

## Chapter udf

# Natural Deduction

### ntd.1 Rules and Derivations

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Natural deduction systems are meant to closely parallel the informal reasoning used in mathematical proof (hence it is somewhat “natural”). Natural deduction proofs begin with assumptions. Inference rules are then applied. Assumptions are “discharged” by the  $\neg$ Intro,  $\rightarrow$ Intro,  $\vee$ Elim and  $\exists$ Elim inference rules, and the label of the discharged assumption is placed beside the inference for clarity.

explanation

**Definition ntd.1** (Initial Formula). An *initial formula* or *assumption* is any formula in the topmost position of any branch.

Derivations in natural deduction are certain trees of sentences, where the topmost sentences are assumptions, and if a sentence stands below one, two, or three other sequents, it must follow correctly by a rule of inference. The sentences at the top of the inference are called the *premises* and the sentence below the *conclusion* of the inference. The rules come in pairs, an introduction and an elimination rule for each logical operator. They introduce a logical operator in the conclusion or remove a logical operator from a premise of the rule. Some of the rules allow an assumption of a certain type to be discharged. To indicate which assumption is discharged by which inference, we also assign labels to both the assumption and the inference. This is indicated by writing the assumption as “[ $\varphi$ ]<sup>n</sup>”.

It is customary to consider rules for all logical operators, even for those (if any) that we consider as defined.

### ntd.2 Propositional Rules

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### Rules for $\wedge$

$$\frac{\varphi \quad \psi}{\varphi \wedge \psi} \wedge\text{Intro} \qquad \frac{\varphi \wedge \psi}{\varphi} \wedge\text{Elim}$$

$$\frac{\varphi \wedge \psi}{\psi} \wedge\text{Elim}$$

### Rules for $\vee$

$$\frac{\varphi}{\varphi \vee \psi} \vee\text{Intro}$$

$$\frac{\psi}{\varphi \vee \psi} \vee\text{Intro}$$

$$n \frac{\varphi \vee \psi \quad \begin{array}{c} [\varphi]^n \\ \vdots \\ \chi \end{array} \quad \begin{array}{c} [\psi]^n \\ \vdots \\ \chi \end{array}}{\chi} \vee\text{Elim}$$

### Rules for $\rightarrow$

$$n \frac{\begin{array}{c} [\varphi]^n \\ \vdots \\ \psi \end{array}}{\varphi \rightarrow \psi} \rightarrow\text{Intro}$$

$$\frac{\varphi \rightarrow \psi \quad \varphi}{\psi} \rightarrow\text{Elim}$$

### Rules for $\neg$

$$n \frac{\begin{array}{c} [\varphi]^n \\ \vdots \\ \perp \end{array}}{\neg\varphi} \neg\text{Intro}$$

$$\frac{\neg\varphi \quad \varphi}{\perp} \neg\text{Elim}$$

### Rules for $\perp$

$$\begin{array}{c}
 \frac{\perp}{\varphi} \perp_I \\
 \\
 \frac{[\neg\varphi]^n \dots \perp}{\varphi} \perp_C
 \end{array}$$

Note that  $\neg$ -Intro and  $\perp_C$  are very similar: The difference is that  $\neg$ -Intro derives a negated **sentence**  $\neg\varphi$  but  $\perp_C$  a positive **sentence**  $\varphi$ .

### ntd.3 Quantifier Rules

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#### Rules for $\forall$

$$\frac{\varphi(a)}{\forall x \varphi(x)} \forall\text{Intro} \qquad \frac{\forall x \varphi(x)}{\varphi(t)} \forall\text{Elim}$$

In the rules for  $\forall$ ,  $t$  is a ground term (a term that does not contain any variables), and  $a$  is a **constant symbol** which does not occur in the conclusion  $\forall x \varphi(x)$ , or in any assumption which is **undischarged** in the **derivation** ending with the premise  $\varphi(a)$ . We call  $a$  the *eigenvariable* of the  $\forall$ Intro inference.

#### Rules for $\exists$

$$\frac{\varphi(t)}{\exists x \varphi(x)} \exists\text{Intro} \qquad \frac{\exists x \varphi(x) \quad [\varphi(a)]^n \dots \chi}{\chi} \exists\text{Elim}$$

Again,  $t$  is a ground term, and  $a$  is a constant which does not occur in the premise  $\exists x \varphi(x)$ , in the conclusion  $\chi$ , or any assumption which is **undischarged** in the **derivations** ending with the two premises (other than the assumptions  $\varphi(a)$ ). We call  $a$  the *eigenvariable* of the  $\exists$ Elim inference.

The condition that an eigenvariable neither occur in the premises nor in any assumption that is **undischarged** in the **derivations** leading to the premises for the  $\forall$ Intro or  $\exists$ Elim inference is called the *eigenvariable condition*.

explanation

We use the term “eigenvariable” even though  $a$  in the above rules is a constant. This has historical reasons.

In  $\exists$ Intro and  $\forall$ Elim there are no restrictions, and the term  $t$  can be anything, so we do not have to worry about any conditions. On the other hand, in the  $\exists$ Elim and  $\forall$ Intro rules, the eigenvariable condition requires that the constant symbol  $a$  does not occur anywhere in the conclusion or in an undischarged assumption. The condition is necessary to ensure that the system is sound, i.e., only derives sentences from undischarged assumptions from which the follow. Without this condition, the following would be allowed:

$$\frac{\exists x \varphi(x) \quad \frac{[\varphi(a)]^1}{\forall x \varphi(x)} * \forall \text{Intro}}{\forall x \varphi(x)} \exists \text{Elim}$$

However,  $\exists x \varphi(x) \not\equiv \forall x \varphi(x)$ .

## ntd.4 Derivations

explanation

We’ve said what an assumption is, and we’ve given the rules of inference. Derivations in the sequent calculus are inductively generated from these: each derivation either is an assumption on its own, or consists of one, two, or three derivations followed by a correct inference.

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**Definition ntd.2 (Derivation).** A *derivation* of a sentence  $\varphi$  from assumptions  $\Gamma$  is a tree of sentences satisfying the following conditions:

1. The topmost sentences of the tree are either in  $\Gamma$  or are discharged by an inference in the tree.
2. The bottommost sentence of the tree is  $\varphi$ .
3. Every sentence in the tree except  $\varphi$  is a premise of a correct application of an inference rule whose conclusion stands directly below that sentence in the tree.

We then say that  $\varphi$  is the *conclusion* of the derivation and that  $\varphi$  is *derivable* from  $\Gamma$ .

**Example ntd.3.** Every assumption on its own is a derivation. So, e.g.,  $\chi$  by itself is a derivation, and so is  $\theta$  by itself. We can obtain a new derivation from these by applying, say, the  $\wedge$ Intro rule,

$$\frac{\varphi \quad \psi}{\varphi \wedge \psi} \wedge \text{Intro}$$

These rules are meant to be general: we can replace the  $\varphi$  and  $\psi$  in it with any sentences, e.g., by  $\chi$  and  $\theta$ . Then the conclusion would be  $\chi \wedge \theta$ , and so

$$\frac{\chi \quad \theta}{\chi \wedge \theta} \wedge\text{Intro}$$

is a correct **derivation**. Of course, we can also switch the assumptions, so that  $\theta$  plays the role of  $\varphi$  and  $\chi$  that of  $\psi$ . Thus,

$$\frac{\theta \quad \chi}{\theta \wedge \chi} \wedge\text{Intro}$$

is also a correct derivation.

We can now apply another rule, say,  $\rightarrow$ Intro, which allows us to conclude a conditional and allows us to **discharge** any assumption that is identical to the conclusion of that conditional. So both of the following would be correct **derivations**:

$$1 \frac{\frac{[\chi]^1 \quad \theta}{\chi \wedge \theta} \wedge\text{Intro}}{\chi \rightarrow (\chi \wedge \theta)} \rightarrow\text{Intro} \quad 1 \frac{\frac{\chi \quad [\theta]^1}{\chi \wedge \theta} \wedge\text{Intro}}{\theta \rightarrow (\chi \wedge \theta)} \rightarrow\text{Intro}$$

## ntd.5 Examples of Derivations

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**Example ntd.4.** Let's give a **derivation** of the **sentence**  $(\varphi \wedge \psi) \rightarrow \varphi$ .

