


# Tightening Faster Model Checking of First-Order Graph Properties, via Tarski's Calculus of Relations

Yo: Tentative

Yoshiki Nakamura ✉ 

Science Tokyo, Japan

Yuya Uezato ✉ 

CyberAgent, Inc., Japan

## Abstract

This is a SUPER-STRONG-PAPER and brings a NEW ERA to the field of FO.

**2012 ACM Subject Classification** Theory of computation → Logic

**Keywords and phrases** First-order Logic, Fine-grained Complexity

**Digital Object Identifier** 10.4230/LIPIcs...

## 1 Notation

(メモ: LIPICSとpLaTeXは異常に組み合わせが悪いので、コメントなどで日本語を書く時はこのようにします。)

Cute round-corner box

コメントを付ける時には、screenで囲うとこういう感じになります

Yo: コメントテスト

Yo: コメントテスト2

We write  $\mathbb{FO}^k$  to denote the set of formulas of First-order predicate logic with  $k$ -variables.

## Important Remark (Unary and Binary Predicates)

We allow unary and binary predicates in our  $\mathbb{FO}^3$ . Therefore, we do not allow terms involving ternary predicates such as  $\forall x. \exists y. \forall z. P(x, y, z)$ .<sup>1</sup>

On this remark, we can identify each model  $\mathcal{M}$  as color graphs as follows:

- Each element corresponds a node (vertex).
- Each unary predicate  $U_i$  means “color- $i$ ” node.
- Each binary predicate  $P_j$  is “color- $j$ ” edge.
- For example, on two nodes  $x, y$ , a term  $(U_i(x) \wedge U_j(y) \wedge P_k(x, y))$  means that  $x$  has the color  $i$ ,  $y$  has the color  $j$ , and there is a color  $k$  edge from  $x$  to  $y$ .

<sup>1</sup> For each unary predicate  $U$ , we can simulate it by a diagonal binary predicate  $B_U(x, y) := x = y \wedge U(x)$ . However, in our later construction, we use some unary predicates; thus, we also allow unary predicates explicitly.



© Yoshiki Nakamura and Yuya Uezato;

licensed under Creative Commons License CC-BY 4.0

Leibniz International Proceedings in Informatics

LIPICs Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

## 29 Quantifier width

Quantifier widthという謎の指標を導入します。

与えられた式の部分項  $\forall/\exists x.(\dots)$  について  $\dots$  部分に「直接」出てくる quantifier の個数を、この部分項の quantifier width と呼ぶことにします。

たとえば、次の部分項

$$\forall x. \left( \left( \forall y. P(y) \right) \vee \left( \forall z. (\forall x. P(z, x)) \wedge Q(z) \right) \right)$$

については、内部に3つの quantifier の出現（下線）があるのですが、直接の出現は赤くした2つだけなので、この部分項の quantifier width は「2」です。

そして、式の quantifier width というのは、最大の quantifier width を持つ部分項における、その数として定義します。

30

31 **2** Introduction

Yo: TODO: (Below is wip.)

32

33 The *model checking problem* is the following problem:

34

given both a sentence  $\varphi$  and a structure  $\mathfrak{A}$ , does  $\mathfrak{A} \models \varphi$  hold?

35

Unfortunately, the model checking problem for  $\mathbb{FO}$  is complete in PSPACE. Nevertheless, when the number of *variables* is fixed, the model checking problem for  $\mathbb{FO}^k$  can be decided in  $\mathcal{O}(\|\varphi\| \cdot n^k)$  time by a naive bottom-up evaluation algorithm (see, *e.g.*, [13, Proposition 3.1]), where  $\|\varphi\|$  is the length of  $\varphi$  and  $n$  is the number of *vertices* in  $\mathfrak{A}$ . A natural question is

36

Can the complexity be improved from  $\mathcal{O}(\|\varphi\| \cdot n^k)$  time?

