

# Chapter udf

## Introduction

### int.1 Constructive Reasoning

In contrast to extensions of classical logic by modal operators or second-order quantifiers, intuitionistic logic is “non-classical” in that it restricts classical logic. Classical logic is *non-constructive* in various ways. Intuitionistic logic is intended to capture a more “constructive” kind of reasoning characteristic of a kind of constructive mathematics. The following examples may serve to illustrate some of the underlying motivations.

Suppose someone claimed that they had determined a natural number  $n$  with the property that if  $n$  is even, the Riemann hypothesis is true, and if  $n$  is odd, the Riemann hypothesis is false. Great news! Whether the Riemann hypothesis is true or not is one of the big open questions of mathematics, and they seem to have reduced the problem to one of calculation, that is, to the determination of whether a specific number is prime or not.

What is the magic value of  $n$ ? They describe it as follows:  $n$  is the natural number that is equal to 2 if the Riemann hypothesis is true, and 3 otherwise.

Angrily, you demand your money back. From a classical point of view, the description above does in fact determine a unique value of  $n$ ; but what you really want is a value of  $n$  that is given *explicitly*.

To take another, perhaps less contrived example, consider the following question. We know that it is possible to raise an irrational number to a rational power, and get a rational result. For example,  $\sqrt{2}^2 = 2$ . What is less clear is whether or not it is possible to raise an irrational number to an *irrational* power, and get a rational result. The following theorem answers this in the affirmative:

**Theorem int.1.** *There are irrational numbers  $a$  and  $b$  such that  $a^b$  is rational.*

*Proof.* Consider  $\sqrt{2}^{\sqrt{2}}$ . If this is rational, we are done: we can let  $a = b = \sqrt{2}$ . Otherwise, it is irrational. Then we have

$$(\sqrt{2}^{\sqrt{2}})^{\sqrt{2}} = \sqrt{2}^{\sqrt{2} \cdot \sqrt{2}} = \sqrt{2}^2 = 2,$$

which is rational. So, in this case, let  $a$  be  $\sqrt{2}^{\sqrt{2}}$ , and let  $b$  be  $\sqrt{2}$ . □

Does this constitute a valid proof? Most mathematicians feel that it does. But again, there is something a little bit unsatisfying here: we have proved the existence of a pair of real numbers with a certain property, without being able to say *which* pair of numbers it is. It is possible to prove the same result, but in such a way that the pair  $a, b$  is given in the proof: take  $a = \sqrt{3}$  and  $b = \log_3 4$ . Then

$$a^b = \sqrt{3}^{\log_3 4} = 3^{1/2 \cdot \log_3 4} = (3^{\log_3 4})^{1/2} = 4^{1/2} = 2,$$

since  $3^{\log_3 x} = x$ .

Intuitionistic logic is designed to capture a kind of reasoning where moves like the one in the first proof are disallowed. Proving the existence of an  $x$  satisfying  $\varphi(x)$  means that you have to give a specific  $x$ , and a proof that it satisfies  $\varphi$ , like in the second proof. Proving that  $\varphi$  or  $\psi$  holds requires that you can prove one or the other.

Formally speaking, intuitionistic logic is what you get if you restrict a proof system for classical logic in a certain way. From the mathematical point of view, these are just formal deductive systems, but, as already noted, they are intended to capture a kind of mathematical reasoning. One can take this to be the kind of reasoning that is justified on a certain philosophical view of mathematics (such as Brouwer's intuitionism); one can take it to be a kind of mathematical reasoning which is more "concrete" and satisfying (along the lines of Bishop's constructivism); and one can argue about whether or not the formal description captures the informal motivation. But whatever philosophical positions we may hold, we can study intuitionistic logic as a formally presented logic; and for whatever reasons, many mathematical logicians find it interesting to do so.

