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Identifying Mappings among Knowledge Graphs by Formal Concept Analysis

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An Introduction to Formal Concept Analysis

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Introduction

Formal Concept Analysis (FCA) is a well-developed mathematical model for clustering individuals and structuring concepts. (Wille 1982; Ganter and Wille 1999)

- Conceptual data analysis.
- Knowledge processing.


Bernhard Ganter and Rudolf Wille. *Formal Concept Analysis - Mathematical Foundations*. Springer, 1999.


Rudolf Wille. “Restructuring Lattice Theory: An Approach Based on Hierarchies of Concepts”. In: *Ordered Sets*. Springer, 1982, pp. 445–470.

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Formal Concept Analysis - Formal Context

Definition

A **formal context** is a triple $\mathbb{K} := (G, M, I)$, where G is a set of **objects**, M is a set of **attributes**, and I is a relation between G and M.

$(g, m) \in I$ reads "object g has attribute m" represented by "×" in the table cell.

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Formal Concept Analysis - Formal Context

Definition

A **formal context** is a triple $\mathbb{K} := (G, M, I)$, where G is a set of **objects**, M is a set of **attributes**, and I is a relation between G and M.

Objects \ Attributes	Asgardian	Avenger	Female	Human	Infinity Stones User	Male	Scientist	Villain
Black Widow		×	×	×				
Captain America		×		×		×		
Hela	×		×					×
Hulk		×		×	×	×	×	
Iron Man		×		×	×	×	×	
Thanos					×	×		×
Thor	×	×				×		

$(g, m) \in I$ reads "object g has attribute m" represented by "×" in the table cell.

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Formal Concept Analysis - Derivation Operators

Definition

For a subset of objects $A \subseteq G$ and a subset of attributes $B \subseteq M$, two **derivation operators** are defined as follows:

- $A^{\uparrow} = \{m \in M \mid \forall g \in A.\ (g, m) \in I\}$
- $B^{\downarrow} = \{g \in G \mid \forall m \in B.\ (g, m) \in I\}$

For example,

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Formal Concept Analysis - Derivation Operators

Objects \ Attributes	Asgardian	Avenger	Female	Human	Infinity Stones User	Male	Scientist	Villain
Black Widow		×	×	×				
Captain America		×		×		×		
Hela	×		×					×
Hulk		×		×	×	×	×	
Iron Man		×		×	×	×	×	
Thanos					×	×		×
Thor	×	×				×		

Example

Given $A = \{\text{Hulk}, \text{Iron Man}\}$. Each object in A has Avenger, Human, Infinity Stones User, Male and Scientist. Then
$A^{\uparrow} = \{\text{Avenger}, \text{Human}, \text{Infinity Stones User}, \text{Male}, \text{Scientist}\}$.

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Formal Concept Analysis - Derivation Operators

Objects \ Attributes	Asgardian	Avenger	Female	Human	Infinity Stones User	Male	Scientist	Villain
Black Widow		×	×	×				
Captain America		×		×		×		
Hela	×		×					×
Hulk		×		×	×	×	×	
Iron Man		×		×	×	×	×	
Thanos					×	×		×
Thor	×	×				×		

Example

Given $B = \{\text{Avenger}, \text{Human}, \text{Male}\}$. Each attribute in B is common to Captain America, Hulk and Iron Man. Then,
$B^{\downarrow} = \{\text{Captain America}, \text{Hulk}, \text{Iron Man}\}$.

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Formal Concept Analysis - Formal Concept

Definition

A **formal concept** of context $\mathbb{K}$ is a pair (A, B), where $A \subseteq G$, $B \subseteq M$ such that $A = B^{\downarrow}$ and $B = A^{\uparrow}$.

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Formal Concept Analysis - Formal Concept

Definition

A **formal concept** of context $\mathbb{K}$ is a pair (A, B), where $A \subseteq G$, $B \subseteq M$ such that $A = B^{\downarrow}$ and $B = A^{\uparrow}$.

Objects \ Attributes	Asgardian	Avenger	Female	Human	Infinity Stones User	Male	Scientist	Villain
Black Widow		×	×	×				
Captain America		×		×		×		
Hela	×		×					×
Hulk		×		×	×	×	×	
Iron Man		×		×	×	×	×	
Thanos					×	×		×
Thor	×	×				×		

Example

$(\{\text{Captain America}, \text{Hulk}, \text{Iron Man}\}, \{\text{Avenger}, \text{Human}, \text{Male}\})$

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Formal Concept Analysis - Concept Lattice

Definition

The subconcept-superconcept relation is formalized by

$$(A_1, B_1) \preceq (A_2, B_2) :\Leftrightarrow A_1 \subseteq A_2 (\Leftrightarrow B_1 \supseteq B_2)$$

All formal concepts of $\mathbb{K}$ ordered by relation $\preceq$ is called the **concept lattice** of $\mathbb{K}$.

For example,

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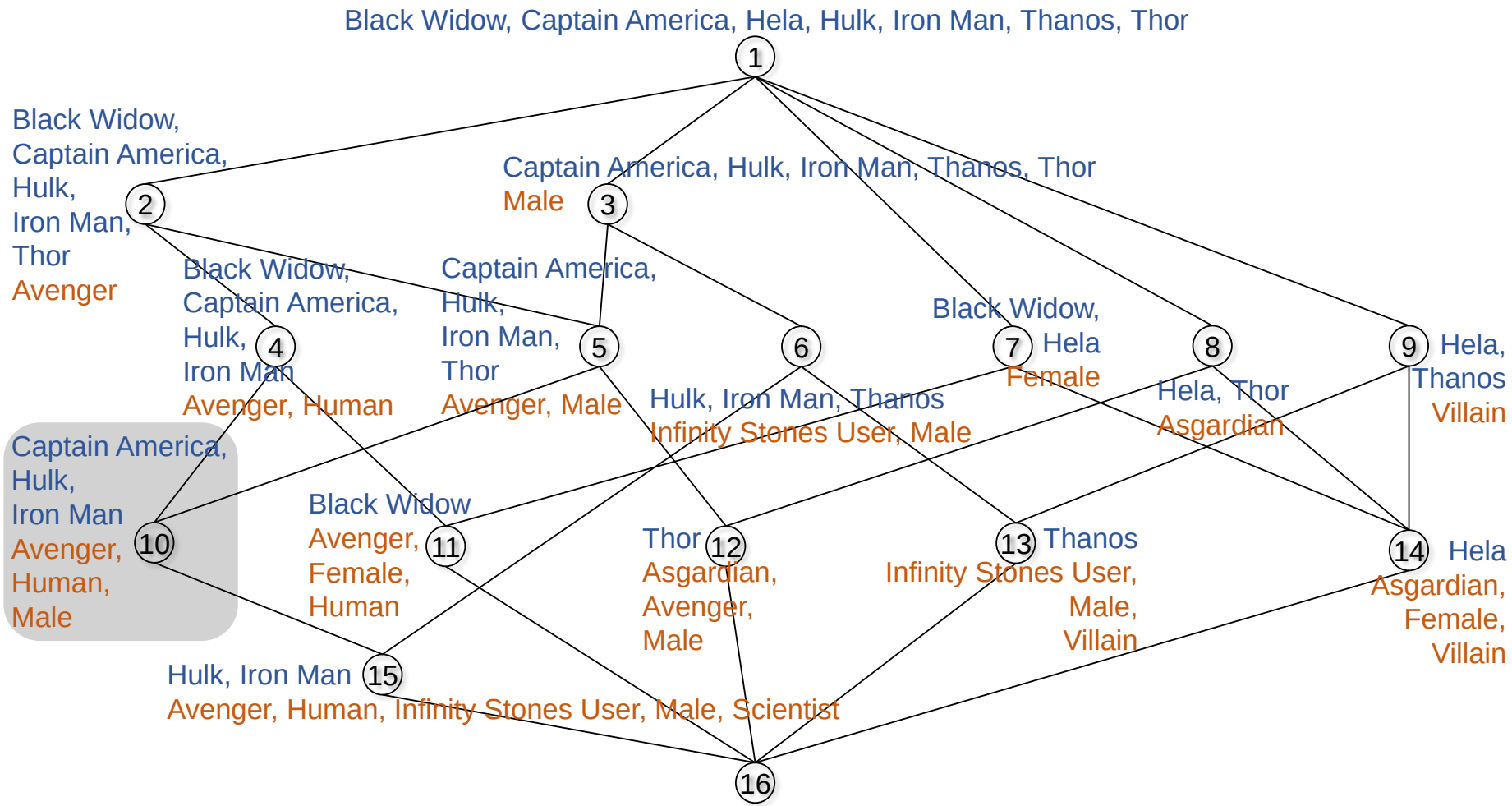
Formal Concept Analysis - Concept Lattice



Our Method

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Our Method

1. Identifying lexical anchors from a token-based formal context.
   - For classes, properties and instances.
   - Using the tokens from strings of labels/names.
2. Identifying additional property mappings from a structural formal context.
   - For properties.
   - Using the structure of the (subject, predicate, object) triples and lexical anchors.

