COGNITIVE COMPUTATION GROUP
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Practical Learning Algorithms for Structured Prediction Models

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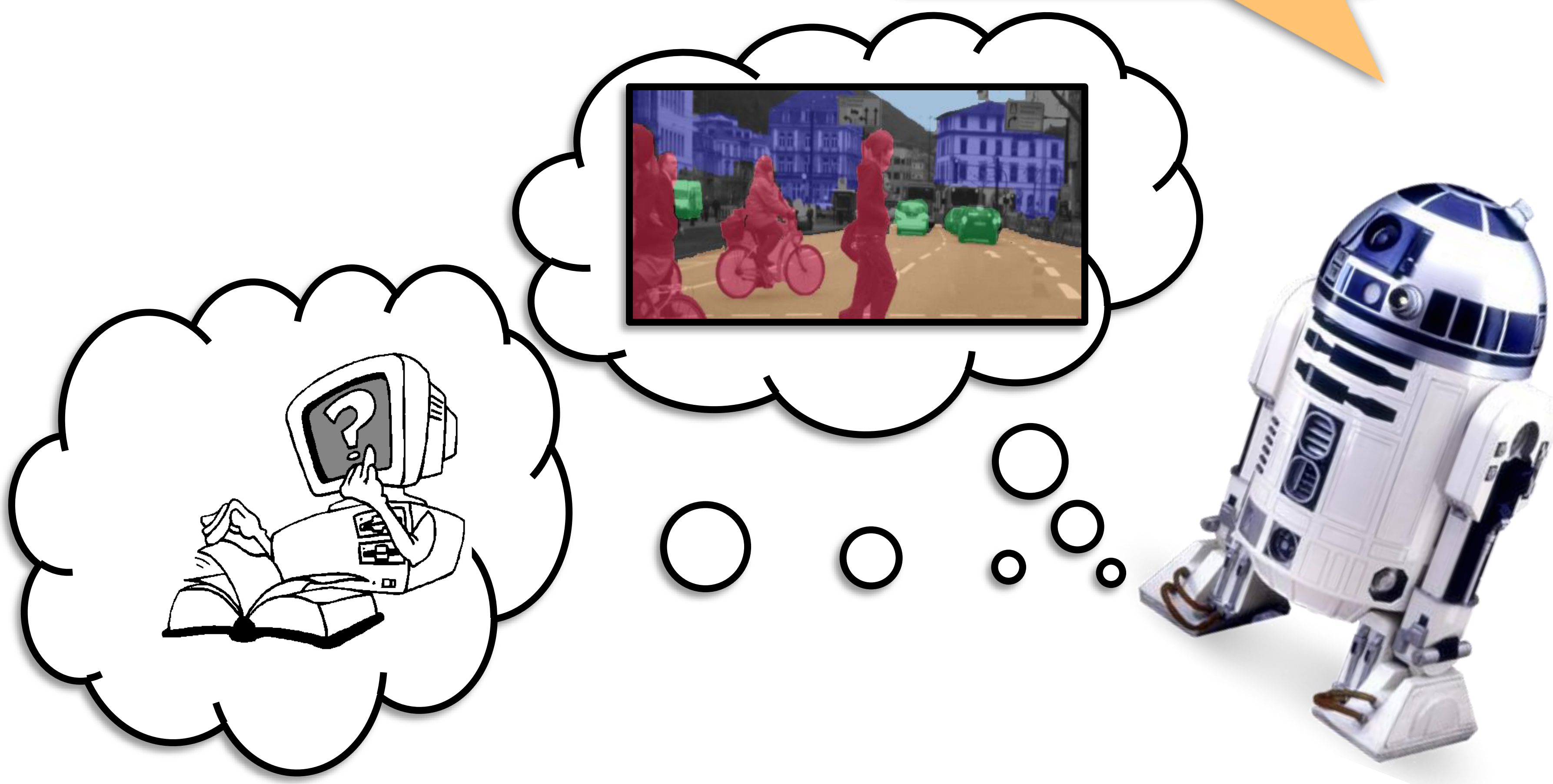
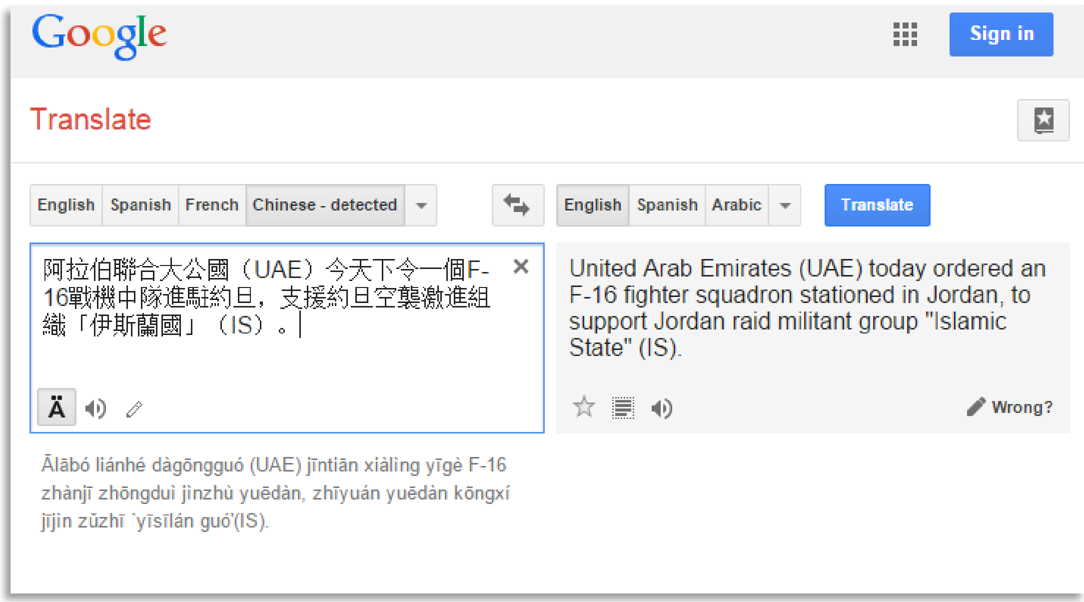
Dream:

Intelligent systems that are able to read, to see, to talk, and to answer questions.

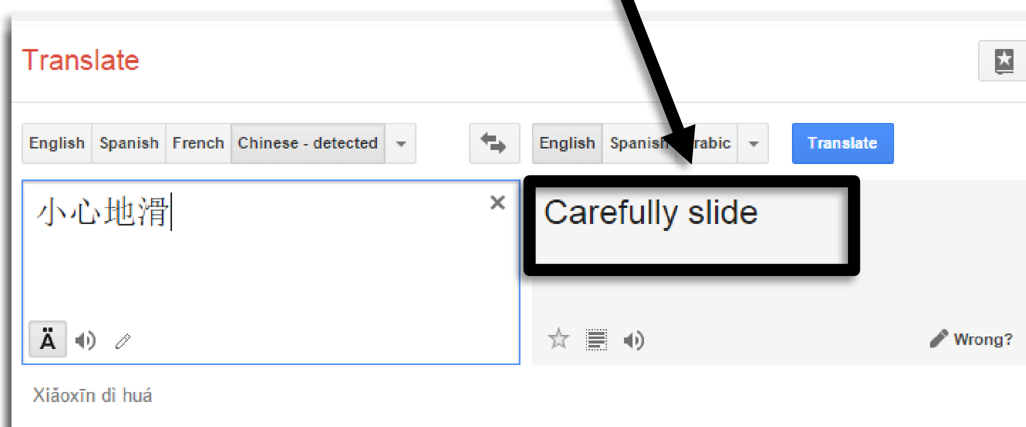


Personal assistant system



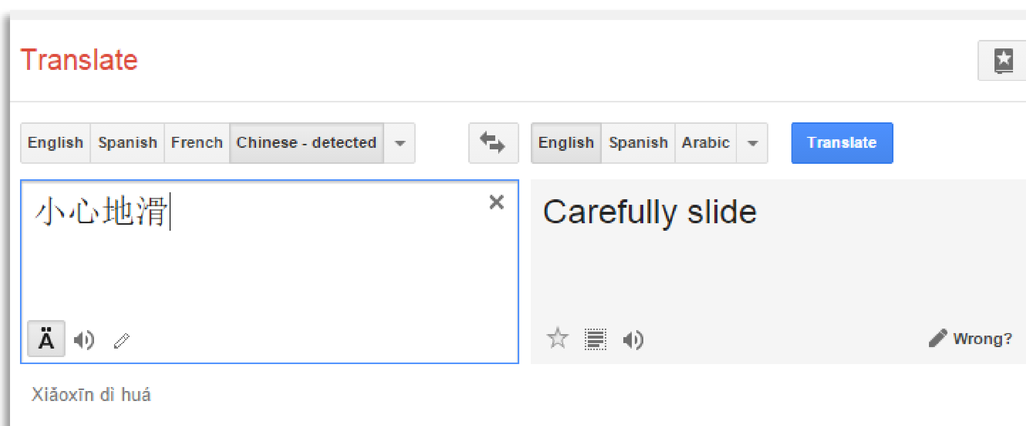
Translation system

Carefully Slide



小心:
Carefully
Careful
Take Care
Caution

地滑:
Slide
Landslip
Wet Floor
Smooth



Q: [Chris] = [Mr. Robin] ?

Christopher Robin is alive and well. **He** is the same person that you read about in the book, **Winnie the Pooh.** As **a boy**, **Chris** lived in a pretty home called **Cotchfield Farm**. When **Chris** was three years old, **his father** wrote a poem about **him**. The poem was printed in a magazine for others to read. **Mr. Robin** then wrote a book

Slide modified from Dan Roth

Complex Decision Structure

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Co-reference Resolution

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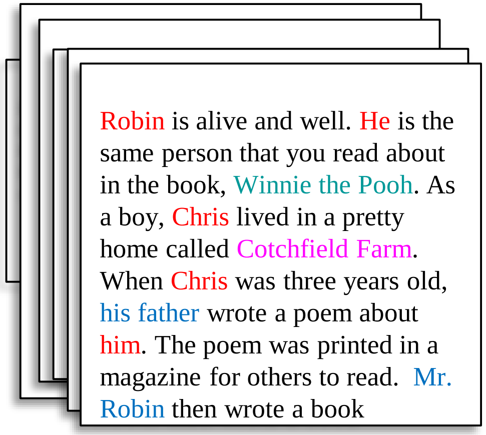
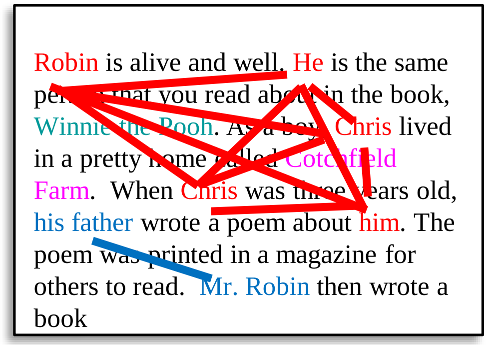
Scalability Issues



