

Deep Deductive Reasoning over Semantic Web Logics



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Neuro-symbolic AI

**Publications on neuro-symbolic AI in major conferences
(research papers only):**



conference	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	total
ICML	0	0	0	0	0	1	3	2	5	6	17
NeurIPS	0	0	0	0	0	0	0	4	2	4	10
AAAI	0	0	0	0	0	1	0	1	1	1	4
IJCAI	1	0	0	0	0	0	2	2	0	2	7
ICLR	N/A	N/A	0	0	0	0	1	1	1	3	6
total	1	0	0	0	0	2	6	10	9	16	44

See

Md Kamruzzaman Sarker, Lu Zhou, Aaron Eberhart, Pascal Hitzler

Neuro-Symbolic Artificial Integration: Current Trends

**AI Communications, to appear; <https://arxiv.org/abs/2105.05330>
for more analysis.**

(Computer Science perspective)

- **Let's try to get the best of both worlds:**
 - very powerful machine learning paradigm
 - robust to data noise
 - easy to understand and assess by humans
 - good at symbol manipulation
 - work seamlessly with background (domain) knowledge
- **How to do that?**
 - Endow connectionist systems with symbolic components?
 - Add connectionist learning to symbolic reasoners?

Historic Perspective

**Workshop Series on Neural-Symbolic Learning and Reasoning, since 2005.
Joint with Artur d'Avila Garcez.**

<http://neural-symbolic.org/>

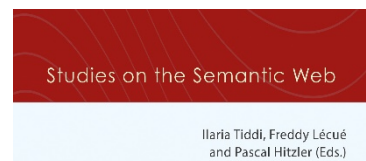
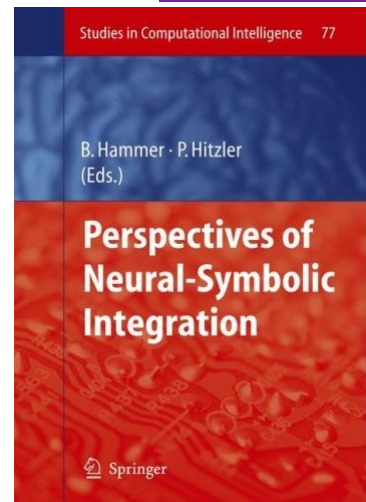
**Barbara Hammer and Pascal Hitzler (eds), Perspectives of
Neural-Symbolic Integration, Springer, 2007**

Neural-Symbolic Learning and Reasoning: A Survey and Interpretation

**Tarek R. Besold, Artur d'Avila Garcez, Sebastian Bader,
Howard Bowman, Pedro Domingos, Pascal Hitzler,
Kai-Uwe Kuehnberger, Luis C. Lamb, Daniel Lowd,
Priscila Machado Vieira Lima, Leo de Penning, Gadi Pinkas,
Hoifung Poon, Gerson Zaverucha**

<https://arxiv.org/abs/1711.03902> (2017)

**Ilaria Tiddi, Freddy Lecue, Pascal Hitzler (eds.), Knowledge Graphs
for eXplainable Artificial Intelligence: Foundations, Applications and
Challenges. Studies on the Semantic Web Vol. 47, IOS Press, 2020.**



Forthcoming Book

Neuro-symbolic Artificial Intelligence: The State of the Art

Pascal Hitzler and Md Kamruzzaman Sarker, editors

IOS Press, FAIA series, to appear

Preliminary TOC:



Preface: The 3rd AI wave is coming, and it needs a theory

Frank van Harmelen

Introduction

Pascal Hitzler, Md Kamruzzaman Sarker

1. Neural-symbolic Learning and Reasoning: A Survey and Interpretation

Tarek R. Besold, Artur d'Avila Garcez, Sebastian Bader, Howard Bowman, Pedro Domingos, Pascal Hitzler, Kai-Uwe Kühnberger, Luis C. Lamb, Priscila Machado Vieira Lima, Leo de Penning, Gadi Pinkas, Hoifung Poon, Gerson Zaverucha

2. Symbolic Reasoning in Latent Space: Classical Planning as an Example

Masataro Asai, Hiroshi Kajino, Alex Fukunaga, Christian Muise

3. Logic meets Learning: From Aristotle to Neural Networks

Vaishak Belle

4. Graph Reasoning Networks and Applications

Qingxing Cao, Wentao Wan, Xiaodan Liang, Liang Lin

5. Answering natural-language questions with neuro-symbolic knowledge bases

William W. Cohen, Haitian Sun, Pat Verga

6. Tractable Boolean and Arithmetic Circuits

Adnan Darwiche

7. Neuro-Symbolic AI = Neural + Logical + Probabilistic AI

Robin Manhaeve, Giuseppe Marra, Thomas Demeester, Sebastijan Dumančić, Angelika Kimmig, Luc De Raedt

