

Course Formal Methods

Module I: Automated Reasoning

Ch. 02: **Satisfiability Modulo Theories (SMT)**

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- 1 Introduction
 - Basics on First-order Logic
 - What is a Theory?
 - Satisfiability Modulo Theories
 - Motivations and Goals of SMT
- 2 Efficient SMT solving
 - Combining SAT with Theory Solvers
 - Theory Solvers for Theories of Interest (hints)
 - SMT for Combinations of Theories
- 3 Beyond Solving: Advanced SMT Functionalities
 - Proofs and Unsatisfiable Cores
 - All-SMT & Predicate Abstraction (hints)
 - SMT with Optimization (Optimization Modulo Theories)

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First-Order Logic (FOL)

- PL assumes world contains **facts**
 - atomic events
- FOL is **structured**: a world/state includes **objects**, each of which may have **attributes** of its own as well as **relationships** to other objects
- FOL assumes the world contains:
 - **Objects**:
e.g., people, houses, numbers, theories, Jim Morrison, colors, basketball games, wars, centuries, ...
 - **Relations**:
e.g., red, round, bogus, prime, tall ...,
brother of, bigger than, inside, part of, has color, occurred after, owns, comes between, ...
 - **Functions**:
e.g., father of, best friend, one more than, end of, ...
- Allows to **quantify** on objects
 - ex: “All man are equal”, “some persons are left-handed”, ...

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Syntax of FOL: Basic Elements

- **Constant symbols:** KingJohn, 2, UniversityofTrento,...
- **Predicate symbols:** Man(.), Brother(.,.), ($. > .$), AllDifferent(...),...
 - may have different arities (1,2,3,...)
 - may be **prefix** (e.g. Brother(.,.)) or **infix** (e.g. ($. > .$))
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- **Variable symbols:** x, y, a, b, ...
- **Propositional Connectives:** $\neg, \wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus$
- **Equality:** “=” (also “ \neq ” s.t. “ $a \neq b$ ” shortcut for “ $\neg(a = b)$ ”)
- **Quantifiers:** “ \forall ” (“forall”), “ \exists ” (“exists”, aka “for some”)
- **Punctuation Symbols:** “,”, “(”, “)”

- Constants symbols are 0-ary function symbols
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- **Signature:** the set of predicate, function & constant symbols

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- Terms:

- constant or variable or *function*($term_1, \dots, term_n$)
- ex: KingJohn, x, LeftLeg(Richard), ($z \cdot \log(2)$)
- denote objects in the real world (aka domain)

- Atomic sentences (aka atomic formulas):

- \top, \perp
- *proposition* or *predicate*($term_1, \dots, term_n$) or $term_1 = term_2$
- ($Length(LeftLeg(Richard)) > Length(LeftLeg(KingJohn))$)
- denote facts

- Non-atomic sentences/formulas:

- $\neg\alpha, \alpha \wedge \beta, \alpha \vee \beta, \alpha \rightarrow \beta, \alpha \leftrightarrow \beta, \alpha \oplus \beta,$
 $\forall x.\alpha, \exists x.\alpha$ s.t. x (typically) occurs in α
- Ex: $\forall y.(Italian(y) \rightarrow President(Mattarella, y))$
 $\exists x\forall y.President(x, y) \rightarrow \forall y\exists x.President(x, y)$
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Truth in FOL: Intuitions

- Sentences are true with respect to a **model**
 - containing a **domain** and an **interpretation**
- The **domain** contains ≥ 1 objects (**domain elements**) and relations and functions over them
- An **interpretation** specifies referents for
 - **variables** \rightarrow objects
 - **constant symbols** \rightarrow objects
 - **predicate symbols** \rightarrow relations
 - **function symbols** \rightarrow functional relations
- An atomic sentence $P(t_1, \dots, t_n)$ is true in an interpretation iff the objects referred to by t_1, \dots, t_n are in the relation referred to by P

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FOL: Semantics

FOL Models (aka possible worlds)

- A model \mathcal{M} is a pair $\langle \mathcal{D}, \mathcal{I} \rangle$ (\langle *domain, interpretation* \rangle)
 - Domain \mathcal{D} : a **non-empty** set of objects (aka **domain elements**)
 - Interpretation \mathcal{I} : a (non-injective) map on elements of the signature
 - **constant symbols** \mapsto **domain elements**:
a constant symbol C is mapped into a particular object $[C]^{\mathcal{I}}$ in \mathcal{D}
 - **predicate symbols** \mapsto **domain relations**:
a k -ary predicate $P(\dots)$ is mapped into a subset $[P]^{\mathcal{I}}$ of \mathcal{D}^k
(i.e., the set of object tuples satisfying the predicate in this world)
 - **functions symbols** \mapsto **domain functions**:
a k -ary function f is mapped into a domain function $[f]^{\mathcal{I}} : \mathcal{D}^k \mapsto \mathcal{D}$ ($[f]^{\mathcal{I}}$ must be total)
- (we denote by $[\cdot]^{\mathcal{I}}$ the result of the interpretation \mathcal{I})

An **Interpretation** \mathcal{I} is extended to assign domain values to variables, domain values to terms and truth values to formulas.

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FOL: Semantics [cont.]

Interpretation of terms

\mathcal{I} maps terms into domain elements

- Variables are assigned domain values
 - variables \mapsto domain elements:
a variable x is mapped into a particular object $[x]^{\mathcal{I}}$ in \mathcal{D}
- A term $f(t_1, \dots, t_k)$ is mapped by \mathcal{I} into the value $[f(t_1, \dots, t_k)]^{\mathcal{I}}$ returned by applying the domain function $[f]^{\mathcal{I}}$, into which f is mapped, to the values $[t_1]^{\mathcal{I}}, \dots, [t_k]^{\mathcal{I}}$ obtained by applying recursively \mathcal{I} to the terms t_1, \dots, t_k :
 - $[f(t_1, \dots, t_k)]^{\mathcal{I}} = [f]^{\mathcal{I}}([t_1]^{\mathcal{I}}, \dots, [t_k]^{\mathcal{I}})$
 - Ex: if “Me, Mother, Father” are interpreted as usual, then “Mother(Father(Me))” is interpreted as my (paternal) grandmother
 - Ex: if “+, -, ·, 0, 1, 2, 3, 4” are interpreted as usual, then “(3 - 1) · (0 + 2)” is interpreted as 4

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- An atomic formula $P(t_1, \dots, t_k)$ is true in \mathcal{I} iff the objects into which the terms t_1, \dots, t_k are mapped by \mathcal{I} comply to the relation into which P is mapped
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 - Ex: if “Me, Mother, Father, Married” are interpreted as tradition, then “Married(Mother(Me), Father(Me))” is interpreted as true
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Interpretation of formulas

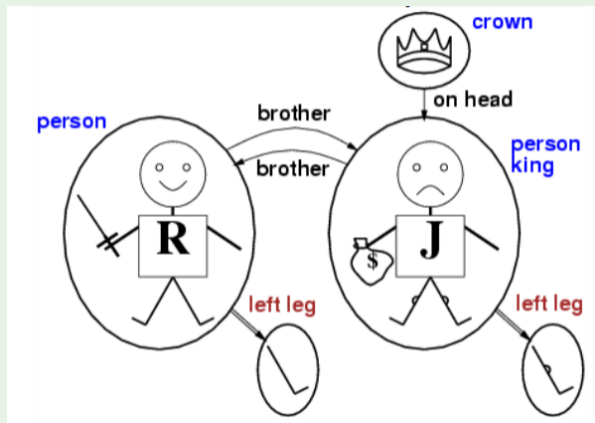
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Models for FOL: Example

Richard Lionheart and John Lackland

- \mathcal{D} : domain at right
- \mathcal{I} : s.t.
 - $[\text{Richard}]^{\mathcal{I}}$: Richard the Lionheart
 - $[\text{John}]^{\mathcal{I}}$: evil King John
 - $[\text{Brother}]^{\mathcal{I}}$: brotherhood
- $[\text{Brother}(\text{Richard}, \text{John})]^{\mathcal{I}}$ is true
- $[\text{LeftLeg}]^{\mathcal{I}}$ maps any individual to his left leg
- ...

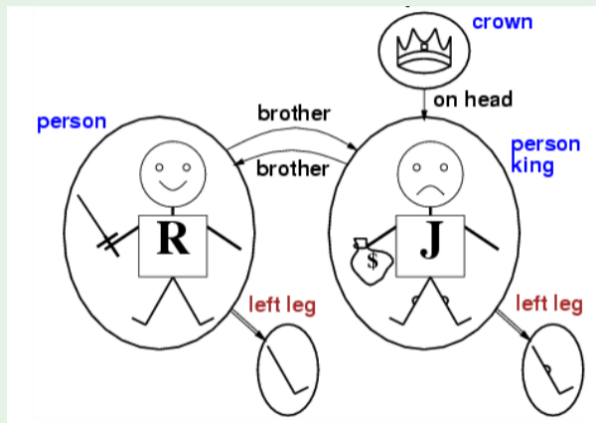


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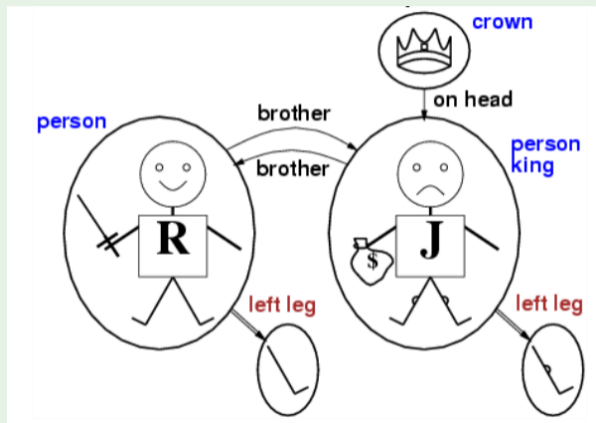


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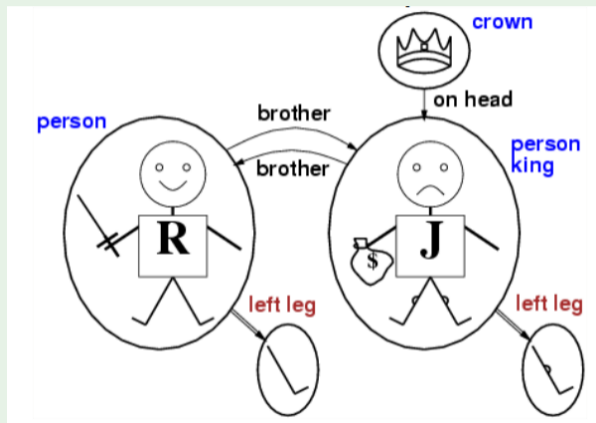


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Equality

- Equality is a special predicate: $t_1 = t_2$ is true under a given interpretation if and only if t_1 and t_2 refer to the same object
 - Ex: $1 = 2$ and $x * x = x$ are satisfiable (!)
 - Ex: $2 = 2$ is valid
- Ex: definition of *Sibling* in terms of *Parent*
 $\forall x, y. (Siblings(x, y) \leftrightarrow [\neg(x = y) \wedge \exists p_1, p_2. (\neg(p_1 = p_2) \wedge Parent(p_1, x) \wedge Parent(p_2, x) \wedge Parent(p_1, y) \wedge Parent(p_2, y))])$)

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 - Basics on First-order Logic
 - **What is a Theory?**
 - Satisfiability Modulo Theories
 - Motivations and Goals of SMT
- 2 Efficient SMT solving
 - Combining SAT with Theory Solvers
 - Theory Solvers for Theories of Interest (hints)
 - SMT for Combinations of Theories
- 3 Beyond Solving: Advanced SMT Functionalities
 - Proofs and Unsatisfiable Cores
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 - SMT with Optimization (Optimization Modulo Theories)

Traditional Definition (FOL)

Given a FOL signature Σ , a Σ -Theory \mathcal{T} (hereafter simply “theory”) is a (possibly infinite) set of FOL closed formulas (axioms)

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Example: A FOL Theory of Positive Integer Numbers (aka “Peano Arithmetic”, \mathcal{P})

- Signature

- (basic) unary predicate symbol: NatNum (“natural number”)
- (basic) unary function symbol: S (“successor”)
- (basic) constant symbol: 0
- (derived) binary function symbols: $+, *$ (infix)
- (derived) constant symbols: $1, 2, 3, 4, 5, 6, \dots$

- Axioms

- 1 $\text{NatNum}(0)$
- 2 $\forall x. (\text{NatNum}(x) \rightarrow \text{NatNum}(S(x)))$
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Given a FOL signature Σ , a Σ -Theory \mathcal{T} (hereafter simply “theory”) is one (or more) model(s) constraining the interpretations of Σ

- Provides an **intended interpretation** to the symbols in Σ
 - constants mapped into domain elements
 - ex: “1” mapped into the number one
 - predicate symbols mapped into relations on domain elements
 - ex: “. < .” mapped into the arithmetical relation “less than”
 - function symbols mapped into functions on domain elements
 - ex: “ $S(\cdot)$ ” mapped into the arithmetical function “successor of”

These symbols are called **interpreted**

- Compliant with previous definition: **model(s) satisfying all axioms**
- Ad hoc “ \mathcal{T} -aware” decision procedures for reasoning on formulas
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Example: Linear Arithmetic on the Integers (\mathcal{LIA})

- Domain: integer numbers
- Numerical constants interpreted as **numbers**
 - ex: “1”, “1346231” mapped directly into the corresponding number
- function and predicates interpreted as **arithmetical operations**
 - “+” as addition, “*” as multiplication, “<” as less-than, . etc.
- **ILP solvers** used to do logical reasoning
 - ex: $(3x - 2y \leq 3) \wedge (4y - 2z < -7) \models (6x - 2z < -1)$

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Satisfiability, Validity, Entailment (Modulo a Theory \mathcal{T})

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- 1 Introduction
 - Basics on First-order Logic
 - What is a Theory?
 - **Satisfiability Modulo Theories**
 - Motivations and Goals of SMT
- 2 Efficient SMT solving
 - Combining SAT with Theory Solvers
 - Theory Solvers for Theories of Interest (hints)
 - SMT for Combinations of Theories
- 3 Beyond Solving: Advanced SMT Functionalities
 - Proofs and Unsatisfiable Cores
 - All-SMT & Predicate Abstraction (hints)
 - SMT with Optimization (Optimization Modulo Theories)

Satisfiability Modulo Theories (SMT(\mathcal{T}))

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The problem of deciding the satisfiability of (typically quantifier-free) formulas in some decidable first-order theory \mathcal{T}

- \mathcal{T} can also be a **combination of theories** $\bigcup_i \mathcal{T}_i$.

SMT(\mathcal{T}): Theories of Interest

Some theories of interest (e.g., for formal verification)

- Equality and Uninterpreted Functions (\mathcal{EUF}):
 $((x = y) \wedge (y = f(z))) \rightarrow (g(x) = g(f(z)))$
- Difference logic (\mathcal{DL}): $((x = y) \wedge (y - z \leq 4)) \rightarrow (x - z \leq 6)$
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- Bit vectors (\mathcal{BV}): $x_{[16]}[15 : 0] = (y_{[16]}[15 : 8] \ll z_{[16]}[7 : 0]) \ll w_{[8]}[3 : 0]$
- Non-Linear arithmetic over the reals ($\mathcal{NLA}(\mathbb{R})$):
 $((c = a \cdot b) \wedge (a_1 = a - 1) \wedge (b_1 = b + 1)) \rightarrow (c = a_1 \cdot b_1 + 1)$
- ...

Satisfiability Modulo Theories (SMT(\mathcal{T})): Example

Example: SMT($\mathcal{LIA} \cup \mathcal{EUF} \cup \mathcal{AR}$)

$$\varphi \stackrel{\text{def}}{=} (d \geq 0) \wedge (d < 1) \wedge \\ ((f(d) = f(0)) \rightarrow (\text{read}(\text{write}(V, i, x), i + d) = x + 1))$$

- involves arithmetical, arrays, and uninterpreted function/predicate symbols, plus Boolean operators
 - Is it satisfiable?
 - No:

$$\begin{aligned} & \varphi \\ \implies_{\mathcal{LIA}} & (d = 0) \\ \implies_{\mathcal{EUF}} & (f(d) = f(0)) \\ \implies_{\text{Bool}} & (\text{read}(\text{write}(V, i, x), i + d) = x + 1) \\ \implies_{\mathcal{LIA}} & (\text{read}(\text{write}(V, i, x), i) = x + 1) \\ \implies_{\mathcal{LIA}} & \neg(\text{read}(\text{write}(V, i, x), i) = x) \\ \implies_{\mathcal{AR}} & \perp \end{aligned}$$

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SMT and SMT solvers

Common fact about SMT problems from various applications

SMT requires capabilities for **heavy Boolean reasoning** combined with capabilities for **reasoning in expressive decidable F.O. theories**

- SAT alone not expressive enough
- standard automated theorem proving inadequate (e.g., arithmetic)
- may involve also numerical computation (e.g., simplex)

Modern SMT solvers

- combine **SAT solvers** with \mathcal{T} -specific **decision procedures** (**theory solvers** or \mathcal{T} -solvers)
 - contributions from SAT, Automated Theorem Proving (ATP), formal verification (FV) and operational research (OR)

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Notational remark (1): most/all examples in \mathcal{LRA}

For better readability, in most/all the examples of this presentation we will use the theory of linear arithmetic on rational numbers (\mathcal{LRA}) because of its intuitive semantics. E.g.:

$$(\neg A_1 \vee (3x_1 - 2x_2 - 3 \leq 5)) \wedge (A_2 \vee (-2x_1 + 4x_3 + 2 = 3))$$

Nevertheless, analogous examples can be built with all other theories of interest.

Notational remark (2): “constants” vs. “variables”

- Consider, e.g., the formula:
 $(\neg A_1 \vee (3x_1 - 2x_2 - 3 \leq 5)) \wedge (A_2 \vee (-2x_1 + 4x_3 + 2 = 3))$
- How do we call A_1, A_2 ?:
 - (a) Boolean/propositional **variables**?
 - (b) uninterpreted **0-ary predicates**?
- How do we call x_1, x_2, x_3 ?:
 - (a) domain **variables**?
 - (b) uninterpreted Skolem **constants/0-ary uninterpreted functions**?
- Hint:
 - (a) typically used in SAT, CSP and OR communities
 - (b) typically used in logic & ATP communities

Hereafter we call A_1, A_2 “Boolean/propositional **variables**” and x_1, x_2, x_3 “domain **variables**”
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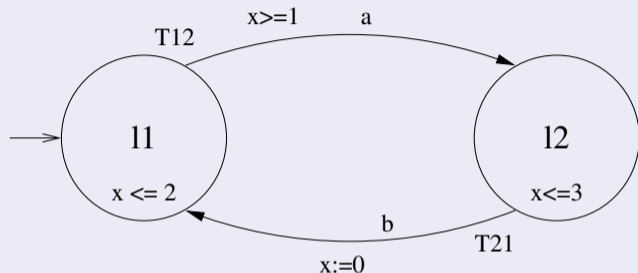
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Some Motivating Applications

Interest in SMT triggered by some real-world applications

- Verification of Hybrid & Timed Systems
- Verification of RTL Circuit Designs & of Microcode
- SW Verification
- Planning with Resources
- Temporal reasoning
- Scheduling
- Compiler optimization
- ...

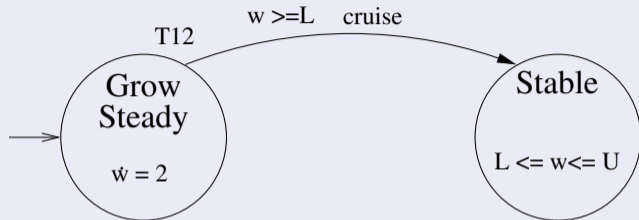
Verification of Timed Systems



- Model checking of Timed Systems [6, 35, 58], ...
- Timed Automata encoded into \mathcal{T} -formulas:
 - discrete information (locations, transitions, events) with Boolean vars.
 - timed information (clocks, elapsed time) with differences ($t_3 - x_3 \leq 2$), equalities ($x_4 = x_3$) and linear constraints ($t_8 - x_8 = t_2 - x_2$) on \mathbb{Q}

⇒ SMT on $\mathcal{DL}(\mathbb{Q})$ or \mathcal{LRA} required

Verification of Hybrid Systems ...

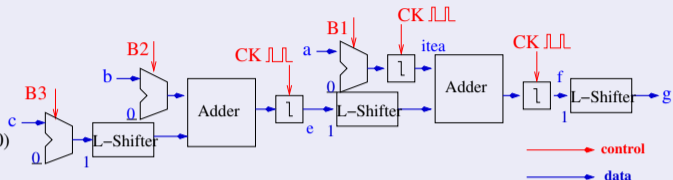


- Model checking of Hybrid Systems [5],...
- Hybrid Automata encoded into \mathcal{L} -formulas:
 - **discrete information** (locs, trans., events) with Boolean vars.
 - **timed information** (clocks, elapsed time) with differences ($t_3 - x_3 \leq 2$), equalities ($x_4 = x_3$) and linear constraints ($t_8 - x_8 = t_2 - x_2$) on \mathbb{Q}
 - **Evolution of Physical Variables** (e.g., speed, pressure) with linear ($\omega_4 = 2\omega_3$) and non-linear constraints ($P_1 V_1 = 4T_1$) on \mathbb{Q}
- **Undecidable** under simple hypotheses!