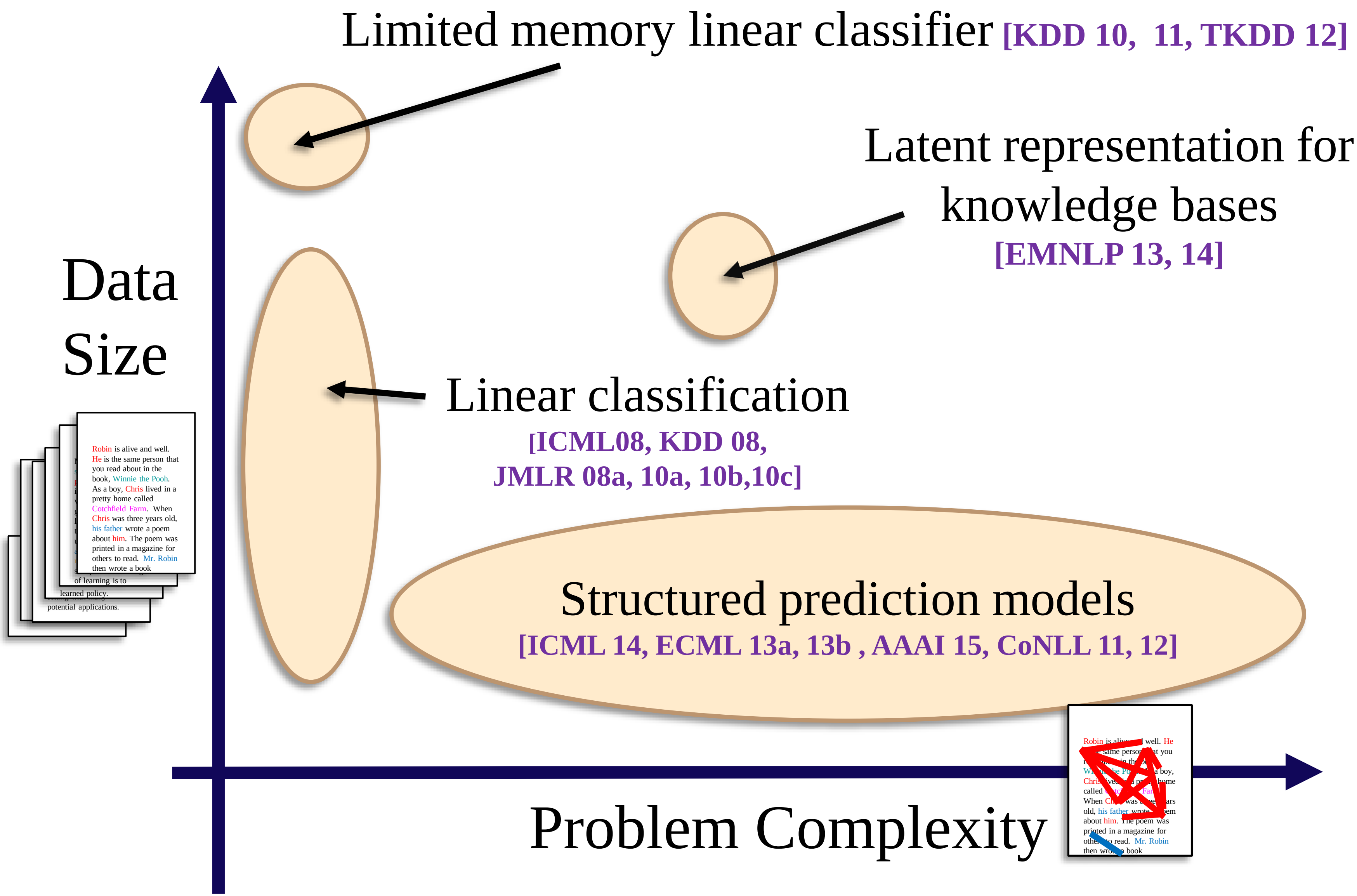


- Large amount of data
- Complex decision structure

Goal: Practical Machine Learning

- [Modeling] Expressive and general formulations
- [Algorithms] Principled and efficient
- [Applications] Support many applications

My Research Contributions



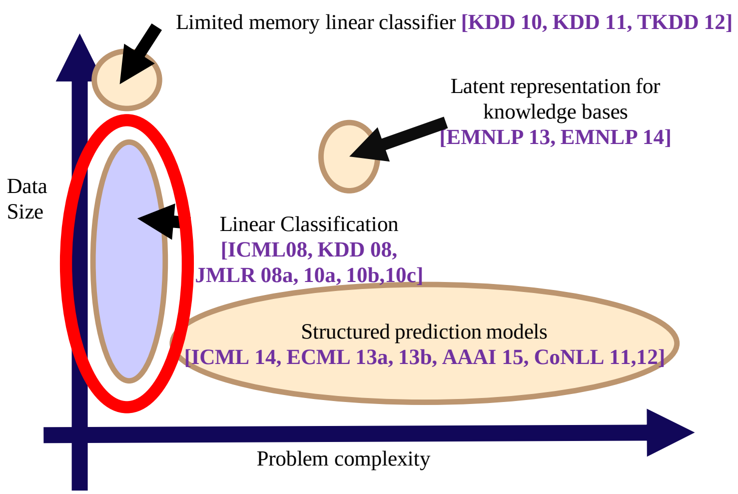
My Research Contributions

LIBLINEAR **[ICML08, KDD 08, JMLR 08a, 10a, 10b,10c]**

- Implements our proposed learning algorithms
- Supports binary and multiclass classification

Impact: > 60,000 downloads, > 2,600 citations in

AI (AAAI, IJCAI), Data Mining (KDD, ICDM), Machine Learning (ICML, NIPS) Computer Vision (ICCV, CVPR), Information Retrieval (WWW, SIGIR), NLP (ACL, EMNLP), Multimedia (ACM-MM), HCI (UIST), System (CCS)



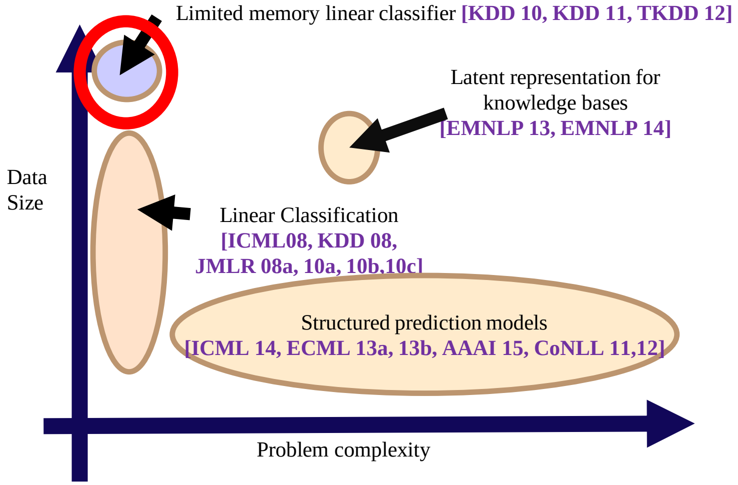
My Research Contributions

(Selective) Block Minimization

[KDD 10, 11, TKDD 12]

Supports learning from large data and streaming data

KDD best paper (2010), Yahoo! KSC award (2011)



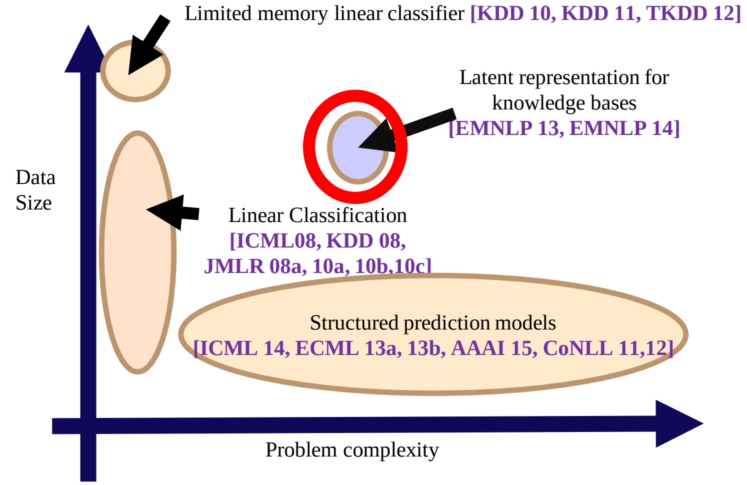
My Research Contributions

Latent Representation for KBs

[EMNLP 13b,14]

Tensor methods for completing missing entries in KBs

Applications: e.g., entity relation extraction,
word relation extraction.

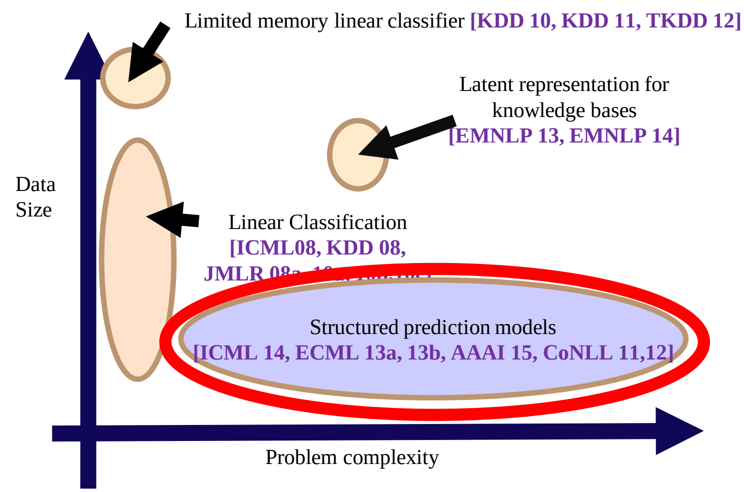


My Research Contributions

Structured Prediction Models

[ECML 13a, 13b, ICML14, CoNLL 11,12, ECML 13a, AAAI15]

- Design tractable, principled, domain specific models
- Speedup general structured models



