Knowledge Graphs and Neuro-Symbolic Artificial Intelligence

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http://www.daselab.org

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  - **Adrita Barua**
  - **Joseph Zalewski**
  - **Joshua Schwartz**
  - **Mohammad Saeid Mahdavinejad**
  - **Patrick Stingley**
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  - **Sanaz Saki Norouzi**
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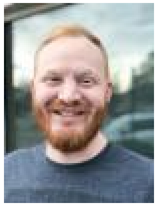
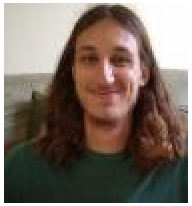
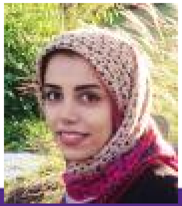
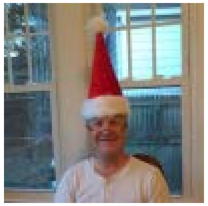










Contents

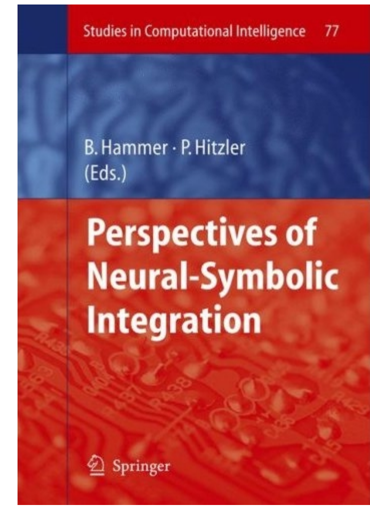
- Two current trends:
  - Neuro-Symbolic Artificial Intelligence
  - Knowledge Graphs
- And their convergence:
  - Added Value for Deep Learning
    - Example: Explainable AI
  - Added Value for Knowledge Graphs
    - Example: Deep Deductive Reasoning

Neuro-Symbolic Artificial Intelligence

Some Background

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

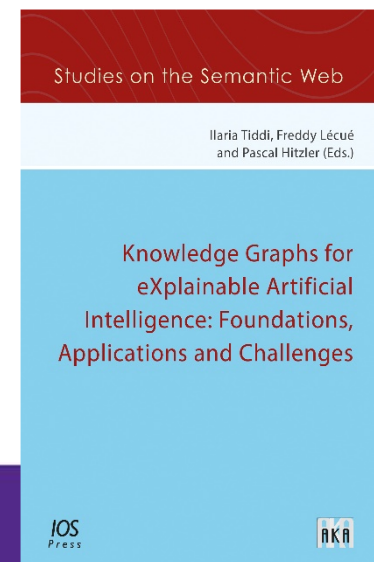


Neural-Symbolic Learning and Reasoning: A Survey and Interpretation

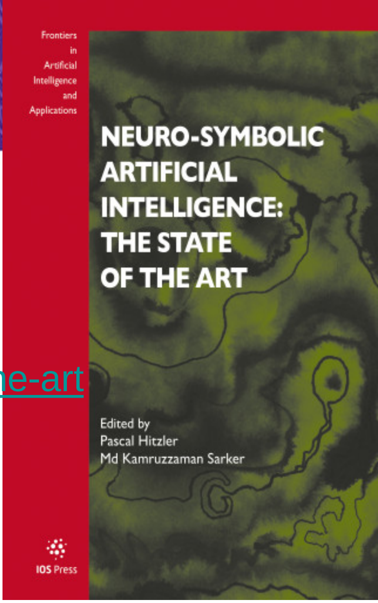
Tarek R. Besold, Artur d'Avila Garcez, Sebastian Bader,
Howard Bowman, Pedro Domingos, Pascal Hitzler,
Kai-Uwe Kuehnberger, Luis C. Lamb, Daniel Lowd,
Priscila Machado Vieira Lima, Leo de Penning, Gadi Pinkas,
Hoifung Poon, Gerson Zaverucha

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.



2022 Book



Neuro-symbolic Artificial Intelligence: The State of the Art

Pascal Hitzler and Md Kamruzzaman Sarker, editors

Fontriers in AI and Applications Vol. 342, IOS Press, Amsterdam, 2022

https://www.iospress.com/catalog/books/neuro-symbolic-artificial-intelligence-the-state-of-the-art

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 34 (3), 197-209, 2022.

New Book for 2023

Compendium of Neuro-Symbolic Artificial Intelligence (tentative)

approx. 30 chapters and 700 pages

Each chapter based on 2 or more related published papers.

Book will provide an even more comprehensive overview of the state of the art.

[We can still add a few chapters – see https://daselab.cs.ksu.edu/content/call-book-chapter-proposals-compendium-neuro-symbolic-artificial-intelligence and send your chapter proposal very quickly.]

Neural

- Refers to computational abstractions of (natural) neural network systems.
- Prominently includes Artificial Neural Networks and Deep Learning as machine learning paradigms.
- More generally sometimes referred to as *connectionist systems*.

- Prominent applications come from the machine learning world.

- And of course, there is the current deep learning hype.

Symbolic

- Refers to (computational) symbol manipulations of all kind.

- Graphs and trees, traversal, data structure operations.
- Knowledge representation in explicit symbolic form (data base, ontology, knowledge graph)
- Inductive and statistical inference.
- Formal logical (deductive or abductive) reasoning.

- Prominent applications all over computer science, including expert systems (and their modern versions), information systems, data management, added value of data annotation, etc.

- Semantic Web data is inherently symbolic.

Neuro-Symbolic

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?**
  - **... ?**

Example Themes

- Learning of knowledge bases
- Improving symbolic algorithms
- Improving deep learning systems
- Commonsense reasoning
- NLP
- Question Answering
- Explaining deep learning systems (XAI)
- Solving complex AI problems

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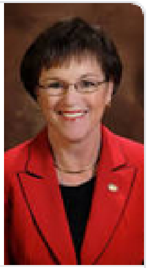
Knowledge Graphs

Google Knowledge Graph

Laura Kelly

Governor of Kansas



Laura Kelly is an American politician serving as the 48th governor of Kansas since 2019. A member of the Democratic Party, she represented the 18th district in the Kansas Senate from 2005 to 2019. Kelly ran for governor in the 2018 election and defeated the Republican nominee, Kansas Secretary of State Kris Kobach. Wikipedia

Born: January 24, 1950 (age 69 years), New York, NY

Spouse: Ted Daughety

Party: Democratic Party

Office: Governor of Kansas since 2019

Education: Indiana University, Bradley University, Indiana University Bloomington

Children: Kathleen Daughety, Molly Daughety

hasEducation

Indiana University

iu.edu

Indiana University is a multi-campus public university system in the state of Indiana, United States. Indiana University has a combined student body of more than 110,000 students, which includes approximately 46,000 students enrolled at the Indiana University Bloomington campus. Wikipedia

Mascot: Referred to as "The Hoosiers"

Endowment: 1.986 billion USD

Students: 110,436 university-wide

President: Michael McRobbie

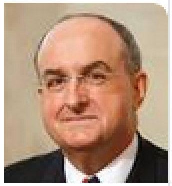
Academic staff: 8,733 university-wide

Subsidiaries: Indiana University Bloomington, MORE

hasPresident

Michael McRobbie

President of Indiana University



president.iu.edu

Michael Alexander McRobbie AO is an Australian-American computer scientist, educator and academic administrator. He became the eighteenth president of Indiana University on July 1, 2007. Wikipedia

