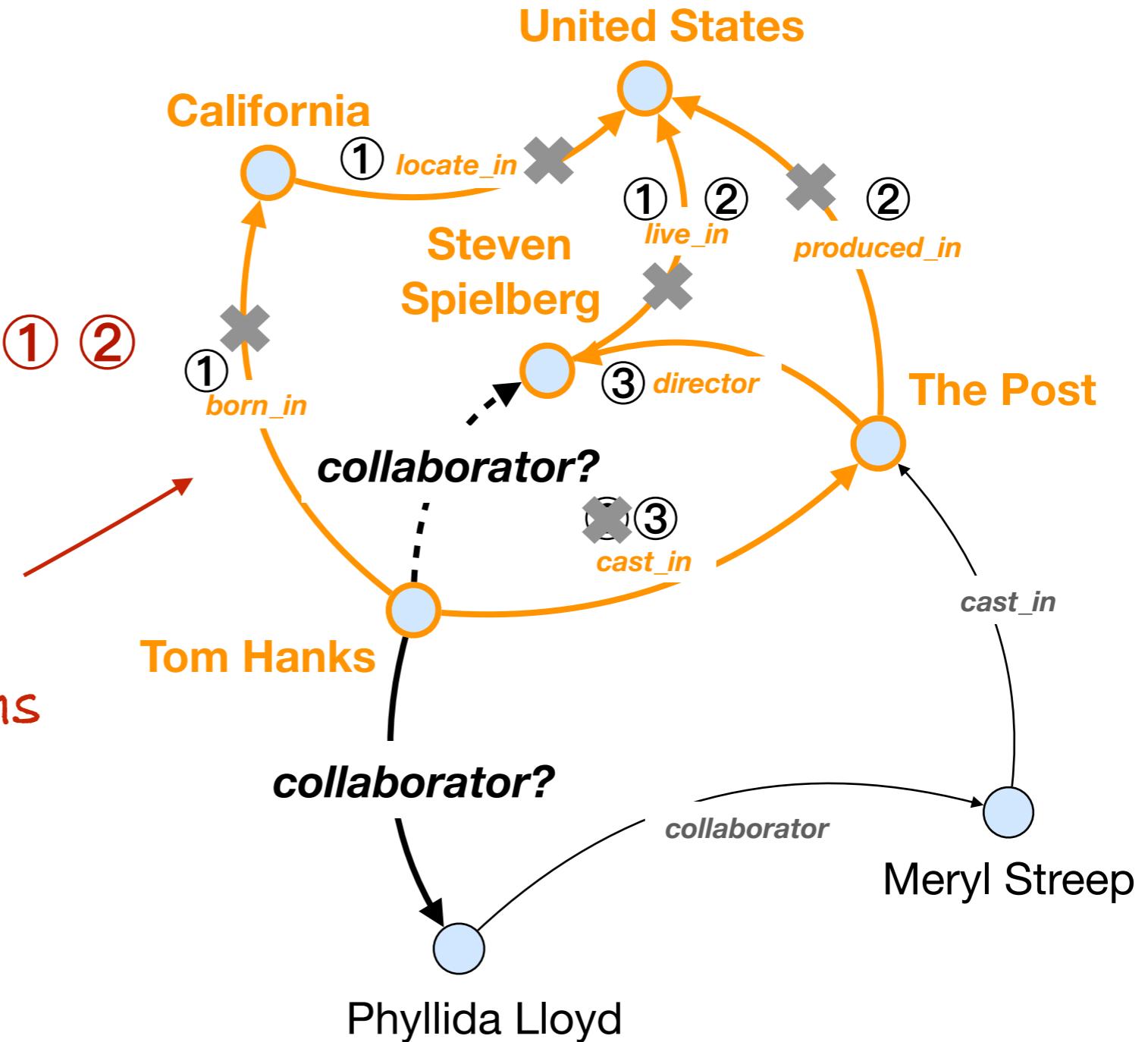


Challenges

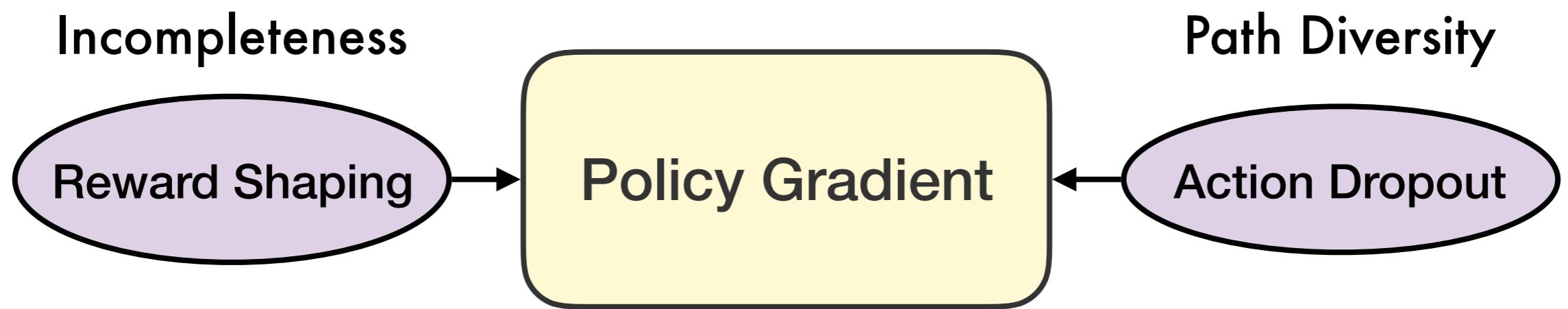
Path Diversity

False positive
(spurious) paths ① ②

Overfit to the
spurious paths



Proposed Solutions



Reinforcement Learning Framework

Environment

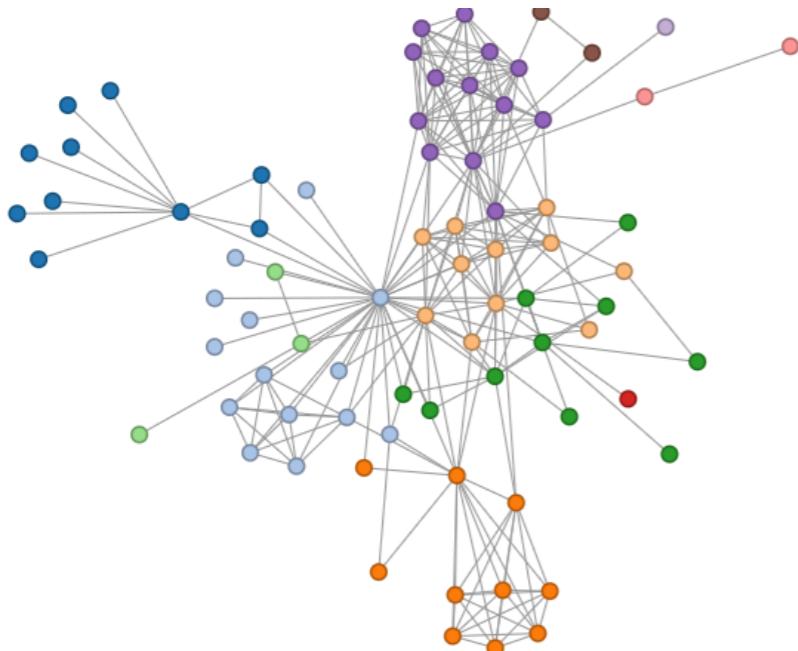
State

Action

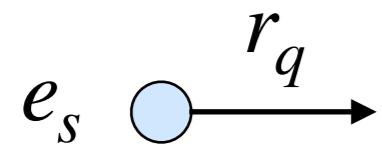
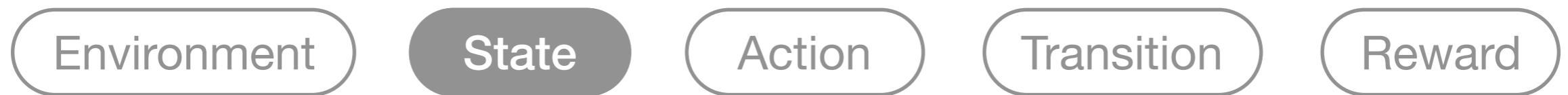
Transition

Reward

$$e_s \quad r_q \rightarrow$$

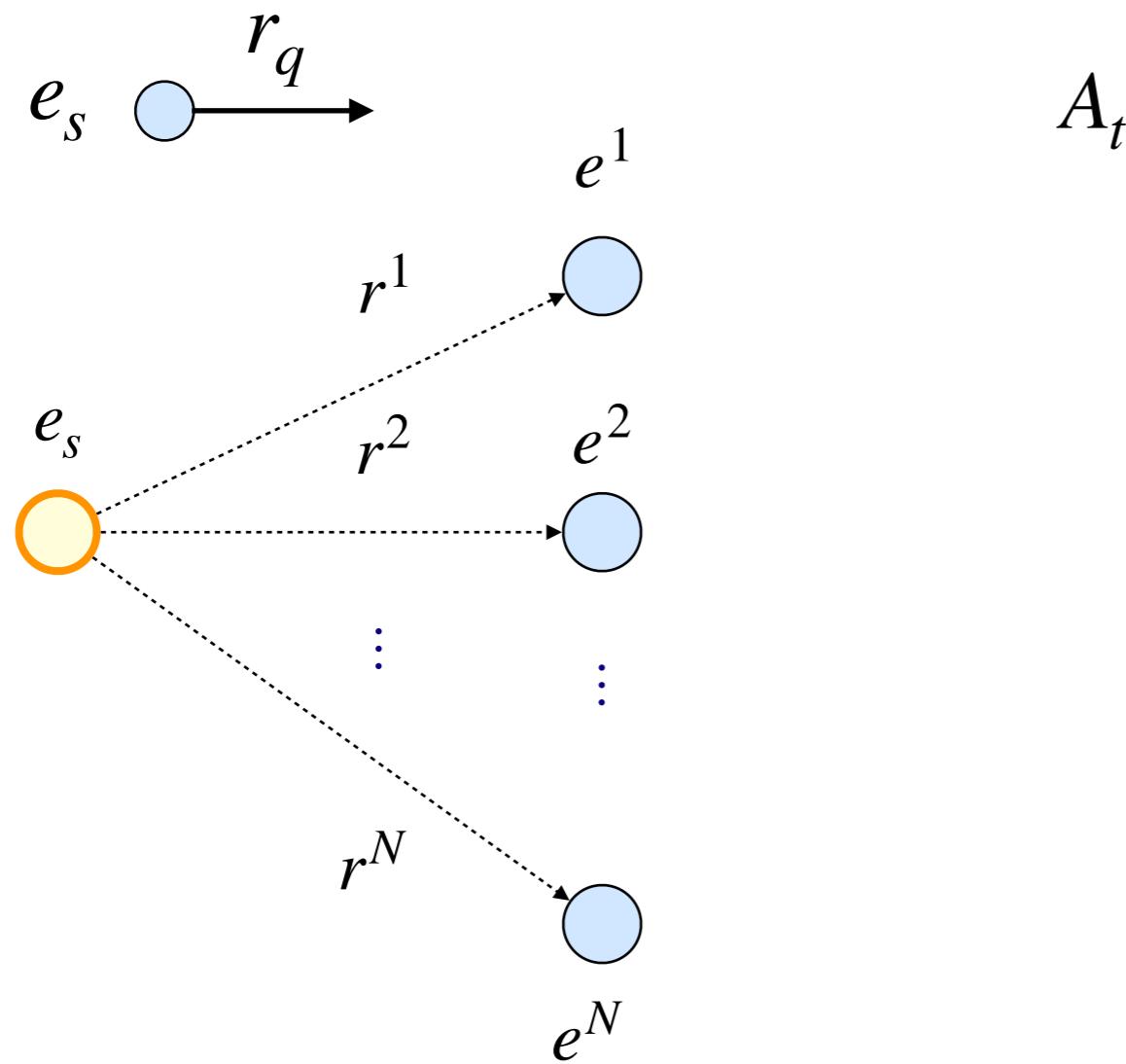


Reinforcement Learning Framework



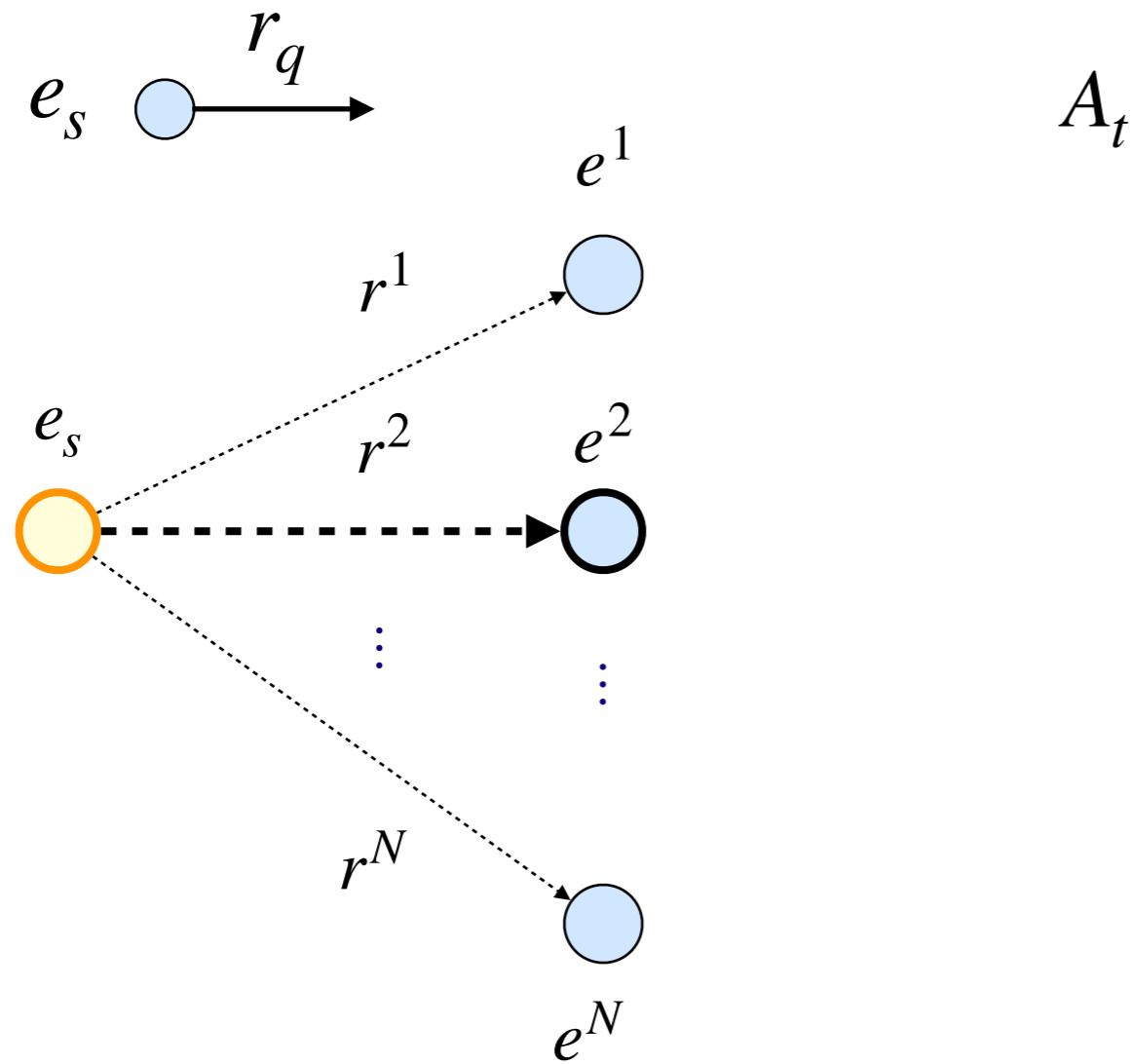
Reinforcement Learning Framework

Environment State **Action** Transition Reward

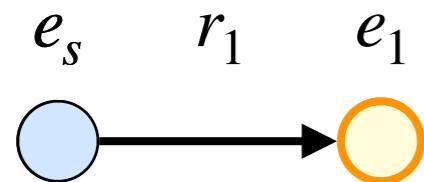
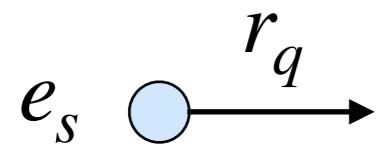
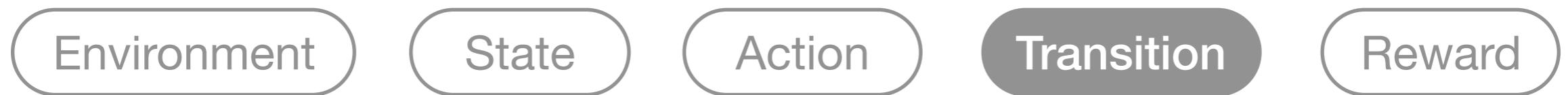