We begin by writing the desired conclusion at the bottom of the **derivation**.

$$\overline{(\varphi \wedge \psi) \rightarrow \varphi}$$

Next, we need to figure out what kind of inference could result in a **sentence** of this form. The **main operator** of the conclusion is  $\rightarrow$ , so we'll try to arrive at the conclusion using the  $\rightarrow$ Intro rule. It is best to write down the assumptions involved and label the inference rules as you progress, so it is easy to see whether all assumptions have been **discharged** at the end of the proof.

$$1 \frac{\begin{array}{c} [\varphi \wedge \psi]^1 \\ \vdots \\ \vdots \\ \varphi \end{array}}{(\varphi \wedge \psi) \rightarrow \varphi} \rightarrow\text{Intro}$$

We now need to fill in the steps from the assumption  $\varphi \wedge \psi$  to  $\varphi$ . Since we only have one connective to deal with,  $\wedge$ , we must use the  $\wedge$  elim rule. This gives us the following proof:

$$1 \frac{\frac{[\varphi \wedge \psi]^1}{\varphi} \wedge\text{Elim}}{(\varphi \wedge \psi) \rightarrow \varphi} \rightarrow\text{Intro}$$

We now have a correct **derivation** of  $(\varphi \wedge \psi) \rightarrow \varphi$ .

**Example ntd.5.** Now let's give a **derivation** of  $(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)$ .

We begin by writing the desired conclusion at the bottom of the derivation.

$$\overline{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)}$$

To find a logical rule that could give us this conclusion, we look at the logical connectives in the conclusion:  $\neg$ ,  $\vee$ , and  $\rightarrow$ . We only care at the moment about the first occurrence of  $\rightarrow$  because it is the **main operator** of the **sentence** in the end-sequent, while  $\neg$ ,  $\vee$  and the second occurrence of  $\rightarrow$  are inside the scope of another connective, so we will take care of those later. We therefore start with the  $\rightarrow$ Intro rule. A correct application must look as follows:

$$1 \frac{\begin{array}{c} [\neg\varphi \vee \psi]^1 \\ \vdots \\ \varphi \rightarrow \psi \end{array}}{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)} \rightarrow\text{Intro}$$

This leaves us with two possibilities to continue. Either we can keep working from the bottom up and look for another application of the  $\rightarrow$ Intro rule, or we can work from the top down and apply a  $\vee$ Elim rule. Let us apply the latter. We will use the assumption  $\neg\varphi \vee \psi$  as the leftmost premise of  $\vee$ Elim. For a valid application of  $\vee$ Elim, the other two premises must be identical to the conclusion  $\varphi \rightarrow \psi$ , but each may be derived in turn from another assumption, namely the two disjuncts of  $\neg\varphi \vee \psi$ . So our **derivation** will look like this:

$$2 \frac{\begin{array}{c} [\neg\varphi]^2 \quad [\psi]^2 \\ \vdots \quad \vdots \\ \varphi \rightarrow \psi \quad \varphi \rightarrow \psi \end{array}}{\varphi \rightarrow \psi} \vee\text{Elim} \\ 1 \frac{\begin{array}{c} [\neg\varphi \vee \psi]^1 \\ \vdots \\ \varphi \rightarrow \psi \end{array}}{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)} \rightarrow\text{Intro}$$

In each of the two branches on the right, we want to **derive**  $\varphi \rightarrow \psi$ , which is best done using  $\rightarrow$ Intro.

$$2 \frac{\begin{array}{c} [\neg\varphi]^2, [\varphi]^3 \quad [\psi]^2, [\varphi]^4 \\ \vdots \quad \vdots \\ \psi \quad \psi \\ 3 \frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro} \quad 4 \frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro} \end{array}}{\varphi \rightarrow \psi} \vee\text{Elim} \\ 1 \frac{\begin{array}{c} [\neg\varphi \vee \psi]^1 \\ \vdots \\ \varphi \rightarrow \psi \end{array}}{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)} \rightarrow\text{Intro}$$

For the two missing parts of the **derivation**, we need **derivations** of  $\psi$  from  $\neg\varphi$  and  $\varphi$  in the middle, and from  $\varphi$  and  $\psi$  on the left. Let's take the former

first.  $\neg\varphi$  and  $\varphi$  are the two premises of  $\neg$ Elim:

$$\frac{[\neg\varphi]^2 \quad [\varphi]^3}{\perp} \neg\text{Elim}$$

$$\vdots$$

$$\psi$$

By using  $\perp_I$ , we can obtain  $\psi$  as a conclusion and complete the branch.

$$\frac{\frac{\frac{[\neg\varphi]^2 \quad [\varphi]^3}{\perp} \perp\text{Intro} \quad \frac{[\psi]^2, [\varphi]^4}{\vdots} \psi}{\frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro}} \rightarrow\text{Intro} \quad \frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro}}{\frac{[\neg\varphi \vee \psi]^1}{\varphi \rightarrow \psi} \vee\text{Elim}} \vee\text{Elim}$$

$$\frac{\varphi \rightarrow \psi}{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)} \rightarrow\text{Intro}$$

Let's now look at the rightmost branch. Here it's important to realize that the definition of **derivation** allows assumptions to be discharged but does not require them to be. In other words, if we can derive  $\psi$  from one of the assumptions  $\varphi$  and  $\psi$  without using the other, that's ok. And to **derive**  $\psi$  from  $\psi$  is trivial:  $\psi$  by itself is such a **derivation**, and no inferences are needed. So we can simply delete the assumption  $\varphi$ .

$$\frac{\frac{[\neg\varphi]^2 \quad [\varphi]^3}{\perp} \neg\text{Elim} \quad \frac{[\psi]^2}{\psi} \rightarrow\text{Intro}}{\frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro}} \rightarrow\text{Intro} \quad \frac{[\psi]^2}{\varphi \rightarrow \psi} \rightarrow\text{Intro}}{\frac{[\neg\varphi \vee \psi]^1}{\varphi \rightarrow \psi} \vee\text{Elim}} \vee\text{Elim}$$

$$\frac{\varphi \rightarrow \psi}{(\neg\varphi \vee \psi) \rightarrow (\varphi \rightarrow \psi)} \rightarrow\text{Intro}$$

Note that in the finished **derivation**, the rightmost  $\rightarrow$ Intro inference does not actually discharge any assumptions.

