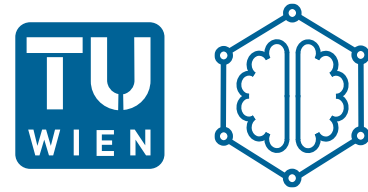


# Neuro-symbolic AI

Emanuel Sallinger

Austrian Academic of Sciences  
AI Winter School  
23 January 2025



Knowledge  
Graph Lab

<https://kg.dbai.tuwien.ac.at>



Institute of  
Logic and  
Computation





## Lecture



Prof. Dr. Emanuel Sallinger

## Hands-on



Alessandro Pesare



Dr. Eleonora Laurenza



Teodoro Baldazzi

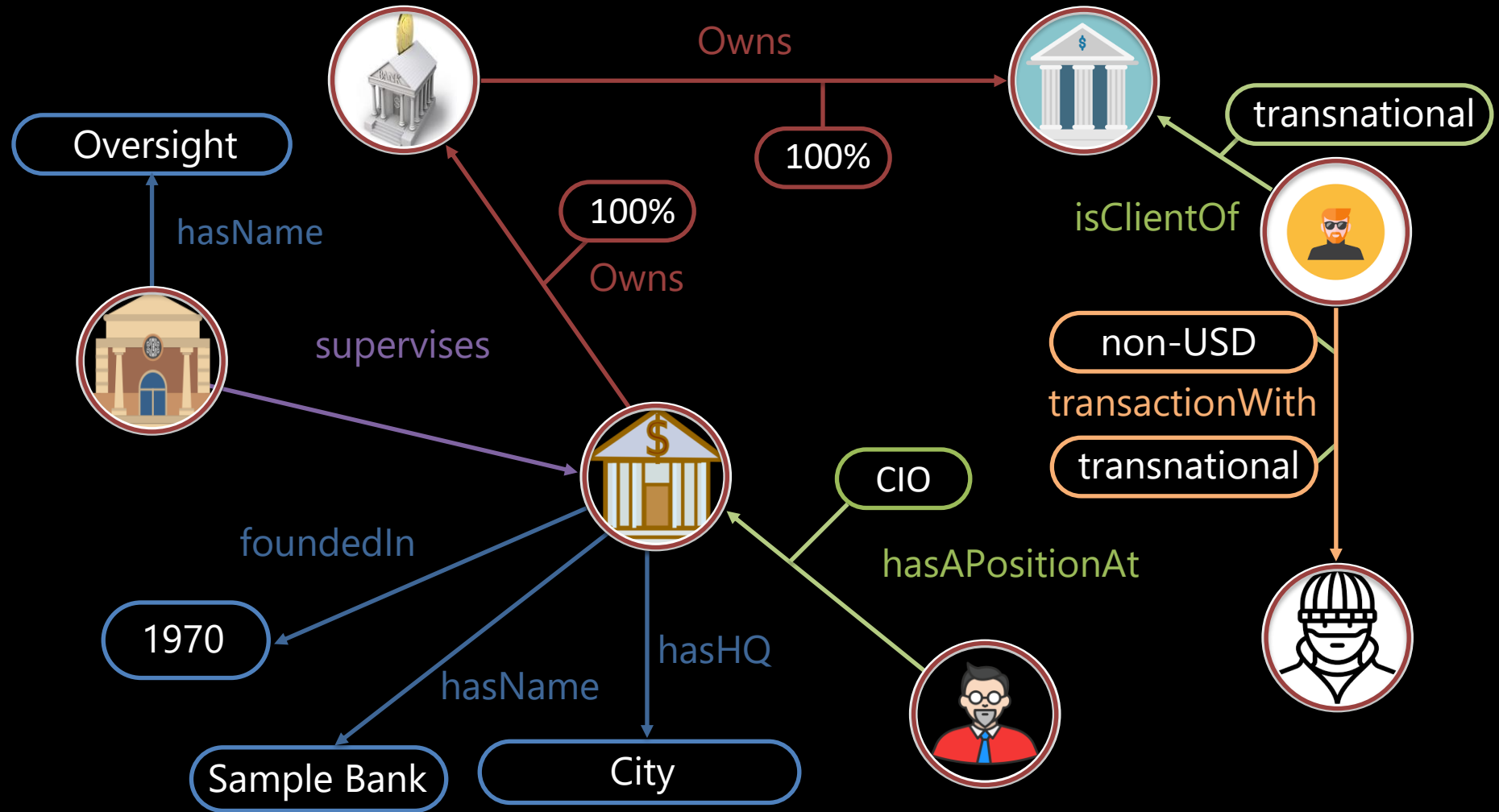


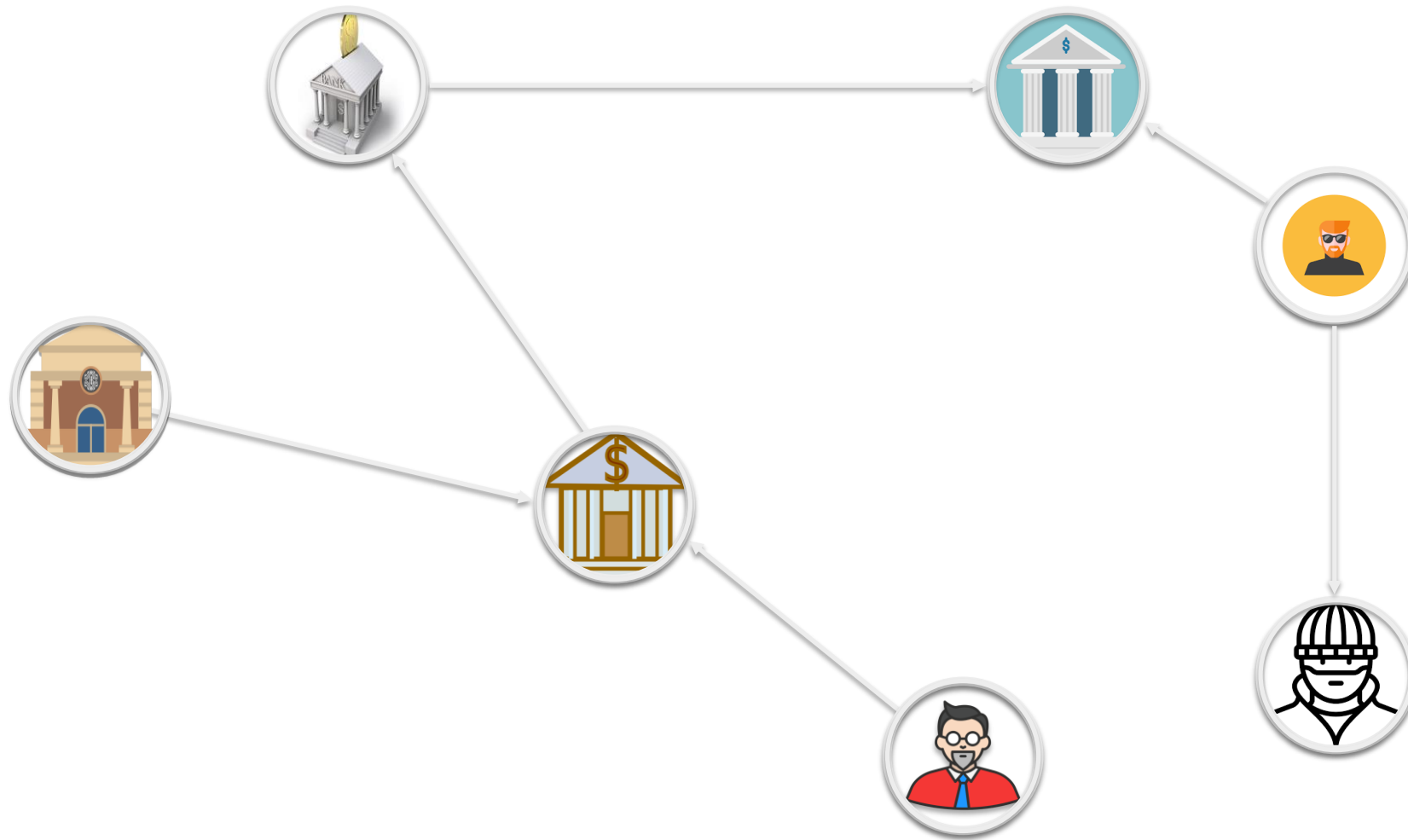
Neuro-symbolic AI

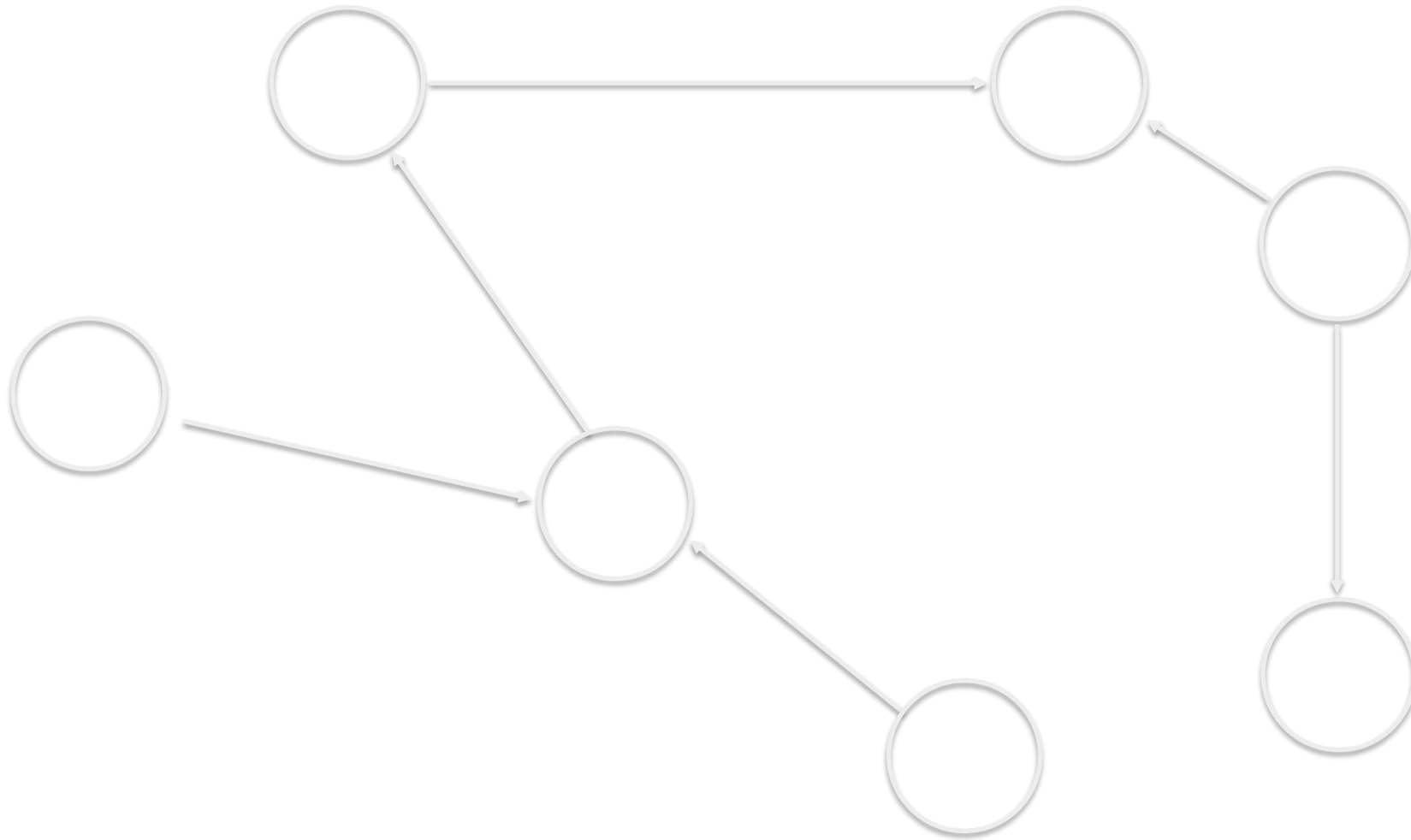


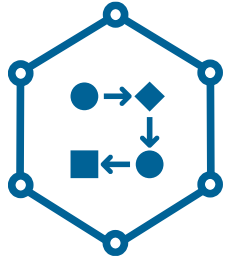
EUROPEAN CENTRAL BANK



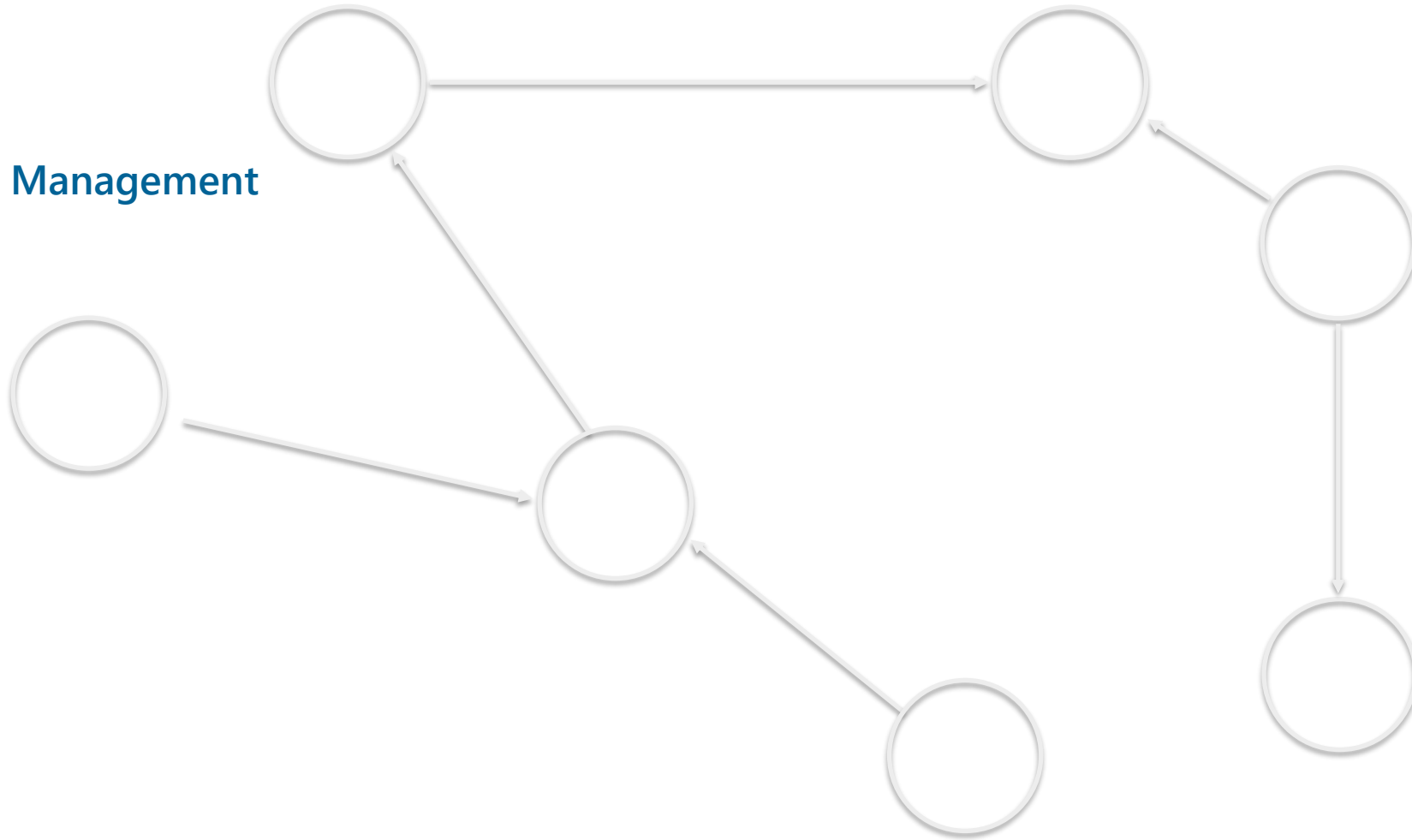




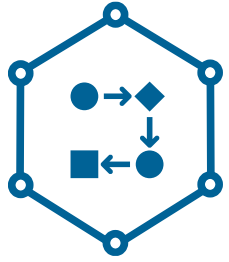




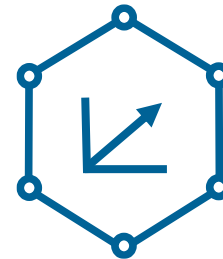
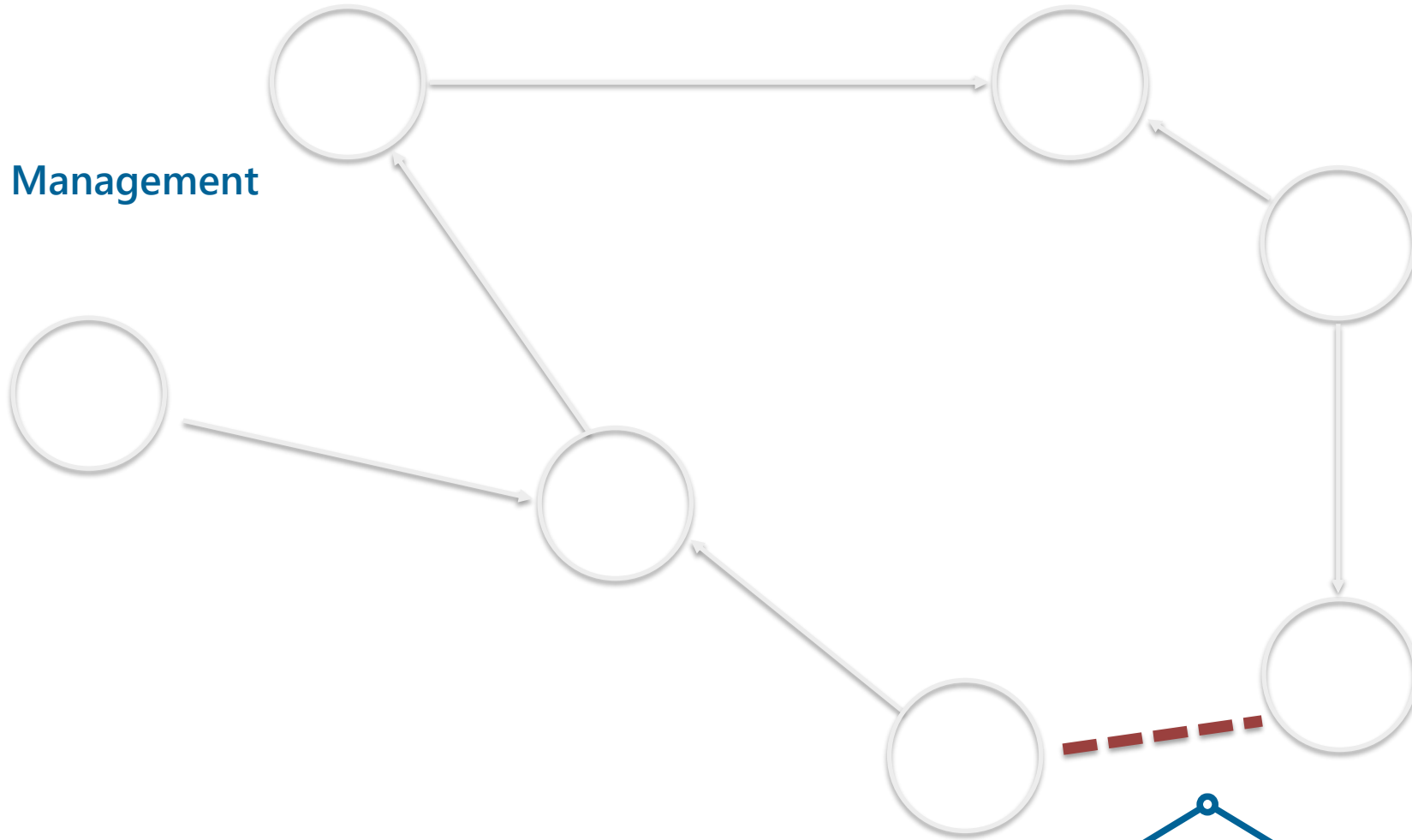
## Data Management



