

Decision Procedures

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Quantifier Elimination

Quantifier Elimination (QE) removes quantifiers from formulae:

- Given a formula with quantifiers, e.g., $\exists x.F[x, y, z]$.
- Goal: find an **equivalent** quantifier-free formula $G[y, z]$.
- The **free** variables of F and G are the same.

$$\exists x.F[x, y, z] \Leftrightarrow G[y, z]$$

Decide satisfiability for a formula F , e.g. in $T_{\mathbb{Q}}$, using quantifier elimination:

- Given a formula F , with free variable x_1, \dots, x_n .
- Build $\exists x_1 \dots \exists x_n. F$.
- Build equivalent quantifier free formula G .
 G contains only constants, functions and predicates
i.e. $0, 1, +, -, \geq, =$.
- Compute truth value of G .

In developing a QE algorithm for theory T , we need only consider formulae of the form

$$\exists x. F$$

for quantifier-free F

Example: For Σ -formula

$$G_1: \exists x. \forall y. \underbrace{\exists z. F_1[x, y, z]}_{F_2[x, y]}$$

$$G_2: \exists x. \forall y. F_2[x, y]$$

$$G_3: \exists x. \underbrace{\neg \exists y. \neg F_2[x, y]}_{F_3[x]}$$

$$G_4: \underbrace{\exists x. \neg F_3[x]}_{F_4}$$

$$G_5: F_4$$

G_5 is quantifier-free and T -equivalent to G_1

Consider the Signature of Rationals: $\Sigma_{\mathbb{Q}} : \{0, 1, +, -, =, \geq\}$

We extend the signature with the predicate $>$, which is defined as

$$x > y :\Leftrightarrow x \geq y \wedge \neg(x = y).$$

Additionally we allow predicates $<$ and \leq :

$$x < y :\Leftrightarrow y > x \quad x \leq y :\Leftrightarrow y \geq x.$$

We extend the signature by fractions:

$$\frac{\cdot}{a} \in \Sigma_{\mathbb{Q}} \text{ for } a \in \mathbb{Z}^+$$

which are unary function symbols, with their usual meaning.

Given a $\Sigma_{\mathbb{Q}}$ -formula $\exists x. F[x]$, where $F[x]$ is quantifier-free
Generate quantifier-free formula F_4 (four steps) s.t.

F_4 is $\Sigma_{\mathbb{Q}}$ -equivalent to $\exists x. F[x]$.

- 1 Put $F[x]$ in NNF.
- 2 Eliminate negated literals.
- 3 Solve the literals s.t. x appears isolated on one side.
- 4 Finite disjunction $\bigvee_{t \in S_F} F[t]$.

$$\exists x. F[x] \Leftrightarrow \bigvee_{t \in S_F} F[t].$$

where S_F depends on the formula F .

Step 1: Put $F[x]$ in NNF. The result is $\exists x. F_1[x]$.

Step 2: Eliminate negated literals and \geq (left to right)

$$\begin{aligned} s \geq t &\Leftrightarrow s > t \vee s = t \\ \neg(s > t) &\Leftrightarrow t > s \vee t = s \\ \neg(s \geq t) &\Leftrightarrow t > s \\ \neg(s = t) &\Leftrightarrow t < s \vee t > s \end{aligned}$$

The result $\exists x. F_2[x]$ does not contain negations.

Solve for x in each atom of $F_2[x]$, e.g.,

$$ax + t_2 < bx + t_1 \quad \Rightarrow \quad x < \frac{t_1 - t_2}{a - b}$$

where $a - b \in \mathbb{Z}^+$.

All atoms containing x in the result $\exists x. F_3[x]$ have form

(A) $x < t$

(B) $t < x$

(C) $x = t$

where t is a term that does not contain x .

Construct from $F_3[x]$

- **left infinite projection** $F_3[-\infty]$ by replacing
 - (A) atoms $x < t$ by \top
 - (B) atoms $t < x$ by \perp
 - (C) atoms $x = t$ by \perp

- **right infinite projection** $F_3[+\infty]$ by replacing
 - (A) atoms $x < t$ by \perp
 - (B) atoms $t < x$ by \top
 - (C) atoms $x = t$ by \perp

Let S be the set of terms t from (A), (B), (C) atoms.

