

Hamilton - Logic for Mathematicians  
Notes and Solutions

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# Chapter 1

## Informal statement calculus

### 1.1 Statements and connectives

#### Solutions to exercises

1. (a)  $(D \wedge P) \rightarrow T$   
(b)  $J \rightarrow E$   
(c)  $\sim J \rightarrow ((S \vee R) \wedge \sim E)$   
(d)  $(X \wedge Y) \rightarrow \sim Z$   
(e)  $M \vee H$   
(f)  $(\sim M) \rightarrow H$   
(g)  $S \leftrightarrow (E \vee O)$   
(h)  $X \rightarrow (Y \rightarrow \sim Z)$
2. (a) The statements (a) and (d) have the same form.  
(b) The statements (d) and (h) have the same meaning ((a) also has the same form as (d), so it could also be interpreted as having the same meaning). The statements (e) and (f) have the same meaning.

### 1.2 Truth functions and truth tables

*Note.* For readability of truth tables, the value 1 will be used for  $T$  and the value 0 will be used for  $F$ . The final operation to be evaluated, which indicates the truth value of the final statement form, will be underlined.

#### Solutions to exercises

3. Because truth tables are tedious to write, only (a) has been done. The rest are done similarly.  
(a) Observe the truth table below.

$((\sim p) \wedge (\sim q))$	$\underline{\phantom{0}}$	$(\sim q)$
0	1	0
0	1	0
1	0	0
1	0	1

4. When  $p$  and  $q$  take on particular values, the values of  $((\sim p) \vee q)$  and  $(p \rightarrow q)$  are identical. This can be shown by constructing truth tables, but that process is omitted here. Similarly,  $((\sim p) \rightarrow (q \vee r))$  can be shown to give rise to the same truth function as  $((\sim q) \rightarrow ((\sim r) \rightarrow p))$  by constructing truth tables.
5. The statement forms (a), (b), and (d) are tautologies.
6. Because truth tables are tedious to write, only (a) has been done. The rest are done similarly.

(a) The truth table for  $(p \rightarrow q)$  is seen below.

$(p \rightarrow q)$	$\underline{\phantom{0}}$	$q$
1	1	1
1	0	0
0	1	1
0	1	0

The truth table for  $((\sim q) \rightarrow (\sim p))$  is seen below.

$((\sim q) \rightarrow (\sim p))$	$\underline{\phantom{0}}$	$(\sim p)$
0	1	0
0	1	1
1	0	0
1	0	1

Notice that when  $p$  and  $q$  take on the same values in both truth tables, the values underneath the underlined  $\rightarrow$ , which indicate the final operation to be evaluated, and therefore the truth value of the statement form, are identical. Therefore, the two statement forms are logically equivalent.

7. When  $p$  and  $q$  are both true, the value  $((\sim p) \rightarrow q) \rightarrow (p \rightarrow (\sim q))$  is false, so the statement form is not a tautology.

Let  $\mathcal{A} = \mathcal{B} = (p \rightarrow p)$ . Notice that this is a tautology, and for that matter, any tautology can be substituted here. The value of  $((\sim \mathcal{A}) \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow (\sim \mathcal{B}))$  can then be seen to be a contradiction by constructing the appropriate truth table or in the same way that the above statement form was seen to be false.

### 1.3 Rules for manipulation and substitution

**Proposition 1.10.** If  $\mathcal{A}$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  are tautologies, then  $\mathcal{B}$  is a tautology.

*Proof.* Suppose for a contradiction that  $\mathcal{A}$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  are tautologies, while  $\mathcal{B}$  is not a tautology. Then there is an assignment of truth values to the statement variables of  $\mathcal{B}$  such that  $\mathcal{B}$  is given the value  $F$ , while  $\mathcal{A}$ , being a tautology is necessarily given the value  $T$ . But then  $(\mathcal{A} \rightarrow \mathcal{B})$  must have the value  $F$ , which contradicts it being a tautology.  $\square$

**Proposition 1.11.** Let  $\mathcal{A}$  be the statement form in which the statement variables  $p_1, p_2, \dots, p_n$  appear, and let  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n$  be any statement forms. If  $\mathcal{A}$  is a tautology, then  $\mathcal{B}$ , the statement form obtained by replacing  $p_i$  in  $\mathcal{A}$  with  $\mathcal{A}_i$ , is also a tautology.

*Proof.* By definition of  $\mathcal{B}$ , any assignment of truth values to  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n$  in  $\mathcal{B}$ , would result in the same truth value of  $\mathcal{A}$  if the same truth values had been assigned to  $p_1, p_2, \dots, p_n$ . The truth value of  $\mathcal{A}$  is  $T$ , and so the truth value of  $\mathcal{B}$  must also be  $T$ , making it a tautology as well.  $\square$

*Note.* This proof is not entirely rigorous. See the note in Proposition 1.15.

*Note.* It is important to note that if  $\mathcal{A}$  is not a tautology, then  $\mathcal{B}$  may not be an equivalent truth function (see Exercise 7). However, if  $\mathcal{A}$  is a contradiction, then  $\mathcal{B}$  must be a contradiction, and the proof of this is nearly identical.

**Proposition 1.12.** For any statement forms  $\mathcal{A}$  and  $\mathcal{B}$ ,  $(\sim (\mathcal{A} \wedge \mathcal{B}))$  is logically equivalent to  $((\sim \mathcal{A}) \vee (\sim \mathcal{B}))$ , and  $(\sim (\mathcal{A} \vee \mathcal{B}))$  is logically equivalent to  $((\sim \mathcal{A}) \wedge (\sim \mathcal{B}))$ .

*Proof.* By Example 1.8 in the book or by creating tables, it can be easily seen that

$$(\sim (p \wedge q)) \leftrightarrow ((\sim p) \vee (\sim q)), \text{ and } (\sim (p \vee q)) \leftrightarrow ((\sim p) \wedge (\sim q))$$

is a tautology. By application of Proposition 1.11, we may conclude that if any statement form with  $p$  and  $q$  substituted for the statement forms  $\mathcal{A}$  and  $\mathcal{B}$  would be a tautology as well, i.e.,

$$(\sim (\mathcal{A} \wedge \mathcal{B})) \leftrightarrow ((\sim \mathcal{A}) \vee (\sim \mathcal{B})), \text{ and } (\sim (\mathcal{A} \vee \mathcal{B})) \leftrightarrow ((\sim \mathcal{A}) \wedge (\sim \mathcal{B}))$$

is a tautology, and therefore  $(\sim (\mathcal{A} \wedge \mathcal{B}))$  is logically equivalent to  $((\sim \mathcal{A}) \vee (\sim \mathcal{B}))$ , and  $(\sim (\mathcal{A} \vee \mathcal{B}))$  is logically equivalent to  $((\sim \mathcal{A}) \wedge (\sim \mathcal{B}))$ .  $\square$

**Proposition 1.14.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be logically equivalent statement forms. Let  $\mathcal{A}'$  be a statement form in which  $\mathcal{A}$  appears. Let  $\mathcal{B}'$  be the statement form in which every instance of  $\mathcal{A}$  is replaced by  $\mathcal{A}'$ . The statement forms  $\mathcal{A}'$  and  $\mathcal{B}'$  are logically equivalent.

*Proof.* We wish to show that  $\mathcal{A}' \leftrightarrow \mathcal{B}'$  is a tautology, which is done by showing that the truth values of  $\mathcal{A}'$  and  $\mathcal{B}'$  always match under some arbitrary assignment of truth values to any statement variables. Consider the truth value of  $\mathcal{A}'$  under some assignment of truth values. The truth value of  $\mathcal{B}'$  must be the same, since it differs only in having  $\mathcal{B}$  in place of  $\mathcal{A}$ , and  $\mathcal{A}$  and  $\mathcal{B}$  are logically equivalent. Therefore,  $\mathcal{A}' \leftrightarrow \mathcal{B}'$  must be a tautology, and so  $\mathcal{A}'$  and  $\mathcal{B}'$  must be logically equivalent.  $\square$

*Note.* This proof is not entirely rigorous. See the note in Proposition 1.15.

For the remainder of Chapter 1, a statement form involving only the connectives  $\sim, \wedge$  and  $\vee$  will be called a *restricted statement form*.

**Proposition 1.15.** Let  $\mathcal{A}$  be a restricted form and let  $\mathcal{A}'$  be the statement form obtained from  $\mathcal{A}$  by interchanging  $\wedge$  and  $\vee$  and replacing every statement variable  $p$  by  $(\sim p)$ . The statement forms  $\mathcal{A}$  and  $\mathcal{A}'$  are logically equivalent.

*Proof.* The proof is by strong induction on  $n$ , the number of connectives which appear in  $\mathcal{A}$ .

(base case) It may be the case that  $n = 0$ , i.e.,  $\mathcal{A}$  has no connectives, so  $\mathcal{A}$  is  $p$ , where  $p$  is any statement variable. Then  $\mathcal{A}'$  must be  $(\sim p)$ , which is logically equivalent to  $(\sim \mathcal{A})$ .

(inductive step) It may be the case that  $n > 0$ , i.e.,  $\mathcal{A}$  has one or more connectives. Suppose as an inductive hypothesis that any restricted statement form with fewer than  $n$  connectives is equivalent to the statement form obtained by interchanging  $\wedge$  and  $\vee$  and replacing each statement variable by its negation. Since  $\mathcal{A}$  has one or more connectives, there are three cases to consider, based on the final connective in  $\mathcal{A}$  to be evaluated.

1. It may be that  $\mathcal{A}$  has the form  $(\sim \mathcal{B})$ , in which case  $\mathcal{A}'$  must be  $(\sim \mathcal{B}')$ , since the only instances of  $\wedge$ ,  $\vee$ , and any statement variables must necessarily appear in  $\mathcal{B}$ . By the inductive hypothesis, since  $\mathcal{B}$  has fewer than  $n$  connectives,  $\mathcal{B}'$  is logically equivalent to  $(\sim \mathcal{B})$ . By Proposition 1.14,  $(\sim \mathcal{B}')$  must be logically equivalent to  $(\sim (\sim \mathcal{B}))$  which is  $(\sim \mathcal{A})$ . Since  $(\sim \mathcal{B}')$  is  $\mathcal{A}'$ , we have proved that  $\mathcal{A}'$  is logically equivalent to  $(\sim \mathcal{A})$ , as desired.
2. It may be that  $\mathcal{A}$  has the form  $(\mathcal{B} \vee \mathcal{C})$ . Then  $\mathcal{A}'$  must be  $(\mathcal{B}' \wedge \mathcal{C}')$ . By the induction hypothesis,  $\mathcal{B}'$ , which must have fewer than  $n$  connectives, is logically equivalent to  $(\sim \mathcal{B})$ . By proposition 1.14,  $(\mathcal{B}' \wedge \mathcal{C}')$  must be logically equivalent to  $((\sim \mathcal{B}) \wedge \mathcal{C}')$ , which must again be equivalent to  $((\sim \mathcal{B}) \wedge (\sim \mathcal{C}))$  by the same reasoning applied to  $\mathcal{C}'$ , which must finally be equivalent to  $(\sim (\mathcal{B} \vee \mathcal{C}))$  by Proposition 1.11, and this final statement form is  $(\sim \mathcal{A})$ , as desired.
3. It may be that  $\mathcal{A}$  has the form  $(\mathcal{B} \wedge \mathcal{C})$ . Then  $\mathcal{A}'$  must be  $(\mathcal{B}' \vee \mathcal{C}')$ . By the induction hypothesis,  $\mathcal{B}'$ , which must have fewer than  $n$  connectives, is logically equivalent to  $(\sim \mathcal{B})$ . By proposition 1.14,  $(\mathcal{B}' \vee \mathcal{C}')$  must be logically equivalent to  $((\sim \mathcal{B}) \vee \mathcal{C}')$ , which must again be equivalent to  $((\sim \mathcal{B}) \vee (\sim \mathcal{C}))$  by the same reasoning applied to  $\mathcal{C}'$ , which must finally be equivalent to  $(\sim (\mathcal{B} \wedge \mathcal{C}))$  by Proposition 1.11, and this final statement form is  $(\sim \mathcal{A})$ , as desired.