Reinforcement Learning Framework

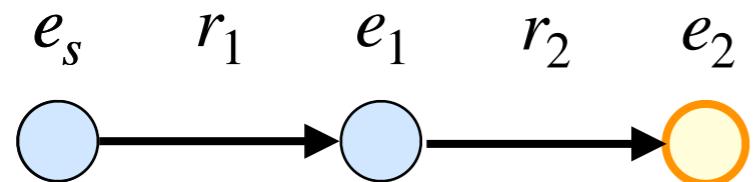
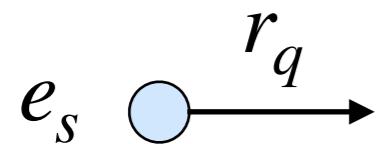
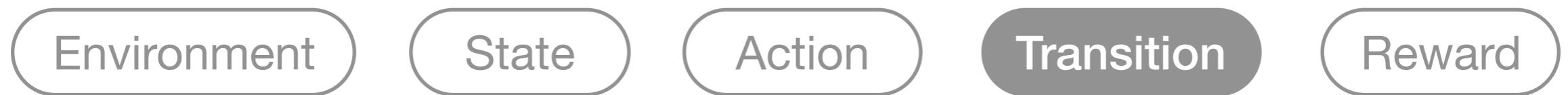
Environment State **Action** Transition Reward



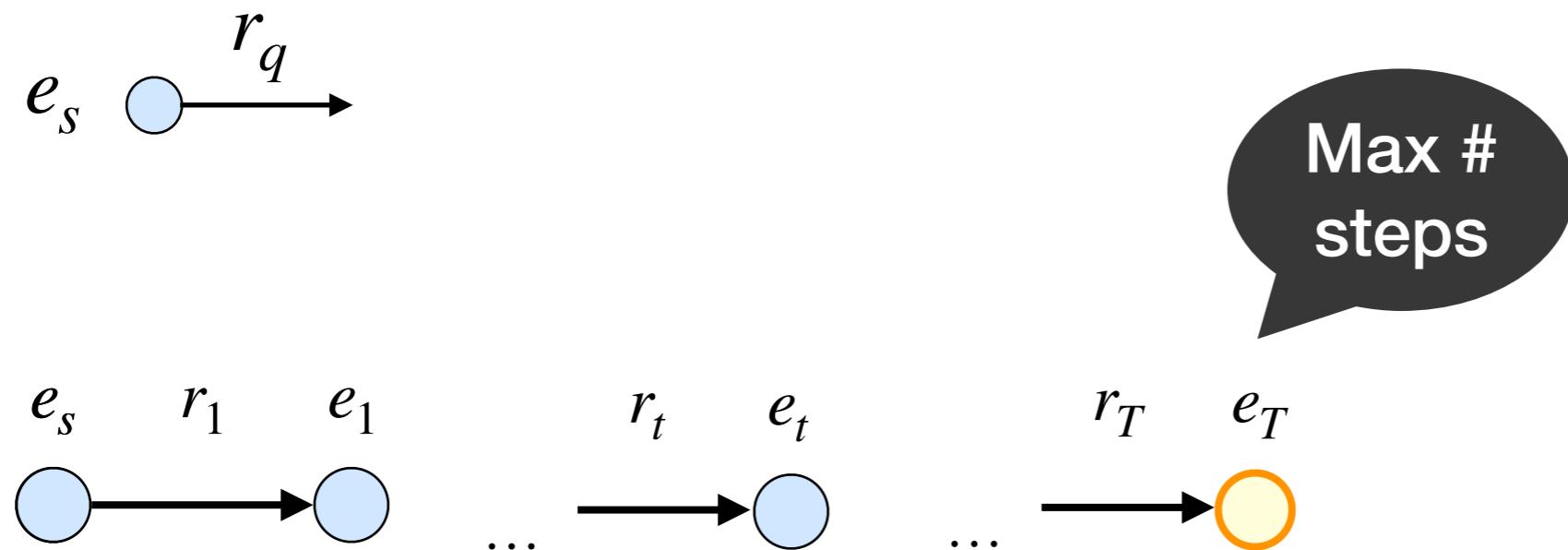
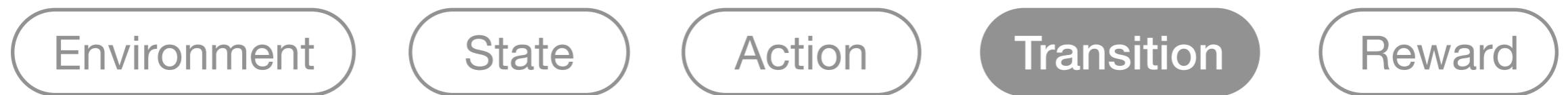
Reinforcement Learning Framework



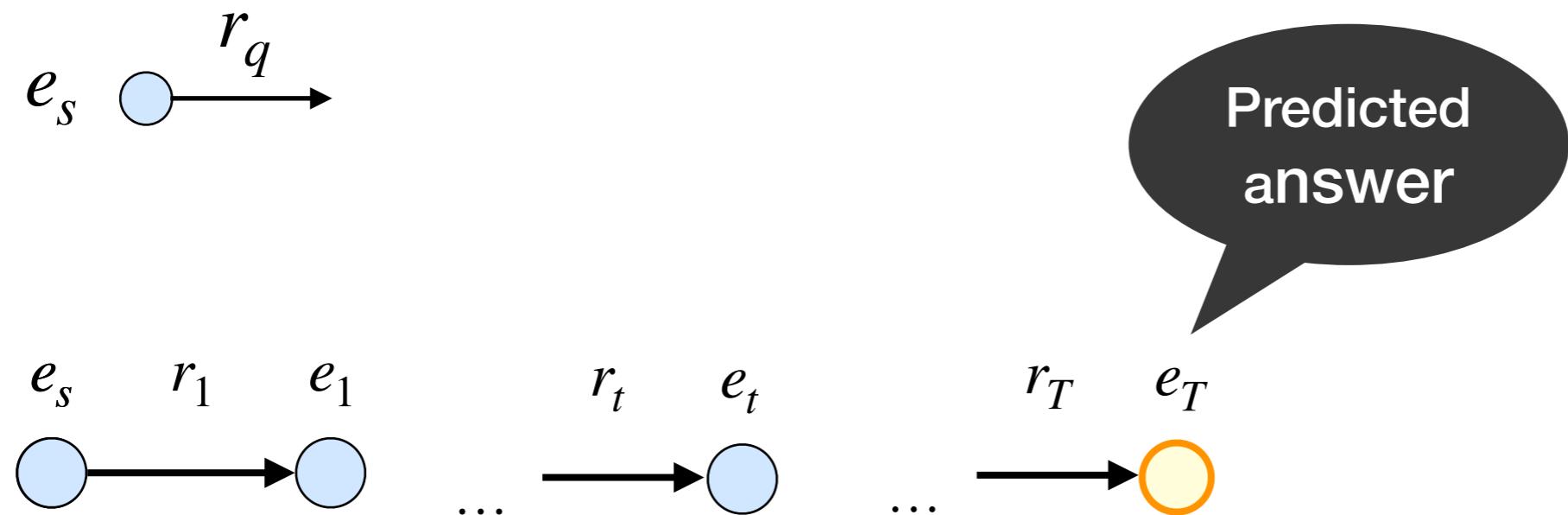
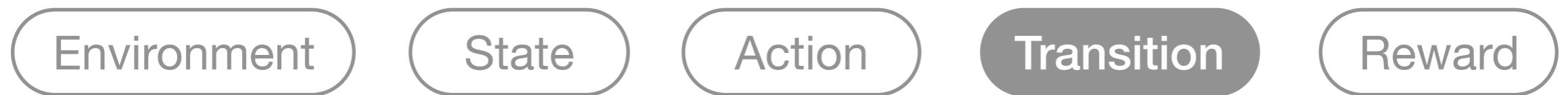
Reinforcement Learning Framework



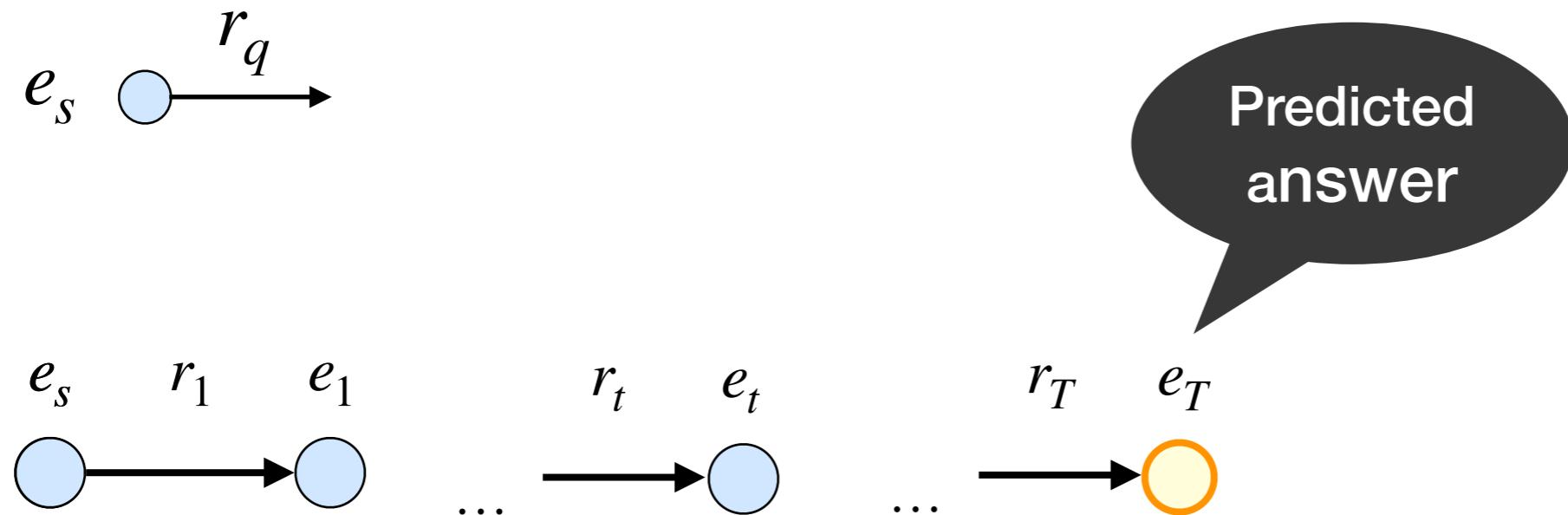
Reinforcement Learning Framework



Reinforcement Learning Framework

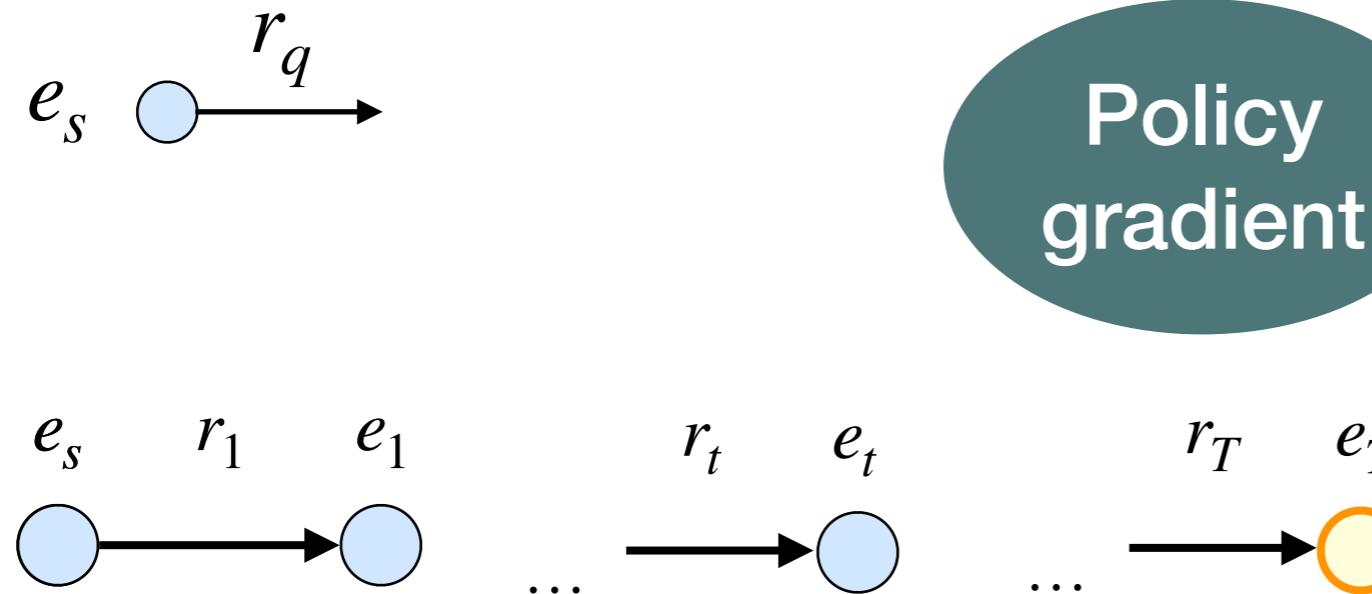
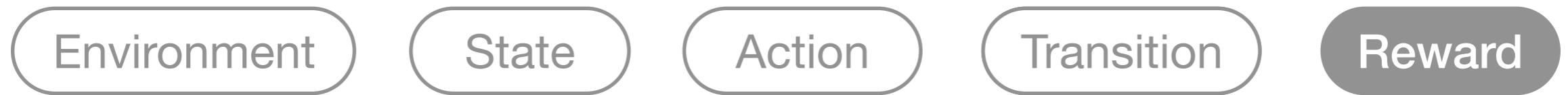