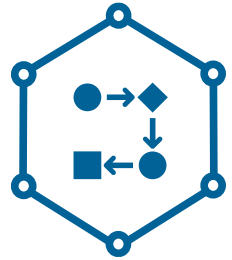




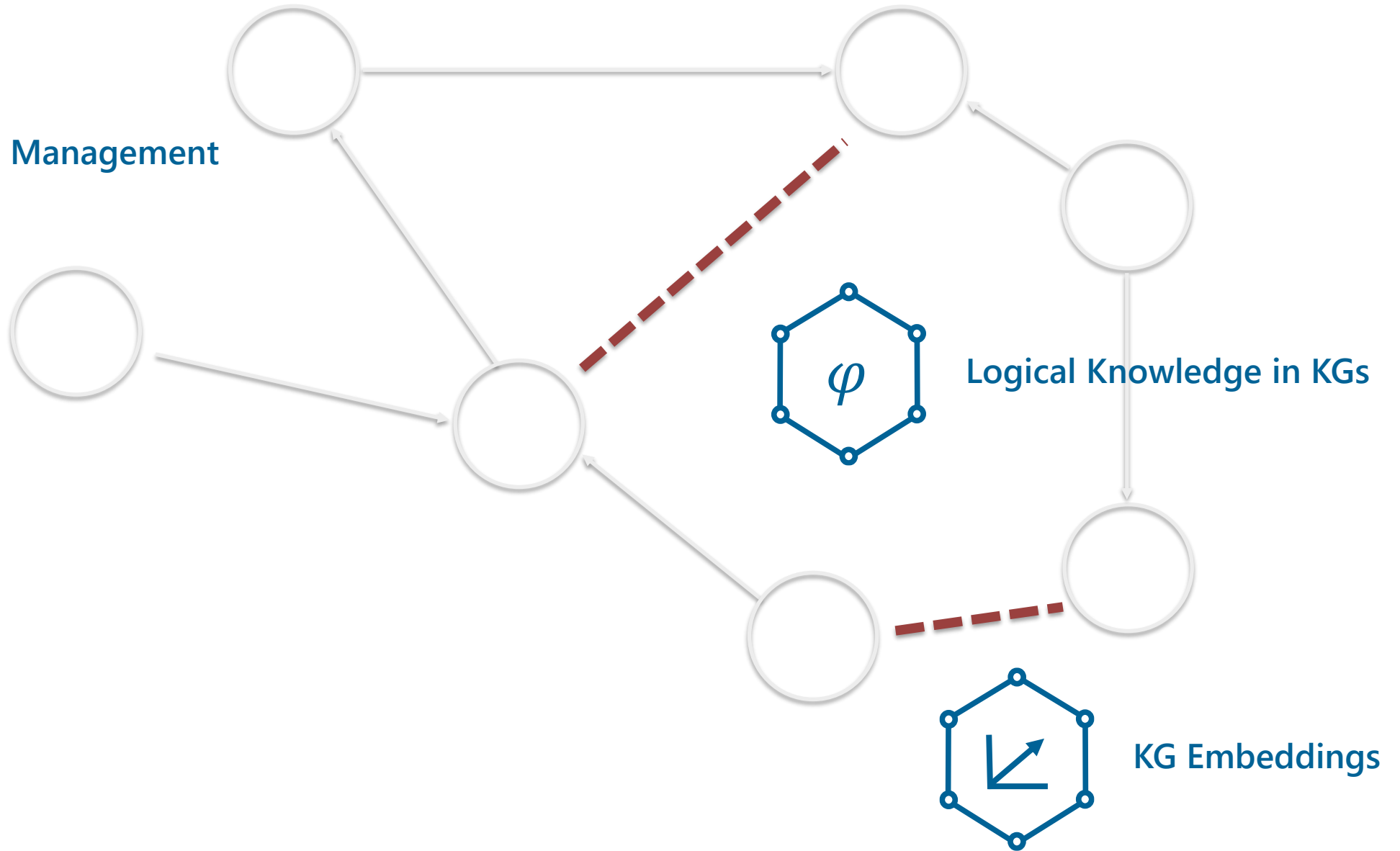
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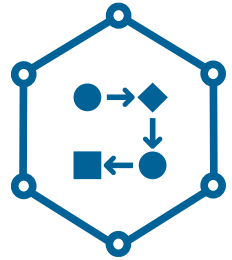


KG Embeddings

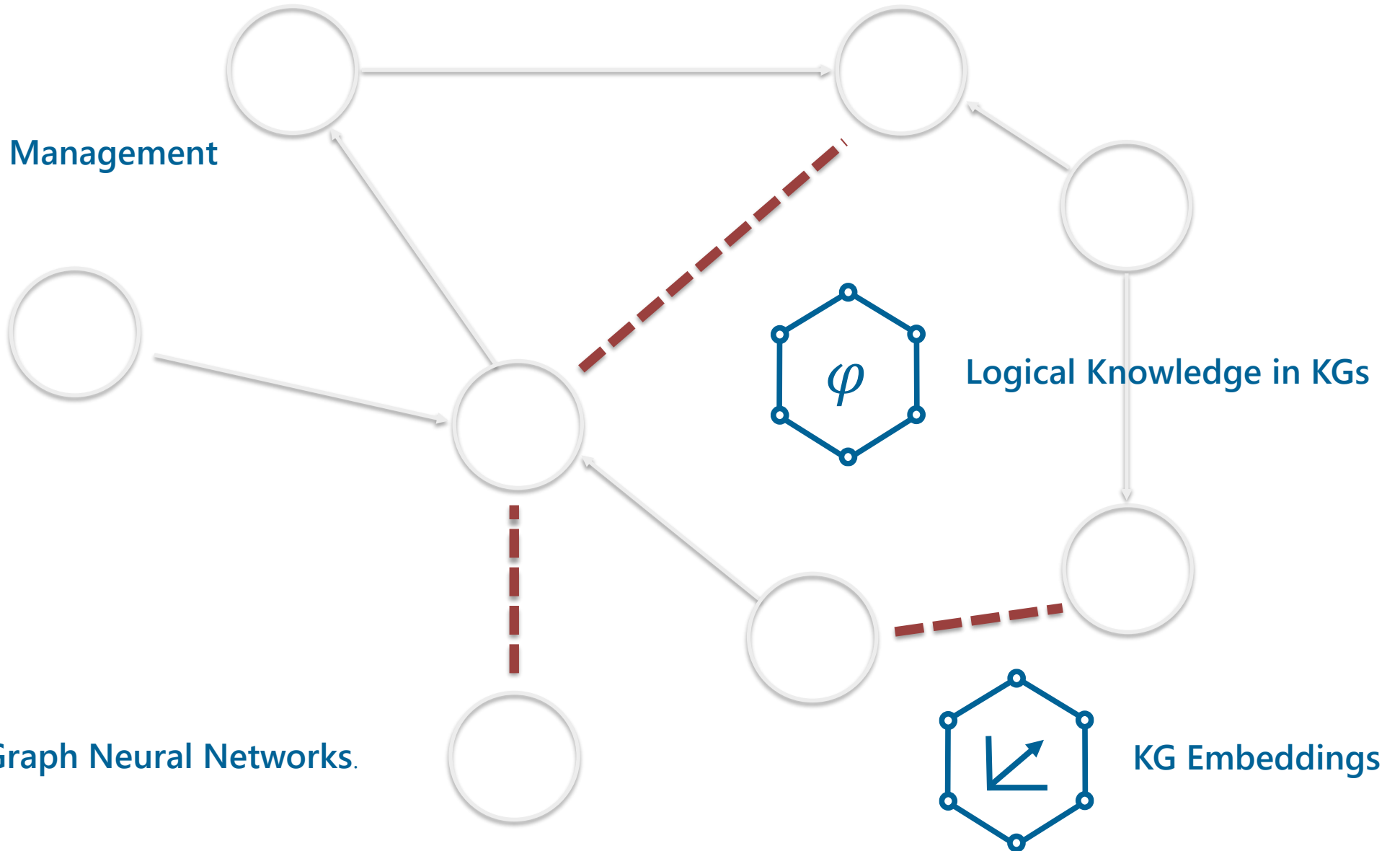


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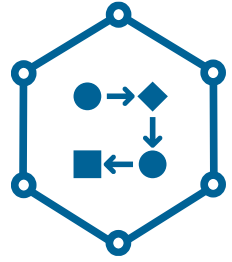




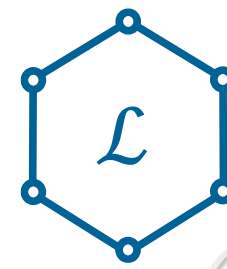
Data Management



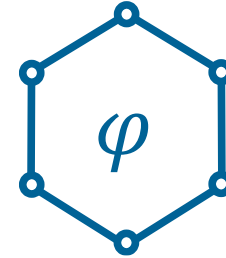
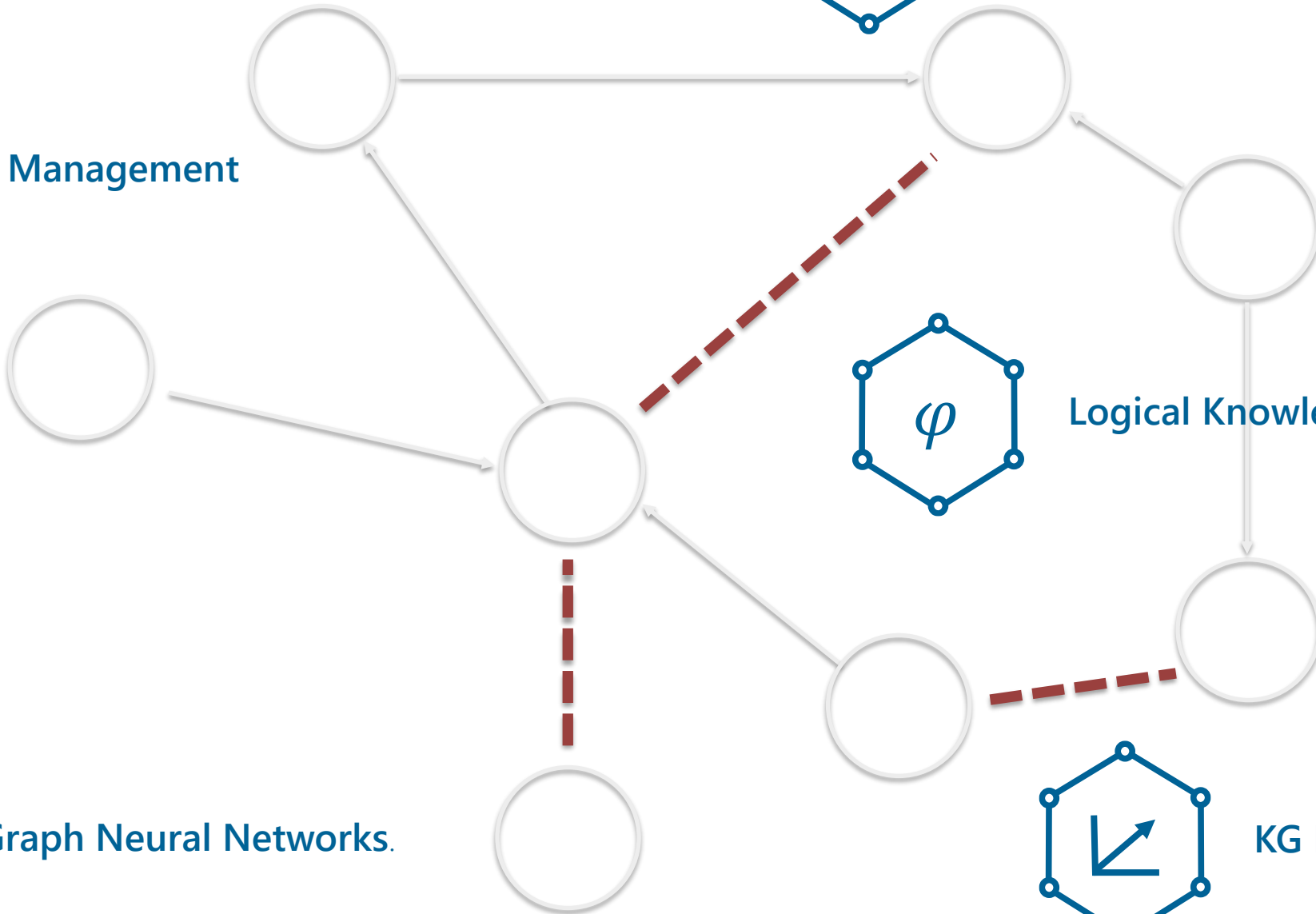
Graph Neural Networks.



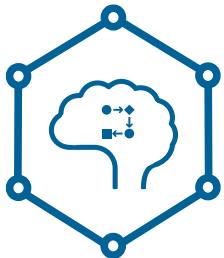
Data Management



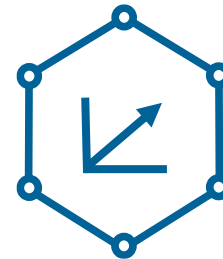
Large Language Models



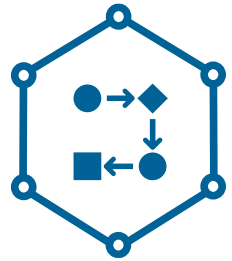
Logical Knowledge in KGs



Graph Neural Networks.