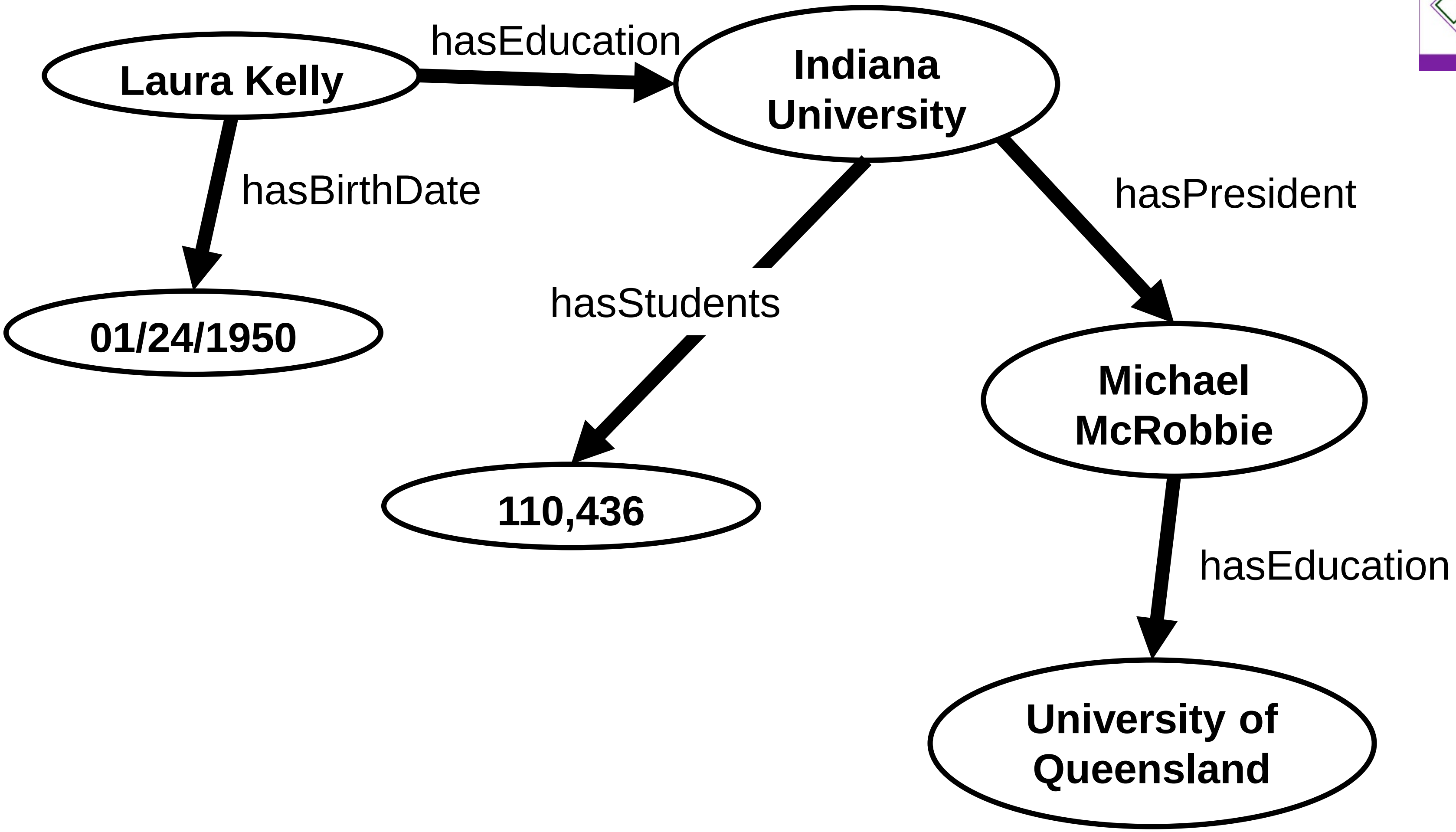
Born: October 11, 1950 (age 69 years), Melbourne, Australia

Spouse: Laurie Burns (m. 2005)

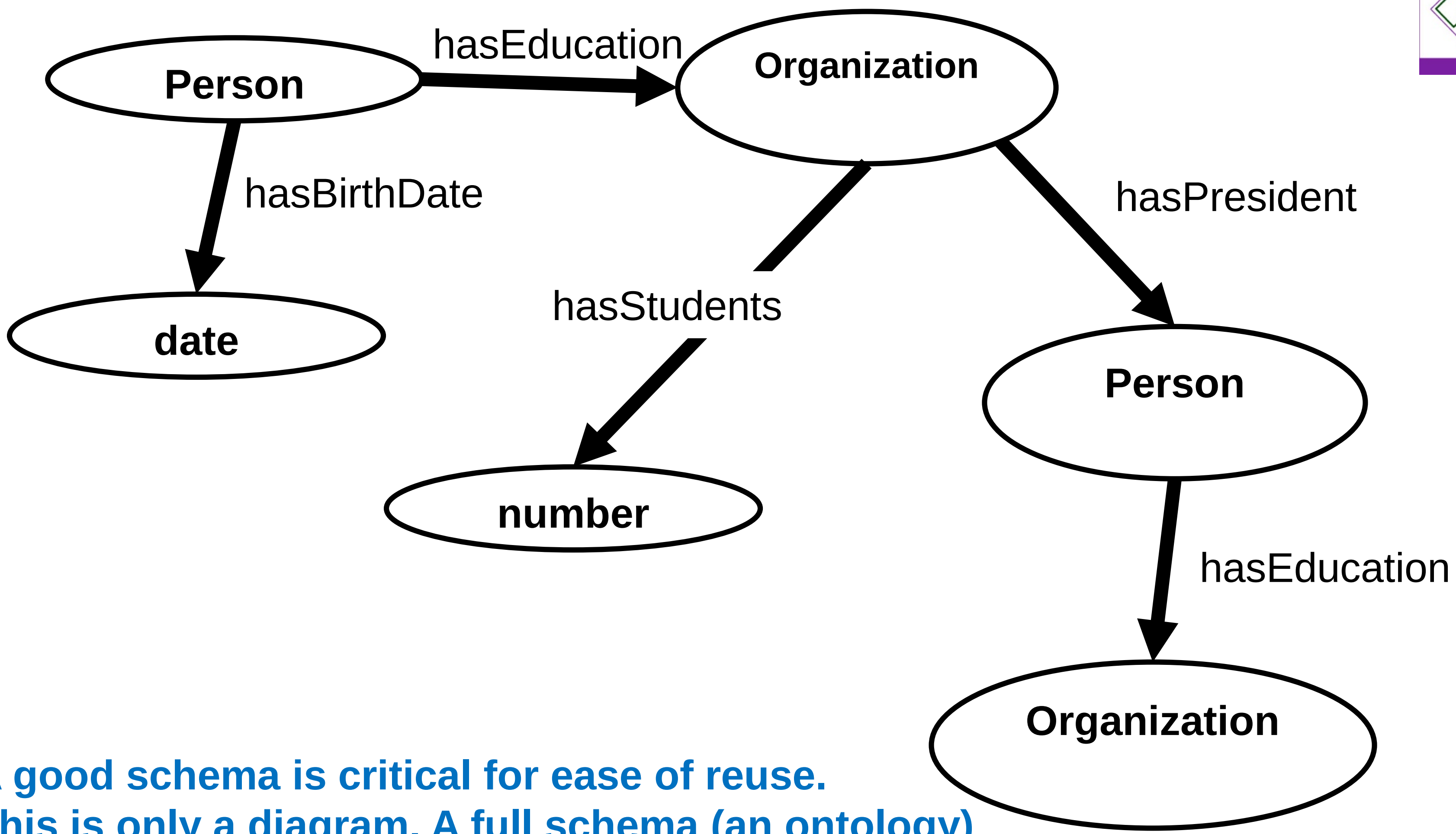
Education: The Australian National University, The University of Queensland

Books: Automated Theorem-proving in Non-classical Logics, Automated Deduction - Cade-13

Knowledge Graphs



Schema (as diagram)



A good schema is critical for ease of reuse.
This is only a diagram. A full schema (an ontology) consists of axioms in a formal logic.

W3C Standards

W3C Recommendation

RDF 1.1 Concepts and Abstract Syntax

W3C Recommendation 25 February 2014

This version:
http://www.w3.org/TR/2014/REC-rdf11-concepts-20140225/
Latest published version:
http://www.w3.org/TR/rdf11-concepts/
Previous version:
http://www.w3.org/TR/2014/PR-rdf11-concepts-20140109/
Previous Recommendation:
http://www.w3.org/TR/rdf-concepts
Editors:
Richard Cyganiak, DERI, NUI Galway
David Wood, 3 Round Stones
Markus Lanthaler, Graz University of Technology

Both established 2004 as versions 1.0.

W3C Recommendation

OWL 2 Web Ontology Language Primer (Second Edition)

W3C Recommendation 11 December 2012

This version:
http://www.w3.org/TR/2012/REC-owl2-primer-20121211/
Latest version (series 2):
http://www.w3.org/TR/owl2-primer/
Latest Recommendation:
http://www.w3.org/TR/owl-primer
Previous version:
http://www.w3.org/TR/2012/PER-owl2-primer-20121018/
Editors:
Pascal Hitzler, Wright State University
Markus Krötzsch, University of Oxford
Bijan Parsia, University of Manchester
Peter F. Patel-Schneider, Nuance Communications
Sebastian Rudolph, FZI Research Center for Information

PRACTICE

Industry-Scale Knowledge Graphs: Lessons and Challenges

By Natasha Noy, Yuqing Gao, Anshu Jain, Anant Narayanan, Alan Patterson, Jamie Taylor
Communications of the ACM, August 2019, Vol. 62 No. 8, Pages 36-43
10.1145/3331166

Credit: Adempercem / Stutterstock

Knowledge graphs are critical to many enterprises today: They provide the structured data and factual knowledge that drive many products and make them more intelligent and "magical."

