

On Sets with Cardinality Constraints in Satisfiability Modulo Theories

EPFL-REPORT-150658, 2010-08-29

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Abstract. Boolean Algebra with Presburger Arithmetic (BAPA) is a decidable logic that can express constraints on sets of elements and their cardinalities. Problems from verification of complex properties of software often contain fragments that belong to quantifier-free BAPA (QFBAPA). Deciding the satisfiability of QFBAPA formulas has been shown to be NP-complete using an eager reduction to quantifier-free Presburger arithmetic that exploits a sparse-solution property. In contrast to many other NP-complete problems (such as quantifier-free first-order logic or linear arithmetic), the applications of QFBAPA to a broader set of problems has so far been hindered by the lack of an efficient implementation that can be used alongside other efficient decision procedures. We overcome these limitations by extending the efficient SMT solver Z3 with the ability to reason about cardinality constraints. Our implementation uses the DPLL(T) mechanism of Z3 to reason about the top-level propositional structure of a QFBAPA formula, improving the efficiency compared to previous implementations. Moreover, we present a new algorithm for automated decomposition of QFBAPA formulas. Our algorithm alleviates the exponential explosion of considering all Venn regions, significantly improving the tractability of formulas with many set variables. Because it is implemented as a theory plugin, our implementation enables Z3 to prove formulas that use QFBAPA constructs alongside constructs from other theories that Z3 supports (e.g. linear arithmetic, uninterpreted function symbols, algebraic data types), as well as in formulas with quantifiers. We have applied our implementation to verification of functional programs; we show it can automatically prove formulas that no automated approach was reported to be able to prove before.

1 Introduction

Sets of values naturally arise in software that performs discrete computation, either explicitly, in the form of built-in data types [2] or container libraries, or implicitly, in the form of program specification constructs [12, 23, 13]. An intrinsic part of reasoning about sets is reasoning about sizes of sets, with well-known associated laws such as the inclusion-exclusion principle $|A \cup B| = |A| + |B| - |A \cap B|$. A natural decidable logic that supports reasoning about set operations

(union, intersection, complement) as well as reasoning about sizes is a logic we call BAPA, for Boolean Algebra with Presburger Arithmetic [3, 8]. We here consider the quantifier-free fragment of BAPA, denoted QFBAPA.

QFBAPA was shown to be NP-complete using a particular encoding into quantifier-free Presburger arithmetic that exploits an integer analogue of Carathéodory theorem [11]. We thus think of QFBAPA as a generalization of SAT that is similar to SAT from a high-level complexity-theory point of view. From the modelling aspect, researchers have studied in depth SAT encoding of bitvectors, uninterpreted function symbols, and linear arithmetic. The richness of QFBAPA is reflected in the fact that, being propositionally closed, it subsumes SAT. Moreover, no encoding is needed to represent integer linear arithmetic. Crucially, it supports set operations and cardinality, whose polynomial encoding into SAT is possible but non-trivial [11]. A number of expressive logics that can impose constraints on sets can be reduced to QFBAPA [20, 10]. This enables not only simpler decision procedures, but, more importantly, combination of formulas from non-disjoint theory signatures that share set operations.

However, although the QFBAPA satisfiability problem is NP complete, the NP algorithm [11] has proven difficult for unsatisfiable QFBAPA instances, and its improvements have primarily helped dealing with satisfiable instances. This empirical observation is in contrast to the situation for propositional logic, for which the community developed SAT solvers that are effective in showing unsatisfiability for large industrial benchmarks. In this paper we present a QFBAPA implementation that is effective both for satisfiable and unsatisfiable instances.

Our implementation incorporates an important new algorithmic component: a decomposition of constraints based on the hypergraphs of common set variables. This component analyzes the variables occurring in different atomic formulas within a QFBAPA formula and uses the structural property of the formula to avoid generating all Venn regions.

Our implementation is integrated into the state-of-the-art SMT solver Z3, whose important feature is efficient support for linear arithmetic [15]. Efficient integration with Z3 was made possible by the recently introduced theory plugin architecture of Z3, as well as by an incremental implementation of our algorithm. In this integration, Z3 processes top level propositional structure of the formula, providing QFBAPA solver with conjunctions of QFBAPA constraints. Our solver generates lemmas in integer linear arithmetic and gives them back to Z3, which incorporates them with other integer constraints. At the same time, Z3 takes care of equality constraints. The net result is (1) dramatic improvement of efficiency compared to previously reported QFBAPA implementations (2) the ability to use QFBAPA cardinality operation alongside all other operations that Z3 supports. We illustrate the usefulness of this approach through experimental results that prove the validity of complex verifications condition arising from the verification of imperative as well as functional programs.

Contributions. In summary, our paper makes the following contributions:

- decomposition theorems and algorithms for efficient handling of QFBAPA cardinality constraints, often avoiding the need for exponentially many Venn regions as in [8], and avoiding complex conditional sums as in [11];
- an incremental algorithm for analyzing QFBAPA syntactic structure and generating integer arithmetic constraints following the decomposition theorems;
- an implementation of these algorithms as a theory plugin of the Z3 solver, with support for detecting equalities entailed by QFBAPA constraints and therefore precise combination with other theories supported by Z3;
- encouraging experimental results for benchmarks arising from verification of imperative and functional programs.

