Learning as Abduction:
Trainable Natural Logic Theorem Prover for Natural Language Inference

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Every man is working

Everybody who is working has an expensive car

Every man owns a car

Entailment

Premise	Label	Hypothesis
A man inspects the uniform of a figure in some East Asian country.	contradiction	The man is sleeping.
An older and younger man smiling.	neutral	Two men are smiling and laughing at the cats playing on the floor.
A soccer game with multiple males playing.	entailment	Some men are playing a sport.

Time Flies Like an Arrow

Fruit Flies Like a Banana

His Bird Flew Outside

Article-Noun-Verb-Location

Noun does Verb in Location

Outside were his Birds that are flying

Location-Article-Noun-Verb

Noun does Verb in Location

flight : N

Noun

Miami : NP

Noun Phrase

X/Y Y ⇒ X

cancel : (S\NP)/NP **Huh??**

Y X\Y ⇒ X

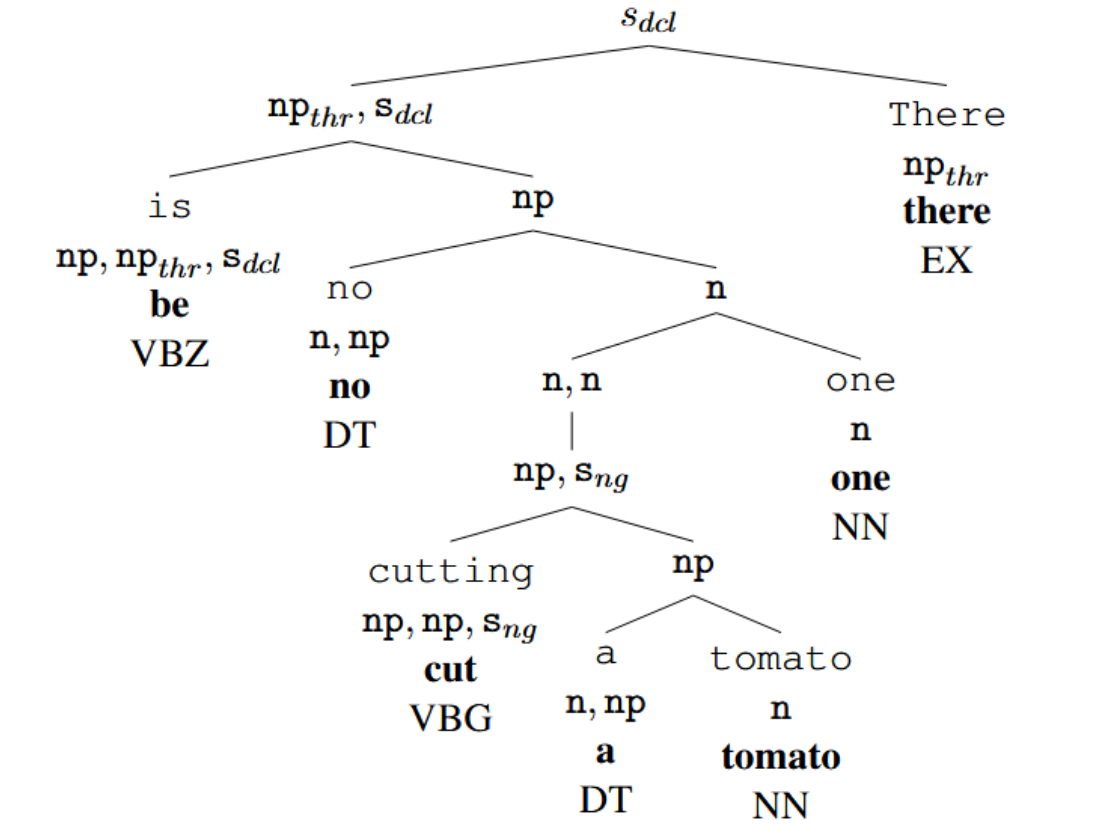
"John" "loves" "Mary"

