Grounded Language Learning from Video Described with Sentences

Haonan Yu Jeffrey Mark Siskind

PURDUE UNIVERSITY™

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Adults Can Recognize What Happened

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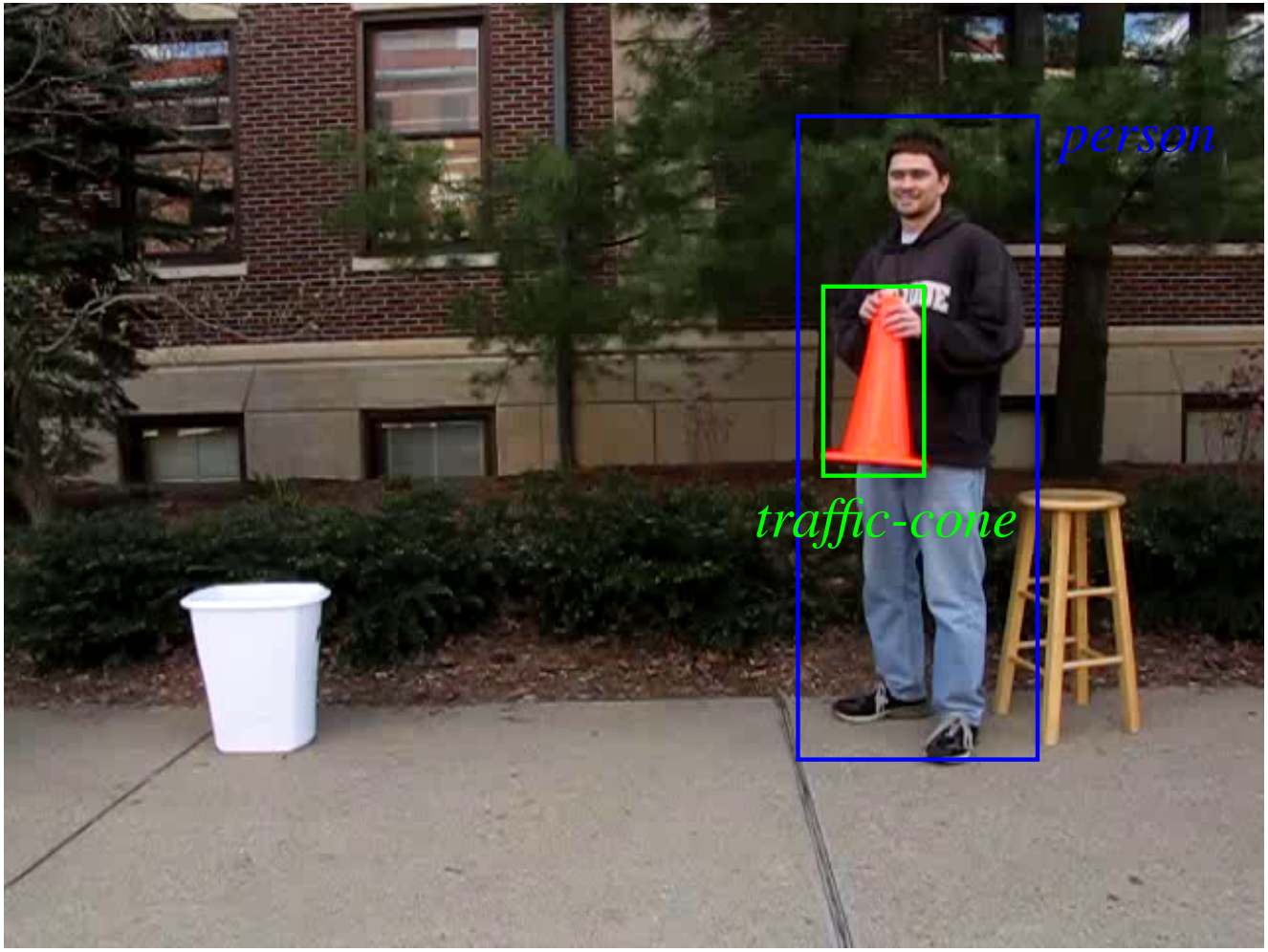
The person carried the traffic-cone.

Adults Can Recognize What Happened



The person carried the traffic-cone.

Adults Can Describe What Happened

The person picked up the backpack.

The chair approached the trash-can.

The person carried the traffic-cone.

. . .

Adults Can Describe What Happened

The person picked up the backpack.

The chair approached the trash-can.

The person carried the traffic-cone.

. . .

Adults Can Describe What Happened

~~*The person picked up the backpack.*~~

~~*The chair approached the trash-can.*~~

The person carried the traffic-cone.

. . .

What Children Learn From

The person picked up the traffic-cone.

What Children Learn From

The person picked up the traffic-cone.

What Children Learn From

The person carried the chair away from the backpack.

What Children Learn From

The person carried the chair away from the backpack.

What Children Learn From

The person picked up the traffic-cone.
The person picked up the traffic-cone to the left of the stool.
The person put down the trash-can quickly.

The person carried the chair.
The person carried the backpack.
The chair approached the backpack.

What Children Learn From

The person picked up the traffic-cone.
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The chair approached the backpack.

↓ training sentences → learned words

person	*traffic-cone*	*chair*	*stool*	*backpack*	*trash-can*
picked up	*carried*	*put down*	*approached*	*to the left of*	*quickly*

What Children Learn From

The person picked up the traffic-cone.
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The person carried the chair.
The person carried the backpack.
The chair approached the backpack.

↓ training sentences → learned words

person	*traffic-cone*	*chair*	*stool*	*backpack*	*trash-can*
picked up	*carried*	*put down*	*approached*	*to the left of*	*quickly*

↓ learned words → new sentences

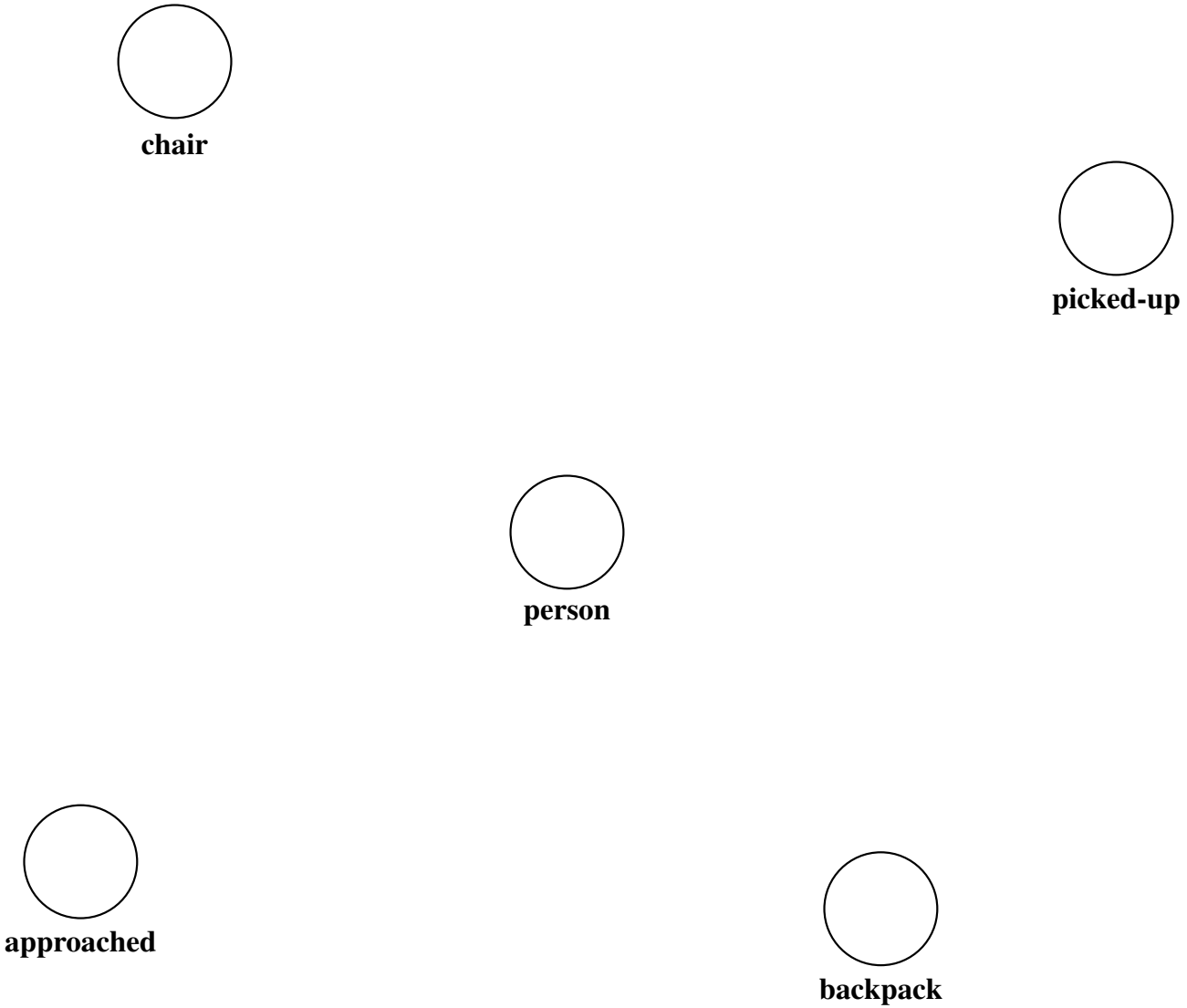
The backpack approached the person.
The person carried the trash-can.

The person put down the chair quickly.
. . .

What Children Learn From

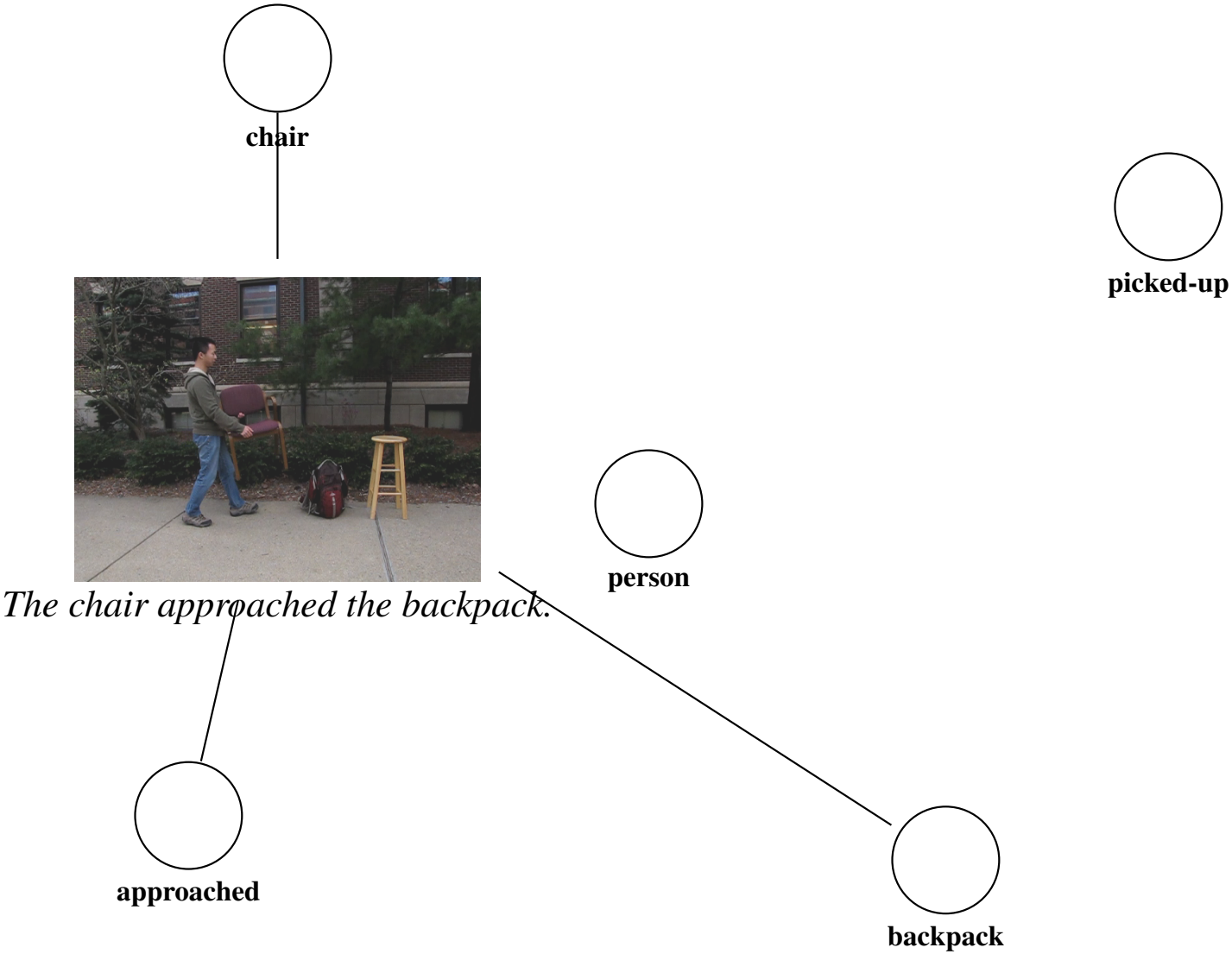
We're going to model this language acquisition problem.

How Can We Do This?



How Can We Do This?

The chair approached the backpack.



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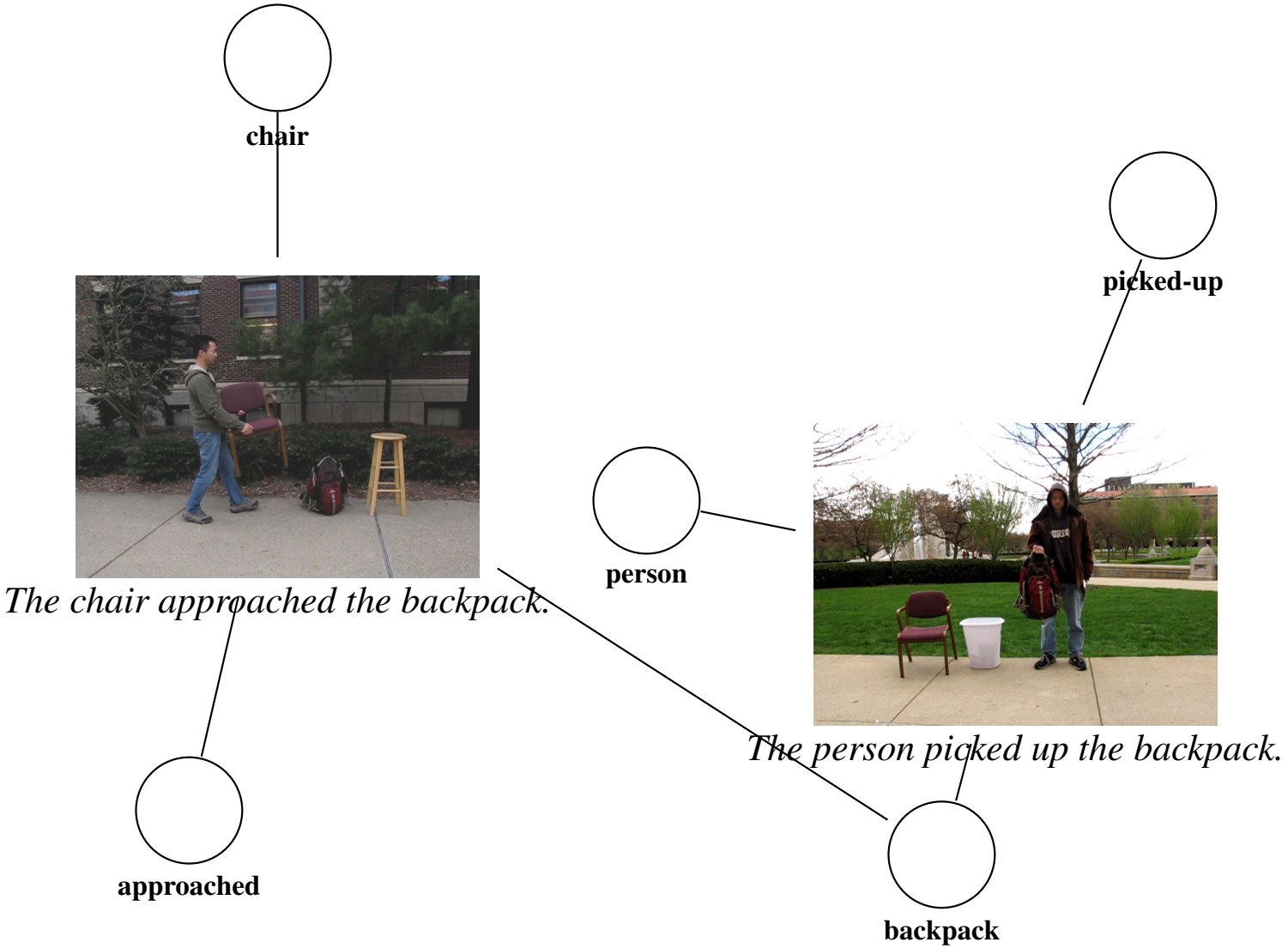

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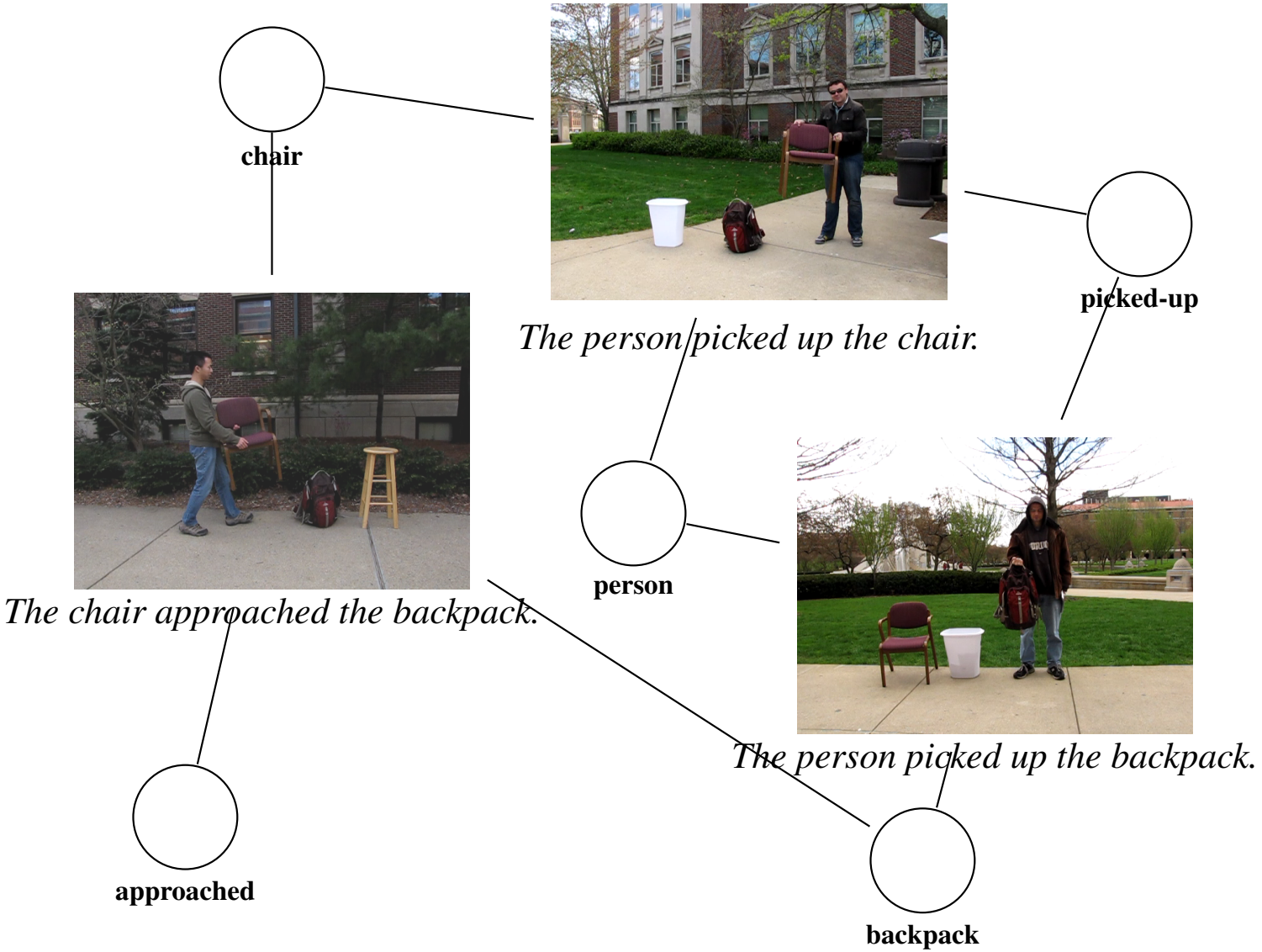
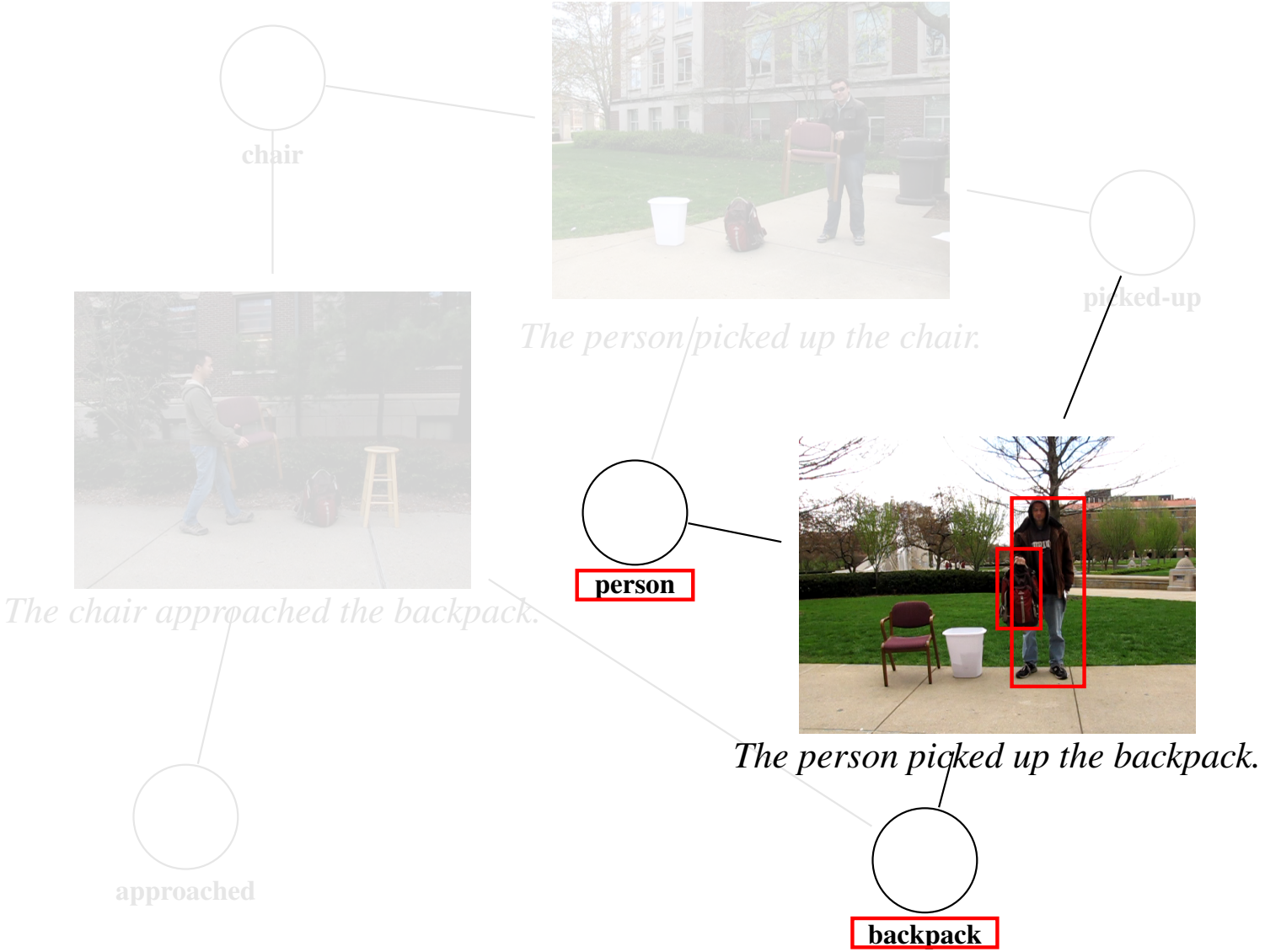


Inference Across *Different* Words in the *Same* Sentence



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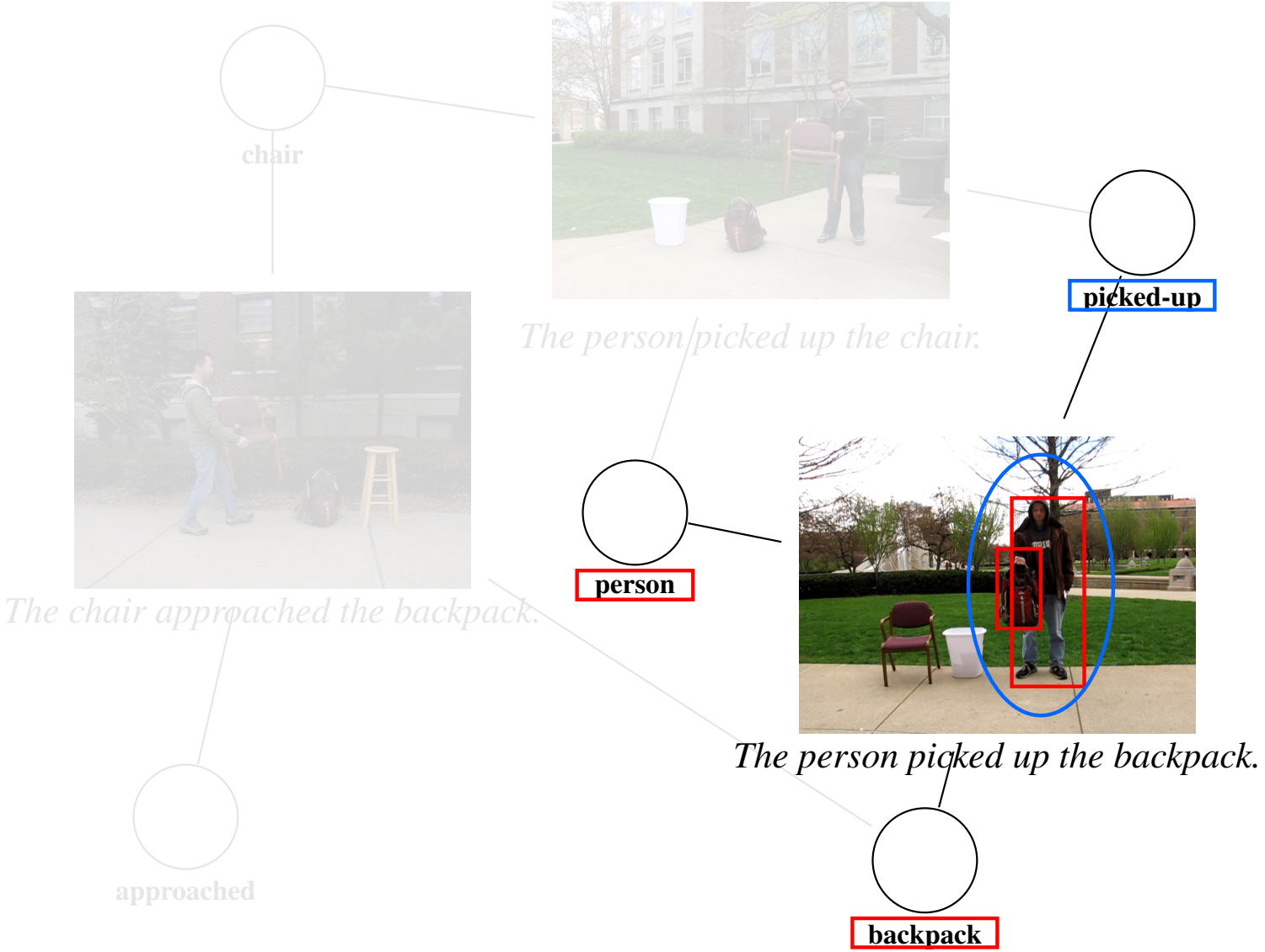

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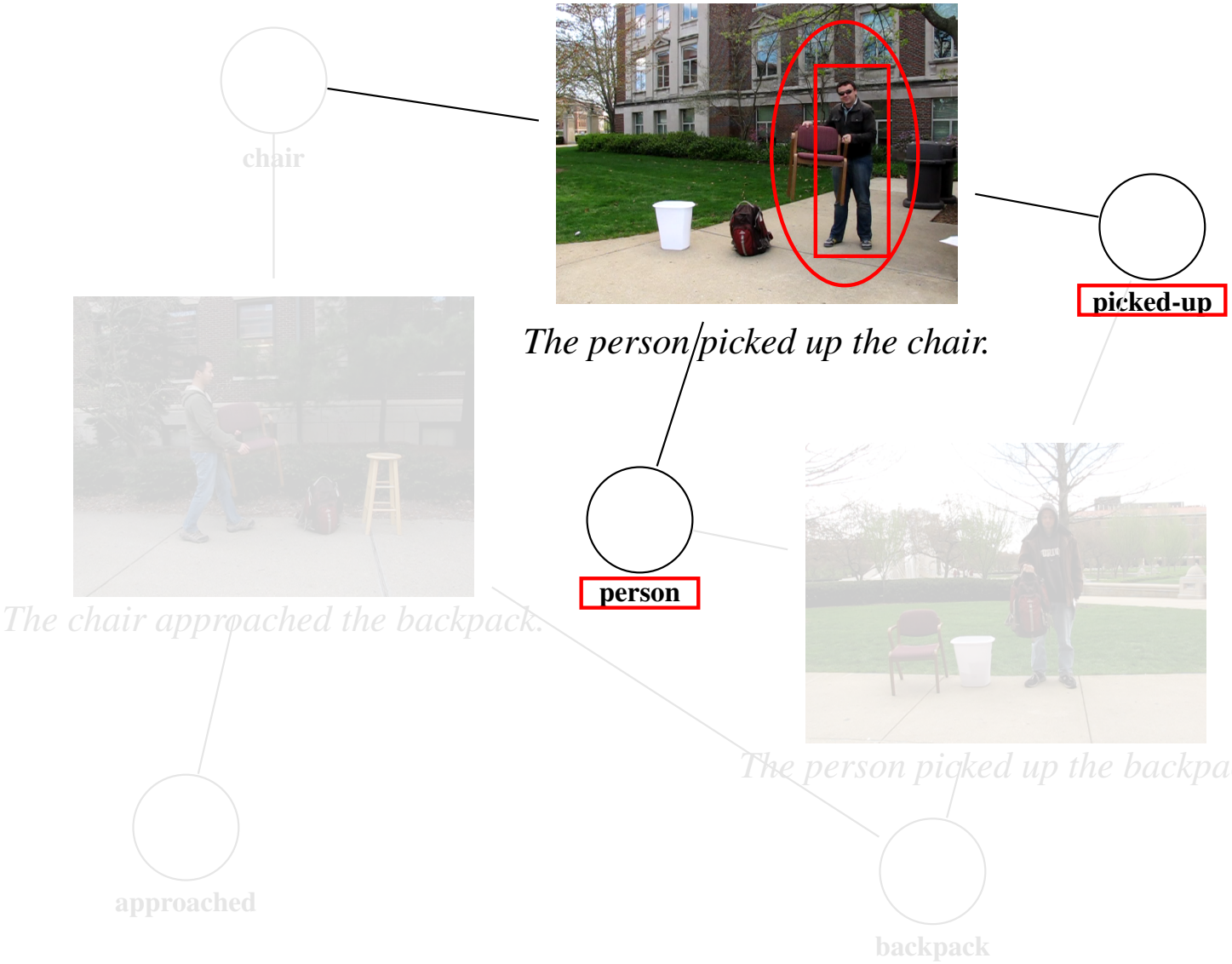

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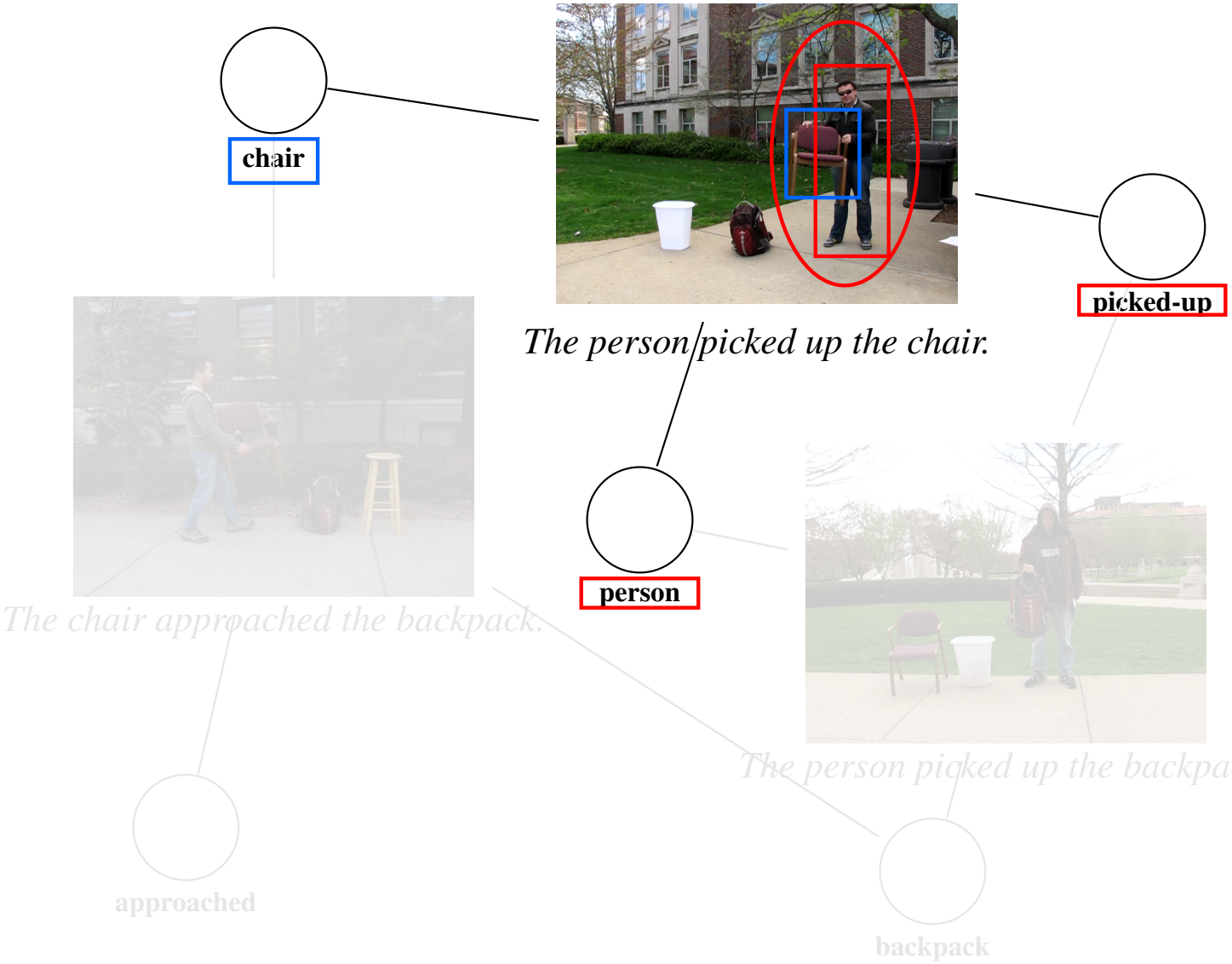

Existing Work on Modeling Events and Objects

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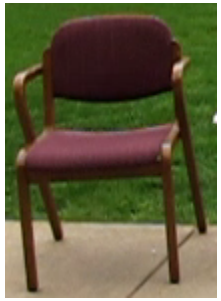

. . .

