How to Train a Theorem Prover for Natural Language Inference

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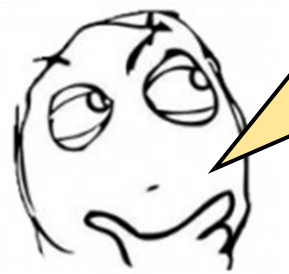
Intro

There is in my opinion no important theoretical difference between natural languages and the artificial languages of logicians

Montague, 1970



The artificial languages of logicians usually come with proof systems.
What do proof systems of natural languages look like?

I will present the **Natural Tableau** that is a semantic tableau-based proof system for English.

Outline

Natural Tableau

Natural language theorem prover

Learning as abduction

Experiments & results

Conclusion & references

Natural Tableau

Natural Tableau

Syntactic parsing, $[\![\ ]\!]$ λ @

$\exists x(lark(x) \wedge \neg move(x))$

$\forall x(bird(x) \rightarrow fly(x))$

Blackburn & Bos (2005)

FOL

A lark is not moving

contradicts

Every bird is flying

contradicts

Syntactic parsing, rewriting

a lark (not (be move))

every bird (be move)

Natural theorem proving

Lambda Logical Forms

Muskens, 2010

John sleeps	$\mathbf{sleep\ john}$
Every bird flies	$\mathbf{every\ bird\ fly}$
No bird flies	$\mathbf{no\ bird\ fly}$
The lark does not fly	$\mathbf{the\ lark\ (not\ fly)}$
John sleeps and Mary sings	$\mathbf{and\ (sleep\ john)\ (sing\ mary)}$
Every man loves a woman	$\mathbf{every\ man}\ (\lambda s.\mathbf{a\ woman}\ (\lambda o.\mathbf{love}\ o\ s))$ $\mathbf{a\ woman}\ (\lambda o.\mathbf{every\ man}\ (\mathbf{love}\ o))$

$$A\ B\ C \equiv (A\ B)\ C$$

No ∧,∨, →, ∃, ¬, ∀ are used

R. Muskens (2010): An analytic tableau system for natural logic

Natural tableau entries

$Term$ | $a_1, a_2 \ldots, a_n$ — $((Term\ a_1)a_2) \ldots\ a_n$ **is true**

$Term$ | $a_1, a_2 \ldots, a_n$ — $((Term\ a_1)a_2) \ldots\ a_n$ **is false**

John sleeps

sleep john

sleep | **john**

It is false that the lark doesn't fly

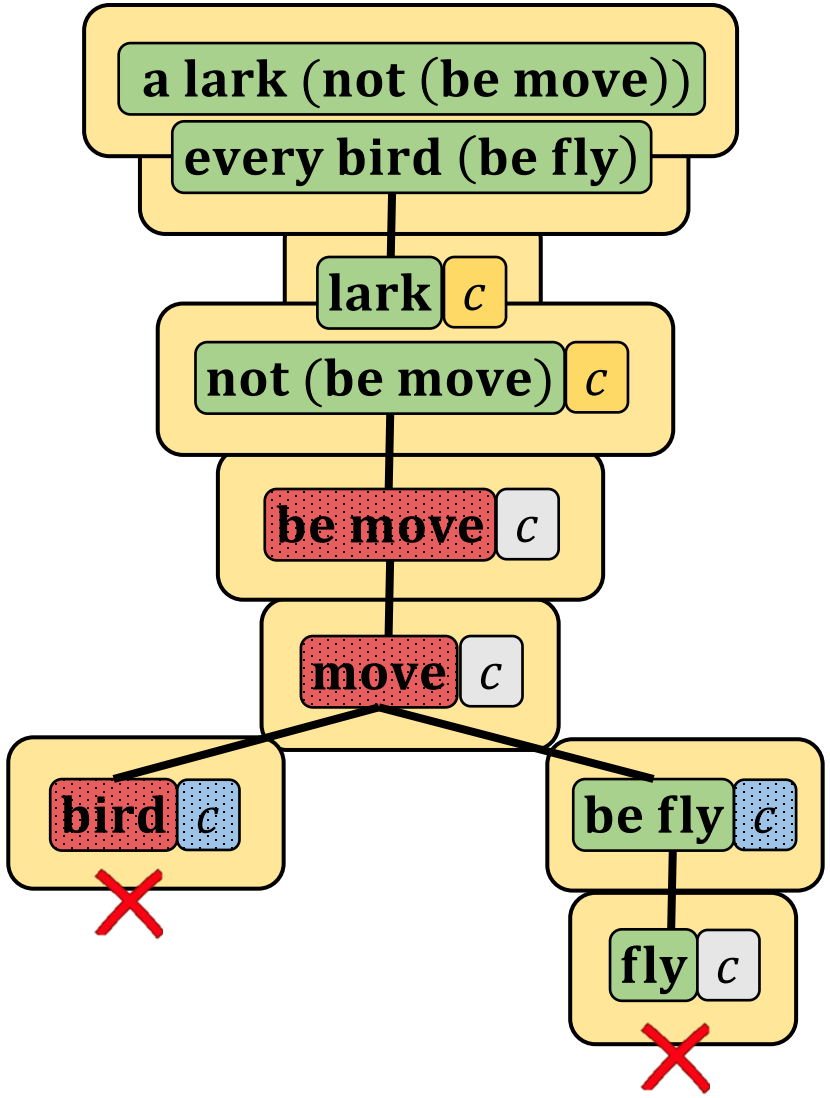
the lark (not fly)

