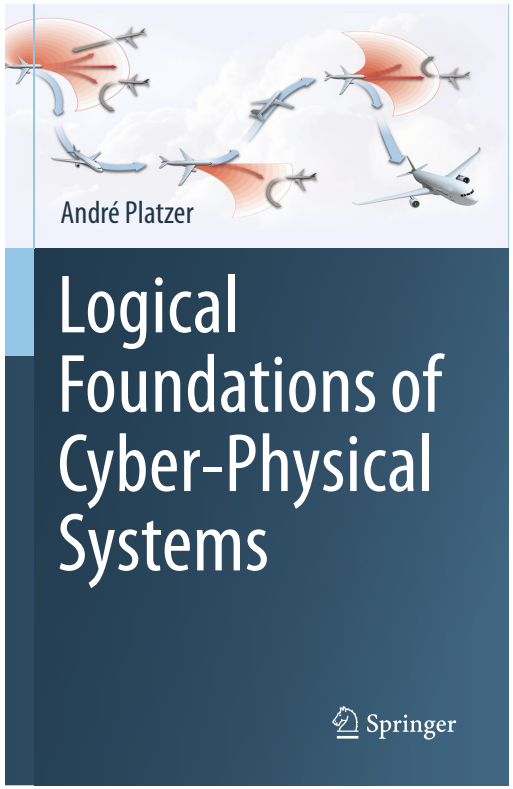
20: Virtual Substitution & Real Equations

Logical Foundations of Cyber-Physical Systems



André Platzer

Carnegie Mellon University
Computer Science Department

Outline

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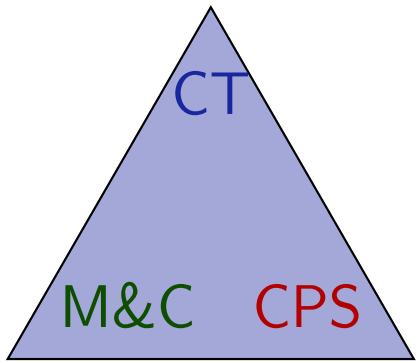
rigorous arithmetical reasoning
miracle of quantifier elimination
logical trinity for reals
switch between syntax & semantics at will
virtual substitution lemma
bridge gap between semantics and inexpressibles



analytic complexity
modeling tradeoffs

verifying CPS at scale

Outline

Evaluating Real Arithmetic Formulas

$$x^2 > 2 \land 2x < 3 \lor x^3 < x^2$$

Evaluating Real Arithmetic Formulas

When $\omega(x) = 2$

$\omega[\![x^2 > 2 \land 2x < 3 \lor x^3 < x^2]\!]$

Evaluating Real Arithmetic Formulas

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When $\nu(x) = -1$

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Evaluating Real Arithmetic Formulas

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Are the following formulas valid, i.e., true in all states?

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Evaluating Real Arithmetic Formulas

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Framing the Miracle: Quiz

Is validity of formulas
decidable/semidecidable/undecidable/not semidecidable for:

1. Propositional logic
2. FOL uninterpreted
3. $\text{FOL}_{\mathbb{N}}[+, \cdot, =]$
4. $\text{FOL}_{\mathbb{R}}[+, \cdot, =, <]$
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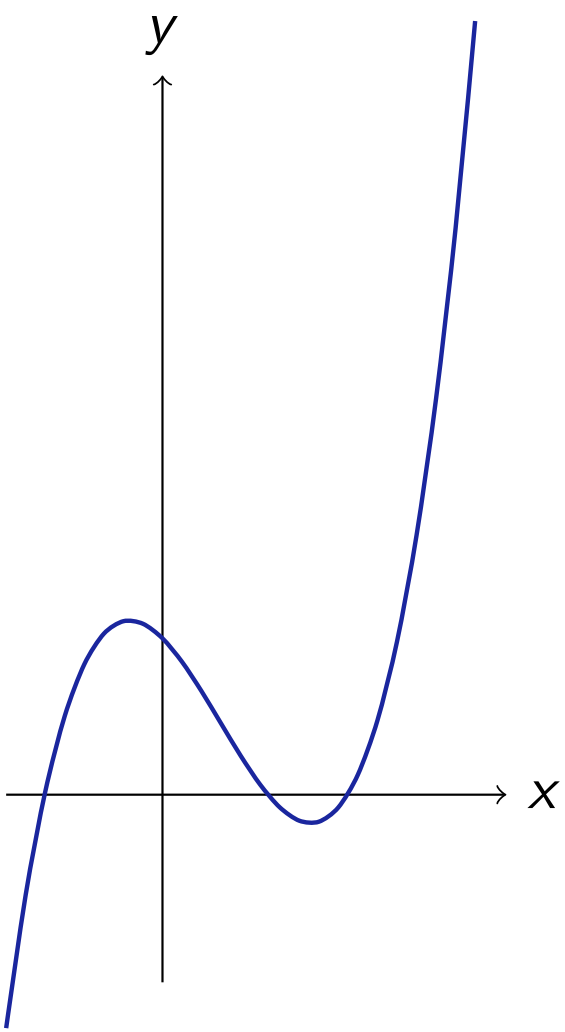
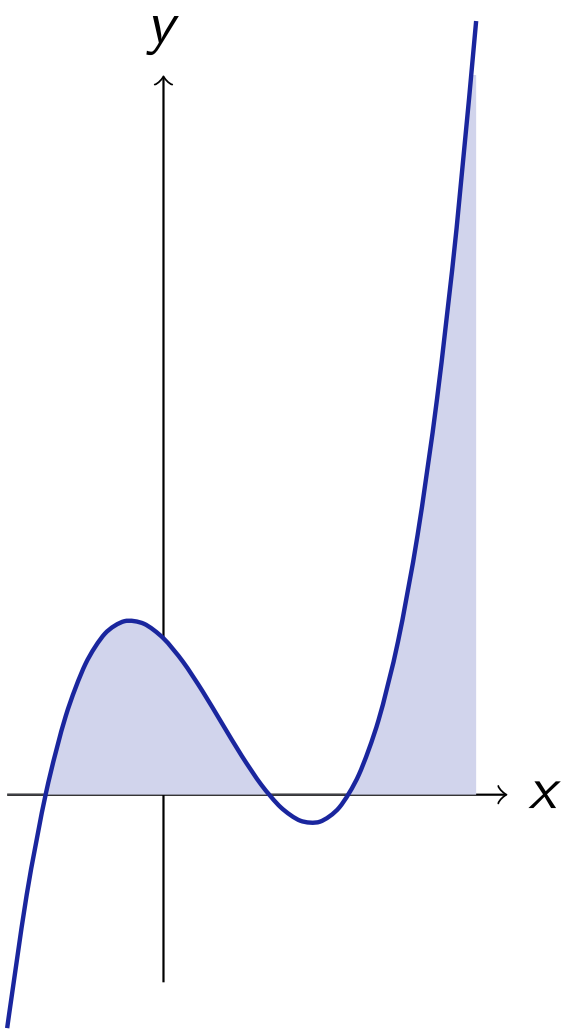
Quantifier Elimination $\leftrightsquigarrow$ Projection