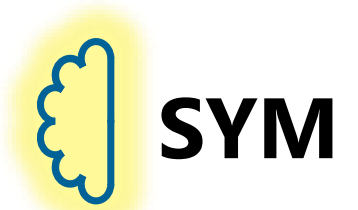
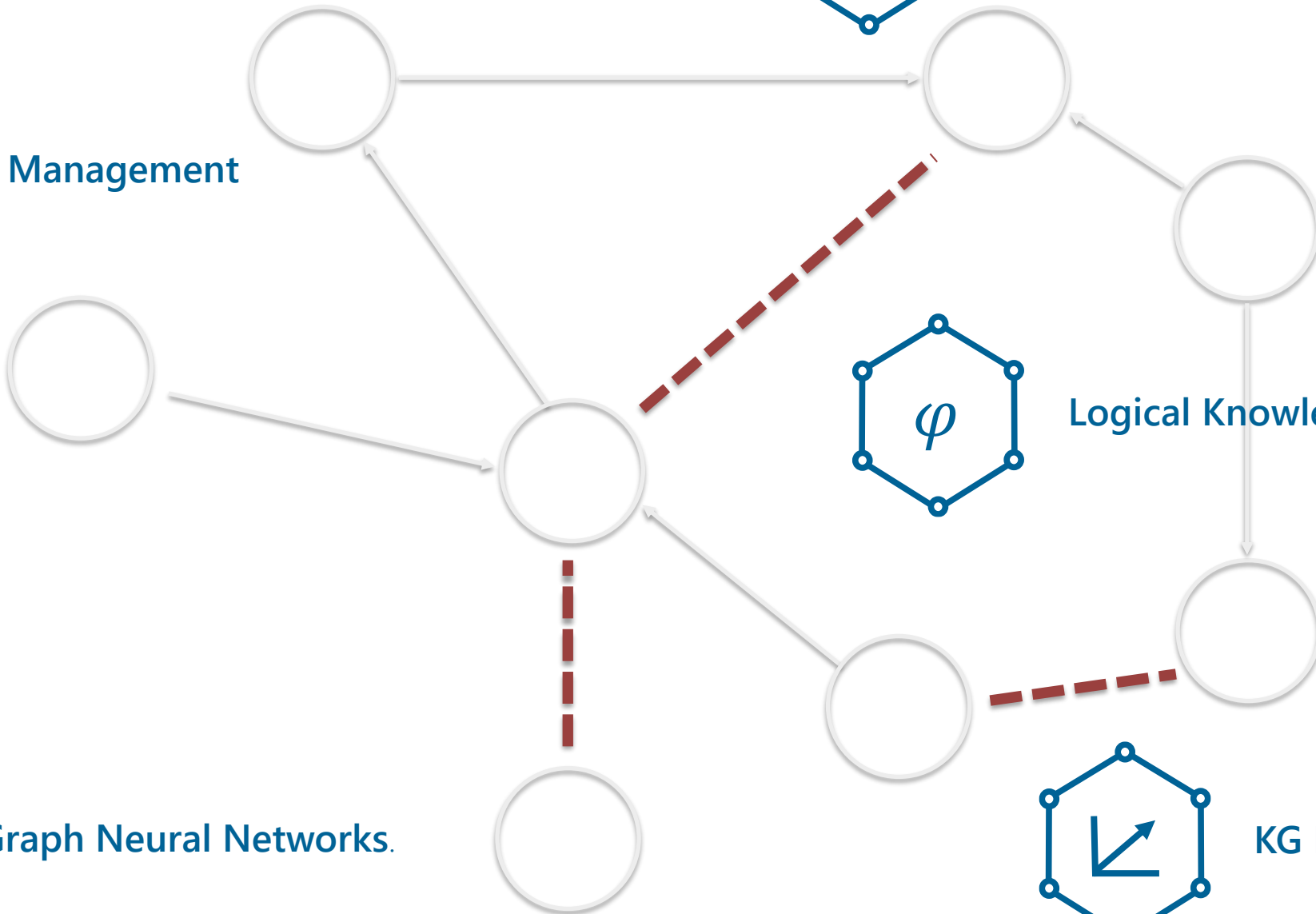
KG Embeddings



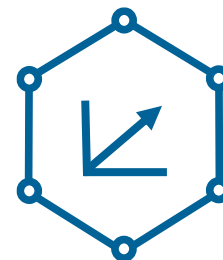
Data Management



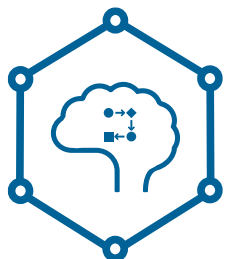
Large Language Models



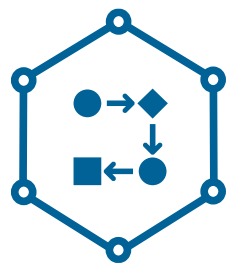
Logical Knowledge in KGs



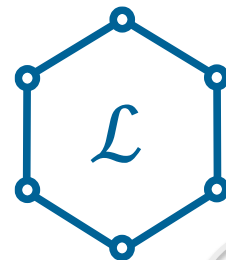
KG Embeddings



Graph Neural Networks.



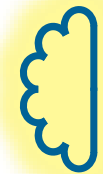
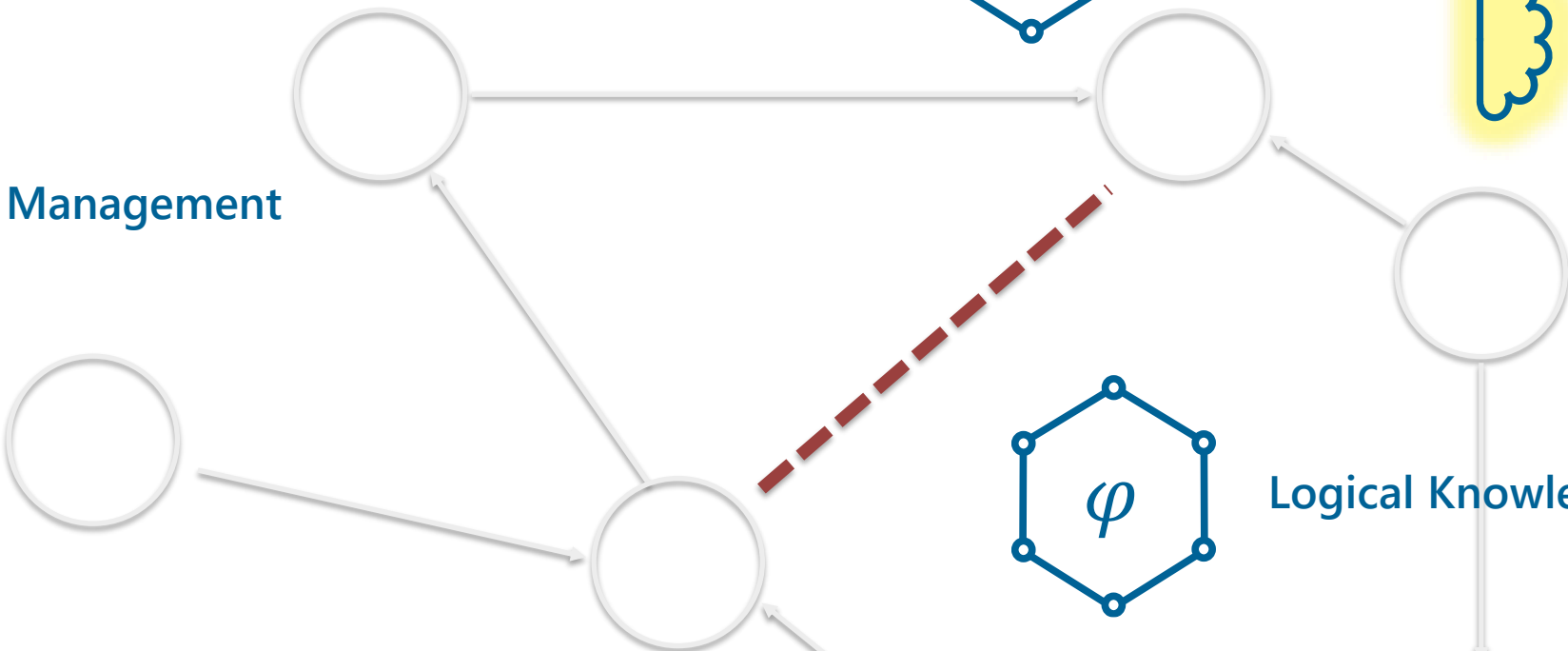
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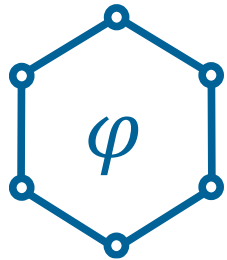
Large Language Models



**ML**



**SYM**



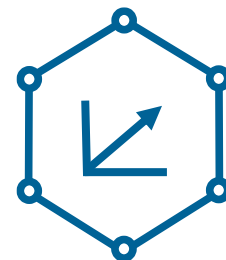
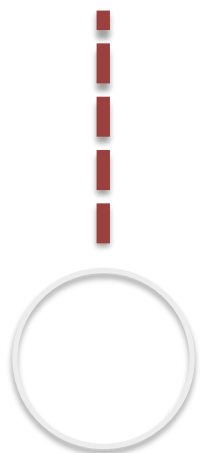
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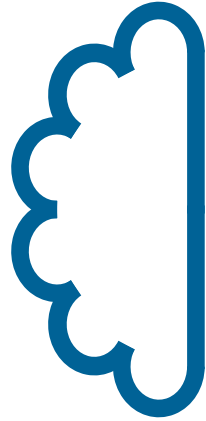
KG Embeddings



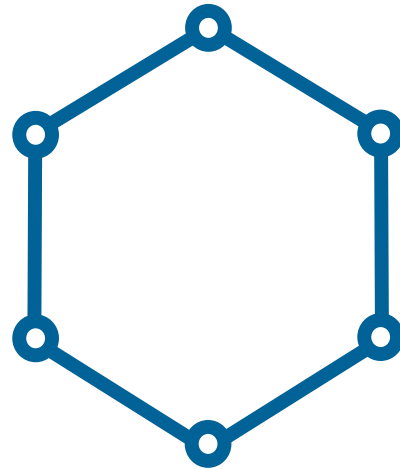
**ML**



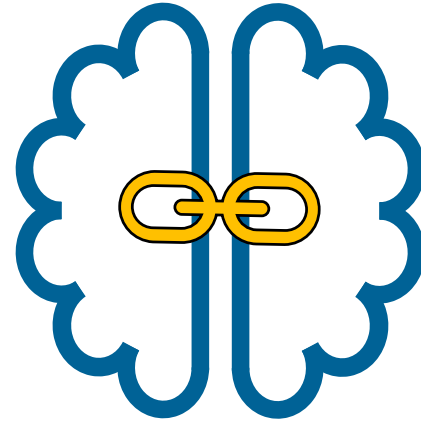
Symbolic AI  
"Logical Reasoning"



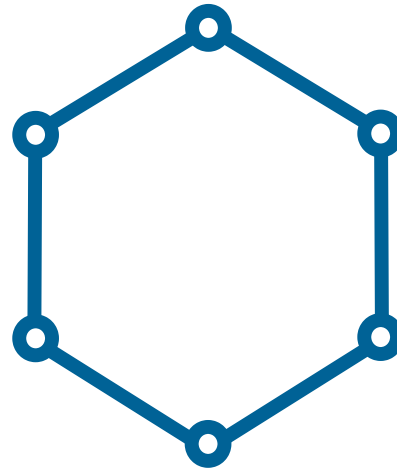
Sub-symbolic AI  
"Machine Learning"