2 Example

We next illustrate the expressive power of the SMT prover we obtained by incorporating our QFBAPA decision procedure into Z3. Given a list datatype in a functional programming language, consider the question of proving that the set of elements contained in the list has a cardinality always less than or equal to the length of the list. The set of elements contained in the list and the length of the list are computed using natural recursive functions, specified below in the syntax of the Scala programming language:

```
def content(list: List[Int]) : Set[Int] = list match {
  case Nil => ∅
  case Cons(x, xs) => {x} ∪ content(xs)
}
def length(list: List[Int]) : Int = list match {
  case Nil => 0
  case Cons(x, xs) => 1 + length(xs)
}
```

Our goal is to prove the property:

$$\forall list : List[Int] . |content(list)| \leq length(list)$$

We proceed by unfolding the recursive definitions sufficiently many times to obtain the following verification condition:

$$\begin{aligned} & list \neq Nil \implies list = Cons(x, xs) \\ & \wedge length(Nil) = 0 \wedge length(Cons(x, xs)) = 1 + length(xs) \\ & \wedge content(Nil) = \emptyset \wedge content(Cons(x, xs)) = \{x\} \cup content(xs) \\ & \wedge |content(xs)| \leq length(xs) \\ \implies & |content(list)| \leq length(list) \end{aligned}$$

Note that the formula includes reasoning about integers, algebraic data types, sets, and cardinalities of sets. To the best of our knowledge, the implementation we present in this paper is the only one that is complete for proving the validity of formulas with such operators. The proof is found using Z3's DPLL(T) algorithm,

which, among others, performs cases analysis on whether *list* is empty. It relies on Z3 to support arithmetic, congruence properties of functions, and algebraic data types. Finally, it crucially relies on invocations of our QFBAPA plugin. In response to currently asserted QFBAPA constraints, our plugin generates integer constraints on Venn regions that are chosen to ensure that the relationships between sets are handled in a complete way. The entire theorem proving process takes negligible time (see Section 6 for experimental results).

3 Decomposition in Solving BAPA Constraints

In this section, we consider formulas over finite sets of uninterpreted elements from a domain \mathbb{E} . We show in Section 4 how we combined QFBAPA with other theories to obtain a theory of sets of interpreted elements.

Syntax. Figure 1 presents the syntax of QFBAPA. We use $\text{vars}(\phi)$ to denote the set of free set variables occurring in ϕ .

$$\begin{aligned}
\phi &::= A \mid \phi_1 \wedge \phi_2 \mid \phi_1 \vee \phi_2 \mid \neg\phi \\
A &::= S_1 = S_2 \mid S_1 \subseteq S_2 \mid T_1 = T_2 \mid T_1 \leq T_2 \\
S &::= s \mid \emptyset \mid \mathcal{U} \mid S_1 \cup S_2 \mid S_1 \cap S_2 \mid S_1 \setminus S_2 \mid S^c \\
T &::= i \mid K \mid T_1 + T_2 \mid K \cdot T \mid |S| \\
K &::= \dots \mid -2 \mid -1 \mid 0 \mid 1 \mid 2 \mid \dots
\end{aligned}$$

Fig. 1. Quantifier-Free Formulas of Boolean Algebra with Presburger Arithmetic (QFBAPA). S^c denotes the complement of the set S with respect to the universe \mathcal{U} , that is, $\mathcal{U} \setminus S$.

Definition 1. *One central notion throughout the presentation of the theorems and the decision procedure is the notion of Venn region. A Venn region of n sets $\mathbf{S} = \{S_1, \dots, S_n\}$ is one of the 2^n sets described by:*

$$\bigcap_{i=1}^n S_i^{\alpha_i}$$

where $S_i^{\alpha_i}$ is either S_i or S_i^c . By construction, the 2^n regions form a partition of \mathcal{U} . We write $\text{venn}(\mathbf{S})$ to denote the set of all Venn regions formed with the sets in \mathbf{S} .

Semantics. An interpretation \mathcal{M} of a QFBAPA formula ϕ is a map from the set variables of ϕ to finite subsets of \mathbb{E} and from the integer variables of ϕ to values in \mathbb{Z} . It is a model of ϕ , denoted $\mathcal{M} \models \phi$ if the following conditions are satisfied:

- $\mathcal{U}^{\mathcal{M}}$ is a finite subset of \mathbb{E} and $\emptyset^{\mathcal{M}}$ is the empty set
- for each set variable S of ϕ , $S^{\mathcal{M}} \subseteq \mathcal{U}^{\mathcal{M}}$
- for each integer variable k of ϕ , $k^{\mathcal{M}} \in \mathbb{Z}$
- when $=, \subseteq, \emptyset, \cup, \cap, \setminus$ and the cardinality function $|\cdot|$ are interpreted as expected, ϕ evaluates to true in \mathcal{M}

Definition 2. We define \sim_V to be the equivalence relation on interpretations, parametrized by a set of set variables V , such that:

$$\mathcal{M}_1 \sim_V \mathcal{M}_2 \iff \forall v \in \text{venn}(V) . |v^{\mathcal{M}_1}| = |v^{\mathcal{M}_2}|$$

Definition 3. Let \mathcal{M} be an interpretation and $f : \mathbb{E} \rightarrow \mathbb{E}$ a bijection from the interpretation domain to itself (a permutation function). We denote by $f[\mathcal{M}]$ the interpretation such that:

- $\mathcal{U}^{f[\mathcal{M}]} = \{f(u) \mid u \in \mathcal{U}^{\mathcal{M}}\}$
- for each set variable S interpreted in \mathcal{M} , $S^{f[\mathcal{M}]} = \{f(u) \mid u \in S^{\mathcal{M}}\}$
- for each integer variable k interpreted in \mathcal{M} , $k^{f[\mathcal{M}]} = k^{\mathcal{M}}$

Theorem 1. Let ϕ be a QFBAPA formula, \mathcal{M} a model of ϕ and $f : \mathbb{E} \rightarrow \mathbb{E}$ a bijection, then $f[\mathcal{M}] \models \phi$.