Existing Work on Modeling Events and Objects

chair model

e.g., [Felzenszwalb et al., 2010]

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- usually only nouns and verbs, no other parts-of-speech
  - e.g., prepositions or adverbs

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- usually only nouns and verbs, no other parts-of-speech
  - e.g., prepositions or adverbs
- We learn other parts-of-speech in addition to nouns and verbs.

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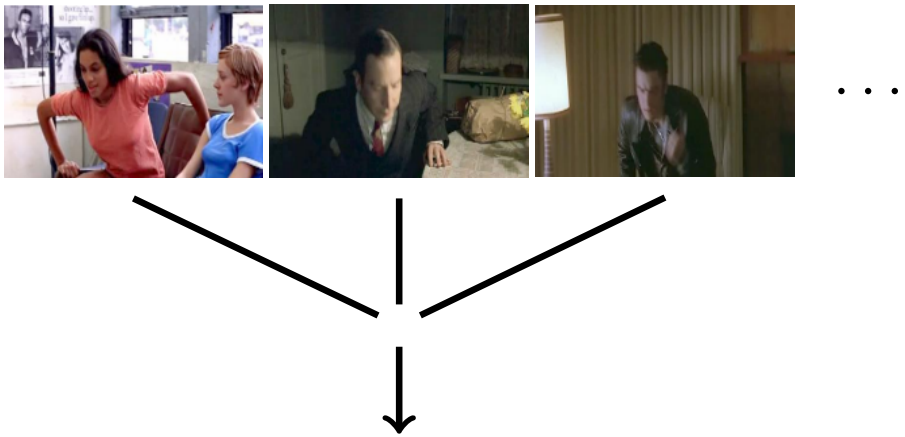

stand-up model
e.g., [Laptev et al., 2008]

- usually only nouns and verbs, no other parts-of-speech
  - e.g., prepositions or adverbs
- We learn other parts-of-speech in addition to nouns and verbs.
- We learn all of them *simultaneously*.

Background Knowledge

Background Knowledge

$$
\begin{aligned}
\text{S} &\rightarrow \text{NP VP} \\
\text{NP} &\rightarrow \text{D N [PP]} \\
\text{PP} &\rightarrow \text{P NP} \\
\text{VP} &\rightarrow \text{V NP [ADV] [PPM]} \\
\text{PPM} &\rightarrow \text{PM NP}
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$$

$$
\begin{aligned}
\text{D} &\rightarrow \textit{the} \\
\text{N} &\rightarrow \textit{person} \mid \textit{backpack} \mid \textit{trash-can} \mid \textit{chair} \mid \textit{traffic-cone} \mid \textit{stool} \\
\text{P} &\rightarrow \textit{to the left of} \mid \textit{to the right of} \\
\text{V} &\rightarrow \textit{picked up} \mid \textit{put down} \mid \textit{carried} \mid \textit{approached} \\
\text{ADV} &\rightarrow \textit{quickly} \mid \textit{slowly} \\
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Examples of Wording Meanings

$\textsc{class}(\mathrm{O}) = \textsc{chair}$

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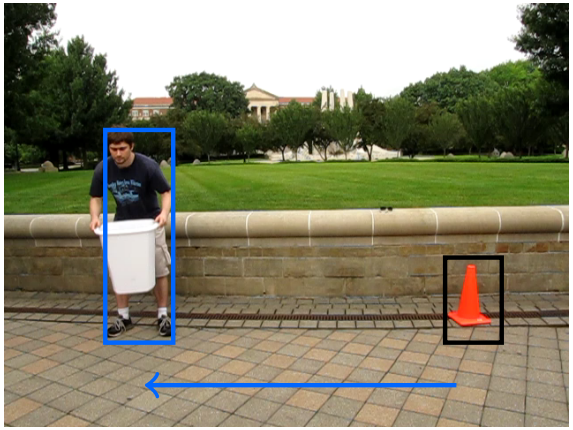

$$x(O1) < x(O2)$$

D	$\rightarrow$	*the*
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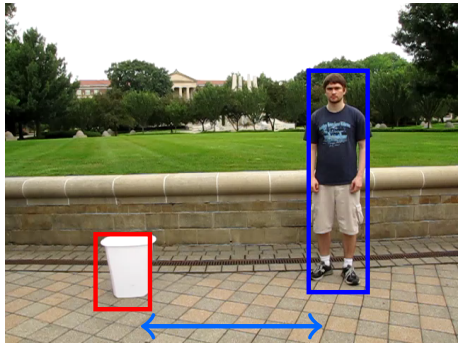
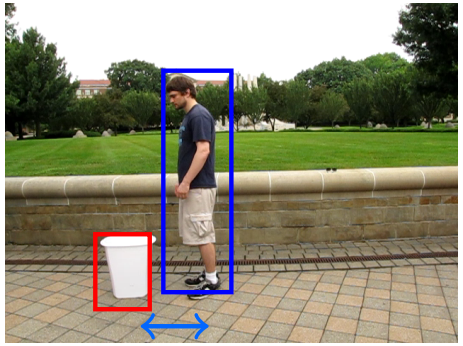


DISTANCE(O1,O2) > T



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D → *the*
N → *person* | *backpack* | *trash-can* | *chair* | *traffic-cone* | *stool*
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Examples of Wording Meanings

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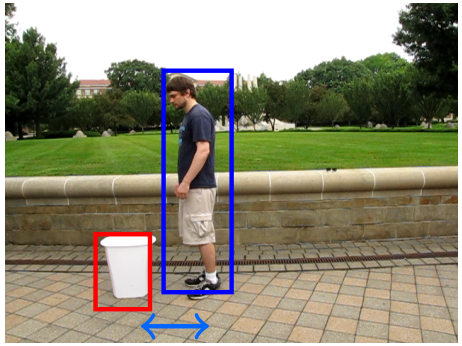
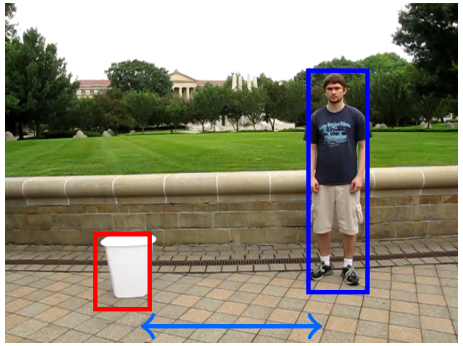


DISTANCE(O1,O2) $<$ T



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Object Detection

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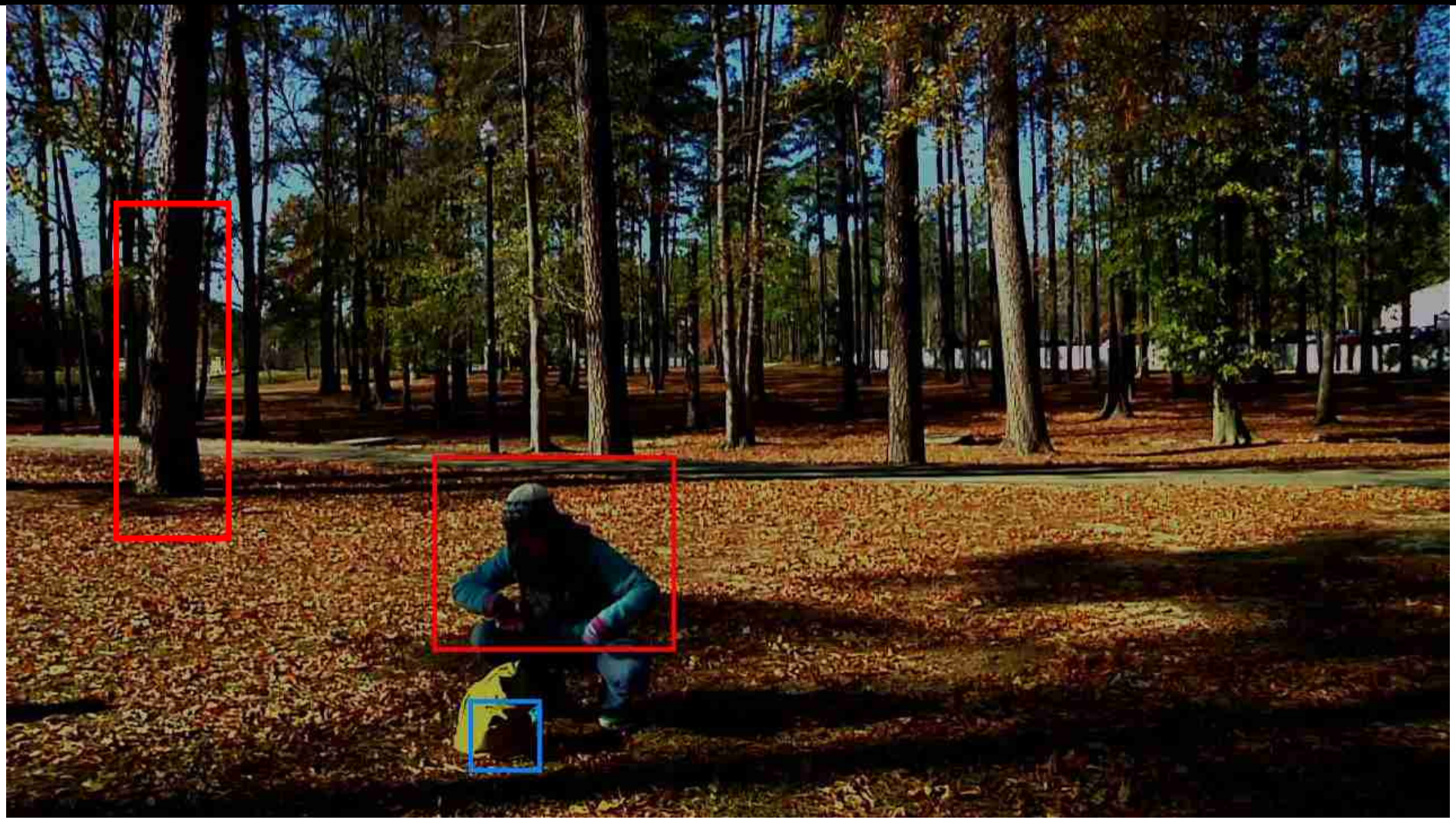
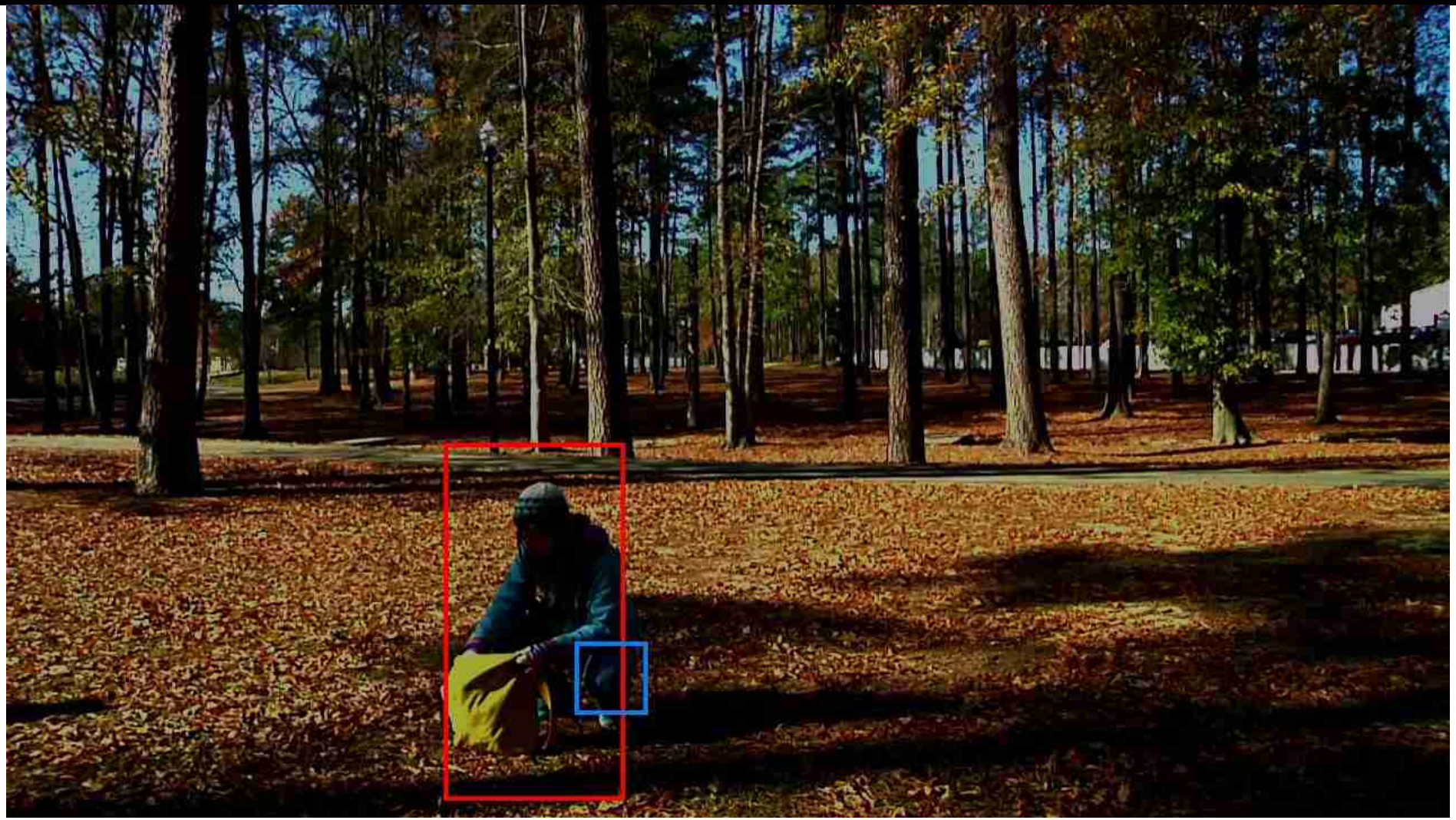


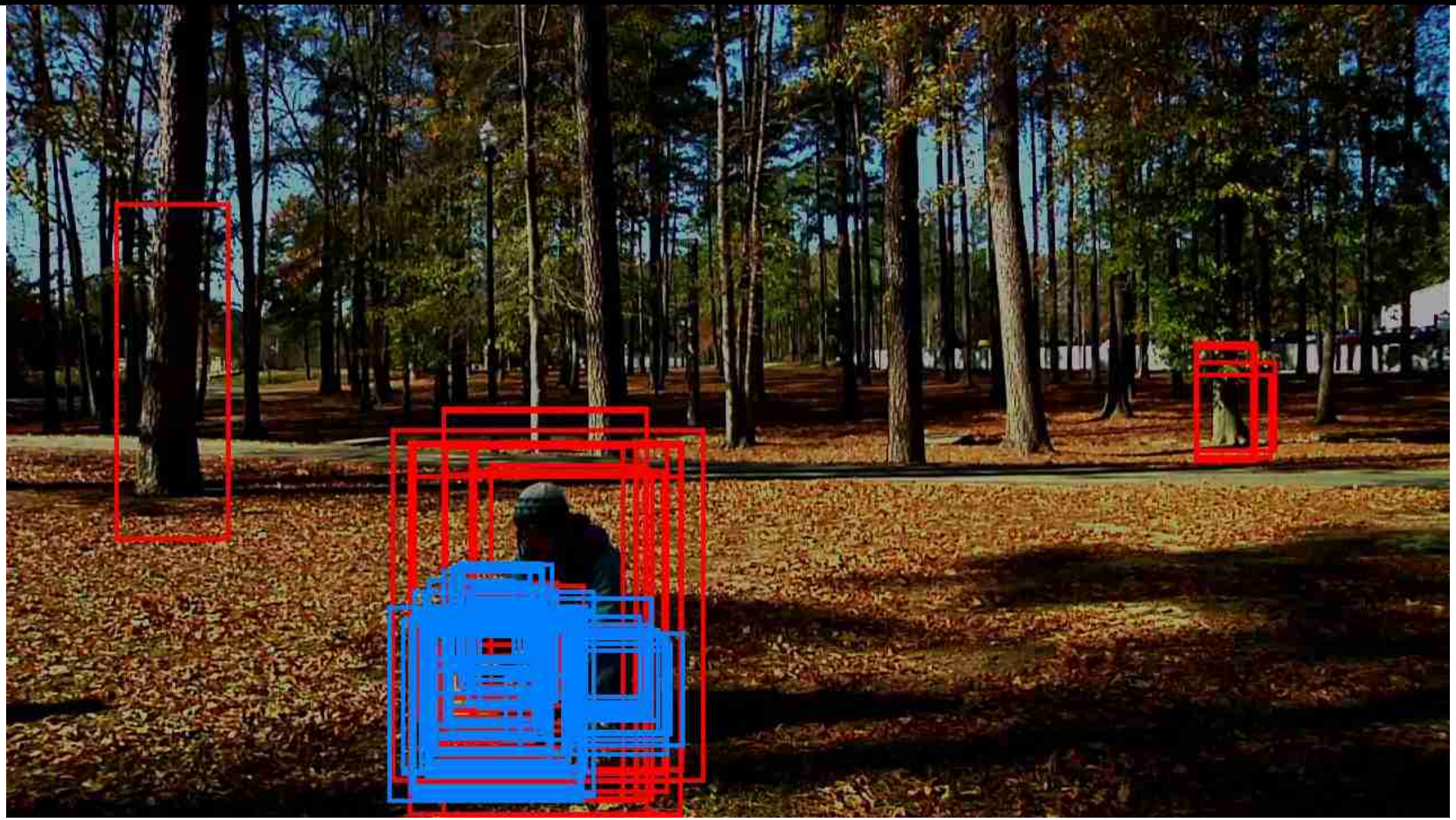
False positives

Object Detection



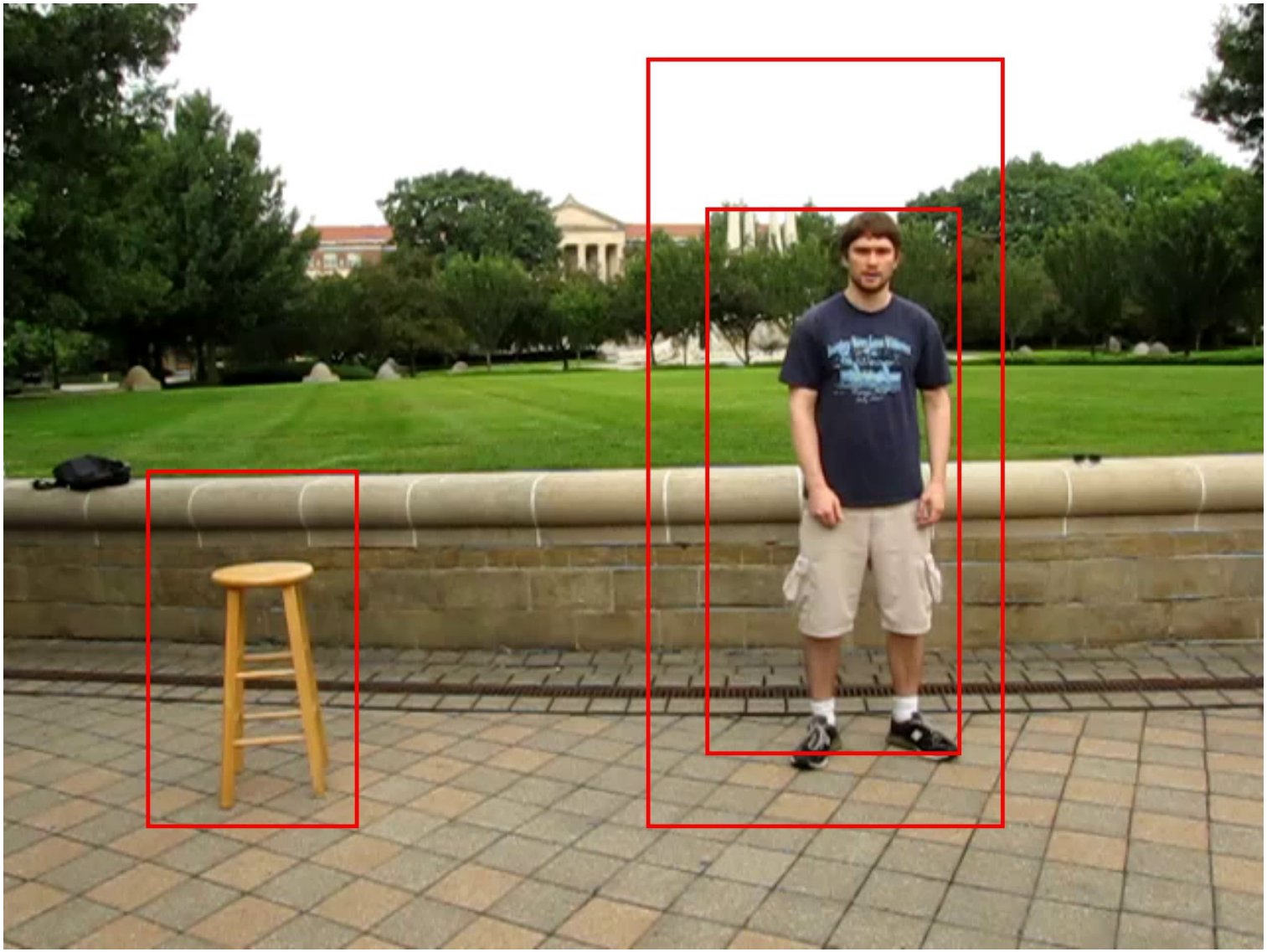
False negatives

Object Detection *and Overgeneration*

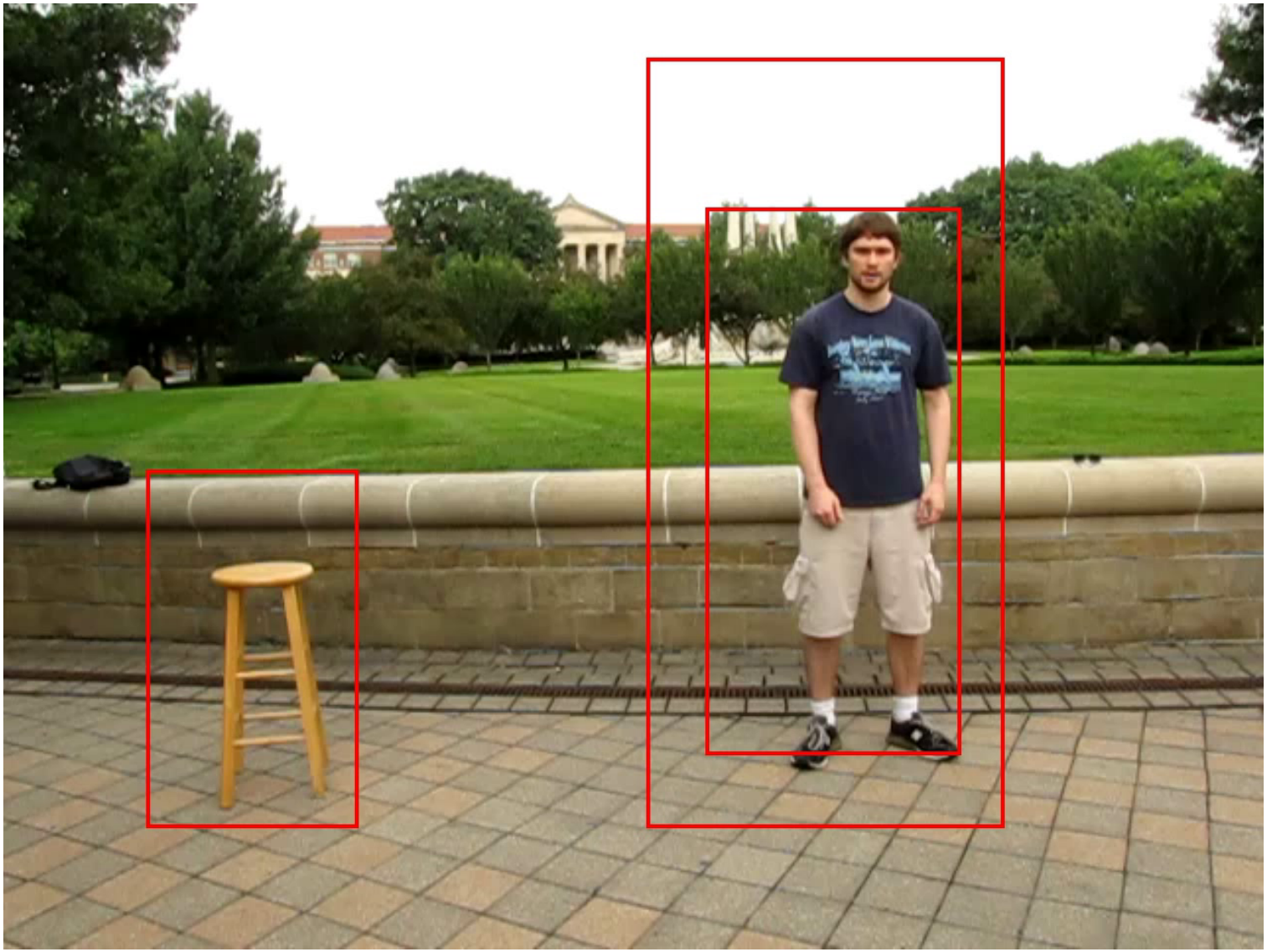


Trade more false positives for fewer false negatives.

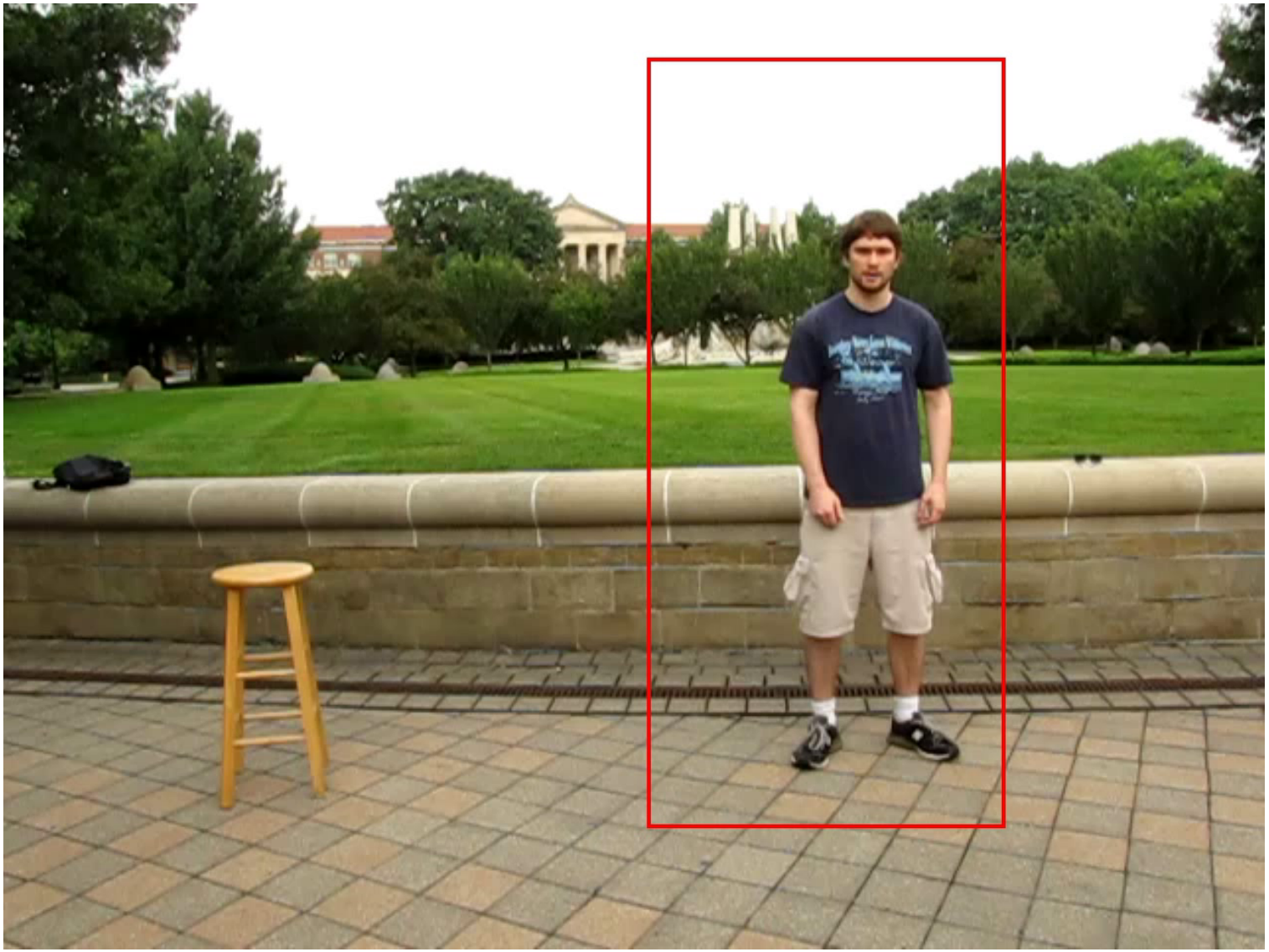
Object Detection *and Overgeneration*



Object Detection *and Overgeneration*



Viterbi Tracker



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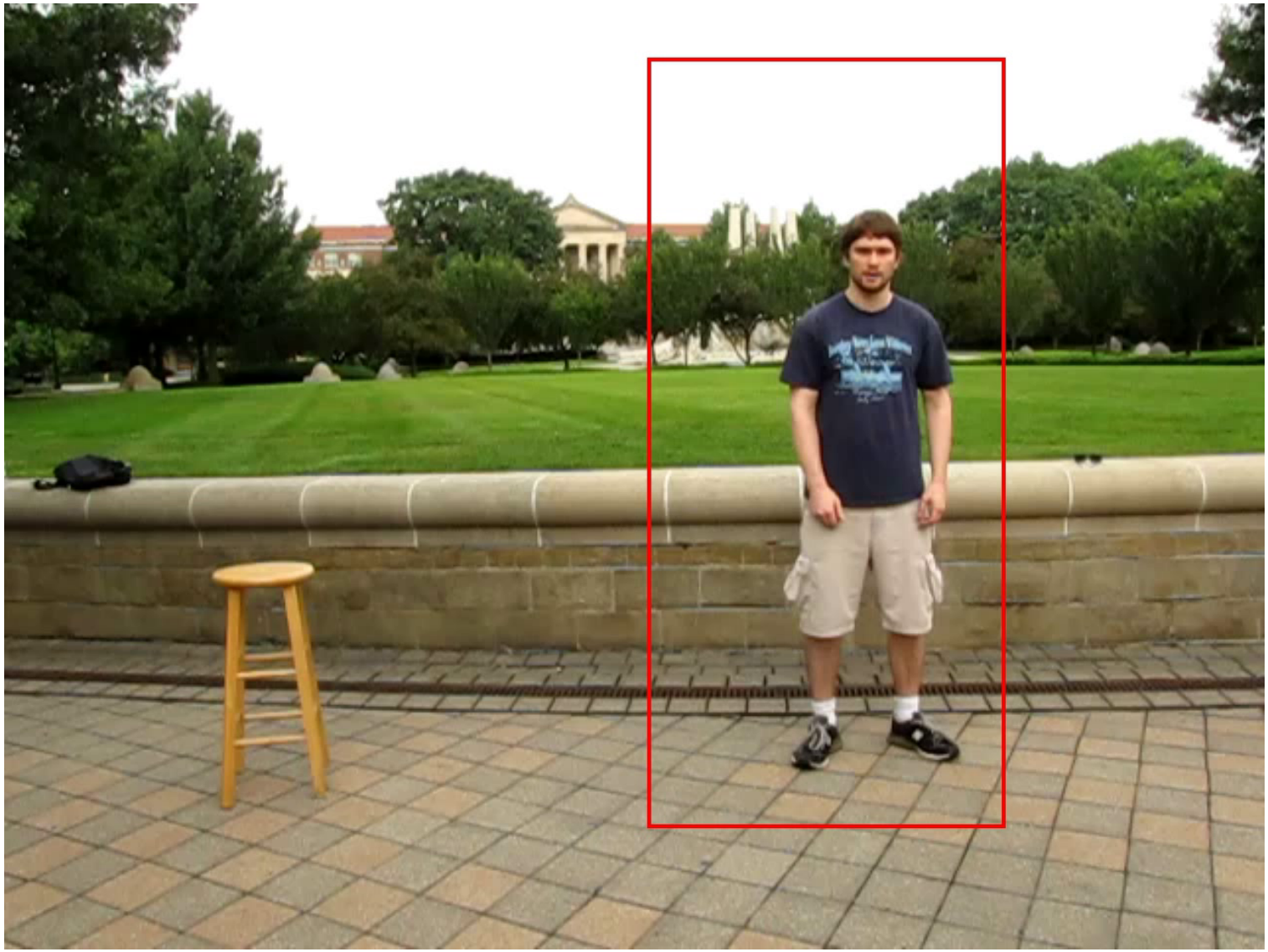