Yo: TODO: Parameterized complexity (*e.g.*, [5, 4, 3, 6]).  
Parameterized complexity for space complexity [2]

40

Williams [14] gave a positive answer to this question. He showed that when  $\varphi$  is *fixed*,  
■ For  $\mathbb{FO}^3$  sentences<sup>2</sup>, the model checking problem can be decided in  $\mathcal{O}(n^\omega)$  time [14, Theorem 1.2][7, Theorem 7], where  $\omega$  is the exponent of matrix multiplication.

42

■ For  $\mathbb{FO}^k$  sentences<sup>3</sup> where  $k \geq 4$ , if the model checking problem can be decided in  $\mathcal{O}(n^{k-1-\varepsilon})$  time for some  $\varepsilon > 0$ , then the *Strong Exponential Time Hypothesis* (SETH) is false [14, Corollary 1.4].

44

However when  $\varphi$  is not fixed, the *Williams–Gao–Impagliazzo’s algorithm* [14, 7] for  $\mathbb{FO}^3$  sentences is  $\mathcal{O}(2^{\|\varphi\|} \cdot n^\omega)$  time. The exponential blowup *w.r.t.*  $\|\varphi\|$  is due to that the algorithm requires a transformation to the *disjunctive normal form* (DNF).

46

...

48

<sup>2</sup> Precisely, Williams [14] shows that for  $\mathbb{FO}^k$  sentences in the *prenex normal form* (so, the number of occurrences of *quantifiers* is at most  $k$ ), the model checking problem is in  $\mathcal{O}(n^{k-3+\omega})$  time for  $k \geq 3$  [14, Corollary 1.3], and in  $n^{k-1+o(1)}$  time for  $k \geq 9$  [14, Theorem 1.3]. Gao and Impagliazzo [7, Theorem 7] claims that the algorithm can be extended for general  $\mathbb{FO}^k$  sentences when  $k = 3$ .

<sup>3</sup> This claims holds even for  $\mathbb{FO}^k$  sentences in  $\exists^*\forall$ -prenex normal form.

In this paper, we first revisit the Williams–Gao–Impagliazzo’s algorithm. We give a perspective from *Tarski’s calculus of relations* (henceforth, *CoR*) [11]. ... We can translate  $\mathbb{FO}^3$  sentences into *CoR* sentences in  $\mathcal{O}(2^{\|\varphi\|})$  time. The original translation is given in [12]. An  $\mathcal{O}(2^{\|\varphi\|})$  time translation is given in [10]; an implementation of the translation [9, 10] can be found in [1].<sup>4</sup> For *CoR* sentences, the model checking problem can be decided in  $\mathcal{O}(\|\varphi\| \cdot n^\omega)$  time by a naive bottom-up evaluation algorithm, where we use the *matrix multiplication* algorithm for the *relational composition* ;. Combining them, we have that the model checking problem for  $\mathbb{FO}^3$  sentences can be decided in  $\mathcal{O}(2^{\|\varphi\|} \cdot n^\omega)$  time.

Now, ...

### 3 Preliminaries

⌈ We write  $\models$

### 4 FPT on $\mathbb{FO}^3$

We write  $\mathbb{FO}_{k,w}^3$  to denote the set of formulas of  $\mathbb{FO}^3$  with  $k$ -predicates and  $w$ -quantifier-width.

► **Theorem 1** ( $\mathbb{FO}_{k,w}^3$  model checkig is FPT).

Let  $\varphi : \mathbb{FO}_{k,w}^3$ .

For a given model (graph)  $\mathcal{G}$ , we can decide if  $\mathcal{G} \models \varphi$  in  $\mathcal{O}(2^{k+w} \cdot |\varphi| \cdot N^\omega)$  where

■  $N$  is the number of vertices in  $\mathcal{G}$ ; and

■  $\omega$  is a complexity constant for the boolean matrix multiplication (BMM): i.e.,  $\mathcal{O}(N^\omega)$ -time is the time complexity for BMM of two  $(N, N)$  matrices.<sup>5</sup>

► **Corollary 2.** If we fix the number of predicates  $k$  and width  $w$ , the model checking problem  $\mathcal{G} \models \varphi$  in  $\mathcal{O}(|\varphi| \cdot N^\omega)$  time-complexity where  $N$  is the number of nodes in  $\mathcal{G}$ .