8. A Constraint-Based Approach to

Learning and Reasoning

Michelangelo Diligenti, Francesco Giannini, Marco Gori, Marco Maggini, Giuseppe Marra

9. Spike-based symbolic computations on bit strings and numbers

Ceca Krašniković, Wolfgang Maass, Robert Legenstein

10. Explainable Neuro-Symbolic Hierarchical Reinforcement Learning

Daoming Lyu, Fangkai Yang, Hugh Kwon, Bo Liu, Wen Dong, Levent Yilmaz

11. Neuro-Symbolic Semantic Reasoning

Bassem Makni, Monireh Ebrahimi, Dagmar Gromann, Aaron Eberhart

12. Learning Reasoning Strategies in End-to-End Differentiable Proving

Pasquale Minervini, Sebastian Riedel, Pontus Stenetorp, Edward Grefenstette, Tim Rocktäschel

13. Generalizable Neuro-symbolic Systems for Commonsense Question Answering

Alessandro Oltramari, Jonathan Francis, Filip Ilievski, Kaixin Ma, Roshanak Mirzaee

14. Combining Probabilistic Logic and Deep Learning for Self-Supervised Learning

Hoifung Poon, Hai Wang, Hunter Lang

15. Human-Centered Concept Explanations for Neural Networks

Chih-Kuan Yeh, Been Kim, Pradeep Ravikumar

16. Abductive Learning

Zhi-Hua Zhou, Yu-Xuan Huang

Deep Deductive Reasoners

Monireh Ebrahimi, Aaron Eberhart, Federico Bianchi, Pascal Hitzler,
Towards Bridging the Neuro-Symbolic Gap: Deep Deductive Reasoners.
Applied Intelligence 51 (9), 6326-6348, 2021.

Pascal Hitzler, Frank van Harmelen
A reasonable Semantic Web.
Semantic Web 1 (1-2), 39-44, 2010.

Deep Deductive Reasoners



- We trained deep learning systems to do deductive reasoning.
- Why is this interesting?
 - For dealing with **noisy data** (where symbolic reasoners do very poorly).
 - For **speed**, as symbolic algorithms are of very high complexity.
 - Out of **principle** because we want to learn about the capabilities of deep learning for complicated cognitive tasks.
 - To perhaps begin to understand how our (neural) brains can learn to do highly symbolic tasks like formal logical reasoning, or in more generality, mathematics.
A fundamental quest in **Cognitive Science**.

Reasoning as Classification



- Given a set of logical formulas (a theory).
- Any formula expressible over the same language is either
 - a logical consequence or
 - not a logical consequence.
- This can be understood as a **classification problem** for machine learning.
- It turns out to be a really hard machine learning problem.

Knowledge Materialization



- Given a set of logical formulas (a theory).
- Produce all logical consequences **under certain constraints**.
- Without **the qualifier** this is in general not possible as the set of all logical consequences is infinite.
- So we have to **constrain** to consequences of, e.g., a certain syntactic form. For relatively simple logics, this is often reasonably possible.

Published deep deductive reasoning work

paper	logic	transfer	generative	scale	performance
[12]	RDFS	yes	no	moderate	high
[25]	RDFS	no	yes	low	high
[10]	\mathcal{EL}^+	yes	no	moderate	low
[20]	OWL RL	no*	no	low	high
[6]	FOL	no	yes	very low	high
(new)	RDFS	yes	yes	moderate	high
(new)	EL+	yes	yes	moderate	high



[12]: Ebrahimi, Sarker, Bianchi, Xie, Eberhart, Doran, Kim, **Hitzler**,
AAAI-MAKE 2021

[25]: Makni, Hendler, SWJ 2019

[10]: Eberhart, Ebrahimi, Zhou, Shimizu, **Hitzler**, AAAI-MAKE 2020

[20]: Hohenecker, Lukasiewicz, JAIR 2020

[6]: Bianchi, **Hitzler**, AAAI-MAKE 2019

(new): Ebrahimi, Eberhart, **Hitzler**, June 2021

Schedule



1. **Intro (Pascal Hitzler)**
2. **Memory Networks for RDFS (Monireh Ebrahimi)**
3. **LSTMs for EL+ (Aaron Eberhart)**
4. **Pointer Networks for RDFS and EL+ (Monireh Ebrahimi)**
5. **LTNs for FOL (Federico Bianchi)**
6. **Conclusion (Pascal Hitzler)**



Thanks!