Viterbi Tracker

Optimal state sequence for HMM (Viterbi 1967)

Viterbi Tracker

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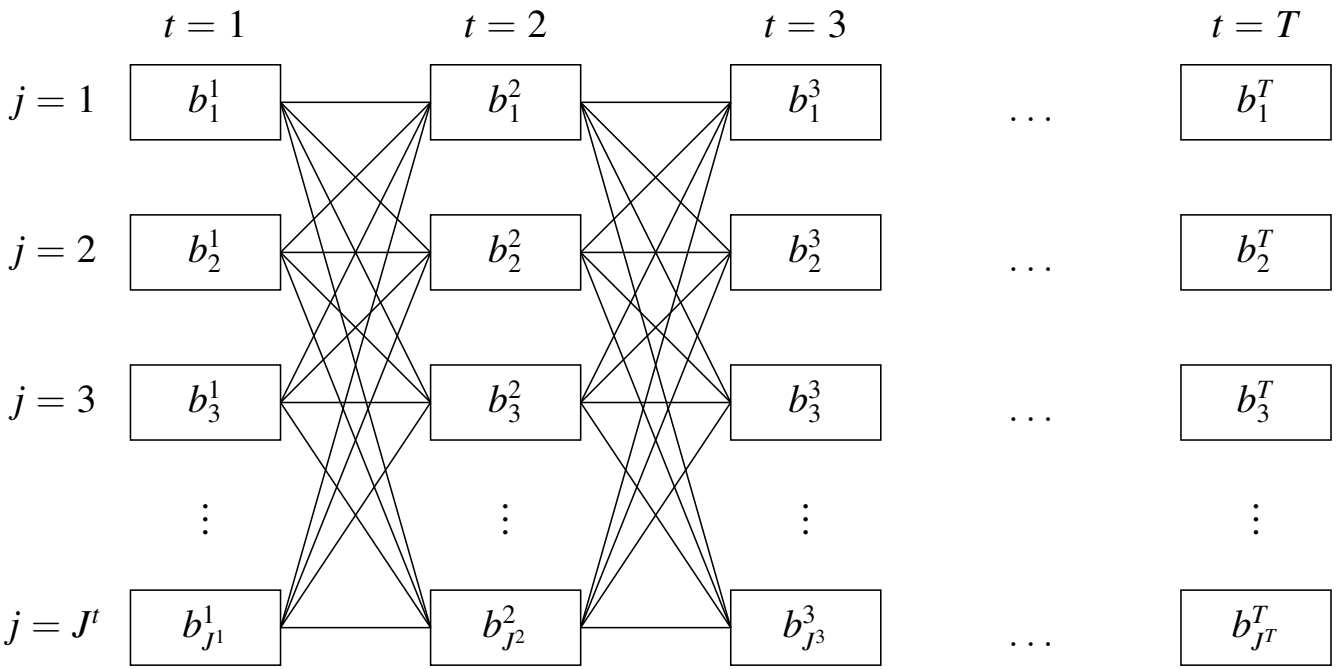
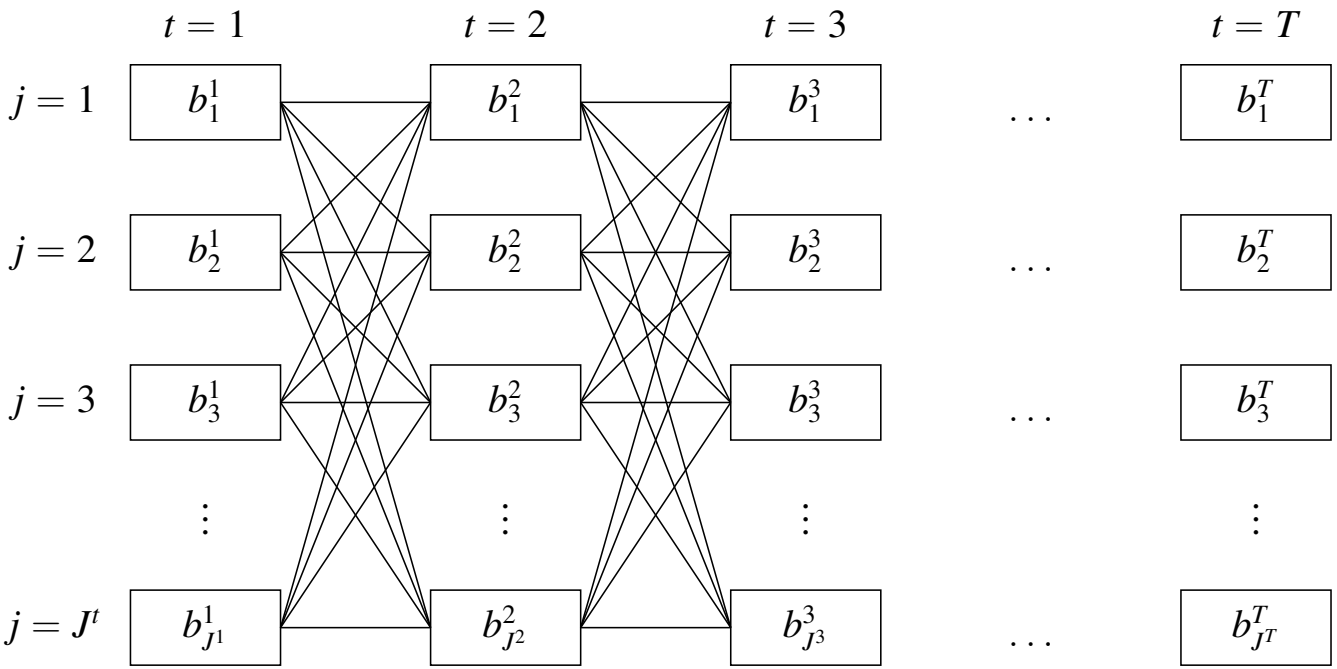


Viterbi Tracker

Optimal state sequence for HMM (Viterbi 1967)
Detection-based tracking (Viterbi 1971)



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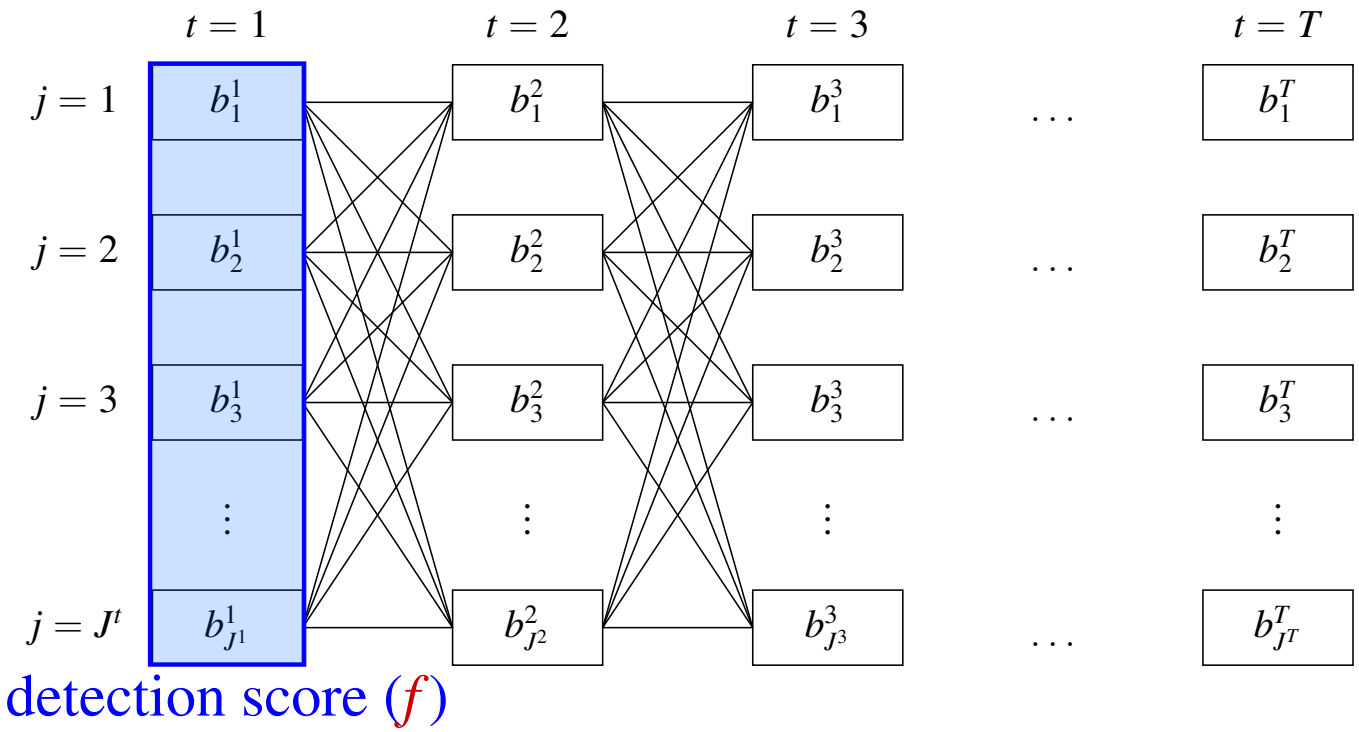

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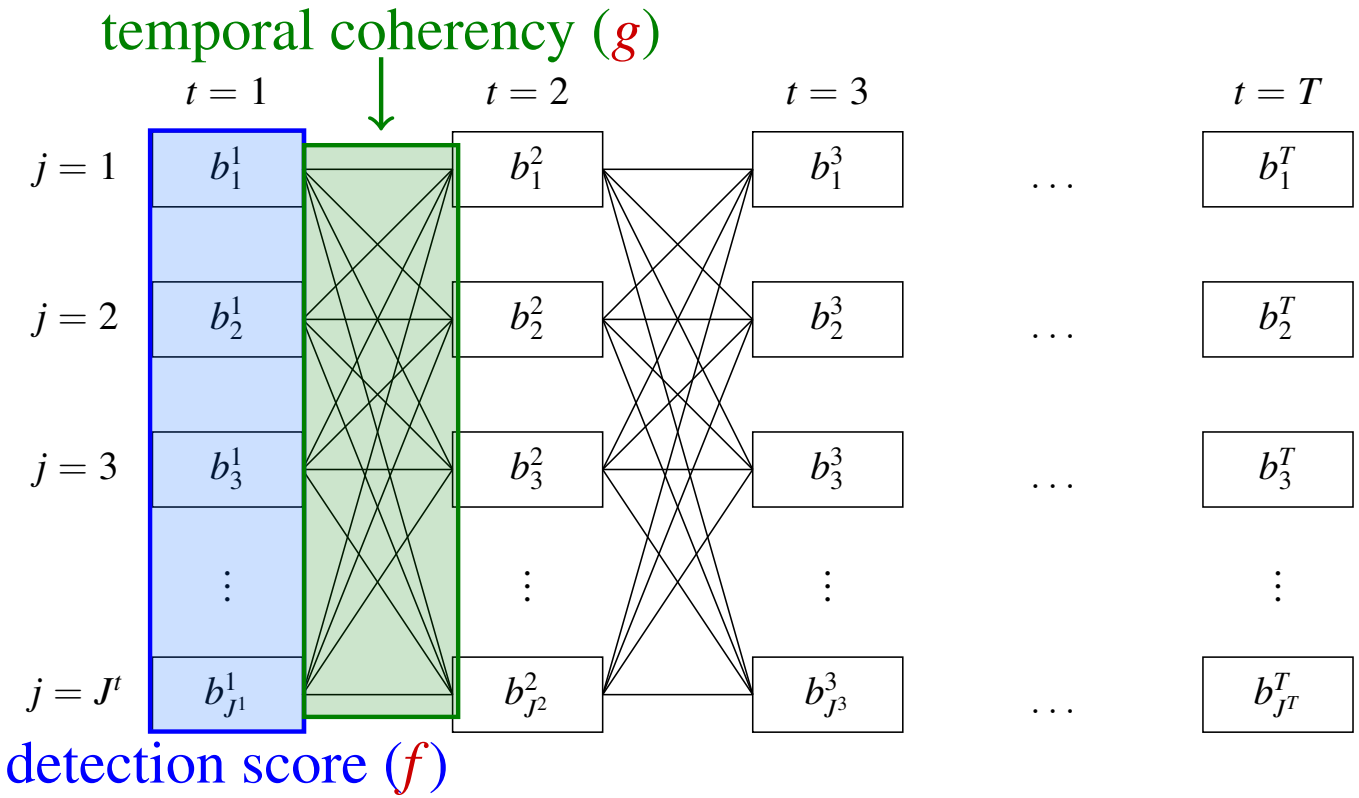

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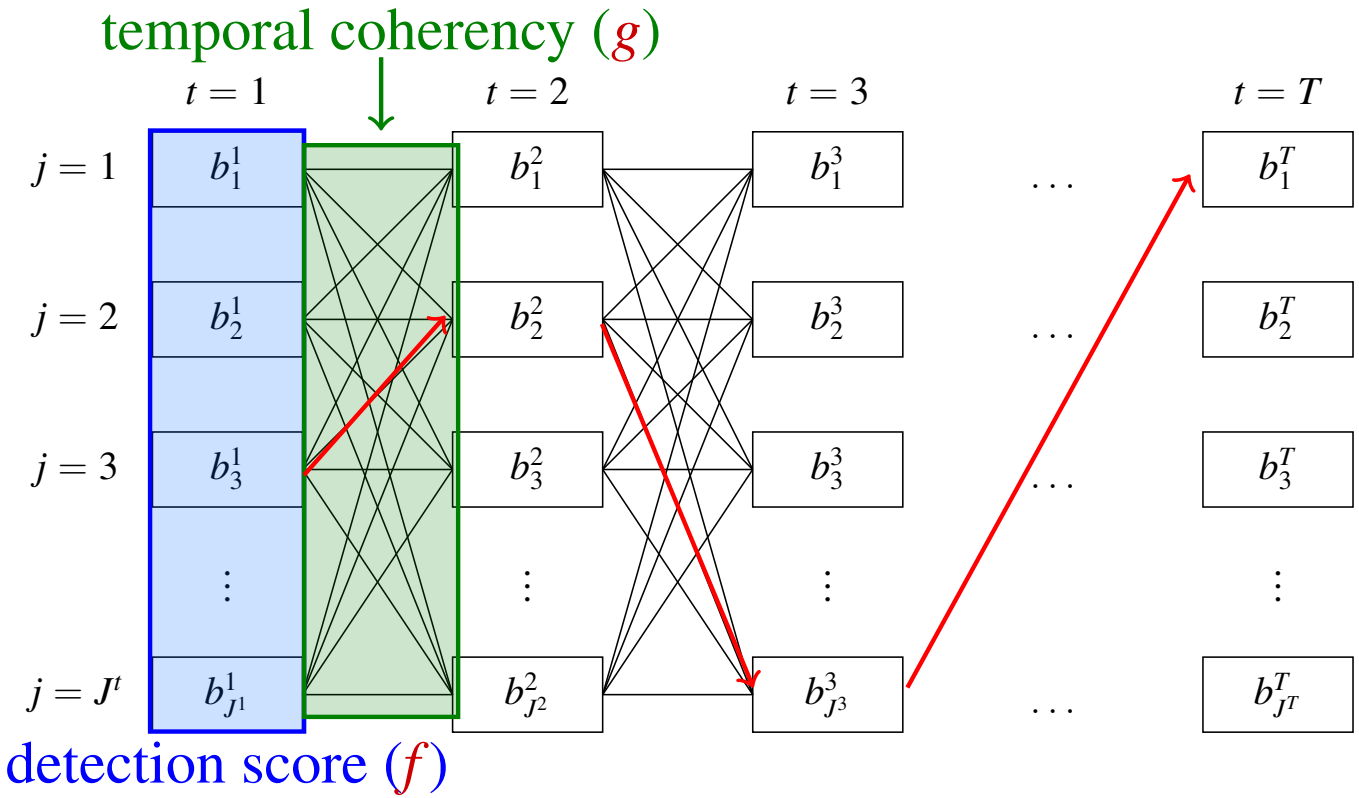

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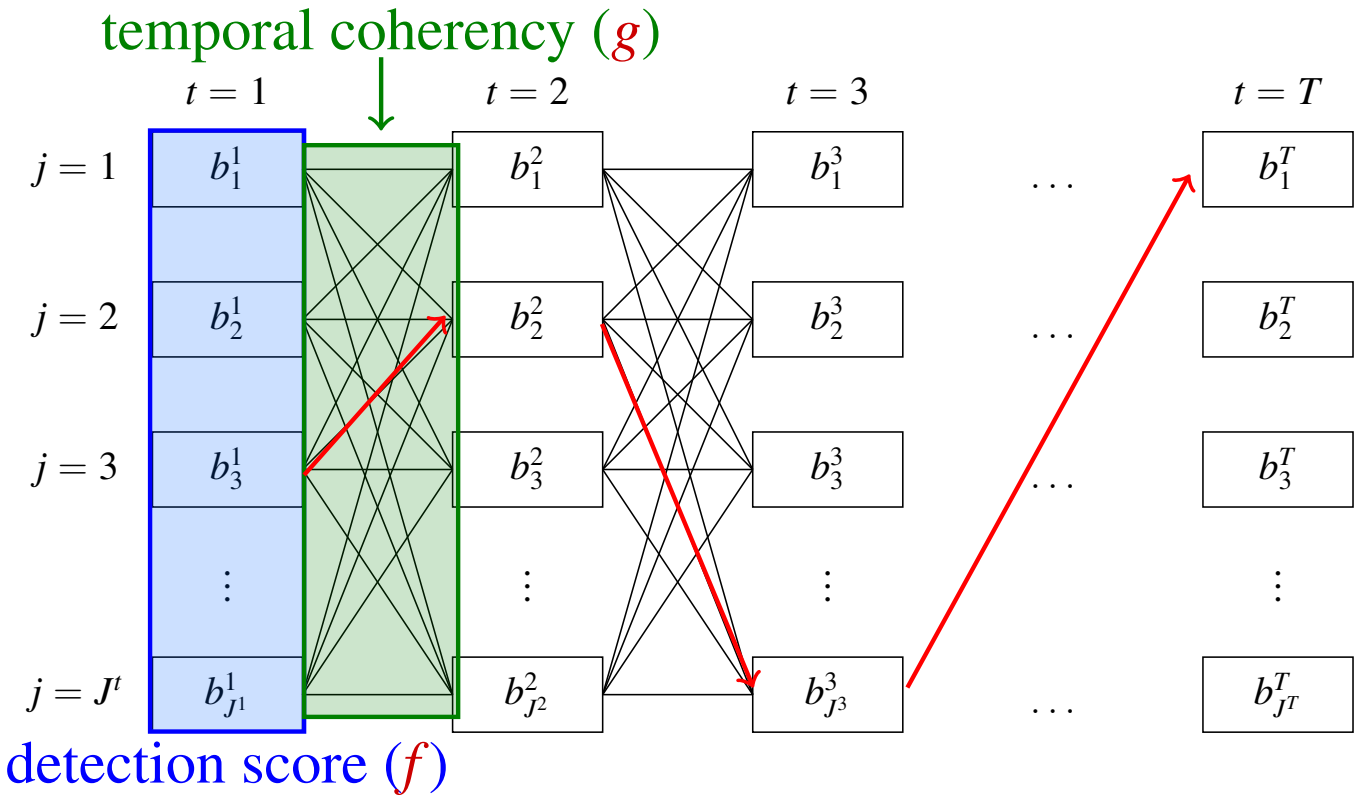
Optimal state sequence for HMM (Viterbi 1967)
Detection-based tracking (Viterbi 1971)



$$\max_{j^1,\ldots,j^T} \sum_{t=1}^{T} f(b_{j^t}^t) + \sum_{t=2}^{T} g(b_{j^{t-1}}^{t-1}, b_{j^t}^t)$$

Background Knowledge

$$
\begin{aligned}
\text{S} &\rightarrow \text{NP VP} \\
\text{NP} &\rightarrow \text{D N [PP]} \\
\text{PP} &\rightarrow \text{P NP} \\
\text{VP} &\rightarrow \text{V NP [ADV] [PPM]} \\
\text{PPM} &\rightarrow \text{PM NP} \\
\text{D} &\rightarrow \textit{the}
\end{aligned}
$$

$$
\begin{aligned}
\text{N} &\rightarrow \textit{person} \mid \textit{backpack} \mid \textit{trash-can} \mid \textit{chair} \mid \textit{traffic-cone} \mid \textit{stool} \\
\text{P} &\rightarrow \textit{to the left of} \mid \textit{to the right of} \\
\text{V} &\rightarrow \textit{picked up} \mid \textit{put down} \mid \textit{carried} \mid \textit{approached} \\
\text{ADV} &\rightarrow \textit{quickly} \mid \textit{slowly} \\
\text{PM} &\rightarrow \textit{towards} \mid \text{emphaway from}
\end{aligned}
$$

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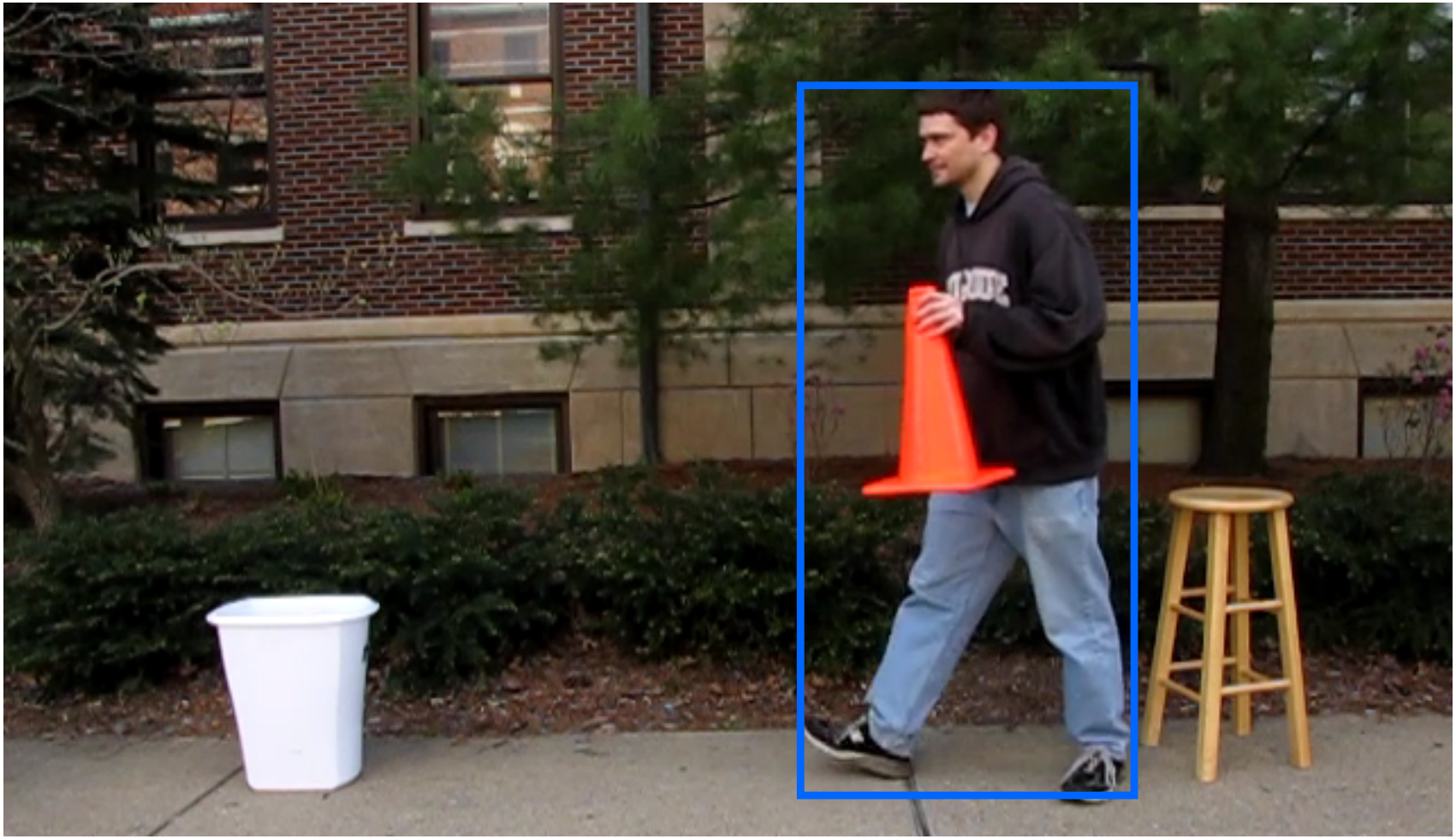
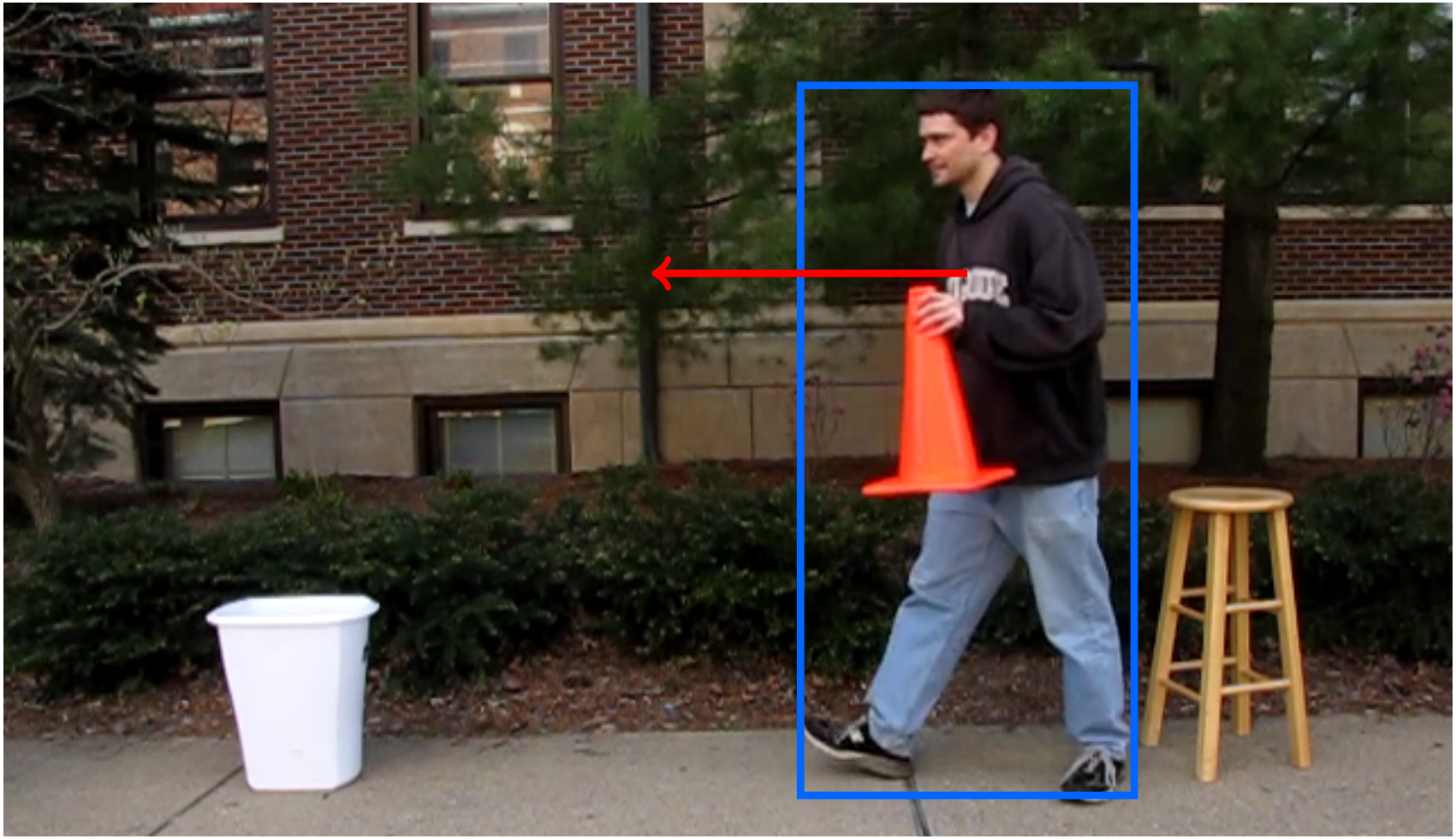
$$

