In Search of True Contextuality in Natural Language

Quantum Contextuality in Quantum Mechanics and Beyond (QCQMB)

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joint work with Mehrnoosh Sadrzadeh (UCL), Samson Abramsky (University of Oxford) and Víctor H. Cervantes (University of Illinois at Urbana-Champaign)

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Introduction

Sheaf-theoretic contextuality

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Framework only works for no-signalling systems

Visualizing contextuality

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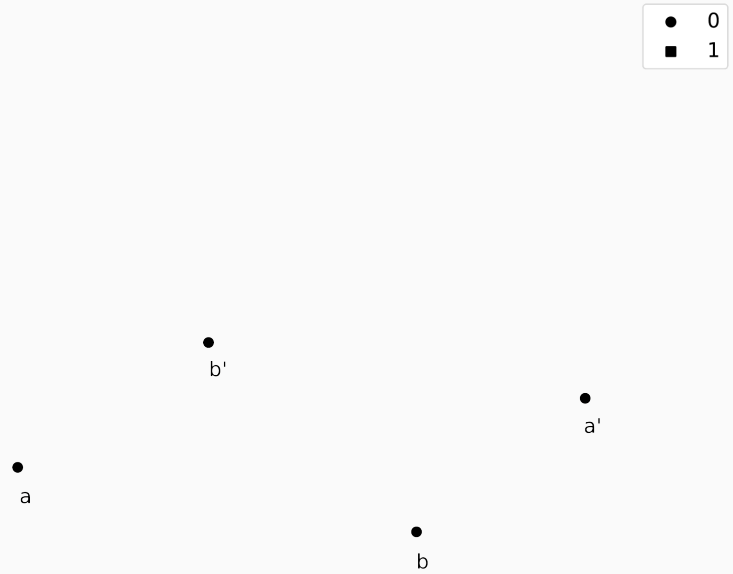

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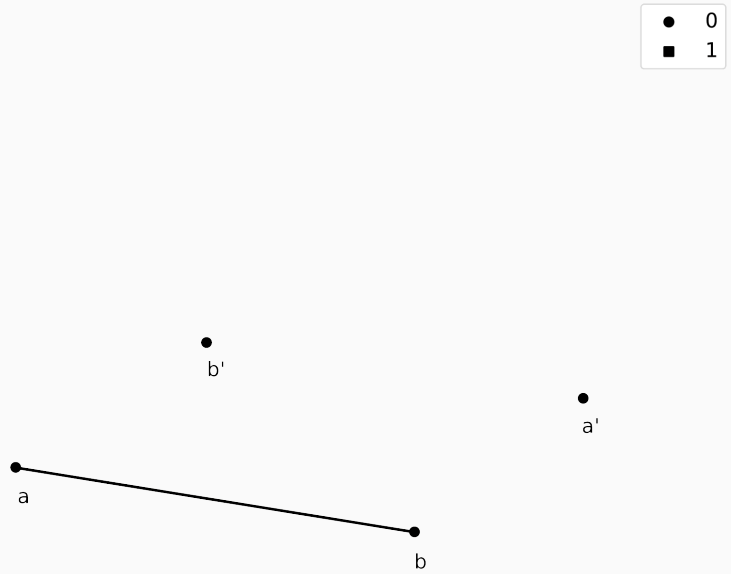

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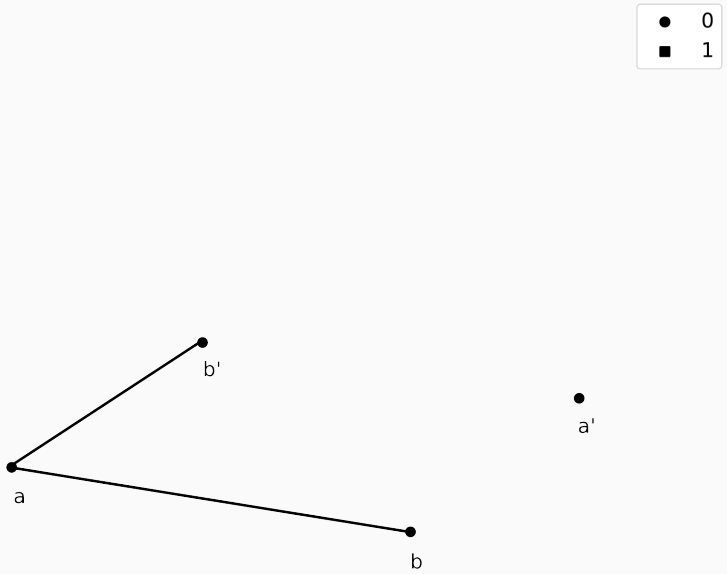

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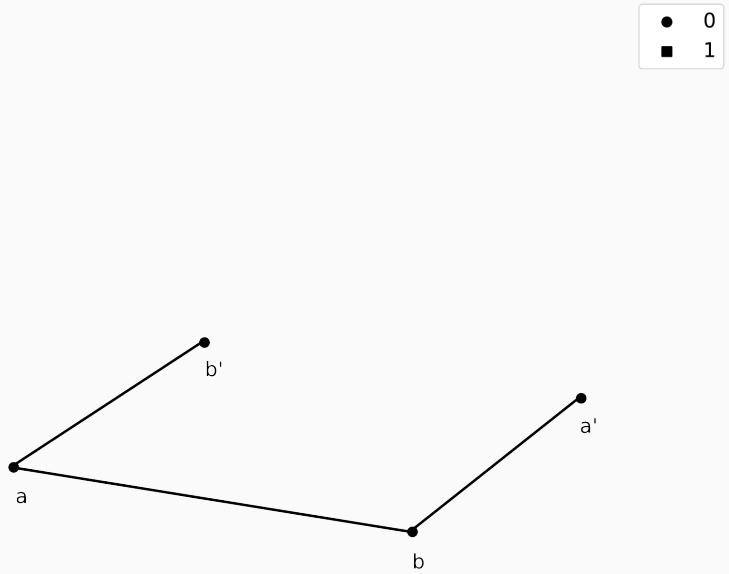

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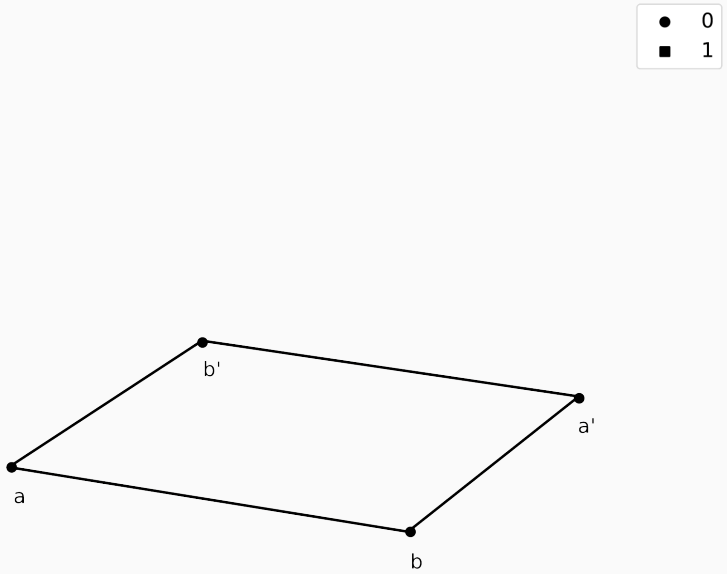

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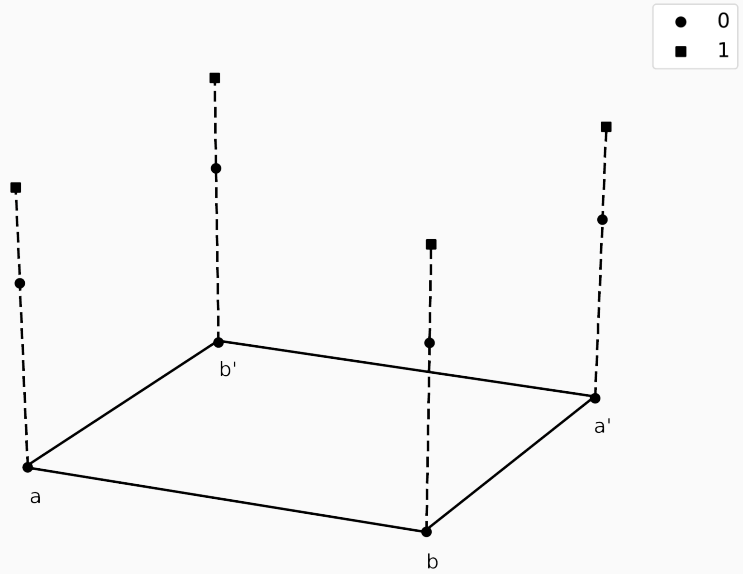

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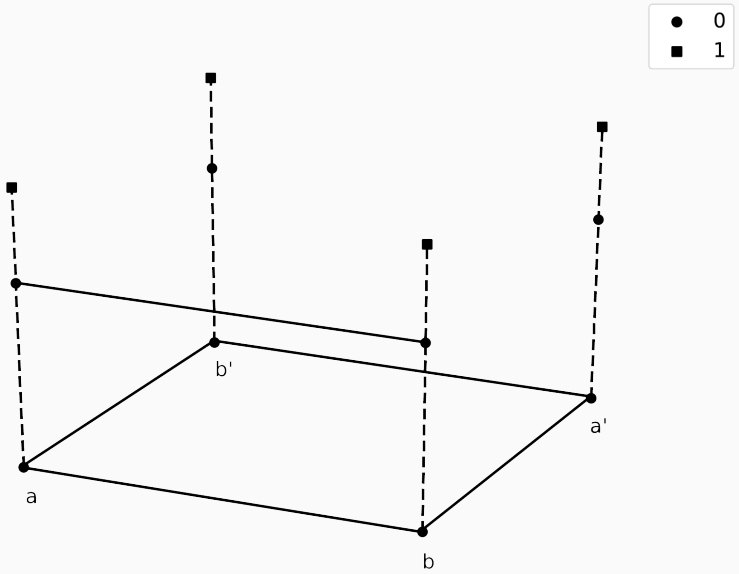