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The Knowledge Graph Track for OAEI 2018

Description

Source	Hub	# Instances	# Properties	# Classes
RuneScape Wiki	Games	200,605	1,998	106
Old School RuneScape Wiki	Games	38,563	488	53
DarkScape Wiki	Games	19,623	686	65
Marvel Database	Comics	56,464	99	2
Hey Kids Comics Wiki	Comics	158,234	1,925	181
DC Database	Comics	128,495	177	5
Memory Alpha	TV	63,240	326	0
Star Trek Expanded Universe	TV	17,659	201	3
Memory Beta	Books	63,223	413	11

For convenience sake, MA stands for Memory Alpha, MB stands for Memory Beta and STEX stands for Star Trek Expanded Universe.

Identifying Lexical Anchors

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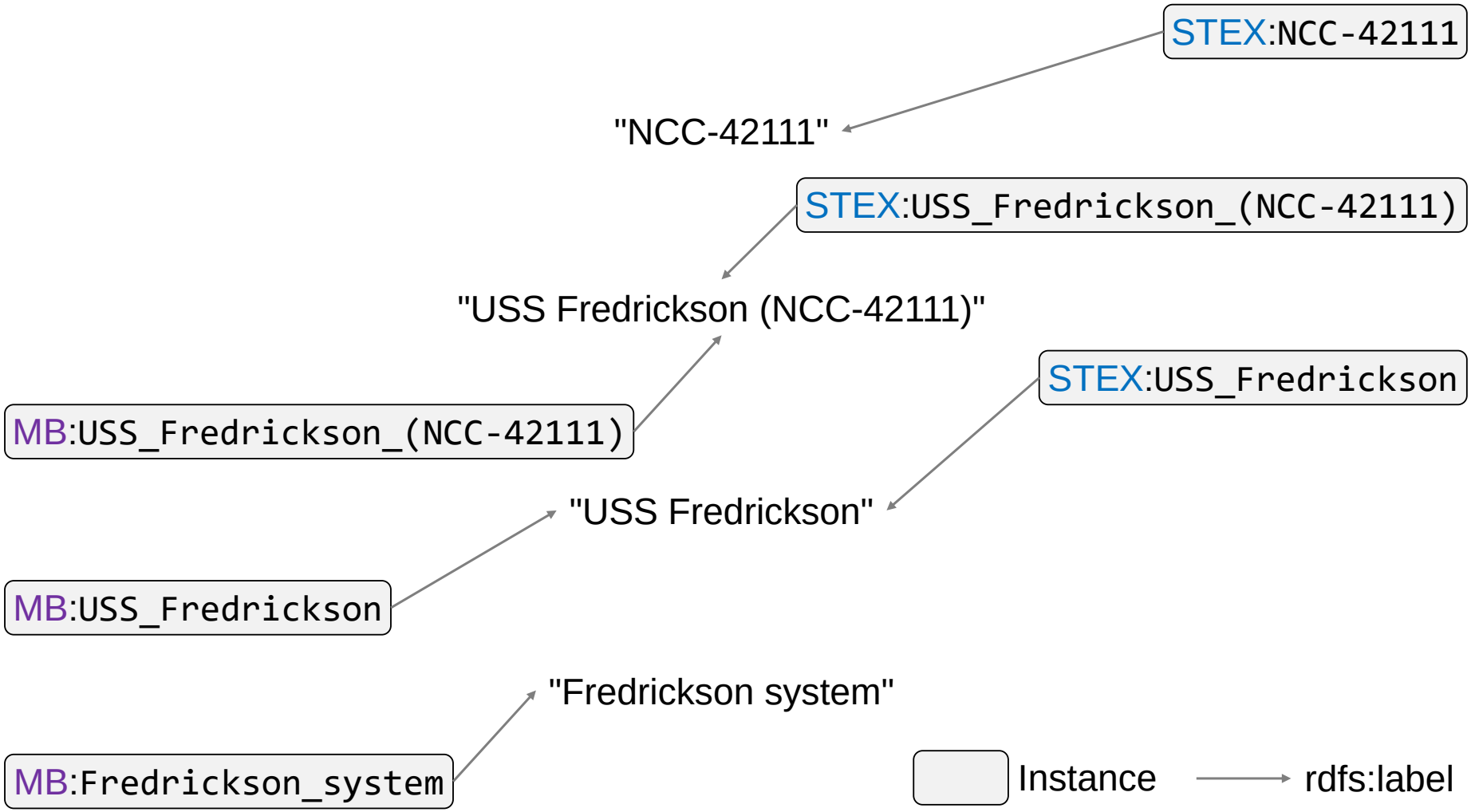

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Lexical Anchors - Token-based Formal Context

	uss	fredrickson	ncc	42111	system
uss fredrickson	×	×			
uss fredrickson (ncc-42111)	×	×	×	×	
ncc-42111			×	×	
fredrickson system		×			×

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Lexical Anchors - Token-based Formal Context

	uss	fredrickson	ncc	42111	system
uss fredrickson	×	×			
uss fredrickson (ncc-42111)	×	×	×	×	
ncc-42111			×	×	
fredrickson system		×			×

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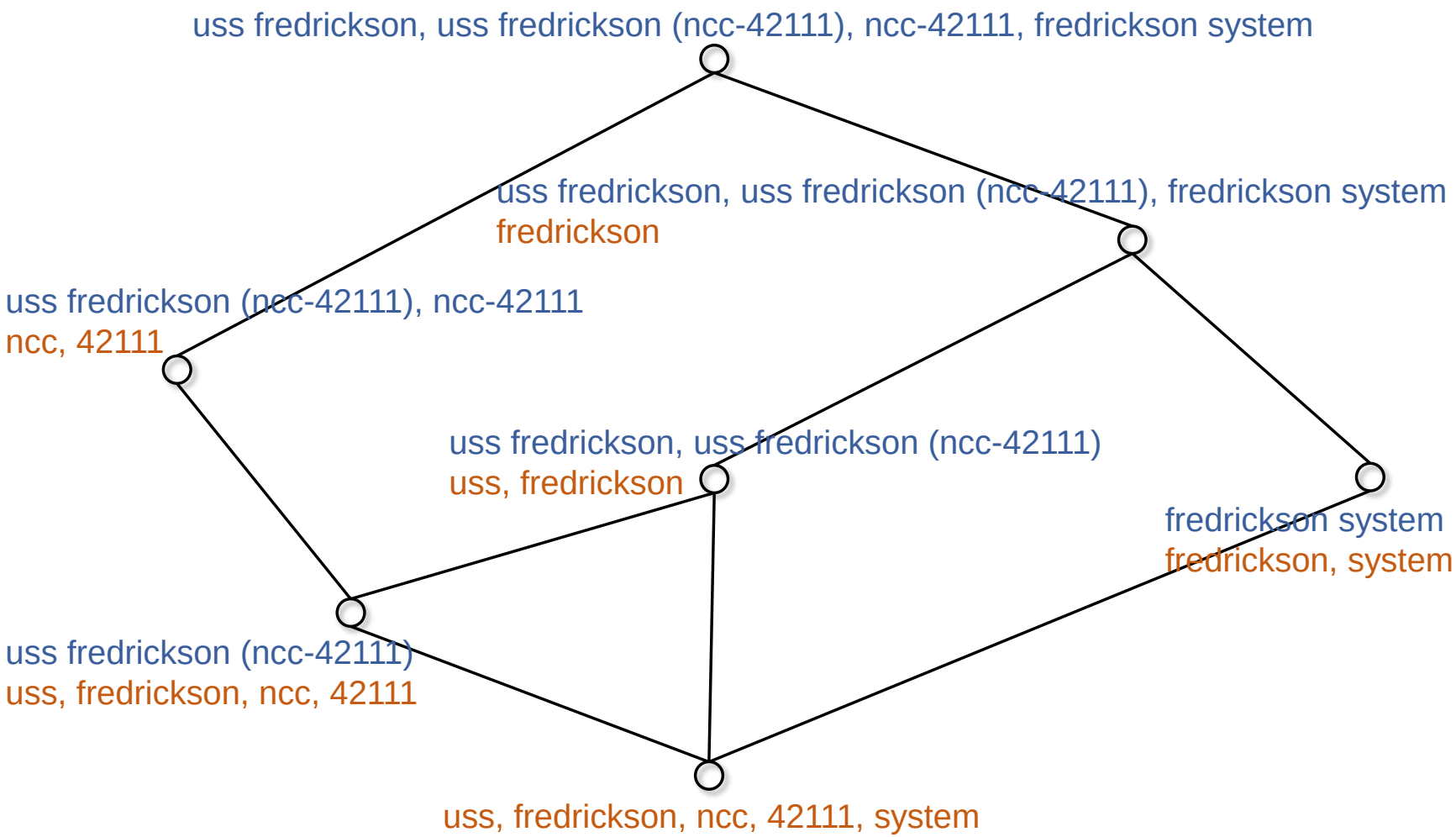
Lexical Anchors - Token-based Concept Lattice