Visual Features

Visual Features

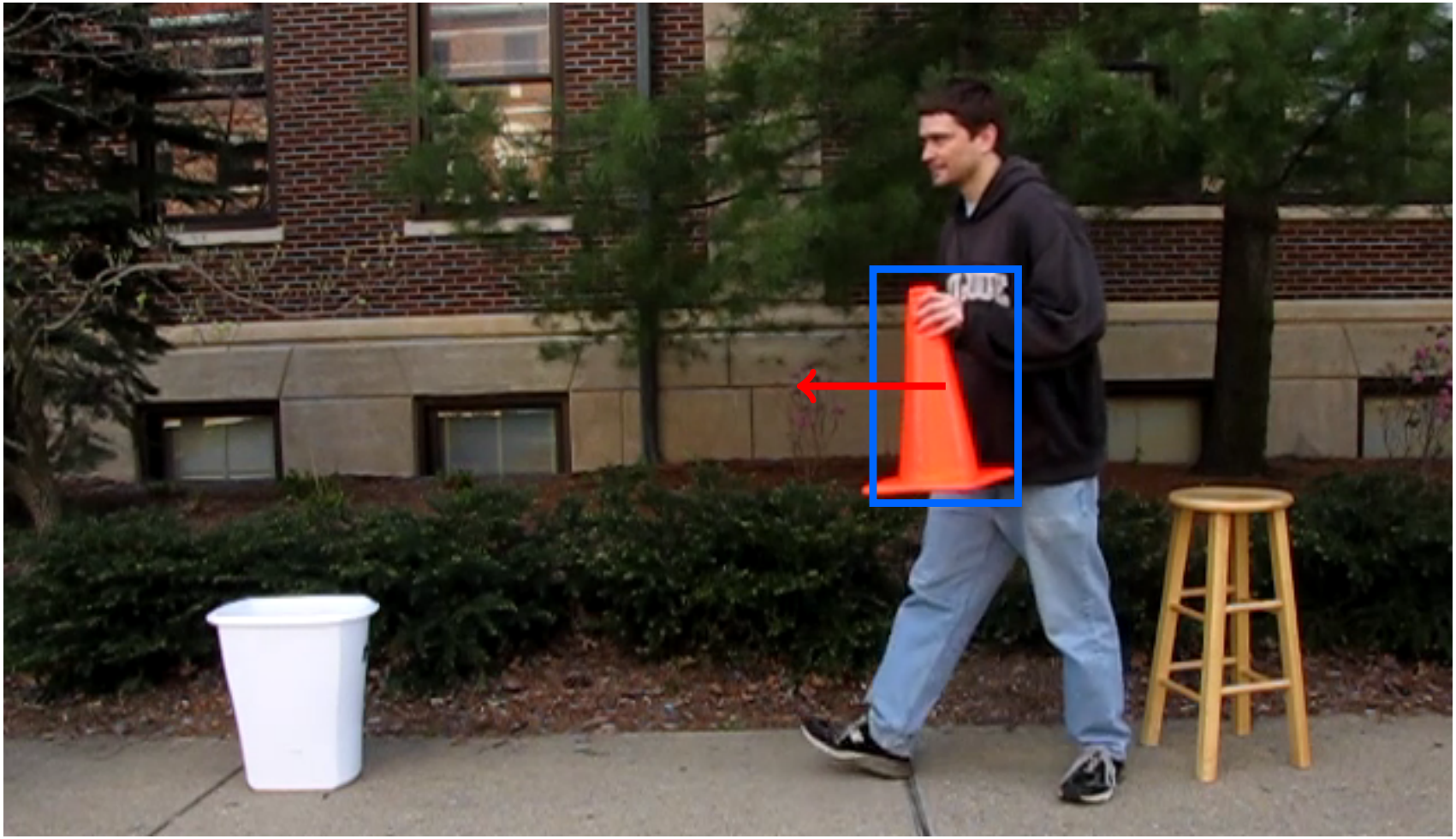


Visual Features



velocity object class distance orientation

Visual Features



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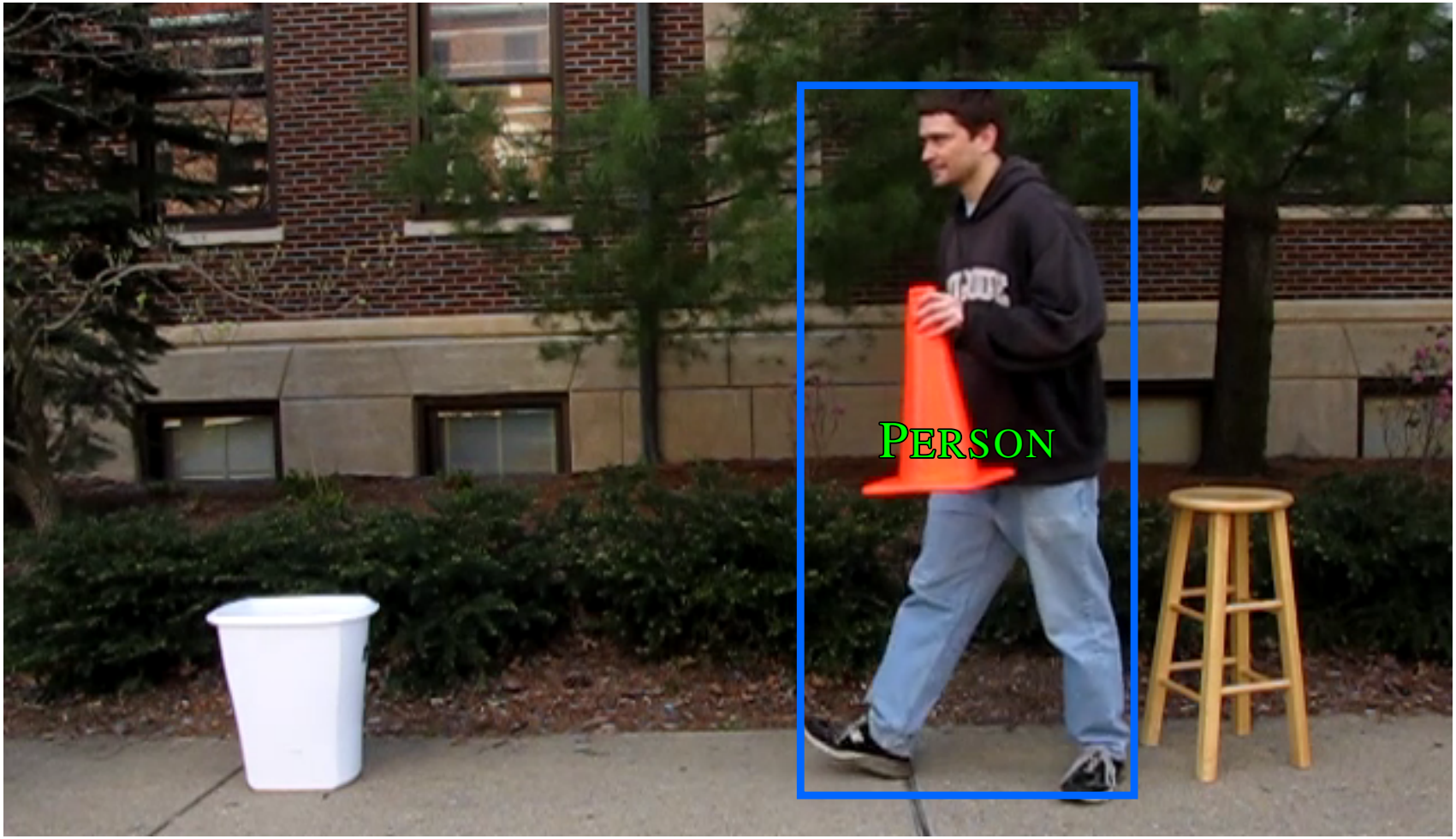
Visual Features



velocity object class distance orientation

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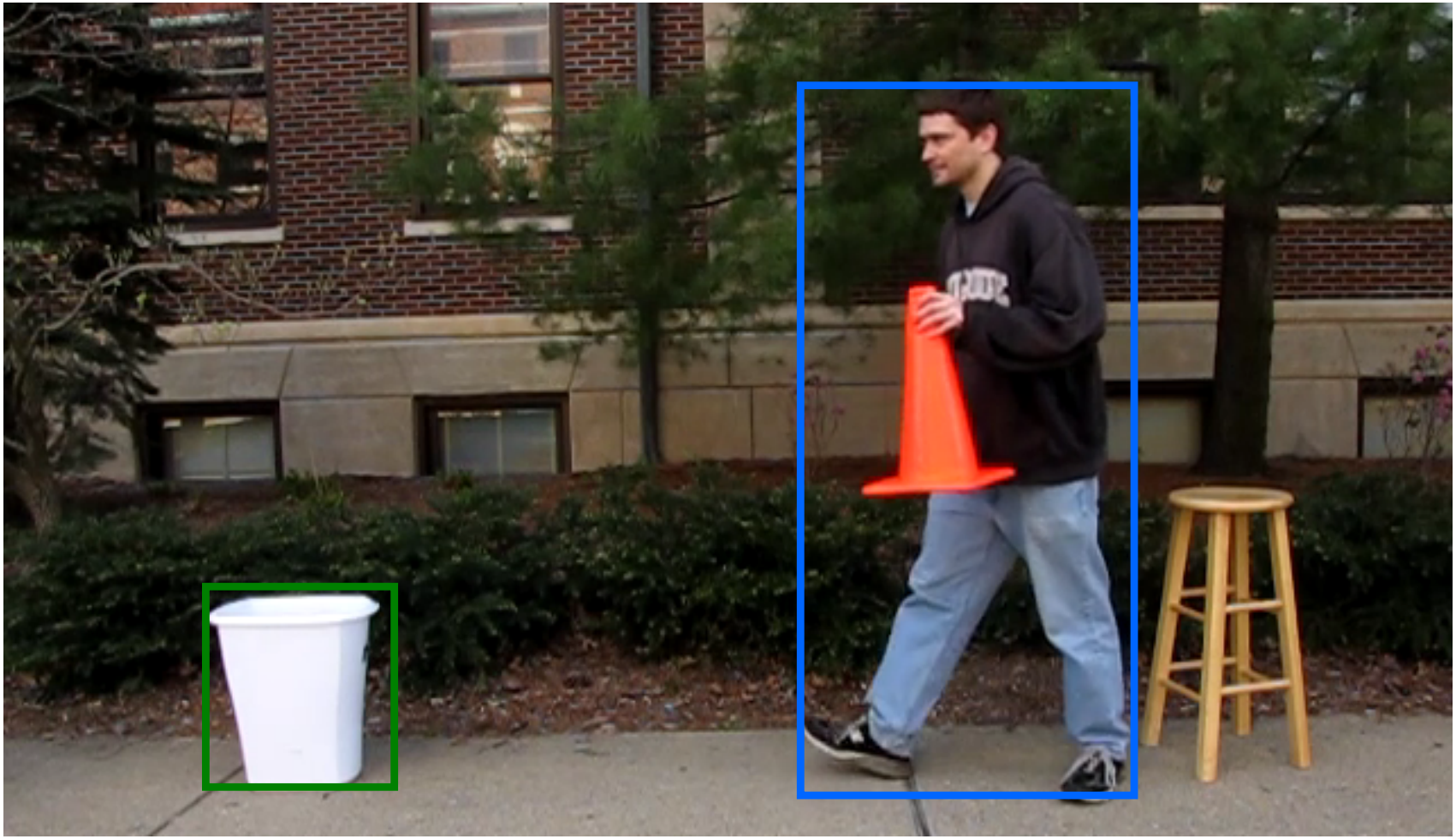
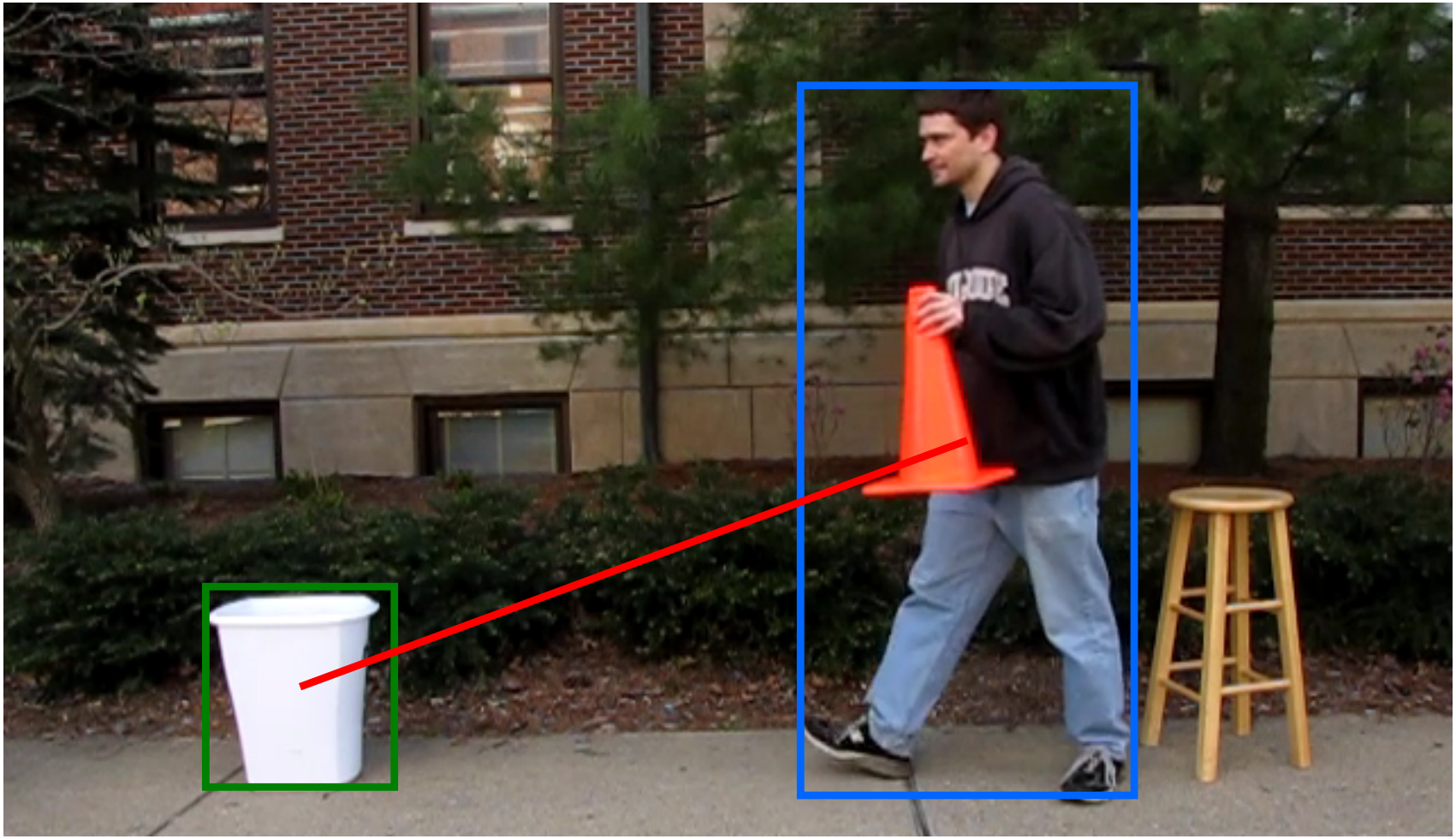


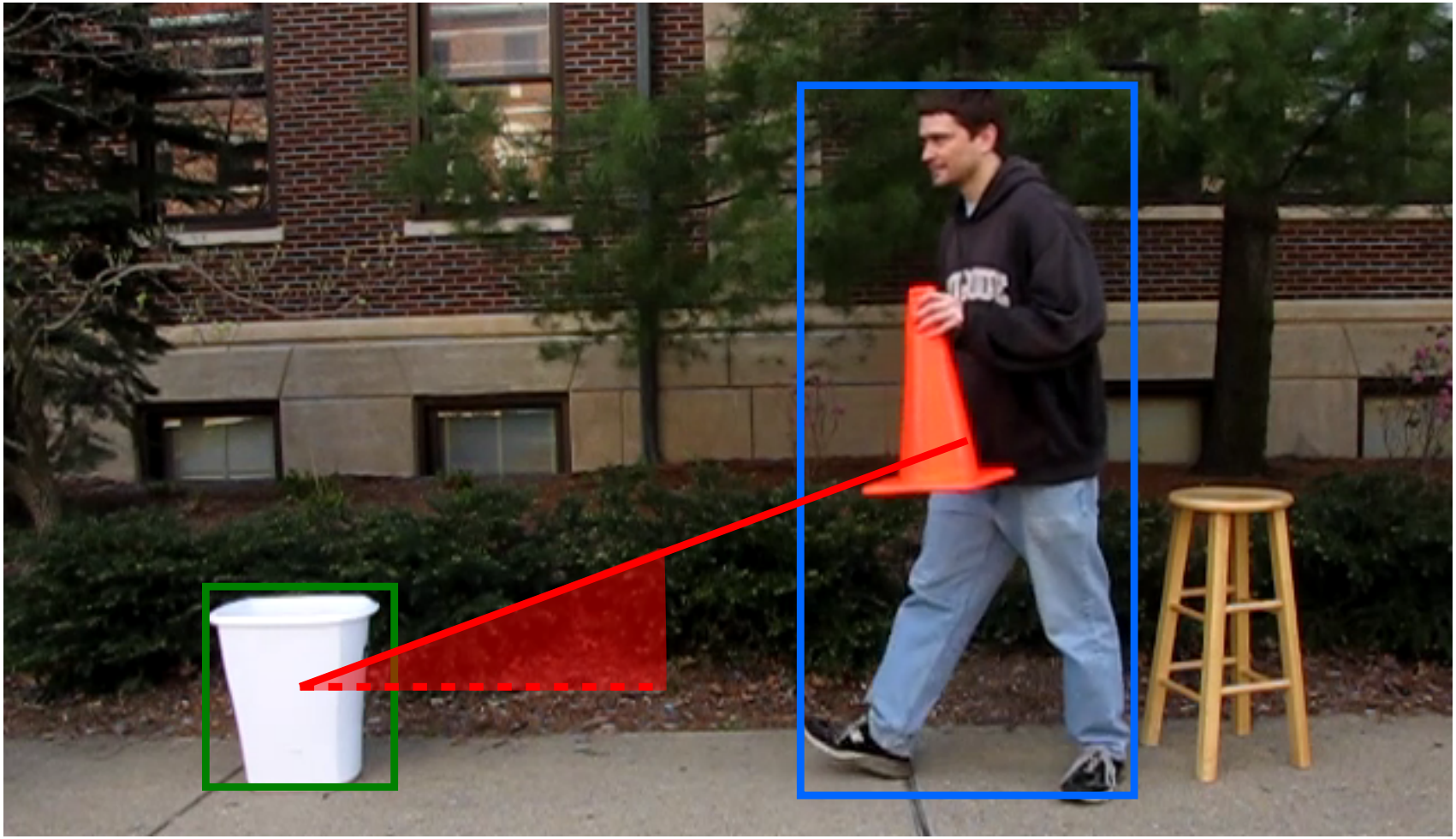
velocity object class distance orientation

Visual Features



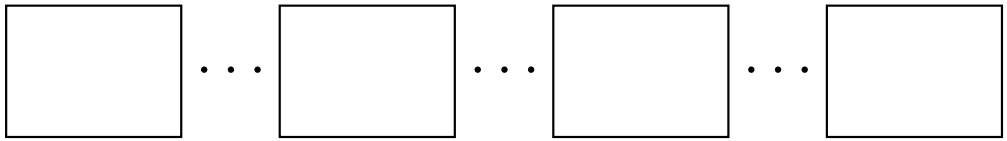
velocity object class distance orientation

Visual Features



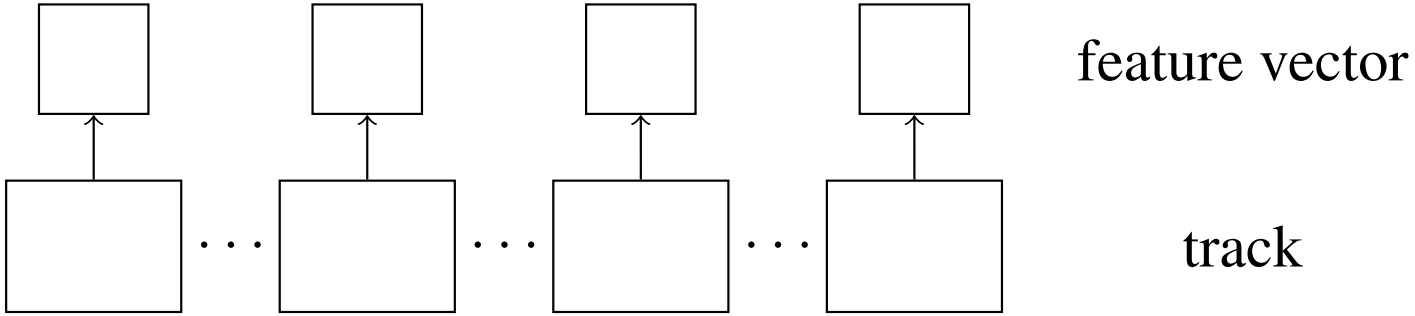
velocity object class distance orientation

Event Recognition with Hidden Markov Models

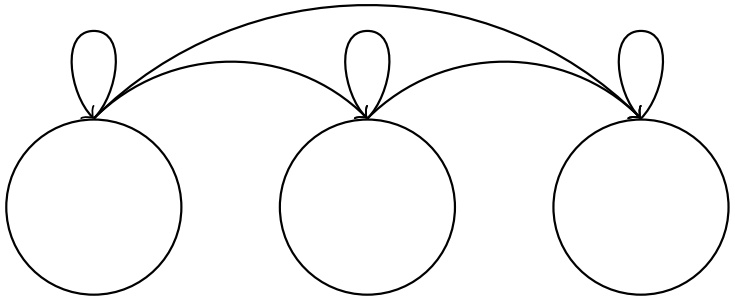


track

Event Recognition with Hidden Markov Models

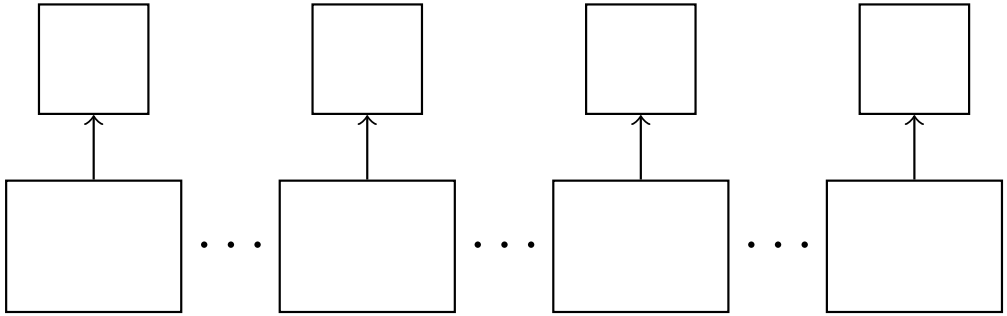


Event Recognition with Hidden Markov Models



a

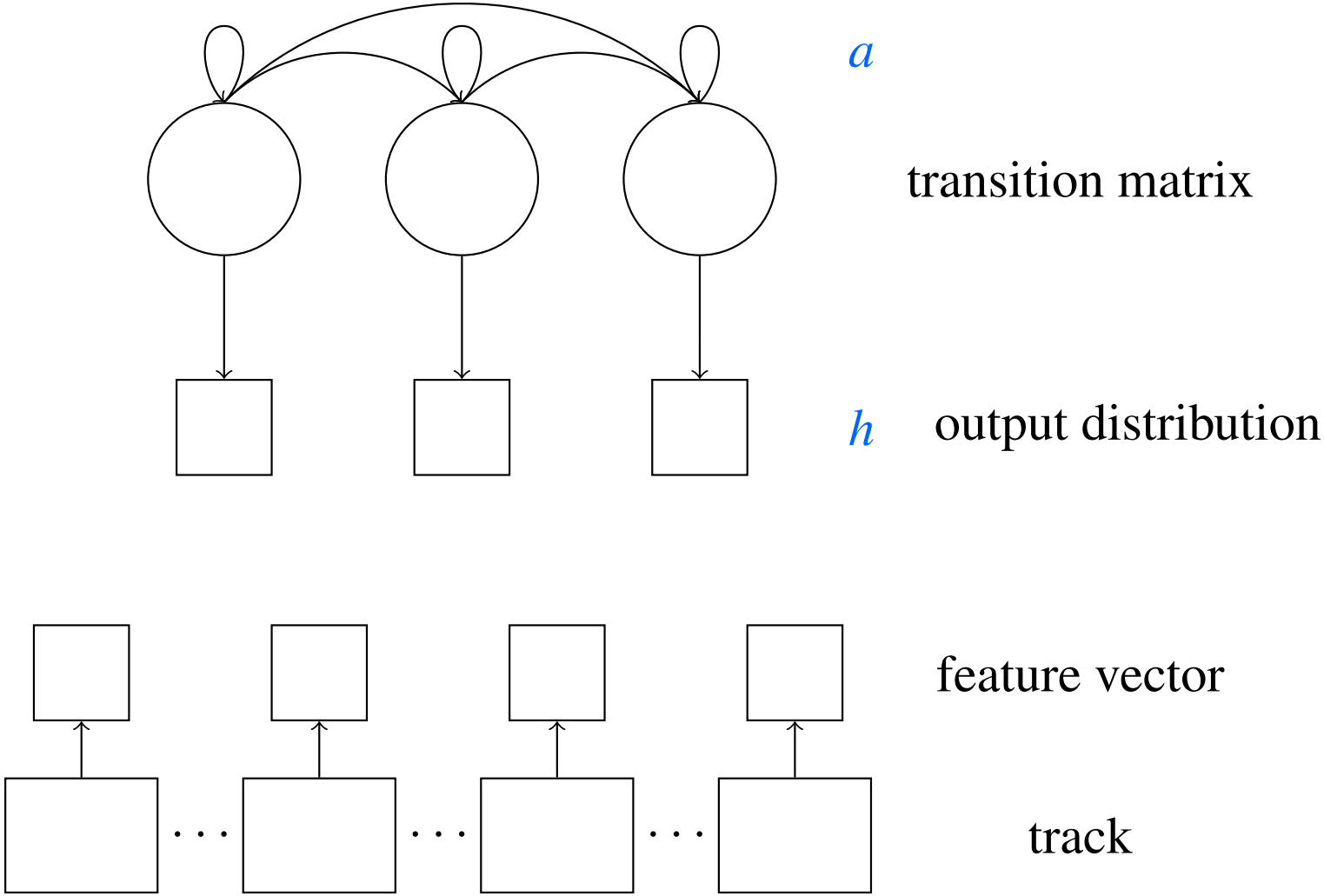
transition matrix



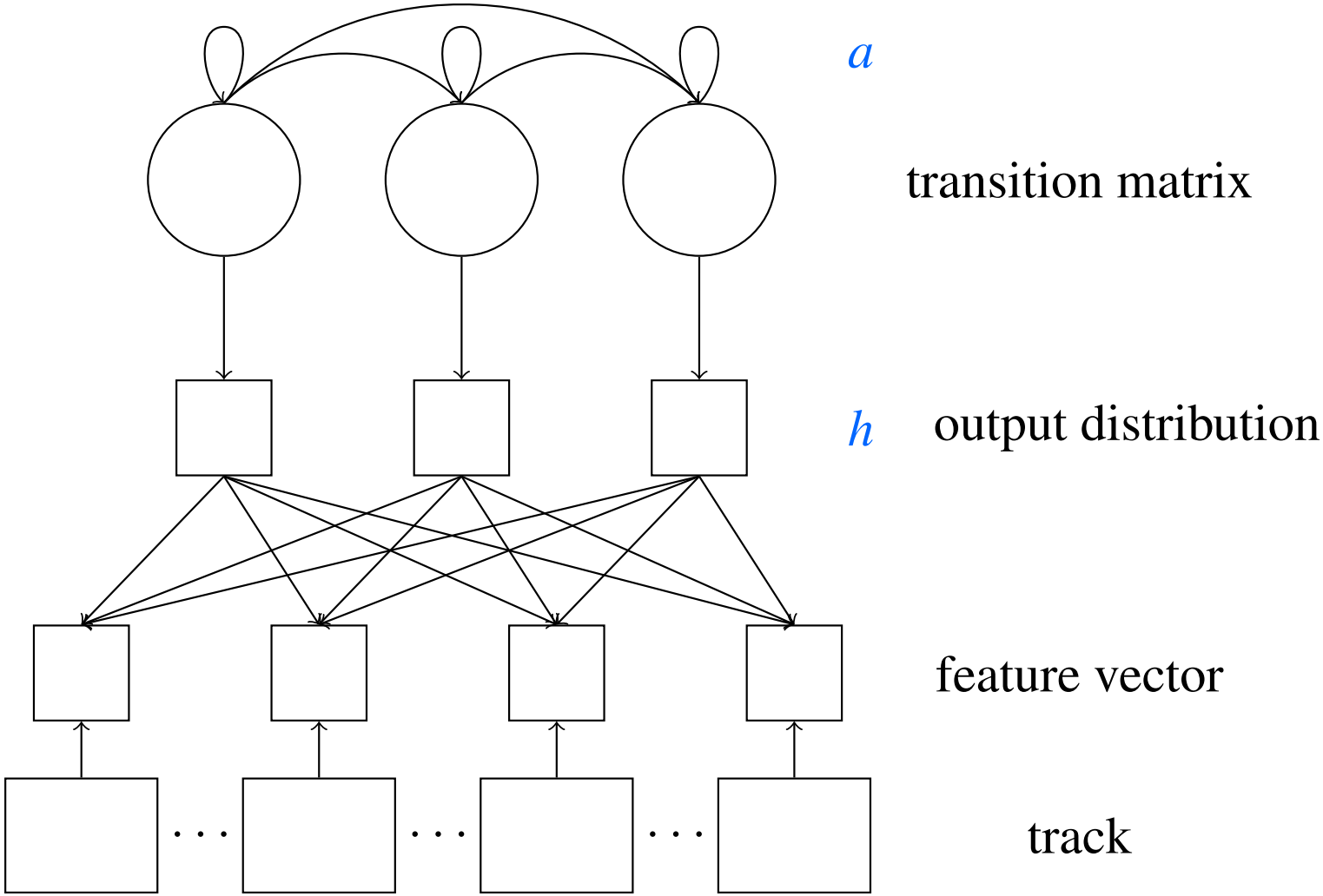
feature vector

track

Event Recognition with Hidden Markov Models

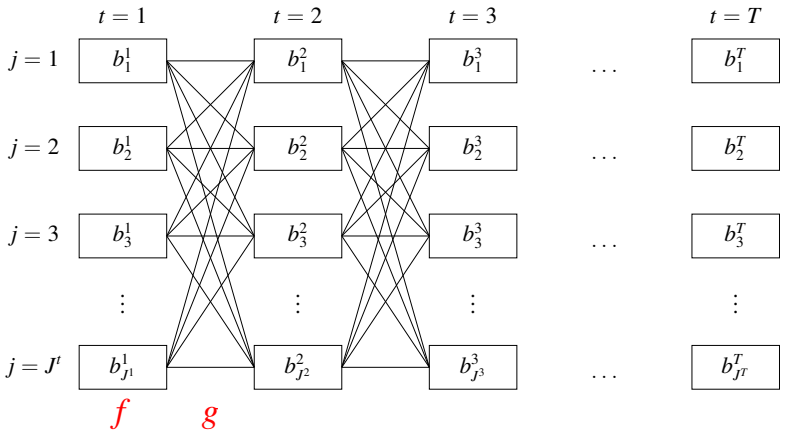


Event Recognition with Hidden Markov Models



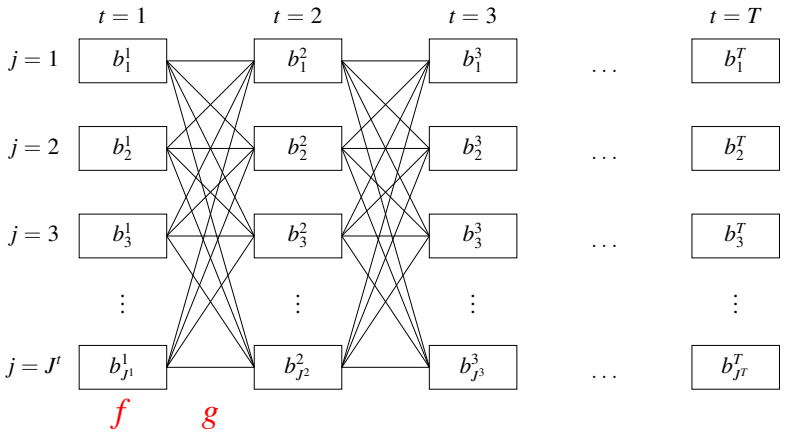
Event Tracker

Event Tracker

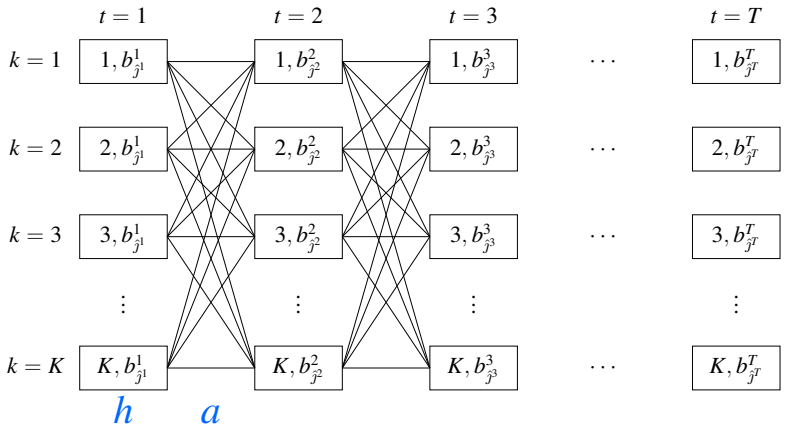


tracker lattice

Event Tracker

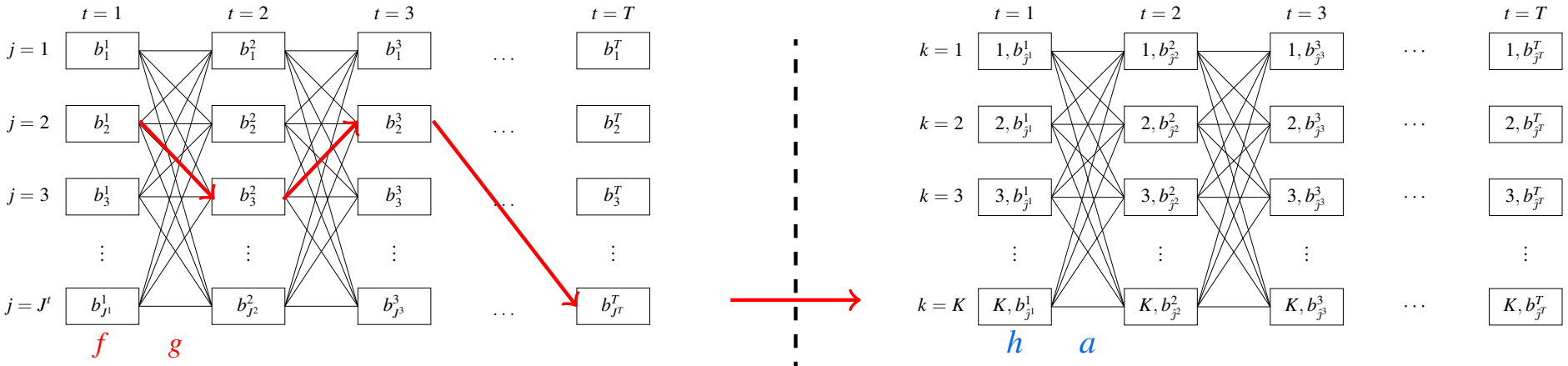


tracker lattice

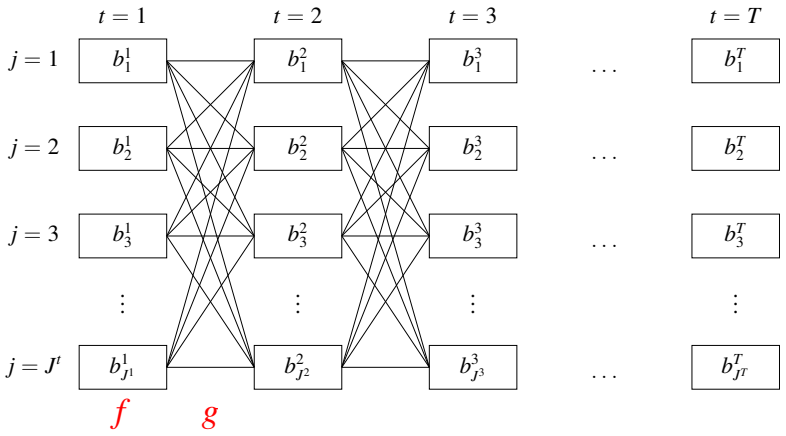


verb lattice

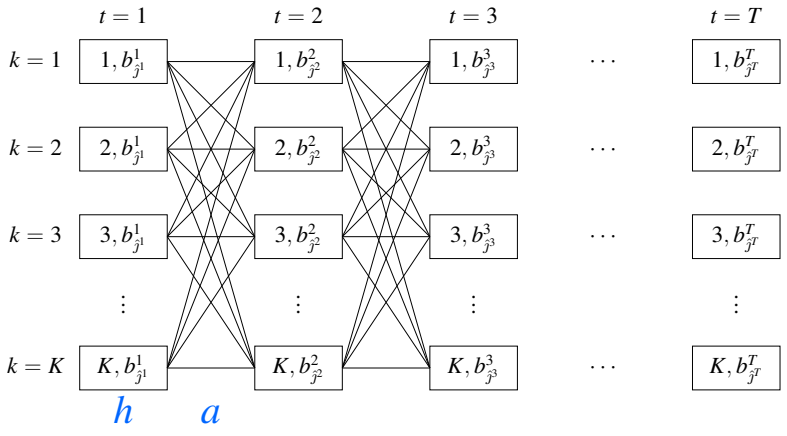
Event Tracker



Event Tracker



tracker lattice

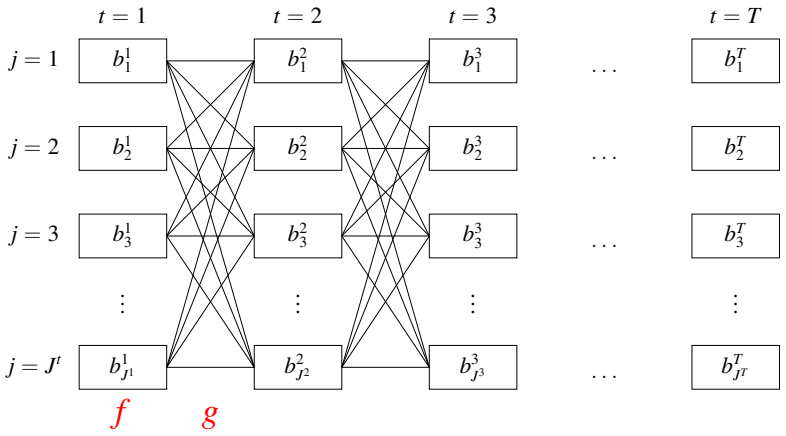


verb lattice

$$\max_{j^1,\ldots,j^T} \sum_{t=1}^{T} f(b_{j^t}^t) + \sum_{t=2}^{T} g(b_{j^{t-1}}^{t-1}, b_{j^t}^t)$$

$$\max_{k^1,\ldots,k^T} \sum_{t=1}^{T} h(k^t, b^t) + \sum_{t=2}^{T} a(k^{t-1}, k^t)$$

