

SAT/SMT solvers

1. Introduction

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- What are SAT and SMT
- How they are made
- Where to use they

Edmund Clarke:

A key technology of the 21st century

Donald Knuth

Evidently a killer app, because it is key to the solution of so many other problems

You are the chief of protocol and you make a diner for an ambassadors. The prince wants to invite either an ambassador from Peru or not to invite ambassador from Qatar. The queen wants to see the ambassadors of Qatar or Romania. The king does not want to see ambassadors from Romania or Peru. Whom to invite for dinner?

- The set of natural numbers was divided into subsets. Does any contain Pythagorean triple?
- Let's the number of subsets is three and original set is $\{1, \dots, N\}$. The minimal N such that it can't be divided is 7825
- There is no answer for number of subsets 3. It's could be shown that $\{1, \dots, 10^7\}$ could be divided

Examples

```
if(!a && !b) h();  
else  
    if(!a) g();  
    else f();
```

```
if(a) f();  
else  
    if(b) g();  
    else h();
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if(a) f();  
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$(\text{if } x \text{ then } y \text{ else } z) \equiv (x \wedge y) \vee (\neg x \wedge z)$

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$(\text{if } x \text{ then } y \text{ else } z) \equiv (x \wedge y) \vee (\neg x \wedge z)$

```
if  $\neg a \wedge \neg b$  then  $h$   
else  
    if  $\neg a$  then  $g$   
    else  $f$ 
```