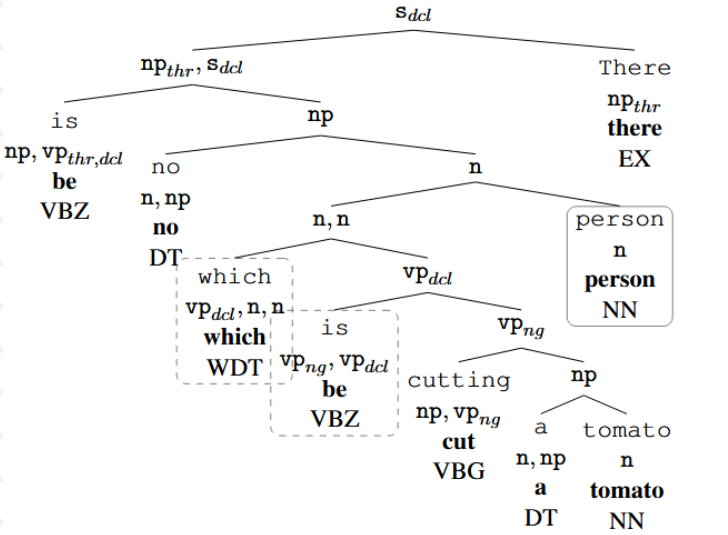
NP (S\NP)/NP NP X/Y Y ⇒ X

NP (S\NP) Y X\Y ⇒ X

S

$$\begin{aligned}
\mathtt{on}_{\mathtt{np},\mathtt{pp}}(\mathtt{ice}_{\mathtt{n}})_{\mathtt{np}} &\longrightarrow \mathtt{on}_{\mathtt{np},\mathtt{pp}}(\mathtt{a}_{\mathtt{n},\mathtt{np}}\,\mathtt{ice}_{\mathtt{n}}) \\
\mathtt{run}_{\mathtt{np},\mathtt{s}}(\mathtt{dogs}_{\mathtt{n}})_{\mathtt{np}} &\longrightarrow \mathtt{run}_{\mathtt{np},\mathtt{s}}(\mathtt{s}_{\mathtt{n},\mathtt{np}}\mathtt{dog}_{\mathtt{n}}) \\
(\mathtt{Dow}^{\mathtt{PER}}_{\mathtt{n},\mathtt{n}}\ \mathtt{Jones}^{\mathtt{PER}}_{\mathtt{n}})_{\mathtt{np}} &\longrightarrow \mathtt{Dow_Jones}_{\mathtt{np}} \\
(\mathtt{two}_{\mathtt{n},\mathtt{n}}\ \mathtt{dogs}_{\mathtt{n}})_{\mathtt{np}} &\longrightarrow \mathtt{two}_{\mathtt{n},\mathtt{np}}\ \mathtt{dogs}_{\mathtt{n}} \\
\mathtt{her}_{(\mathtt{pp},\mathtt{n}),\mathtt{np}}\ \mathtt{car}_{\mathtt{pp},\mathtt{n}} &\longrightarrow \mathtt{her}_{\mathtt{n},\mathtt{np}}\ \mathtt{car}_{\mathtt{n}} \\
\mathtt{who}_{\mathtt{w}} V(Q_{\mathtt{n},\mathtt{np}} N) &\longrightarrow Q_{\mathtt{n},\mathtt{np}}(\mathtt{who}_{\mathtt{w}'} V N) \\
\mathtt{nobody} &\longrightarrow \mathtt{no}_{\mathtt{n},\mathtt{np}}\ \mathtt{person}_{\mathtt{n}}
\end{aligned}$$


s_{dcl}
$\mathbf{np}_{thr}, \mathbf{s}_{dcl}$
There
$\mathbf{np}_{thr}$
there
EX
is
$\mathbf{np}, \mathbf{np}_{thr}, \mathbf{s}_{dcl}$
be
VBZ
np
no
n, np
no
DT
n
n, n
one
n
one
NN
$\mathbf{np}, \mathbf{s}_{ng}$
cutting
$\mathbf{np}, \mathbf{np}, \mathbf{s}_{ng}$
cut
VBG
np
a
n, np
a
DT
tomato
n
tomato
NN



$$\mathbf{b(no(w(b(c(a\ t)))p))th}$$

$$\mathbf{no}\ \big(\mathbf{w}(\mathbf{b}(\lambda x.\ \mathbf{a}\ \mathbf{t}(\lambda y.\ \mathbf{c}yx)))\mathbf{p}\big)\ \big(\lambda z.\ \mathbf{b}\ z\ \mathbf{th}\big)$$

$$\mathbf{a\ t}(\lambda x.\ \mathbf{no}\ \big(\mathbf{w}(\mathbf{b}(\mathbf{c}x))\mathbf{p}\big)\ \big(\lambda z.\ \mathbf{b}\ z\ \mathbf{th}\big))$$

$$\frac{X\ A\ B : [\,] : \mathbb{F}}{\begin{array}{c} A : [c] : \mathbb{T} \\ B : [c] : \mathbb{F} \\ \text{s.t. } X \in \{\texttt{all}, \texttt{every}\} \\ \text{and } c \text{ is a } \textit{fresh} \text{ term} \end{array}} \forall_F$$

$$\frac{A\ B : [\vec{C}] : \mathbb{X}}{A : [B, \vec{C}] : \mathbb{X}}\ \text{PUSH}$$

$$\frac{A : [B, \vec{C}] : \mathbb{X}}{A\ B : [\vec{C}] : \mathbb{X}}\ \text{PULL}$$

$$\frac{\begin{array}{c} A : [\vec{C}] : \mathbb{T} \\ B : [\vec{C}] : \mathbb{F} \end{array}}{\begin{array}{c} \times \\ \text{s.t. } A \leq B \end{array}} \leq\!\times$$

$$\frac{X\ A\ B : [\,] : \mathbb{F}}{A : [d] : \mathbb{F} \qquad B : [d] : \mathbb{F}} \exists_F$$
s.t. $X \in \{\texttt{some}, \texttt{a}\}$ and d is an *old* term

$$\frac{\texttt{not}\ A : [\vec{C}] : \mathbb{X}}{A : [\vec{C}] : \overline{\mathbb{X}}}\ \text{NOT}$$