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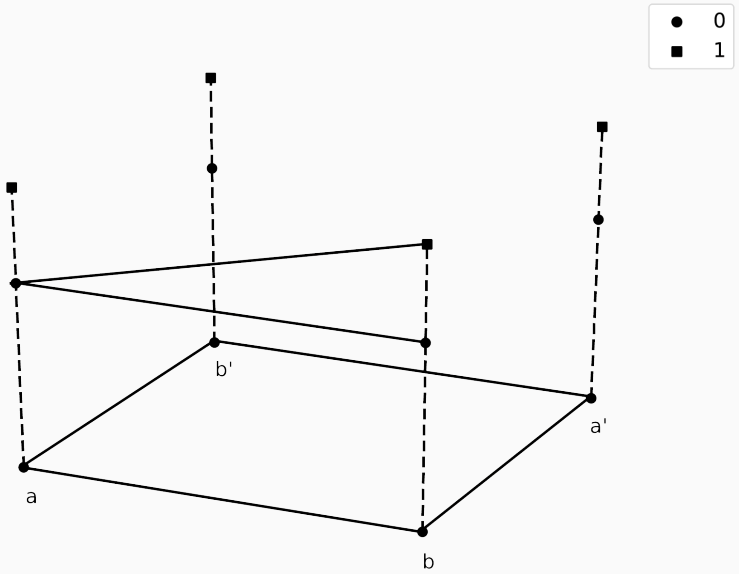

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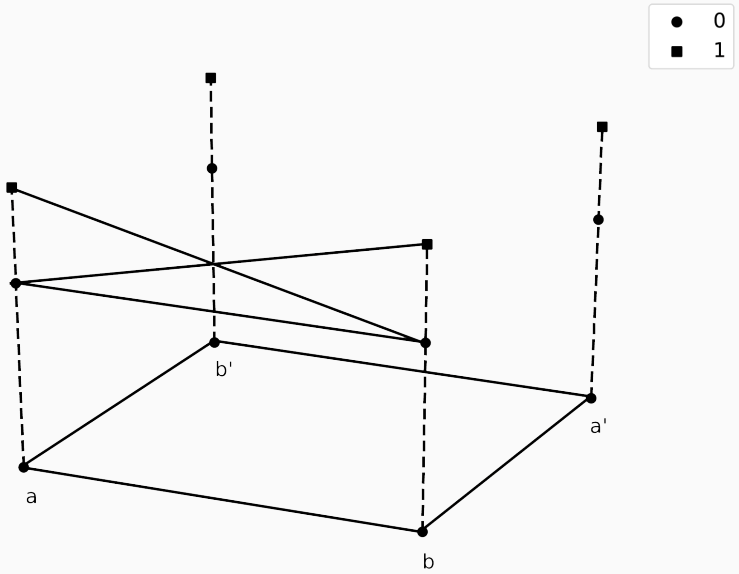

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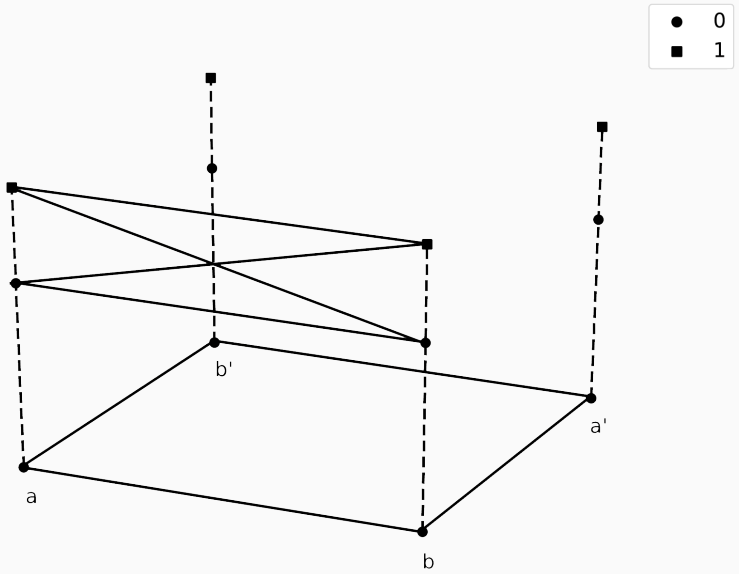

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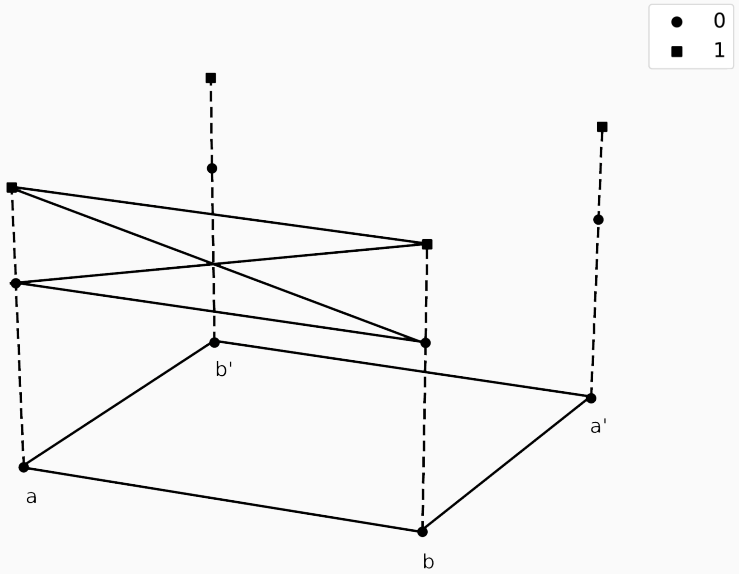

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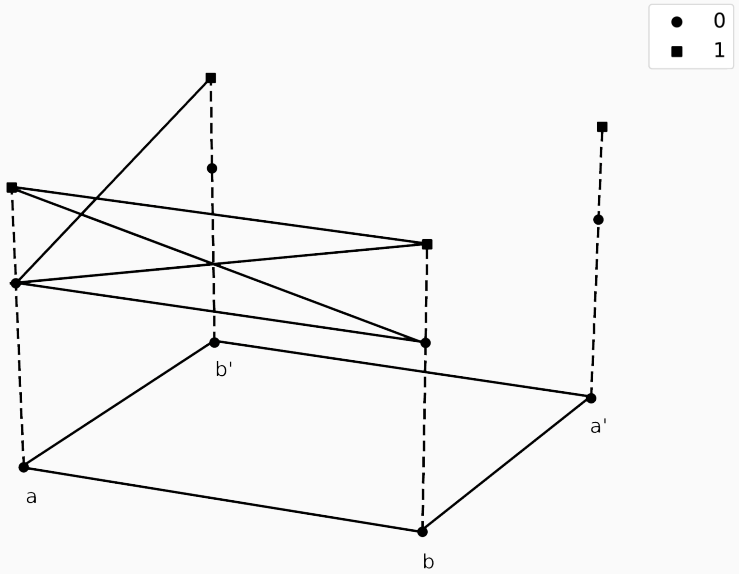

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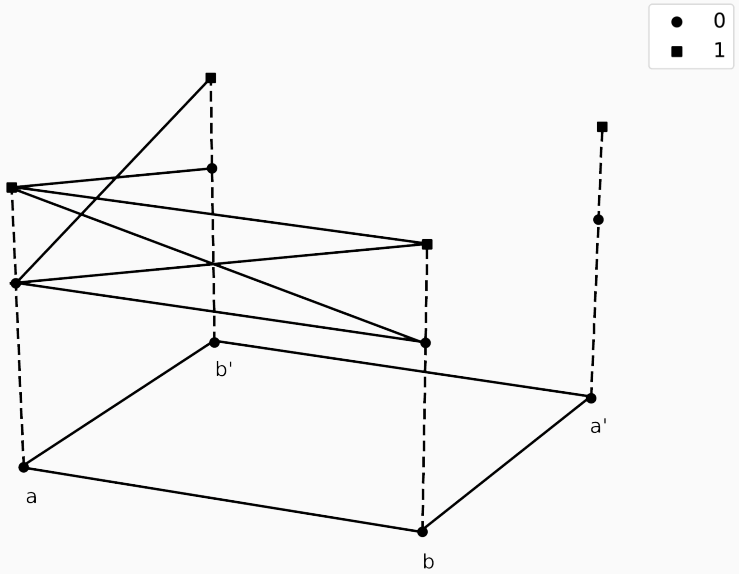

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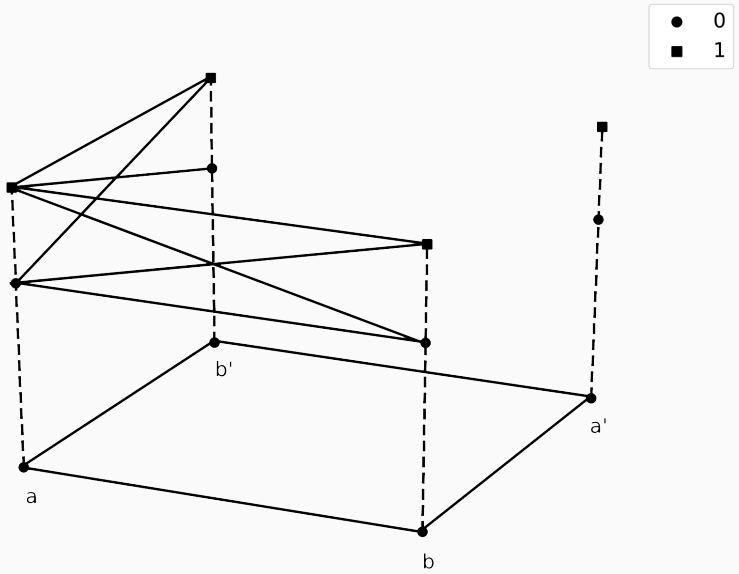

