

# Proof Theory: Logical and Philosophical Aspects

## Class 5: Semantics and beyond

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To introduce *proof theory*, with a focus in its applications in philosophy, linguistics and computer science.

Examine the behaviour of quantifiers  
from the perspective of proof theory.

## Today's Plan

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First-Order Predicate Logic

Free Logic

Quantified Modal Logic

Other Topics

# FIRST-ORDER PREDICATE LOGIC

# Quantifier Derivations

$$\frac{\frac{Fa \succ Fa}{\forall x Fx \succ Fa} [\forall L] \quad \frac{\frac{Ga \succ Ga}{\forall x Gx \succ Ga} [\forall L]}{\forall x Fx, \forall x Gx \succ Fa \wedge Ga} [\wedge R]$$
$$\frac{\forall x Fx \wedge \forall x Gx \succ Fa \wedge Ga}{\forall x Fx \wedge \forall x Gx \succ \forall x (Fx \wedge Gx)} [\wedge L]$$
$$\frac{\forall x Fx \wedge \forall x Gx \succ \forall x (Fx \wedge Gx)}{\forall x Fx \wedge \forall x Gx \succ \forall x (Fx \wedge Gx)} [\forall R]$$

# Quantifier Derivations

$$\begin{array}{c} \frac{Fa \succ Fa}{Fa \succ \exists x Fx} [\exists R] \quad \frac{Ga \succ Ga}{Ga \succ \exists x Gx} [\exists R] \\ \hline Fa \vee Ga \succ \exists x Fx, \exists x Gx \quad [\vee L] \\ \hline Fa \vee Ga \succ \exists x Fx \vee \exists x Gx \quad [\vee R] \\ \hline \exists x(Fx \vee Gx) \succ \exists x Fx \vee \exists x Gx \quad [\exists L] \end{array}$$

# Quantifier Derivations

$$\begin{array}{c} \frac{Fa \succ Fa \quad Ga \succ Ga}{Fa \vee Ga \succ Fa, Ga} [\vee I] \\ \frac{Fa \vee Ga \succ Fa, Ga}{\forall x(Fx \vee Gx) \succ Fa, Ga} [\vee L] \\ \frac{\forall x(Fx \vee Gx) \succ Fa, Ga}{\forall x(Fx \vee Gx) \succ Fa, \exists x Gx} [\exists R] \\ \frac{\forall x(Fx \vee Gx) \succ Fa, \exists x Gx}{\forall x(Fx \vee Gx) \succ \forall x Fx, \exists x Gx} [\forall R] \\ \frac{\forall x(Fx \vee Gx) \succ \forall x Fx, \exists x Gx}{\forall x(Fx \vee Gx) \succ \forall x Fx \vee \exists x Gx} [\vee R] \end{array}$$



# Quantifier Rules

$$\text{(any } t) \frac{X, A(t) \succ Y}{X, \forall x A(x) \succ Y} [\forall L]$$

$$\text{(n fresh)} \frac{X, A(n) \succ Y}{X, \exists x A(x) \succ Y} [\exists L]$$

$$\text{(n fresh)} \frac{X \succ A(n), Y}{X \succ \forall x A(x), Y} [\forall R]$$

$$\text{(any } t) \frac{X \succ A(t), Y}{X \succ \exists x A(x), Y} [\exists R]$$

In  $[\forall R]$  and  $[\exists L]$ , the condition that  $n$  is fresh means that  $n$  is an *eigenvariable*, not occurring in  $X$  and  $Y$ .

# What is an eigenvariable?

An eigenvariable is a singular term  $n$   
that is *inferentially general*.

That is, if  $\pi(n)$  is a derivation of  $X(n) \succ Y(n)$ ,  
then for any term  $t$ ,  $\pi(t)$  is a derivation of  $X(t) \succ Y(t)$   
(where we have replaced  $n$  by  $t$  through all the ancestors  
of each  $n$  occurring in  $X(n) \succ Y(n)$  through  $\pi(n)$ .)

