

Quantifier elimination

Things you already know

Things you already know

It is possible to express that

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c ,

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier.

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

$$\alpha(a, b, c) : ((a \neq 0) \wedge (b^2 - 4ac \geq 0)) \vee ((a = 0) \wedge ((b \neq 0) \vee (c = 0))).$$

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

$$\alpha(a, b, c) : ((a \neq 0) \wedge (b^2 - 4ac \geq 0)) \vee ((a = 0) \wedge ((b \neq 0) \vee (c = 0))).$$

It is possible to express that there exists an inverse to $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ in the ring $M_2(\mathbb{R})$ using quantifiers:

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

$$\alpha(a, b, c) : ((a \neq 0) \wedge (b^2 - 4ac \geq 0)) \vee ((a = 0) \wedge ((b \neq 0) \vee (c = 0))).$$

It is possible to express that there exists an inverse to $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ in the ring $M_2(\mathbb{R})$ using quantifiers:

$$\varphi(a, b, c, d) : (\exists t)(\exists u)(\exists v)(\exists w) \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} t & u \\ v & w \end{bmatrix} = \begin{bmatrix} t & u \\ v & w \end{bmatrix} \cdot \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right)$$

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

$$\alpha(a, b, c) : ((a \neq 0) \wedge (b^2 - 4ac \geq 0)) \vee ((a = 0) \wedge ((b \neq 0) \vee (c = 0))).$$

It is possible to express that there exists an inverse to $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ in the ring $M_2(\mathbb{R})$ using quantifiers:

$$\varphi(a, b, c, d) : (\exists t)(\exists u)(\exists v)(\exists w) \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} t & u \\ v & w \end{bmatrix} = \begin{bmatrix} t & u \\ v & w \end{bmatrix} \cdot \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right)$$

or without:

Things you already know

It is possible to express that

$$\varphi(a, b, c) : (\exists x)(ax^2 + bx + c = 0)$$

is true in the ordered field \mathbb{R} , for a given choice of a, b, c , in a different way that doesn't use a quantifier. Namely,

$$\alpha(a, b, c) : ((a \neq 0) \wedge (b^2 - 4ac \geq 0)) \vee ((a = 0) \wedge ((b \neq 0) \vee (c = 0))).$$

It is possible to express that there exists an inverse to $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ in the ring $M_2(\mathbb{R})$ using quantifiers:

$$\varphi(a, b, c, d) : (\exists t)(\exists u)(\exists v)(\exists w) \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} t & u \\ v & w \end{bmatrix} = \begin{bmatrix} t & u \\ v & w \end{bmatrix} \cdot \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right)$$

or without:

$$\alpha(a, b, c, d) : ad - bc \neq 0.$$

q.e.

q.e.

Definition.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

- 1 The theory of $\langle \mathbb{N}; < \rangle$ in the language of ordered sets.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

- 1 The theory of $\langle \mathbb{N}; < \rangle$ in the language of ordered sets.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

- 1 The theory of $\langle \mathbb{N}; < \rangle$ in the language of ordered sets.
- 2 The theory of the real numbers in the ring/field language.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

- 1 The theory of $\langle \mathbb{N}; < \rangle$ in the language of ordered sets.
- 2 The theory of the real numbers in the ring/field language.

Definition. A theory T has **quantifier elimination** if for every formula $\varphi(\mathbf{x})$ there is a quantifier-free formula $\alpha(\mathbf{x})$ such that

$$T \models (\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow \alpha(\mathbf{x})).$$

Examples.

- 1 The theory of infinite sets in the language of equality.
- 2 The theory of dense linear order in the language of ordered sets.
- 3 The theory of algebraically closed fields in the ring/field language.
- 4 The theory of the real numbers in the language of ordered fields.

Non-examples.

- 1 The theory of $\langle \mathbb{N}; < \rangle$ in the language of ordered sets.
- 2 The theory of the real numbers in the ring/field language.

Why do we care?

Why do we care?

If T has q.e., then

Why do we care?

If T has q.e., then

- 1 $A \leq B$ implies $A \prec B$

Why do we care?

If T has q.e., then

- 1 $A \leq B$ implies $A \prec B$

Why do we care?

If T has q.e., then

- ① $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,

Why do we care?

If T has q.e., then

- ① $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- ② all embeddings between models are elementary,
- ③ easier to check completeness of T :

Why do we care?

If T has q.e., then

- ① $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- ② all embeddings between models are elementary,
- ③ easier to check completeness of T :

Why do we care?

If T has q.e., then

- ① $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- ② all embeddings between models are elementary,
- ③ easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence.

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.
- 4 easier to establish \aleph_0 -categoricity of some T 's:

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.
- 4 easier to establish \aleph_0 -categoricity of some T 's:

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.
- 4 easier to establish \aleph_0 -categoricity of some T 's: any complete theory in a finite relational language which has q.e. and which has an infinite model will be \aleph_0 -categorical.