Proof. Prove by induction that $t^{f[\mathcal{M}]} = f[t^{\mathcal{M}}]$ for every set algebra term t . By bijectivity of f , $|t^{f[\mathcal{M}]}| = |f[t^{\mathcal{M}}]|$, so values of all integer-valued terms remain invariant under f . Finally, note that $S_1 \subseteq S_2$ reduces to $|S_1 \setminus S_2| = 0$ whereas $S_1 = S_2$ reduces to $|S_1 \setminus S_2| = 0 \wedge |S_2 \setminus S_1| = 0$.

3.1 A Simple Decision Procedure for QFBAPA

A simple technique for solving QFBAPA formulas is to reduce the problem to integer linear arithmetic as follows. Introduce a fresh integer variable for each Venn region in $\text{venn}(\text{vars}(\phi))$. Rewrite each constraint of the form $S_1 = S_2$ as $S_1 \subseteq S_2 \wedge S_2 \subseteq S_1$, and each constraint of the form $S_1 \subseteq S_2$ as $|S_1 \setminus S_2| = 0$. Finally, use sums over the integer variables representing the Venn regions to rewrite the cardinality constraints. As an example, consider the formula

$$|A| > 1 \wedge A \subseteq B \wedge |B \cap C| \leq 2$$

and the naming of the Venn regions $\text{venn}(\{A, B, C\})$ shown in Figure 2. Rewrite the constraints as

$$k_1 + k_4 + k_5 + k_7 > 1 \wedge k_1 + k_5 = 0 \wedge k_7 + k_6 \leq 2 \wedge k_i \geq 0 \text{ for } i \in \{0, \dots, 7\}$$

A model for this integer formula is, for example,

$$k_4 = 1, k_7 = 1, k_i = 0 \text{ for } i \notin \{4, 7\}$$

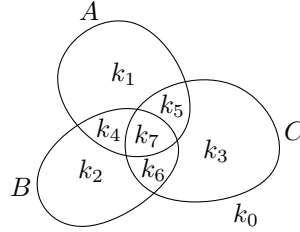


Fig. 2. Naming of the Venn regions of set variables A , B , and C using integer variables.

From the model for integer variables we can build a model for the QFBAPA formula by picking distinct elements from \mathbb{E} for each Venn region. In this case we can construct, for example,

$$\mathcal{U} = \{e_1, e_2\}, A = \{e_1, e_2\}, B = \{e_1, e_2\}, C = \{e_2\}$$

This reduction is simple to understand and to implement, but always requires 2^N integer variables, where N is the number of elements in $\text{vars}(\phi)$. In the following, we show how to reduce this number considerably in many cases that arise in practice.

Note that what we describe below is largely orthogonal to the NP procedure in [11]. Our results should in principle apply both to the naive procedure sketched above, and to the sparse encoding procedure in [11]. Note that the NP procedure from [11], although theoretically optimal, has so far been shown to be practically useful only for satisfiable cases. For unsatisfiable cases the sparse encoding generates quantifier-free Presburger arithmetic formulas that are difficult for current SMT solver implementations.

3.2 Decomposing Conjunctions of QFBAPA Formulas

The decision procedure presented in Section 3.1 requires many integer variables because it uses a variable for the intersection of *every* combination of set variables. The intuition behind the following result is that permutation of elements between sets that are not related by a constraint in a formula does not affect the satisfiability of that formula.

Theorem 2. *Let ϕ_1 and ϕ_2 be two QFBAPA formulas. Let V_1 and V_2 denote the sets of set variables appearing in ϕ_1 and ϕ_2 respectively. Let $V_S = V_1 \cap V_2$ be the set of shared variables. Let K_S represent the set of shared integer variables. The QFBAPA formula $\phi \equiv \phi_1 \wedge \phi_2$ is satisfiable if and only if there exists a model \mathcal{M}_1 for ϕ_1 and a model \mathcal{M}_2 for ϕ_2 such that, for each integer variable $k \in K_S$, $k^{\mathcal{M}_1} = k^{\mathcal{M}_2}$, and such that $\mathcal{M}_1 \sim_{V_S} \mathcal{M}_2$.*

Proof. We construct a model \mathcal{M} for ϕ by extending \mathcal{M}_1 to the variables in $V_2 \setminus V_S$. (The other direction is immediate.) We show that there exists a permutation f

on \mathbb{E} such that $f[S^{\mathcal{M}_2}] = S^{\mathcal{M}_1}$ for each Venn region of $\text{venn}(V_S)$. In other words, f is a bijection that projects the interpretation in \mathcal{M}_2 of all intersections of the shared variables to their interpretation in \mathcal{M}_1 . We construct f as follows: for each Venn region $v \in \text{venn}(V_S)$, let f_v be a bijection from $v^{\mathcal{M}_2}$ to $v^{\mathcal{M}_1}$. Note that f_v always exists because $v^{\mathcal{M}_1}$ and $v^{\mathcal{M}_2}$ have the same cardinality. Let f^* be $\bigcup_{v \in \text{venn}(V_S)} f_v$. Observe that f^* is a bijection from $\mathcal{U}^{\mathcal{M}_2}$ to $\mathcal{U}^{\mathcal{M}_1}$, because $\text{venn}(V_S)$ is a partition of \mathcal{U} in both models. To obtain the desired f , we can extend f^* to the domain and range \mathbb{E} by taking its union with any bijection from $\mathbb{E} \setminus \mathcal{U}^{\mathcal{M}_2}$ to $\mathbb{E} \setminus \mathcal{U}^{\mathcal{M}_1}$. The model $\mathcal{M} = \mathcal{M}_1 \cup f[\mathcal{M}_2]$ is a model of ϕ_1 (trivially) and of ϕ_2 (by Theorem 1), therefore, it is a model of ϕ .

