

Quantifiers and Computational Complexity

Jakub Szymanik

Outline

Preliminaries

- Quantifiers in finite models
- Computational complexity

Almost all complex quantifiers are simple

Some complex GQs are intractable

- Branching quantifiers
- Strong reciprocity

A complexity perspective on shifts in meaning

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Generalized Quantifier Theory

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- ▶ They influence language expressivity.
- ▶ Classical GQT studies definability issues.

Computational complexity of quantifiers

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- ▶ Input: \mathbb{M} , φ . Output: $\varphi^{\mathbb{M}}$.
- ▶ W.r.t. to model size.
- ▶ Restriction to finite models.

Lindström quantifiers

Definition

Let $t = (n_1, \dots, n_k)$ be a k -tuple of positive integers. A *generalized quantifier* of type t is a class Q of models of a vocabulary $\tau_t = \{R_1, \dots, R_k\}$, such that R_i is n_i -ary for $1 \leq i \leq k$, and Q is closed under isomorphisms.

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Definition

If in the above definition for all i : $n_i = 1$, then we say that a quantifier is *monadic*, otherwise we call it *polyadic*.

GQs as classes of models

$$\forall = \{(M, P) \mid P = M\}.$$

$$\exists = \{(M, P) \mid P \subseteq M \text{ \& } P \neq \emptyset\}.$$

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$$\text{most} = \{(M, P, S) \mid P, S \subseteq M \ \& \ \text{card}(P \cap S) > \text{card}(P - S)\}.$$

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$$W = \{(M, R) \mid R \subseteq M^2 \text{ \& } R \text{ is a well-order}\}.$$

$$\text{Ram} = \{(M, A, R) \mid A \subseteq M, R \subseteq M^2 \text{ \& } \forall a, b \in A R(a, b)\}.$$

Monadic GQs - some examples

- ▶ Every poet has low self-esteem.
- ▶ Some dean danced nude on the table.
- ▶ At least 3 grad students prepared presentations.
- ▶ An even number of the students saw a ghost.
- ▶ Most of the students think they are smart.
- ▶ Less than half of the students received good marks.

Monadic GQs

1. They are easy to compute: FA, PDA.
2. Computational model is neuropsychologically plausible.

Polyadic quantifiers in language

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Question

1. *What about c.c. of polyadic quantifiers?*

Polyadic quantifiers in language

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 2. Three PMs referred to each other indirectly
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Question

1. *What about c.c. of polyadic quantifiers?*
2. *How various readings differ w.r.t. complexity?*

Quantifiers in finite models

- ▶ Finite models can be encoded as strings.
- ▶ GQs as classes of such finite strings are languages.

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Definition

By the *complexity of a quantifier* Q we mean the computational complexity of the corresponding class of finite models.

Question

$M \in Q?$ (equivalently $M \models Q?$)

Coding

Definition

Let $\tau = \{R_1, \dots, R_k\}$ be a relational vocabulary and \mathbb{M} a τ -model of the following form: $\mathbb{M} = (U, R_1^M, \dots, R_k^M)$, where $U = \{1, \dots, n\}$ is the universe of model \mathbb{M} and $R_i^M \subseteq U^{n_i}$ is an n_i -ary relation over U , for $1 \leq i \leq k$. We define a *binary encoding for τ -models*. The code for \mathbb{M} is a word over $\{0, 1, \#\}$ of length $O((\text{card}(U))^c)$, where c is the maximal arity of the predicates in τ (or $c = 1$ if there are no predicates).

The code has the following form:

$$\tilde{n}\# \tilde{R}_1^M \# \dots \# \tilde{R}_n^M, \text{ where:}$$

- ▶ \tilde{n} is the part coding the universe of the model and consists of n 1s.
- ▶ \tilde{R}_i^M — the code for the n_i -ary relation R_i^M — is an n^{n_i} -bit string whose j -th bit is 1 iff the j -th tuple in U^{n_i} (ordered lexicographically) is in R_i^M .
- ▶ $\#$ is a separating symbol.