Verifying the desired property for all three cases finishes the inductive step, thereby concluding the induction and the proof.  $\square$

*Note.* Whenever induction appears in the textbook, it is referring to strong induction. The general framework for induction seen in this proof will resemble all other inductive proofs seen throughout the manual. Strictly speaking, strong induction has no base case, but practically speaking, there are usually one or more special values of the number being inducted on which require special attention since they do not rely on the inductive hypothesis. These will be referred to as the base cases.

*Note.* The proofs of Proposition 1.14 and Proposition 1.10 could have been made rigorous by being done similarly, but an inductive proof would have been unnecessarily lengthy to prove the propositions, which were obvious.

**Corollary 1.16.** Let  $p_1, p_2, \dots, p_n$  be statement variables.

(i) The statement forms

$$(\sim (p_1 \wedge p_2 \wedge \cdots \wedge p_n)) \text{ and } ((\sim p_1) \vee (\sim p_2) \vee \cdots \vee (\sim p_n))$$

are logically equivalent.

(ii) The statement forms

$$(\sim (p_1 \vee p_2 \vee \cdots \vee p_n)) \text{ and } ((\sim p_1) \wedge (\sim p_2) \wedge \cdots \wedge (\sim p_n))$$

are logically equivalent.

*Proof.* For (i), let  $\mathcal{A}$  be the statement form

$$(p_1 \wedge p_2 \wedge \cdots \wedge p_n).$$

Then interchanging  $\wedge$  and  $\vee$  and negating each statement variable results in

$$((\sim p_1) \vee (\sim p_2) \vee \cdots \vee (\sim p_n)).$$

By Proposition 1.15, this is equivalent to  $(\sim \mathcal{A})$ , which is

$$(\sim (p_1 \wedge p_2 \wedge \cdots \wedge p_n)),$$

as desired. Part (ii) is proved in the same way as (i).  $\square$

**Proposition 1.17** (De Morgan's Laws). Let  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n$  be statement forms.

(i) The statement forms

$$(\sim (\mathcal{A}_1 \wedge \mathcal{A}_2 \wedge \cdots \wedge \mathcal{A}_n)) \text{ and } ((\sim \mathcal{A}_1) \vee (\sim \mathcal{A}_2) \vee \cdots \vee (\sim \mathcal{A}_n))$$

are logically equivalent.

(ii) The statement forms

$$(\sim (\mathcal{A}_1 \vee \mathcal{A}_2 \vee \cdots \vee \mathcal{A}_n)) \text{ and } ((\sim \mathcal{A}_1) \wedge (\sim \mathcal{A}_2) \wedge \cdots \wedge (\sim \mathcal{A}_n))$$

are logically equivalent.

*Proof.* This is an application of Proposition 1.10 to Corollary 1.16.  $\square$

## Solutions to exercises

8. Since (a) - (d) are proved in the same way, only (a) will be done, and the rest will be omitted.

(a) Let  $p, q, r$  be statement letters. The following truth table demonstrates that  $((p \vee (q \vee r)) \leftrightarrow ((p \vee q) \vee r))$  is a tautology.

$((p$	$\vee$	$(q$	$\vee$	$r))$	$\leftrightarrow$	$((p$	$\vee$	$q)$	$\vee$	$r))$
1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	0	1	1	1	1	1	0
1	1	0	1	1	1	1	1	0	1	1
1	1	0	0	0	1	1	1	0	1	0
0	1	1	1	1	1	0	1	1	1	1
0	1	1	1	0	1	0	1	1	1	0
0	1	0	1	1	1	0	0	0	1	1
0	0	0	0	0	1	0	0	0	0	0

By proposition 1.10, the statement form  $((\mathcal{A} \vee (\mathcal{B} \vee \mathcal{C})) \leftrightarrow ((\mathcal{A} \vee \mathcal{B}) \vee \mathcal{C}))$  is a tautology, where  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  are any statement forms. Therefore,  $((\mathcal{A} \vee (\mathcal{B} \vee \mathcal{C}))$  is logically equivalent to  $((\mathcal{A} \vee \mathcal{B}) \vee \mathcal{C}))$ .

9. (a) The statement form  $((p \wedge q) \rightarrow p)$  can be seen to be a tautology by creating a truth table for it. By Proposition 1.10,  $((\mathcal{A} \wedge \mathcal{B}) \rightarrow \mathcal{A})$  must be a tautology as well.
- (b) The statement form  $((p \wedge q) \rightarrow q)$  can be seen to be a tautology by creating a truth table for it. By Proposition 1.10,  $((\mathcal{A} \wedge \mathcal{B}) \rightarrow \mathcal{B})$  must be a tautology as well.
10. By part (a) of Example 1.4 in the book, it can be seen that  $((\sim p) \vee q)$  is logically equivalent to  $(p \rightarrow q)$ , and so  $((\sim p) \vee q) \rightarrow (p \rightarrow q)$  is a tautology. By Proposition 1.10, for any statements forms  $\mathcal{A}$  and  $\mathcal{B}$ ,  $((\sim \mathcal{A}) \vee \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})$  must be a tautology as well, and so  $((\sim \mathcal{A}) \vee \mathcal{B})$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  must be logically equivalent. This equivalence will be referred to as  $(\star)$ .

Therefore, the following statement forms must be equivalent by the substitution on the right and Proposition 1.14. Note that  $\mathcal{C} \equiv \mathcal{D}$  indicates that the statement forms  $\mathcal{C}$  and  $\mathcal{D}$  are logically equivalent.

$$\begin{array}{ll}
 ((p \rightarrow q) \rightarrow r) & \\
 ((\sim (p \rightarrow q)) \vee r) & ((p \rightarrow q) \rightarrow r) \equiv ((\sim (p \rightarrow q)) \vee r), \text{ by } (\star) \\
 ((\sim ((\sim p) \vee q)) \vee r) & (p \rightarrow q) \equiv ((\sim p) \vee q), \text{ by } (\star)
 \end{array}$$

11. Let  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  be statement forms. The following equivalences will be used.

- (i)  $(\mathcal{A} \vee \mathcal{B})$  is logically equivalent to  $(\mathcal{B} \vee \mathcal{A})$ .
- (ii)  $(\mathcal{A} \rightarrow \mathcal{B})$  is logically equivalent to  $((\sim \mathcal{A}) \vee \mathcal{B})$ .
- (iii)  $(\sim (\sim \mathcal{A}))$  is logically equivalent to  $\mathcal{A}$ .
- (iv)  $(\mathcal{A} \rightarrow \mathcal{B})$  is logically equivalent to  $((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A}))$ .
- (v)  $(\mathcal{A} \vee \mathcal{A})$  is logically equivalent to  $\mathcal{A}$ .

In the sub-exercises, successive statement forms are equivalent by substitution via Proposition 1.14 of an equivalent statement form indicated by the braces. The column on the right justifies the equivalence of substituted statement forms.

- (a) The statement form  $((\sim (p \vee (\sim q))) \rightarrow (q \rightarrow r))$  is equivalent to:

$$((\sim \underbrace{((\sim q) \vee p)}) \rightarrow (q \rightarrow r)) \quad \text{(i)}$$

$$((\sim \underbrace{(q \rightarrow p)}) \rightarrow (q \rightarrow r)) \quad \text{(ii)}$$

$$((\sim (q \rightarrow p)) \rightarrow \underbrace{((\sim q) \vee r)}) \quad \text{(ii)}$$



(b) The statement form  $((\sim(p \vee (\sim q))) \rightarrow (q \rightarrow r))$  is equivalent to:

$$\begin{aligned}
 & \underbrace{(((\sim p) \wedge (\sim(\sim q))))}_{\text{Proposition 1.17}} \rightarrow (q \rightarrow r)) \\
 & (((\sim p) \wedge \underbrace{q}_{\text{(iii)}}) \rightarrow (q \rightarrow r)) \quad \text{(iii)} \\
 & (((\sim p) \wedge q) \rightarrow \underbrace{((\sim q) \vee r)}) \quad \text{(ii)} \\
 & (((\sim p) \wedge q) \rightarrow \underbrace{(\sim(\sim((\sim q) \vee r))))}_{\text{(iii)}})) \quad \text{(iii)} \\
 & (((\sim p) \wedge q) \rightarrow \underbrace{(\sim((\sim(\sim q)) \wedge (\sim r))))}_{\text{Proposition 1.17}})) \\
 & (((\sim p) \wedge q) \rightarrow \underbrace{(\sim(\underbrace{q}_{\text{(iii)}} \wedge (\sim r))))}_{\text{(iii)}})) \quad \text{(iii)}
 \end{aligned}$$

(c) The statement form  $((\sim(p \vee (\sim q))) \rightarrow (q \rightarrow r))$  is equivalent to:

$$\begin{aligned}
 & \underbrace{((\sim(q \rightarrow r)) \rightarrow (\sim(\sim(p \vee (\sim q))))))}_{\text{(iv)}} \quad \text{(iv)} \\
 & ((\sim(q \rightarrow r)) \rightarrow \underbrace{(p \vee (\sim q))}_{\text{(iii)}})) \quad \text{(iii)} \\
 & ((\sim(q \rightarrow r)) \rightarrow \underbrace{((\sim q) \vee p)}) \quad \text{(i)} \\
 & ((\sim(q \rightarrow r)) \rightarrow \underbrace{(q \rightarrow p)}) \quad \text{(ii)} \\
 & ((\sim(\underbrace{((\sim q) \vee r)})_{\text{(ii)}}) \rightarrow (q \rightarrow p)) \quad \text{(ii)}
 \end{aligned}$$

(d) The statement form  $((\sim(p \vee (\sim q))) \rightarrow (q \rightarrow r))$  is equivalent to:

$$\begin{aligned}
 & \underbrace{((\sim((\sim q) \vee r)) \rightarrow (q \rightarrow p))}_{\text{Exercise 11, part (c)}} \quad \text{Exercise 11, part (c)} \\
 & \underbrace{(((\sim(\sim q)) \wedge (\sim r)) \rightarrow (q \rightarrow p))}_{\text{Proposition 1.17}} \quad \text{Proposition 1.17} \\
 & ((\underbrace{q}_{\text{(iii)}} \wedge (\sim r)) \rightarrow (q \rightarrow p)) \quad \text{(iii)} \\
 & \underbrace{((\sim(q \wedge (\sim r))) \vee (q \rightarrow p))}_{\text{(ii)}} \quad \text{(ii)} \\
 & \underbrace{(((\sim q) \vee (\sim(\sim r))) \vee (q \rightarrow p))}_{\text{Proposition 1.17}} \quad \text{Proposition 1.17} \\
 & (((\sim q) \vee \underbrace{r}_{\text{(iii)}}) \vee (q \rightarrow p)) \quad \text{(iii)} \\
 & (((\sim q) \vee r) \vee \underbrace{((\sim q) \vee p)}) \quad \text{(ii)} \\
 & \underbrace{((r \vee (\sim q)) \vee ((\sim q) \vee p))}_{\text{(i)}} \quad \text{(i)} \\
 & \underbrace{(((\sim q) \vee (\sim q)) \vee (p \vee r))}_{\text{associativity and commutativity of } \vee} \quad \text{associativity and commutativity of } \vee \\
 & \underbrace{((\sim q) \vee (p \vee r))}_{\text{(v)}} \quad \text{(v)} \\
 & (q \rightarrow (p \vee r)) \quad \text{(ii)}
 \end{aligned}$$

*Note.* In (d), a few tedious steps were skipped when invoking the associativity and commutativity of  $\vee$ . An inductive proof could be used to prove that any parenthesization of  $\mathcal{A}_1 \vee \mathcal{A}_2 \vee \dots \mathcal{A}_n$  is equivalent to  $\mathcal{A}_1 \vee \mathcal{A}_2 \vee \dots \mathcal{A}_n$  to make the proof more rigorous, but it is more pedantic than necessary.