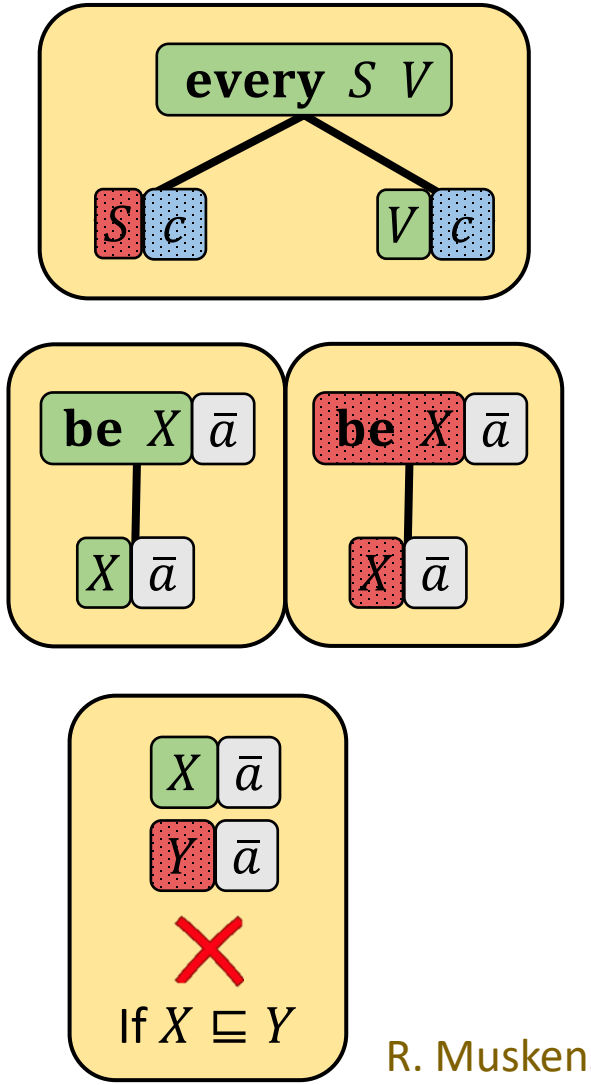
the lark | **not fly**

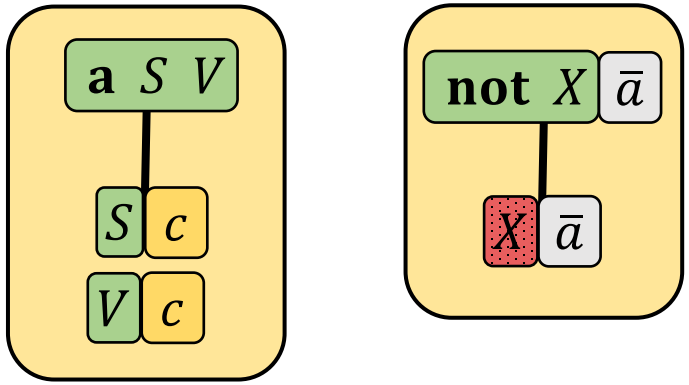
the | **lark, not fly**

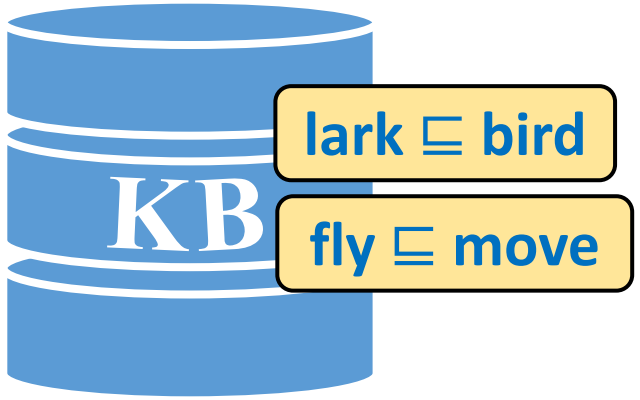
R. Muskens (2010): An analytic tableau system for natural logic

Natural tableau proof









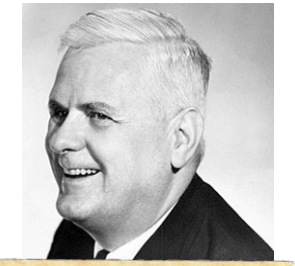
R. Muskens (2010): An analytic tableau system for natural logic

Natural tableau for natural logic

Natural logic is the study of inference in natural language, done as close as possible to the "surface forms" (Moss, 2010)

LLFs are terms of **higher-order logic**, namely, simple type theory:

$$\dfrac{\dfrac{\textbf{a}\ \boxed{(et)(et)t} \qquad \textbf{lark}\ \boxed{et}}{\textbf{a lark}\ \boxed{(et)t}} \qquad \dfrac{\textbf{not}\ \boxed{(et)et} \qquad \dfrac{\textbf{be}\ \boxed{(et)et} \qquad \textbf{move}\ \boxed{et}}{\textbf{be move}\ \boxed{et}}}{\textbf{not (be move)}\ \boxed{et}}}{\textbf{a lark (not (be move))}\ \boxed{t}}$$