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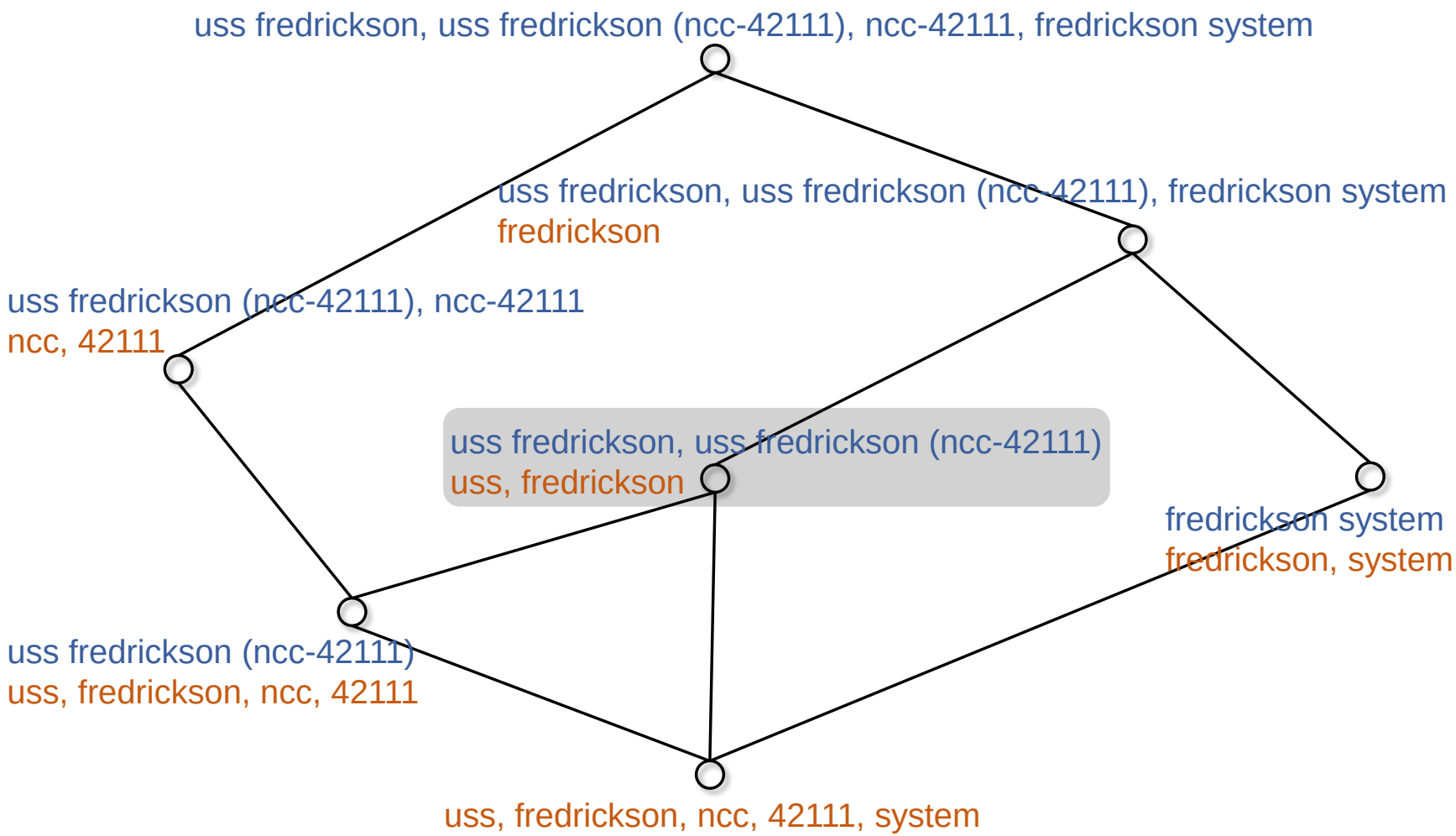
Lexical Anchors - Token-based Concept Lattice



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Lexical Anchors

String	Instance
uss fredrickson	MB:USS_Fredrickson STEX:USS_Fredrickson
uss fredrickson (ncc-42111)	MB:USS_Fredrickson_(NCC-42111) STEX:USS_Fredrickson_(NCC-42111)

Four instance mappings can be extracted as follows:

⟨MB:USS_Fredrickson_(NCC-42111), STEX:USS_Fredrickson_(NCC-42111)⟩
⟨MB:USS_Fredrickson_(NCC-42111), STEX:USS_Fredrickson⟩
⟨MB:USS_Fredrickson, STEX:USS_Fredrickson_(NCC-42111)⟩
⟨MB:USS_Fredrickson, STEX:USS_Fredrickson⟩

Identifying Structural Mappings

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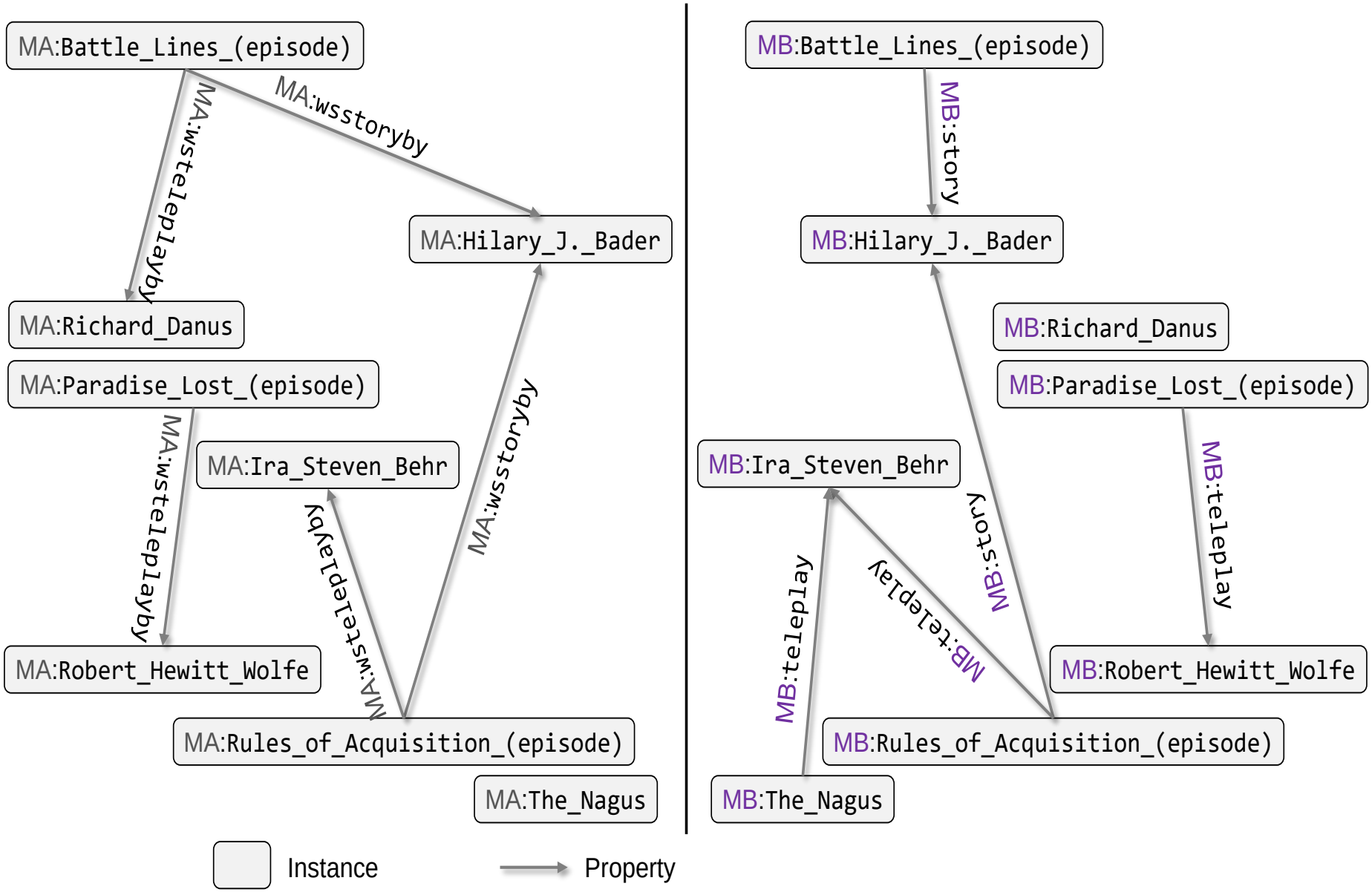