$$F \equiv \exists y\,(y \geq 0 \wedge 1 - x - 1.83x^2 + 1.66x^3 > y)$$

Quantifier Elimination $\leftrightsquigarrow$ Projection



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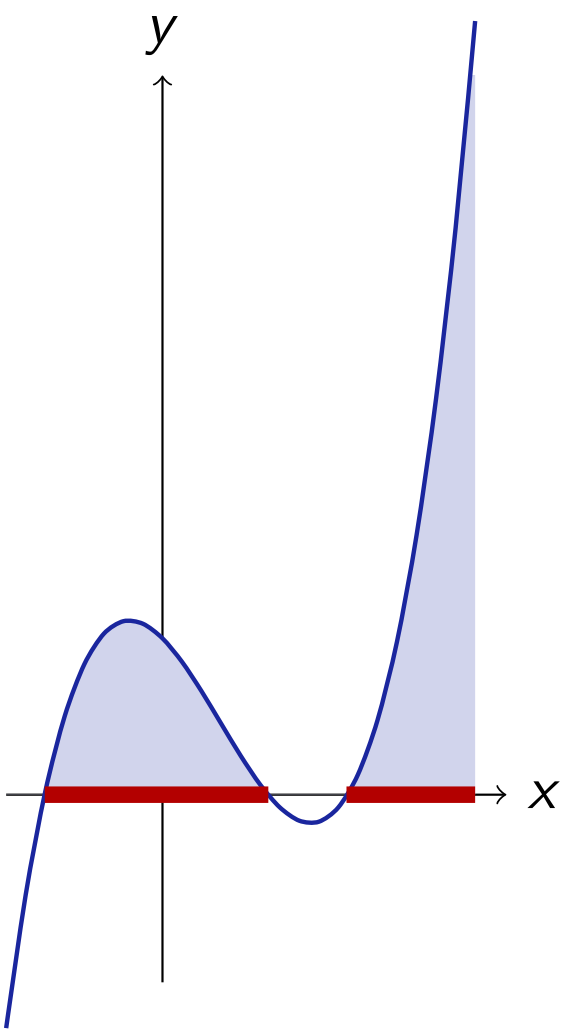

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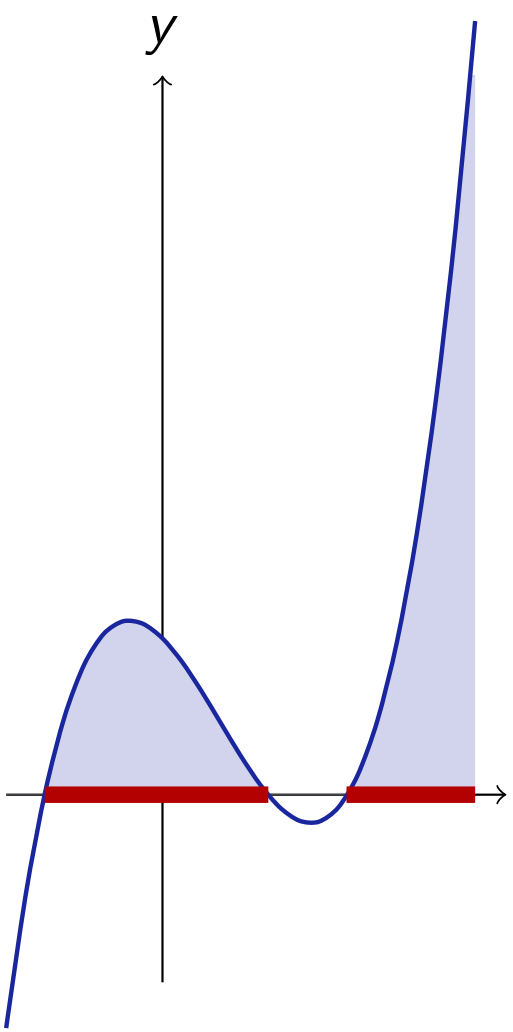