$k$ をfixしない、素朴な  $\{(x, y, z)\}$  構築アルゴリズムだと  $\mathcal{O}(|\varphi| \cdot N^3)$  になって、その設定だと Theorem 1 は 係数 が大きくなりすぎて遅いということを、意味のある形で言及した方が良い。

以降、Theorem 1 の証明をやっていきます。

#### 4.1 Proof of Theorem 1

Here we use  $P, Q, R \dots$  to denote binary predicates and  $U, \dots$  for unary predicates.

For a given graph (model)  $\mathcal{G}$ , we write  $N_{\mathcal{G}}$  or simply  $N$  to denote the number of vertices of  $\mathcal{G}$ .

#### Our idea: Quantifier elimination (Simple case)

Our query evaluation strategy is evaluating the innermost (quantifier-free formula) to the outermost along with quantifier eliminating.

<sup>4</sup> Williams–Gao–Impagliazzo’s algorithm takes almost the same steps as in the translation in [10]... (TODO: revise)

<sup>5</sup> 何らかの論文をciteして、今の記録がどれくらい書いておくと分かりやすい

Let us consider the following situation:

$$Qx \cdots (Qy \cdots (Qz \cdots (Qx \cdots (Qy \cdots (\exists x. (P(y, x) \wedge R(x, z))))))))$$

To eliminate  $\exists z. P(y, x) \wedge R(x, z)$ , we introduce a new predicate defined as follows:

$$S(x, y) := \exists z. P(x, z) \wedge Q(z, y).$$

81 It is worth noting that  $S$  is just the composed predicate of  $P$  and  $Q$ . So, we write  $P \odot Q$   
82 instead of  $S$ .

Using this predicate, we can rewrite the above one to the following one:

$$Qx \cdots (Qy \cdots (Qz \cdots (Qx. (Qy. (P \odot R)(y, z))))))$$

83

84 Continuing this process, if we eventually enter  $\forall x. \exists y. T(x, y)$ :

- 85 1. building a unary predicate  $T_y(x) := \exists y. T(x, y)$  in  $O(N^2)$ -time, we rewrite it to  $\forall x. T_y(x)$ .  
86 2. we then simply evaluate  $\forall x. T_y(x)$  as  $\bigwedge_{1 \leq i \leq N} T_y(i)$  in  $O(N)$ -time.

### 87 Time-complexity of basic operations

88 Here we enumerate the time-complexity of our basic operations, which will be used later:

- 89 ■ Building a new predicate  $Q(x, y) := P(x, y) \bowtie R(x, y)$  ( $\bowtie \in \{\wedge, \vee\}$ ) needs  $O(N^2)$ -time.  
90 ■ Transposing a predicate  $P^T(x, y) := P(y, x)$  needs  $O(N^2)$ -time.  
91 ■ Evaluating unary predicates  $Qx. P(x)$  ( $Q \in \{\forall, \exists\}$ ) needs  $O(N)$ -time.  
92 ■ Building a new predicate  $Q(x) := Qy. P(x, y)$  ( $Q \in \{\exists, \forall\}$ ) needs  $O(N^2)$ -time.

93 So, the remaining operator is predicate composing  $(P \odot Q)(x, y) := \exists z. P(x, z) \wedge Q(z, y)$   
94 from predicates  $P$  and  $Q$ . Although a very simple matrix multiplication requires  $O(N^3)$ -time,  
95 we can build such  $P \odot Q$  using fast matrix multiplication algorithms.