Reinforcement Learning Framework



$$R_b(s_T) = \mathbf{1}\{(e_s, r_q, e_T) \in G\}$$

Reinforcement Learning Framework



Policy
gradient

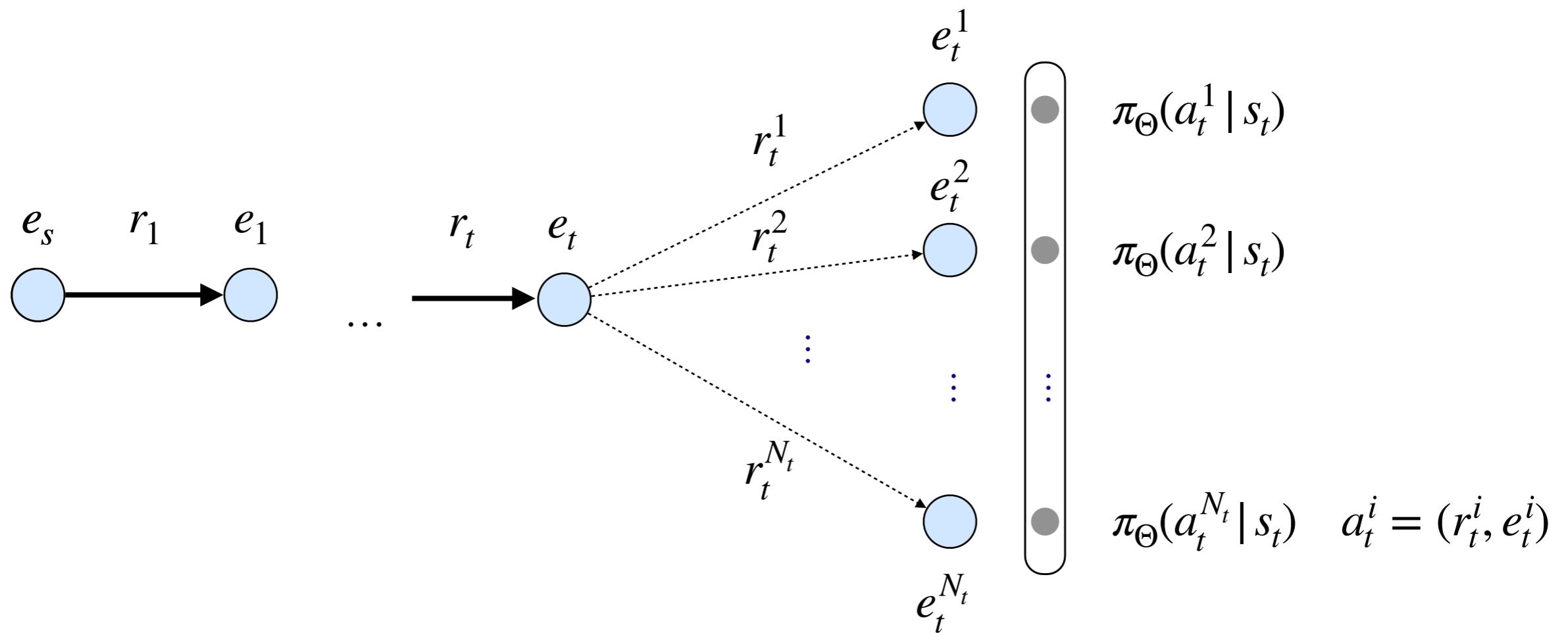
Learn **which**
action to choose
given a state

$$R_b(s_T) = \mathbf{1}\{(e_s, r_q, e_T) \in G\}$$

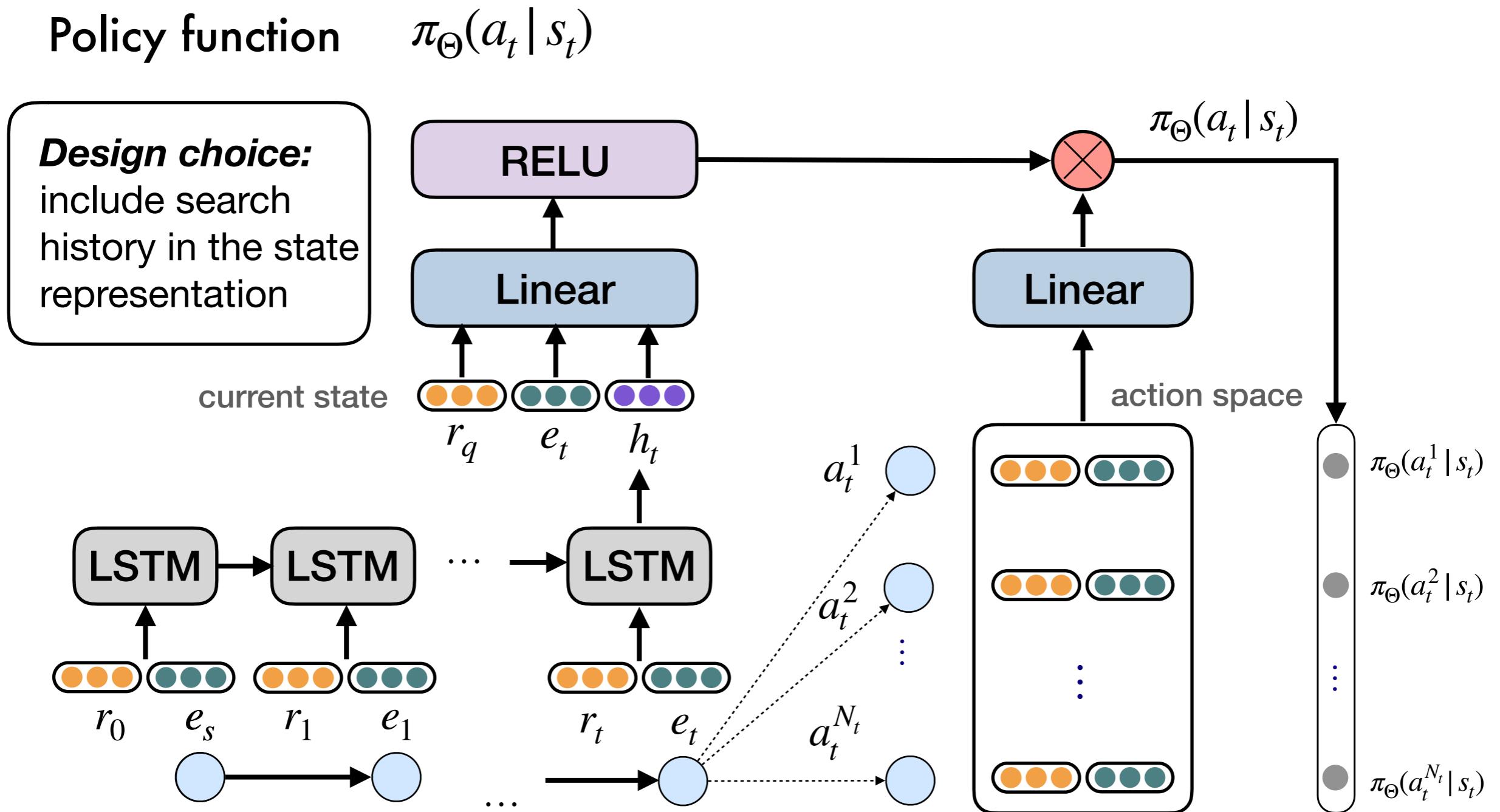
Policy Gradient

Policy function $\pi_{\Theta}(a_t | s_t)$

Probability of choosing
an action given the
current state



Policy Gradient

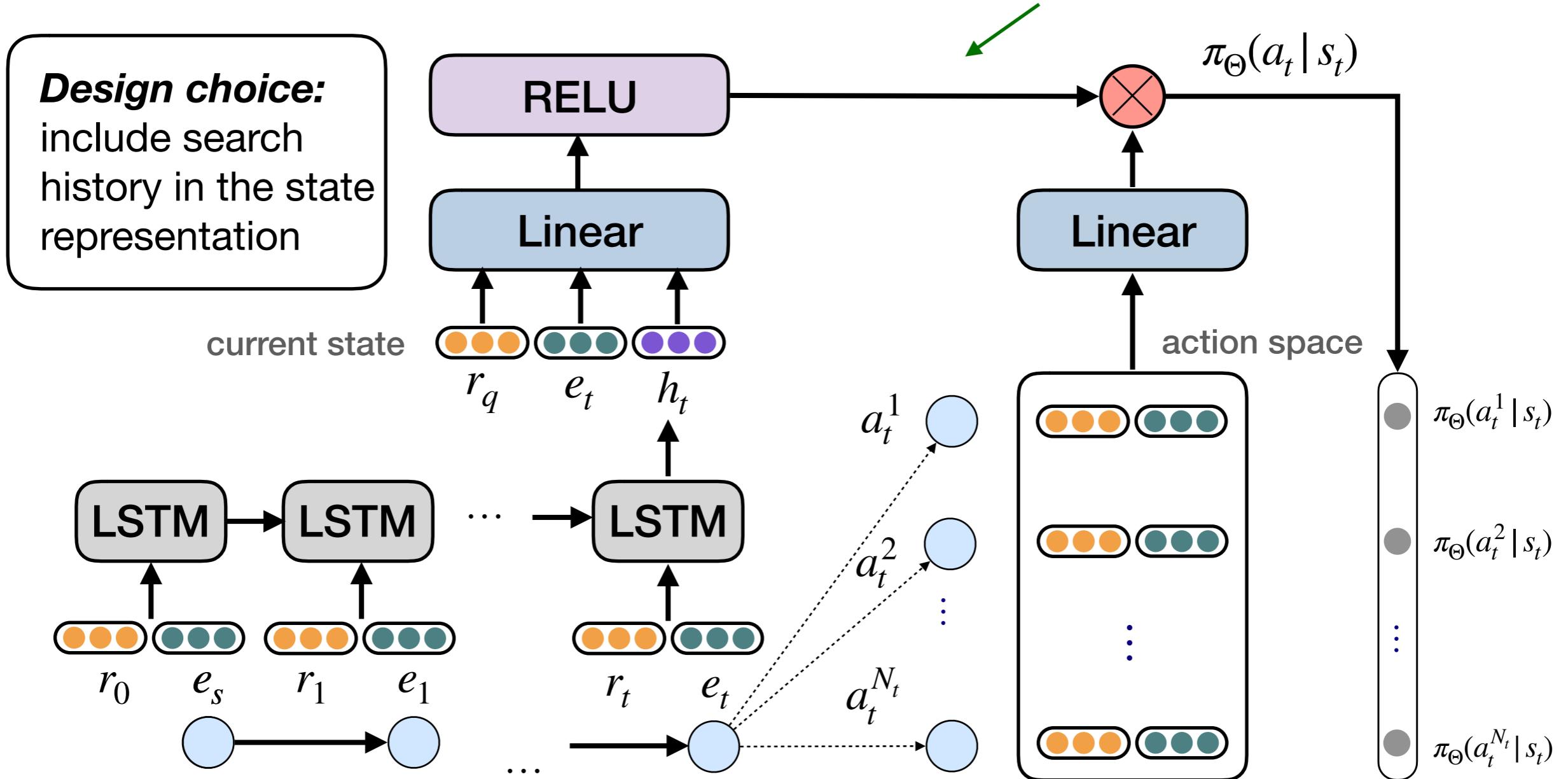


Policy Gradient

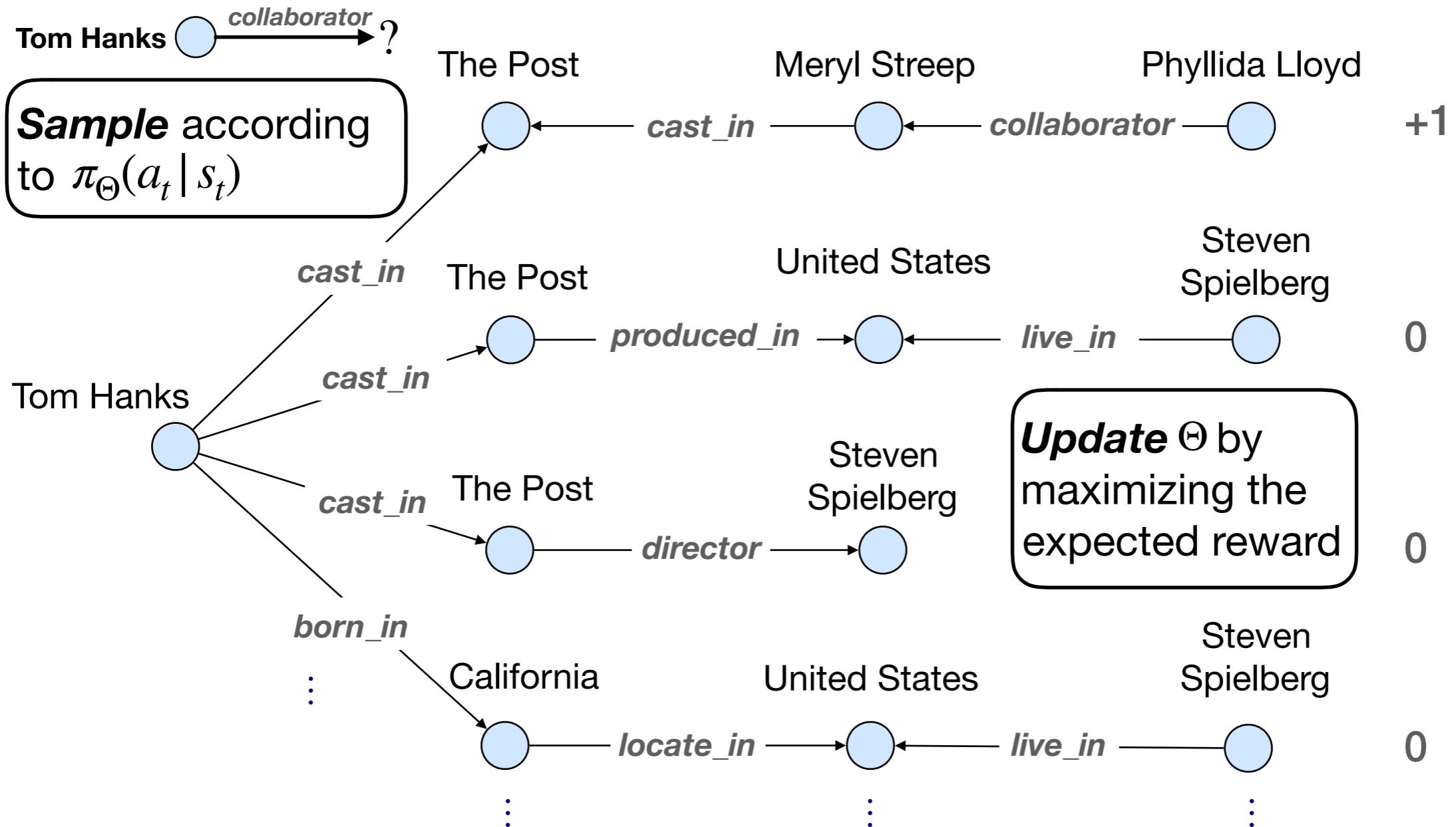
Policy function

$$\pi_{\Theta}(a_t | s_t)$$

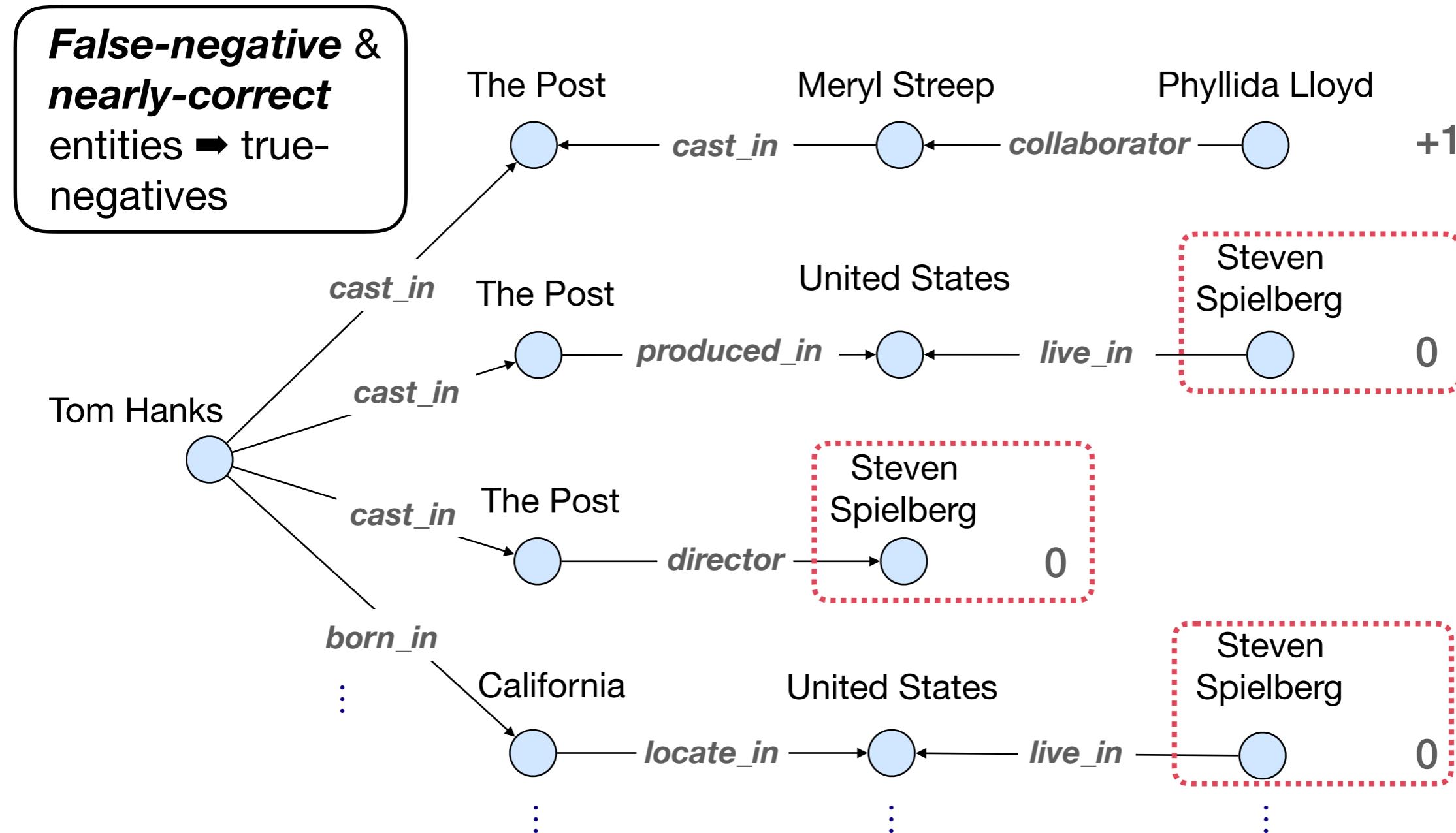
Our model extensions are applicable
to any parameterization of π_{Θ}