\Rightarrow SMT on $\mathcal{DL}(\mathbb{Q})$, \mathcal{LRA} or $\mathcal{NLA}(\mathbb{R})$ required

Verification of HW circuit designs & microcode

$g = 2 * f$
 $f = itea + 2 * e$
 $itea' = ITE(B1; a; 0)$
 $e' = ITE(B2; b; 0) + 2 * ite(B3; c; 0)$



- SAT/SMT-based **Model Checking & Equiv. Checking** of RTL designs, **symbolic simulation** of μ -code [25, 22, 42]
 - **Control paths** handled by Boolean reasoning
 - **Data paths** information abstracted into theory-specific terms
 - **words** (bit-vectors, integers, \mathcal{EUF} vars, ...): $\underline{a}[31 : 0]$, a
 - **word operations**: $(BV, \mathcal{EUF}, \mathcal{AR}, \mathcal{LIA}, \mathcal{NLA}(\mathbb{Z}))$ operators
 $x_{[16]}[15 : 0] = (y_{[16]}[15 : 8] :: z_{[16]}[7 : 0]) \ll w_{[8]}[3 : 0]$, $(a = a_L + 2^{16}a_H)$, $(m_1 = store(m_0, l_0, v_0))$,
 ...
 - Trades **heavy Boolean reasoning** ($\approx 2^{64}$ factors) with **\mathcal{T} -solving**
- \Rightarrow SMT on $BV, \mathcal{EUF}, \mathcal{AR}$, modulo- $\mathcal{LIA} [\mathcal{NLA}(\mathbb{Z})]$ required

Verification of SW systems

```
...  
10. i = 0;  
11. acc = 0.0;  
12. while (i < dim) {  
13.   acc += V[i];  
14.   i++;  
15. }  
...
```

```
...  
(pc = 10) → ((i' = 0) ∧ (pc' = 11))  
(pc = 11) → ((acc' = 0.0) ∧ (pc' = 12))  
(pc = 12) → ((i < dim) → ∧(pc' = 13))  
(pc = 12) → (¬(i < dim) → ∧(pc' = 16))  
(pc = 13) → ((acc' = acc + read(V, i)) ∧ (pc' = 14))  
(pc = 14) → (i' = i + 1) ∧ (pc' = 15))  
(pc = 15) → (pc' = 12))  
...
```

- Verification of SW code

- BMC, K-induction, Check of proof obligations, interpolation-based model checking, symbolic simulation, concolic testing, ...

⇒ SMT on BV , \mathcal{EUF} , \mathcal{AR} , (modulo-) \mathcal{LIA} [$\mathcal{NLA}(\mathbb{Z})$] required

Planning with Resources [80]

- SAT-bases planning augmented with numerical constraints
- Straightforward to encode into into $SMT(\mathcal{LRA})$

Example (sketch) [80]

```
(Deliver)                 $\wedge$  // goal
(MaxLoad)                 $\wedge$  // load constraint
(MaxFuel)                 $\wedge$  // fuel constraint
(Move  $\rightarrow$  MinFuel)    $\wedge$  // move requires fuel
(Move  $\rightarrow$  Deliver)    $\wedge$  // move implies delivery
(GoodTrip  $\rightarrow$  Deliver)  $\wedge$  // a good trip requires
(GoodTrip  $\rightarrow$  AllLoaded)  $\wedge$  // a full delivery
-----
(MaxLoad  $\rightarrow$  (load  $\leq$  30))  $\wedge$  // load limit
(MaxFuel  $\rightarrow$  (fuel  $\leq$  15))  $\wedge$  // fuel limit
(MinFuel  $\rightarrow$  (fuel  $\geq$  7 + 0.5load))  $\wedge$  // fuel constraint
(AllLoaded  $\rightarrow$  (load = 45)) //
```

(Disjunctive) Temporal Reasoning & Scheduling [77, 2]

- Temporal reasoning problems encoded as disjunctions of difference constraints

$$\begin{aligned} & ((x_1 - x_2 \leq 6) \quad \vee \quad (x_3 - x_4 \leq -2)) \quad \wedge \\ & ((x_2 - x_3 \leq -2) \quad \vee \quad (x_4 - x_5 \leq 5)) \quad \wedge \\ & ((x_2 - x_1 \leq 4) \quad \vee \quad (x_3 - x_7 \leq -6)) \quad \wedge \\ & \dots \end{aligned}$$

- Straightforward to encode into into $\text{SMT}(\mathcal{DL})$

Goal

Provide an overview of standard “lazy” SMT:

- foundations
- SMT-solving techniques
- beyond solving: advanced SMT functionalities
- ongoing research

We do **not** cover related approaches like:

- Eager SAT encodings
- Rewrite-based approaches

We refer to [70, 10] for an overview and references.

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Modern “lazy” SMT(\mathcal{T}) solvers

A prominent “lazy” approach [45, 2, 80, 3, 8, 35] (aka “DPLL(\mathcal{T})”)

- a **CDCL SAT solver** is used to enumerate truth assignments μ_i for (the Boolean abstraction φ^D of) the input formula φ
 - the Boolean abstraction φ^D of φ maps theory atoms in φ into fresh Boolean variables
- a theory-specific solver **\mathcal{T} -solver** checks the \mathcal{T} -satisfiability of the **set of \mathcal{T} -literals** corresponding to each assignment

- Built on top of modern SAT CDCL solvers
 - benefit for free from all modern CDCL techniques (e.g., Boolean preprocessing, backjumping & learning, restarts,...)
 - benefit for free from all state-of-the-art data structures and implementation tricks (e.g., two-watched literals,...)
- Many techniques to maximize the benefits of integration [70, 10]
- Many lazy SMT tools available
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Basic schema: example

$\varphi =$

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true, false

$$\mu^p = \{\neg B_5, B_8, B_6, \neg B_1, \neg B_3, A_1, A_2, B_2\}$$

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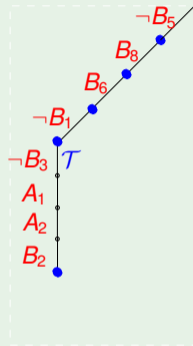
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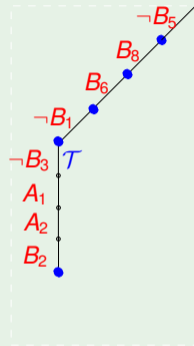
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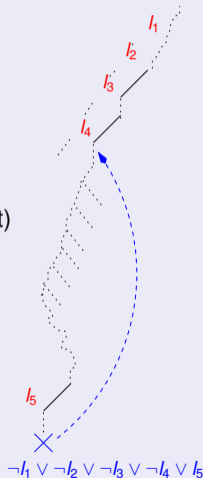
$$\mu^p = \{-B_5, B_8, B_6, \neg B_1, \neg B_3, A_1, A_2, B_2\}$$

$$\mu = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_2 - v_4 \leq 6), \neg(2v_2 - v_3 > 2), \neg(3v_1 - 2v_2 \leq 3), (v_1 - v_5 \leq 1)\}$$

\implies unsatisfiable in $\mathcal{LRA} \implies$ backtrack

\mathcal{T} -Backjumping & \mathcal{T} -learning [50, 80, 3, 8, 35]

- Similar to Boolean backjumping & learning
- important property of \mathcal{T} -solver:
 - **extraction of \mathcal{T} -conflict sets**: if μ is \mathcal{T} -unsatisfiable, then \mathcal{T} -solver(μ) returns the subset η of μ causing the \mathcal{T} -unsatisfiability of μ (\mathcal{T} -conflict set)
- If so, the **\mathcal{T} -conflict clause** $C := \neg\eta$ is used to drive the backjumping & learning mechanism of the SAT solver
⇒ lots of search saved
- **the less redundant is η , the more search is saved**

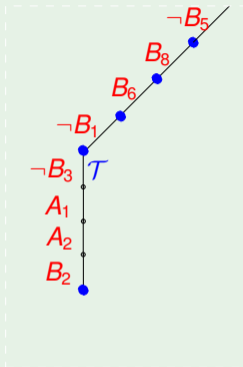


\mathcal{T} -Backjumping & \mathcal{T} -learning: example

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \\ c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \end{array}$$

$$\begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \\ B_5 \vee \neg B_8 \vee \neg B_2 \end{array}$$

true, false



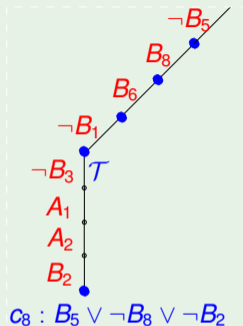
$$\begin{array}{l} \mu^p = \{\neg B_5, B_8, B_6, \neg B_1, \neg B_3, A_1, A_2, B_2\} \\ \mu = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_2 - v_4 \leq 6), \neg(2v_2 - v_3 > 2), \\ \neg(3v_1 - 2v_2 \leq 3), (v_1 - v_5 \leq 1)\} \\ \eta = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_1 - v_5 \leq 1)\} \\ \eta^p = \{\neg B_5, B_8, B_2\} \end{array}$$

\mathcal{T} -Backjumping & \mathcal{T} -learning: example

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \\ c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \end{array}$$

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true, false



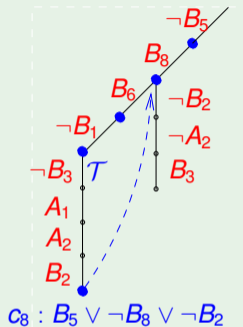
$$\begin{array}{l} \mu^p = \{\neg B_5, B_8, B_6, \neg B_1, \neg B_3, A_1, A_2, B_2\} \\ \mu = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_2 - v_4 \leq 6), \neg(2v_2 - v_3 > 2), \\ \neg(3v_1 - 2v_2 \leq 3), (v_1 - v_5 \leq 1)\} \\ \eta = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_1 - v_5 \leq 1)\} \\ \eta^p = \{\neg B_5, B_8, B_2\} \end{array}$$

\mathcal{T} -Backjumping & \mathcal{T} -learning: example

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \\ c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \end{array}$$

$$\begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \\ B_5 \vee \neg B_8 \vee \neg B_2 \end{array}$$

true, false

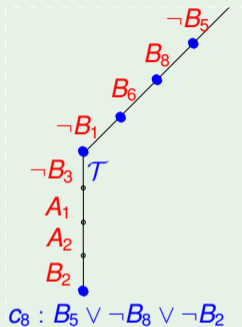


$$\begin{array}{l} \mu^p = \{\neg B_5, B_8, B_6, \neg B_1, \neg B_3, A_1, A_2, B_2\} \\ \mu = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_2 - v_4 \leq 6), \neg(2v_2 - v_3 > 2), \\ \neg(3v_1 - 2v_2 \leq 3), (v_1 - v_5 \leq 1)\} \\ \eta = \{\neg(3v_1 - v_3 \leq 6), (v_3 = 3v_5 + 4), (v_1 - v_5 \leq 1)\} \\ \eta^p = \{\neg B_5, B_8, B_2\} \end{array}$$

\mathcal{T} -Backjumping & \mathcal{T} -learning: example (2)

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \\ c_8' : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \\ c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \\ \text{true, false} \end{array}$$

$$\begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \\ B_5 \vee \neg B_8 \vee B_1 \\ B_5 \vee \neg B_8 \vee \neg B_2 \end{array}$$



$$\begin{array}{c} c_8: \text{theory conflicting clause} \\ \frac{\overbrace{B_5 \vee \neg B_8 \vee \neg B_2}^{c_2} \quad \overbrace{\neg A_2 \vee B_2}^{c_2}}{B_5 \vee \neg B_8 \vee \neg A_2} \quad (B_2) \quad \overbrace{B_3 \vee A_2}^{c_3} \\ \frac{\overbrace{B_5 \vee \neg B_8 \vee \neg A_2} \quad \overbrace{\neg A_2}^{(\neg A_2)}}{B_5 \vee \neg B_8 \vee B_3} \quad \overbrace{B_5 \vee B_1 \vee \neg B_3}^{c_T} \quad (B_3) \\ \frac{\overbrace{B_5 \vee \neg B_8 \vee B_3} \quad \overbrace{B_5 \vee B_1 \vee \neg B_3}}{B_5 \vee \neg B_8 \vee B_1} \\ c_8': \text{mixed Boolean+theory conflict clause} \end{array}$$

\mathcal{T} -Backjumping & \mathcal{T} -learning: example (2)

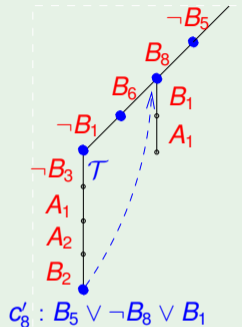
$\varphi =$

- $c_1 : \neg(2v_2 - v_3 > 2) \vee A_1$
- $c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1)$
- $c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2$
- $c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1$
- $c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3)$
- $c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1$
- $c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2$
- $c_8' : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots$
- $c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots$

true, false

$\varphi^p =$

- $\neg B_1 \vee A_1$
- $\neg A_2 \vee B_2$
- $B_3 \vee A_2$
- $\neg B_4 \vee \neg B_5 \vee \neg A_1$
- $A_1 \vee B_3$
- $B_6 \vee B_7 \vee \neg A_1$
- $A_1 \vee B_8 \vee A_2$
- $B_5 \vee \neg B_8 \vee B_1$
- $B_5 \vee \neg B_8 \vee \neg B_2$

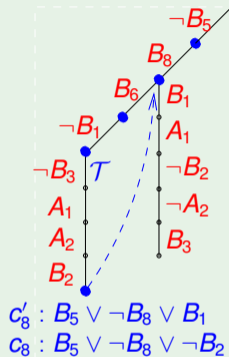


$$\begin{array}{c}
 c_8: \text{theory conflicting clause} \\
 \frac{\overbrace{B_5 \vee \neg B_8 \vee \neg B_2}^{c_2} \quad \overbrace{\neg A_2 \vee B_2}^{c_2}}{B_5 \vee \neg B_8 \vee \neg A_2} \quad (B_2) \quad \overbrace{B_3 \vee A_2}^{c_3} \quad (\neg A_2) \quad \overbrace{B_5 \vee B_1 \vee \neg B_3}^{c_T} \quad (B_3) \\
 \frac{B_5 \vee \neg B_8 \vee \neg A_2 \quad B_3 \vee A_2}{B_5 \vee \neg B_8 \vee B_3} \\
 \frac{B_5 \vee \neg B_8 \vee B_3 \quad B_5 \vee B_1 \vee \neg B_3}{B_5 \vee \neg B_8 \vee B_1} \\
 c'_8: \text{mixed Boolean+theory conflict clause}
 \end{array}$$

\mathcal{T} -Backjumping & \mathcal{T} -learning: example (2)

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \\ c_8' : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \\ c_8 : (3v_1 - v_3 \leq 6) \vee \neg(v_3 = 3v_5 + 4) \vee \dots \\ \text{true, false} \end{array}$$

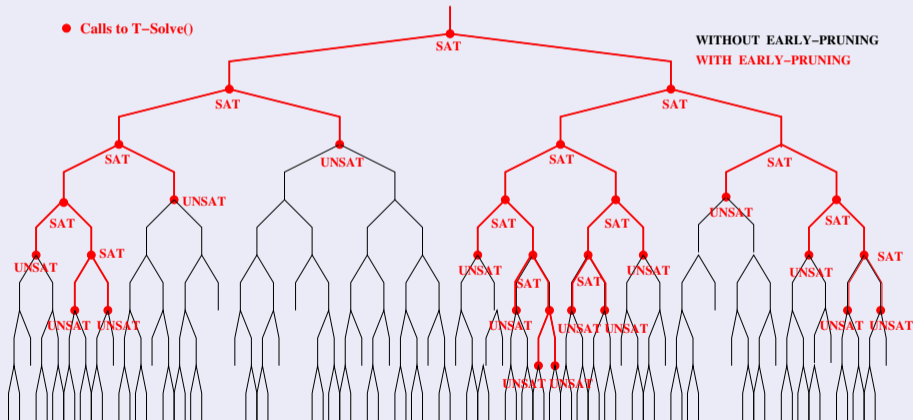
$$\begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \\ B_5 \vee \neg B_8 \vee B_1 \\ B_5 \vee \neg B_8 \vee \neg B_2 \end{array}$$



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Early Pruning [45, 2, 80]

- Introduce a \mathcal{T} -satisfiability test on **intermediate assignments**:
if \mathcal{T} -solver returns UNSAT, the procedure backtracks.
 - benefit: prunes drastically the Boolean search
 - Drawback: possibly **many useless calls to \mathcal{T} -solver**



Early pruning: example

$$\begin{aligned}\varphi = & \{ \neg(2v_2 - v_3 > 2) \vee A_1 \} \wedge \\ & \{ \neg A_2 \vee (2v_1 - 4v_5 > 3) \} \wedge \\ & \{ (3v_1 - 2v_2 \leq 3) \vee A_2 \} \wedge \\ & \{ \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \} \wedge \\ & \{ A_1 \vee (3v_1 - 2v_2 \leq 3) \} \wedge \\ & \{ (v_1 - v_5 \leq 1) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \} \wedge \\ & \{ A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \} . \\ \varphi^p = & \{ \neg B_1 \vee A_1 \} \wedge \\ & \{ \neg A_2 \vee B_2 \} \wedge \\ & \{ B_3 \vee A_2 \} \wedge \\ & \{ \neg B_4 \vee \neg B_5 \vee \neg A_1 \} \wedge \\ & \{ A_1 \vee B_3 \} \wedge \\ & \{ B_6 \vee B_7 \vee \neg A_1 \} \wedge \\ & \{ A_1 \vee B_8 \vee A_2 \} .\end{aligned}$$

- Suppose it is built the intermediate assignment:

$$\mu'^p = \neg B_1 \wedge \neg A_2 \wedge B_3 \wedge \neg B_5.$$

corresponding to the following set of \mathcal{T} -literals

$$\mu' = \neg(2v_2 - v_3 > 2) \wedge \neg A_2 \wedge (3v_1 - 2v_2 \leq 3) \wedge \neg(3v_1 - v_3 \leq 6).$$

- If \mathcal{T} -solver is invoked on μ' , then it returns UNSAT, and DPLL backtracks **without exploring any extension of μ'** .

Early Pruning [45, 2, 80] (cont.)

- Different strategies for interleaving Boolean search steps and \mathcal{T} -solver calls
 - **Eager E.P.** [80, 11, 78, 44]: invoke \mathcal{T} -solver every time a new \mathcal{T} -atom is added to the assignment (unit propagations included)
 - **Selective E.P.**: Do not call \mathcal{T} -solver if the have been added only literals which hardly cause any \mathcal{T} -conflict with the previous assignment (e.g., Boolean literals, disequalities $(x - y \neq 3)$, \mathcal{T} -literals introducing new variables $(x - z = 3)$)
 - **Weakened E.P.**: for intermediate checks only, use **weaker** but faster versions of \mathcal{T} -solver (e.g., check μ on \mathbb{R} rather than on \mathbb{Z}): $\{(x - y \leq 4), (z - x \leq -6), (z = y), (3x + 2y - 3z = 4)\}$

Early pruning: remark

Incrementality & Backtrackability of \mathcal{T} -solvers

- With early pruning, lots of **incremental calls to \mathcal{T} -solver**:

\mathcal{T} -solver (μ_1)	\Rightarrow Sat	Undo μ_4, μ_3, μ_2	
\mathcal{T} -solver ($\mu_1 \cup \mu_2$)	\Rightarrow Sat	\mathcal{T} -solver ($\mu_1 \cup \mu'_2$)	\Rightarrow Sat
\mathcal{T} -solver ($\mu_1 \cup \mu_2 \cup \mu_3$)	\Rightarrow Sat	\mathcal{T} -solver ($\mu_1 \cup \mu'_2 \cup \mu'_3$)	\Rightarrow Sat
\mathcal{T} -solver ($\mu_1 \cup \mu_2 \cup \mu_3 \cup \mu_4$)	\Rightarrow Unsat	...	