Every penguin is working

Every bird who is working has an expensive car

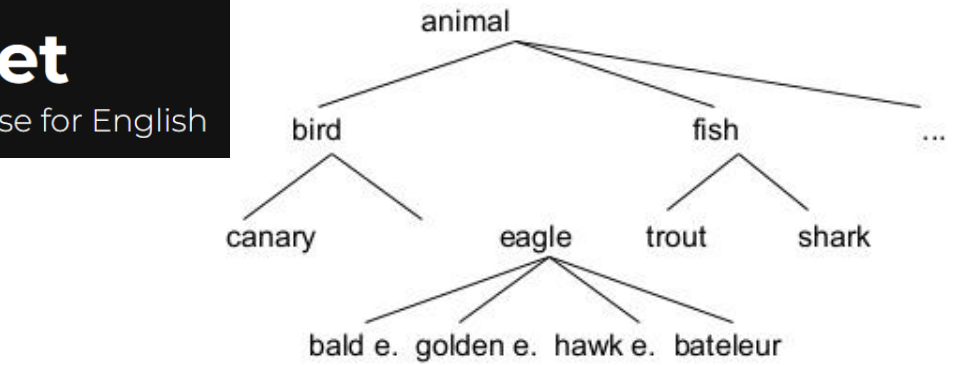
Every penguin owns a car

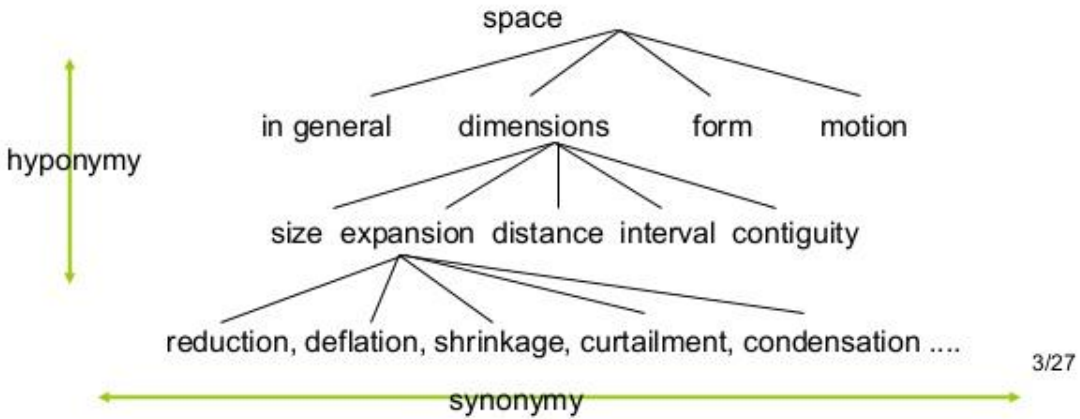
ENTAILMENT

PRINCETON UNIVERSITY

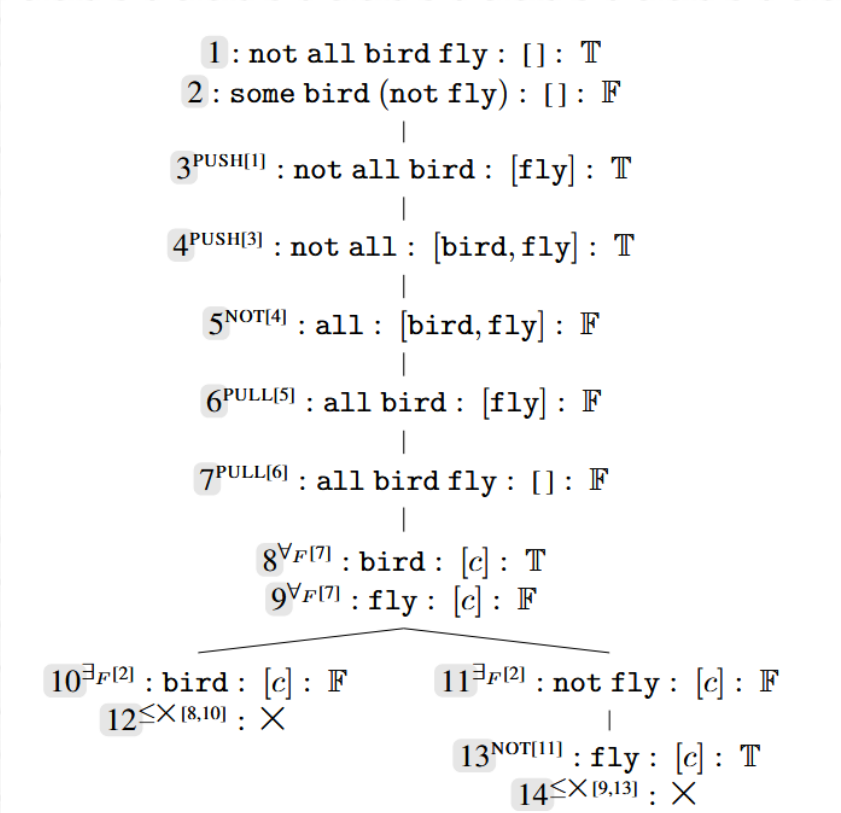
WordNet

A Lexical Database for English





not all birds fly → some bird does not fly



ID	Gold/LP	Problem (premise ? conclusion)
3670	E/N	It is raining on a walking man ? A man is walking in the rain
219	E/N	There is no girl in white dancing ? A girl in white is dancing
5248	N/E	Someone is playing with a toad ? Someone is playing with a frog
8490	N/C	A man with a shirt is holding a football ? A man with no shirt is holding a football
7402	N/C	There is no man and child kayaking through gentle waters ? A man and a young boy are riding in a yellow kayak
1431	C/C	A man is playing a guitar ? A man is not playing a guitar
8913	N/C	A couple is not looking at a map ? A couple is looking at a map