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QE

$$\mathrm{QE}(F) \equiv 0.75 < x \wedge x < 0.68 \vee x > 1.17$$

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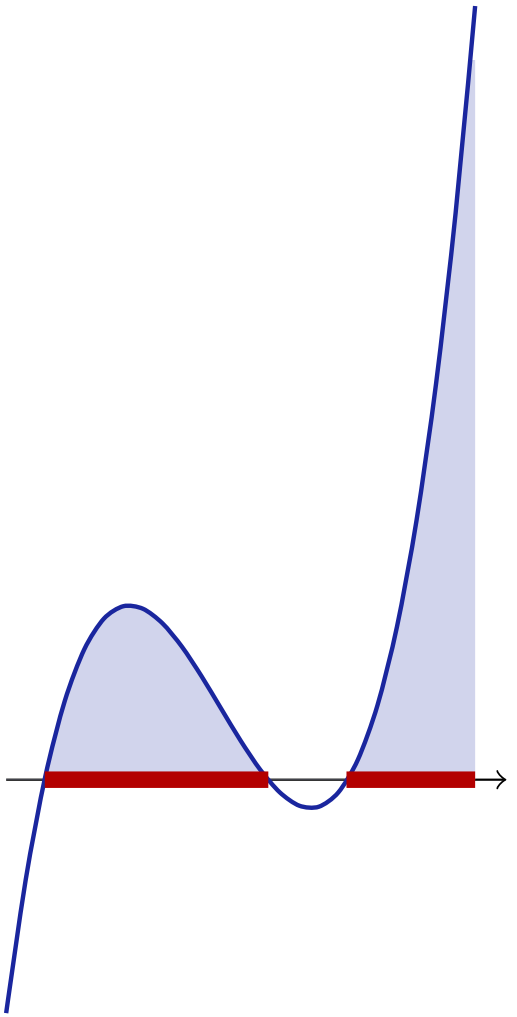
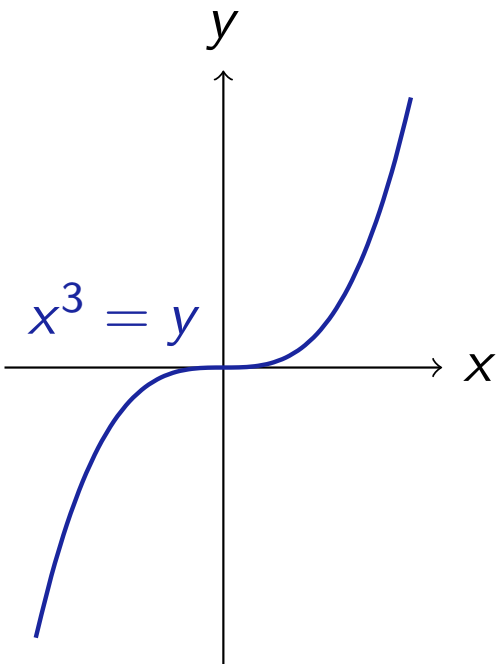
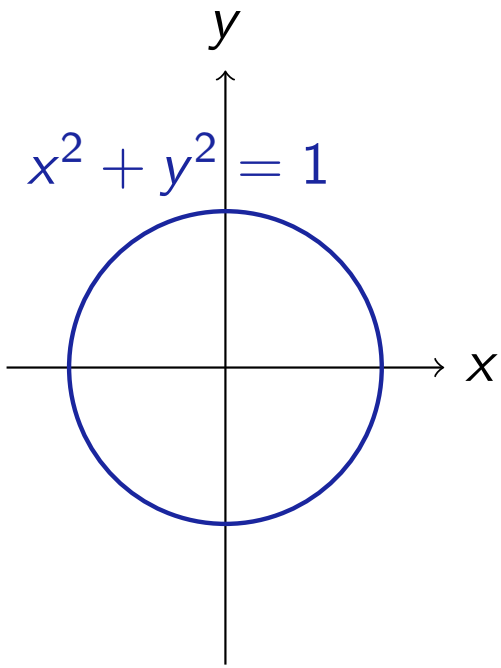


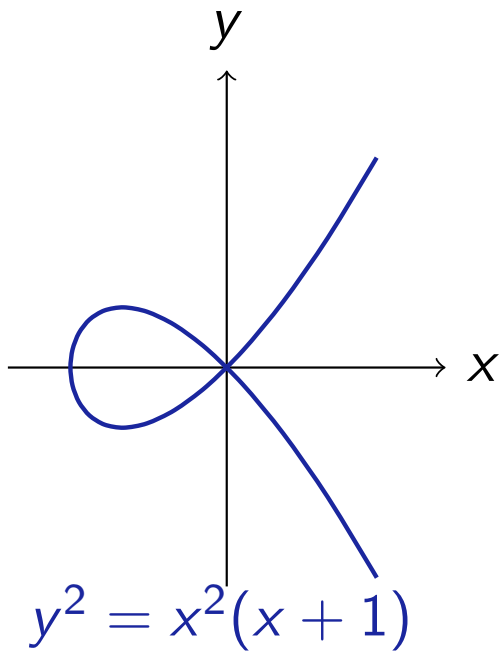
$$\mathrm{QE}(F) \equiv 0.75 < x \wedge x < 0.68 \vee x > 1.17$$

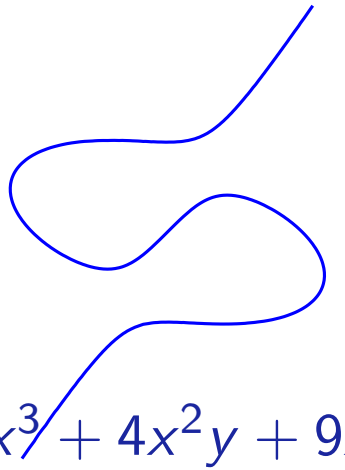
If all but one variable fixed: Finite union of intervals.
Univariate polynomials have finitely many roots. Sign changes finitely often.

Polynomial Equations ⇜⇝ Algebraic Varieties



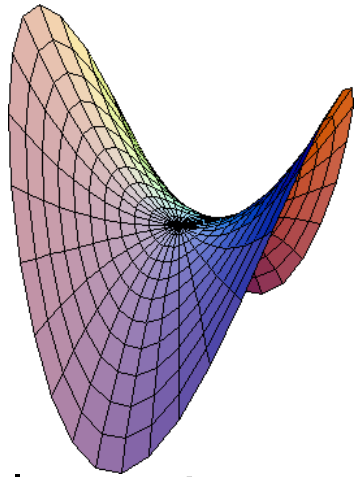






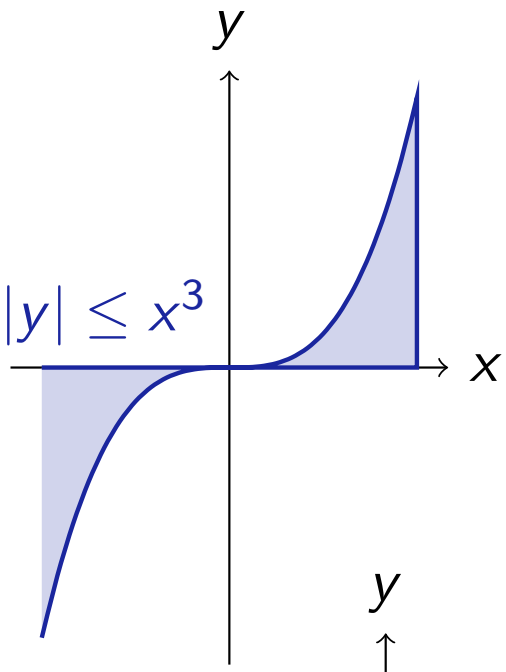
$4x^3 + 4x^2y + 9xy^2 - 9y^3 - 36x + 36y = 0$