\Rightarrow Desirable features of \mathcal{T} -solvers:

- **incrementality**: \mathcal{T} -solver($\mu_1 \cup \mu_2$) reuses computation of \mathcal{T} -solver(μ_1) without restarting from scratch
- **backtrackability (resettability)**: \mathcal{T} -solver can efficiently undo steps and return to a previous status on the stack

\Rightarrow \mathcal{T} -solver requires a **stack-based interface**

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$\mathcal{T}\text{-solver}(\mu_1 \cup \mu_2 \cup \mu_3)$	$\Rightarrow \text{Sat}$	$\mathcal{T}\text{-solver}(\mu_1 \cup \mu'_2 \cup \mu'_3)$	$\Rightarrow \text{Sat}$
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$\mathcal{T}\text{-solver}(\mu_1 \cup \mu_2 \cup \mu_3)$	$\Rightarrow \text{Sat}$	$\mathcal{T}\text{-solver}(\mu_1 \cup \mu'_2 \cup \mu'_3)$	$\Rightarrow \text{Sat}$
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\Rightarrow \mathcal{T} -solver requires a **stack-based interface**

\mathcal{T} -Propagation [2, 3, 44]

- strictly related to early pruning
- important property of \mathcal{T} -solver:
 - **\mathcal{T} -deduction**: when a partial assignment μ is \mathcal{T} -satisfiable, \mathcal{T} -solver may be able to return also an assignment η to some unassigned atom occurring in φ s.t. $\mu \models_{\mathcal{T}} \eta$.
- If so:
 - the literal η is then unit-propagated;
 - optionally, a **\mathcal{T} -deduction clause** $C := \neg\mu' \vee \eta$ can be learned, μ' being the subset of μ which caused the deduction ($\mu' \models_{\mathcal{T}} \eta$)
 - **lazy explanation**: compute C only if needed for conflict analysis

⇒ may prune drastically the search

Both \mathcal{T} -deduction clauses and \mathcal{T} -conflict clauses are called **\mathcal{T} -lemmas** since they are valid in \mathcal{T}

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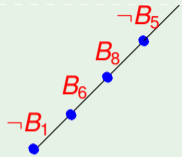
\Rightarrow may prune drastically the search

Both \mathcal{T} -deduction clauses and \mathcal{T} -conflict clauses are called \mathcal{T} -lemmas since they are valid in \mathcal{T}

\mathcal{T} -propagation: example

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \end{array} \quad \begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \end{array}$$

true, false



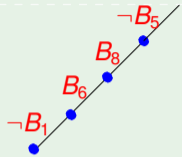
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\Rightarrow propagate $\neg B_3$ [and learn the deduction clause $B_5 \vee B_1 \vee \neg B_3$]

\mathcal{T} -propagation: example

$$\begin{array}{l} \varphi = \\ c_1 : \neg(2v_2 - v_3 > 2) \vee A_1 \\ c_2 : \neg A_2 \vee (v_1 - v_5 \leq 1) \\ c_3 : (3v_1 - 2v_2 \leq 3) \vee A_2 \\ c_4 : \neg(2v_3 + v_4 \geq 5) \vee \neg(3v_1 - v_3 \leq 6) \vee \neg A_1 \\ c_5 : A_1 \vee (3v_1 - 2v_2 \leq 3) \\ c_6 : (v_2 - v_4 \leq 6) \vee (v_5 = 5 - 3v_4) \vee \neg A_1 \\ c_7 : A_1 \vee (v_3 = 3v_5 + 4) \vee A_2 \end{array} \quad \begin{array}{l} \varphi^p = \\ \neg B_1 \vee A_1 \\ \neg A_2 \vee B_2 \\ B_3 \vee A_2 \\ \neg B_4 \vee \neg B_5 \vee \neg A_1 \\ A_1 \vee B_3 \\ B_6 \vee B_7 \vee \neg A_1 \\ A_1 \vee B_8 \vee A_2 \end{array}$$

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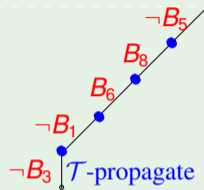
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If we have non-Boolean \mathcal{T} -atoms occurring only positively [negatively] in the original formula φ (learned clauses are not considered), we can drop every negative [positive] occurrence of them from the assignment to be checked by \mathcal{T} -solver (and from the \mathcal{T} -deducible ones).

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- eliminates unnecessary “nasty” negated literals
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Source of inefficiency:

Semantically equivalent but syntactically different atoms are not recognized to be identical [resp. one the negation of the other]

⇒ they may be assigned different [resp. identical] truth values.

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- Often possible to quickly detect a priori short and “obviously unsatisfiable” pairs or triplets of literals occurring in φ .
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Other optimization techniques

- \mathcal{T} -deduced-literal filtering
- Ghost-literal filtering
- \mathcal{T} -solver layering
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- ...

(see [70, 10] for an overview)

Other SAT-solving techniques for SMT?

Frequently-asked question:

Are CDCL SAT solvers the only suitable Boolean Engines for SMT?

Some previous attempts:

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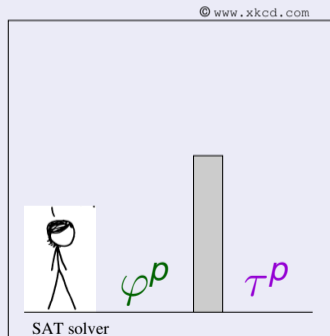
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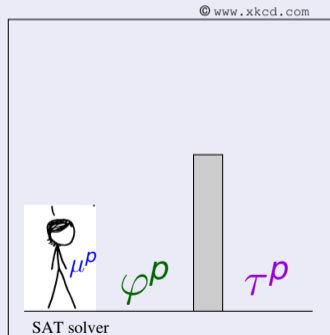
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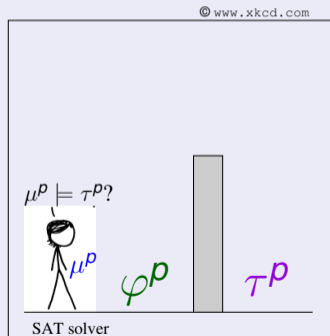
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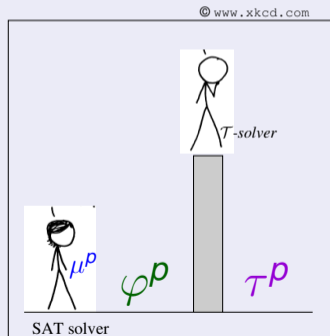
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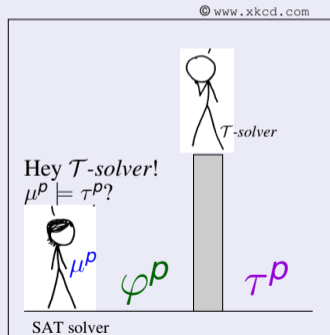
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 - if no, returns UNSAT and some falsified clauses $c_1^p, \dots, c_k^p \in \tau^p$



SMT formulas = “partially-invisible” SAT formulas

An SMT problem φ from the perspective of a SAT solver:

- a “partially-invisible” Boolean CNF formula $\varphi^p \wedge \tau^p$:
 - φ^p : the Boolean abstraction of the input formula φ
 - τ^p : (the Boolean abstraction of) the set τ of all \mathcal{T} -lemmas on atoms in φ .

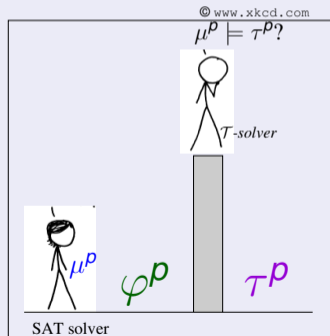
φ \mathcal{T} -satisfiable iff $\varphi^p \wedge \tau^p$ satisfiable.

- the SAT solver:

- “sees” only φ^p
- finds μ^p s.t. $\mu^p \models \varphi^p$
- cannot state if $\mu^p \models \tau^p$
- invokes \mathcal{T} -solver on μ^p

- the \mathcal{T} -solver:

- “sees” τ^p
- checks if $\mu^p \models \tau^p$:
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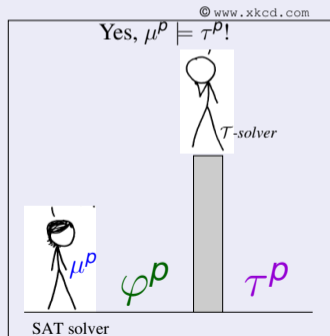
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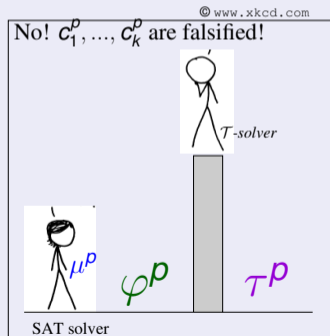
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- checks if $\mu^p \models \tau^p$:
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 - if no, returns UNSAT and some falsified clauses $c_1^p, \dots, c_k^p \in \tau^p$



Example

φ :

$$c_1 : \{A_1\}$$

$$c_2 : \{\neg A_1 \vee (x - z > 4)\}$$

$$c_3 : \{\neg A_3 \vee A_1 \vee (y \geq 1)\}$$

$$c_4 : \{\neg A_2 \vee \neg(x - z > 4) \vee \neg A_1\}$$

$$c_5 : \{(x - y \leq 3) \vee \neg A_4 \vee A_5\}$$

$$c_6 : \{\neg(y - z \leq 1) \vee (x + y = 1) \vee \neg A_5\}$$

$$c_7 : \{A_3 \vee \neg(x + y = 0) \vee A_2\}$$

$$c_8 : \{\neg A_3 \vee (z + y = 2)\}$$

τ : (all possible \mathcal{T} -lemmas on the \mathcal{T} -atoms of φ)

$$c_9 : \{\neg(x + y = 0) \vee \neg(x + y = 1)\}$$

$$c_{10} : \{\neg(x - z > 4) \vee \neg(x - y \leq 3) \vee \neg(y - z \leq 1)\}$$

$$c_{11} : \{(x - z > 4) \vee (x - y \leq 3) \vee (y - z \leq 1)\}$$

$$c_{12} : \{\neg(x - z > 4) \vee \neg(x + y = 1) \vee \neg(z + y = 2)\}$$

$$c_{13} : \{\neg(x - z > 4) \vee \neg(x + y = 0) \vee \neg(z + y = 2)\}$$

...

$$\mu_1^p : \{A_1, B_1, \neg A_2, A_3, \neg A_4, \neg A_5, \neg B_6, B_5, B_3, B_4, B_7, \neg B_2\}$$

$$\mu_1 : \{\underline{(x - z > 4)}, \neg(x + y = 0), \underline{(x + y = 1)}, \underline{(x - y \leq 3)}, \underline{(y - z \leq 1)}, \underline{(z + y = 2)}, \neg(y \geq 1)\}$$

satisfies φ^p , but violates both c_{10} and c_{12} in τ^p .

φ^p :

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$$c_2 : \{\neg A_1 \vee B_1\}$$

$$c_3 : \{\neg A_3 \vee A_1 \vee B_2\}$$

$$c_4 : \{\neg A_2 \vee \neg B_1 \vee \neg A_1\}$$

$$c_5 : \{B_3 \vee \neg A_4 \vee A_5\}$$

$$c_6 : \{\neg B_4 \vee B_5 \vee \neg A_5\}$$

$$c_7 : \{A_3 \vee \neg B_6 \vee A_2\}$$

$$c_8 : \{\neg A_3 \vee B_7\}$$

τ^p :

$$c_9 : \{\neg B_6 \vee \neg B_5\}$$

$$c_{10} : \{\neg B_1 \vee \neg B_3 \vee \neg B_4\}$$

$$c_{11} : \{B_1 \vee B_3 \vee B_4\}$$

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satisfies φ^p , but violates both c_{10} and c_{12} in τ^p .

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c_2 : $\{\neg A_1 \vee B_1\}$

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...

Exercise

Consider the following formula in the theory \mathcal{EUF} .

$$\begin{aligned}\varphi = & \{(f(x) = f(f(y))) \vee A_2\} \wedge \\ & \{\neg(h(x, f(y)) = h(g(x), y)) \vee \underline{\neg(h(x, g(z) = h(f(x), y))} \vee \neg A_1\} \wedge \\ & \{A_1 \vee (h(x, y) = h(y, x))\} \wedge \\ & \{\underline{x = f(x)} \vee A_3 \vee \neg A_1\} \wedge \\ & \{\underline{\neg(w(x) = g(f(y)))} \vee A_1\} \wedge \\ & \{\underline{\neg A_2} \vee (w(g(x)) = w(f(x)))\} \wedge \\ & \{A_1 \vee \underline{y = g(z)} \vee A_2\}\end{aligned}$$

and consider the partial truth assignment μ given by the underlined literals above:

$$\{\neg(w(x) = g(f(y))), \neg A_2, \neg(h(x, g(z) = h(f(x), y))), (x = f(x)), (y = g(z))\}.$$

- 1 Does (the Boolean abstraction of) μ propositionally satisfy (the Boolean abstraction of) φ ?
- 2 Is μ satisfiable in \mathcal{EUF} ?
 - 1 If no, find a minimal conflict set for μ and the corresponding conflict clause C .
 - 2 If yes, show one unassigned literal which can be deduced from μ , and show the corresponding deduction clause C .

- 1 Introduction
 - Basics on First-order Logic
 - What is a Theory?
 - Satisfiability Modulo Theories
 - Motivations and Goals of SMT
- 2 **Efficient SMT solving**
 - Combining SAT with Theory Solvers
 - **Theory Solvers for Theories of Interest (hints)**
 - SMT for Combinations of Theories
- 3 Beyond Solving: Advanced SMT Functionalities
 - Proofs and Unsatisfiable Cores
 - All-SMT & Predicate Abstraction (hints)
 - SMT with Optimization (Optimization Modulo Theories)

Summary: desirable properties for \mathcal{T} -solver

- Correctness & Completeness: be correct & complete
- Time efficiency: be fast
- Incrementality & backtrackability: $\mathcal{T}\text{-solver}(\mu_1 \cup \mu_2)$ reuses computation of $\mathcal{T}\text{-solver}(\mu_1)$
- Diagnosis capabilities: $\mathcal{T}\text{-solver}$ able to produce conflict sets
- Deduction capabilities: $\mathcal{T}\text{-solver}$ able to deduce assignments

\mathcal{T} -solvers for Equality and Uninterpreted Functions (\mathcal{EUF})

- Typically used as a “core” \mathcal{T} -solver
- \mathcal{EUF} polynomial: $O(n \cdot \log(n))$
- Fully incremental and backtrackable (stack-based)
- Uses a congruence closure data structures (**E-Graphs**) [39, 64, 34],
 - based on the Union-Find data-structure for equivalence classes
- Supports efficient \mathcal{T} -propagation
 - Exhaustive for positive equalities
 - Incomplete for disequalities
- Supports Lazy explanations and conflict generation
 - However, minimality not guaranteed
- Supports efficient extensions
(e.g., Integer offsets, Bit-vector slicing and concatenation)

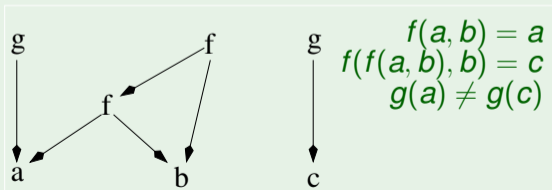
\mathcal{T} -solvers for \mathcal{EUF} : Example

Idea (sketch), based on **E-Graphs**:

given the set of terms occurring in the formula represented as nodes in a DAG (aka **term bank**):

- if $(t = s)$, then merge the eq. classes of t and s
 - e.g. use the **union-find** data structure
- if $\forall i \in 1 \dots k, t_i$ and s_i pairwise belong to the same eq. classes, then merge the eq. classes of $f(t_1, \dots, t_k)$ and $f(s_1, \dots, s_k)$
- if $(t \neq s)$ and t and s belong to the same eq. class, then conflict

E-Graph:



Example borrowed from [39].

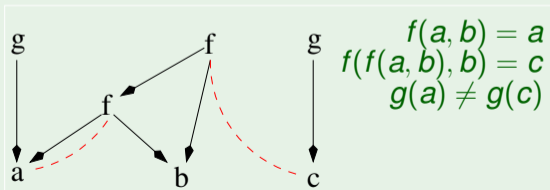
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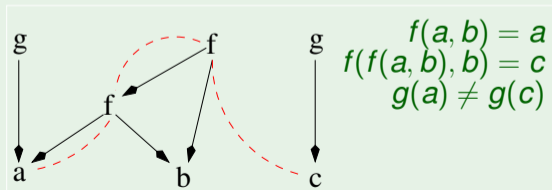
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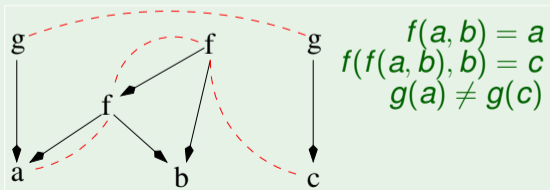
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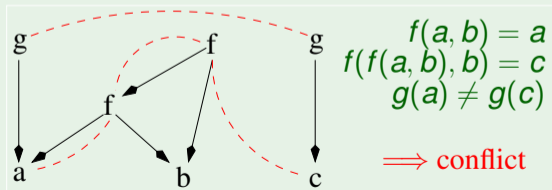
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E-Graph:



Example borrowed from [39].

Exercises

For each of the following sets of \mathcal{EUF} -literals

- 1 build the E-graph
- 2 say if the set is \mathcal{EUF} -satisfiable or not
- 3 if \mathcal{EUF} -unsatisfiable, return a \mathcal{EUF} -conflict set

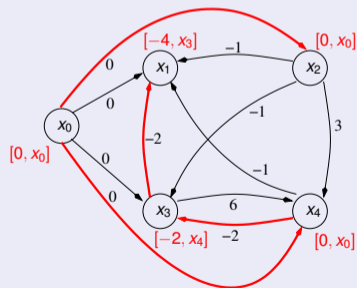
Sets of \mathcal{EUF} -literals:

- (a) $\{g(a) = b, h(b) = a, h(a) = c, g(h(b)) = c, h(h(g(a))) \neq c\}$
(b) $\{g(a) = b, h(b) = a, h(a) = c, f(h(g(a)), g(h(b))) \neq f(a, b)\}$
(c) [... invent your own sets of \mathcal{EUF} -literals]

\mathcal{T} -solvers for Difference logic (\mathcal{DL})

- \mathcal{DL} polynomial: $O(\#vars \cdot \#constraints)$
- variants of the Bellman-Ford shortest-path algorithm: a negative cycle reveals a conflict [65, 33]
- Ex:

$$\{(x_1 - x_2 \leq -1), (x_1 - x_4 \leq -1), (x_1 - x_3 \leq -2), (x_2 - x_1 \leq 2), \\ (x_3 - x_4 \leq -2), (x_3 - x_2 \leq -1), (x_4 - x_2 \leq 3), (x_4 - x_3 \leq 6)\}$$

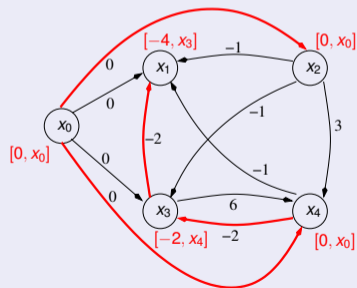


\Rightarrow Sat

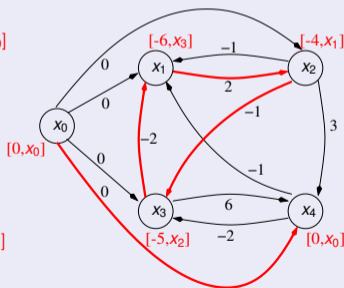
T-solvers for Difference logic (\mathcal{DL})

- \mathcal{DL} polynomial: $O(\#vars \cdot \#constraints)$
- variants of the Bellman-Ford shortest-path algorithm: a negative cycle reveals a conflict [65, 33]
- Ex:

$$\{(x_1 - x_2 \leq -1), (x_1 - x_4 \leq -1), (x_1 - x_3 \leq -2), (x_2 - x_1 \leq 2), \\ (x_3 - x_4 \leq -2), (x_3 - x_2 \leq -1), (x_4 - x_2 \leq 3), (x_4 - x_3 \leq 6)\}$$



\Rightarrow Sat



\Rightarrow Unsat

Exercises

For each of the following sets of \mathcal{DL} -literals

- 1 build the minimum-path graph
- 2 say if the set is \mathcal{DL} -satisfiable or not
- 3 if \mathcal{DL} -unsatisfiable, return a \mathcal{DL} -conflict set

Sets of \mathcal{DL} -literals:

$$(a) \left\{ \begin{array}{l} (x_1 - x_3 \leq 5), (x_1 - x_2 \leq -2), (x_1 - x_4 \leq -3), (x_2 - x_4 \leq 0), (x_3 - x_5 \leq -2), \\ (x_4 - x_5 \leq 8), (x_5 - x_1 \leq -4) \end{array} \right\}$$

$$(b) \left\{ \begin{array}{l} (x_1 - x_2 \leq 3), (x_1 - x_4 \leq -1), (x_1 - x_5 \leq 4), (x_2 - x_3 \leq 0), (x_2 - x_5 \leq -1) \\ (x_3 - x_1 \leq 1), (x_3 - x_2 \leq 2), (x_4 - x_3 \leq 1), (x_5 - x_3 \leq -2), (x_5 - x_4 \leq -5) \end{array} \right\}$$

(c) [... invent your own sets of \mathcal{DL} -literals]

\mathcal{T} -solvers for Linear arithmetic over the rationals (\mathcal{LRA})

- EX: $\{(s_1 - s_2 \leq 5.2), (s_1 = s_0 + 3.4 \cdot t - 3.4 \cdot t_0), \neg(s_1 = s_0)\}$
- \mathcal{LRA} polynomial
- variants of the simplex LP algorithm [41]
- [41] allows for detecting conflict sets & performing \mathcal{T} -propagation
- strict inequalities $t < 0$ rewritten as $t + \epsilon \leq 0$, ϵ treated symbolically

$$\begin{array}{c} \mathcal{B} \\ \left[\begin{array}{c} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_N \end{array} \right] \end{array} = \begin{array}{c} \left[\begin{array}{ccc} \dots & A_{1j} & \dots \\ & \vdots & \\ A_{i1} & \dots & A_{ij} & \dots & A_{iM} \\ & \vdots & & & \\ \dots & A_{Nj} & \dots \end{array} \right] \end{array} \begin{array}{c} \mathcal{N} \\ \left[\begin{array}{c} x_{N+1} \\ \vdots \\ x_j \\ \vdots \\ x_{N+M} \end{array} \right] \end{array} ;$$

Invariant: $\beta(x_j) \in [l_j, u_j] \forall x_j \in \mathcal{N}$

Remark: infinite precision arithmetic

In order to avoid incorrect results due to numerical errors and to overflows, all \mathcal{T} -solvers for \mathcal{LRA} , \mathcal{LIA} and their subtheories which are based on numerical algorithms must be implemented on top of infinite-precision-arithmetic software packages.