## Isn't every term inferentially general?

- ▶ Function terms aren't.

We can prove  $(\exists x)(fx = \underline{fn})$ , but not  $(\exists x)(fx = t)$  for arbitrary  $t$ .

- ▶ In sequent presentations of *theories*, constants can be inferentially specific. For example, in PA we can prove  $(\forall x)(0 \neq x')$  but not  $(\forall x)(t \neq x')$ .

# The Point of Inferential Generality: Eliminating Cut

$$\begin{array}{c}
 \begin{array}{c} \vdots \delta_l(n) \\ X \succ A(n), Y \end{array} \quad \begin{array}{c} \vdots \delta_r \\ X, A(t) \succ Y \end{array} \\
 \hline
 \begin{array}{c} X \succ \forall x A(x), Y \end{array} \quad \begin{array}{c} X, \forall x A(x) \succ Y \end{array} \quad \begin{array}{c} [\forall R] \quad [\forall L] \end{array} \\
 \hline
 X \succ Y \quad [\text{Cut}]
 \end{array}$$

We need to transform  $\delta_l(n)$  into a proof of  $X \succ A(t), Y$  in order to simplify the Cut.

$$\begin{array}{c}
 \begin{array}{c} \vdots \delta_l(t) \\ X \succ A(t), Y \end{array} \quad \begin{array}{c} \vdots \delta_r \\ X, A(t) \succ Y \end{array} \\
 \hline
 X \succ Y \quad [\text{Cut}]
 \end{array}$$

# FREE LOGIC

# Non-Denoting Terms

$$\frac{1}{0} \quad \lim_{x \rightarrow 0} \frac{\sin x}{x} \quad \sum_{n=0}^{\infty} f(n)$$

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*Pegasus*

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It is difficult to eliminate non-denoting terms as a matter of *syntax*.

$$(\forall x)(x < 0 \vee x = 0 \vee x > 0) \not\equiv (\frac{1}{0} < 0 \vee \frac{1}{0} = 0 \vee \frac{1}{0} > 0)$$

# Non-Denoting Terms

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It is difficult to eliminate non-denoting terms as a matter of *syntax*.

$$(\forall x)(x < 0 \vee x = 0 \vee x > 0) \not\equiv (\frac{1}{0} < 0 \vee \frac{1}{0} = 0 \vee \frac{1}{0} > 0)$$

How can we modify the quantifier rules  
to allow for non-denoting terms?

## *Pro* and *Con* attitudes to Terms

To rule a term *in* is to take it as suitable  
to substitute into a quantifier,  
i.e., to take the term to *denote*.

To rule a term *out* is to take it as unsuitable  
to substitute into a quantifier,  
i.e., to take the term to *not denote*.

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to substitute into a quantifier,  
i.e., to take the term to *not denote*.

We add terms to the LHS and RHS of sequents  $X \succ Y$ .

## Structural Rules remain as before

$$\star \succ \star \text{ [Id]}$$

$$\frac{X \succ Y}{X, \star \succ Y} \text{ [KL]}$$

$$\frac{X \succ Y}{X \succ \star, Y} \text{ [KR]}$$

$$\frac{X, \star, \star \succ Y}{X, \star \succ Y} \text{ [WL]}$$

$$\frac{X \succ \star, \star, Y}{X \succ \star, Y} \text{ [WR]}$$

$$\frac{X \succ \star, Y \quad X, \star \succ Y}{X \succ Y} \text{ [Cut]}$$

Here  $\star$  is either a *sentence* or a *term*.