Construct the formula

$$F_4 : \bigvee_{t \in S_F} F_3[t], \quad \text{where } S_F := \{-\infty, \infty\} \cup \left\{ \frac{s+t}{2} \mid s, t \in S \right\}$$

which is $T_{\mathbb{Q}}$ -equivalent to $\exists x. F[x]$.

- $F_3[-\infty]$ captures the case when small $x \in \mathbb{Q}$ satisfy $F_3[x]$
- $F_3[\infty]$ captures the case when large $x \in \mathbb{Q}$ satisfy $F_3[x]$
- if $s \equiv t$, $\frac{s+t}{2} = s$ captures the case when $s \in S$ satisfies $F_3[s]$
if $s < t$ are adjacent numbers, $\frac{s+t}{2}$ represents the whole interval (s, t) .

Four cases are possible:

- 1 All numbers x smaller than the smallest term satisfy $F[x]$.

$$\leftarrow) t_1 t_2 \cdots t_n$$

- 2 All numbers x larger than the largest term satisfy $F[x]$.

$$t_1 t_2 \cdots t_n \rightarrow$$

- 3 Some t_i , satisfies $F[x]$.

$$t_1 \cdots t_i \cdots t_n$$

$$\uparrow$$

- 4 On an open interval between two terms every element satisfies $F[x]$.

$$t_1 \cdots t_i \left(\longleftrightarrow \right) t_{i+1} \cdots t_n$$

$$\frac{t_i + t_{i+1}}{2}$$

Theorem

Let S_F be the set of terms constructed from $F_3[x]$ as in Step 4. Then $\exists x. F_3[x] \Leftrightarrow \bigvee_{t \in S_F} F_3[t]$.

Proof of Theorem

- \Leftarrow If $\bigvee_{t \in S_F} F_3[t]$ is true, then $F_3[t]$ for some $t \in S_F$ is true.
 - If $F_3[\frac{s+t}{2}]$ is true, then obviously $\exists x. F_3[x]$ is true.
 - If $F_3[-\infty]$ is true, choose some $x < t$ for all $t \in S$. Then $F_3[x]$ is true.
 - If $F_3[\infty]$ is true, choose some $x > t$ for all $t \in S$. Then $F_3[x]$ is true.

\Rightarrow If $I \models \exists x. F_3[x]$ then there is value v such that

$$I \triangleleft \{x \mapsto v\} \models F_3.$$

If $v < \alpha_I[t]$ for all $t \in S$, then $I \models F_3[-\infty]$.

If $v > \alpha_I[t]$ for all $t \in S$, then $I \models F_3[\infty]$.

If $v = \alpha_I[t]$ for some $t \in S$, then $I \models F[\frac{t+t}{2}]$.

Otherwise choose largest $s \in S$ with $\alpha_I[s] < v$ and smallest $t \in S$ with $\alpha_I[t] > v$.

Since no atom of F_3 can distinguish between values in interval (s, t) , $F_3[v] \Leftrightarrow F_3[\frac{s+t}{2}]$. Hence, $I \models F[\frac{s+t}{2}]$.

In all cases $I \models \bigvee_{t \in S_F} F_3[t]$.

$$\exists x. \underbrace{3x + 1 < 10 \wedge 7x - 6 > 7}_{F[x]}$$

Solving for x

$$\exists x. \underbrace{x < 3 \wedge x > \frac{13}{7}}_{F_3[x]}$$

Step 4:

$$F_4 : \bigvee_{t \in S_F} \underbrace{\left(t < 3 \wedge t > \frac{13}{7} \right)}_{F_3[t]}$$

$$S_F = \{-\infty, +\infty, 3, \frac{13}{7}, \frac{3 + \frac{13}{7}}{2}\}.$$

$$F_3[x] = x < 3 \wedge x > 13/7$$

$$F_{-\infty} \Leftrightarrow \top \wedge \perp \Leftrightarrow \perp \quad F_{+\infty} \Leftrightarrow \perp \wedge \top \Leftrightarrow \perp$$

$$F_3[3] \perp \wedge \top \Leftrightarrow \perp \quad F_3\left[\frac{13}{7}\right] \Leftrightarrow \top \wedge \perp \Leftrightarrow \perp$$

$$F_3\left[\frac{\frac{13}{7} + 3}{2}\right] : \frac{\frac{13}{7} + 3}{2} < 3 \wedge \frac{\frac{13}{7} + 3}{2} > \frac{13}{7} \Leftrightarrow \top$$

