

Boolean Equi-propagation for Optimized SAT Encoding

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Abstract. We present an approach to propagation based SAT encoding, Boolean equi-propagation, where constraints are modelled as Boolean functions which propagate information about equalities between Boolean literals. This information is then applied as a form of partial evaluation to simplify constraints prior to their encoding as CNF formulae. We demonstrate for a variety of benchmarks that our approach leads to a considerable reduction in the size of CNF encodings and subsequent speed-ups in SAT solving times.

1 Introduction

In recent years, Boolean SAT solving techniques have improved dramatically. Today's SAT solvers are considerably faster and able to manage far larger instances than yesterday's. Moreover, encoding and modeling techniques are better understood and increasingly innovative. SAT is currently applied to solve a wide variety of hard and practical combinatorial problems, often outperforming dedicated algorithms. The general idea is to encode a (typically, NP) hard problem instance, P , to a Boolean formula, φ_P , such that the solutions of P correspond to the satisfying assignments of φ_P . Given an encoding from problem instances to Boolean formula, a SAT solver is then applied to solve the problem instances.

Tailgating the success of SAT technology are a variety of tools which can be applied to specify and then compile problem instances to corresponding SAT instances. Typically, a constraint based modelling language is introduced and used to model instances. Then encoding techniques are applied to compile constraints to the language of an underlying solver such as SAT, SMT, or others. Some examples follow: In [5], Cadoli and Schaerf introduce NP-SPEC, a logic-based specification language which allows to specify combinatorial problems in a declarative way. At the core of this system is a compiler which translates specifications to CNF formula. Sugar [20], is a SAT-based constraint solver. To solve a finite domain linear constraint satisfaction problem it is first encoded to a CNF formula by Sugar, and then solved using the MiniSat solver [8]. MiniZinc [15], is a constraint modeling language which is compiled by a variety of solvers to the low-level target language FlatZinc. FlatZinc instances are solved by `fzntini` [13] by encoding them to CNF and in `fzn2smt` by encoding to SMT-LIB [2].

The objective of all of these tools is to facilitate the process of providing a high-level description of how the (constraint) problem at hand is to be solved. Taking the analogy to programming languages, given such a description, a compiler can then provide a low-level executable for the underlying machine. Namely, in our context, a formula for the underlying SAT or SMT solver.

This paper takes a new approach, introducing the notion of equi-propagation. Similar to how unit propagation is about inferring unit clauses which can then be applied to simplify CNF formulae, equi-propagation is about inferring equational consequences. In contrast to unit propagation, equi-propagation derives information from the higher-level constraints, prior to their encoding to CNF. Each individual constraint is modelled as a Boolean function which propagates equalities between Boolean literals that it implies. Given this information, all of the constraints are simplified by partial evaluation, possibly leading to further equi-propagation. When equi-propagation provides no further information, the residual constraints are encoded to CNF.

Drawing on the programming languages analogy, we view our contribution as an optimizing compiler for SAT encoding where equi-propagation and partial evaluation facilitate optimization of the constraint model. This, fast (polynomial-time) optimization phase is followed by the more costly (exponential-time) SAT solving phase. A novel and efficient implementation of equi-propagation using binary decision diagrams (BDD's) [4] is described. Experiments demonstrate for a variety of constraint problems that equi-propagation significantly reduces the size of their encoding to CNF formulae as well as the solving time required for a SAT solver to find a solution.

2 Overview

In this section we illustrate the main ideas we apply to simplify a constraint model prior to its encoding as a CNF formula. To support the presentation we first introduce a core portion of the underlying modelling language. Here, constraints are about finite domain integer variables and viewed as Boolean functions about the low-level bit representation of these variables. Our compiler supports both unary and binary integer representations, however in the paper we focus on a unary representation, the *order encoding*. Consider the following three constructs in the modelling language.

$$\boxed{1} \text{ unary}_n(X, [a, b]) \quad \boxed{2} \text{ diff}(X_1, X_2) \quad \boxed{3} \text{ allDiff}([X_1, \dots, X_n])$$

A constraint $\text{unary}_n(X, [a, b])$ where $0 \leq a \leq b \leq n$ specifies a finite domain integer variable $X = \langle x_1, \dots, x_n \rangle$, represented in n bits, which takes values in the interval $[a, b]$. We denote by $\text{dom}(X)$ the finite set of values that variable X can take. Initially, $\text{dom}(X) = \{a, \dots, b\}$. When clear from the context, we drop n from the notation. A constraint, $\text{diff}(X_1, X_2)$, specifies that integer variables (bit vectors) X_1 and X_2 take different values from their respective domains. The third construct, $\text{allDiff}(Xs)$, specifies that integer variables $Xs = [X_1, \dots, X_m]$ all take different values from their respective domains. The argument of this constraint is a list of bit vectors. We denote $\text{dom}(Xs) = \cup \{ \text{dom}(X_i) \mid 1 \leq i \leq m \}$.

In the *order encoding* (see e.g. [6, 1]), the bit vector representation of integer variable $X = \langle x_1, \dots, x_n \rangle$ constitutes a monotonic decreasing sequence. For example, the value 3 in 5 bits is represented as $\langle 1, 1, 1, 0, 0 \rangle$. The bit x_i (for $1 \leq i \leq n$) is interpreted as the statement $X \geq i$. Throughout the paper, for a bit vector $X = \langle x_1, \dots, x_n \rangle$ representing an integer in the order-encoding, we assume implicit bits $x_0 = 1$ and $x_{n+1} = 0$, and denote $X(i) = x_i$ for $0 \leq i \leq n+1$.

An important property of a Boolean representation for finite domain integers is the ability to represent changes in the set of values a variable can take. It is well-known that the order-encoding facilitates the propagation of bounds. Consider an integer variable $X = \langle x_1, \dots, x_n \rangle$ with values in the interval $[0, n]$. To restrict X to take values in the range $[a, b]$ (for $1 \leq a \leq b \leq n$), it is sufficient to assign $x_a = 1$ and $x_{b+1} = 0$ (if $b < n$). The variables $x_{a'}$ for $0 \geq a' > a$ and $b < b' \leq n$ are then determined true and false, respectively, by *unit propagation*. For example, given $X = \langle x_1, \dots, x_9 \rangle$, assigning $x_3 = 1$ and $x_6 = 0$ propagates to give $X = \langle 1, 1, 1, x_4, x_5, 0, 0, 0, 0 \rangle$, signifying that $\text{dom}(X) \subseteq \{3, \dots, 5\}$. This property is exploited in Sugar [20] which also applies the order encoding.