96 ► **Proposition 3 (Fact).** *From two predicates  $P$  and  $Q$ , we can build the composited predicate*  
97  *$P \odot Q$  in  $O(N^\omega)$ -time.*

## 98 4.2 Quantifier elimination: General case

99 If we encounter terms of the very restricted form like  $\exists z. P(x, z) \wedge Q(z, y)$ , we can replace it  
100 by  $(P \odot Q)(x, y)$  with eliminating the quantifier occurrence  $\exists z$ .

In other words, if we encounter more general form of  $\exists z. \dots$ , we need to translate it to some adequate form for quantifier elimination. Let us consider the following term:

$$\exists z. \left( (P(x, z) \vee P(y, z) \vee P(x, y)) \wedge (Q(x, z) \vee Q(x, y)) \wedge (R(y, z) \vee R(x, y)) \right).$$

101 We cannot directly apply our quantifier elimination strategy because  $\exists$ -quantifiers do not  
102 distribute on  $\wedge$ : i.e.,  $(\exists z. \varphi_1 \wedge \varphi_2) \neq (\exists z. \varphi_1) \wedge (\exists z. \varphi_2)$ .

To apply our quantifier elimination procedure, DNF is an adequate form. However, as well-known, converting-to-DNF translation generates an exponential-large expression in the worst case. For our example, we first translate the first  $(\dots) \wedge (\dots)$  subterm as follows:

$$\begin{aligned} & (P(x, z) \vee P(y, z) \vee P(x, y)) \wedge (Q(x, z) \vee Q(x, y)) \\ & \Rightarrow \\ & (P(x, z) \wedge Q(x, z)) \vee (P(y, z) \wedge Q(x, z)) \vee (P(x, y) \wedge Q(x, z)) \\ & \vee (P(x, z) \wedge Q(x, y)) \vee (P(y, z) \wedge Q(x, y)) \vee (P(x, y) \wedge Q(x, y)). \end{aligned}$$

103 We continue to normalize this term with  $R(y, z) \vee R(x, y)$  and it generates DNF with 12  
 104 bases of the form  $P(\_, \_) \wedge Q(\_, \_)$ .

105 Since our goal is to design an  $O(F(k, w) \cdot |\varphi| \cdot N^\omega)$ -time algorithm, we cannot adopt  
 106 converting-to-DNF transformations.

### 107 4.3 Tseytin-like (?) transformation for General Cases

108 As we have seen above, explicit translations to DNF does not work well since it may explode  
 109 given expression to an exponential size.

110 We here develop a translation inspired by Tseytin's transformation.<sup>6</sup>

実際はインスパイアされたという程でもないんですが、とはいえよく知られた構成  
 な気もするので、何かciteできるものがあればしたいという感じ。

111

Let us revisit the above example:

$$\exists z. \left( (P(x, z) \vee P(y, z) \vee P(x, y)) \wedge (Q(x, z) \vee Q(x, y)) \wedge (R(y, z) \vee R(x, y)) \right).$$

First, we generate all possible *assignments* to predicates. For our example, we have the following assignments:

	$P(x, z)$	$P(y, z)$	$P(x, y)$	$Q(x, z)$	$Q(x, y)$	$R(y, z)$	$R(x, y)$
$\alpha_1$	0	0	0	0	0	0	0
$\alpha_2$	0	0	0	0	0	0	1
$\alpha_3$	0	0	0	0	0	1	0
$\vdots$							
$\alpha$	1	0	1	0	1	0	0
$\vdots$							
$\alpha_\star$	1	1	1	1	1	1	1

112 Let  $\mathcal{A}$  be the set of all assignments.

113 Let  $\llbracket \Psi \rrbracket_\alpha$  be a boolean value obtained by evaluationg  $\Psi$  under an assignment  $\alpha$ .

114 For our example expression  $\psi$ ,  $\llbracket \psi \rrbracket_\alpha = 0$  using  $\alpha$  appearing in the above table.