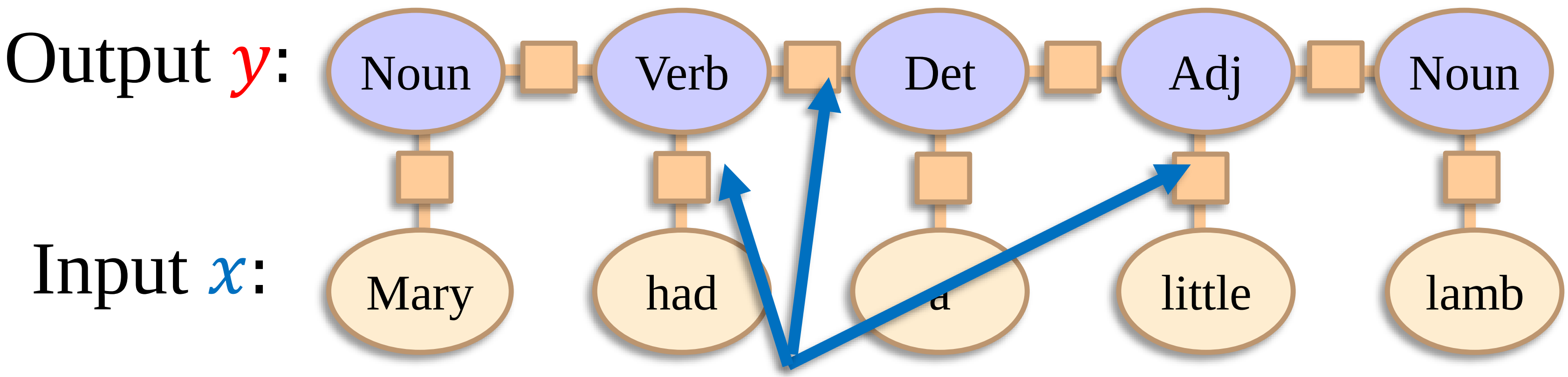
Structured Prediction

Assign values to a set of interdependent output variables

Task	Input	Output
Part-of-speech Tagging	They operate ships and banks.	Pronoun Verb Noun And Noun
Dependency Parsing	They operate ships and banks.	**Root** They operate ships and banks .
Segmentation		

Structured Prediction Models

- Learn a scoring function:
  $Score\ (output\ y \mid input\ x\ , model\ w\ )$
- Linear model: $S(y \mid x, w) = \sum_i w_i\, \phi_i(x, y)$
- Features: **e.g., Verb-Noun, Mary-Noun**



Features based on both input and output

Inference

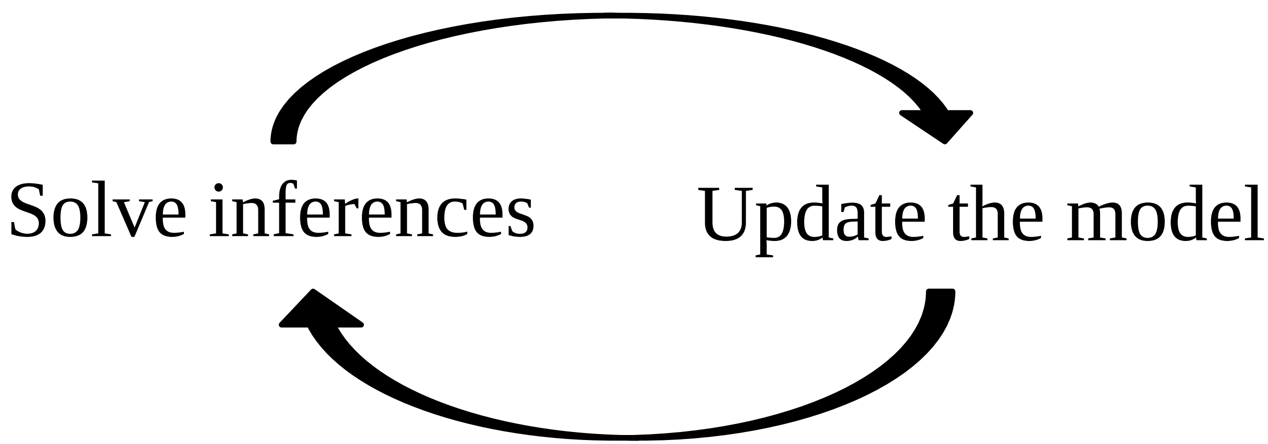
- Find the best scoring output given the model

$$\underset{y}{\operatorname{argmax}}\, Score\,(output\ y \mid input\ x\ , model\ w\ )$$

- Output space is usually exponentially large
- Inference algorithms:
  - Specific: e.g., Viterbi (linear chain)
  - General: Integer linear programming (ILP)
  - Approximate inference algorithms:
    e.g., belief propagation, dual decomposition

Learning Structured Models

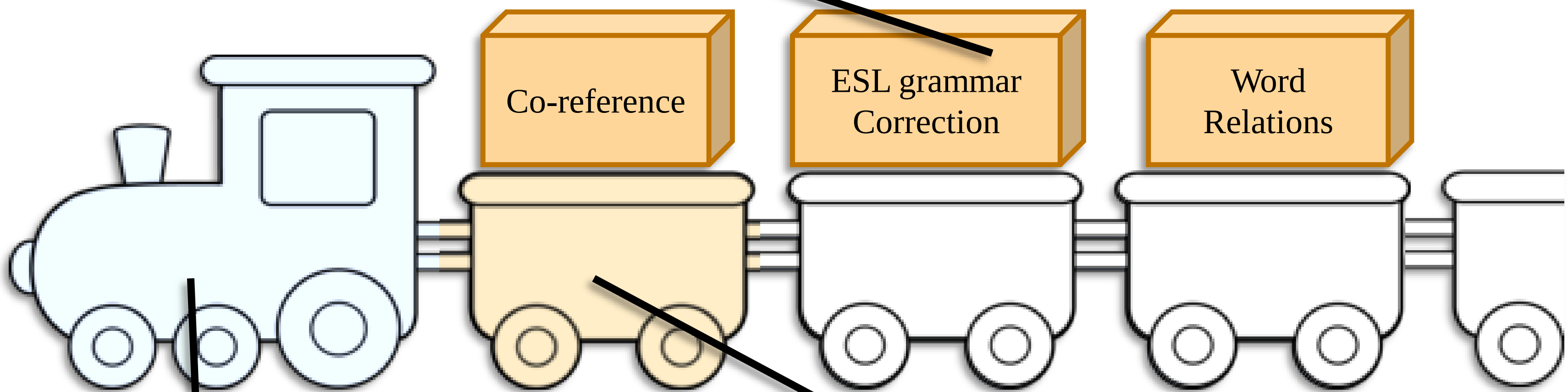
- Online, e.g., Structured Perceptron [Collins 02]
- Batch e.g., Structured SVM
  - Cutting plane: [Tsochantaridis+ 05, Joachims+ 09]
  - Dual Coordinate Descent: [Shevade+ 11, Chang+ 13]
  - Block-Coordinate Frank-Wolfe: [Lacoste-Julien+ 13]
  - Parallel Dual Coordinate Descent: [ECML 13a]



Outline

1. Applications:

Co-reference; ESL Grammar Correction; Word Relation;



2. Modeling: Supervised Clustering Model

3. Algorithms: Learning with Amortized Inference

Outline

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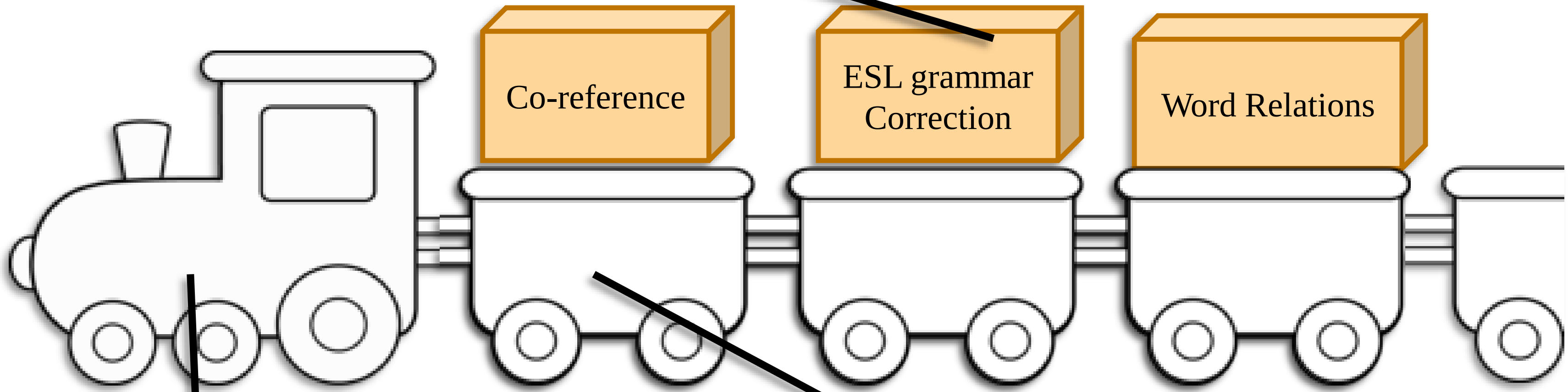

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Co-reference Resolution

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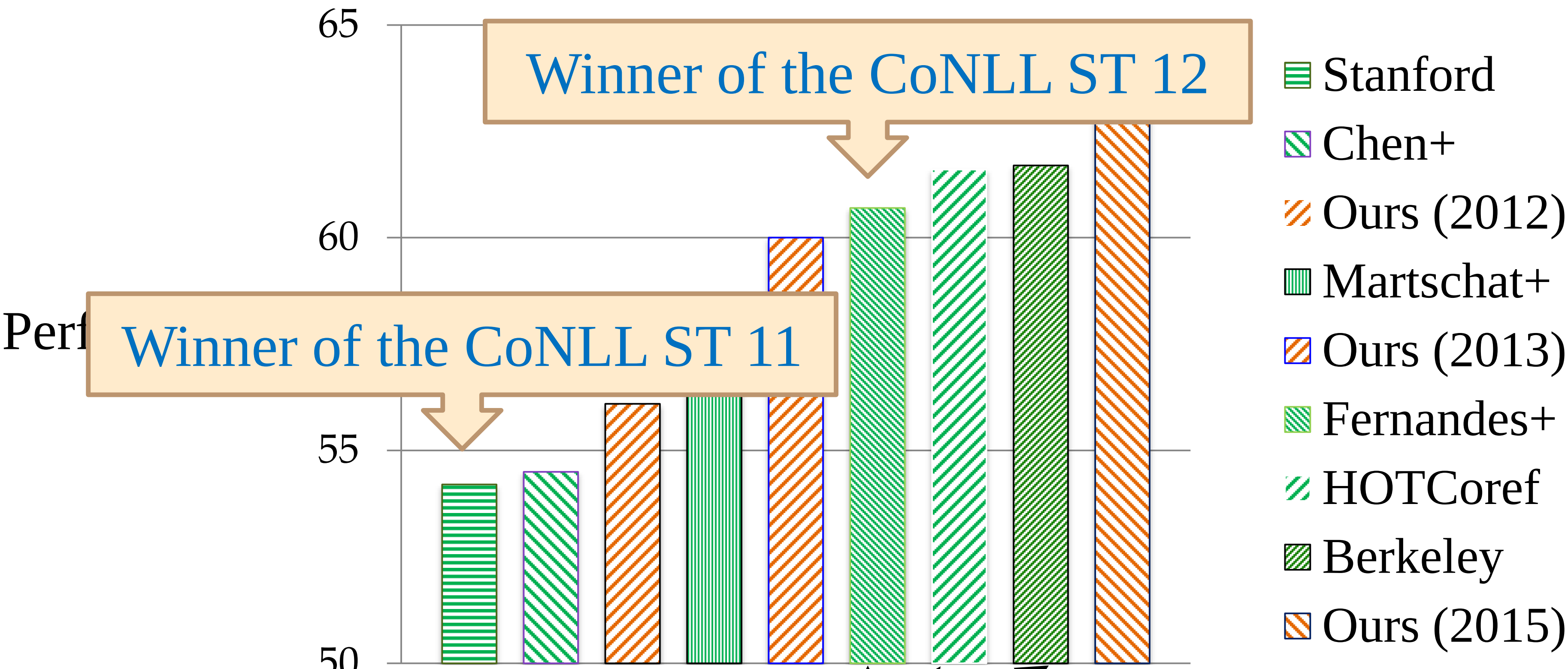
Co-reference Resolution