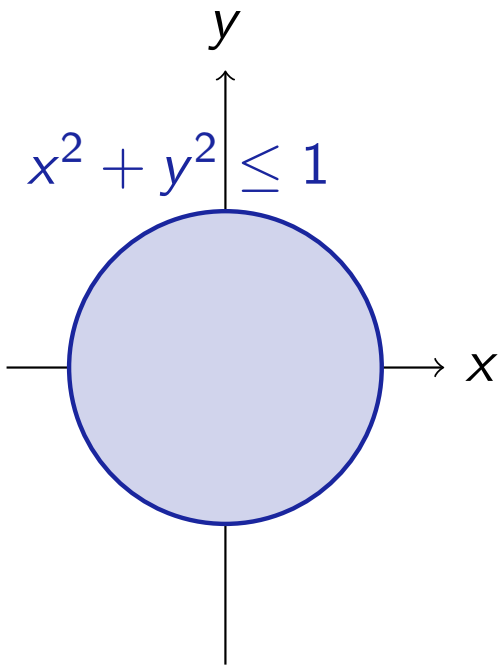
$z = x^2 - y^2$

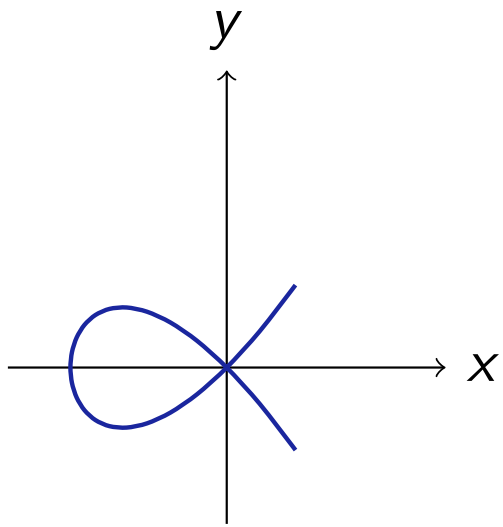


Algebraic variety: defined by conjunction of polynomial equations

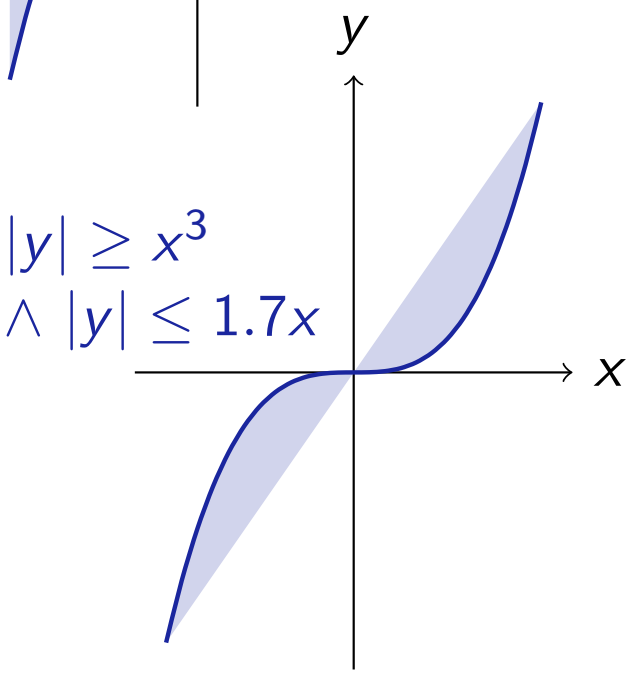
Polynomial Inequalities ⇜⇝ Semialgebraic Sets







$y^2 = x^2(x+1)$
$\wedge\ x \leq 0.44$



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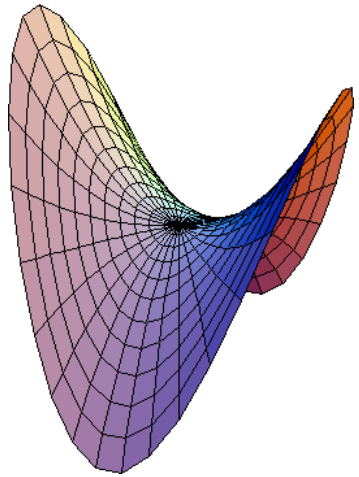

Theorem (Tarski'31)

First-order logic of real arithmetic is decidable since it admits quantifier elimination, i.e., with each formula ϕ, a quantifier-free formula $\mathsf{QE}(\phi)$ can be associated effectively that is equivalent, i.e., $\phi \leftrightarrow \mathsf{QE}(\phi)$ is valid.

Quantifier Elimination in Real Arithmetic

Theorem (Tarski'31)

First-order logic of real arithmetic is decidable since it admits quantifier elimination, i.e., with each formula ϕ, a quantifier-free formula $\mathsf{QE}(\phi)$ can be associated effectively that is equivalent, i.e., $\phi \leftrightarrow \mathsf{QE}(\phi)$ is valid.

Theorem (Complexity, Davenport&Heintz'88,Weispfenning'88)

(Time and space) complexity of QE *for* $\mathbb{R}$ *is doubly exponential in the number of quantifier (alternations).*

$$2^{2^{O(n)}}$$

Quantifier Elimination Examples

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- $\mathrm{QE}(\exists x\,(a = b + x^2)) \equiv a \geq b$

Framework: Logical Normalization for QE

$$\begin{aligned}
\mathrm{QE}(A \wedge B) &\equiv \\
\mathrm{QE}(A \vee B) &\equiv \\
\mathrm{QE}(\neg A) &\equiv \\
\mathrm{QE}(\forall x\, A) &\equiv \\
\mathrm{QE}(\exists x\, A) &\equiv
\end{aligned}$$

A has quantifiers

Framework: Logical Normalization for QE

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Framework: Logical Normalization for QE

Normal Form $\mathrm{QE}(\exists x\,(A_1 \wedge \ldots \wedge A_k))$ with atomic A_i

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\end{aligned}$$

Framework: Arithmetical Normalization for QE

Normal Form $\mathsf{QE}(\exists x\,(p_1 \sim_i 0 \wedge \ldots \wedge p_k \sim_k 0))$ and $\sim_i \in \{>, =, \geq, \neq\}$

$$p = q \equiv p - q = 0$$
$$p \geq q \equiv p - q \geq 0$$
$$p > q \equiv p - q > 0$$
$$p \neq q \equiv p - q \neq 0$$
$$p \leq q \equiv q - p \geq 0$$
$$p < q \equiv q - p > 0$$
$$\neg(p \geq q) \equiv p < q$$
$$\neg(p > q) \equiv p \leq q$$
$$\neg(p = q) \equiv p \neq q$$
$$\neg(p \neq q) \equiv p = q$$

Virtual Substitution

$$\exists x\, F \leftrightarrow \bigvee_{t \in T} A_t \wedge F_x^t$$

where terms T substituted (virtually) into F depend on F
where A_t are quantifier-free additional compatibility conditions