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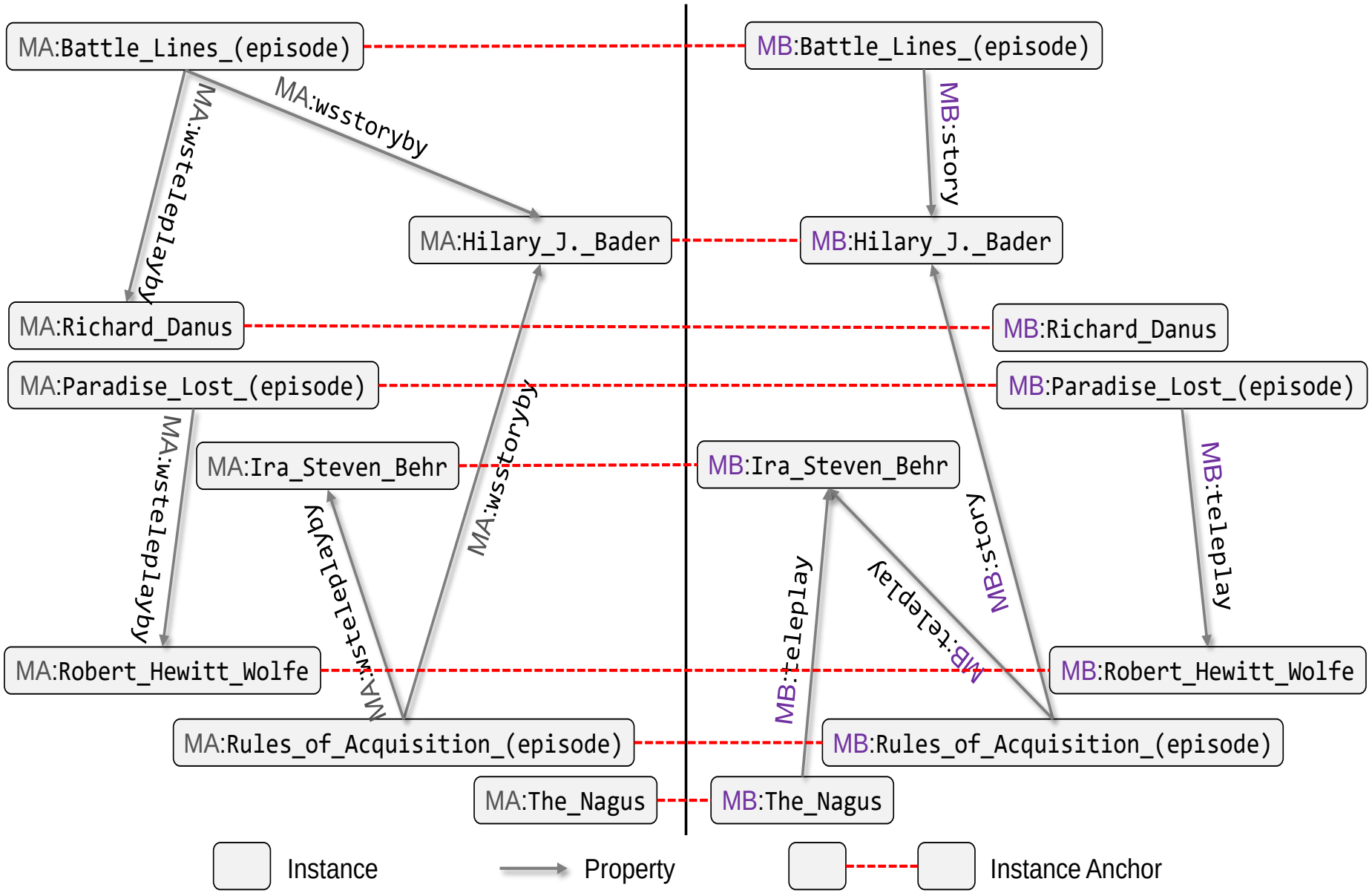

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	(d, g)	(e, c)	(e, b)	(a, b)	(a, f)	(h, c)
MA:wsteleplayby	×	×			×	
MB:teleplay	×	×				×
MA:wsstoryby			×	×		
MB:story			×	×		

a = ⟨MA:Battle_Lines_(episode), MB:Battle_Lines_(episode)⟩
b = ⟨MA:Hilary_J._Bader, MB:Hilary_J._Bader⟩
c = ⟨MA:Ira_Steven_Behr, MB:Ira_Steven_Behr⟩
d = ⟨MA:Paradise_Lost_(episode), MB:Paradise_Lost_(episode)⟩
e = ⟨MA:Rules_of_Acquisition_(episode), MB:Rules_of_Acquisition_(episode)⟩
f = ⟨MA:Richard_Danus, MB:Richard_Danus⟩
g = ⟨MA:Robert_Hewitt_Wolfe, MB:Robert_Hewitt_Wolfe⟩
h = ⟨MA:The_Nagus, MB:The_Nagus⟩

e.g. MA:Paradise_Lost_(episode) $\xrightarrow{\text{MA:wsteleplayby}}$ MA:Robert_Hewitt_Wolfe

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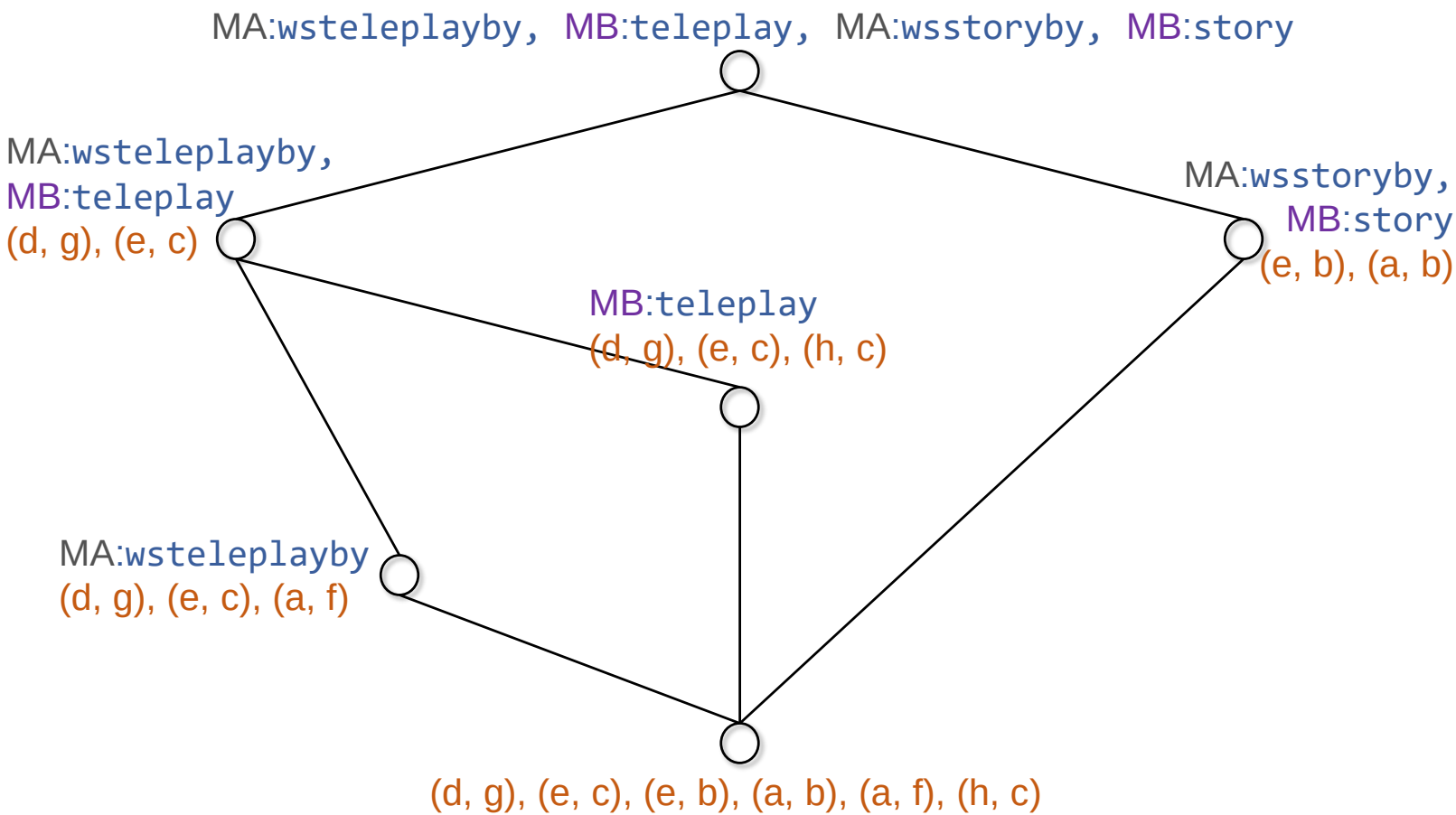

