

1 Towards Practical First-Order Model Counting

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11 — Abstract —

12 First-order model counting (FOMC) is the problem of counting the number of models of a sentence in
13 first-order logic. Since lifted inference techniques rely on reductions to variants of FOMC, the design
14 of scalable methods for FOMC has attracted attention from both theoreticians and practitioners over
15 the past decade. Recently, a new approach based on first-order knowledge compilation was proposed.
16 This approach, called CRANE, instead of simply providing the final count, generates definitions of
17 (possibly recursive) functions that can be evaluated with different arguments to compute the model
18 count for any domain size. However, this approach is not fully automated, as it requires manual
19 evaluation of the constructed functions. The primary contribution of this work is a fully automated
20 compilation algorithm, called GANTRY, which transforms the function definitions into C++ code
21 equipped with arbitrary-precision arithmetic. These additions allow the new FOMC algorithm to
22 scale to domain sizes over 500,000 times larger than the current state of the art, as demonstrated
23 through experimental results.

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For the entire paper:

- Finish adding DOIs or URLs to (non-book) references (and reformatting indentation)
(and check reference formatting) (is the part about non-book references correct?
Check previous proceedings) (maybe one more exception (graded logics)?) (I might
be done)
- Sentence vs formula: be consistent and not confusing
- 15 pages excluding references
- Go through the rest of formatting instructions (in GTD)
- Make sure all the references (e.g., to examples are still valid)
- Maybe add extra references to subsections

1 Introduction

- We would like to clarify that the main contribution of this work consists of everything needed to complement recursive function definitions with the necessary base cases. This process includes identifying the base cases and their corresponding formulas, transforming them (including applying a new smoothing procedure), and recursively reusing Crane. C++ code generation, although relatively straightforward, is crucial for the usability of the algorithm.
- Focus more on current work

First-order model counting (FOMC) is the task of determining the number of models for a sentence in first-order logic over a specified domain. The weighted variant, WFOMC, computes the total weight of these models, linking logical reasoning with probabilistic frameworks [31]. It builds upon earlier efforts in weighted model counting for propositional logic [4] and broader attempts to bridge logic and probability [15, 17, 20]. WFOMC is central to *lifted inference*, which enhances the efficiency of probabilistic calculations by exploiting symmetries [12]. Lifted inference continues to advance, with applications extending to constraint satisfaction problems [24] and probabilistic answer set programming [1]. Moreover, WFOMC has proven effective at reasoning over probabilistic databases [8] and probabilistic logic programs [18]. FOMC algorithms have also facilitated breakthroughs in discovering integer sequences [22] and developing recurrence relations for these sequences [6]. Recently, these algorithms have been extended to perform sampling tasks [32].

The complexity of FOMC is generally measured by *data complexity*, with a formula classified as *liftable* if it can be solved in polynomial time relative to the domain size [10]. While all formulas with up to two variables are known to be liftable [28, 30], Beame et al. [3] demonstrated that liftability does not extend to all formulas, identifying an unliftable formula with three variables. Recent work has further extended the liftable fragment with additional axioms [23, 27] and counting quantifiers [13], expanding our understanding of liftability.

FOMC algorithms are diverse, with approaches ranging from *first-order knowledge compilation* (FOKC) to cell enumeration [26], local search [16], and Monte Carlo sampling [7]. Among these, FOKC-based algorithms are particularly prominent, transforming formulas into structured representations such as circuits or graphs. Even when multiple algorithms are able to solve the same instance, FOKC algorithms are known to find polynomial-time solutions, where the polynomial has a lower degree compared to other approaches [6]. The recently developed ability of a FOKC algorithm to formulate solutions in terms of recursive functions [6] is also noteworthy as the only other proposed alternative is to guess recursive relations [2]. Notable examples of FOKC algorithms include FORCLIFT [31] and its successor CRANE [6].

The CRANE algorithm marked a significant step forward, expanding the range of formulas handled by FOMC algorithms. However, it had notable limitations: it required manual evaluation of function definitions to compute model counts and introduced recursive functions without proper base cases, making it more complex to use. To address these shortcomings, we present GANTRY, a fully automated FOMC algorithm that overcomes the constraints of its predecessor. GANTRY can handle domain sizes over 500,000 times larger than previous algorithms and simplifies the user experience by automatically handling base cases and compiling function definitions into efficient C++ programs.

In Section 2, we cover some preliminaries, and in Section 3, we detail all our technical contributions. Finally, in Section 4, we present our experimental results, demonstrating GANTRY’s performance compared to other FOMC algorithms, and, in Section 5, we conclude

the paper by discussing promising avenues for future work.

2 Preliminaries

- If I need more space elsewhere, shortening the preliminaries to two pages (perhaps skipping Section 2.2 altogether?)
- Adjust the introductory paragraph below to the new structure (with more subsections)

In Section 2.1, we summarise the basic principles of first-order logic. Then, in Section 2.2, we formally define (W)FOMC and discuss the distinctions between three variations of first-order logic used for FOMC. Finally, in Section 2.5, we introduce the terminology used to describe the output of the original CRANE algorithm, i.e., functions and equations that define them.

Notation

We use \mathbb{N}_0 to represent the set of non-negative integers. In both algebra and logic, we write $S\sigma$ to denote the application of a *substitution* σ to an expression S , where $\sigma = [x_1 \mapsto y_1, x_2 \mapsto y_2, \dots, x_n \mapsto y_n]$ signifies the replacement of all instances of x_i with y_i for all $i = 1, \dots, n$. Additionally, for any variable n and $a, b \in \mathbb{N}_0$, let $[a \leq n \leq b] := \begin{cases} 1 & \text{if } a \leq n \leq b \\ 0 & \text{otherwise} \end{cases}$.

2.1 First-Order Logic

In this section, we will review the basic concepts of first-order logic as they are used in FOKC algorithms. We begin by introducing the format used internally by FORCLIFT and its descendants. Afterwards, we provide a high-level description of how an arbitrary sentence in first-order logic is transformed into this internal format.

A *term* can be either a variable or a constant. An *atom* can be either $P(t_1, \dots, t_m)$ (i.e., $P(\mathbf{t})$) for some predicate P and terms t_1, \dots, t_m or $x = y$ for some terms x and y . The *arity* of a predicate is the number of arguments it takes, i.e., m in the case of the predicate P mentioned above. We write P/m to denote a predicate along with its arity. A *literal* can be either an atom (i.e., a *positive* literal) or its negation (i.e., a *negative* literal). An atom is *ground* if it contains no variables, i.e., only constants. A *clause* is of the form $\forall x_1 \in \Delta_1. \forall x_2 \in \Delta_2 \dots \forall x_n \in \Delta_n. \phi(x_1, x_2, \dots, x_n)$, where ϕ is a disjunction of literals that only contain variables x_1, \dots, x_n (and any constants). We say that a clause is a (*positive*) *unit clause* if there is only one literal with a predicate, and it is a positive literal. Finally, a *formula* is a conjunction of clauses. Throughout the paper, we will use set-theoretic notation, interpreting a formula as a set of clauses and a clause as a set of literals.

