

# Computational Complexity in Semantics

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# Outline

Computational Complexity

Predicting Processing Load

Distribution and Semantic Complexity

# Inherent complexity

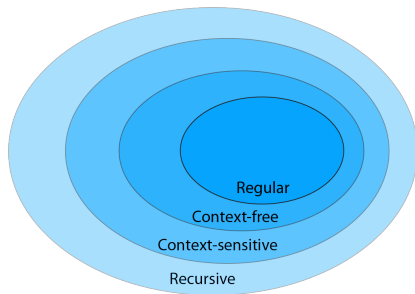
# Inherent complexity

- ▶ Inherent complexity of the problem (e.g., time and memory)

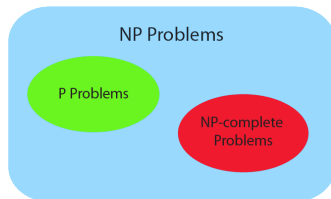
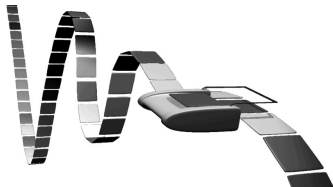
## Inherent complexity

- ▶ Inherent complexity of the problem (e.g., time and memory)
- ▶ and not the particular algorithmic implementation.

E.g. in terms of Chomsky's Hierarchy



# Or (in)tractability Border



# Various semantic problems

- ▶ Inferential meaning
  - ↔ complexity of reasoning (satisfiability)
- ▶ **Referential meaning**
  - ↔ complexity of verification (model-checking)



# Outline

Computational Complexity

**Predicting Processing Load**

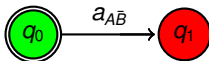
Distribution and Semantic Complexity

## Quantifiers . . .

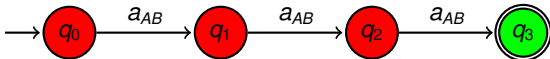
1. **All** poets have low self-esteem.
2. **Some** dean danced nude on the table.
3. **At least 3** grad students prepared presentations.
4. **An even number** of the students saw a ghost.
5. **Most** of the students think they are smart.
6. **Less than half** of the students received good marks.
7. **Many** of the soldiers have not eaten for **several** days.
8. **A few** of the conservatives complained about taxes.

## ... and Chomsky's Hierarchy

All As are B.

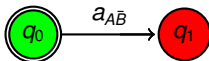


More than 2 As are B.

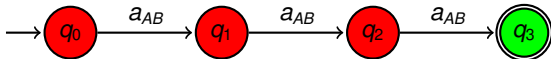


## ... and Chomsky's Hierarchy

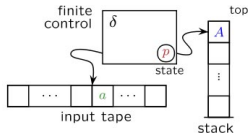
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More than 2 As are B.

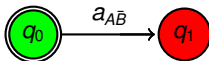


Most As are B.

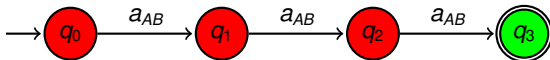


## ... and Chomsky's Hierarchy

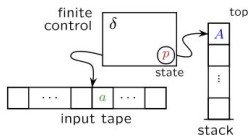
All As are B.



More than 2 As are B.



Most As are B.



van Benthem, Essays in logical semantics, 1986



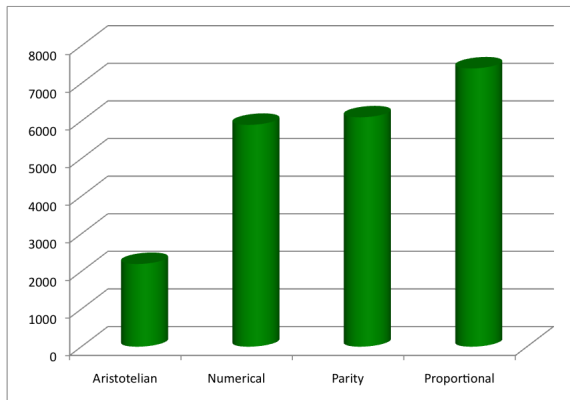
Mostowski, Computational semantics for monadic quantifiers, 1998

## A simple study

*More than half of the cars are yellow.*



## Verification times can be predicted by complexity



Szymanik & Zajenkowski, Comprehension of simple quantifiers. Empirical evaluation of a computational model, *Cognitive Science*, 2010

# Neurobehavioral prediction wrt working memory is satisfied

Differences in brain activity.

- ▶ Only proportional quantifiers activate working-memory capacity: recruit right dorsolateral prefrontal cortex.



McMillan et al., Neural basis for generalized quantifiers comprehension, *Neuropsychologia*, 2005



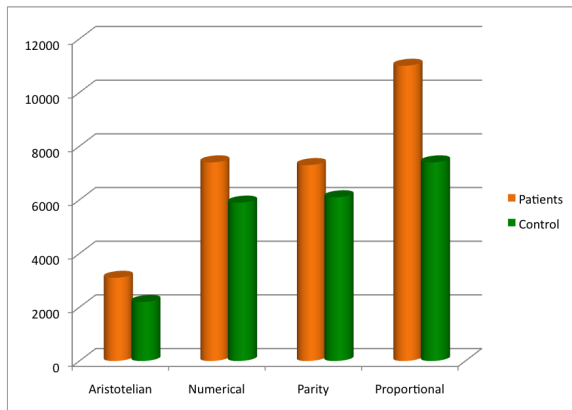
Szymanik, A Note on some neuroimaging study of natural language quantifiers comprehension, *Neuropsychologia*, 2007