The following result is a generalization of Theorem 2 for a conjunction of arbitrarily many constraints.

Theorem 3. *Let ϕ_1, \dots, ϕ_n be n QFBAPA formulas. Let V_i denote $\text{vars}(\phi_i)$ for $i \in \{1, \dots, n\}$. Let*

$$V_S = \bigcup_{1 \leq i < j \leq n} V_i \cap V_j$$

be the set of all variables that appear in at least two sets V_i and V_j . The formula $\phi_1 \wedge \dots \wedge \phi_n$ is satisfiable if and only if: 1) there exist models $\mathcal{M}_1, \dots, \mathcal{M}_n$ such that, for each i , $\mathcal{M}_i \models \phi_i$ and 2) there exists an interpretation \mathcal{M} of the variables V_S such that $\mathcal{M} \sim_{V_S \cap V_i} \mathcal{M}_i$ for each $1 \leq i \leq n$.

(Note that the conditions imply that $|U^{\mathcal{M}}| = |\mathcal{U}^{\mathcal{M}_i}|$ for each i .) The proof follows the idea of the proof of Theorem 2: it suffices to show that one can extend the model \mathcal{M} to each model \mathcal{M}_i by finding a bijection f_i . Note that f_i is guaranteed to exist because $\mathcal{M} \sim_{V_S \cap V_i} \mathcal{M}_i$.

Remark. It is not sufficient that for each $0 \leq i < j \leq n$, $\mathcal{M}_i \sim_{(V_i \cap V_j)} \mathcal{M}_j$ (i.e. that there exists bijections between each model \mathcal{M}_i and \mathcal{M}_j pairwise). A simple counter-example is given by the (unsatisfiable) constraints:

$$\begin{aligned} \phi_1 &\equiv |A| = 1 \wedge |B| = 1 \wedge |A \cap B| = 1 \\ \phi_2 &\equiv |A| = 1 \wedge |C| = 1 \wedge |A \cap C| = 1 \\ \phi_3 &\equiv |B| = 1 \wedge |C| = 1 \wedge |B \cap C| = 0 \end{aligned}$$

Although any conjunction $\phi_i \wedge \phi_j$ can be shown satisfiable using Theorem 2, the conjunction $\phi_1 \wedge \phi_2 \wedge \phi_3$ is unsatisfiable, because a common model \mathcal{M} cannot be built from models for each three constraints.

Lemma 1. *Let ϕ_1, \dots, ϕ_n be n QFBAPA formulas, and let V_1, \dots, V_n, V_S be defined as above. Assume there exist $\mathcal{M}, \mathcal{M}_1, \dots, \mathcal{M}_n$ satisfying the conditions of Theorem 3 and the additional condition that:*

$$|\mathcal{U}^{\mathcal{M}}| \geq \left| \bigcup_{S \in V_S} S^{\mathcal{M}} \right| + \sum_{i=1}^n \left| \bigcup_{S \in V_i \setminus V_S} S^{\mathcal{M}_i} \right|$$

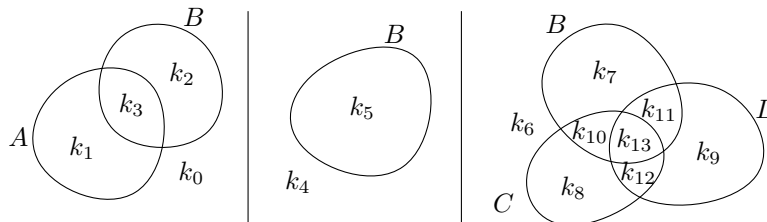


Fig. 3. Independent naming of the Venn regions of set variables $V_1 = \{A, B\}$, $V_S = \{B\}$, and $V_2 = \{B, C, D\}$.

Then there exists a model \mathcal{M}_d such that, for any two sets $S_i \in V_i \setminus V_S$ and $S_j \in V_j \setminus V_S$ (with $i \neq j$), if (1) $\forall S \in V_S \cap V_i . \mathcal{M}_i \models S_i \neq S$ and (2) $\forall S \in V_S \cap V_j . \mathcal{M}_j \models S_j \neq S$, and (3) either $\mathcal{M}_i \models S_i \neq \emptyset$ or $\mathcal{M}_j \models S_j \neq \emptyset$, then $\mathcal{M}_d \models S_i \neq S_j$.

Intuitively, Lemma 1 states that for two sets variables that appear in different constraints and that are not shared, if there exists a model in which these sets are not empty and are not equal to some shared set variable, then there exists a model in which the two sets are not equal. The correctness follows from the fact that with $\mathcal{U}^{\mathcal{M}}$ sufficiently large, it is always possible to find bijections f_i such that for each i the non-shared sets are mapped to a different subset of \mathcal{U} . We omit the details in the interest of space.

Lemma 2. *The additional conditions of Lemma 1 are fulfilled is when \mathbb{E} is infinite and $|\mathcal{U}|$ is not constrained in any formula ϕ_i .*

This result is important for the combination of QFBAPA with other theories, as explained in Section 4. The proof follows from the fact that with an infinite domain \mathbb{E} and an unconstrained universe \mathcal{U} , if there exists a model, we can extend it to a model \mathcal{M} where $|\mathcal{U}^{\mathcal{M}}|$ is sufficiently large.