Thus, $F_4 : \bigvee_{t \in S_F} F_3[t] \Leftrightarrow \top$ is $T_{\mathbb{Q}}$ -equivalent to $\exists x. F[x]$,
 so $\exists x. F[x]$ is $T_{\mathbb{Q}}$ -valid.

$$\exists x. \underbrace{2x > y \wedge 3x < z}_{F[x]}$$

Solving for x

$$\exists x. \underbrace{x > \frac{y}{2} \wedge x < \frac{z}{3}}_{F_3[x]}$$

Step 4: $F_{-\infty} \Leftrightarrow \perp$, $F_{+\infty} \Leftrightarrow \perp$, $F_3[\frac{y}{2}] \Leftrightarrow \perp$ and $F_3[\frac{z}{3}] \Leftrightarrow \perp$.

$$F_4 : \frac{\frac{y}{2} + \frac{z}{3}}{2} > \frac{y}{2} \wedge \frac{\frac{y}{2} + \frac{z}{3}}{2} < \frac{z}{3}$$

which simplifies to:

$$F_4 : 2z > 3y$$

$\Sigma_{\mathbb{Z}} : \{\dots, -2, -1, 0, 1, 2, \dots, -3\cdot, -2\cdot, 2\cdot, 3\cdot, \dots, +, -, =, <\}$

Consider the formula

$$F : \exists x. 2x = y$$

Which quantifier free formula $G[y]$ is equivalent to F ?

There is **no** such formula!

Lemma

Given quantifier-free $\Sigma_{\mathbb{Z}}$ -formula F s.t. $\text{free}(F) = \{y\}$. Let

$$S_F : \{n \in \mathbb{Z} : F\{y \mapsto n\} \text{ is } T_{\mathbb{Z}}\text{-valid}\} .$$

Either $\mathbb{Z}^+ \cap S_F$ or $\mathbb{Z}^+ \setminus S_F$ is finite.

where \mathbb{Z}^+ is the set of positive integers

Proof (Structural Induction over F)

Base case: F is an atomic formula:

$$\top, \perp, t_1 = t_2, a \cdot y = t, t_1 < t_2, a \cdot y < t.$$

- $\mathbb{Z}^+ \setminus S_{\top} = \mathbb{Z}^+ \cap S_{\perp} = \emptyset$ is finite
- $S_{t_1=t_2}$ and $S_{t_1 < t_2}$ are either S_{\top} or S_{\perp} .
- $\mathbb{Z}^+ \cap S_{a \cdot y = t}$, ($a \neq 0$) has at most one element.
- $\mathbb{Z}^+ \cap S_{a \cdot y < t}$, $a > 0$ is finite.
- $\mathbb{Z}^+ \setminus S_{a \cdot y < t}$, $a < 0$ is finite.

Lemma

Given quantifier-free $\Sigma_{\mathbb{Z}}$ -formula F s.t. $\text{free}(F) = \{y\}$. Let

$$S_F : \{n \in \mathbb{Z} : F\{y \mapsto n\} \text{ is } T_{\mathbb{Z}}\text{-valid}\}.$$

Either $\mathbb{Z}^+ \cap S_F$ or $\mathbb{Z}^+ \setminus S_F$ is finite.

where \mathbb{Z}^+ is the set of positive integers

Proof (Structural Induction over F)

Induction step: Assume property holds for F, G . Show it for $\neg F, F \wedge G, F \vee G, F \rightarrow G, F \leftrightarrow G$.

- $\neg F$: We have $\mathbb{Z}^+ \cap S_{\neg F} = \mathbb{Z}^+ \setminus S$ and $\mathbb{Z}^+ \setminus S_{\neg F} = \mathbb{Z}^+ \cap S$ and by ind.-hyp one of these sets is finite.
- $F \wedge G$: We have $\mathbb{Z}^+ \cap S_{F \wedge G} = (\mathbb{Z}^+ \cap S_F) \cap (\mathbb{Z}^+ \cap S_G)$ and $\mathbb{Z}^+ \setminus S_{F \wedge G} = (\mathbb{Z}^+ \setminus S_F) \cup (\mathbb{Z}^+ \setminus S_G)$.
If the latter set is not finite then one of $\mathbb{Z}^+ \cap S_F$ or $\mathbb{Z}^+ \cap S_G$ is finite.
In both cases $\mathbb{Z}^+ \cap S_{F \wedge G}$ is finite.