115 If we change  $\alpha$  as  $\alpha(R(y, z)) \leftarrow 1$ , then  $\llbracket \psi \rrbracket_\alpha = 1$ .

116 Introducing assignment leads to the following useful proposition.

► **Proposition 4.**

$$\Psi(x, y, z) \iff \bigvee_{\alpha \in \mathcal{A}} (\alpha \wedge \llbracket \Psi \rrbracket_\alpha).$$

*Epecially, let  $\mathcal{V} = \{\alpha \in \mathcal{A} : \llbracket \Psi \rrbracket_\alpha\}$ , then we have:*

$$\Psi(x, y, z) \iff \bigvee_{\alpha \in \mathcal{V}} \alpha(x, y, z). \quad (\star)$$

By the definition of assignments,  $\alpha$  takes the following form:

$$\alpha(x, y, z) \equiv P_1(x, y) \wedge P_1(x, z) \wedge P_2(y, z) \wedge \cdots \wedge P_k(x, z).$$

<sup>6</sup> [https://en.wikipedia.org/wiki/Tseytin\\_transformation](https://en.wikipedia.org/wiki/Tseytin_transformation)

It means that the right-hand side of  $(\star)$  takes DNF. Therefore,

$$\exists z. \Psi(x, y, z) \iff (\exists z. \alpha_1(x, y, z)) \vee (\exists z. \alpha_2(x, y, z)) \vee \dots \vee (\exists z. \alpha_{|\mathcal{V}|}(x, y, z)).$$

117 It suffices to eliminating an  $\exists$ -quantifier from  $\exists z. \alpha(x, y, z)$  for an assignment  $\alpha$ .

We first divide  $\alpha(x, y, z)$  into two parts  $\alpha_z$  and  $\alpha_{-z}$  as follows:

$$\alpha(x, y, z) \equiv \underbrace{(P_1(x, z) \wedge P_2(z, x) \wedge P_1(y, z) \wedge \dots)}_{\alpha_z: z\text{-involving-terms}} \wedge \underbrace{(P_1(x, y) \wedge P_1(y, x) \wedge P_2 \wedge \dots)}_{\alpha_{-z}: z\text{-non-involving-terms}}$$

We now have the following:

$$(\exists z. \alpha(x, y, z)) \iff (\alpha_{-z}(x, y) \wedge (\exists z. \alpha_z(x, y, z))).$$

118 Finally, we transform  $\alpha_z$  in the following steps (order):

- 119 1. If  $\alpha_z$  has a term  $P(z, x)$ , we replace it with  $\tilde{P}(x, z)$  where  $\tilde{P}(a, b) = P(b, a)$ .
- 120 2. Similarly, we change terms of the form  $P(y, z)$  to  $\tilde{P}(z, y)$ .
3. At this point,

$$\alpha_z(x, y, z) \equiv \underbrace{(P_1(x, z) \wedge P_3(x, z) \wedge P_4(x, z) \wedge \dots)}_{\Psi_x} \wedge \underbrace{(P_2(z, y) \wedge P_3(z, y) \wedge P_5(z, y) \wedge \dots)}_{\Psi_y}.$$

- 121 4. Let  $\Psi_x$  (resp.  $\Psi_y$ ) be the set of predicates appearing in the above former (resp. latter) part.
- 122 5. Let us introduce two new predicates:

$$\pi(x, z) := \bigwedge_{P \in \Psi_x} P(x, z), \quad \lambda(z, y) := \bigwedge_{Q \in \Psi_y} Q(z, y).$$

6. We reach our goal:

$$\alpha_z(x, y, z) = \pi(x, z) \wedge \lambda(z, y).$$

Using the final form, we obtain the following:

$$\begin{aligned} (\exists z. \alpha(x, y, z)) &\iff (\alpha_{-z}(x, y) \wedge (\exists z. \pi(x, z) \wedge \lambda(z, y))) \\ &\iff (\alpha_{-z}(x, y) \wedge (\pi \odot \lambda)(x, y)) \\ &\iff (\alpha_{-z} \wedge (\pi \odot \lambda))(x, y) \end{aligned}$$

## 123 4.4 Considering Complexity

- 124 To eliminate an  $\exists$ -quantifier from an assignment  $\alpha$ , we introduce a new single predicate
- 125  $\alpha_{-z} \wedge (\pi \odot \lambda)$ .