# Modified Quantifier Rules

$$\text{(any } t) \frac{X, A(t) \succ Y \quad X \succ t, Y}{X, \forall x A(x) \succ Y} [\forall L]$$

$$\text{(n fresh)} \frac{X, n, A(n) \succ Y}{X, \exists x A(x) \succ Y} [\exists L]$$

$$\text{(n fresh)} \frac{X, n \succ A(n), Y}{X \succ \forall x A(x), Y} [\forall R]$$

$$\text{(any } t) \frac{X \succ A(t), Y \quad X \succ t, Y}{X \succ \exists x A(x), Y} [\exists R]$$

In  $[\forall R]$  and  $[\exists L]$ , the condition that  $n$  is fresh means that  $n$  is an *eigenvariable*, not occurring in  $X$  and  $Y$ .

# Making Denotation Explicit

$$\frac{X, t \succ Y}{X, t \downarrow \succ Y} [\downarrow L]$$

$$\frac{X \succ t, Y}{X \succ t \downarrow, Y} [\downarrow R]$$

# Example Derivations

$$\begin{array}{c}
 \frac{Fn, n \succ Fn \quad Gn \succ Gn}{Fn \supset Gn, n, Fn \succ Gn} [\supset L] \quad \frac{Fn \supset Gn, n, Fn \succ n}{\forall x(Fx \supset Gx), n, Fn \succ Gn} [\forall L] \quad \frac{\forall x(Fx \supset Gx), n, Fn \succ n}{\forall x(Fx \supset Gx), n, Fn \succ \exists x Gx} [\forall R] \\
 \frac{\forall x(Fx \supset Gx), n, Fn \succ \exists x Gx}{\forall x(Fx \supset Gx), \exists x Fx \succ \exists x Gx} [\exists L] \\
 \frac{\forall x(Fx \supset Gx), \exists x Fx \succ \exists x Gx}{\forall x(Fx \supset Gx) \succ \exists x Fx \supset \exists x Gx} [\supset R]
 \end{array}$$



# Example Derivations

$$\frac{\frac{Ft \succ Ft \quad t \succ t}{\forall x Fx, t \succ Ft} [\forall L]}{\forall x Fx, t \downarrow \succ Ft} [\downarrow L]$$

SOLOMON FEFERMAN\*

## DEFINEDNESS

**ABSTRACT.** Questions of definedness are ubiquitous in mathematics. Informally, these involve reasoning about expressions which may or may not have a value. This paper surveys work on logics in which such reasoning can be carried out directly, especially in computational contexts. It begins with a general logic of “partial terms”, continues with partial combinatory and lambda calculi, and concludes with an expressively rich theory of partial functions and polymorphic types, where termination of functional programs can be established in a natural way.

*Erkenntnis* 43: 295–320, 1995.

# Definedness, function terms and predicates

$$\frac{t_i, X \succ Y}{f(t_1, \dots, t_n), X \succ Y} \text{ [fL]}$$

$$\frac{t_i, X \succ Y}{Ft_1 \dots t_n, X \succ Y} \text{ [FL]}$$

A MODEL for the logic DL is a structure  $\mathfrak{M}$  consisting of

1. A *domain*  $D$ .
2. An  $n$ -ary predicate  $F$  is interpreted as a subset  $F^{\mathfrak{M}}$  of  $D^n$  (as usual).
3. An  $n$ -ary function symbol  $f$  is interpreted as a *partial function*  $f^{\mathfrak{M}} : D^n \rightharpoonup D$ .

# Assigning Values

- ▶  $\alpha$  is a (partial) assignment of values to variables.
- ▶  $\llbracket x \rrbracket_{\mathfrak{M}, \alpha} = \alpha(x)$
- ▶  $\llbracket f(t_1, \dots, t_n) \rrbracket_{\mathfrak{M}, \alpha} = f^{\mathfrak{M}}(\llbracket t_1 \rrbracket_{\mathfrak{M}, \alpha}, \dots, \llbracket t_n \rrbracket_{\mathfrak{M}, \alpha})$  if each  $\llbracket t_i \rrbracket_{\mathfrak{M}, \alpha}$  is defined, and  $f^{\mathfrak{M}}$  is defined on the inputs  $\llbracket t_1 \rrbracket_{\mathfrak{M}, \alpha}, \dots, \llbracket t_n \rrbracket_{\mathfrak{M}, \alpha}$ .