Event Tracker



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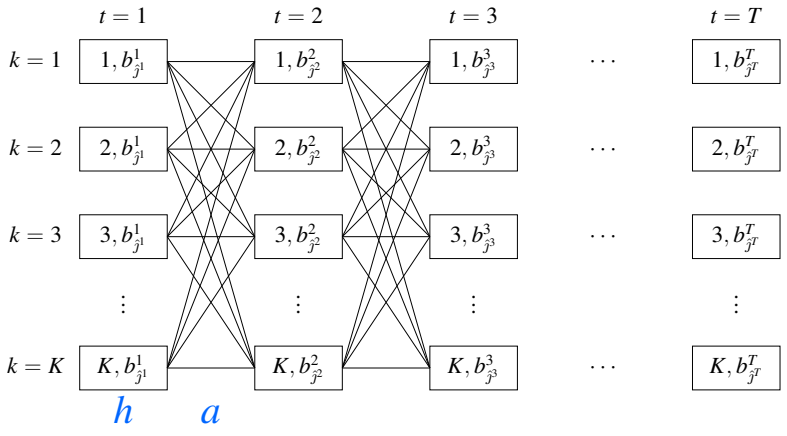

verb lattice

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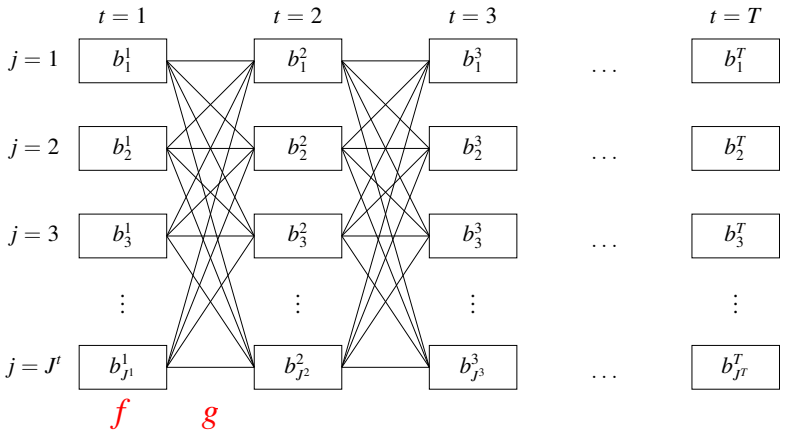
Event Tracker



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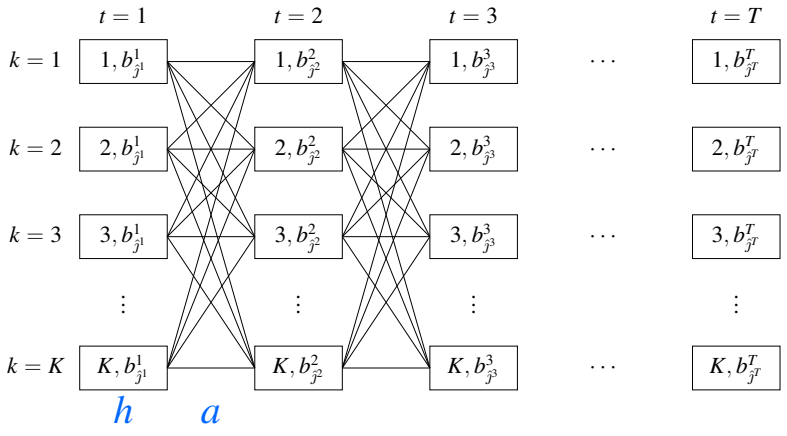

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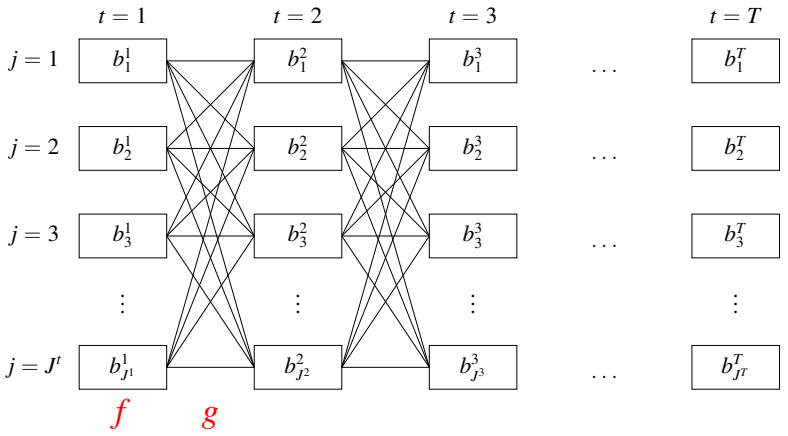
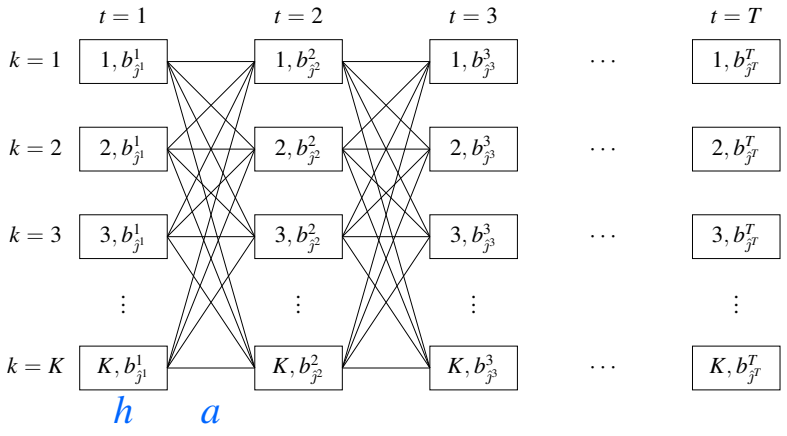
Event Tracker



tracker lattice

$\times$



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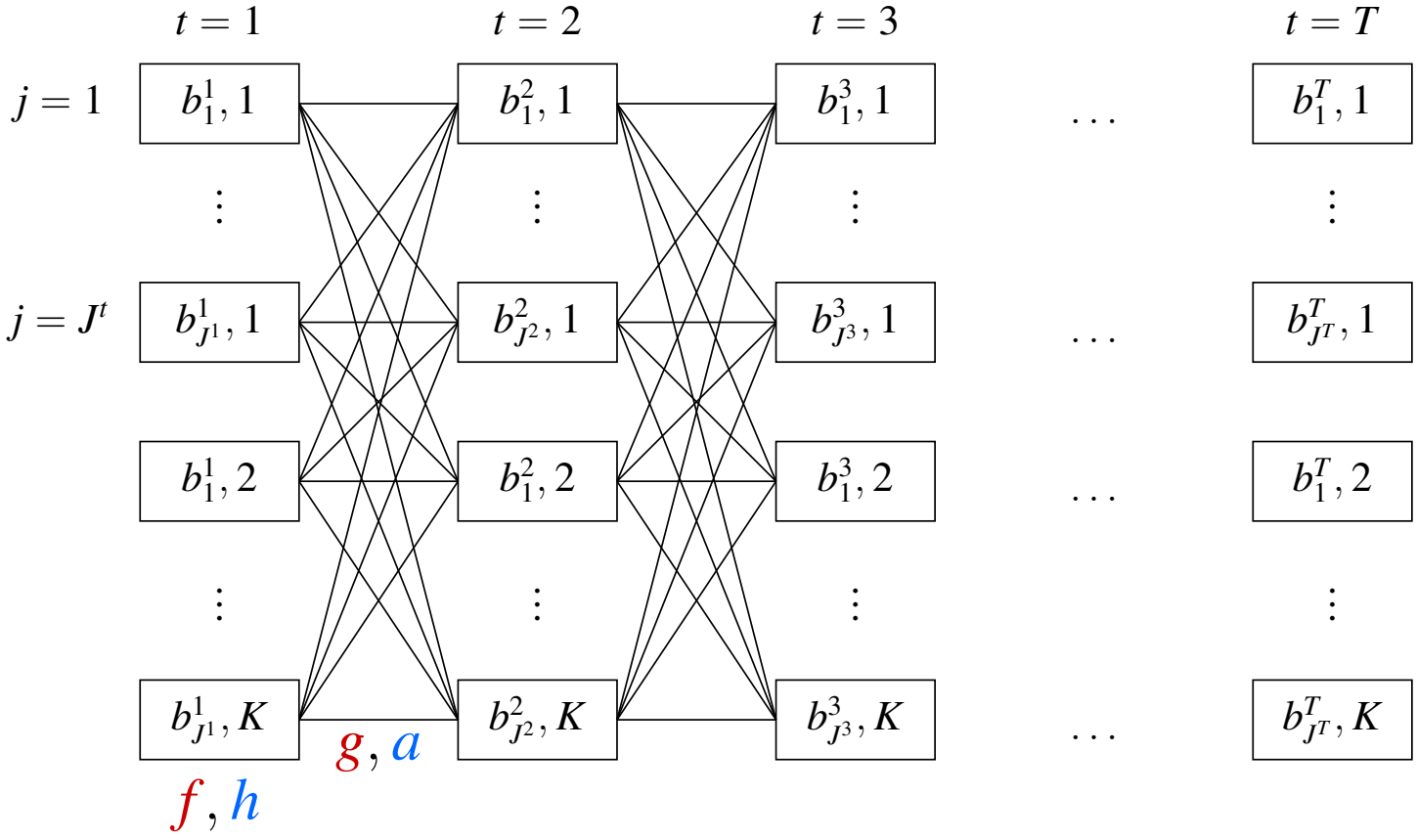
Event Tracker



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\text{PPM} &\rightarrow \text{PM NP} \\
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\text{ADV} &\rightarrow \textit{quickly} \mid \textit{slowly} \\
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\end{aligned}
$$

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\end{aligned}
$$

- model other words also as HMMs

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\text{NP} &\rightarrow \text{D N [PP]} \\
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\end{aligned}
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- model other words also as HMMs

  *The **jump** was fast.* (Some nouns are dynamic.)

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- model other words also as HMMs

  *The **jump** was fast.* (Some nouns are dynamic.)

  *The person **held** the backpack.* (Some verbs are static.)

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- model other words also as HMMs

  *The **jump** was fast.* (Some nouns are dynamic.)

  *The person **held** the backpack.* (Some verbs are static.)

- unified learning algorithm

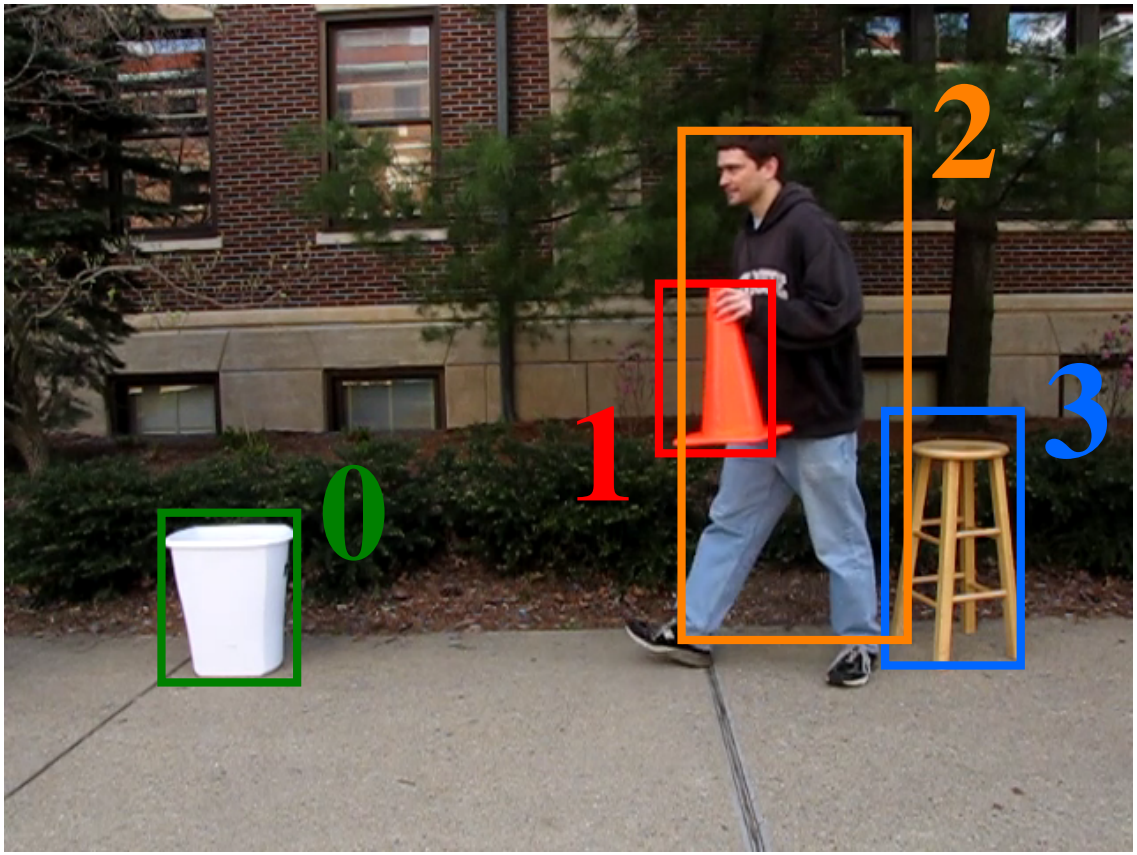
Sentence Tracker

The person to the left of the stool carried the traffic-cone towards the trash-can.

Sentence Tracker

The person to the left of the stool carried the traffic-cone towards the trash-can.

object 0 **object 1** **object 2** **object 3**

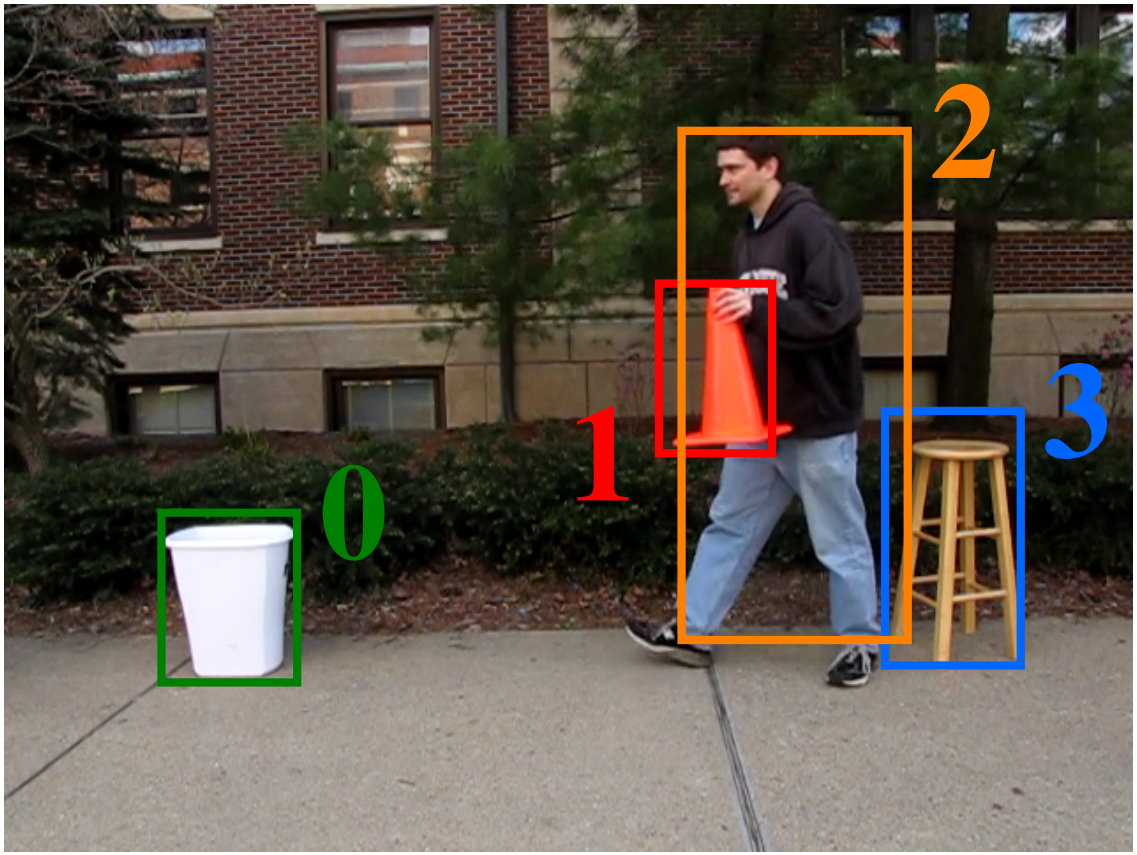


Sentence Tracker

The person to the left of the stool carried the traffic-cone towards the trash-can.

agent-tracker

object 0 **object 1** **object 2** **object 3**



Sentence Tracker

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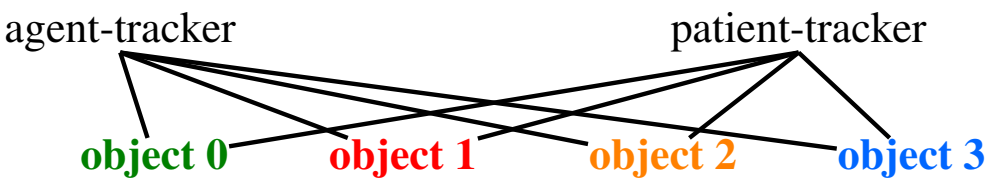
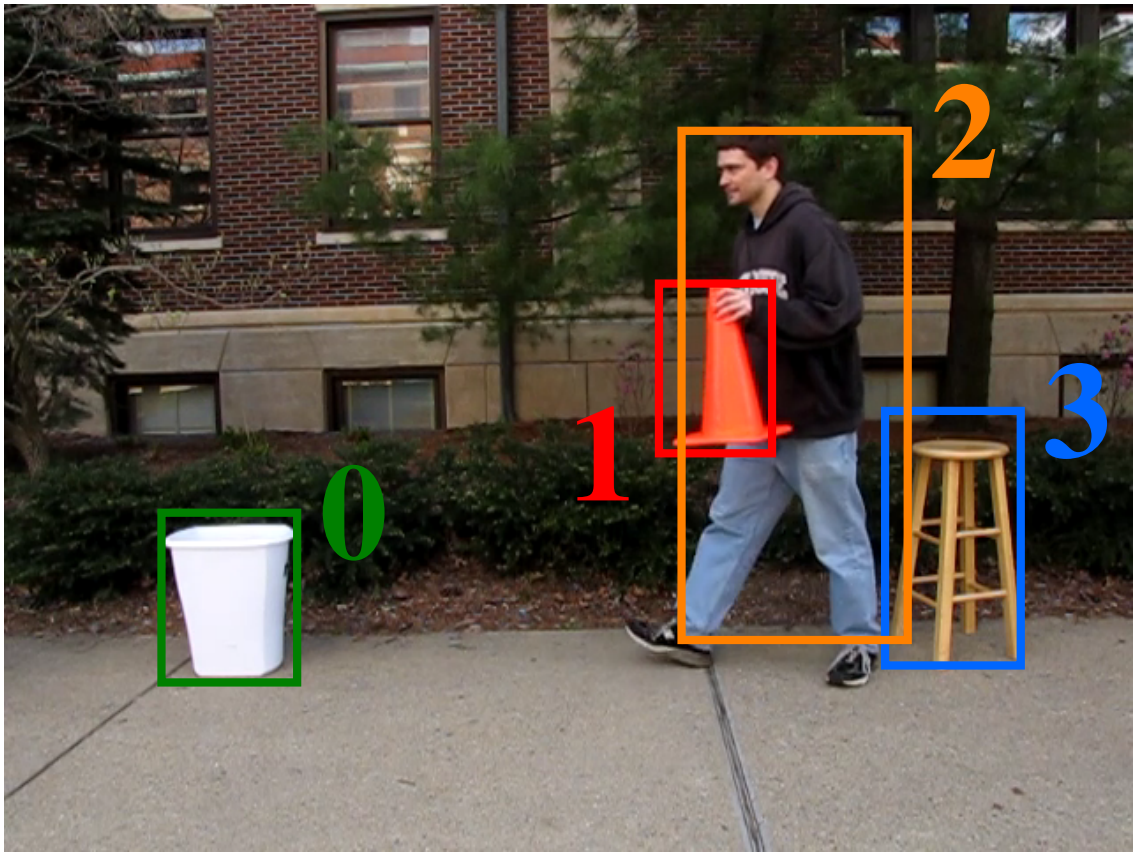
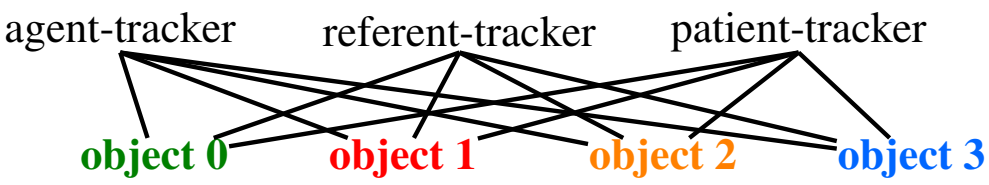
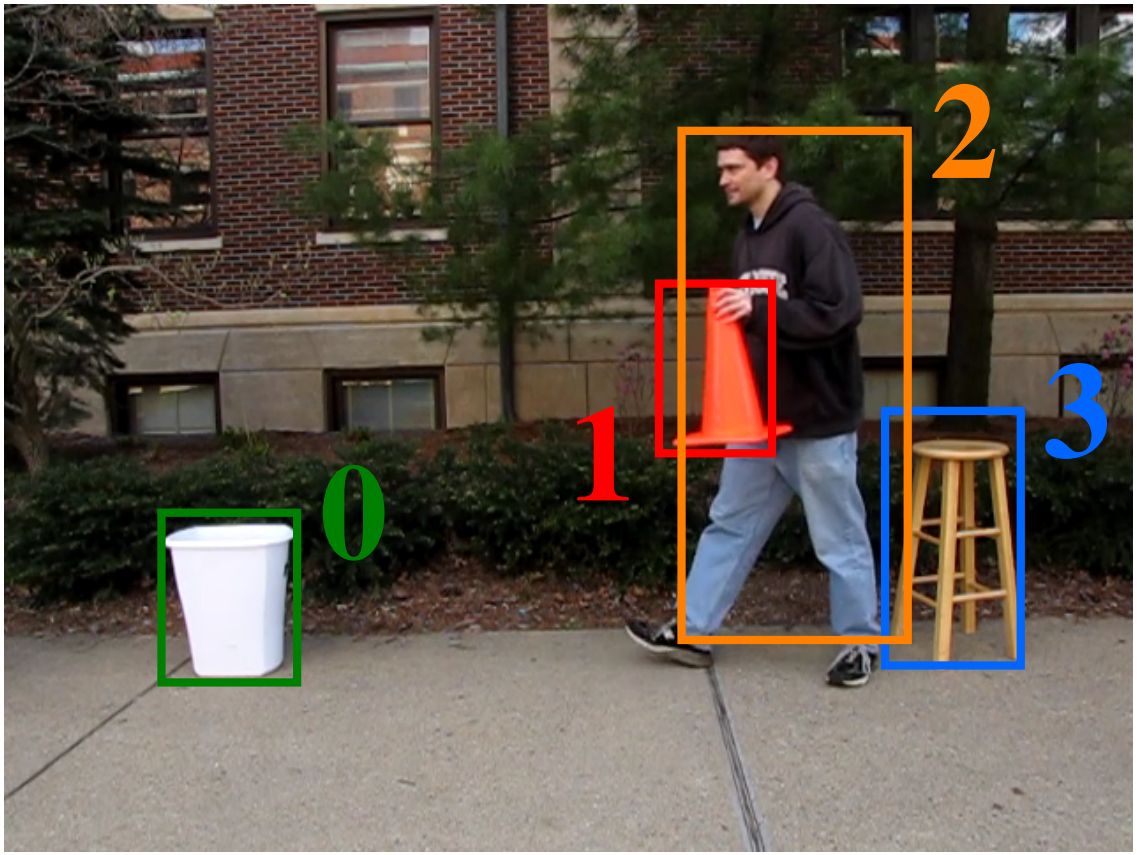




Sentence Tracker

The person to the left of the stool carried the traffic-cone towards the trash-can.





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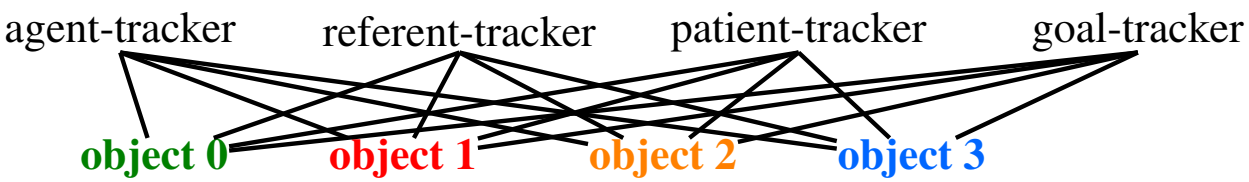

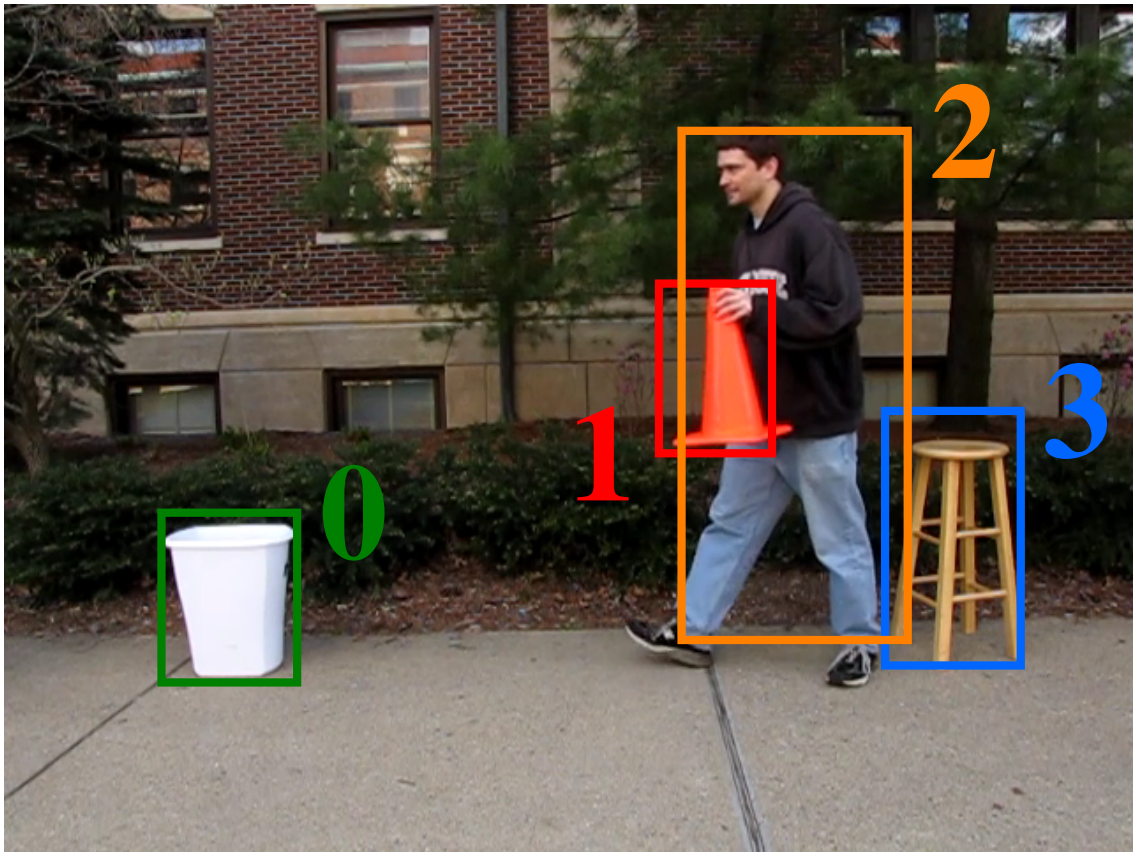

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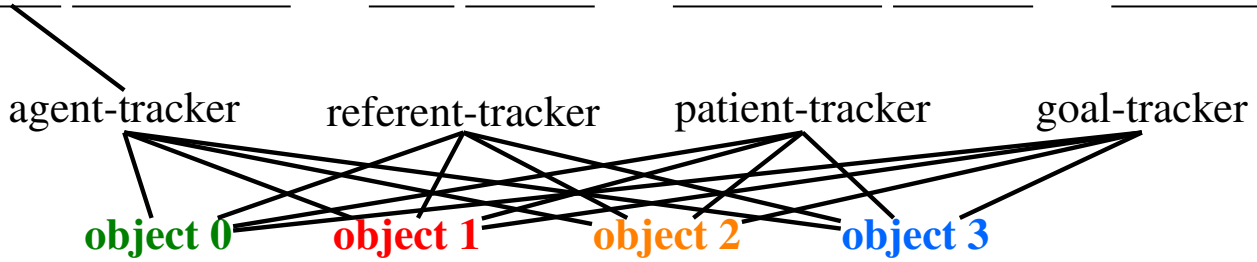