REINFORCE Training



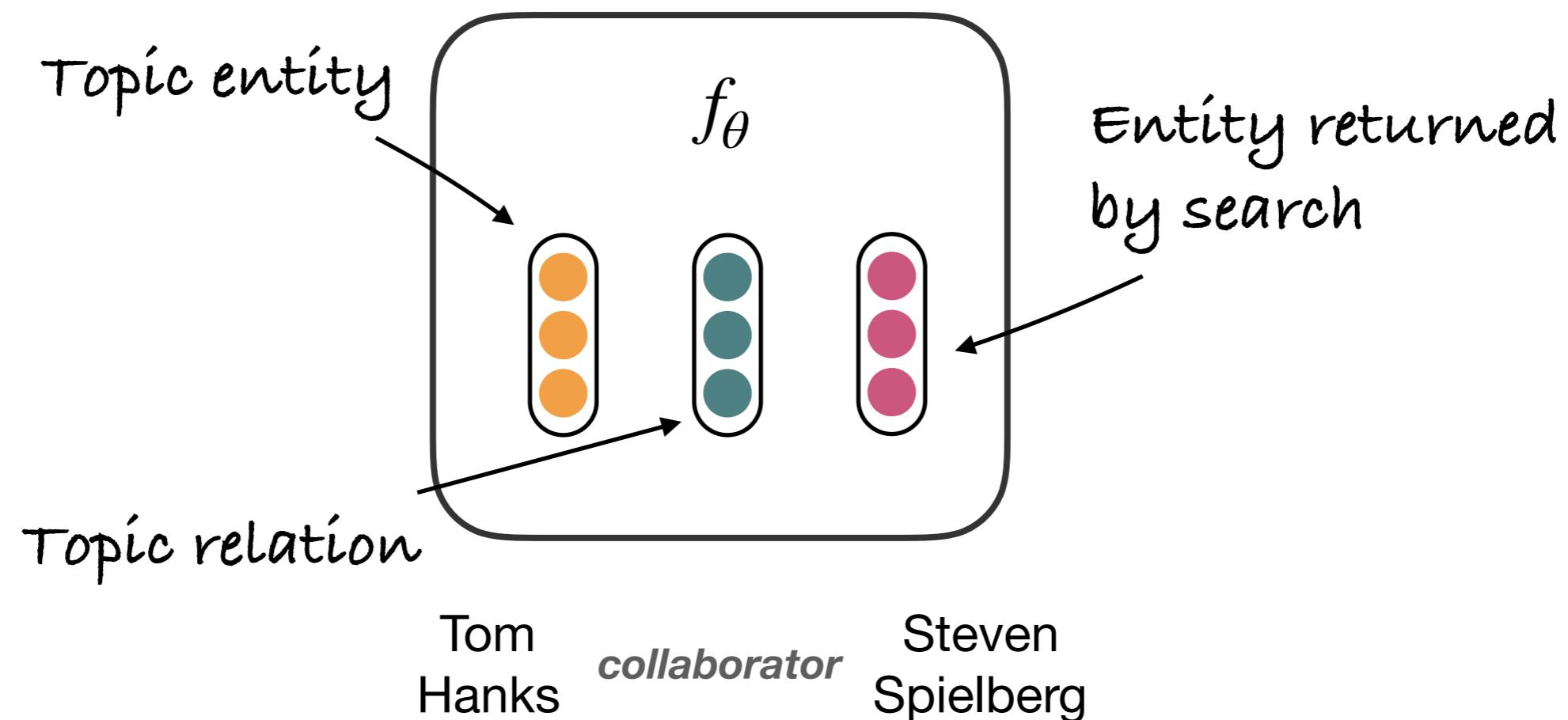
REINFORCE Training



Reward Shaping

Unobserved facts

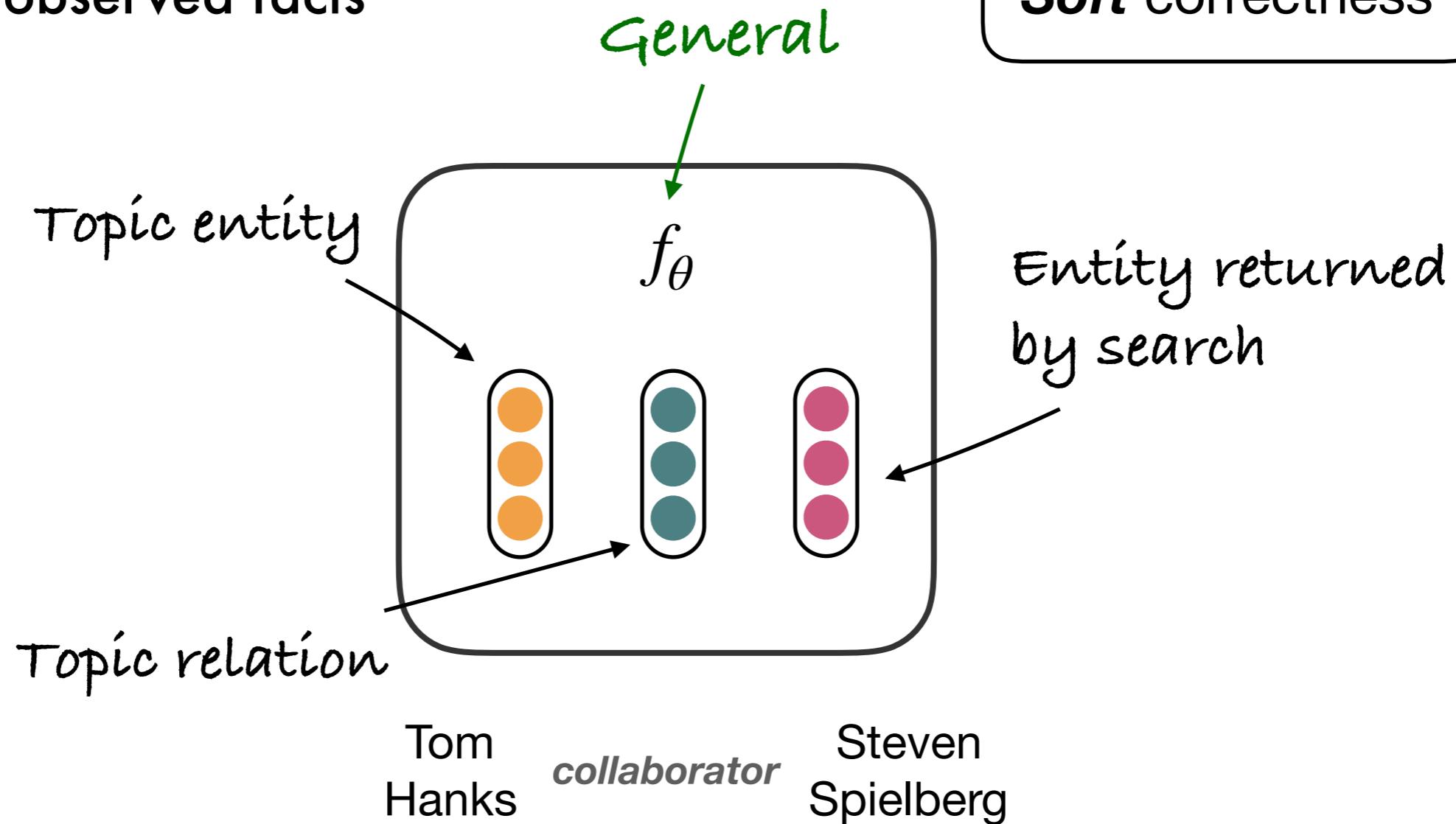
Soft correctness



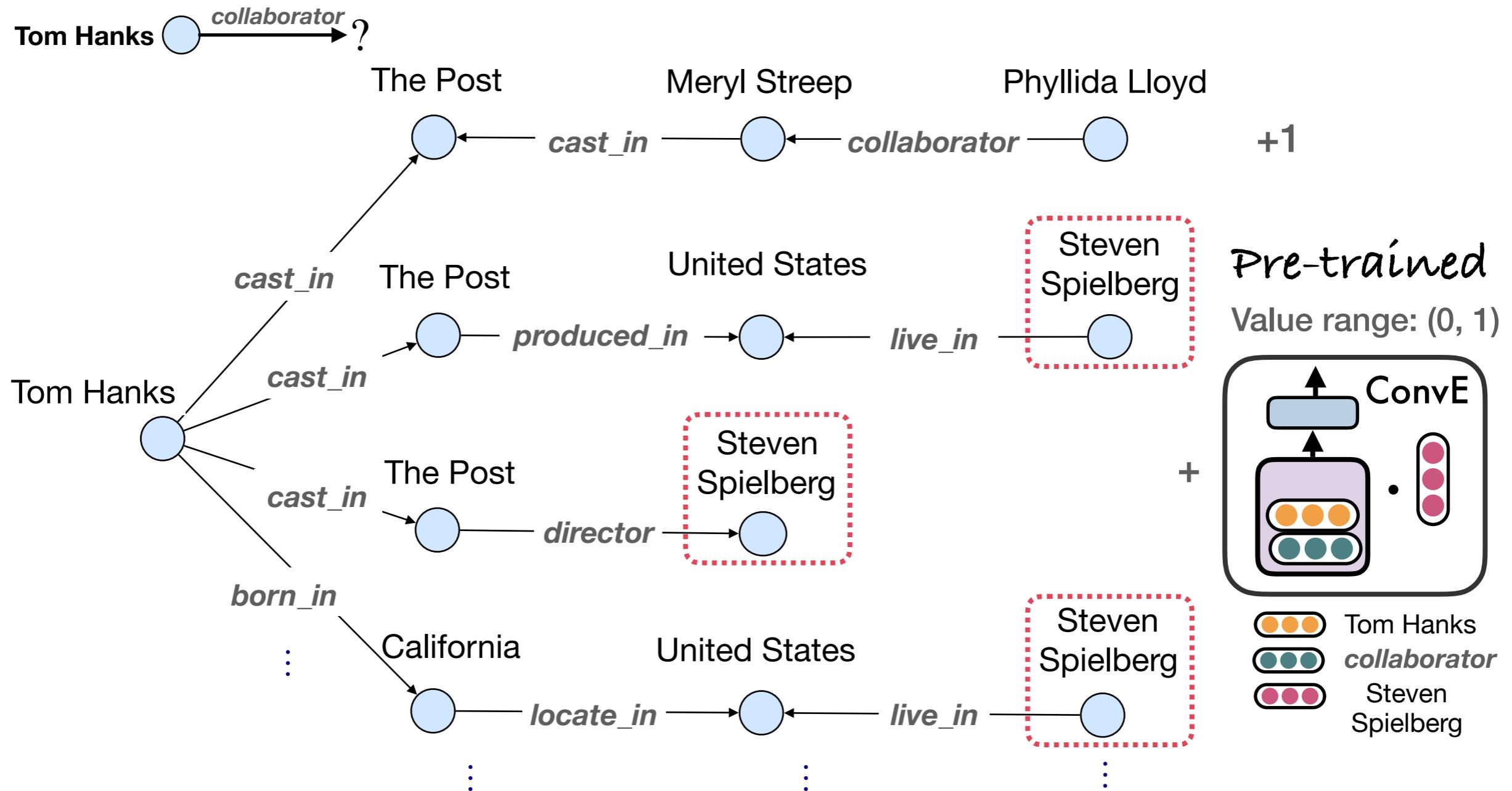
Reward Shaping

Unobserved facts

Soft correctness



Reward Shaping



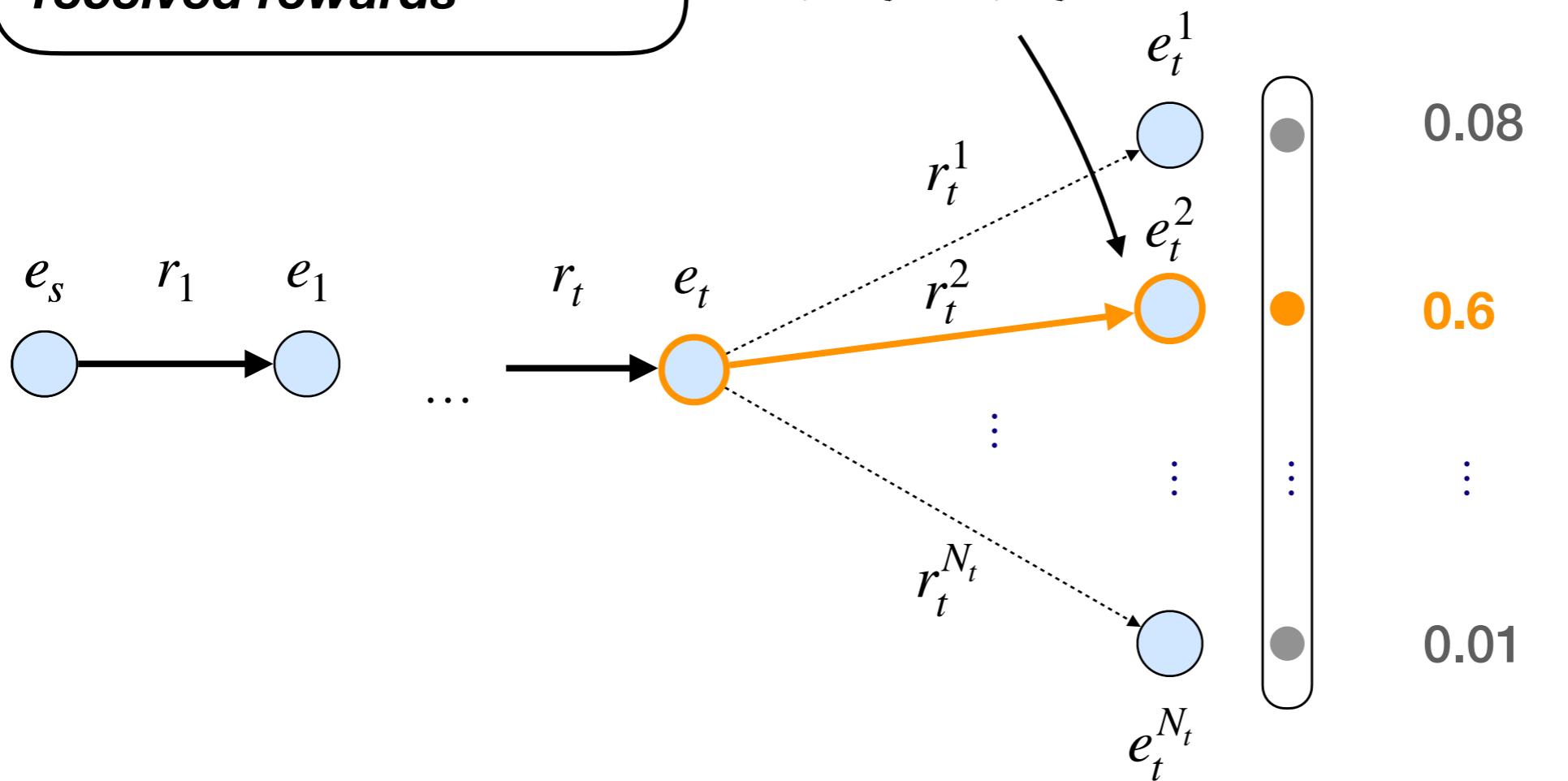
Action Dropout

Intuition: ***avoid sticking to past actions that *had received rewards****

Action Dropout

Intuition: **avoid sticking to**
past actions that **had**
received rewards

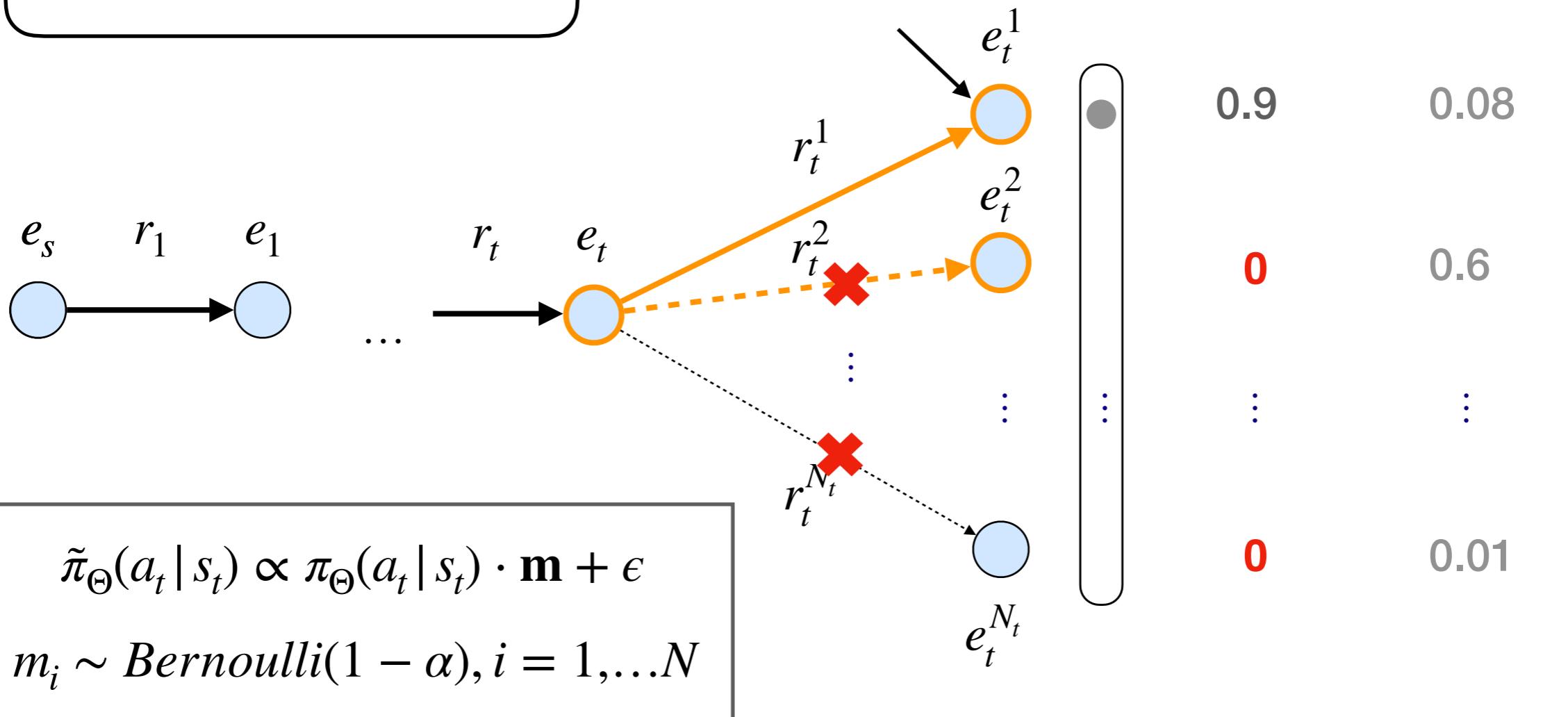
More likely
to be chosen



Action Dropout

Randomly offset the **sampling probabilities** w/
rate α and renormalize

More likely
to be chosen



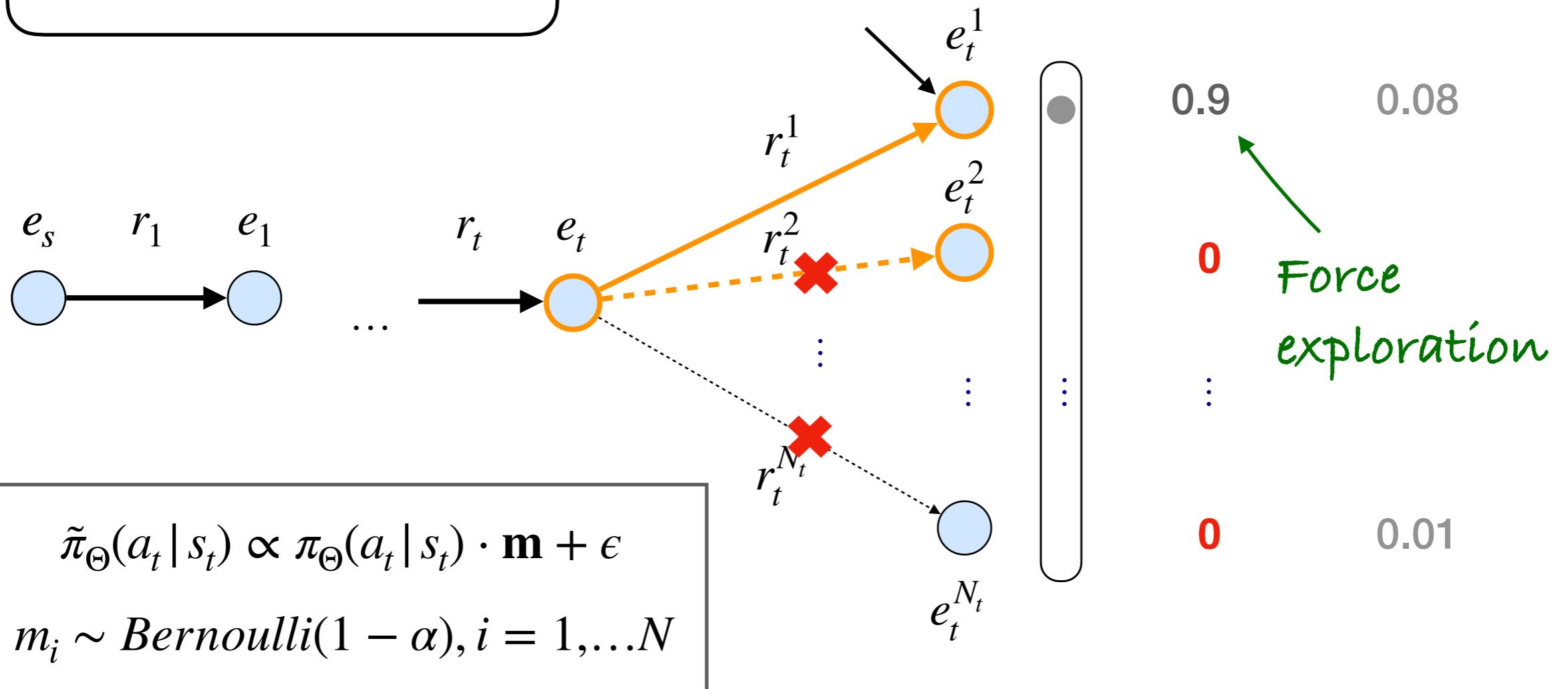
$$\tilde{\pi}_{\Theta}(a_t | s_t) \propto \pi_{\Theta}(a_t | s_t) \cdot \mathbf{m} + \epsilon$$

$$m_i \sim \text{Bernoulli}(1 - \alpha), i = 1, \dots, N$$