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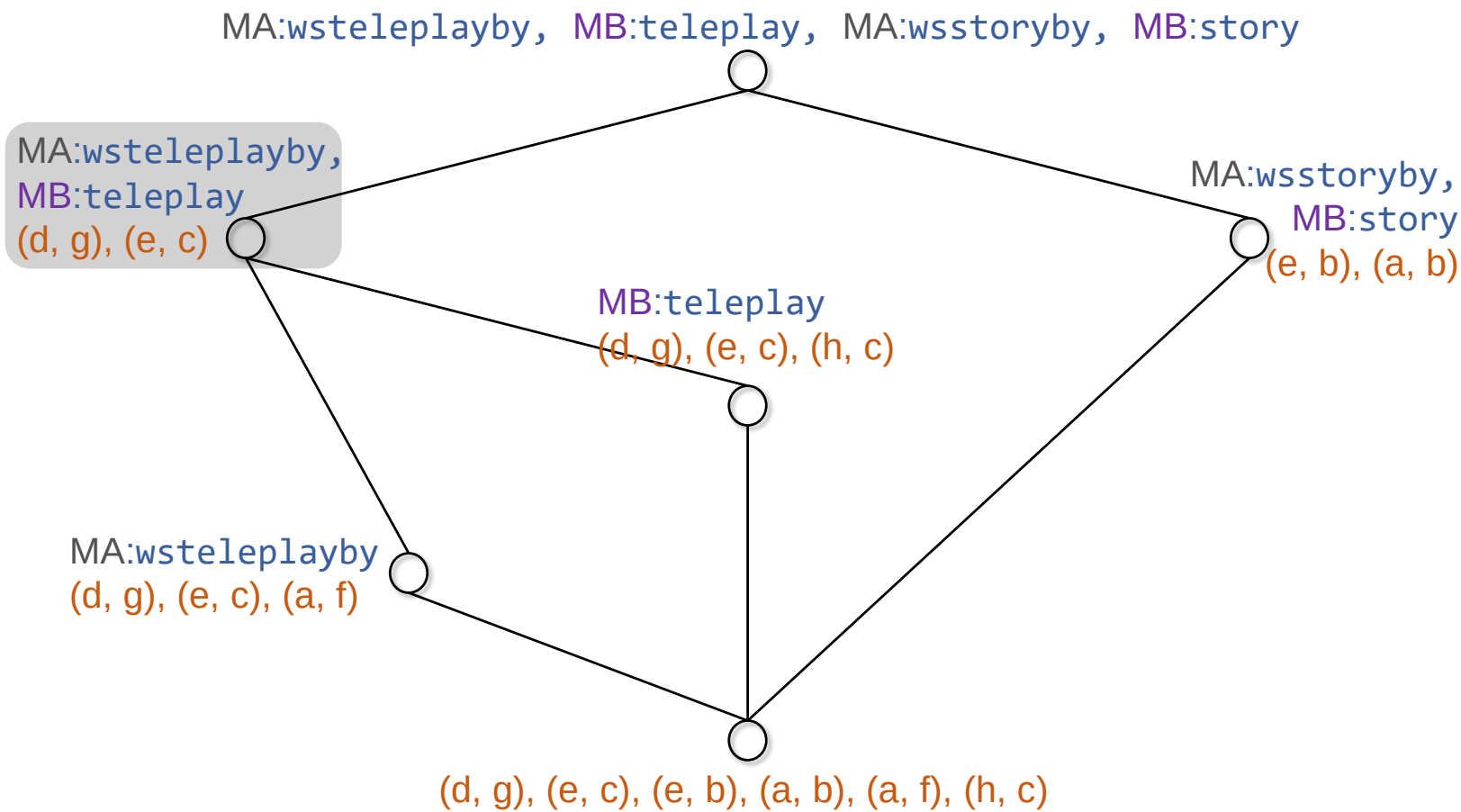

⟨MA:wsteleplayby, MB:teleplay⟩

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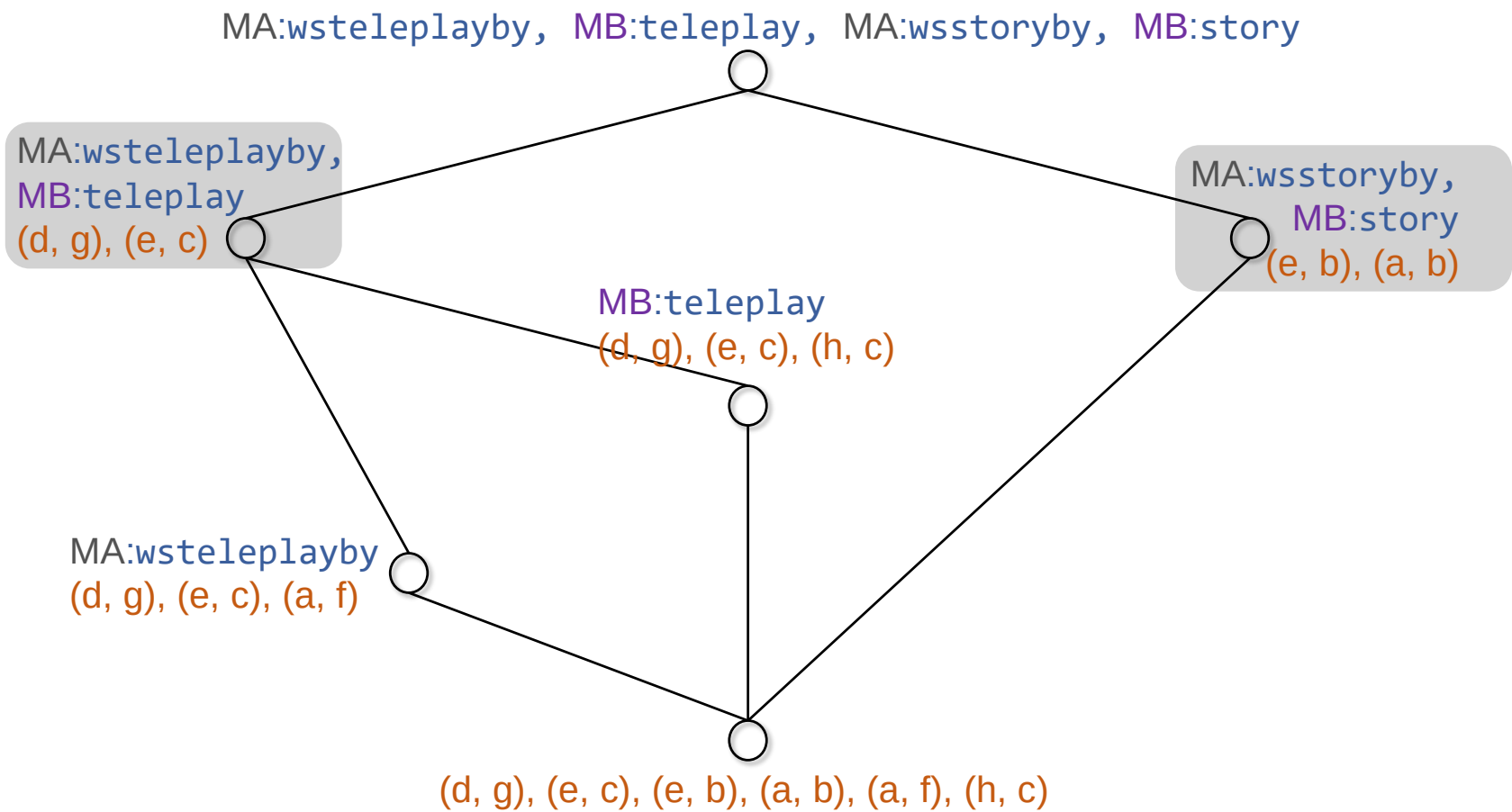