Coding example

Consider vocabulary $\sigma = \{P, R\}$, where P is a unary predicate and R a binary relation. Take the σ -model $\mathbb{M} = (M, P^M, R^M)$, where the universe $M = \{1, 2, 3\}$, the unary relation $P^M \subseteq M$ is equal to $\{2\}$ and the binary relation $R^M \subseteq M^2$ consists of the pairs $(2, 2)$ and $(3, 2)$.

- ▶ \tilde{n} consists of three 1s as there are three elements in M .
- ▶ \tilde{P}^M is the string of length three with 1s in places corresponding to the elements from M belonging to P^M . Hence $\tilde{P}^M = 010$ as $P^M = \{2\}$.
- ▶ \tilde{R}^M is obtained by writing down all $3^2 = 9$ binary strings of elements from M in lexicographical order and substituting 1 in places corresponding to the pairs belonging to R^M and 0 in all other places. As a result $\tilde{R}^M = 000010010$.

Adding all together the code for \mathbb{M} is $111\#010\#000010010$.

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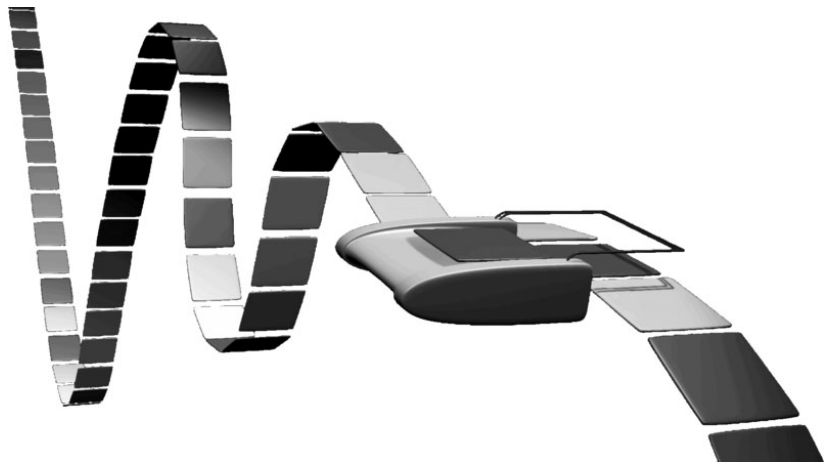
Some complex GQs are intractable

Branching quantifiers

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A complexity perspective on shifts in meaning

Model of computation



Computational Complexity Theory

Question

What amount of resources TM needs to solve a task?

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Theorem (determinism vs. non-determinism)

If there is a non-deterministic Turing machine N recognizing a language L , then there exists a deterministic Turing machine M for language L .

Computational Complexity Theory

Question

What amount of resources TM needs to solve a task?

Theorem (determinism vs. non-determinism)

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Question

*The simulation takes $O(c^{f(n)})$. Can we do it **significantly** faster?*

Time complexity

Let $f : \omega \longrightarrow \omega$.

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Definition

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Definition

$\text{TIME}(f)$ is the class of languages (problems) which can be recognized by a deterministic Turing machine in time bounded by f with respect to the length of the input.

Definition

$\text{NTIME}(f)$, is the class of languages L for which there exists a non-deterministic Turing machine M such that for every $x \in L$ all branches in the computation tree of M on x are bounded by $f(n)$ and moreover M decides L .

Complexity classes P and NP

Definition

- ▶ $\text{PTIME} = \bigcup_{k \in \omega} \text{TIME}(n^k)$
- ▶ $\text{NPTIME} = \bigcup_{k \in \omega} \text{NTIME}(n^k)$

Complexity classes P and NP

Definition

- ▶ $\text{PTIME} = \bigcup_{k \in \omega} \text{TIME}(n^k)$
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Question (Millenium Problem)

$P=NP?$

(In)tractability

Definition

We say that a function $f : A \longrightarrow A$ is a *polynomial time computable function* iff there exists a deterministic Turing machine computing $f(w)$ for every $w \in A$ in polynomial time.