In general, a knowledge graph describes objects of interest and connections between them. For example, a knowledge graph may have nodes for a movie, the actors in this movie, the director, and so on. Each node may have properties such as an actor's name and age. There may be nodes for multiple movies involving a particular actor. The user can then traverse the knowledge graph to collect information on all the movies in which the actor appeared or, if applicable, directed.

Many practical implementations impose constraints on the links in knowledge graphs by defining a *schema* or *ontology*. For example, a link from a movie to its director must connect an object of type Movie to an object of type Person. In some cases the links themselves might have their own properties: a link connecting an actor and a movie might have the name of the specific role the actor

ARTICLE CONTENTS:

WIKIDATA

Main Page | Discussion | Read | View source | View history | Search Wikidata

collaborative
open
free
multilingu

Welcome to Wikidata

the free knowledge base with 97,501,043 data items that anyone can edit.

Introduction • Project Chat • Community Portal • Help

Want to help translate? Translate the missing messages.

Welcome!

Wikidata is a free and open knowledge base that can be read and edited by both humans and machines.

Wikidata acts as central storage for the **structured data** of its Wikimedia sister projects including Wikipedia, Wikivoyage, Wiktionary, Wikisource, and others.

Wikidata also provides support to many other sites and services beyond just Wikimedia projects! The content of Wikidata is available under a free license, exported using standard formats, and can be interlinked to other open data sets on the linked data web.

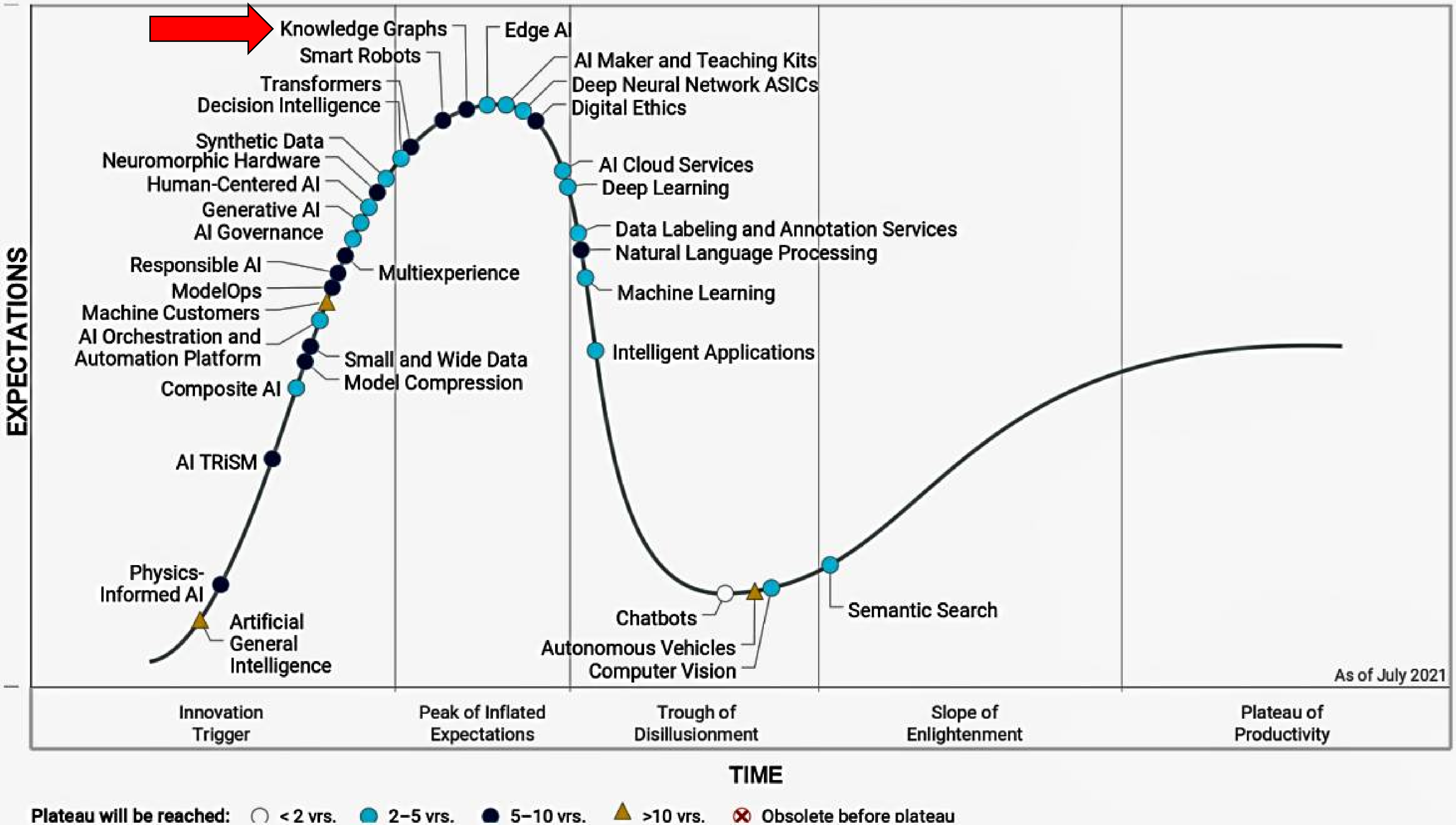
Learn about data

New to the wonderful world of data? Develop and improve your data literacy through content designed to get you up to speed and feeling comfortable with the fundamentals in no time.

Item: *Earth (Q2)*

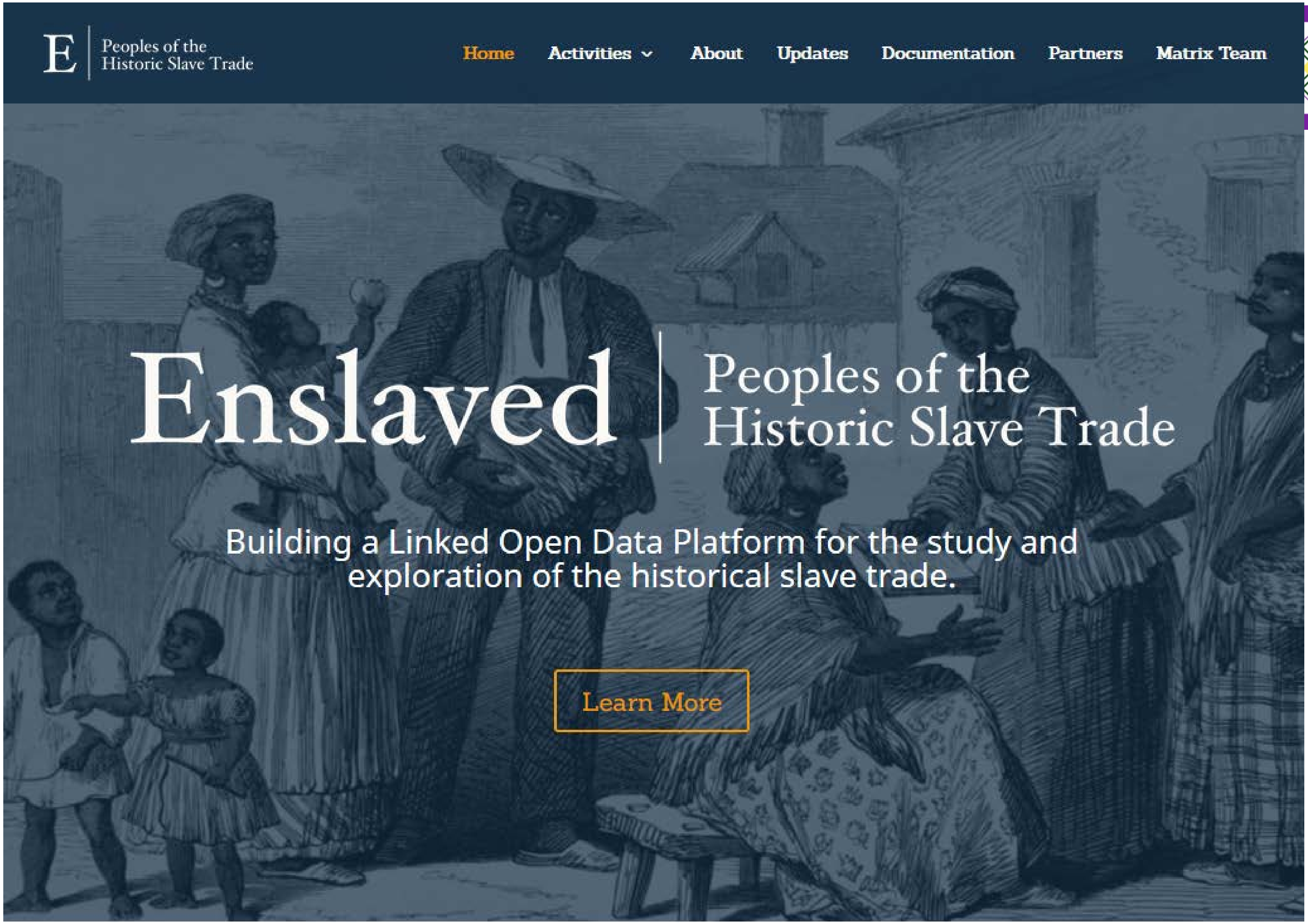
Property: *highest point*

Gartner, 2021



enslaved.org

https://enslaved.org/ https://lod.enslaved.org



DaSe Lab

enslaved.org process

1. **Quality Graph Design.**
2. **Realization in Wikibase. (Engine for Wikidata)**
3. **Knowledge graph construction and interaction through Wikibase as.**
4. **Additional front-end (simplified view)**