We observe an additional property of the order-encoding: its ability to specify that a variable cannot take a specific value $0 \leq v \leq n$ in its domain by equating two variables: $x_v = x_{v+1}$. This indicates that the order-encoding is well-suited not only to propagate lower and upper bounds, but also to represent integer variables with an arbitrary, finite set, domain. For example, for $X = \langle x_1, \dots, x_9 \rangle$, equating $x_2 = x_3$ imposes that $X \neq 2$. Likewise $x_5 = x_6$ and $x_7 = x_8$ impose that $X \neq 5$ and $X \neq 7$. Applying these equalities to X gives, $X = \langle x_1, x_2, x_2, x_4, x_5, x_5, x_7, x_7, x_9 \rangle$, signifying that $\text{dom}(X) = \{0, 1, 3, 4, 6, 8, 9\}$.

The Boolean functions corresponding to constraints $\boxed{1} - \boxed{3}$ are as follows (where $1 \leq a \leq b \leq n$):

$$\begin{aligned} \text{unary}(\langle x_1, \dots, x_n \rangle, [a, b]) &= \bigwedge_{i=1}^n (x_{i-1} \leftarrow x_i) \wedge x_a \wedge \neg x_{b+1} \\ \text{diff}(\langle x_1, \dots, x_n \rangle, \langle y_1, \dots, y_n \rangle) &= \bigvee_{i=1}^n (x_i \text{ xor } y_i) \\ \text{allDiff}([X_1, \dots, X_m]) &= \bigwedge_{1 \leq i < j \leq m} \text{diff}(X_i, X_j) \end{aligned} \tag{1}$$

For constraint c with integer variable arguments, we denote by c_u the conjunction of c with the statement that its arguments are represented in the order-encoding. For example, $\text{diff}_u(X, Y) = \text{diff}(X, Y) \wedge \text{unary}_n(X, [0, n]) \wedge \text{unary}_n(Y, [0, n])$.

The idea in this paper is to simplify constraints, prior to their encoding to CNF, using a technique we call *equi-propagation*. We distinguish between *low-level constraints*, such as $\text{unary}(X, [a, b])$ and $\text{diff}(X_1, X_2)$, which are about a fixed number (one and two) of integer variables, and *high-level constraints*, such as $\text{allDiff}([X_1, \dots, X_m])$. Low-level constraints are simplified and then encoded directly to CNF, while high-level constraints are simplified and then decomposed to low-level constraints. We now demonstrate three types of simplification rules on the constraint $\text{diff}(X, Y)$ where $X = \langle x_1, x_2, x_3, x_4 \rangle$ and $Y = \langle y_1, y_2, y_3, y_4 \rangle$ are integer variables in the unary, order-encoding.

(1) *equi-propagation*, where we propagate information about equalities between Boolean literals and constants. For example, assuming that $Y = \langle 1, 1, 0, 0 \rangle$ we

propagate that $(x_2 = x_3)$ because $\text{diff}_u(\langle x_1, x_2, x_3, x_4 \rangle, \langle 1, 1, 0, 0 \rangle) \models (x_2 = x_3)$. To see why, consider that X is in the order-encoding, so $x_2 \geq x_3$. Furthermore, also $x_2 \leq x_3$ as otherwise $x_2 = 1$ and $x_3 = 0$ which implies that $X = \langle 1, 1, 0, 0 \rangle$ (because also $x_1 \geq x_2$ and $x_3 \geq x_4$), contradicting $\text{diff}(X, Y)$. When we detect such equalities, we apply them to simplify the constraints in a model.

(2) *redundant constraint elimination*, where we discover that, given information about equalities between Boolean literals and constants, a constraint is redundant. For example, when $Y = \langle 1, 1, 0, 0 \rangle$ and $x_2 = x_3$, then $\text{diff}(X, Y)$ is redundant because $\text{unary}(X, [0, 4]) \wedge (Y = \langle 1, 1, 0, 0 \rangle) \wedge (x_2 = x_3) \models \text{diff}(X, Y)$.

(3) *constraint restriction*, where we discover that some bits in a constraint c are “dont-cares” and project c to the remaining variables. For example, when $x_1=1$ and $x_2=1$ then y_1 is a don’t care and $\text{diff}(X, Y)$ is equivalent to $\text{diff}(X', Y')$ where $X' = \langle x_2, x_3, x_4 \rangle$ and $Y' = \langle y_2, y_3, y_4 \rangle$. To see why $\text{unary}(X, [0, 4]) \wedge \text{unary}(Y, [0, 4]) \wedge x_1 = 1 \wedge x_2 = 1 \models \text{diff}(X, Y) \leftrightarrow \text{diff}(X', Y')$, consider that if $y_1 = 0$ then also $y_2 = 0$ and both diff constraints are true, and if $y_1 = 1$ then $x_1 \text{ xor } y_1 = \text{false}$ and $\text{diff}(X, Y) \leftrightarrow \text{diff}(X', Y')$ follows.

In addition to simplification rules, we apply *decomposition rules* to high-level constraints. For example, an `allDiff` constraint decomposes naturally to a set of constituent `diff` constraints. The rule we apply to decompose `allDiff` constraints is as follows:

$$\text{allDiff}([U_1, \dots, U_m]) \mapsto \{ \text{diff}(U_i, U_j) \mid 1 \leq i < j \leq m \}, \quad (2)$$

$$\text{permutation}_{\#}([U_1, \dots, U_m])$$

where $\text{permutation}_{\#}$ is a redundant constraint.⁴ Its role is to introduce redundant clauses to accelerate SAT solving for the special case when the `allDiff` constraint specifies a permutation (m variables taking m different values). By delaying the special treatment of `allDiff` constraints which specify permutations we can often detect more permutations than prior to constraint simplification. The precise specification of the $\text{permutation}_{\#}$ constraint is given in Section 4.

3 Boolean Equi-Propagation

Let \mathcal{B} be a set of Boolean variables. A *literal* is a Boolean variable $b \in \mathcal{B}$ or its negation $\neg b$. The negation of a literal ℓ , denoted $\neg \ell$, is defined as $\neg b$ if $\ell = b$ and as b if $\ell = \neg b$. The Boolean constants 1 and 0 represent *true* and *false*, respectively. The set of literals is denoted \mathcal{L} and $\mathcal{L}_{0,1} = \mathcal{L} \cup \{0, 1\}$.