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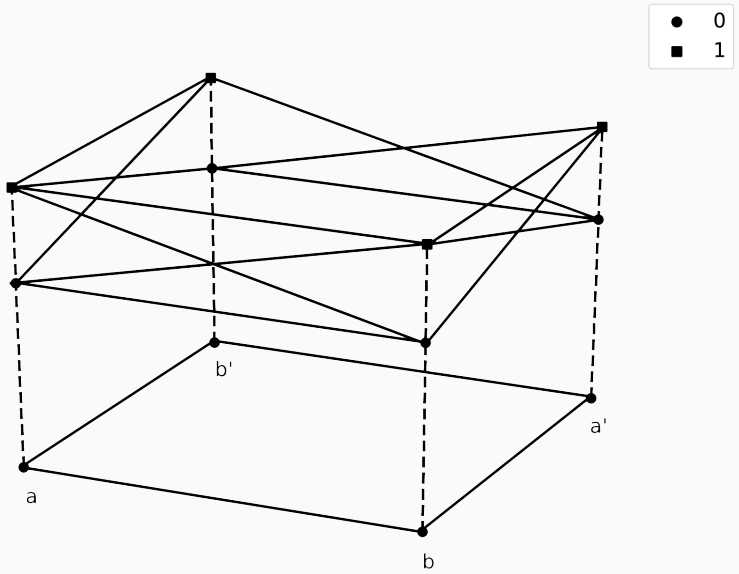

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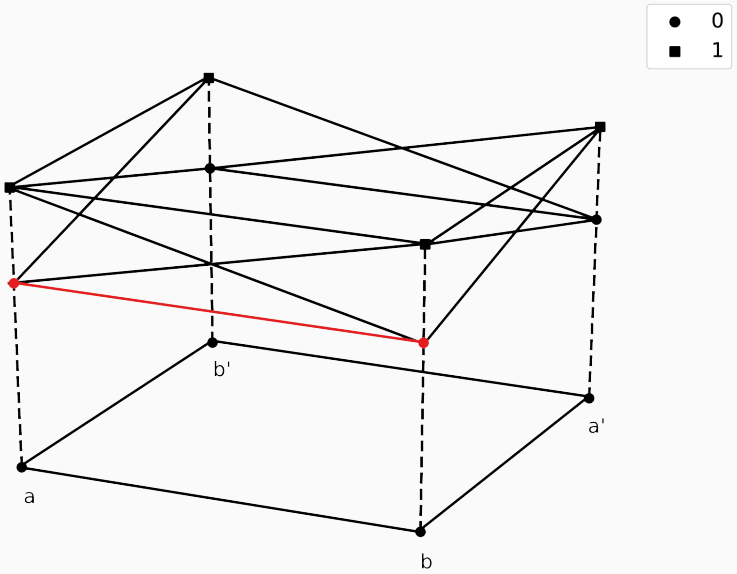

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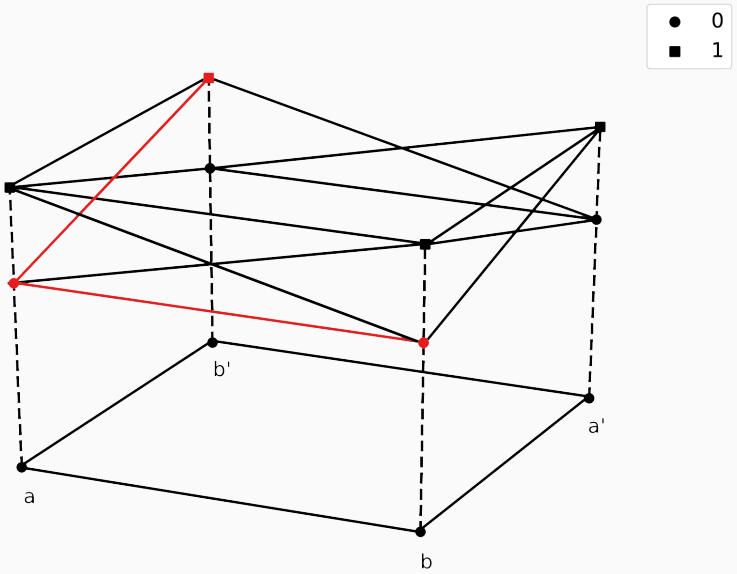

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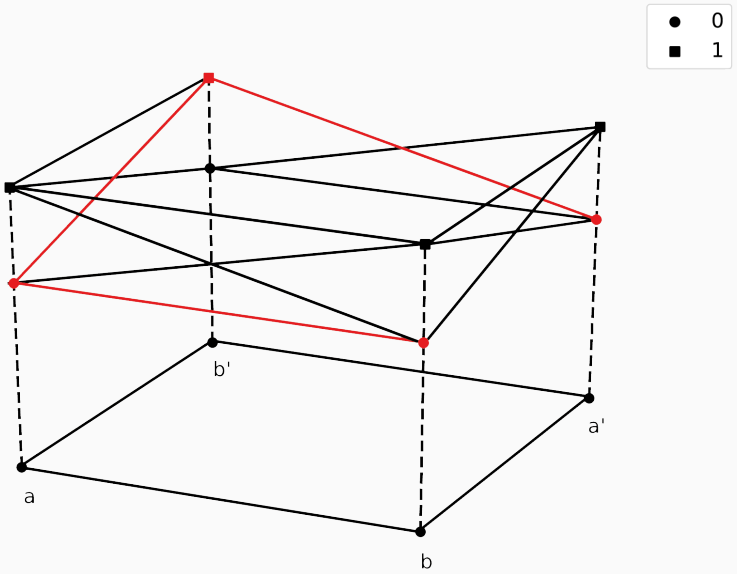

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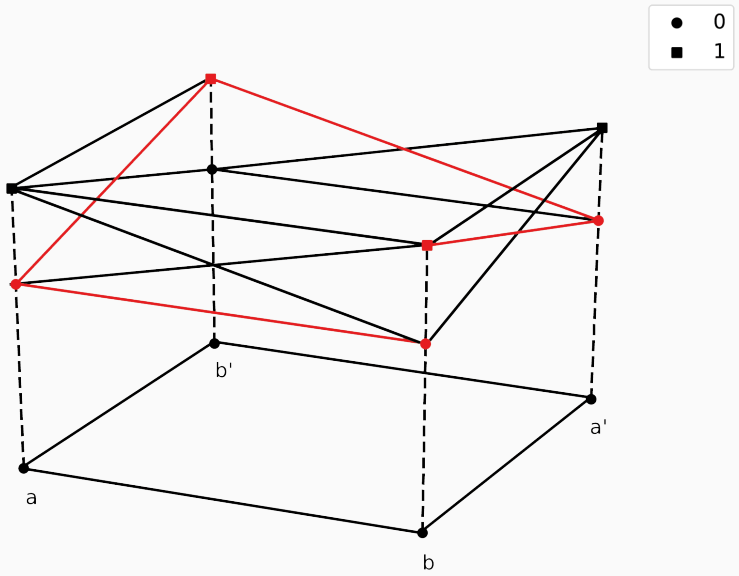

Contextuality-by-Default

Motivation for Contextuality-by-Default (CbD)

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- More general definition of *contexts*

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Definition

A system is a *cyclic system* if every content if binary, if every context contains exactly 2 contents, and every content is contained in exactly 2 contexts.

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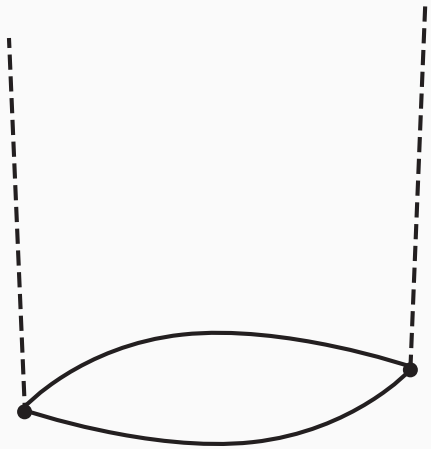
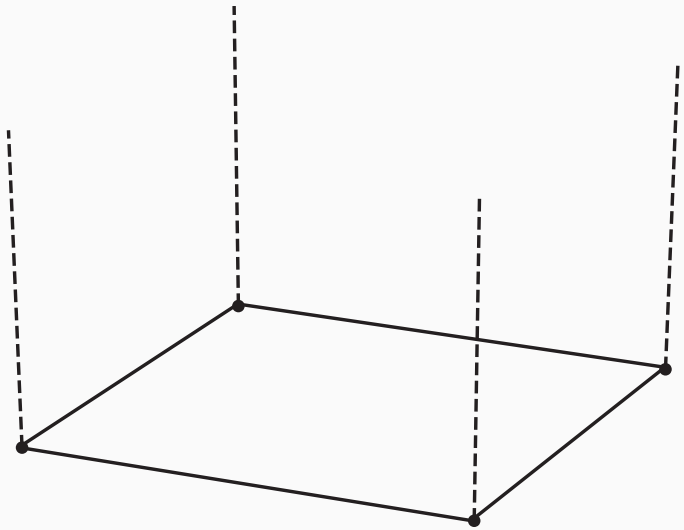


Rank-2



Rank-4

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(Non)Contextuality criterion for cyclic systems

A cyclic system is non-contextual within the CbD framework iff:

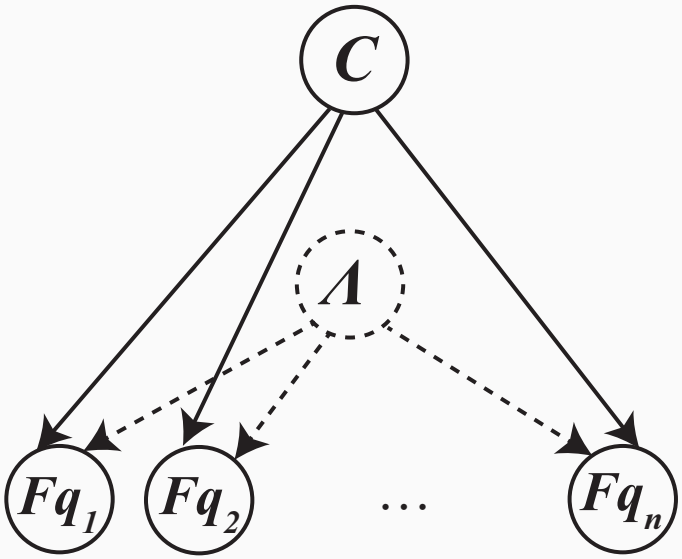
$$s_{odd}\left(\left\langle R_i^i R_{i\oplus 1}^i \right\rangle\right)_{i=1,\ldots,n} \leq n-2+\Delta \tag{1}$$

where:

$$\Delta = \sum_{i=1}^{n} \left| \left\langle R_i^i \right\rangle - \left\langle R_i^{i\ominus 1} \right\rangle \right| \tag{2}$$

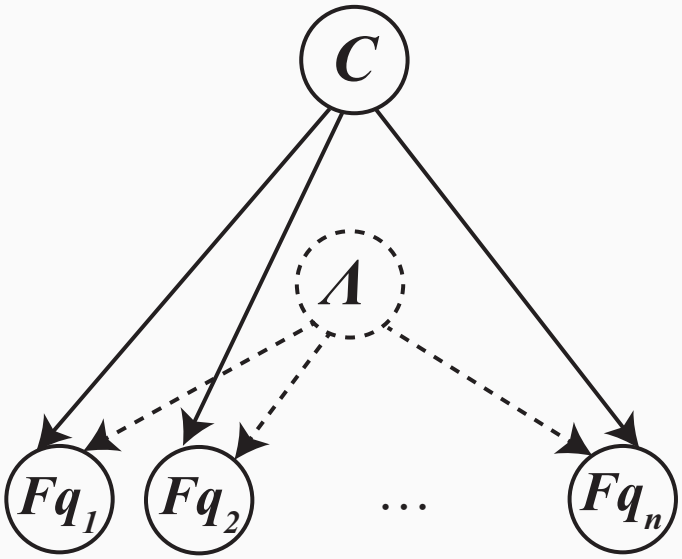
Contextuality-by-Default

Direct influences via M-Contextuality



Canonical model

Direct influences via M-Contextuality



Canonical model

Direct Influence

Given a pair of contexts c, c' in a given canonical model, the *direct influence* on content variable F_q is quantified as:

$$\Delta_{c,c'}(F_q) = Pr[\lambda | F_q(\lambda, c) \neq F_q(\lambda, c')] \quad (1)$$

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M-Contextuality and CbD

- M-Contextuality is equivalent to CbD-contextuality
- If $\Delta^*_{c_q, c'_q}(F_q)$ is the minimal direct influence across all canonical models:

$$\Delta = 2 \sum_q \Delta^*_{c_q, c'_q}(F_q) \tag{1}$$

Ambiguity in Natural Language

Lexical Ambiguity

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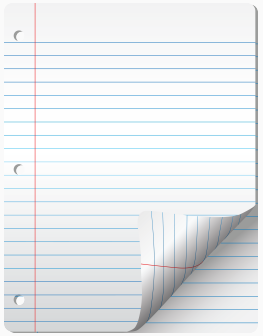

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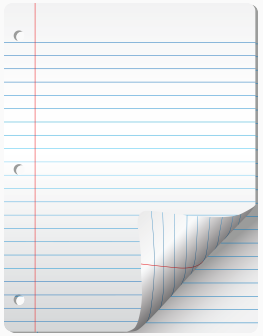

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- Verbs VS Nouns:
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  - Verbs: wait to know its arguments first (for homonymous verbs) or end of clause/sentence (for polysemous verbs).

Contextuality in Natural language

Logical contextuality

Bell scenarios in Natural Language

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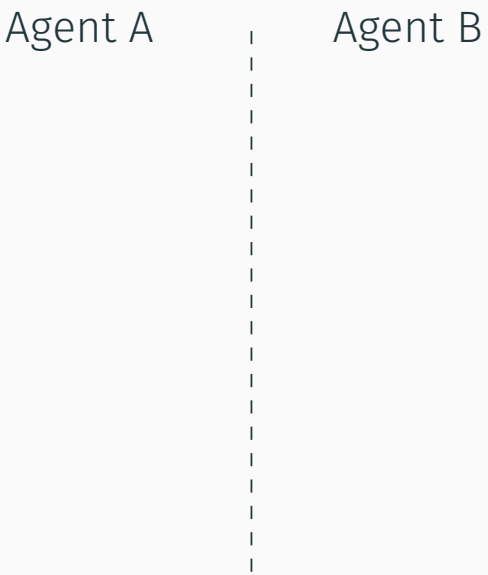

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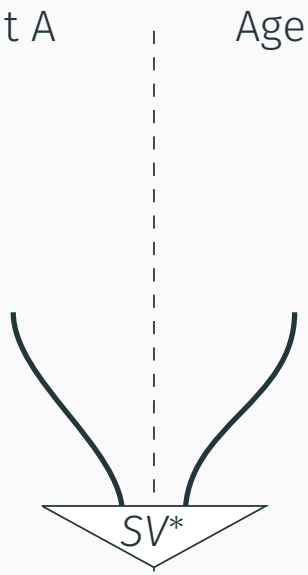

Initial state

* *subject-verb*

Logical contextuality

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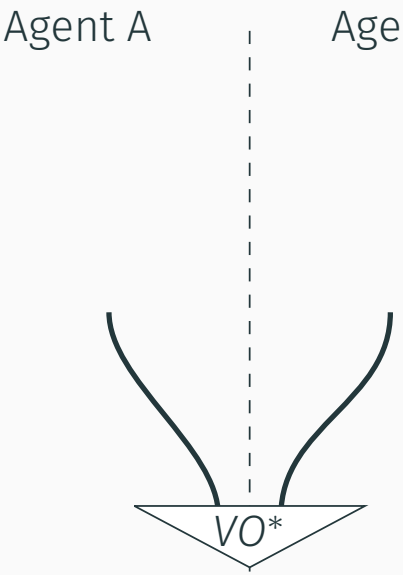

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Logical contextuality

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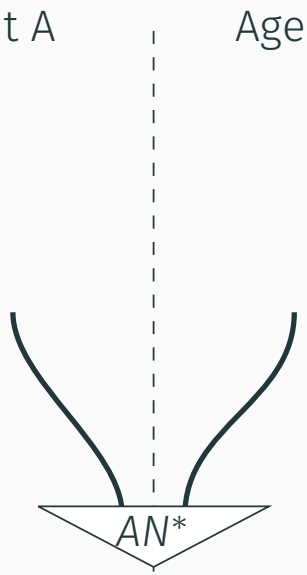

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Logical contextuality

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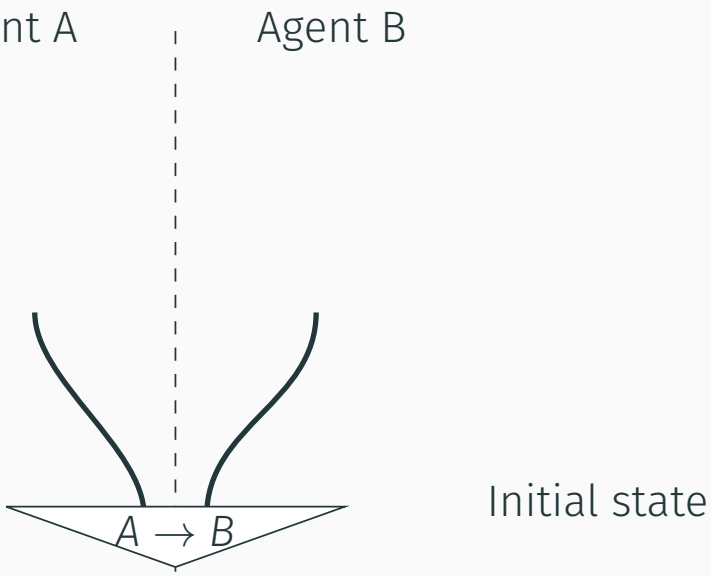

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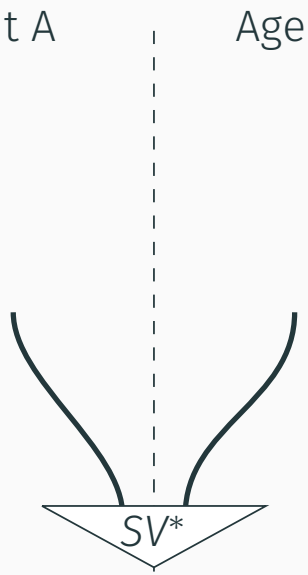
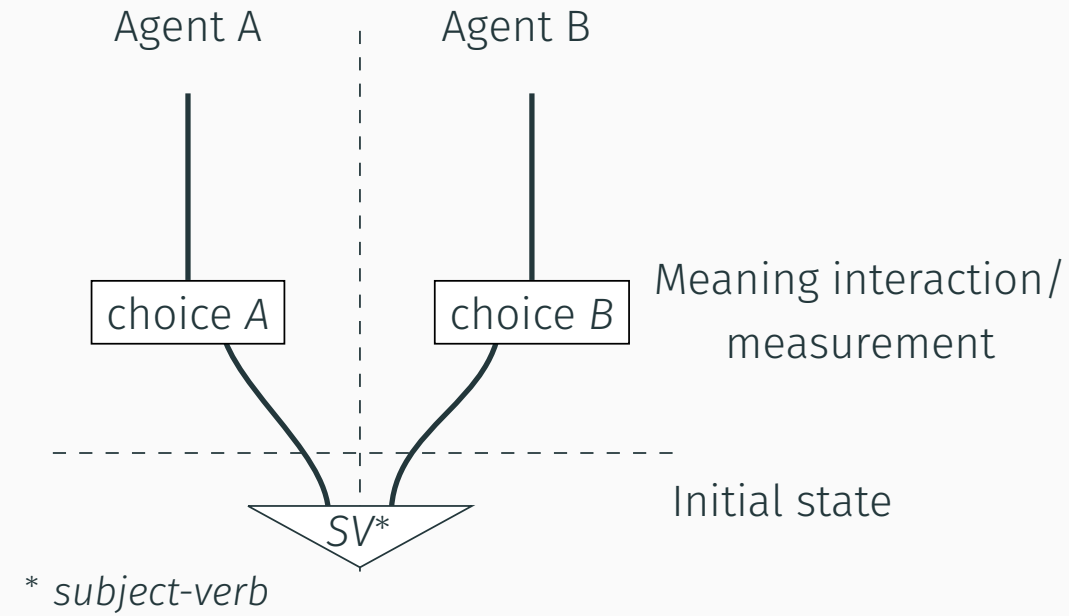