Lemma

Given quantifier-free $\Sigma_{\mathbb{Z}}$ -formula F s.t. $\text{free}(F) = \{y\}$. Let

$$S_F : \{n \in \mathbb{Z} : F\{y \mapsto n\} \text{ is } T_{\mathbb{Z}}\text{-valid}\}.$$

Either $\mathbb{Z}^+ \cap S_F$ or $\mathbb{Z}^+ \setminus S_F$ is finite.

where \mathbb{Z}^+ is the set of positive integers

Proof (Structural Induction over F)

Induction step: Assume property holds for F, G . Show it for $\neg F, F \wedge G, F \vee G, F \rightarrow G, F \leftrightarrow G$.

- $F \vee G$ follows from previous, since $S_{F \vee G} = S_{\neg(\neg F \wedge \neg G)}$.
- $F \rightarrow G$ follows from $S_{F \rightarrow G} = S_{(\neg F \vee G)}$.
- $F \leftrightarrow G$ follows from $S_{F \leftrightarrow G} = S_{(F \rightarrow G) \wedge (G \rightarrow F)}$.

Lemma

Given quantifier-free $\Sigma_{\mathbb{Z}}$ -formula F s.t. $\text{free}(F) = \{y\}$. Let

$$S_F : \{n \in \mathbb{Z} : F\{y \mapsto n\} \text{ is } T_{\mathbb{Z}}\text{-valid}\} .$$

Either $\mathbb{Z}^+ \cap S_F$ or $\mathbb{Z}^+ \setminus S_F$ is finite.

where \mathbb{Z}^+ is the set of positive integers

$\Sigma_{\mathbb{Z}}$ -formula $F : \exists x. 2x = y$ (with quantifier)

S_F : even integers

$\mathbb{Z}^+ \cap S_F$: positive even integers — infinite

$\mathbb{Z}^+ \setminus S_F$: positive odd integers — infinite

Therefore, by the lemma, there is no quantifier-free $T_{\mathbb{Z}}$ -formula that is $T_{\mathbb{Z}}$ -equivalent to F .

Thus, $T_{\mathbb{Z}}$ does not admit QE.

$\widehat{\Sigma}_{\mathbb{Z}}$: $\Sigma_{\mathbb{Z}}$ with countable number of unary **divisibility predicates**
 $\Sigma_{\mathbb{Z}} \cup \{1|\cdot, 2|\cdot, 3|\cdot, \dots\}$

Intended interpretations:

$k \mid x$ holds iff k divides x without any remainder

Axioms of $\widehat{T}_{\mathbb{Z}}$: axioms of $T_{\mathbb{Z}}$ with additional countable set of axioms

$$\forall x. k \mid x \leftrightarrow \exists y. x = ky \quad \text{for } k \in \mathbb{Z}^+$$

Example:

$$x > 1 \wedge y > 1 \wedge 2 \mid x + y$$

is satisfiable (choose $x = 2, y = 2$).

$$\neg(2 \mid x) \wedge 4 \mid x$$

is not satisfiable.

Algorithm: Given $\widehat{\Sigma}_{\mathbb{Z}}$ -formula $\exists x. F[x]$, where F is quantifier-free
Construct quantifier-free $\widehat{\Sigma}_{\mathbb{Z}}$ -formula that is equivalent to $\exists x. F[x]$.

- 1 Put $F[x]$ into Negation Normal Form (NNF).
- 2 Normalize literals: $s < t$, $k|t$, or $\neg(k|t)$.
- 3 Put x in $s < t$ on one side: $hx < t$ or $s < hx$.
- 4 Replace hx with x' without a factor.
- 5 Replace $F[x']$ by $\bigvee F[j]$ for finitely many j .

Put $F[x]$ in NNF $F_1[x]$, that is,

$\exists x. F_1[x]$ has negations only in literals (only \wedge, \vee)
and $\widehat{T}_{\mathbb{Z}}$ -equivalent to $\exists x. F[x]$

Example:

$$\exists x. \neg(x - 6 < z - x \wedge 4 \mid 5x + 1 \rightarrow 3x < y)$$

is equivalent to

$$\exists x. \neg(3x < y) \wedge x - 6 < z - x \wedge 4 \mid 5x + 1$$

Replace (left to right)

$$\begin{aligned}s = t &\Leftrightarrow s < t + 1 \wedge t < s + 1 \\ \neg(s = t) &\Leftrightarrow s < t \vee t < s \\ \neg(s < t) &\Leftrightarrow t < s + 1\end{aligned}$$

The output $\exists x. F_2[x]$ contains only literals of form

$$s < t, \quad k \mid t, \quad \text{or} \quad \neg(k \mid t),$$

where s, t are $\widehat{T}_{\mathbb{Z}}$ -terms and $k \in \mathbb{Z}^+$.