Church, 1940

Tableau method is very intuitive: theorem-proving as a model construction

Natural Language Theorem Prover

Scaling up the natural tableau

Fine-grained entries: $m_1, \ldots, m_k$ | $Term$ | $a_1, \ldots, a_n$

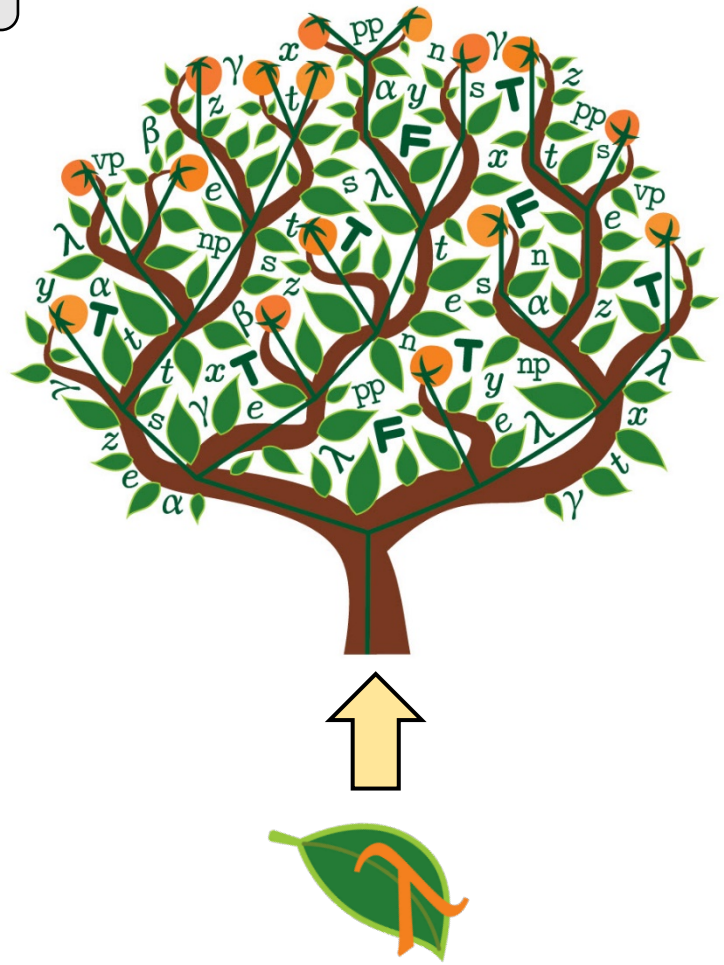
Syntactic types: $\{e, t\} + \{\boldsymbol{n}, \boldsymbol{np}, \boldsymbol{s}, \boldsymbol{pp}\}$

$\boldsymbol{s} <: t \qquad e <: \boldsymbol{np} \qquad \boldsymbol{n} <: et \qquad \boldsymbol{pp} <: et$

$\alpha\beta <: \gamma\delta$ if $\gamma <: \alpha$ and $\beta <: \delta$

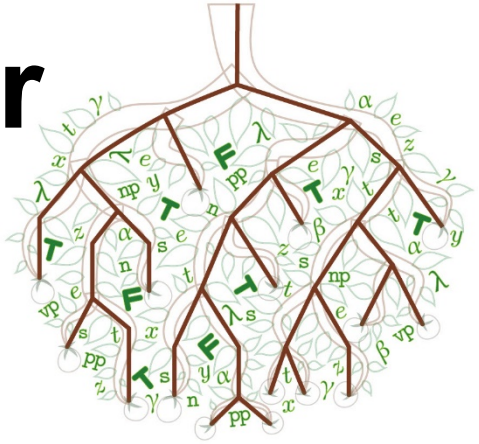
More tableau rules:

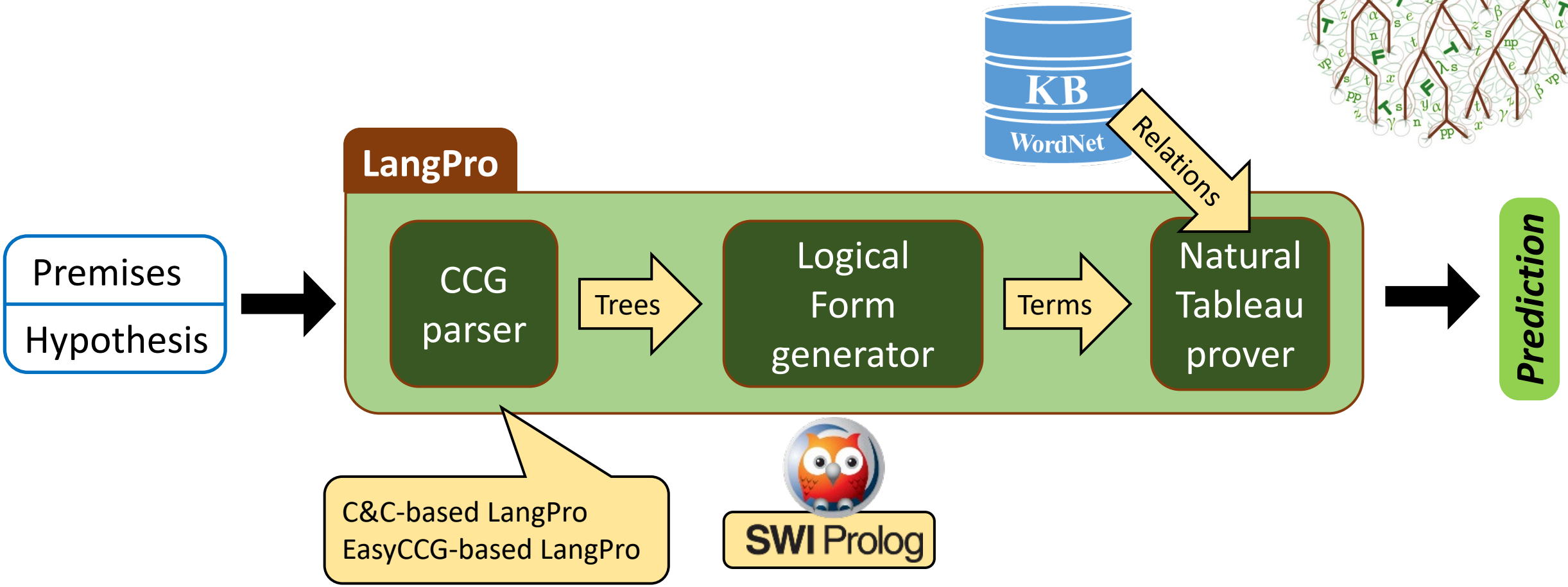
- Adjectives
- Prepositions/particles
- Passive constrictions
- Subcategorization
- Definite NPs
- Expletives
- Open compound nouns
- Light verb constructions
- Attitude verbs
- PP attachments