► **Remark.** Conforming with previous work [31], the definition of a clause includes universal quantifiers for all variables within. While it is possible to rewrite the entire formula with all quantifiers at the front [9], the format we describe has proven itself convenient to work with.

2.2 The Three Logics of FOMC

There are three first-order logics commonly used in FOMC: FO, C^2 , and $UFO^2 + CC$. First, FO is the input format for FORCLIFT* and its extensions CRANE† and GANTRY. Second, C^2 is often used in the literature on FASTWFOMC‡ and related methods [13, 14]. Finally, $UFO^2 + CC$ is the input format supported by the most recent implementation of FASTWFOMC [25]. All three logics are function-free, and domains are always assumed to be finite. As usual, we presuppose the *unique name assumption*, which states that two constants are equal if and only if they are the same constant [19].

In FO, each term is assigned to a *sort*, and each predicate P/n is assigned to a sequence of n sorts. Each sort has its corresponding domain. These assignments to sorts are typically left implicit and can be reconstructed from the quantifiers. For example, $\forall x, y \in \Delta. P(x, y)$ implies that variables x and y have the same sort. On the other hand, $\forall x \in \Delta. \forall y \in \Gamma. P(x, y)$ implies that x and y have different sorts, and it would be improper to write, for example, $\forall x \in \Delta. \forall y \in \Gamma. P(x, y) \vee x = y$. FO is also the only logic to support constants, formulas with more than two variables, and the equality predicate. While we do not explicitly refer to sorts in subsequent sections of this paper, the many-sorted nature of FO is paramount to the algorithms presented therein.

► **Remark.** In the case of FORCLIFT and its extensions, support for a formula as valid input does not imply that the algorithm can compile the formula into a circuit or graph suitable for lifted model counting. However, it is known that FORCLIFT compilation is guaranteed to succeed on any FO formula without constants and with at most two variables [28, 30].

Compared to FO, C^2 and $UFO^2 + CC$ lack support for constants, the equality predicate, multiple domains, and formulas with more than two variables. The advantage that C^2 brings over FO is the inclusion of *counting quantifiers*. That is, alongside \forall and \exists , C^2 supports $\exists=^k$, $\exists \leq^k$, and $\exists \geq^k$ for any positive integer k . For example, $\exists=^1 x. \phi(x)$ means that there exists *exactly one* x such that $\phi(x)$, and $\exists \leq^2 x. \phi(x)$ means that there exist *at most two* such x . $UFO^2 + CC$, on the other hand, does not support any existential quantifiers but instead incorporates (*equality*) *cardinality constraints*. For example, $|P| = 3$ constrains all models to have *precisely three positive literals with the predicate P* .

2.3 First-Order Model Counting

In this section, we will formally define FOMC and its weighted variant. Note that, although this work focuses on FOMC, for sentences with existential quantifiers, computing the FOMC using GANTRY requires the use of WFOMC. For such sentences, preprocessing (described in Section 2.4) introduces predicates with non-unary weights that must be accounted for to compute the correct model count.

► **Definition 1** (Structure, model). *Let ϕ be a formula in FO. For each predicate P/n in ϕ , let $(\Delta_i^P)_{i=1}^n$ be a list of the corresponding domains. Let σ be a map from the domains of ϕ to their interpretations as finite sets such that the sets are pairwise disjoint, and the constants in ϕ are included in the corresponding domains. A structure of ϕ is a set M of ground literals defined by adding to M either $P(\mathbf{t})$ or $\neg P(\mathbf{t})$ for every predicate P/n in ϕ and n -tuple $\mathbf{t} \in \prod_{i=1}^n \sigma(\Delta_i^P)$. A structure is a model if it makes ϕ valid.*

* <https://github.com/UCLA-StarAI/Forclift>

† <https://doi.org/10.5281/zenodo.8004077>

‡ <https://github.com/jan-toth/FastWFOMC.jl>

148 ► **Example 2** (Counting bijections). Let us consider the following formula (previously examined
 149 by Dilkas and Belle [6]) that defines predicate P as a bijection between two domains Γ and
 150 Δ :

$$\begin{aligned}
 & (\forall x \in \Gamma. \exists y \in \Delta. P(x, y)) \wedge \\
 & (\forall y \in \Delta. \exists x \in \Gamma. P(x, y)) \wedge \\
 & (\forall x \in \Gamma. \forall y, z \in \Delta. P(x, y) \wedge P(x, z) \Rightarrow y = z) \wedge \\
 & (\forall x, z \in \Gamma. \forall y \in \Delta. P(x, y) \wedge P(z, y) \Rightarrow x = z).
 \end{aligned} \tag{1}$$

152 Let σ be defined as $\sigma(\Gamma) := \{1, 2\}$, and $\sigma(\Delta) := \{a, b\}$. Then Formula (1) has two models:

$$\{P(1, a), P(2, b), \neg P(1, b), \neg P(2, a)\} \quad \text{and} \quad \{P(1, b), P(2, a), \neg P(1, a), \neg P(2, b)\}.$$

154 ► **Remark.** The distinctness of domains is important in two ways. First, in terms of
 155 expressiveness, a clause such as $\forall x \in \Delta. P(x, x)$ is valid if predicate P is defined over two
 156 copies of the same domain and invalid otherwise. Second, having more distinct domains
 157 makes the problem more decomposable for the FOKC algorithm. With distinct domains, the
 158 algorithm can make assumptions or deductions about, e.g., the first domain of predicate P
 159 without worrying how (or if) they apply to the second domain.

160 ► **Definition 3** (WFOMC instance). A WFOMC instance *comprises*: a formula ϕ in FO, two
 161 (rational) weights $w^+(P)$ and $w^-(P)$ assigned to each predicate P in ϕ , and σ as described
 162 in Definition 1. Unless specified otherwise, we assume all weights to be equal to 1.

163 ► **Definition 4** (WFOMC [31]). Given a WFOMC instance (ϕ, w^+, w^-, σ) as in Definition 3,
 164 the (symmetric) weighted first-order model count (WFOMC) of ϕ is

$$\sum_{M \models \phi} \prod_{P(\mathbf{t}) \in M} w^+(P) \prod_{\neg P(\mathbf{t}) \in M} w^-(P), \tag{2}$$

166 where the sum is over all models of ϕ .