An *assignment*, A , is a partial mapping from Boolean variables to constants, often viewed as the set of literals: $\{ b \mid A(b) = 1 \} \cup \{ \neg b \mid A(b) = 0 \}$. For a formula φ and $b \in \mathcal{B}$, we denote by $\varphi[b]$ (likewise $\varphi[\neg b]$) the formula obtained by substituting all occurrences of $b \in \mathcal{B}$ in φ by *true* (*false*). This notation extends in the natural way for sets of literals. We say that A satisfies φ if $\varphi[A]$ evaluates to *true*. A *Boolean Satisfiability (SAT) problem* consists of a Boolean formula φ

⁴ The symbol $\#$ in the name of a constraint indicates that it is redundant.

and determines if there exists an assignment which satisfies φ . The set of (free) Boolean variables that appear in a Boolean formula φ is denoted $\text{vars}(\varphi)$.

A *Boolean equality* is a constraint $\ell = \ell'$ where $\ell, \ell' \in \mathcal{L}_{0,1}$. An *equi-formula* E is a set of Boolean equalities understood as a conjunction. The set of equi-formulae is denoted \mathcal{E} , and (bi-)implication of equi-formulae is denoted $(\leftrightarrow) \supset$.

Equi-propagation is the process of inferring new equational consequences from the constraints of a model and existing equational information. An *equi-propagator* for Boolean formula φ is an extensive function $\mu_\varphi : \mathcal{E} \rightarrow \mathcal{E}$ defined s.t. for all equi-formula E , $\wedge \{ e \in \mathcal{E} \mid \varphi \wedge E \models e \} \supset \mu_\varphi(E) \supset E$. That is, a conjunction of Boolean equalities, at least as strong as E , made true by $\varphi \wedge E$. We say that equi-propagator μ_φ is complete if $\mu_\varphi(E) \leftrightarrow \{ e \in \mathcal{E} \mid \varphi \wedge E \models e \}$. We denote a complete equi-propagator for φ as $\hat{\mu}_\varphi$.

Example 1. Let $X = \langle x_1, x_2, x_3, x_4 \rangle$ and $Y = \langle y_1, y_2, y_3, y_4 \rangle$ and consider $E_1 = \{ y_1 = 1, y_2 = 1, y_3 = 0, y_4 = 0 \}$ and $E_2 = \{ x_2 = \neg y_3, x_3 = y_2 \}$. Then, $\hat{\mu}_{\text{diff}_u(X,Y)}(E_1) = E_1 \cup \{ x_2 = x_3 \}$ and also $\hat{\mu}_{\text{diff}_u(X,Y)}(E_2) = E_2 \cup E_1$.

The following theorem states that complete equi-propagation for a Boolean formula φ will determine at least as many fixed literals as unit propagation for *any* clausal representation of φ .

Theorem 1. *Complete equi-propagation is uniformly stronger than unit propagation.*

Proof. Let φ be a Boolean formula, $E \in \mathcal{E}$, and let ℓ be a literal that follows from unit propagation from some clausal representation of φ and E . Then $\varphi \wedge E \models \ell$ and hence $(\ell = 1) \in \hat{\mu}_\varphi(E)$.

Boolean Unifiers It is convenient to view equi-formula in a generic “solved-form” as a substitution, θ_E , which is a (most general) unifier for the equations in E . Boolean substitutions generalize assignments in that variables can be bound also to literals. A Boolean *substitution* is an idempotent mapping $\theta : \mathcal{B} \rightarrow \mathcal{L}_{0,1}$ such that $\text{dom}(\theta) = \{ b \in \mathcal{B} \mid \theta(b) \neq b \}$ is finite and $\forall b \in \mathcal{B}. \theta(b) \neq \neg b$. It is viewed as the set $\theta = \{ b \mapsto \theta(b) \mid b \in \text{dom}(\theta) \}$. We can apply θ to another substitution θ' , to obtain substitution $(\theta \cdot \theta') = \{ b \mapsto \theta(\theta'(b)) \mid b \in \text{dom}(\theta) \cup \text{dom}(\theta') \}$. A *unifier* for equi-formula E is a substitution θ such that $\models \theta(e)$, for each $e \in E$. A *most-general unifier* for E is a substitution θ such that for any unifier θ' of E , there exists substitution γ where $\theta' = \gamma \cdot \theta$.

Example 2. Consider the equi-formula $E \equiv \{ b_1 = \neg b_2, \neg b_3 = \neg b_4, b_5 = b_6, b_6 = b_4, b_7 = 1, b_8 = \neg b_7 \}$ then a unifier θ for E is $\{ b_2 \mapsto \neg b_1, b_4 \mapsto b_3, b_5 \mapsto b_3, b_6 \mapsto b_3, b_7 \mapsto 1, b_8 \mapsto 0 \}$. Note that $\theta(E)$ is the trivially true equi-formula $\{ b_1 = \neg \neg b_1, \neg b_3 = \neg b_3, b_3 = b_3, b_3 = b_3, 1 = 1, 0 = \neg 1 \}$.

Let \prec be a total (strict) order on \mathcal{B} , extended to an order on $\mathcal{L}_{0,1}$ such that $0 \prec 1$ and $\forall b \in \mathcal{B}. 1 \prec b$ and $b \approx \neg b$. We define a canonical most-general unifier for any satisfiable equi-formula E : $\text{unify}_E = \lambda b. \min \{ \ell \in \mathcal{L}_{0,1} \mid E \models b = \ell \}$. We can compute unify_E in almost linear (amortized) time using a variation of the union-find algorithm [21].

Example 3. For the equi-formula E and substitution θ from Example 2 we have that $\text{unify}_E = \theta$ where the ordering is $0 \prec 1 \prec b_1 \prec b_2 \prec \dots \prec b_8$.

The following allows us to replace formula φ by $\text{unify}_E(\varphi)$, and provides an alternative, more efficient to implement, definition for complete equi-propagation.

Proposition 1.

$$\varphi \wedge E \leftrightarrow \text{unify}_E(\varphi) \wedge E$$

Proposition 2.

$$\hat{\mu}_\varphi(E) \leftrightarrow E \wedge \{e \in \mathcal{E} \mid \text{unify}_E(\varphi) \models e\}$$

Implementing complete equi-propagators A complete equi-propagator is straightforward to implement using binary decision diagrams (BDDs). Consider Boolean formula φ and equi-formula E . Then, for equation $(\ell_1 = \ell_2)$, based on Proposition 2, we can test the condition, $\text{unify}_E(\varphi) \models (\ell_1 \leftrightarrow \ell_2)$ using a standard BDD containment test e.g., “`bddLeq`” in [19]. This test can be performed for all relevant equations involving variables from $\text{unify}_E(\varphi)$ (and constants 0,1).