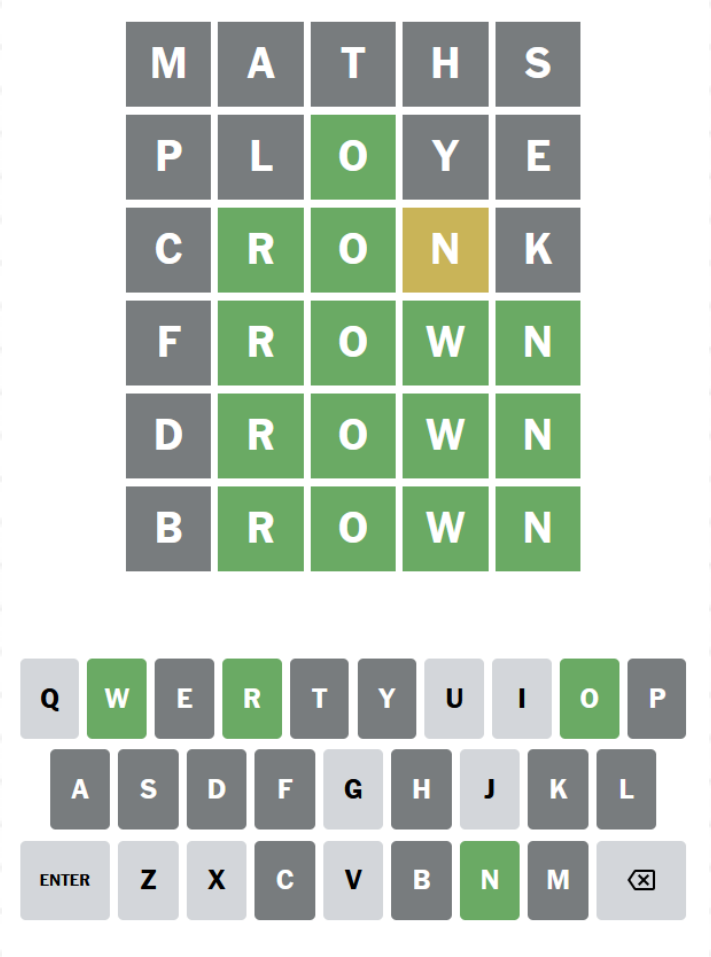
System \ Measure+	Acc%
Illinois-LH	**84.57**
ECNU	83.64
UNAL-NLP	83.05
SemantiKLUE	82.32
The Meaning Factory	81.59
LangPro Hybrid-800	81.35
UTexas	73.23
Prob-FOL	76.52
Nutcracker	78.40
Baseline (majority)	56.69


CLUEDO
CLUEDO
MISS SCARLETT

Information: John has a gun and was in the kitchen
Victim was shot in kitchen

Hypothesis: John was the murderer

Answer: Correct


M A T H S
P L O Y E
C R O N K
F R O W N
D R O W N
B R O W N
Q W E R T Y U I O P
A S D F G H J K L
ENTER Z X C V B N M

Hypothesis: Cronk
Answer: Incorrect

→

Information: R, O 2nd/3rd letter
N in the word
C, K not in word

Premise&Hypothesis + Rules = Entailment

$1 : \texttt{not all bird fly} : [\,] : \mathbb{T}$
$2 : \texttt{some bird (not fly)} : [\,] : \mathbb{F}$

$$\frac{X\ A\ B : [\,] : \quad}{\begin{array}{l} A : [c] : \\ B : [c] : \end{array}} \quad \text{s.t. } X \in \{\texttt{all}, \texttt{every}\} \text{ and } c \text{ is a } \textit{fresh} \text{ term}$$

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Conclusion

$1 : \texttt{not all bird fly} : [\,] : \mathbb{T}$
$2 : \texttt{some bird (not fly)} : [\,] : \mathbb{F}$
$3^{\text{PUSH}[1]} : \texttt{not all bird} : [\texttt{fly}] : \mathbb{T}$
$4^{\text{PUSH}[3]} : \texttt{not all} : [\texttt{bird}, \texttt{fly}] : \mathbb{T}$
$5^{\text{NOT}[4]} : \texttt{all} : [\texttt{bird}, \texttt{fly}] : \mathbb{F}$
$6^{\text{PULL}[5]} : \texttt{all bird} : [\texttt{fly}] : \mathbb{F}$
$7^{\text{PULL}[6]} : \texttt{all bird fly} : [\,] : \mathbb{F}$
$8^{\forall_F[7]} : \texttt{bird} : [c] : \mathbb{T}$
$9^{\forall_F[7]} : \texttt{fly} : [c] : \mathbb{F}$
$10^{\exists_F[2]} : \texttt{bird} : [c] : \mathbb{F}$
$12^{\leq\times[8,10]} : \times$
$11^{\exists_F[2]} : \texttt{not fly} : [c] : \mathbb{F}$
$13^{\text{NOT}[11]} : \texttt{fly} : [c] : \mathbb{T}$
$14^{\leq\times[9,13]} : \times$