## int.2 Syntax of Intuitionistic Logic

The syntax of intuitionistic logic is the same as that for propositional logic. In classical propositional logic it is possible to define connectives by others, e.g., one can define  $\varphi \rightarrow \psi$  by  $\neg\varphi \vee \psi$ , or  $\varphi \vee \psi$  by  $\neg(\neg\varphi \wedge \neg\psi)$ . Thus, presentations of classical logic often introduce some connectives as abbreviations for these definitions. This is not so in intuitionistic logic, with two exceptions:  $\neg\varphi$  can be—and often is—defined as an abbreviation for  $\varphi \rightarrow \perp$ . Then, of course,  $\perp$  must not itself be defined! Also,  $\varphi \leftrightarrow \psi$  can be defined, as in classical logic, as  $(\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$ . int:int:syn:  
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**Formulas** of propositional intuitionistic logic are built up from *propositional variables* and the propositional constant  $\perp$  using *logical connectives*. We have:

1. A denumerable set  $\text{At}_0$  of **propositional variables**  $p_0, p_1, \dots$
2. The propositional constant for **falsity**  $\perp$ .

3. The logical connectives:  $\wedge$  (conjunction),  $\vee$  (disjunction),  $\rightarrow$  (conditional)
4. Punctuation marks:  $(, )$ , and the comma.

int:int:syn:  
defn:formulas

**Definition int.2** (Formula). The set  $\text{Frm}(\mathcal{L}_0)$  of *formulas* of propositional intuitionistic logic is defined inductively as follows:

1.  $\perp$  is an atomic formula.
2. Every propositional variable  $p_i$  is an atomic formula.
3. If  $\varphi$  and  $\psi$  are formulas, then  $(\varphi \wedge \psi)$  is a formula.
4. If  $\varphi$  and  $\psi$  are formulas, then  $(\varphi \vee \psi)$  is a formula.
5. If  $\varphi$  and  $\psi$  are formulas, then  $(\varphi \rightarrow \psi)$  is a formula.
6. Nothing else is a formula.

In addition to the primitive connectives introduced above, we also use the following *defined* symbols:  $\neg$  (negation) and  $\leftrightarrow$  (**biconditional**). Formulas constructed using the defined operators are to be understood as follows:

1.  $\neg\varphi$  abbreviates  $\varphi \rightarrow \perp$ .
2.  $\varphi \leftrightarrow \psi$  abbreviates  $(\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$ .

Although  $\neg$  is officially treated as an abbreviation, we will sometimes give explicit rules and clauses in definitions for  $\neg$  as if it were primitive. This is mostly so we can state practice problems.

### int.3 The Brouwer-Heyting-Kolmogorov Interpretation

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Proofs of validity of intuitionistic propositions using the BHK interpretation are confusing; they have to be explained better.

There is an informal constructive interpretation of the intuitionist connectives, usually known as the Brouwer-Heyting-Kolmogorov interpretation. It uses the notion of a “construction,” which you may think of as a constructive proof. (We don’t use “proof” in the BHK interpretation so as not to get confused with the notion of a *derivation* in a formal proof system.) Based on this intuitive notion, the BHK interpretation explains the meanings of the intuitionistic connectives.

1. We assume that we know what constitutes a construction of an atomic statement.

2. A construction of  $\varphi_1 \wedge \varphi_2$  is a pair  $\langle M_1, M_2 \rangle$  where  $M_1$  is a construction of  $\varphi_1$  and  $M_2$  is a construction of  $\varphi_2$ .
3. A construction of  $\varphi_1 \vee \varphi_2$  is a pair  $\langle s, M \rangle$  where  $s$  is 1 and  $M$  is a construction of  $\varphi_1$ , or  $s$  is 2 and  $M$  is a construction of  $\varphi_2$ .
4. A construction of  $\varphi \rightarrow \psi$  is a function that converts a construction of  $\varphi$  into a construction of  $\psi$ .
5. There is no construction for  $\perp$  (absurdity).
6.  $\neg\varphi$  is defined as synonym for  $\varphi \rightarrow \perp$ . That is, a construction of  $\neg\varphi$  is a function converting a construction of  $\varphi$  into a construction of  $\perp$ .