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.
- 4 easier to establish \aleph_0 -categoricity of some T 's: any complete theory in a finite relational language which has q.e. and which has an infinite model will be \aleph_0 -categorical. (This statement need not be true if T does not have q.e.!)

Why do we care?

If T has q.e., then

- 1 $\mathbf{A} \leq \mathbf{B}$ implies $\mathbf{A} \prec \mathbf{B}$ whenever \mathbf{A} and \mathbf{B} are models of T .
- 2 all embeddings between models are elementary,
- 3 easier to check completeness of T : if there is a constant in the language, check whether the theory decides the truth of every quantifier-free sentence. If no constant, must also check whether the theory decides the truth of $(\exists x)\alpha(x)$ for every q.f., 1-variable, atomic formula $\alpha(x)$, where $T \models (\forall x)(\forall y)(\alpha(x) \leftrightarrow \alpha(y))$.
- 4 easier to establish \aleph_0 -categoricity of some T 's: any complete theory in a finite relational language which has q.e. and which has an infinite model will be \aleph_0 -categorical. (This statement need not be true if T does not have q.e.!)
- 5 becomes easier to classify definable sets in models.

What's language got to do with it?

What's language got to do with it?

How to cheat.

What's language got to do with it?

How to cheat.

The **Morleyization** (or **atomization**) of an L -theory T is the theory T' in an expanded language having a new relation symbol $R_\varphi(x_1, \dots, x_n)$ for every L -formula $\varphi(x_1, \dots, x_n)$ where we add to T the sentences

What's language got to do with it?

How to cheat.

The **Morleyzation** (or **atomization**) of an L -theory T is the theory T' in an expanded language having a new relation symbol $R_\varphi(x_1, \dots, x_n)$ for every L -formula $\varphi(x_1, \dots, x_n)$ where we add to T the sentences

$$(\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow R_\varphi(\mathbf{x})).$$

What's language got to do with it?

How to cheat.

The **Morleyization** (or **atomization**) of an L -theory T is the theory T' in an expanded language having a new relation symbol $R_\varphi(x_1, \dots, x_n)$ for every L -formula $\varphi(x_1, \dots, x_n)$ where we add to T the sentences

$$(\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow R_\varphi(\mathbf{x})).$$

It is obvious that the models of T and T' are essentially the same, and that T' has q.e.

What's language got to do with it?

How to cheat.

The **Morleyization** (or **atomization**) of an L -theory T is the theory T' in an expanded language having a new relation symbol $R_\varphi(x_1, \dots, x_n)$ for every L -formula $\varphi(x_1, \dots, x_n)$ where we add to T the sentences

$$(\forall \mathbf{x})(\varphi(\mathbf{x}) \leftrightarrow R_\varphi(\mathbf{x})).$$

It is obvious that the models of T and T' are essentially the same, and that T' has q.e.

This is of theoretical value, and typically doesn't bypass any practical complications.

The field of real numbers is an interesting example.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement:

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

Macintyre's Theorem.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

Macintyre's Theorem. The only theories of fields with q.e. are the algebraically closed fields.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

Macintyre's Theorem. The only theories of fields with q.e. are the algebraically closed fields. In particular, $\langle \mathbb{R}; +, -, 0, \cdot, 1 \rangle$ does not have q.e.

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

Macintyre's Theorem. The only theories of fields with q.e. are the algebraically closed fields. In particular, $\langle \mathbb{R}; +, -, 0, \cdot, 1 \rangle$ does not have q.e.

Thus every use of a quantifier in a formula for \mathbb{R} can be reduced to

The field of real numbers is an interesting example.

Tarski-Seidenberg Theorem. Implies that the theory of the ordered field $\langle \mathbb{R}; +, -, 0, \cdot, 1, \leq \rangle$ has q.e.

(Theorem statement: The projection of a semialgebraic set $X \subseteq \mathbb{R}^{n+1}$ onto its first n -coordinates is a semialgebraic set in \mathbb{R}^n .)

Macintyre's Theorem. The only theories of fields with q.e. are the algebraically closed fields. In particular, $\langle \mathbb{R}; +, -, 0, \cdot, 1 \rangle$ does not have q.e.

Thus every use of a quantifier in a formula for \mathbb{R} can be reduced to

$$\varphi_{\leq}(x, y) : \quad (\exists z)(y = x + z^2).$$

Methods for establishing q.e.

① BRUTE FORCE!!

① BRUTE FORCE!!

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 \approx

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion \approx

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx \approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx \approx \approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx \approx \approx \approx \approx$

Methods for establishing q.e.

- 1 BRUTE FORCE!! (Requires analysis/classification of the q.f. formulas.)
- 2 $\approx \approx$ gentle \approx persuasion $\approx \approx \approx \approx \approx \approx$

Brute force example

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\bigvee \wedge \pm \text{atomic})$.

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\bigvee \bigwedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\bigvee \bigwedge \pm \text{atomic})$.

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\bigvee \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\bigvee \wedge \pm \text{atomic})$.