**Example ntd.6.** So far we have not needed the  $\perp_C$  rule. It is special in that it allows us to discharge an assumption that isn't a sub-formula of the conclusion of the rule. It is closely related to the  $\perp_I$  rule. In fact, the  $\perp_I$  rule is a special case of the  $\perp_C$  rule—there is a logic called “intuitionistic logic” in which only  $\perp_I$  is allowed. The  $\perp_C$  rule is a last resort when nothing else works. For instance, suppose we want to **derive**  $\varphi \vee \neg\varphi$ . Our usual strategy would be to attempt to **derive**  $\varphi \vee \neg\varphi$  using  $\vee$ Intro. But this would require us to **derive** either  $\varphi$  or  $\neg\varphi$  from no assumptions, and this can't be done.  $\perp_C$  to the rescue!

$$\frac{[\neg(\varphi \vee \neg\varphi)]^1 \quad \vdots \quad \perp}{1 \quad \frac{\perp}{\varphi \vee \neg\varphi} \perp_C} \perp_C$$

Now we're looking for a **derivation** of  $\perp$  from  $\neg(\varphi \vee \neg\varphi)$ . Since  $\perp$  is the conclusion of  $\neg$ -Elim we might try that:

$$\frac{[\neg(\varphi \vee \neg\varphi)]^1 \quad \vdots \quad \neg\varphi \quad \quad \quad [\neg(\varphi \vee \neg\varphi)]^1 \quad \vdots \quad \varphi}{1 \quad \frac{\perp}{\varphi \vee \neg\varphi} \perp_C} \neg\text{-Elim}$$

Our strategy for finding a **derivation** of  $\neg\varphi$  calls for an application of  $\neg$ -Intro:

$$\frac{[\neg(\varphi \vee \neg\varphi)]^1, [\varphi]^2 \quad \vdots \quad \perp \quad \quad \quad [\neg(\varphi \vee \neg\varphi)]^1 \quad \vdots \quad \varphi}{1 \quad \frac{\perp}{\varphi \vee \neg\varphi} \perp_C} \begin{array}{l} \neg\text{-Intro} \\ \neg\text{-Elim} \end{array}$$

Here, we can get  $\perp$  easily by applying  $\neg$ -Elim to the assumption  $\neg(\varphi \vee \neg\varphi)$  and  $\varphi \vee \neg\varphi$  which follows from our new assumption  $\varphi$  by  $\vee$ -Intro:

$$\frac{[\neg(\varphi \vee \neg\varphi)]^1 \quad \frac{[\varphi]^2}{\varphi \vee \neg\varphi} \vee\text{Intro} \quad \quad \quad [\neg(\varphi \vee \neg\varphi)]^1 \quad \vdots \quad \varphi}{2 \quad \frac{\perp}{\neg\varphi} \neg\text{-Intro} \quad \quad \quad \neg\text{-Elim}} \quad \quad \quad \neg\text{-Elim}$$

$$1 \quad \frac{\perp}{\varphi \vee \neg\varphi} \perp_C$$

On the right side we use the same strategy, except we get  $\varphi$  by  $\perp_C$ :

$$\frac{[\neg(\varphi \vee \neg\varphi)]^1 \quad \frac{[\varphi]^2}{\varphi \vee \neg\varphi} \vee\text{Intro} \quad \quad \quad [\neg(\varphi \vee \neg\varphi)]^1 \quad \frac{[\neg\varphi]^3}{\varphi \vee \neg\varphi} \vee\text{Intro}}{2 \quad \frac{\perp}{\neg\varphi} \neg\text{-Intro} \quad \quad \quad 3 \quad \frac{\perp}{\varphi} \perp_C} \quad \quad \quad \neg\text{-Elim}$$

$$1 \quad \frac{\perp}{\varphi \vee \neg\varphi} \perp_C$$

**Problem ntd.1.** Give **derivations** of the following:

1.  $\neg(\varphi \rightarrow \psi) \rightarrow (\varphi \wedge \neg\psi)$
2.  $(\varphi \rightarrow \chi) \vee (\psi \rightarrow \chi)$  from the assumption  $(\varphi \wedge \psi) \rightarrow \chi$



## ntd.6 Derivations with Quantifiers

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**Example ntd.7.** When dealing with quantifiers, we have to make sure not to violate the eigenvariable condition, and sometimes this requires us to play around with the order of carrying out certain inferences. In general, it helps to try and take care of rules subject to the eigenvariable condition first (they will be lower down in the finished proof).

Let's see how we'd give a **derivation** of the **formula**  $\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)$ . Starting as usual, we write

$$\overline{\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)}$$

We start by writing down what it would take to justify that last step using the  $\rightarrow$ Intro rule.

$$\frac{\begin{array}{c} [\exists x \neg\varphi(x)]^1 \\ \vdots \\ \neg\forall x \varphi(x) \end{array}}{\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)} \rightarrow\text{Intro}$$

Since there is no obvious rule to apply to  $\neg\forall x \varphi(x)$ , we will proceed by setting up the **derivation** so we can use the  $\exists$ Elim rule. Here we must pay attention to the eigenvariable condition, and choose a constant that does not appear in  $\exists x \varphi(x)$  or any assumptions that it depends on. (Since no **constant symbols** appear, however, any choice will do fine.)

$$\frac{\begin{array}{c} [\neg\varphi(a)]^2 \\ \vdots \\ \neg\forall x \varphi(x) \end{array}}{\frac{\begin{array}{c} [\exists x \neg\varphi(x)]^1 \quad \neg\forall x \varphi(x) \\ \neg\forall x \varphi(x) \end{array}}{\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)} \rightarrow\text{Intro}} \exists\text{Elim}$$

In order to derive  $\neg\forall x \varphi(x)$ , we will attempt to use the  $\neg$ Intro rule: this requires that we derive a contradiction, possibly using  $\forall x \varphi(x)$  as an additional assumption. Of course, this contradiction may involve the assumption  $\neg\varphi(a)$  which will be discharged by the  $\rightarrow$ Intro inference. We can set it up as follows:

$$\frac{\begin{array}{c} [\neg\varphi(a)]^2, [\forall x \varphi(x)]^3 \\ \vdots \\ \perp \end{array}}{\frac{\begin{array}{c} [\exists x \neg\varphi(x)]^1 \quad \frac{\frac{\perp}{\neg\forall x \varphi(x)} \neg\text{Intro}}{\neg\forall x \varphi(x)} \exists\text{Elim} \end{array}}{\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)} \rightarrow\text{Intro}} \exists\text{Elim}$$

It looks like we are close to getting a contradiction. The easiest rule to apply is the  $\forall$ Elim, which has no eigenvariable conditions. Since we can use any term we want to replace the universally quantified  $x$ , it makes the most sense to continue using  $a$  so we can reach a contradiction.

$$\begin{array}{c}
 \frac{[\neg\varphi(a)]^2 \quad \frac{[\forall x \varphi(x)]^3}{\varphi(a)} \forall\text{Elim}}{\perp} \neg\text{Elim} \\
 \frac{2 \quad \frac{[\exists x \neg\varphi(x)]^1}{\neg\forall x \varphi(x)} \exists\text{Elim} \quad \frac{3 \quad \perp}{\neg\forall x \varphi(x)} \neg\text{Intro}}{\exists x \neg\varphi(x) \rightarrow \neg\forall x \varphi(x)} \rightarrow\text{Intro}
 \end{array}$$

It is important, especially when dealing with quantifiers, to double check at this point that the eigenvariable condition has not been violated. Since the only rule we applied that is subject to the eigenvariable condition was  $\exists$ Elim, and the eigenvariable  $a$  does not occur in any assumptions it depends on, this is a correct derivation.

**Example ntd.8.** Sometimes we may derive a **formula** from other **formulas**. In these cases, we may have undischarged assumptions. It is important to keep track of our assumptions as well as the end goal.

Let's see how we'd give a **derivation** of the **formula**  $\exists x \chi(x, b)$  from the assumptions  $\exists x (\varphi(x) \wedge \psi(x))$  and  $\forall x (\psi(x) \rightarrow \chi(x, b))$ . Starting as usual, we write the conclusion at the bottom.

$$\overline{\exists x \chi(x, b)}$$

We have two premises to work with. To use the first, i.e., try to find a **derivation** of  $\exists x \chi(x, b)$  from  $\exists x (\varphi(x) \wedge \psi(x))$  we would use the  $\exists$ Elim rule. Since it has an eigenvariable condition, we will apply that rule first. We get the following:

$$\begin{array}{c}
 [\varphi(a) \wedge \psi(a)]^1 \\
 \vdots \\
 \frac{1 \quad \frac{\exists x (\varphi(x) \wedge \psi(x)) \quad \exists x \chi(x, b)}{\exists x \chi(x, b)} \exists\text{Elim}}{\exists x \chi(x, b)} \exists\text{Elim}
 \end{array}$$

The two assumptions we are working with share  $\psi$ . It may be useful at this point to apply  $\wedge$ Elim to separate out  $\psi(a)$ .