A decision procedure based on decompositions. Theorem 3 yields a decision procedure for the satisfiability of conjunctions of QFBAPA constraints $\phi_1 \wedge \dots \wedge \phi_n$: independently for ϕ_1 to ϕ_n , introduce integer variables for the regions of $\text{venn}(V_1)$, \dots , $\text{venn}(V_n)$ respectively, then introduce fresh variables for the regions of $\text{venn}(V_S)$, where V_S is computed as in the theorem. Finally, constrain the sums of variables representing the same regions to be equal. (This ensures that the bijections f_i can be constructed in the satisfiable case.) As an example, consider the formula

$$|A \setminus B| > |A \cap B| \wedge B \cap C \cap D = \emptyset \wedge |B \setminus D| > |B \setminus C|$$

Let ϕ_1 be the first conjunct and ϕ_2 the other two. We have $V_1 = \{A, B\}$ and $V_2 = \{B, C, D\}$. Using the naming for regions shown in Figure 3, we obtain the

integer constraints

$$\begin{array}{ll}
 k_1 > k_3 & \text{reduction of } \phi_1 \\
 \wedge k_{13} = 0 \wedge k_7 + k_{10} > k_7 + k_{11} & \text{reduction of } \phi_2 \\
 \wedge k_4 = k_0 + k_1 = k_6 + k_8 + k_9 + k_{12} & \text{representations of } |B^c| \\
 \wedge k_5 = k_2 + k_3 = k_7 + k_{10} + k_{11} + k_{13} & \text{representations of } |B|
 \end{array}$$

A possible satisfying assignment for the integer variables is $k_4 = 2$, $k_0 = k_1 = k_2 = k_5 = k_8 = k_9 = k_{10} = 1$, and $k_3 = k_6 = k_7 = k_{11} = k_{12} = k_{13} = 0$. From these values, we can build the assignment to set variables

$$\begin{array}{ll}
 \mathcal{U}_1 = \{e_1, e_2, e_3\}, A = \{e_1\}, B = \{e_2\} & \text{for } \phi_1 \\
 \mathcal{U}_2 = \{e_4, e_5, e_6\}, B = \{e_4\}, C = \{e_4, e_5\}, D = \{e_6\} & \text{for } \phi_2
 \end{array}$$

Finally, to build a model for $\phi_1 \wedge \phi_2$, we need to construct two bijections f_1 and f_2 such that $f_1(e_4) = f_2(e_2)$ and $f_1[\{e_5, e_6\}] = f_2[\{e_1, e_3\}]$. This is always possible in this decision procedure, because we constrain the sizes of the Venn regions of shared variables to be equal. Intuitively, the freedom in the construction for this example comes from the fact that when we merge the models, the overlapping between C or D and A is unconstrained: we can choose to map either e_5 or e_6 to the same element as e_1 , in which case either C or D will share an element with A . So one possible model for ϕ is

$$A = \{e_1\}, B = \{e_2\}, C = \{e_1, e_2\}, D = \{e_3\}$$

(Here we chose the identity function for f_1 .) Note that this model also satisfies the property of models described in Lemma 1, since in this interpretation, $A \neq C$ and $A \neq D$.

3.3 Hypertree Decompositions

In general, and as in the previous example, the constraints ϕ_i in Theorem 3 can contain top-level conjunctions. It is thus in principle possible to decompose them further. In this section, we introduce a hypergraph representation of constraints from which it is straightforward to apply the decision procedure presented above recursively.

Definition 4. *Let ϕ a QFBAPA formula and let $V = \text{vars}(\phi)$. Let ϕ_1, \dots, ϕ_n be top-level conjuncts of ϕ and V_1, \dots, V_n the sets of variables appearing in them respectively. We assume without loss of generality that $V_i \neq V_j$ for $i \neq j$. (If two constraints ϕ_i and ϕ_j have the same set of variables, consider instead the constraint $\phi_i \wedge \phi_j$.) Let \mathbf{V} denote $\{V_1, \dots, V_n\}$. Let $\mathcal{H} = (\mathbf{V}, \mathbf{E})$ be a hypergraph on the set of sets of variables \mathbf{V} (so $\mathbf{E} \subseteq 2^{\mathbf{V}}$). Let $l : \mathbf{E} \rightarrow 2^V$ be a labeling function that associates to each hyperedge a subset of the set variables of ϕ (that subset need not be one of V_i). We call \mathcal{H} a hypertree decomposition of ϕ if the*

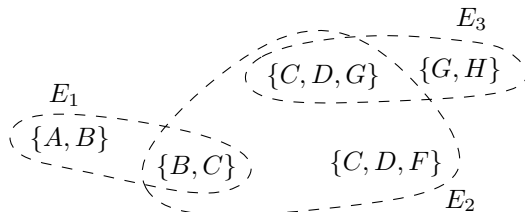


Fig. 4. A hypertree decomposition of (1). The labeling is given by: $l(E_1) = \{B\}$, $l(E_2) = \{C, D\}$, $l(E_3) = \{G\}$.

following properties hold:

$$(H1) \forall V_i, V_j . V_i \cap V_j \neq \emptyset \implies \exists E \in \mathbf{E} . (V_i \cup V_j) \subseteq E \wedge (V_i \cap V_j) \subseteq l(E)$$

$$(H2) \forall E \in \mathbf{E}, \forall V \in \mathbf{V} . V \in E \iff V \cap l(E) \neq \emptyset$$

$$(H3) \mathcal{H} \text{ is acyclic}^1$$

Property (H1) states that two nodes that share at least one variable must be connected with an hyperedge whose label contains at least their shared variables, and Property (H2) states that a node is contained in a hyperedge if and only if the label of that hyperedge shares at least one set variable with the node. Note that a formula ϕ admits in general many distinct hypertree decompositions. For instance, the hypergraph $\mathcal{H} = (\mathbf{V}, \mathbf{E})$ with a single hyperedge $E = \mathbf{V}$ and $l(E) = \mathbf{V}$ always satisfies Definition 4. To illustrate hypertree decompositions, consider the (unsatisfiable) formula

$$|A \cup B| \leq 3 \wedge C \subseteq B \wedge |(C \cap D) \setminus F| = 2 \wedge |(C \cap G) \setminus D| = 2 \wedge H \subseteq G \quad (1)$$