[EMNLP 13a, ICML14, In submission]

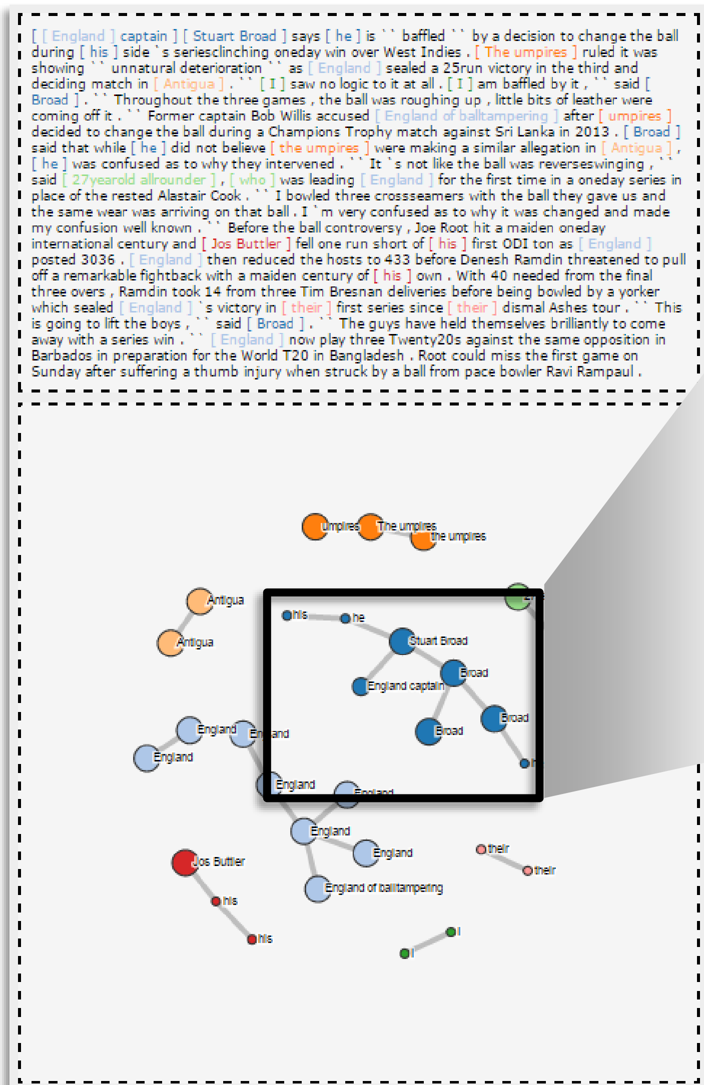
Proposed a novel, principled, linguistically motivated model

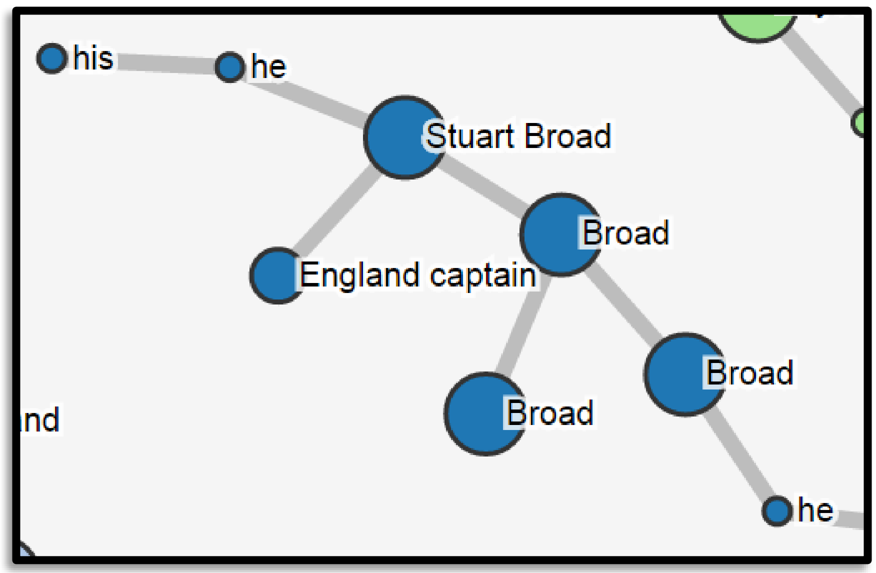


***Avg (MUC, B^3, CEAF)**

Latent forest structure

Co-reference Resolution Demo





http://bit.ly/illinoisCoref

ESL Grammar Error Correction

[CoNLL 13, 14]

They believe that such situation must be avoided.

- ✗ situation
- ✓ a situation
- ✓ situations
- ✗ a situations

First place in CoNLL Shared tasks 13' 14'

Identifying Relations between Words

[EMNLP 14]

- GRE antonym task (no context):

Which word is the opposite of adulterate?

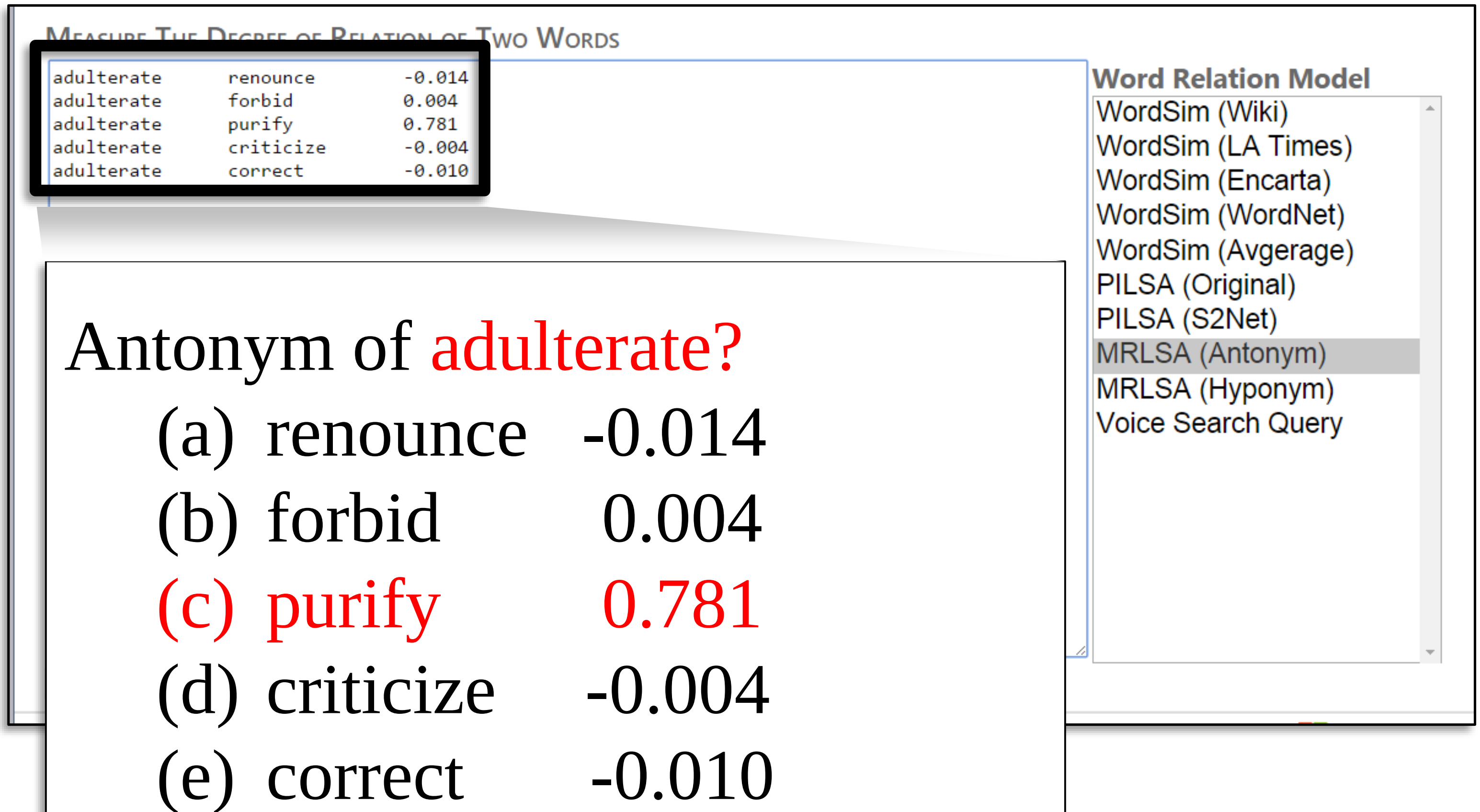
(a) renounce (b) forbid (c) purify (d) criticize (e) correct

- Look up in a thesaurus [Encarta]: 56%
- Our tensor method [EMNLP 13b]: 77% (the best result so far)
- Why?
  - Considers multiple word relations simultaneously

    e.g., inanimate ← Ant → alive ← Syn → living

Word Relation Demo

http://bit.ly/wordRelation



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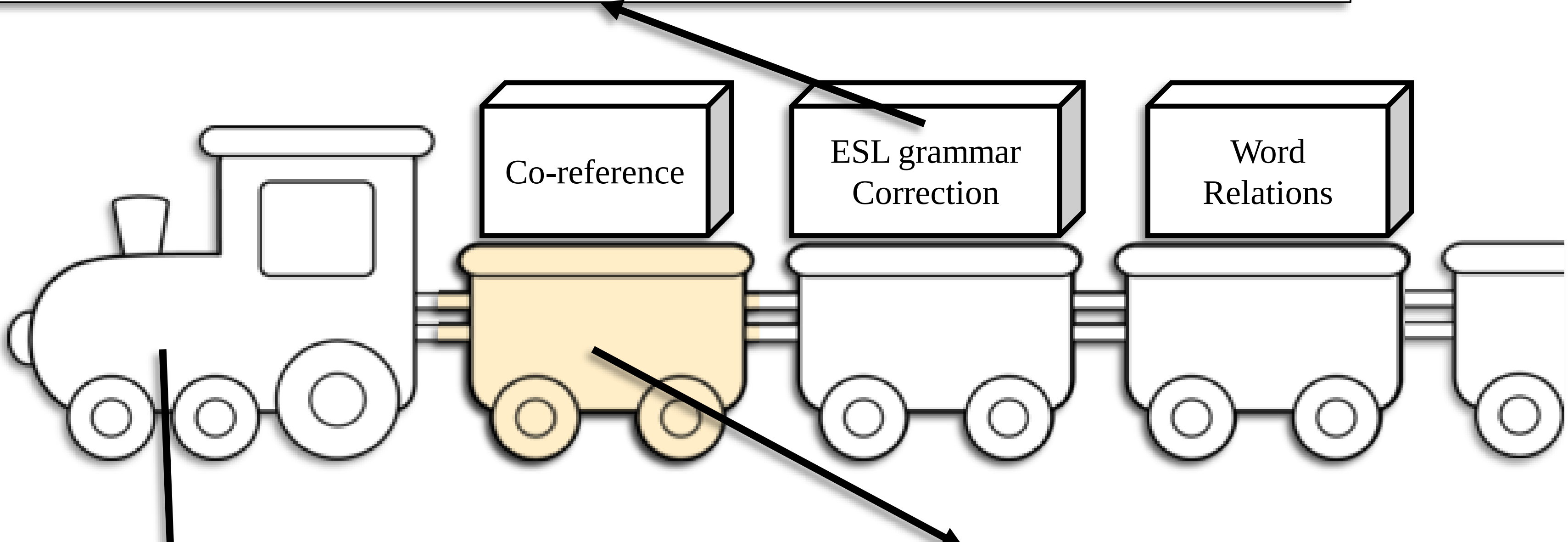