⟨MA:wsteleplayby, MB:teleplay⟩
⟨MA:wsstoryby, MB:story⟩

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Evaluation on Knowledge Graph track for OAEI 2018

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Evaluation - Knowledge Graph Track

Description

Source	Hub	# Instances	# Properties	# Classes
RuneScape Wiki	Games	200,605	1,998	106
Old School RuneScape Wiki	Games	38,563	488	53
DarkScape Wiki	Games	19,623	686	65
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Memory Alpha	TV	63,240	326	0
Star Trek Expanded Universe	TV	17,659	201	3
Memory Beta	Books	63,223	413	11

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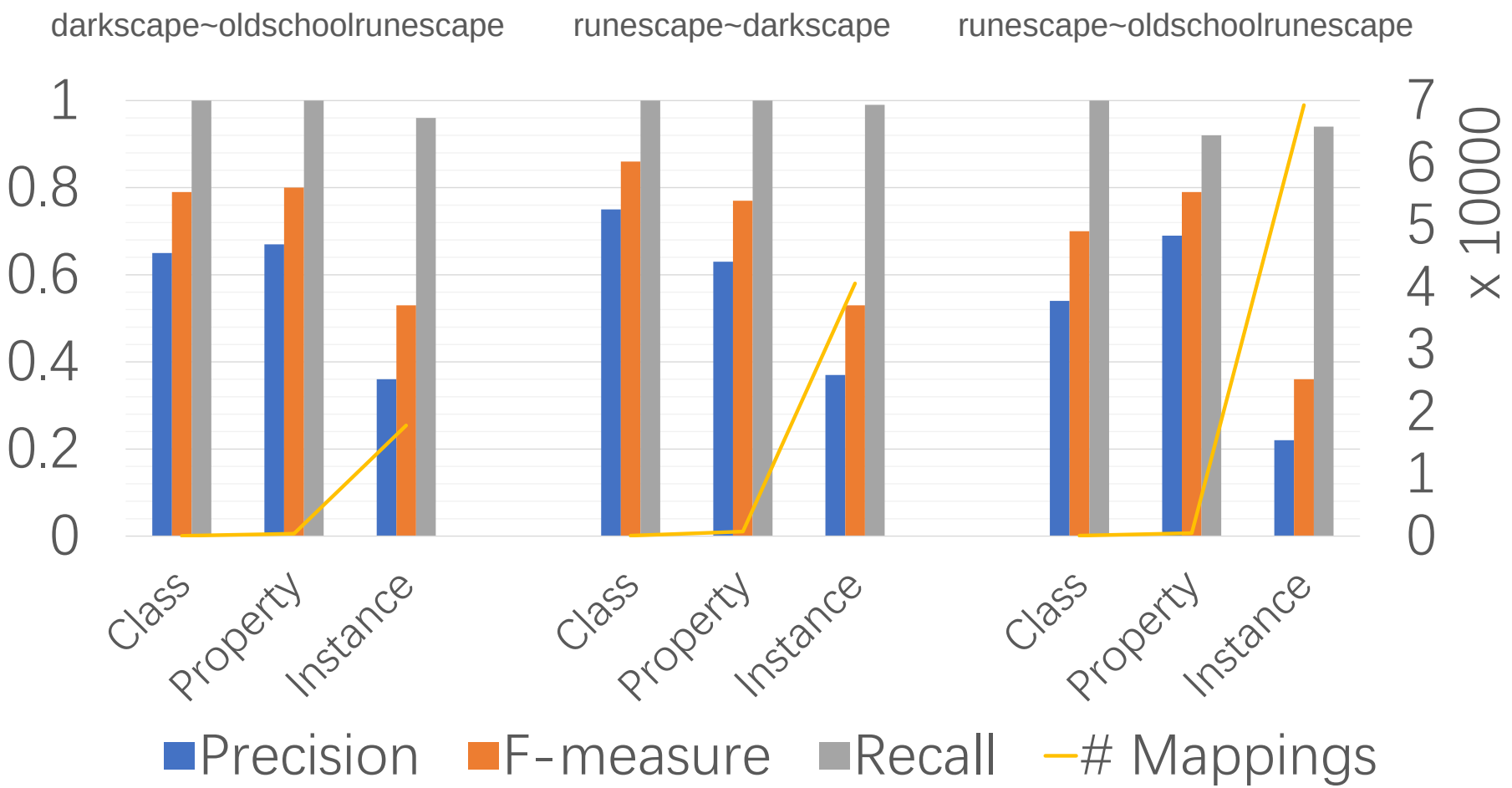
Evaluation on Lexical Matching - Games



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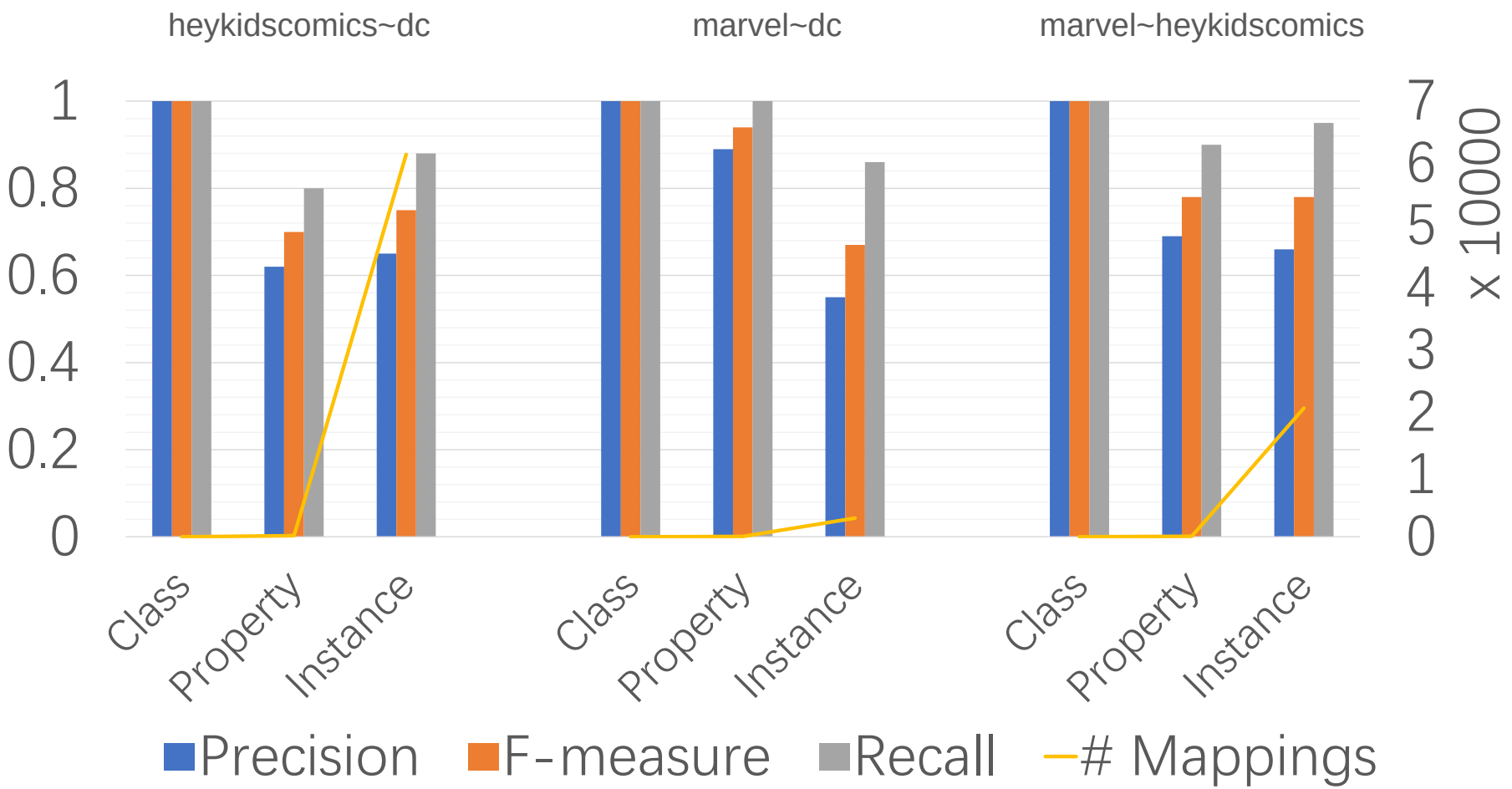
Evaluation on Lexical Matching - Comics