167 2.4 Crane and First-Order Knowledge Compilation

168 As our work builds on CRANE, in this section we will briefly outline the steps CRANE goes
 169 through to compile an FO formula into a set of function definitions. We divide the inner
 170 workings of the algorithm into two stages: preprocessing and compilation.

171 2.4.1 Preprocessing

172 The goal of this stage is to transform an arbitrary FO formula into the format described in
 173 Section 2.1, most importantly by eliminating existential quantifiers. For example, the first
 174 conjunct of Formula (1), i.e.,

$$\forall x \in \Gamma. \exists y \in \Delta. P(x, y) \tag{3}$$

176 is transformed into

$$\begin{aligned}
 & (\forall x \in \Gamma. Z(x)) \wedge \\
 & (\forall x \in \Gamma. \forall y \in \Delta. Z(x) \vee \neg P(x, y)) \wedge \\
 & (\forall x \in \Gamma. S(x) \vee Z(x)) \wedge \\
 & (\forall x \in \Gamma. \forall y \in \Delta. S(x) \vee \neg P(x, y)),
 \end{aligned} \tag{4}$$

178 where $Z/1$ and $S/1$ are two new predicates with $w^-(S) = -1$. One can check that the
 179 WFOMC of Formulas (3) and (4) is the same.

2.4.2 Compilation

At this stage, the preprocessed formula is compiled into the set \mathcal{E} of equations and two auxiliary maps \mathcal{F} and \mathcal{D} . \mathcal{F} maps function names to formulas, and \mathcal{D} maps function names and argument indices to domains. \mathcal{E} can contain any number of functions, one of which (which we will always denote by f) represents the solution to the FOMC problem. To compute the FOMC for particular domain sizes, f must be evaluated with those domain sizes as arguments. \mathcal{D} records this correspondence between function arguments and domains.

► **Example 5.** CRANE compiles Formula (1) for bijection counting into

$$\mathcal{E} = \left\{ \begin{array}{l} f(m, n) = \sum_{l=0}^n \binom{n}{l} (-1)^{n-l} g(l, m), \\ g(l, m) = \sum_{k=0}^m [0 \leq k \leq 1] \binom{m}{k} g(l-1, m-k) \end{array} \right\};$$

$$\mathcal{D} = \{ (f, 1) \mapsto \Gamma, (f, 2) \mapsto \Delta, (g, 1) \mapsto \Delta^\top, (g, 2) \mapsto \Gamma \},$$

where Δ^\top is a newly introduced domain. (We omit the definition of \mathcal{F} as the formulas can get quite verbose.) To compute the number of bijections between two sets of cardinality 3, one would evaluate $f(3, 3)$, however, the definition of g is incomplete: g is a recursive function presented without any base cases. \mathcal{D} encodes that in $f(m, n)$, m and n represent $|\Gamma|$ and $|\Delta|$, respectively. Similarly, in $g(l, m)$, l represents $|\Delta^\top|$, and m represents $|\Gamma|$.

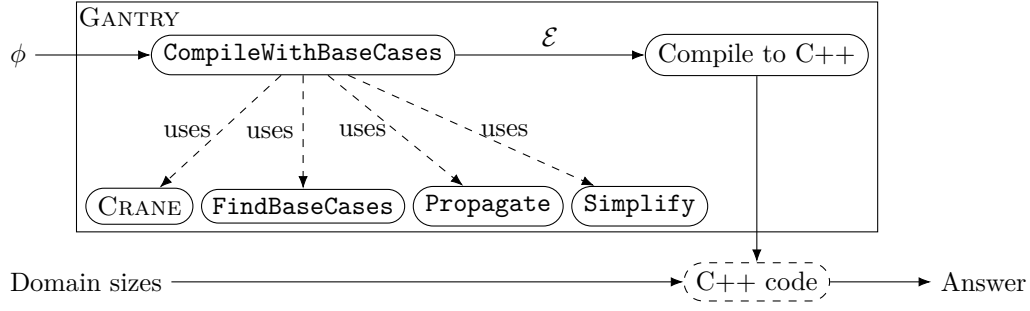
Compilation is performed primarily by applying (*compilation*) rules to formulas. CRANE has two modes depending on how the algorithm chooses which compilation rule to apply to a formula (in case several alternatives are available). The first option is to use greedy search: there is a list of rules, and the first applicable rule is the one that gets used, disregarding all the others. The second option is to use a combination of greedy and *breadth-first search* (BFS). That is, each compilation rule is identified as either greedy or non-greedy. Greedy rules are applied as soon as possible at any stage of the compilation process. BFS is executed over all applicable non-greedy rules, identifying the solution that can be constructed using the smallest number of such rules.

2.5 Algebra

In this paper, we use both logical and algebraic constructs. While the rest of Section 2 focused on the former, this section describes the latter. We write **expr** for an arbitrary algebraic expression. In the context of algebra, a *constant* is a non-negative integer. Likewise, a *variable* can either be a parameter of a function or a variable introduced through summation, such as i in the expression $\sum_{i=1}^n \mathbf{expr}$. A *function call* is $f(x_1, \dots, x_n)$ (or $f(\mathbf{x})$ for short), where f is an n -ary function, and each x_i is an algebraic expression consisting of variables and constants. A (function) *signature* is function call that contains only variables. Given two function calls $f(\mathbf{x})$ and $f(\mathbf{y})$, we say that $f(\mathbf{y})$ *matches* $f(\mathbf{x})$ if $x_i = y_i$ whenever $x_i, y_i \in \mathbb{N}_0$. An *equation* is $f(\mathbf{x}) = \mathbf{expr}$, where $f(\mathbf{x})$ is a function call.

► **Definition 6** (Base case). *Let $f(\mathbf{x})$ be a function call where each x_i is either a constant or a variable. Then function call $f(\mathbf{y})$ is a base case of $f(\mathbf{x})$ if $f(\mathbf{y}) = f(\mathbf{x})\sigma$, where σ is a substitution that replaces one or more x_i with a constant.*

► **Example 7.** In equation $f(m, n) = f(m-1, n) + nf(m-1, n-1)$, the only constant is 1, and the variables are m and n . The equation contains three function calls: one on the



■ **Figure 1** The outline of using GANTRY to compute the model count of a formula ϕ . First, the formula is compiled into a set of equations, which are then used to create a C++ program. This program can be executed with different command line arguments to calculate the model count of ϕ for different domain sizes. To accomplish this, the `CompileWithBaseCases` procedure uses CRANE, algebraic simplification techniques (denoted as `Simplify`), and two other auxiliary procedures.

219 left-hand side (LHS), and two on the right-hand side (RHS). The function call on the LHS is
 220 a signature. Function calls such as $f(4, n)$, $f(m, 0)$, and $f(8, 1)$ are all considered base cases
 221 of $f(m, n)$ (only some of which are useful).