**Example int.3.** Take  $\neg\perp$  for example. A construction of it is a function which, given any construction of  $\perp$  as input, provides a construction of  $\perp$  as output. Obviously, the identity function  $\text{Id}$  is such a construction: given a construction  $M$  of  $\perp$ ,  $\text{Id}(M) = M$  yields a construction of  $\perp$ .

Generally speaking,  $\neg\varphi$  means “A construction of  $\varphi$  is impossible”.

**Example int.4.** Let us prove  $\varphi \rightarrow \neg\neg\varphi$  for any proposition  $\varphi$ , which is  $\varphi \rightarrow ((\varphi \rightarrow \perp) \rightarrow \perp)$ . The construction should be a function  $f$  that, given a construction  $M$  of  $\varphi$ , returns a construction  $f(M)$  of  $(\varphi \rightarrow \perp) \rightarrow \perp$ . Here is how  $f$  constructs the construction of  $(\varphi \rightarrow \perp) \rightarrow \perp$ : We have to define a function  $g$  which, when given a construction  $h$  of  $\varphi \rightarrow \perp$  as input, outputs a construction of  $\perp$ . We can define  $g$  as follows: apply the input  $h$  to the construction  $M$  of  $\varphi$  (that we received earlier). Since the output  $h(M)$  of  $h$  is a construction of  $\perp$ ,  $f(M)(h) = h(M)$  is a construction of  $\perp$  if  $M$  is a construction of  $\varphi$ .

**Example int.5.** Let us give a construction for  $\neg(\varphi \wedge \neg\varphi)$ , i.e.,  $(\varphi \wedge (\varphi \rightarrow \perp)) \rightarrow \perp$ . This is a function  $f$  which, given as input a construction  $M$  of  $\varphi \wedge (\varphi \rightarrow \perp)$ , yields a construction of  $\perp$ . A construction of a conjunction  $\psi_1 \wedge \psi_2$  is a pair  $\langle N_1, N_2 \rangle$  where  $N_1$  is a construction of  $\psi_1$  and  $N_2$  is a construction of  $\psi_2$ . We can define functions  $p_1$  and  $p_2$  which recover from a construction of  $\psi_1 \wedge \psi_2$  the constructions of  $\psi_1$  and  $\psi_2$ , respectively:

$$\begin{aligned} p_1(\langle N_1, N_2 \rangle) &= N_1 \\ p_2(\langle N_1, N_2 \rangle) &= N_2 \end{aligned}$$

Here is what  $f$  does: First it applies  $p_1$  to its input  $M$ . That yields a construction of  $\varphi$ . Then it applies  $p_2$  to  $M$ , yielding a construction of  $\varphi \rightarrow \perp$ . Such a construction, in turn, is a function  $p_2(M)$  which, if given as input a construction of  $\varphi$ , yields a construction of  $\perp$ . In other words, if we apply  $p_2(M)$  to  $p_1(M)$ , we get a construction of  $\perp$ . Thus, we can define  $f(M) = p_2(p_1(M))$ .

**Example int.6.** Let us give a construction of  $((\varphi \wedge \psi) \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \rightarrow \chi))$ , i.e., a function  $f$  which turns a construction  $g$  of  $(\varphi \wedge \psi) \rightarrow \chi$  into a construction of  $(\varphi \rightarrow (\psi \rightarrow \chi))$ . The construction  $g$  is itself a function (from constructions of  $\varphi \wedge \psi$  to constructions of  $\chi$ ). And the output  $f(g)$  is a function  $h_g$  from constructions of  $\varphi$  to functions from constructions of  $\psi$  to constructions of  $\chi$ .