2. Modeling: Supervised Clustering Model

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Co-reference Resolution

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Co-reference Resolution

- Learn a pairwise similarity measure (local predictor)

  Example features:
  - same sub-string?
  - positions in the paragraph
  - other 30+ feature types
- Key questions:
  - How to learn the similarity function
  - How to do clustering

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Decoupling Approach

A heuristic to learn the model [Soon+ 01, Bengtson+ 08, CoNLL11]

- Decouple learning and inference:

Learn a pairwise similarity function

Cluster based on this function

Decoupling Approach-Learning

As a **boy**, **Chris**$_1$ lived in a pretty home called **Cotchfield Farm.** When **Chris**$_2$ was three years old, **his father**$_3$ wrote a poem about **him**$_4$. The poem was printed in a magazine for others to read. **Mr. Robin**$_5$ then wrote a book

Positive Samples

(Chris$_1$, him$_4$)

(Chris$_2$, him$_4$)

(Chris$_1$, Chris$_2$)

(his father$_3$, Mr. Robin$_5$)

Negative Samples

(Chris$_1$, his father$_3$)

(Chris$_2$, his father$_3$)

(him$_4$, his father$_3$)

(Chris$_1$, Mr. Robin$_5$)

(Chris$_2$, Mr. Robin$_5$)

(him$_4$, Mr. Robin$_5$)

Greedy Best-Left-Link Clustering

[Bill Clinton], recently elected as the **[President of the USA]**, **has been invited by the [Russian President], [Vladimir Putin], to visit [Russia]. [President Clinton] said that [he] looks forward to strengthening** ties between **[USA]** and **[Russia]**.

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Greedy Best-Left-Link Clustering

[Soon+ 01, Bengtson+ 08, CoNLL11]

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[Bill Clinton]

[Russian President]

[Russia].

[President of the USA]

[Vladimir Putin]

[Russia].

[President Clinton]

[he]

Best Left-Linking Forest

Challenges

- Decoupling may lose information

Christopher Robin is alive and well. **He** is the same person that you read about in the book, **Winnie the Pooh**. As a **boy**, **Chris** lived in a pretty home called **Cotchfield Farm.** When **Chris** was three years old, **his father** wrote a poem about **him**. The poem was printed in a magazine for others to read. **Mr. Robin** then wrote a book

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Challenges

- In addition, we need world knowledge

As a **boy**, **Chris** lived in a pretty home called **Cotchfield Farm.** When **Chris** was three years old, **his father** wrote a poem about **him**.

1. Complexity: need an efficient algorithm
2. Modeling: learn the metric while clustering
3. Knowledge: augment with knowledge

Structured Learning Approach

Update the similarity function

Cluster based on this function.

Learn the similarity function while clustering

Attempt: All-Links Clustering

[Mccallum+ 03, CoNLL 11]

- Define a global scoring function:

  Attempt: using all within-cluster pairs:

  - Inference problem is too hard

> **Christopher Robin** is alive and well. **He** is the same person that you read about in the book, **Winnie the Pooh**. As a **boy**, **Chris** lived in a pretty home called **Cotchfield Farm.** When **Chris** was three years old, **his father** wrote a poem about **him**. The poem was printed in a magazine for others to read. **Mr. Robin** then wrote a book

<u>Latent</u> Left-Linking Model (L3M)

[ICML 14, EMNLP 13]

Score (a clustering C)

= Score (the best left-linking forest that is consistent with C)

= ∑ Score of edges in the forests

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Linguistic Constraints

- Must-link constraints:
  - E.g., SamePropername, …
- Cannot-link constraints:
  - E.g., ModifierMismatch, …

[Bill Clinton], recently elected as the **[President of the USA]**, has been invited by the **[Russian President]**, **[Vladimir Putin]**, to visit **[Russia]**. **[President Clinton]** said that **[he]** looks forward to strengthening ties between **[USA]** and **[Russia]**.

Inference in L3M [ICML 14, EMNLP 13]

- Solved by a greedy algorithm or formulated as an Integer Linear Program (ILP)

$y_{i,j} = 1 \iff i, j$ is an edge in the forest

$$\arg\max_{\boldsymbol{y}} \quad \sum_c S_{i,j} \boxed{y_{i,j}}$$

$$s.t \quad \boxed{A\boldsymbol{y} \leq b;} \quad y_{i,j} \in \{0,1\}$$

- Modeling constraints
- Linguistic constraints

Learning L3M (simplified version)[ICML 14, EMNLP 13a]

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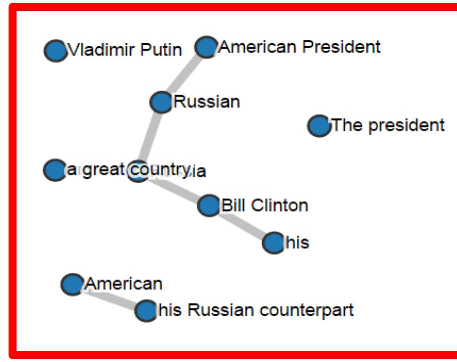

predicted forest

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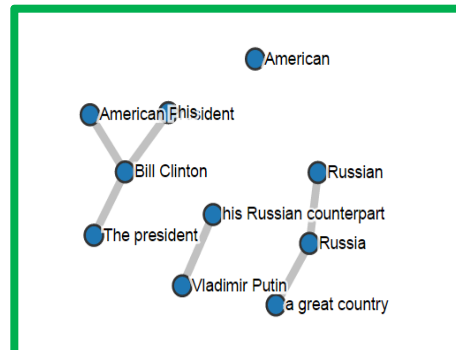
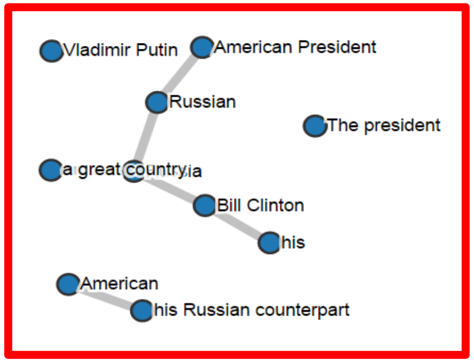
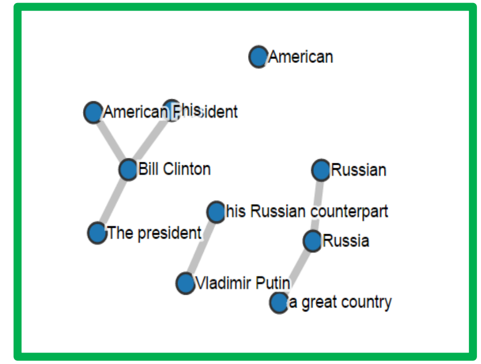


latent forest

Learning L3M (simplified version)[ICML 14, EMNLP 13a]



predicted forest



latent forest

Loop until stopping condition is met:

For each $(\boldsymbol{x}_i, \boldsymbol{y}_i)$ pair:

$$\bar{\boldsymbol{y}}, \bar{\boldsymbol{h}} = \arg\max_{\boldsymbol{y},\boldsymbol{h}} \boldsymbol{w}^T \phi(\boldsymbol{x}_i, \boldsymbol{y}, \boldsymbol{h})$$

$$\mathbf{h_i} = \arg\max_{\boldsymbol{h}} \boldsymbol{w}^T \phi(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{h})$$

$$\boldsymbol{w} \leftarrow \boldsymbol{w} + \eta\left(\phi(\boldsymbol{x}_i, \boldsymbol{y}_i, \boldsymbol{h}_i) - \phi(\boldsymbol{x}_i, \bar{\boldsymbol{y}}, \bar{\boldsymbol{h}})\right), \ \eta\text{: learning rate}$$

Extension: Probabilistic L3M

[ICML 14, EMNLP 13a]