Premise&Hypothesis + Entailment = Rules

$1 : \texttt{not all bird fly} : [] : \mathbb{T}$
$2 : \texttt{some bird (not fly)} : [] : \mathbb{F}$

Conclusion

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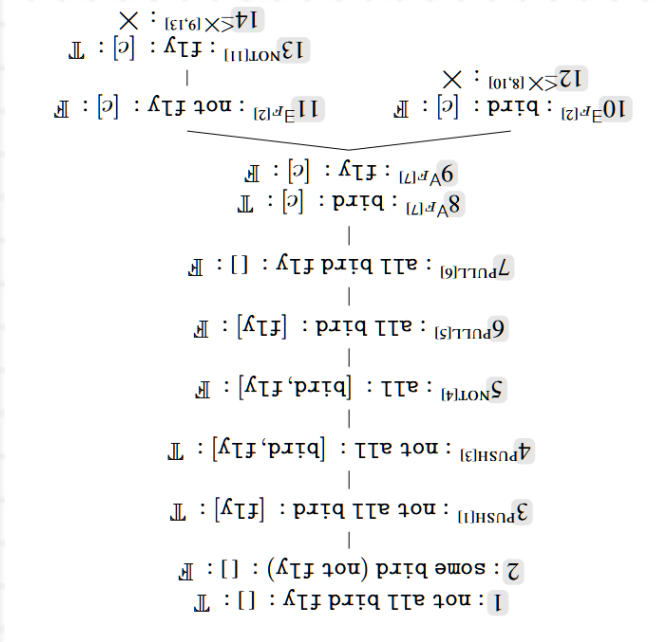
$$\frac{A\ B : [] : \mathbb{F}}{A : [c] : \mathbb{T} \quad B : [c] : \mathbb{F}}\ \forall_F$$
s.t. $X \in \{\texttt{all}, \texttt{every}\}$
and c is a *fresh* term



Inventory of Rules (The logic we can use to take relationships from the sentence)

$$\frac{X\ A\ B:\ [\,]:\ \mathbb{F}}{\begin{array}{c}A:\ [c]:\ \mathbb{T}\\ B:\ [c]:\ \mathbb{F}\\ \text{s.t. } X \in \{\texttt{all}, \texttt{every}\}\\ \text{and } c \text{ is a } \textit{fresh} \text{ term}\end{array}}\forall_F$$

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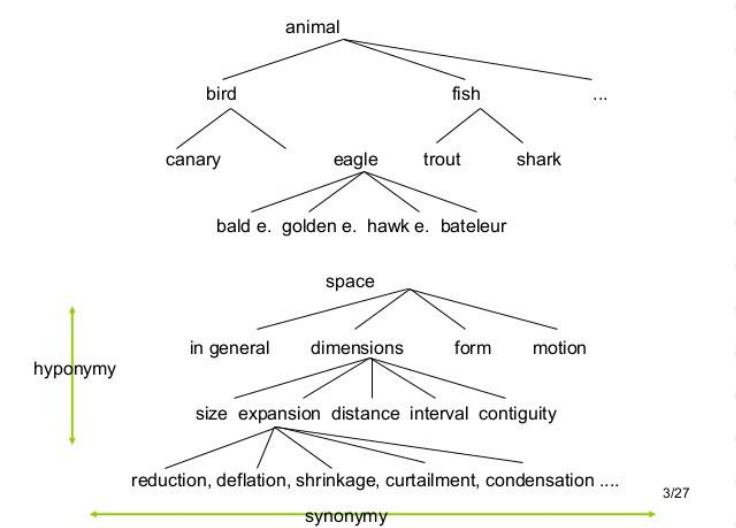
$$\frac{X\ A\ B:\ [\,]:\ \mathbb{F}}{\begin{array}{cc}A:\ [d]:\ \mathbb{F} & B:\ [d]:\ \mathbb{F}\\ \multicolumn{2}{c}{\text{s.t. } X \in \{\texttt{some}, \texttt{a}\} \text{ and } d \text{ is an } \textit{old} \text{ term}}\end{array}}\exists_F$$