\mathcal{T} -solvers for Linear arithmetic over the integers (\mathcal{LIA})

- EX: $\{(x := x_l + 2^{16}x_h), (x \geq 0), (x \leq 2^{16} - 1)\}$
- \mathcal{LIA} NP-complete
- combination of many techniques: simplex, branch&bound, cutting planes, ... [41, 47]

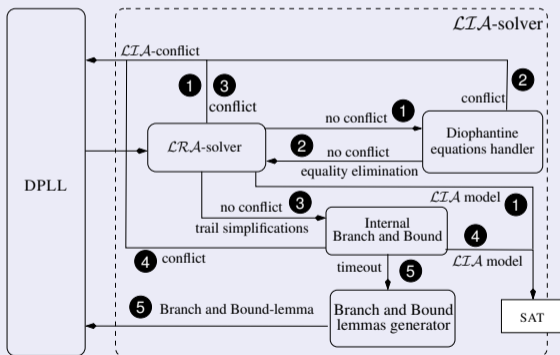


Figure courtesy of A. Griggio [47]

\mathcal{T} -solvers for Arrays (\mathcal{AR})

- EX: $(write(A, i, v) = write(B, i, w)) \wedge \neg(v = w)$
- NP-complete
- congruence closure (\mathcal{EUF}) plus on-the-fly instantiation of array's axioms:

$$\forall a. \forall i. \forall e. (read(write(a, i, e), i) = e), \quad (1)$$

$$\forall a. \forall i. \forall j. \forall e. ((i \neq j) \rightarrow read(write(a, i, e), j) = read(a, j)), \quad (2)$$

$$\forall a. \forall b. (\forall i. (read(a, i) = read(b, i)) \rightarrow (a = b)). \quad (3)$$

- EX:

Input : $(write(A, i, v) = write(B, i, w)) \wedge \neg(v = w)$

inst. (1) : $(read(write(A, i, v), i) = v)$
 $(read(write(B, i, w), i) = w)$

$\models_{\mathcal{EUF}} (v = w)$

$\models_{Bool} \perp$

- many strategies discussed in the literature (e.g., [39, 46, 20, 38])

Exercises

For each of the following sets of \mathcal{AR} -literals, try to infer \perp by instantiating the \mathcal{AR} axioms and applying \mathcal{EUF} -inference and \mathcal{BOOL} -inference.

Sets of \mathcal{AR} -literals:

- (a) $\{ A_1 = \text{Write}(A_0, i, x), A_2 = \text{Write}(A_0, j, y), (i = j), \neg(k = i), \neg(\text{Read}(A_2, k) = \text{Read}(A_1, k)) \}$
- (b) $\{ A_1 = \text{Write}(A_0, i, x), A_2 = \text{Write}(A_0, i, y), \neg(x = y), (A_1 = A_2) \}$
- (c) $\{ A_1 = \text{Write}(A_0, i, x), \text{Read}(A_0, i) = \text{Read}(A_1, i), \neg(A_1 = A_0) \}$
- (d) [... invent your own sets of \mathcal{AR} -literals]

\mathcal{T} -solvers for Bit vectors (\mathcal{BV})

Bit vectors (\mathcal{BV})

- EX: $\{(x_{[16]}[15 : 0] = (y_{[16]}[15 : 8] :: z_{[16]}[7 : 0]) \ll w_{[16]}[3 : 0]), \dots\}$
- NP-hard
- involve complex word-level operations: word partition/concat, modulo- 2^N arithmetic, shifts, bitwise-operations, multiplexers, ...
- \mathcal{T} -solving: combination of rewriting & simplification techniques with either:
 - final encoding into \mathcal{LIA} [19, 22]
 - final encoding into SAT (**lazy bit-blasting**) [25, 43, 21, 42]

Eager approach

Most solvers use an **eager** approach for \mathcal{BV} (e.g., [21]):

- Heavy preprocessing, based on rewriting rules
- bit-blasting

\mathcal{T} -solvers for Bit vectors (\mathcal{BV})

Bit vectors (\mathcal{BV})

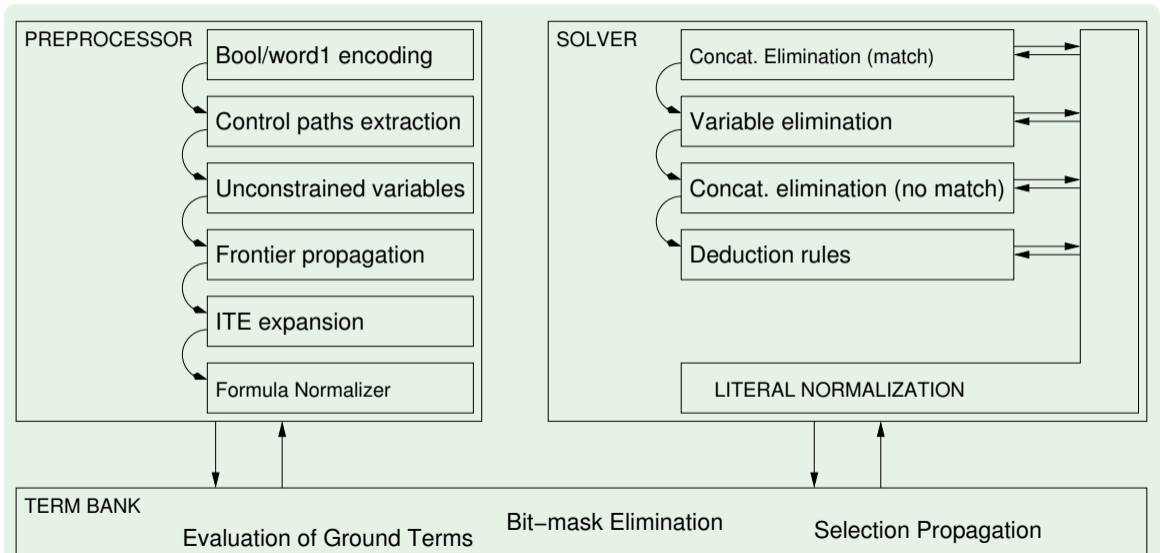
- EX: $\{(x_{[16]}[15 : 0] = (y_{[16]}[15 : 8] :: z_{[16]}[7 : 0]) \ll w_{[16]}[3 : 0]), \dots\}$
- NP-hard
- involve complex word-level operations: word partition/concat, modulo- 2^N arithmetic, shifts, bitwise-operations, multiplexers, ...
- \mathcal{T} -solving: combination of rewriting & simplification techniques with either:
 - final encoding into \mathcal{LIA} [19, 22]
 - final encoding into SAT (**lazy bit-blasting**) [25, 43, 21, 42]

Eager approach

Most solvers use an **eager** approach for \mathcal{BV} (e.g., [21]):

- Heavy preprocessing, based on rewriting rules
- bit-blasting

\mathcal{T} -solvers for Bit vectors (BV) [cont.]



Example borrowed from [22]

\mathcal{T} -solvers for Bit vectors (\mathcal{BV}) [cont.]

Lazy bit-blasting

- Two nested SAT solvers

- bit-blast each \mathcal{BV} atom ψ_i

$$\implies \Phi \stackrel{\text{def}}{=} \bigwedge_i (A_i \leftrightarrow BB(\psi_i)),$$

A_i fresh variables labeling \mathcal{BV} -atoms ψ_i in φ

$\implies \varphi$ \mathcal{BV} -satisfiable iff $\varphi^p \wedge \Phi$ satisfiable

- Exploit SAT under assumptions

- let μ^p an assignment for φ^p , s.t. $\mu^p \stackrel{\text{def}}{=} \{[\neg]A_1, \dots, [\neg]A_n\}$

- \mathcal{T} -solver for \mathcal{BV} : $SAT_{\text{assumption}}(\Phi, \mu^p)$

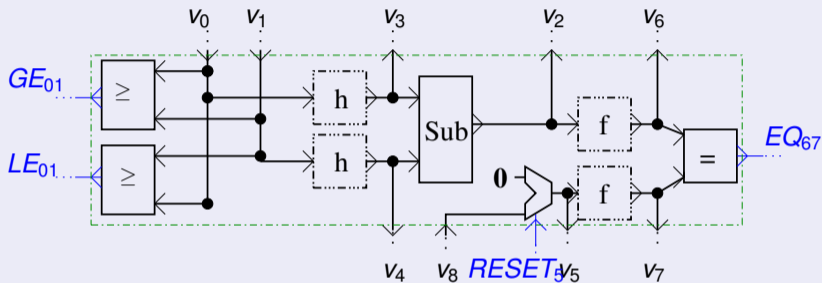
- If UNSAT, generate the **unsat core** $\eta^p \subseteq \mu^p$

$\implies \neg\eta^p$ used as blocking clause

- 1 Introduction
 - Basics on First-order Logic
 - What is a Theory?
 - Satisfiability Modulo Theories
 - Motivations and Goals of SMT
- 2 **Efficient SMT solving**
 - Combining SAT with Theory Solvers
 - Theory Solvers for Theories of Interest (hints)
 - **SMT for Combinations of Theories**
- 3 Beyond Solving: Advanced SMT Functionalities
 - Proofs and Unsatisfiable Cores
 - All-SMT & Predicate Abstraction (hints)
 - SMT with Optimization (Optimization Modulo Theories)

SMT for combined theories: $SMT(\cup_i T_i)$

Problem: Many problems can be expressed as SMT problems only in combination of theories



$\cup_i T_i - SMT(\cup_i T_i)$

$\mathcal{L}IA$: $(GE_{01} \leftrightarrow (v_0 \geq v_1)) \wedge (LE_{01} \leftrightarrow (v_0 \leq v_1)) \wedge$

$\mathcal{E}UF$: $(v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge$

$\mathcal{L}IA$: $(v_2 = v_3 - v_4) \wedge (RESET_5 \rightarrow (v_5 = 0)) \wedge$

$\mathcal{E}UF$ or $\mathcal{L}IA$: $(\neg RESET_5 \rightarrow (v_5 = v_8)) \wedge$

$\mathcal{E}UF$: $(v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge$

$\mathcal{E}UF$ or $\mathcal{L}IA$: $(EQ_{67} \leftrightarrow (v_6 = v_7)) \wedge \dots$

SMT for combined theories: $\text{SMT}(\mathcal{T}_1 \cup \mathcal{T}_2)$

- Combined theories may be much harder to decide [Pratt'77]
- Solvers have to be combined
- Standard approach for combining \mathcal{T}_i -solvers:
(deterministic) Nelson-Oppen/Shostak (N.O.) [61, 63, 75]
 - based on deduction and exchange of equalities on shared variables
 - combined \mathcal{T}_i -solvers integrated with a SAT tool
- SMT-specific approaches: Delayed Theory Combination [15, 14] and Model-Based Theory Combination [36]
 - based on Boolean search on equalities on shared variables
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Background: Pure Formulas

Consider two theories $\mathcal{T}_1, \mathcal{T}_2$ with equality and disjoint signatures Σ_1, Σ_2

- W.l.o.g. we assume all input formulas $\phi \in \mathcal{T}_1 \cup \mathcal{T}_2$ are **pure**.
 - A formula ϕ is **pure** iff every atom in ϕ is i -pure for some $i \in \{1, 2\}$.
 - An atom/literal ψ in ϕ is i -**pure** if only $=$, variables and symbols from Σ_i can occur in ψ

Purification:

Maps a formula into an equisatisfiable pure formula by labeling terms with fresh variables

$$\begin{array}{ccc} (f(x + 3y) = g(2x - y)) & & \text{[not pure]} \\ \underbrace{\quad\quad\quad}_w & & \underbrace{\quad\quad\quad}_t \\ \downarrow & & \\ (w = x + 3y) \wedge (t = 2x - y) \wedge (f(w) = g(t)) & & \text{[pure]} \end{array}$$

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Exercise

- Purify the following $\mathcal{LIA} \cup \mathcal{EUF} \cup \mathcal{AR}$ -formula (see beginning of chapter):

$$\varphi \stackrel{\text{def}}{=} (d \geq 0) \wedge (d < 1) \wedge \\ ((f(d) = f(0)) \rightarrow (\text{read}(\text{write}(V, i, x), i + d) = x + 1))$$

Background: Interface equalities

Interface variables & equalities

- A variable v occurring in a pure formula ϕ is an **interface variable** iff it occurs in both 1-pure and 2-pure atoms of ϕ .
- An equality $(v_i = v_j)$ is an **interface equality** for ϕ iff v_i, v_j are interface variables for ϕ .
- We denote the interface equality $v_i = v_j$ by “ e_{ij} ”

Example:

$$\begin{aligned} \mathcal{LIA} : & \quad (GE_{01} \leftrightarrow (v_0 \geq v_1)) \wedge (LE_{01} \leftrightarrow (v_0 \leq v_1)) \wedge \\ \mathcal{EUF} : & \quad (v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge \\ \mathcal{LIA} : & \quad (v_2 = v_3 - v_4) \wedge (RESET_5 \rightarrow (v_5 = 0)) \wedge \\ \mathcal{EUF} \text{ or } \mathcal{LIA} : & \quad (\neg RESET_5 \rightarrow (v_5 = v_8)) \wedge \\ \mathcal{EUF} : & \quad (v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge \\ \mathcal{EUF} \text{ or } \mathcal{LIA} : & \quad (EQ_{67} \leftrightarrow (v_6 = v_7)) \wedge \dots \end{aligned}$$

$v_0, v_1, v_2, v_3, v_4, v_5$ are interface variables, v_6, v_7, v_8 are not
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A Σ -theory \mathcal{T} is **stably-infinite** iff every quantifier-free \mathcal{T} -satisfiable formula is satisfiable in an infinite model of \mathcal{T} .

- \mathcal{EUF} , \mathcal{DL} , \mathcal{LRA} , \mathcal{LIA} are stably-infinite
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Intuition: a variable can be given an infinite amount of distinct values

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A Σ -theory \mathcal{T} is **convex** iff, for every collection l_1, \dots, l_k, l', l'' of literals in \mathcal{T} s.t. l', l'' are in the form $(x = y)$, x, y being variables, we have that:

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SMT($\bigcup_i \mathcal{T}_i$) via “classic” Nelson-Oppen

Main Problem

- Given $\mu \stackrel{\text{def}}{=} \bigcup_i \mu_i$ s.t. each μ_i contains i-pure literals
 - distinct \mathcal{T}_i -solver can be invoked separately on each μ_i ...
 - ...producing distinct \mathcal{T}_i -specific models \mathcal{M}_i
- If the theories share no constant, function or predicate symbol \implies trivial
- Problem: One predicate (nearly) always shared between distinct theories \mathcal{T}_i : equality “=”

\implies all models must agree on interface equalities:

$$\mathcal{M}_i \models_{\mathcal{T}_i} (v_k = v_l) \text{ iff } \mathcal{M}_j \models_{\mathcal{T}_j} (v_k = v_l),$$

for every pair of shared variables v_k, v_l

Main idea

Combine two or more \mathcal{T}_i -solvers into one $(\bigcup_i \mathcal{T}_i)$ -solver via Nelson-Oppen/Shostak (N.O.) combination procedure [62, 76]

- based on the deduction and exchange of equalities between shared variables/terms (interface equalities, e_{ij} s)
- important improvements and evolutions [68, 7, 39]

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Combine two or more \mathcal{T}_i -solvers into one $(\bigcup_i \mathcal{T}_i)$ -solver via Nelson-Oppen/Shostak (N.O.) combination procedure [62, 76]

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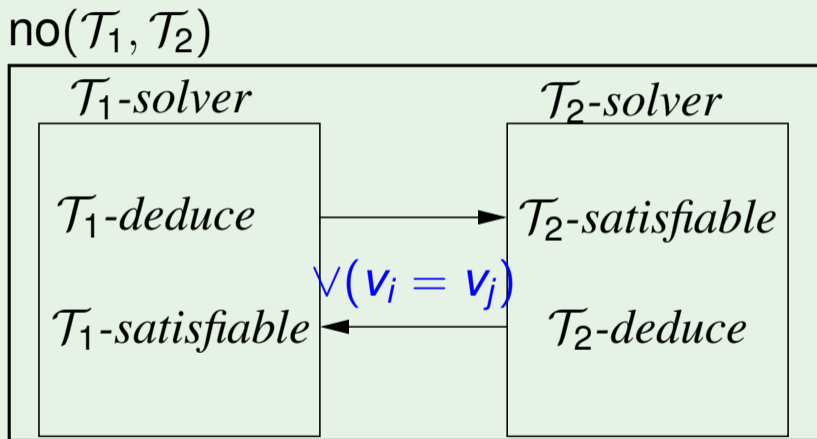
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Schema of N.O. combination of T-solvers: $\text{no}(\mathcal{T}_1, \mathcal{T}_2)$



N.O. Example (Convex Theory)

\mathcal{EUF} : $(v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge (v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge$

\mathcal{LRA} : $(v_0 \geq v_1) \wedge (v_0 \leq v_1) \wedge (v_2 = v_3 - v_4) \wedge (RESET_5 \rightarrow (v_5 = 0)) \wedge$

Both : $(\neg RESET_5 \rightarrow (v_5 = v_8)) \wedge \neg(v_6 = v_7)$.

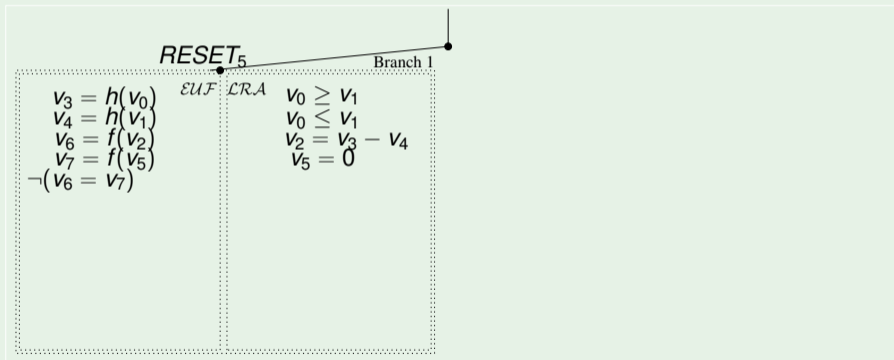


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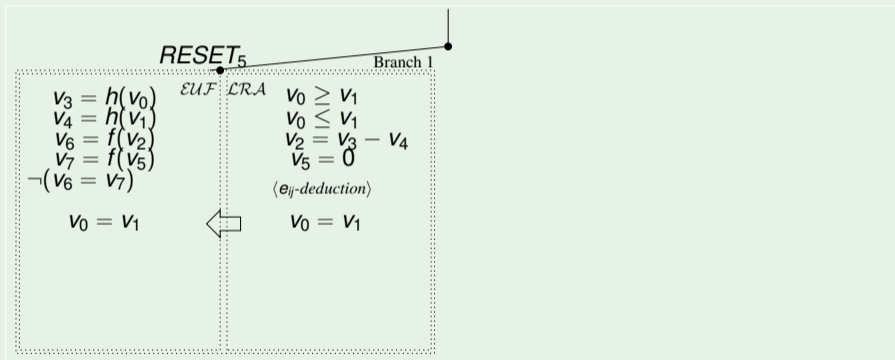


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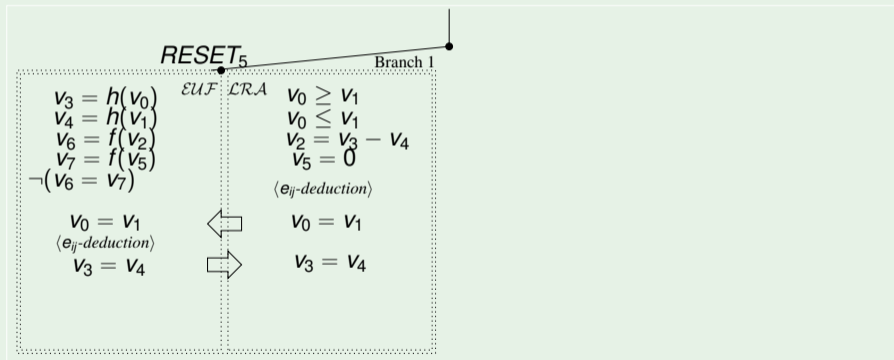


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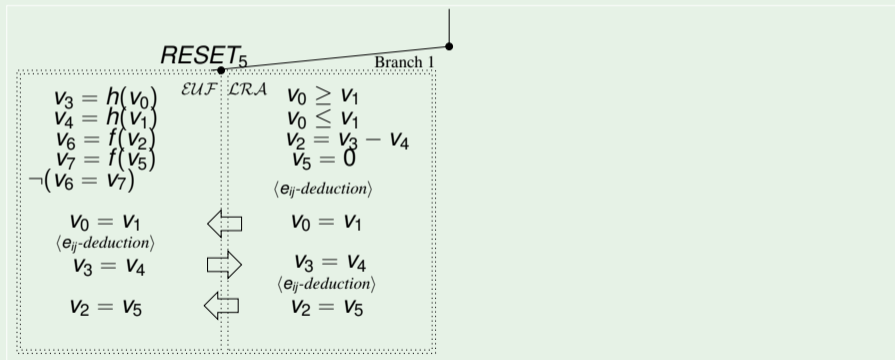


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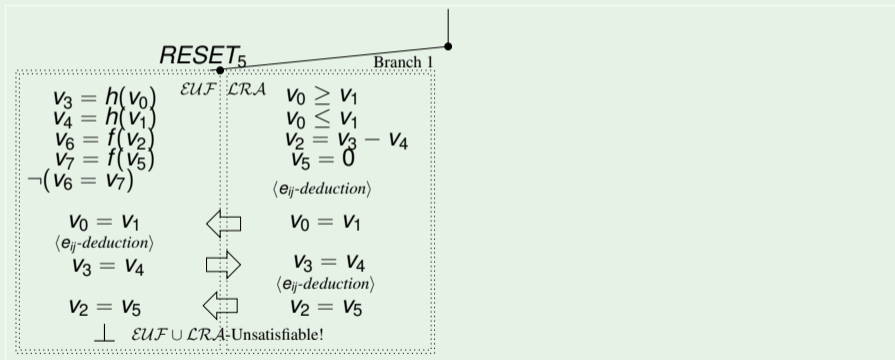