Ok, this is confusing. We have to construct a certain function  $h_g$ , which will be the output of  $f$  for input  $g$ . The input of  $h_g$  is a construction  $M$  of  $\varphi$ . The output of  $h_g(M)$  should be a function  $k_M$  from constructions  $N$  of  $\psi$  to constructions of  $\chi$ . Let  $k_{g,M}(N) = g(\langle M, N \rangle)$ . Remember that  $\langle M, N \rangle$  is a construction of  $\varphi \wedge \psi$ . So  $k_{g,M}$  is a construction of  $\psi \rightarrow \chi$ : it maps constructions  $N$  of  $\psi$  to constructions of  $\chi$ . Now let  $h_g(M) = k_{g,M}$ . That's a function that maps constructions  $M$  of  $\varphi$  to constructions  $k_{g,M}$  of  $\psi \rightarrow \chi$ . Now let  $f(g) = h_g$ . That's a function that maps constructions  $g$  of  $(\varphi \wedge \psi) \rightarrow \chi$  to constructions of  $\varphi \rightarrow (\psi \rightarrow \chi)$ . Whew!

The statement  $\varphi \vee \neg\varphi$  is called the Law of Excluded Middle. We can prove it for some specific  $\varphi$  (e.g.,  $\perp \vee \neg\perp$ ), but not in general. This is because the intuitionistic disjunction requires a construction of one of the disjuncts, but there are statements which currently can neither be proved nor refuted (say, Goldbach's conjecture). However, you can't refute the law of excluded middle either: that is,  $\neg\neg(\varphi \vee \neg\varphi)$  holds.

**Example int.7.** To prove  $\neg\neg(\varphi \vee \neg\varphi)$ , we need a function  $f$  that transforms a construction of  $\neg(\varphi \vee \neg\varphi)$ , i.e., of  $(\varphi \vee (\varphi \rightarrow \perp)) \rightarrow \perp$ , into a construction of  $\perp$ . In other words, we need a function  $f$  such that  $f(g)$  is a construction of  $\perp$  if  $g$  is a construction of  $\neg(\varphi \vee \neg\varphi)$ .

Suppose  $g$  is a construction of  $\neg(\varphi \vee \neg\varphi)$ , i.e., a function that transforms a construction of  $\varphi \vee \neg\varphi$  into a construction of  $\perp$ . A construction of  $\varphi \vee \neg\varphi$  is a pair  $\langle s, M \rangle$  where either  $s = 1$  and  $M$  is a construction of  $\varphi$ , or  $s = 2$  and  $M$  is a construction of  $\neg\varphi$ . Let  $h_1$  be the function mapping a construction  $M_1$  of  $\varphi$  to a construction of  $\varphi \vee \neg\varphi$ : it maps  $M_1$  to  $\langle 1, M_1 \rangle$ . And let  $h_2$  be the function mapping a construction  $M_2$  of  $\neg\varphi$  to a construction of  $\varphi \vee \neg\varphi$ : it maps  $M_2$  to  $\langle 2, M_2 \rangle$ .

Let  $k$  be  $g \circ h_1$ : it is a function which, if given a construction of  $\varphi$ , returns a construction of  $\perp$ , i.e., it is a construction of  $\varphi \rightarrow \perp$  or  $\neg\varphi$ . Now let  $l$  be  $g \circ h_2$ . It is a function which, given a construction of  $\neg\varphi$ , provides a construction of  $\perp$ . Since  $k$  is a construction of  $\neg\varphi$ ,  $l(k)$  is a construction of  $\perp$ .

Together, what we've done is describe how we can turn a construction  $g$  of  $\neg(\varphi \vee \neg\varphi)$  into a construction of  $\perp$ , i.e., the function  $f$  mapping a construction  $g$  of  $\neg(\varphi \vee \neg\varphi)$  to the construction  $l(k)$  of  $\perp$  is a construction of  $\neg\neg(\varphi \vee \neg\varphi)$ .