People	552009
Events	341732
Places	14376
Sources	2599

>53M RDF triples from Wikibase export

(4) https://enslaved.org/

(3) https://lod.enslaved.org/

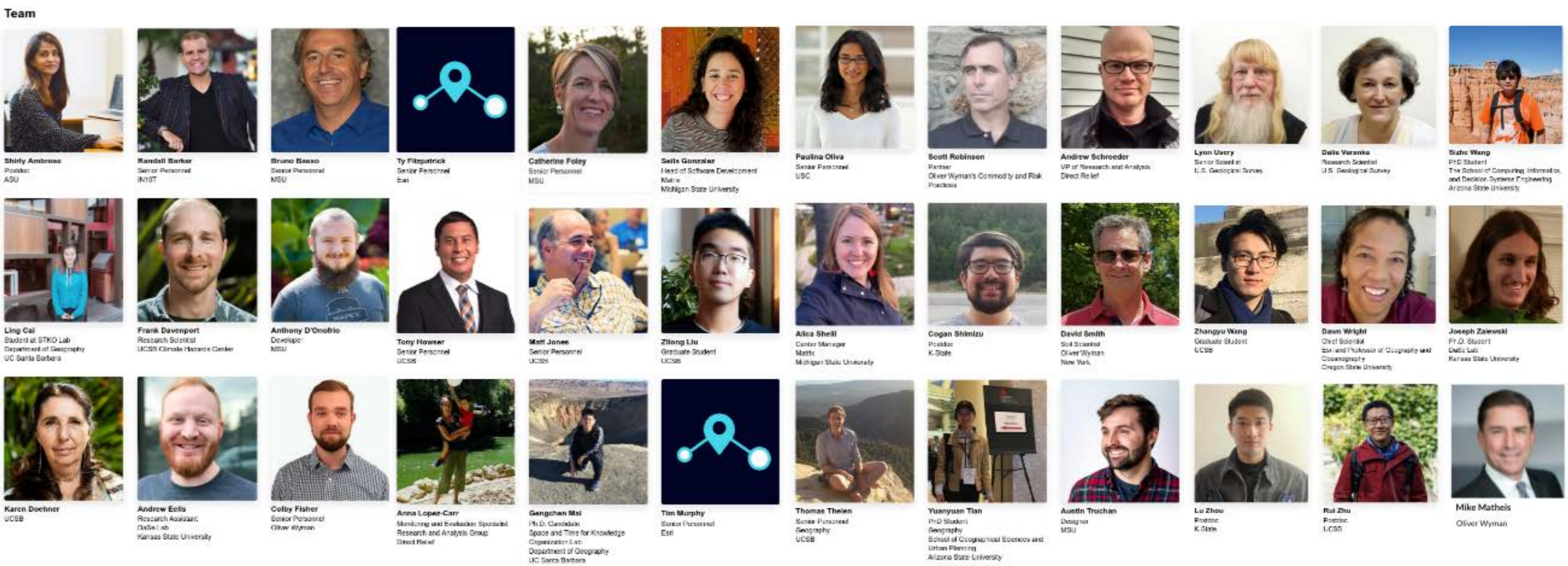
KnowWhereGraph

- **2 years, \$5M. Follows a \$1M, 1-year pilot.**
- **NSF "Open Knowledge Networks" (OKN) program. 21 phase 1 projects; 5 phase 2 projects.**

Team and Partnership

PI: Krzysztof Janowicz, UCSB
Co-PIs: Mark Schildhauer, Wenwen Li, Dean Rehberger, Pascal Hitzler

KnowWhereGraph



Know Where Graph

(some) project goals

- pushing the state of the art in spatiotemporal Knowledge Graph (KG) engineering
- transfer of KG technology towards adoptable practice
- application showcases

Addressing the bottleneck in data science:

80% is data processing
20% is deriving insights

http://KnowWhereGraph.org/

Public release

- Knowledge Graph with about >12B triples
  – One of the currently largest public knowledge graphs.
  – Focus on spatial data related to environment and natural disasters
- (forthcoming)
  – open source software for access and management

http://knowwheregraph.org/

Thematic Datasets

Dataset Name/ Theme	Source Agency	Key Attributes	Spatial Coverage	Temporal Coverage
Soil Properties	USDA	soil type, farmland class	Targeted regions in US	Current
Wildfires	USGS, USDA, USFS, NIFC	wildfire type, burn severity, num. acres burned, contained date	US	1984–current
Earthquakes	USGS	magnitude, length, width, geometry	Global (mag. over 4.5)	2011-01-01 to 2022-01-18
Climate Hazards	NOAA	injuries, deaths, property damages	US	1950–2022
Expert - Covid-19 Mobility	Direct Relief (DR)	name, affiliation, expertise	Global	2021
Expert - General	KWG, UC System, DR, Semantic Scholar	name, affiliation, expertise with spatiotemporal scopes	Global	unlimited
Cropland Types	USDA	crop types (raster data)	US	2008-2021
Air Qual. Obs.	U.S. EPA	AQI value, CO concentration	US	1980–2022
Smoke Plumes	NOAA	daily smoke plumes extent	US	2010-2022
Climate Observations	NOAA	temperature, precipitation, PDSI, PHSI	US	1950 - 2022
Disaster Declaration	FEMA	designated area, program, amount approved, program designated date	US	1953 - 2022
Smoke Plume Extents	NOAA	Smoke extent	US	2017 - 2022
BlueSky Forecasts	Bluesky	PM10, PM5	US	2022-03-07
Transportation (highway network)	DOT	road type, road length, road sign	US	2014
Public Health	CDC, US Census	below poverty level percent, diabetes age adjusted 20 plus percent, obesity age adjusted 20 plus percent	US	2017
Social Vulnerability	CDC/ATSDR	social vulnerability index	US	2018
Hurricane Tracks	NOAA	max wind speed, min pressure	US	1851-2020

Place-Centric Datasets

Place-Centric Dataset	Defining Authority	Spatial Coverage
S2 Cells	Google	Lvl 9 (Global), Lvl 13 (US),
Global Administrative Regions	University of Berkeley, Museum of Vertebrate Zoology and the International Rice Research Institute	Global
US Federal Judicial District	DoJ, ESRI	US
National Weather Zones	NOAA	US
FIPS Codes	NRCS	US
Designated Market Area	Nielen	US
ZIP	ZCTA	US
Climate Division	NOAA	US
Census Metropolitan Area	US Census	US
Drought Zone	NDMC, USDA,NOAA	US
Geographic Name Information System	USGS	US

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Added Value for Deep Learning

Prospects

- KGs are a rich source of structured training data
- KGs are a rich source of background knowledge

- Improved performance and trainability of DL systems
- Interpreting and explaining DL systems via background knowledge

Explaining Deep Learning via Symbolic Background Knowledge

Md. Kamruzzaman Sarker, Ning Xie, Derek Doran, Michael Raymer, Pascal Hitzler, Explaining Trained Neural Networks with Semantic Web Technologies: First Steps. In: Tarek R. Besold, Artur S. d'Avila Garcez, Isaac Noble (eds.), Proceedings of the Twelfth International Workshop on Neural-Symbolic Learning and Reasoning, NeSy 2017, London, UK, July 17-18, 2017. CEUR Workshop Proceedings 2003, CEUR-WS.org 2017

Md Kamruzzaman Sarker, Pascal Hitzler, Efficient Concept Induction for Description Logics. In: The Thirty-Third AAAI Conference on Artificial Intelligence, AAAI 2019, The Thirty-First Innovative Applications of Artificial Intelligence Conference, IAAI 2019, The Ninth AAAI Symposium on Educational Advances in Artificial Intelligence, EAAI 2019, Honolulu, Hawaii, USA, January 27 – February 1, 2019. AAAI Press 2019 , pp. 3036-3043.