Conclusions

Conclusions



- **Bridging the neuro-symbolic gap is still a major quest.**
- **Research on Deep Deductive Reasoning is at the heart of neuro-symbolic Artificial Intelligence**
- **It's difficult!**
- **Research is needed to push the envelope with respect to core aspects such as**
 - **more complex logics**
 - **higher reasoning accuracy**
 - **better transfer**
 - **scalability**

Thanks!

References



Monireh Ebrahimi, Aaron Eberhart, Federico Bianchi, Pascal Hitzler, Towards Bridging the Neuro-Symbolic Gap: Deep Deductive Reasoners. Applied Intelligence 51 (9), 6326-6348, 2021.

Barbara Hammer and Pascal Hitzler (eds), Perspectives on Neural-Symbolic Integration. Springer, 2007

Tarek R. Besold, Artur d'Avila Garcez, Sebastian Bader, Howard Bowman, Pedro Domingos, Pascal Hitzler, Kai-Uwe Kuehnberger, Luis C. Lamb, Daniel Lowd, Priscila Machado Vieira Lima, Leo de Penning, Gadi Pinkas, Hoifung Poon, Gerson Zaverucha, Neural-Symbolic Learning and Reasoning: A Survey and Interpretation. <https://arxiv.org/abs/1711.03902> (2017)

**Md Kamruzzaman Sarker, Lu Zhou, Aaron Eberhart, Pascal Hitzler
Neuro-Symbolic Artificial Integration: Current Trends
AI Communications, to appear.**

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Federico Bianchi, Pascal Hitzler, On the Capabilities of Logic Tensor Networks for Deductive Reasoning. In: Andreas Martin, Knut Hinkelmann, Aurna Gerber, Doug Lenat, Frank van Harmelen, Peter Clark (eds.), Proceedings of the AAI 2019 Spring Symposium on Combining Machine Learning with Knowledge Engineering (AAI-MAKE 2019) Stanford University, Palo Alto, California, USA, March 25-27, 2019, Stanford University, Palo Alto, California, USA, March 25-27, 2019. CEUR Workshop Proceedings 2350, CEUR-WS.org 2019.



Aaron Eberhart, Monireh Ebrahimi, Lu Zhou, Cogan Shimizu, Pascal Hitzler, Completion Reasoning Emulation for the Description Logic EL+. In: Andreas Martin, Knut Hinkelmann, Hans-Georg Fill, Aurna Gerber, Doug Lenat, Reinhard Stolle, Frank van Harmelen (eds.), Proceedings of the AAI 2020 Spring Symposium on Combining Machine Learning and Knowledge Engineering in Practice, AAI-MAKE 2020, Palo Alto, CA, USA, March 23-25, 2020, Volume I.

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Monireh Ebrahimi, Md Kamruzzaman Sarker, Federico Bianchi, Ning Xie, Aaron Eberhart, Derek Doran, Hyeongsik Kim, Pascal Hitzler, Neuro-Symbolic Deductive Reasoning for Cross-Knowledge Graph Entailment. In: Proc. AAAI-MAKE 2021.



Bassem Makni, James Hendler, Deep learning for noise-tolerant RDFS reasoning. Semantic Web 10(5): 823-862 (2019)

Monireh Ebrahimi, Aaron Eberhart, Pascal Hitzler, On the Capabilities of Pointer Networks for Deep Deductive Reasoning. June 2021.

<https://arxiv.org/abs/2106.09225>

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Federico Bianchi, Matteo Palmonari, Pascal Hitzler, Luciano Serafini, Complementing Logical Reasoning with Sub-symbolic Commonsense. In: Paul Fodor, Marco Montali, Diego Calvanese, Dumitru Roman, Rules and Reasoning - Third International Joint Conference, RuleML+RR 2019, Bolzano, Italy, September 16-19, 2019, Proceedings. Lecture Notes in Computer Science 11784, Springer 2019, pp. 161-170.

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Pascal Hitzler, Semantic Web: A Review of the Field. Communications of the ACM 64 (2), 76-82, 2021.



Thanks!