As you can see, using the BHK interpretation to show the intuitionistic validity of **formulas** quickly becomes cumbersome and confusing. Luckily, there are better **derivation** systems for intuitionistic logic, and more precise semantic interpretations.

## int.4 Natural Deduction

Natural deduction without the  $\perp_C$  rules is a standard **derivation** system for intuitionistic logic. We repeat the rules here and indicate the motivation using the BHK interpretation. In each case, we can think of a rule which allows us to conclude that if the premises have constructions, so does the conclusion. int:int:ntd:  
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Since natural deduction **derivations** have undischarged assumptions, we should consider such a **derivation**, say, of  $\varphi$  from **undischarged** assumptions  $\Gamma$ , as a function that turns constructions of all  $\psi \in \Gamma$  into a construction of  $\varphi$ . If there is a **derivation** of  $\varphi$  from no **undischarged** assumptions, then there is a construction of  $\varphi$  in the sense of the BHK interpretation. For the purpose of the discussion, however, we'll suppress the  $\Gamma$  when not needed.

An assumption  $\varphi$  by itself is a **derivation** of  $\varphi$  from the **undischarged** assumption  $\varphi$ . This agrees with the BHK-interpretation: the identity function on constructions turns any construction of  $\varphi$  into a construction of  $\varphi$ .

### Conjunction

$$\frac{\varphi_1 \quad \varphi_2}{\varphi_1 \wedge \varphi_2} \wedge\text{Intro} \qquad \frac{\varphi_1 \wedge \varphi_2}{\varphi_i} \wedge\text{Elim}_i \quad i \in \{1, 2\}$$

Suppose we have constructions  $N_1, N_2$  of  $\varphi_1$  and  $\varphi_2$ , respectively. Then we also have a construction  $\varphi_1 \wedge \varphi_2$ , namely the pair  $\langle N_1, N_2 \rangle$ .

A construction of  $\varphi_1 \wedge \varphi_2$  on the BHK interpretation is a pair  $\langle N_1, N_2 \rangle$ . So assume we have such a pair. Then we also have a construction of each conjunct:  $N_1$  is a construction of  $\varphi_1$  and  $N_2$  is a construction of  $\varphi_2$ .

### Conditional

$$\frac{[\varphi]^u \quad \vdots \quad \psi}{\varphi \rightarrow \psi} \rightarrow\text{Intro} \qquad \frac{\varphi \rightarrow \psi \quad \varphi}{\psi} \rightarrow\text{Elim}$$

If we have a **derivation** of  $\psi$  from **undischarged** assumption  $\varphi$ , then there is a function  $f$  that turns constructions of  $\varphi$  into constructions of  $\psi$ . That same function is a construction of  $\varphi \rightarrow \psi$ . So, if the premise of  $\rightarrow$ Intro has a construction conditional on a construction of  $\varphi$ , the conclusion  $\varphi \rightarrow \psi$  has a construction.

On the other hand, suppose there are constructions  $N$  of  $\varphi$  and  $f$  of  $\varphi \rightarrow \psi$ . A construction of  $\varphi \rightarrow \psi$  is a function that turns constructions of  $\varphi$  into

constructions of  $\psi$ . So,  $f(N)$  is a construction of  $\psi$ , i.e., the conclusion of  $\rightarrow$ Elim has a construction.

## Disjunction

$$\begin{array}{c}
 \frac{\varphi_i}{\varphi_1 \vee \varphi_2} \vee\text{Intro}_i \quad i \in \{1, 2\} \\
 \\
 \begin{array}{c}
 [\varphi_1]^u \quad [\varphi_2]^u \\
 \vdots \quad \quad \quad \vdots \\
 \chi \quad \quad \quad \chi \\
 \hline
 u \frac{\varphi_1 \vee \varphi_2}{\chi} \vee\text{Elim}
 \end{array}
 \end{array}$$