Md Kamruzzaman Sarker, Joshua Schwartz, Pascal Hitzler, Lu Zhou, Srikanth Nadella, Brandon Minnery, Ion Juvina, Michael L. Raymer, William R. Aue, Wikipedia Knowledge Graph for Explainable AI. In: Boris Villazón-Terrazas, Fernando Ortiz-Rodríguez, Sanju M. Tiwari, Shishir K. Shandilya (eds.), Knowledge Graphs and Semantic Web. Second Iberoamerican Conference and First Indo-American Conference, KGSWC 2020, Mérida, Mexico, November 26-27, 2020, Proceedings. Communications in Computer and Information Science, vol. 1232, Springer, Heidelberg, 2020, pp. 72-87.

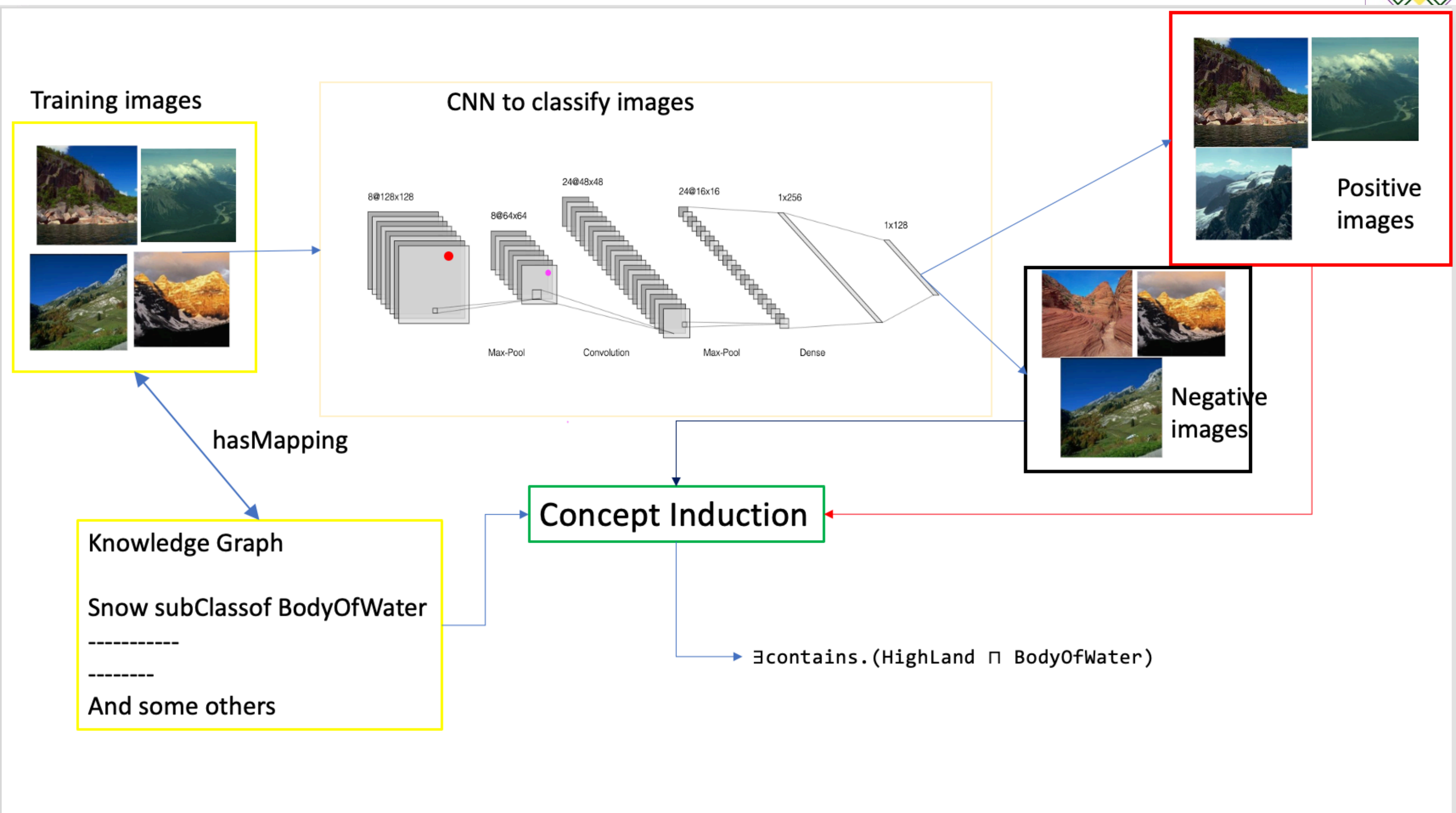
Explainable AI

- **Explain behavior of trained (deep) NNs.**

- **Idea:**
  - **Use background knowledge in the form of linked data and ontologies to help explain.**
  - **Link inputs and outputs to background knowledge.**
  - **Use a symbolic learning system to generate an explanatory theory.**

- **We have key components for this now, but it's still early stages.**

Concept

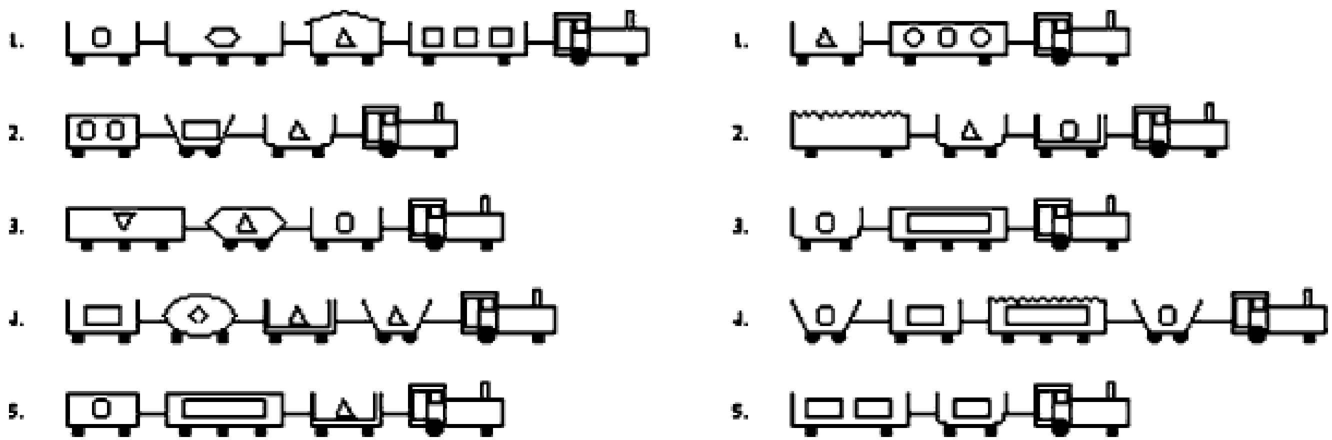

Training images
CNN to classify images
8@128x128
8@64x64
24@48x48
24@16x16
1x256
1x128
Max-Pool
Convolution
Max-Pool
Dense
Positive images
Negative images
hasMapping
Concept Induction
Knowledge Graph
Snow subClassof BodyOfWater

And some others
∃contains.(HighLand ⊓ BodyOfWater)

DL-Learner [Lehmann, Hitzler]

Approach similar to inductive logic programming, but using Description Logics (the logic underlying OWL).

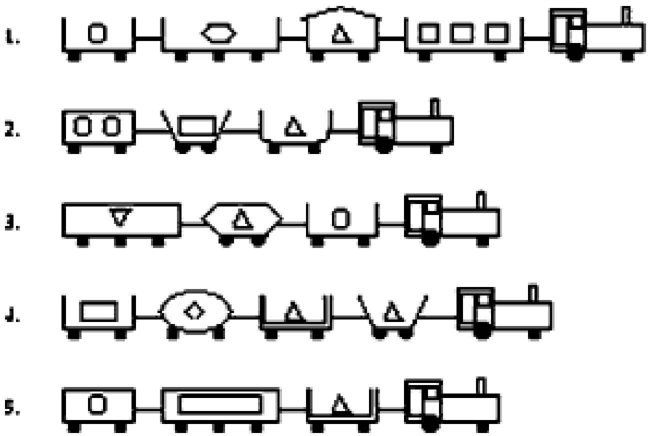
Positive examples: **negative examples:**



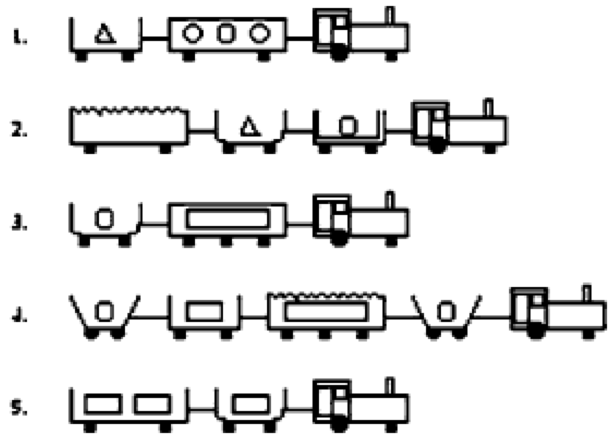
Task: find a class description (logical formula) which separates positive and negative examples.