## 1.4 Normal forms

**Proposition 1.18.** Every statement form is equivalent to a restricted statement form.

*Proof.* Let  $\mathcal{A}$  be a statement form in which the statement variables  $p_1, \dots, p_n$  occur. It may be the case that  $\mathcal{A}$  is a contradiction, in which case  $\mathcal{A}$  is equivalent to

$$((p_1 \wedge (\sim p_1)) \wedge p_2 \wedge \dots \wedge p_n),$$

a statement form with  $n$  statement variables which is a contradiction.

Now if  $\mathcal{A}$  is not a contradiction, then consider the  $2^n$  possible assignments of truth values to the statement variables. For each assignment indexed by  $k$ , let  $Q_k$  be the statement form defined by

$$q_1 \wedge \dots \wedge q_n,$$

where each  $q_i$  is defined as  $p_i$  if  $p_i$  is true under the particular assignment or  $(\sim p_i)$  if  $p_i$  is false under the particular assignment.

Notice that, by construction,  $Q_k$  is true under the  $k$ th assignment. Consider a different assignment of truth values to  $p_1, \dots, p_n$ . Then it must assign some statement variable, say  $p_i$ , a different truth value. Therefore, by construction,  $q_i$  must be either  $(\sim p_i)$  if  $p_i$  is true or  $p_i$  if  $p_i$  is false. In either case  $q_i$  be false, and so  $Q_k$  must be false under the assignment which is not the  $k$ th one.

Therefore,  $Q_k$  is true if and only if the assignment of statement variables is the  $k$ th one. In other words, there is a one-to-one correspondence between each  $Q_i$  and each assignment of truth values to the statement variables.

So let  $\{R_1, R_2, \dots, R_j\}$  be a set such that each element is a distinct  $Q_i$  that corresponds to an assignment of truth values which makes  $\mathcal{A}$  true. Notice that  $\mathcal{A}$  was assumed to not be a contradiction, so the set exists. Consider the statement form  $R_1 \vee \dots \vee R_j$ . By construction, it is a restricted statement form and is true only when  $\mathcal{A}$  is true, i.e., it is logically equivalent to  $\mathcal{A}$ , as desired.  $\square$

*Note.* This proposition is slightly different in meaning from the textbook.

A statement form of the form  $P_1 \vee \dots \vee P_n$ , where each  $P_i$  is  $(p_1 \wedge \dots \wedge p_j)$  for statement variables  $p_i, \dots, p_j$  is said to be in *disjunctive normal form*.

A statement form of the form  $P_1 \wedge \dots \wedge P_n$ , where each  $P_i$  is  $(p_1 \vee \dots \vee p_j)$  for statement variables  $p_i, \dots, p_j$  is said to be in *conjunctive normal form*.

*Note.* These definitions are slightly more general than the ones in the textbook. Here, every  $P_i$  need not be of a fixed length.

**Corollary 1.20.** Every statement form which is not a contradiction is equivalent to a statement form in disjunctive normal form.

*Proof.* Let  $\mathcal{A}$  be a statement form. The constructed statement form in Proposition 1.18 is in disjunctive normal form and logically equivalent to  $\mathcal{A}$ . Therefore,  $\mathcal{A}$  is equivalent to a statement form in disjunctive normal form.  $\square$

*Note.* By the definition used in this manual, we need not restrict the statement form to not be a contradiction.

**Corollary 1.21.** Every statement form which is not a tautology is equivalent to a statement form in conjunctive normal form.

*Proof.* Let  $\mathcal{A}$  be a statement form which is not a tautology in which the statement variables  $p_1, \dots, p_n$  appear. Then  $(\sim \mathcal{A})$  is not a contradiction, so it is equivalent to a statement form  $Q$  which has the form  $(Q_1 \vee \dots \vee Q_k)$ , where each  $Q_i$  is of the form  $q_1 \wedge \dots \wedge q_n$ , where each  $q_j$  is either  $p_j$  or  $(\sim p_j)$ . By Proposition 1.17,  $(\sim Q)$  must be

$$((\sim q_1) \wedge \dots \wedge (\sim q_n))$$

which is logically equivalent to  $(\sim (\sim \mathcal{A}))$ , which is logically equivalent to  $\mathcal{A}$ . Now replacing each  $(\sim (\sim p_i))$  occurring in  $(\sim Q)$  with  $p_i$  using Proposition 1.14 yields a statement form in conjunctive normal form which is equivalent to  $\mathcal{A}$ , as desired.  $\square$

*Note.* By the definition used in this manual, we need not restrict the statement form to not be a tautology.

## Solutions to exercises

12. (a) First we find all assignments of truth values such that  $(p \leftrightarrow q)$  is true. The only assignments are when  $p$  and  $q$  are both assigned the value  $T$  or both assigned the value  $F$ . So continuing in the way described in Proposition 1.18, we see that the statement form

$$(p \wedge q) \vee ((\sim p) \wedge (\sim q))$$

is in disjunctive normal form and logically equivalent to  $(p \leftrightarrow q)$ .

The remaining sub-exercises are done in the same way.

- (b) The statement form

$$\begin{array}{ccccccc} (p \wedge q \wedge r) & & & & & & \vee \\ (p \wedge (\sim q) \wedge r) & \vee & (p \wedge (\sim q) \wedge (\sim r)) & & & & \vee \\ ((\sim p) \wedge q \wedge r) & \vee & ((\sim p) \wedge q \wedge (\sim r)) & & & & \vee \\ ((\sim p) \wedge (\sim q) \wedge r) & \vee & ((\sim p) \wedge (\sim q) \wedge (\sim r)) & & & & \end{array}$$

in disjunctive normal form is logically equivalent to  $(p \rightarrow ((\sim q) \vee r))$ .

- (c) The statement form  $((p \wedge q) \vee ((\sim q) \leftrightarrow r))$  is logically equivalent to

$$((\sim p) \wedge (\sim q) \wedge r) \vee ((\sim p) \wedge q \wedge (\sim r)) \vee (p \wedge (\sim q) \wedge r) \vee (p \wedge q \wedge (\sim r)) \vee (p \wedge q \wedge r),$$

which is in disjunctive normal form.

- (d) The statement form  $\sim ((p \rightarrow (\sim q)) \rightarrow r)$  is logically equivalent to

$$(((\sim p) \wedge (\sim q) \wedge (\sim r)) \vee (p \wedge (\sim q) \wedge r) \vee (p \wedge (\sim q) \wedge (\sim r))),$$

which is in disjunctive normal form.

- (e) The statement form  $((p \rightarrow q) \rightarrow r) \rightarrow s$  is logically equivalent to

$$\begin{aligned}
 & ((\sim p) \wedge (\sim q) \wedge (\sim r) \wedge (\sim s)) \quad \vee \\
 & ((\sim p) \wedge (\sim q) \wedge (\sim r) \wedge s) \quad \vee \\
 & (p \wedge q \wedge (\sim r) \wedge (\sim s)) \quad \vee \\
 & (p \wedge q \wedge (\sim r) \wedge s) \quad \vee \\
 & ((\sim p) \wedge q \wedge (\sim r) \wedge s) \quad \vee \\
 & ((\sim p) \wedge q \wedge r \wedge s) \quad \vee \\
 & ((\sim p) \wedge q \wedge r \wedge (\sim s)) \quad \vee \\
 & (p \wedge (\sim q) \wedge r \wedge s) \quad \vee \\
 & (p \wedge q \wedge (\sim r) \wedge (\sim s)) \quad \vee \\
 & (p \wedge q \wedge (\sim r) \wedge s) \quad \vee \\
 & (p \wedge q \wedge r \wedge s)
 \end{aligned}$$

which is in disjunctive normal form.

13. (a) We first negate the statement form to obtain  $\sim (((\sim p) \vee q) \rightarrow r)$ , and by using the method used in the previous exercise, we find that the statement form

$$(((\sim p) \wedge (\sim q) \wedge (\sim r)) \vee ((\sim p) \wedge q \wedge (\sim r)) \vee (p \wedge q \wedge (\sim r)))$$

is in disjunctive normal form and is logically equivalent. By Proposition 1.17, we negate the above statement form to obtain

$$((p \vee q \vee r) \wedge (p \vee (\sim q) \vee r) \wedge ((\sim p) \vee (\sim q) \vee r)),$$

which is logically equivalent to  $((\sim p) \vee q) \rightarrow r$  and is in conjunctive normal form, as desired.

The remaining sub-exercises are done similarly.

- (b) The statement form  $((p \vee (\sim q)) \wedge ((\sim p) \vee q))$  is in conjunctive normal form and is logically equivalent to  $(p \leftrightarrow q)$ .
- (c) The statement form  $\sim ((p \wedge q \wedge r) \vee ((\sim p) \wedge (\sim q) \wedge r))$  is logically equivalent to the statement form

$$\begin{aligned}
 & ((\sim p) \wedge (\sim q) \wedge (\sim r)) \quad \vee \\
 & ((\sim p) \wedge q \wedge (\sim r)) \quad \vee \\
 & ((\sim p) \wedge q \wedge r) \quad \vee \\
 & (p \wedge (\sim q) \wedge (\sim r)) \quad \vee \\
 & (p \wedge (\sim q) \wedge r) \quad \vee \\
 & (p \wedge q \wedge (\sim r)),
 \end{aligned}$$

which is in disjunctive normal form. Therefore,  $(p \wedge q \wedge r) \vee ((\sim p) \wedge (\sim q) \wedge r)$  is logically equivalent, by Proposition 1.17, to

$$\begin{aligned}
 & (p \vee q \vee r) \quad \wedge \\
 & (p \vee (\sim q) \vee r) \quad \wedge \\
 & (p \vee (\sim q) \vee (\sim r)) \quad \wedge \\
 & ((\sim p) \vee q \vee r) \quad \wedge \\
 & ((\sim p) \vee q \vee (\sim r)) \quad \wedge \\
 & ((\sim p) \vee (\sim q) \vee r),
 \end{aligned}$$

which is a statement form in conjunctive normal form, as desired.

(d) The statement form  $((p \rightarrow q) \rightarrow r) \rightarrow s$  is logically equivalent to

$$\begin{aligned} & ((\sim p) \vee (\sim q) \vee r \vee (\sim s)) \quad \wedge \\ & ((\sim p) \vee q \vee r \vee (\sim s)) \quad \wedge \\ & (p \vee (\sim q) \vee (\sim r) \vee (\sim s)) \quad \wedge \\ & (p \vee (\sim q) \vee r \vee (\sim s)) \quad \wedge \\ & (p \vee q \vee r \vee (\sim s)), \end{aligned}$$

which is a statement form in conjunctive normal form, as desired.