If we have a construction  $N_i$  of  $\varphi_i$  we can turn it into a construction  $\langle i, N_i \rangle$  of  $\varphi_1 \vee \varphi_2$ . On the other hand, suppose we have a construction of  $\varphi_1 \vee \varphi_2$ , i.e., a pair  $\langle i, N_i \rangle$  where  $N_i$  is a construction of  $\varphi_i$ , and also functions  $f_1, f_2$ , which turn constructions of  $\varphi_1, \varphi_2$ , respectively, into constructions of  $\chi$ . Then  $f_i(N_i)$  is a construction of  $\chi$ , the conclusion of  $\vee$ Elim.

## Absurdity

$$\frac{\perp}{\varphi} \perp_I$$

If we have a **derivation** of  $\perp$  from **undischarged** assumptions  $\psi_1, \dots, \psi_n$ , then there is a function  $f(M_1, \dots, M_n)$  that turns constructions of  $\psi_1, \dots, \psi_n$  into a construction of  $\perp$ . Since  $\perp$  has no construction, there cannot be any constructions of all of  $\psi_1, \dots, \psi_n$  either. Hence,  $f$  also has the property that *if*  $M_1, \dots, M_n$  are constructions of  $\psi_1, \dots, \psi_n$ , respectively, *then*  $f(M_1, \dots, M_n)$  is a construction of  $\varphi$ .

## Rules for $\neg$

Since  $\neg\varphi$  is defined as  $\varphi \rightarrow \perp$ , we strictly speaking do not need rules for  $\neg$ . But if we did, this is what they'd look like:

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

## Examples of Derivations

1.  $\vdash \varphi \rightarrow (\neg\varphi \rightarrow \perp)$ , i.e.,  $\vdash \varphi \rightarrow ((\varphi \rightarrow \perp) \rightarrow \perp)$

$$\frac{\frac{\frac{[\varphi]^2}{\perp} \rightarrow\text{Elim}}{(\varphi \rightarrow \perp) \rightarrow \perp} \rightarrow\text{Intro}}{\varphi \rightarrow ((\varphi \rightarrow \perp) \rightarrow \perp)} \rightarrow\text{Intro}}{[\varphi \rightarrow \perp]^1}$$

2.  $\vdash ((\varphi \wedge \psi) \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \rightarrow \chi))$

$$\frac{\frac{\frac{\frac{[\varphi]^2}{\chi} \rightarrow\text{Intro}}{\psi \rightarrow \chi} \rightarrow\text{Intro}}{(\varphi \wedge \psi) \rightarrow \chi} \rightarrow\text{Intro}}{[(\varphi \wedge \psi) \rightarrow \chi]^3} \rightarrow\text{Elim}}{\frac{\frac{[\psi]^1}{\varphi \wedge \psi} \wedge\text{Intro}}{\varphi \rightarrow (\psi \rightarrow \chi)} \rightarrow\text{Intro}}{((\varphi \wedge \psi) \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \rightarrow \chi))} \rightarrow\text{Intro}}$$

3.  $\vdash \neg(\varphi \wedge \neg\varphi)$ , i.e.,  $\vdash (\varphi \wedge (\varphi \rightarrow \perp)) \rightarrow \perp$

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

4.  $\vdash \neg\neg(\varphi \vee \neg\varphi)$ , i.e.,  $\vdash ((\varphi \vee (\varphi \rightarrow \perp)) \rightarrow \perp) \rightarrow \perp$

$$\frac{\frac{\frac{\frac{[\varphi]^1}{\varphi \vee (\varphi \rightarrow \perp)} \vee\text{Intro}}{((\varphi \vee (\varphi \rightarrow \perp)) \rightarrow \perp)^2} \rightarrow\text{Elim}}{\frac{\frac{\perp}{\varphi \rightarrow \perp} \rightarrow\text{Intro}}{\varphi \vee (\varphi \rightarrow \perp)} \vee\text{Intro}} \rightarrow\text{Elim}}{\frac{\perp}{((\varphi \vee (\varphi \rightarrow \perp)) \rightarrow \perp) \rightarrow \perp} \rightarrow\text{Intro}} \rightarrow\text{Intro}}$$