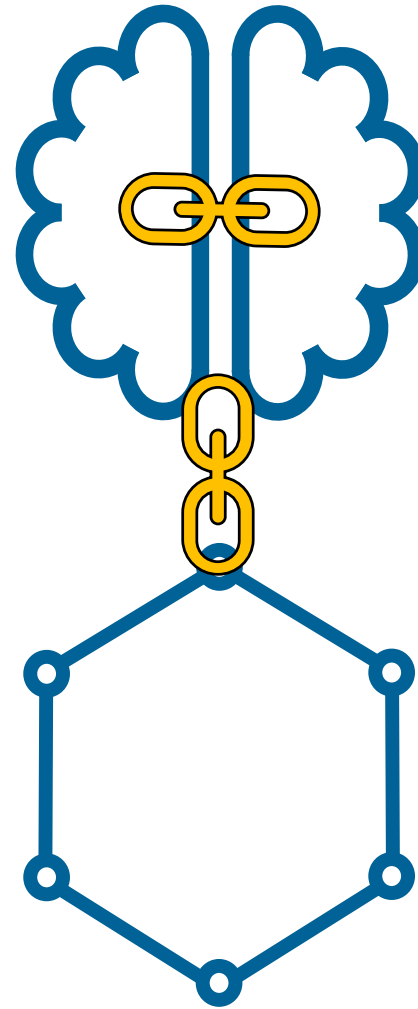
Scalable Graph  
Data Management

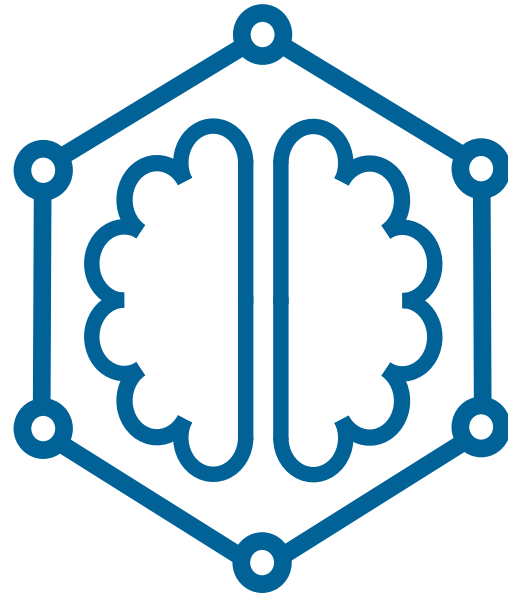


Neuro-symbolic AI







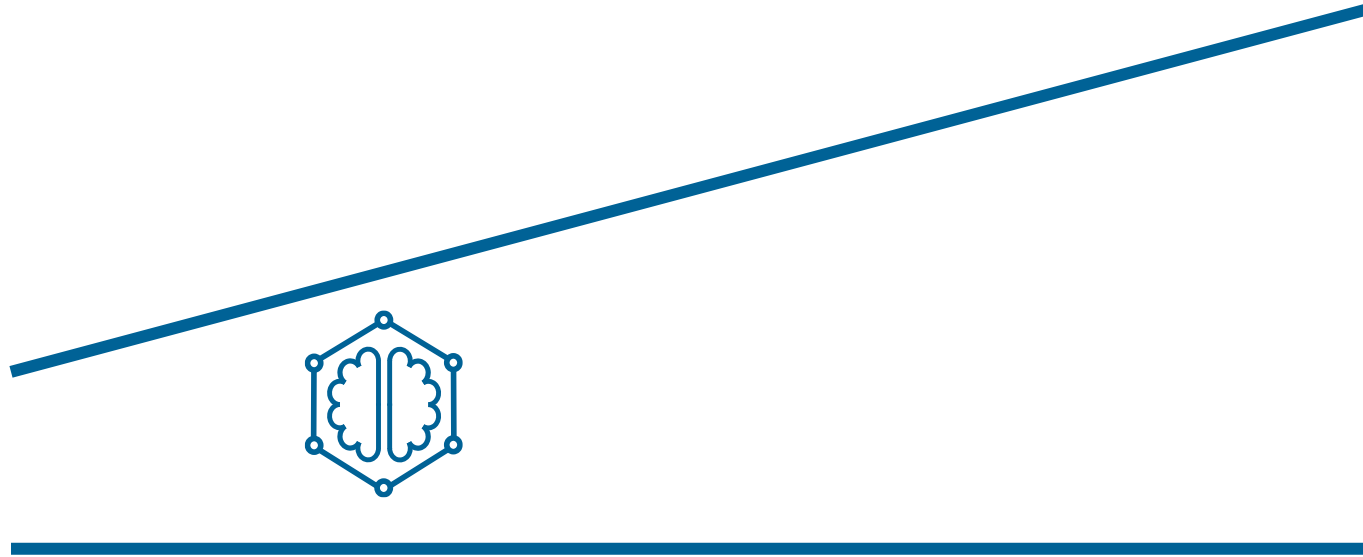


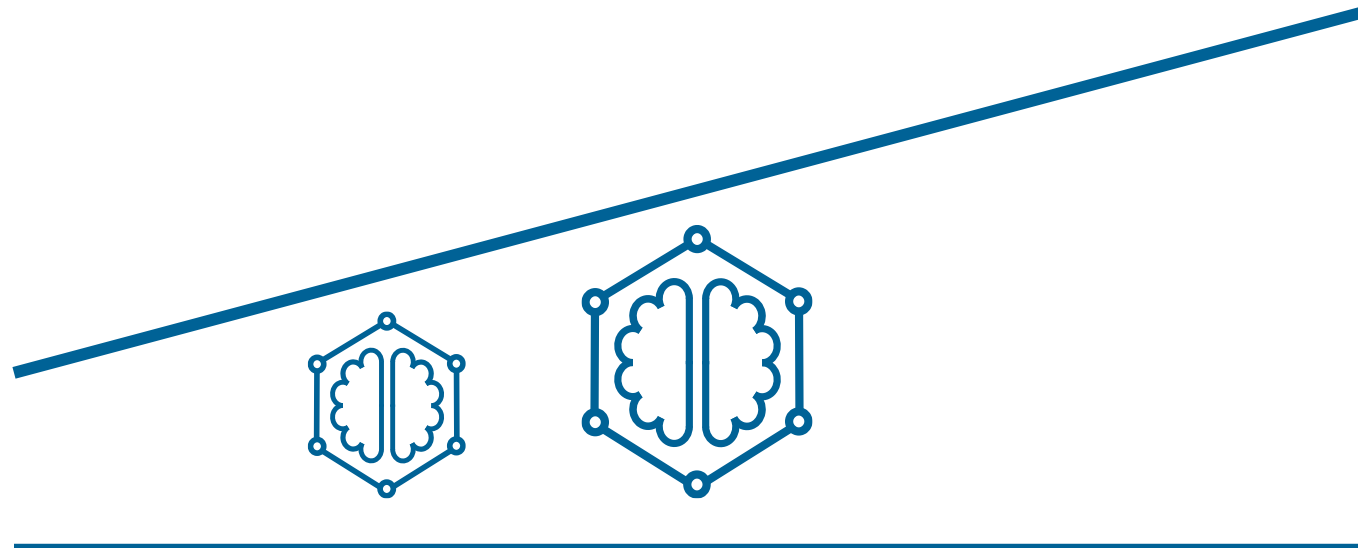
Scalable  
Neuro-symbolic AI

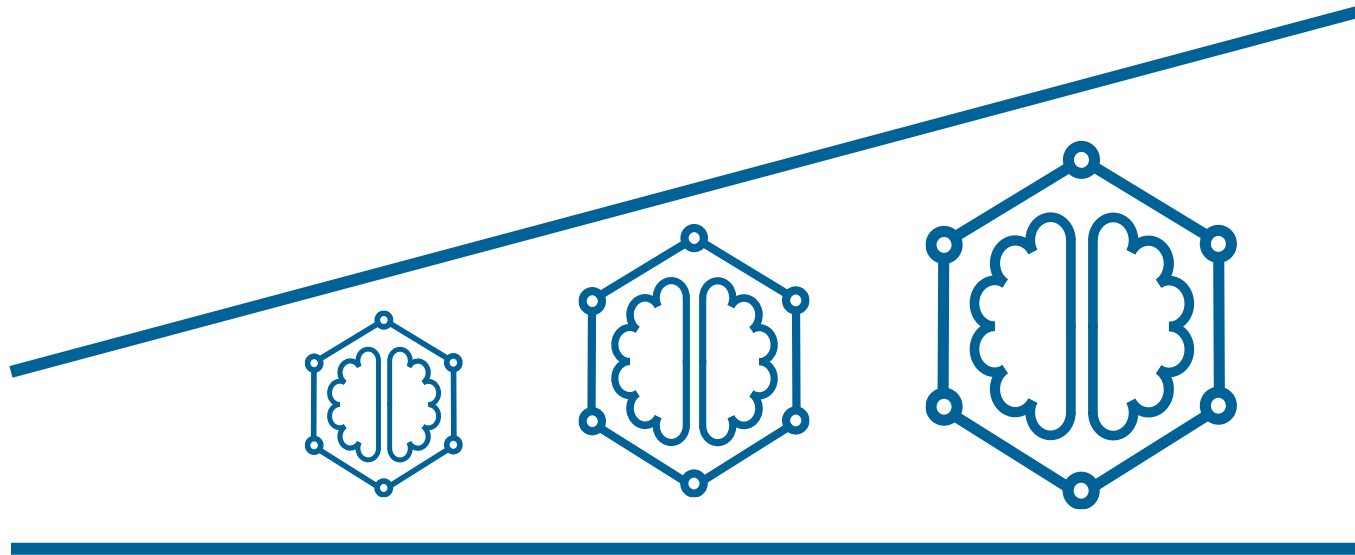


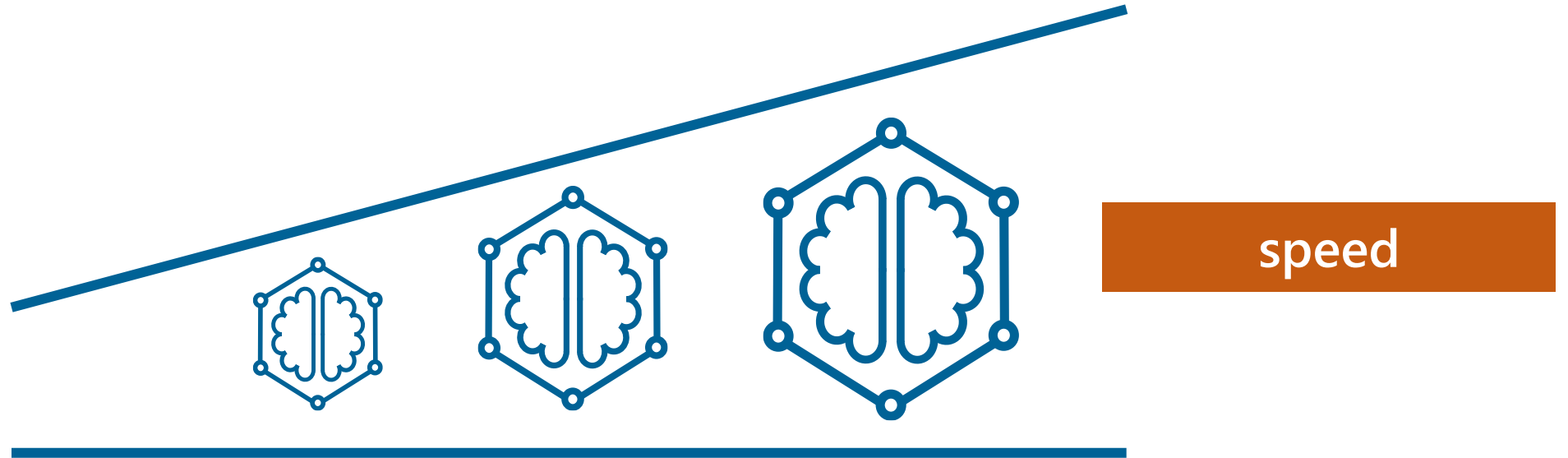
# Is this all a fantasy?

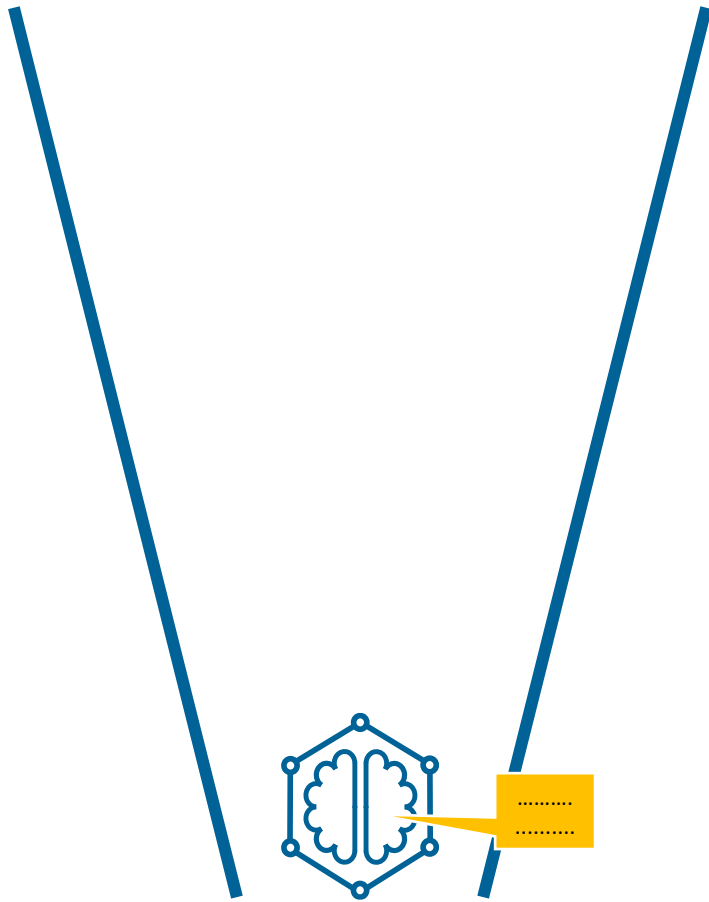






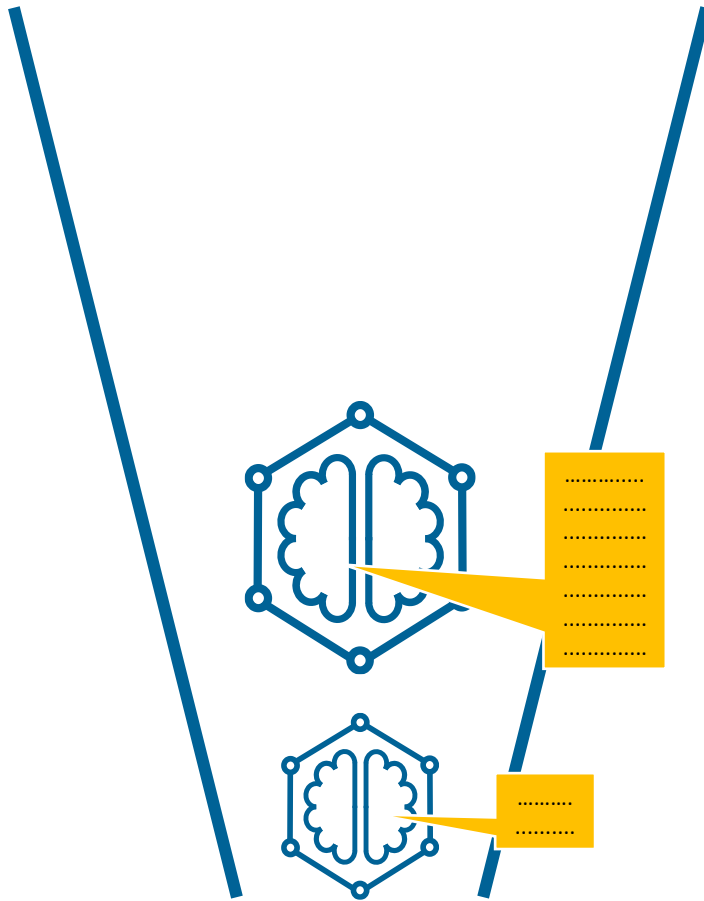




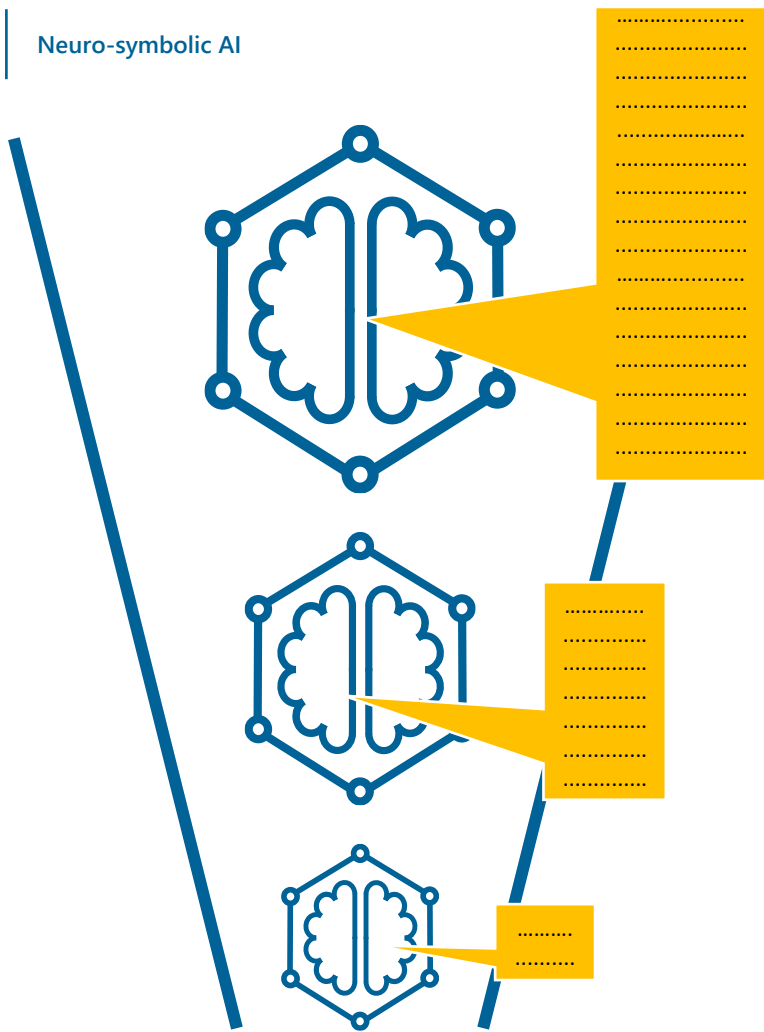


**explainability**





**explainability**



**explainability**



**KG Roar**

**Knowledge Pal**

Prompt: `Is DunkelMeier in close link with IberianBank?`  
`close_link(DunkelMeier,IberianBank)`

Response: CerberusCapitalM... owns a significant portion of both DunkelMeier and IberianBank shares, with ownership percentages of 20.68% and 20.18% respectively. As such, DunkelMeier and IberianBank are considered to have a close link relationship.

Ask me something

**Graph operations**

- All
- General
- Ownership structure
- Shareholding structure
- Banking supervision
- Collateral eligibility
- Corporate economics
- KG language model
- Graph exploration

General Search | Ownership structure ↑ Ownership structure | Ownership structure ↑ Company control





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1billion+ props.



Teodoro Baldazzi, Luigi Bellomarini, Stefano Ceri, Andrea Colombo, Andrea Gentili, Emanuel Sallinger: "Please, Vadalog, tell me why": Interactive Explanation of Datalog-based Reasoning. EDBT 2024: 834-837



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**KG Roar**

**Knowledge Pal**

Prompt: `controls("Darrows","DunkelMeier")`

Response:

Darrows owns 78% of the shares in Sverigsbank, giving it control over the company. Through its control of Sverigsbank, Darrows indirectly controls 27.8% of CreditoNazionale shares and 67.8% of EchoLine shares. Darrows also owns 100% of the shares in Vesta, giving it control over this company as well. Through its control of Vesta, Darrows indirectly controls 19.8% of GTHolding shares. Darrows controls EchoLine, which owns 37.7% of GTHolding shares. Combining this with the shares controlled via Vesta, Darrows controls a total of 57.5% of GTHolding shares, giving it control over this company. Through its control of GTHolding, Darrows indirectly controls an additional 25.1% of CreditoNazionale shares. Combining this with the shares controlled via Sverigsbank, Darrows controls a total of 52.9% of CreditoNazionale shares, giving it control over this company. Darrows also controls 6.2% of Lausebga shares through GTHolding and 45% through CreditoNazionale, giving it control over 51.2% of Lausebga shares and thus control over the company. Through its control of CreditoNazionale, Darrows indirectly controls 38.7% of DunkelMeier shares. Through Lausebga, it controls an additional 30% of DunkelMeier shares. In total, Darrows controls 68.7% of DunkelMeier shares, giving it control over this company.



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**DM**



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**SYM**

**DM**



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General  
Q Search

Ownership structure  
↑ Ownership structure

Ownership structure  
+ Company control

**ML**  
KGE  
GNN

**SYM**

**DM**



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**ML LLM**

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  KG language model
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**ML KGE GNN**