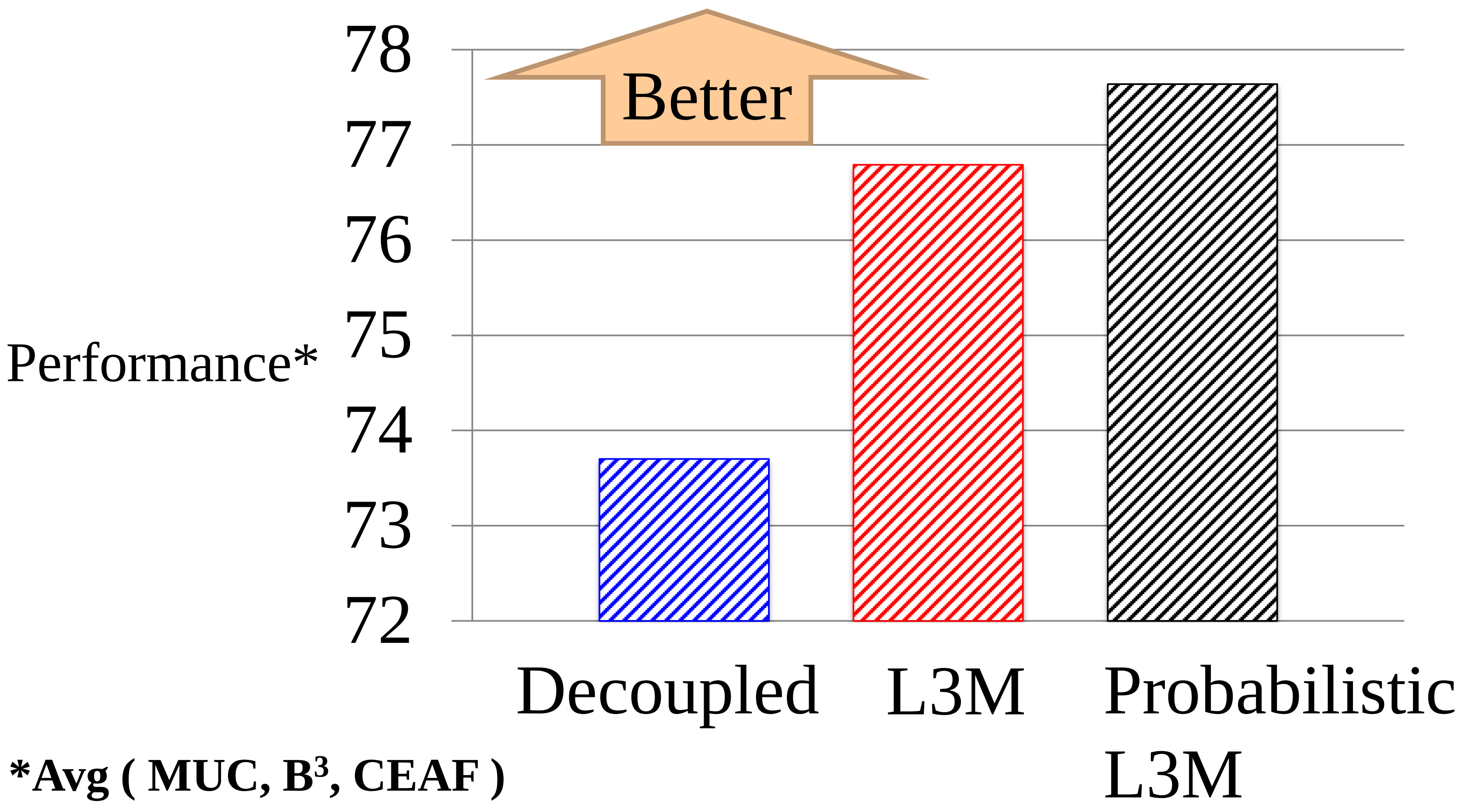
- Define a log-linear model

> Pr [a clustering C]
> = ∑ Pr [forests that are consistent with C]
> = ∑∑ Pr [edges in the forest]
>
> Pr [edge] ~ Pr $[\sum_{j \in e} \exp(\boldsymbol{w} \cdot \phi(i,j)/\gamma)]$ (° : a parameter)

- Regularized Maximum Likelihood Estimation:

$$\min_{\mathbf{w}} \ \mathrm{LL}(\mathbf{w}) = \beta ||\mathbf{w}||^2 + \sum_d \log Z_d(\boldsymbol{w}) - \sum_d \sum_i \log\left(\sum_{j<i} \exp(\boldsymbol{w} \cdot \phi(i,j)/\gamma) C_d(i,j)\right)$$

Coreference: OntoNotes-5.0 (with gold mentions)



***Avg (MUC, B^3, CEAF)**

Latent Left-Linking Model (L3M)

[ICML 14, EMNLP 13]

Advantages:

- Complexity: Very efficient
- Modeling: Learn the metric while clustering
- Knowledge: Easy to incorporate constraints (must-link or cannot-link)

Can be applied to other supervised clustering problems!
e.g., the posts in a forum, error reports from users …

Outline

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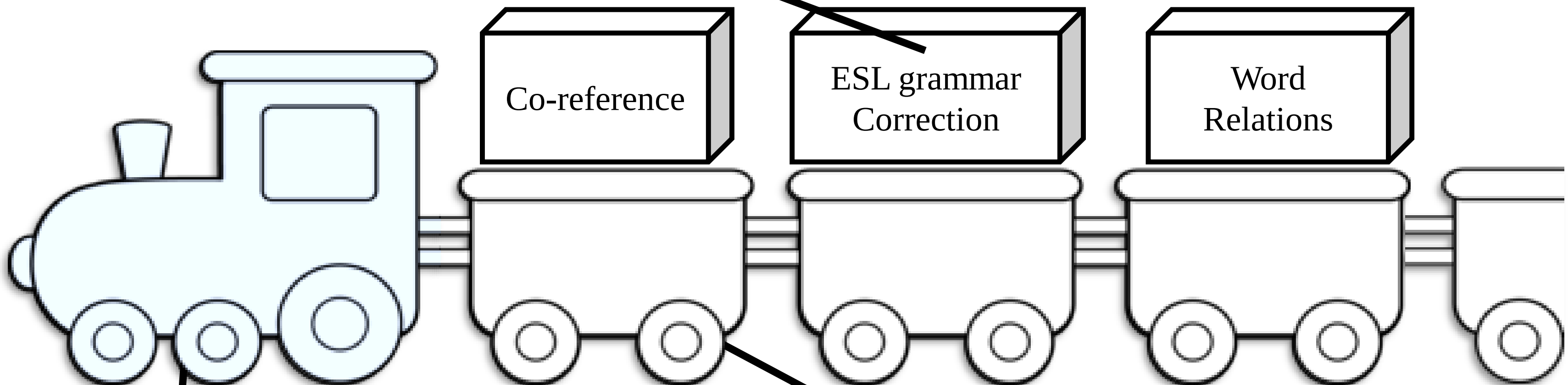


2. Modeling: Supervised Clustering Model

3. Algorithms: Learning with Amortized Inference

Learning Structured Models

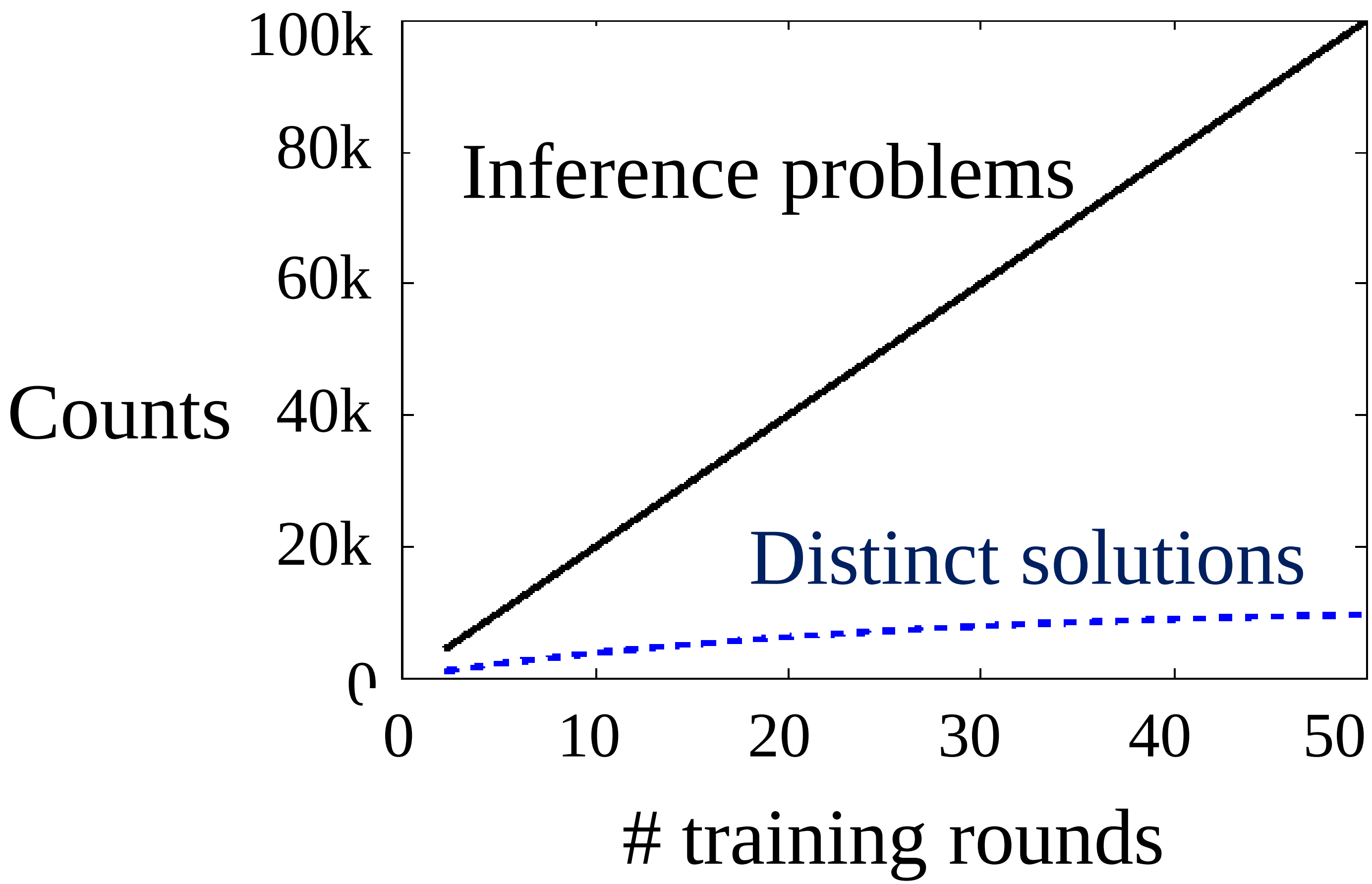
- Online, e.g., Structured Perceptron [Collins 02]
- Batch e.g., Structured SVM
  - Cutting plane: [Tsochantaridis+ 05, Joachims+ 09]
  - Dual Coordinate Descent: [Shevade+ 11, Chang+ 13]
  - Block-Coordinate Frank-Wolfe: [Lacoste-Julien+ 13]
  - Parallel Dual Coordinate Descent: [ECML 13a]

Solve inferences Update the model

Redundancy in Learning Phase

[AAAI 15]

Recognizing Entities and Relations Task



Redundancy of Solutions[Kundu+13]