Example 4. Consider the BDD shown in Figure 3(a) which represents the formula: $\varphi \equiv \text{unary}_3(A, [0, 3]) \wedge \text{unary}_3(B, [0, 3]) \wedge \text{diff}(A, B)$. Suppose that E is $\{B_1 = 1, B_2 = 1, B_3 = 0\}$. The BDD for $\text{unify}_E(\varphi)$ is shown in Figure 3(b). It is easy to see from the BDD that equi-propagation determines that $\text{unify}_E(\varphi) \models A_2 = A_3$. Indeed $\hat{\mu}_\varphi(E) = E' = E \cup \{A_2 = A_3\}$.

We apply complete equi-propagation in cases when BDDs are guaranteed to be polynomial in the size of the constraints they propagate for. The following result holds for an arbitrary constraint φ , so it also holds for $\text{unify}_E(\varphi)$.

Proposition 3. *Let $c(Xs)$ be an arbitrary constraint about integer variables $Xs = [X_1, \dots, X_k]$ each represented with n bits in the order encoding. Then, the number of nodes in the BDD representing $c(Xs)$ is bound by $O(n^k)$.*

Proof. (Sketch) There are only $n + 1$ legitimate states for each n bit unary variable, and the BDD cannot have more nodes than possible states. \square

Implementing ad-hoc equi-propagators Most simple constraints have a fixed small arity and hence complete equi-propagators using BDD are polynomially bounded. However, this is not the case for global constraints where the arity is not fixed. In this case we define an ad-hoc, possibly incomplete, equi-propagator. We demonstrate this for the `allDiff`($[U_1, \dots, U_m]$) constraint.

Example 5. Consider $Us = [U_1, \dots, U_5]$ where the $U_i = \langle x_{i1}, \dots, x_{i9} \rangle$ are integer variables in the range $[0, 9]$. Given E , we denote $\text{unify}_E(Us) = [U'_1, \dots, U'_5]$ and illustrate equi-propagator $\mu_\varphi(E) = E \cup E'$ for $\varphi = \text{allDiff}_u(Us)$: **(1)** Consider $E = \{x_{12}=1, x_{13}=0\}$. Denoting $E_a = \{x_{1j} = j \leq 2 \mid 1 \leq j \leq 9\}$ (e.g. $U'_1 = 2$), and $E_b = \{x_{i2} = x_{i3} \mid 2 \leq i \leq 5\}$ (e.g. $U'_i \neq 2$ for $i > 1$), the propagator adds $E' = E_a \cup E_b$. **(2)** Consider $E = E_b \cup E_c$ where $E_c = \{x_{i5} = 0 \mid 1 \leq i \leq 5\}$ (e.g. $U_i \leq 4$) and E_b is from the previous case. In this case, only U_1 can take the value 2. So a propagator adds equations imposing that $U'_1 = \langle 1, 1, 0, \dots, 0 \rangle$. **(3)** Consider $E = E_c \cup E_d$ where $E_d = \bigcup \{x_{i1} = x_{i2}, x_{i3} = x_{i4} \mid 3 \leq i \leq 5\}$ (e.g. only U_1 and U_2 can take the values 1 and 3) and E_c is from the previous case. A propagator adds $E' = \bigcup \{x_{i1} = 1, x_{i2} = x_{i3}, x_{i4} = 0 \mid i \in \{1, 2\}\}$.

The following is essentially the usual domain consistent propagator for the `allDiff` constraint [18] applied to the unary encoding.

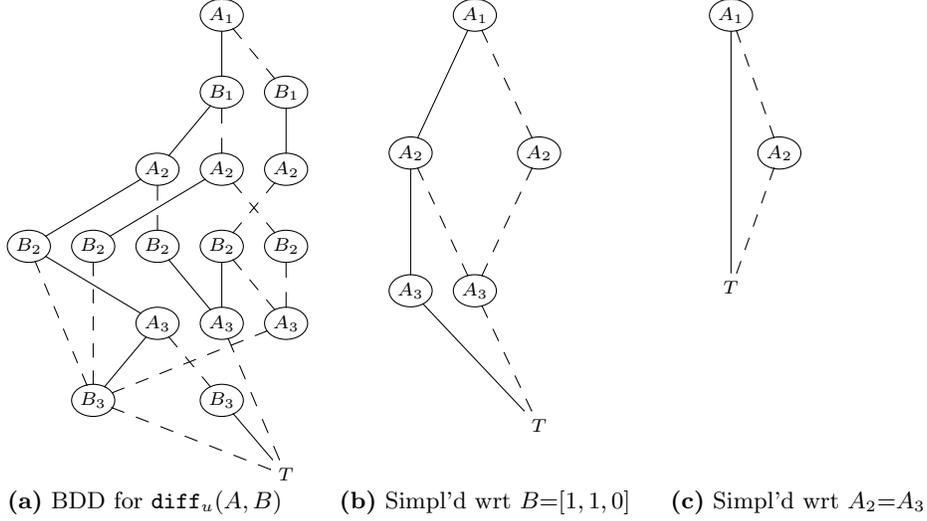


Fig. 1. BDDs for (a) $\varphi \equiv \text{unary}_3(A, [0, 3]) \wedge \text{unary}_3(B, [0, 3]) \wedge \text{diff}(A, B)$ (b) $\text{unify}_E(\varphi)$ where $E = \{B_1=1, B_2=1, B_3=0\}$ and (c) $\text{unify}_{E'}(\varphi)$ where $E' = E \cup \{A_2=A_3\}$. Full (dashed) lines correspond to true (false) edges. Target “F” node is omitted for brevity.

Definition 1 (ad-hoc equi-propagator for allDiff). An equi-propagator for $\varphi = \text{allDiff}_u(Us)$ where $Us = [U_1, \dots, U_m]$ is defined as $\mu_\varphi(E) = E \cup E'$ where $E' = \{U'_i(v) = U'_i(v+1) \mid i \in \{1, \dots, m\} - H, v \in V\}$ if there exists a Hall set $H \subseteq \{1, \dots, m\}$ where $V = \cup_{i \in H} \text{dom}(U'_i)$, $|V| = |H|$ and denoting $\text{unify}_E(Us) = [U'_1, \dots, U'_m]$. Otherwise, $E' = \emptyset$.

After a Hall set H is detected (and equi-propagation has triggered), we also apply an additional decomposition rule:

$$\text{allDiff}(Us) \mapsto \text{allDiff}([U_i \mid i \in H]) \wedge \text{allDiff}([U_i \mid i \in \{1, \dots, m\} - H])$$

The benefit arises because the first allDiff constraint is guaranteed to represent a permutation so the $\text{permutation}_\#$ constraint gives an advantage.