**SYM**

**DM**

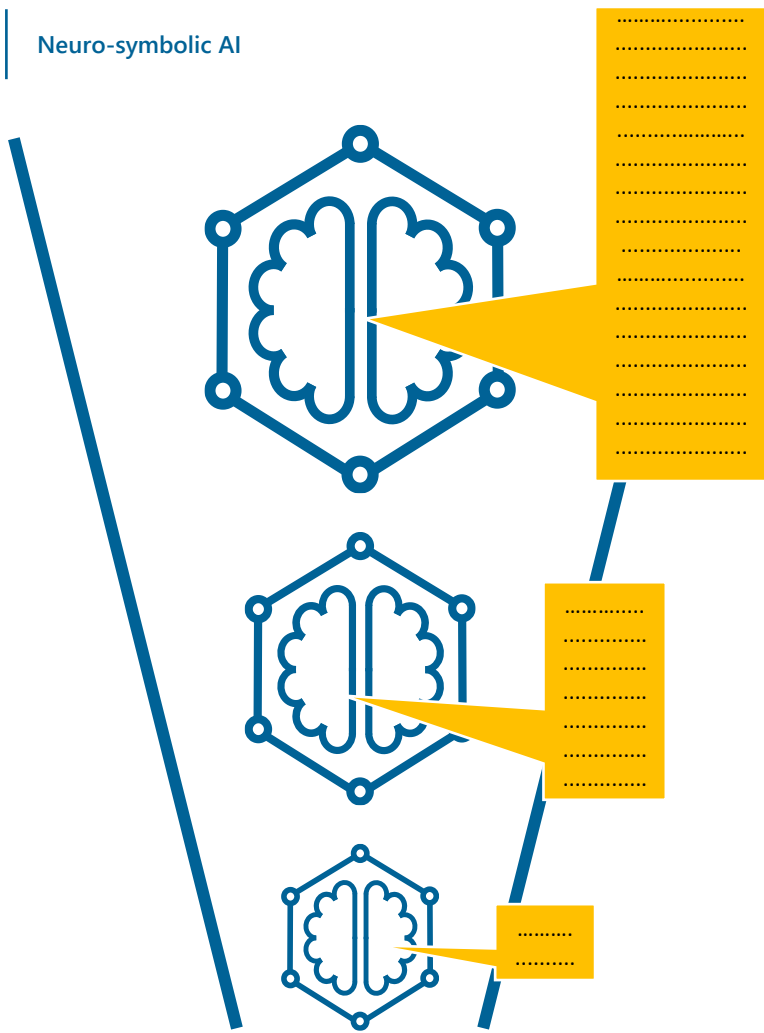


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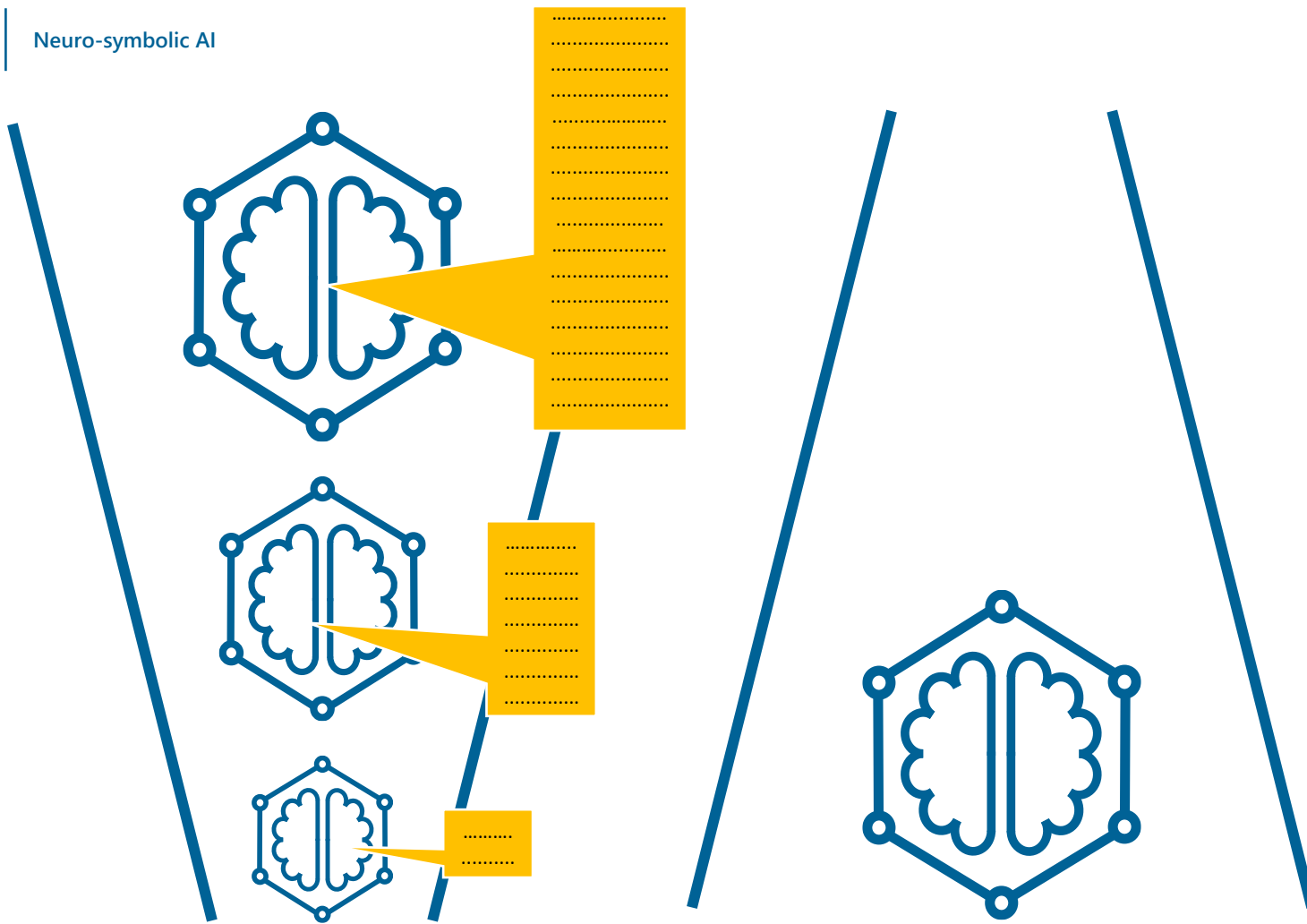
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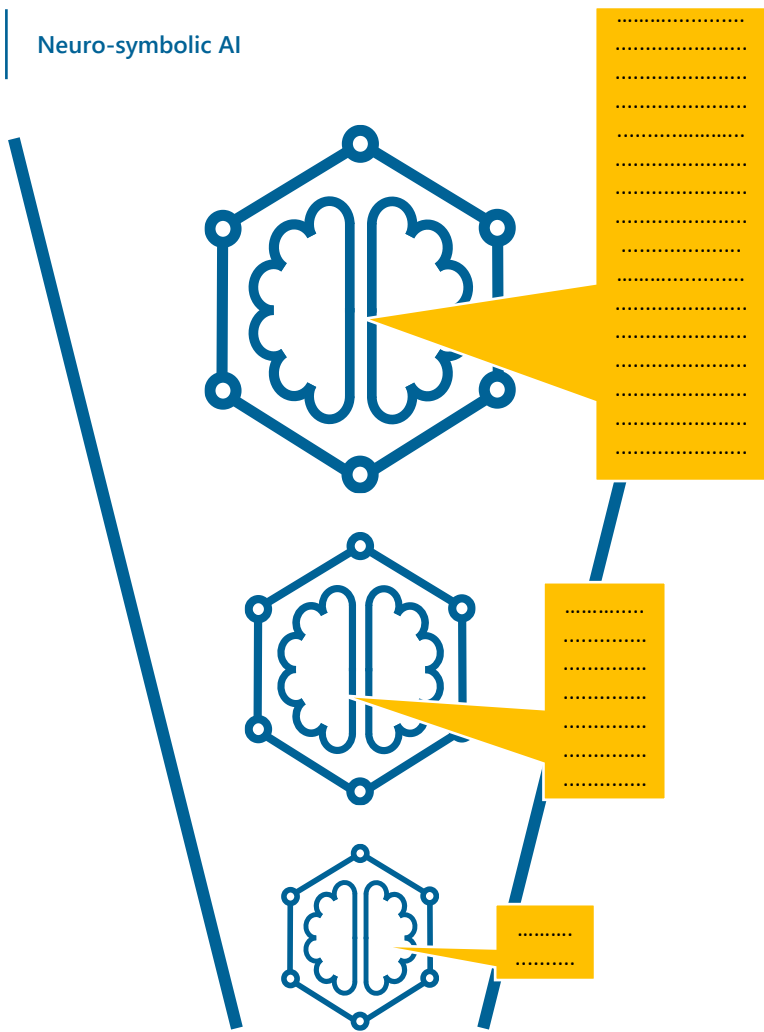


**explainability**

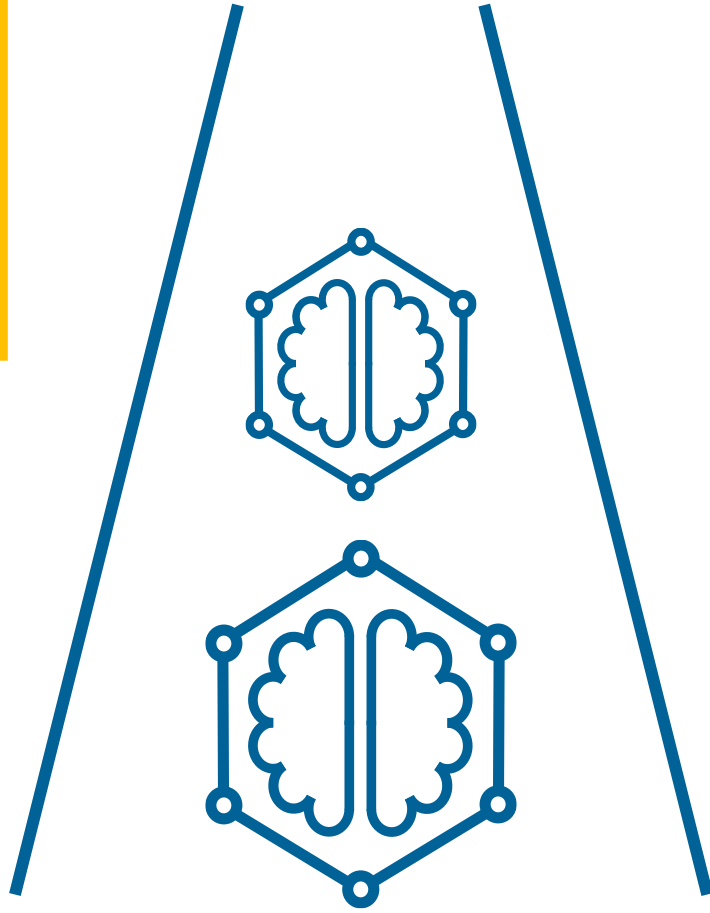


explainability

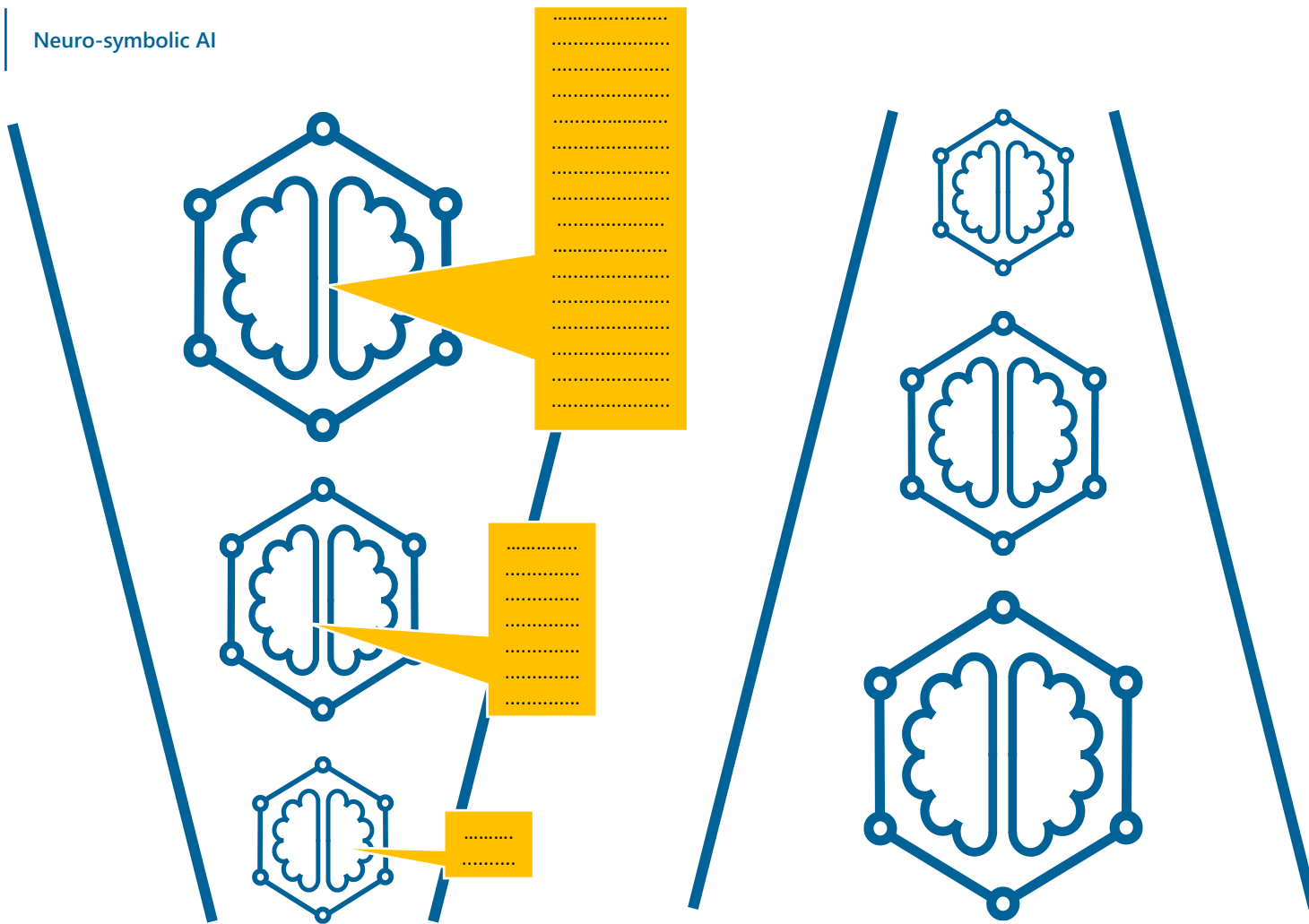
sustainability



**explainability**



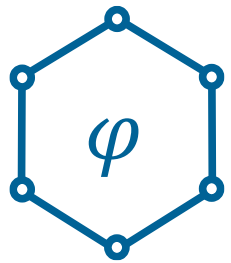
**sustainability**



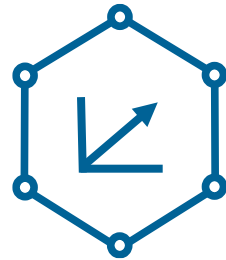
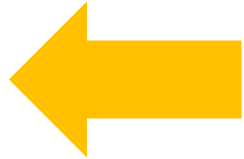
explainability

sustainability





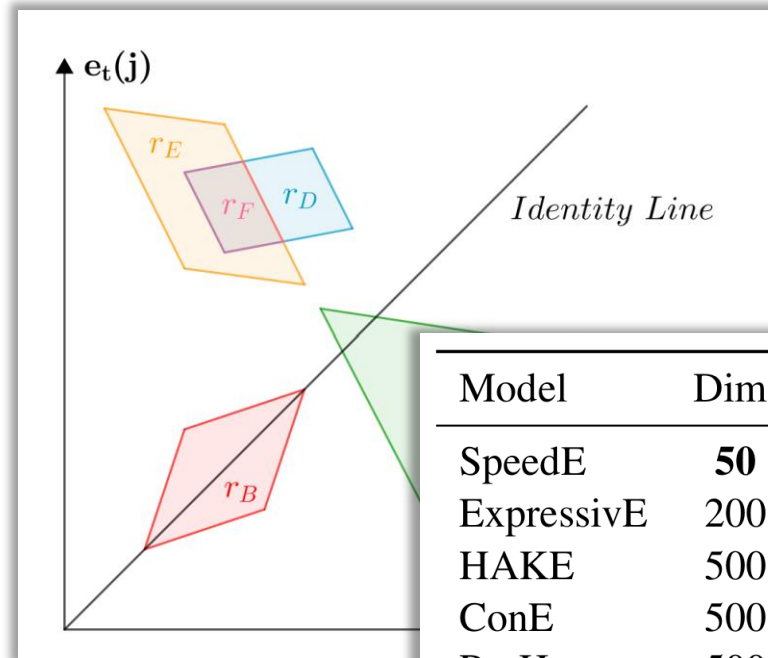
Logical Knowledge



Knowledge Graph Embeddings



Graph Neural Networks



Model	Dim.	MRR	Conv. Time	#Parameters
SpeedE	<b>50</b>	<b>.500</b>	<b>6min</b>	<b>2M</b>
ExpressivE	200	<b>.500</b>	31min	8M
HAKE	500	.497	50min	41M
ConE	500	.496	1.5h	20M
RotH	500	.496	2h	21M



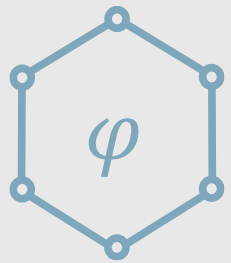
Aleksandar Pavlovic, Emanuel Sallinger: ExpressivE: A Spatio-Functional Embedding For Knowledge Graph Completion. ICLR 2023



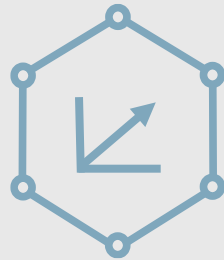
Aleksandar Pavlovic, Emanuel Sallinger: SpeedE: Euclidean Geometric Knowledge Graph Embedding Strikes Back. NAACL 2024



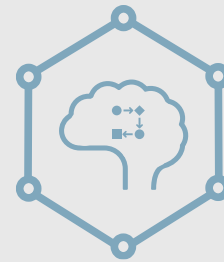
Aleksandar Pavlovic, Emanuel Sallinger, Steven Schockaert: Differentiable Reasoning about Knowledge Graphs with Region-based Graph Neural Networks. *Preprint 2024*



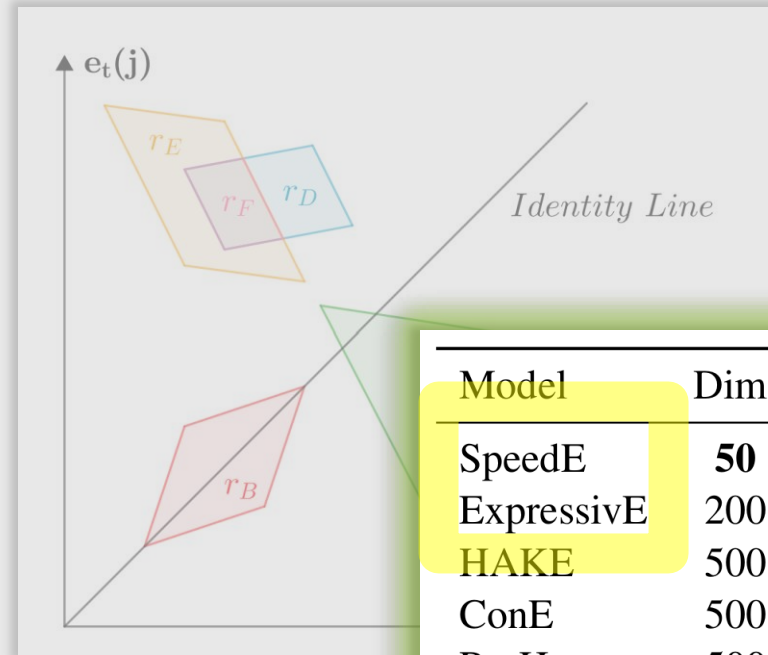
Logical Knowledge



Knowledge Graph Embeddings



Graph Neural Networks



Model	Dim.	MRR	Conv. Time	#Parameters
SpeedE	50	.500	6min	2M
ExpressivE	200	.500	31min	8M
HAKE	500	.497	50min	41M
ConE	500	.496	1.5h	20M
RotH	500	.496	2h	21M



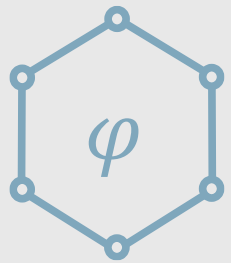
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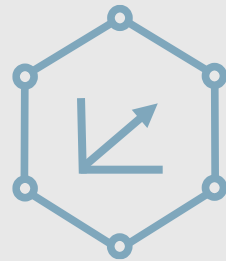
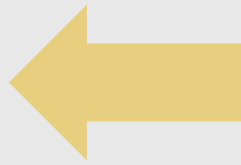
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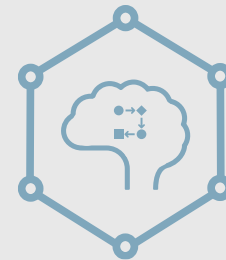
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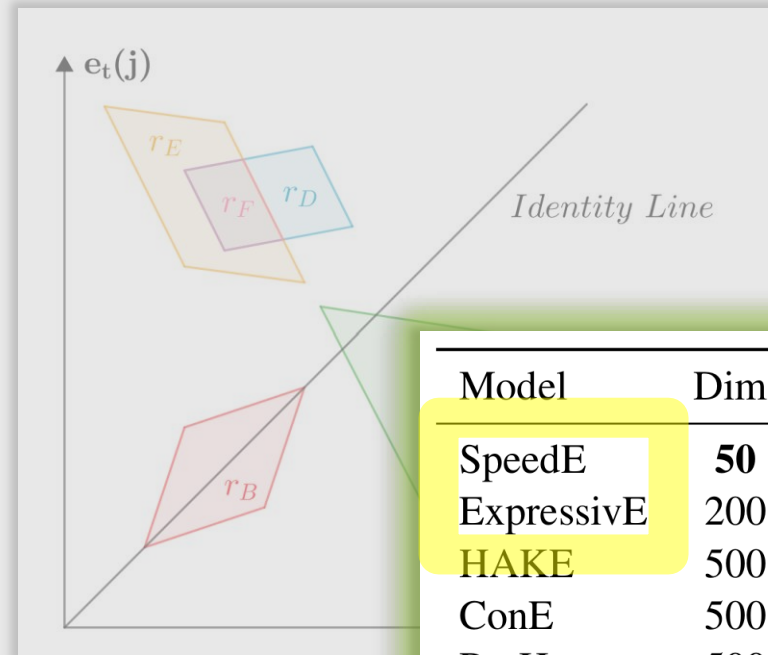
Logical Knowledge