$$\begin{array}{c}
 \frac{[\varphi(a) \wedge \psi(a)]^1}{\psi(a)} \wedge\text{Elim} \\
 \vdots \\
 \frac{1 \quad \frac{\exists x (\varphi(x) \wedge \psi(x)) \quad \exists x \chi(x, b)}{\exists x \chi(x, b)} \exists\text{Elim}}{\exists x \chi(x, b)} \exists\text{Elim}
 \end{array}$$

The second assumption we have to work with is  $\forall x (\psi(x) \rightarrow \chi(x, b))$ . Since there is no eigenvariable condition we can instantiate  $x$  with the **constant symbol**  $a$  using  $\forall$ Elim to get  $\psi(a) \rightarrow \chi(a, b)$ . We now have both  $\psi(a) \rightarrow \chi(a, b)$  and  $\psi(a)$ . Our next move should be a straightforward application of the  $\rightarrow$ Elim rule.

$$\begin{array}{c}
 \frac{\frac{\forall x (\psi(x) \rightarrow \chi(x, b))}{\psi(a) \rightarrow \chi(a, b)} \forall\text{Elim} \quad \frac{[\varphi(a) \wedge \psi(a)]^1}{\psi(a)} \wedge\text{Elim}}{\chi(a, b)} \rightarrow\text{Elim} \\
 \vdots \\
 \frac{\exists x (\varphi(x) \wedge \psi(x)) \quad \exists x \chi(x, b)}{\exists x \chi(x, b)} \exists\text{Elim}
 \end{array}$$

We are so close! One application of  $\exists$ Intro and we have reached our goal.

$$\begin{array}{c}
 \frac{\frac{\forall x (\psi(x) \rightarrow \chi(x, b))}{\psi(a) \rightarrow \chi(a, b)} \forall\text{Elim} \quad \frac{[\varphi(a) \wedge \psi(a)]^1}{\psi(a)} \wedge\text{Elim}}{\chi(a, b)} \rightarrow\text{Elim} \\
 \frac{\exists x (\varphi(x) \wedge \psi(x)) \quad \frac{\chi(a, b)}{\exists x \chi(x, b)} \exists\text{Intro}}{\exists x \chi(x, b)} \exists\text{Elim}
 \end{array}$$

Since we ensured at each step that the eigenvariable conditions were not violated, we can be confident that this is a correct derivation.

**Example ntd.9.** Give a **derivation** of the **formula**  $\neg\forall x \varphi(x)$  from the assumptions  $\forall x \varphi(x) \rightarrow \exists y \psi(y)$  and  $\neg\exists y \psi(y)$ . Starting as usual, we write the target **formula** at the bottom.

$$\overline{\neg\forall x \varphi(x)}$$

The last line of the **derivation** is a negation, so let's try using  $\neg$ Intro. This will require that we figure out how to **derive** a contradiction.

$$\begin{array}{c}
 [\forall x \varphi(x)]^1 \\
 \vdots \\
 \perp \\
 \frac{}{\neg\forall x \varphi(x)} \neg\text{Intro}
 \end{array}$$

So far so good. We can use  $\forall$ Elim but it's not obvious if that will help us get to our goal. Instead, let's use one of our assumptions.  $\forall x \varphi(x) \rightarrow \exists y \psi(y)$

together with  $\forall x \varphi(x)$  will allow us to use the  $\rightarrow$ Elim rule.

$$\frac{\forall x \varphi(x) \rightarrow \exists y \psi(y) \quad [\forall x \varphi(x)]^1}{\exists y \psi(y)} \rightarrow\text{Elim}$$

$$\vdots$$

$$1 \frac{\perp}{\neg \forall x \varphi(x)} \neg\text{Intro}$$

We now have one final assumption to work with, and it looks like this will help us reach a contradiction by using  $\neg$ Elim.

$$\frac{\neg \exists y \psi(y) \quad \frac{\forall x \varphi(x) \rightarrow \exists y \psi(y) \quad [\forall x \varphi(x)]^1}{\exists y \psi(y)} \rightarrow\text{Elim}}{1 \frac{\perp}{\neg \forall x \varphi(x)} \neg\text{Intro}} \neg\text{Elim}$$

**Problem ntd.2.** Give **derivations** of the following:

1.  $\exists y \varphi(y) \rightarrow \psi$  from the assumption  $\forall x (\varphi(x) \rightarrow \psi)$
2.  $\exists x (\varphi(x) \rightarrow \forall y \varphi(y))$

## ntd.7 Proof-Theoretic Notions

explanation

Just as we've defined a number of important semantic notions (validity, entailment, satisfiability), we now define corresponding *proof-theoretic notions*. These are not defined by appeal to satisfaction of **sentences** in **structures**, but by appeal to the **derivability** or **non-derivability** of certain **sentences** from others. It was an important discovery, due to Gödel, that these notions coincide. That they do is the content of the *completeness theorem*.

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**Definition ntd.10** (Theorems). A **sentence**  $\varphi$  is a *theorem* if there is a **derivation** of  $\varphi$  in natural deduction in which all assumptions are **discharged**. We write  $\vdash \varphi$  if  $\varphi$  is a theorem and  $\not\vdash \varphi$  if it is not.

**Definition ntd.11** (Derivability). A **sentence**  $\varphi$  is *derivable* from a set of **sentences**  $\Gamma$ ,  $\Gamma \vdash \varphi$ , if there is a **derivation** with conclusion  $\varphi$  and in which every assumption is either **discharged** or is in  $\Gamma$ . If  $\varphi$  is not **derivable** from  $\Gamma$  we write  $\Gamma \not\vdash \varphi$ .

**Definition ntd.12** (Consistency). A set of **sentences**  $\Gamma$  is *inconsistent* iff  $\Gamma \vdash \perp$ . If  $\Gamma$  is not inconsistent, i.e., if  $\Gamma \not\vdash \perp$ , we say it is *consistent*.

**Proposition ntd.13** (Reflexivity). If  $\varphi \in \Gamma$ , then  $\Gamma \vdash \varphi$ .

fol:ntd:ptn:  
prop:reflexivity

*Proof.* The assumption  $\varphi$  by itself is a **derivation** of  $\varphi$  where every **undischarged** assumption (i.e.,  $\varphi$ ) is in  $\Gamma$ .  $\square$

*fol.ntd:ptn:  
prop:monotony*

**Proposition ntd.14** (Monotony). *If  $\Gamma \subseteq \Delta$  and  $\Gamma \vdash \varphi$ , then  $\Delta \vdash \varphi$ .*

*Proof.* Any **derivation** of  $\varphi$  from  $\Gamma$  is also a **derivation** of  $\varphi$  from  $\Delta$ . □

*fol.ntd:ptn:  
prop:transitivity*

**Proposition ntd.15** (Transitivity). *If  $\Gamma \vdash \varphi$  for every  $\varphi \in \Delta$  and  $\Delta \vdash \psi$ , then  $\Gamma \vdash \psi$ .*

*Proof.* If  $\Delta \vdash \psi$ , then there is a **derivation**  $\delta_0$  of  $\psi$  with all **undischarged** assumptions in  $\Delta$ . We show that  $\Gamma \vdash \psi$  by induction on the number  $n$  of **undischarged** assumptions in  $\delta_0$ .

If  $n = 0$ , then  $\delta_0$  has no **undischarged** assumptions, and so also counts as a **derivation** of  $\psi$  from  $\Gamma$ .