Action Dropout

Randomly offset the **sampling probabilities** w/
rate α and renormalize

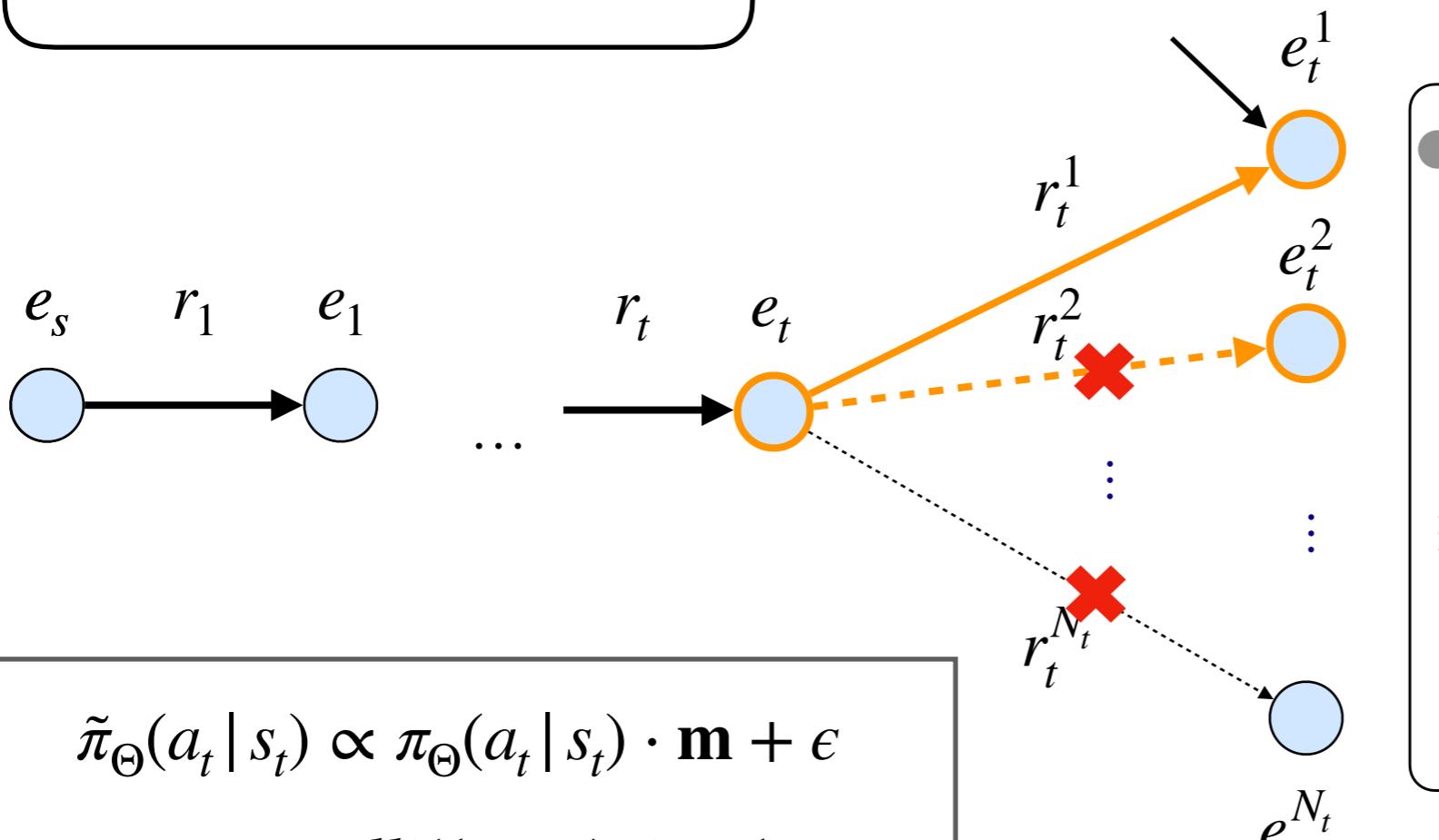
More likely
to be chosen



Action Dropout

Randomly offset the **sampling probabilities** w/
rate α and renormalize

More likely
to be chosen

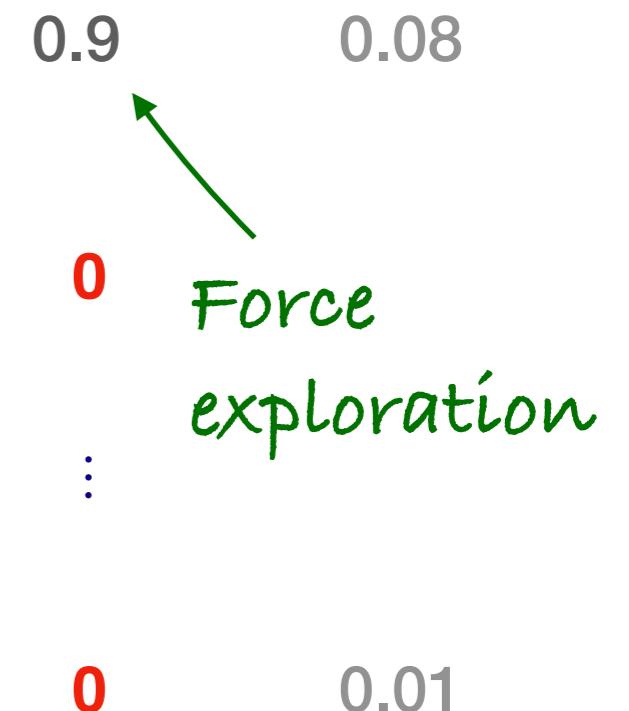


$$\tilde{\pi}_{\Theta}(a_t | s_t) \propto \pi_{\Theta}(a_t | s_t) \cdot \mathbf{m} + \epsilon$$

$$m_i \sim \text{Bernoulli}(1 - \alpha), i = 1, \dots, N$$

Up to $\times 8$ # path
traversed

$$\tilde{\pi}_{\Theta}(a_t^i | s_t) \quad \pi_{\Theta}(a_t^i | s_t)$$



Experiment Setup

KG Benchmarks

Name	# Ent.	# Rel.	# Fact	# Degree Avg	# Degree Median
Kinship	104	25	8,544	85.15	82
UMLS	135	46	5,216	38.63	28
FB15k-237	14,505	237	272,115	19.74	14
WN18RR	40,945	11	86,835	2.19	2
NELL-995	75,492	200	154,213	4.07	1

Decreasing
connectivity

Evaluation Protocol: MRR (Mean Reciprocal Rank)