Knowledge Graph Embeddings



Graph Neural Networks



**10-20x**  
**more resource efficient**

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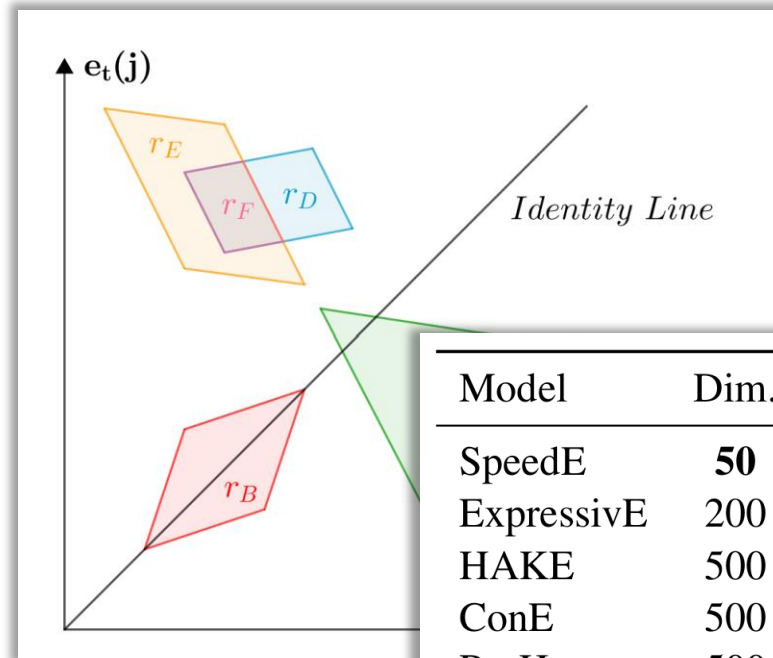
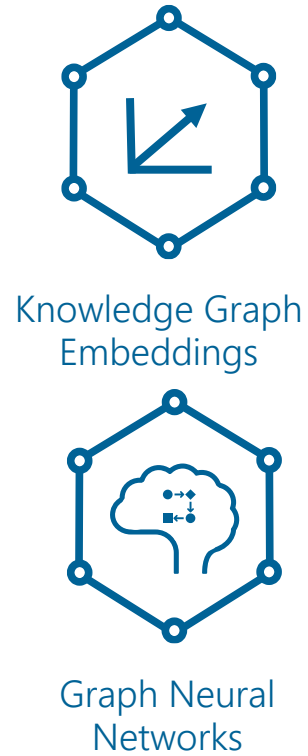
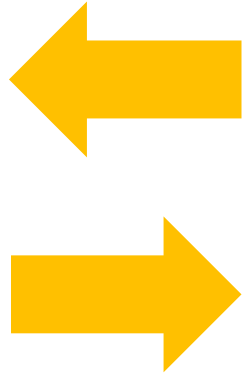
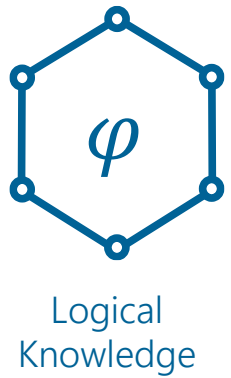
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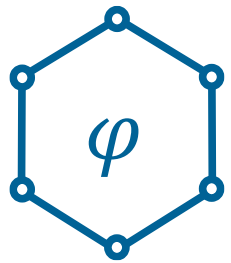
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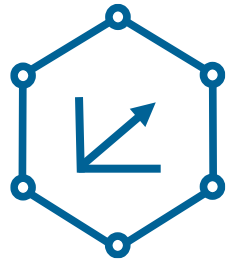
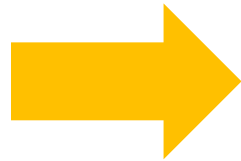
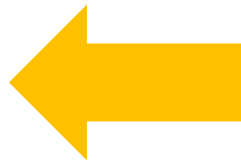
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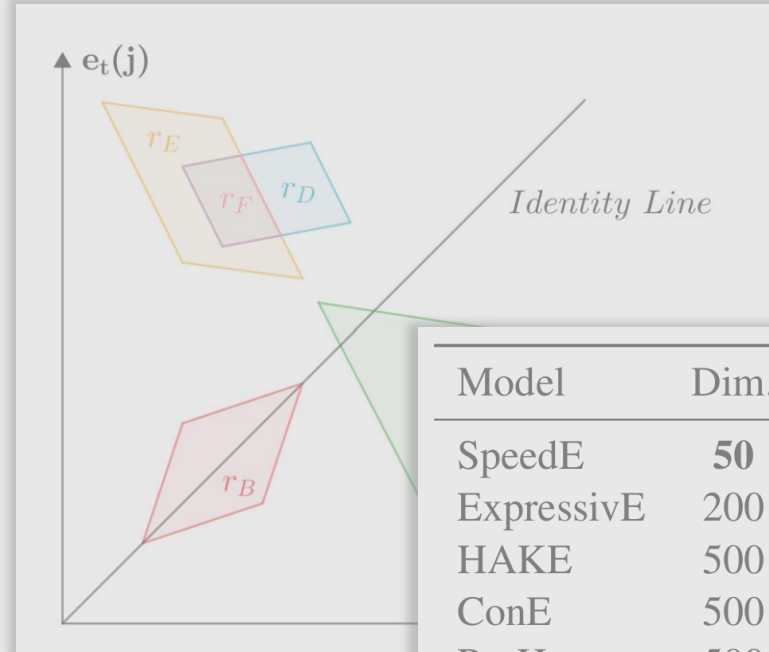
Logical Knowledge



Knowledge Graph Embeddings



Graph Neural Networks



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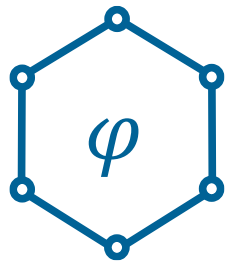
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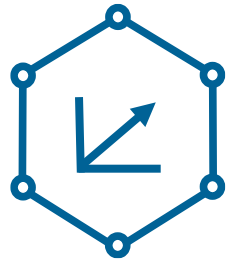
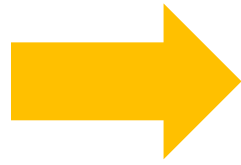
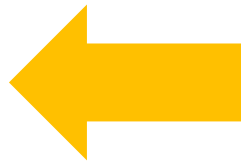
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Logical Knowledge

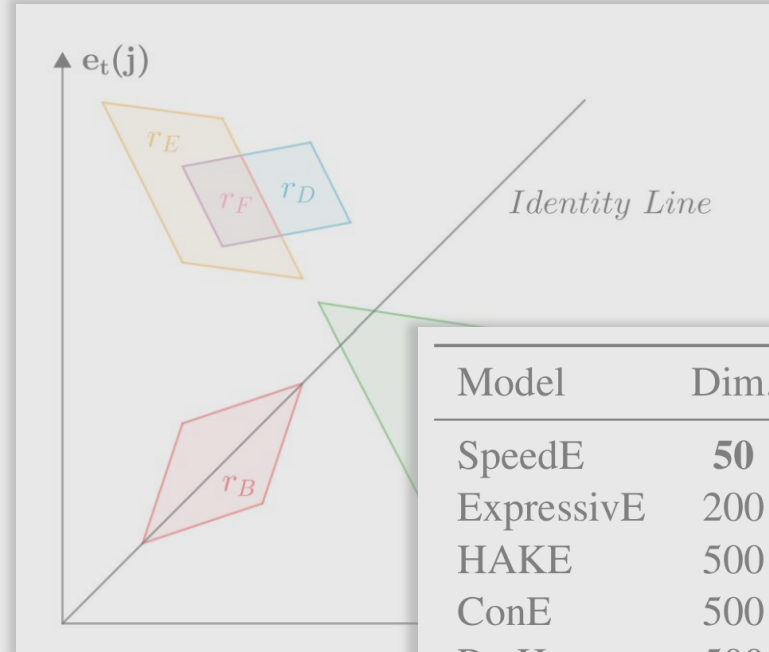


Knowledge Graph Embeddings



Graph Neural Networks

**SYM**



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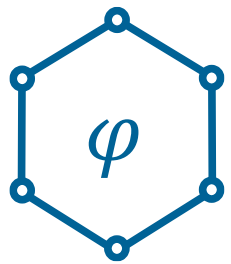
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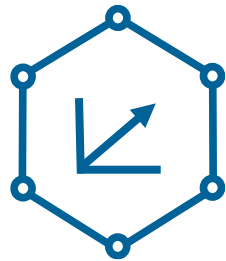
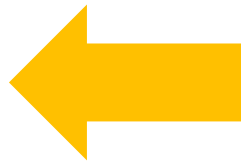
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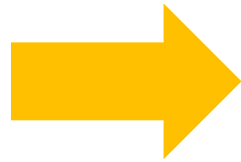
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Logical Knowledge

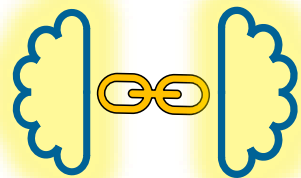


Knowledge Graph Embeddings

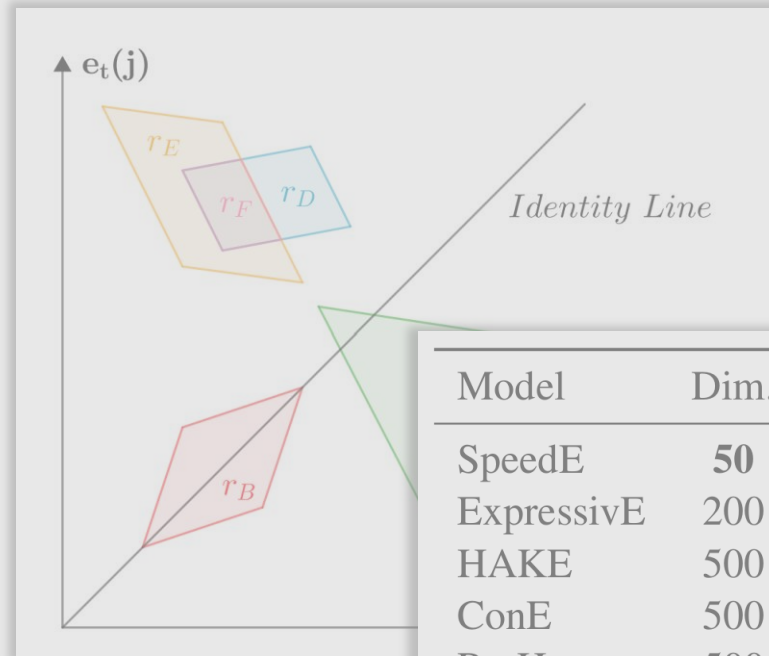


Graph Neural Networks

**SYM**



**ML**



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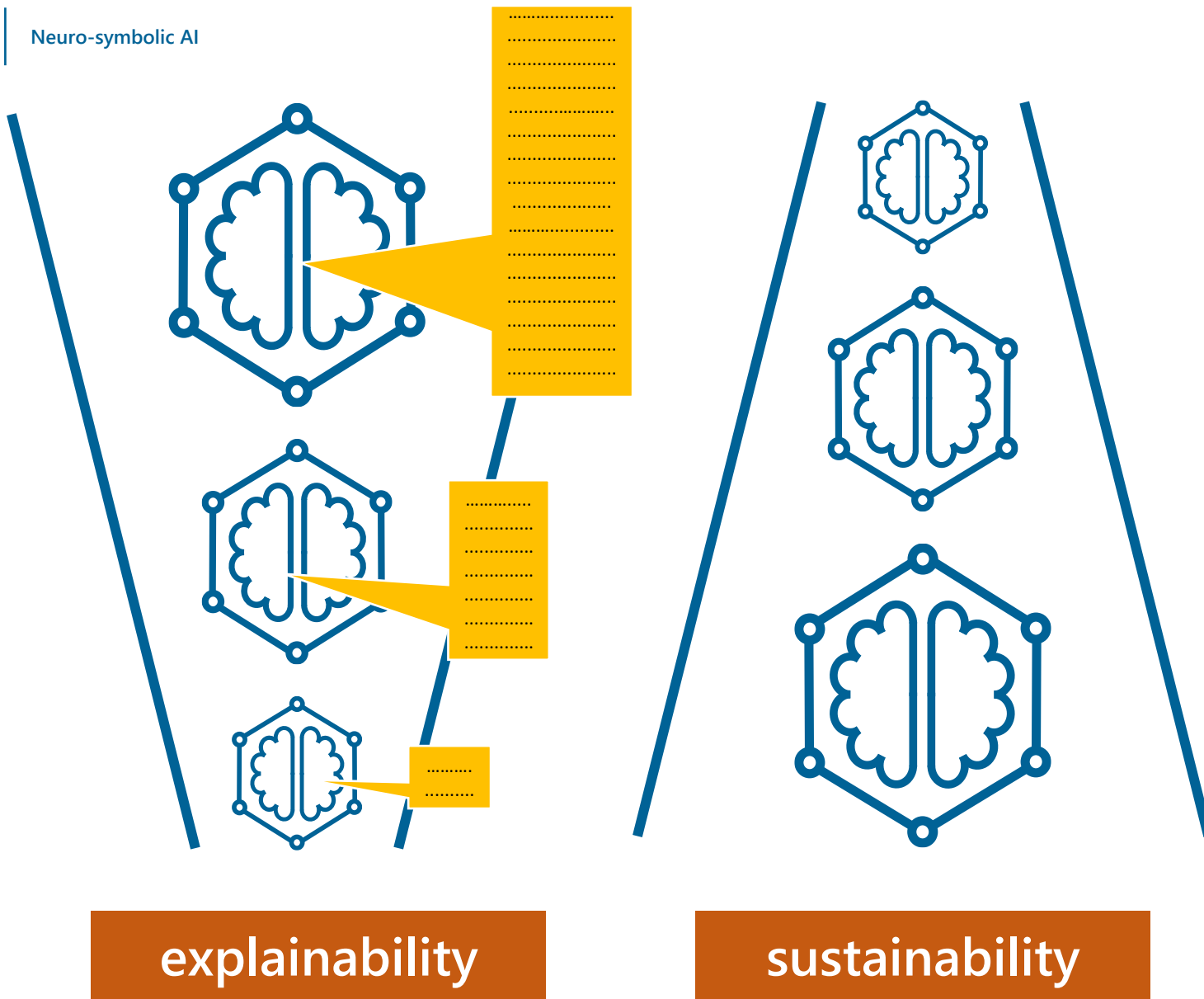
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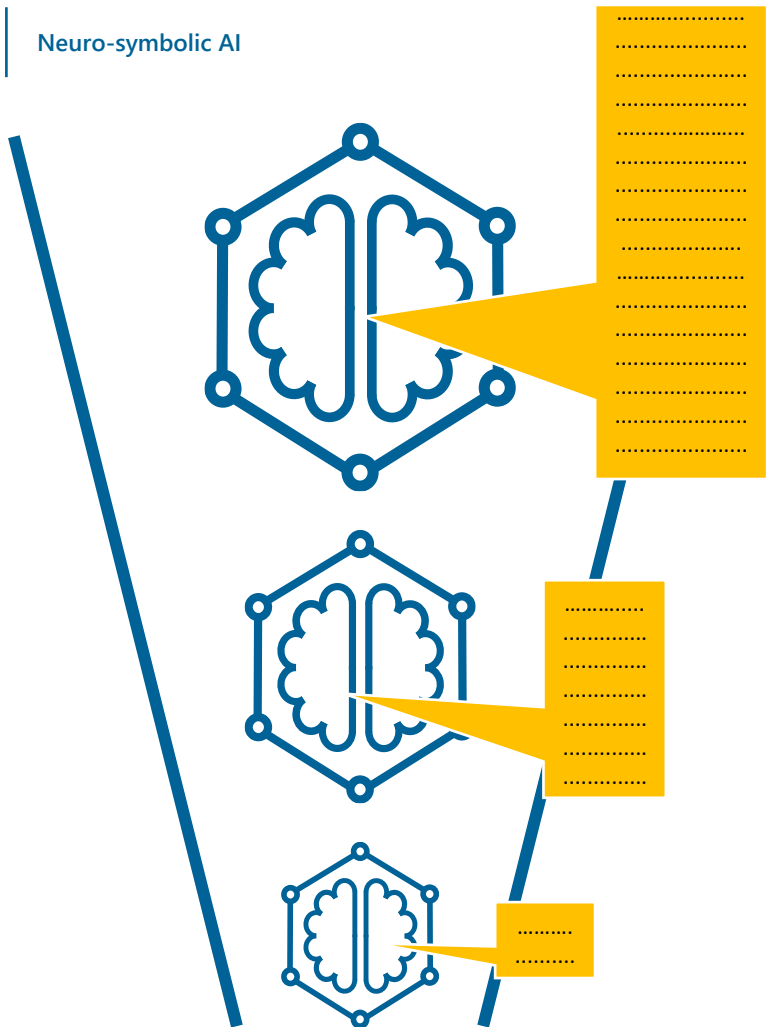