222 3 Technical Contributions

223 Figure 1 provides an overview of GANTRY’s workflow. Below we briefly describe and motivate
 224 each procedure before going into more detail in the corresponding subsection.

225 `CompileWithBaseCases` (see Section 3.1), the core procedure of GANTRY, is responsible
 226 for completing the function definitions produced by CRANE with the necessary base cases.
 227 To do so, it may recursively call itself (and CRANE) on other formulas. We prove that the
 228 number of such recursive calls is upper bounded by the number of domains in the formula.

229 Section 3.1 also describes the `Simplify` procedure for algebraic simplification. It is crucial
 230 for simplifying, e.g., a sum of n terms, only two of which are non-zero. More generally, the
 231 equations returned by CRANE often benefit from easy-to-detect algebraic simplifications such
 232 as $0 \cdot \text{anything} = 0$ and $\text{anything}^0 = 1$.

233 `FindBaseCases` (described in Section 3.2) inspects a set of equations to identify a sufficient
 234 set of base cases for a given set of equations. We prove that the returned set of base cases is
 235 sufficient, and the evaluation of the resulting function definitions will never get stuck in an
 236 infinite loop.

237 Section 3.3 introduces the `Propagate` procedure that takes a formula ϕ , a domain Δ ,
 238 and $n \in \mathbb{N}_0$. It returns ϕ transformed with the assumption that $|\Delta| = n$, introducing n new
 239 constants and removing all variables quantified over Δ . For example, when computing a
 240 base case such as $f(0, y)$, `Propagate` will significantly simplify ϕ with the assumption that
 241 the domain associated with the first parameter of f (i.e., $\mathcal{D}(f, 1)$) is empty. When run on
 242 this simplified formula, `CompileWithBaseCases` will return the equations for the base case
 243 $f(0, y)$.

244 Section 3.4 describes a new kind of *smoothing* used to ensure that `Propagate` preserves
 245 the correct model count. Smoothing is a well-known technique in knowledge compilation
 246 algorithms for propositional model counting [5]. Although it has been applied to FOMC
 247 before [31], our setting requires a novel approach.

248 `CompileWithBaseCases`, together with the other procedures outlined above, return a set
 249 of equations that fully cover the base cases of all recursive functions. While these equations

Algorithm 1 `CompileWithBaseCases(ϕ)

---`

Input: formula ϕ
Output: set \mathcal{E} of equations

```

1  $(\mathcal{E}, \mathcal{F}, \mathcal{D}) \leftarrow \text{CRANE}(\phi);$ 
2  $\mathcal{E} \leftarrow \text{Simplify}(\mathcal{E});$ 
3 foreach base case  $f(\mathbf{x}) \in \text{FindBaseCases}(\mathcal{E})$  do
4    $\psi \leftarrow \mathcal{F}(f);$ 
5   foreach index  $i$  such that  $x_i \in \mathbb{N}_0$  do  $\psi \leftarrow \text{Propagate}(\psi, \mathcal{D}(f, i), x_i);$ 
6    $\mathcal{E} \leftarrow \mathcal{E} \cup \text{CompileWithBaseCases}(\psi);$ 

```

can be interesting and valuable in their own right, the users of FOMC algorithms typically expect a numerical answer. Thus, Section 3.5 describes how these equations are compiled into a C++ program that can be executed with different command-line arguments to compute the model count for different combinations of domain sizes.

3.1 Completing the Definitions of Functions

Algorithm 1 presents our overall approach for compiling a formula into equations that include the necessary base cases. To begin, we use `CRANE` to compile the formula into the three components: \mathcal{E} , \mathcal{F} , and \mathcal{D} (as described in Section 2.4.2). After some algebraic simplifications (described below), \mathcal{E} is passed to the `FindBaseCases` procedure (see Section 3.2). For each base case $f(\mathbf{x})$, we retrieve the logical formula $\mathcal{F}(f)$ associated with the function name f and simplify it using the `Propagate` procedure (explained in detail in Section 3.3). We do this by iterating over all indices of \mathbf{x} , where x_i is a constant, and using `Propagate` to simplify ψ by assuming that domain $\mathcal{D}(f, i)$ has size x_i . Finally, on line 6, `CompileWithBaseCases` recurses on these simplified formulas and adds the resulting base case equations to \mathcal{E} .

Simplify

The main responsibility of the `Simplify` procedure is to handle the algebraic pattern $\sum_{m=0}^n [a \leq m \leq b] f(m)$. Here: n is a variable, $a, b \in \mathbb{N}_0$ are constants, and f is an expression that may depend on m . `Simplify` transforms this pattern into $f(a) + f(a+1) + \dots + f(\min\{n, b\})$.

► **Example 8.** Let us return to the bijection-counting problem from Example 2 and its initial solution described in Example 5. `Simplify` transforms $g(l, m) = \sum_{k=0}^m [0 \leq k \leq l] \binom{m}{k} g(l-1, m-k)$ into $g(l, m) = g(l-1, m) + mg(l-1, m-1)$. Then `FindBaseCases` identifies two base cases: $g(0, m)$ and $g(l, 0)$. In both cases, `CompileWithBaseCases` recurses on the formula $\mathcal{F}(g)$ simplified by assuming that one of the domains is empty. In the first case, we recurse on the formula $\forall x \in \Gamma. S(x) \vee \neg S(x)$, where S is a predicate introduced by preprocessing with weights $w^+(S) = 1$ and $w^-(S) = -1$. Hence, we obtain the base case $g(0, m) = 0^m$. In the case of $g(l, 0)$, `Propagate`($\psi, \Gamma, 0$) returns an empty formula, resulting in $g(l, 0) = 1$. While these base cases overlap when $l = m = 0$, they remain consistent since $0^0 = 1$.

We end this section by proving that `CompileWithBaseCases` terminates since each recursive call on line 6 reduces the number of domains in the formula.