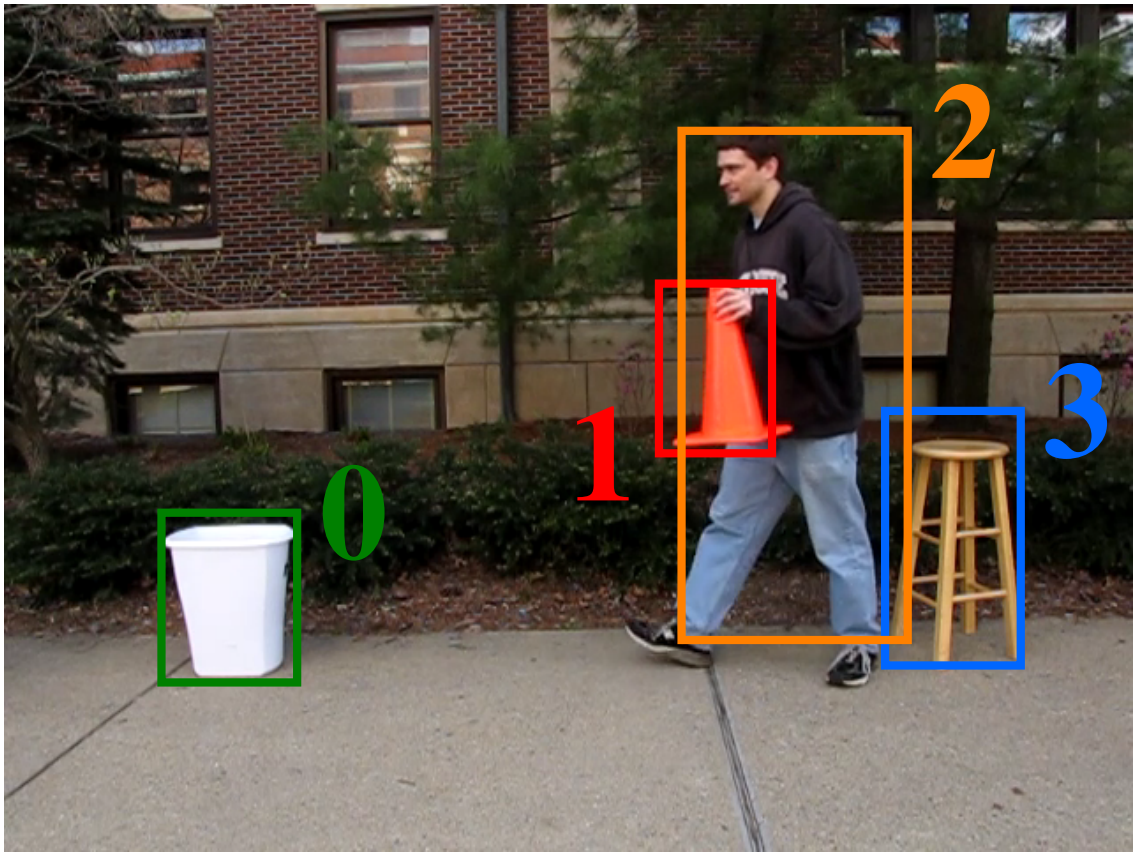

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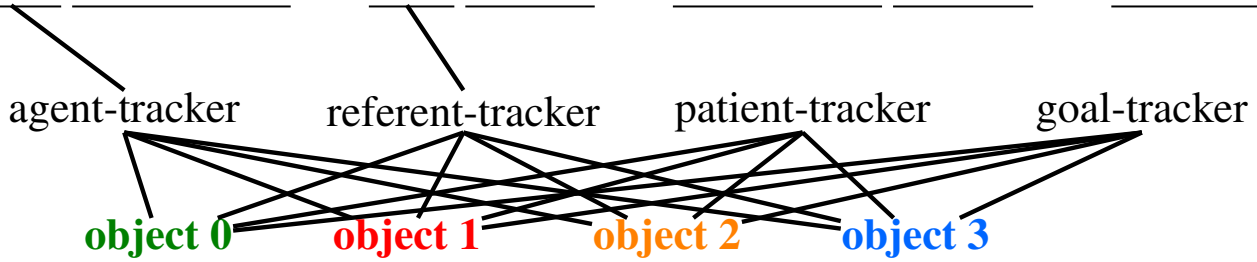

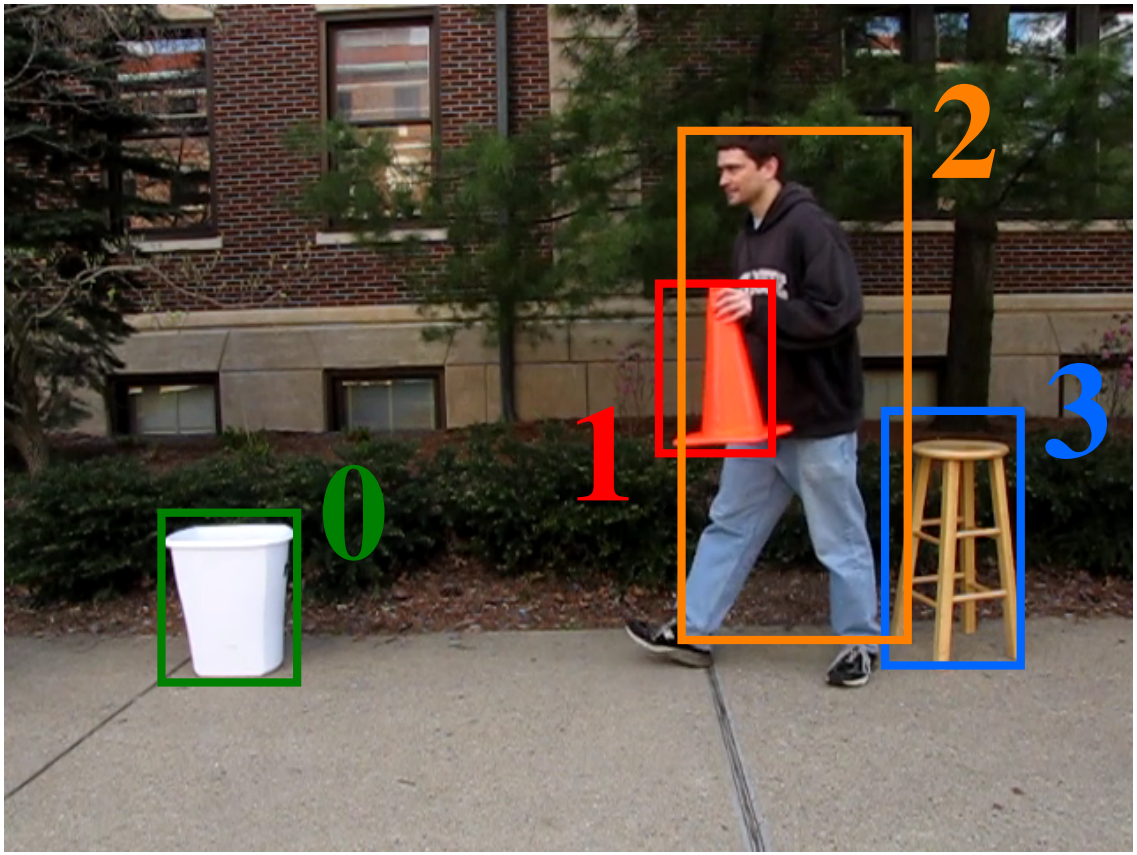

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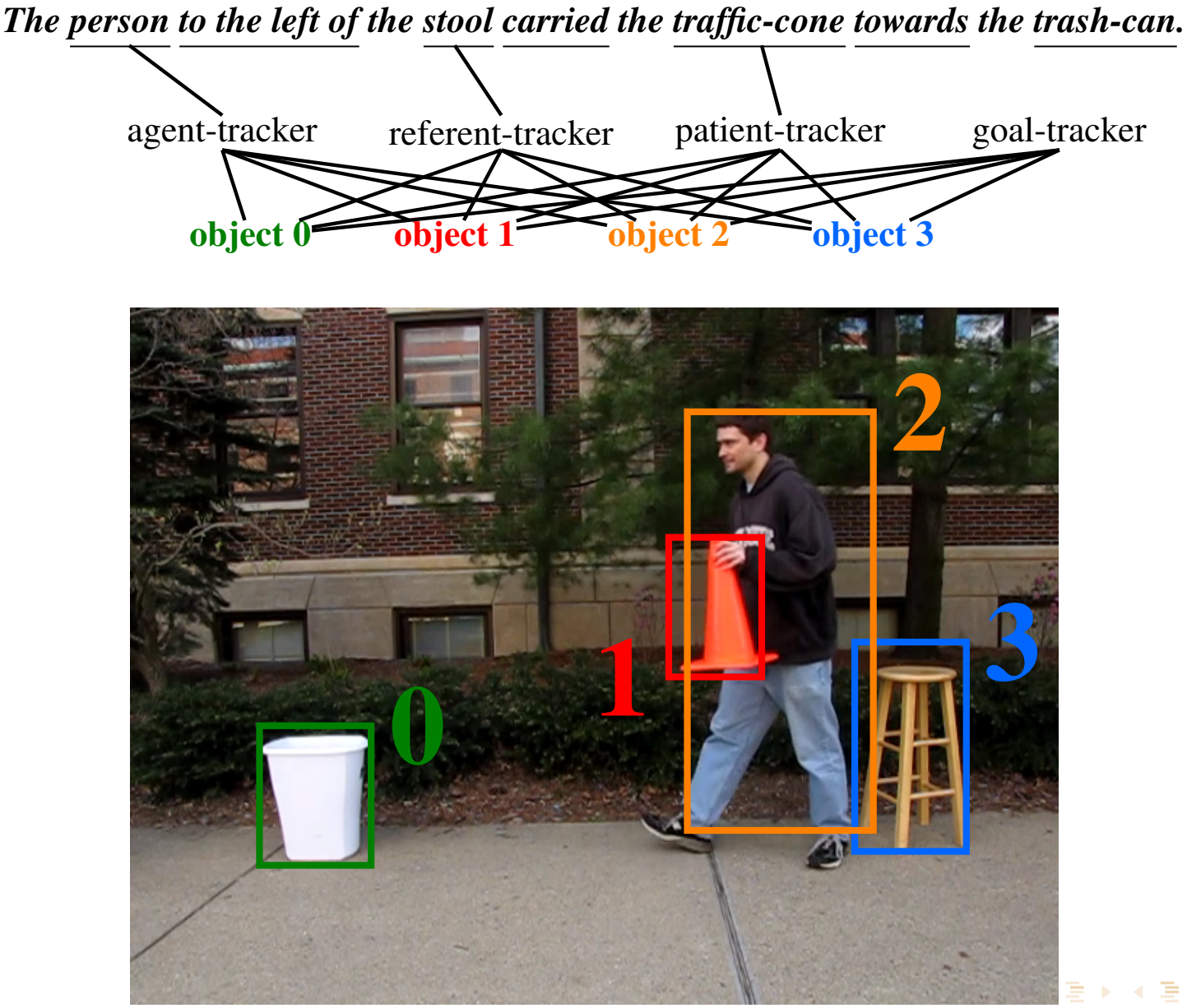

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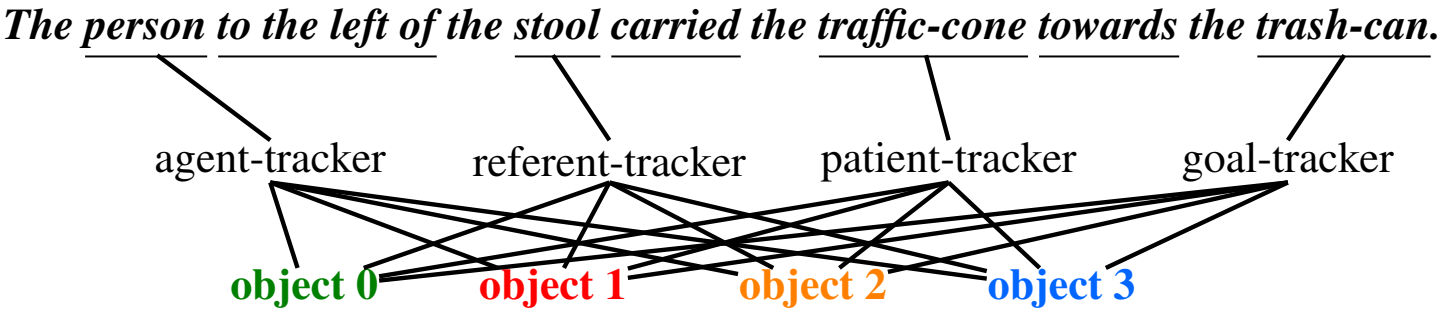

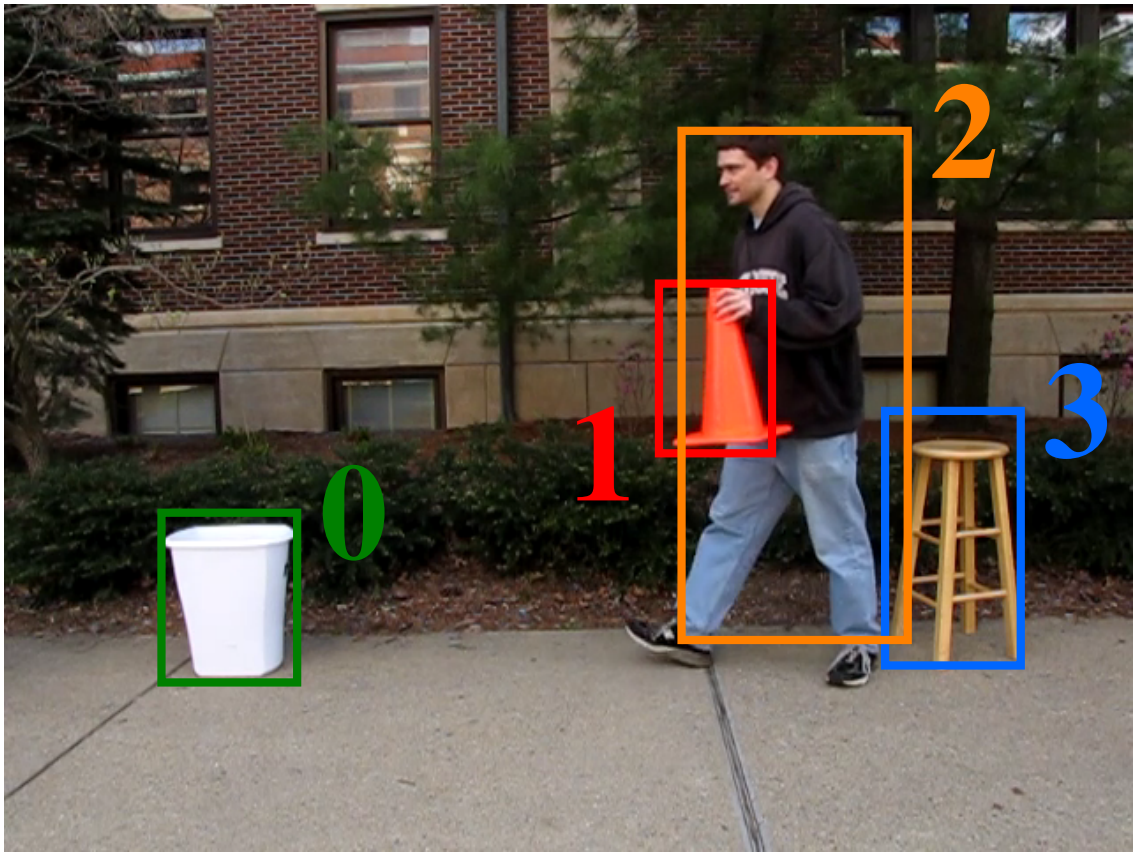

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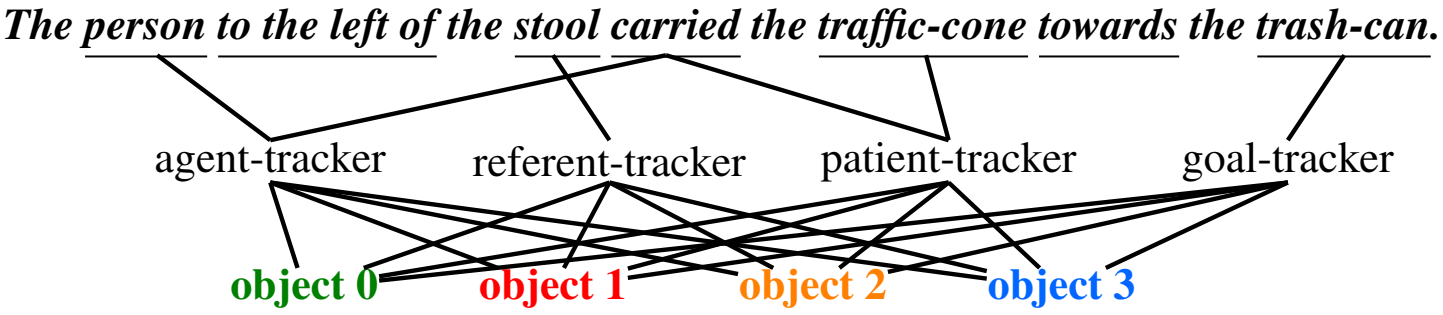

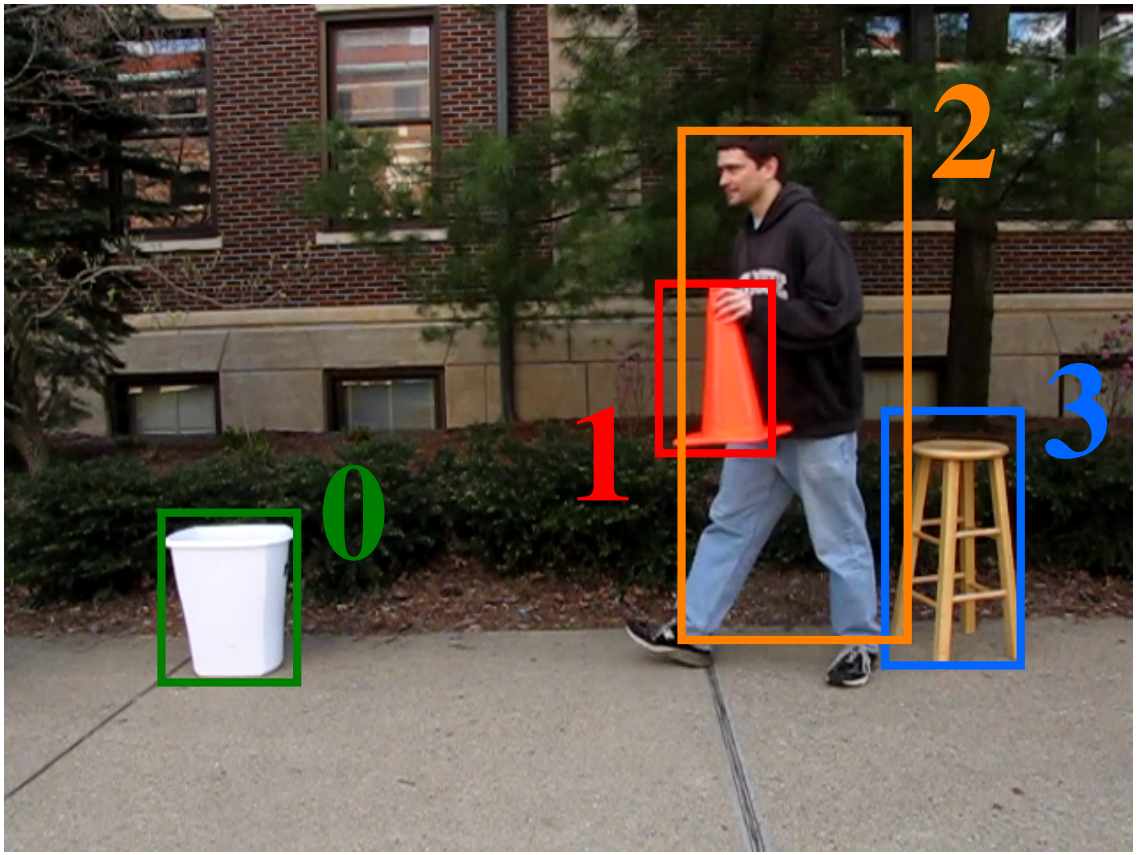

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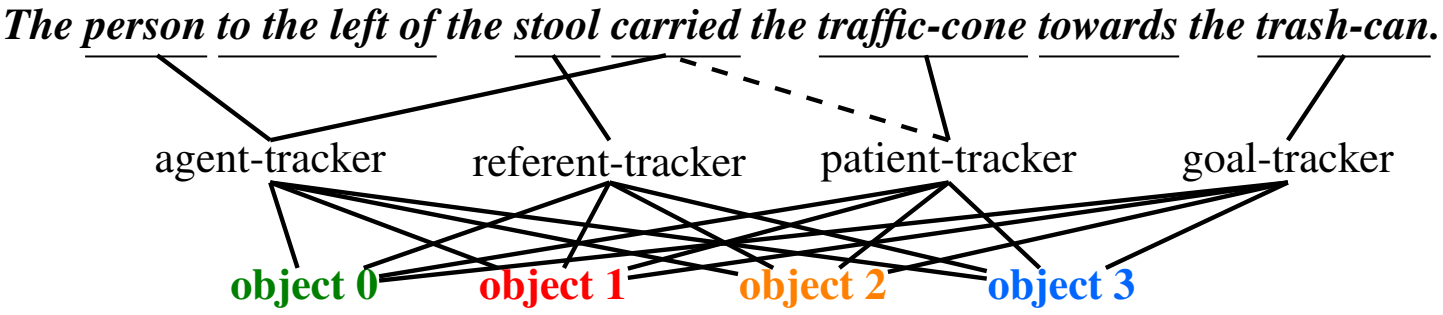

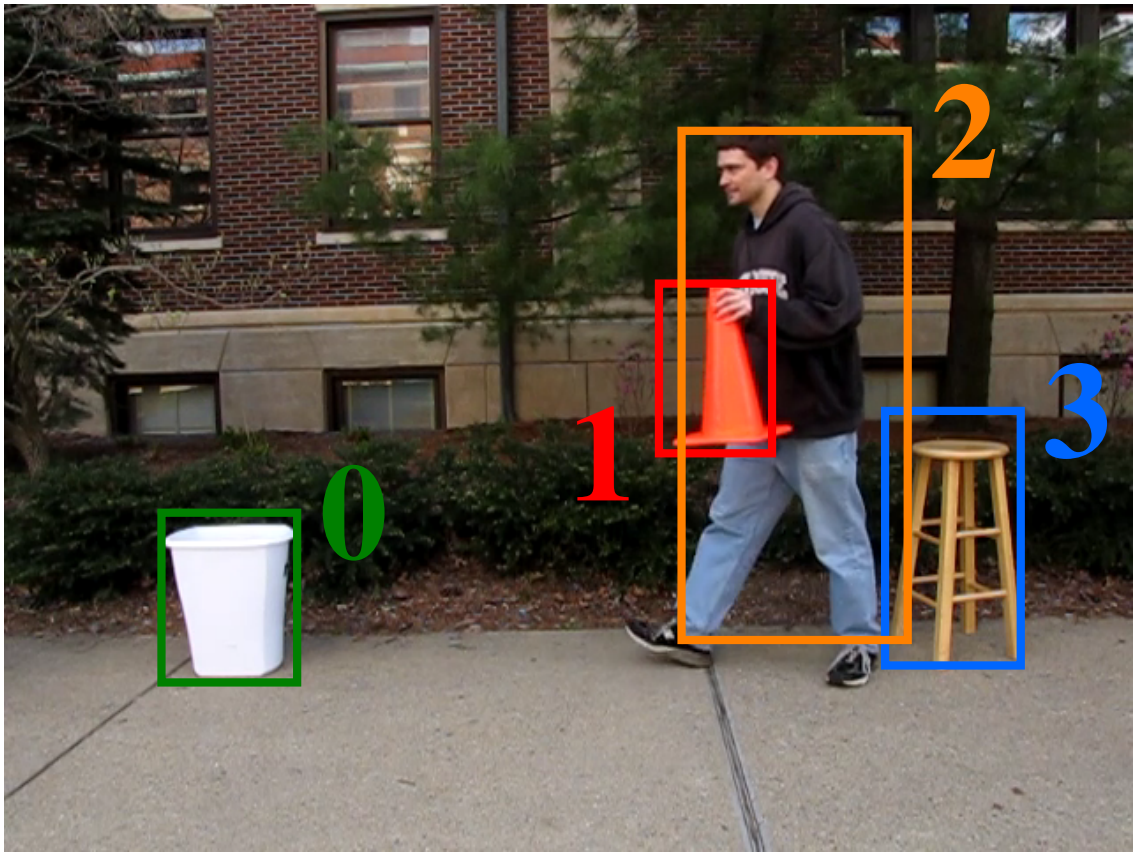

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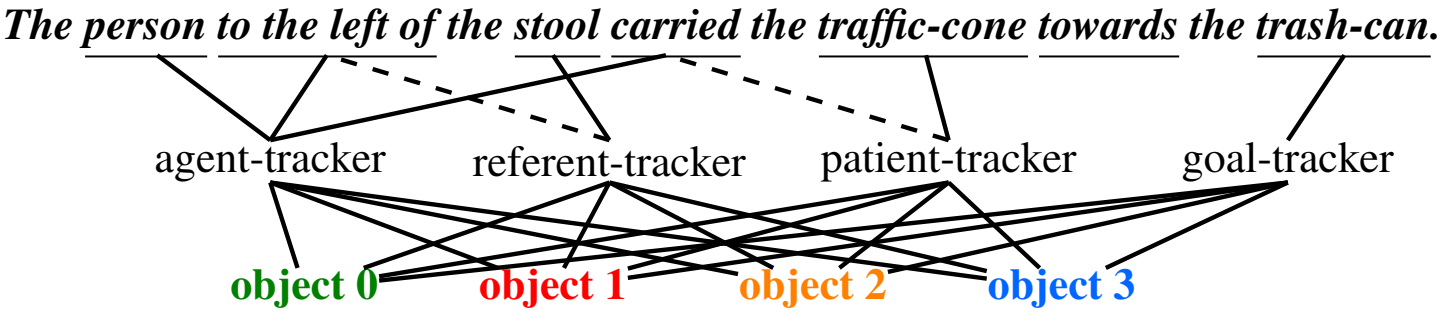

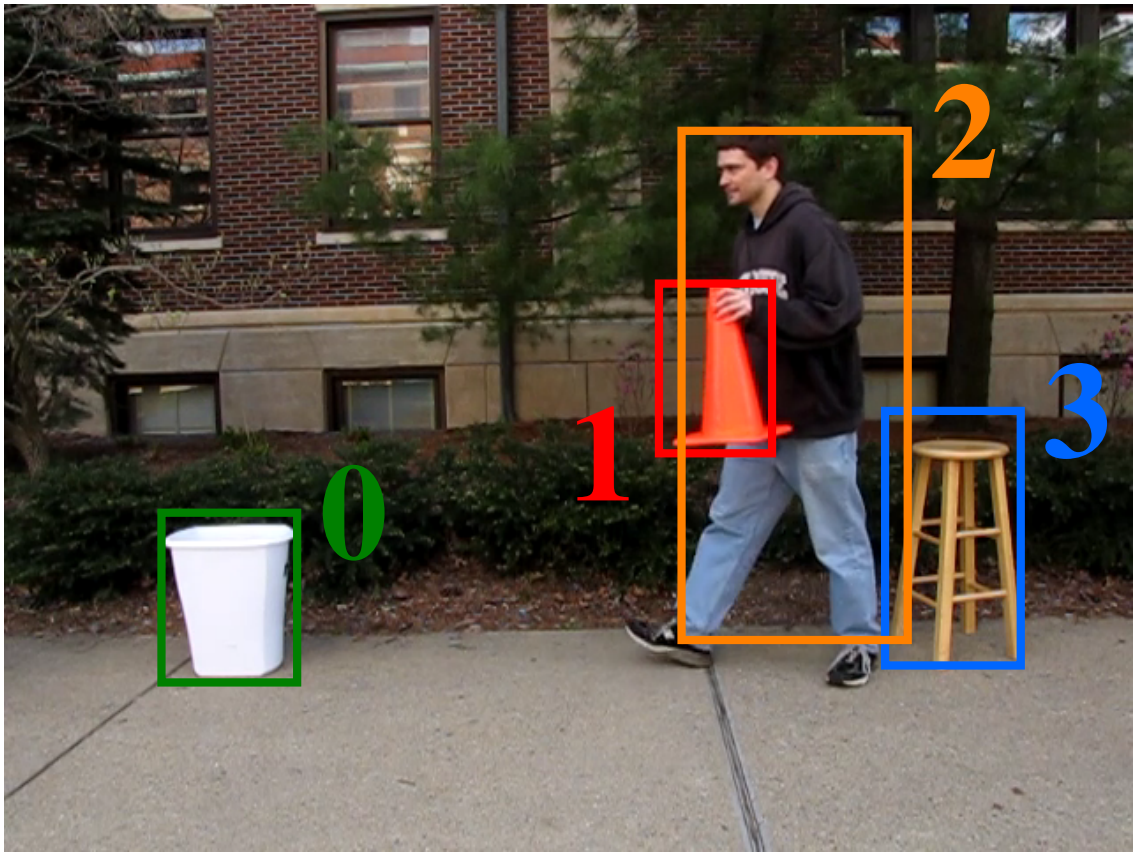

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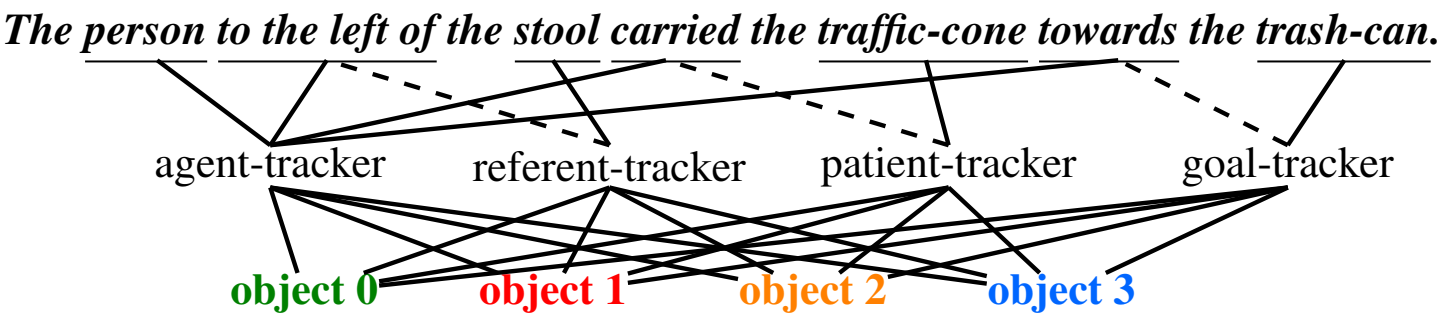

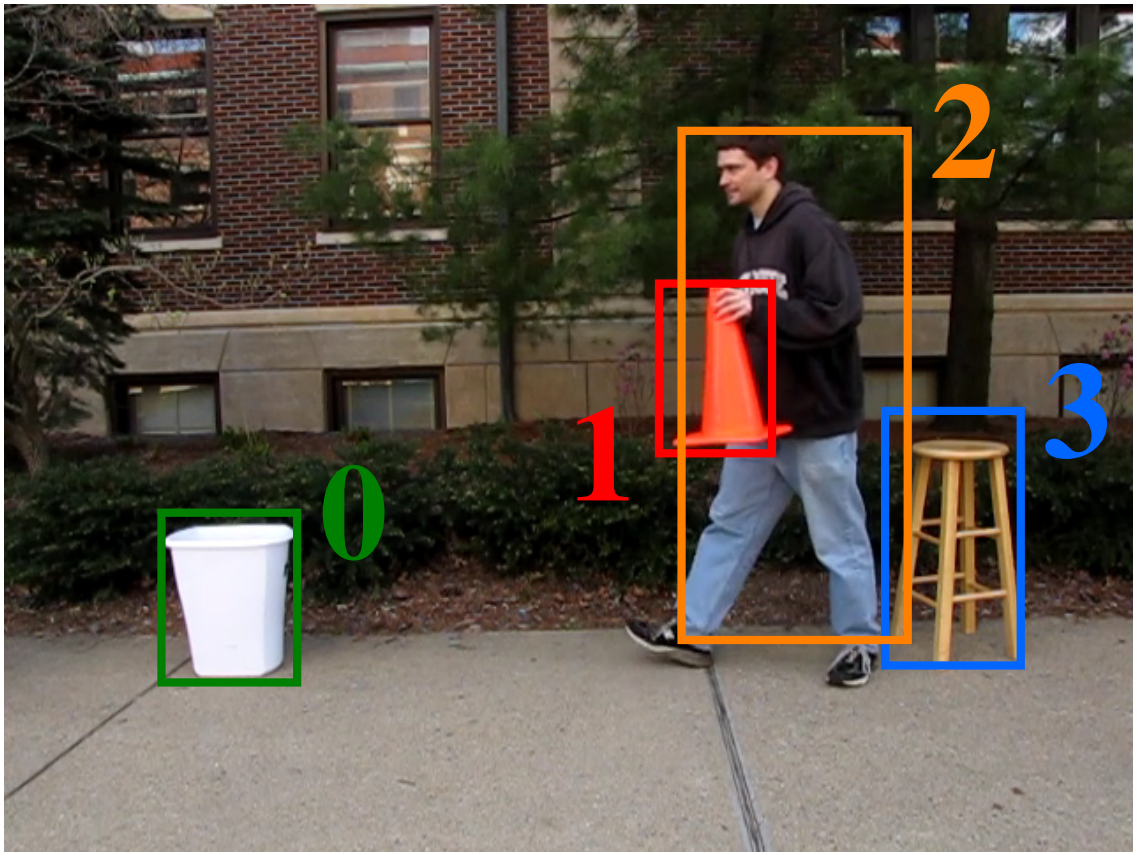

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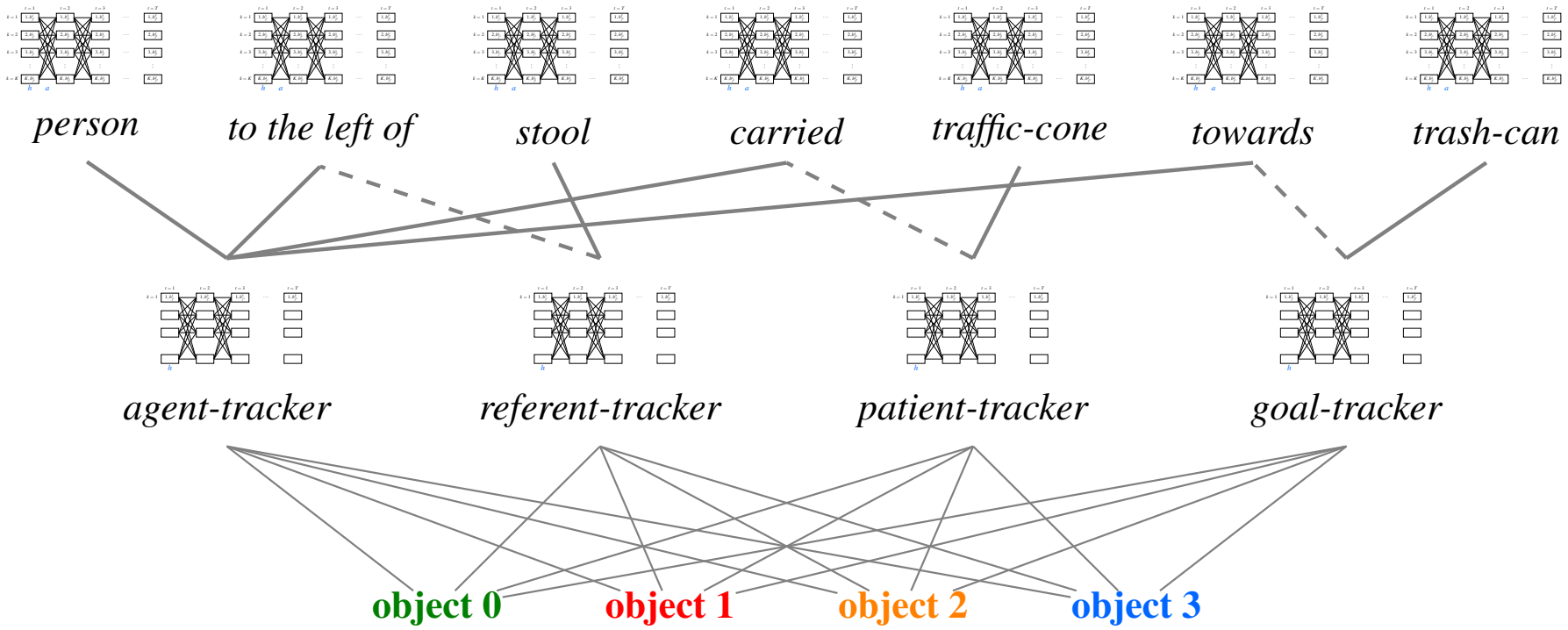