DL-Learner

Positive examples:



negative examples:



DL-Learner result:

$$\exists \mathtt{hasCar}.(\mathtt{Closed} \sqcap \mathtt{Short})$$

In FOL:

$$\{x \mid \exists y(\mathrm{hasCar}(x, y) \wedge \mathrm{Closed}(y) \wedge \mathrm{Short}(y))\}$$

Scalability Issues with DL-Learner

- For large-scale experiments, DL-Learner took 2 hours or more for one run.
- We knew we needed at least thousands of runs.

- So we needed a more scalable solution.
- The provably correct algorithms have very high complexity.

- Hence we had to develop a heuristic which trades (some) correctness for speed.

- It is also currently restricted to using a class hierarchy as underlying knowledge base.

ECII algorithm and system

- **We thus implemented our own system, ECII (Efficient Concept Induction from Instances) which trades some correctness for speed. [Sarker, Hitzler, AAAI-19]**

Experiment Name	Number of Logical Axioms	Runtime (sec)					Accuracy (α_3)		Accuracy α_2			
		DL[a]	DL FIC(1)[b]	DL FIC(2)[c]	ECII DF[d]	ECII KCT[e]	DL[a]	ECII DF[d]	DL FIC(1)[b]	DL FIC(2)[c]	ECII DF[d]	ECII KCT[e]
Yinyang_examples	157	0.065	0.0131	0.019	0.089	0.143	1.000	0.610	1.000	1.000	0.799	1.000
Trains	273	0.01	0.020	0.047	0.05	0.095	1.000	1.000	1.000	1.000	1.000	1.000
Forte	341	2.5	1.169	6.145	0.95	0.331	0.965	0.642	0.875	0.875	0.733	1.000
Poker	1,368	0.066	0.714	0.817	1	0.281	1.000	1.000	0.981	0.984	1.000	1.000
Moral Reasoner	4,666	0.1	3.106	4.154	5.47	6.873	1.000	0.785	1.000	1.000	1.000	1.000
ADE20k I	4,714	577.3[f]	4.268	31.887	1.966	23.775	0.926	0.416	0.263	0.814	0.744	1.000
ADE20k II	7,300	983.4[f]	16.187	307.65	20.8	293.44	1.000	0.673	0.413	0.413	0.846	0.900
ADE20k III	12,193	4,500[g]	13.202	263.217	51	238.8	0.375	0.937	0.375	0.375	0.930	0.937
ADE20k IV	47,468	4,500[g]	93.658	523.673	116	423.349	0.375	NA	0.608	0.608	0.660	0.608

[a] DL : DL-Learner
[b] DL FIC (1) : DL-Learner fast instance check with runtime capped at execution time of ECII DF
[c] DL FIC (2) : DL-Learner fast instance check with runtime capped at execution time of ECII KCT
[d] ECII DF : ECII default parameters
[e] ECII KCT : ECII keep common types and other default parameters
[f] Runtimes for DL-Learner were capped at 600 seconds.
[g] Runtimes for DL-Learner were capped at 4,500 seconds.

ECII vs. DL-Learner

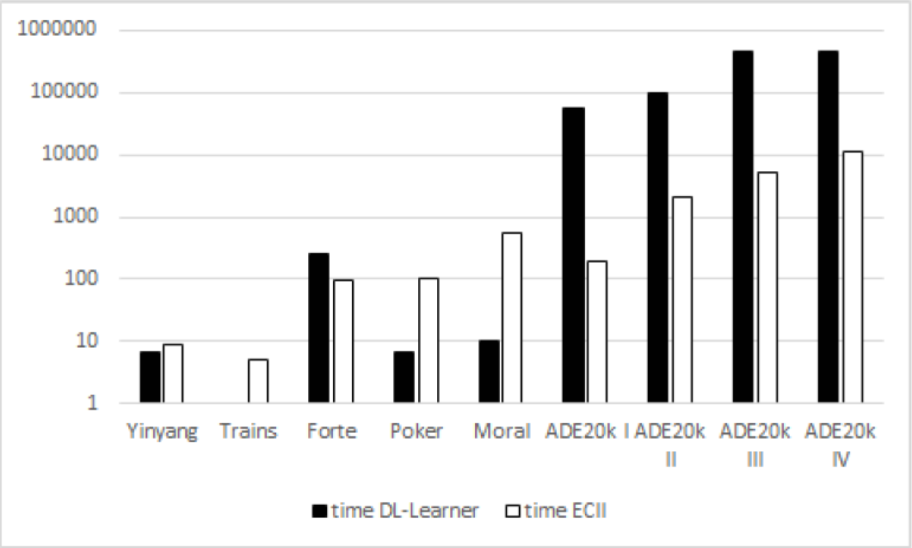


Figure 1: Runtime comparison between DL-Learner and ECII. The vertical scale is logarithmic in hundredths of seconds, and note that DL-Learner runtime has been capped at 4,500 seconds for ADE20k III and IV. For ADE20k I it was capped at each run at 600 seconds.

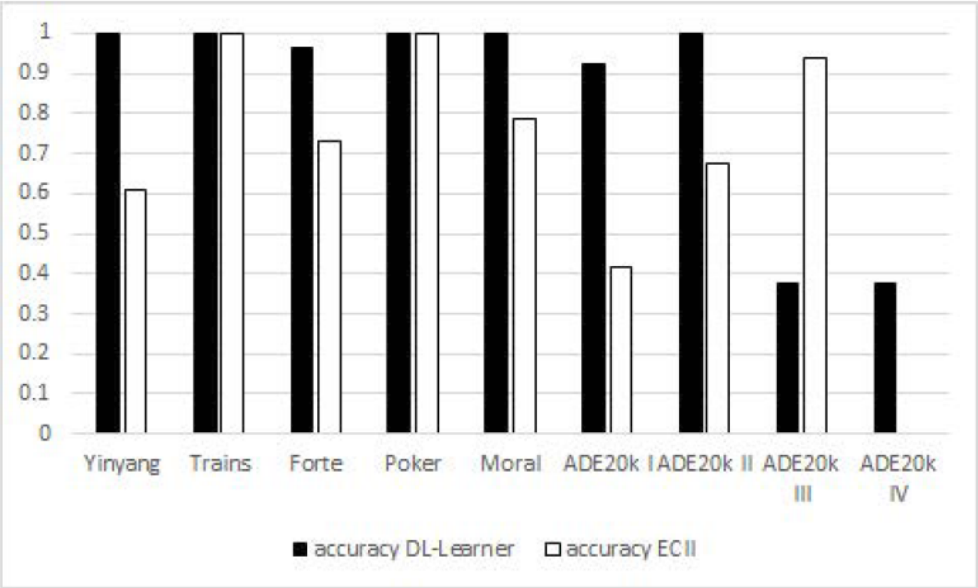
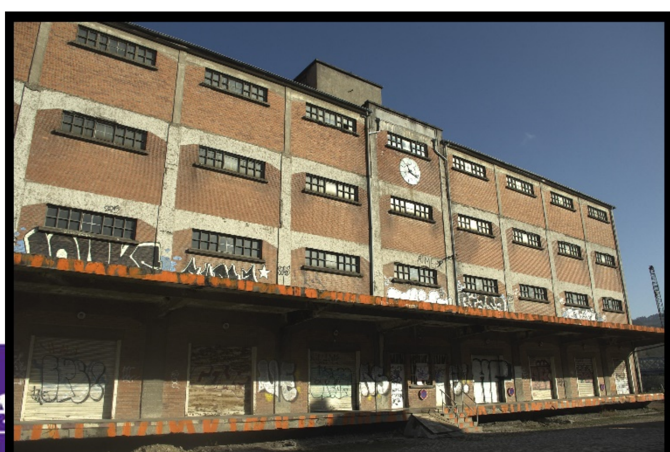


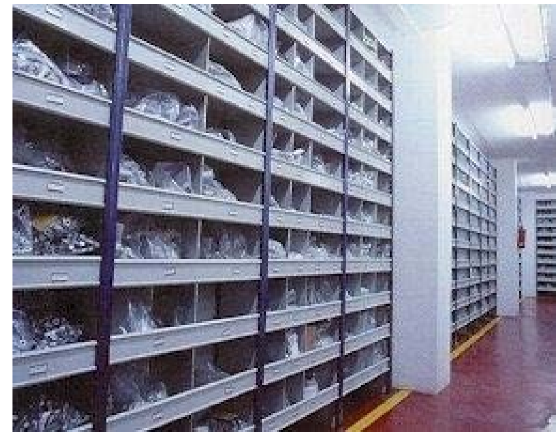
Figure 2: Accuracy (α_3) comparison between DL-Learner and ECII. For ADE20k IV it was not possible to compute an accuracy score within 3 hours for ECII as the input ontology was too large.