Otherwise, pick an **undischarged** assumption  $\varphi$  in  $\delta_0$  and let  $\Delta_1$  be the remaining **undischarged** assumptions. We obtain the **derivation**  $\delta_1$ :

$$\frac{\begin{array}{c} \Delta_1, [\varphi]^1 \\ \vdots \\ \delta_0 \\ \vdots \\ \psi \end{array}}{\varphi \rightarrow \psi} \rightarrow \text{Intro}$$

Since the number of **undischarged** assumptions in  $\delta_1$  is  $n - 1$ , the inductive hypothesis applies: there is a **derivation**  $\delta_2$  of  $\varphi \rightarrow \psi$  from  $\Gamma$ . Since  $\Gamma \vdash \varphi$  there is also a **derivation**  $\delta_3$  of  $\varphi$  from  $\Gamma$ . Now consider:

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_2 \\ \vdots \\ \varphi \rightarrow \psi \end{array} \quad \begin{array}{c} \Gamma \\ \vdots \\ \delta_3 \\ \vdots \\ \varphi \end{array}}{\psi} \rightarrow \text{Elim}$$

This shows  $\Gamma \vdash \psi$ . □

*fol.ntd:ptn:  
prop:incons*

**Proposition ntd.16.**  *$\Gamma$  is inconsistent iff  $\Gamma \vdash \varphi$  for every **sentence**  $\varphi$ .*

*Proof.* Exercise. □

**Problem ntd.3.** Prove [Proposition ntd.16](#)

*fol.ntd:ptn:  
prop:proves-compact*

**Proposition ntd.17** (Compactness).

1. *If  $\Gamma \vdash \varphi$  then there is a finite subset  $\Gamma_0 \subseteq \Gamma$  such that  $\Gamma_0 \vdash \varphi$ .*
2. *If every finite subset of  $\Gamma$  is consistent, then  $\Gamma$  is consistent.*

*Proof.* 1. If  $\Gamma \vdash \varphi$ , then there is a **derivation**  $\delta$  of  $\varphi$  from  $\Gamma$ . Let  $\Gamma_0$  be the set of **undischarged** assumptions of  $\delta$ . Since any **derivation** is finite,  $\Gamma_0$  can only contain finitely many **sentences**. So,  $\delta$  is a **derivation** of  $\varphi$  from a finite  $\Gamma_0 \subseteq \Gamma$ .

2. This is the contrapositive of (1) for the special case  $\varphi \equiv \perp$ . □

## ntd.8 Derivability and Consistency

We will now establish a number of properties of the **derivability** relation. fol:ntd:prv:sec They are independently interesting, but each will play a role in the proof of the completeness theorem.

**Proposition ntd.18.** *If  $\Gamma \vdash \varphi$  and  $\Gamma \cup \{\varphi\}$  is inconsistent, then  $\Gamma$  is inconsistent.* fol:ntd:prv:prop:provability-contr

*Proof.* Let the **derivation** of  $\varphi$  from  $\Gamma$  be  $\delta_1$  and the **derivation** of  $\perp$  from  $\Gamma \cup \{\varphi\}$  be  $\delta_2$ . We can then **derive**:

$$\frac{\begin{array}{c} \Gamma, [\varphi]^1 \\ \vdots \\ \delta_2 \\ \vdots \\ \perp \\ \hline \neg\varphi \quad \neg\text{Intro} \end{array}}{\perp} \quad \frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_1 \\ \vdots \\ \varphi \\ \hline \varphi \quad \neg\text{Elim} \end{array}}{\perp} \quad \neg\text{Elim}$$

In the new **derivation**, the assumption  $\varphi$  is **discharged**, so it is a **derivation** from  $\Gamma$ . □

**Proposition ntd.19.**  *$\Gamma \vdash \varphi$  iff  $\Gamma \cup \{\neg\varphi\}$  is inconsistent.* fol:ntd:prv:prop:prov-incons

*Proof.* First suppose  $\Gamma \vdash \varphi$ , i.e., there is a **derivation**  $\delta_0$  of  $\varphi$  from **undischarged** assumptions  $\Gamma$ . We obtain a **derivation** of  $\perp$  from  $\Gamma \cup \{\neg\varphi\}$  as follows:

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_0 \\ \vdots \\ \varphi \\ \hline \varphi \quad \neg\text{Elim} \end{array}}{\perp} \quad \neg\varphi$$

Now assume  $\Gamma \cup \{\neg\varphi\}$  is inconsistent, and let  $\delta_1$  be the corresponding derivation of  $\perp$  from **undischarged** assumptions in  $\Gamma \cup \{\neg\varphi\}$ . We obtain a **derivation** of  $\varphi$  from  $\Gamma$  alone by using  $\perp_C$ :

$$\frac{\begin{array}{c} \Gamma, [\neg\varphi]^1 \\ \vdots \\ \delta_1 \\ \vdots \\ \perp \\ \hline \varphi \quad \perp_C \end{array}}{\varphi}$$

□

**Problem ntd.4.** Prove that  $\Gamma \vdash \neg\varphi$  iff  $\Gamma \cup \{\varphi\}$  is inconsistent.

**Proposition ntd.20.** *If  $\Gamma \vdash \varphi$  and  $\neg\varphi \in \Gamma$ , then  $\Gamma$  is inconsistent.* fol:ntd:prv:prop:explicit-inc

*Proof.* Suppose  $\Gamma \vdash \varphi$  and  $\neg\varphi \in \Gamma$ . Then there is a **derivation**  $\delta$  of  $\varphi$  from  $\Gamma$ . Consider this simple application of the  $\neg$ Elim rule:

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta \\ \vdots \\ \varphi \end{array}}{\perp} \neg\text{Elim}$$

Since  $\neg\varphi \in \Gamma$ , all **undischarged** assumptions are in  $\Gamma$ , this shows that  $\Gamma \vdash \perp$ .  $\square$

*fol:ntd:prv:  
prop:provability-exhaustive*

**Proposition ntd.21.** *If  $\Gamma \cup \{\varphi\}$  and  $\Gamma \cup \{\neg\varphi\}$  are both inconsistent, then  $\Gamma$  is inconsistent.*

*Proof.* There are **derivations**  $\delta_1$  and  $\delta_2$  of  $\perp$  from  $\Gamma \cup \{\varphi\}$  and  $\perp$  from  $\Gamma \cup \{\neg\varphi\}$ , respectively. We can then **derive**

$$\frac{\begin{array}{c} \Gamma, [\neg\varphi]^2 \\ \vdots \\ \delta_2 \\ \vdots \\ \perp \end{array} \quad \begin{array}{c} \Gamma, [\varphi]^1 \\ \vdots \\ \delta_1 \\ \vdots \\ \perp \end{array}}{\perp} \frac{\frac{2}{\neg\neg\varphi} \neg\text{Intro} \quad \frac{1}{\neg\varphi} \neg\text{Intro}}{\neg\text{Elim}}$$

Since the assumptions  $\varphi$  and  $\neg\varphi$  are **discharged**, this is a **derivation** of  $\perp$  from  $\Gamma$  alone. Hence  $\Gamma$  is inconsistent.  $\square$

## ntd.9 Derivability and the Propositional Connectives

*fol:ntd:ppr:  
sec*

**Proposition ntd.22.**

*fol:ntd:ppr:  
prop:provability-land  
fol:ntd:ppr:  
prop:provability-land-left  
fol:ntd:ppr:  
prop:provability-land-right*

1. Both  $\varphi \wedge \psi \vdash \varphi$  and  $\varphi \wedge \psi \vdash \psi$
2.  $\varphi, \psi \vdash \varphi \wedge \psi$ .

*Proof.* 1. We can **derive** both

$$\frac{\varphi \wedge \psi}{\varphi} \wedge\text{Elim} \quad \frac{\varphi \wedge \psi}{\psi} \wedge\text{Elim}$$

2. We can **derive**:

$$\frac{\varphi \quad \psi}{\varphi \wedge \psi} \wedge\text{Intro}$$

$\square$

**Proposition ntd.23.**

*fol.ntd.ppr:  
prop:provability-lor*

1.  $\varphi \vee \psi, \neg\varphi, \neg\psi$  is inconsistent.
2. Both  $\varphi \vdash \varphi \vee \psi$  and  $\psi \vdash \varphi \vee \psi$ .

