Equivalences with quantifiers

Renaming bound variables

Bound variables

$$\forall_x[P{:}Q] \stackrel{val}{=} \forall_y[P[y/x]{:}Q[y/x]]$$

$$\exists_x[P{:}Q] \stackrel{val}{=} \exists_y[P[y/x]{:}Q[y/x]]$$

if y does not occur in
P or Q (not even in ∀y, ∃y)

Domain splitting

Examples:

$$\forall_x[x \leqslant 1 \vee x \geqslant 5\colon x^2 - 6x + 5 \geqslant 0]$$
$$\overset{val}{=} \forall_x[x \leqslant 1\colon x^2 - 6x + 5 \geqslant 0] \wedge \forall_x[x \geqslant 5\colon x^2 - 6x + 5 \geqslant 0]$$

Domain splitting

Examples:

$$\forall_x[x \leqslant 1 \vee x \geqslant 5\colon x^2 - 6x + 5 \geqslant 0]$$
$$\stackrel{val}{=} \forall_x[x \leqslant 1\colon x^2 - 6x + 5 \geqslant 0] \wedge \forall_x[x \geqslant 5\colon x^2 - 6x + 5 \geqslant 0]$$

$$\exists_k[0 \leqslant k \leqslant n : k^2 \leqslant 10]$$
$$\stackrel{val}{=} \exists_k[0 \leqslant k \leqslant n-1 \vee k = n : k^2 \leqslant 10]$$
$$\stackrel{val}{=} \exists_k[0 \leqslant k \leqslant n-1 : k^2 \leqslant 10] \vee \exists_k[k = n : k^2 \leqslant 10]$$

Domain splitting

Examples:

$$\begin{aligned} & \forall_x[x \leqslant 1 \vee x \geqslant 5 \colon x^2 - 6x + 5 \geqslant 0] \\ \overset{val}{=} \; & \forall_x[x \leqslant 1 \colon x^2 - 6x + 5 \geqslant 0] \wedge \forall_x[x \geqslant 5 \colon x^2 - 6x + 5 \geqslant 0] \end{aligned}$$

$$\begin{aligned} & \exists_k[0 \leqslant k \leqslant n : k^2 \leqslant 10] \\ \overset{val}{=} \; & \exists_k[0 \leqslant k \leqslant n-1 \vee k = n : k^2 \leqslant 10] \\ \overset{val}{=} \; & \exists_k[0 \leqslant k \leqslant n-1 : k^2 \leqslant 10] \vee \exists_k[k = n : k^2 \leqslant 10] \end{aligned}$$

Domain splitting

$$\forall_x[P \vee Q : R] \overset{val}{=} \forall_x[P : R] \wedge \forall_x[Q : R]$$

$$\exists_x[P \vee Q : R] \overset{val}{=} \exists_x[P : R] \vee \exists_x[Q : R]$$

Equivalences with quantifiers

One-element domain

$$\forall_x[x = n\colon Q] \overset{val}{=} Q[n/x]$$

$$\exists_x[x = n\colon Q] \overset{val}{=} Q[n/x]$$

Equivalences with quantifiers

One-element domain

$$\forall_x[x = n : Q] \stackrel{val}{=} Q[n/x]$$

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Example:

$$\forall_x[x = 3 : 2 \cdot x \geqslant 1] \stackrel{val}{=} 2 \cdot 3 \geqslant 1$$

Equivalences with quantifiers

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Example:

$$\forall_x[x = 3 : 2 \cdot x \geqslant 1] \stackrel{val}{=} 2 \cdot 3 \geqslant 1$$

Empty domain

$$\forall_x[F : Q] \stackrel{val}{=} T$$

$$\exists_x[F : Q] \stackrel{val}{=} F$$

Equivalences with quantifiers

One-element domain

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Empty domain

$$\forall_x[F : Q] \stackrel{val}{=} T$$

$$\exists_x[F : Q] \stackrel{val}{=} F$$

"All Marsians are green"

Domain weakening

Intuition: The following are equivalent

$$\forall_x [x \in D : A(x)] \quad \text{and} \quad \forall_x [x \in D \Rightarrow A(x)]$$
$$\exists_x [x \in D : A(x)] \quad \text{and} \quad \exists_x [x \in D \land A(x)]$$

The same can be done to parts of the domain

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The same can be done to parts of the domain

Domain weakening

$$\forall_x[P \wedge Q : R] \stackrel{val}{=} \forall_x[P : Q \Rightarrow R]$$
$$\exists_x[P \wedge Q : R] \stackrel{val}{=} \exists_x[P : Q \wedge R]$$