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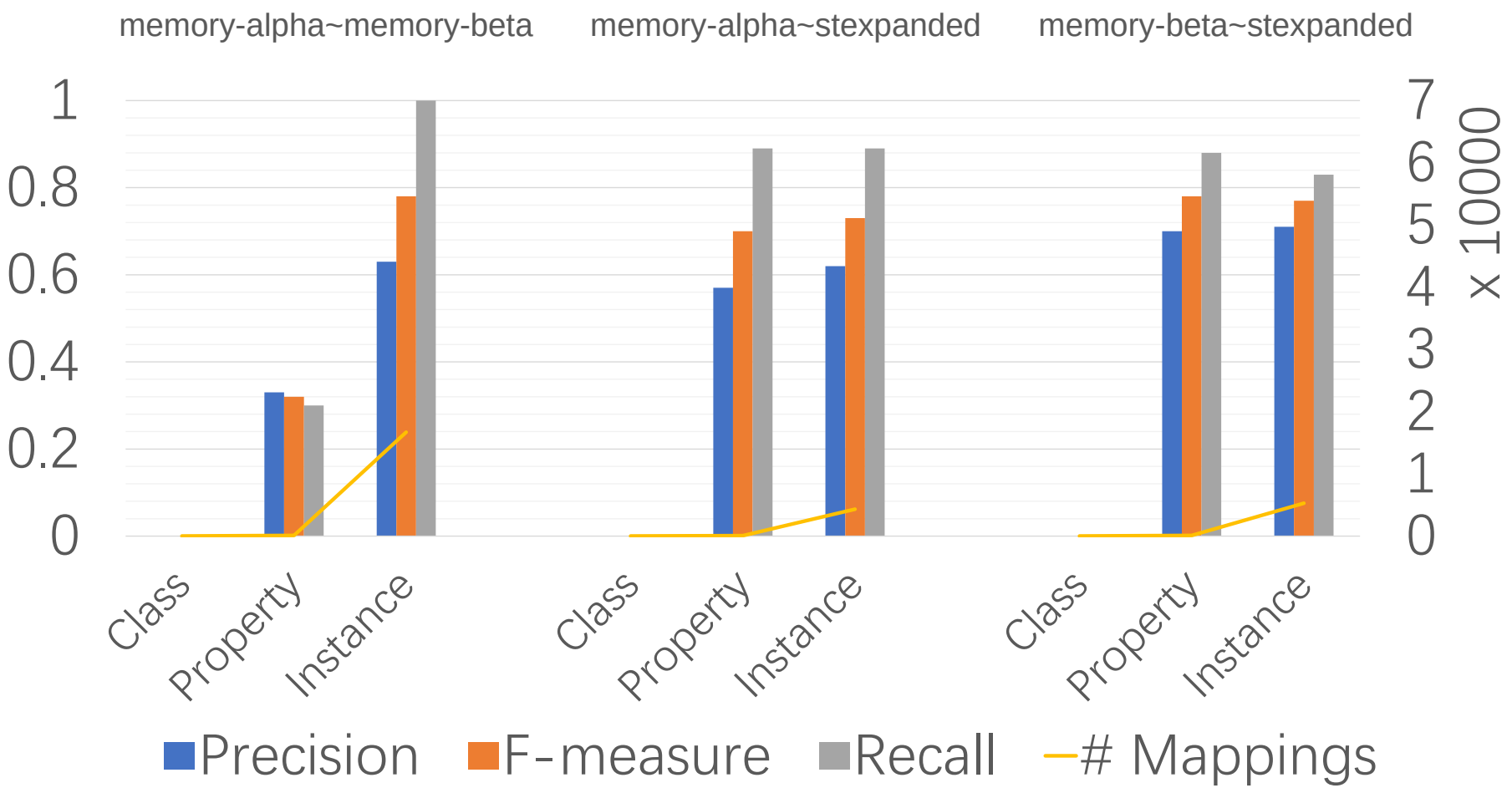
Evaluation on Lexical Matching - TV & Books



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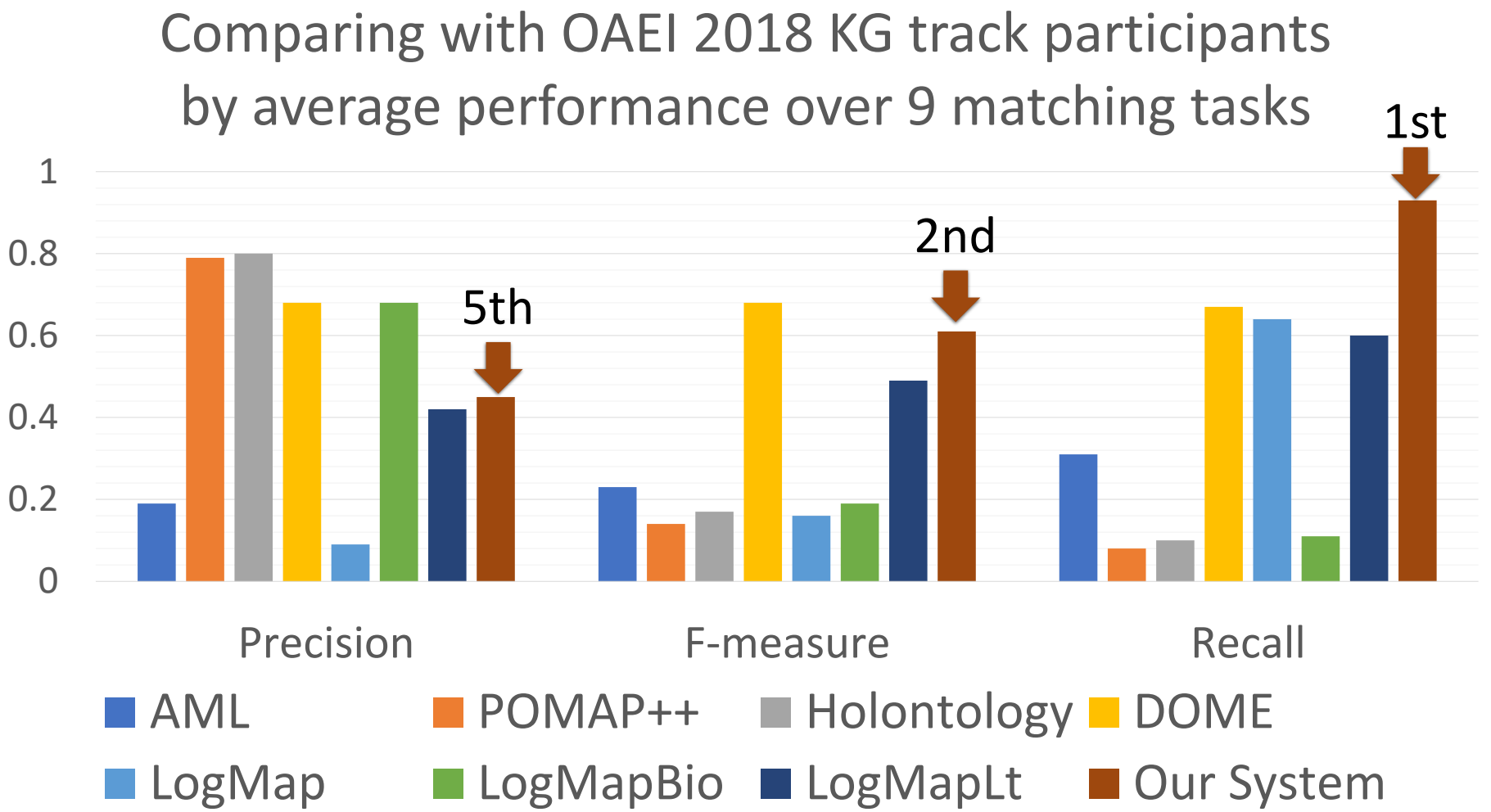
Comparison - OAEI 2018