For the three cases in Example 5 we have: **(1)** $H=\{1\}$ and $V=\{2\}$, **(2)** $H=\{2, 3, 4, 5\}$, and $V=\{0, 1, 3, 4\}$, and **(3)** $H=\{3, 4, 5\}$ and $V=\{0, 2, 4\}$. Indeed we can convert any finite domain propagator to an equi-propagator. The following holds simply because the unary encoding can represent arbitrary domains.

Proposition 4. Let $E \in \mathcal{E}$ and $c(Xs)$ be a constraint over integer variables $Xs = [X_1, \dots, X_m]$. Let $\text{unify}_E(Xs) = [X'_1, \dots, X'_m]$. Suppose D is the mapping from variables to sets of value $D(X_i) = \text{dom}(X'_i)$ and suppose propagator f for $c(Xs)$ maps D to D' . Then a correct equi-propagator for $c(Xs)$ discovers new equality literals $E' = \{X'_i(v) = X'_i(v+1) \mid i \in \{1, \dots, m\}, v \in D(X_i) - D'(X_i)\}$.

Note that complete equi-propagators can determine more information than finite domain propagation as illustrated by the example for E_2 in Example 1. To complete this section, consider the following example.

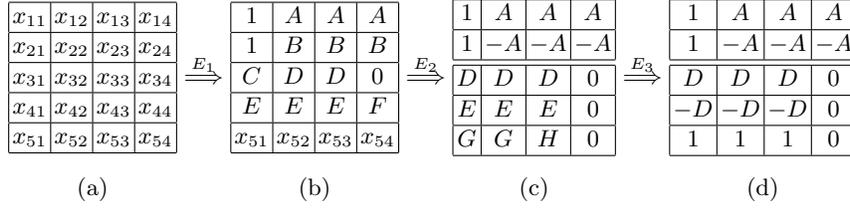


Fig. 2. An example of equi-propagation (See Example 6)

Example 6. Consider constraint $\varphi = \text{allDiff}(Xs)$ where $Xs = [X_1, \dots, X_5]$ with each X_i in the interval $[0, 4]$, depicted as Fig. 2(a). Consider also the equi-formula E_1 which specifies that $X_1, X_2 \in \{1, 4\}$, $X_3 \in \{0, 1, 3\}$, $X_4 \in \{0, 3, 4\}$. Fig. 2(b) depicts $\text{unify}_{E_1}(Xs)$. Constraint simplification proceeds in two steps. First, equi-propagation adds equi-formula E_2 , the affect of which is depicted as Fig. 2(c) where φ is also decomposed: The upper part, $\text{allDiff}(X_1, X_2)$, and the lower part $\text{allDiff}(X_3, X_4, X_5)$. In the second step equi-propagation adds equi-formula E_3 , the impact of which is depicted as Fig. 2(d). Constraint φ is now fully solved, Xs is represented using only 2 propositional variables and the CNF encoding will contain no clauses.

4 Optimized SAT encodings using Equi-propagation

Boolean equi-propagation is at the foundation of our optimizing CNF compiler. The compiler repeatedly applies: equi-propagation, constraint decomposition, restriction and elimination, and finally outputs CNF encodings. We assume that each constraint comes with an associated equi-propagator.

Given a conjunction Φ of constraints, we first apply equi-propagators. Each such application effectively removes at least one bit from the Boolean representation of Φ . During this process, when no further equi-propagators can be applied, we may apply a decomposition rule to a high-level constraint, introducing additional low-level constraints, but without introducing additional bits in the system. The actual implementation is of course less naive. It takes care to wakeup equi-propagators only when they may generate new information, and it makes use of the most efficient implementation of the equi-propagator possible, so avoiding BDD based propagators if we have an equivalent propagator implemented directly.

The complexity of the compiler is measured in the size of the constraint system Φ it is optimizing. Denote by $|\Phi|_c$, the total number of low-level constraints in Φ after decomposing all high-level constraints, and by $|\Phi|_b$ the total number of Boolean variables in the bit representation of Φ . Assuming that equi-propagators are of polynomial cost, then so is the cost of running the compiler itself.

Proposition 5. *Let Φ be a conjunction of high- and low-level (finite domain) constraints. Then the number of equi-propagation steps performed when compiling Φ is bound by $O(|\Phi|_c \times |\Phi|_b)$.*

Proof. (sketch) Each pass of the algorithm covers at most $|\Phi|_c$ constraints and removes at least one of the $|\Phi|_b$ Boolean variables from Φ . \square

After equi-propagation and constraint decomposition triggers no more, we apply constraint restriction and elimination rules. We say that a constraint φ is redundant with respect to an equi-formula E if either (a) $\text{unify}_E(\varphi)$ is a tautology or (b) there exists another constraint φ' in the constraint store such that $\text{unify}_E(\varphi') \models \text{unify}_E(\varphi)$. Our implementation is tuned to identify a collection of ad-hoc cases. However in general, where BDDs have been applied to implement complete propagators, such tests are particularly easy. Testing for (a) is trivial. Testing for (b) is also straightforward for BDDs e.g., using “bddLeq” in [19]. However we only apply this rule in a restricted form due to the quadratic time-complexity of examining all pairs of constraints. Namely, to determine cases of the form $\text{true}_u(X_1, \dots, X_n) \models c(X_1, \dots, X_n)$ where the constraint is redundant with respect to the unary encoding of its variables.

Example 7. Take $\varphi = \text{diff}_u(A, B)$ and E' from Example 4. The BDD for $\varphi'' = \text{unify}_{E'}(\varphi)$ is shown in Figure 3(c). One can check that $\text{unary}(A, [0, 4]) \models \varphi''$ using “bddLeq” indicating that the original constraint $\text{diff}(A, B)$ is redundant.

In the final stage, when no further simplification applies, constraints are encoded to CNF formula. This can be performed either using their Boolean specification, or if BDD based propagators were applied, then we can read off the encoding from the BDD using standard techniques.

Redundant constraints (with subscript $\#$ in the name) that were introduced in the model only to improve equi-propagation need not be encoded to CNF clauses. However, when we expect such redundant clauses to facilitate unit propagation during SAT solving, then we do add them. For instance, we add clauses to encode redundant **permutation $\#$** constraints. Each such constraint $\varphi' = \text{permutation}_\#([U_1, \dots, U_m])$ is affiliated with a corresponding **allDiff** constraint. If $S = \cup_{i=1}^m \text{dom}(U_i)$, $|S| \neq m$ then the **allDiff** constraint does not represent a permutation and nothing is added. Otherwise we create additional Boolean variables b_{iv} to represent the expressions $U_i = v, v \in S$. Let the unary encoding of U_i be $\langle u_1, \dots, u_k \rangle$. We add clauses encoding $b_{iv} \leftrightarrow (u_v \wedge \neg u_{v+1})$ to connect these to the unary encoding, and the clauses $\bigvee_{i=1}^m b_{iv}, \forall v \in S$ to get better propagation from permutations.