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$$\forall_x[P \wedge Q : R] \overset{val}{=} \forall_x[P : Q \Rightarrow R]$$
$$\exists_x[P \wedge Q : R] \overset{val}{=} \exists_x[P : Q \wedge R]$$

$$P \wedge Q \overset{val}{\models} P$$

De Morgan with quantifiers

De Morgan

$$\neg\forall_x[P:Q] \stackrel{val}{=} \exists_x[P:\neg Q]$$
$$\neg\exists_x[P:Q] \stackrel{val}{=} \forall_x[P:\neg Q]$$

De Morgan with quantifiers

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not for all = at least for one not

not exists = for all not

De Morgan with quantifiers

De Morgan

$$\neg \forall_x [P : Q] \stackrel{val}{=} \exists_x [P : \neg Q]$$
$$\neg \exists_x [P : Q] \stackrel{val}{=} \forall_x [P : \neg Q]$$

not for all = at least for one not

not exists = for all not

Hence: $\neg\forall = \exists\neg$ and $\neg\exists = \forall\neg$

De Morgan with quantifiers

De Morgan

$$\neg\forall_x[P:Q] \overset{val}{=} \exists_x[P:\neg Q]$$
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not for all = at least for one not

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Hence: $\neg\forall = \exists\neg$ and $\neg\exists = \forall\neg$

It holds further that:

$$\neg\forall_x\neg = \exists_x\neg\neg = \exists_x$$
$$\neg\exists_x\neg = \forall_x\neg\neg = \forall_x$$

Substitution

meta rule

Simple

$$\frac{\phi \overset{val}{=} \psi}{\phi[\xi/P] \overset{val}{=} \psi[\xi/P]}$$

EVERY occurrence of P is substituted!

Sequential

$$\frac{\phi \overset{val}{=} \psi}{\phi[\xi/P][\eta/Q] \overset{val}{=} \psi[\xi/P][\eta/Q]}$$

Simultaneous

$$\frac{\phi \overset{val}{=} \psi}{\phi[\xi/P, \eta/Q] \overset{val}{=} \psi[\xi/P, \eta/Q]}$$

Substitution

holds also for quantified formulas!

meta rule

Simple

$$\frac{\phi \stackrel{val}{=} \psi}{\phi[\xi/P] \stackrel{val}{=} \psi[\xi/P]}$$

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$$\frac{\phi \stackrel{val}{=} \psi}{\phi[\xi/P, \eta/Q] \stackrel{val}{=} \psi[\xi/P, \eta/Q]}$$

The rule of Leibnitz

meta rule

Leibnitz

$$\frac{\phi \stackrel{val}{=} \psi}{C[\phi] \stackrel{val}{=} C[\psi]}$$

formula that has ϕ as a sub formula

single occurrence is replaced!

The rule of Leibnitz

holds also for quantified formulas!

meta rule

Leibnitz

$$\frac{\phi \overset{val}{=} \psi}{C[\phi] \overset{val}{=} C[\psi]}$$

formula that has ϕ as a sub formula

single occurrence is replaced!

Other equivalences with quantifiers

Exchange trick

$$\forall_x[P{:}Q] \stackrel{val}{=} \forall_x[\neg Q{:}\neg P]$$

$$\exists_x[P{:}Q] \stackrel{val}{=} \exists_x[Q{:}P]$$

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$$\exists_x[P{:}Q] \stackrel{val}{=} \exists_x[Q{:}P]$$

No wonder as

$$\forall_x[P{:}Q] \stackrel{val}{=} \forall_x[P \Rightarrow Q]$$

$$\exists_x[P{:}Q] \stackrel{val}{=} \exists_x[P \wedge Q]$$

Other equivalences with quantifiers

Exchange trick

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$$\exists_x[P{:}Q] \overset{val}{=} \exists_x[P \wedge Q]$$

Term splitting

$$\forall_x[P{:}Q \wedge R] \overset{val}{=} \forall_x[P{:}Q] \wedge \forall_x[P{:}R]$$

$$\exists_x[P{:}Q \vee R] \overset{val}{=} \exists_x[P{:}Q] \vee \exists_x[P{:}R]$$

Other equivalences with quantifiers

Monotonicity of quantifiers

$$\forall_x[P{:}Q \Rightarrow R] \Rightarrow (\forall_x[P{:}Q] \Rightarrow \forall_x[P{:}R]) \overset{val}{=} T$$

$$\forall_x[P{:}Q \Rightarrow R] \Rightarrow (\exists_x[P{:}Q] \Rightarrow \exists_x[P{:}R]) \overset{val}{=} T$$

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tautologies

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tautologies

Lemma E1: $P \overset{val}{=} Q$ iff $P \Leftrightarrow Q$ is a tautology.