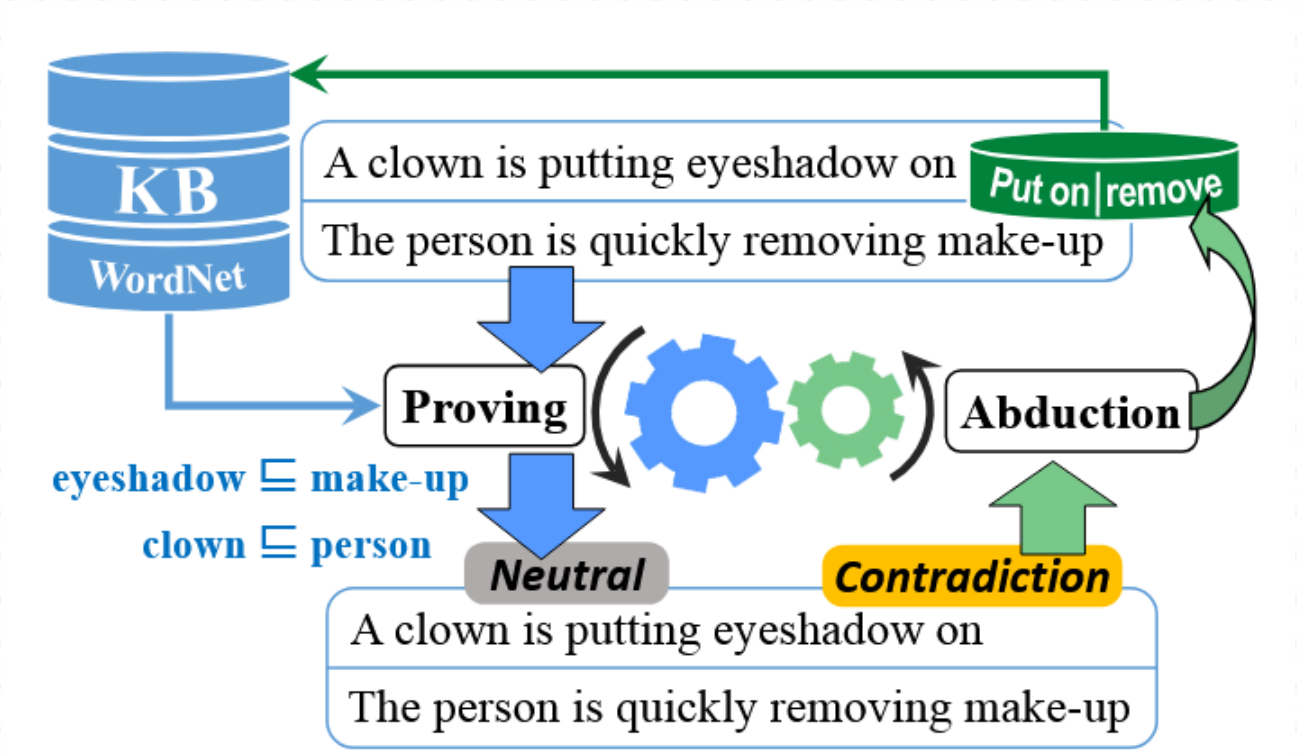
$$\frac{\texttt{not}\ A:\ [\vec{C}]:\ \mathbb{X}}{A:\ [\vec{C}]:\ \overline{\mathbb{X}}}\text{NOT}$$

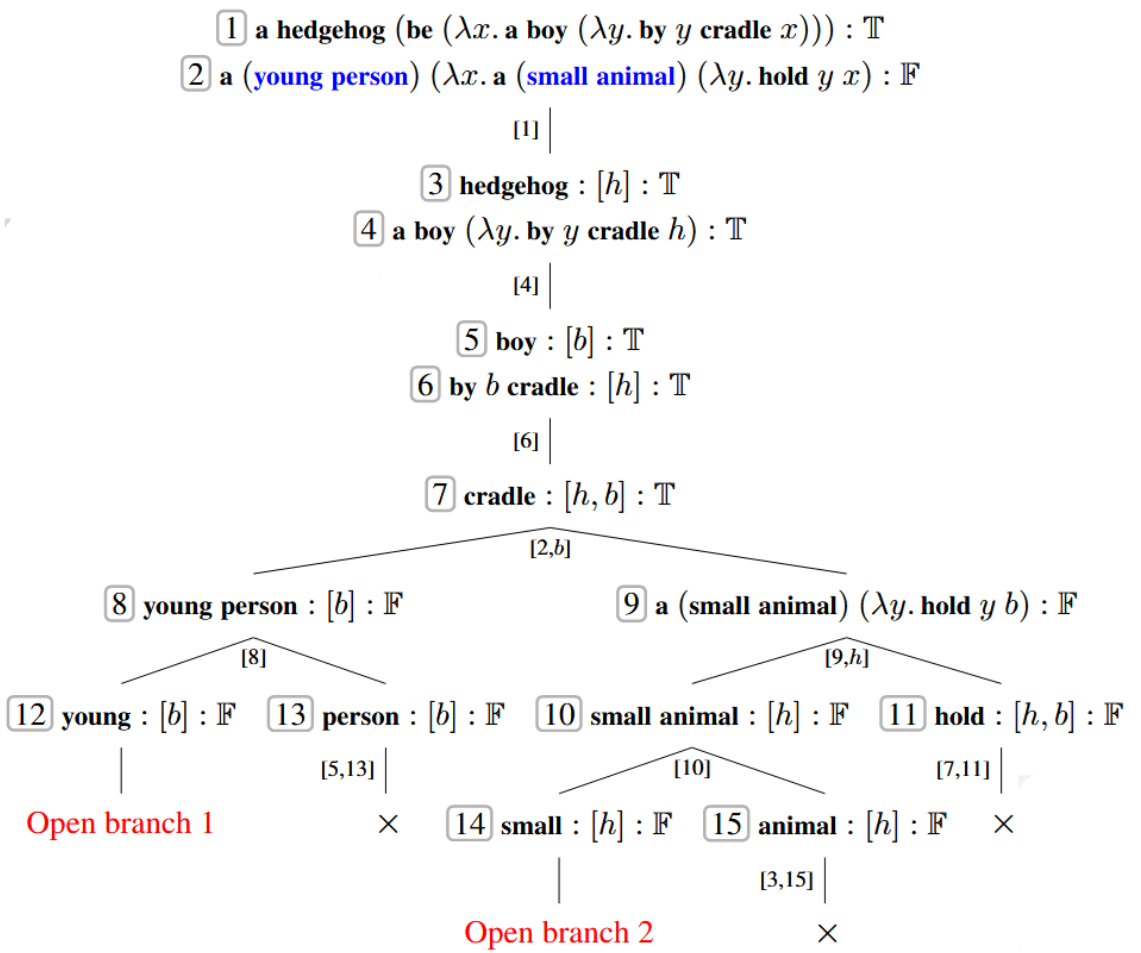
Knowledge Base (The relationships we have hardcoded in before we begin the problem)