Ablation Studies

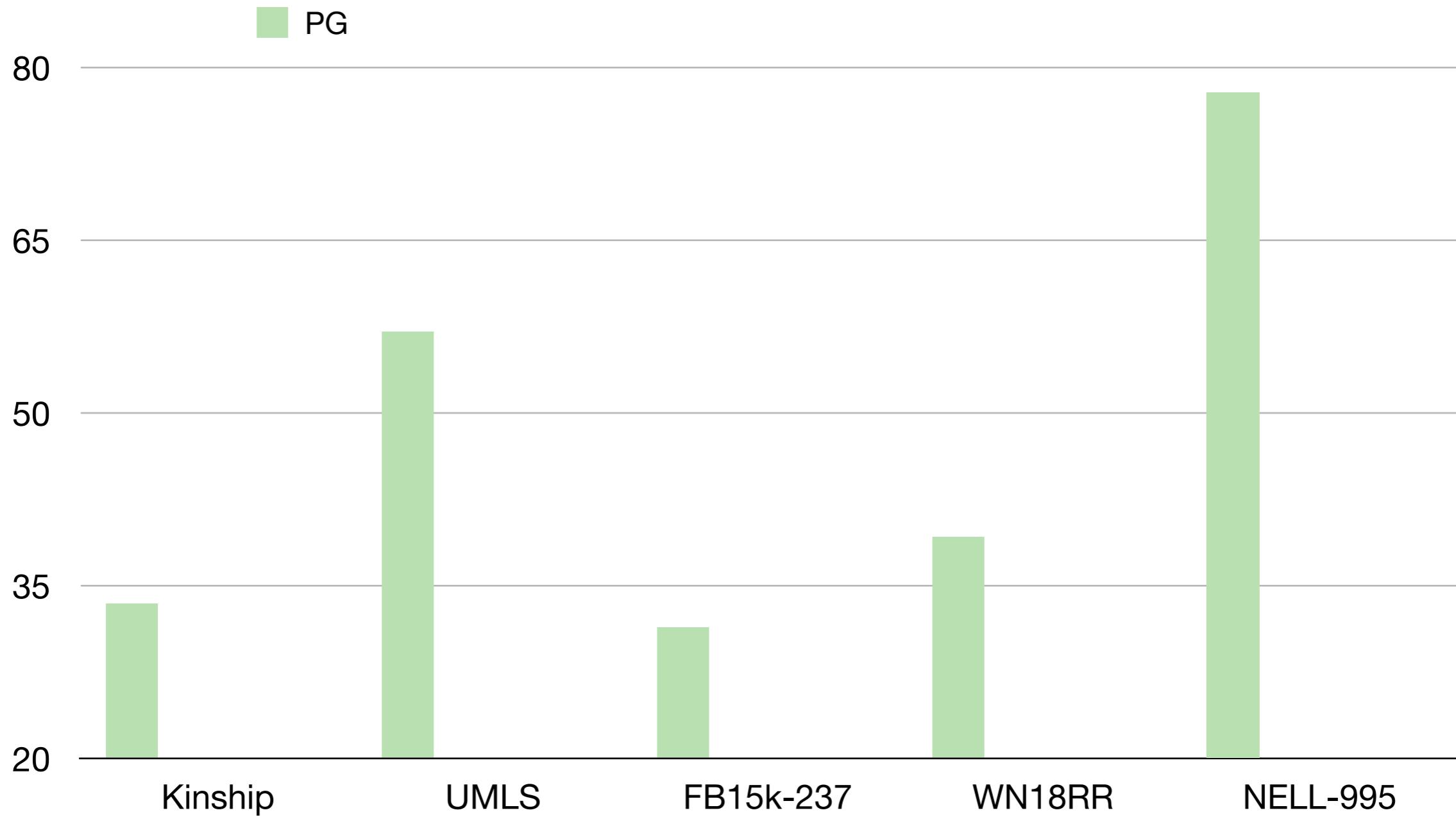


Fig 2. Dev set MRR (x100) comparison

Ablation Studies

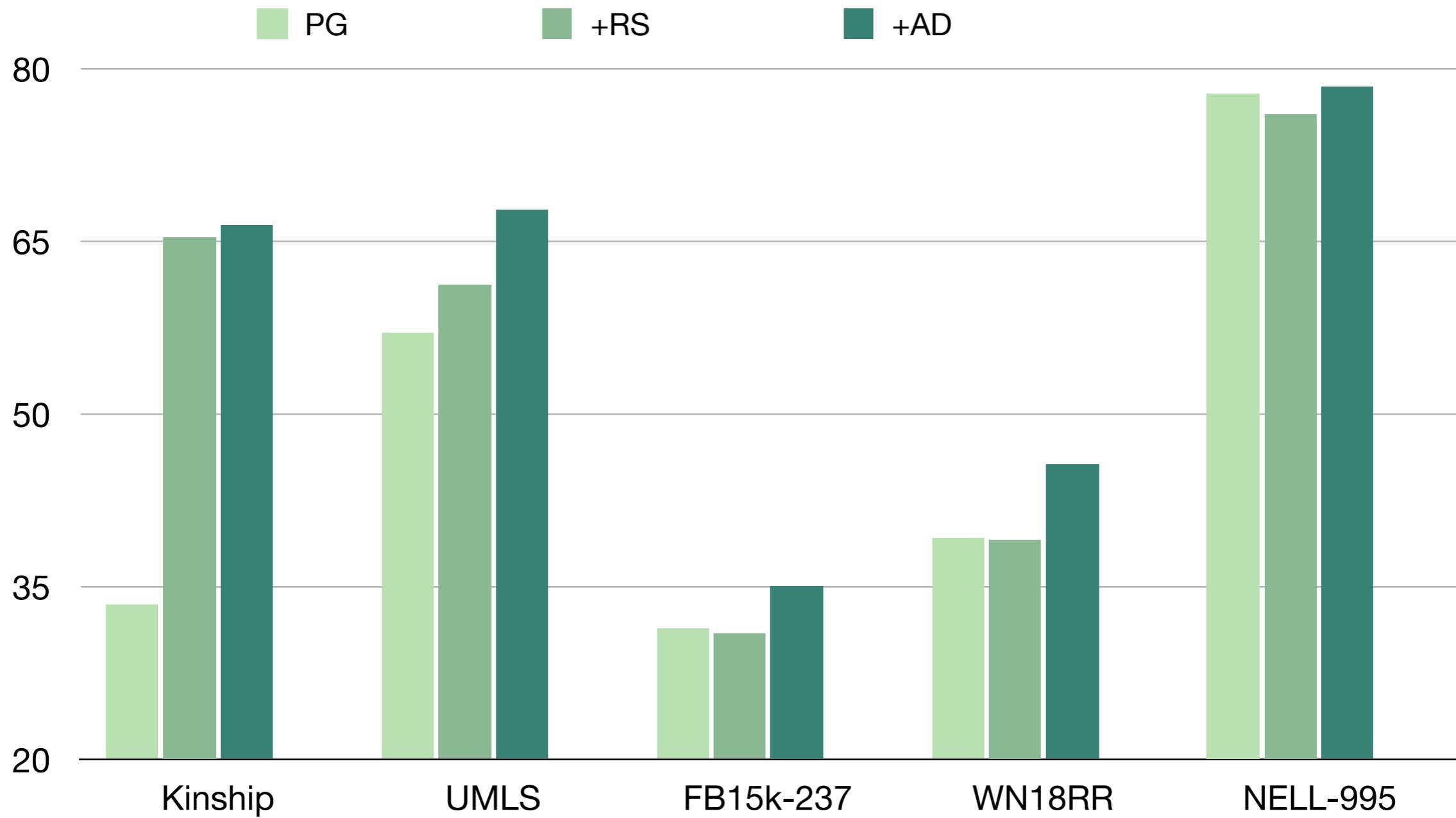


Fig 2. Dev set MRR (x100) comparison

Ablation Studies

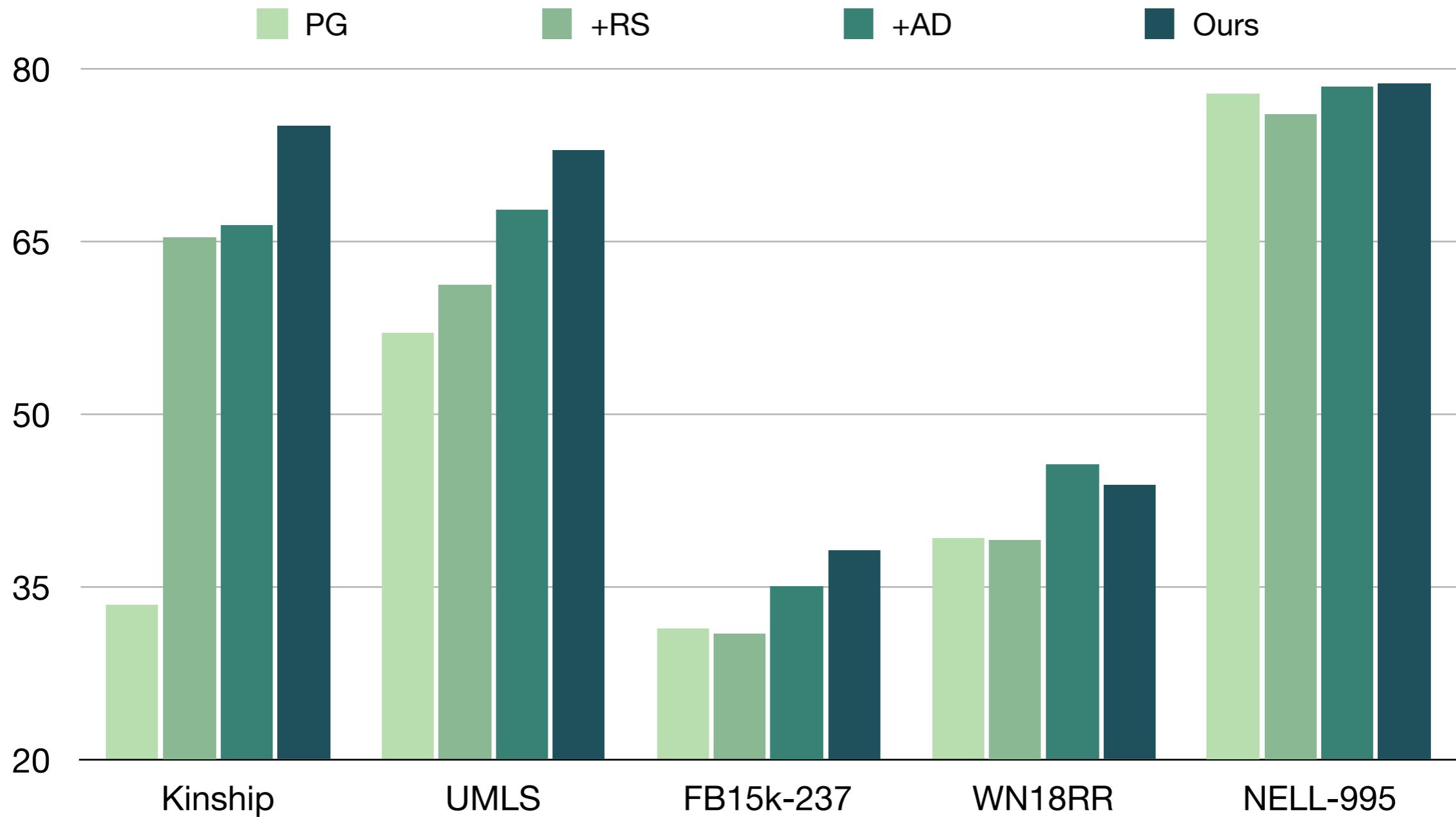


Fig 2. Dev set MRR (x100) comparison

Ablation Studies

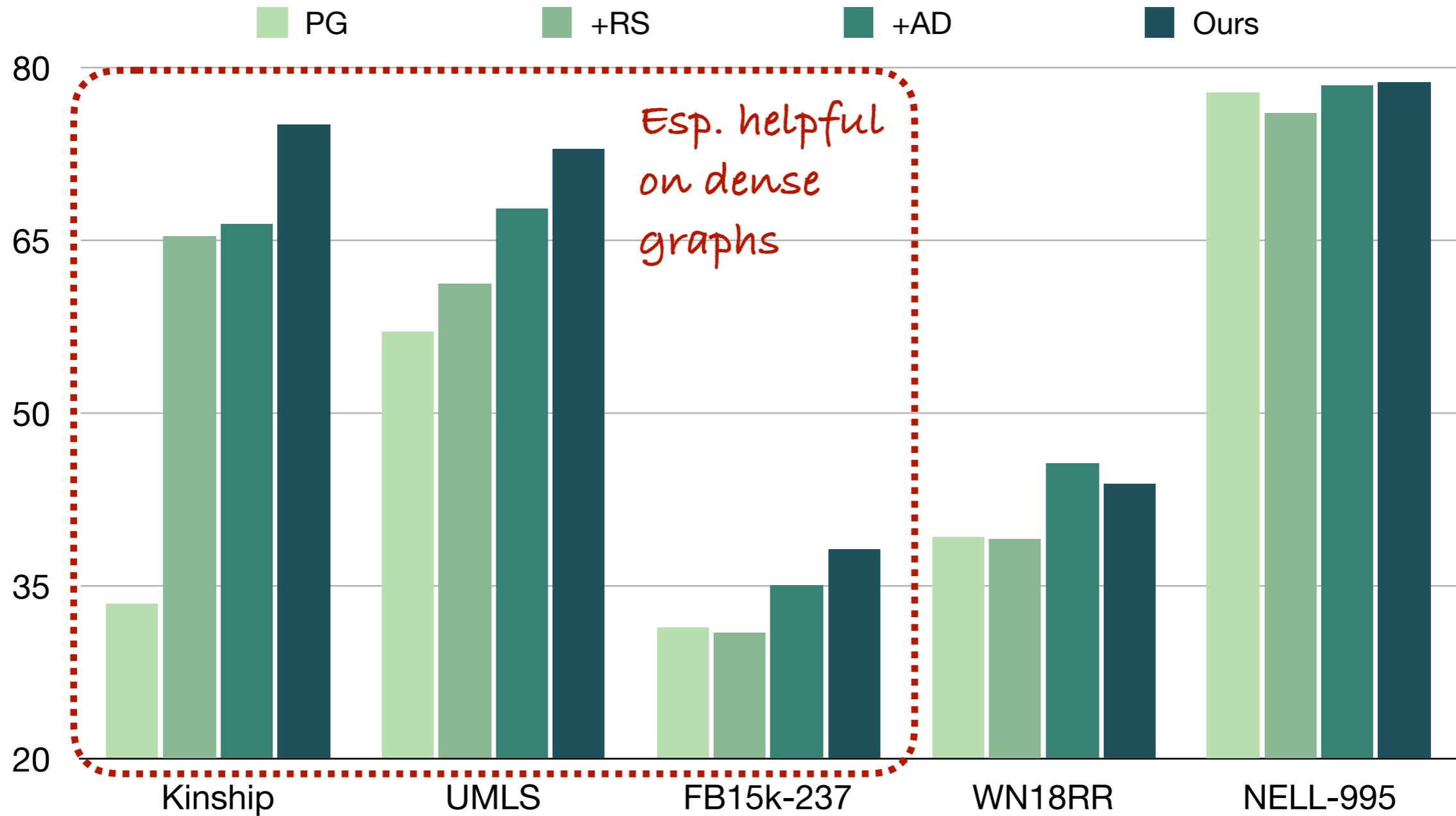


Fig 2. Dev set MRR (x100) comparison

Main Results

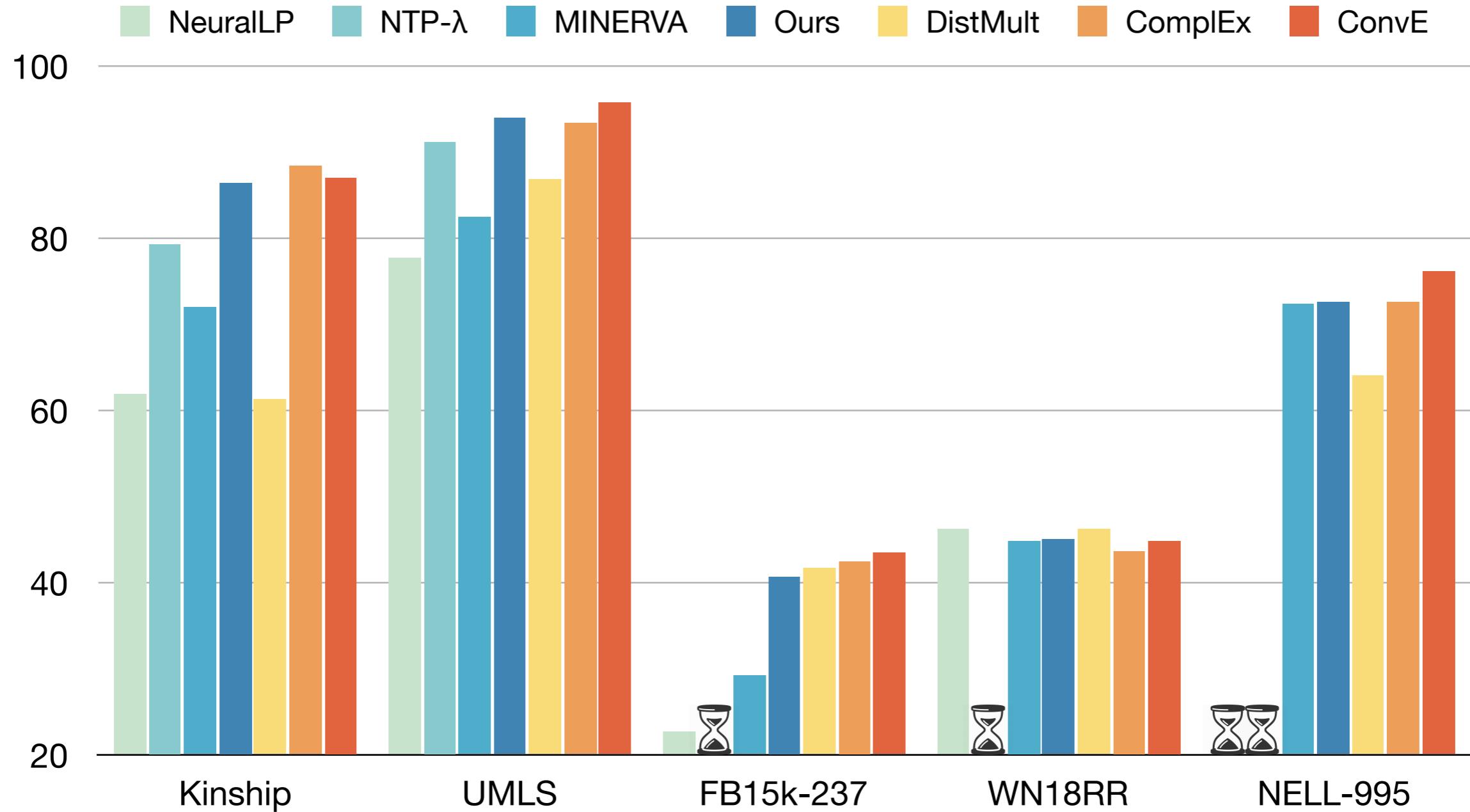


Fig 3. Test set MRR (x100) compared to SOTA multi-hop reasoning and embedding-based approaches