```
if  $a$  then  $f$   
else  
    if  $b$  then  $g$   
    else  $h$ 
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    if  $b$  then  $g$   
    else  $h$ 
```

$$\begin{aligned} & (\neg a \wedge \neg b) \wedge h \vee \neg(\neg a \wedge \neg b) \wedge (\neg a \wedge g \vee a \wedge f) \\ \iff & a \wedge f \vee \neg a \wedge (b \wedge g \vee \neg b \wedge h). \end{aligned}$$

Propositional formula

Given a set V , brackets, \vee , \wedge , \rightarrow , \neg , let define an formulas as:

- all variables V are formula.
- if A is formula, then $\neg(A)$ - formula
- if A, B are formulas, then $(A) \vee (B)$, $(A) \wedge (B)$, $(A) \rightarrow (B)$ is formula.

Assignment

Given a formula φ , an *assignment* of φ from a domain D is a function mapping φ 's variables to elements of D . An assignment to φ is full if all of φ 's variables are assigned, and partial otherwise.

Satisfiability, Validity, and Contradiction

- A formula is *satisfiable* if there exists an assignment of its variables under which the formula evaluates to true.
- A formula is a *contradiction* if it is not *satisfiable*.
- A formula is *valid* (also called a *tautology*) if it evaluates to true under all assignments.

The decision problem for formulas

The decision problem for a given formula φ is to determine whether φ is valid.

Soundness of a procedure

A procedure for a decision problem is sound if, when it returns *Valid*, the input formula is *valid*.

Completeness of a procedure

A procedure for a decision problem is *complete* if

- it always terminates, and
- it returns *Valid* when the input formula is valid

Decision procedure

A procedure is called a decision procedure for T if it is sound and complete with respect to every formula of T

Decidability of a theory

A theory is decidable if and only if there is a decision procedure for it

Negation Normal Form (NNF)

A formula is in negation normal form (NNF) if negation is allowed only over variables, and \vee , \wedge , \neg are the only allowed Boolean connectives

Literal

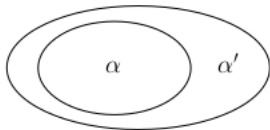
A *literal* is either an variable or its negation. We say that a literal is negative if it is a negated variable, and positive otherwise

State of a literal under an assignment

A positive literal is satisfied if its variable is assigned TRUE. Similarly, a negative literal is satisfied if its variable is assigned FALSE

Monotonicity of NNF

Let φ be a formula in NNF and let α be an assignment of its variables. Let the positive set of α with respect to φ , denoted $pos(\alpha, \varphi)$, be the literals that are satisfied by α . For every assignment α' to φ 's variables such that $pos(\alpha, \varphi) \subseteq pos(\alpha', \varphi)$, $\alpha \models \varphi \rightarrow \alpha' \models \varphi$



$$\alpha \models \varphi \implies \alpha' \models \varphi$$

Disjunctive Normal Form (DNF)

A formula is in disjunctive normal form if it is a disjunction of conjunctions of literals, i.e., a formula of the form $\bigvee_i \bigwedge_j l_{ij}$, where l_{ij} is the j -th literal in the i -th term (a term is a conjunction of literals)