S1	POS
He	Pronoun
is	VerbZ
reading	VerbG
a	Det
book	Noun

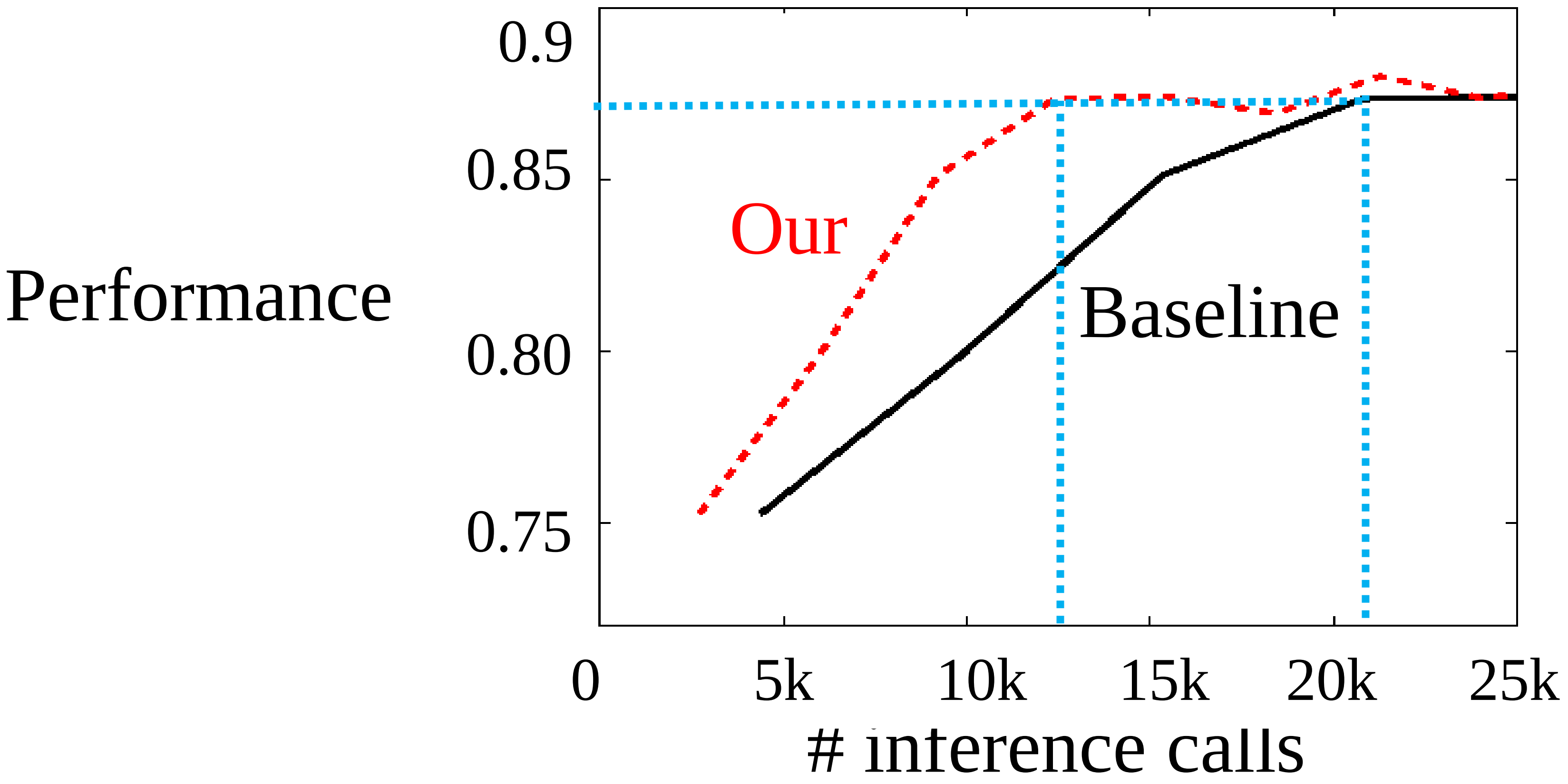
POS	S2
Pronoun	She
VerbZ	is
VerbG	watching
Det	a
Noun	movie

Although the inference problems are different, their solutions might be the same

Fewer Inference Calls [AAAI 15]

Recognizing Entities and Relations Task

Obtain the same model with fewer inference calls



Learning with Amortized Inference

[AAAI 15]

- A general inference framework

… to represent inference problems

- A condition

… to check if two problems have the same solution

```
If CONDITION(problem cache, new problem)
  then (no need to call the solver)
     SOLUTION(new problem) = old solution
Else
     Call base solver and update cache
End
```

0.04 ms

2 ms

A General Inference Framework

Integer Linear Programming (ILP)

$$\arg\max_{\boldsymbol{y}} \quad \sum_c S_c y_c \quad s.t \quad A\boldsymbol{y} \leq b; \;\; y_c \in \{0,1\}$$

- Widely used in NLP & Vision tasks [Roth+ 04]
  - E.g., Dependency Parsing, Sentence Compression
- Any MAP problem w.r.t. any probabilistic model, can be formulated as an ILP [Roth+ 04, Sontag 10]
- Only used for verifying amortized conditions

Amortized Inference Theorem [Kundu+13]

- Theorem 1: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i, \quad \left(2\boldsymbol{x}^*_{p,i} - 1\right)(c_{Q,i} - c_{P,i}) \geq 0$

  (The solution is not sensitive to the changes of the coefficients.)

  then the optimal solution of Q is $\boldsymbol{x}^*_p$

  - x^*_P: the solution to P
  - **c**: the coefficients of ILPs

Amortized Inference Theorem [Kundu+13]

- Theorem 1: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i, \quad \left(2\boldsymbol{x}^*_{p,i} - 1\right)(\mathrm{c}_{Q,i} - c_{P,i}) \geq 0$

  then the optimal solution of Q is $\boldsymbol{x}^*_p$

P:

max $2x_1+3x_2+2x_3+1x_4$
$x_1 + x_2 \leq 1$
$x_3 + x_4 \leq 1$

Q:

max $2x_1+4x_2+2x_3+0.5x_4$
$x_1 + x_2 \leq 1$
$x_3 + x_4 \leq 1$

$\boldsymbol{x}^*_p$: <0, 1, 1, 0> $\rightarrow$ 6

x': <1, 0, 1, 0> $\rightarrow$ 4

Amortized Inference Theorem [Kundu+13]

- Theorem 1: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i, \quad \left(2\boldsymbol{x}_{p,i}^{*} - 1\right)(c_{Q,i} - c_{P,i}) \geq 0$

  if $\boldsymbol{x}_{p,i}^{*} = 1$ then $(c_{Q,i} - c_{P,i}) \geq 0$
  if $\boldsymbol{x}_{p,i}^{*} = 0$ then $(c_{Q,i} - c_{P,i}) \leq 0$

  then the optimal solution of Q is $\boldsymbol{x}_{p}^{*}$

  - x_P^*: the solution to P
  - **c**: the coefficients of ILPs

Approx. Amortized Inference [AAAI 15]

- Theorem 2: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i, \ \left(2x^*_{p,i} - 1\right)(c_{Q,i} - c_{P,i}) \geq -\epsilon|c_{Q,i}|$

  then x^*_P is a $(\frac{1}{1+M\epsilon})$-approximate solution to Q

  - x^*_P: the solution to P
  - M: a constant
  - **c**: the coefficients of ILPs

Approx. Amortized Inference [AAAI 15]

- Theorem 2: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i, \ \left(2x^*_{p,i} - 1\right)(c_{Q,i} - c_{P,i}) \geq -\epsilon|c_{Q,i}|$

  then x^*_P is a $(\frac{1}{1+M\epsilon})$-approximate solution to Q

Corollary 1:

Learning Structured SVM with approximate amortized inference gives a model with bounded empirical risk

Approx. Amortized Inference [AAAI 15]

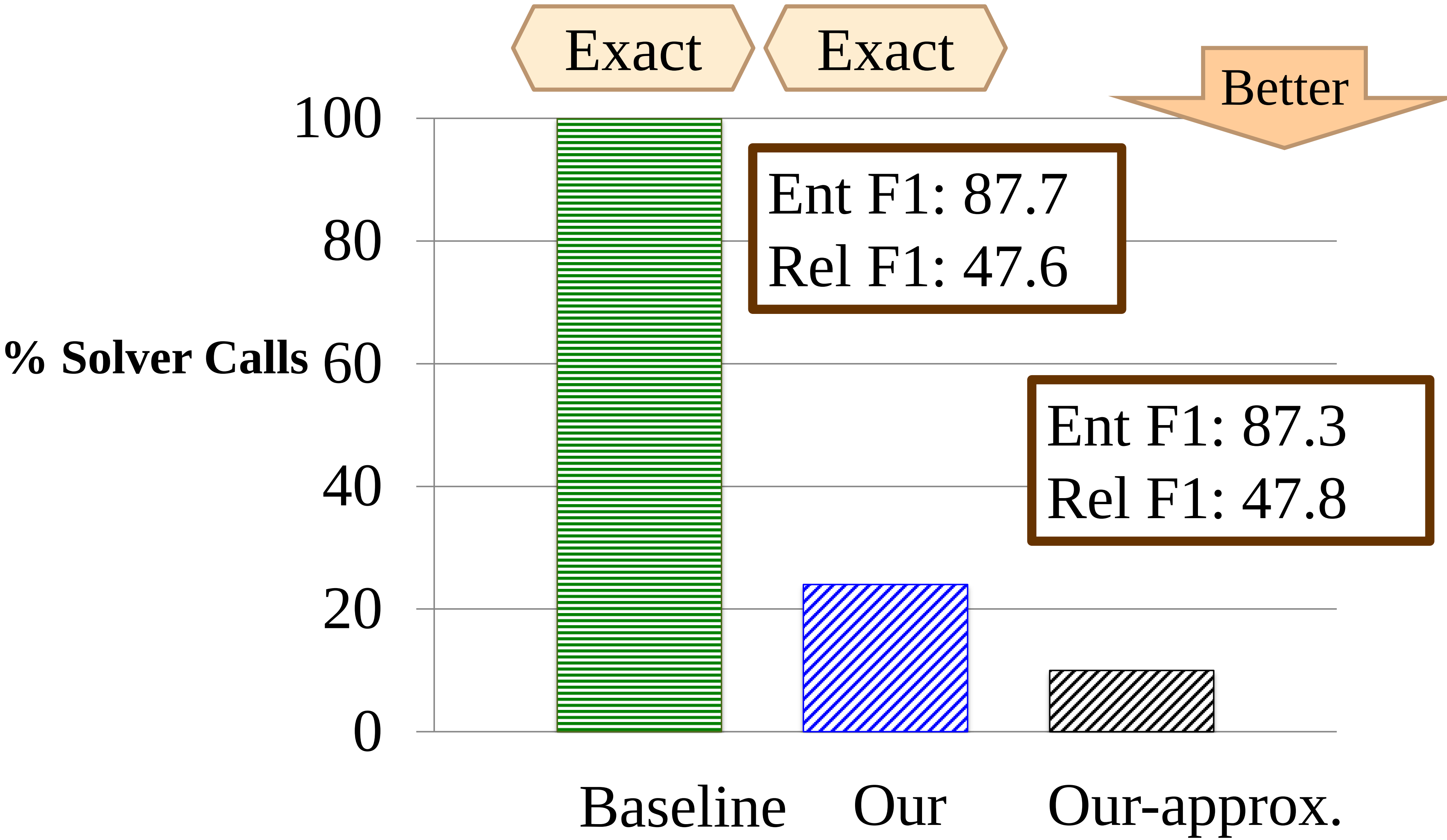
- Theorem 2: If the following conditions are satisfied
  1. Same # variables & same constraints
  2. $\forall i,\ \left(2x^*_{p,i} - 1\right)(c_{Q,i} - c_{P,i}) \geq -\epsilon |c_{Q,i}|$

  then x^*_P is a $(\frac{1}{1+M\epsilon})$-approximate solution to Q

Corollary 2:

Dual coordinate descent for structured SVM can still return an exact model even if approx. amortized inference is used.