*Proof.* 1. Consider the following **derivation**:

$$\frac{\frac{\frac{\varphi \vee \psi}{1} \quad \frac{\frac{\neg\varphi \quad [\varphi]^1}{\perp} \neg\text{Elim}}{\perp} \vee\text{Elim}}{\perp} \neg\text{Elim}}{\perp} \vee\text{Elim}}$$

This is a **derivation** of  $\perp$  from **undischarged** assumptions  $\varphi \vee \psi, \neg\varphi$ , and  $\neg\psi$ .

2. We can **derive** both

$$\frac{\varphi}{\varphi \vee \psi} \vee\text{Intro} \qquad \frac{\psi}{\varphi \vee \psi} \vee\text{Intro}$$

□

**Proposition ntd.24.**

*fol.ntd.ppr:  
prop:provability-lif*

1.  $\varphi, \varphi \rightarrow \psi \vdash \psi$ .
2. Both  $\neg\varphi \vdash \varphi \rightarrow \psi$  and  $\psi \vdash \varphi \rightarrow \psi$ .

*fol.ntd.ppr:  
prop:provability-lif-left*

*fol.ntd.ppr:  
prop:provability-lif-right*

*Proof.* 1. We can **derive**:

$$\frac{\frac{\varphi \rightarrow \psi \quad \psi}{\psi} \rightarrow\text{Elim}}{\psi} \rightarrow\text{Elim}$$

2. This is shown by the following two **derivations**:

$$\frac{\frac{\frac{\frac{\neg\varphi \quad [\varphi]^1}{\perp} \neg\text{Elim}}{\perp} \perp_I}{\varphi \rightarrow \psi} \rightarrow\text{Intro}}{\varphi \rightarrow \psi} \rightarrow\text{Intro} \qquad \frac{\psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro}$$

Note that  $\rightarrow$ Intro may, but does not have to, **discharge** the assumption  $\varphi$ .

□



## ntd.10 Derivability and the Quantifiers

fol:ntd:qpr:  
sec

fol:ntd:qpr:  
thm:strong-generalization

**Theorem ntd.25.** *If  $c$  is a constant not occurring in  $\Gamma$  or  $\varphi(x)$  and  $\Gamma \vdash \varphi(c)$ , then  $\Gamma \vdash \forall x \varphi(x)$ .*

*Proof.* Let  $\delta$  be a **derivation** of  $\varphi(c)$  from  $\Gamma$ . By adding a  $\forall$ Intro inference, we obtain a proof of  $\forall x \varphi(x)$ . Since  $c$  does not occur in  $\Gamma$  or  $\varphi(x)$ , the eigenvariable condition is satisfied.  $\square$

fol:ntd:qpr:  
prop:provability-quantifiers

**Proposition ntd.26.**

1.  $\varphi(t) \vdash \exists x \varphi(x)$ .

2.  $\forall x \varphi(x) \vdash \varphi(t)$ .

*Proof.* 1. The following is a **derivation** of  $\exists x \varphi(x)$  from  $\varphi(t)$ :

$$\frac{\varphi(t)}{\exists x \varphi(x)} \exists\text{Intro}$$

2. The following is a **derivation** of  $\varphi(t)$  from  $\forall x \varphi(x)$ :

$$\frac{\forall x \varphi(x)}{\varphi(t)} \forall\text{Elim}$$

$\square$

## ntd.11 Soundness

fol:ntd:sou:  
sec

A **derivation** system, such as natural deduction, is *sound* if it cannot **derive** explanation things that do not actually follow. Soundness is thus a kind of guaranteed safety property for **derivation** systems. Depending on which proof theoretic property is in question, we would like to know for instance, that

1. every **derivable sentence** is valid;
2. if a **sentence** is **derivable** from some others, it is also a consequence of them;
3. if a set of **sentences** is inconsistent, it is unsatisfiable.

These are important properties of a **derivation** system. If any of them do not hold, the **derivation** system is deficient—it would **derive** too much. Consequently, establishing the soundness of a **derivation** system is of the utmost importance.

fol:ntd:sou:  
thm:soundness

**Theorem ntd.27** (Soundness). *If  $\varphi$  is **derivable** from the **undischarged assumptions**  $\Gamma$ , then  $\Gamma \models \varphi$ .*

*Proof.* Let  $\delta$  be a **derivation** of  $\varphi$ . We proceed by induction on the number of inferences in  $\delta$ .

For the induction basis we show the claim if the number of inferences is 0. In this case,  $\delta$  consists only of an initial **formula**. Every initial **formula**  $\varphi$  is an **undischarged** assumption, and as such, any **structure**  $\mathfrak{M}$  that satisfies all of the **undischarged** assumptions of the proof also satisfies  $\varphi$ .

Now for the inductive step. Suppose that  $\delta$  contains  $n$  inferences. The premise(s) of the lowermost inference are **derived** using sub-**derivations**, each of which contains fewer than  $n$  inferences. We assume the induction hypothesis: The premises of the last inference follow from the **undischarged** assumptions of the sub-**derivations** ending in those premises. We have to show that  $\varphi$  follows from the **undischarged** assumptions of the entire proof.

We distinguish cases according to the type of the lowermost inference. First, we consider the possible inferences with only one premise.

1. Suppose that the last inference is  $\neg$ -Intro: The **derivation** has the form

$$\begin{array}{c} \Gamma, [\varphi]^n \\ \vdots \\ \vdots \delta_1 \\ \vdots \\ \perp \\ \hline n \frac{}{\neg\varphi} \neg\text{Intro} \end{array}$$

By inductive hypothesis,  $\perp$  follows from the **undischarged** assumptions  $\Gamma \cup \{\varphi\}$  of  $\delta_1$ . Consider a **structure**  $\mathfrak{M}$ . We need to show that, if  $\mathfrak{M} \models \Gamma$ , then  $\mathfrak{M} \models \neg\varphi$ . Suppose for reductio that  $\mathfrak{M} \models \Gamma$ , but  $\mathfrak{M} \not\models \neg\varphi$ , i.e.,  $\mathfrak{M} \models \varphi$ . This would mean that  $\mathfrak{M} \models \Gamma \cup \{\varphi\}$ . This is contrary to our inductive hypothesis. So,  $\mathfrak{M} \models \neg\varphi$ .

2. The last inference is  $\wedge$ Elim: There are two variants:  $\varphi$  or  $\psi$  may be inferred from the premise  $\varphi \wedge \psi$ . Consider the first case. The derivation  $\delta$  looks like this:

$$\begin{array}{c} \Gamma \\ \vdots \\ \vdots \delta_1 \\ \vdots \\ \varphi \wedge \psi \\ \hline \varphi \wedge\text{Elim} \end{array}$$

By inductive hypothesis,  $\varphi \wedge \psi$  follows from the **undischarged** assumptions  $\Gamma$  of  $\delta_1$ . Consider a **structure**  $\mathfrak{M}$ . We need to show that, if  $\mathfrak{M} \models \Gamma$ , then  $\mathfrak{M} \models \varphi$ . Suppose  $\mathfrak{M} \models \Gamma$ . By our inductive hypothesis ( $\Gamma \models \varphi \vee \psi$ ), we know that  $\mathfrak{M} \models \varphi \wedge \psi$ . By definition,  $\mathfrak{M} \models \varphi \wedge \psi$  iff  $\mathfrak{M} \models \varphi$  and  $\mathfrak{M} \models \psi$ . (The case where  $\psi$  is inferred from  $\varphi \wedge \psi$  is handled similarly.)

3. The last inference is  $\vee$ Intro: There are two variants:  $\varphi \vee \psi$  may be inferred from the premise  $\varphi$  or the premise  $\psi$ . Consider the first case. The derivation has the form

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_1 \\ \vdots \\ \varphi \end{array}}{\varphi \vee \psi} \vee\text{Intro}$$

By inductive hypothesis,  $\varphi$  follows from the **undischarged** assumptions  $\Gamma$  of  $\delta_1$ . Consider a **structure**  $\mathfrak{M}$ . We need to show that, if  $\mathfrak{M} \models \Gamma$ , then  $\mathfrak{M} \models \varphi \vee \psi$ . Suppose  $\mathfrak{M} \models \Gamma$ ; then  $\mathfrak{M} \models \varphi$  since  $\Gamma \models \varphi$  (the inductive hypothesis). So it must also be the case that  $\mathfrak{M} \models \varphi \vee \psi$ . (The case where  $\varphi \vee \psi$  is inferred from  $\psi$  is handled similarly.)