## 1.5 Adequate sets of connectives

**Definition 1.23.** An *adequate* set of connectives is a set such that every truth function can be represented by a statement form containing only connectives from that set.

In the last chapter, we have seen that  $\{\sim, \vee, \wedge\}$  is an adequate set of connectives. We will use this fact to prove the next proposition.

**Proposition 1.24.** The sets  $\{\sim, \wedge\}$ ,  $\{\sim, \vee\}$ , and  $\{\sim, \rightarrow\}$  are adequate sets of connectives.

*Proof.* The proof is done by showing that any statement form using the connectives in the set  $\{\sim, \vee, \wedge\}$  can be formed by using only the connectives in the sets described above. Since the set  $\{\sim, \vee, \wedge\}$  is an adequate set of connectives, this method is sufficient to demonstrate that the other sets are adequate.

Let  $\mathcal{A}$  and  $\mathcal{B}$  be arbitrary statement forms.

Any statement form of the form  $\mathcal{A} \vee \mathcal{B}$  can be expressed, via Proposition 1.17, as  $((\sim \mathcal{A}) \wedge (\sim \mathcal{B}))$ . Therefore,  $\{\sim, \wedge\}$  is an adequate set of connectives.

Any statement form of the form  $\mathcal{A} \wedge \mathcal{B}$  can be expressed, via Proposition 1.17, as  $((\sim \mathcal{A}) \vee (\sim \mathcal{B}))$ . Therefore,  $\{\sim, \vee\}$  is an adequate set of connectives.

Any statement form of the form  $\mathcal{A} \vee \mathcal{B}$  can be expressed as  $(\sim \mathcal{A} \rightarrow \mathcal{B})$  and any statement form of the form  $\mathcal{A} \wedge \mathcal{B}$  can be expressed as  $(\sim (\mathcal{A} \rightarrow (\sim \mathcal{B})))$ . These equivalences can be easily verified by constructing truth tables. Therefore,  $\{\sim, \rightarrow\}$  is an adequate set of connectives.  $\square$

The *Nor* connective, denoted by  $\downarrow$  is defined such that  $p \downarrow q$  is true if and only if  $p$  and  $q$  are both false.

The *Nand* connective, denoted by  $\uparrow$  is defined such that  $p \uparrow q$  is false if and only if  $p$  and  $q$  are both true. In other words, it indicates that one of its operands is false.

*Note.* In the book, the symbol  $|$  is used for the Nand connective.

**Proposition 1.26.** The singleton sets  $\{\downarrow\}$  and  $\{\uparrow\}$  are adequate sets of connectives.

*Proof.* Let  $p$  and  $q$  be statement variables.

The statement form  $\sim p$  can be represented as  $p \downarrow p$ , and the statement form  $p \wedge q$  can be represented as  $(p \downarrow p) \downarrow (q \downarrow q)$ . Since the set  $\{\sim, \wedge\}$  is an adequate set of connectives, the set  $\{\downarrow\}$  must also be an adequate set of connectives.

The statement form  $\sim p$  can be represented as  $p \uparrow p$ , and the statement form  $p \vee q$  can be represented as  $(p \uparrow p) \uparrow (q \uparrow q)$ . Since the set  $\{\sim, \vee\}$  is an adequate set of connectives, the set  $\{\uparrow\}$  must also be an adequate set of connectives.  $\square$

## Solutions to exercises

*Note.* The solutions for exercises 14 through 16 have not been verified and were done quickly. They likely contain mistakes.

14. (a)  $(\sim p \vee ((\sim q) \vee r))$   
 (b)  $((\sim (\sim (p \vee q))) \vee (\sim (r \vee (\sim s))))$   
 (c)  $((\sim ((\sim p) \vee q)) \vee (\sim ((\sim q) \vee p)))$
15. (a)  $(\sim (p \wedge (q \wedge (\sim r))))$   
 (b)  $((\sim ((\sim p) \wedge (\sim q))) \wedge (\sim r)) \wedge (\sim ((p \wedge q) \wedge r))$   
 (c)  $((\sim (((\sim (p \wedge q)) \wedge (\sim ((\sim q) \wedge (\sim p)))) \wedge (\sim r))) \wedge (\sim (r \wedge (\sim ((\sim (p \wedge q)) \wedge (\sim q) \wedge (\sim p))))))$
16. (a)  $((p \rightarrow (\sim q)) \rightarrow (\sim (r \rightarrow (\sim s))))$   
 (b)  $(\sim ((p \rightarrow q) \rightarrow (\sim (q \rightarrow p))))$   
 (c)  $(\sim ((\sim (p \rightarrow (\sim q))) \rightarrow (\sim r)))$
17. (a) The value of a statement form consisting of only  $\wedge$  and  $\vee$  when all statement variables take value  $T$  must also be  $T$ , since  $\mathcal{B} \wedge \mathcal{C}$  and  $\mathcal{B} \vee \mathcal{C}$  both take value  $T$  when arbitrary statement forms  $\mathcal{B}$  and  $\mathcal{C}$  both take value  $T$ .  
 Thus, no contradiction can be formed by only the connectives  $\wedge$  and  $\vee$ , so the set  $\{\wedge, \vee\}$  is not an adequate set of connectives.  
 (b) We will first prove that if  $\mathcal{A}$  is a statement form in which only two statement variables  $p$  and  $q$  appear and consists of only the connectives  $\sim$  and  $\leftrightarrow$ , the value that  $\mathcal{A}$  takes when  $p$  is true and  $q$  is false is the same as the value that it takes when  $p$  is false and  $q$  is true. The proof is by strong induction on the number of connectives appearing in  $\mathcal{A}$ .  
 (base case) It is impossible for  $\mathcal{A}$  to have zero connective. It may be that  $\mathcal{A}$  has only one connective, and this connective must necessarily be  $\leftrightarrow$ , in which case  $\mathcal{A}$  is  $p \leftrightarrow q$ . When  $p$  is true and  $q$  is false, the value of  $\mathcal{A}$  is false, and when  $p$  is false and  $q$  is true, the value of  $\mathcal{A}$  is also false, as desired.  
 (inductive step) It may be that  $\mathcal{A}$  has  $n$  connectives, where  $n > 1$ . Suppose as an induction hypothesis that any statement form consisting of only the statement variables  $p$  and  $q$  and fewer than  $n$  of the connectives  $\sim$  and  $\leftrightarrow$  has the above property. There are two cases to check.  
 i. It may be that  $\mathcal{A}$  is of the form  $\sim \mathcal{B}$ . If the value that  $\mathcal{B}$  takes when  $p$  is true and  $q$  is false is  $T$ , then  $\sim \mathcal{B}$  must take value  $F$ . By the induction hypothesis,  $\mathcal{B}$  must also take the value  $T$  when  $p$  is false and  $q$  is true, and so  $\sim \mathcal{B}$  must take value  $F$ , as desired. The other case for when  $\sim \mathcal{B}$  identically takes the value  $T$  under both assignments of  $p$  and  $q$  can be verified in the same way.  
 ii. It may be that  $\mathcal{A}$  is of the form  $\mathcal{B} \leftrightarrow \mathcal{C}$ . The statement forms  $\mathcal{B}$  and  $\mathcal{C}$  will take certain values when  $p$  is true and  $q$  is false. By the induction hypothesis, they will take the same values when  $p$  is false and  $q$  is true. Therefore, the value of  $\mathcal{B} \leftrightarrow \mathcal{C}$  will remain constant, as desired.

Now that the above property has been proved, we may see that any truth function equivalent to the one generated by  $p \rightarrow q$  can not be represented by a statement form generated by only the connectives  $\leftrightarrow$  and  $\sim$ . For if a statement form were to consist of only  $p, q$ , the connectives  $\leftrightarrow$  and  $\sim$ , then by the above proof, either it would take value  $T$  with  $p$  true and  $q$  false, or otherwise it would identically take value  $F$  with  $p$  false and  $q$  true.

Since the set of connectives  $\{\sim, \leftrightarrow\}$  is unable to generate a statement form representing a particular truth function, the set of connectives must not be adequate.

18.  $((p \uparrow p) \uparrow (p \uparrow p)) \uparrow (q \uparrow q)$

19. Let  $\star$  be a *singularly adequate* binary connective in the sense that  $\{\star\}$  is an adequate set of connectives.

It must be able to express  $\sim p$ , where  $p$  is a statement variable, in terms of  $p$  and  $\star$ . It may be that when both  $p$  and  $q$  take value  $T$ ,  $p \star q$  takes value  $T$ . But then any contradiction involving  $p$  and  $q$  cannot be expressed using only  $\star$ , for the assignment of truth values of  $T$  to both  $p$  and  $q$  would result in the contradiction having a true value, which would be contradictory. Similarly, if  $p \star q$  takes value  $F$  when both  $p$  and  $q$  take value  $F$ , then no tautology involving only  $\star$  can be expressed.

Thus, a partial truth table for  $\star$  can be built.

$p$	$q$	$p \star q$
1	1	0
1	0	-
0	1	-
0	0	1

Now suppose that the truth table for  $\star$  is either of the ones shown below.

$p$	$q$	$p \star q$
1	1	0
1	0	1
0	1	0
0	0	1

$p$	$q$	$p \star q$
1	1	0
1	0	0
0	1	1
0	0	1

Then any statement form involving  $p, q$  and  $\star$  as its sole connective cannot be a tautology, since its truth value when  $p$  is true and  $q$  is false is different from its value when  $p$  is true and  $q$  is false <sup>1</sup>. So we may conclude that  $\star$  cannot have one of the above truth tables.

On the other hand, the other possible truth tables for  $\star$  correspond to  $\uparrow$  and  $\downarrow$ , which are both singularly adequate. So  $\star$  must be either  $\uparrow$  or  $\downarrow$ , as desired.

<sup>1</sup>This can be made rigorous by a tedious induction similar to one done in part (b) of Exercise 17.

## 1.6 Arguments and validity

An *argument form* is a finite sequence of statement forms. The last statement form is called the *conclusion* and the other statement forms are called the *premises*.

**Definition 1.28.** The argument form  $\mathcal{A}_1, \dots, \mathcal{A}_n \therefore \mathcal{A}$  is *invalid* if it is possible to assign truth values to the statement variables occurring in such a way as to make each of the premises take value  $T$  while making the conclusion take value  $F$ . Otherwise, the argument form is *valid*.

**Proposition 1.32.** The argument form  $\mathcal{A}_1, \dots, \mathcal{A}_n \therefore \mathcal{A}$  is valid if and only if the statement form  $((\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n) \rightarrow \mathcal{A})$  is a tautology.

*Proof.*  $\Rightarrow$  Suppose that the argument form  $\mathcal{A}_1, \dots, \mathcal{A}_n \therefore \mathcal{A}$  is valid. For a contradiction, suppose that  $((\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n) \rightarrow \mathcal{A})$  is not a tautology. This will only occur when there exists some assignment of truth values to the statement variables occurring such that  $(\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n)$  takes value  $T$  and  $\mathcal{A}$  takes value  $F$ . This is to say that each  $\mathcal{A}_i$  takes value  $T$ , while  $\mathcal{A}$  takes value  $F$ , contradicting the validity of the argument form  $\mathcal{A}_1, \dots, \mathcal{A}_n \therefore \mathcal{A}$ .