Example:

$$\begin{aligned}\exists x. \neg(3x < y) \wedge x - 6 < z - x \wedge 4 \mid 5x + 1 \\ \text{is equivalent to} \\ \exists x. y < 3x + 1 \wedge x - 6 < z - x \wedge 4 \mid 5x + 1\end{aligned}$$

Collect terms containing x so that literals have the form

$$hx < t, \quad t < hx, \quad k \mid hx + t, \quad \text{or} \quad \neg(k \mid hx + t),$$

where t is a term and $h, k \in \mathbb{Z}^+$. The output is the formula $\exists x. F_3[x]$, which is $\widehat{T}_{\mathbb{Z}}$ -equivalent to $\exists x. F[x]$.

Example:

$$\exists x. y < 3x + 1 \wedge x - 6 < z - x \wedge 4 \mid 5x + 1$$

is equivalent to

$$\exists x. y - 1 < 3x \wedge 2x < z + 6 \wedge 4 \mid 5x + 1$$

Let

$$\delta = \text{lcm}\{h : h \text{ is a coefficient of } x \text{ in } F_3[x]\},$$

where lcm is the least common multiple. Multiply atoms in $F_3[x]$ by constants so that δ is the coefficient of x everywhere:

$$\begin{array}{lll} hx < t & \Leftrightarrow & \delta x < h't & \text{where } h'h = \delta \\ t < hx & \Leftrightarrow & h't < \delta x & \text{where } h'h = \delta \\ k \mid hx + t & \Leftrightarrow & h'k \mid \delta x + h't & \text{where } h'h = \delta \\ \neg(k \mid hx + t) & \Leftrightarrow & \neg(h'k \mid \delta x + h't) & \text{where } h'h = \delta \end{array}$$

The result $\exists x. F'_3[x]$, in which all occurrences of x in $F'_3[x]$ are in terms δx .

Replace δx terms in F'_3 with a fresh variable x' to form

$$F''_3 : F_3\{\delta x \mapsto x'\}$$

Finally, construct

$$\exists x'. \underbrace{F_3''[x'] \wedge \delta \mid x'}_{F_4[x']}$$

$\exists x'. F_4[x']$ is equivalent to $\exists x. F[x]$ and each literal of $F_4[x']$ has one of the forms:

- (A) $x' < t$
- (B) $t < x'$
- (C) $k \mid x' + t$
- (D) $\neg(k \mid x' + t)$

where t is a term that does not contain x , and $k \in \mathbb{Z}^+$.

Example: $\widehat{T}_{\mathbb{Z}}$ -formula

$$\exists x. \underbrace{2x < z + 6 \wedge y - 1 < 3x \wedge 4 \mid 5x + 1}_{F_3[x]}$$

Collecting coefficients of x :

$$\delta = \text{lcm}(2, 3, 5) = 30$$

Multiply when necessary

$$\exists x. 30x < 15z + 90 \wedge 10y - 10 < 30x \wedge 24 \mid 30x + 6$$

Replacing $30x$ with fresh x'

$$\exists x'. \underbrace{x' < 15z + 90 \wedge 10y - 10 < x' \wedge 24 \mid x' + 6 \wedge 30 \mid x'}_{F_4[x']}$$

$\exists x'. F_4[x']$ is equivalent to $\exists x. F_3[x]$

$\exists x'. F_4[x']$ is equivalent to $\exists x. F[x]$ and each literal of $F_4[x']$ has one of the forms:

(A) $x' < t$

(B) $t < x'$

(C) $k \mid x' + t$

(D) $\neg(k \mid x' + t)$

where t is a term that does not contain x , and $k \in \mathbb{Z}^+$.