Now we have a question: To eliminate the  $\exists$ -quantifier from  $\exists z. \Psi(x, y, z)$ , from the following characterization

$$(\exists z. \Psi(x, y, z)) \iff \left( \exists z. \bigvee_{\alpha \in \mathcal{V}} \alpha(x, y, z) \right) \iff \bigvee_{\alpha \in \mathcal{V}} \left( \exists z. \alpha(x, y, z) \right) \iff \bigvee_{\alpha \in \mathcal{V}} (\alpha_{-z} \wedge (\pi \odot \lambda))(x, y)$$

can we avoid to introduce  $O(2^k)$  predicates if we have  $k$ -predicates?? Please recall that each assignment is a choice from  $9k$ -literals from  $\mathcal{L}$  where

$$\mathcal{L} = \{Q(a, b) : a, b \in \{x, y, z\}, Q \in \{P_1, P_2, \dots, P_k\}\}.$$

**Yes. We can avoid introducing a large number of predicates** because we just need to introduce the following single (but large) predicate:

$$(\alpha_{-z}^1 \wedge (\pi^1 \odot \lambda^1)) \vee (\alpha_{-z}^2 \wedge (\pi^2 \odot \lambda^2)) \vee \cdots \vee (\alpha_{-z}^n \wedge (\pi^n \odot \lambda^n))$$

126 for  $\mathcal{V} = \{\alpha^1, \alpha^2, \dots, \alpha^n\}$ .

Let us consider what happens when repeatedly eliminating quantifiers from the innermost to the outermost:

$$\begin{aligned} & \exists y. \left( (\exists z. \dots) \bowtie (\exists z. \dots) \bowtie \cdots \bowtie (\exists z. \dots) \right) \\ & \Rightarrow \\ & \exists y. \left( \begin{array}{l} \text{Q. how many predicates appear in this scope?} \\ \text{A. } k + w \text{ where } w \text{ is the quantifier width of } \psi \end{array} \right) \\ & \Rightarrow \\ & \text{Eliminating } (\exists y.) \text{ introduces a single new predicate.} \end{aligned}$$

127 Since the required number of quantifier elimination (= the quantifier depth) is bounded  
128 by the size of a given expression  $|\psi|$ , we obtain the following our theorem in the end.

129 ► **Theorem 1 (Restatement).** Let  $\varphi : \mathbb{FO}_{k,w}^3$ .

130 For a given model (graph)  $\mathcal{G}$ , we can decide if  $\mathcal{G} \models \varphi$  in  $O(2^{k+w} \cdot |\varphi| \cdot N^w)$ .

## 131 5 FO2 model checking

$\mathbb{FO}^2$ の論理式  $\psi$  と、グラフ  $\mathcal{G}$  について  $\mathcal{G} \models \psi$  のモデル検査問題は  $O(|\psi| \cdot |\mathcal{G}|)$  で解ける気がします。ただし、 $|\mathcal{G}|$ は頂点数ではなく、述語（つまり辺）の定義の記述長も合わせたものです。面白そうなら書いても良いかと思うのですが、 $\mathbb{FO}^3$ の話だけにしたほうが、話がぼやけないならなくても良いかなという気がします。

Dense graphについては  $(x, y)$  の値の集合を構築する方法で  $O(|\psi| \cdot N^2)$  になります。この  $N$  は  $\mathcal{G}$  の頂点数の方です。ただ、sparse graphの時には  $N^2$  は  $|\mathcal{G}|$  について線形ではないので、そこを改良したいという感じです。

アイディアは、 $\mathbb{FO}^3$ の時と比べると、 $\exists y. P(x, y) \wedge Q(y, x) \simeq (P \odot Q)$  の計算について  $(P \odot Q)(x, x)$  の diagonal な形しか要求しないので、行列積を全部やる必要が多分なさそうとかそういう感じです。

Sparse graphの話なので、もしかすると Impagliazzo たちがやっているかもしれません。

Yo: [8] Lemma 9.1 Base Case は  $O(|\psi| \cdot |\mathcal{G}|)$  ??