5 Implementation, Experiments, and Extensions

All experiments were performed on an Intel Core 2 Duo E8400 3.00GHz CPU with 4GB memory under Linux (Ubuntu lucid, kernel 2.6.32-24-generic).⁵ Our prototype constraint compiler is written in Prolog and run using SWI Prolog v5.10.2 64-bits. Complete propagators are implemented using the BDD package, CUDD v2.4.2. Comparisons with Sugar (v1.14.7) are based on the use of identical

⁵ The benchmark instances and encodings can be viewed at <http://www.cs.bgu.ac.il/~mcodish/Benchmarks/CP2011/>.

instance		compiler			Sugar		3D		CSP'08	OSC'09	FS'09
num	un/sat	compl	cnf size	SAT	cnf size	SAT	cnf size	SAT	(sec.)	(sec.)	(sec.)
		(sec.)	(clauses)	(sec.)	(clauses)	(sec.)	(clauses)	(sec.)			
1	sat	0.41	6509	2.46	140315	37.36	6507	0.09	31.55	34.81	6.44
2	sat	0.33	7475	0.02	140920	234.70	7438	0.74	137.60	99.84	44.80
4	sat	0.38	6818	0.61	141581	90.64	6811	0.08	47.24	273.36	157.58
5	sat	0.35	7082	0.32	140431	206.03	7099	0.14	27.33	24.87	22.30
6	sat	0.33	7055	0.45	140625	67.84	7044	1.11	35.78	108.60	12.58
7	sat	0.33	7711	2.36	142200	60.97	7684	0.08	57.23	67.32	341.62
11	unsat	0.45	6491	0.05	140603	39.02	6534	0.03	19.47	30.92	5.30
12	unsat	0.23	1	0.00	139037	0.58	7393	0.00	0.36	0.05	0.81
14	unsat	0.28	1	0.00	140706	2.25	7173	0.00	1.40	0.29	0.80
15	unsat	0.38	6063	0.05	140224	35.93	6104	0.06	32.39	58.41	4.77

Table 1. QCP results for 25×25 instances with 264 holes

constraint models, apply the same SAT solver (CryptoMiniSat v2.5.1), and run on the same machine. Comparisons with Minion (v0.10) are based on the use of identical constraint models, and run on the same machine (with minor differences due to syntax). For each of the example problems we extend (our description of) the constraint modelling language as required for the benchmarks.

Quasigroup Completion Problems (QCP) are given as an $n \times n$ board of integer variables (in the range $[1, n]$) in which some are assigned integer values. The task is to assign values to all variables, so that no column or row contains the same value twice. A model is a conjunction of `allDiff` constraints.

Table 1 illustrates results for 10 (of the largest) instances from the 2008 CSP competition⁶ with data for our compiler (compilation time, number of clauses, SAT solving time), Sugar (number of clauses, subsequent SAT solving time), the so-called 3D SAT encoding of [12] (number of clauses after unit propagation, SAT solving time), and from: CSP'08 (the winning result from the 2008 competition), OSC'09 and FS'09 (results for lazy clause generation solvers reported in [16] and [9]). It is, by now, accepted that the 3D encoding is strong for QCP problems, a fact echoed by the results of Table 1. Observe that for 2 instances, unsatisfiable is detected directly by the compiler (where the CNF contains 1 empty clause).

Table 2 shows results for larger (40×40 , satisfiable) instances⁷ with 800-1000 holes. We compare the order-encoding (compiled) and the 3D-encoding (with unit propagation). The CNF sizes before compilation/unit propagation are circa 2.74 million clauses for the order-encoding and 3.74 for the 3D-encoding. The advantage of the 3D encoding is no longer clear.

This experiment indicates that our compiler competes with the 3D encoding for QCP. Other high level models are clearly inferior. The comparison with Sugar

inst.	order enc.		3D enc.		inst.	order enc.		3D enc.	
	CNF mCl	SAT (sec)	CNF mCl	SAT (sec)		CNF mCl	SAT (sec)	CNF mCl	SAT (sec)
800 holes					1000 holes				
1	0.11	18.24	0.13	6.87	1	0.31	0.40	0.38	27.78
2	0.11	2.88	0.13	3.70	2	0.31	0.39	0.38	0.33
3	0.11	6.54	0.13	2.50	3	0.31	0.39	0.39	19.76
4	0.11	0.34	0.13	1.47	4	0.31	0.39	0.38	8.73
5	0.11	21.50	0.13	7.09	5	0.31	0.39	0.38	0.35
total	50.05		22.28		total	1.96		56.95	

Table 2. QCP 40×40 . CNF size in **million's** clauses

⁶ <http://www.cril.univ-artois.fr/CPAI08/>

⁷ Generated using lencode from <http://www.cs.cornell.edu/gomes/SOFT>.

(stunning reduction in CNF size and faster SAT solving) is representative of all other experiments and hence not highlighted in the following result tables.

Nonogram Problems are boards of cells to color black or white, given clues per row and column of a board. A clue is a number sequence indicating blocks of cells to be colored black. For example, the clue $\langle 4, 8, 3 \rangle$ on a row indicates that it should contain contiguous blocks of 4, 8 and 3 black cells (in that order) separated by non-empty sequences of white cells. A Nonogram puzzle is modeled as a Boolean matrix with constraints per row and column, each about a clue (number sequence) $\langle b_1, \dots, b_k \rangle$, and about a Boolean vector, Vec (a row or column of the matrix). Each b_i is associated with an integer variable indicating the index in Vec where block b_i starts. For notation, if $U = \langle u_1, \dots, u_n \rangle$ is an integer variable (order-encoding) then U^{+c} is U prefixed by c ones representing $U+c$. Similarly, if U is greater than c then $U^{-c} = \langle u_{c+1}, \dots, u_n \rangle$ represents $U-c$. We introduce two additional constraints

$$\boxed{4} \text{ block}(U_1, U_2, Vec)$$

$$\boxed{5} \text{ leq}(U_1, U_2)$$

The first specifies that for a bit vector Vec the variables in the indices greater than value U_1 and less equal value U_2 (with $U_1 \leq U_2$) are true. The second specifies that for integer variables U_1 and U_2 in the order-encoding, $U_1 \leq U_2$. The Boolean functions corresponding to constraints of these forms are as follows:

$$\begin{aligned} \text{block}(U_1, U_2, \langle x_1, \dots, x_n \rangle) &= \bigwedge_{i=1}^n (\neg U_1(i) \wedge U_2(i) \rightarrow x_i) \\ \text{leq}(\langle x_1, \dots, x_n \rangle, \langle y_1, \dots, y_n \rangle) &= \bigwedge_{i=1}^n x_i \rightarrow y_i \end{aligned} \quad (3)$$