If we number the conjuncts from 1 to 5, we have $V_1 = \{A, B\}$, $V_2 = \{B, C\}$, $V_3 = \{C, D, F\}$, $V_4 = \{C, D, G\}$, $V_5 = \{G, H\}$. Figure 4 shows a possible hypertree decomposition of (1). The intuition behind hypertree decompositions is that hyperedges represent set of constraints, and that models for these sets need to agree only on the variables they share in their common nodes.

Reduction to integer arithmetic from hypertrees. We show now how to adapt the decision procedure presented at the end of Section 3.2 to hypertree decompositions. We proceed as follows: for each set of set variables V_i (each node in the hypertree), we introduce integer variables for all regions $\text{venn}(V_i)$. Then, for each hyperedge E , we add variables for the regions $\text{venn}(l(E))$. Finally, for each node V_i and each hyperedge E such that $V_i \in l(E)$, we constrain the sums of variables describing the same Venn regions to be equal. For each $v \in$

¹ We define as a cycle any set of at least two hyperedges such that there exists a node reachable from itself by traversing all hyperedges in the set. This implies in particular that no two hyperedges intersect on more than one node. Note that this is more restrictive than the definition of a hypertree as a hypergraph that admits a tree as a host graph.

$\text{venn}(V_i \cap l(E))$, we generate the constraint:

$$\sum_{\substack{v_1 \in \text{venn}(V_i) \\ \text{s.t. } v_1 \subseteq v}} k_{V_i}(v_1) = \sum_{\substack{v_2 \in \text{venn}(l(E)) \\ \text{s.t. } v_2 \subseteq v}} k_{l(E)}(v_2)$$

where $k_{V_i}(\cdot)$ and $k_{l(E)}(\cdot)$ denote the integer variable representing a Venn region in the naming scheme for the Venn regions of V_i and $l(E)$ respectively.

4 Combination

We now consider the question of combining QFBAPA with other theories interpreted over infinite domains. We identify two points of interest: 1) the range of the cardinality function is the integers 2) sets should be built over an interpreted domain. For these two reasons, the combined theories are non-disjoint and we cannot simply apply Nelson-Oppen combination [17] or similar techniques. In the following we show how we handled these points and how, as a result, our integrated decision procedure can prove constraints such as, for example,

$$(S_1 = \{1, 2, 3, 4\} \wedge S_2 \subseteq S_1 \wedge S_2 \neq \emptyset) \implies |S_2| \in S_1$$

Reduction to the integers. We handle constraints on sets with cardinalities by reducing them to integer linear arithmetic using the translation presented in Section 3.3. Assume for now a fixed naming of Venn regions (we describe in Section 5 how we maintain a hypertree and thus a naming in the presence of incremental reasoning). For each set constraint $S_1 \subseteq S_2$ or $S_1 = S_2$, we add an axiom constraining the integer representation of the set variables in the atom. For instance, using the naming of Venn regions in Figure 2, we would add for the constraint $A \cup B \subseteq C$ the implication

$$A \cup B \subseteq C \implies k_1 + k_2 + k_4 = 0$$

Similarly, for each cardinality term $|S|$, we add an axiom expressing the cardinality in terms of integer variables. Using the same naming as above, we would for instance add for the term $|C \setminus B|$ the equality $|C \setminus B| = k_3 + k_5$. These axioms enforce that whichever boolean values the SMT solver assigns to the set predicate, it will be forced to maintain for the integer variables an assignment that is consistent with the constraints on the sizes of Venn regions.

Interpreted elements. When considering sets in combination with other theories, it is natural to allow the use of the predicate $e \in S$ denoting that a given set contains a particular (interpreted) element, or constant sets $\{e_1, e_2\}$. For the simplicity of the argument, we assume here that all sets have the same underlying element sort \mathbb{E} . We handle interpreted elements such as e , e_1 and e_2 by adding to the logic two connecting functions, $\text{singleton} : \mathbb{E} \rightarrow \text{Set}$ and $\text{element} : \text{Set} \rightarrow \mathbb{E}$. We create for each interpreted element that appears in a

predicate $e \in S$ or in a constant set a singleton set term $\text{singleton}(e)$, and we add the axioms $|\text{singleton}(e)| = 1$ and $\text{element}(\text{singleton}(e)) = e$. So singleton is interpreted as a constructor that builds a singleton set from an element, and element as a function that for singleton sets computes its element, and that is uninterpreted otherwise. We can thus rewrite $e \in S$ as $\text{singleton}(e) \subseteq S$ and constant sets as unions of singletons. The connecting functions are used to propagate equalities: when two elements are found to be equal in their theory, congruence closure will conclude that their singleton sets (if they exist) need to be equal as well. The other direction is covered in the following paragraph.