4. The last inference is  $\rightarrow$ Intro:  $\varphi \rightarrow \psi$  is inferred from a subproof with assumption  $\varphi$  and conclusion  $\psi$ , i.e.,

$${}^n \frac{\begin{array}{c} \Gamma, [\varphi]^n \\ \vdots \\ \delta_1 \\ \vdots \\ \psi \end{array}}{\varphi \rightarrow \psi} \rightarrow\text{Intro}$$

By inductive hypothesis,  $\psi$  follows from the **undischarged** assumptions of  $\delta_1$ , i.e.,  $\Gamma \cup \{\varphi\} \models \psi$ . Consider a **structure**  $\mathfrak{M}$ . The **undischarged** assumptions of  $\delta$  are just  $\Gamma$ , since  $\varphi$  is discharged at the last inference. So we need to show that  $\Gamma \models \varphi \rightarrow \psi$ . For reductio, suppose that for some **structure**  $\mathfrak{M}$ ,  $\mathfrak{M} \models \Gamma$  but  $\mathfrak{M} \not\models \varphi \rightarrow \psi$ . So,  $\mathfrak{M} \models \varphi$  and  $\mathfrak{M} \not\models \psi$ . But by hypothesis,  $\psi$  is a consequence of  $\Gamma \cup \{\varphi\}$ , i.e.,  $\mathfrak{M} \models \psi$ , which is a contradiction. So,  $\Gamma \models \varphi \rightarrow \psi$ .

5. The last inference is  $\perp_I$ : Here,  $\delta$  ends in

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_1 \\ \vdots \\ \perp \end{array}}{\varphi} \perp_I$$

By induction hypothesis,  $\Gamma \models \perp$ . We have to show that  $\Gamma \models \varphi$ . Suppose not; then for some  $\mathfrak{M}$  we have  $\mathfrak{M} \models \Gamma$  and  $\mathfrak{M} \not\models \varphi$ . But we always have  $\mathfrak{M} \models \perp$ , so this would mean that  $\Gamma \not\models \perp$ , contrary to the induction hypothesis.

6. The last inference is  $\perp_C$ : Exercise.
7. The last inference is  $\forall$ Intro: Then  $\delta$  has the form

$$\frac{\begin{array}{c} \Gamma \\ \vdots \\ \delta_1 \\ \vdots \\ \varphi(a) \end{array}}{\forall x \varphi(x)} \forall\text{Intro}$$

The premise  $\varphi(a)$  is a consequence of the **undischarged** assumptions  $\Gamma$  by induction hypothesis. Consider some structure,  $\mathfrak{M}$ , such that  $\mathfrak{M} \models \Gamma$ . We need to show that  $\mathfrak{M} \models \forall x \varphi(x)$ . Since  $\forall x \varphi(x)$  is a **sentence**, this means we have to show that for every variable assignment  $s$ ,  $\mathfrak{M}, s \models \varphi(x)$  (??). Since  $\Gamma$  consists entirely of sentences,  $\mathfrak{M}, s \models \psi$  for all  $\psi \in \Gamma$  by ???. Let  $\mathfrak{M}'$  be like  $\mathfrak{M}$  except that  $a^{\mathfrak{M}'} = s(x)$ . Since  $a$  does not occur in  $\Gamma$ ,  $\mathfrak{M}' \models \Gamma$  by ???. Since  $\Gamma \models A(a)$ ,  $\mathfrak{M}' \models A(a)$ . Since  $\varphi(a)$  is a **sentence**,  $\mathfrak{M}, s \models \varphi(a)$  by ??.  $\mathfrak{M}', s \models \varphi(x)$  iff  $\mathfrak{M}' \models \varphi(a)$  by ?? (recall that  $\varphi(a)$  is just  $\varphi(x)[a/x]$ ). So,  $\mathfrak{M}', s \models \varphi(x)$ . Since  $a$  does not occur in  $\varphi(x)$ , by ??,  $\mathfrak{M}, s \models \varphi(x)$ . But  $s$  was an arbitrary variable assignment, so  $\mathfrak{M} \models \forall x \varphi(x)$ .

8. The last inference is  $\exists$ Intro: Exercise.
9. The last inference is  $\forall$ Elim: Exercise.

Now let's consider the possible inferences with several premises:  $\forall$ Elim,  $\wedge$ Intro,  $\rightarrow$ Elim, and  $\exists$ Elim.

1. The last inference is  $\wedge$ Intro.  $\varphi \wedge \psi$  is inferred from the premises  $\varphi$  and  $\psi$  and  $\delta$  has the form

$$\frac{\begin{array}{c} \Gamma_1 \\ \vdots \\ \delta_1 \\ \vdots \\ \varphi \end{array} \quad \begin{array}{c} \Gamma_2 \\ \vdots \\ \delta_2 \\ \vdots \\ \psi \end{array}}{\varphi \wedge \psi} \wedge\text{Intro}$$

By induction hypothesis,  $\varphi$  follows from the **undischarged** assumptions  $\Gamma_1$  of  $\delta_1$  and  $\psi$  follows from the **undischarged** assumptions  $\Gamma_2$  of  $\delta_2$ . The **undischarged** assumptions of  $\delta$  are  $\Gamma_1 \cup \Gamma_2$ , so we have to show that  $\Gamma_1 \cup \Gamma_2 \models \varphi \wedge \psi$ . Consider a **structure**  $\mathfrak{M}$  with  $\mathfrak{M} \models \Gamma_1 \cup \Gamma_2$ . Since  $\mathfrak{M} \models \Gamma_1$ , it must be the case that  $\mathfrak{M} \models \varphi$  as  $\Gamma_1 \models \varphi$ , and since  $\mathfrak{M} \models \Gamma_2$ ,  $\mathfrak{M} \models \psi$  since  $\Gamma_2 \models \psi$ . Together,  $\mathfrak{M} \models \varphi \wedge \psi$ .

2. The last inference is  $\forall$ Elim: Exercise.

3. The last inference is  $\rightarrow$ Elim.  $\psi$  is inferred from the premises  $\varphi \rightarrow \psi$  and  $\varphi$ . The derivation  $\delta$  looks like this:

$$\frac{\begin{array}{c} \Gamma_1 \\ \vdots \\ \delta_1 \\ \vdots \\ \varphi \rightarrow \psi \end{array} \quad \begin{array}{c} \Gamma_2 \\ \vdots \\ \delta_2 \\ \vdots \\ \varphi \end{array}}{\psi} \rightarrow\text{Elim}$$

By induction hypothesis,  $\varphi \rightarrow \psi$  follows from the **undischarged** assumptions  $\Gamma_1$  of  $\delta_1$  and  $\varphi$  follows from the **undischarged** assumptions  $\Gamma_2$  of  $\delta_2$ . Consider a **structure**  $\mathfrak{M}$ . We need to show that, if  $\mathfrak{M} \models \Gamma_1 \cup \Gamma_2$ , then  $\mathfrak{M} \models \psi$ . Suppose  $\mathfrak{M} \models \Gamma_1 \cup \Gamma_2$ . Since  $\Gamma_1 \models \varphi \rightarrow \psi$ ,  $\mathfrak{M} \models \varphi \rightarrow \psi$ . Since  $\Gamma_2 \models \varphi$ , we have  $\mathfrak{M} \models \varphi$ . This means that  $\mathfrak{M} \models \psi$  (For if  $\mathfrak{M} \not\models \psi$ , since  $\mathfrak{M} \models \varphi$ , we'd have  $\mathfrak{M} \not\models \varphi \rightarrow \psi$ , contradicting  $\mathfrak{M} \models \varphi \rightarrow \psi$ ).