Example 8. The constraints below model the position of block sequence $s = \langle 3, 1, 2 \rangle$ in $X = \langle x_1, \dots, x_9 \rangle$. In the first column, integer variables, U_1, U_2, U_3 model the start positions of the three blocks. In the second column, the start position of a block is required to be at least one after the end position of its predecessor. In the third column, **block** constraints specify the black cells in the vector X , and in the fourth column the white cells in the block $\bar{X} = \langle \neg x_1, \dots, \neg x_9 \rangle$.

$$\begin{array}{llll} \text{unary}(U_1, [1, 9]) & & \text{block}(U_1^{-1}, U_1^{+3}, X) & \text{block}(0, U_1, \bar{X}) \\ \text{unary}(U_2, [1, 9]) & \text{leq}(U_1^{+4}, U_2) & \text{block}(U_2^{-1}, U_2^{+1}, X) & \text{block}(U_1^{+4}, U_2, \bar{X}) \\ \text{unary}(U_3, [1, 9]) & \text{leq}(U_2^{+2}, U_3) & \text{block}(U_3^{-1}, U_3^{+2}, X) & \text{block}(U_2^{+2}, U_3, \bar{X}) \end{array}$$

Tables 3 & 4 compare ours to the two fastest documented Nonogram solvers: BGU (v1.0.2) [17] and Wolter (v1.09) [24].

Table 3 is about “human-designed” instances from [22]. These are the 10 hardest problems for the BGU solver. The first 8 puzzles have at least 2 solutions. The last 2 have a single solution.

Solving time is for determining the number of solutions (0, 1, or more). For our

instance		compiler				
id	size	comp	cnf	sat	BGU	Walt.
9717	(30x30)	0.13	14496	124.43	∞	∞
10000	(50x40)	0.28	44336	40.66	∞	∞
9892	(40x50)	0.57	30980	0.44	∞	∞
2556	(45x65)	0.13	2870	0.00	15.85	0.4
10088	(63x52)	0.64	78482	1.26	0.27	0.08
2712	(47x47)	0.31	43350	0.92	5.98	4.95
6727	(80x80)	1.11	156138	2.86	0.5	0.17
8098	(19x19)	0.02	3296	0.06	209.54	8.63
6574	(25x25)	0.10	7426	0.03	37.56	2.94

Table 3. Human Nonograms Results

solver	time (sec)	0.20	0.50	1.00	10.00	30.00	60.00
	BGU	279	3161	4871	4978	4989	4995
Wolter	4635	4782	4840	4952	4974	4976	
Compiler	13	4878	4994	5000	5000	5000	5000

Table 4. 5,000 Random Nonograms Results

compiler, the columns indicate: compilation time, cnf size (number of clauses) and sat solving time. The final two columns are about the solution times for the BGU and Wolter solvers (running on the same machine). The timeout for these solvers (indicated by ∞) is 300 sec. Table 4 reports on a collection of 5,000 random puzzles from [23]. For each of the three solvers we indicate how many puzzles it solves within the given allocated time. This experiment indicates that our compiler is superior to other known methods for Nonograms. We apply generic SAT solving compared to the other systems which are nonogram-specific.

BIBD Problems (CSplib problem 28) are defined by a 5-tuple of positive integers $\langle v, b, r, k, \lambda \rangle$ and require to partition v distinct objects into b blocks such that each block contains k different objects, exactly r objects occur in each block, and every two distinct objects occur in exactly λ blocks. To model BIBD problems we introduce three additional constraints

$$\boxed{6} \text{ sumBits}([B_1, \dots, B_n], U) \qquad \boxed{7} \text{ uadder}(U_1, U_2, U_3)$$

$$\boxed{8} \text{ pairwise_and}([A_1, \dots, A_n], [B_1, \dots, B_n], [C_1, \dots, C_n])$$

The first (high-level) constraint states that the sum of bits, $[B_1, \dots, B_n]$ is the unary value U . It is defined by decomposition: split the bits into two parts, sum the parts, then add the resulting (unary) numbers. The sum of two unary numbers, $U_1 + U_2 = U_3$, is specified by the (low-level) constraint $\text{uadder}(U_1, U_2, U_3)$. To compute the scalar product of vectors $[A_1, \dots, A_n]$ and $[B_1, \dots, B_n]$ we use the pairwise_and constraint in combination with sumBits .

instance $\langle v, b, r, k, \lambda \rangle$	compiler (SymB)			Minion			SATELITE (SymB)		
	comp (sec.)	cnf size (clauses)	SAT (sec.)	[M'06] (sec.)	SymB (sec.)	SymB ⁺ (sec.)	prepro (sec.)	cnf size (clauses)	SAT (sec.)
$\langle 7, 420, 180, 3, 60 \rangle$	1.65	698579	1.73	0.54	1.36	0.42	1.67	802576	2.18
$\langle 7, 560, 240, 3, 80 \rangle$	3.73	1211941	13.60	0.66	1.77	0.52	2.73	1397188	5.18
$\langle 12, 132, 33, 3, 6 \rangle$	0.95	180238	0.73	5.51	∞	1.76	1.18	184764	0.57
$\langle 15, 45, 24, 8, 12 \rangle$	0.51	116016	8.46	∞	∞	75.87	0.64	134146	∞
$\langle 15, 70, 14, 3, 2 \rangle$	0.56	81563	0.39	12.22	1.42	0.31	1.02	79542	0.20
$\langle 16, 80, 15, 3, 2 \rangle$	0.81	109442	0.56	107.43	13.40	0.35	1.14	105242	0.35
$\langle 19, 19, 9, 9, 4 \rangle$	0.23	39931	0.09	53.23	38.30	0.31	0.4	44714	0.09
$\langle 19, 57, 9, 3, 1 \rangle$	0.34	113053	0.17	∞	1.71	0.35	10.45	111869	0.14
$\langle 21, 21, 5, 5, 1 \rangle$	0.02	0	0.00	1.26	0.67	0.15	0.01	0	0.00
$\langle 25, 25, 9, 9, 3 \rangle$	0.64	92059	1.33	∞	∞	0.92	1.01	97623	8.93
$\langle 25, 30, 6, 5, 1 \rangle$	0.10	24594	0.06	∞	1.37	0.31	1.2	23828	0.05
Total	36.66			81.24			> 219.14		