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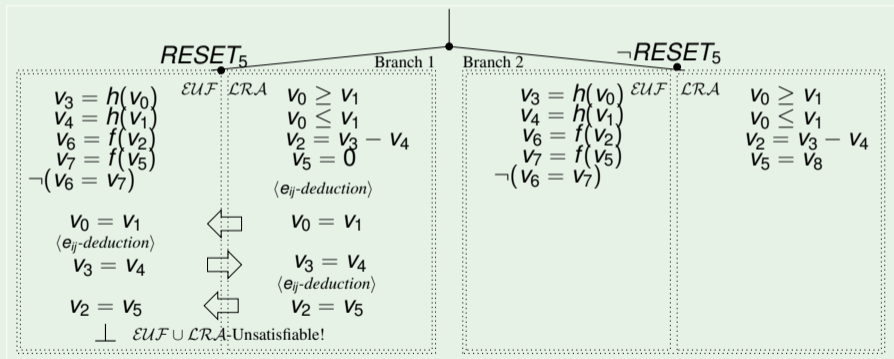


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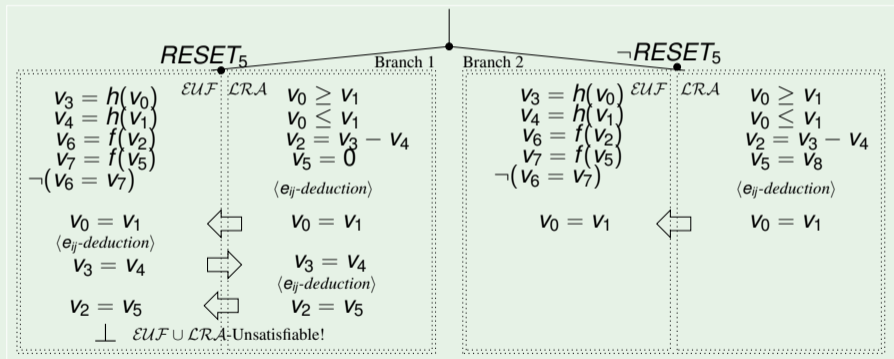


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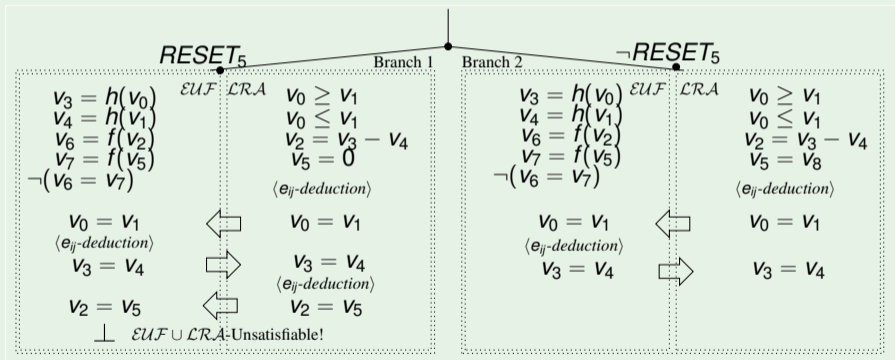


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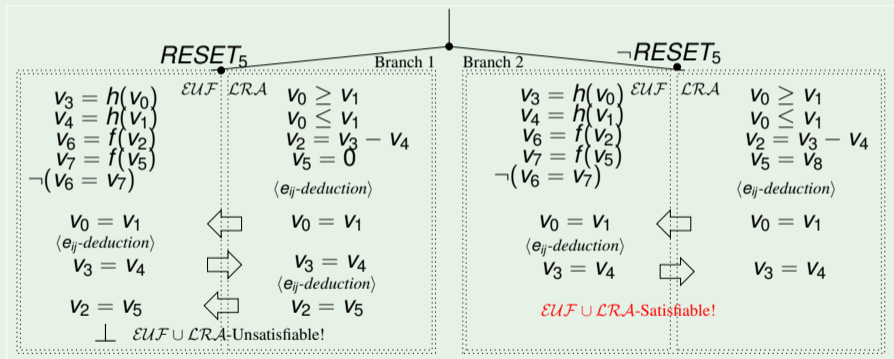


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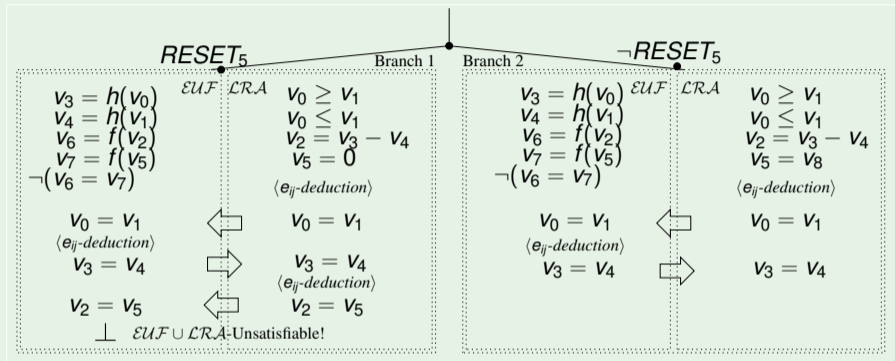
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N.O.: example (convex theory) [cont.]



EUF -conflict : $((v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge \neg(v_6 = v_7) \wedge (v_2 = v_5)) \rightarrow \perp$
 LRA -deduction : $((v_2 = v_3 - v_4) \wedge (v_5 = 0) \wedge (v_3 = v_4)) \rightarrow (v_2 = v_5)$
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 LRA -deduction : $((v_0 \geq v_1) \wedge (v_0 \leq v_1)) \rightarrow (v_0 = v_1)$
 \Rightarrow
 $EUF \cup LRA$ -conflict : $((v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge \neg(v_6 = v_7) \wedge (v_2 = v_3 - v_4) \wedge (v_5 = 0) \wedge (v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge (v_0 \geq v_1)) \rightarrow \perp$

For the previous N.O. example:

- write the (minimal) clauses corresponding to each e_{ij} -deduction
- find the final conflict clauses by resolving the e_{ij} -deduction clauses

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N.O.: example (non-convex theory)

μ_{LIA}

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

μ_{EUF}

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

N.O.: example (non-convex theory)

μ_{LIA}

$$v_1 \geq 0 \quad v_5 = v_4 - 1$$

$$v_1 \leq 1 \quad v_3 = 0$$

$$v_2 \geq v_6 \quad v_4 = 1$$

$$v_2 \leq v_6 + 1$$

(e_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$

μ_{EUF}

$$\neg(f(v_1) = f(v_2))$$

$$\neg(f(v_2) = f(v_4))$$

$$f(v_3) = v_5$$

$$f(v_1) = v_6$$

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

(e_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$



$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

(θ_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$



$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

(θ_{ij} -deduction)

$$v_5 = v_6$$

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_1 = v_3 \vee v_1 = v_4$$

$$v_5 = v_6$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_2 = v_3 \vee v_2 = v_4$$

$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_5 = v_6$$

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

(e_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$

$$v_5 = v_6$$

(e_{ij} -deduction)

$$v_2 = v_3 \vee v_2 = v_4$$

$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

(e_{ij} -deduction)

$$v_5 = v_6$$

$$v_2 = v_3$$

\perp

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

(e_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$

$$v_5 = v_6$$

(e_{ij} -deduction)

$$v_2 = v_3 \vee v_2 = v_4$$

$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

(e_{ij} -deduction)

$$v_5 = v_6$$

$$\begin{array}{ll} v_2 = v_3 & v_2 = v_4 \\ \perp & \perp \end{array}$$

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

(e_{ij} -deduction)

$$v_1 = v_3 \vee v_1 = v_4$$

$$v_5 = v_6$$

(e_{ij} -deduction)

$$v_2 = v_3 \vee v_2 = v_4$$

$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

(e_{ij} -deduction)

$$v_5 = v_6$$

$$v_1 = v_4$$

SAT!

$$v_2 = v_3$$

\perp

$$v_2 = v_4$$

\perp

N.O.: example (non-convex theory)

$\mu\mathcal{LIA}$

$$\begin{array}{ll} v_1 \geq 0 & v_5 = v_4 - 1 \\ v_1 \leq 1 & v_3 = 0 \\ v_2 \geq v_6 & v_4 = 1 \\ v_2 \leq v_6 + 1 & \end{array}$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_1 = v_3 \vee v_1 = v_4$$

$$v_5 = v_6$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_2 = v_3 \vee v_2 = v_4$$

$\mu\mathcal{EUF}$

$$\begin{array}{l} \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}$$

$$v_1 = v_3$$

$\langle e_{ij}\text{-deduction} \rangle$

$$v_5 = v_6$$

$$v_1 = v_4$$

SAT!

3 e_{ij} -deductions,

3 branches

$$v_2 = v_3$$

\perp

$$v_2 = v_4$$

\perp

SMT($\bigcup_i \mathcal{T}_i$) via “classic” Nelson-Oppen

Main idea

Combine two or more \mathcal{T}_i -solvers into one $(\bigcup_i \mathcal{T}_i)$ -solver via **Nelson-Oppen/Shostak (N.O.) combination procedure** [62, 76]

- based on the deduction and exchange of equalities between shared variables/terms (**interface equalities, e_{ij} s**)
- important improvements and evolutions [68, 7, 39]
- drawbacks [23, 24]:
 - require (possibly expensive) deduction capabilities from \mathcal{T}_i -solvers
 - [with non-convex theories] case-splits forced by the deduction of disjunctions of e_{ij} 's
 - generate (typically long) $(\bigcup_i \mathcal{T}_i)$ -lemmas, without interface equalities
⇒ **no backjumping & learning from e_{ij} -reasoning**

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Combine two or more \mathcal{T}_i -solvers into one ($\bigcup_i \mathcal{T}_i$)-solver via **Nelson-Oppen/Shostak (N.O.) combination procedure** [62, 76]

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 - generate (typically long) ($\bigcup_i \mathcal{T}_i$)-lemmas, without interface equalities
 \implies **no backjumping & learning from e_{ij} -reasoning**

Exercise (cont.)

- Purify the following $\mathcal{LIA} \cup \mathcal{EUF} \cup \mathcal{AR}$ -formula (see beginning of chapter):

$$\varphi \stackrel{\text{def}}{=} (d \geq 0) \wedge (d < 1) \wedge \\ ((f(d) = f(0)) \rightarrow (\text{read}(\text{write}(V, i, x), i + d) = x + 1))$$

- Solve it via Nelson-Oppen procedure

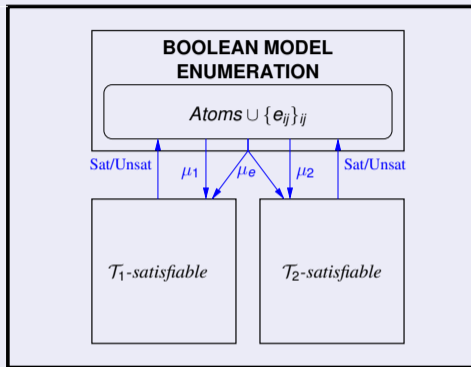
SMT($\bigcup_i \mathcal{T}_i$) via Delayed Theory Combination (DTC)

Main idea

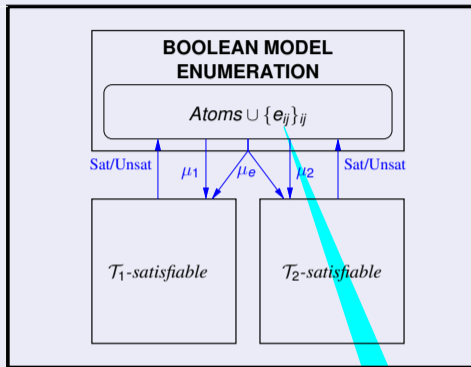
Delegate to the CDCL SAT solver part/most of the (possibly very expensive) reasoning effort on interface equalities previously due to the \mathcal{T}_i -solvers (e_{ij} -deduction, case-split). [15, 16, 24]

- based on Boolean reasoning on interface equalities via CDCL (plus \mathcal{T} -propagation)
- important improvements and evolutions [36, 9]
- feature wrt N.O. [23, 24]
 - do not require (possibly expensive) deduction capabilities from \mathcal{T}_i -solvers
 - with non-convex theories, case-splits on e_{ij} 's handled by SAT solver
 - generate \mathcal{T}_i -lemmas with interface equalities
 \implies **backjumping & learning from e_{ij} -reasoning**

DTC: Basic schema



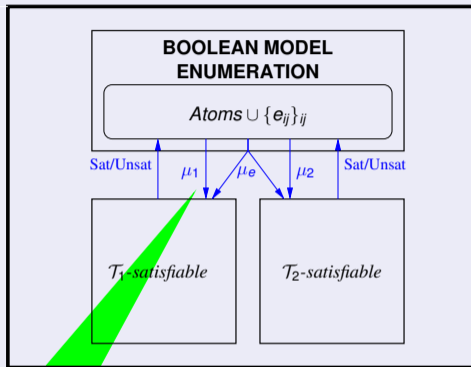
DTC: Basic schema



The boolean solver assigns values not only to atoms in $Atoms(\phi)$, but also to interface equalities $\{(v_i = v_j)\}_{ij}$:

$$\mu = \mu_1 \cup \mu_2 \cup \mu_e, \quad \mu_e := \{[\neg](v_i = v_j) \mid v_i, v_j \in \mu_1 \cup \mu_2\}$$

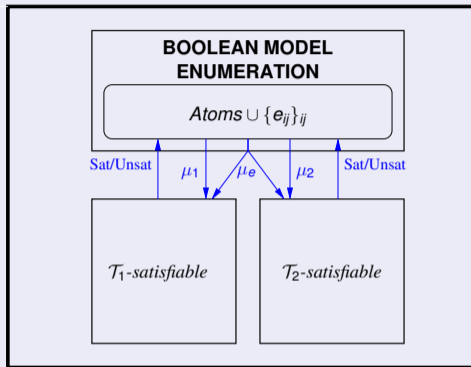
DTC: Basic schema



Each \mathcal{T}_i -solver interacts only with the boolean solver

- receives $\mu'_i := \mu_i \cup \mu_e$ from Bool
- checks the \mathcal{T}_i -satisfiability of μ'_i

DTC: Basic schema



...until either:

- some μ propositionally satisfies ϕ and both $\mu'_i := \mu_i \cup \mu_e$ are \mathcal{T}_i -consistent
 $\implies (\phi \text{ is } \mathcal{T}_1 \cup \mathcal{T}_2\text{-sat})$
- no more assignment μ are available
 $\implies (\phi \text{ is } \mathcal{T}_1 \cup \mathcal{T}_2\text{-unsat})$

DTC: enhanced schema

- **CDCL-based assignment enumeration** on $Atoms(\phi) \cup \{e_{ij}\}_{ij}$,
⇒ benefits of state-of-the-art SAT techniques
- **Early pruning**: invoke the \mathcal{T}_i -solver's before every Boolean decision
⇒ total assignments generated only when strictly necessary
- **Branching**: branching on e_{ij} 's postponed
⇒ Boolean search on e_{ij} 's performed only when strictly necessary
- **Theory-Backjumping & Learning**: e_{ij} 's are involved in conflicts
⇒ e_{ij} 's can be assigned by unit propagation
- **Theory-deduction & learning**: if \mathcal{T}_i -solver deduces unassigned literals I on $Atoms(\phi) \cup \{e_{ij}\}_{ij}$
 - I is passed back to the Boolean solver, which unit-propagates it
 - the deduction $\mu' \models I$ is learned as a clause $\mu' \rightarrow I$ (deduction clause)
- ...

DTC: example w.out \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l} \mu_{\text{EUF}}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array} \quad \left. \vphantom{\begin{array}{l} \mu_{\text{EUF}}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array}} \right\} \begin{array}{l} \mu_{\text{LIA}}: \\ v_1 \geq 0 \\ v_1 \leq 1 \\ v_2 \geq v_6 \\ v_2 \leq v_6 + 1 \end{array} \quad \begin{array}{l} v_5 = v_4 - 1 \\ v_3 = 0 \\ v_4 = 1 \end{array}$$

DTC: example w.out \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l} \mu_{\mathcal{EUF}}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array} \quad \begin{array}{l} \mu_{\mathcal{LIA}}: \\ v_1 \geq 0 \\ v_1 \leq 1 \\ v_2 \geq v_6 \\ v_2 \leq v_6 + 1 \end{array} \quad \begin{array}{l} v_5 = v_4 - 1 \\ v_3 = 0 \\ v_4 = 1 \end{array}$$

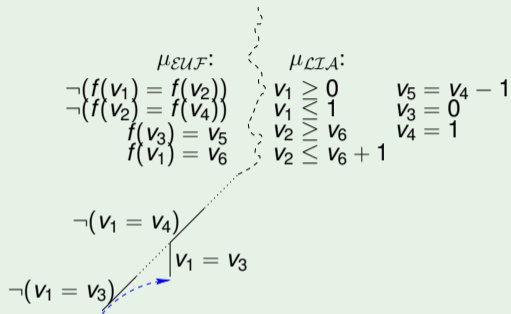
$$\neg(v_1 = v_4)$$

$$\neg(v_1 = v_3)$$

\mathcal{LIA} -unsat, C_{13}

$$C_{13} : (\mu'_{\mathcal{LIA}}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

DTC: example w.out \mathcal{T} -prop. (non-convex theory)



$$G_{13} : (\mu'_{LIA}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

DTC: example w.out \mathcal{T} -prop. (non-convex theory)

$\mu_{\mathcal{EUF}}:$	$\mu_{\mathcal{LIA}}:$	
$\neg(f(v_1) = f(v_2))$	$v_1 \geq 0$	$v_5 = v_4 - 1$
$\neg(f(v_2) = f(v_4))$	$v_1 \leq 1$	$v_3 = 0$
$f(v_3) = v_5$	$v_2 \geq v_6$	$v_4 = 1$
$f(v_1) = v_6$	$v_2 \leq v_6 + 1$	

$$\neg(v_1 = v_4) \quad | \quad v_1 = v_3$$

$$\neg(v_1 = v_3)$$

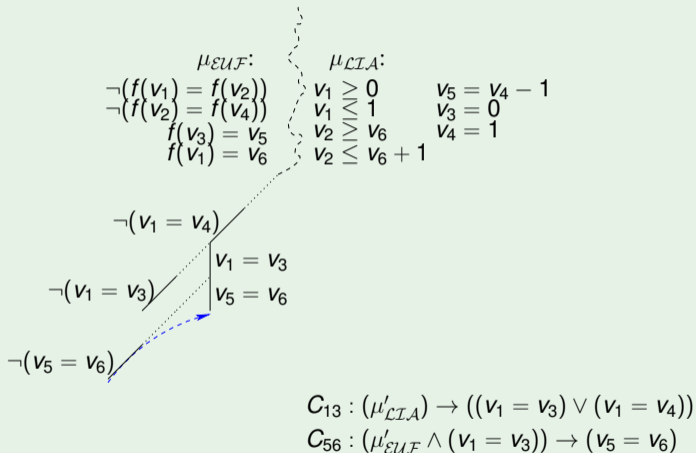
$$\neg(v_5 = v_6)$$

\mathcal{EUF} -unsat, C_{56}

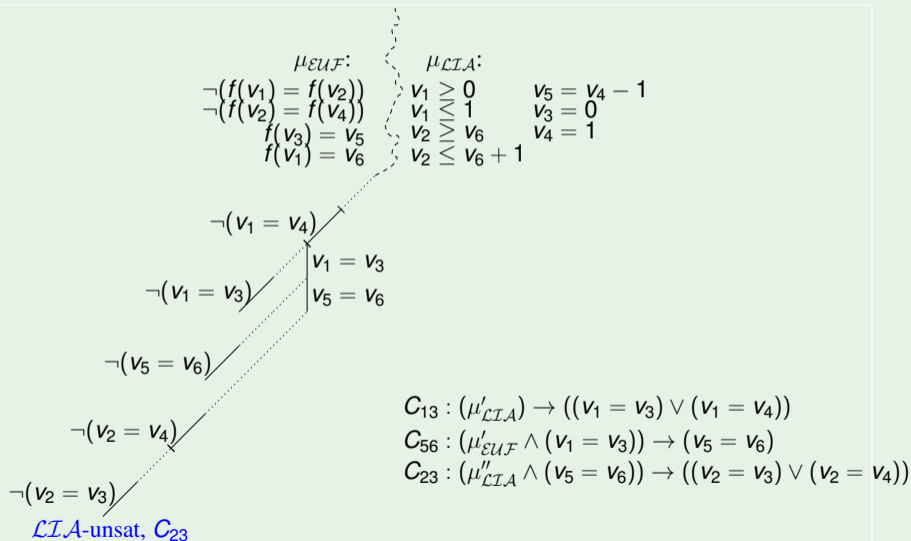
$$C_{13} : (\mu'_{\mathcal{LIA}}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

$$C_{56} : (\mu'_{\mathcal{EUF}} \wedge (v_1 = v_3)) \rightarrow (v_5 = v_6)$$

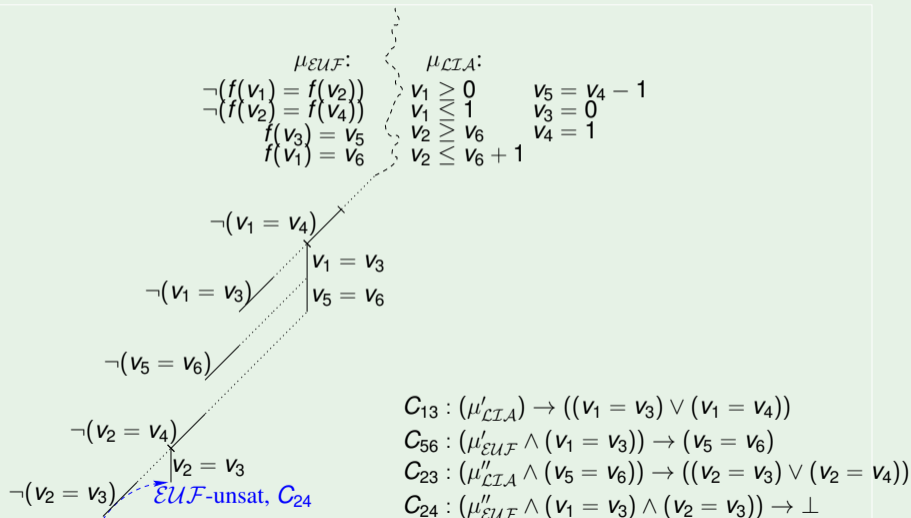
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