# Interpreting a Language

- ▶  $\mathfrak{M} \models_{\alpha} t \downarrow$  iff  $\llbracket t \rrbracket_{\mathfrak{M}, \alpha}$  is defined.
- ▶  $\mathfrak{M} \models_{\alpha} Ft_1 \cdots t_n$  iff for each  $i$ , the value  $\llbracket t_i \rrbracket_{\mathfrak{M}, \alpha}$  is defined, and the  $n$ -tuple  $\langle \llbracket t_1 \rrbracket_{\mathfrak{M}, \alpha}, \dots, \llbracket t_n \rrbracket_{\mathfrak{M}, \alpha} \rangle \in F^{\mathfrak{M}}$
- ▶  $\mathfrak{M} \models_{\alpha} A \wedge B$  iff  $\mathfrak{M} \models_{\alpha} A$  and  $\mathfrak{M} \models_{\alpha} B$ .
- ▶  $\mathfrak{M} \models_{\alpha} A \vee B$  iff  $\mathfrak{M} \models_{\alpha} A$  or  $\mathfrak{M} \models_{\alpha} B$ .
- ▶  $\mathfrak{M} \models_{\alpha} A \supset B$  iff  $\mathfrak{M} \not\models_{\alpha} A$  or  $\mathfrak{M} \models_{\alpha} B$ .
- ▶  $\mathfrak{M} \models_{\alpha} \neg A$  iff  $\mathfrak{M} \not\models_{\alpha} A$ .
- ▶  $\mathfrak{M} \models_{\alpha} (\forall x)A(x)$  iff  $\mathfrak{M} \models_{\alpha[x:=d]} A(x)$  for every  $d$  in  $D$ .
- ▶  $\mathfrak{M} \models_{\alpha} (\exists x)A(x)$  iff  $\mathfrak{M} \models_{\alpha[x:=d]} A(x)$  for some  $d$  in  $D$ .

# Eliminating Cut

$$\frac{\displaystyle \frac{\vdots \delta_l(n)}{X, n \succ A(n), Y} [\forall R] \quad \displaystyle \frac{\displaystyle \frac{\vdots \delta_r}{X, A(t) \succ Y} \quad \vdots \delta'_r}{X, \forall x A(x) \succ Y} [\forall L]}{X \succ Y} [\text{Cut}]$$

simplifies to

$$\frac{\displaystyle \frac{\vdots \delta'_r}{X \succ t, Y} \quad \displaystyle \frac{\displaystyle \frac{\vdots \delta_l(t)}{X, t \succ A(t), Y} \quad \vdots \delta_r}{X, t \succ Y} [\text{Cut}]}{X \succ Y} [\text{Cut}]$$

# QUANTIFIED MODAL LOGIC



# Flat hypersequents

A *flat hypersequent* is a non-empty multiset of sequents.

$$X_1 \succ Y_1 \mid X_2 \succ Y_2 \mid \cdots \mid X_n \succ Y_n$$

# Modal Rules

$$\frac{\mathcal{H}[X \succ Y \mid X', A \succ Y']}{\mathcal{H}[X, \Box A \succ Y \mid X' \succ Y']} [\Box L]$$

$$\frac{\mathcal{H}[X', A \succ Y']}{\mathcal{H}[X', \Box A \succ Y']} [\Box L]$$

$$\frac{\mathcal{H}[X \succ Y \mid X' \succ A, Y']}{\mathcal{H}[X \succ \Diamond A, Y \mid X' \succ Y']} [\Diamond R]$$

$$\frac{\mathcal{H}[X' \succ A, Y']}{\mathcal{H}[X' \succ \Diamond A, Y']} [\Diamond R]$$

$\mathcal{H}[X \succ Y \mid X' \succ Y']$  is a hypersequent  
in which  $X \succ Y$  and  $X' \succ Y'$  are components.