Needs simplifier for intermediate results

Quantifier Elimination by Virtual Substitution

Virtual Substitution

Quantifier $\exists x\, F \leftrightarrow \bigvee_{t \in T} A_t \wedge F_x^t$ Quantifier-free

where terms T substituted (virtually) into F depend on F
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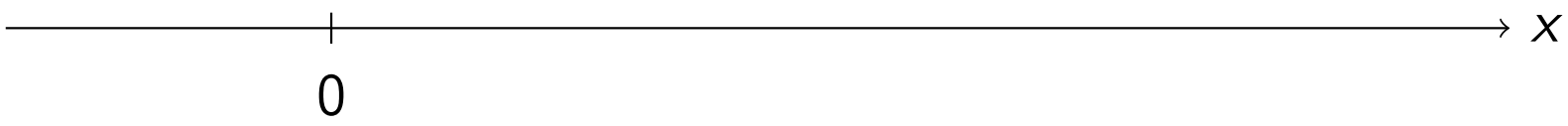
Needs simplifier for intermediate results

Virtual Substitution by Example



Can we get rid of the quantifier without changing the semantics?

$$\exists x(x > 2 \land x < \tfrac{17}{5})$$

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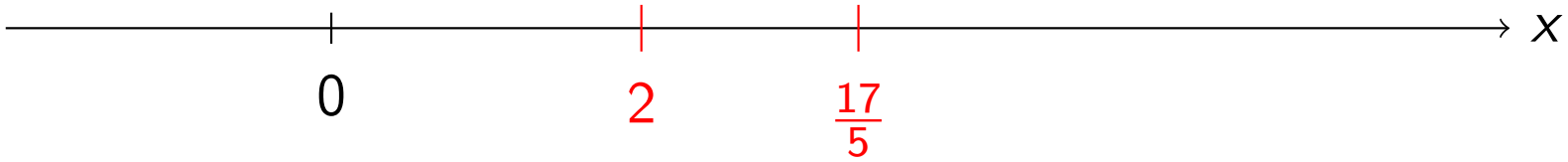

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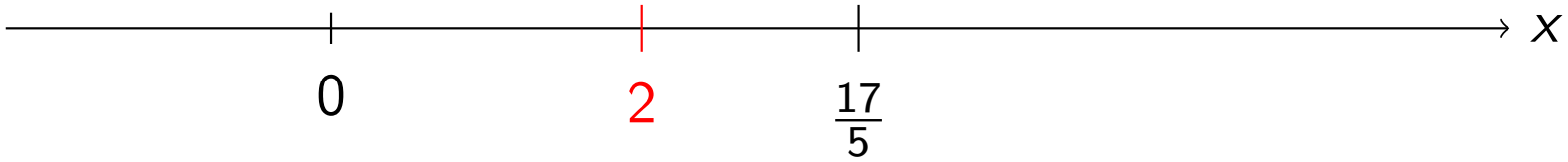

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$$\begin{array}{lll} & \exists x(x > 2 \land x < \frac{17}{5}) & \\ \equiv & (2 > 2 \land 2 < \frac{17}{5}) & \text{boundary case } \text{“}x = 2\text{”} \end{array}$$

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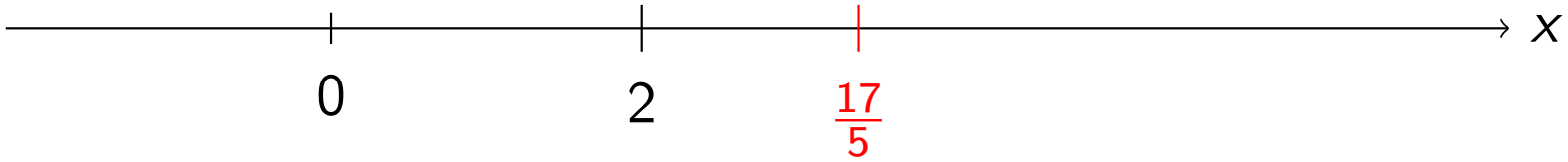

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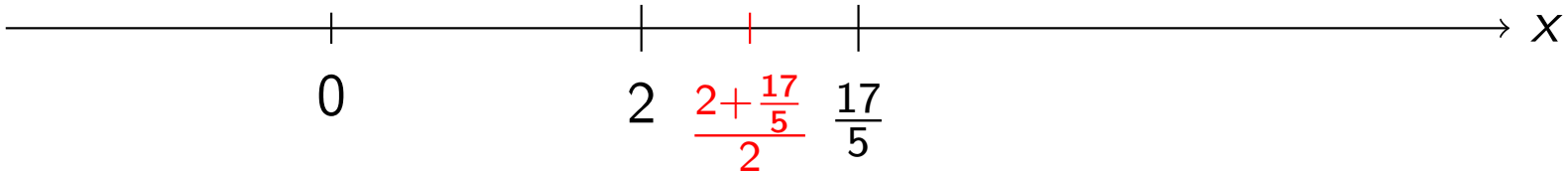

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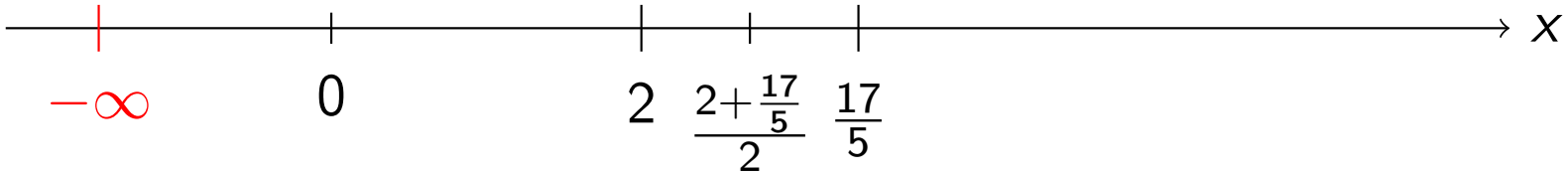

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\lor & (-\infty > 2 \land -\infty < \frac{17}{5}) & \text{extremal case } \text{“}x = -\infty\text{”}
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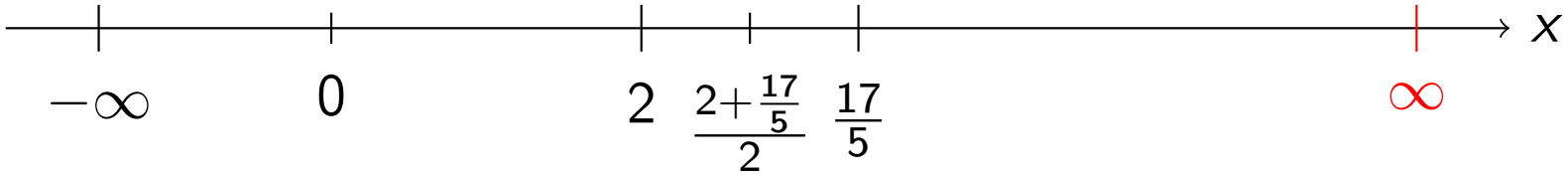