Main Results

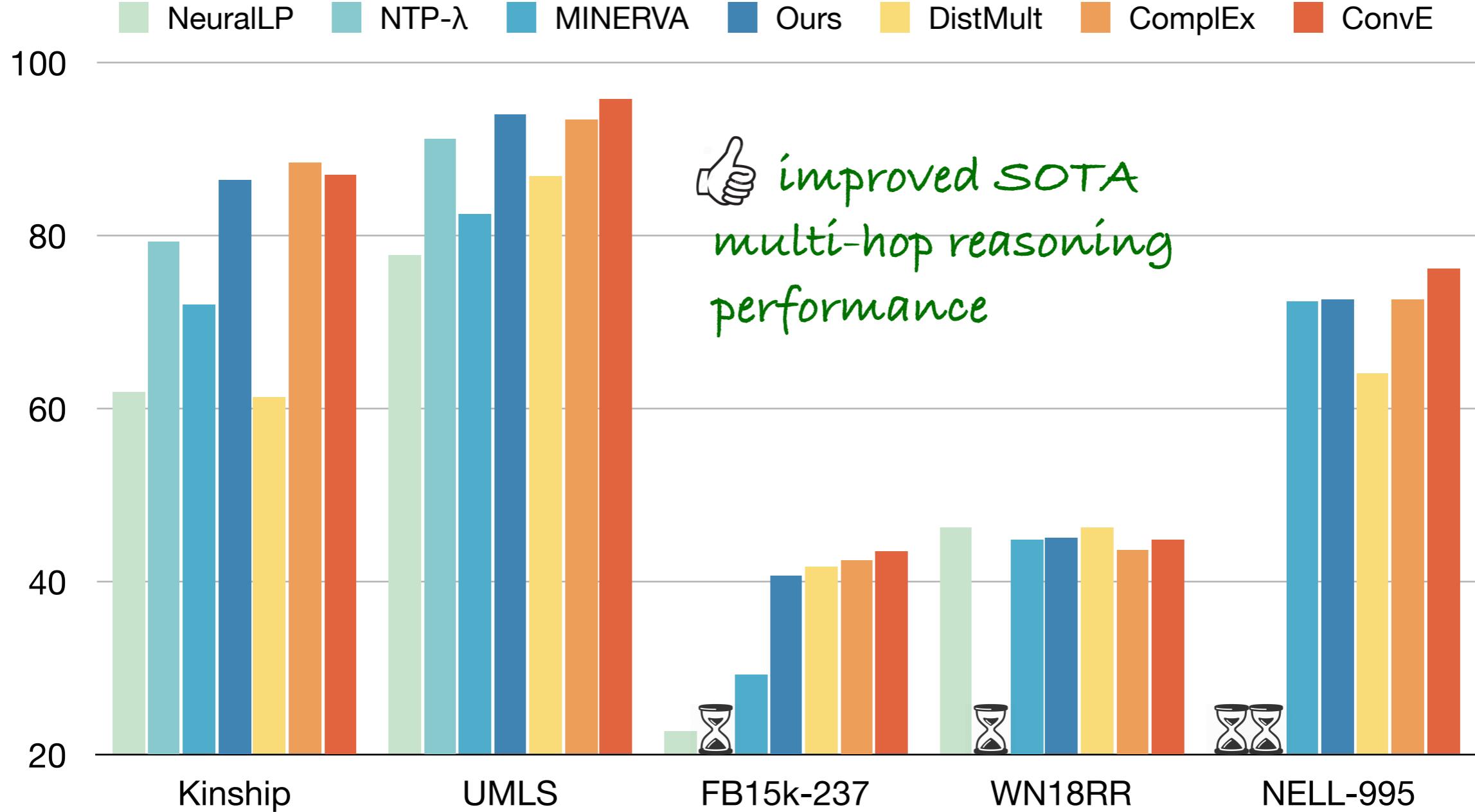


Fig 3. Test set MRR (x100) compared to SOTA multi-hop reasoning and embedding-based approaches

Main Results

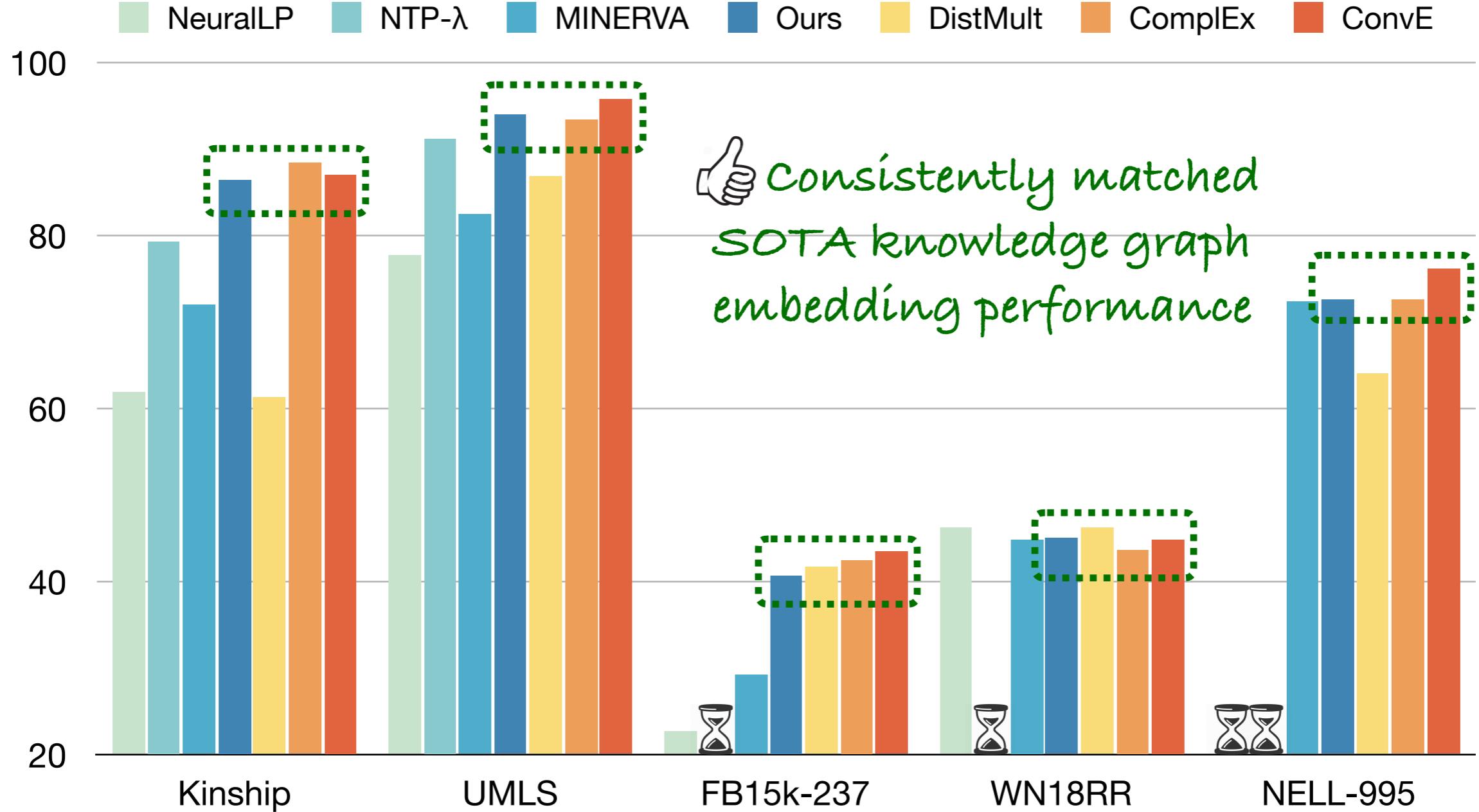
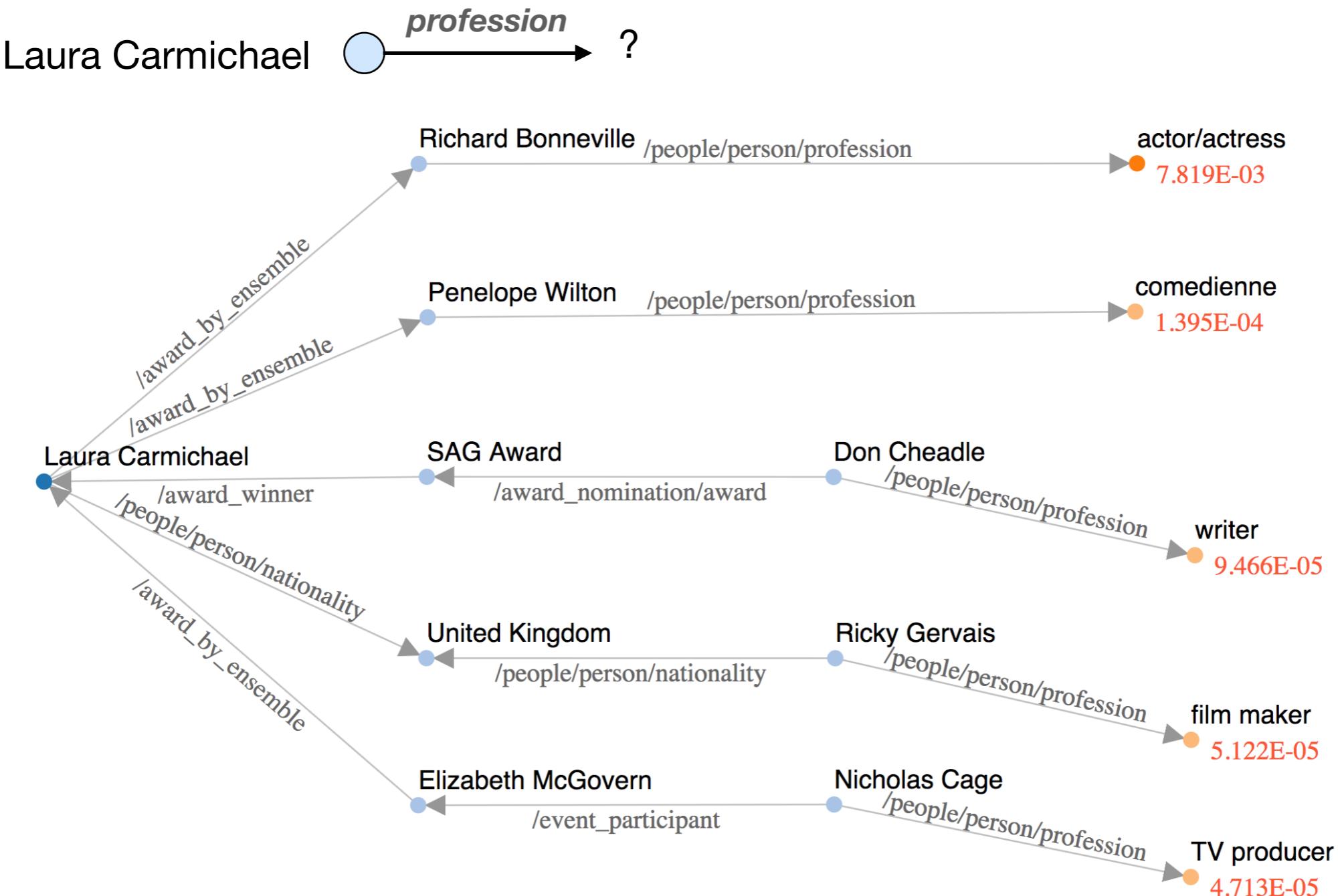
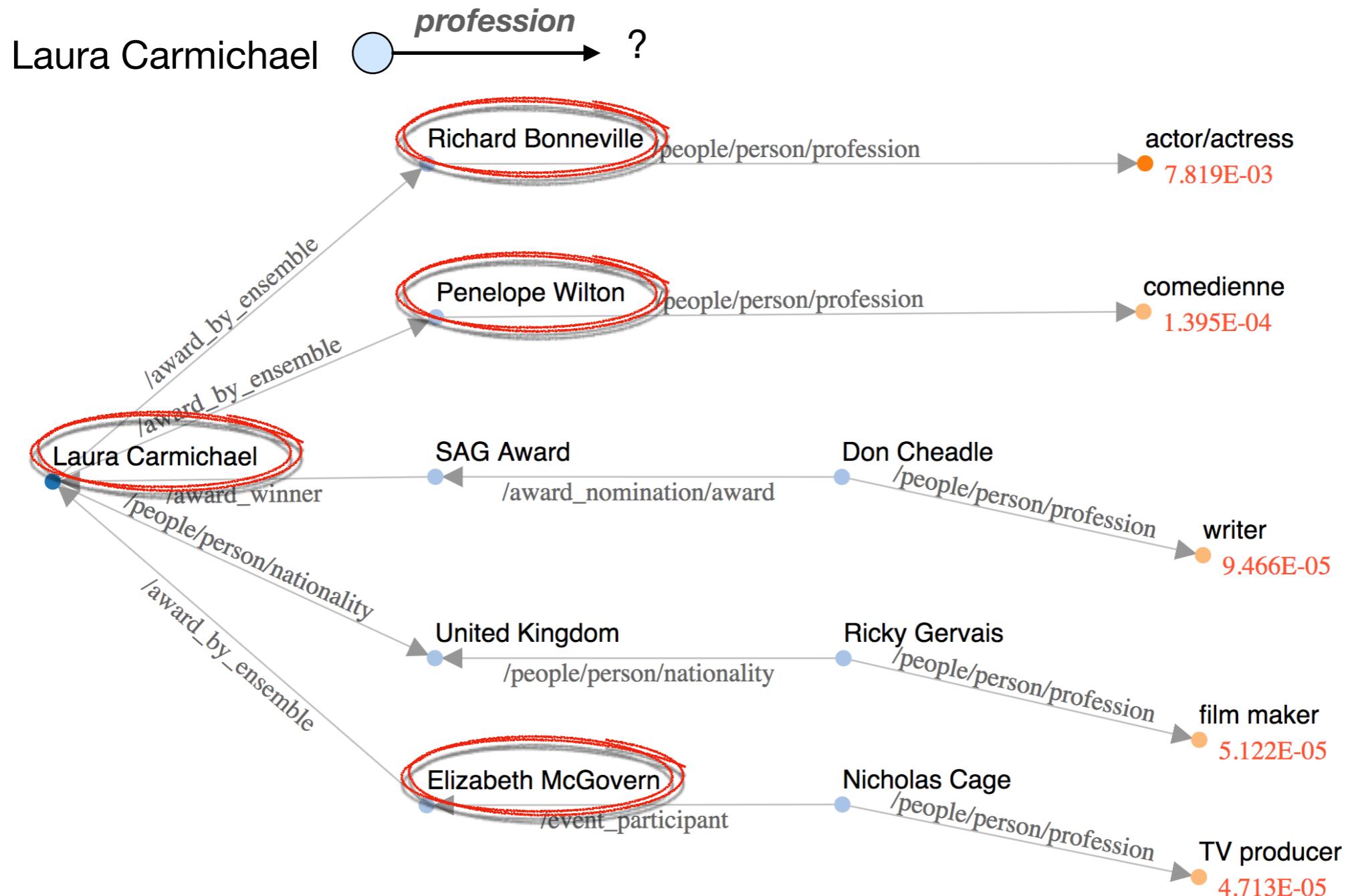


Fig 3. Test set MRR (x100) compared to SOTA multi-hop reasoning and embedding-based approaches