Table 5. BIBD results (180 sec. timeout)

The model for BIBD instance $\langle v, b, r, k, \lambda \rangle$ is a Boolean incidence matrix with constraints: $\text{sumBits}(C, k)$ ($\text{sumBits}(R, r)$) for each column C (row R); and for each pair of rows R_i, R_j ($i < j$), $\text{pairwise_and}(R_i, R_j, Vs)$ and $\text{sumBits}(Vs, \lambda)$. To break symmetry, we reorder rows and columns of the matrix to assign fixed values in the first two rows and leftmost column: the first row contains r ones, followed by zeros. The second row contains λ ones, $r - \lambda$ zeros, $r - \lambda$ ones, and then zeros. The left column contains k ones followed by zeros. This information enables the compiler to simplify constraints.

Table 5 shows results comparing our compiler (compilation time, cnf size, and sat solving time) using the model we call **SymB** (for symmetry breaking) with the Minion constraint solver [11]. Ignore for now the last 3 columns about SATELITE. We will come back to explain these in Section 6. All experiments were run on the same computer. We consider three different models for Minion: [M’06] indicates results using the BIBD model described in [11], **SymB** uses the same model we use for the SAT approach, **SymB**⁺, is an enhanced symmetry breaking model with all of the tricks applied also in the [M’06] model. For the columns with no timeouts we show total times (for the compiler this includes compile time and sat solving). Note that by using a clever modeling of the problem we have improved also the previous runtimes for Minion.

This experiment indicates that our compiler is significantly faster than Minion on its BIBD models ([M’06]). Only when tailoring our **SymB** model, Minion becomes competitive with ours (and still total Minion time is double).

Word Design for DNA (Problem 033 of CSPLib) seeks the largest parameter n , s.t. there exist a set S of n eight-letter words over the alphabet $\Sigma = \{A, C, G, T\}$ with the following properties: (1) Each word in S has 4 symbols from $\{C, G\}$; (2) Each pair of distinct words in S differ in at least 4 positions; and (3) For every $x, y \in S$: x^R (the reverse of x) and y^C (the word obtained by replacing each A by T , each C by G , and vice versa) differ in at least 4 positions.

In [10], the authors present the “*template-map*” strategy for this problem. Letters are modelled by bit-pairs $\langle t_i, m_i \rangle$. For each eight-letter word, $\langle t_1, \dots, t_8 \rangle$ is the *template* and $\langle m_1, \dots, m_8 \rangle$ is the *map*. The authors pose conditions on a set of templates T and a set of maps M so that the Cartesian product $S = T \times M$ will satisfy the requirements of the original problem. It is this template-map strategy that we model in our encoding. The authors report a solution composed from two template-maps $\langle T_1, M_1 \rangle$ and $\langle T_2, M_2 \rangle$ where $|T_1| = 6$, $|M_1| = 16$, $|T_2| = 2$, $|M_2| = 6$. This forms a set S with $(6 \times 16) + (2 \times 6) = 108$ DNA words. Marc van Dongen reports a larger solution with 112 words.⁸ To model this problem we introduce the two constraints (where V_i are vectors of bits).

$$\boxed{9} \text{ lexleq}([V_1, \dots, V_n]) \qquad \boxed{10} \text{ lexleq}(V_1, V_2)$$

The first specifies that a list of vectors is ordered in the lexicographic order. It decomposes to low-level constraints (of the second form) that specify that pairs of vectors are ordered in the lexicographic order.

Using our compiler, we find a template and map of size 14 and 8, the Cartesian product of which gives a solution with $14 \times 8 = 112$ words. The SAT solving time is less than 0.2 seconds. Håkan Kjellerstrand reports finding a 112 word solution in 36.5s using Comet.⁹ To show that there is no template of size 15 and no map of size 9 takes 0.14 and 3.32 seconds respectively. This is a new result not obtainable using previous solving techniques. We obtain this result when symmetries are broken by ordering the vectors in T and in M lexicographically. Proving that there is no solution to the original DNA word problem with more than 112 words (not via the template-map strategy) is still an open problem.

⁸ See <http://www.cs.st-andrews.ac.uk/~ianm/CSPLib/>.

⁹ See http://www.hakank.org/comet/word_design_dna1.co.

6 Related Work and Conclusion

There is a considerable body of work on CNF simplification techniques with a clear trade-off between amount of reduction achieved and invested time. Most of these approaches determine binary clauses implied by the CNF, which is certainly enough to determine Boolean equalities. The problem is that determining all binary clauses implied by the CNF is prohibitive when the SAT model may involve many thousands of variables. Typically only some of the implied binary clauses are determined, such as those visible by unit propagation. The trade-off is regulated by the choice of the techniques applied to infer binary clauses, considering the power and cost. See for example [7] and the references therein. There are also approaches [14] that detect and use Boolean equalities during runtime, which are complementary to our approach.

In our approach, the beast is tamed by introducing a notion of locality. We do not consider the full CNF. Instead, by maintaining the original representation, a conjunction of constraints, each viewed as a Boolean formula, we can apply powerful reasoning techniques to separate parts of the model and maintain efficient preprocessing. Our specific choice, using BDD's for bounded sized formula, guarantees that reasoning is always polynomial in cost.

To illustrate one difference consider again Example 6 where equi-propagation simplifies the constraint so that it is expressed in 2 propositional variables and requires 0 clauses. In contrast, the CNF representing the `allDiff` constraint with the initial equations E_1 consists of 76 clauses with 23 variables and after applying SATELITE [7] this is reduced to 57 clauses with 16 variables. Examining this reduced CNF reveals that it contains binary clauses corresponding to the equations in E_2 but not those from E_3 .

Finally, we come back to (the last 3 columns in) Table 5 where a comparison with SATELITE is presented. It is interesting to note that in some cases preprocessing results in smaller CNF and faster SAT solving, however in total (even if not counting the timeout for BIBD instance (15, 45, 24, 8, 12)) equi-propagation is stronger.

Using equi-propagation on a high level view of the problem allows us to simplify the problem more aggressively than is possible with a CNF representation. The resulting CNF models can be significantly smaller than those resulting from straight translation, and significantly faster to solve. Hence we believe that Boolean equi-propagation, combined with CNF simplification tools (such as SATELITE), makes an important contribution to the encoding of CSPs to SAT.

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