$\Leftarrow$  Suppose that the statement form  $((\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n) \rightarrow \mathcal{A})$  is a tautology. For a contradiction, suppose that the argument form  $\mathcal{A}_1, \dots, \mathcal{A}_n \therefore \mathcal{A}$  is invalid. This will only occur when there exists some assignment of truth values to the statement variables occurring such that each  $\mathcal{A}_i$  takes value  $T$ , while  $\mathcal{A}$  takes value  $F$ , which is to say that  $((\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n) \rightarrow \mathcal{A})$  is true while  $\mathcal{A}$  is false. Then, under this assignment, the statement form  $((\mathcal{A}_1 \wedge \dots \wedge \mathcal{A}_n) \rightarrow \mathcal{A})$  must be false, contradicting the fact that it is a tautology.  $\square$

### Solutions to exercises

20. (a) The corresponding argument form,

$$((\sim F) \rightarrow (\sim G)), G \therefore F,$$

is valid.

- (b) The corresponding argument form,

$$(C \rightarrow (S \vee B)), (\sim B) \therefore ((\sim S) \rightarrow (\sim C)),$$

is valid.

- (c) The corresponding argument form,

$$(D \rightarrow (E \vee (\sim G))), ((\sim O) \vee (\sim E)) \therefore G,$$

is invalid.

- (d) The corresponding argument form,

$$(P \rightarrow (Q \wedge R \wedge S)), Q, (S \rightarrow R) \therefore (S \rightarrow P)$$

is invalid.



21. Suppose that  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n \therefore \mathcal{A}$  is a valid argument form. Then whenever  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_n$  are all true,  $\mathcal{A}$  is true as well.

Now suppose that  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_{n-1}$  are all true. It may be that  $\mathcal{A}_n$  is true, in which case, by the above,  $\mathcal{A}$  is true, so  $(\mathcal{A}_n \rightarrow \mathcal{A})$  is true. Otherwise,  $\mathcal{A}_n$  is false, so  $(\mathcal{A}_n \rightarrow \mathcal{A})$  is vacuously true.

Therefore,  $(\mathcal{A}_n \rightarrow \mathcal{A})$  is always true when  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_{n-1}$  are all true, and so  $\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_{n-1} \therefore (\mathcal{A}_n \rightarrow \mathcal{A})$  is a valid argument form.

22. Suppose that the premises  $p$  and  $(p \uparrow (q \uparrow r))$  are true. Then  $p$  must be true. For  $(p \uparrow (q \uparrow r))$  to be true,  $(q \uparrow r)$  must be false, and this only occurs when  $q$  and  $r$  are both true. Since the conclusion  $r$  must be true, the argument form is valid.

# Chapter 2

## Formal statement calculus

### 2.1 The formal system $L$

A *formal system* is a mathematical structure representing a deductive system. It consists of

1. A set of symbols called an *alphabet*.
2. A set of finite strings of these symbols representing the valid sentences in the system. Each string is called a *well-formed formula*, or *wf* for short.  
There is usually a formula, called a *grammar*, for determining which strings are wfs.
3. A subset of the set of wfs representing the axioms.
4. A finite set of *inference rules*, functions which take a set of wfs and return a *wf*. The returned *wf* is said to be deduced from the set of wfs.

This chapter is devoted to a particular formal system described below.

**Definition 2.1.** The *formal system  $L$  of statement calculus* is defined by the following:

1. The alphabet consists of the symbols  $\sim, \rightarrow, ($ , and  $)$ , along with the countably infinite set of symbols  $p_1, p_2, p_3, \dots$
2. The set of wfs is defined recursively by the following rules:
  - (a) For any  $i$ ,  $p_i$  is a *wf*.
  - (b) If  $\mathcal{A}$  and  $\mathcal{B}$  are wfs, then  $(\sim \mathcal{A})$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  are wfs.  
*This rule also defines the semantics of the parentheses, and, because one set of parentheses will always contain only one of  $\sim$  or  $\rightarrow$  not in parentheses, it also eliminates the need for an order of operations.*
  - (c) The set of all wfs is generated by the above rules.
3. Let  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  be wfs. All axioms take on one of the following forms:
  - (a) Axiom scheme 1 (L1):  $(\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ .
  - (b) Axiom scheme 2 (L2):  $((\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C})))$ .

(c) Axiom scheme 3 (L3):  $((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A})$ .

4. There is one rule of deduction known as *modus ponens* (MP): from  $\mathcal{A}$  and  $\mathcal{A} \rightarrow \mathcal{B}$ ,  $\mathcal{B}$  is a direct consequence, where  $\mathcal{A}, \mathcal{B}$  are any wfs of  $L$ .

**Definition 2.2.** A proof of  $\mathcal{A}_n$  in  $L$ , or just a proof in  $L$ , is a sequence of wfs  $\mathcal{A}_1, \dots, \mathcal{A}_n$  such that for any  $i$ ,  $\mathcal{A}_i$  is an axiom of  $L$  or  $\mathcal{A}_i$  follows from MP and two previous wfs in the sequence. The wf  $\mathcal{A}_n$  is said to be a *theorem* of  $L$ .

Instead of using the word theorem to discuss a result about formal system, we will instead use the word *metatheorem* to prevent confusion with the word *theorem* in the sense of the previous definition.

**Definition 2.5.** Let  $\Gamma$  be a set of wfs of  $L$ . A proof in  $L$  with the members of  $\Gamma$  regarded as additional axioms is called a *deduction from  $\Gamma$* . The last wf in the proof, call it  $\mathcal{A}$ , is said to be *deducible from  $\Gamma$*  or a *consequence of  $\Gamma$*  and is symbolized by  $\Gamma \vdash_L \mathcal{A}$ . If  $\Gamma = \emptyset$  then we instead write  $\vdash_L \mathcal{A}$ , which is to say that  $\mathcal{A}$  is a theorem of  $L$ .

**Proposition 2.8** (The Deduction Theorem). If  $\Gamma \cup \{\mathcal{A}\} \vdash_L \mathcal{B}$ , then  $\Gamma \vdash_L (\mathcal{A} \rightarrow \mathcal{B})$ , where  $\mathcal{A}$  and  $\mathcal{B}$  are wfs of  $L$ , and  $\Gamma$  is a set of wfs of  $L$  (possibly empty).

*Proof.* The proof is by strong induction on the number of wfs in the sequence forming the deduction of  $\mathcal{B}$  from  $\Gamma \cup \{\mathcal{A}\}$ .

(base case) There is only one wf in the deduction of  $\mathcal{B}$  from  $\Gamma \cup \{\mathcal{A}\}$ , which is to say that the proof consists of only  $\mathcal{B}$ , and there are two cases in which this can happen:

1. The wf  $\mathcal{B}$  is an axiom of  $L$  or a member of  $\Gamma$ . In either case the deduction of  $\mathcal{A} \rightarrow \mathcal{B}$  proceeds as follows:

1	$\mathcal{B}$	$\mathcal{B}$ is an axiom or a member of $\Gamma$
2	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	(L1)
3	$(\mathcal{A} \rightarrow \mathcal{B})$	1, 2, MP

The above is a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$ .

2. The wf  $\mathcal{B}$  is  $\mathcal{A}$ , and so  $(\mathcal{A} \rightarrow \mathcal{B})$  is  $(\mathcal{A} \rightarrow \mathcal{A})$ .

1	$((\mathcal{A} \rightarrow ((\mathcal{A} \rightarrow \mathcal{A}) \rightarrow \mathcal{A})) \rightarrow ((\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{A})))$	(L2)
2	$(\mathcal{A} \rightarrow ((\mathcal{A} \rightarrow \mathcal{A}) \rightarrow \mathcal{A}))$	(L1)
3	$((\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{A}))$	1, 2, MP
4	$(\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A}))$	(L1)
5	$(\mathcal{A} \rightarrow \mathcal{A})$	3, 4, MP

The above is a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  (which is  $(\mathcal{A} \rightarrow \mathcal{A})$ ) from  $\Gamma$ . Note that it is also a general theorem of  $L$ .

(inductive step) Suppose that for any deduction of  $\mathcal{C}$  from  $\Gamma \cup \{\mathcal{A}\}$  with up to and including  $n$  members, it is possible to deduce  $(\mathcal{A} \rightarrow \mathcal{C})$  from  $\Gamma$  alone. This is the hypothesis of strong induction.

Additionally suppose that there exists a deduction of  $\mathcal{B}$  from  $\Gamma \cup \{\mathcal{A}\}$  with  $n + 1$  members. We now provide a proof that there exists a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$  alone. There are three cases to consider:

1. The *wf*  $\mathcal{B}$  is an axiom of  $L$  or a member of  $\Gamma$ . A deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$  is shown in case 1 in the base case.
2. The *wf*  $\mathcal{B}$  is  $\mathcal{A}$ . A deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$  is shown in case 2 in the base case.
3. The *wf*  $\mathcal{B}$  is obtained applying MP along with two *wfs*, which are necessarily of the form  $\mathcal{C}$  and  $(\mathcal{C} \rightarrow \mathcal{B})$ , where  $\mathcal{C}$  is any *wf*. The deduction of  $\mathcal{B}$  from  $\Gamma \cup \{\mathcal{A}\}$  must be the sequence

$$(\dots, \mathcal{C}, \dots, (\mathcal{C} \rightarrow \mathcal{B}), \dots, \mathcal{B}) \text{ or } (\dots, (\mathcal{C} \rightarrow \mathcal{B}), \dots, \mathcal{C}, \dots, \mathcal{B}),$$

from which it can be seen that the subsequences  $(\dots, \mathcal{C})$  and  $(\dots, (\mathcal{C} \rightarrow \mathcal{B}))$  are both deductions of  $\mathcal{C}$  and  $(\mathcal{C} \rightarrow \mathcal{B})$  from  $\Gamma \cup \{\mathcal{A}\}$  with  $n$  members or less. Therefore, by the hypothesis,  $\Gamma \vdash_L (\mathcal{A} \rightarrow \mathcal{C})$  and  $\Gamma \vdash_L (\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$ , which is to say that  $(\mathcal{A} \rightarrow \mathcal{C})$  and  $(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$  are both deducible from  $\Gamma$  alone.

So appending the proof of  $(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$  to  $(\mathcal{A} \rightarrow \mathcal{C})$ , yields the sequence

$$(\dots, (\mathcal{A} \rightarrow \mathcal{C}), \dots, (\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))).$$

which may have redundant *wfs*, but is nevertheless a valid deduction from  $\Gamma$ . The following proof builds on the sequence.

		$\vdots$	
k		$(\mathcal{A} \rightarrow \mathcal{C})$	deduced from $\Gamma$
		$\vdots$	
1		$(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$	deduced from $\Gamma$
1 + 1	$((\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})))$		(L2)
1 + 2	$((\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$		1, 1 + 1
1 + 3	$((\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})))$		(L2)

And so in all three cases,  $(\mathcal{A} \rightarrow \mathcal{B})$  can be deduced from  $\Gamma$  alone, which concludes the induction.  $\square$

**Proposition 2.9** (Converse of The Deduction Theorem). If  $\Gamma \vdash_L (\mathcal{A} \rightarrow \mathcal{B})$  then  $\Gamma \cup \{\mathcal{A}\} \vdash_L \mathcal{B}$ , where  $\mathcal{A}$  and  $\mathcal{B}$  are *wfs* of  $L$  and  $\Gamma$  is a (possibly empty) set of *wfs* of  $L$ .

*Proof.* The following is a deduction of  $\mathcal{B}$  from  $\Gamma \cup \{\mathcal{A}\}$ , provided that  $\Gamma \vdash_L (\mathcal{A} \rightarrow \mathcal{B})$ .