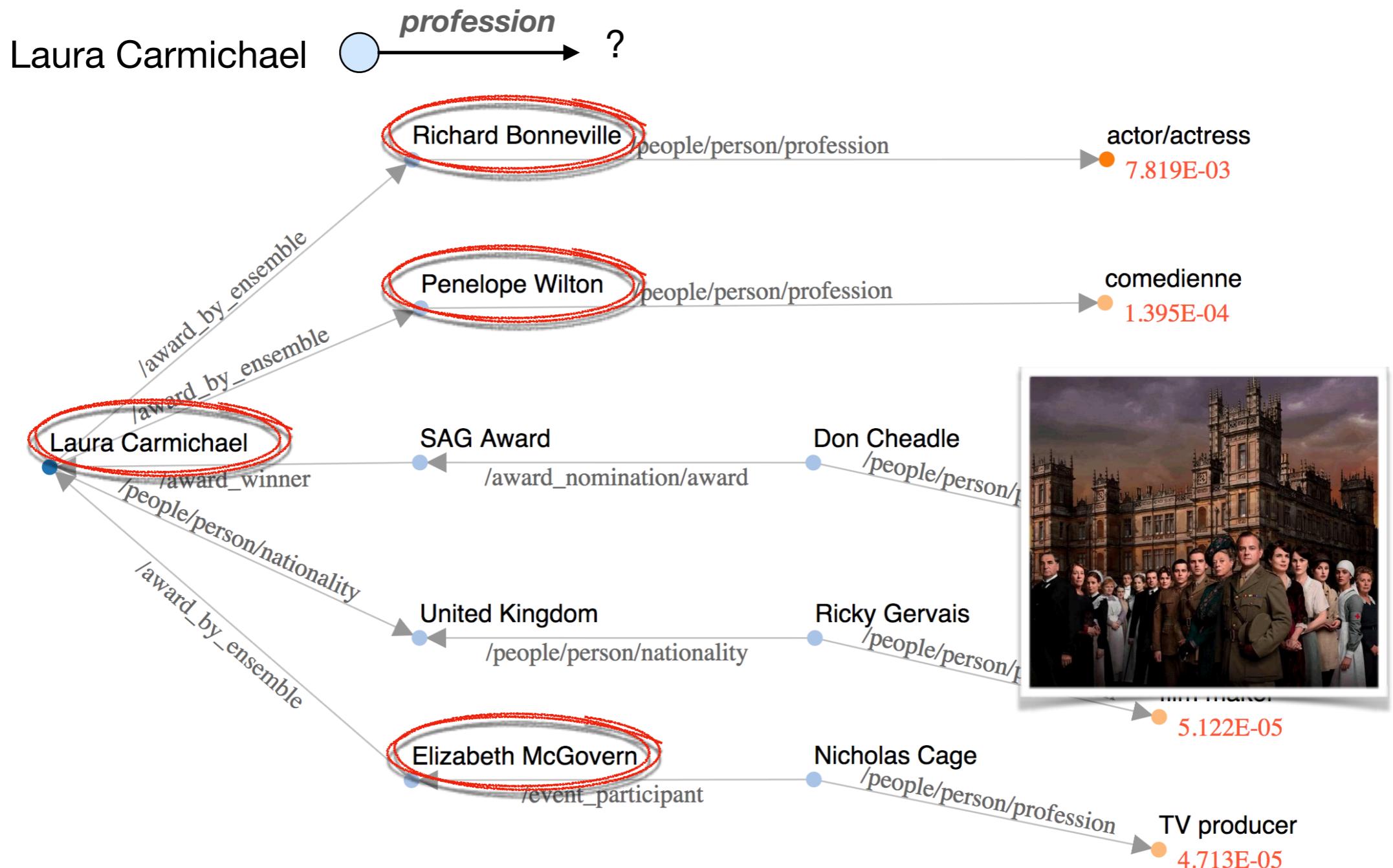
Interpretable Results



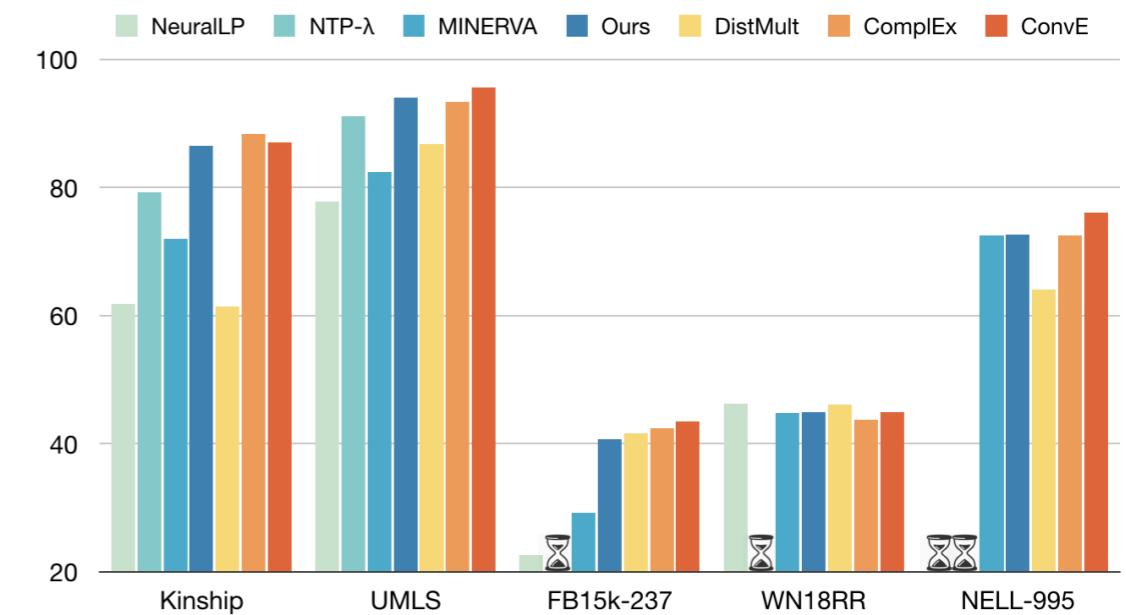
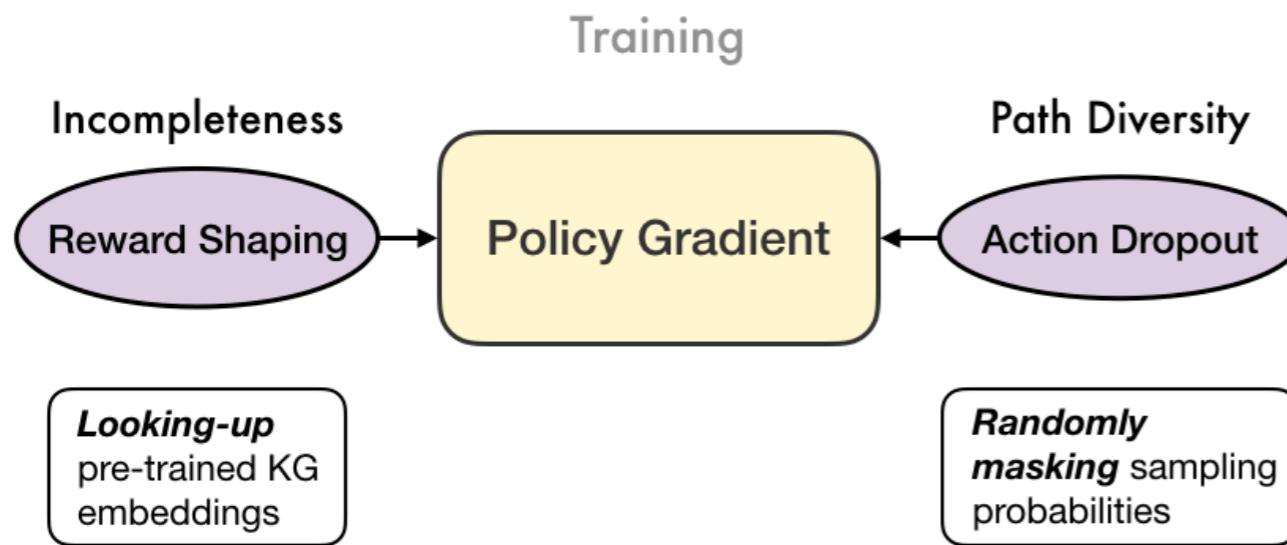
Interpretable Results



Interpretable Results



Code: <https://github.com/salesforce/MultiHopKG>



Future directions

- Learn better reward shaping functions
- Investigate similar techniques for other RL paradigms (e.g. Q-learning)
- Extend to more complicated structured queries (e.g. more than one topic entities)
- Extend to natural language QA



BKI - Error Analysis

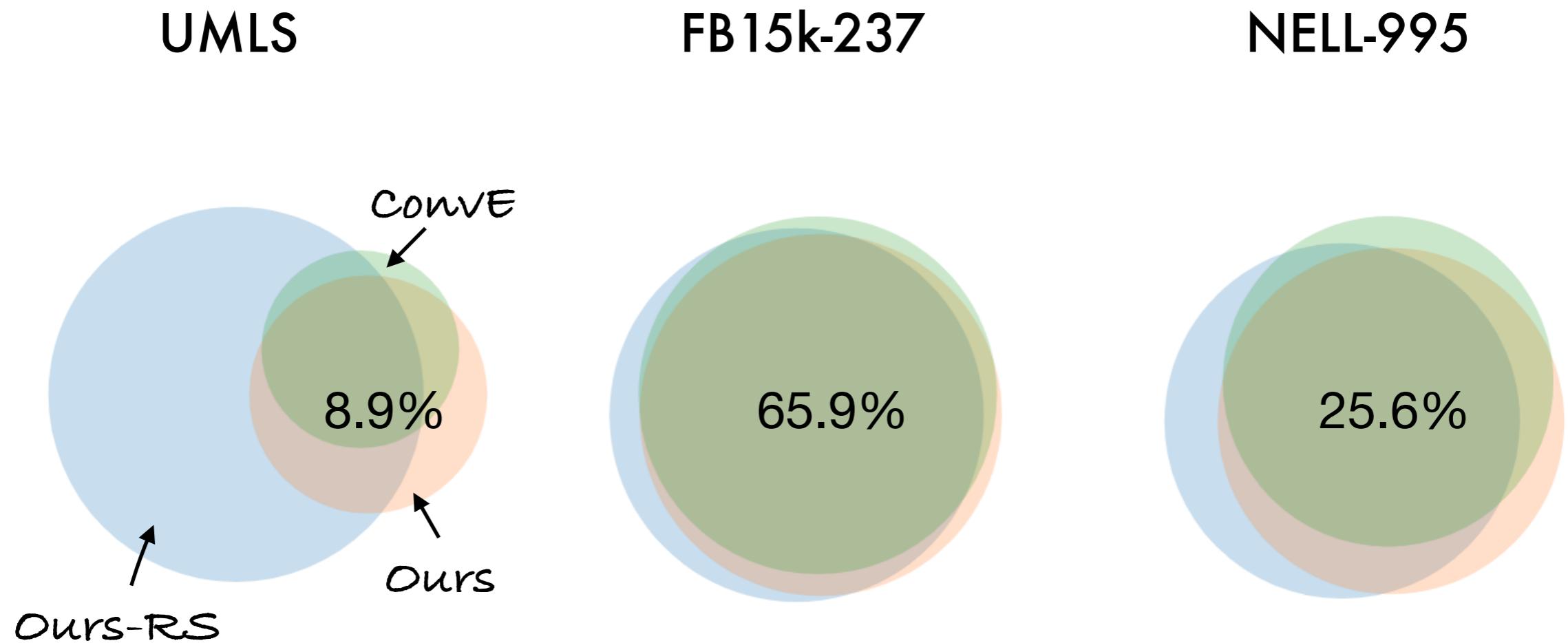


Fig 4. Dev set top-1 prediction error overlap of ConvE, Ours and Ours-RS. The absolute error rate of Ours is shown.

BK II - Challenges

Incompleteness

$\approx 30\%$ false negative feedback

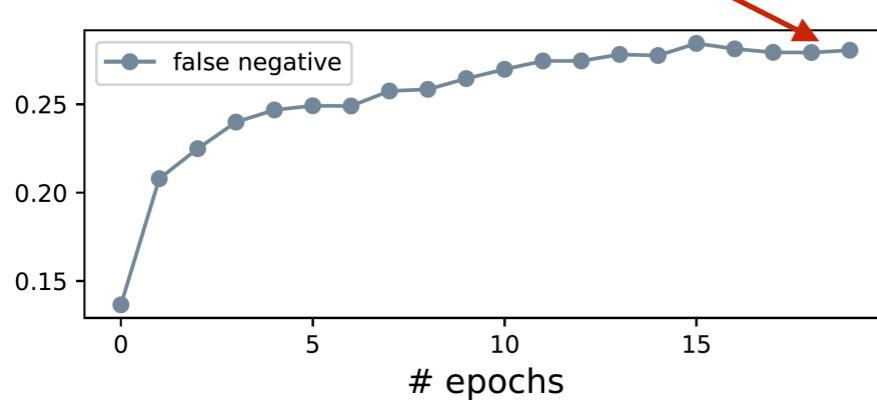
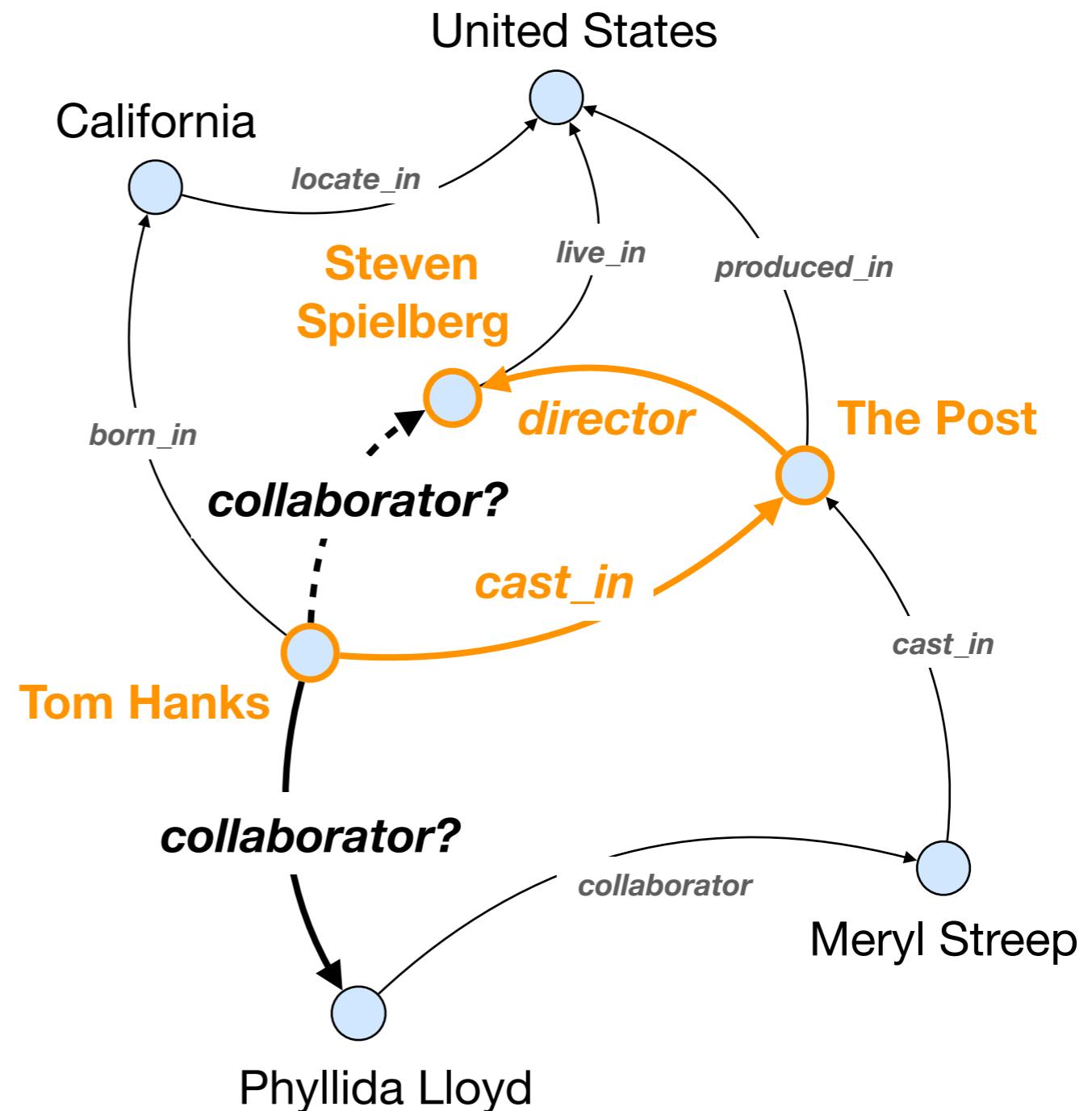


Fig 1. % of false negative hit in the first 20 epochs of RL training on the UMLS KG benchmark (Kok and Domingos 2007)



Acknowledgement upon slides release - I

These slides benefit tremendously from the constructive feedback offered by Salesforce Research team members, including Caiming Xiong, Richard Socher, Yingbo Zhou, Alex Trott, Jin Qu, Lily Hu, Vena Li, Kazuma Hashimoto, Stephan Zheng, Jason Wu (intern) and others.

Acknowledgement upon slides release - II

I am grateful to Prof. Michael Ernst and his co-authors who released the slides of all of their paper presentations (and the source files in most case).

Especially, the **Hand Font** and the **Baloon** highlighters were borrowed from slides 1 and slides 2.

Victoria Lin
Nov. 4, 2018