Initial state

* *subject-verb*

Logical contextuality

Bell scenarios in Natural Language



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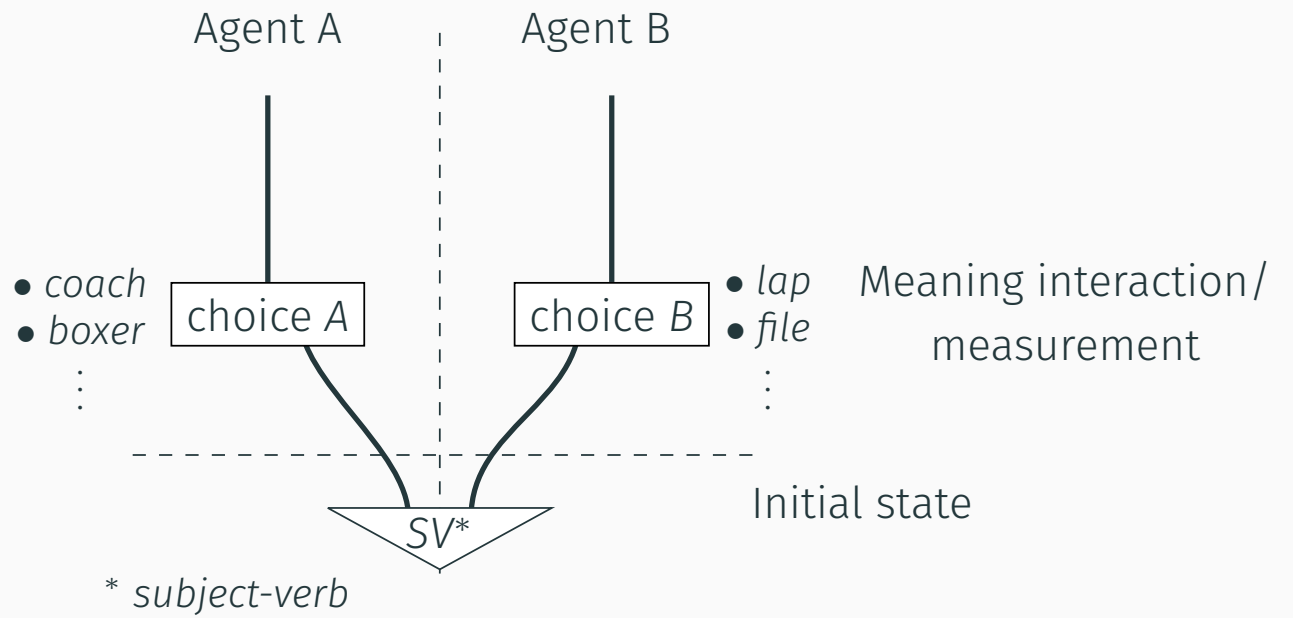

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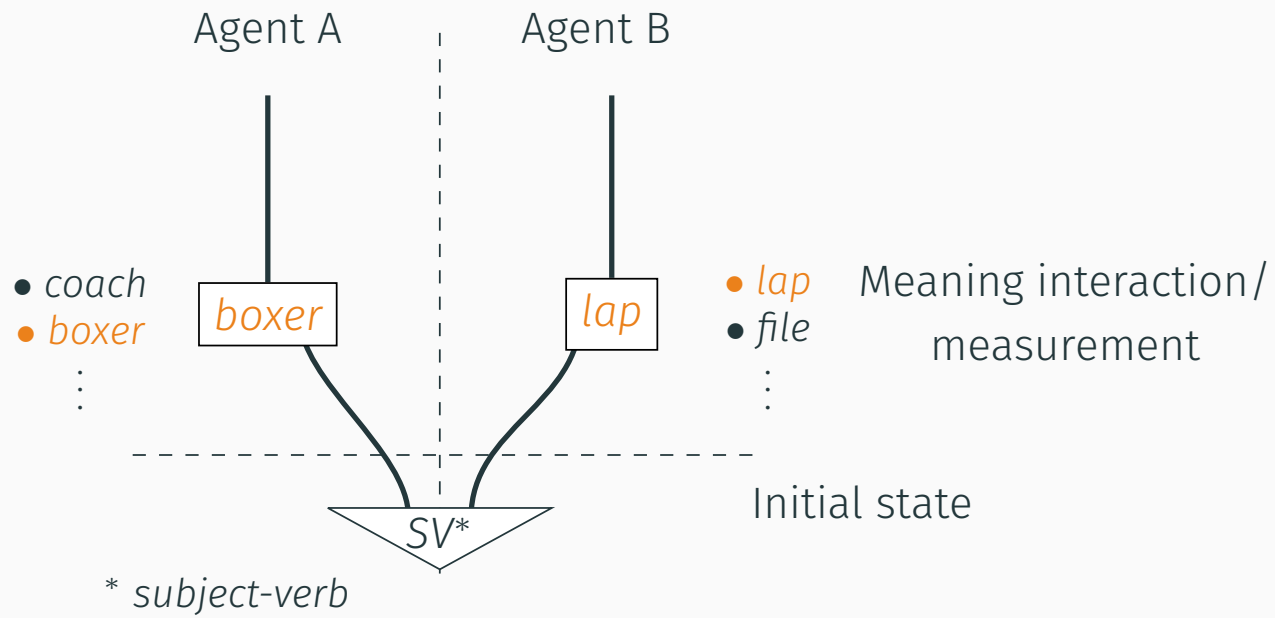

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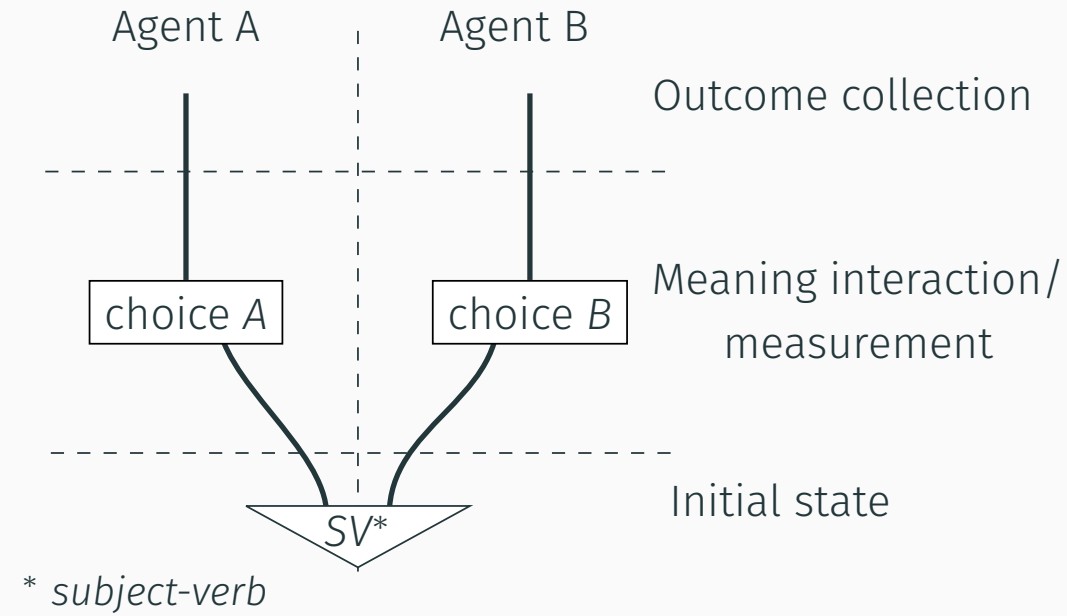