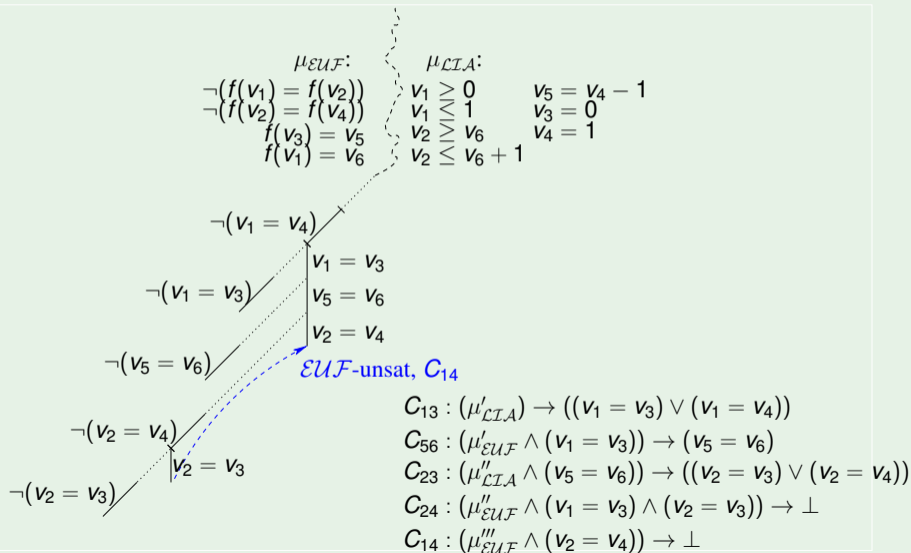
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



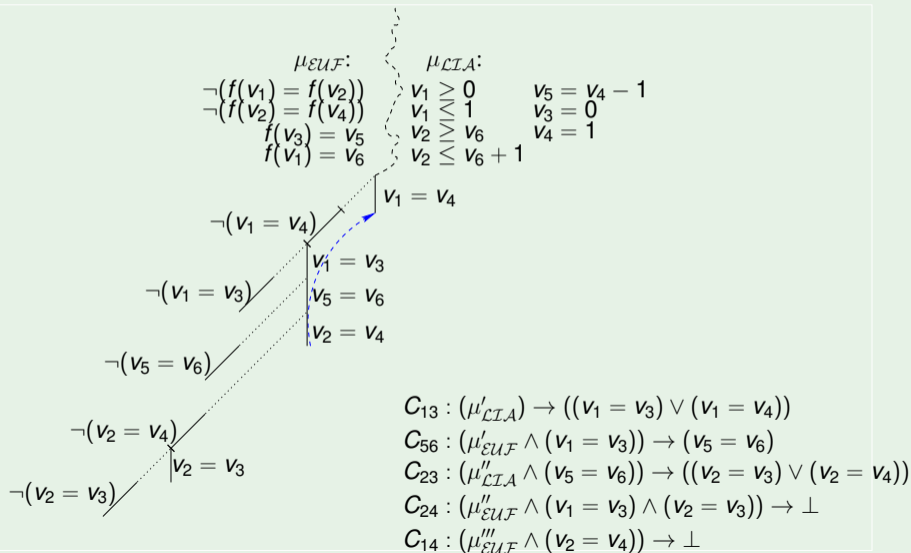
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



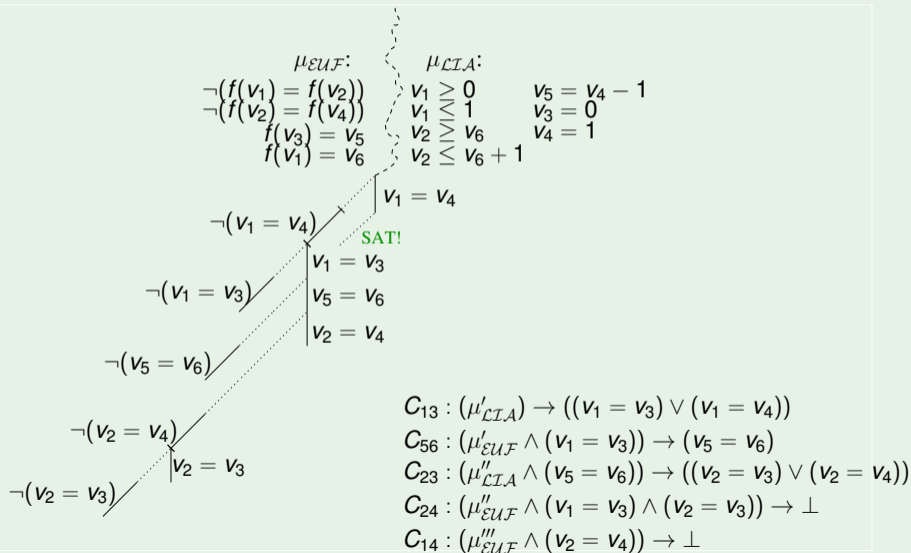
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



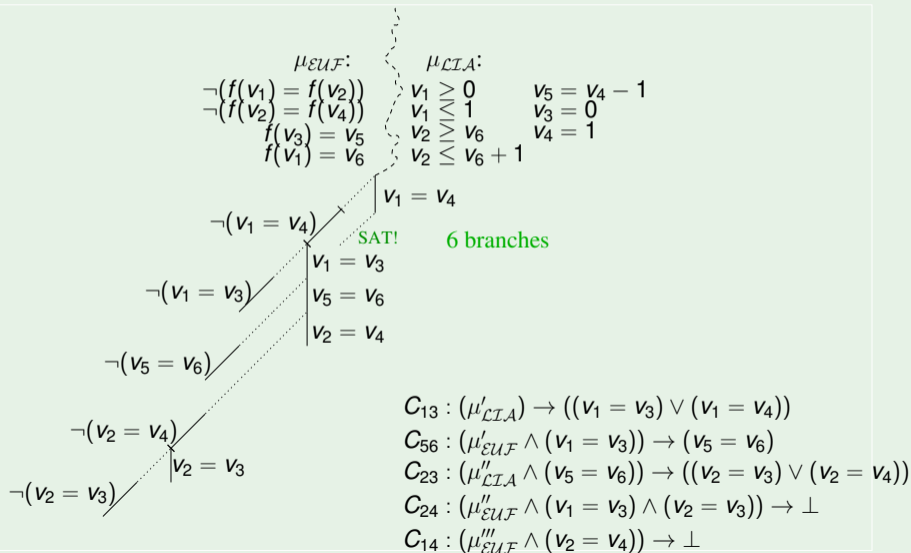
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



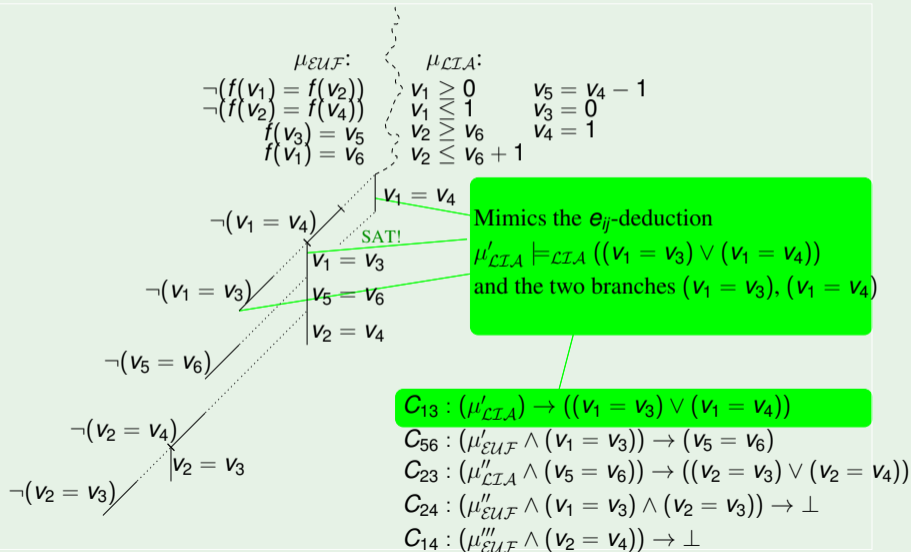
DTC: example w.out \mathcal{T} -prop. (non-convex theory)



DTC: example w.out \mathcal{T} -prop. (non-convex theory)



DTC: example w.out \mathcal{T} -prop. (non-convex theory)



DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l} \mu_{EUF}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array} \quad \begin{array}{l} \mu_{LIA}: \\ v_1 \geq 0 \\ v_1 \leq 1 \\ v_2 \geq v_6 \\ v_2 \leq v_6 + 1 \end{array} \quad \begin{array}{l} v_5 = v_4 - 1 \\ v_3 = 0 \\ v_4 = 1 \end{array}$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l} \mu_{EUF}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array} \quad \begin{array}{l} \mu_{LIA}: \\ v_1 \geq 0 \\ v_1 \leq 1 \\ v_2 \geq v_6 \\ v_2 \leq v_6 + 1 \end{array} \quad \begin{array}{l} v_5 = v_4 - 1 \\ v_3 = 0 \\ v_4 = 1 \end{array}$$

\mathcal{LIA} -deduce $(v_1 = v_4) \vee (v_1 = v_3)$, C_{13}

$$C_{13} : (\mu'_{LIA}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l} \mu_{EUF}: \\ \neg(f(v_1) = f(v_2)) \\ \neg(f(v_2) = f(v_4)) \\ f(v_3) = v_5 \\ f(v_1) = v_6 \end{array} \quad \begin{array}{l} \mu_{LIA}: \\ v_1 \geq 0 \\ v_1 \leq 1 \\ v_2 \geq v_6 \\ v_2 \leq v_6 + 1 \end{array} \quad \begin{array}{l} v_5 = v_4 - 1 \\ v_3 = 0 \\ v_4 = 1 \end{array}$$

$$\begin{array}{l} \neg(v_1 = v_4) \\ v_1 = v_3 \end{array}$$

$$C_{13} : (\mu'_{LIA}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l}
 \mu_{\mathcal{EUF}}: \\
 \neg(f(v_1) = f(v_2)) \\
 \neg(f(v_2) = f(v_4)) \\
 f(v_3) = v_5 \\
 f(v_1) = v_6 \\
 \\
 \mu_{\mathcal{LIA}}: \\
 v_1 \geq 0 \\
 v_1 \leq 1 \\
 v_2 \geq v_6 \\
 v_2 \leq v_6 + 1 \\
 \\
 v_5 = v_4 - 1 \\
 v_3 = 0 \\
 v_4 = 1
 \end{array}$$

$$\begin{array}{l}
 \neg(v_1 = v_4) \\
 v_1 = v_3 \\
 v_5 = v_6
 \end{array}
 \left| \begin{array}{l}
 \mathcal{EUF}\text{-deduce } (v_5 = v_6), C_{56}
 \end{array} \right.$$

$$C_{13} : (\mu'_{\mathcal{LIA}}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4))$$

$$C_{56} : (\mu'_{\mathcal{EUF}} \wedge (v_1 = v_3)) \rightarrow (v_5 = v_6)$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l}
 \mu_{\mathcal{EUF}}: \\
 \neg(f(v_1) = f(v_2)) \\
 \neg(f(v_2) = f(v_4)) \\
 f(v_3) = v_5 \\
 f(v_1) = v_6 \\
 \\
 \mu_{\mathcal{LIA}}: \\
 v_1 \geq 0 \\
 v_1 \leq 1 \\
 v_2 \geq v_6 \\
 v_2 \leq v_6 + 1 \\
 \\
 v_5 = v_4 - 1 \\
 v_3 = 0 \\
 v_4 = 1 \\
 \\
 \neg(v_1 = v_4) \\
 v_1 = v_3 \\
 v_5 = v_6 \quad \mathcal{LIA}\text{-deduce } (v_2 = v_4) \vee (v_2 = v_3), C_{23}
 \end{array}$$

$$\begin{array}{l}
 C_{13} : (\mu'_{\mathcal{LIA}}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4)) \\
 C_{56} : (\mu'_{\mathcal{EUF}} \wedge (v_1 = v_3)) \rightarrow (v_5 = v_6) \\
 C_{23} : (\mu''_{\mathcal{LIA}} \wedge (v_5 = v_6)) \rightarrow ((v_2 = v_3) \vee (v_2 = v_4))
 \end{array}$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$$\begin{array}{l}
 \mu_{\mathcal{EUF}}: \\
 \neg(f(v_1) = f(v_2)) \\
 \neg(f(v_2) = f(v_4)) \\
 f(v_3) = v_5 \\
 f(v_1) = v_6 \\
 \\
 \mu_{\mathcal{LIA}}: \\
 v_1 \geq 0 \\
 v_1 \leq 1 \\
 v_2 \geq v_6 \\
 v_2 \leq v_6 + 1 \\
 \\
 v_5 = v_4 - 1 \\
 v_3 = 0 \\
 v_4 = 1
 \end{array}$$

$$\begin{array}{l}
 \neg(v_1 = v_4) \\
 v_1 = v_3 \\
 v_5 = v_6 \\
 \neg(v_2 = v_4) \\
 v_2 = v_3
 \end{array}$$

\mathcal{EUF} -unsat, C_{24}

$$\begin{array}{l}
 C_{13} : (\mu'_{\mathcal{LIA}}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4)) \\
 C_{56} : (\mu'_{\mathcal{EUF}} \wedge (v_1 = v_3)) \rightarrow (v_5 = v_6) \\
 C_{23} : (\mu''_{\mathcal{LIA}} \wedge (v_5 = v_6)) \rightarrow ((v_2 = v_3) \vee (v_2 = v_4)) \\
 C_{24} : (\mu''_{\mathcal{EUF}} \wedge (v_1 = v_3) \wedge (v_2 = v_3)) \rightarrow \perp
 \end{array}$$

DTC: example with \mathcal{T} -prop. (non-convex theory)

$\mu_{EUF}:$	$\mu_{LIA}:$	
$\neg(f(v_1) = f(v_2))$	$v_1 \geq 0$	$v_5 = v_4 - 1$
$\neg(f(v_2) = f(v_4))$	$v_1 \leq 1$	$v_3 = 0$
$f(v_3) = v_5$	$v_2 \geq v_6$	$v_4 = 1$
$f(v_1) = v_6$	$v_2 \leq v_6 + 1$	

$$\begin{array}{l} \neg(v_1 = v_4) \\ v_1 = v_3 \\ v_5 = v_6 \\ \neg(v_2 = v_4) \\ v_2 = v_3 \end{array} \quad \begin{array}{l} v_2 = v_4 \\ \text{EUF-unsat, } C_{14} \end{array}$$

$$\begin{aligned} C_{13} &: (\mu'_{LIA}) \rightarrow ((v_1 = v_3) \vee (v_1 = v_4)) \\ C_{56} &: (\mu'_{EUF} \wedge (v_1 = v_3)) \rightarrow (v_5 = v_6) \\ C_{23} &: (\mu''_{LIA} \wedge (v_5 = v_6)) \rightarrow ((v_2 = v_3) \vee (v_2 = v_4)) \\ C_{24} &: (\mu''_{EUF} \wedge (v_1 = v_3) \wedge (v_2 = v_3)) \rightarrow \perp \\ C_{14} &: (\mu'''_{EUF} \wedge (v_2 = v_4)) \rightarrow \perp \end{aligned}$$

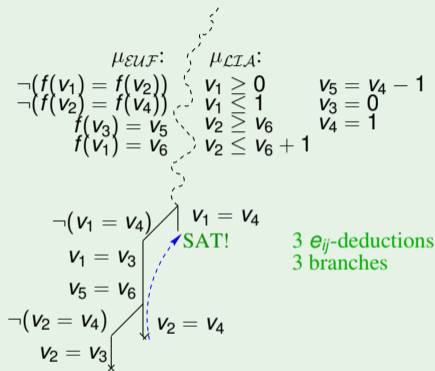
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$$\begin{array}{l}
 \mu_{EUF}: \\
 \neg(f(v_1) = f(v_2)) \\
 \neg(f(v_2) = f(v_4)) \\
 f(v_3) = v_5 \\
 f(v_1) = v_6 \\
 \mu_{LIA}: \\
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 v_1 \leq 1 \\
 v_2 \geq v_6 \\
 v_2 \leq v_6 + 1 \\
 v_5 = v_4 - 1 \\
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 v_4 = 1
 \end{array}$$

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 \text{SAT!} \\
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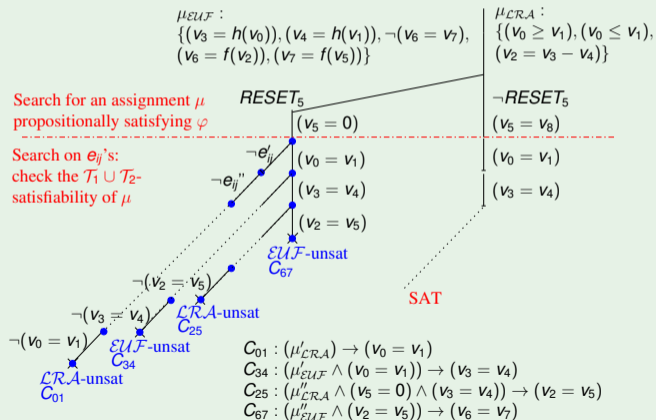
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DTC: example without \mathcal{T} -propagation (convex theory)

$$\begin{aligned} \mathcal{EUF} : & (v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge (v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge \\ \mathcal{LRA} : & (v_0 \geq v_1) \wedge (v_0 \leq v_1) \wedge (v_2 = v_3 - v_4) \wedge (\text{RESET}_5 \rightarrow (v_5 = 0)) \wedge \\ \text{Both} : & (\neg \text{RESET}_5 \rightarrow (v_5 = v_8)) \wedge \neg(v_6 = v_7). \end{aligned}$$



DTC: example with \mathcal{T} -propagation (convex theory)

\mathcal{EUF} : $(v_3 = h(v_0)) \wedge (v_4 = h(v_1)) \wedge (v_6 = f(v_2)) \wedge (v_7 = f(v_5)) \wedge$

\mathcal{LRA} : $(v_0 \geq v_1) \wedge (v_0 \leq v_1) \wedge (v_2 = v_3 - v_4) \wedge (\text{RESET}_5 \rightarrow (v_5 = 0)) \wedge$

Both : $(\neg \text{RESET}_5 \rightarrow (v_5 = v_8)) \wedge \neg(v_6 = v_7).$

$\mu_{\mathcal{EUF}}$:

$\{(v_3 = h(v_0)), (v_4 = h(v_1)), \neg(v_6 = v_7),$
 $(v_6 = f(v_2)), (v_7 = f(v_5))\}$

RESET_5

$(v_5 = 0)$

\mathcal{LRA} -deduce $(v_0 = v_1)$
 learn C_{01}

\mathcal{EUF} -deduce $(v_3 = v_4)$
 learn C_{34}

\mathcal{LRA} -deduce $(v_2 = v_5)$
 learn C_{25} ✗

\mathcal{EUF} -unsat
 C_{67}

$C_{01} : (\mu'_{\mathcal{LRA}}) \rightarrow (v_0 = v_1)$

$C_{34} : (\mu'_{\mathcal{EUF}} \wedge (v_0 = v_1)) \rightarrow (v_3 = v_4)$

$C_{25} : (\mu''_{\mathcal{LRA}} \wedge (v_5 = 0) \wedge (v_3 = v_4)) \rightarrow (v_2 = v_5)$

$C_{67} : (\mu''_{\mathcal{EUF}} \wedge (v_2 = v_5)) \rightarrow (v_6 = v_7)$

$\mu_{\mathcal{LRA}}$:

$\{(v_0 \geq v_1), (v_0 \leq v_1),$
 $(v_2 = v_3 - v_4)\}$

$\neg \text{RESET}_5$

$(v_5 = v_8)$

$(v_0 = v_1)$

$(v_3 = v_4)$

SAT

DTC + Model-based heuristic (aka Model-Based Theory Combination) [36]

- Initially, no interface equalities generated
- When a model is found, check against all the possible interface equalities
 - If \mathcal{T}_1 and \mathcal{T}_2 agree on the implied equalities, then return SAT
 - Otherwise, branch on equalities **implied by \mathcal{T}_1 -model but not by \mathcal{T}_2 -model**
- “Optimistic” approach, similar to axiom instantiation

Exercises

For each of the previous DTC examples:

- write the (minimal) clauses corresponding to each e_{ij} -deduction (as clauses rather than as implications)
- compute the conflict-analysis steps leading to the backjumping steps in the figures.

For each of the previous DTC examples, draw the case in which the \mathcal{EUF} -solver has deduction capabilities and the \mathcal{LRA} -solver (resp. the \mathcal{LIA} -solver) does not.

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Exercise (cont.)