clean | dirty

cradle $\sqsubseteq$ hold


KB
WordNet
A clown is putting eyeshadow on
The person is quickly removing make-up
Put on | remove
Proving
Abduction
eyeshadow ⊑ make-up
clown ⊑ person
Neutral
Contradiction
A clown is putting eyeshadow on
The person is quickly removing make-up



Open branch 2

1
2
3
4
5
6
7
9
10
14

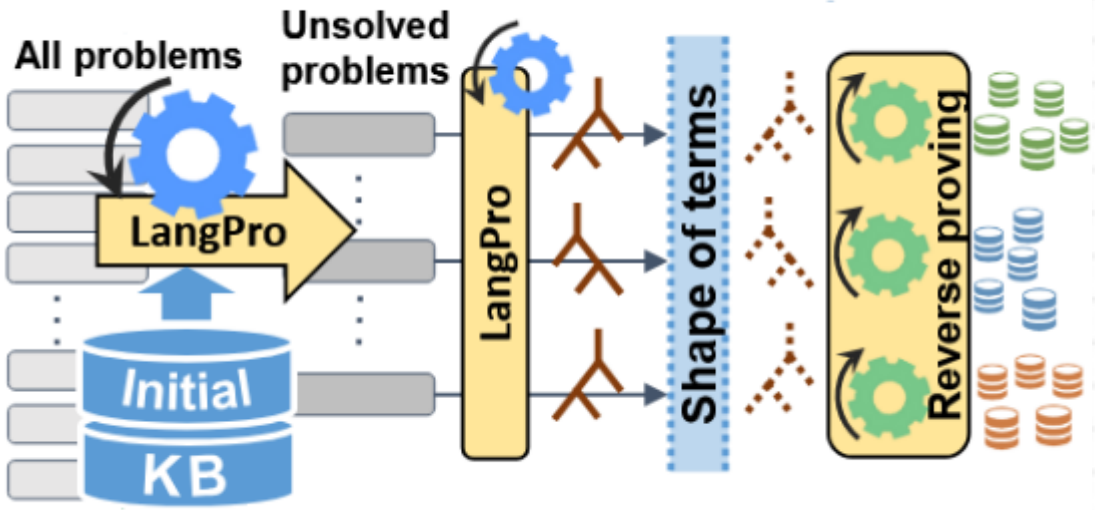
$b_1^2 : \{\textbf{hedgehog} \sqsubseteq \textbf{small animal}\}$

$b_2^2 : \{\textbf{hedgehog} \sqsubseteq \textbf{small}\}$

~~$b_3^2 : \{\textbf{hedgehog} \mid \textbf{by } b \textbf{ cradle}\}$~~

~~$b_4^2 : \{\textbf{by } b \textbf{ cradle} \sqsubseteq \textbf{small}\}$~~

~~$b_5^2 : \{\textbf{by } b \textbf{ cradle} \sqsubseteq \textbf{small animal}\}$~~


All problems
Unsolved problems
LangPro
Initial
KB
LangPro
Shape of terms
Reverse proving

Filter 1 (Using comparable terms):

To avoid pseudo knowledge we want the types of words added to our KB to match or make sense

$$\textbf{boy} \sqsubseteq \textbf{young} \qquad \textbf{boy} \mid \textbf{hedgehog}$$

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Filter 2 (KB Consistent):

We want to avoid any inconsistencies with our established knowledge base.

$$\mathbf{hedgehog} \mid \mathbf{animal}$$

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We want to avoid any inconsistencies with our established knowledge base.