Conjunctive Normal Form (CNF)

A formula is in conjunctive normal form if it is a conjunction of disjunctions of literals, i.e., it has the form $\bigwedge_i \bigvee_j l_{ij}$, where l_{ij} is the j -th literal in the i -th clause (a clause is a disjunction of literals)

$$\phi := ((p \vee q) \wedge r) \rightarrow (\neg s)$$

Equisatisfiability

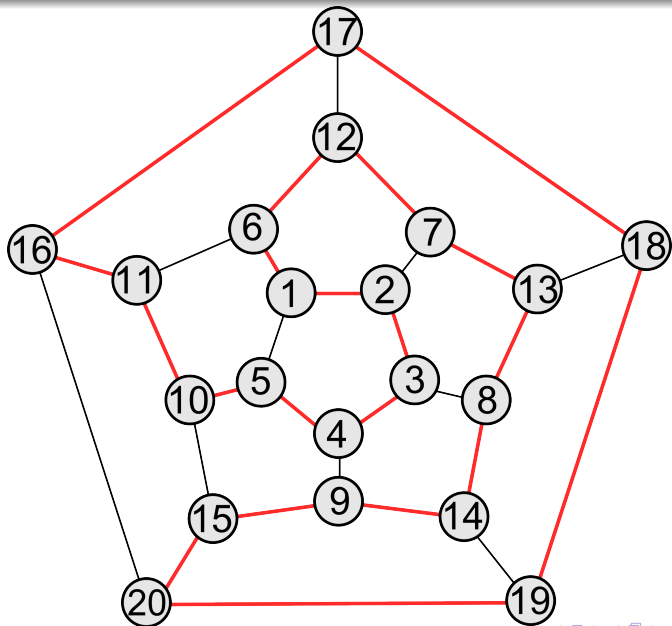
Two formulas are equisatisfiable if they are both satisfiable or they are both unsatisfiable

Given a propositional formula f over n propositional variables $V = x_1, \dots, x_n$, is there an assignment $\alpha : V \rightarrow \{0, 1\}$ with $\alpha(f) = 1$?

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- SAT belongs to NP (for $n > 2$)
- SAT is complete for NP

Examples



Examples

- $AtLeastOne(x_1, \dots, x_n)$
- $AtMostOne(x_1, \dots, x_n)$
- Lazy approach

- $(x = 4) \wedge ((y = 7) \vee (x = y))$
- $(x + y = 3) \wedge (y - z = 7) \wedge (z * 2 = 4)$
- $(length(s) = 3) \wedge (s[0] = 'a') \wedge (s[1] = 'b') \wedge (s[2] = 'c')$

First-order logic

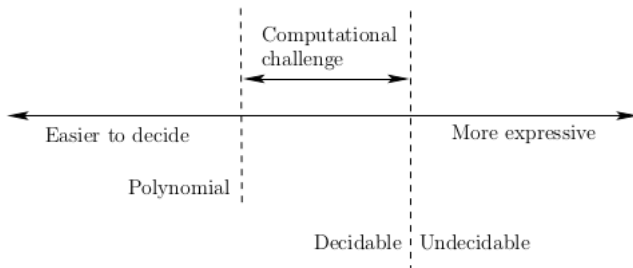
- Variables: a set of variables
 - Logical symbols: the standard Boolean connectives (e.g., \wedge, \vee, \neg), quantifiers (\exists and \forall), and parentheses
 - Nonlogical symbols: function, predicate, and constant symbols
 - Syntax: rules for constructing formulas. Formulas adhering to these rules are said to be well formed
-
- A domain
 - An interpretation of the nonlogical symbols, in the form of a mapping from each function and predicate symbol to a function and a predicate, respectively, and an assignment of a domain element to each of the constant symbols
 - An assignment of a domain element to each of the free (unquantified) variables

Satisfiability

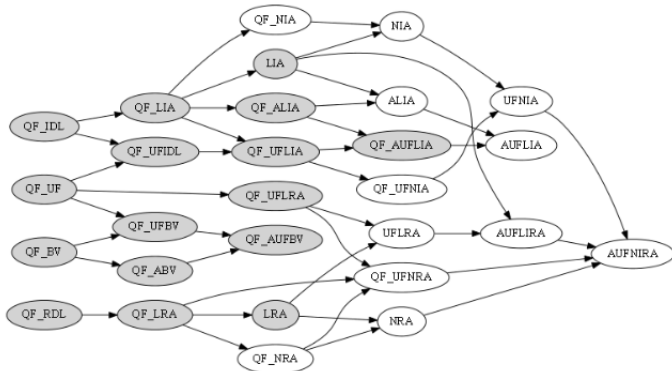
The formula φ is satisfiable if and only if there exists a structure under which the formula is true.

Expressiveness

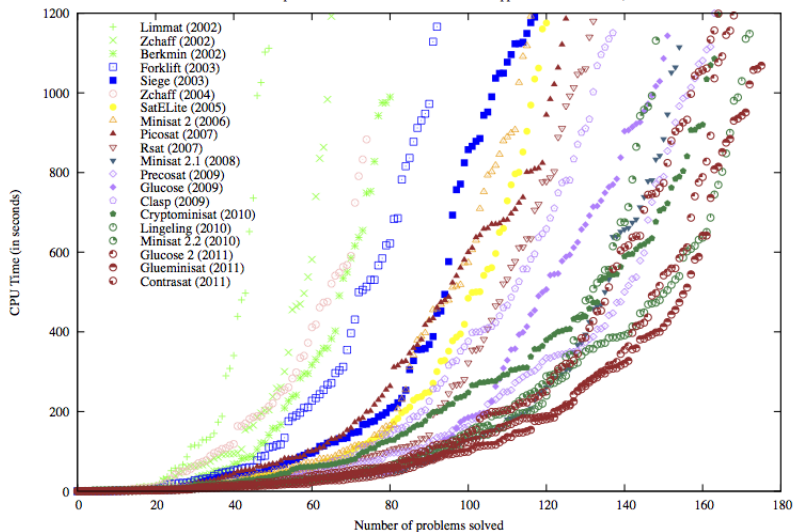
Theory A is more expressive than theory B if every language that can be defined by a B-formula can also be defined by an A-formula, and there exists at least one language definable by an A-formula that cannot be defined by a B-formula. We denote the fact that theory B is less expressive than theory A by $B \prec A$.



- Propositional Logic
- Equalities and Uninterpreted Functions
- Linear Arithmetic
- Bit Vectors
- Arrays
- Pointer Logic



Results of the SAT competition/race winners on the SAT 2009 application benchmarks, 20mn timeout



Listing 3. Integer Example in SMT-LIB

```
(set-logic QF_LIA)
(declare-fun x () Int)
(declare-fun y () Int)
(declare-fun z () Int)
(assert (= (+ (* 6 x) (* 2 y) (* 12 z)) 30))
(assert (= (+ (* 3 x) (* 6 y) (* 3 z)) 12))
(check-sat)
```

- $(a \vee b \vee \neg c) \wedge (\neg a \vee \neg b \vee c) \wedge (b \vee c \vee \neg d)$

- c example

p cnf 4 3

1 2 -3 0

-1 -2 3 0

2 3 -4 0

- Decision Procedures An Algorithmic Point of View, Daniel Kroening, Ofer Strichman
- Handbook of satisfiability, Edmund Clarke
- The art of Computer Programming, volume 4, part 6, Donald Knuth