4. The last inference is  $\neg$ Elim: Exercise.  
5. The last inference is  $\exists$ Elim: Exercise.

□

**Problem ntd.5.** Complete the proof of [Theorem ntd.27](#).

*fol:ntd:sou:*  
*cor:weak-soundness*

**Corollary ntd.28.** *If  $\vdash \varphi$ , then  $\varphi$  is valid.*

*fol:ntd:sou:*  
*cor:consistency-soundness*

**Corollary ntd.29.** *If  $\Gamma$  is satisfiable, then it is consistent.*

*Proof.* We prove the contrapositive. Suppose that  $\Gamma$  is not consistent. Then  $\Gamma \vdash \perp$ , i.e., there is a **derivation** of  $\perp$  from **undischarged** assumptions in  $\Gamma$ . By [Theorem ntd.27](#), any **structure**  $\mathfrak{M}$  that satisfies  $\Gamma$  must satisfy  $\perp$ . Since  $\mathfrak{M} \not\models \perp$  for every **structure**  $\mathfrak{M}$ , no  $\mathfrak{M}$  can satisfy  $\Gamma$ , i.e.,  $\Gamma$  is not satisfiable. □

## ntd.12 Derivations with Identity predicate

*fol:ntd:ide:*  
*sec*

**Derivations with identity predicate** require additional inference rules.

$\frac{}{t = t} =\text{Intro}$	$\frac{t_1 = t_2 \quad \varphi(t_1)}{\varphi(t_2)} =\text{Elim}$ $\frac{t_1 = t_2 \quad \varphi(t_2)}{\varphi(t_1)} =\text{Elim}$
--------------------------------	---

In the above rules,  $t$ ,  $t_1$ , and  $t_2$  are closed terms. The =Intro rule allows us to **derive** any identity statement of the form  $t = t$  outright, from no assumptions.

**Example ntd.30.** If  $s$  and  $t$  are closed terms, then  $\varphi(s), s = t \vdash \varphi(t)$ :

$$\frac{s = t \quad \varphi(s)}{\varphi(t)} =\text{Elim}$$

This may be familiar as the “principle of substitutability of identicals,” or Leibniz’ Law.

**Problem ntd.6.** Prove that  $=$  is both symmetric and transitive, i.e., give **derivations** of  $\forall x \forall y (x = y \rightarrow y = x)$  and  $\forall x \forall y \forall z ((x = y \wedge y = z) \rightarrow x = z)$

**Example ntd.31.** We **derive** the **sentence**

$$\forall x \forall y ((\varphi(x) \wedge \varphi(y)) \rightarrow x = y)$$

from the **sentence**

$$\exists x \forall y (\varphi(y) \rightarrow y = x)$$

We develop the **derivation** backwards:

$$\begin{array}{c} \exists x \forall y (\varphi(y) \rightarrow y = x) \quad [\varphi(a) \wedge \varphi(b)]^1 \\ \vdots \\ a = b \\ \frac{1 \quad \frac{(\varphi(a) \wedge \varphi(b)) \rightarrow a = b}{(\varphi(a) \wedge \varphi(b)) \rightarrow a = b} \rightarrow\text{Intro}}{\forall y ((\varphi(a) \wedge \varphi(y)) \rightarrow a = y)} \forall\text{Intro} \\ \frac{\forall y ((\varphi(a) \wedge \varphi(y)) \rightarrow a = y)}{\forall x \forall y ((\varphi(x) \wedge \varphi(y)) \rightarrow x = y)} \forall\text{Intro} \end{array}$$

We’ll now have to use the main assumption: since it is an existential **formula**, we use  $\exists\text{Elim}$  to **derive** the intermediary conclusion  $a = b$ .

$$\begin{array}{c} [\forall y (\varphi(y) \rightarrow y = c)]^2 \\ [\varphi(a) \wedge \varphi(b)]^1 \\ \vdots \\ \frac{2 \quad \frac{\exists x \forall y (\varphi(y) \rightarrow y = x) \quad a = b}{a = b} \exists\text{Elim}}{\frac{1 \quad \frac{(\varphi(a) \wedge \varphi(b)) \rightarrow a = b}{(\varphi(a) \wedge \varphi(b)) \rightarrow a = b} \rightarrow\text{Intro}}{\forall y ((\varphi(a) \wedge \varphi(y)) \rightarrow a = y)} \forall\text{Intro}}{\forall x \forall y ((\varphi(x) \wedge \varphi(y)) \rightarrow x = y)} \forall\text{Intro} \end{array}$$

The sub-**derivation** on the top right is completed by using its assumptions to show that  $a = c$  and  $b = c$ . This requires two separate **derivations**. The derivation for  $a = c$  is as follows:

$$\frac{\frac{[\forall y (\varphi(y) \rightarrow y = c)]^2}{\varphi(a) \rightarrow a = c} \forall\text{Elim} \quad \frac{[\varphi(a) \wedge \varphi(b)]^1}{\varphi(a)} \wedge\text{Elim}}{a = c} \rightarrow\text{Elim}$$

From  $a = c$  and  $b = c$  we derive  $a = b$  by  $=\text{Elim}$ .

**Problem ntd.7.** Give derivations of the following formulas:

1.  $\forall x \forall y ((x = y \wedge \varphi(x)) \rightarrow \varphi(y))$
2.  $\exists x \varphi(x) \wedge \forall y \forall z ((\varphi(y) \wedge \varphi(z)) \rightarrow y = z) \rightarrow \exists x (\varphi(x) \wedge \forall y (\varphi(y) \rightarrow y = x))$

### ntd.13 Soundness with Identity predicate

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sec

**Proposition ntd.32.** *Natural deduction with rules for  $=$  is sound.*

*Proof.* Any formula of the form  $t = t$  is valid, since for every structure  $\mathfrak{M}$ ,  $\mathfrak{M} \models t = t$ . (Note that we assume the term  $t$  to be ground, i.e., it contains no variables, so variable assignments are irrelevant).

Suppose the last inference in a derivation is  $=\text{Elim}$ , i.e., the derivation has the following form:

$$\frac{\begin{array}{c} \Gamma_1 \\ \vdots \\ \delta_1 \\ \vdots \\ t_1 = t_2 \end{array} \quad \begin{array}{c} \Gamma_2 \\ \vdots \\ \delta_2 \\ \vdots \\ \varphi(t_1) \end{array}}{\varphi(t_2)} =\text{Elim}$$

The premises  $t_1 = t_2$  and  $\varphi(t_1)$  are derived from undischarged assumptions  $\Gamma_1$  and  $\Gamma_2$ , respectively. We want to show that  $\varphi(t_2)$  follows from  $\Gamma_1 \cup \Gamma_2$ . Consider a structure  $\mathfrak{M}$  with  $\mathfrak{M} \models \Gamma_1 \cup \Gamma_2$ . By induction hypothesis,  $\mathfrak{M} \models \varphi(t_1)$  and  $\mathfrak{M} \models t_1 = t_2$ . Therefore,  $\text{Val}^{\mathfrak{M}}(t_1) = \text{Val}^{\mathfrak{M}}(t_2)$ . Let  $s$  be any variable assignment, and  $s'$  be the  $x$ -variant given by  $s'(x) = \text{Val}^{\mathfrak{M}}(t_1) = \text{Val}^{\mathfrak{M}}(t_2)$ . By ??,  $\mathfrak{M}, s \models \varphi(t_1)$  iff  $\mathfrak{M}, s' \models \varphi(x)$  iff  $\mathfrak{M}, s \models \varphi(t_2)$ . Since  $\mathfrak{M} \models \varphi(t_1)$ , we have  $\mathfrak{M} \models \varphi(t_2)$ .  $\square$

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# Bibliography