L. Abzianidze (2016): A natural proof system for natural language

Natural Language Theorem Prover





ONLINE DEMO

https://naturallogic.pro/LangPro

L. Abzianidze (2017): LangPro: Natural language theorem prover

Natural Language Inference (NLI)

aka Recognizing Textual Entailment (RTE)

A man in a hat is playing a **harp**	
E	A man is playing an **instrument**

Gold inference label =
Entailment | **C**ontradiction | **N**eutral

The woman is **not** wearing glasses **or** a headdress	
C	A woman is wearing an **Egyptian** headdress

A woman is dancing and singing with other woman	
N	A woman is dancing and singing **in the rain**

From SICK (**S**entences **I**nvolving **C**ompositional **K**nowledge) (Marelli et al., 2014)

Findings on SICK

Wrong gold

Someone is playing with a **toad**	
N/**E**	Someone is playing with a **frog**

A couple is **not** looking at **a** map	
N/**C**	**A** couple is looking at **a** map

Inconsistent gold

A soccer ball is **not** rolling into **a** goal net	
C/**C**	**A** soccer ball is rolling into **a** goal net

A man in a hat is playing a **harp**	
E	A man is playing an **instrument**

Solved *hard* problems

The woman is **not** wearing glasses **or** a headdress	
C	A woman is wearing an **Egyptian** headdress

L. Abzianidze (2015): A tableau prover for natural logic and language

Failed proofs

Parser error

A small boy in a yellow shirt is laughing on the beach	
C/N	There is no small boy [in a yellow shirt [laughing on the beach]]

A man and a woman are shaking hands	
E/N	**Two persons** are shaking hands

Missing inference rule

25% of errors

It is **raining** on a walking man	
E/N	A man is walking in the **rain**

A man and woman are **talking**	
C/N	A man and a woman are **silent**

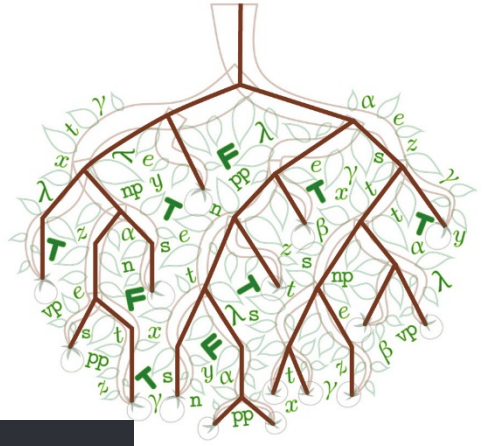
Missing lexical knowledge

50% of errors

Someone is holding a **hedgehog**	
E/N	Someone is holding a **small animal**

L. Abzianidze (2015): A tableau prover for natural logic and language

Pros & Cons



- ✓ Higher-order logic
- ✓ Semantic parsing ≈ syntactic parsing
- ✓ Highly reliable proofs
- ✗ Heavily hinges on syntactic parsing
- ✗ Knowledge is restricted to KBs

```
is_(european, person).
is_('boy', 'young man').
is_('young man', 'boy').
is_('polish', 'clean').
is_('jump', 'bounce').
is_('run', 'sprint').
is_('bikini', 'swimming suite').
is_(note, paper).
is_(fit, apply).
is_(wrestler, ringer).
is_(pour, put).
is_(vegetable, ingredient).
is_(fight, match).
is_(crowd, group).
```