Other equivalences with quantifiers

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tautologies

Lemma E1: $P \stackrel{val}{=} Q$ iff $P \Leftrightarrow Q$ is a tautology.

Lemma W4: $P \stackrel{val}{\models} Q$ iff $P \Rightarrow Q$ is a tautology.

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still hold (in predicate logic)

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Lemma W4: $P \stackrel{val}{\models} Q$ iff $P \Rightarrow Q$ is a tautology.

still hold (in predicate logic)

Lemma W5: If $Q \stackrel{val}{\models} R$ then $\forall_x[P{:}Q] \stackrel{val}{\models} \forall_x[P{:}R]$.

Derivations / Reasoning

Limitations of proofs by calculation

Proofs by calculation are formal and well-structured, but often undirected and not particularly intuitive.

Example

$$
\begin{aligned}
P \wedge (P \vee Q) &\overset{val}{=} (P \vee F) \wedge (P \vee Q) \\
&\overset{val}{=} P \vee (F \wedge Q) \\
&\overset{val}{=} P \vee F \\
&\overset{val}{=} P
\end{aligned}
$$

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Conclusions

$P \wedge (P \vee Q) \overset{val}{=} P$ $\quad$ $P \wedge (P \vee Q) \Leftrightarrow P \overset{val}{=} T$

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Conclusions

$P \wedge (P \vee Q) \overset{val}{=} P$ $\quad$ $P \wedge (P \vee Q) \Leftrightarrow P \overset{val}{=} T$

we can prove this more intuitively by reasoning

An example of a mathematical proof

Theorem

If x^2 is even, then x is even ($x \in \mathbb{Z}$).

Proof

Let $x \in \mathbb{Z}$ be such that x^2 is even.

We need to prove that x is even too.

Assume that x is odd, towards a contradiction.

If x is odd than $x = 2y+1$ for some $y \in \mathbb{Z}$.

Then $x^2 = (2y+1)^2 = 4y^2 + 4y + 1 = 2(2y^2 + 2y) + 1$
and $2y^2 + 2y \in \mathbb{Z}$.

So, x^2 is odd too, and we have a contradiction.

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pure hypothesis

An example of a mathematical proof

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and $2y^2 + 2y \in \mathbb{Z}$.

So, x^2 is odd too, and we have a contradiction.

(sub)goal

generating hypothesis

pure hypothesis

conclusion

Thanks to Bas Luttik

Exposing logical structure

Theorem

If x^2 is even, then x is even ($x \in \mathbb{Z}$).

Proof

Let $x \in \mathbb{Z}$

Assume x^2 is even.

Assume that x is odd.

Then $x = 2y+1$ for some $y \in \mathbb{Z}$.

Then $x^2 = (2y+1)^2 = 4y^2 + 4y + 1 = 2(2y^2 + 2y) + 1$ and $2y^2 + 2y \in \mathbb{Z}$.

So, x^2 is odd

a contradiction.

So, x is even

(sub)goal

generating hypothesis

pure hypothesis

conclusion

Thanks to Bas Luttik

Single inference rule

Q is a correct conclusion from n premises $P_1, .., P_n$

iff

$$(P_1 \wedge P_2 \wedge \ldots \wedge P_n) \overset{val}{\models} Q$$

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Note that $T \vDash Q$ means that $Q \overset{val}{=} T$

Single inference rule

Q is a correct conclusion from n premises $P_1, .., P_n$
iff
$(P_1 \wedge P_2 \wedge \ldots \wedge P_n) \overset{val}{\models} Q$

If n=0, then $P_1 \wedge P_2 \wedge \ldots \wedge P_n \overset{val}{=} T$

Note that $T \models Q$ means that $Q \overset{val}{=} T$

Q holds unconditionally

Derivation

Q is a correct conclusion from n premises $P_1, .., P_n$

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a formal system
based on the single
inference rule
for proofs that closely
follow our
intuitive reasoning

Derivation

a formal system based on the single inference rule for proofs that closely follow our intuitive reasoning

Q is a correct conclusion from n premises $P_1, .., P_n$
iff
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Two types of inference rules:

elimination rules

introduction rules

Derivation

a formal system based on the single inference rule for proofs that closely follow our intuitive reasoning

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Two types of inference rules:

(particularly useful) instances of the single inference rule

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a formal system based on the single inference rule for proofs that closely follow our intuitive reasoning

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Two types of inference rules:

(particularly useful) instances of the single inference rule

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and one new special rule!