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A problem L is polynomial reducible to a problem L' if there is a polynomial time computable function such that

$$w \in L \iff f(w) \in L'.$$

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Definition

A problem L is polynomial reducible to a problem L' if there is a polynomial time computable function such that

$$w \in L \iff f(w) \in L'.$$

Definition

A language L is NP-complete if $L \in NP$ and every language in NP is reducible to L .

NP Problems

P Problems

NP Complete

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A complexity perspective on shifts in meaning

Boolean combinations of determiners

1. At least 5 or at most 10 departments can win EU grants.
2. Between 100 and 200 students run in the marathon.
3. Not all students passed.
4. All students did not pass.

Boolean combinations of quantifiers

Definition

Let Q, Q' be generalized quantifiers, both of type (n_1, \dots, n_k) .
We define:

$$(Q \wedge Q')_M[R_1, \dots, R_k] \iff Q_M[R_1, \dots, R_k] \text{ and } Q'_M[R_1, \dots, R_k]$$

$$(Q \vee Q')_M[R_1, \dots, R_k] \iff Q_M[R_1, \dots, R_k] \text{ or } Q'_M[R_1, \dots, R_k]$$

$$(\neg Q)_M[R_1, \dots, R_k] \iff \text{not } Q_M[R_1, \dots, R_k]$$

$$(Q\neg)_M[R_1, \dots, R_k] \iff Q_M[R_1, \dots, R_{k-1}, M - R_k]$$

Boolean operations are tractable

Theorem

Let Q and Q' be generalized quantifiers computable in PTIME. Then the quantifiers: (1) $\neg Q$; (2) $Q\neg$; (3) $Q \wedge Q'$; (3) $Q \vee Q'$ are PTIME computable.

Iteration

1. Most logicians criticized some papers.
2. It(most, some)[Logicians, Papers, Criticized].

Definition

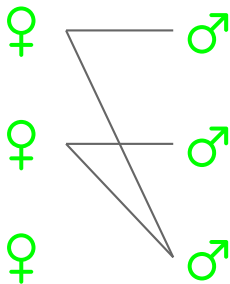
Let Q and Q' be generalized quantifiers of type $(1, 1)$. Let A, B be subsets of the universe and R a binary relation over the universe. Suppressing the universe, we will define the *iteration* operator as follows:

$$\text{It}(Q, Q')[A, B, R] \iff Q[A, \{a \mid Q'[B, R_{(a)}]\}],$$

where $R_{(a)} = \{b \mid R(a, b)\}$.

Illustration

- ▶ Most girls and most boys hate each other.



Iteration is easy

Theorem

Let Q and Q' be generalized quantifiers computable in PTIME. Then the quantifier $It(Q, Q')$ is also PTIME computable.

Cumulation

- ▶ Eighty professors taught sixty courses at ESSLLI'08.

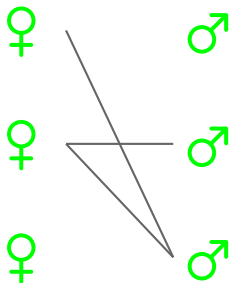
Definition

$\text{Cum}(Q, Q')[A, B, R] \iff$

$$\text{It}(Q, \text{some})[A, B, R] \wedge \text{It}(Q', \text{some})[B, A, R^{-1}]$$

Illustration

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Cumulation is easy

Theorem

*Let Q and Q' be generalized quantifiers computable in PTIME.
Then the quantifier $\text{Cum}(Q, Q')$ is PTIME computable.*

Resumption

- ▶ Most twins never separate.