Learning as Abduction

Approaches to NLI

Reasoning with Logic

Learn Lexical Knowledge

Interpretability

reasoning

puppy ⊑ young dog

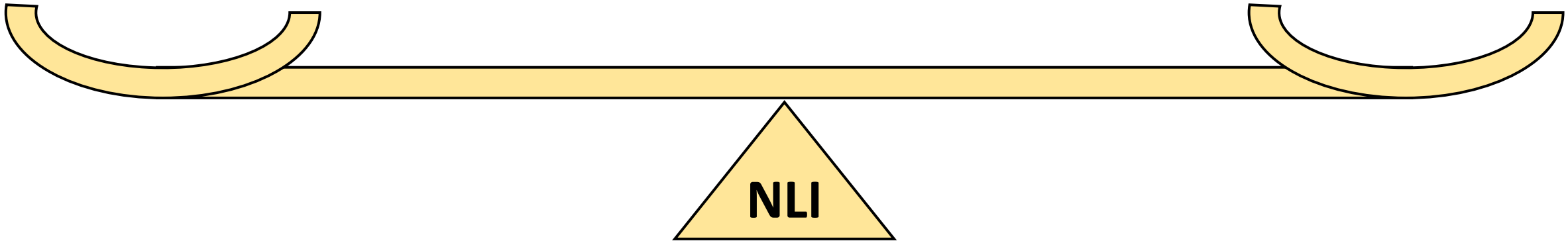
slice ⊑ cut

guitar | person

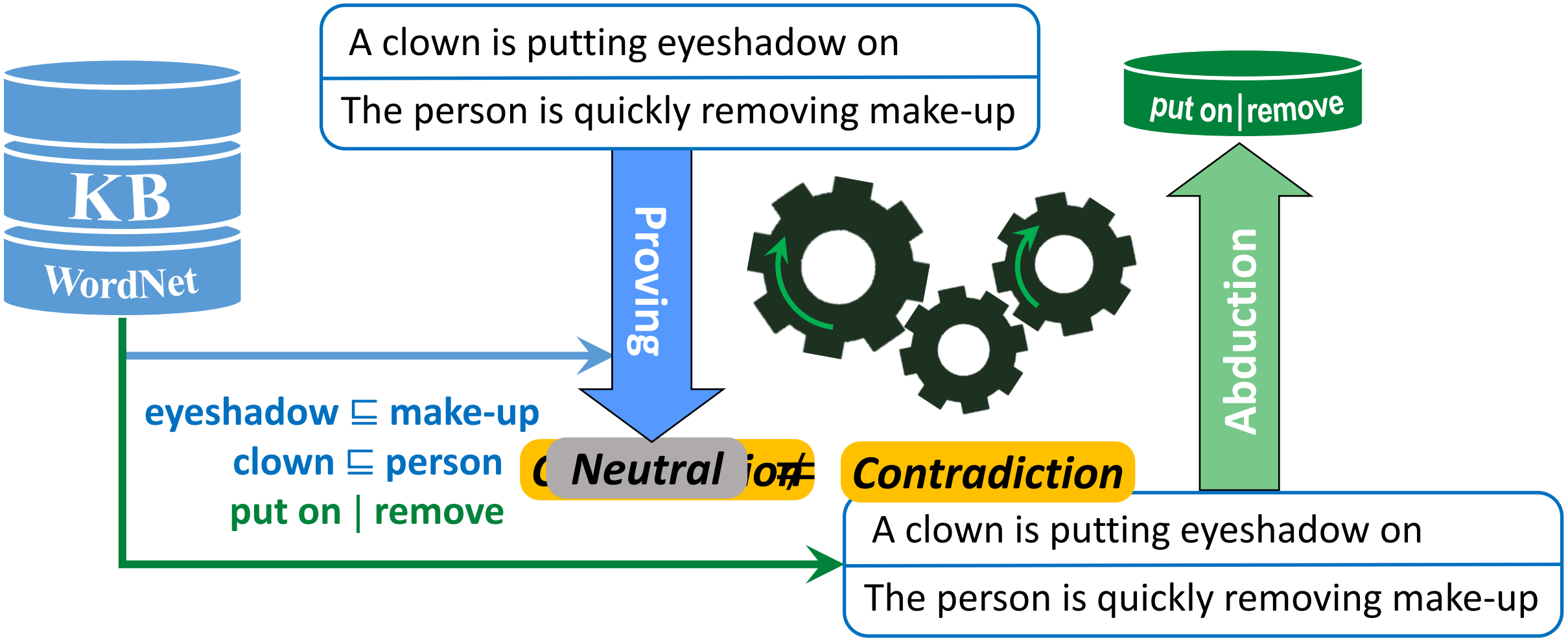
put on | take off

Learn from Data

- robust
- scalable
- easy to deploy
- no semanticists



Learning as abduction



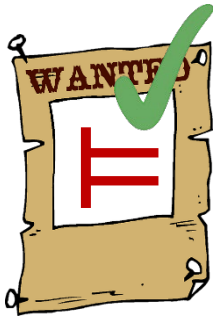
Questions

1. What is a feasible way to learn from data via abduction?
2. How to prevent learning pseudo-knowledge?
3. Is the learned knowledge enough alone?
4. How does the learned knowledge boosts performance?