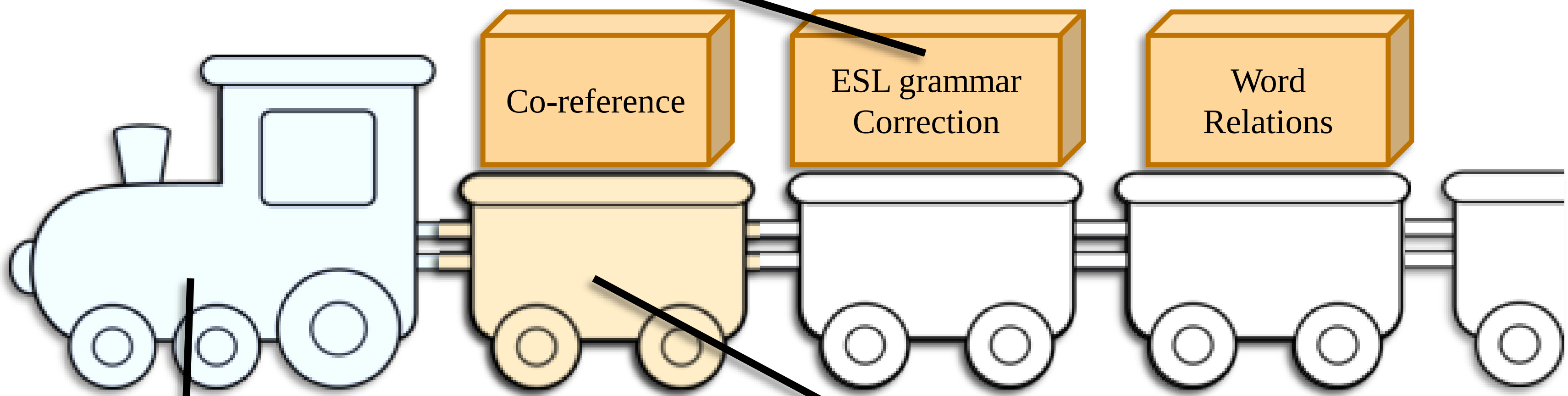
Solver Calls (Entity-Relation Extraction)



Outline

1. Applications:

Co-reference; ESL Grammar Correction; Word Relation;

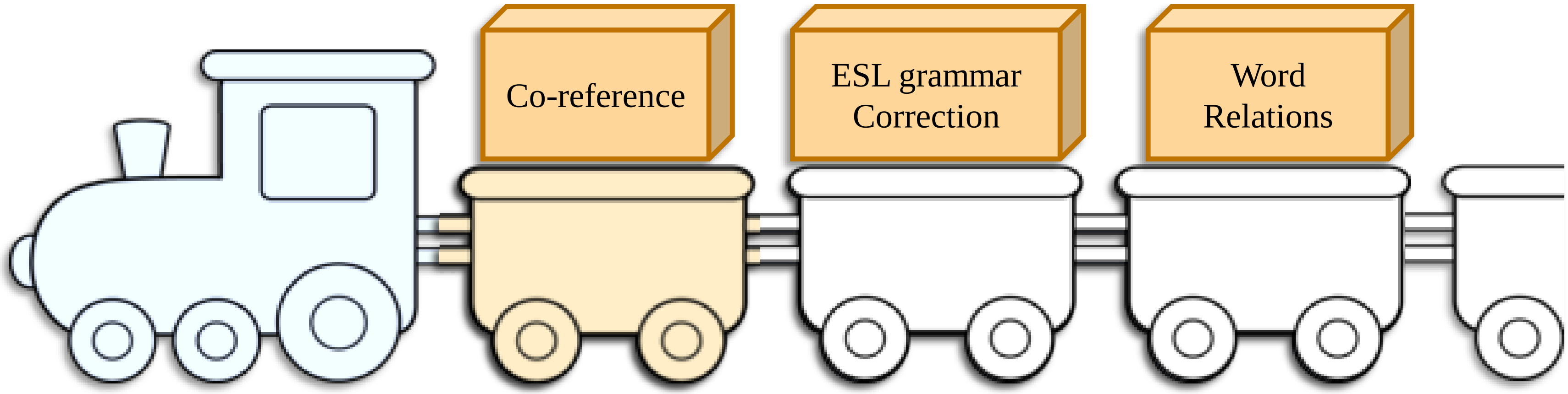


2. Modeling: Supervised Clustering Model

3. Algorithms: Learning with Amortized Inference

Other Related Work

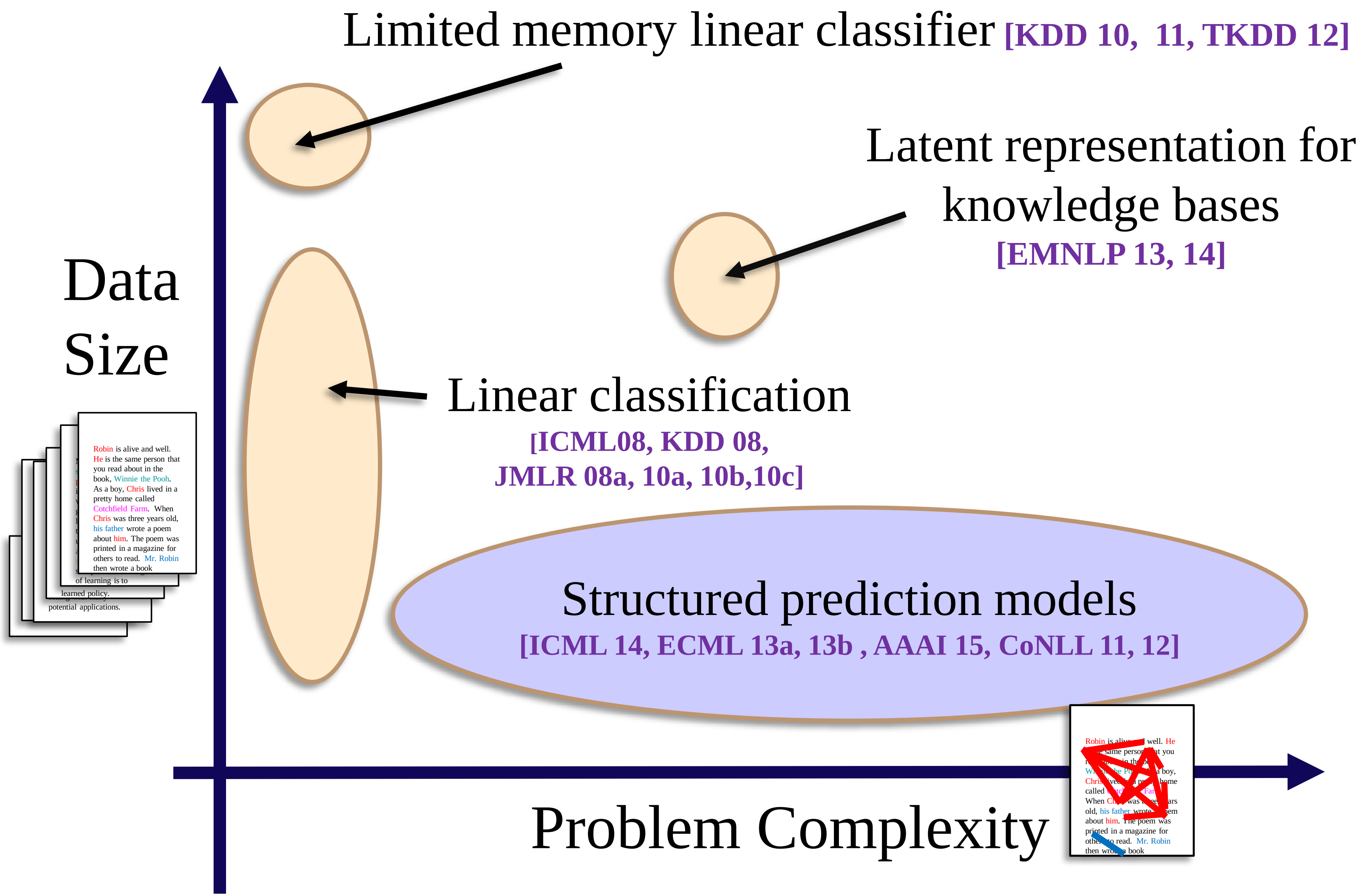
1. Applications: Co-reference; ESL Grammar Correction; Word Relation; Dependency Parsing [Arxiv 15 b]; Multi-label Classification [ECML13]



2. Modeling: Supervised Clustering Model
Semi-Supervised Learning [ECML 13a] Search-Based Model [Arxiv 15 a]

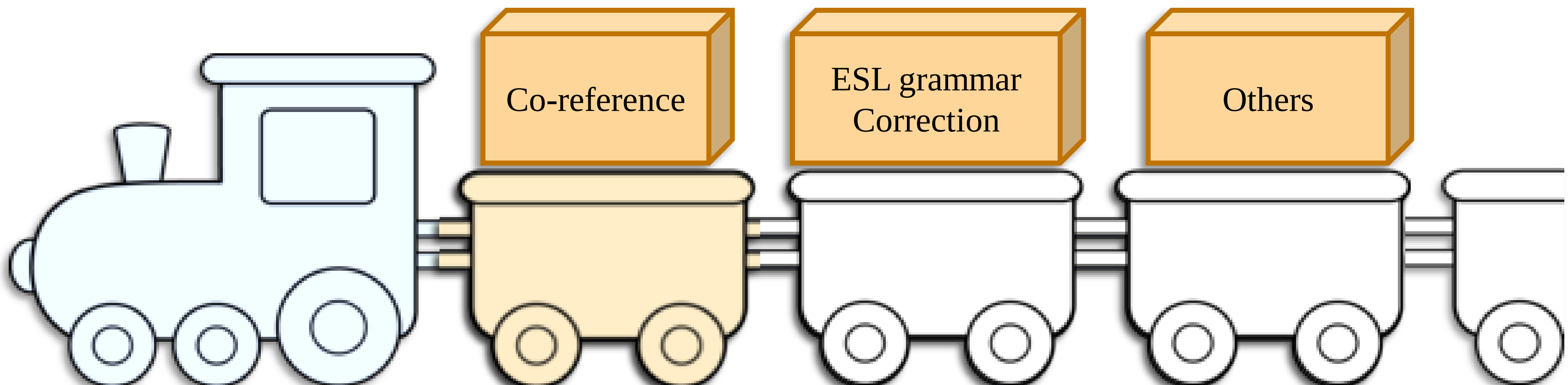
3. Algorithms: Learning with Amortized Inference
Parallel learning algorithms [ECML 13b]

My Research Contributions



Future Work: Practical Machine Learning

1. **Applications:** More applications, easy access tools



2. **Modeling:** Learning from heterogeneous information

3. **Algorithms:** Handle large & complex data

Learning From World Knowledge

- Go beyond supervised learning
  - Learning from indirect supervision signals

After the vessel suffered a catastrophic torpedo detonation, Kursk sank in the waters of Barents Sea with all hands lost.

Learning From World Knowledge

- Massive textual data on the Internet
  - Wikipedia: 4.7 M English articles 35M in total
  - Tweets: 500 M per day & 200 Billion per year

- Learn world knowledge to support target tasks
  - Extract knowledge from free text [EMNLP 13a, 14, ICML 14]
  - Handle large-scale data [Liblinear, KDD 12]
  - Inference on knowledge bases [EMNLP 14b, 14]

Applications & Tools

- LIBLINEAR: library for classification
- Streaming Data SVM:
  - Support training on very large data
- Illinois-SL: library for structured prediction
  - Support various algorithms; parallel ⇒ very fast

Provide a nice platform

- for developing novel methods
- for collaboration
- for education

More easy-access tools; More collaborations

Conclusion

Goal: Practical Machine Learning

- [Modeling] Expressive and general formulations
- [Algorithms] Principled and efficient
- [Applications] Support many applications

Code and Demos:

http://www.illinois.edu/~kchang10