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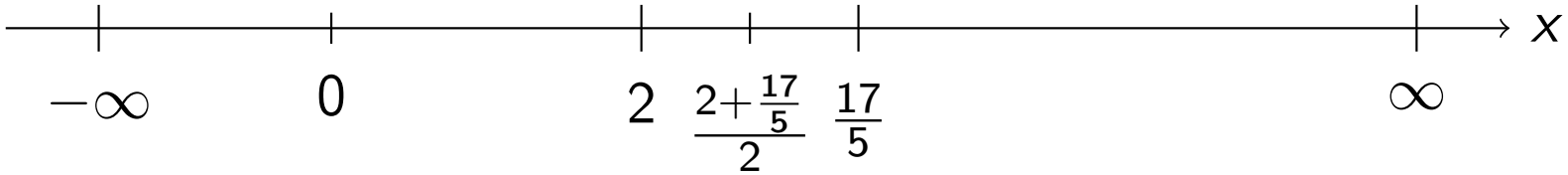

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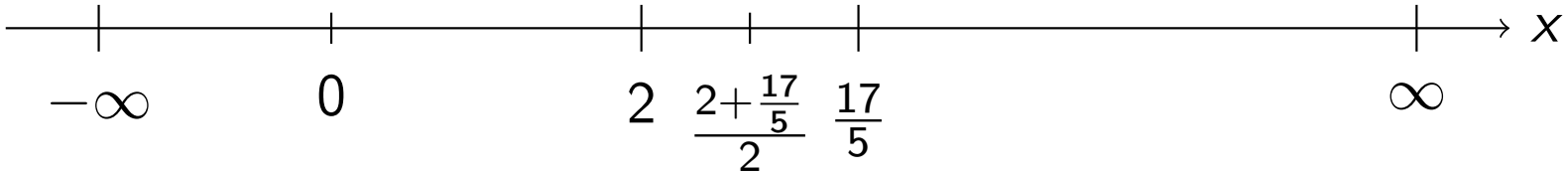

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- ∞ is not in $\text{FOL}_{\mathbb{R}}$
- Interior points aren't always terms in $\text{FOL}_{\mathbb{R}}$ if nonlinear
- Substituting them into formulas requires attention

Theorem (Virtual Substitution: Linear Equation)

$$\exists x\,(bx + c = 0 \wedge F) \;\leftrightarrow$$

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$$\exists x\,(bx + c = 0 \wedge F) \;\leftrightarrow\; F_x^{-c/b}$$

Linear solution

Theorem (Virtual Substitution: Linear Equation)

$$\exists x\,(bx + c = 0 \wedge F) \;\leftrightarrow\; b \neq 0 \wedge F_x^{-c/b}$$

Don't divide by 0

Linear Virtual Substitution

Theorem (Virtual Substitution: Linear Equation)

$$b \neq 0 \rightarrow \left(\exists x \left(bx + c = 0 \wedge F\right) \;\leftrightarrow\; b \neq 0 \wedge F_x^{-c/b}\right)$$

Only actually linear solution if $b \neq 0$

Linear Virtual Substitution

Theorem (Virtual Substitution: Linear Equation $x \notin b, c$)

$$b \neq 0 \rightarrow \left(\exists x \left(bx + c = 0 \wedge F\right) \leftrightarrow b \neq 0 \wedge F_x^{-c/b}\right) \quad \text{if } x \notin b, c$$

Only linear if no x in b, c

Linear Virtual Substitution

Theorem (Virtual Substitution: Linear Equation $x \notin b, c$)

$$b \neq 0 \rightarrow \big(\exists x\,(bx + c = 0 \wedge F) \;\leftrightarrow\; b \neq 0 \wedge F_x^{-c/b}\big) \quad \text{if } x \notin b, c$$

Conditional equivalence, so conditions may need to be checked or case-split

Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation)

$$\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$

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$$\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$

$$F_x^{(-b+\sqrt{b^2-4ac})/(2a)}$$

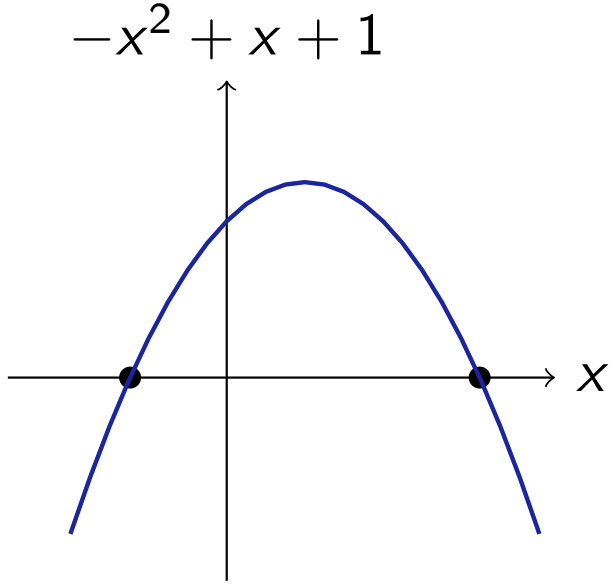
Quadratic solution

Theorem (Virtual Substitution: Quadratic Equation)

$$\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$

$$\left(F_x^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F_x^{(-b-\sqrt{b^2-4ac})/(2a)}\right)$$

Or negative square root solution



Quadratic Virtual Substitution

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$$a \neq 0 \wedge \left(F_x^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F_x^{(-b-\sqrt{b^2-4ac})/(2a)}\right)$$

Don't divide by 0

Quadratic Virtual Substitution

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$$\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$

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Real solution if square root exists by discriminant