## 135 6 from

136 [14]

## 137 7 Conclusion

### 138 — References —

- 139 1 Anthony Brogni and Sebastiaan J. C. Joosten. Translating first-order predicate logic to relation  
140 algebra, implemented using z3, 2023. [arXiv:2308.02513](#), doi:10.48550/arXiv.2308.02513.
- 141 2 Yijia Chen, Michael Elberfeld, and Moritz Müller. The parameterized space complexity of  
142 model-checking bounded variable first-order logic. *Logical Methods in Computer Science*,  
143 Volume 15, Issue 3, 2019. doi:10.23638/LMCS-15(3:31)2019.
- 144 3 Joerg Flum and Martin Grohe. Model-checking problems as a basis for parameterized  
145 intractability. *Logical Methods in Computer Science*, Volume 1, Issue 1, 2005. doi:10.2168/  
146 LMCS-1(1:2)2005.
- 147 4 Jörg Flum and Martin Grohe. Fixed-parameter tractability, definability, and model-checking.  
148 *SIAM Journal on Computing*, 31(1):113–145, 2001. doi:10.1137/S0097539799360768.
- 149 5 Jörg Flum and Martin Grohe. *Parameterized Complexity Theory*. Texts in Theoretical  
150 Computer Science. An EATCS Series. Springer, 2006. doi:10.1007/3-540-29953-X.
- 151 6 Markus Frick and Martin Grohe. The complexity of first-order and monadic second-order  
152 logic revisited. *Annals of Pure and Applied Logic*, 130(1-3):3–31, 2004. doi:10.1016/J.APAL.  
153 2004.01.007.
- 154 7 Jiawei Gao and Russell Impagliazzo. The fine-grained complexity of strengthenings of first-order  
155 logic, 2019. URL: <https://eccc.weizmann.ac.il/report/2019/009/>.
- 156 8 Jiawei Gao, Russell Impagliazzo, Antonina Kolokolova, and Ryan Williams. Completeness  
157 for first-order properties on sparse structures with algorithmic applications. *ACM Trans.*  
158 *Algorithms*, 15(2):23:1–23:35, 2018. doi:10.1145/3196275.
- 159 9 Yoshiki Nakamura. Expressive power and succinctness of the positive calculus of re-  
160 lations. In *RAMICS*, volume 12062 of *LNTCS*, pages 204–220. Springer, 2020. doi:  
161 10.1007/978-3-030-43520-2\_13.
- 162 10 Yoshiki Nakamura. Expressive power and succinctness of the positive calculus of binary  
163 relations. *Journal of Logical and Algebraic Methods in Programming*, 127:100760, 2022.  
164 doi:10.1016/j.jlamp.2022.100760.
- 165 11 Alfred Tarski. On the calculus of relations. *The Journal of Symbolic Logic*, 6(3):73–89, 1941.  
166 doi:10.2307/2268577.
- 167 12 Alfred Tarski and Steven Givant. *A Formalization of Set Theory without Variables*, volume 41.  
168 American Mathematical Society, 1987. doi:10.1090/coll/041.
- 169 13 Moshe Y. Vardi. On the complexity of bounded-variable queries (extended abstract). In  
170 *PODS*, PODS, page 266–276. ACM, 1995. doi:10.1145/212433.212474.
- 171 14 Ryan Williams. Faster decision of first-order graph properties. In *CSL-LICS*, page 1–6. ACM,  
172 2014. doi:10.1145/2603088.2603121.