Proof of Concept Experiment

Positive:



Negative:



Images

Come from the MIT ADE20k dataset
http://groups.csail.mit.edu/vision/datasets/ADE20K/
They come with annotations of objects in the picture:

```
001 # 0 # 0 # sky # sky # ""
002 # 0 # 0 # road, route # road # ""
005 # 0 # 0 # sidewalk, pavement # sidewalk # ""
006 # 0 # 0 # building, edifice # building # ""
007 # 0 # 0 # truck, motortruck # truck # ""
008 # 0 # 0 # hovel, hut, hutch, shack, shanty # hut # ""
009 # 0 # 0 # pallet # pallet # ""
011 # 0 # 0 # box # boxes # ""
001 # 1 # 0 # door # door # ""
002 # 1 # 0 # window # window # ""
009 # 1 # 0 # wheel # wheel # ""
```

Mapping to SUMO

Simple approach: for each known object in image, create an individual for the ontology which is in the appropriate SUMO class:

contains road1
contains window1
contains door1
contains wheel1
contains sidewalk1
contains truck1
contains box1
contains building1

SUMO

- Suggested Merged Upper Ontology
  http://www.adampease.org/OP/

- Approx. 25,000 common terms
  covering a wide range of domains

- Centrally, a relatively naïve class hierarchy.

- Objects in image annotations became individuals (constants), which were then typed using SUMO classes.

DL-Learner input

Positive:

- img1: road, window, door, wheel, sidewalk, truck, box, building
- img2: tree, road, window, timber, building, lumber
- img3: hand, sidewalk, clock, steps, door, face, building, window, road

Negative:

- img4: shelf, ceiling, floor
- img5: box, floor, wall, ceiling, product
- img6: ceiling, wall, shelf, floor, product

DL-Learner results include:

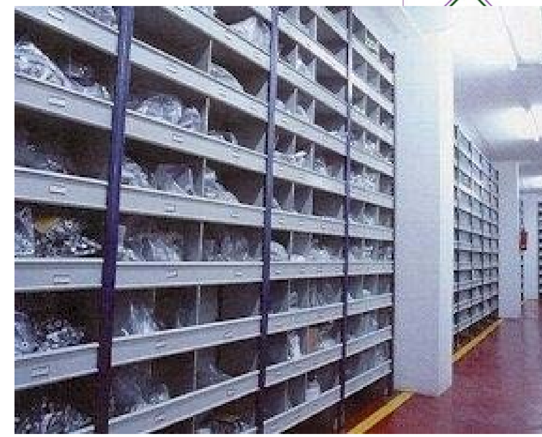
$$\exists \text{contains.Transitway}$$

$$\exists \text{contains.LandArea}$$

Proof of Concept Experiment

Positive:

Negative:



$$\exists \mathrm{contains.Transitway}$$

$$\exists \mathrm{contains.LandArea}$$

Experiment 2

Positive (selection):

$$\exists \mathrm{contains}.\mathrm{SentientAgent}$$

Negative (selection):

Experiment 5

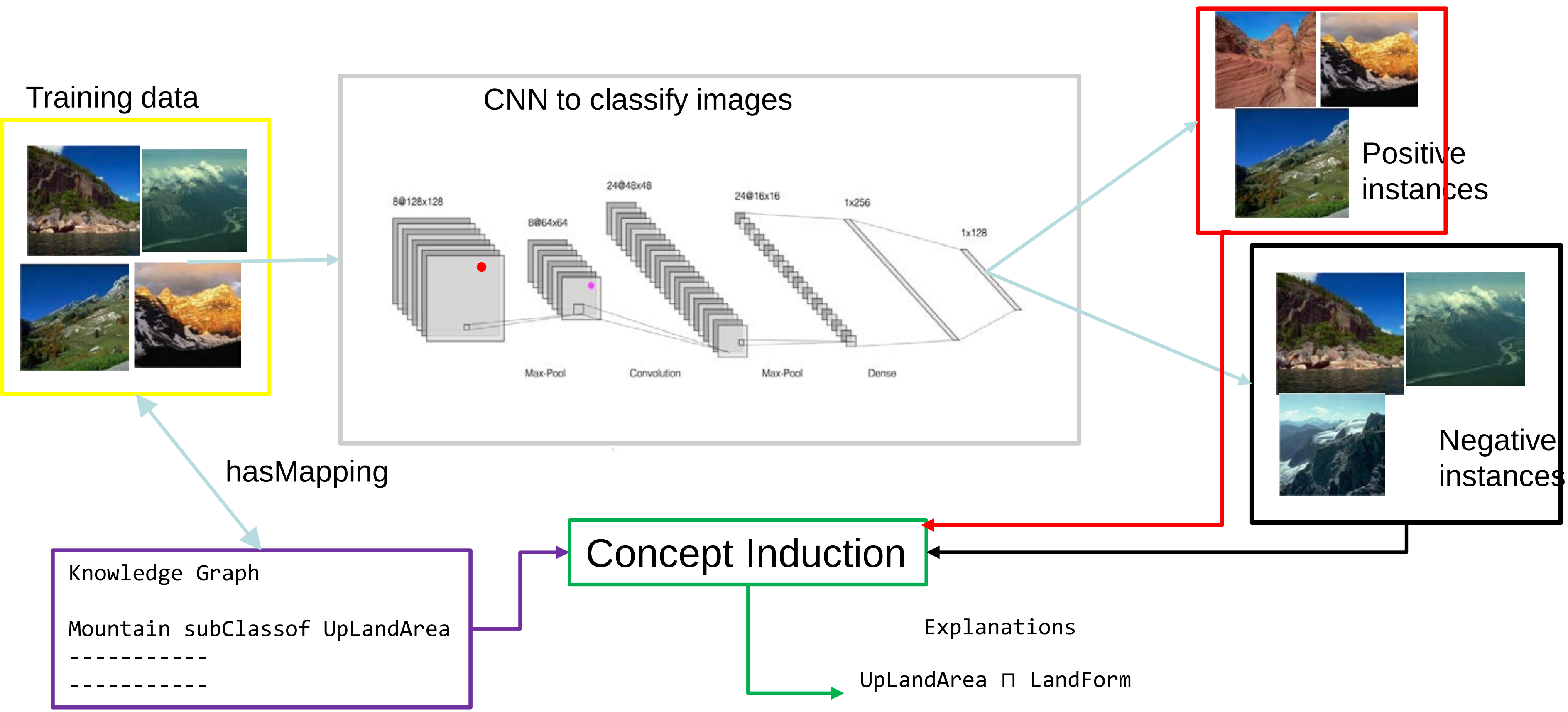
Positive:

Negative (selection):

$$\exists \text{contains.BodyOfWater}$$

Idea Recap

- Generate explanation of the whole model
- Global explanation



From SUMO to Wikipedia Concept Hierarchy

- Wikipedia CH (curated) produces better coverage score
- Reason behind this is the large number of concepts it has.
  - approx. 2M concepts

Experiment name	#Images	#Positive images	Wikipedia		SUMO	
			#Solution	Coverage	#Solution	Coverage
Market vs. WorkRoom and wareHouse	96	37	286	.72	240	.72
Mountain vs. Market and workRoom	181	85	195	.61	190	.53
OutdoorWarehouse vs. IndoorWarehouse	55	3	128	.94	102	.89
Warehouse vs. Workroom	59	55	268	.56	84	.24
Workroom vs. Warehouse	59	4	128	.93	93	.84

Work in Progress

- Value of Explanations (end-to-end) to
  - humans
  - detect bias
  - improve deep learning accuracy
- Explaining hidden neuron activation patterns
  - scalability challenges
  - background knowledge challenges

Contents

- Two current trends:
  - Neuro-Symbolic Artificial Intelligence
  - Knowledge Graphs
- And their convergence:
  - Added Value for Deep Learning
    - Example: Explainable AI
  - Added Value for Knowledge Graphs
    - Example: Deep Deductive Reasoning

Added Value for Knowledge Graphs

Prospects

DL systems to assist with

- schema (ontology) modeling
- KG construction based on schema
- schema alignment
- co-reference resolution
- data quality assurance
- KG reasoning

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]	$\mathcal{EL}^+$	no	yes	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