	$\vdots$	
k	$(\mathcal{A} \rightarrow \mathcal{B})$	deduction from $\Gamma$
k + 1	$\mathcal{A}$	member of $\Gamma \cup \{\mathcal{A}\}$
k + 2	$\mathcal{B}$	k, k + 1, MP

$\square$

**Corollary 2.10** (The Hypothetical Syllogism (HS)). For any *wfs*  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  of  $L$ ,

$$\{(\mathcal{A} \rightarrow \mathcal{B}), (\mathcal{B} \rightarrow \mathcal{C})\} \vdash_L (\mathcal{A} \rightarrow \mathcal{C}).$$

*Proof.* We will first prove  $S \vdash_L \mathcal{C}$ , where  $S = \{(\mathcal{A} \rightarrow \mathcal{B}), (\mathcal{B} \rightarrow \mathcal{C})\} \cup \{\mathcal{A}\}$ .

1	$\mathcal{A} \rightarrow \mathcal{B}$	member of $S$
2	$\mathcal{B} \rightarrow \mathcal{C}$	member of $S$
3	$\mathcal{A}$	member of $S$
4	$\mathcal{B}$	1, 3, MP
5	$\mathcal{C}$	2, 4, MP

Seeing as though we have proved

$$\{(\mathcal{A} \rightarrow \mathcal{B}), (\mathcal{B} \rightarrow \mathcal{C})\} \cup \{\mathcal{A}\} \vdash_L \mathcal{C}$$

we may use the deduction theorem to conclude that

$$\{(\mathcal{A} \rightarrow \mathcal{B}), (\mathcal{B} \rightarrow \mathcal{C})\} \vdash_L (\mathcal{A} \rightarrow \mathcal{C}).$$

□

**Proposition 2.11.** For any wfs  $\mathcal{A}$  and  $\mathcal{B}$  of  $L$ , the following are theorems of  $L$ .

(a)  $((\sim \mathcal{A}) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$

(b)  $((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A}$

*Proof.* (a) 1  $((\sim \mathcal{B}) \rightarrow ((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})))$  (L1)  
 2  $((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A})$  (L3)

Application of HS and the above two lines yields  $((\sim \mathcal{B}) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ , as desired.

(b) We will first prove that  $\{((\sim \mathcal{A}) \rightarrow \mathcal{A})\} \vdash_L \mathcal{A}$ .

1	$((\sim \mathcal{A}) \rightarrow \mathcal{A})$	assumption
2	$((\sim \mathcal{A}) \rightarrow ((\sim (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A}))) \rightarrow (\sim \mathcal{A})))$	(L1)
3	$((\sim (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A}))) \rightarrow (\sim \mathcal{A})) \rightarrow$ $(\mathcal{A} \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A})))$	(L3)
4	$((\sim \mathcal{A}) \rightarrow (\mathcal{A} \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A}))))$	2, 3, HS
5	$((\sim \mathcal{A}) \rightarrow (\mathcal{A} \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A})))) \rightarrow$ $((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow ((\sim \mathcal{A}) \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A})))$	(L2)
6	$((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow ((\sim \mathcal{A}) \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A})))$	4, 5, MP
7	$((\sim \mathcal{A}) \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A})))$	1, 6, MP
8	$((\sim \mathcal{A}) \rightarrow (\sim ((\sim \mathcal{A}) \rightarrow \mathcal{A}))) \rightarrow$ $((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A}$	(L3)
9	$((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A}$	7, 8, MP
10	$\mathcal{A}$	1, 9, MP

By the deduction theorem, we may conclude that  $((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A}$ .

□

*Note.* Because of the use of HS in line 4, which is a metatheorem, the above proof is not technically a proof in  $L$ . An actual proof would require a few additional lines.

## Solutions to exercises

*Note.* All formulas are fully parenthesized, so they may look different from how they appear in the book. Additionally, any metatheorems are referenced as if they were rules of deduction, just like in the book.

1. (a)
- |   |  |          |
|---|--|----------|
| 1 | $((\sim p_1 \rightarrow \sim p_2) \rightarrow (p_2 \rightarrow p_1))$  | (L3)     |
| 2 | $((\sim p_1 \rightarrow \sim p_2) \rightarrow (p_2 \rightarrow p_1)) \rightarrow$<br>$((p_1 \rightarrow p_2) \rightarrow ((\sim p_1 \rightarrow \sim p_2) \rightarrow (p_2 \rightarrow p_1)))$ | (L1)     |
| 3 | $((p_1 \rightarrow p_2) \rightarrow ((\sim p_1 \rightarrow \sim p_2) \rightarrow (p_2 \rightarrow p_1)))$  | 1, 2, MP |
- (b)
- |   |  |          |
|---|--|----------|
| 1 | $\underbrace{((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow (p_1 \rightarrow p_2))}_{\mathcal{A}} \rightarrow \underbrace{((p_1 \rightarrow p_2) \rightarrow (p_1 \rightarrow p_3))}_{\mathcal{B}} \rightarrow \underbrace{((p_1 \rightarrow p_2) \rightarrow (p_1 \rightarrow p_3))}_{\mathcal{C}}$ |          |
|   | $((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow (p_1 \rightarrow p_2)) \rightarrow ((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow (p_1 \rightarrow p_3))$  | (L2)     |
| 2 | $((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow ((p_1 \rightarrow p_2) \rightarrow (p_1 \rightarrow p_3)))$  | (L2)     |
| 3 | $((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow (p_1 \rightarrow p_2)) \rightarrow ((p_1 \rightarrow (p_2 \rightarrow p_3)) \rightarrow (p_1 \rightarrow p_3))$  | 1, 2, MP |
- (c)
- |   |  |          |
|---|--|----------|
| 1 | $\underbrace{(((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_1)) \rightarrow (p_1 \rightarrow p_2))}_{\mathcal{A}} \rightarrow \underbrace{((p_1 \rightarrow p_1) \rightarrow (p_1 \rightarrow p_2))}_{\mathcal{B}} \rightarrow \underbrace{((p_1 \rightarrow p_1) \rightarrow (p_1 \rightarrow p_2))}_{\mathcal{C}}$ |          |
|   | $((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_1)) \rightarrow ((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_2))$  | (L2)     |
| 2 | $((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow ((p_1 \rightarrow p_1) \rightarrow (p_1 \rightarrow p_2)))$  | (L2)     |
| 3 | $((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_1)) \rightarrow ((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_2))$  | 1, 2, MP |
| 4 | $(p_1 \rightarrow ((p_1 \rightarrow p_2) \rightarrow p_1))$  | (L1)     |
| 5 | $((p_1 \rightarrow ((p_1 \rightarrow p_2) \rightarrow p_1)) \rightarrow ((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_1)))$  | (L2)     |
| 6 | $((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_1))$  | 4, 5, MP |
| 7 | $((p_1 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow p_2))$  | 3, 6, MP |

Lines 1-3 are identical to exercise (b) with  $p_1$  substituted for  $p_2$  and  $p_2$  substituted for  $p_3$ .

Lines 4-6 are identical to example 2.4 in the book with  $(p_1 \rightarrow p_2)$  substituted for  $p_2$ .

- (d)
- |   |   |          |
|---|---|----------|
| 1 | $(p_2 \rightarrow (p_1 \rightarrow p_2))$   | (L1)     |
| 2 | $\underbrace{((p_2 \rightarrow (p_1 \rightarrow p_2)) \rightarrow (p_1 \rightarrow (p_2 \rightarrow (p_1 \rightarrow p_2))))}_{\mathcal{A}} \rightarrow \underbrace{(p_1 \rightarrow (p_2 \rightarrow (p_1 \rightarrow p_2)))}_{\mathcal{B}}$ | (L1)     |
| 3 | $(p_1 \rightarrow (p_2 \rightarrow (p_1 \rightarrow p_2)))$   | 1, 2, MP |

2. (a)
- |   |   |            |
|---|---|------------|
| 1 | $(\sim \mathcal{A})$  | assumption |
| 2 | $((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})$ | (L3)       |
| 3 | $((\sim \mathcal{A}) \rightarrow ((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A})))$                  | (L1)       |
| 4 | $((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A}))$   | 1, 3, MP   |
| 5 | $(\mathcal{A} \rightarrow \mathcal{B})$   | 2, 4, MP   |

(b)	1	$(\sim(\sim \mathcal{A}))$	assumption
	2	$((\sim(\mathcal{A}) \rightarrow (\sim(\sim(\sim \mathcal{A})))) \rightarrow ((\sim(\sim \mathcal{A})) \rightarrow \mathcal{A}))$	(L3)
	3	$((\sim(\sim(\sim(\sim \mathcal{A})))) \rightarrow (\sim(\sim \mathcal{A})) \rightarrow$ $((\sim \mathcal{A}) \rightarrow (\sim(\sim(\sim \mathcal{A}))))$	(L3)
	4	$((\sim(\sim \mathcal{A})) \rightarrow ((\sim(\sim(\sim(\sim \mathcal{A})))) \rightarrow (\sim(\sim \mathcal{A}))))$	(L1)
	5	$((\sim(\sim(\sim(\sim \mathcal{A})))) \rightarrow (\sim(\sim \mathcal{A})))$	1, 4, MP
	6	$((\sim \mathcal{A}) \rightarrow (\sim(\sim(\sim \mathcal{A}))))$	3, 5, MP
	7	$((\sim(\sim \mathcal{A})) \rightarrow \mathcal{A})$	2, 6, MP
	8	$\mathcal{A}$	1, 7, MP
(c)	1	$(\mathcal{A} \rightarrow \mathcal{B})$	assumption
	2	$(\sim(\mathcal{B} \rightarrow \mathcal{C}) \rightarrow (\sim \mathcal{A}))$	assumption
	3	$((\sim(\mathcal{B} \rightarrow \mathcal{C})) \rightarrow (\sim \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C}))$	(L3)
	4	$(\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C}))$	2, 3, MP
	5	$((\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C})))$	(L2)
	6	$((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C}))$	4, 5, MP
	7	$(\mathcal{A} \rightarrow \mathcal{C})$	1, 6, MP
(d)	1	$(\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C}))$	assumption
	2	$((\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C})))$	(L2)
	3	$((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C}))$	1, 2, MP
	4	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	(L1)
	5	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{C}))$	3, 4, HS

3. (a) We apply the deduction theorem to exercise to the result of exercise 2(b) and get  $\vdash_L (\sim(\sim \mathcal{A}) \rightarrow \mathcal{A})$ , which will be referred to as  $\star$ .

1	$\mathcal{A}$	assumption
2	$(\sim(\sim(\sim \mathcal{A})) \rightarrow (\sim \mathcal{A}))$	$\star$
3	$((\sim(\sim(\sim \mathcal{A})) \rightarrow (\sim \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow (\sim(\sim \mathcal{A}))))$	(L3)
4	$(\mathcal{A} \rightarrow (\sim(\sim \mathcal{A})))$	2, 3, MP
5	$(\sim(\sim \mathcal{A}))$	1, 4, MP

By the deduction theorem,  $\vdash_L (\mathcal{A} \rightarrow (\sim(\sim \mathcal{A})))$ .

- (b) This solution relies on the solutions for 3(a) and 2(b).