**Proposition int.8.** *If  $\Gamma \vdash \varphi$  in classical logic,  $\Gamma \vdash \varphi$  in intuitionistic logic. In particular, if  $\varphi$  is an intuitionistic theorem, it is also a classical theorem.*

*Proof.* Every natural deduction rule is also a rule in classical natural deduction, so every **derivation** in intuitionistic logic is also a **derivation** in classical logic.  $\square$



## int.5 Axiomatic Derivations

int:int:axd:  
sec  
Axiomatic **derivations** for intuitionistic propositional logic are the conceptually simplest, and historically first, **derivation** systems. They work just as in classical propositional logic.

**Definition int.9 (Derivability).** If  $\Gamma$  is a set of **formulas** of  $\mathcal{L}$  then a **derivation** from  $\Gamma$  is a finite sequence  $\varphi_1, \dots, \varphi_n$  of **formulas** where for each  $i \leq n$  one of the following holds:

1.  $\varphi_i \in \Gamma$ ; or
2.  $\varphi_i$  is an axiom; or
3.  $\varphi_i$  follows from some  $\varphi_j$  and  $\varphi_k$  with  $j < i$  and  $k < i$  by modus ponens, i.e.,  $\varphi_k \equiv \varphi_j \rightarrow \varphi_i$ .

**Definition int.10 (Axioms).** The set of  $Ax_0$  of *axioms* for the intuitionistic propositional logic are all **formulas** of the following forms:

int:int:axd:	$(\varphi \wedge \psi) \rightarrow \varphi$	(int.1)
ax:land1 int:int:axd:	$(\varphi \wedge \psi) \rightarrow \psi$	(int.2)
ax:land2 int:int:axd:	$\varphi \rightarrow (\psi \rightarrow (\varphi \wedge \psi))$	(int.3)
ax:land3 int:int:axd:	$\varphi \rightarrow (\varphi \vee \psi)$	(int.4)
ax:lor1 int:int:axd:	$\varphi \rightarrow (\psi \vee \varphi)$	(int.5)
ax:lor2 int:int:axd:	$(\varphi \rightarrow \chi) \rightarrow ((\psi \rightarrow \chi) \rightarrow ((\varphi \vee \psi) \rightarrow \chi))$	(int.6)
ax:lor3 int:int:axd:	$\varphi \rightarrow (\psi \rightarrow \varphi)$	(int.7)
ax:lif1 int:int:axd:	$(\varphi \rightarrow (\psi \rightarrow \chi)) \rightarrow ((\varphi \rightarrow \psi) \rightarrow (\varphi \rightarrow \chi))$	(int.8)
ax:lif2 int:int:axd:	$\perp \rightarrow \varphi$	(int.9)
ax:false1		(int.10)

**Definition int.11 (Derivability).** A **formula**  $\varphi$  is **derivable** from  $\Gamma$ , written  $\Gamma \vdash \varphi$ , if there is a **derivation** from  $\Gamma$  ending in  $\varphi$ .

**Definition int.12 (Theorems).** A **formula**  $\varphi$  is a *theorem* if there is a **derivation** of  $\varphi$  from the empty set. We write  $\vdash \varphi$  if  $\varphi$  is a theorem and  $\not\vdash \varphi$  if it is not.

**Proposition int.13.** *If  $\Gamma \vdash \varphi$  in classical logic,  $\Gamma \vdash \varphi$  in intuitionistic logic. In particular, if  $\varphi$  is an intuitionistic theorem, it is also a classical theorem.*

*Proof.* Every intuitionistic axiom is also a classical axiom, so every **derivation** in intuitionistic logic is also a **derivation** in classical logic.  $\square$

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