Definition

Let Q be any monadic quantifier with n arguments, U a universe, and $R_1, \dots, R_n \subseteq U^k$ for $k \geq 1$. We define the *resumption* operator as follows:

$$\text{Res}^k(Q)_U[R_1, \dots, R_n] \iff (Q)_{U^k}[R_1, \dots, R_n].$$

Resumption is easy

Theorem

*Let Q and Q' be generalized quantifiers computable in PTIME.
Then the quantifier $\text{Res}(Q, Q')$ is PTIME computable.*

Basic operations are tractable

Theorem

Let Q and Q' be generalized quantifiers computable in PTIME. Then the quantifiers: (1) $\neg Q$; (2) $Q\neg$; (3) $Q \wedge Q'$; (4) $\text{It}(Q, Q')$; (5) $\text{Cum}(Q, Q')$; (6) $\text{Res}(Q)$ are PTIME computable.

Take home message

Everyday simple determiners in NL are in PTIME.

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PTIME quantifiers are closed under the common polyadic lifts.

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Common polyadic quantifiers in NL are tractable.

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A complexity perspective on shifts in meaning

Possibly branching sentences

1. Most villagers and most townsmen hate each other.
2. One third of villagers and half of townsmen hate each other.
3. 5 villagers and 7 townsmen hate each other.

Branching reading

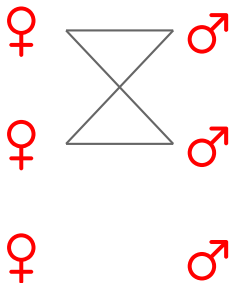
- ▶ Most girls and most boys hate each other.

$$\begin{array}{l} \text{most } x : G(x) \\ \text{most } y : B(y) \end{array} H(x, y).$$

$$\exists A \exists A' [\text{most}(G, A) \wedge \text{most}(B, A') \wedge \forall x \in A \forall y \in A' H(x, y)].$$

Illustration

- ▶ Most girls and most boys hate each other.



Definition

Definition

Let Q and Q' be both $\text{MON}\uparrow$ quantifiers of type $(1, 1)$. Define the *branching* of quantifier symbols Q and Q' as the type $(1, 1, 2)$ quantifier symbol $\text{Br}(Q, Q')$.

A structure $\mathbb{M} = (M, A, B, R) \in \text{Br}(Q, Q')$ if the following holds:

$$\exists X \subseteq A \exists Y \subseteq B [(X, A) \in Q \wedge (Y, B) \in Q' \wedge X \times Y \subseteq R].$$

Branching readings are intractable

Theorem

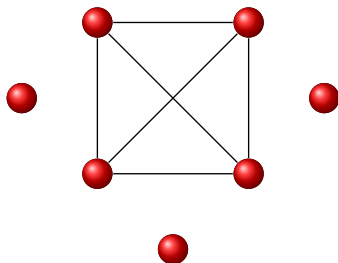
Proportional branching sentences are NP-complete.

Potentially strong reciprocal sentences

1. Andi, Jarmo and Jakub laughed at **one another**.
2. 15 men are hitting **one another**.
3. Most of the PMs refer to **each other**.

Strong reading

- ▶ Most of the PMs refer to each other.



Strong reciprocal lift

Definition

Let Q be a right monotone increasing quantifier of type $(1, 1)$.
We define:

$$\text{Ram}_S(Q)[A, R] \iff \exists X \subseteq A [Q(A, X) \\ \wedge \forall x, y \in X (x \neq y \implies R(x, y))].$$

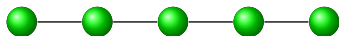
Strong reciprocity is intractable

Theorem

Model-checking for strong reciprocal sentences with proportional quantifiers is NP-complete.

Intermediate reading

- ▶ Most Boston pitchers sat alongside each other.