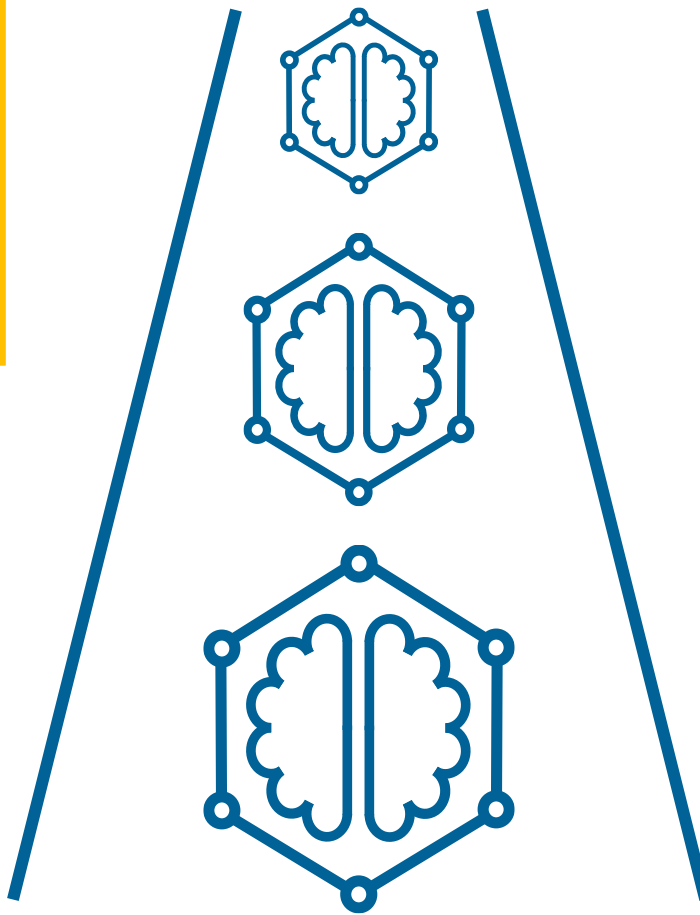


explainability

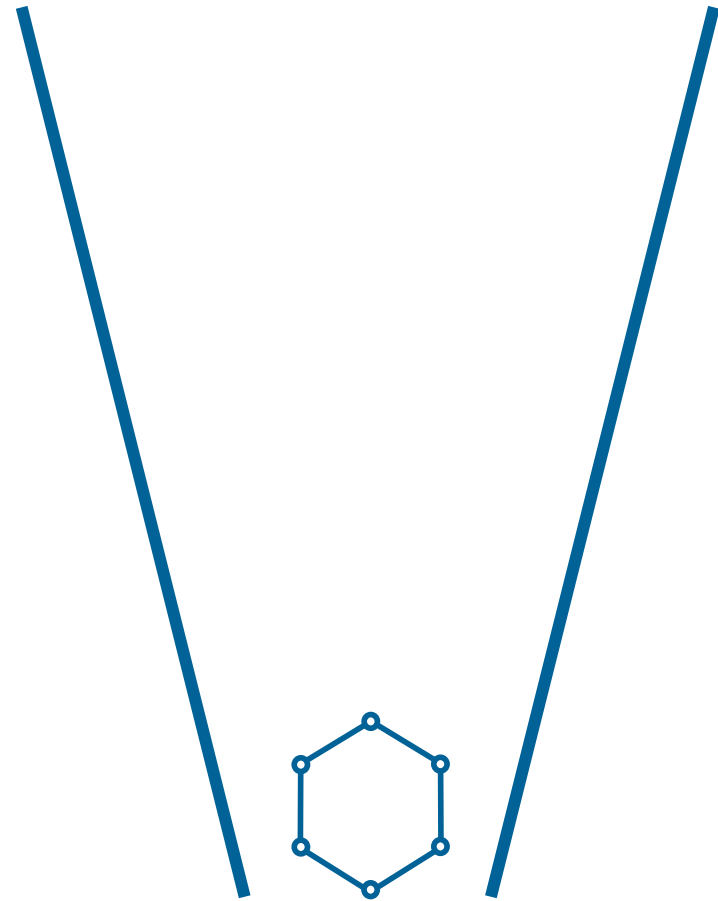
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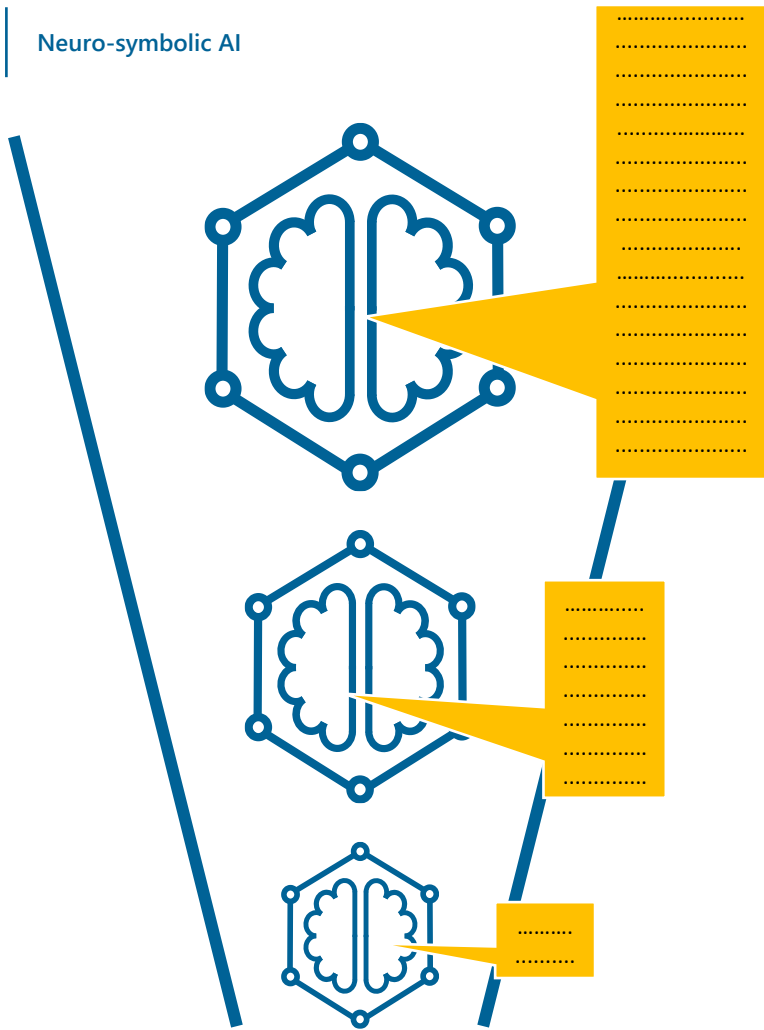
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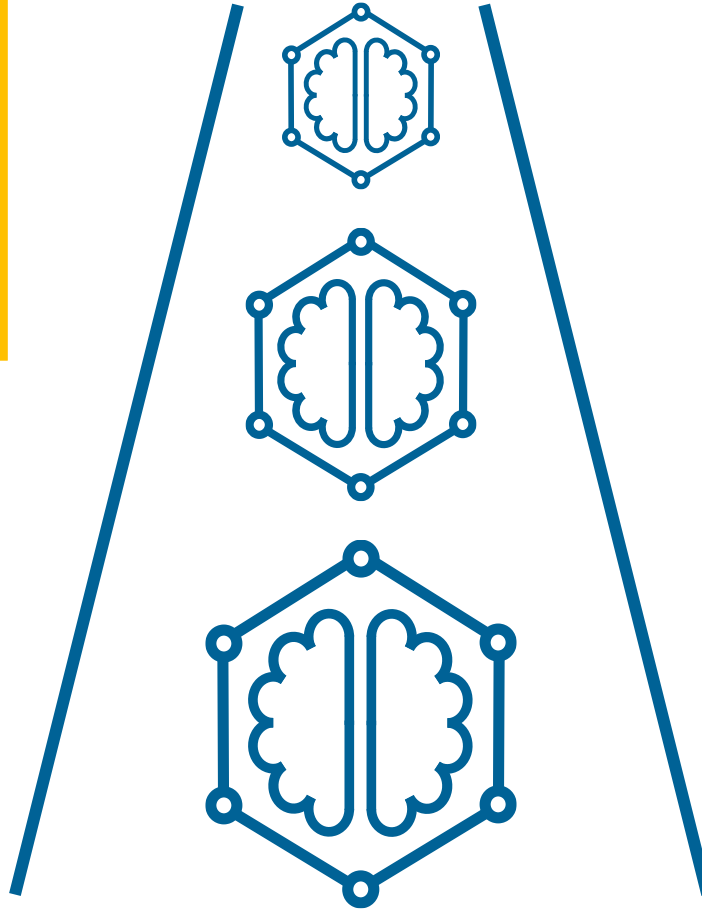
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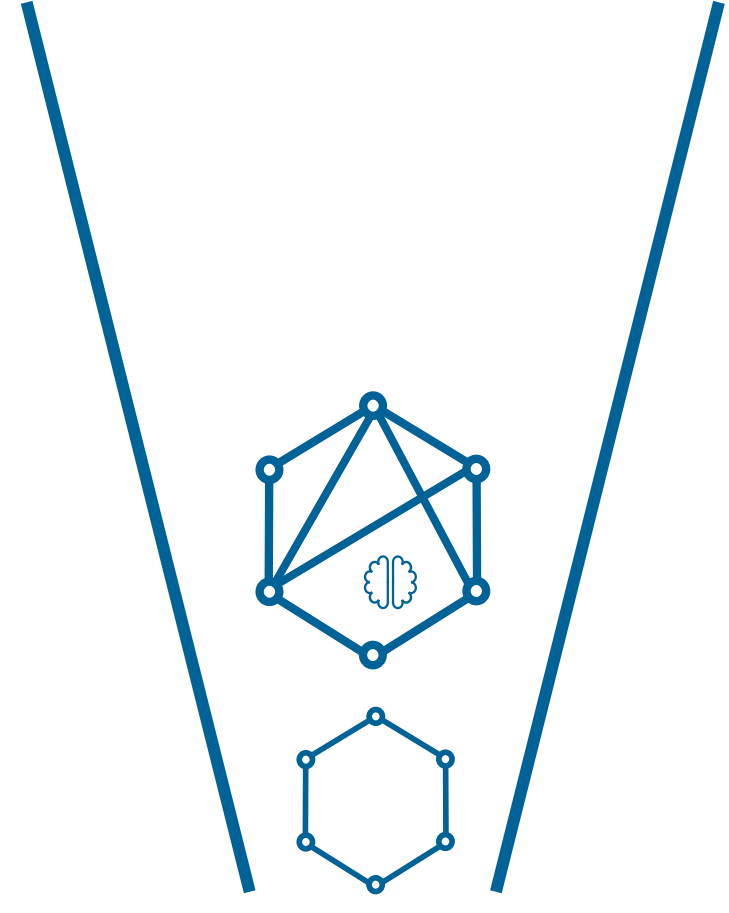
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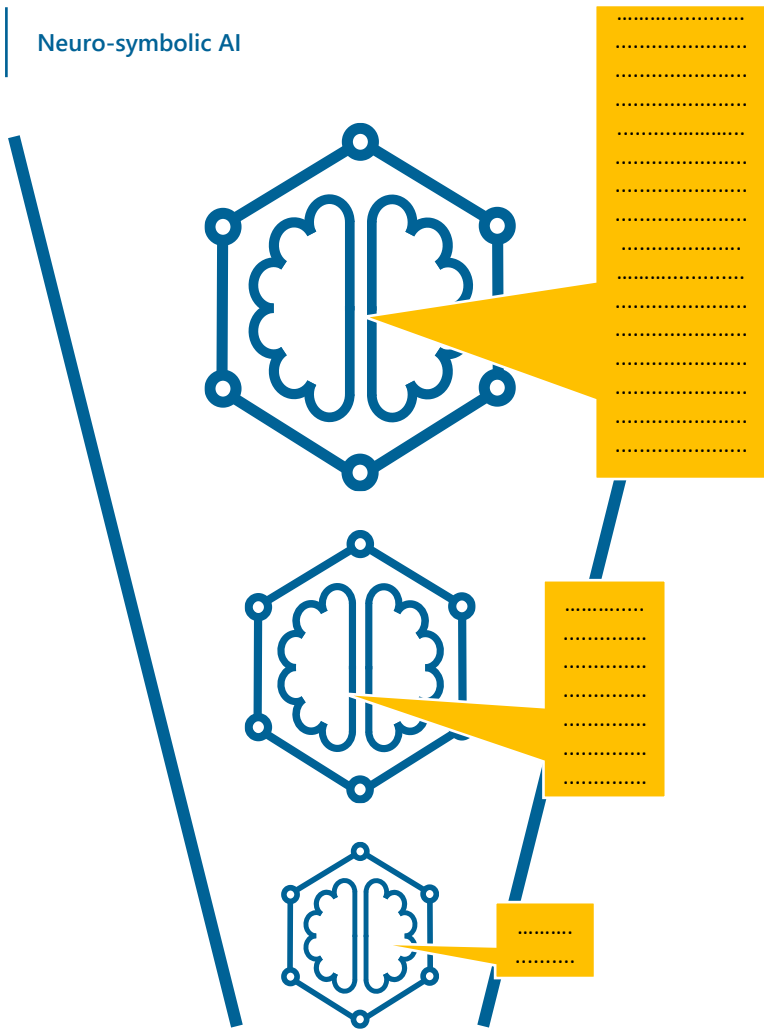
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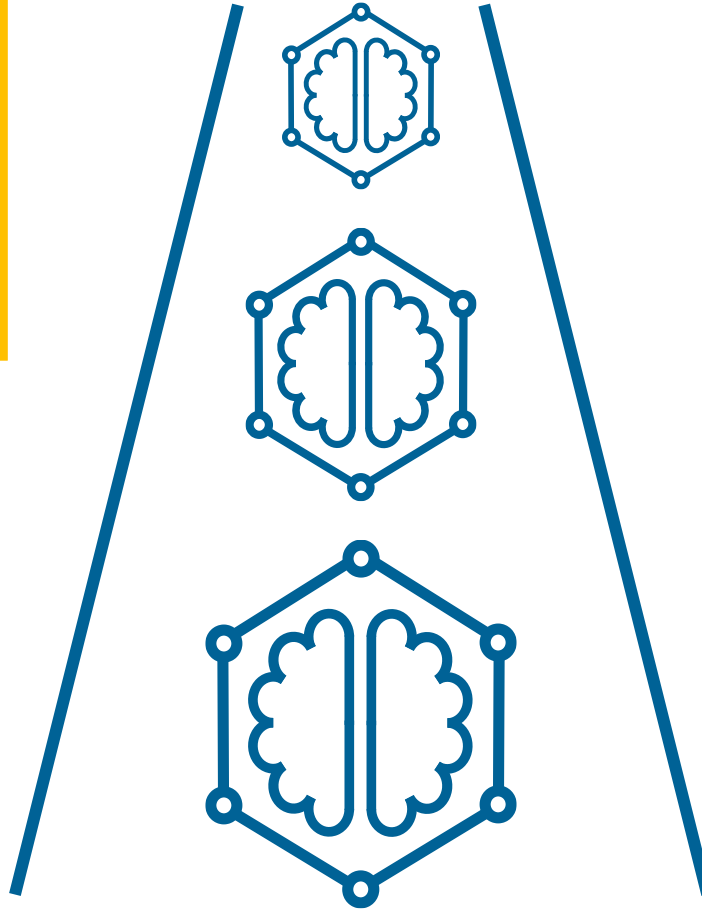
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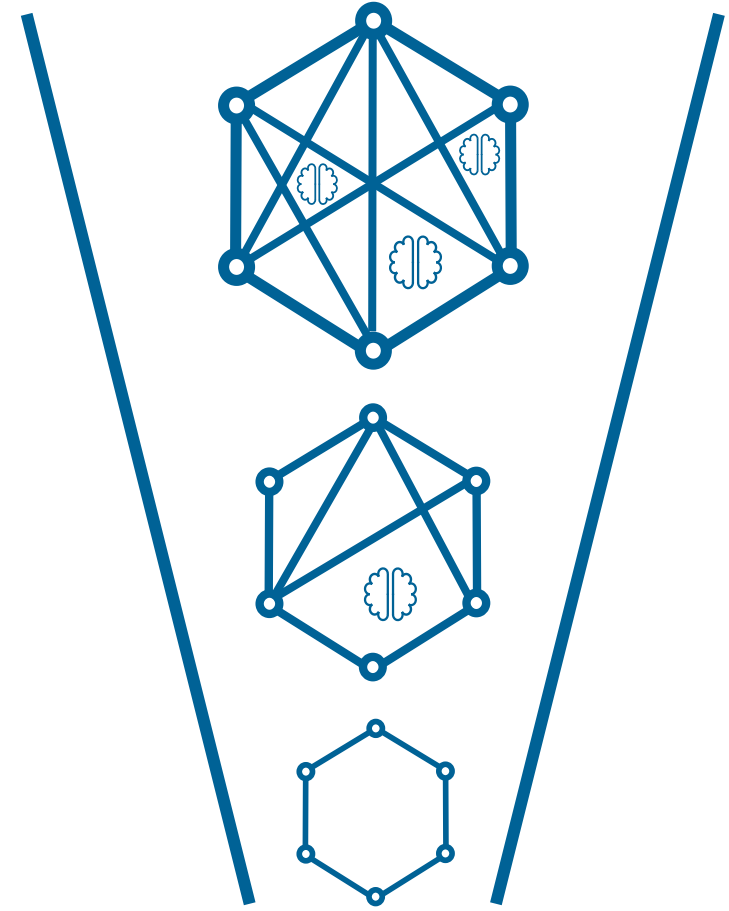
**complexity**