1	$(\mathcal{B} \rightarrow \mathcal{A})$	assumption
2	$(\mathcal{A} \rightarrow (\sim(\sim \mathcal{A})))$	$\star$
3	$((\sim(\sim \mathcal{B})) \rightarrow \mathcal{B})$	exercise 3(a)
4	$(\mathcal{B} \rightarrow (\sim(\sim \mathcal{A})))$	1, 2, HP
5	$((\sim(\sim \mathcal{B})) \rightarrow (\sim(\sim \mathcal{A})))$	3, 4, HP
6	$((\sim(\sim \mathcal{B})) \rightarrow (\sim(\sim \mathcal{A}))) \rightarrow ((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B}))$	(L3)
7	$((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B}))$	5, 6, MP

By the deduction theorem,  $\vdash_L ((\mathcal{B} \rightarrow \mathcal{A}) \rightarrow ((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})))$ .

- (c)
- |   |  |                     |
|---|--|---------------------|
| 1 | $((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \mathcal{A})$        | assumption          |
| 2 | $((\sim \mathcal{A}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$ | Proposition 2.11(a) |
| 3 | $(\sim \mathcal{A} \rightarrow \mathcal{A})$                             | 1, 2, HS            |
| 4 | $((\sim \mathcal{A} \rightarrow \mathcal{A}) \rightarrow \mathcal{A})$   | Proposition 2.11(b) |
| 5 | $\mathcal{A}$  | 3, 4, MP            |

By the deduction theorem,  $\vdash_L (((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A})$ .

- (d)
- |   |   |                     |
|---|---|---------------------|
| 1 | $(\sim (\mathcal{A} \rightarrow \mathcal{B}))$  | assumption          |
| 2 | $((\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B})) \rightarrow (\sim (\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\sim \mathcal{B})))$ | exercise 3(b)       |
| 3 | $(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$   | (L1)                |
| 4 | $(\sim (\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\sim \mathcal{B}))$   | 2, 3, MP            |
| 5 | $(\sim \mathcal{B})$  | 1, 4, MP            |
| 6 | $(\sim \mathcal{B} \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$  | Proposition 2.11(a) |
| 7 | $(\mathcal{B} \rightarrow \mathcal{A})$   | 5, 6, MP            |

By the deduction theorem,  $\vdash_L ((\sim (\mathcal{A} \rightarrow \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ .

4. (i)
- |   |  |            |
|---|--|------------|
| 1 | $((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B}))$  | assumption |
| 2 | $((\sim \mathcal{A}) \rightarrow \mathcal{B})$   | assumption |
| 3 | $((\sim (\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ | (L3)       |
| 4 | $(\mathcal{B} \rightarrow \mathcal{A})$  | 1, 3, MP   |
| 5 | $((\sim \mathcal{A}) \rightarrow \mathcal{A})$   | 2, 4, HS   |
| 6 | $((\sim (\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A})$                                  | 2.11(b)    |
| 7 | $\mathcal{A}$  | 5, 6, MP   |

By the deduction theorem, which is valid since its proof relies only on (L'1) and (L'2),  $\vdash_{L'} (((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (((\sim \mathcal{A}) \rightarrow \mathcal{B}) \rightarrow \mathcal{A}))$ .

(ii) We will prove  $\{((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})), \mathcal{B}\} \vdash_{L'} \mathcal{A}$

- |   |   |            |
|---|---|------------|
| 1 | $((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B}))$   | assumption |
| 2 | $\mathcal{B}$   | assumption |
| 3 | $((\sim (\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (((\sim \mathcal{A}) \rightarrow \mathcal{B}) \rightarrow \mathcal{A}))$ | (L'3)      |
| 4 | $((\sim (\sim \mathcal{A}) \rightarrow \mathcal{B}) \rightarrow \mathcal{A})$   | 1, 3, MP   |
| 5 | $(\mathcal{B} \rightarrow ((\sim \mathcal{A}) \rightarrow \mathcal{B}))$  | (L'2)      |
| 6 | $((\sim \mathcal{A}) \rightarrow \mathcal{B})$  | 2, 5, MP   |
| 7 | $\mathcal{A}$   | 4, 6, MP   |

By the deduction theorem twice,  $\vdash_{L'} (((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ .

Suppose a *wf* is proved in  $L$ . By definition, it follows from (L1), (L2), and (L3) and MP. Since (L1), (L2) and MP are properties of  $L'$ , and since we just proved that  $\vdash_{L'} (L3)$ , the *wf* can also be proved in  $L'$ . The other direction is argued for in the same way, so a *wf* is a theorem in  $L$  if and only if it is a theorem in  $L'$ .

5. The rule is valid, see example 2.6 (where  $\mathcal{A}$  and  $\mathcal{B}$  in the exercise appear switched in the example).



## 2.2 The Adequacy Theorem for $L$

**Definition 2.12.** A *valuation* of  $L$  is a function  $v$  whose domain is the set of *wfs* of  $L$  and whose range is the set  $\{T, F\}$  such that, for any *wfs*  $\mathcal{A}, \mathcal{B}$  of  $L$ ,

- (i)  $v(\mathcal{A}) \neq v((\sim \mathcal{A}))$  and
- (ii)  $v((\mathcal{A} \rightarrow \mathcal{B})) = F$  if and only if  $v(\mathcal{A}) = T$  and  $v(\mathcal{B}) = F$ .

This definition formalizes the previous idea of truth functions for statement forms. Note that (i) and (ii) simply define the behavior of the two logic operators in  $L$  such that they correspond to the truth tables introduced in the last chapter.

**Definition 2.13.** A *wf*  $\mathcal{A}$  of  $L$  is a *tautology* if for every valuation  $v$ ,  $v(\mathcal{A}) = T$ . If for every valuation  $v$ ,  $v(\mathcal{A}) = F$ , it is a *contradiction*.

*Note.* The definition of a contradiction isn't in the book, but the term is used later on.

The goal of this chapter is to prove that every *wf* in  $L$  is a tautology if and only if it is a theorem in  $L$ . One direction can be done immediately.

**Proposition 2.14** (The Soundness Theorem). Every theorem of  $L$  is a tautology.

*Proof.* Let  $\mathcal{A}$  be a *wf* in  $L$ . It is a theorem if and only if it is the last member of a proof in  $L$ . The proof is by strong induction on the number of *wfs* in the proof of  $\mathcal{A}$ .

Suppose that all theorems containing up to  $n$  *wfs* in their proofs are tautologies. Now suppose that  $\mathcal{A}$  has  $n$  *wfs* in its proof. In the proof, any *wf* preceding  $\mathcal{A}$  must necessarily be a tautology because it is a theorem with fewer than  $n$  *wfs* in its proof. So the only thing to prove is that  $\mathcal{A}$  is a tautology, and  $\mathcal{A}$  can either be an axiom, in which case it is a tautology (see Exercise 6) or a product of MP and two previous *wfs*. These two *wfs* must necessarily be of the form  $\mathcal{B}$  and  $(\mathcal{B} \rightarrow \mathcal{A})$ . By Proposition 1.9 (see the note below),  $\mathcal{A}$  must be a tautology.  $\square$

*Note.* Proposition 1.9 is actually not strictly applicable here because it uses the previous informal notion of a tautology. But re-proving it using  $v$  would be nearly identical.

*Note.* A formal system is said to be sound if everything statement that is provable in it is true, and  $L$  has this property, as seen from this theorem, hence the name.

**Definition 2.15.** An *extension* of  $L$  is a formal system obtained by altering or enlarging the set of axioms so that all theorems of  $L$  remain theorems.

*Note.* By this definition,  $L$  is not an extension on  $L$ . Additionally, an extension of  $L$  may not actually extend the list of theorems of  $L$ .

**Definition 2.16.** An extension of  $L$  or  $L$  itself is *consistent* if for no *wf*  $\mathcal{A}$  of  $L$  are both  $\mathcal{A}$  and  $(\sim \mathcal{A})$  theorems of the extension.

*Note.* This definition has been generalized slightly to be defined for  $L$ .

**Proposition 2.17.**  $L$  is consistent.

*Proof.* Suppose that  $L$  is not consistent. Then there exists a *wf*  $\mathcal{A}$  such that  $\mathcal{A}$  and  $(\sim \mathcal{A})$  are both theorems of  $L$ . Since all theorems of  $L$  are tautologies (Proposition 2.14),  $\mathcal{A}$  and  $(\sim \mathcal{A})$  must be tautologies, meaning that for any valuation  $v$ ,  $v(\mathcal{A}) = v((\sim \mathcal{A})) = T$ . But this contradicts  $v$  being a valuation (see Definition 2.12(i)).  $\square$

*Note.* Therefore, consistency of  $L$  is a consequence of its soundness, Proposition 2.14.

**Proposition 2.18.** An extension  $L^*$  of  $L$  is consistent if and only if there is a *wf* which is not a theorem of  $L^*$ .

*Proof.*  $\Rightarrow$  Let  $L^*$  be consistent. Then, for any *wf*  $\mathcal{A}$ , either  $\mathcal{A}$  or  $\sim \mathcal{A}$  is not a theorem.

$\Leftarrow$  For the other direction, we use contrapositive reasoning. Suppose that  $L^*$  is not consistent, which is to say that there exists a *wf*  $\mathcal{B}$  such that  $\mathcal{B}$  and  $(\sim \mathcal{B})$  are both theorems of  $L^*$ . Now let  $\mathcal{A}$  be any *wf* of  $L^*$ . Since, by Proposition 2.11(a),  $((\sim \mathcal{B}) \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$  is a theorem of  $L$ , it is a theorem of  $L^*$ . So by MP and since  $(\sim \mathcal{B})$  is a theorem,  $(\mathcal{B} \rightarrow \mathcal{A})$  is a theorem. By MP and since  $\mathcal{B}$  is a theorem,  $\mathcal{A}$  is a theorem. Therefore, there any *wf*  $\mathcal{A}$  is a theorem of  $L^*$ .  $\square$

*Note.* The above proposition says that in a system with a contradiction in it, that contradiction can be used to vacuously prove anything, so a consistent system need only have one *wf* which is not a theorem.

Adding axioms to  $L$  or any of its extension can break its consistency. Consider a *wf*  $\mathcal{A}$ . Either it is true or false or maybe even both in  $L^*$  in the sense that  $\vdash_{L^*} \mathcal{A}$  and/or  $\vdash_{L^*} (\sim \mathcal{A})$ , or it is undecidable in the sense that neither  $\vdash_{L^*} \mathcal{A}$  or  $\vdash_{L^*} (\sim \mathcal{A})$ . In the latter case, would arbitrarily adding  $\mathcal{A}$  or  $(\sim \mathcal{A})$  break the consistency of  $L$ ? The answer is no, as the following proposition shows.

**Proposition 2.19.** Let  $L^*$  be a consistent extension of  $L$  and let  $\mathcal{A}$  be a *wf* of  $L$  which is not a theorem of  $L^*$ . Then  $L^{**}$  also consistent, where  $L^{**}$  is the extension of  $L$  obtained from  $L^*$  by including  $(\sim \mathcal{A})$  as an additional axiom.