Communicating equalities. The reduction to integer linear arithmetic ensures that if two sets must be equal, then the sizes of the Venn regions of their symmetric difference will be constrained to be 0. However, we may also need to detect that if their symmetric difference is constrained to be empty by some integer constraints, then the sets must be equal. To enforce this, we could, for each pair of set variables (S_1, S_2) generate an axiom equivalent to

$$(|S_1 \setminus S_2| = 0 \wedge |S_2 \setminus S_1| = 0) \implies S_1 = S_2$$

where the cardinality terms would be rewritten using the naming of set regions for S_1 and S_2 . However, because not every pair of set variable appears together in some constraint, our hypertree decomposition does not in general define names for the intersections of any variables S_1 and S_2 . Our solution is to generate such axioms for all pairs of variables that appear together in a node of the hypergraph. Additionally, for each set variable we generate the axiom $|S| = 0 \iff S = \emptyset$. We argue that, for sets that range over an infinite domain (such as the integers), this is sufficient. Consider two set variables S_1 and S_2 that do not appear in a common node. From lemmas 1 and 2, we have that as long as S_1 or S_2 is non-empty or distinct from a shared set variable, there exists a model in which $S_1 \neq S_2$. Both cases are covered by the introduced axioms. Indeed, even if the two variables are equal to a different shared variable, by transitivity of the equality, their equality will be propagated. We thus have the property that any two set variables that are not constrained to be equal can be set to be distinct in a model. This is consistent with the theory combination approach taken in Z3 [15].

5 Implementation

We implemented a reduction from QFBAPA constraints on sets of interpreted elements² using the results from Section 3 as an extension of the state-of-the-art SMT solver Z3 [16]. Although we are in effect performing non-disjoint theory combination as explained in the previous section, we used the mechanism of theory plugin extensions to interface with the prover. Because such extensions can add arbitrary axioms (i.e. that are not restricted to theory elements) to the logical context at any time, this was not a major limitation. We wrote our theory

² In the current implementation, we handle only sets of integers

extension in Scala and used the Java Native Interface [14] to access the C API of Z3.³ We did not observe any significant overhead in the forwarding of function calls from and to the Java virtual machine.

Incremental introduction of Venn regions. Our theory extension receives messages from the core solver whenever a constraint on sets or an application of the cardinality operator is added to the logical context. We maintain at all times a hypertree decomposition \mathcal{H} of the conjunction of all constraints that are on the stack. Whenever a new constraint ϕ_i is pushed to the stack, we apply the following steps:

1. We compute $V_i = \text{vars}(\phi_i)$.
2. If there is a node in \mathcal{H} labeled with V_i , we use the naming of Venn regions in that node to generate the axiom expressing the reduction of ϕ_i and skip the following steps.
3. Else we introduce a new node V_i and we create fresh integer variables for each region of $\text{venn}(V_i)$.
4. For each node V_j in \mathcal{H} such that $V_i \cap V_j \neq \emptyset$, we add a hyperedge $E = \{V_i, V_j\}$ labeled with $l(E) = V_i \cap V_j$.
5. In the new graph, we collapse any introduced cycle as follows: let E_1, \dots, E_n be the hyperedges that participate in the cycle. We introduce a new hyperedge E labeled with $\bigcup_{i \in \{1, \dots, n\}} l(E_i)$ and whose content is the union of the contents of E_1, \dots, E_n . We then remove from the graph the edges E_1 to E_n .
6. For each newly created edge E in the obtained, acyclic, hypergraph we introduce fresh integer variables to denote the regions of $\text{venn}(l(E))$.
7. Finally, for each node in the new edge, we constrain the sums of integer variables that denote the same Venn regions to be equal.

Note that all introduced integer variables are additionally constrained to be non-negative. When constraints are popped from the stack:

1. We remove from \mathcal{H} all nodes that were created for these constraints, if any.
2. For each hyperedge E edge that contained at least one removed variable, we check whether it now contains only one node, in which case we delete it.

Removing such nodes and edges provides two benefits: constraints added in a different search branch may generate a smaller (less connected) hypertree, and Z3 has the opportunity to remove from its clause database reduction axioms that have become useless.

We efficiently detect cycles by maintaining equivalence classes between nodes that correspond to the connected components in the hypertree. We can then check, when we introduce a new hyperedge, whether it connects nodes from different equivalence classes, which corresponds to our definition of a cycle. We use a union-find data-structure to maintain the equivalence classes.

³ Our Scala interface to Z3 is available at <http://lara.epfl.ch/dokuwiki/jniz3>.

6 Evaluation

We evaluated our implementation using benchmarks from two verification sources. Figure 5 shows our experimental results.⁴