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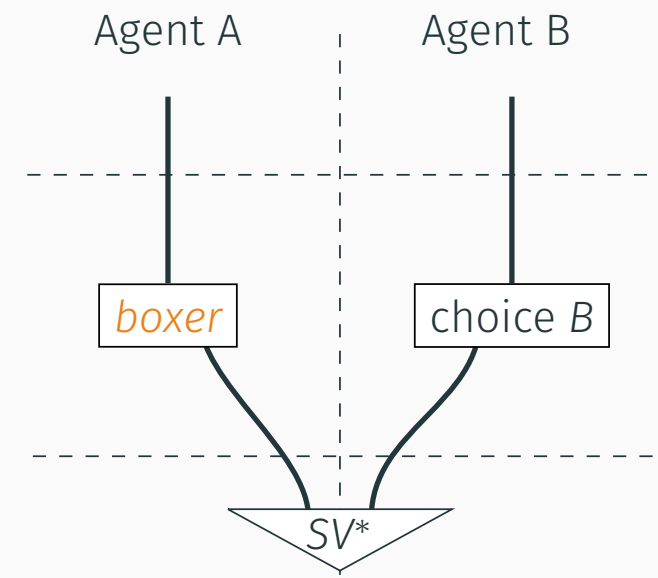
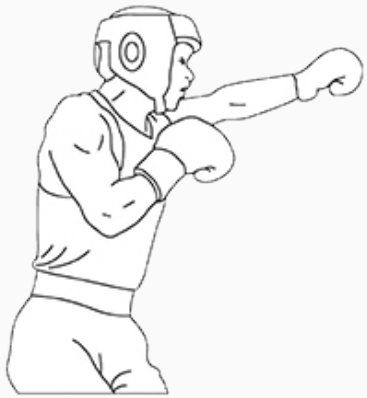
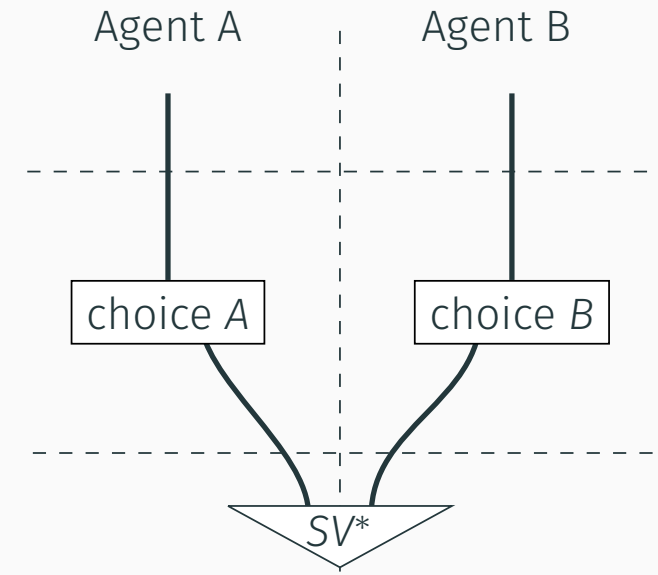


* *subject-verb*

Possible outcomes for *boxer*	
0	
1	

Logical contextuality

Bell scenarios in Natural Language : Possibilistic models



* *subject-verb*

subject	*verb*	(0,0)	(0,1)	(1,0)	(1,1)
coach	*lap*	1	1	1	0
coach	*file*	1	1	0	0
boxer	*lap*	1	1	1	1
boxer	*file*	1	1	0	0

Logical contextuality

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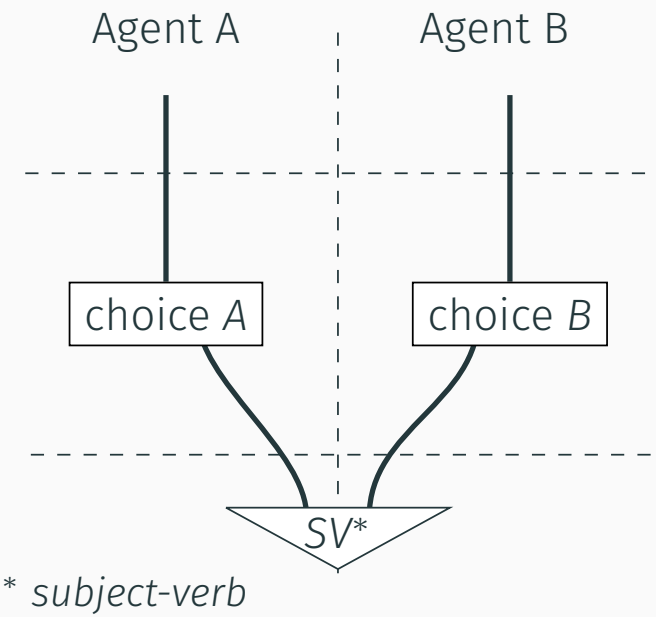

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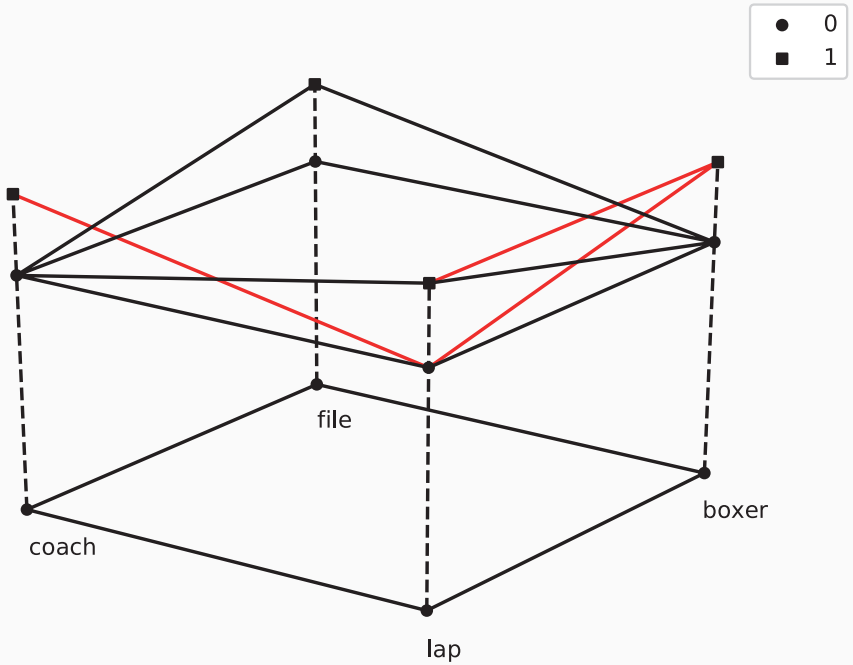

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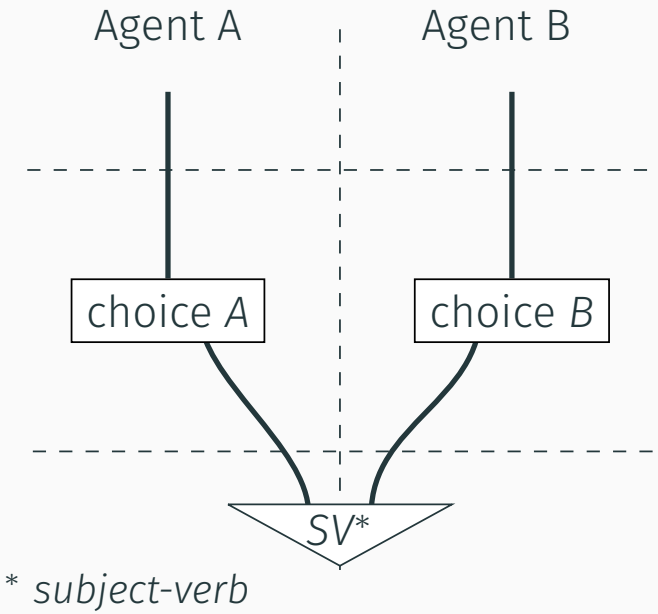