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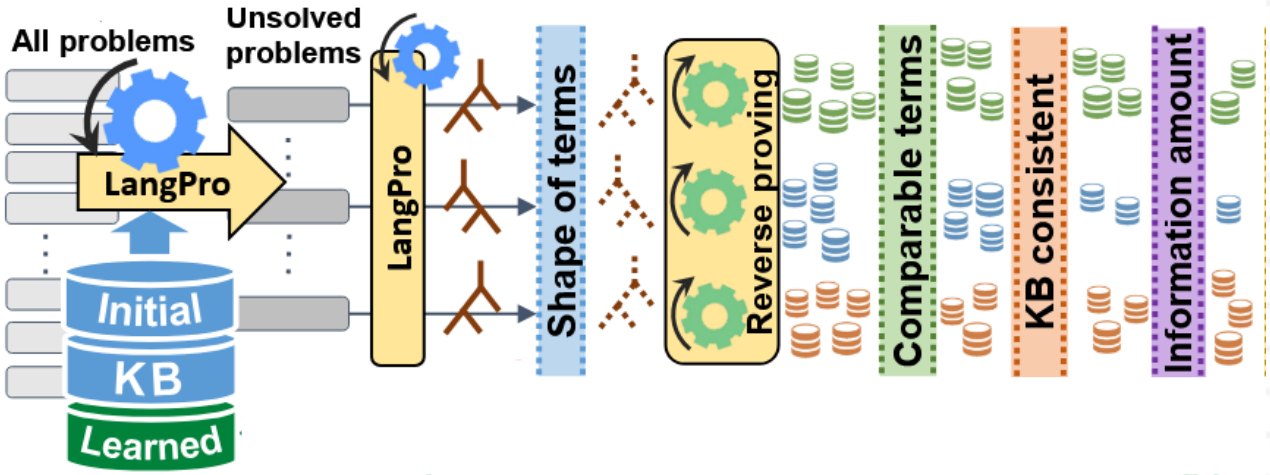
Filter 3 (Information amount):

We will not store hyperspecific information. Limit it to 4 terms

$$(\mathbf{and\ big\ brown})\ \mathbf{dog}$$


All problems
Unsolved problems
LangPro
LangPro
Initial
KB
Learned
Shape of terms
Reverse proving
Comparable terms
KB consistent
Information amount

Tie Breaker 1 (Semantic consistency):

How much a gained piece of knowledge is relevant to other NLI problems.

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Tie Breaker 2 (Impact on Accuracy):

How many previous problems does it improve/unimprove

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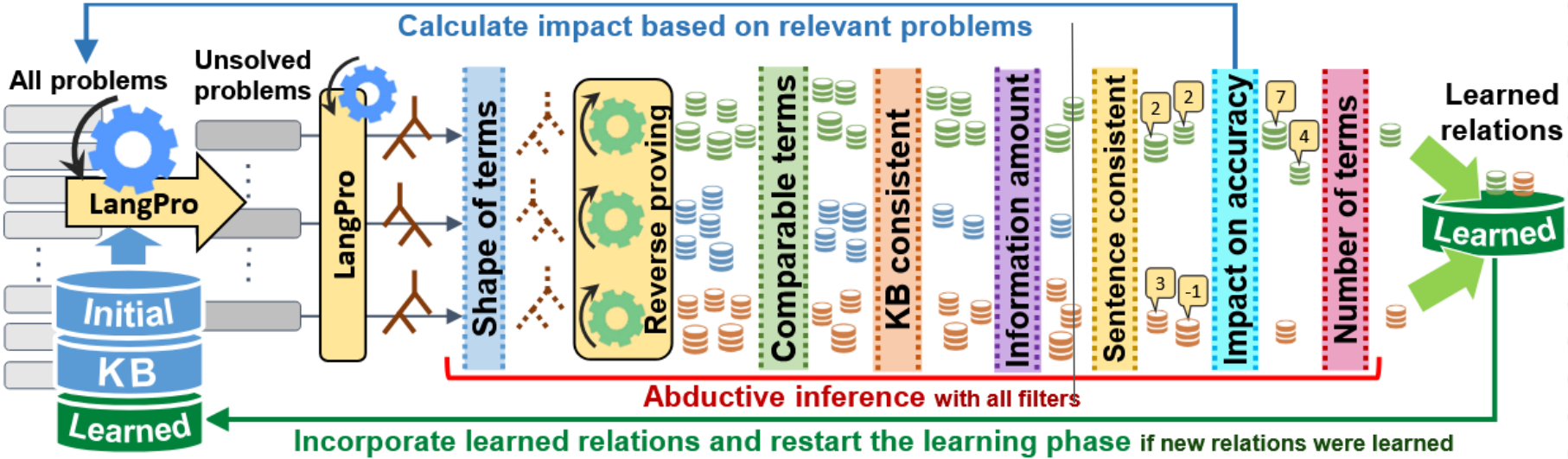
How much a gained piece of knowledge is relevant to other NLI problems.

Tie Breaker 2 (Impact on Accuracy):

How many previous problems does it improve/unimprove

Tie Breaker 3 (Amount of Knowledge gained):

How many lexical relations do we actually return


Calculate impact based on relevant problems
All problems
Unsolved problems
LangPro
LangPro
Initial
KB
Learned
Shape of terms
Reverse proving
Comparable terms
KB consistent
Information amount
Sentence consistent
Impact on accuracy
Number of terms
2
2
3
-1
7
4
Learned relations
Learned
Abductive inference with all filters
Incorporate learned relations and restart the learning phase if new relations were learned

LangPro + Abductive learning: All filters + WordNet	Train av. acc%	CPU time
max 800 rule applications	89.02	2041
max 50 rule applications	88.57	220