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Two types of inference rules:

(particularly useful) instances of the single inference rule

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Derivation

a formal system based on the single inference rule for proofs that closely follow our intuitive reasoning

Q is a correct conclusion from n premises $P_1, .., P_n$
iff
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Two types of inference rules:

(particularly useful) instances of the single inference rule

elimination rules

for drawing conclusions out of premises

introduction rules

for simplifying goals

and one new special rule!

Conjunction elimination

How do we use a conjunction in a proof?

Conjunction elimination

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$$P \wedge Q \overset{val}{\models} P$$

$$P \wedge Q \overset{val}{\models} Q$$

Conjunction elimination

How do we use a conjunction in a proof?

$P \wedge Q \overset{val}{\models} P$

$P \wedge Q \overset{val}{\models} Q$

|| ||

(k) $P \wedge Q$

|| ||

{$\wedge$-elim on (k)}

(m) P

(k < m)

Conjunction elimination

How do we use a conjunction in a proof?

$P \wedge Q \overset{val}{\models} P$

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|| ||

(k) $P \wedge Q$

|| ||

{∧-elim on (k)}

(m) P

$(k < m)$

|| ||

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Conjunction elimination

How do we use a conjunction in a proof?

$P \wedge Q \overset{val}{\models} P$

$P \wedge Q \overset{val}{\models} Q$

$\wedge$-elimination

|| ||

(k) $P \wedge Q$

|| ||

{$\wedge$-elim on (k)}
(m) P

(k < m)

|| ||

(k) $P \wedge Q$

|| ||

{$\wedge$-elim on (k)}
(m) Q

(k < m)

Implication elimination

How do we use an implication in a proof?

Implication elimination

How do we use an implication in a proof?

$P \Rightarrow Q \overset{val}{\models} ???$

$(P \Rightarrow Q) \wedge P \overset{val}{\models} Q$

Implication elimination

How do we use an implication in a proof?

$P \Rightarrow Q \overset{val}{\models}$???

$(P \Rightarrow Q) \wedge P \overset{val}{\models} Q$

|| ||

(k) $P \Rightarrow Q$

|| ||

(l) P

|| ||

{$\Rightarrow$-elim on (k) and (l)}

(m) Q

$(k < m, l < m)$

Implication elimination

How do we use an implication in a proof?

$P \Rightarrow Q \overset{val}{\models}$???

$(P \Rightarrow Q) \wedge P \overset{val}{\models} Q$

⇒-elimination

|| ||

(k) $P \Rightarrow Q$

|| ||

(l) P

|| ||

{⇒-elim on (k) and (l)}

(m) Q

$(k < m, l < m)$

Conjunction introduction

How do we prove a conjunction?

Conjunction introduction

How do we prove a conjunction?

$P \land Q \overset{\text{val}}{\models} P \land Q$

Conjunction introduction

How do we prove a conjunction?

$P \wedge Q \overset{val}{\models} P \wedge Q$

$\ldots$

(k) P

$\ldots$

(l) Q

$\ldots$

$\{\wedge$-intro on (k) and (l)$\}$

(m) $P \wedge Q$

($k < m, l < m$)

Conjunction introduction

How do we prove a conjunction?

$P \wedge Q \overset{val}{\models} P \wedge Q$

$\wedge$-introduction

...

(k) P

...

(l) Q

...

{$\wedge$-intro on (k) and (l)}

(m) $P \wedge Q$

($k < m$, $l < m$)

Implication introduction

How do we prove an implication?

Implication introduction

How do we prove an implication?

…
{Assume}
(k) $\boxed{P}$

…

(l-1) Q
{⇒-intro on (k) and (l-1)}
(l) P⇒Q

Implication introduction

How do we prove an implication?

⇒-introduction

...

{Assume}

(k) $\boxed{P}$

...

(l-1) Q

{⇒-intro on (k) and (l-1)}

(l) P⇒Q

Implication introduction

How do we prove an implication?

⇒-introduction

…

{Assume}

(k) $\boxed{P}$

…

(l-1) Q

{⇒-intro on (k) and (l-1)}

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flag shows the validity of a hypothesis

Implication introduction

How do we prove an implication?

truly new
and
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hypothesis

⇒-introduction

$$
\begin{array}{ll}
 & \ldots \\
 & \{\text{Assume}\} \\
(k) & \boxed{P} \\
 & \ldots \\
(l\text{-}1) & Q \\
 & \{\Rightarrow\text{-intro on } (k) \text{ and } (l\text{-}1)\} \\
(l) & P \Rightarrow Q
\end{array}
$$

flag shows the validity of a hypothesis

Implication introduction

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time for an example!