But \exists distributes over \bigvee , so it suffices to eliminate $\exists y$ from $(\exists y)(\bigwedge \pm \text{atomic})$.

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1x_{i_1}) \cdots (Q_nx_{i_n})(\bigvee \wedge \pm\text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\bigvee \wedge \pm\text{atomic})$.

But \exists distributes over \bigvee , so it suffices to eliminate $\exists y$ from $(\exists y)(\bigwedge \pm\text{atomic})$.
Such formulas are “primitive formulas”.

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\forall \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\forall \wedge \pm \text{atomic})$.

But \exists distributes over \forall , so it suffices to eliminate $\exists y$ from $(\exists y)(\wedge \pm \text{atomic})$.

Such formulas are “primitive formulas”.

(“primitive” =

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\forall \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\forall \wedge \pm \text{atomic})$.

But \exists distributes over \forall , so it suffices to eliminate $\exists y$ from $(\exists y)(\wedge \pm \text{atomic})$.
Such formulas are “primitive formulas”.

(“primitive” = existential conjunction of \pm atomic.)

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\forall \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\forall \wedge \pm \text{atomic})$.

But \exists distributes over \forall , so it suffices to eliminate $\exists y$ from $(\exists y)(\wedge \pm \text{atomic})$.

Such formulas are “primitive formulas”.

(“primitive” = existential conjunction of \pm atomic.)

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\forall \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\forall \wedge \pm \text{atomic})$.

But \exists distributes over \forall , so it suffices to eliminate $\exists y$ from $(\exists y)(\wedge \pm \text{atomic})$.
Such formulas are “primitive formulas”.

(“primitive” = existential conjunction of \pm atomic.)

“Arrangement” of variables: For some equivalence relation E on $\{1, \dots, n\}$

$$\text{Arr}_E(x_1, \dots, x_n) = \bigwedge_{(i,j) \in E} (x_i = x_j) \wedge \bigwedge_{(i,j) \notin E} \neg(x_i = x_j).$$

Brute force example

The theory T of infinite sets in the language of equality has q.e.

Any formula can be put in the form $(Q_1 x_{i_1}) \cdots (Q_n x_{i_n})(\forall \wedge \pm \text{atomic})$.

To eliminate Q 's, it suffices to eliminate $\exists y$ from $(\exists y)(\forall \wedge \pm \text{atomic})$.

But \exists distributes over \forall , so it suffices to eliminate $\exists y$ from $(\exists y)(\wedge \pm \text{atomic})$.
Such formulas are “primitive formulas”.

(“primitive” = existential conjunction of \pm atomic.)

“Arrangement” of variables: For some equivalence relation E on $\{1, \dots, n\}$

$$\text{Arr}_E(x_1, \dots, x_n) = \bigwedge_{(i,j) \in E} (x_i = x_j) \wedge \bigwedge_{(i,j) \notin E} \neg(x_i = x_j).$$

This is a conjunction of \pm atomic.

Brute force example: more

Brute force example: more

Lemma.

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .)

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$)

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements.

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Let E^* be the restriction of E from $\{x_1, \dots, x_n, y\}$ to $\{x_1, \dots, x_n\}$.

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Let E^* be the restriction of E from $\{x_1, \dots, x_n, y\}$ to $\{x_1, \dots, x_n\}$. Then note that

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Let E^* be the restriction of E from $\{x_1, \dots, x_n, y\}$ to $\{x_1, \dots, x_n\}$. Then note that

$$T \models (\forall \mathbf{x})((\exists y)\text{Arr}_E(\mathbf{x}, y) \leftrightarrow \text{Arr}_{E^*}(\mathbf{x})).$$

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Let E^* be the restriction of E from $\{x_1, \dots, x_n, y\}$ to $\{x_1, \dots, x_n\}$. Then note that

$$T \models (\forall \mathbf{x})((\exists y)\text{Arr}_E(\mathbf{x}, y) \leftrightarrow \text{Arr}_{E^*}(\mathbf{x})).\square$$

Brute force example: more

Lemma. (Classification of q.f. formulas modulo T .) Any q.f. formula is either inconsistent (e.g. $\neg(x_i = x_i)$) or is equivalent to a disjunction of finitely many arrangements. \square

Hence, if $\varphi(\mathbf{x}, y)$ is q.f., $T \models (\forall \mathbf{x})((\exists y)\varphi(\mathbf{x}, y) \leftrightarrow (\exists y)(\bigvee_k \text{Arr}_{E_k}(\mathbf{x}, y)))$.

Hence suffices to eliminate $\exists y$ in $(\exists y)\text{Arr}_E(x_1, \dots, x_n, y)$.

Let E^* be the restriction of E from $\{x_1, \dots, x_n, y\}$ to $\{x_1, \dots, x_n\}$. Then note that

$$T \models (\forall \mathbf{x})((\exists y)\text{Arr}_E(\mathbf{x}, y) \leftrightarrow \text{Arr}_{E^*}(\mathbf{x})).\square$$

A brute force argument that DLO has q.e. can be modeled on this one.