Construct

left infinite projection $F_{-\infty}[x']$

of $F_4[x']$ by

(A) replacing literals $x' < t$ by \top

(B) replacing literals $t < x'$ by \perp

idea: very small numbers satisfy (A) literals but not (B) literals

Let

$$\delta = \text{lcm} \left\{ \begin{array}{l} k \text{ of (C) literals } k \mid x' + t \\ k \text{ of (D) literals } \neg(k \mid x' + t) \end{array} \right\}$$

and B be the set of terms t appearing in (B) literals. Construct

$$F_5 : \bigvee_{j=1}^{\delta} F_{-\infty}[j] \vee \bigvee_{j=1}^{\delta} \bigvee_{t \in B} F_4[t + j].$$

F_5 is quantifier-free and $\widehat{T}_{\mathbb{Z}}$ -equivalent to F .

$$\exists x'. \underbrace{x' < 15z + 90 \wedge 10y - 10 < x' \wedge 24 \mid x' + 6 \wedge 30 \mid x'}_{F_4[x']}$$

Compute lcm: $\delta = \text{lcm}(24, 30) = 120$

Then

$$F_5 = \bigvee_{j=1}^{120} \top \wedge \perp \wedge 24 \mid j + 6 \wedge 30 \mid j$$

$$\vee \bigvee_{j=1}^{120} 10y - 10 + j < 15z + 90 \wedge 10y - 10 < 10y - 10 + j$$

$$\wedge 24 \mid 10y - 10 + j + 6 \wedge 30 \mid 10y - 10 + j$$

The formula can be simplified to:

$$F_5 = \bigvee_{j=1}^{120} 10y - 10 + j < 15z + 90 \wedge 24 \mid 10y - 10 + j + 6 \wedge 30 \mid 10y - 10 + j$$

Theorem

Let F_5 be the formula constructed from $\exists x'. F_4[x']$ as in Step 5. Then $\exists x'. F_4[x'] \Leftrightarrow F_5$.

Lemma[Periodicity]: For all atoms $k \mid x' + t$ in F_4 , we have $k \mid \delta$.

Therefore, $k \mid x' + t$ iff $k \mid x' + \lambda\delta + t$ for all $\lambda \in \mathbb{Z}$.

Proof of Theorem

\Leftarrow If F_5 is true, there are two cases: $F_{-\infty}[j]$ is true or $F_4[t + j]$ is true. If $F_4[t + j]$ is true, then obviously $\exists x'. F_4[x']$ is true. If $F_{-\infty}[j]$ is true, then (due to periodicity) $F_{-\infty}[j + \lambda \cdot \delta]$ is true.

If $\lambda < t - 1$ for all $t \in A \cup B$, then

$j + \lambda \cdot \delta < \delta + (t - 1)\delta = \delta t \leq t$. Thus,

$$F_{-\infty}[j + \lambda \cdot \delta] \Leftrightarrow F_4[j + \lambda \cdot \delta] \Rightarrow \exists x'. F_4[x'].$$

Correctness of Step 5

⇒ Assume for some x' , $F_4[x']$ is true. If $\neg(t < x')$ for all $t \in B$, then choose $j_{x'} \in \{1, \dots, \delta\}$ such that $\delta \mid (j_{x'} - x')$. $j_{x'}$ will satisfy all (C) and (D) literals that x' satisfies. x' does not satisfy any (B) literal. Therefore if $F_4[x']$ is true, $F_{-\infty}[j]$ must be true. Therefore F_5 is true. If $t < x'$ for some $t \in B$, then let

$$t_{x'} = \max\{t \in B \mid t < x'\}$$

and choose $j_{x'} \in \{1, \dots, \delta\}$ such that $\delta \mid (t_{x'} + j_{x'} - x')$. We claim that $F_4[t_{x'} + j_{x'}]$ is true.

Since $x' = t_{x'} + j_{x'} + \lambda\delta$, x' and $t_{x'} + j_{x'}$ satisfy the same (C) and (D) literals (due to periodicity).

Since $t_{x'} + j_{x'} > t_{x'} = \max\{t \in B \mid t < x'\}$, $t_{x'} + j_{x'}$ satisfies all (B) literals that are satisfied by x' .

Since $t_{x'} < x' = t_{x'} + j_{x'} + \lambda\delta \leq t_{x'} + (\lambda + 1)\delta$, we conclude that $\lambda \geq 0$. Hence, $x' \geq t_{x'} + j_{x'}$ and $t_{x'} + j_{x'}$ satisfies all (A) literals satisfied by x' .