| Benchmark | status | sets | cons. | Venn regs. | prop. | prev. best | our time |
|----------------|--------|------|-------|------------|--------|------------|----------|
| CADE07-1 | unsat | 1 | 1 | 2 | 1.00 | < 0.1 | < 0.1 |
| CADE07-2 | unsat | 2 | 1 | 4 | 1.00 | < 0.1 | < 0.1 |
| CADE07-2a | unsat | 6 | 5 | 28 | 0.44 | 1.8 | < 0.1 |
| CADE07-2b | sat | 6 | 5 | 28 | 0.44 | < 0.1 | < 0.1 |
| CADE07-3 | unsat | 2 | 1 | 4 | 1.00 | < 0.1 | < 0.1 |
| CADE07-3a | unsat | 5 | 4 | 16 | 0.50 | 0.4 | < 0.1 |
| CADE07-3b | sat | 5 | 4 | 16 | 0.50 | < 0.1 | < 0.1 |
| CADE07-4 | unsat | 5 | 5 | 80 | 2.50 | 0.5 | < 0.1 |
| CADE07-4b | sat | 5 | 5 | 76 | 2.38 | 0.1 | < 0.1 |
| CADE07-5 | unsat | 7 | 5 | 168 | 1.31 | 13.6 | < 0.1 |
| CADE07-5b | sat | 7 | 5 | 168 | 1.31 | 0.4 | < 0.1 |
| CADE07-6 | unsat | 6 | 6 | 32 | 0.50 | 0.4 | < 0.1 |
| CADE07-6a | unsat | 16 | 20 | 596 | 0.01 | > 100 | 0.3 |
| CADE07-6b | sat | 16 | 22 | 1120 | 0.02 | 0.8 | 0.3 |
| CADE07-6c | sat | 16 | 20 | 596 | 0.01 | 0.9 | 0.4 |
| listContent | sat | 3 | 4 | 14 | 1.75 | | < 0.1 |
| listContent-ax | unsat | 4 | 5 | 16 | 1.00 | | < 0.1 |
| listReverse | sat | 6 | 6 | 26 | 0.41 | | < 0.1 |
| listReverse-ax | unsat | 9 | 11 | 308 | 0.60 | | 0.2 |
| setToList | sat | 6 | 8 | 76 | 1.19 | | < 0.1 |
| setToList-ax | unsat | 7 | 9 | 114 | 0.89 | | < 0.1 |
| listConcat | sat | 11 | 19 | 54 | 0.03 | | 0.2 |
| listConcat-ax | unsat | 28 | 33 | 268 | < 0.01 | | 0.4 |
| treeContent | sat | 4 | 5 | 24 | 1.50 | | 0.1 |
| treeContent-ax | unsat | 6 | 7 | 28 | 0.44 | | 0.1 |
| treeMirror | sat | 6 | 6 | 20 | 0.31 | | < 0.1 |
| treeMirror-ax | unsat | 11 | 11 | 572 | 0.28 | | 0.3 |
| treeToList | sat | 8 | 10 | 24 | 0.09 | | 0.1 |
| treeToList-ax | unsat | 29 | 35 | 2362 | < 0.01 | | 1.7 |

Fig. 5. Experimental results. The column “sets” is the number of set variables, “cons.” is the maximal number of constraints on the stack, “Venn regs.” is the maximal number of distinct Venn regions created from the hypertree structure, “prop.” is the proportion of created Venn regions compared to the 2^N naive naming scheme, “prev. best” indicates the previously best solving time, and “time” is the running time with the new implementation. All times are in seconds. The experiment was conducted using a 2.66GHz Quad-core machine running Ubuntu, and using Z3 2.11.

⁴ All benchmarks and the set of axioms we used are available from <http://lara.epfl.ch/~psuter/vmcai2011/>.

Jahob benchmarks. We included all benchmarks from [11] in our evaluation. These formulas express verification conditions generated with the Jahob system [7] for programs manipulating (abstractions of) pointer-based data-structures such as linked lists. In [11], the benchmarks were used to compare the efficiency of the sparse encoding into linear arithmetic with the explicit one (as in Section 3.1). We indicate for these benchmarks the previously best time using either method. It is important to note that it was shown in [11] that the two methods were complementary: the sparse encoding outperformed the explicit one for **sat** instances and vice-versa. We do not claim that the absolute difference in time is a significant measure of our algorithmic improvements, but rather provide these numbers to illustrate that our new techniques can be used to efficiently handle **sat** and **unsat** instances.

Functional programs. We also included new benchmarks consisting of verification conditions for Scala functions without side effects. Additionally to sets and elements, these examples contain constraints on algebraic data types and functions symbols. Each verification condition contains at least one (recursive) function call. We first treated these function symbols as uninterpreted. We then used universally quantified axioms to define the interpretation of the functions and used Z3’s pattern-based instantiation mechanism to apply the axioms. Without the axioms, all formulas were invalid (**sat**), and with the axioms, they were all proved valid.

7 Related Work

To the best of our knowledge, the only previous implementation that is complete for QFBAPA and reports performance on benchmarks is [11]. We show significant improvement over the existing benchmarks. While results in [11] were unable to handle unsatisfiable formulas with 16 variables, we report success on formulas with 29 variables, which were automatically generated from verification of functional programs.

The quantifier-free complexity of QFBAPA was settled in [11], and the complexity of the quantified case as well as the first quantifier elimination implementation was described in [8]. The logic itself dates back at least to [3]; among more recent descriptions in multi-sorted form is [22].

The work of combination of QFBAPA with other decidable theories has so far included implementation as part of the Jahob system [7], which requires manual decomposition steps to be complete [23, 24]. A complete methodology for using QFBAPA as a glue logic for non-disjoint combination was introduced in [20], with additional useful cases introduced in [19, 21, 9], some of which are and surveyed in [10]. The combination method we describe is simple, in that it does not require exchanging set constraints between different theories that share sets of objects. In that sense, it corresponds to the multi-sorted combination setup of [22], which introduces a non-deterministic procedure that was, to the best of our knowledge, not implemented. Combinations of theories that have finite domains has been explored in [6]. In this paper we have focused on combinations with integers, but we believe that our approach can be adapted to more general cases.

Our decomposition of formulas was inspired by the algorithms for bounded (hyper)tree width from constraint satisfaction literature [4], although we do not directly follow any particular decomposition algorithm from the literature. These algorithms are typically used to reduce subclasses of NP-hard constraint satisfaction problems over finite domains to polynomial-time algorithms. To the best of our knowledge, they have not been applied before to satisfiability of sets with cardinality operators. Our results suggest that this approach is very promising and we expect it to extend to richer logics containing QFBAPA, such as [21].

Research in program analysis has used cardinality constraints in abstract domains [5, 18], typically avoiding the need for a full-fledged QFBAPA decision procedure. Thanks to our efficient implementation of QFBAPA, we expect that precise predicate abstraction approaches [1] will now also be able to use QFBAPA constraints.

Acknowledgments

We thank Nikolaj Bjørner and Leonardo de Moura for their help with Z3.

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