Quadratic Virtual Substitution

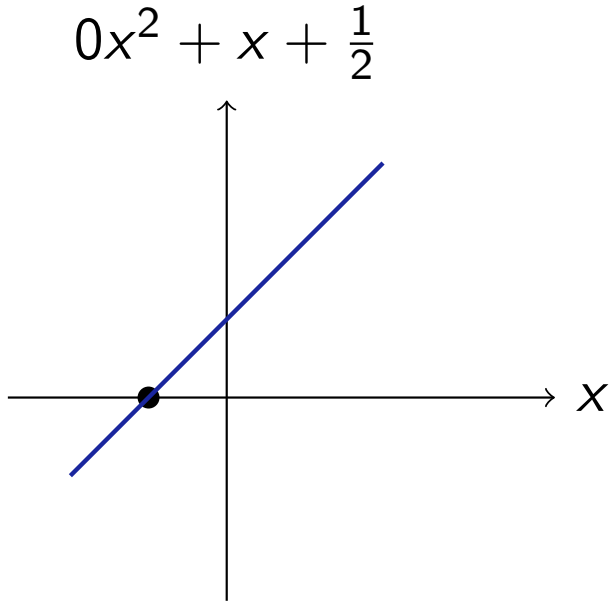
Theorem (Virtual Substitution: Quadratic Equation)

$$\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$

$$a = 0 \wedge b \neq 0 \wedge F_x^{-c/b}$$

$$\vee\ a \neq 0 \wedge b^2 - 4ac \geq 0 \wedge \left(F_x^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F_x^{(-b-\sqrt{b^2-4ac})/(2a)}\right)$$

Instead linear solution if $a = 0$ (may case-split)



Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation)

$$a \neq 0 \vee b \neq 0 \vee c \neq 0 \rightarrow$$
$$\Big(\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$
$$a = 0 \wedge b \neq 0 \wedge F_x^{-c/b}$$
$$\vee\, a \neq 0 \wedge b^2 - 4ac \geq 0 \wedge \big(F_x^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F_x^{(-b-\sqrt{b^2-4ac})/(2a)}\big)\Big)$$

Only equivalent solution if not all 0 which gives trivial equation

Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation $x \notin a, b, c$)

$$a \neq 0 \vee b \neq 0 \vee c \neq 0 \rightarrow$$
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Only linear or quadratic if no x in a, b, c

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1. Quantifier-free equivalent

Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation $x \notin a, b, c$)

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1. Quantifier-free equivalent
2. Just not a formula . . .

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1. Quantifier-free equivalent
2. Just not a formula ...
3. $(-b + \sqrt{b^2 - 4ac})/(2a)$ is not in $\mathrm{FOL}_{\mathbb{R}}$ and neither is $-c/b$

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4. Virtual substitution $F_{\not x}^{(a+b\sqrt{c})/d}$ acts as if it were to substitute $(a + b\sqrt{c})/d$ for x in F

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Theorem (Virtual Substitution: Quadratic Equation $x \notin a, b, c$)

$$
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5. $\exists r\,(r^2 = c)$ would do it for $\sqrt{c}$

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$$\Big(\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$
$$a = 0 \wedge b \neq 0 \wedge F\reflectbox{F}^{-c/b}$$
$$\vee\, a \neq 0 \wedge b^2 - 4ac \geq 0 \wedge \Big(F\reflectbox{F}^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F\reflectbox{F}^{(-b-\sqrt{b^2-4ac})/(2a)}\Big)\Big)$$

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5. $\exists r\,(r^2 = c)$ would do it for $\sqrt{c}$ but that's going in circles

Outline

Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation $x \notin a, b, c$)

$$
\begin{aligned}
&a \neq 0 \lor b \neq 0 \lor c \neq 0 \rightarrow \\
&\Big(\exists x\, (ax^2 + bx + c = 0 \land F) \leftrightarrow \\
&\quad a = 0 \land b \neq 0 \land F_{\not x}^{-c/b} \\
&\quad \lor\, a \neq 0 \land b^2 - 4ac \geq 0 \land \big(F_{\not x}^{(-b+\sqrt{b^2-4ac})/(2a)} \lor F_{\not x}^{(-b-\sqrt{b^2-4ac})/(2a)}\big)\Big)
\end{aligned}
$$

Virtual Substitution into Polynomial

Virtually substitute $(a + b\sqrt{c})/d$ into a polynomial p:

$$p\not{(}^{(a+b\sqrt{c})/d} \stackrel{\text{def}}{=}$$

Convention: On this slide c' is not a derivative but just another name ...

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$$p^{(a+b\sqrt{c})/d} \stackrel{\text{def}}{=} p((a + b\sqrt{c})/d) \quad \text{algebraic evaluation of } +, \cdot$$

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Square Root Expression Algebra

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$\sqrt{c}$-algebra

Algebra of terms $(a + b\sqrt{c})/d$ with polynomials $a, b, c, d \in \mathbb{Q}[x_1, .., x_n]$:

$$((a + b\sqrt{c})/d) + ((a' + b'\sqrt{c})/d') =$$
$$((a + b\sqrt{c})/d) \cdot ((a' + b'\sqrt{c})/d') =$$

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where $c \geq 0, d, d' \neq 0$

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$$((a + b\sqrt{c})/d) \cdot ((a' + b'\sqrt{c})/d') = ((aa' + bb'c) + (ab' + ba')\sqrt{c})/(dd')$$

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$$(p \sim 0)\not{}^{(a+b\sqrt{c})/d} \equiv$$

Virtual Substitution into Comparisons

Virtually substitute $(a + b\sqrt{c})/d$ into a comparison $p \sim 0$:

$$(p \sim 0)^{(a+b\sqrt{c})/d}_{x} \equiv (p^{(a+b\sqrt{c})/d}_{x} \sim 0)$$

Virtual $\sqrt{\cdot}$ Substitution

Virtual Substitution into Comparisons

Virtually substitute $(a + b\sqrt{c})/d$ into a comparison $p \sim 0$:

$$(p \sim 0)^{(a+b\sqrt{c})/d}_{\not x} \equiv (p^{(a+b\sqrt{c})/d}_{\not x} \sim 0)$$

$\sqrt{c}$-comparisons $d \neq 0 \land c \geq 0$

$$(a + 0\sqrt{c})/d = 0 \equiv$$
$$(a + 0\sqrt{c})/d \leq 0 \equiv$$
$$(a + 0\sqrt{c})/d < 0 \equiv$$
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$\sqrt{c}$-comparisons

$d \neq 0 \land c \geq 0$

$$(a + 0\sqrt{c})/d = 0 \equiv a = 0$$
$$(a + 0\sqrt{c})/d \leq 0 \equiv ad \leq 0$$
$$(a + 0\sqrt{c})/d < 0 \equiv ad < 0$$
$$(a + b\sqrt{c})/d = 0 \equiv ab \leq 0 \land a^2 - b^2c = 0$$
$$(a + b\sqrt{c})/d \leq 0 \equiv ad \leq 0 \land a^2 - b^2c \geq 0 \lor bd \leq 0 \land a^2 - b^2c \leq 0$$
$$(a + b\sqrt{c})/d < 0 \equiv ad < 0 \land a^2 - b^2c > 0 \lor bd \leq 0 \land (ad < 0 \lor a^2 - b^2c < 0)$$