# Deriving the Barcan Formula

$$\begin{array}{c} \frac{Fn \succ Fn}{\Box Fn \succ | \succ Fn} [\Box L] \\ \frac{\Box Fn \succ | \succ Fn}{\forall x \Box Fx \succ | \succ Fn} [\forall L] \\ \frac{\forall x \Box Fx \succ | \succ Fn}{\forall x \Box Fx \succ | \succ \forall x Fx} [\forall R] \\ \frac{\forall x \Box Fx \succ | \succ \forall x Fx}{\forall x \Box Fx \succ \Box \forall x Fx} [\Box R] \\ \frac{\forall x \Box Fx \succ \Box \forall x Fx}{\succ \forall x \Box Fx \supset \Box \forall x Fx} [\supset R] \end{array}$$

This derivation is blocked if we use the rules from free logic

$$\frac{\frac{\frac{Fn \succ Fn}{\Box Fn \succ \mid \succ Fn} [\Box L] \quad n \succ n \mid \succ}{\forall x \Box Fx, n \succ \mid \succ Fn} [\forall L]}{\forall x \Box Fx \succ \mid \succ \forall x Fx} [??]$$

The term  $n$  is in the wrong component for the derivation to go through

Weakening a copy of  $n$  into the right component will violate the eigenvariable condition on  $[\forall R]$

## Migration rules

The addition of these rules would permit the derivation of the Barcan formula

$$\frac{\mathcal{H}[t, X \succ Y \mid X' \succ Y']}{\mathcal{H}[X \succ Y \mid t, X' \succ Y']} \text{ [MigrateL]}$$

$$\frac{\mathcal{H}[X \succ Y, t \mid X' \succ Y']}{\mathcal{H}[X \succ Y \mid X' \succ Y', t]} \text{ [MigrateR]}$$

But why think *these* rules should be adopted?

# Unrestricted quantifiers

$$(\text{any } t) \frac{\mathcal{H}[X, A(t) \succ Y]}{\mathcal{H}[X, \Pi x A(x) \succ Y]} [\Pi L]$$

$$(n \text{ fresh}) \frac{\mathcal{H}[X, A(n) \succ Y]}{\mathcal{H}[X, \Sigma x A(x) \succ Y]} [\Sigma L]$$

$$(n \text{ fresh}) \frac{\mathcal{H}[X \succ Y, A(n)]}{\mathcal{H}[X \succ Y, \Pi x A(x)]} [\Pi R]$$

$$(\text{any } t) \frac{\mathcal{H}[X \succ Y, A(t)]}{\mathcal{H}[X \succ Y, \Sigma x A(x)]} [\Sigma R]$$

# Unrestricted quantifiers

The derivation of the Barcan formula will go through with these rules

But, one can also derive  $\succ \Sigma x (\frac{1}{0} = x)$

Does this vindicate Meinongian views about existence?

There are other possible ways to adjust the quantifier rules, such as permitting the term  $n$  in  $[\forall R]$  to appear in *some* zone

# OTHER TOPICS



We have not introduced rules that deal much with terms occurring in formulas

Let's look at Identity rules

## Left rules

The left rules for identity are fairly straightforward

$$\frac{X, \phi(a) \succ Y}{X, a = b, \phi(b) \succ Y} [= L]$$

$$\frac{X \succ Y, \phi(a)}{X, a = b \succ Y, \phi(b)} [= L]$$

The identity on the right rule is a bit trickier

## Right rule

The natural idea is

$$\frac{X, \phi(a) \succ \phi(b), Y \quad X, \phi(b) \succ \phi(a), Y}{X \succ Y, a = b} [= R?]$$