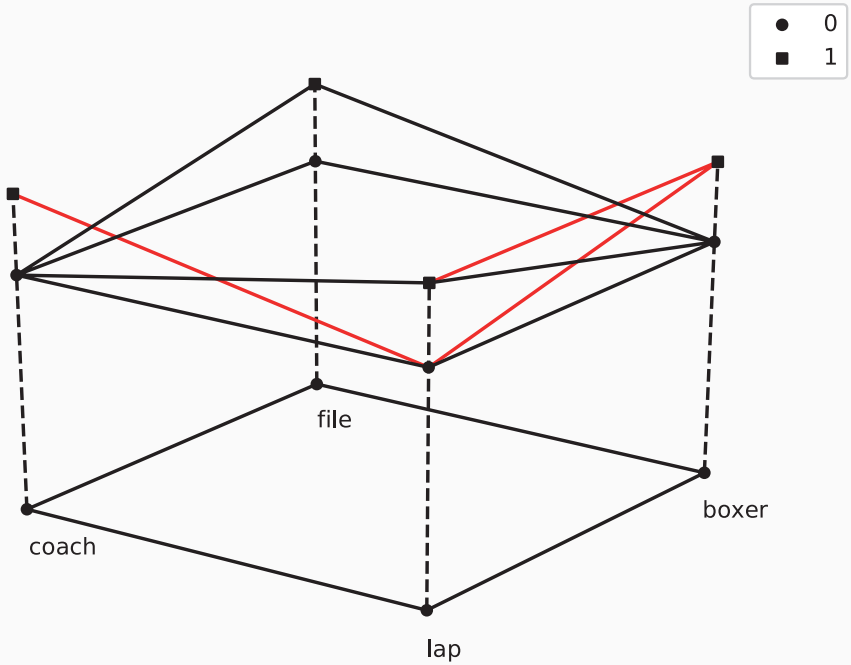

Signalling

Logical contextuality

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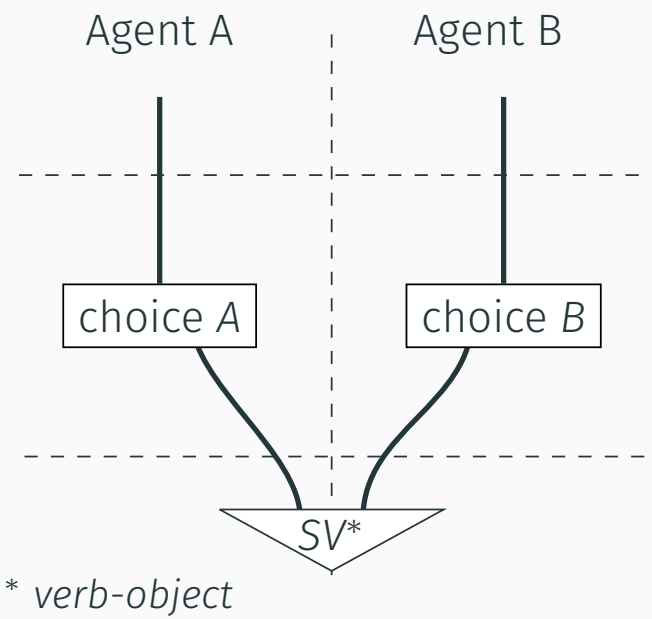
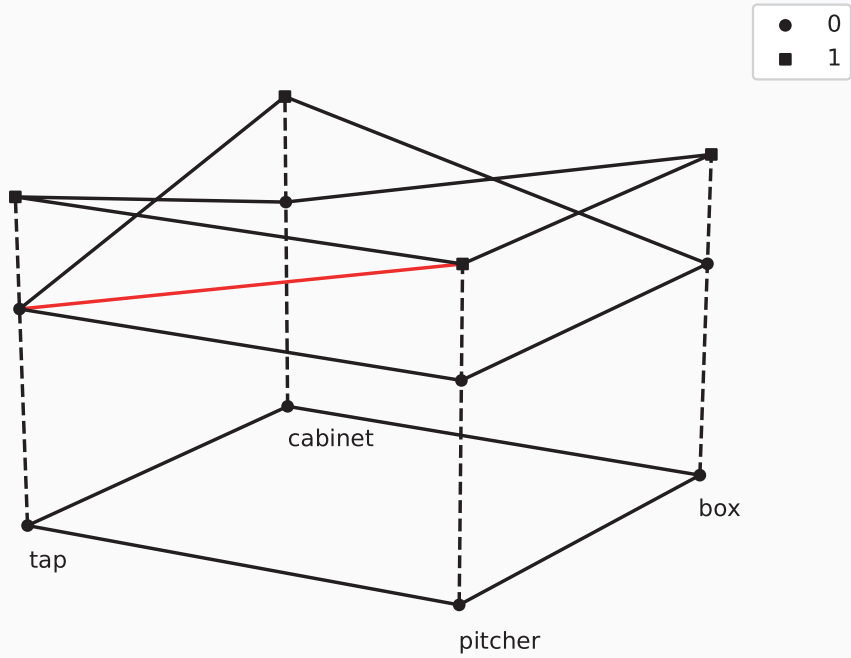


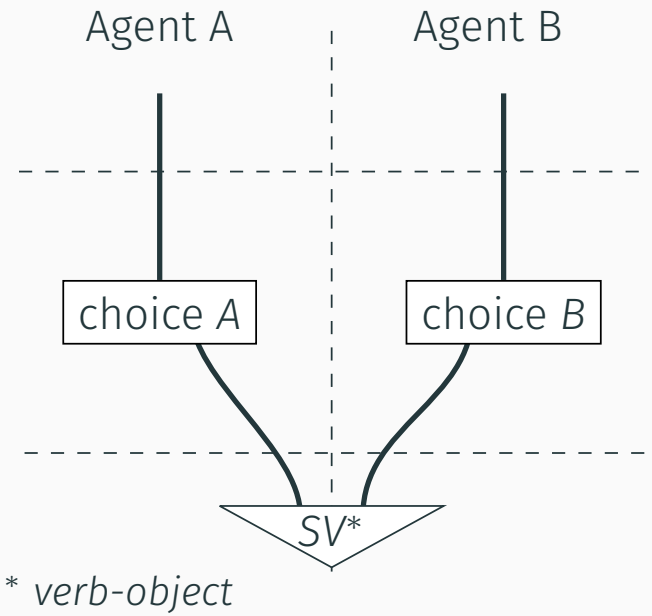
* *verb-object*



(Weakly) logically contextual

Logical contextuality

Bell scenarios in Natural Language : Probabilistic models



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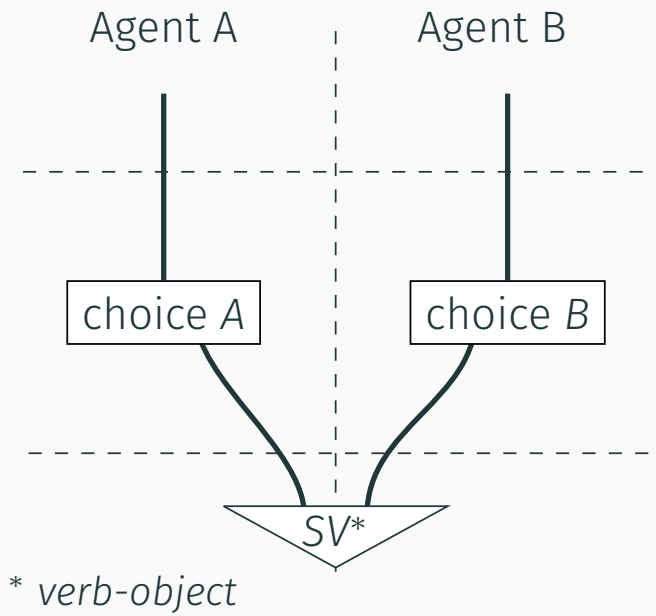
Logical contextuality

Bell scenarios in Natural Language : Probabilistic models

Probabilities from corpora:



Logical contextuality

Bell scenarios in Natural Language : Probabilistic models

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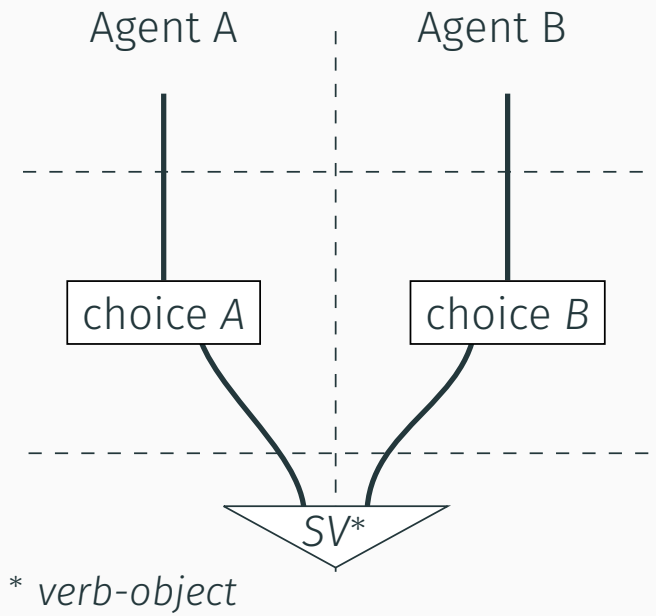

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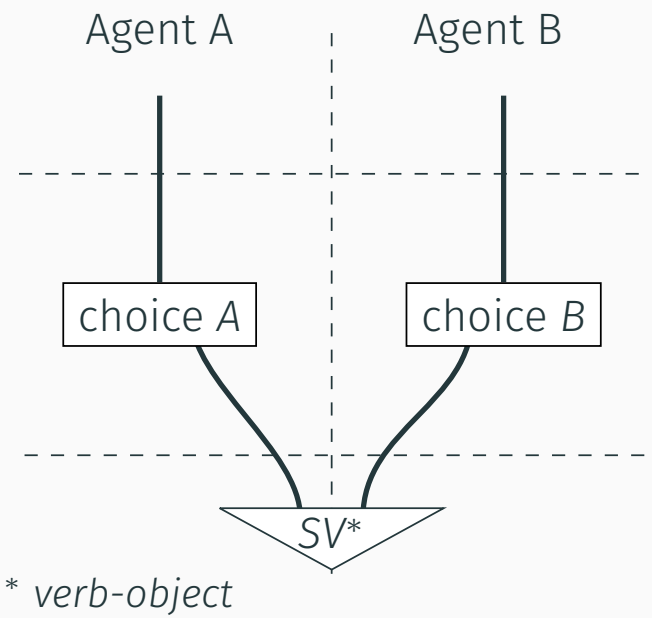

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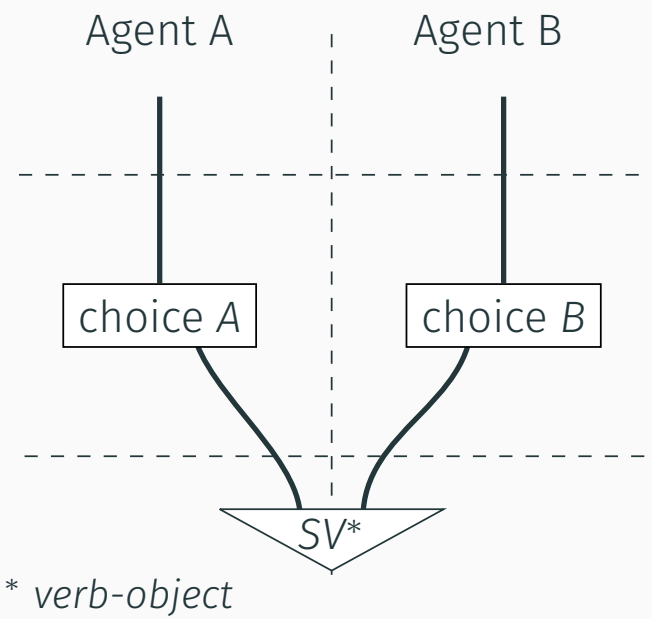

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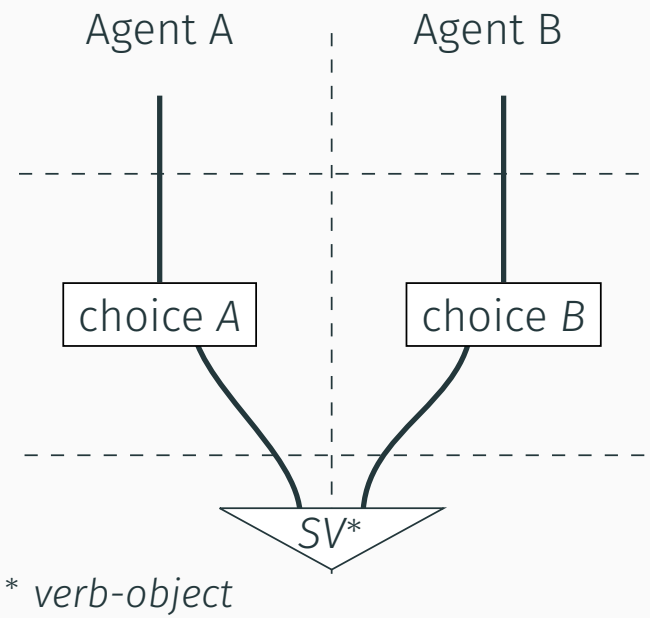