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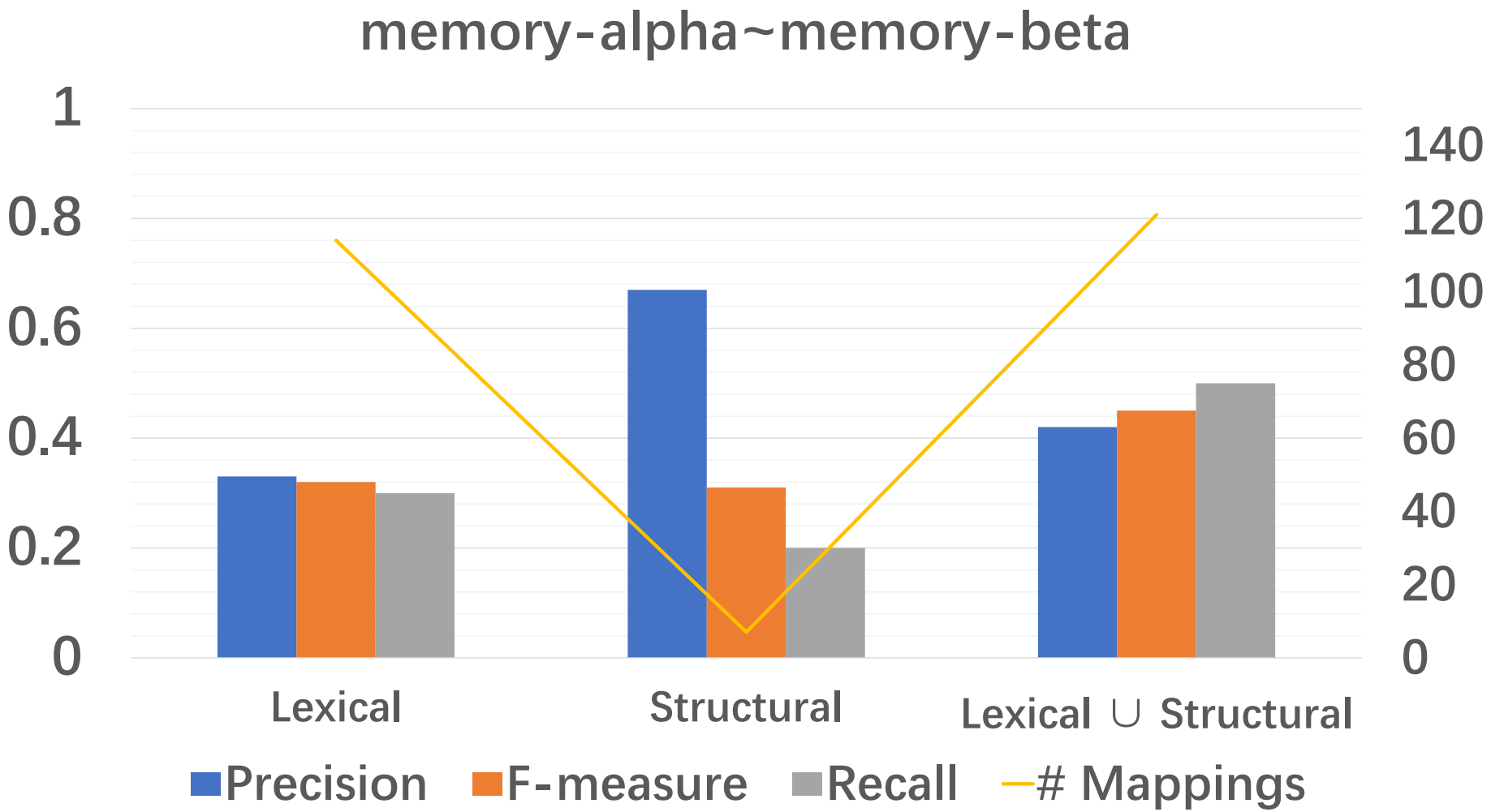
Evaluation - Structural Property Matching



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Additional Property Mappings

Solely Identified Structurally

	Additional property mappings	
Those in the gold standard	⟨MA:relative,	MB:otherRelatives⟩
	⟨MA:wsteleplayby,	MB:teleplay⟩
Those not in the gold standard	⟨MA:wsstoryby,	MB:story⟩
	⟨MA:prev,	MB:before⟩
	⟨MA:next,	MB:after⟩
	⟨MA:abreadby,	MB:narrator⟩
	⟨MA:relative,	MB:grandparents⟩

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Results on the Knowledge Graph track for OAEI 2019

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Results for OAEI 2019 - Knowledge Graph Track

System	#	Class			
		Size	Precision	Recall	F-measure
baselineAltLabel	5	16.4	1.00	0.59	0.74
baselineLabel	5	16.4	1.00	0.59	0.74
Wiktionary	5	21.4	1.00	0.67	0.80
DOME	4	22.5	0.74	0.53	0.62
AML	4	27.5	0.78	0.61	0.69
LogMapLt	4	23.0	0.80	0.43	0.56
LogMapKG	5	26.0	0.95	0.76	0.84
FCAMap-KG	5	18.6	1.00	0.70	0.82

http://oaei.ontologymatching.org/2019/results/knowledgegraph/

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Results for OAEI 2019 - Knowledge Graph Track

System	#	Property			
		Size	Precision	Recall	F-measure
baselineAltLabel	5	47.8	0.99	0.66	0.79
baselineLabel	5	47.8	0.99	0.66	0.79
Wiktionary	5	75.8	0.97	0.98	0.98
DOME	4	75.5	0.79	0.75	0.77
AML	4	58.2	0.72	0.49	0.59
LogMapLt	4	0.0	0.00	0.00	0.00
LogMapKG	5	0.0	0.00	0.00	0.00
FCAMap-KG	5	69.0	1.00	0.96	0.98

http://oaei.ontologymatching.org/2019/results/knowledgegraph/

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Results for OAEI 2019 - Knowledge Graph Track

System	#	Instance			
		Size	Precision	Recall	F-measure
baselineAltLabel	5	4674.2	0.89	0.80	0.84
baselineLabel	5	3641.2	0.95	0.71	0.81
Wiktionary	5	3483.6	0.91	0.70	0.79
DOME	4	4895.2	0.74	0.67	0.70
AML	4	7529.8	0.72	0.69	0.71
LogMapLt	4	6653.8	0.73	0.62	0.67
LogMapKG	5	29190.4	0.40	0.86	0.54
FCAMap-KG	5	4530.6	0.90	0.79	0.84

http://oaei.ontologymatching.org/2019/results/knowledgegraph/

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Results for OAEI 2019 - Knowledge Graph Track

System	#	Overall			
		Size	Precision	Recall	F-measure
baselineAltLabel	5	4739.0	0.89	0.80	0.84
baselineLabel	5	3706.0	0.95	0.71	0.81
Wiktionary	5	3581.8	0.91	0.71	0.80
DOME	4	4994.8	0.74	0.67	0.70
AML	4	7615.5	0.72	0.69	0.70
LogMapLt	4	6676.8	0.73	0.61	0.66
LogMapKG	5	29216.4	0.40	0.84	0.54
FCAMap-KG	5	4792.6	0.91	0.79	0.85

http://oaei.ontologymatching.org/2019/results/knowledgegraph/

Conclusions

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FCA-based Systems - Ontology Matching

Systems	Objects	Attributes	External resources
FCA-Merge (Stumme and Maedche 2001)	Documents	Classes of ontologies	Textual documents from the Web
(Souza and Davis 2004; Zhao, Wang, and Halang 2006; Xu, Wu, and Chen 2010)	Classes of ontologies	Terms in thesaurus	Domain thesuarus
FCA-OntMerge (Guan-yu and Shu-peng 2010)	Classes of ontologies	Properties of ontologies	None
FCA-Map (Zhao and Zhang 2016; Zhao et al. 2018)	Names/labels/synonyms and classes of ontologies	Tokens and relations/axioms among classes	Domain thesuarus

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Conclusions

- This work reveals the advantage of our FCA-based approach to knowledge graph matching.
- The lexical matching part already achieved high recall in class, property, and instance matching for *OAEI 2018 Knowledge Graph* track.
- The structural matching part using a property-based lattice is able to identify additional property mappings.

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Future Work

- An alternative validation strategy so as to ensure the quality of mappings.
- An iterative framework so as to perform class, property, and instance matching in an augmented way until no further matches can be found.
- A formal context constructed from multiple sources so as to apply it to three or more knowledge graphs matching directly.
- This work is ongoing and the source code is open. (Chen 2019)

Guowei Chen. *FCA-Map source code*. 2019. URL: https://github.com/icgw/FCA-Map (visited on 10/26/2019).

Thanks for your attention!