Thus $F_4[t_{x'} + j_{x'}]$ is true. Therefore, F_5 is true.

Construct

left infinite projection $F_{-\infty}[x']$

of $F_4[x']$ by

(A) replacing literals $x' < t$ by \top

(B) replacing literals $t < x'$ by \perp

Let

$$\delta = \text{lcm} \left\{ \begin{array}{l} k \text{ of (C) literals } k \mid x' + t \\ k \text{ of (D) literals } \neg(k \mid x' + t) \end{array} \right\}$$

and B be the set of terms t appearing in (B) literals. Construct

$$F_5 : \bigvee_{j=1}^{\delta} F_{-\infty}[j] \vee \bigvee_{j=1}^{\delta} \bigvee_{t \in B} F_4[t + j].$$

F_5 is quantifier-free and $\widehat{T}_{\mathbb{Z}}$ -equivalent to F .

In step 5, if there are fewer

(A) literals $x' < t$

than

(B) literals $t < x'$.

Construct the right infinite projection $F_{+\infty}[x']$ from $F_4[x']$ by replacing

each (A) literal $x' < t$ by \perp

and

each (B) literal $t < x'$ by \top .

Then right elimination.

$$F_5 : \bigvee_{j=1}^{\delta} F_{+\infty}[-j] \vee \bigvee_{j=1}^{\delta} \bigvee_{t \in A} F_4[t - j].$$

$$\exists x'. \underbrace{x' < 15z + 90 \wedge 10y - 10 < x' \wedge 24 \mid x' + 6 \wedge 30 \mid x'}_{F_4[x']}$$

Compute lcm: $\delta = \text{lcm}(24, 30) = 120$

Then

$$F_5 = \bigvee_{j=1}^{120} \perp \wedge \top \wedge 24 \mid -j + 6 \wedge 30 \mid -j$$

$$\vee \bigvee_{j=1}^{120} 15z + 90 - j < 15z + 90 \wedge 10y - 10 < 15z + 90 - j$$

$$\wedge 24 \mid 15z + 90 - j + 6 \wedge 30 \mid 15z + 90 - j$$

The formula can be simplified to:

$$F_5 = \bigvee_{j=1}^{120} 10y - 10 < 15z + 90 - j \wedge 24 \mid 15z + 90 - j + 6 \wedge 30 \mid 15z + 90 - j$$

$$\underbrace{\exists x. (3x + 1 < 10 \vee 7x - 6 > 7) \wedge 2 \mid x}_{F[x]}$$

Isolate x terms

$$\exists x. (3x < 9 \vee 13 < 7x) \wedge 2 \mid x ,$$

so

$$\delta = \text{lcm}\{3, 7\} = 21 .$$

After multiplying coefficients by proper constants,

$$\exists x. (21x < 63 \vee 39 < 21x) \wedge 42 \mid 21x ,$$

we replace $21x$ by x' :

$$\exists x'. \underbrace{(x' < 63 \vee 39 < x') \wedge 42 \mid x' \wedge 21 \mid x'}_{F_4[x']} .$$

Then

$$F_{-\infty}[x'] : (\top \vee \perp) \wedge 42 \mid x' \wedge 21 \mid x' ,$$

or, simplifying,

$$F_{-\infty}[x'] : 42 \mid x' \wedge 21 \mid x' .$$

Finally,

$$\delta = \text{lcm}\{21, 42\} = 42 \quad \text{and} \quad B = \{39\} ,$$

so

$$F_5 : \bigvee_{j=1}^{42} (42 \mid j \wedge 21 \mid j) \vee \bigvee_{j=1}^{42} ((39 + j < 63 \vee 39 < 39 + j) \wedge 42 \mid 39 + j \wedge 21 \mid 39 + j) .$$

Since $42 \mid 42$ and $21 \mid 42$, the left main disjunct simplifies to \top , so that F is $\widehat{T}_{\mathbb{Z}}$ -equivalent to \top . Thus, F is $\widehat{T}_{\mathbb{Z}}$ -valid.

Quantifier elimination decides validity/satisfiable **quantified** formulae.

Can also be used for quantifier free formulae:

To decide **satisfiability** of $F[x_1, \dots, x_n]$,
apply QE on $\exists x_1, \dots, x_n. F[x_1, \dots, x_n]$.

But high complexity (doubly exponential for $T_{\mathbb{Q}}$).

Therefore, we are looking for a fast procedure.