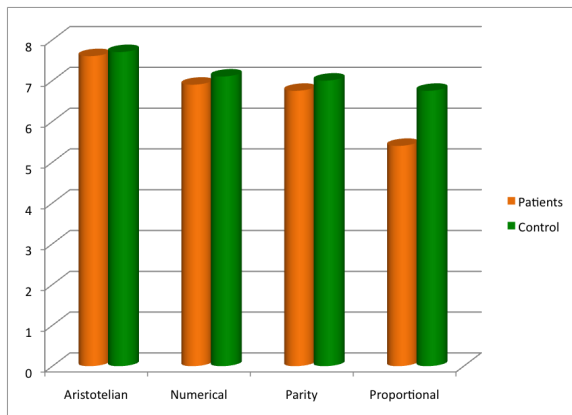
# Experiment with schizophrenic patients

- ▶ Compare performance of:
  - ▶ Healthy subjects.
  - ▶ Patients with schizophrenia.
    - ▶ Known WM deficits.

## Patients are generally slower



# Patients are only less accurate with proportional quantifiers



Zajenkowski et al., A computational approach to quantifiers as an explanation for some language impairments in schizophrenia, *Journal of Communication Disorders*, 2011.

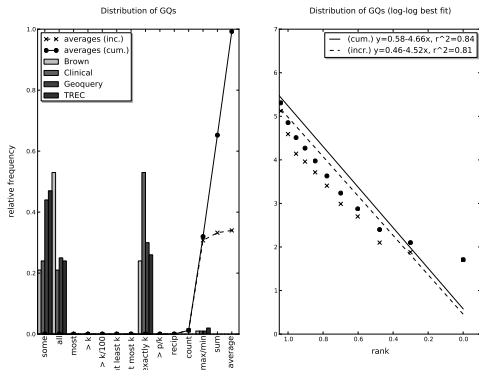
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Distribution and Semantic Complexity

# Distribution is skewed towards quantifiers of low complexity

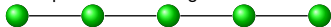


Thorne & Szymanik. Generalized Quantifier Distribution and Semantic Complexity, 2013.

# (In)tractable Reciprocal Constructions

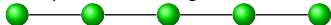
## (In)tractable Reciprocal Constructions

Most pitchers sat alongside each other.



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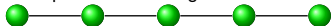
Pirates were staring at each other.





# (In)tractable Reciprocal Constructions

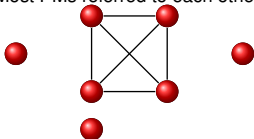
Most pitchers sat alongside each other.



Pirates were staring at each other.

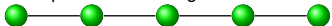


Most PMs referred to each other.



# (In)tractable Reciprocal Constructions

Most pitchers sat alongside each other.

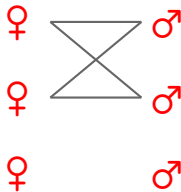
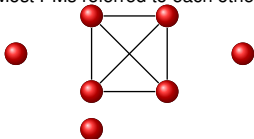


Pirates were staring at each other.



Most girls and most boys hate each other

Most PMs referred to each other.



Gierasimczuk & Szymanik, *Branching Quantification vs. Two-way Quantification*, *Journal of Semantics*, 2009



Szymanik, *Computational complexity of polyadic lifts of generalized quantifiers in natural language*. *Linguistics & Philosophy* 2010.

# Comprehension and verification are influenced by complexity

## 1. Draw and verify:

- ▶ All/Most of the dots are directly connected to each other.

# Comprehension and verification are influenced by complexity

1. Draw and verify:
  - ▶ All/Most of the dots are directly connected to each other.
2. In line with complexity:
  - ▶ Fewer strong pictures for 'most'
  - ▶ Better performance on complete graphs for 'All'-condition



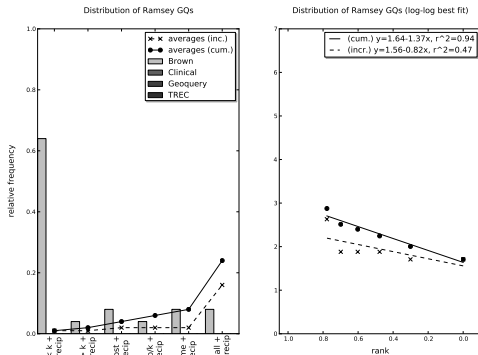
Bott et al., Interpreting Tractable versus Intractable Reciprocal Sentences, Proceedings of the International Conference on Computational Semantics, 2011.



Schlotterbeck & Bott, Easy solutions for a hard problem? The computational complexity of reciprocals with quantificational antecedents, Proc. of the Logic & Cognition Workshop at ESSLLI 2012.

# Few Intractable Expressions in NL

Distribution in corpora is again skewed towards tractable constructions.



Thorne & Szymanik, Generalized Quantifier Distribution and Semantic Complexity, 2013

# Beyond everyday language

- ▶ Some expressions may be even too hard to appear in NL.
  - ▶ E.g, some collective quantifiers can be crazy complex!



Kontinen & Szymanik, A remark on collective quantification, *Journal of Logic, Language and Information*, 2008



Mostowski & Szymanik, Semantic bounds for everyday language, *Semiotica* 2008

# Summing up

## Ristad's Thesis

*Complexity as a test of methodological plausibility of linguistic theories.*



Ristad, The Language Complexity Game, MIT 1993



Mostowski & Szymanik, Semantic bounds for everyday language, Semiotica 2008