This presupposes that if  $a$  is not identical to  $b$ , then there is formula,  $\phi$ , that can distinguish them

One's present vocabulary may not be up to that task

## Right rule done right

The solution to the problem is to recognize that identity is a higher-order notion

Use schematic letters, here  $G$ , as a way to consider possible extensions of the language

$$(F \text{ fresh}) \frac{X, G(a) \succ G(b), Y \quad X, G(b) \succ G(a), Y}{X \succ Y, a = b} [= R]$$

As with term eigenvariables, predicate eigenvariables need to be inferentially general

## Eliminating Cut

Want something like the following, although this is highly dependent on how the system is set up

$$\frac{
 \frac{
 \begin{array}{c} \vdots \delta_l(G) \\ X, G(a) \succ G(b), Y \end{array}
 \quad
 \begin{array}{c} \vdots \delta_r \\ X, G(b) \succ G(a), Y \end{array}
 }{X \succ Y, a = b} [= R]
 \quad
 \frac{
 \begin{array}{c} \vdots \delta' \\ X \succ \phi(a), Y \end{array}
 }{X, a = b \succ \phi(b), Y} [= L]
 }{X \succ \phi(b), Y} [\text{Cut}]$$

simplifies to

$$\frac{
 \begin{array}{c} \vdots \delta' \\ X \succ \phi(a), Y \end{array}
 \quad
 \begin{array}{c} \vdots \delta_l(\phi) \\ X, \phi(a) \succ \phi(b), Y \end{array}
 }{X \succ \phi(b), Y} [\text{Cut}]$$

## Identity, alternative rules

Alternative rules may make it easier to eliminate Cut

$$\frac{a = a, X \succ Y}{X \succ Y} [= R]$$

$$\frac{s = t, A(t), A(s), X \succ Y}{s = t, A(t), X \succ Y} [= L]$$

One can use the Dragalin-style proof to show that Cut can be eliminated

# Higher-Order Quantifiers

The treatment of first-order quantifiers extends to second-order quantifiers in a fairly straightforward way

We use predicate eigenvariables, which must be inferentially general

Second-order quantifiers range over properties, and there may be a property that is not expressed by any formula in the language

## Second-Order Quantifier rules

$$\text{(any F)} \frac{X, F(t) \succ Y}{X, (\forall Z)Z(t) \succ Y} [\forall^2 L]$$

$$\text{(G fresh)} \frac{X, G(t) \succ Y}{X, (\exists Z)Z(t) \succ Y} [\exists^2 L]$$

$$\text{(G fresh)} \frac{X \succ G(t), Y}{X \succ (\forall Z)Z(t), Y} [\forall^2 R]$$

$$\text{(any F)} \frac{X \succ F(t), Y}{X \succ (\exists Z)Z(t), Y} [\exists^2 R]$$

In  $[\forall^2 R]$  and  $[\exists^2 L]$ , the condition that  $G$  is fresh means that  $G$  is an *eigenvariable*, not occurring in  $X$  and  $Y$ .



# Uniqueness

Suppose that we had two second-order universal quantifiers,  $(\forall X)$  and  $(X)$ , both governed by the rules  $[\forall^2 L]$  and  $[\forall^2 R]$

They can be shown to be interderivable

$$\frac{\frac{Ga \succ Ga}{(\forall Z)Za \succ Ga} [\forall^2 L]}{(\forall Z)Za \succ (Z)Za} [\forall^2 R]$$

$$\frac{\frac{Ga \succ Ga}{(Z)Za \succ Ga} [\forall^2 L]}{(Z)Za \succ (\forall Z)Za} [\forall^2 R]$$

This appears to be a sense in which the rules uniquely pick out the second-order universal quantifier

This may be surprising, given that there is some leeway on what the interpretations for second-order quantifiers can be

## ***Semantics and beyond***

Speech Acts and Norms

Proofs and Models

Where to go from here

# THANK YOU!

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