explainability



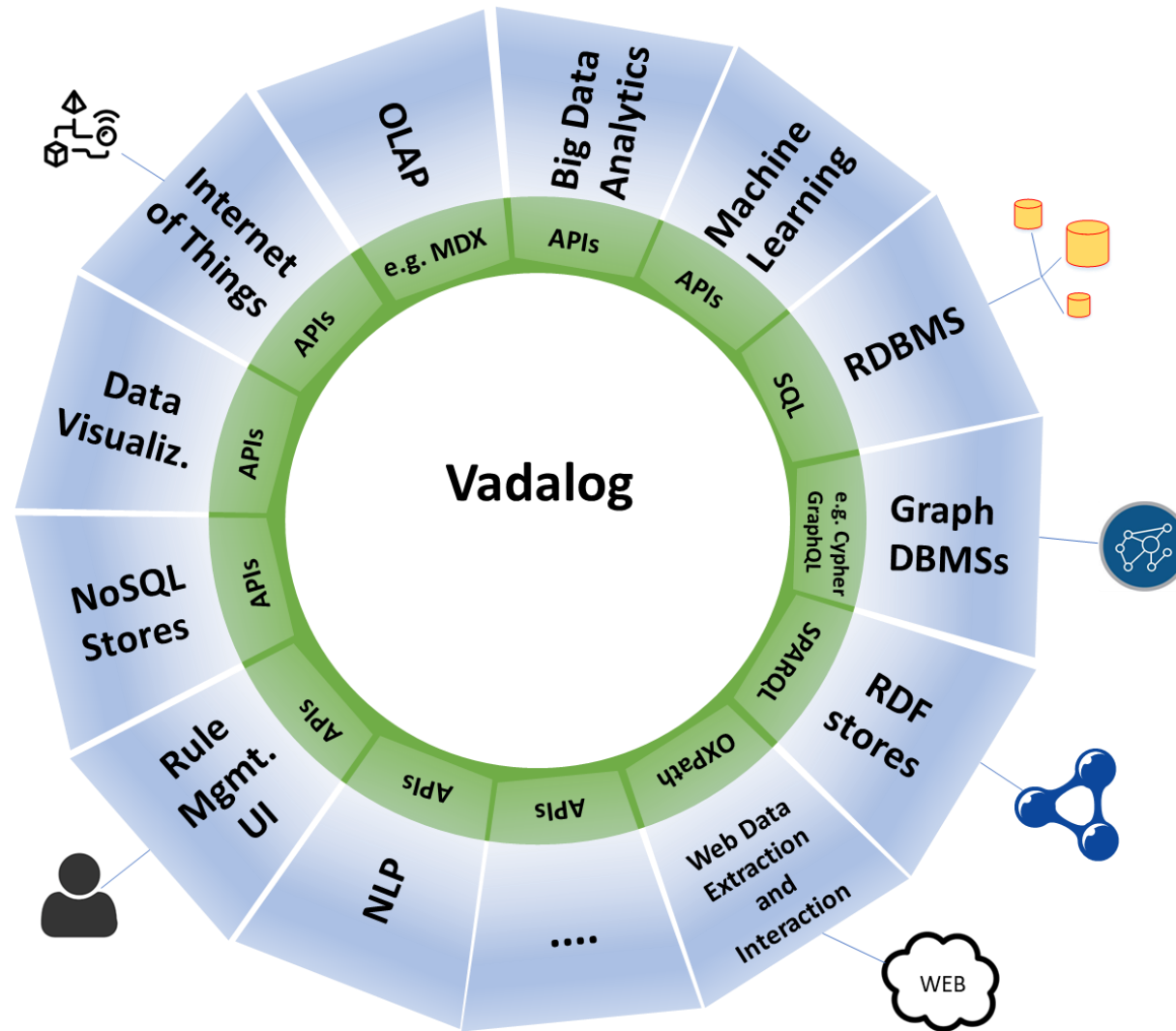
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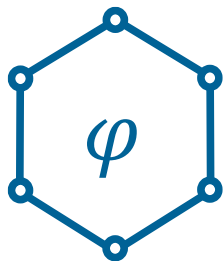
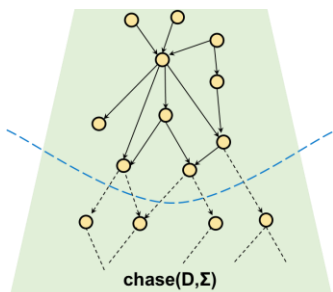
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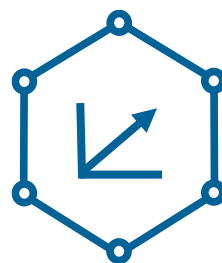
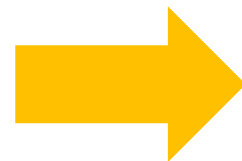
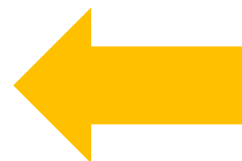
# The Vadalog System



Luigi Bellomarini, Davide Benedetto, Georg Gottlob, Emanuel Sallinger: Vadalog: A modern architecture for automated reasoning with large knowledge graphs. Inf. Syst. 105: 101528 (2022)



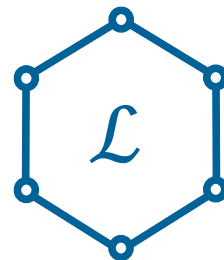
Logical Knowledge



Knowledge Graph Embeddings

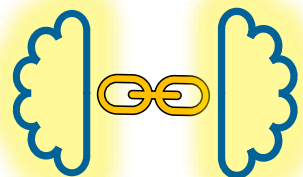


Graph Neural Networks



Large Language Models

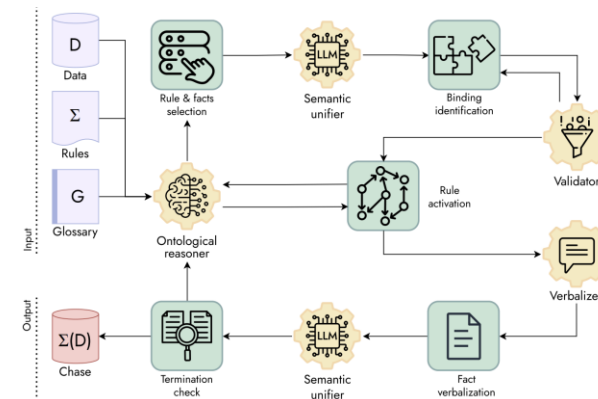
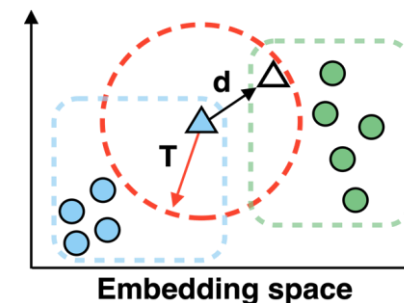
**SYM**



**ML**

△ New fact    ▴ Isomorphic

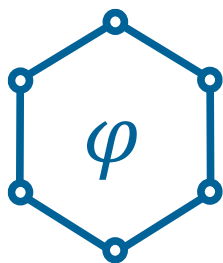
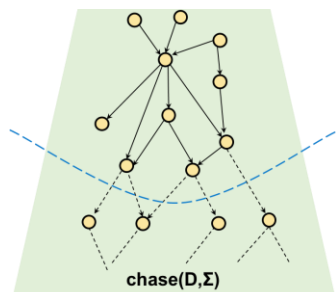
● Reasoning clusters



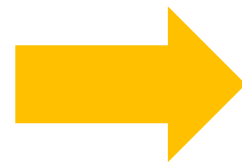
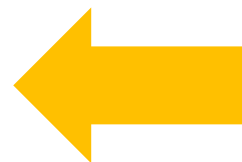
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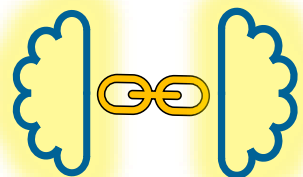
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Logical Knowledge



**SYM**



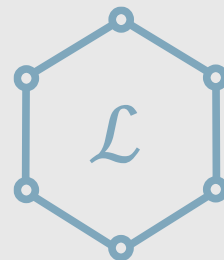
**ML**



Knowledge Graph Embeddings



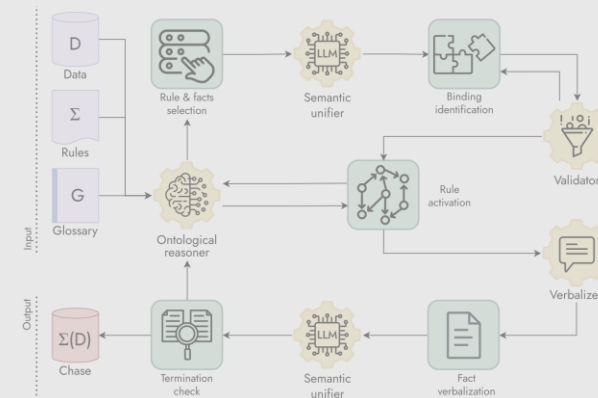
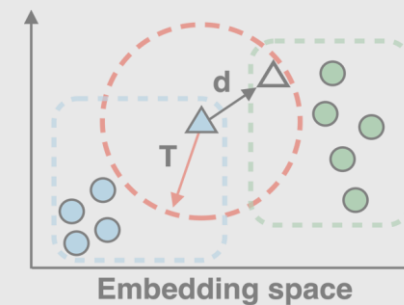
Graph Neural Networks



Large Language Models

△ New fact    ▴ Isomorphic

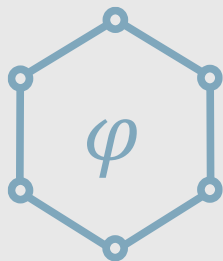
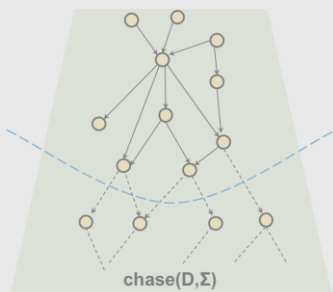
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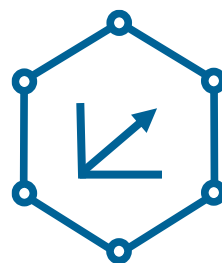
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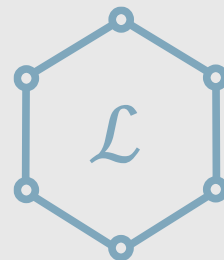
Logical Knowledge



Knowledge Graph Embeddings

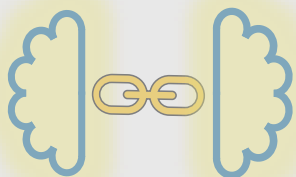


Graph Neural Networks



Large Language Models

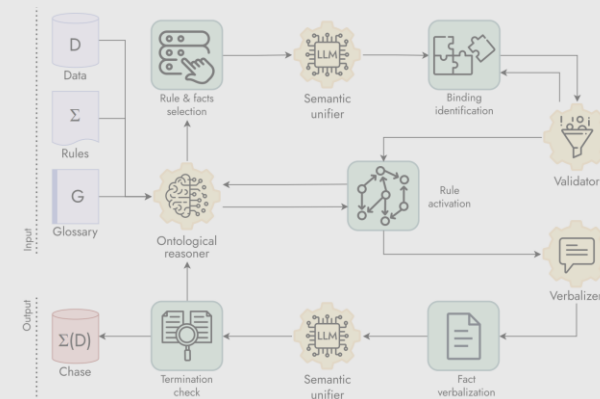
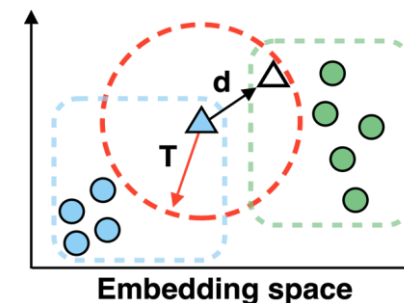
SYM



ML

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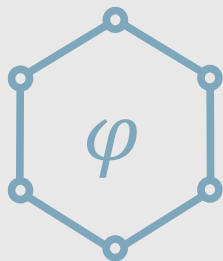
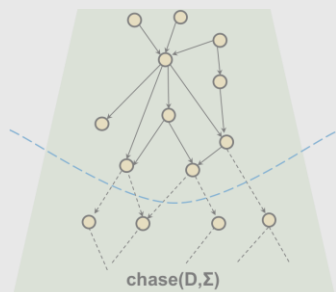
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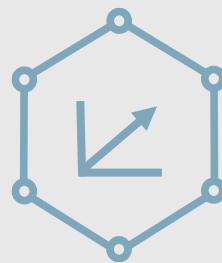
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Logical Knowledge



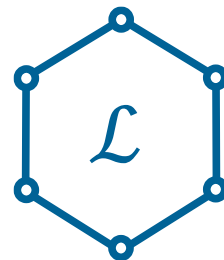
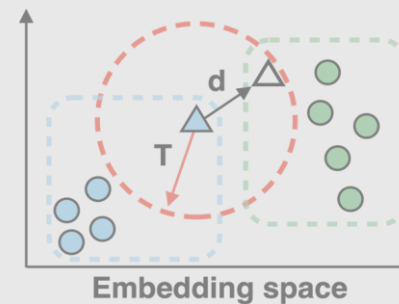
Knowledge Graph Embeddings



Graph Neural Networks

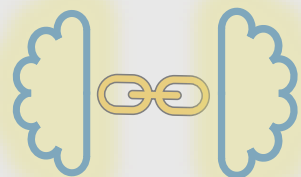
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● Reasoning clusters

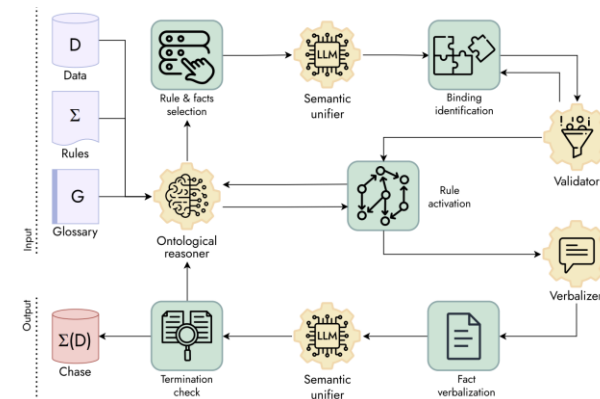


Large Language Models

SYM



ML



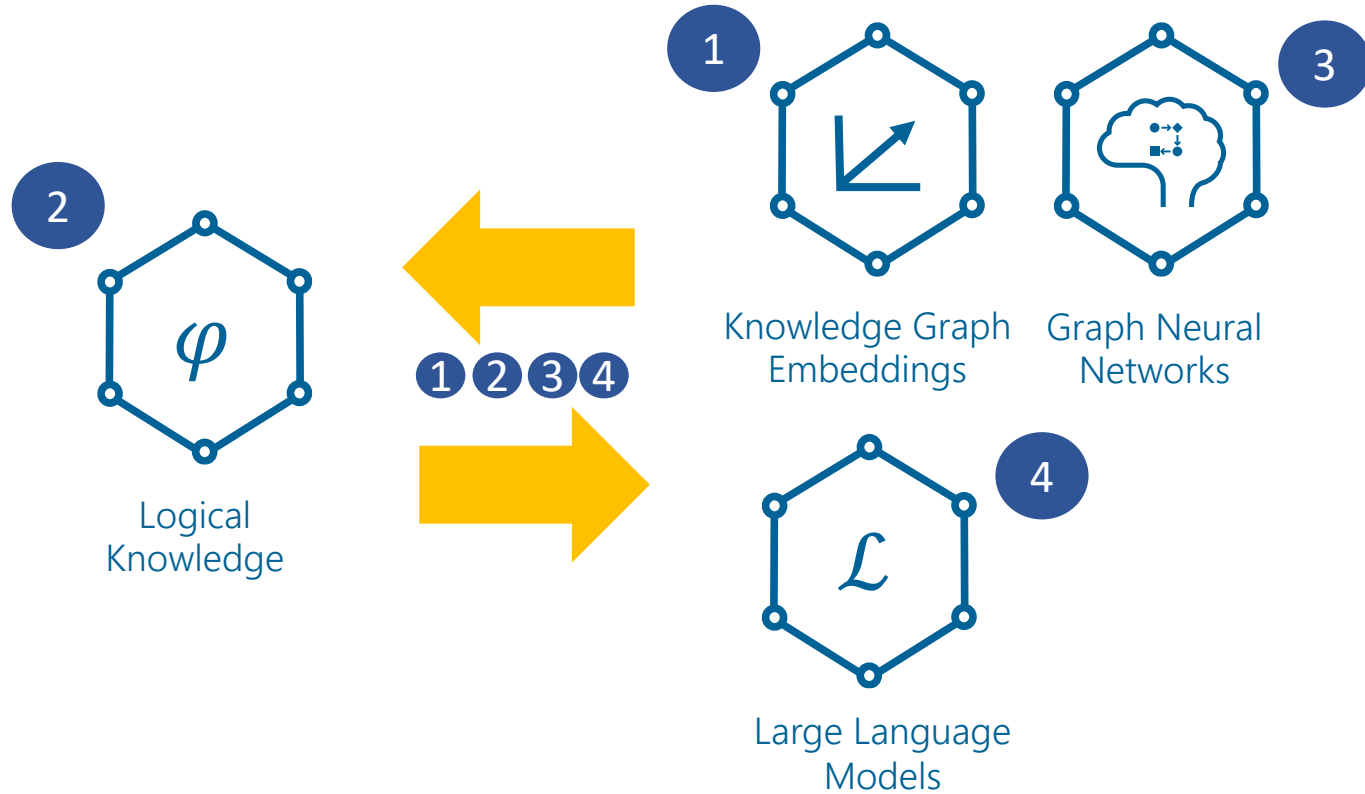
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# Topics in the following units...



**SYM**

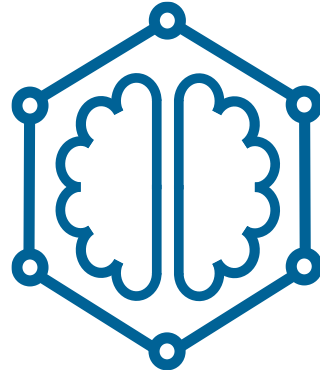


**ML**



## More Information

<https://kg.dbai.tuwien.ac.at>



# Neuro-symbolic AI

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AI Winter School  
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