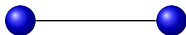
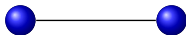
Intermediate reciprocal lift

Definition

$$\text{Ram}_1(Q)[A, R] \iff \exists X \subseteq A[Q(A, X) \\ \wedge \forall x, y \in X (x \neq y \implies \exists \text{ sequence } z_1, \dots, z_\ell \in X \text{ such that} \\ (z_1 = x \wedge R(z_1, z_2) \wedge \dots \wedge R(z_{\ell-1}, z_\ell) \wedge z_\ell = y))].$$

Weak reading

- ▶ Some pirates were staring at each other in surprise.



Weak reciprocal lift

Definition

$$\text{Ram}_W(Q)[A, R] \iff \exists X \subseteq A[Q(A, X) \\ \wedge \forall x \in X \exists y \in X (x \neq y \wedge R(x, y))].$$

Complexity dichotomy

As opposed to the strong case:

Complexity dichotomy

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Theorem

If Q is PTIME, then also $\text{Ram}_I(Q)$ and $\text{Ram}_W(Q)$ are in PTIME.

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Strong Meaning Hypothesis

Hypothesis

Reading associated with the reciprocal in a given sentence is the strongest available reading which is consistent with relevant information supplied by the context.

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Hypothesis

Reading associated with the reciprocal in a given sentence is the strongest available reading which is consistent with relevant information supplied by the context.

Example

1. The children followed each other into the church.
2. The children followed each other around the Maypole.



Dalrymple et al., Reciprocal expressions and the concept of reciprocity.
Linguistics and Philosophy, 1998.

P-Cognition Thesis

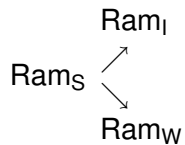
Hypothesis

Human cognitive (linguistic) capacities are constrained by polynomial time computability.

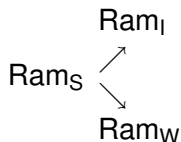


Frixione, Tractable competence. Minds and Machines, 2001.

Shifts forced by intractability



Shifts forced by intractability



Example

What is the default meaning of:

Most members of parliament refer to each other indirectly?

Summary

- ▶ Standard multi-quantifier constructions are tractable.

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- ▶ Computational dichotomy between different readings.

Summary

- ▶ Standard multi-quantifier constructions are tractable.
- ▶ Computational dichotomy between different readings.
- ▶ Revising the Strong Meaning Hypothesis with complexity.



Szymanik, Computational Complexity of Polyadic Lifts of Generalized Quantifiers in Natural Language, Linguistics and Philosophy, 2010.

Experimental question

Question

Is there any empirical support for those claims?

Experimental question

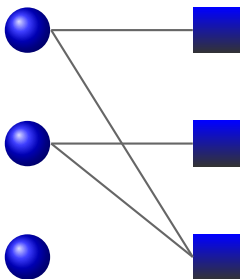
Question

Is there any empirical support for those claims?

Well ...

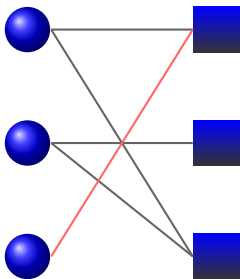
Two-way quantification

$$\text{It}(Q_1, Q_2) \wedge \text{It}(Q_2, Q_1)$$



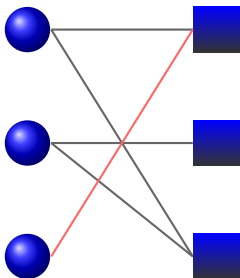
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Two-way quantification

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Subjects are happy to accept such interpretation.



Gierasimczuk and Szymanik, Branching quantification vs. two-way quantification, Journal of Semantics, 2009

Default meanings differ

Draw:

1. All/Most of the dots are connected to each other.

Default meanings differ

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1. All/Most of the dots are connected to each other.
 - ▶ Against SMH:
 - ▶ Ambiguous between strong and intermediate.

Default meanings differ

Draw:

1. All/Most of the dots are connected to each other.
 - ▶ Against SMH:
 - ▶ Ambiguous between strong and intermediate.
 - ▶ In line with complexity: fewer strong pictures for 'most'.



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