Abductive reasoning in logic

Inference to the best explanation

$E \wedge$ ***Premise***



$\models$ ***Conclusion***

In the NLI context

Lovely little puppy is sleeping
~~lovely | little~~
lovely ⊑ little

E is **consistent** with *Premise*

~~puppy ⊑ dog; lovely ⊑ little~~
puppy ⊑ dog

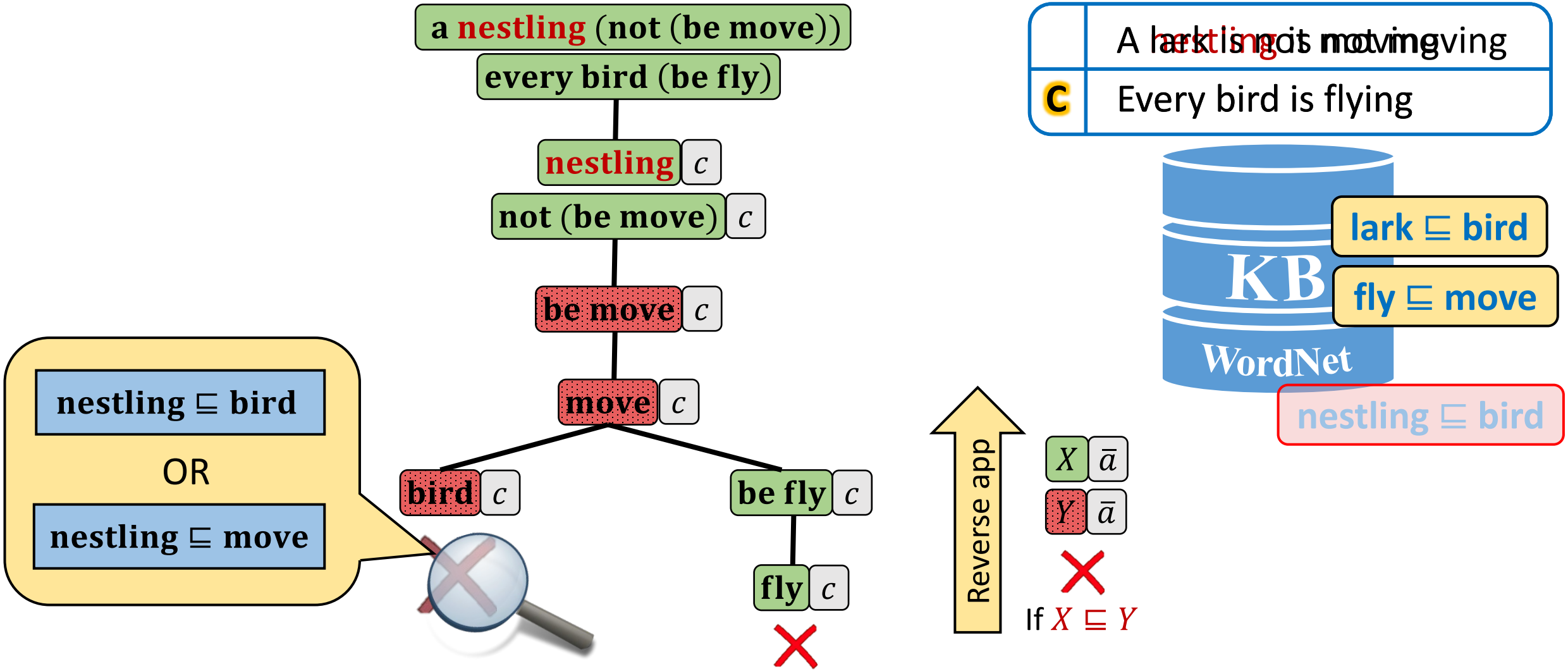
E is **minimal**

~~lovely little black puppy ⊑ dog~~
puppy ⊑ dog

E has a **pre-defined forms**

Mayer & Pirri (1993)