Virtual Substitution into Comparisons

Virtually substitute $(a + b\sqrt{c})/d$ into a comparison $p \sim 0$:

$$(p \sim 0)\overset{(a+b\sqrt{c})/d}{\not\ast} \equiv (p\overset{(a+b\sqrt{c})/d}{\not\ast} \sim 0) \quad \text{accordingly for } \wedge, \vee, \ldots$$

$\sqrt{c}$-comparisons $d \neq 0 \wedge c \geq 0$

$$(a + 0\sqrt{c})/d = 0 \equiv a = 0$$
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Quadratic Virtual Substitution

Theorem (Virtual Substitution: Quadratic Equation $x \notin a, b, c$)

$$a \neq 0 \vee b \neq 0 \vee c \neq 0 \rightarrow$$
$$\Big(\exists x\,(ax^2 + bx + c = 0 \wedge F) \leftrightarrow$$
$$a = 0 \wedge b \neq 0 \wedge F_{\not x}^{-c/b}$$
$$\vee\ a \neq 0 \wedge b^2 - 4ac \geq 0 \wedge \big(F_{\not x}^{(-b+\sqrt{b^2-4ac})/(2a)} \vee F_{\not x}^{(-b-\sqrt{b^2-4ac})/(2a)}\big)\Big)$$

Lemma (Virtual Substitution Lemma for $\sqrt{\cdot}$)

$$F_x^{(a+b\sqrt{c})/d} \equiv F_{\not x}^{(a+b\sqrt{c})/d}$$

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Lemma (Virtual Substitution Lemma for $\sqrt{\cdot}$)

Extended logic $F_x^{(a+b\sqrt{c})/d} \equiv F_{\not x}^{(a+b\sqrt{c})/d}$ $\mathrm{FOL}_{\mathbb{R}}$

$\omega_x^r \in [\![F]\!]$ *iff* $\omega \in [\![F_{\not x}^{(a+b\sqrt{c})/d}]\!]$ *where* $r = (\omega[\![a]\!] + \omega[\![b]\!]\sqrt{\omega[\![c]\!]})/\omega[\![d]\!] \in \mathbb{R}$

Example: Curiosity

$$a \neq 0 \to (\exists x\,(ax^2+bx+c = 0 \wedge ax^2+bx+c \leq 0) \leftrightarrow b^2-4ac \geq 0 \wedge \mathit{true})$$

$$(ax^2+bx+c)^{(-b+\sqrt{b^2-4ac})/(2a)}$$

$$= a((-b+\sqrt{b^2-4ac})/(2a))^2 + b((-b+\sqrt{b^2-4ac})/(2a)) + c$$

$$= a((b^2+b^2-4ac+(-b-b)\sqrt{b^2-4ac})/(4a^2)) + (-b^2+b\sqrt{b^2-4ac})/(2a) + c$$

$$= (ab^2+ab^2-4a^2c+(-ab-ab)\sqrt{b^2-4ac})/(4a^2) + (-b^2+2ac+b\sqrt{b^2-4ac})/(2a)$$

$$= ((ab^2+ab^2-4a^2c)2a + (-b^2+2ac)4a^2 + ((-ab-ab)2a+b4a^2)\sqrt{b^2-4ac})/(4a^2)$$

$$= (\cancel{2a^2b^2} + \cancel{2a^2b^2} - \cancel{8a^3c} - \cancel{4a^2b^2} + \cancel{8a^3c} + (-\cancel{2a^2b} - \cancel{2a^2b} + \cancel{4a^2b})\sqrt{b^2-4ac})/(4a^2)$$

$$= (0 + 0\sqrt{b^2-4ac})/1 = 0$$

$$(ax^2+bx+c = 0)^{(-b+\sqrt{b^2-4ac})/(2a)} \equiv ((0+0\sqrt{\cdot\cdot})/1 = 0) \equiv (0 \cdot 1 = 0) \equiv \mathit{true}$$

$$(ax^2+bx+c \leq 0)^{(-b+\sqrt{b^2-4ac})/(2a)} \equiv (\underbrace{(0+0\sqrt{\cdot\cdot})/1}_{0} \leq 0) \equiv (0 \cdot 1 \leq 0) \equiv \mathit{true}$$

Example: Nonnegative Roots

$$a \neq 0 \rightarrow \big(\exists x\,(ax^2 + bx + c = 0 \wedge x \geq 0)$$
$$\leftrightarrow b^2 - 4ac \geq 0 \wedge (2ba \leq 0 \wedge 4ac \geq 0 \vee -2a \leq 0 \wedge 4ac \leq 0$$
$$\vee 2ba \leq 0 \wedge 4ac \geq 0 \vee 2a \leq 0 \wedge 4ac \leq 0)\big)$$

$$-(-b + \sqrt{b^2-4ac})/(2a) = ((-1 + 0\sqrt{b^2-4ac})/1) \cdot ((-b + \sqrt{b^2-4ac})/(2a)$$
$$= (b - \sqrt{b^2-4ac})/(2a)$$

$$(-x \leq 0)^{(b-\sqrt{b^2-4ac})/(2a)}$$
$$\equiv b2a \leq 0 \wedge \cancel{b^2} - (-1)^2(\cancel{b^2} - 4ac) \geq 0 \vee -1 \cdot 2a \leq 0 \wedge \cancel{b^2} - (-1)^2(\cancel{b^2} - 4ac) \leq 0$$
$$\equiv 2ba \leq 0 \wedge 4ac \geq 0 \vee -2a \leq 0 \wedge 4ac \leq 0$$

$$(-x \leq 0)^{(b+\sqrt{b^2-4ac})/(2a)}$$
$$\equiv b2a \leq 0 \wedge \cancel{b^2} - 1^2(\cancel{b^2} - 4ac) \geq 0 \vee 1 \cdot 2a \leq 0 \wedge \cancel{b^2} - 1^2(\cancel{b^2} - 4ac) \leq 0$$
$$\equiv 2ba \leq 0 \wedge 4ac \geq 0 \vee 2a \leq 0 \wedge 4ac \leq 0$$

Outline

Square Root Expression Algebra

Virtual Substitution into Polynomial

Virtually substitute $(a + b\sqrt{c})/d$ into a polynomial p:

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