► **Theorem 9.** *Given any FO formula ϕ , `CompileWithBaseCases`(ϕ) terminates.*

Algorithm 2 FindBaseCases(\mathcal{E})

Input: set \mathcal{E} of equations**Output:** set \mathcal{B} of base cases

```

1  $\mathcal{B} \leftarrow \emptyset$ ;
2 foreach function call  $f(\mathbf{y})$  on the RHS of an equation in  $\mathcal{E}$  do
3    $\mathbf{x} \leftarrow$  the parameters of  $f$  in its definition;
4   foreach  $y_i \in \mathbf{y}$  do
5     if  $y_i \in \mathbb{N}_0$  then  $\mathcal{B} \leftarrow \mathcal{B} \cup \{f(\mathbf{x})[x_i \mapsto y_i]\}$ ;
6     else if  $y_i = x_i - c_i$  for some  $c_i \in \mathbb{N}_0$  then
7       for  $j \leftarrow 0$  to  $c_i - 1$  do  $\mathcal{B} \leftarrow \mathcal{B} \cup \{f(\mathbf{x})[x_i \mapsto j]\}$ ;

```

282 To prove the theorem, we rely on two observations about the algorithms presented in
 283 Sections 3.2 and 3.3.

284 ► **Observation 10.** *Each base case returned by FindBaseCases has at least one constant (in*
 285 *line with Definition 6).*

286 ► **Observation 11.** *For any formula ϕ , domain Δ , and $n \in \mathbb{N}_0$, Propagate(ϕ, Δ, n) returns*
 287 *a formula with no variables quantified over Δ .*

288 **Proof.** We proceed by induction on the number of domains that variables in ϕ are quantified
 289 over. If there are no domains, then ϕ is essentially a propositional formula, and CRANE
 290 compiles it into an equation of the form $f = \text{expr}$ with no ‘function calls’. Suppose that
 291 CompileWithBaseCases terminates for all formulas with at most $n \in \mathbb{N}_0$ domains. Let ϕ be
 292 a formula with $n + 1$ domains. By Observation 10, each base case on line 3 of Algorithm 1
 293 has at least one constant. Therefore, by Observation 11, after line 5, formula ψ has at most
 294 n domains. Thus, line 6 terminates by the inductive hypothesis, completing the proof that
 295 CompileWithBaseCases terminates for an arbitrary formula with $n + 1$ domains. ◀

296 3.2 Identifying a Sufficient Set of Base Cases

297 Algorithm 2 summarises the implementation of FindBaseCases. It considers two types of
 298 arguments when a function f calls itself recursively: constants and arguments of the form
 299 $x_i - c_i$. Here, c_i is a constant, and x_i is the i -th argument of the signature of f . When the
 300 argument is a constant c_i , a base case with c_i is added. In the second case, a base case is
 301 added for each constant from 0 up to (but not including) c_i .

302 ► **Example 12.** Consider the recursive function g from Example 5. FindBaseCases iterates
 303 over two function calls: $g(l - 1, m)$ and $g(l - 1, m - 1)$. The former produces the base case
 304 $g(0, m)$, while the latter produces both $g(0, m)$ and $g(l, 0)$.

305 It can be shown that the base cases identified by FindBaseCases are sufficient for the
 306 algorithm to terminate.⁴ For the remainder of this section, let \mathcal{E} denote the equations
 307 returned by CompileWithBaseCases.

⁴ Note that characterising the fine-grained complexity of the solutions found by GANTRY or other FOMC algorithms is an emerging area of research. These questions have been partially addressed in previous work [6, 25] and are orthogonal to the goals of this section.

308 ► **Theorem 13.** *Let f be an n -ary function in \mathcal{E} and $\mathbf{x} \in \mathbb{N}_0^n$. Then the evaluation of $f(\mathbf{x})$*
 309 *terminates.*

310 We prove Theorem 13 using double induction. First, we apply induction to the number
 311 of functions in \mathcal{E} . Then, we use induction on the arity of the ‘last’ function in \mathcal{E} according to
 312 some topological ordering. We begin with a few observations that stem from previous [6, 31]
 313 and this work.

314 ► **Observation 14.** *For each function f , there is precisely one equation $e \in \mathcal{E}$ with $f(\mathbf{x})$*
 315 *on the LHS where all x_i ’s are variables (i.e., e is not a base case). We refer to e as the*
 316 *definition of f .*

317 ► **Observation 15.** *There is a topological ordering of all functions $(f_i)_i$ in \mathcal{E} such that*
 318 *equations in \mathcal{E} with f_i on the LHS do not contain function calls to f_j with $j > i$. This*
 319 *condition prevents mutual recursion and other cyclic scenarios.*

320 ► **Observation 16.** *For each equation $(f(\mathbf{x}) = \text{expr}) \in \mathcal{E}$, the evaluation of expr terminates*
 321 *when provided with the values of all relevant function calls.*

322 ► **Corollary 17.** *If f is a non-recursive function with no function calls on the RHS of its*
 323 *definition, then the evaluation of any function call $f(\mathbf{x})$ terminates.*

324 ► **Observation 18.** *For each equation $(f(\mathbf{x}) = \text{expr}) \in \mathcal{E}$, if \mathbf{x} contains only constants, then*
 325 *expr cannot include any function calls to f .*

326 Additionally, we introduce an assumption about the structure of recursion.

327 ► **Assumption 19.** *For each equation $(f(\mathbf{x}) = \text{expr}) \in \mathcal{E}$, every recursive function call*
 328 *$f(\mathbf{y}) \in \text{expr}$ satisfies the following:*

329 ■ *Each y_i is either $x_i - c_i$ or c_i for some constant c_i .*

330 ■ *There exists i such that $y_i = x_i - c_i$ for some $c_i > 0$.*

331 Finally, we assume a particular order of evaluation for function calls using the equations
 332 in \mathcal{E} . Specifically, we assume that base cases are considered before the recursive definition.
 333 The exact order in which base cases are considered is immaterial.

334 ► **Assumption 20.** *When multiple equations in \mathcal{E} match a function call $f(\mathbf{x})$, preference is*
 335 *given to an equation with the most constants on its LHS.*

336 With the observations and assumptions mentioned above, we are ready to prove Theo-
 337 rem 13. For readability, we divide the proof into several lemmas of increasing generality.

338 ► **Lemma 21.** *Assume that \mathcal{E} consists of just one unary function f . Then the evaluation of*
 339 *a function call $f(x)$ terminates for any $x \in \mathbb{N}_0$.*

340 **Proof.** If $f(x)$ is captured by a base case, then its evaluation terminates by Corollary 17
 341 and Observation 18. If f is not recursive, the evaluation of $f(x)$ terminates by Corollary 17.