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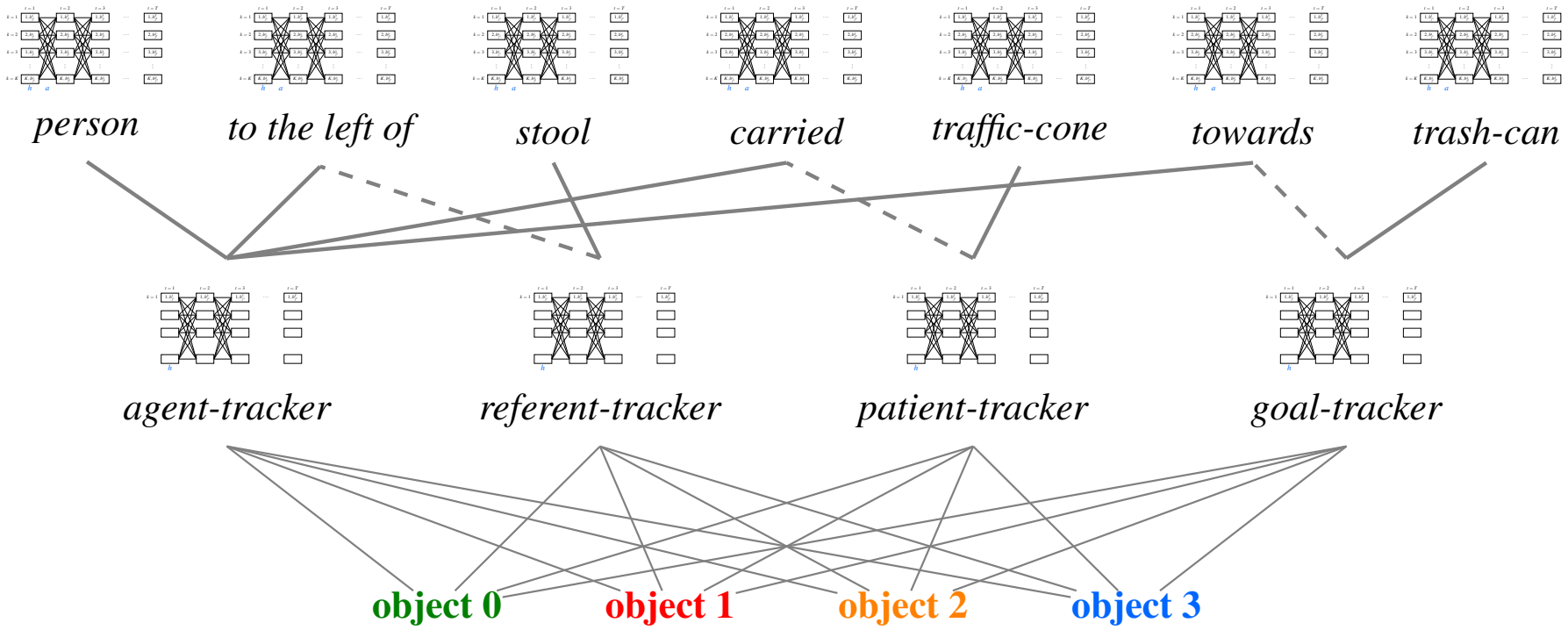
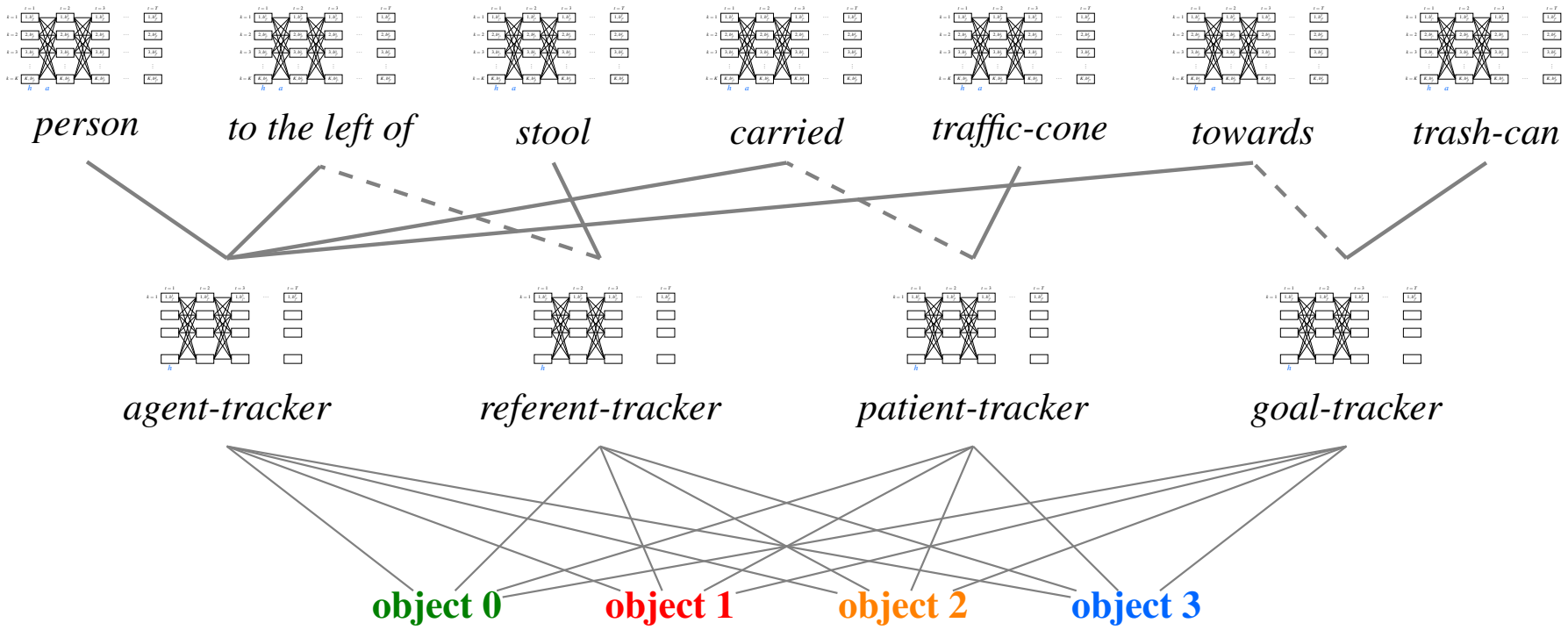


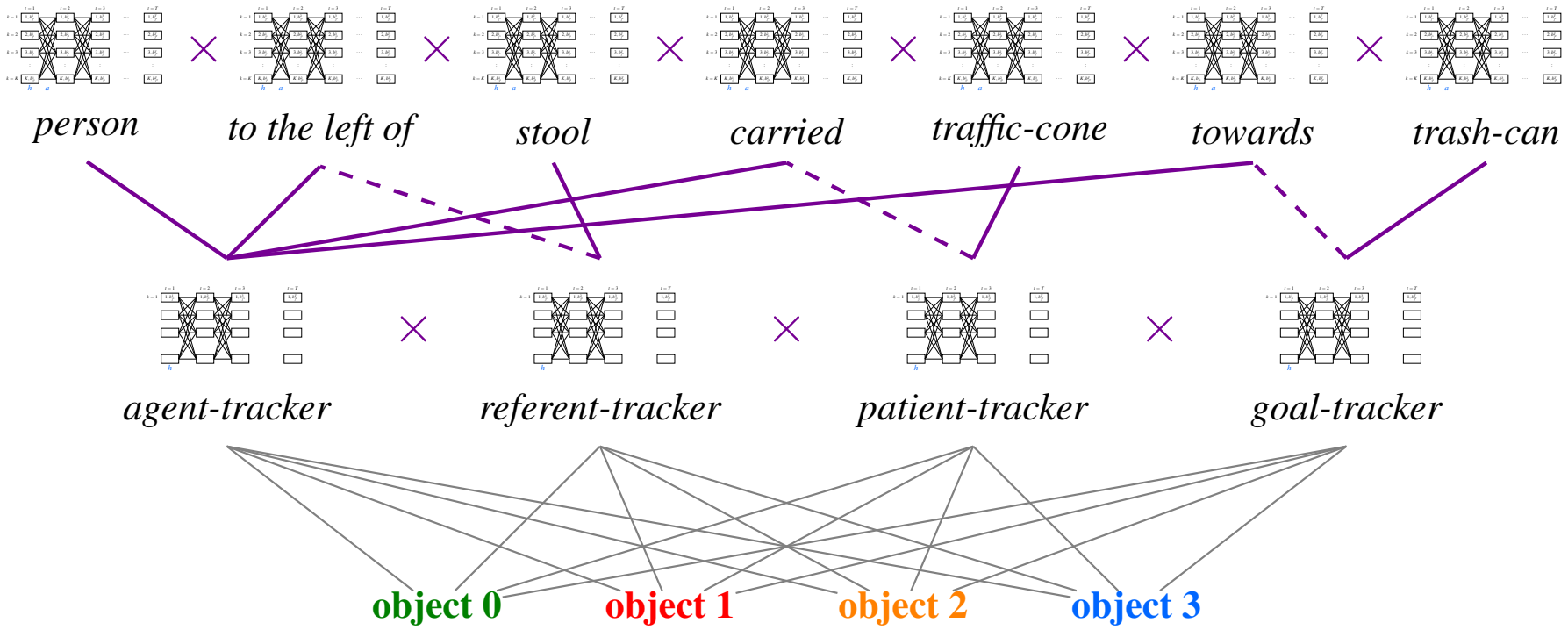
$$\max_{\substack{j_1^1,\ldots,j_1^T \\ j_L^1,\ldots,j_L^T}} \left(\sum_{l=1}^{L} \sum_{t=1}^{T} f(b_{j_l^t}^t) + \sum_{t=2}^{T} g(b_{j_l^{t-1}}^{t-1}, b_{j_l^t}^t) \right) + \max_{\substack{k_1^1,\ldots,k_1^T \\ k_W^1,\ldots,k_W^T}} \left(\sum_{w=1}^{W} \sum_{t=1}^{T} h_w(k_w^t, b_{w,1}^t, b_{w,2}^t) + \sum_{t=2}^{T} a_w(k_w^{t-1}, k_w^t) \right)$$

Sentence Tracker



$$\max_{\substack{j_1^1,\ldots,j_1^T \\ j_L^1,\ldots,j_L^T}} \max_{\substack{k_1^1,\ldots,k_1^T \\ k_W^1,\ldots,k_W^T}} \sum_{l=1}^{L}\sum_{t=1}^{T} f(b^t_{j^t_l}) + \sum_{t=2}^{T} g(b^{t-1}_{j^{t-1}_l}, b^t_{j^t_l}) + \sum_{w=1}^{W}\sum_{t=1}^{T} h_w(k^t_w, b^t_{j^t_{\theta^1_w}}, b^t_{j^t_{\theta^2_w}}) + \sum_{t=2}^{T} a_w(k^{t-1}_w, k^t_w)$$

Sentence Tracker



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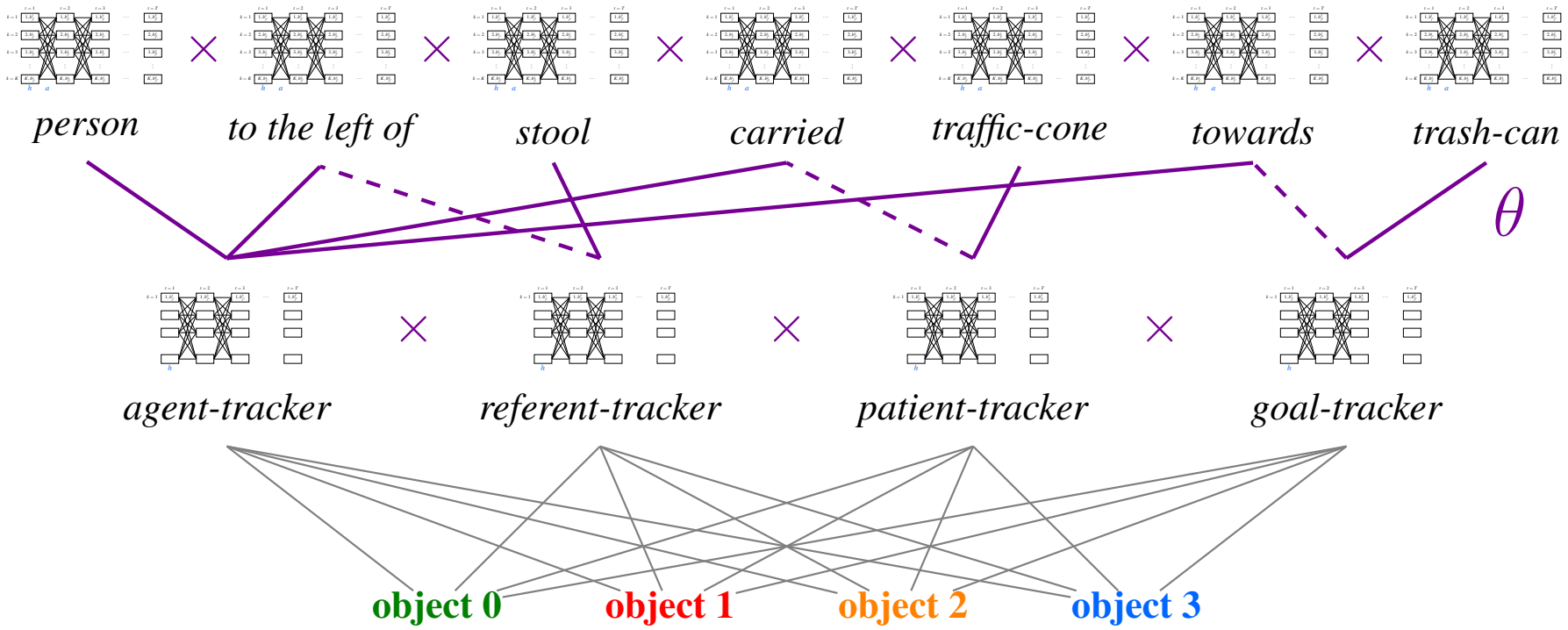

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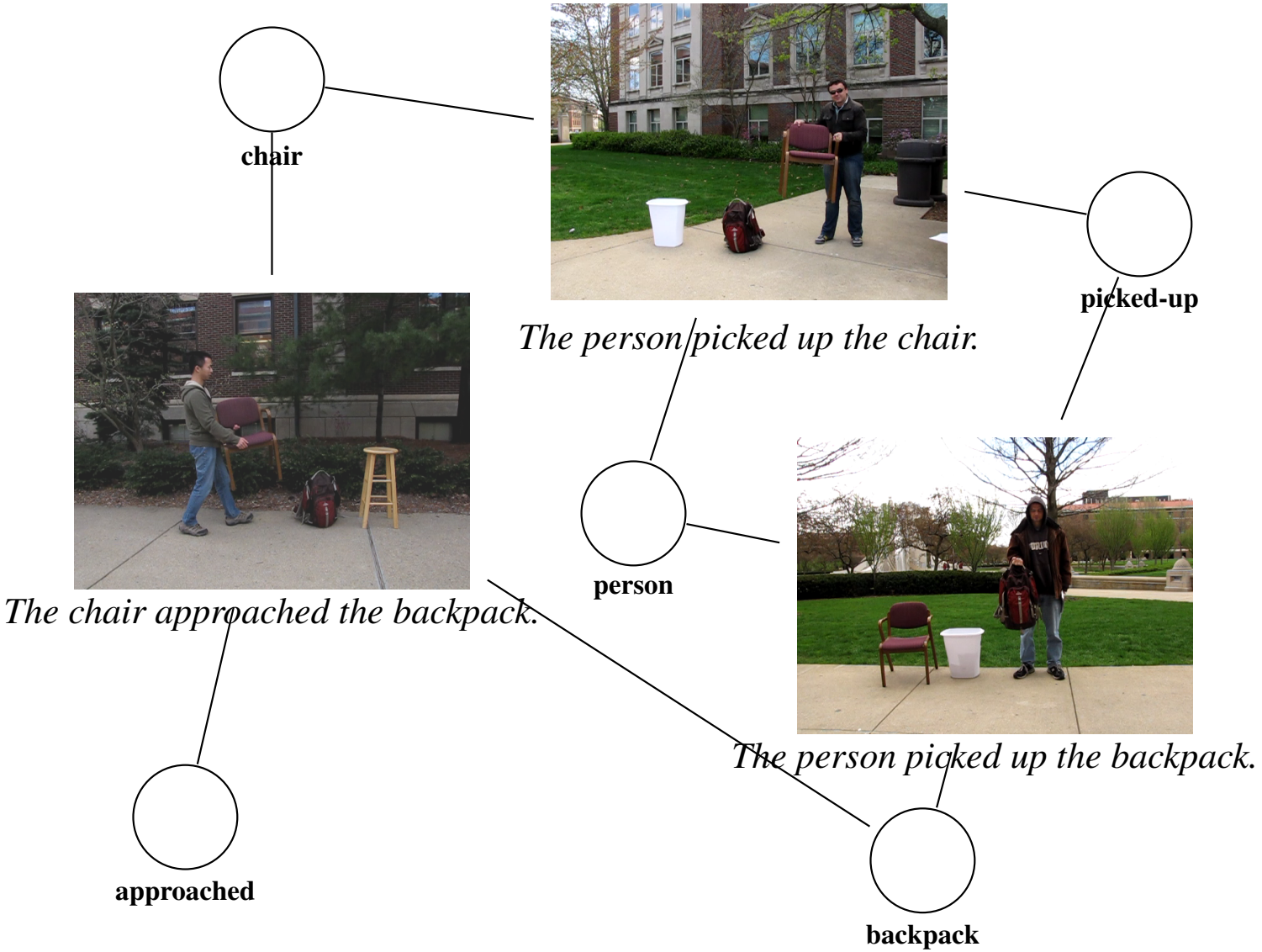
Sentence Tracker in EM



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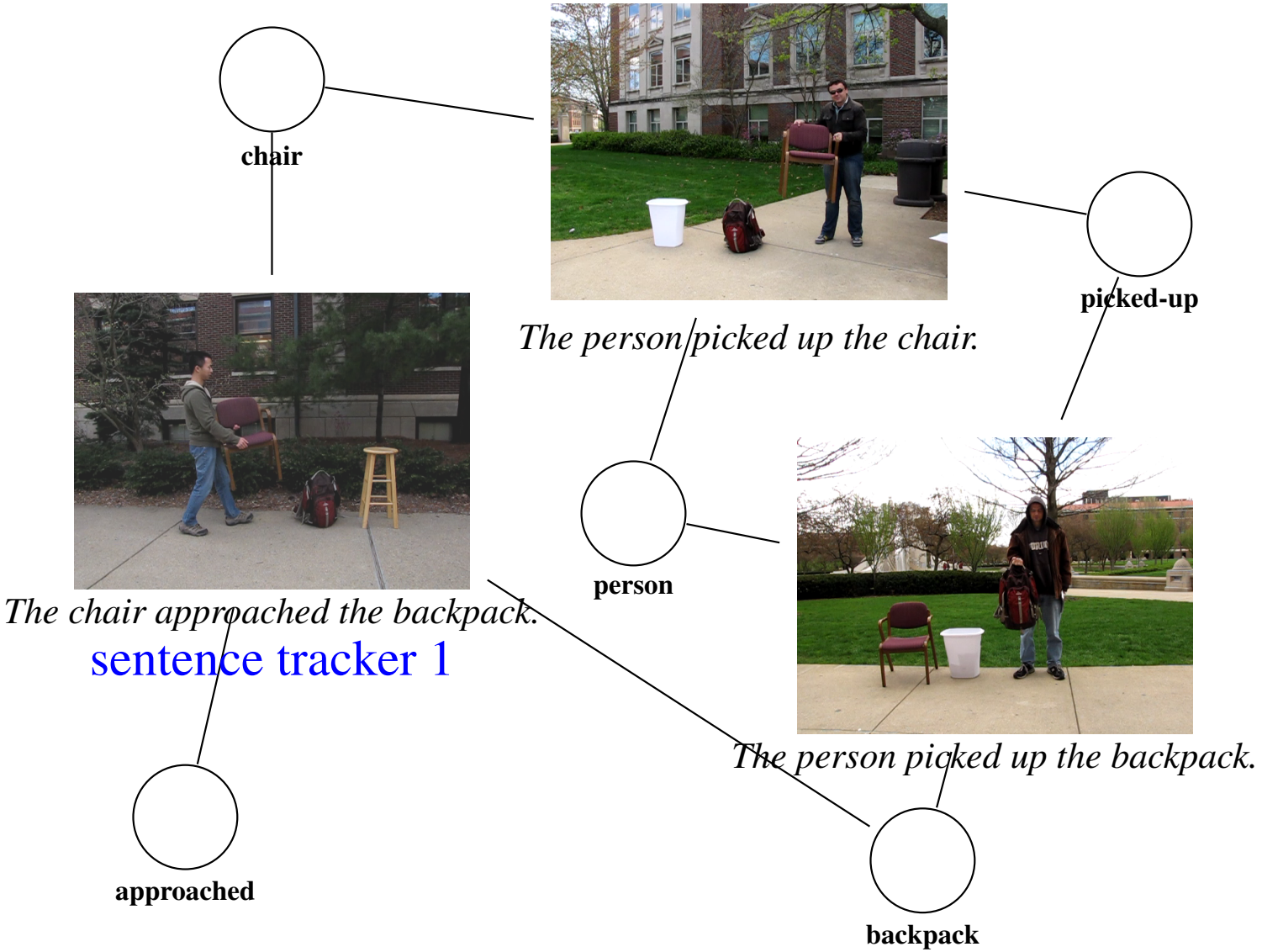

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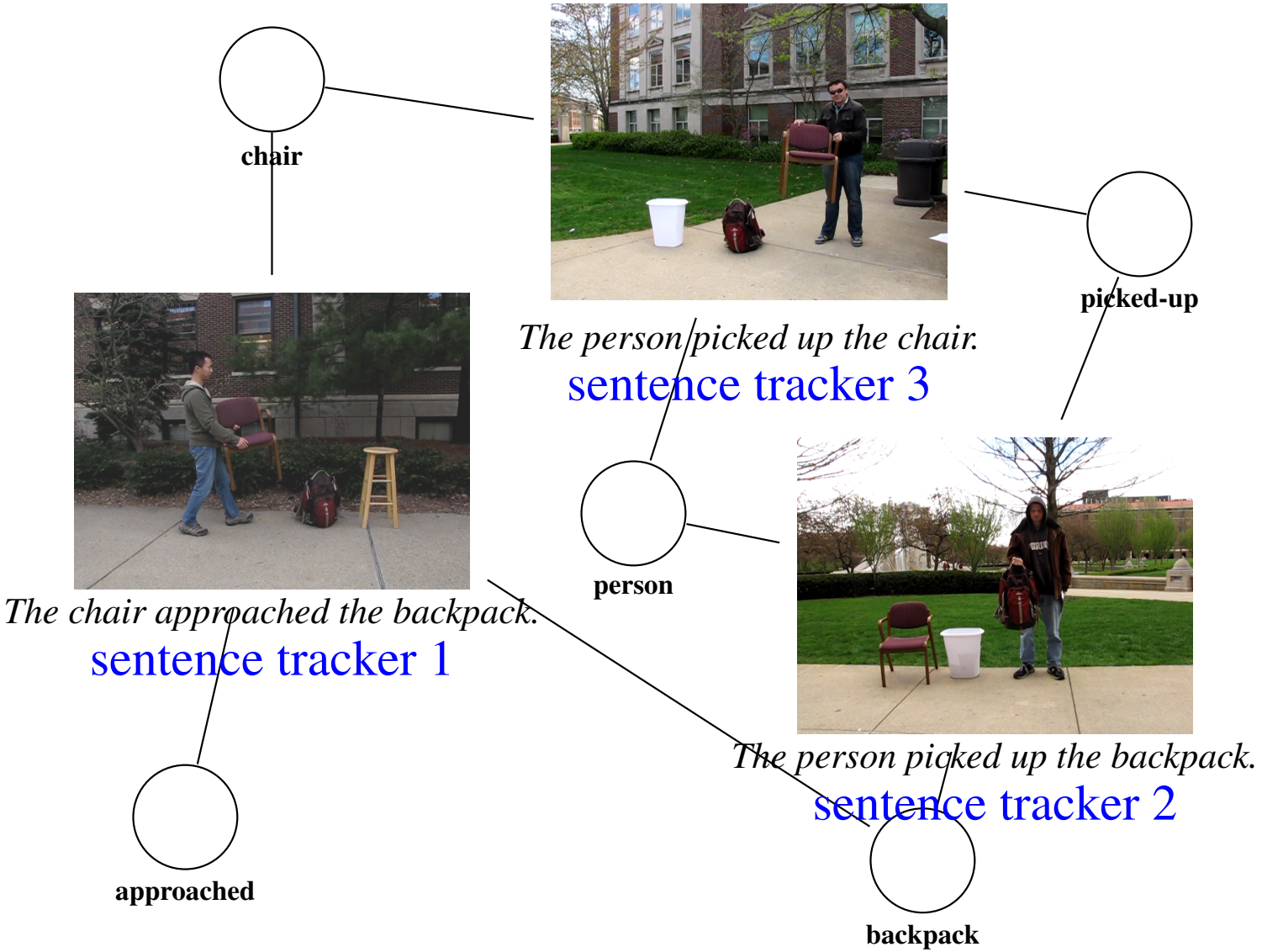

Sentence Tracker in EM

$$\max_{\substack{j_1^1,\ldots,j_1^T \\ j_L^1,\ldots,j_L^T}} \max_{\substack{k_1^1,\ldots,k_1^T \\ k_W^1,\ldots,k_W^T}} \begin{array}{l} \sum_{l=1}^{L} \sum_{t=1}^{T} f(b_{j_l^t}^t) + \sum_{t=2}^{T} g(b_{j_l^{t-1}}^{t-1}, b_{j_l^t}^t) + \\ \sum_{w=1}^{W} \sum_{t=1}^{T} h_w(k_w^t, b_{j_{\theta_w^1}^t}^t, b_{j_{\theta_w^2}^t}^t) + \sum_{t=2}^{T} a_w(k_w^{t-1}, k_w^t) \end{array}$$

Sentence Tracker in EM

$$\log \sum_{\substack{j_1^1,\ldots,j_1^T \\ j_L^1,\ldots,j_L^T}} \sum_{\substack{k_1^1,\ldots,k_1^T \\ k_W^1,\ldots,k_W^T}} \exp\left[\begin{array}{l} \sum_{l=1}^{L} \sum_{t=1}^{T} f(b_{j_l^t}^t) + \sum_{t=2}^{T} g(b_{j_l^{t-1}}^{t-1}, b_{j_l^t}^t) + \\ \sum_{w=1}^{W} \sum_{t=1}^{T} h_w(k_w^t, b_{j^t_{\theta_w^1}}^t, b_{j^t_{\theta_w^2}}^t) + \sum_{t=2}^{T} a_w(k_w^{t-1}, k_w^t) \end{array} \right]$$

Sentence Tracker in EM

$$\log \sum_{\substack{j_1^1,\ldots,j_1^T \\ j_L^1,\ldots,j_L^T}} \sum_{\substack{k_1^1,\ldots,k_1^T \\ k_W^1,\ldots,k_W^T}} \exp\left[\begin{array}{l} \sum_{l=1}^{L} \sum_{t=1}^{T} f(b_{j_l^t}^t) + \sum_{t=2}^{T} g(b_{j_l^{t-1}}^{t-1}, b_{j_l^t}^t) + \\ \sum_{w=1}^{W} \sum_{t=1}^{T} h_w(k_w^t, b_{j_{\theta_w^1}^t}^t, b_{j_{\theta_w^2}^t}^t) + \sum_{t=2}^{T} a_w(k_w^{t-1}, k_w^t) \end{array} \right]$$

- Wrap the sum of log likelihoods of all video-sentence pairs in EM.

Sentence Tracker in EM

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Sentence Tracker in EM

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- Wrap the sum of log likelihoods of all video-sentence pairs in EM.
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- In the M-step, the transition matrix $a_w(k_w^{t-1}, k_w^t)$ and output distribution $h_w(k_w^t, b_{j_{\theta_w^1}^t}^t, b_{j_{\theta_w^2}^t}^t)$ are re-estimated.