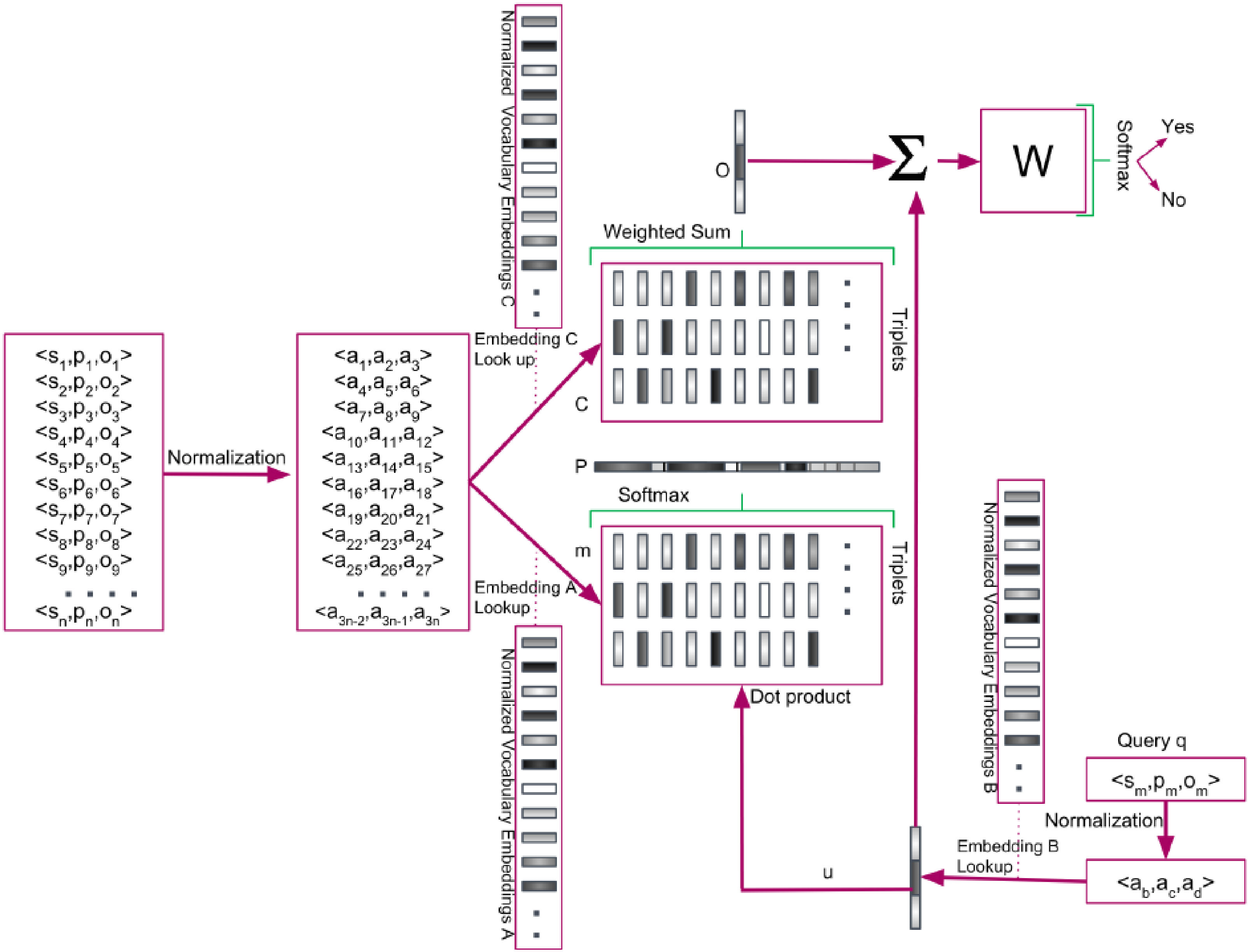
(new): Ebrahimi, Eberhart, Hitzler (preliminary report)

RDFS Reasoning using Memory Networks

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.

additional analysis by Sulogna Chowdhury, Aaron Eberhart
and Brayden Pankaskie

Memory Network based on MemN2N



Experiments: Performance

Test Dataset	#KG	Base						Inferred						Invalid
		#Facts	#Ent.	%Class	%Indv	%R.	%Axiom.	#Facts	#Ent.	%Class	%Indv	%R.	%Axiom.	#Facts
OWL-Centric	2464	996	832	14	19	3	0	494	832	14	0.01	1	20	462
Linked Data	20527	999	787	3	22	5	0	124	787	3	0.006	1	85	124
OWL-Centric Test Set	21	622	400	36	41	3	0	837	400	36	3	1	12	476
Synthetic Data	2	752	506	52	0	1	0	126356	506	52	0	1	0.07	700

Table 2: Statistics of various datasets used in experiments

Baseline: non-normalized embeddings, same architecture

Training Dataset	Test Dataset	Valid Triples Class			Invalid Triples Class			Accuracy
		Precision	Recall /Sensitivity	F-measure	Precision	Recall /Specificity	F-measure	
OWL-Centric Dataset	Linked Data	93	98	96	98	93	95	**96**
OWL-Centric Dataset (90%)	OWL-Centric Dataset (10%)	88	91	89	90	88	89	**90**
OWL-Centric Dataset	OWL-Centric Test Set [b]	79	62	68	70	84	76	**69**
OWL-Centric Dataset	Synthetic Data	65	49	40	52	54	42	**52**
OWL-Centric Dataset	Linked Data [a]	54	98	70	91	16	27	86
OWL-Centric Dataset [a]	Linked Data [a]	62	72	67	67	56	61	91
OWL-Centric Dataset(90%) [a]	OWL-Centric Dataset(10%) [a]	79	72	75	74	81	77	80
OWL-Centric Dataset	OWL-Centric Test Set [ab]	58	68	62	62	50	54	58
OWL-Centric Dataset [a]	OWL-Centric Test Set [ab]	77	57	65	66	82	73	73
OWL-Centric Dataset	Synthetic Data [a]	70	51	40	47	52	38	51
OWL-Centric Dataset [a]	Synthetic Data [a]	67	23	25	52	80	62	50
Baseline								
OWL-Centric Dataset	Linked Data	73	98	83	94	46	61	43
OWL-Centric Dataset (90%)	OWL-Centric Dataset (10%)	84	83	84	84	84	84	82
OWL-Centric Dataset	OWL-Centric Test Set [b]	62	84	70	80	40	48	61
OWL-Centric Dataset	Synthetic Data	35	41	32	48	55	45	48

[a] More Tricky Nos & Balanced Dataset
[b] Completely Different Domain.

Table 3: Experimental results of proposed model

Experiments: Reasoning Depth

Test Dataset	Hop 0			Hop 1			Hop 2			Hop 3			Hop 4			Hop 5			Hop 6			Hop 7			Hop 8			Hop 9			Hop 10		
	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F	P	R	F
Linked Data[a]	0	0	0	80	99	88	89	97	93	77	98	86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Linked Data[b]	2	0	0	82	91	86	89	98	93	79	100	88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OWL-Centric[c]	19	5	9	31	75	42	78	80	78	48	47	44	4	34	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Synthetic	32	46	33	31	87	38	66	55	44	25	45	32	29	46	33	26	46	33	25	46	33	25	46	33	24	43	31	25	43	31	22	36	28

[a] LemonUby Ontology
[b] Agrovoc Ontology
[c] Completely Different Domain

Table 4: Experimental results over each reasoning hop

Dataset	Hop 1	Hop 2	Hop 3	Hop 4	Hop 5	Hop 6	Hop 7	Hop 8	Hop 9	Hop 10
OWL-Centric [a]	8%	67%	24%	0.01%	0%	0%	0%	0%	0%	0%
Linked Data[b]	31%	50%	19%	0%	0%	0%	0%	0%	0%	0%
Linked Data[c]	34%	46%	20%	0%	0%	0%	0%	0%	0%	0%
OWL-Centric[d]	5%	64%	30%	1%	0%	0%	0%	0%	0%	0%
Synthetic Data	0.03%	1.42%	1%	1.56%	3.09%	6.03%	11.46%	20.48%	31.25%	23.65%

[a] *Training Set*
[b] LemonUby Ontology
[c] Agrovoc Ontology
[d] Completely Different Domain

Table 5: Data distribution per knowledge graph over each reasoning hop

Training time: just over a full day

Published deep deductive reasoning work

paper	logic	transfer	generative	scale	performance
[12]	RDFS	yes	no	moderate	high
[25]	RDFS	no	yes	low	high
[10]	$\mathcal{EL}^+$	no	yes	moderate	low
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[6]: Bianchi, Hitzler, AAAI-MAKE 2019

(new): Ebrahimi, Eberhart, Hitzler (preliminary report)

Conclusions

Conclusions

- Two current trends:
  - Knowledge Graphs
  - Neuro-Symbolic AI
- Plenty of opportunities
  - Improving DL systems with KG-based background knowledge
  - Solving key KG problems using DL approaches.

Thanks!

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Thanks!