342 Otherwise, let $f(y)$ be an arbitrary function call on the RHS of the definition of $f(x)$. If
 343 y is a constant, then there is a base case for $f(y)$. Otherwise, let $y = x - c$ for some $c > 0$.
 344 Then there exists $k \in \mathbb{N}_0$ such that $0 \leq x - kc \leq c - 1$. So, after k iterations, the sequence of
 345 function calls $f(x), f(x - c), f(x - 2c), \dots$ will be captured by the base case $f(x \bmod c)$. ◀

346 ► **Lemma 22.** *Generalising Lemma 21, let \mathcal{E} be a set of equations for one n -ary function f*
 347 *for some $n \geq 1$. Then the evaluation of $f(\mathbf{x})$ terminates for any $\mathbf{x} \in \mathbb{N}_0^n$.*

Algorithm 3 $\text{Propagate}(\phi, \Delta, n)$

Input: formula ϕ , domain Δ , $n \in \mathbb{N}_0$
Output: formula ϕ'

```

1  $\phi' \leftarrow \emptyset$ ;
2 if  $n = 0$  then
3   foreach clause  $C \in \phi$  do
4     if  $\Delta \notin \text{Doms}(C)$  then  $\phi' \leftarrow \phi' \cup \{C\}$ ;
5     else
6        $C' \leftarrow \{l \in C \mid \Delta \notin \text{Doms}(l)\}$ ;
7       if  $C' \neq \emptyset$  then
8          $l \leftarrow$  an arbitrary literal in  $C'$ ;
9          $\phi' \leftarrow \phi' \cup \{C' \cup \{\neg l\}\}$ ;
10 else
11    $D \leftarrow$  a set of  $n$  new constants in  $\Delta$ ;
12   foreach clause  $C \in \phi$  do
13      $(x_i)_{i=1}^m \leftarrow$  the variables in  $C$  with domain  $\Delta$ ;
14     if  $m = 0$  then  $\phi' \leftarrow \phi' \cup \{C\}$ ;
15     else  $\phi' \leftarrow \phi' \cup \{C[x_1 \mapsto c_1, \dots, x_m \mapsto c_m] \mid (c_i)_{i=1}^m \in D^m\}$ ;

```

348 **Proof.** If f is non-recursive, the evaluation of $f(\mathbf{x})$ terminates by previous arguments. We
 349 proceed by induction on n , with the base case of $n = 1$ handled by Lemma 21. Assume that
 350 $n > 1$. Any base case of f can be seen as a function of arity $n - 1$, since one of the parameters
 351 is fixed. Thus, the evaluation of any base case terminates by the inductive hypothesis. It
 352 remains to show that the evaluation of the recursive equation for f terminates, but that
 353 follows from Observation 16. \blacktriangleleft

354 **Proof of Theorem 13.** We proceed by induction on the number of functions n . The base
 355 case of $n = 1$ is handled by Lemma 22. Let $(f_i)_{i=1}^n$ be some topological ordering of these
 356 $n > 1$ functions. If $f = f_j$ for $j < n$, then the evaluation of $f(\mathbf{x})$ terminates by the inductive
 357 hypothesis since f_j cannot call f_n by Observation 15. Using the inductive hypothesis that
 358 all function calls to f_j (with $j < n$) terminate, the proof proceeds similarly to the Proof of
 359 Lemma 22. \blacktriangleleft

3.3 Propagating Domain Size Assumptions

361 Algorithm 3, called **Propagate**, modifies the formula ϕ based on the assumption that $|\Delta| = n$.
 362 When $n = 0$, some clauses become vacuously satisfied and can be removed. When $n > 0$,
 363 partial grounding is performed by replacing all variables quantified over Δ with constants.
 364 (None of the formulas examined in this work had $n > 1$.) Algorithm 3 handles these two
 365 cases separately. For a literal or a clause C , the set of corresponding domains is denoted as
 366 $\text{Doms}(C)$.

367 In the case of $n = 0$, there are three types of clauses to consider:

- 368 1. those that do not mention Δ ,
- 369 2. those in which every literal contains variables quantified over Δ , and
- 370 3. those that have some literals with variables quantified over Δ and some without.

371 Clauses of Type 1 are transferred to the new formula ϕ' without any changes. For clauses of
 372 Type 2, C' is empty, so these clauses are filtered out. As for clauses of Type 3, a new kind of
 373 smoothing is performed, which will be explained in Section 3.4.

374 In the case of $n > 0$, n new constants are introduced. Let C be an arbitrary clause in ϕ ,
 375 and let $m \in \mathbb{N}_0$ be the number of variables in C quantified over Δ . If $m = 0$, C is added
 376 directly to ϕ' . Otherwise, a clause is added to ϕ' for every possible combination of replacing
 377 the m variables in C with the n new constants.

378 ► **Example 23.** Let $C \equiv \forall x \in \Gamma. \forall y, z \in \Delta. \neg P(x, y) \vee \neg P(x, z) \vee y = z$. Then $\text{Doms}(C) =$
 379 $\text{Doms}(\neg P(x, y)) = \text{Doms}(\neg P(x, z)) = \{\Gamma, \Delta\}$, and $\text{Doms}(y = z) = \{\Delta\}$. A call to
 380 **Propagate**($\{C\}, \Delta, 3$) would result in the following formula with nine clauses:

$$\begin{aligned}
 381 \quad & (\forall x \in \Gamma. \neg P(x, c_1) \vee \neg P(x, c_1) \vee c_1 = c_1) \wedge \\
 382 \quad & (\forall x \in \Gamma. \neg P(x, c_1) \vee \neg P(x, c_2) \vee c_1 = c_2) \wedge \\
 & \vdots \\
 383 \quad & \\
 384 \quad & (\forall x \in \Gamma. \neg P(x, c_3) \vee \neg P(x, c_3) \vee c_3 = c_3).
 \end{aligned}$$

385 Here, c_1 , c_2 , and c_3 are the new constants.

386 **3.4 Smoothing the Base Cases**

387 Smoothing modifies a circuit to reintroduce eliminated atoms, ensuring the correct model
 388 count [5, 31]. In this section, we describe a similar process performed on lines 7–9 of
 389 Algorithm 3. Line 7 checks if smoothing is necessary, and lines 8 and 9 execute it. If the
 390 condition on line 7 is not satisfied, the clause is not smoothed but omitted.

391 Suppose **Propagate** is called with arguments $(\phi, \Delta, 0)$, i.e., we are simplifying the formula
 392 ϕ by assuming that the domain Δ is empty. Informally, if there is a predicate P in ϕ unrelated
 393 to Δ , smoothing preserves all occurrences of P even if all clauses with P become vacuously
 394 satisfied.

395 ► **Example 24.** Let ϕ be

$$396 \quad (\forall x \in \Delta. \forall y, z \in \Gamma. Q(x) \vee P(y, z)) \wedge \tag{5}$$

$$397 \quad (\forall y, z \in \Gamma'. P(y, z)), \tag{6}$$

398 where $\Gamma' \subseteq \Gamma$ is a domain introduced by a compilation rule. It should be noted that P , as a
 399 relation, is a subset of $\Gamma \times \Gamma$.

400 Now, let us reason manually about the model count of ϕ when $\Delta = \emptyset$. Predicate Q can
 401 only take one value, $Q = \emptyset$. The value of P is fixed over $\Gamma' \times \Gamma'$ by Clause (6), but it can vary
 402 freely over $(\Gamma \times \Gamma) \setminus (\Gamma' \times \Gamma')$ since Clause (5) is vacuously satisfied by all structures. Therefore,
 403 the correct FOMC should be $2^{|\Gamma|^2 - |\Gamma'|^2}$. However, without line 9, **Propagate** would simplify
 404 ϕ to $\forall y, z \in \Gamma'. P(y, z)$. In this case, P is a subset of $\Gamma' \times \Gamma'$. This simplified formula has
 405 only one model: $\{P(y, z) \mid y, z \in \Gamma'\}$. By including line 9, **Propagate** transforms ϕ to

$$406 \quad (\forall y, z \in \Gamma. P(y, z) \vee \neg P(y, z)) \wedge (\forall y, z \in \Gamma'. P(y, z)),$$

407 which retains the correct model count.