Learning as abduction

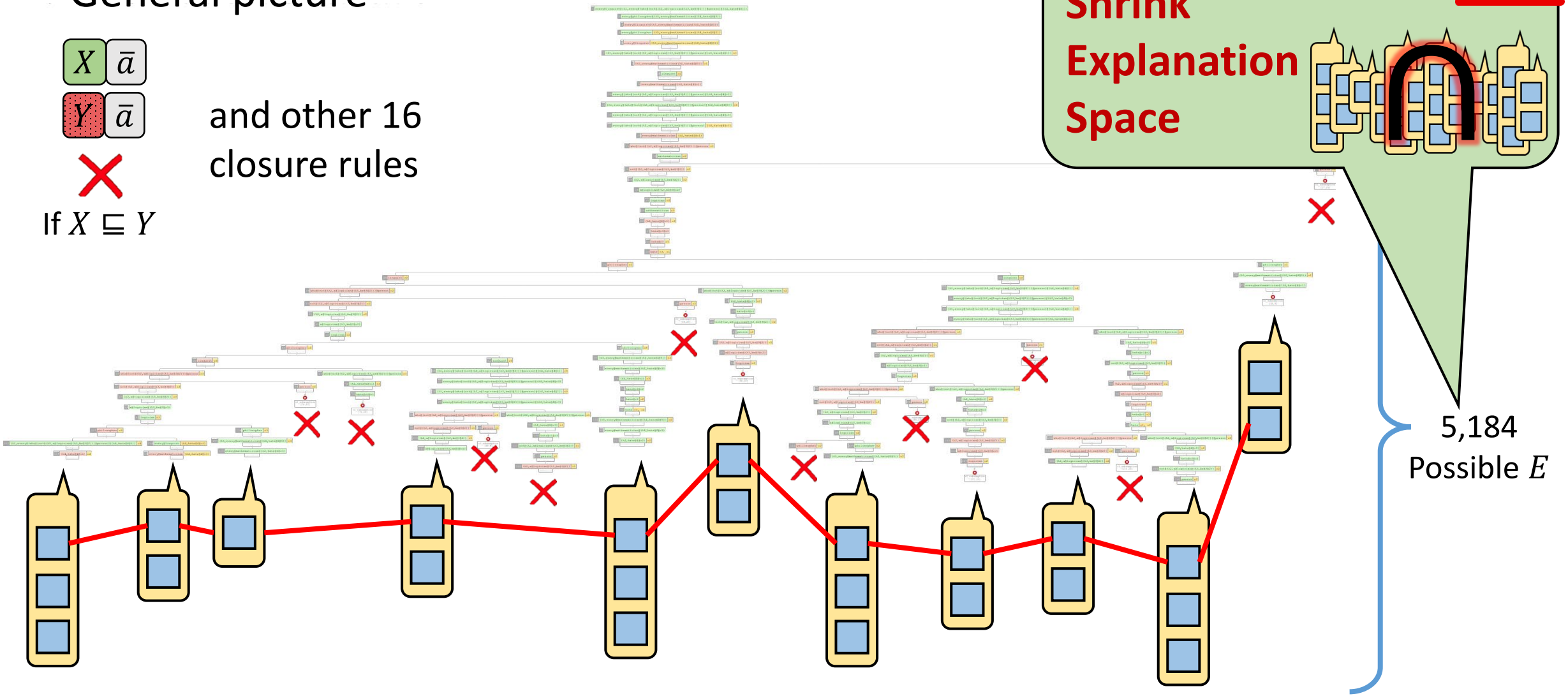


Abduction in Natural Tableau

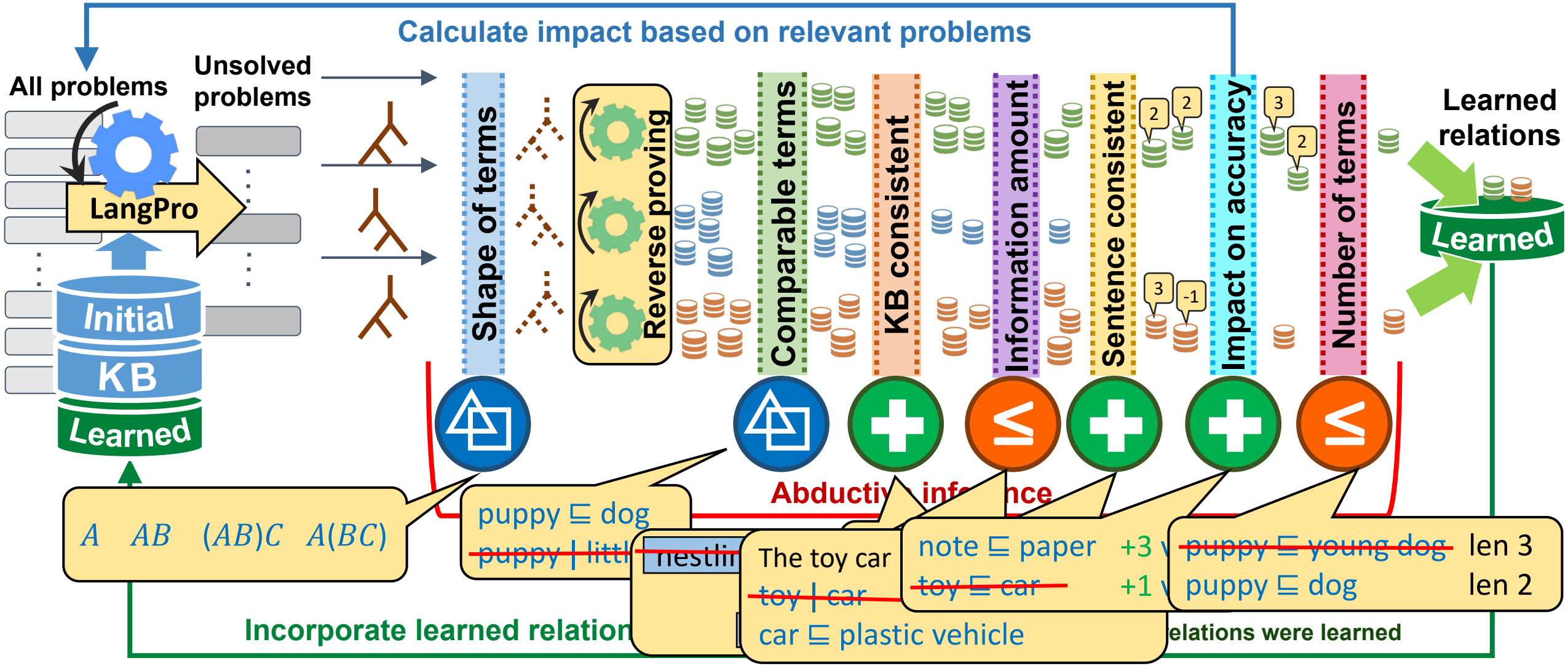
General picture

If $X \sqsubseteq Y$

and other 16 closure rules



Abductive learning workflow

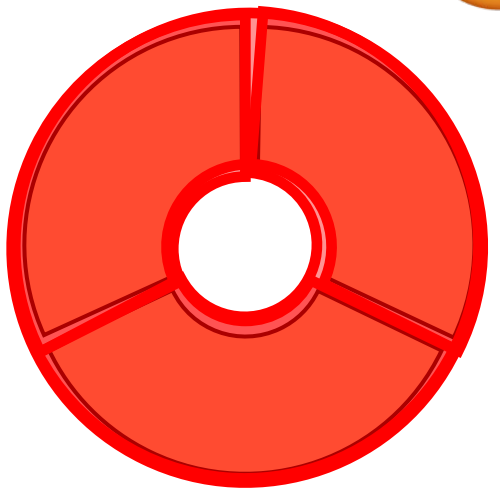


Experiments & Results

Experiment setup

Sentences Involving Compositional Knowledge (SICK, Marelli et al., 2014)

Train	5,000	3-fold cross validation
Test	4,927	unseen data



CCG parsers:

- **C&C** (Clark and Curran, 2007)
- **EasyCCG** (Lewis and Steedman, 2014)
- **DepCCG** (Yoshikawa et al., 2017)

LangPro:

Rule application limit: 50 & 800

https://github.com/kovvalsky/LangPro

Ablation & efficiency

3-fold CV on the **training data**, using only C&C parser

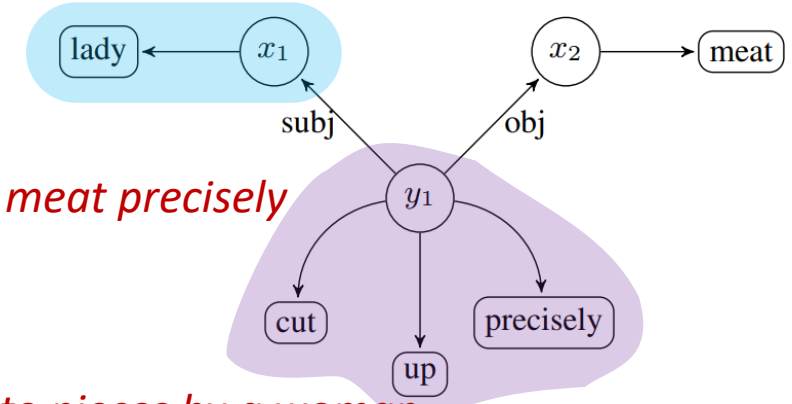
LangPro + Abduction All filters + WordNet	Av. accuracy on train fold %	Av. accuracy on test fold %
≤ 800 rule app.	89.02	82.90
≤ 50 rule app.	88.57	82.64
	Δ	Δ
−WordNet	−0.98	−2.44
+ KB	+0.04	+0.36

~10×faster

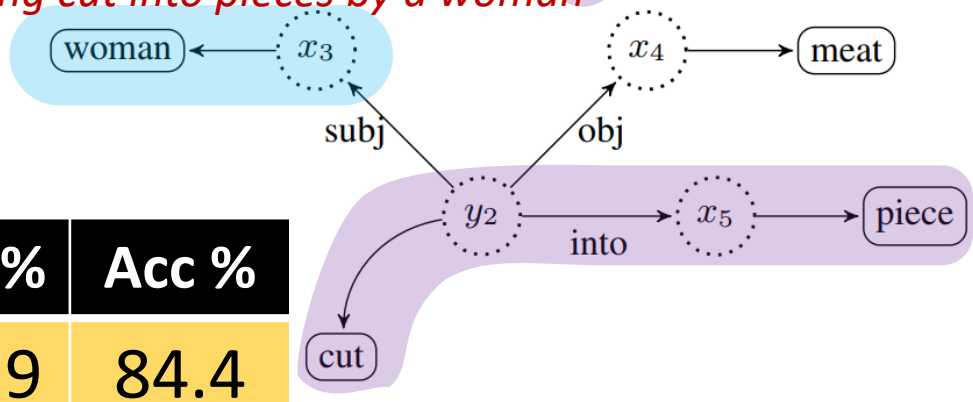
Results & comparison

LangPro + WN (accuracy % on test)		+ Abduction
C&C	81.3	+1.4
EasyCCG	81.1	+1.4
DepCCG	81.8	+1.2
D E C&C	83.0	+1.4
Abzianidze & Kogkalidis (2021): A Logic-Based Framework for Natural Language Inference in Dutch	77.2	+1.6

A lady is cutting up some meat precisely



Some meat is being cut into pieces by a woman



	Prec %	Rec%	Acc %
D E C&C	94.3	67.9	84.4
CCG2Lambda +P2P	84.2	77.3	84.3
Yanaka et al. (2018) D E C&C			

$\mathbf{precisely}\ m\ \mathbf{cut\_up}\ \boxed{w}$

$\mathbf{s\ piece}\ (\lambda x.\mathbf{cut}(\mathbf{into}\ x)m)\ \boxed{w}$

Learned *knowledge*

Correct	26,60%
Wrong	28,80%
Contextual	28,90%
Reversed	15,70%

In total 312

star ⊑ sky

	A barefoot man in pajamas is looking toward the **stars** and …
E	A barefoot man in pajamas is looking toward the **sky** and …

ride \| get

	A small girl is **riding in** a toy car
C	A small girl is **getting out of** a toy car

in ⊑ at

	A cyclist is biking in a snowy forest **in** the dark
E	A cyclist is biking in a snowy forest **at** night

cap ⊑ hat

	A man in a **cap** is playing a harp
E	A man in a **hat** is playing a harp

person ⊑ man

	Someone is drilling a hole in a strip of wood with a power drill
E	**A man** is drilling a hole in a piece of wood

dog ⊑ bulldog

	A monkey is brushing the **dog**
C	The monkey is not brushing a **bull dog**

acrobatics ⊑ trick

	… and performing **acrobatics** on a rail
E	… and performing a **trick** on a rail

lie down \| run around

	A squirrel is **lying down**
C	A squirrel is **running around** in circles

Answers

1. What is a feasible way to learn from data via abduction?
   Reduce the explanation space & apply the filters.

2. How to prevent learning pseudo-knowledge?
   The filters partially prevent pseudo-knowledge. However, it doesn't harm the performance.

3. Is the learned knowledge enough alone?
   No. WordNet is crucial for reaching the state-of-the-art results.

4. How does the learned knowledge boosts performance?
   It consistently increases Acc. while Prec. is still high

Conclusion

Natural proof system for natural logic (and language)

Learning as abduction: revesre rule applications to abduce knowledge from labeled inferences (currently severely restricted due to efficiency)

The tableau proofs are rarely wrong:

- helps to detects errors in gold labels of NLI datasets
- can be used to validate labels in NLI datasets
- provides explanatory reasoning

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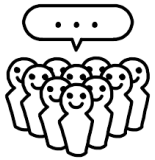

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