- Purify the following $\mathcal{LIA} \cup \mathcal{EUF} \cup \mathcal{AR}$ -formula (see beginning of chapter):

$$\varphi \stackrel{\text{def}}{=} (d \geq 0) \wedge (d < 1) \wedge \\ ((f(d) = f(0)) \rightarrow (\text{read}(\text{write}(V, i, x), i + d) = x + 1))$$

- Solve it via the DTC procedure
 - assuming no \mathcal{T} -deduction capabilities of the \mathcal{T} -solvers
 - assuming \mathcal{T} -deduction capabilities of the \mathcal{T} -solvers

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 - SMT for Combinations of Theories
- 3 **Beyond Solving: Advanced SMT Functionalities**
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Advanced SMT functionalities (very important in FV):

- Building **proofs of \mathcal{T} -unsatisfiability**
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- [Computing Craig interpolants]
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Building (Resolution) Proofs of \mathcal{T} -Unsatisfiability

Resolution proof of \mathcal{T} -unsatisfiability

Very similar to building proofs with plain SAT:

- resolution proofs whose leaves are original clauses and \mathcal{T} -lemmas returned by the \mathcal{T} -solver (i.e., \mathcal{T} -conflict and \mathcal{T} -deduction clauses)
- built by backward traversal of implication graphs, as in CDCL SAT
- Sub-proofs of \mathcal{T} -lemmas can be built in some \mathcal{T} -specific deduction framework if requested

Important for:

- certifying \mathcal{T} -unsatisfiability results
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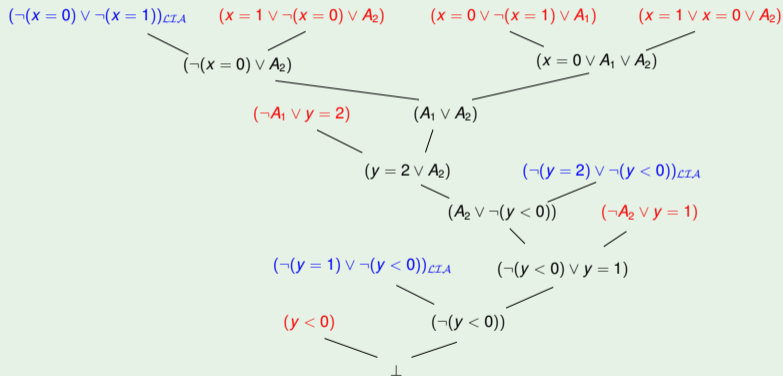
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Building Proofs of \mathcal{T} -Unsatisfiability: example

$$(x = 0 \vee \neg(x = 1) \vee A_1) \wedge (x = 0 \vee x = 1 \vee A_2) \wedge (\neg(x = 0) \vee x = 1 \vee A_2) \wedge$$

$$(\neg A_2 \vee y = 1) \wedge (\neg A_1 \vee x + y > 3) \wedge (y < 0) \wedge (A_2 \vee x - y = 4) \wedge (y = 2 \vee \neg A_1) \wedge (x \geq 0),$$



relevant original clauses, irrelevant original clauses, \mathcal{T} -lemmas

Example: proof on non-strict \mathcal{LRA} inequalities

- A proof of unsatisfiability for a set of non-strict \mathcal{LRA} inequalities can be obtained by building a linear combination (with positive coefficients) of such inequalities, each time eliminating one or more variables, until you get a contradictory inequality on constant values.
- Example:

$$\varphi \stackrel{\text{def}}{=} (0 \leq x_1 - 3x_2 + 1), (0 \leq x_1 + x_2), (0 \leq x_3 - 2x_1 - 3), (0 \leq 1 - 2x_3).$$

A proof of unsatisfiability P for φ is the following:

$$\frac{\frac{(0 \leq x_1 - 3x_2 + 1) \quad (0 \leq x_1 + x_2)}{\text{COMB } (0 \leq 4x_1 + 1) \text{ with coefficients } 1 \text{ and } 3} \quad \frac{(0 \leq x_3 - 2x_1 - 3) \quad (0 \leq 1 - 2x_3)}{\text{COMB } (0 \leq -4x_1 - 5) \text{ with coefficients } 2 \text{ and } 1}}{\text{COMB } (0 \leq -4) \text{ with coefficients } 1 \text{ and } 1}$$

- It is possible to produce such proof from an unsatisfiable tableau in Simplex procedure for \mathcal{LRA} [29, 31]
- It is straightforward to produce such proof from a negative cycle in the graph-based procedure for \mathcal{DL} [29, 31]

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Exercises

- Given the following \mathcal{LRA} -unsatisfiable sets of \mathcal{LRA} -inequalities, produce a proof of unsatisfiability by means of the technique described in the previous slides.

$$\bullet \left\{ \begin{array}{l} (0 \leq +2x_1 - 2x_2 \quad +6x_4 + 1) \\ (0 \leq -x_1 + 2x_2 \quad -x_4 - 2) \\ (0 \leq \quad -2x_2 + 2x_3 \quad + 3) \\ (0 \leq \quad \quad -x_3 - x_4 - 2) \\ (0 \leq \quad +2x_2 \quad +x_4 + 2) \end{array} \right\}$$

- [create your own \mathcal{LRA} -unsatisfiable set of \mathcal{LRA} -inequalities]
- Given the following \mathcal{DL} -unsatisfiable sets of \mathcal{DL} -inequalities, produce a proof of unsatisfiability by means of the technique described in the previous slides.
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Extraction of \mathcal{T} -unsatisfiable cores

The problem

Given a \mathcal{T} -unsatisfiable set of clauses, extract from it a (possibly small/minimal/minimum) \mathcal{T} -unsatisfiable subset (\mathcal{T} -unsatisfiable core)

- Wide literature in SAT
- Some implementations, very few literature for SMT [28, 56]
- We recognize three approaches:
 - **Proof-based** approach (CVC4, MathSAT):
byproduct of finding a resolution proof
 - **Assumption-based** approach (Yices):
use extra variables labeling clauses, as in the plain Boolean case
 - **Lemma-Lifting** approach [28] :
use an external (possibly-optimized) Boolean unsat-core extractor

The proof-based approach to \mathcal{T} -unsat cores

Idea (adapted from [82])

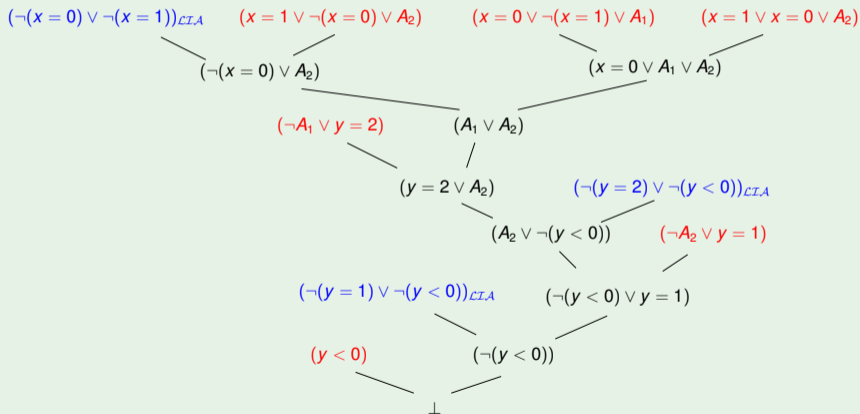
Unsatisfiable core of φ :

- in SAT: the set of leaf clauses of a resolution proof of unsatisfiability of φ
- in $\text{SMT}(\mathcal{T})$: the set of leaf clauses of a resolution proof of \mathcal{T} -unsatisfiability of φ , minus the \mathcal{T} -lemmas

The proof-based approach to \mathcal{T} -unsat cores: example

$$(x = 0 \vee \neg(x = 1) \vee A_1) \wedge (x = 0 \vee x = 1 \vee A_2) \wedge (\neg(x = 0) \vee x = 1 \vee A_2) \wedge$$

$$(\neg A_2 \vee y = 1) \wedge (\neg A_1 \vee x + y > 3) \wedge (y < 0) \wedge (A_2 \vee x - y = 4) \wedge (y = 2 \vee \neg A_1) \wedge (x \geq 0),$$



The Assumption-based approach to \mathcal{T} -unsat cores

Idea (adapted from [57])

Let φ be $\bigwedge_{i=1}^n C_i$ s.t. φ unsatisfiable.

- 1 each clause C_i in φ is substituted by $\neg S_i \vee C_i$, s.t. S_i fresh “selector” variable
- 2 the resulting formula is checked for **satisfiability under the assumption of all S_i 's**
- 3 final conflict clause at dec. level 0: $\bigvee_j \neg S_j$
 $\implies \{C_j\}_j$ is the unsat core

Extends straightforwardly to $\text{SMT}(\mathcal{T})$.

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Extends straightforwardly to $\text{SMT}(\mathcal{T})$.

The assumption-based approach to \mathcal{T} -unsat cores: Example

$$\begin{aligned} & (\mathcal{S}_1 \rightarrow (x = 0 \vee \neg(x = 1) \vee A_1)) \wedge (\mathcal{S}_2 \rightarrow (x = 0 \vee x = 1 \vee A_2)) \wedge \\ & \quad (\mathcal{S}_3 \rightarrow (\neg(x = 0) \vee x = 1 \vee A_2)) \wedge (\mathcal{S}_4 \rightarrow (\neg A_2 \vee y = 1)) \wedge \\ & \quad (\mathcal{S}_5 \rightarrow (\neg A_1 \vee x + y > 3)) \wedge (\mathcal{S}_6 \rightarrow y < 0) \wedge \\ & \quad (\mathcal{S}_7 \rightarrow (A_2 \vee x - y = 4)) \wedge (\mathcal{S}_8 \rightarrow (y = 2 \vee \neg A_1)) \wedge (\mathcal{S}_9 \rightarrow x \geq 0) \end{aligned}$$

Conflict analysis (Yices 1.0.6) returns:

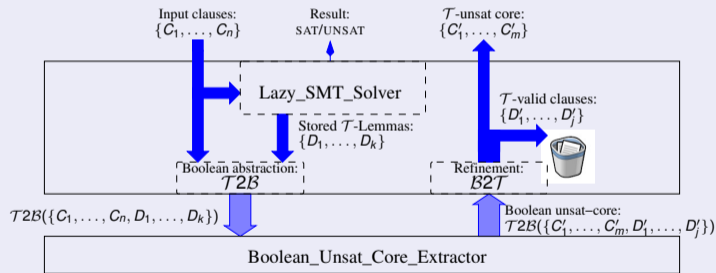
$$\neg \mathcal{S}_1 \vee \neg \mathcal{S}_2 \vee \neg \mathcal{S}_3 \vee \neg \mathcal{S}_4 \vee \neg \mathcal{S}_6 \vee \neg \mathcal{S}_7 \vee \neg \mathcal{S}_8,$$

corresponding to the unsat core in red.

The lemma-lifting approach to \mathcal{T} -unsat cores

Idea [28, 32]

- (i) The \mathcal{T} -lemmas D_i are valid in \mathcal{T}
- (ii) The conjunction of φ with all the \mathcal{T} -lemmas D_1, \dots, D_k is propositionally unsatisfiable:
 $\mathcal{T}2\mathcal{B}(\varphi \wedge \bigwedge_{i=1}^n D_i) \models \perp$.



- interfaces with an external Boolean Unsat-core Extractor

⇒ benefits for free of all state-of-the-art size-reduction techniques

The lemma-lifting approach to \mathcal{T} -unsat cores (cont.)

```
<SatValue, Clause_set>  $\mathcal{T}$ -Unsat_Core(Clause_set  $\varphi$ ) {  
  //  $\varphi$  is  $\{C_1, \dots, C_n\}$   
  if (Lazy_SMT_Solver( $\varphi$ ) == SAT)  
    then return  $\langle \text{SAT}, \emptyset \rangle$ ;  
  //  $D_1, \dots, D_k$  are the  $\mathcal{T}$ -lemmas stored by Lazy_SMT_Solver  
   $\psi^p = \text{Boolean\_Core\_Extractor}(\mathcal{T}2\mathcal{B}(\{C_1, \dots, C_n, D_1, \dots, D_k\}))$ ;  
  //  $\psi^p$  is  $\mathcal{T}2\mathcal{B}(\{C'_1, \dots, C'_m, D'_1, \dots, D'_j\})$ ;  
  return  $\langle \text{UNSAT}, \{C'_1, \dots, C'_m\} \rangle$ ;  
}
```

The lemma-lifting approach to \mathcal{T} -unsat cores: example

$$(x = 0 \vee \neg(x = 1) \vee A_1) \wedge (x = 0 \vee x = 1 \vee A_2) \wedge (\neg(x = 0) \vee x = 1 \vee A_2) \wedge \\ (\neg A_2 \vee y = 1) \wedge (\neg A_1 \vee x + y > 3) \wedge (y < 0) \wedge (A_2 \vee x - y = 4) \wedge (y = 2 \vee \neg A_1) \wedge (x \geq 0),$$

1 The SMT solver generates the following set of \mathcal{LIA} -lemmas:

$$\{(\neg(x = 1) \vee \neg(x = 0)), (\neg(y = 2) \vee \neg(y < 0)), (\neg(y = 1) \vee \neg(y < 0))\}.$$

2 The following formula is passed to the external Boolean core extractor

$$(B_0 \vee \neg B_1 \vee A_1) \wedge (B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee B_1 \vee A_2) \wedge \\ (\neg A_2 \vee B_2) \wedge (\neg A_1 \vee B_3) \wedge B_4 \wedge (A_2 \vee B_5) \wedge (B_6 \vee \neg A_1) \wedge B_7 \wedge \\ (\neg B_1 \vee \neg B_0) \wedge (\neg B_6 \vee \neg B_4) \wedge (\neg B_2 \vee \neg B_4)$$

which returns the unsat core in red.

3 The unsat-core is mapped back, the three \mathcal{T} -lemmas are removed
 \implies the final \mathcal{T} -unsat core (in red above).

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Exercise

Consider the following set of clauses φ in \mathcal{EUF} .

$$\left\{ \begin{array}{l} (\neg(x = y) \vee (f(x) = f(y))), \\ (\neg(x = y) \vee \neg(f(x) = f(y))), \\ ((x = y) \vee (f(x) = f(y))), \\ ((x = y) \vee \neg(f(x) = f(y))) \end{array} \right\}$$

Find a minimal \mathcal{EUF} -unsatisfiable core.

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All-SAT/All-SMT (hints)

- **All-SAT:** enumerate all truth assignments satisfying φ
- All-SMT: enumerate all \mathcal{T} -satisfiable truth assignments propositionally satisfying φ
- All-SMT over an “important” subset of atoms $\Gamma \stackrel{\text{def}}{=} \{\gamma_i\}_i$: enumerate all assignments over Γ which can be extended to \mathcal{T} -satisfiable truth assignments propositionally satisfying φ
 \implies can compute **predicate abstraction**
- Algorithms:
 - **BCLT** [53]
each time a \mathcal{T} -satisfiable assignment $\{l_1, \dots, l_n\}$ is found, perform conflict-driven backjumping as if the restricted clause $(\bigvee_i \neg l_i) \downarrow \Gamma$ belonged to the clause set
 - **MathSAT/NuSMV** [26]
As above, plus the Boolean search of the SMT solver is driven by an OBDD.

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Predicate Abstraction

Predicate abstraction

if $\varphi(\mathbf{v})$ is a SMT formula over the domain variables $\mathbf{v} \stackrel{\text{def}}{=} \{v_j\}_j$, $\{\gamma_i\}_i$ is a set of “relevant” predicates over \mathbf{v} , and $\mathbf{P} \stackrel{\text{def}}{=} \{P_i\}_i$ a set of fresh Boolean labels, then:

$$\begin{aligned} & \text{PredAbs}_{\mathbf{P}}(\varphi) \\ \stackrel{\text{def}}{=} & \exists \mathbf{v}. (\varphi(\mathbf{v}) \wedge \bigwedge_i P_i \leftrightarrow \gamma_i(\mathbf{v})) \\ = & \bigvee \left\{ \mu \mid \begin{array}{l} \mu \text{ truth assignment on } \mathbf{P} \\ \text{s.t. } \mu \wedge \varphi \wedge \bigwedge_i (P_i \leftrightarrow \gamma_i) \text{ is } \mathcal{T}\text{-satisfiable} \end{array} \right\} \end{aligned}$$

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Predicate Abstraction: example

$$\varphi \stackrel{\text{def}}{=} (v_1 + v_2 > 12)$$

$$\gamma_1 \stackrel{\text{def}}{=} (v_1 + v_2 = 2)$$

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$$\begin{aligned} \text{PreAbs}(\varphi)_{\{P_1, P_2\}} &\stackrel{\text{def}}{=} \exists v_1 v_2 . \left(\begin{array}{l} (v_1 + v_2 > 12) \quad \wedge \\ (P_1 \leftrightarrow (v_1 + v_2 = 2)) \quad \wedge \\ (P_2 \leftrightarrow (v_1 - v_2 < 10)) \end{array} \right) \\ &= (\neg P_1 \wedge \neg P_2) \vee (\neg P_1 \wedge P_2) \\ &= \neg P_1. \end{aligned}$$

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↓

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Optimization Modulo Theories: General Case

Ingredients: $\langle \varphi, cost \rangle$

- a **SMT formula** φ in some background theory $\mathcal{T} = \mathcal{T}_{\preceq} \cup \bigcup_i \mathcal{T}_i$
 - $\bigcup_i \mathcal{T}_i$ may be empty
 - \mathcal{T}_{\preceq} has a predicate \preceq representing a **total order**
- a \mathcal{T}_{\preceq} -**variable/term** “*cost*” occurring in φ

Optimization Modulo $\mathcal{T}_{\preceq} \cup \bigcup_i \mathcal{T}_i$ (OMT($\mathcal{T}_{\preceq} \cup \bigcup_i \mathcal{T}_i$))

The problem of finding a model \mathcal{M} for φ whose value of *cost* is minimum according to \preceq .

- maximization is dual

Note

The cost term can be rewritten as a variable

$$\langle \varphi, term \rangle \implies \langle \varphi \wedge (cost = term), cost \rangle, \quad cost \text{ fresh}$$

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Optimization Modulo Theories with $\mathcal{L}\mathcal{A}$ costs

Ingredients

- an **SMT formula** φ on $\mathcal{L}\mathcal{A} \cup \mathcal{T}$
 - $\mathcal{L}\mathcal{A}$ can be $\mathcal{L}\mathcal{R}\mathcal{A}$, $\mathcal{L}\mathcal{I}\mathcal{A}$ or a combination of both
 - $\mathcal{T} \stackrel{\text{def}}{=} \bigcup_i \mathcal{T}_i$, possibly empty
 - $\mathcal{L}\mathcal{A}$ and \mathcal{T}_i Nelson-Oppen theories
(i.e. signature-disjoint infinite-domain theories)
- a $\mathcal{L}\mathcal{A}$ **variable [term] “cost”** occurring in φ
- (optionally) two constant numbers **lb (lower bound)** and **ub (upper bound)** s.t.
 $\text{lb} \leq \text{cost} < \text{ub}$ (lb, ub may be $\mp\infty$)

Optimization Modulo Theories with $\mathcal{L}\mathcal{A}$ costs (OMT($\mathcal{L}\mathcal{A} \cup \mathcal{T}$))

Find a model for φ whose value of **cost** is minimum.

- maximization dual

We first restrict to the case $\mathcal{L}\mathcal{A} = \mathcal{L}\mathcal{R}\mathcal{A}$ and $\bigcup_i \mathcal{T}_i = \{\}$ (OMT($\mathcal{L}\mathcal{R}\mathcal{A}$)).

Optimization Modulo Theories with \mathcal{LRA} costs

Ingredients

- an SMT formula φ on $\mathcal{LRA} \cup \mathcal{T}$
 - \mathcal{LA} can be \mathcal{LRA} , \mathcal{LIA} or a combination of both
 - $\mathcal{T} \stackrel{\text{def}}{=} \bigcup_i \mathcal{T}_i$, possibly empty
 - \mathcal{LRA} and \mathcal{T}_i Nelson-Oppen theories
(i.e. signature-disjoint infinite-domain theories)
- a \mathcal{LRA} variable [term] “cost” occurring in φ
- (optionally) two constant numbers lb (lower bound) and ub (upper bound) s.t.
 $lb \leq \text{cost} < ub$ (lb, ub may be $\mp\infty$)

Optimization Modulo Theories with \mathcal{LRA} costs ($\text{OMT}(\mathcal{LRA} \cup \mathcal{T})$)

Find a model for φ whose value of *cost* is minimum.

- maximization dual

We first restrict to the case $\mathcal{LA} = \mathcal{LRA}$ and $\bigcup_i \mathcal{T}_i = \{\}$ ($\text{OMT}(\mathcal{LRA})$).

Solving OMT(\mathcal{LRA}) [71, 72]

General idea

Combine standard SMT and LP minimization techniques.