408 It is worth mentioning that the choice of l on line 8 of Algorithm 3 is inconsequential
 409 because any choice achieves the same goal: constructing a tautological clause that retains
 410 the literals in C' .

■ **Algorithm 4** A sketch of the C++ program for the equations in Example 5, particularly highlighting the recursive definition of function g .

```

1 initialise  $\text{Cache}_{g(0,m)}$ ,  $\text{Cache}_{g(l,0)}$ ,  $\text{Cache}_g$ , and  $\text{Cache}_f$ ;
2 Function  $g_{0,m}(m)$ : ...
3 Function  $g_{l,0}(l)$ : ...
4 Function  $g(l, m)$ :
5   if  $(l, m) \in \text{Cache}_g$  then return  $\text{Cache}_g(l, m)$ ;
6   if  $l = 0$  then return  $g_{0,m}(m)$ ;
7   if  $m = 0$  then return  $g_{l,0}(l)$ ;
8    $r \leftarrow g(l-1, m) + mg(l-1, m-1)$ ;
9    $\text{Cache}_g(l, m) \leftarrow r$ ;
10  return  $r$ ;
11 Function  $f(m, n)$ : ...
12 Function Main:
13    $(m, n) \leftarrow \text{ParseCommandLineArguments}()$ ;
14   return  $f(m, n)$ ;

```

3.5 Generating C++ Code

In this section, we will describe the final step of GANTRY as outlined in Figure 1, i.e., translating the set of equations \mathcal{E} into C++ code. Recall that this step is crucial for the usability of the algorithm, otherwise function definitions would remain purely mathematical, with no convenient way to compute the model count for particular domain sizes. Once a C++ program is produced, it can be executed with different command-line arguments to compute the model count of the formula for various domain sizes.

See Algorithm 4 for the typical structure of a generated C++ program. Each equation in \mathcal{E} is compiled into a C++ function, along with a separate cache for memoisation. Hence, Algorithm 4 has a function and a cache for $f(\cdot, \cdot)$, $g(\cdot, \cdot)$, $g(\cdot, 0)$, and $g(0, \cdot)$. The implementation of an equation consists of three parts. First (on line 5), we check if the arguments are already present in the corresponding cache. If so, we simply return the cached value. Second (on lines 6 and 7), for each base case, we check if the arguments match the base case (as defined in Section 2.5). If so, the arguments are redirected to the C++ function for that base case. Finally, if none of the above cases apply, we evaluate the arguments based on the expression on the RHS of the equation, store the result in the cache, and return it.

4 Experimental Evaluation

Expand the section, adding a more thorough and independent practical assessment

Our empirical evaluation sought to compare the runtime performance of GANTRY with the current state of the art, namely FASTWFOMC and FORCLIFT. It is worth remarking that FORCLIFT does not support arbitrary precision, and returns error for cases that requires arbitrary precision reasoning. Our experiments involve two versions of GANTRY: GANTRY-GREEDY and GANTRY-BFS. Like its predecessor, GANTRY has two modes for applying compilation rules to formulas: one that uses a greedy search algorithm similar to FORCLIFT and another that combines greedy and BFS.

The experiments were conducted using an Intel Skylake 2.4 GHz CPU with 188 GiB of

memory and CentOS 7. C++ programs were compiled using the Intel C++ Compiler 2020u4. FASTWFOMC ran on Julia 1.10.4, while the other algorithms were executed on the Java Virtual Machine 1.8.0_201.

4.1 Benchmarks

- More benchmarks from NOT my work
- Make sure it's clear what the 'raw' instances are
- Don't emphasise that the benchmarks come from my previous work
- Integrate the example below into the text, possibly moving irrelevant details (such as the formulas in other logics) to supplementary material

► **Example 25** (Counting functions). To define predicate P as a function from a domain Δ to itself, in \mathcal{C}^2 one would write $\forall x \in \Delta. \exists^=1 y \in \Delta. P(x, y)$. In $\text{UFO}^2 + \text{CC}$, the same could be written as

$$(\forall x, y \in \Delta. S(x) \vee \neg P(x, y)) \wedge (|P| = |\Delta|), \quad (7)$$

where $w^-(S) = -1$. Although Formula (7) has more models compared to its counterpart in \mathcal{C}^2 , the negative weight $w^-(S) = -1$ makes some of the terms in Equation (2) cancel out.

Equivalently, in FO we would write

$$(\forall x \in \Gamma. \exists y \in \Delta. P(x, y)) \wedge (\forall x \in \Gamma. \forall y, z \in \Delta. P(x, y) \wedge P(x, z) \Rightarrow y = z). \quad (8)$$

The first clause asserts that each x must have at least one corresponding y , while the second statement adds the condition that if x is mapped to both y and z , then y must equal z . It is important to note that Formula (8) is written with two domains instead of just one. However, we can still determine the correct number of functions by assuming that the sizes of Γ and Δ are equal. This formulation, as observed by Dilkas and Belle [6], can prove beneficial in enabling FOKC algorithms to find efficient solutions.

We compare these algorithms using three benchmarks from previous studies. The first benchmark is the function-counting problem from Example 25, previously examined by Dilkas and Belle [6]. The second benchmark is a variant of the well-known 'Friends and Smokers' Markov logic network [21, 29]. In \mathcal{C}^2 , FO , and $\text{UFO}^2 + \text{CC}$, this problem can be formulated as

$$(\forall x, y \in \Delta. S(x) \wedge F(x, y) \Rightarrow S(y)) \wedge (\forall x \in \Delta. S(x) \Rightarrow C(x))$$

or, equivalently, in conjunctive normal form as

$$(\forall x, y \in \Delta. S(y) \vee \neg S(x) \vee \neg F(x, y)) \wedge (\forall x \in \Delta. C(x) \vee \neg S(x)).$$

Finally, we include the bijection-counting problem previously utilised by Dilkas and Belle [6]. Its formulation in FO is described in Example 2. The equivalent formula in \mathcal{C}^2 is

$$(\forall x \in \Delta. \exists^=1 y \in \Delta. P(x, y)) \wedge (\forall y \in \Delta. \exists^=1 x \in \Delta. P(x, y)).$$

Similarly, in $\text{UFO}^2 + \text{CC}$ the same formula can be written as

$$(\forall x, y \in \Delta. R(x) \vee \neg P(x, y)) \wedge (\forall x, y \in \Delta. S(x) \vee \neg P(y, x)) \wedge (|P| = |\Delta|),$$

where $w^-(R) = w^-(S) = -1$.