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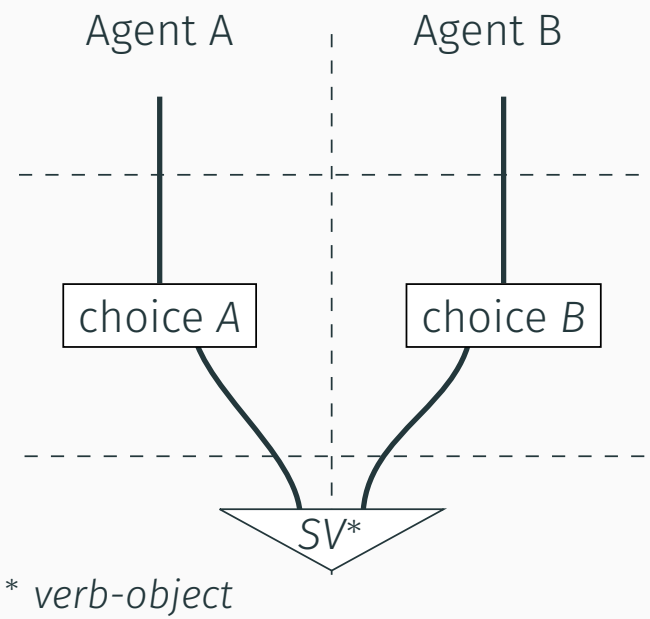

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All signalling

Contextuality-by-Default contextuality

Bell Scenarios: Cyclic systems of rank 4

[1] Out of 1682 models

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Cyclic systems of rank 2

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Contextuality-by-Default contextuality

Cyclic systems of rank 2

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Verb: *eat* Noun: *chicken*

Context	Example
Verb-object:	*Humans eat chicken.*
Subject-verb:	*The chicken eats grains.*

Contextuality-by-Default contextuality

Adopting boxers and Boxers adopting

	Adopt	*Boxer*
0	*They are thinking about adopting a child*	*The heavyweight boxer won the fight*
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- Contextual!

$$2 > 28/15$$

- Contextuality measure: **1/30**
- Non-contextuality probability: **> 0.56**

Contextuality-by-Default contextuality

Throwing pitchers and Pitchers throwing

	Throw	***Pitcher***
0	*She threw the ball across the field.*	*The pitcher was filled with water.*
1	*They are throwing a party.*	*In baseball, pitchers usually bats as well.*

(*throw*, *pitcher*)	(0,0)	(0,1)	(1,0)	(1,1)
throw pitcher	2/5	0	1/10	1/2
pitcher throws	0	2/3	1/3	0

- Also contextual!

$$9/5 > 13/15$$

- Contextuality measure: **7/30**
- Non-contextuality probability: **> 0.08**

Beyond contextuality: analysis of signalling

Analysis of signalling

- Models considered are signalling

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Can we use the "measures" of signalling to detect context effects in natural language?

- Focus on cyclic models of rank 2
- Compare the data for models in the following categories:

Verbs with multiple	meanings	-	Noun with multiple	meanings
Verbs with multiple	meanings	-	Noun with multiple	senses
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Analysis of signalling

Degree of signalling (Δ)

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Nouns \ Verbs	Meanings	Senses	Overall
Meanings	1.24 ± 0.29	1.36 ± 0.15	1.33 ± 0.14
Senses	1.50 ± 0.43	1.38 ± 0.36	1.41 ± 0.29
Overall	1.30 ± 0.25	1.36 ± 0.14	1.35 ± 0.12

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Classes of models	SD
Verbs with multi. meanings	1.04
Verbs with multi senses	1.20
Nouns with multi meanings	1.18
Nouns with multi senses	1.11

Analysis of signalling

Proportion of direct influence from the verb
$(2\Delta^*_{c_1,c_2}(F_v)/\Delta)$

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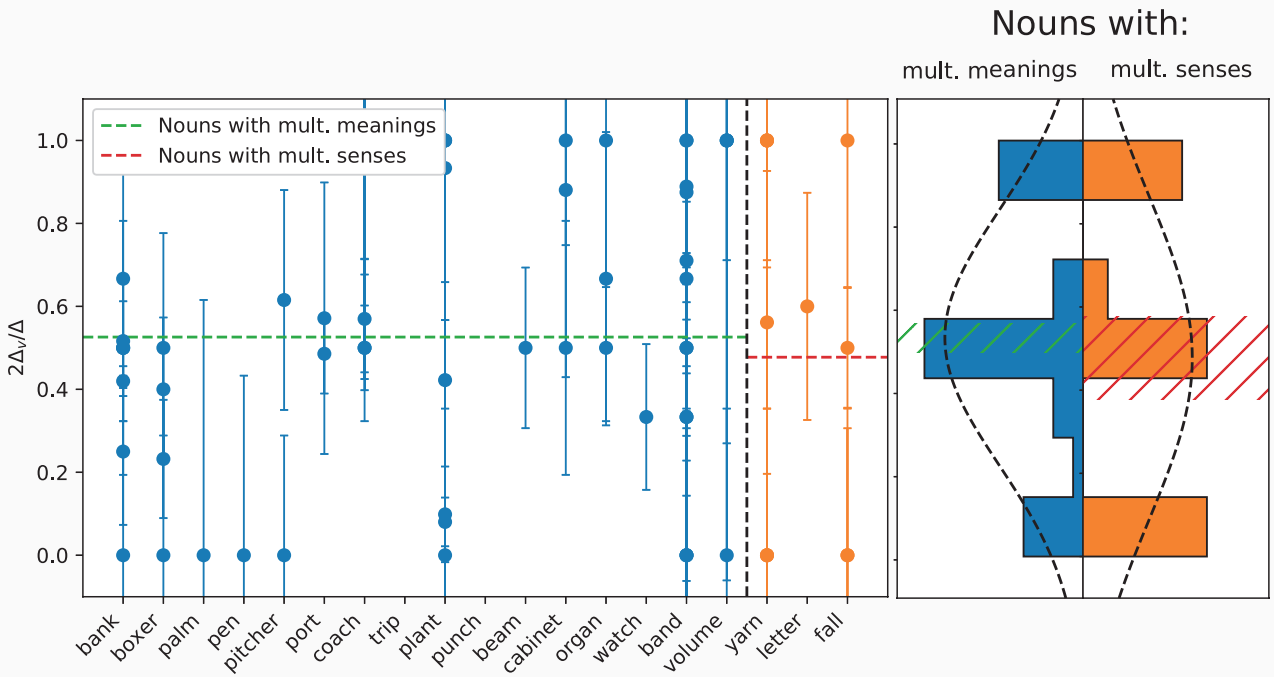

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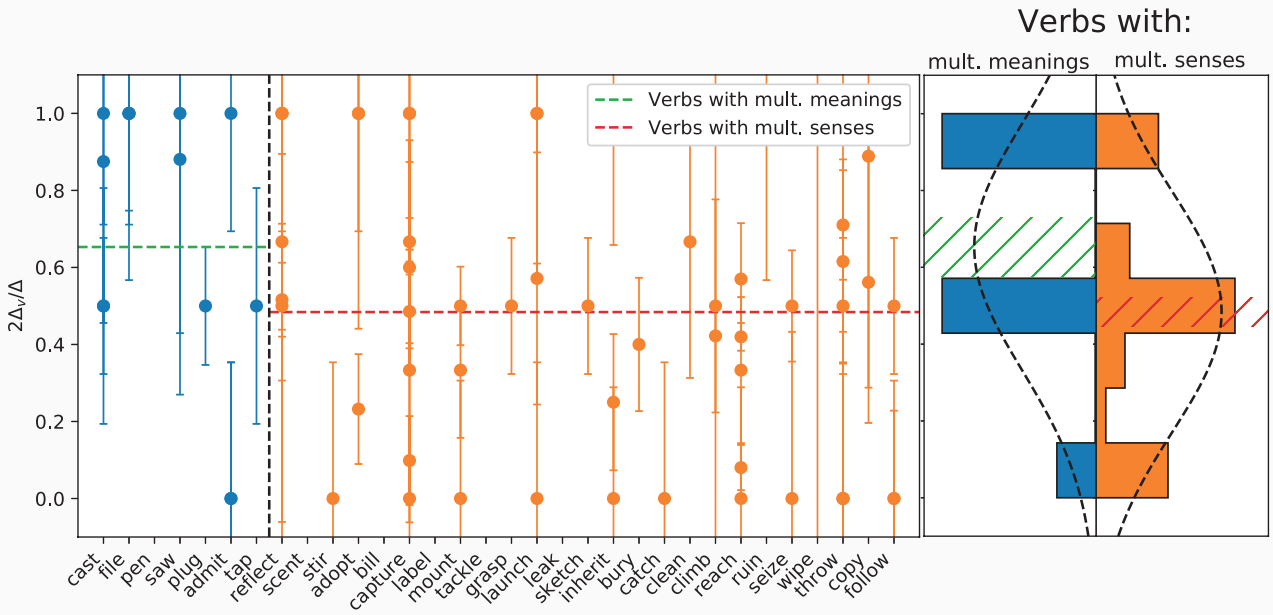

Conclusion

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  - Quantification of influences of context

Future work

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    e.g. *The old man the boat*
  - Senses following rules
    e.g. *chicken* (animal) $\rightarrow$ *chicken*(meat)

Background References i

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