Experiment Results

Experiment Results

- learn all content words in the lexicon

Experiment Results

$$
\begin{aligned}
\text{N} &\rightarrow \textit{person} \mid \textit{backpack} \mid \textit{trash-can} \mid \textit{chair} \mid \textit{traffic-cone} \mid \textit{stool} \\
\text{P} &\rightarrow \textit{to the left of} \mid \textit{to the right of} \\
\text{V} &\rightarrow \textit{picked up} \mid \textit{put down} \mid \textit{carried} \mid \textit{approached} \\
\text{ADV} &\rightarrow \textit{quickly} \mid \textit{slowly} \\
\text{PM} &\rightarrow \textit{towards} \mid \textit{away from}
\end{aligned}
$$

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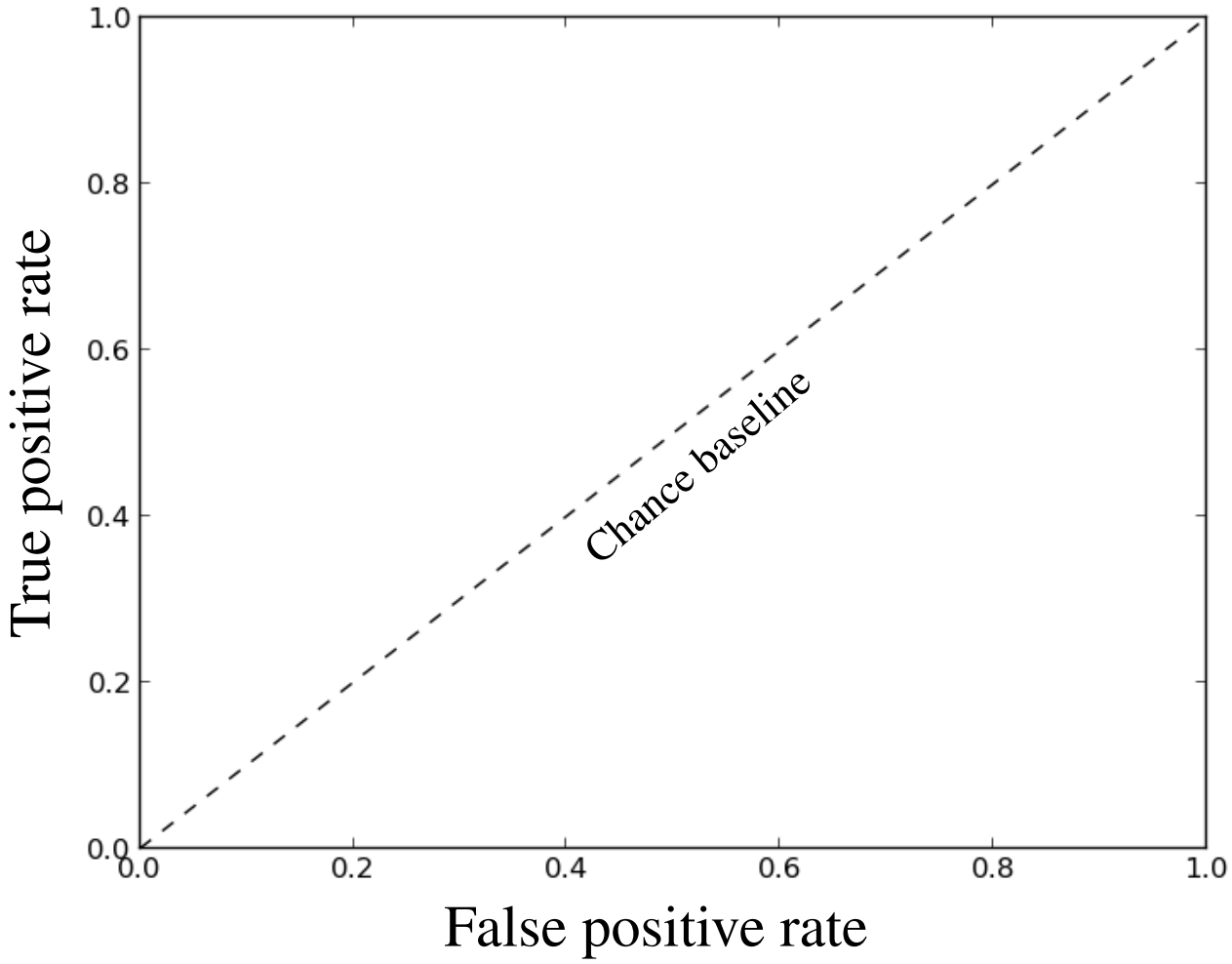
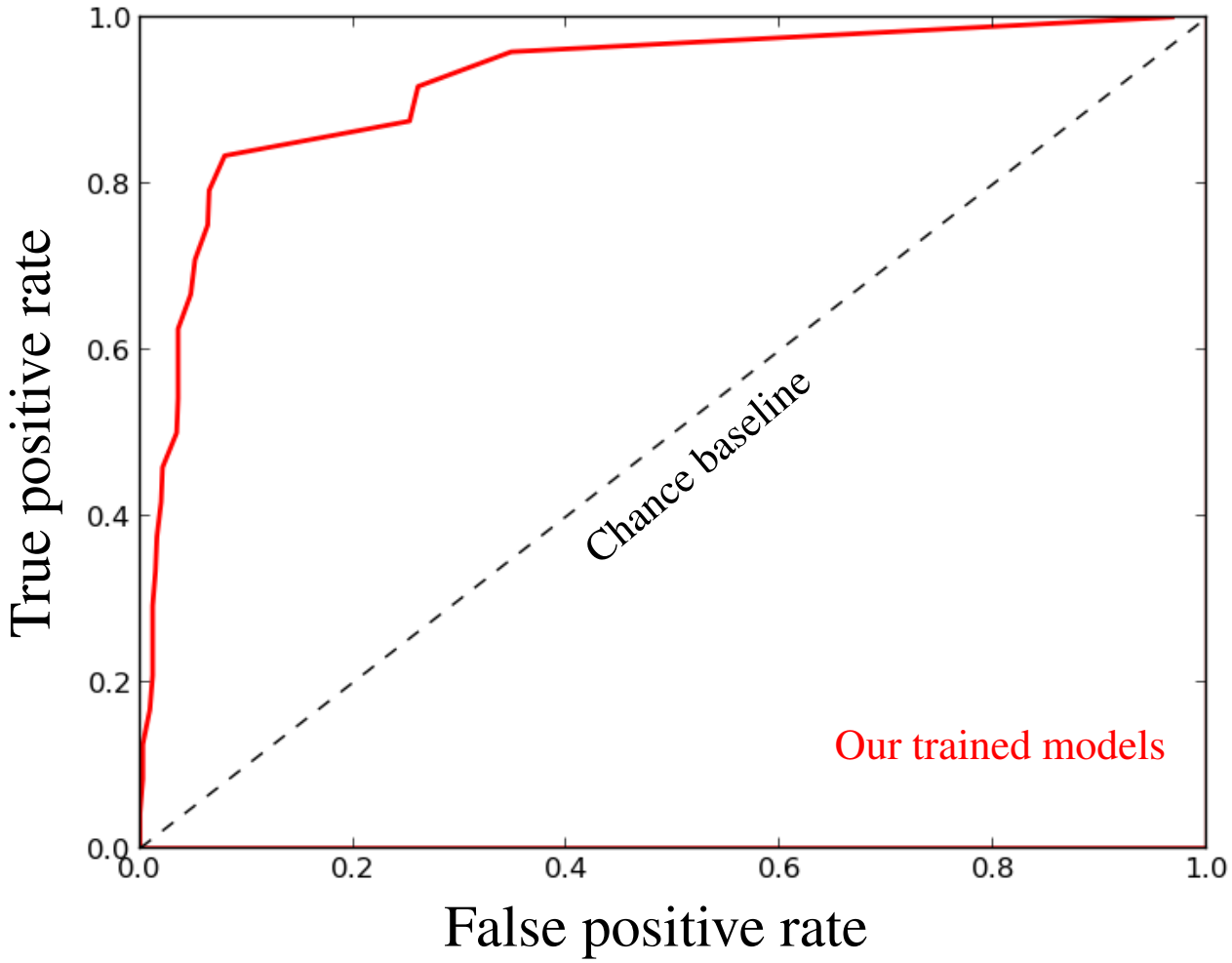
ROC curves


1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
True positive rate
False positive rate
Chance baseline

ROC curves


1.0
0.8
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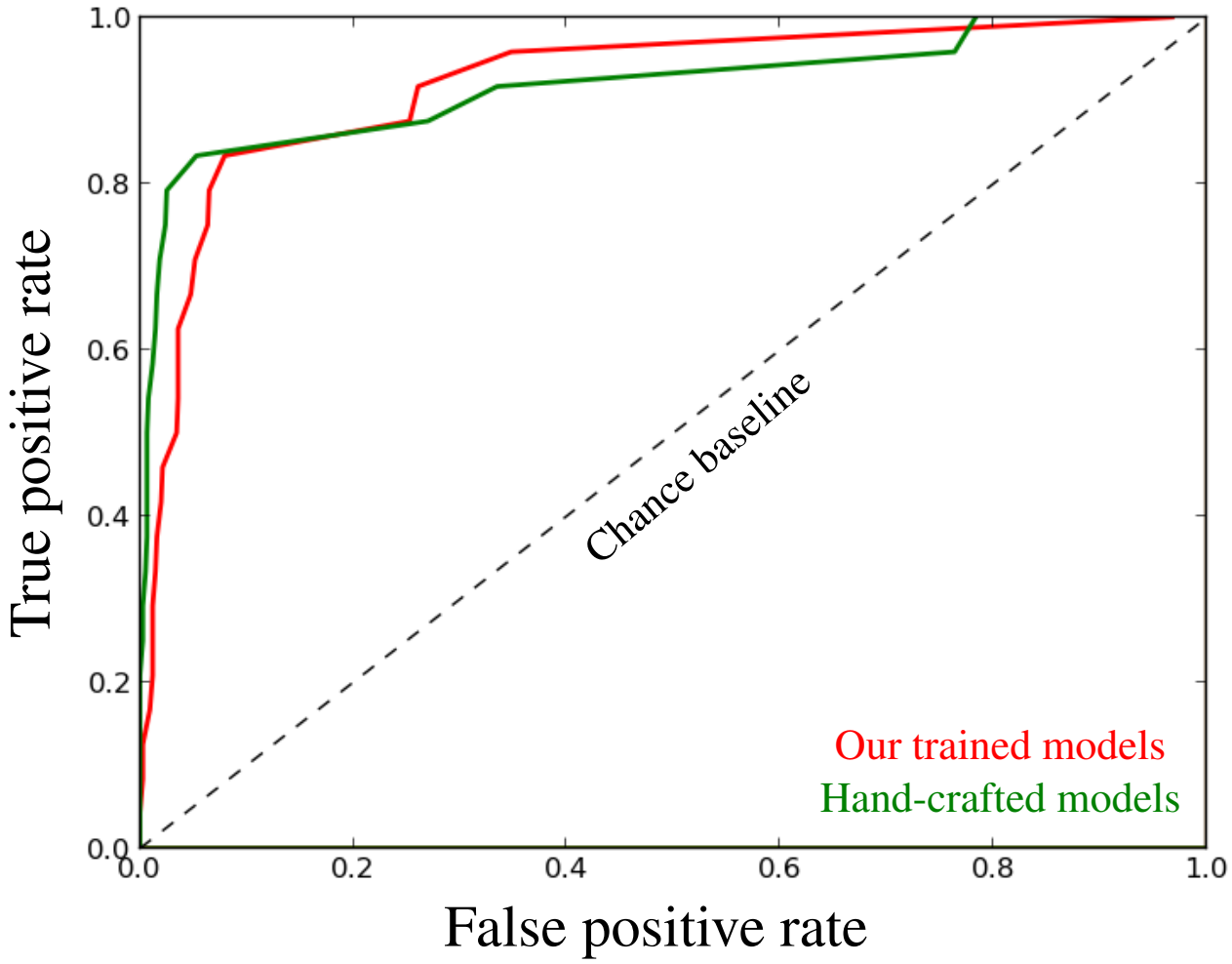
0.8
1.0
True positive rate
False positive rate
Chance baseline
Our trained models

ROC curves


1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
True positive rate
False positive rate
Chance baseline
Our trained models
Hand-crafted models

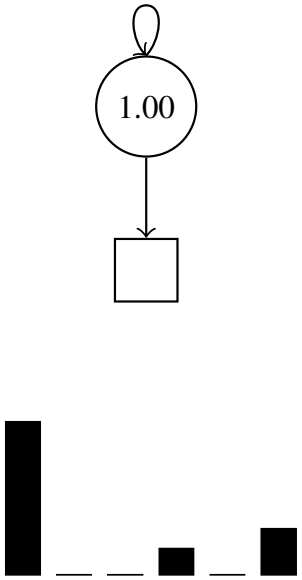
Examples of Trained Models

nouns

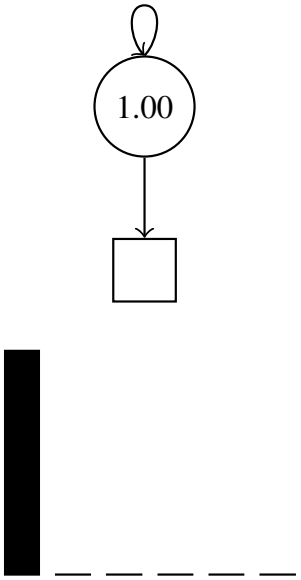
Examples of Trained Models

nouns

person



trained



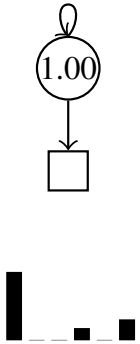
hand-crafted

OBJECT CLASS

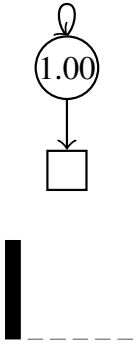
Examples of Trained Models

nouns

person



trained

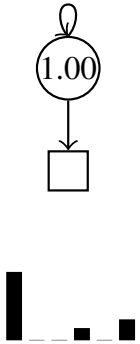


hand-crafted

Examples of Trained Models

nouns

person



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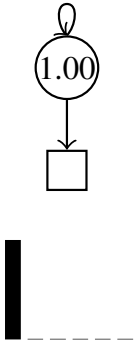
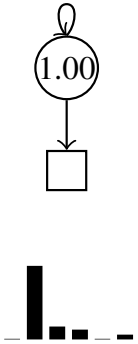


hand-crafted

backpack



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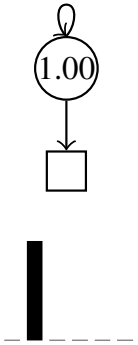
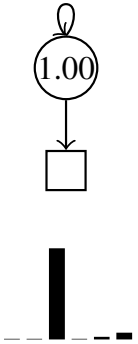


hand-crafted

chair



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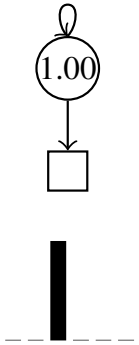
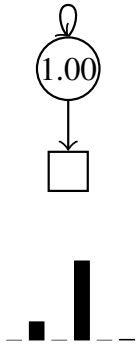


hand-crafted

trash-can



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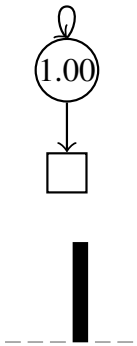
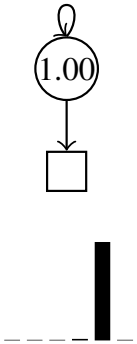


hand-crafted

stool



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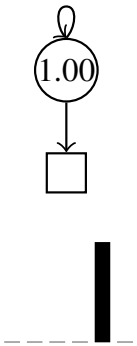
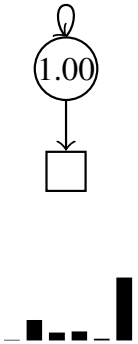


hand-crafted

traffic-cone



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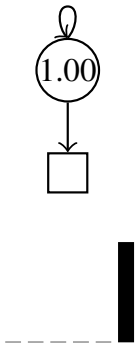
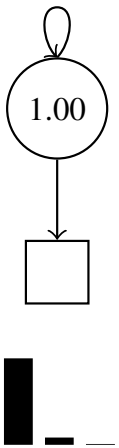


hand-crafted

Examples of Trained Models

spatial-relation prepositions

to-the-left-of



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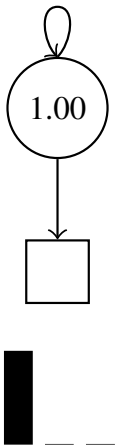
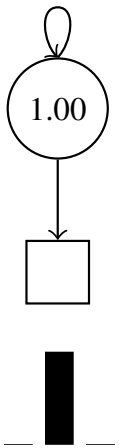


hand-crafted

RELATIVE X-POSITION

to-the-right-of



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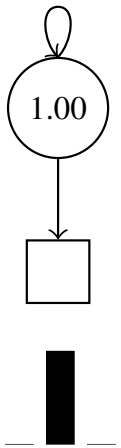


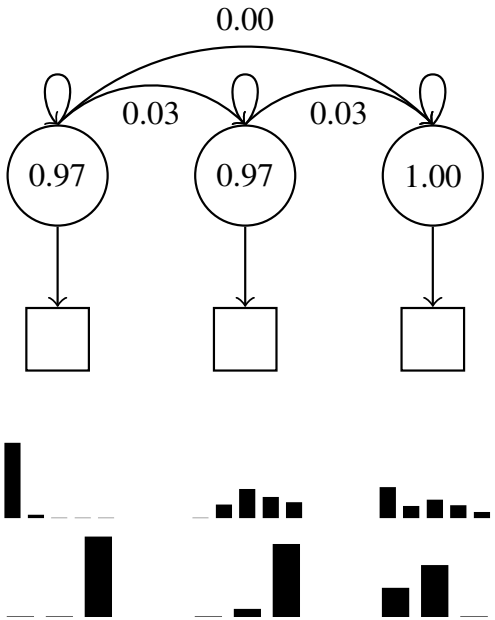
hand-crafted

Examples of Trained Models

motion prepositions

towards

trained



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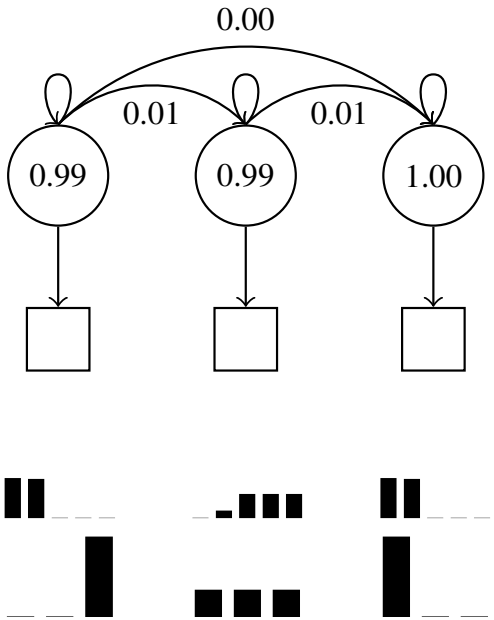


VELOCITY

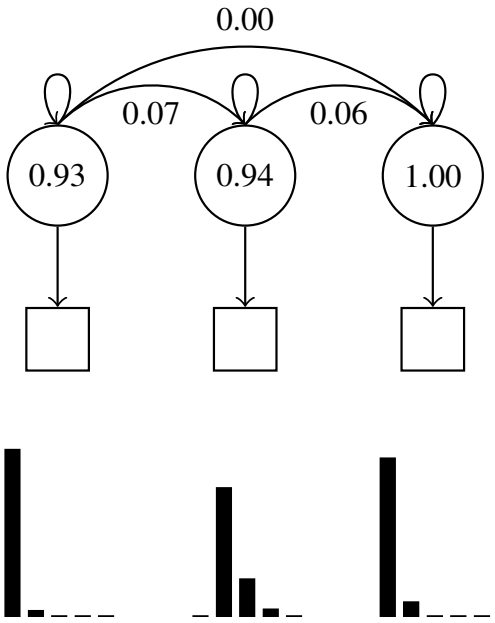
DISTANCE

Examples of Trained Models

adverbs

slowly

trained



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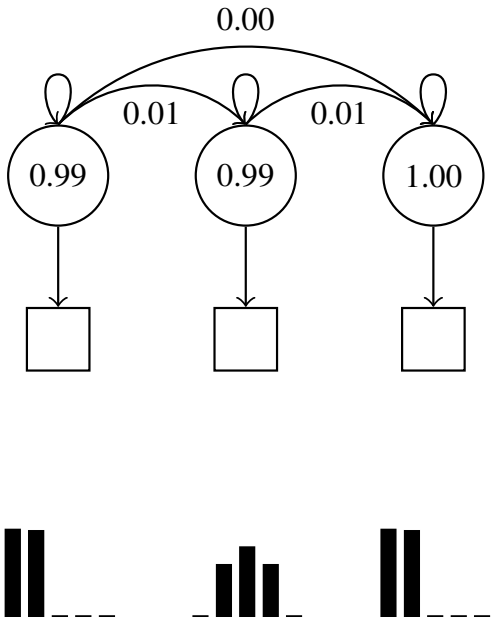


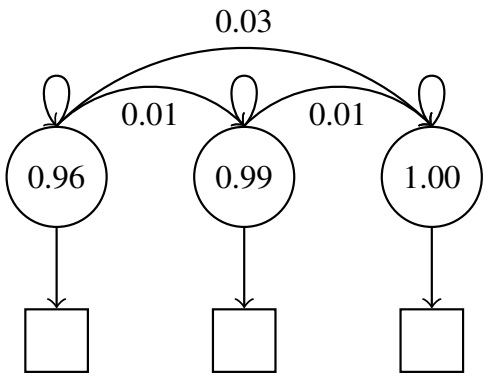
VELOCITY

Examples of Trained Models

verbs

approached

trained



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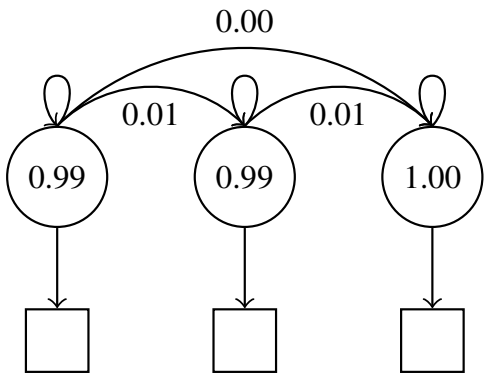
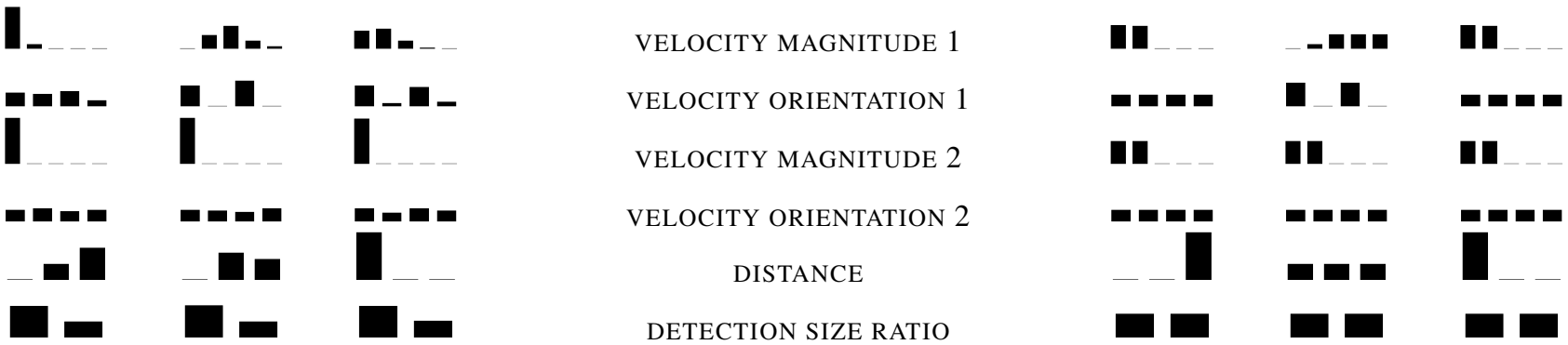
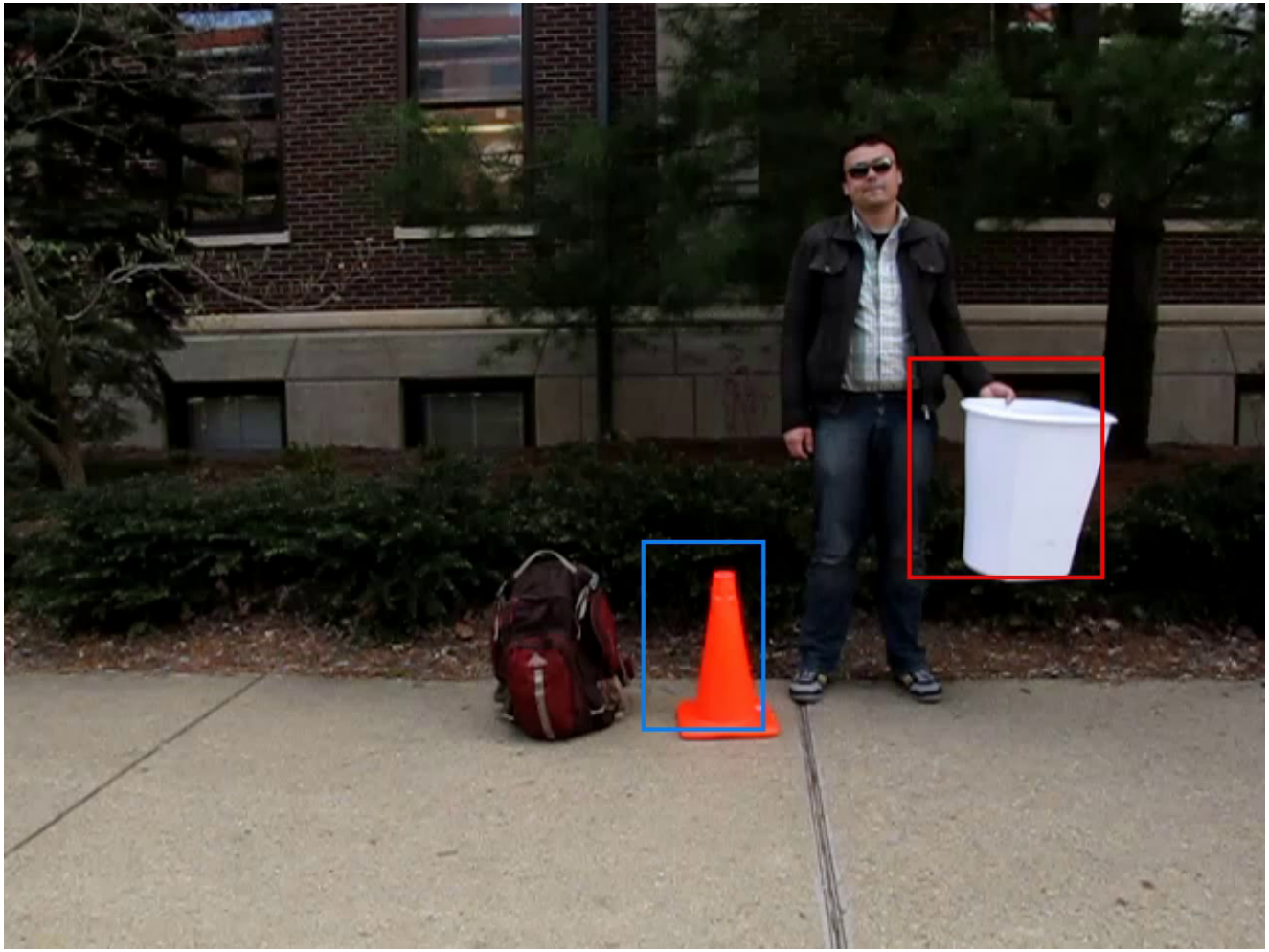




New Sentence Generation with Trained Models

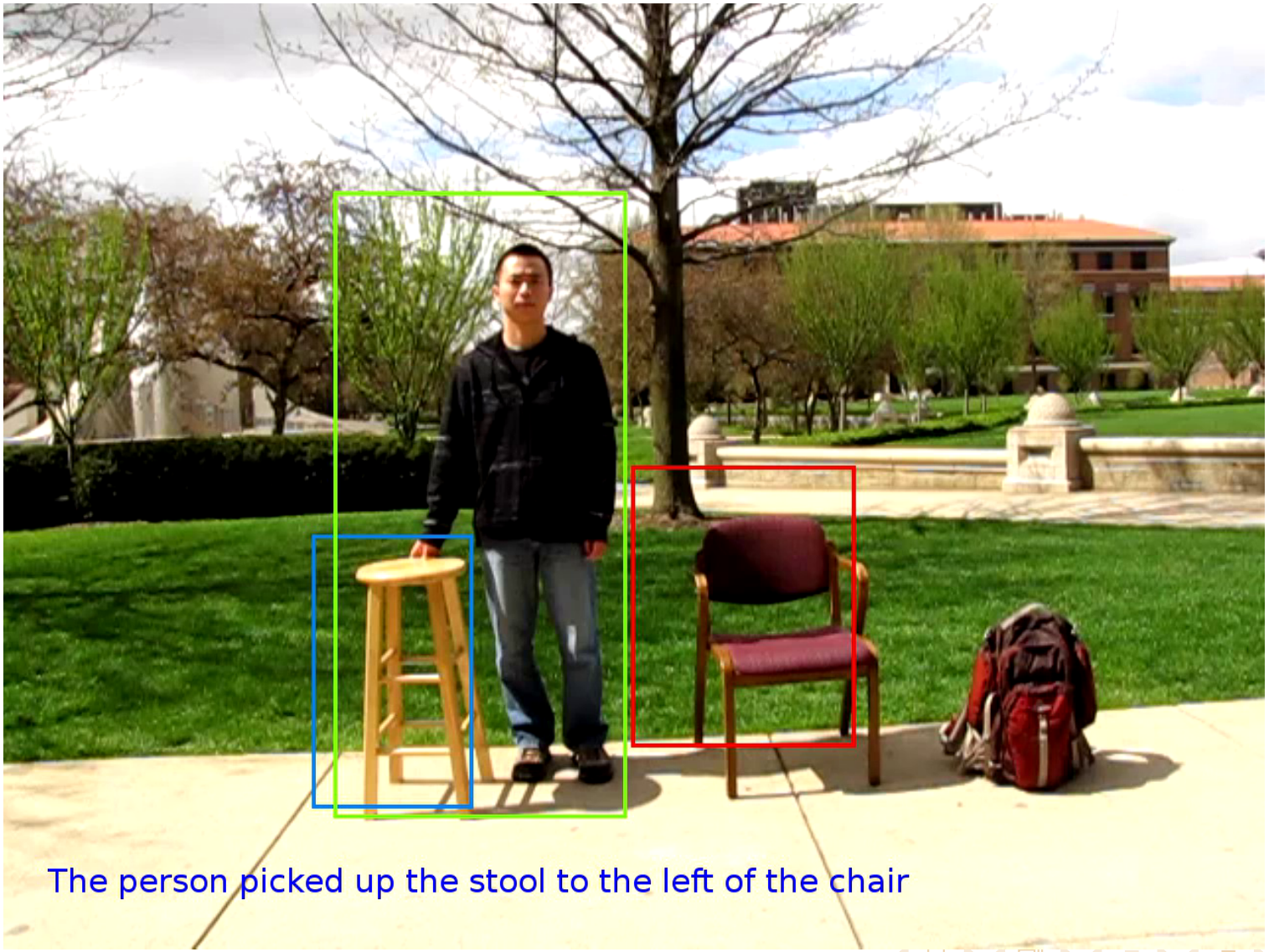
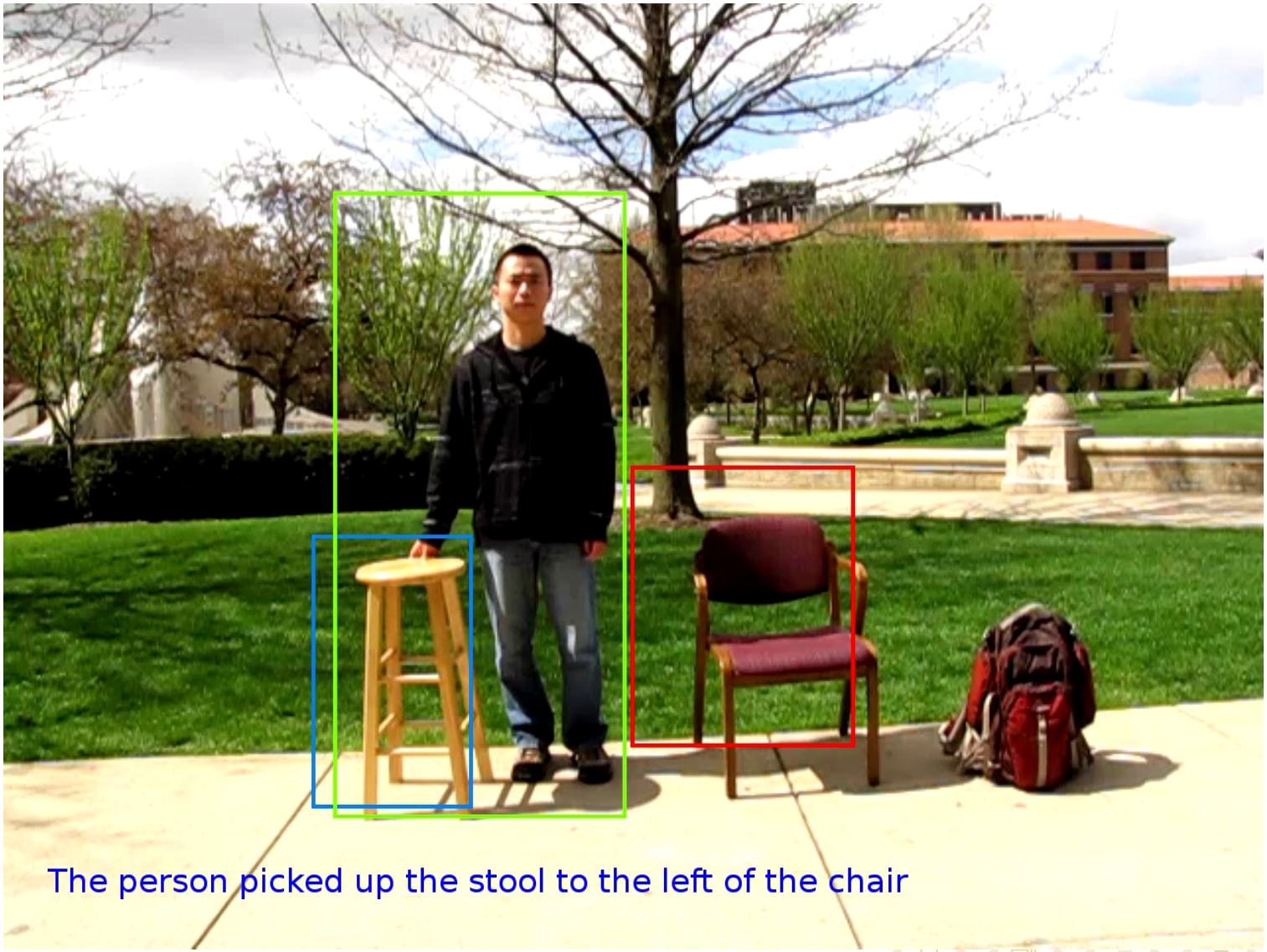


The trash-can approached the traffic-cone.

New Sentence Generation with Trained Models

The trash-can approached the traffic-cone.

New Sentence Generation with Trained Models



New Sentence Generation with Trained Models