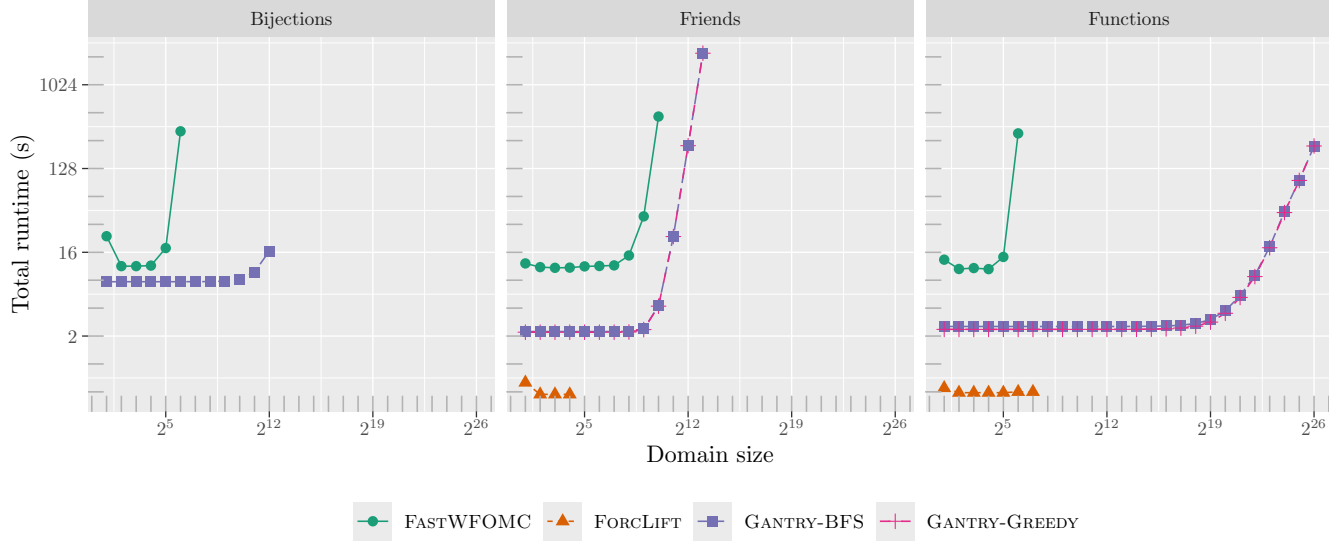


Figure 2 The runtime of the algorithms as a function of the domain size. Note that both axes are on a logarithmic scale.

Shrink/restructure to fit into the margins

The three benchmark families cover a wide range of possibilities. The ‘friends’ benchmark stands out as it uses multiple predicates and can be expressed in FO using just two variables without cardinality constraints or counting quantifiers. The ‘functions’ benchmark, on the other hand, can still be handled by all the algorithms, but it requires cardinality constraints, counting quantifiers, or more than two variables. Lastly, the ‘bijections’ benchmark is an example of a formula that FASTWFOMC can handle but FORCLIFT cannot.

For evaluation purposes, we ran each algorithm on each benchmark using domains of sizes $2^1, 2^2, 2^3$, and so on, until an algorithm failed to handle a domain size due to timeout, out of memory error, or out of precision errors. While we separately measured compilation and inference time, we primarily focus on total runtime, dominated by the latter.

4.2 Results

- On the ‘friends’ and ‘functions’ benchmarks, FORCLIFT runs until the model count exceeds $2^{31} - 1$.
- We are not aware of any formulas on which GANTRY scales worse compared to either FORCLIFT or FASTWFOMC. The one advantage that FASTWFOMC has over GANTRY is its support for counting quantifiers.
- Regarding programming languages and accuracy, we verified that the answers match for smaller domain sizes. Also, although written in different languages, both GANTRY and FASTWFOMC use the GNU Multiple Precision Arithmetic Library.

Figure 2 presents a summary of the experimental results. Only FASTWFOMC and GANTRY-BFS could handle the bijection-counting problem. For this benchmark, the largest domain sizes these algorithms could accommodate were 64 and 4096, respectively. On the other two benchmarks, FORCLIFT had the lowest runtime. However, due to its finite precision, it only scaled up to domain sizes of 16 and 128 for ‘friends’ and ‘functions’, respectively.

FASTWFOMC outperformed FORCLIFT in the case of ‘friends’, but not ‘functions’, as it could handle domains of size 1024 and 64, respectively. Furthermore, both GANTRY-BFS and GANTRY-GREEDY performed similarly on both benchmarks. Similarly to the ‘bijections’ benchmark, GANTRY significantly outperformed the other two algorithms, scaling up to domains of size 8192 and 67,108,864, respectively.

Another aspect of the experimental results that deserves separate discussion is compilation. Both Julia and Scala use just-in-time (JIT) compilation, which means that FASTWFOMC and FORCLIFT take longer to run on the smallest domain size, where most JIT compilation occurs. In the case of GANTRY, it is only run once per benchmark, so the JIT compilation time is included in its overall runtime across all domain sizes. Additionally, while FORCLIFT’s compilation is generally faster than that of GANTRY, neither significantly affects overall runtime. Specifically, FORCLIFT compilation typically takes around 0.5s, while GANTRY compilation takes around 2.3s.

Based on our experiments, which algorithm should be used in practice? If the formula can be handled by FORCLIFT and the domain sizes are reasonably small, FORCLIFT is likely the fastest algorithm. In other situations, GANTRY is expected to be significantly more efficient than FASTWFOMC regardless of domain size, provided both algorithms can handle the formula.

5 Conclusion and Future Work

In this work, we have presented a scalable automated FOKC-based approach to FOMC. Our algorithm involves completing the definitions of recursive functions and subsequently translating all function definitions into C++ code. Empirical results demonstrate that GANTRY can scale to larger domain sizes than FASTWFOMC while supporting a wider range of formulas than FORCLIFT. The ability to efficiently handle large domain sizes is particularly crucial in the weighted setting, as illustrated by the ‘friends’ example discussed in Section 4, where the model captures complex social networks with probabilistic relationships. Without this scalability, the practical usefulness of these models would be limited.

Future directions for research include conducting a comprehensive experimental comparison of FOMC algorithms to better understand their comparative performance across various formulas. The capabilities of GANTRY could also be characterised theoretically, e.g. by proving completeness for specific logic fragments like C^2 . Additionally, the efficiency of FOMC algorithms can be further analysed using fine-grained complexity, which would provide more detailed insights into the computational demands of different formulas.

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