Offline Schema

- Minimizer: based on the Simplex \mathcal{LRA} -solver by [40]
 - Handles strict inequalities
- Search Strategies:
 - Linear-Search strategy
 - Mixed Linear/Binary strategy

A toy example (linear search)

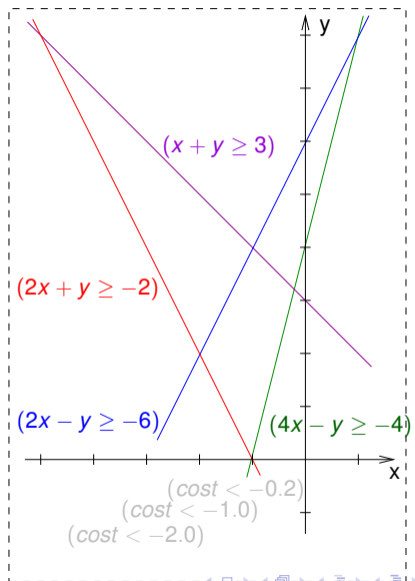
[w. pure-literal filt. \implies partial assignments]

- OMT(\mathcal{LRA}) problem:

$$\begin{aligned}\varphi &\stackrel{\text{def}}{=} (\neg A_1 \vee (2x + y \geq -2)) \\ &\wedge (A_1 \vee (x + y \geq 3)) \\ &\wedge (\neg A_2 \vee (4x - y \geq -4)) \\ &\wedge (A_2 \vee (2x - y \geq -6)) \\ &\wedge (\text{cost} < -0.2) \\ &\wedge (\text{cost} < -1.0) \\ &\wedge (\text{cost} < -2.0)\end{aligned}$$

$$\text{cost} \stackrel{\text{def}}{=} x$$

- $\mu = \left\{ \begin{array}{l} A_1, \neg A_1, A_2, \neg A_2, \\ (4x - y \geq -4), \\ (x + y \geq 3), \\ (2x + y \geq -2), \\ (2x - y \geq -6) \\ (\text{cost} < -0.2) \\ (\text{cost} < -1.0) \\ (\text{cost} < -2.0) \end{array} \right\}$



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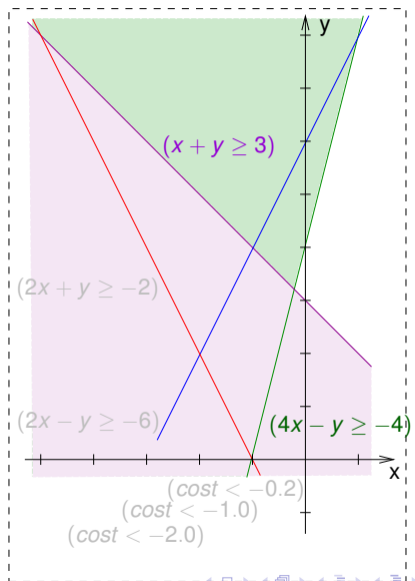
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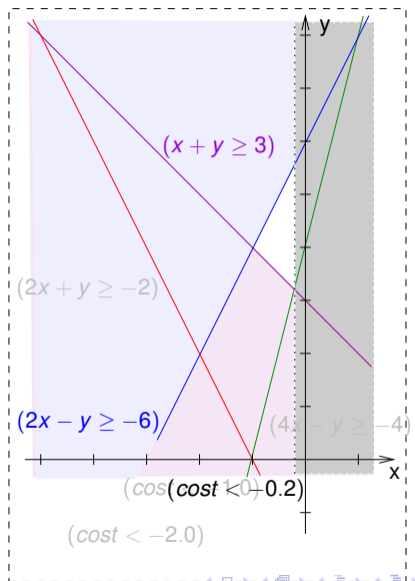
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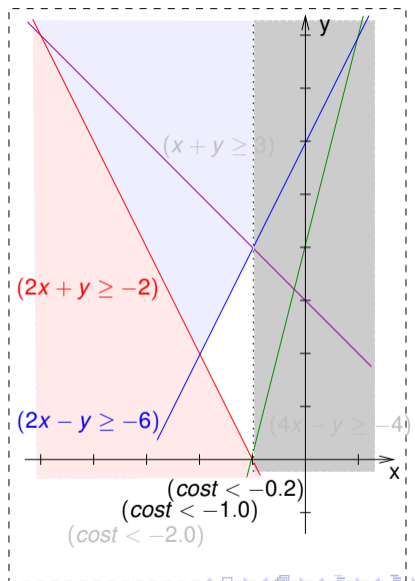
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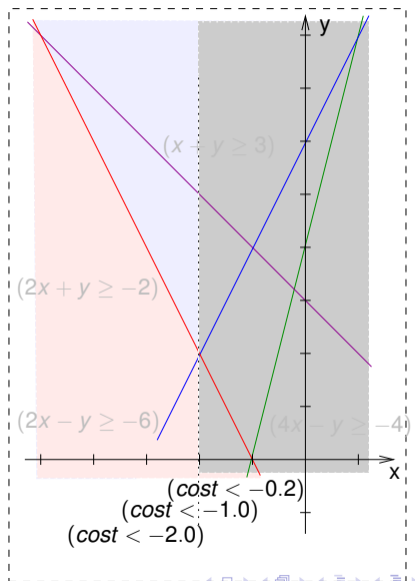
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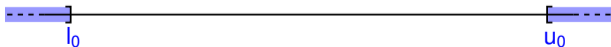
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\implies UNSAT, $\min = -2.0$



Offline Schema: Mixed Linear/Binary-Search Strategy

Input: $\langle \varphi, cost, lb, ub \rangle$ // lb can be $-\infty$, ub can be $+\infty$
 $l \leftarrow lb$; $u \leftarrow ub$; $\mathcal{M} \leftarrow \emptyset$; $\varphi \leftarrow \varphi \cup \{ \neg(cost < lb), (cost < ub) \}$;
while ($l < u$) **do**



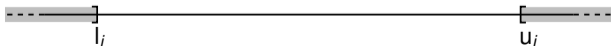
Offline Schema: Mixed Linear/Binary-Search Strategy

Input: $\langle \varphi, cost, lb, ub \rangle$ // lb can be $-\infty$, ub can be $+\infty$
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$

while ($l < u$) **do**

if (BinSearchMode()) **then** // Binary-search Mode

else // Linear-search Mode



Offline Schema: Mixed Linear/Binary-Search Strategy

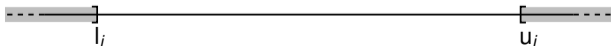
Input: $\langle \varphi, cost, lb, ub \rangle$ // lb can be $-\infty$, ub can be $+\infty$
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$

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else // Linear-search Mode

$\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi);$



Offline Schema: Mixed Linear/Binary-Search Strategy

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 $l \leftarrow lb$; $u \leftarrow ub$; $\mathcal{M} \leftarrow \emptyset$; $\varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\}$;

while ($l < u$) **do**

if (BinSearchMode()) **then** // Binary-search Mode

else // Linear-search Mode

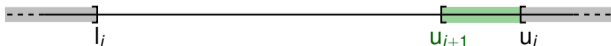
$\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi)$;

if ($res = \text{SAT}$) **then**

$\langle \mathcal{M}, u \rangle \leftarrow \text{LRA-Solver.Minimize}(cost, \mu)$;

$\varphi \leftarrow \varphi \cup \{(cost < u)\}$;

else { $res = \text{UNSAT}$ }



Offline Schema: Mixed Linear/Binary-Search Strategy

```
Input:  $\langle \varphi, cost, lb, ub \rangle$  //  $lb$  can be  $-\infty$ ,  $ub$  can be  $+\infty$   
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$   
while ( $l < u$ ) do  
  if (BinSearchMode()) then // Binary-search Mode  
  else // Linear-search Mode  
     $\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi);$   
    if ( $res = \text{SAT}$ ) then  
      else { $res = \text{UNSAT}$ }  
       $l \leftarrow u;$   
return  $\langle \mathcal{M}, u \rangle$ 
```



Offline Schema: Mixed Linear/Binary-Search Strategy

Input: $\langle \varphi, cost, lb, ub \rangle$ // lb can be $-\infty$, ub can be $+\infty$
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$

while ($l < u$) **do**

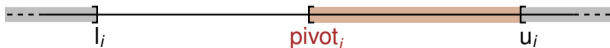
if (BinSearchMode()) **then** // Binary-search Mode

$pivot \leftarrow \text{ComputePivot}(l, u);$

$\varphi \leftarrow \varphi \cup \{(cost < pivot)\};$

$\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi);$

else // Linear-search Mode



Offline Schema: Mixed Linear/Binary-Search Strategy

Input: $\langle \varphi, cost, lb, ub \rangle$ // lb can be $-\infty$, ub can be $+\infty$
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$

while ($l < u$) **do**

if (BinSearchMode()) **then** // Binary-search Mode

 pivot \leftarrow ComputePivot(l, u);

$\varphi \leftarrow \varphi \cup \{(cost < pivot)\};$

$\langle res, \mu \rangle \leftarrow$ SMT.IncrementalSolve(φ);

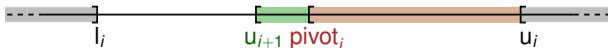
else // Linear-search Mode

if ($res = SAT$) **then**

$\langle \mathcal{M}, u \rangle \leftarrow$ \mathcal{LRA} -Solver.Minimize($cost, \mu$);

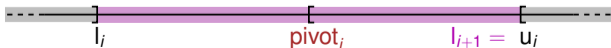
$\varphi \leftarrow \varphi \cup \{(cost < u)\};$

else { $res = UNSAT$ }



Offline Schema: Mixed Linear/Binary-Search Strategy

```
Input:  $\langle \varphi, cost, lb, ub \rangle$  // lb can be  $-\infty$ , ub can be  $+\infty$   
 $l \leftarrow lb; u \leftarrow ub; \mathcal{M} \leftarrow \emptyset; \varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\};$   
while ( $l < u$ ) do  
  if (BinSearchMode()) then // Binary-search Mode  
     $pivot \leftarrow \text{ComputePivot}(l, u);$   
     $\varphi \leftarrow \varphi \cup \{(cost < pivot)\};$   
     $\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi);$   
  else // Linear-search Mode  
    if ( $res = \text{SAT}$ ) then  
      return  $\langle \mathcal{M}, u \rangle$   
    else { $res = \text{UNSAT}$ }  
      if  $((cost < pivot) \notin \text{SMT.ExtractUnsatCore}(\varphi))$  then  
         $l \leftarrow u;$   
      else
```



Offline Schema: Mixed Linear/Binary-Search Strategy

```
Input:  $\langle \varphi, cost, lb, ub \rangle$  //  $lb$  can be  $-\infty$ ,  $ub$  can be  $+\infty$   
 $l \leftarrow lb$ ;  $u \leftarrow ub$ ;  $\mathcal{M} \leftarrow \emptyset$ ;  $\varphi \leftarrow \varphi \cup \{\neg(cost < lb), (cost < ub)\}$ ;  
while ( $l < u$ ) do  
  if (BinSearchMode()) then // Binary-search Mode  
     $pivot \leftarrow \text{ComputePivot}(l, u)$ ;  
     $\varphi \leftarrow \varphi \cup \{(cost < pivot)\}$ ;  
     $\langle res, \mu \rangle \leftarrow \text{SMT.IncrementalSolve}(\varphi)$ ;  
  else // Linear-search Mode  
    if ( $res = \text{SAT}$ ) then  
      if ( $res = \text{UNSAT}$ )  
        if ( $(cost < pivot) \notin \text{SMT.ExtractUnsatCore}(\varphi)$ ) then  
          else  
             $l \leftarrow pivot$ ;  
             $\varphi \leftarrow (\varphi \setminus \{(cost < pivot)\}) \cup \{\neg(cost < pivot)\}$ ;
```



OMT with Independent Objectives (aka Boxed OMT) [55, 74]

The problem: $\langle \varphi, \{cost_1, \dots, cost_k\} \rangle$ [55]

Given $\langle \varphi, \mathcal{C} \rangle$ s.t.:

- φ is the input formula
- $\mathcal{C} \stackrel{\text{def}}{=} \{cost_1, \dots, cost_k\}$ is a set of \mathcal{LA} -terms on variables in φ ,

$\langle \varphi, \mathcal{C} \rangle$ is the problem of finding a set of independent \mathcal{LA} -models $\mathcal{M}_1, \dots, \mathcal{M}_k$ s.t. each \mathcal{M}_i makes $cost_i$ minimum.

Notes

- derives from SW verification problems [55]
- equivalent to k independent problems $\langle \varphi, cost_1 \rangle, \dots, \langle \varphi, cost_k \rangle$
- intuition: share search effort for the different objectives
- generalizes to $OMT(\mathcal{LA} \cup \mathcal{T})$ straightforwardly

OMT with Multiple Objectives [55, 13, 74]

Solution

- Intuition: when a \mathcal{T} -satisfiable satisfying assignment μ is found,

```
  foreach  $cost_i$ 
```

```
     $min_i := \min\{min_i, \mathcal{T}solver.minimize(\mu, cost_i)\};$ 
```

```
  learn  $\bigvee_i (cost_i < min_i);$  //  $(cost_i < -\infty) \equiv \perp$ 
```

```
  proceed until UNSAT;
```

- Notice:

- for each μ , guaranteed improvement of at least one min_i
- in practice, for each μ , multiple $cost_i$ minima are improved

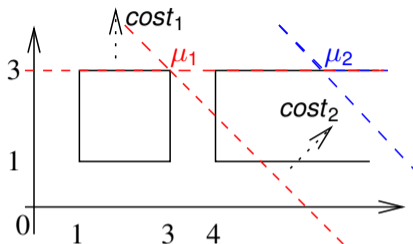
- Implemented improvements:

(a) drop previous clauses $\bigvee_i (cost_i < min_i)$

(b) $(cost_i < min_i)$ pushed in μ first: if \mathcal{T} -unsatisfiable, skip minimization

(c) learn $\neg(cost_i < min_i) \vee (cost_i < min_i^{old})$, s.t. min_i^{old} previous min_i
 \implies reuse previously-learned clauses like $\neg(cost_i < min_i^{old}) \vee C$

Boxed OMT: Example [55, 74]



$$\begin{aligned} \varphi &= (1 \leq y) \wedge (y \leq 3) \wedge (((1 \leq x) \wedge (x \leq 3)) \vee (x \geq 4)) \\ &\wedge (cost_1 = -y) \wedge (cost_2 = -x - y) \end{aligned}$$

$$\mu_1 = \{(1 \leq y), (y \leq 3), (1 \leq x), (x \leq 3)\} \implies \text{SAT} \implies [-3, -6]$$

$$\implies \text{learn} \quad \{(cost_1 < -3) \vee (cost_2 < -6)\}$$

$$\mu_2 = \{(1 \leq y), (y \leq 3), (x \geq 4)\} \implies \text{SAT} \implies [-3, -\infty]$$

$$\implies \text{learn} \quad \{(cost_1 < -3)\}$$

$$\implies \text{UNSAT}$$

OMT with Lexicographic Combination of Objectives [13]

The problem

Find one optimal model \mathcal{M} minimizing $\underline{c} \stackrel{\text{def}}{=} cost_1, cost_2, \dots, cost_k$ lexicographically.

Solution

- Intuition:

{ minimize $cost_1$ }

when UNSAT

{ substitute unit clause ($cost_1 < min_1$) with ($cost_1 = min_1$) }

{ minimize $cost_2$ }

...

- improvement:

- each time UNSAT is found, add $\bigwedge_i (cost_i \leq \mathcal{M}_i(cost_i))$ to φ

Optimization problems encoded into $\text{OMT}(\mathcal{L}\mathcal{A} \cup \mathcal{T})$ I

SMT with Pseudo-Boolean Constraints & Weighted MaxSMT

$$\text{OMT} + \text{PB} : \quad \sum_j w_j \cdot A_j, \quad w_i > 0 \quad // (\sum_j \text{ite}(A_j, w_j, 0))$$

\Downarrow

$$\begin{aligned} & \sum_j x_j, \quad x_j \text{ fresh} \\ \text{s.t.} \quad & \dots \wedge \bigwedge_j (A_j \rightarrow (x_j = w_j)) \wedge (\neg A_j \rightarrow (x_j = 0)) \\ & \wedge (x_j \geq 0) \wedge (x_j \leq w_j) \end{aligned}$$

$$\text{MaxSMT} : \quad \langle \varphi_h, \bigwedge_j \psi_j \rangle \quad \text{s.t. } \psi_j \text{ soft}, \quad w_j = \text{weight}(\psi_j), \quad w_i > 0$$

\Downarrow

$$\begin{aligned} & \text{minimize } \sum_j x_j, \quad x_j, A_j \text{ fresh} \\ & \varphi_h \wedge \bigwedge_j (A_j \vee \psi_j) \wedge \bigwedge_j (\neg A_j \vee (x_j = w_j)) \wedge (A_j \vee (x_j = 0)) \\ & \wedge (x_j \geq 0) \wedge (x_j \leq w_j) \end{aligned}$$

Remark: range constraints “ $(x_j \geq 0) \wedge (x_j \leq w_j)$ ”

$$\begin{aligned} OMT + PB : \quad & \sum_j w_j \cdot A_j, \quad w_j > 0 \quad // (\sum_j \text{ite}(A_j, w_j, 0)) \\ & \downarrow \\ & \sum_j x_j, \quad x_j \text{ fresh} \\ \text{s.t.} \quad & \dots \wedge \bigwedge_j (A_j \rightarrow (x_j = w_j)) \wedge (\neg A_j \rightarrow (x_j = 0)) \\ & \quad \wedge (x_j \geq 0) \wedge (x_j \leq w_j) \end{aligned}$$

Range constraints “ $(x_j \geq 0) \wedge (x_j \leq w_j)$ ” logically redundant, but essential for efficiency:

- Without range constraints, the SMT solver can detect the violation of a bound **only after all A_i 's are assigned** :
Ex: $w_1 = 4, w_2 = 7, \sum_{i=1} x_i < 10, A_1 = A_2 = \top, A_i = * \forall i > 2$.
- With range constraints, the SMT solver detects the violation as soon as the assigned A_i 's violate a bound
 \implies drastic pruning of the search
- same for weighted MaxSMT

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$$\begin{aligned} OMT + PB : \quad & \sum_j w_j \cdot A_j, \quad w_i > 0 \quad // (\sum_j \text{ite}(A_j, w_j, 0)) \\ & \downarrow \\ & \sum_j x_j, \quad x_j \text{ fresh} \\ \text{s.t.} \quad & \dots \wedge \bigwedge_j (A_j \rightarrow (x_j = w_j)) \wedge (\neg A_j \rightarrow (x_j = 0)) \\ & \wedge (x_j \geq 0) \wedge (x_j \leq w_j) \end{aligned}$$

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$$\begin{aligned} OMT + PB : \quad & \sum_j w_j \cdot A_j, w_i > 0 \quad //(\sum_j \text{ite}(A_j, w_j, 0)) \\ & \downarrow \\ & \sum_j x_j, x_j \text{ fresh} \\ \text{s.t.} \quad & \dots \wedge \bigwedge_j (A_j \rightarrow (x_j = w_j)) \wedge (\neg A_j \rightarrow (x_j = 0)) \\ & \wedge (x_j \geq 0) \wedge (x_j \leq w_j) \end{aligned}$$

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Optimization problems encoded into OMT($\mathcal{L}\mathcal{A} \cup \mathcal{T}$) II

OMT with Min-Max [Max-Min] optimization

Given $\langle \varphi, \{cost_1, \dots, cost_k\} \rangle$, find a solution which minimizes the maximum value among $\{cost_1, \dots, cost_k\}$. (Max-Min dual.)

- Frequent in some applications (e.g. [72, 79])

\Rightarrow encode into OMT($\mathcal{L}\mathcal{A} \cup \mathcal{T}$) problem $\{\varphi \wedge \bigwedge_i (cost_i \leq cost), cost\}$ s.t. $cost$ fresh.

OMT with linear combinations of costs

Given $\langle \varphi, \{cost_1, \dots, cost_k\} \rangle$ and a set of weights $\{w_1, \dots, w_k\}$, find a solution which minimizes $\sum_i w_i \cdot cost_i$.

\Rightarrow encode into OMT($\mathcal{L}\mathcal{A} \cup \mathcal{T}$) problem $\{\varphi \wedge (cost = \sum_i w_i \cdot cost_i), cost\}$ s.t. $cost$ fresh.

These objectives can be composed with other OMT($\mathcal{L}\mathcal{A}$) objectives.

Other OMT Functionalities [hints]

Incremental interface [13, 74]

Allows for pushing/popping sub-formulas into a stack, and then run OMT incrementally over them, reusing previous search.

- useful in some applications (e.g., BMC with parametric systems)
- straightforward variant of incremental SAT and SMT solvers

Pareto Fronts [13, 12]

- Given $cost_1, cost_2$, compute $\mathcal{M}_1, \dots, \mathcal{M}_i, \dots, \mathcal{M}_j, \dots$ s.t.:
 - either $\mathcal{M}_i(cost_1) > \mathcal{M}_j(cost_1)$ or $\mathcal{M}_i(cost_2) > \mathcal{M}_j(cost_2)$ and $\mathcal{M}_i(cost_1) < \mathcal{M}_j(cost_1)$ or $\mathcal{M}_i(cost_2) < \mathcal{M}_j(cost_2)$
 - for each \mathcal{M}_i , no \mathcal{M}' dominates \mathcal{M}_i
- no objective can be improved without degrading some other one

Some OMT tools

- **BCLT** [66, 54]
<https://www.cs.upc.edu/~oliveras/bclt-main.html>
- **OPTIMATHSAT** [71, 72, 74, 73], on top of MATHSAT [27]
<https://optimathsat.disi.unitn.it>
- **SYMBA** [55], on top of Z3 [37]
<https://bitbucket.org/arieg/symba/src>
- **ν Z** [13, 12], on top of Z3 [37]
<https://z3.codeplex.com>

- survey papers:
 - Roberto Sebastiani: "Lazy Satisfiability Modulo Theories".
Journal on Satisfiability, Boolean Modeling and Computation, JSAT. Vol. 3, 2007. Pag 141–224, ©IOS Press.
 - Clark Barrett, Roberto Sebastiani, Sanjit Seshia, Cesare Tinelli "Satisfiability Modulo Theories".
Part II, Chapter 33, The Handbook of Satisfiability, II ed. 2021. ©IOS press.
 - Leonardo de Moura and Nikolaj Bjørner. "Satisfiability modulo theories: introduction and applications".
Communications of the ACM, 54 (9), 2011. ©ACM press.
- web links:
 - The SMT library SMT-LIB: <https://goedel.cs.uiowa.edu/smtlib/>
 - The SMT Competition SMT-COMP: <https://www.smtcomp.org/>
 - The SAT/SMT Schools <https://satassociation.org/sat-smt-school.html>

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