*Proof.* Suppose that  $L^{**}$  is not consistent. Then there exists some *wf*  $\mathcal{B}$  such that both  $\mathcal{B}$  and  $(\sim \mathcal{B})$  are theorems of  $L^{**}$ . Now by Proposition 2.18 (see the note below),  $\mathcal{A}$  must be a theorem of  $L^{**}$ . But since any theorem of  $L^{**}$  is a deduction from  $(\sim \mathcal{A})$  in  $L^*$ , which is to say that  $\{(\sim \mathcal{A})\} \vdash_{L^*} \mathcal{A}$  it follows from the deduction theorem that  $\vdash_{L^*} ((\sim \mathcal{A}) \rightarrow \mathcal{A})$ . From Proposition 2.11(b) and since all theorems of  $L$  are theorems of  $L^*$ , we have  $\vdash_{L^*} ((\sim \mathcal{A}) \rightarrow \mathcal{A}) \rightarrow \mathcal{A}$ , and so  $\vdash_{L^*} \mathcal{A}$  by MP. But this contradicts  $\mathcal{A}$  not being a theorem of  $L^*$ . Therefore,  $L^{**}$  must be consistent.  $\square$

*Note.* Proposition 2.18 is not strictly applicable here, but its proof can be easily generalized to  $L^{**}$ .

*Note.* Clearly if  $(\sim \mathcal{A})$  is a theorem of  $L^*$ , then adding it as an axiom in  $L^{**}$  will not break consistency. Only when  $\mathcal{A}$  is "neither true nor false" is this theorem interesting.

**Definition 2.20.** An extension of  $L$  is *complete* if for each *wf*  $\mathcal{A}$ , either  $\mathcal{A}$  or  $(\sim \mathcal{A})$  is a theorem of the extension.

*Note.* Completeness is the converse of soundness.

**Proposition.** The set of *wfs* of  $L$  is countable.

*Proof.* See the appendix.  $\square$

**Proposition 2.21.** Let  $L^*$  be a consistent extension of  $L$ . Then there is a consistent complete extension of  $L^*$ .

*Proof.* Since the set of all *wfs* of  $L$  is countable, let  $\mathcal{A}_1, \mathcal{A}_2, \mathcal{A}_3$  be an enumerations of the *wfs*. Define a sequence  $J_0, J_1, J_2, \dots$  by the following rules.

1. If  $n = 0$ , let  $J_0$  be  $L^*$ .
2. If  $n > 0$ , let  $J_n$  be  $J_{n-1}$  if  $\vdash_{J_{n-1}} \mathcal{A}_n$ .
3. If  $n > 0$ , let  $J_n$  be  $J_{n-1}$  extended with  $(\sim \mathcal{A}_n)$  as an additional axiom if  $\mathcal{A}_n$  is not a theorem of  $J_{n-1}$ .

Notice that since  $J_0 = L^*$  is consistent and every following member of the sequence is either the previous member or a consistent extension by Proposition 2.19, every member of the sequence is consistent.

Now define  $J$  to be an extension of  $L^*$  such that a *wf* is an axiom of  $J$  if and only if it is an axiom of  $J_n$  for any  $n$ . Notice that by construction of the sequence, for any  $k$ , either  $\mathcal{A}_k$  or  $(\sim \mathcal{A}_k)$  is a theorem of  $J_k$ . So  $J_k$  or  $(\sim J_k)$  must be a theorem of  $J$ , which extends  $J_k$ . Therefore,  $J$  is complete.

Now suppose that  $J$  is not consistent. Then there is a *wf*  $\mathcal{A}$  such that  $\vdash_J \mathcal{A}$  and  $\vdash_J (\sim \mathcal{A})$ . Now in these proofs, there are a finite number of axioms used, and each axiom must of course appear in the list of all numbered *wfs*. Let  $\mathcal{A}_k$  refer to the axiom with the highest index  $k$ . So both  $\vdash_{J_k} \mathcal{A}_k$  and  $\vdash_{J_k} (\sim \mathcal{A}_k)$ , contradicting the consistency of  $J_k$ . Hence,  $J$  must be consistent.  $\square$

*Note.* An extension of  $L^*$  is defined in the same way as an extension of  $L$  is.

*Note.* The set of *wfs* is purposely indexed starting from 1 instead of 0 like in the book so that  $\mathcal{A}_n$  or  $(\sim \mathcal{A}_n)$  is a theorem of  $\mathcal{B}_n$ .

**Proposition 2.22.** If  $L^*$  is a consistent extension of  $L$  then there is a valuation in which each theorem of  $L^*$  takes value  $T$ .

*Proof.* Let  $J$  be the consistent complete extension of  $L^*$  given in the proof of Proposition 2.21. Define  $v$  on *wfs* of  $L$  by  $v(\mathcal{A}) = T$  if  $\mathcal{A}$  is a theorem of  $J$  and  $v(\mathcal{A}) = F$  otherwise.

Now it remains to be shown that  $v$  is a valuation consistent with Definition 2.12. Since  $J$  is complete,  $v$  is defined on all *wfs*. For any  $\mathcal{A}$ ,  $v(\mathcal{A}) \neq v((\sim \mathcal{A}))$ , since  $J$  is consistent. It remains to show that  $v(\mathcal{A} \rightarrow \mathcal{B}) = F$  if and only if  $v(\mathcal{A}) = T$  and  $v(\mathcal{B}) = F$ .

$\Rightarrow$  Suppose that  $v(\mathcal{A} \rightarrow \mathcal{B}) = F$  and that either  $v(\mathcal{A}) = F$  or  $v(\mathcal{B}) = T$ . Since  $J$  is consistent,  $(\sim (\mathcal{A} \rightarrow \mathcal{B}))$  must be a theorem of  $J$  and either  $(\sim \mathcal{A})$  or  $\mathcal{B}$  is also theorem of  $J$ . If  $(\sim \mathcal{A})$ , then

1	$(\sim \mathcal{A})$	assumption
2	$((\sim \mathcal{A}) \rightarrow ((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A})))$	(L1)
3	$((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A}))$	1, 2, MP
4	$((\sim \mathcal{B}) \rightarrow (\sim \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})$	(L3)
5	$(\mathcal{A} \rightarrow \mathcal{B})$	3, 4, MP

or if  $\mathcal{B}$ , then

1	$\mathcal{B}$	assumption
2	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	(L2)
3	$(\mathcal{A} \rightarrow \mathcal{B})$	1, 2, MP

and so in either case,  $(\mathcal{A} \rightarrow \mathcal{B})$  is a theorem of  $J$  along with  $(\sim (\mathcal{A} \rightarrow \mathcal{B}))$ , contradicting the consistency of  $J$ . Therefore, if  $v(\mathcal{A} \rightarrow \mathcal{B})$ , then  $v(\mathcal{A}) = T$  and  $v(\mathcal{B}) = F$ .

$\Leftarrow$  Suppose that  $v(\mathcal{A}) = T$ ,  $v(\mathcal{B}) = F$  and that  $v((\mathcal{A} \rightarrow \mathcal{B})) = T$ . Then  $\mathcal{A}$ ,  $(\sim \mathcal{B})$ , and  $(\mathcal{A} \rightarrow \mathcal{B})$  are theorems of  $J$ . Then by MP,  $\mathcal{A}$ , and  $(\mathcal{A} \rightarrow \mathcal{B})$ , it follows that  $\mathcal{B}$  is a theorem of  $J$  as well along with  $(\sim \mathcal{B})$ , contradicting the consistency of  $J$ . Therefore, if  $v(\mathcal{A}) = T$ ,  $v(\mathcal{B}) = F$  implies that  $v((\mathcal{A} \rightarrow \mathcal{B})) = F$ .

In conclusion,  $v$  is indeed a valuation and so if  $\mathcal{A}$  is a theorem of  $L^*$ , then it must be a theorem of the extension  $J$ , in which case it takes the value  $T$  under the valuation  $v$ , making  $v$  a valuation in which each theorem of  $L^*$  takes value  $T$ .  $\square$

**Proposition 2.23** (The Adequacy Theorem for  $L$ ). If  $\mathcal{A}$  is a *wf* of  $L$  and  $\mathcal{A}$  is a tautology, then  $\mathcal{A}$  is a theorem of  $L$ .

*Proof.* Let  $\mathcal{A}$  be a tautology and suppose that it is not a theorem of  $L$ . Then  $(\sim \mathcal{A})$  must be a theorem of the extension  $L^*$  by Proposition 2.21. Therefore, by Proposition 2.22, there exists a valuation  $v$  in which  $v(\sim \mathcal{A}) = T$ . But  $v(\mathcal{A}) = T$ , since  $\mathcal{A}$  is a tautology. This contradiction demonstrates that  $\mathcal{A}$  must be a theorem of  $L$ .  $\square$

**Proposition 2.24.**  $L$  is *decidable*, i.e., there is an effective method for deciding, given any *wf* of  $L$ , whether it is a theorem of  $L$ .

*Proof.* The effective method of determining whether a *wf* is a tautology is to show that any valuation assigns the *wf* the value of  $T$ . If so, then it is a tautology, and by Proposition 2.23, it must be a theorem of  $L$ .  $\square$

*Note.* Showing that any valuation assigns the *wf* the value of  $T$  can be done by creating truth tables like in the first chapter.

## Solutions to exercises

6. The truth tables for each scheme of  $L$  are shown below, and since the values for any assignment of  $T$  or  $F$  to the *wfs* is  $T$ , the axioms must all be tautologies.

For (L1),

$(\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$
1    1    1    1    1
1    1    0    1    1
0    1    1    0    0
0    1    0    1    0

For (L2),

$((\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C})))$
1    1    1    1    1    1    1    1    1    1    1    1
1    0    1    0    0    1    1    1    1    0    1    0    0
1    1    0    1    1    1    1    0    0    1    1    1    1
1    1    0    1    0    1    1    0    0    1    1    0    0
0    1    1    1    1    1    0    1    1    1    0    1    1
0    1    1    0    0    1    0    1    1    1    1    0    0
0    1    0    1    1    1    0    1    0    1    0    1    1
0    1    0    1    0    1    0    1    0    1    0    1    0

For (L3),

$$\begin{array}{ccccccc}
 (((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A})) & \rightarrow & (\mathcal{B} \rightarrow \mathcal{A}) \\
 \begin{array}{cccccc}
 0 & 1 & 1 & 0 & 1 & 1 \\
 0 & 1 & 1 & 1 & 0 & 1 \\
 1 & 0 & 0 & 0 & 1 & 1 \\
 1 & 0 & 1 & 1 & 0 & 1
 \end{array}
 \end{array}$$

7. Let  $\mathcal{A}$  be a *wf* of  $L$  and let  $L^+$  be the extension of  $L$  obtained by including  $\mathcal{A}$  as a new axiom. It is to be proved that the set of theorems of  $L^+$  is different from the set of theorems of  $L$  if and only if  $\mathcal{A}$  is not a theorem of  $L$ .

$\Rightarrow$  Proceeding by contrapositive, suppose that  $\mathcal{A}$  is a theorem of  $L$ . Then let  $\mathcal{B}$  any theorem of  $L^+$ . We will demonstrate that  $\mathcal{B}$  is a theorem of  $L$ .

If the proof of  $\mathcal{B}$  does not involve the axiom  $\mathcal{A}$ , then  $\mathcal{B}$  is a theorem of  $L$ , since  $L$  differs from  $L^+$  only in not having  $\mathcal{A}$  as an axiom.

Otherwise, the proof of  $\mathcal{B}$  does involve the axiom  $\mathcal{A}$ , which is to say that  $\{\mathcal{A}\} \vdash_L \mathcal{B}$ , and by the deduction theorem  $\vdash_L (\mathcal{A} \rightarrow \mathcal{B})$ . By MP and  $\mathcal{A}$  being a theorem in  $L$ ,  $\mathcal{B}$  is a theorem in  $L$ .

Therefore, any theorem in  $L^+$  is a theorem in  $L$ .

$\Leftarrow$  Suppose that  $\mathcal{A}$  is not a theorem of  $L$ . Then since  $\mathcal{A}$  is a theorem of  $L^+$  by virtue of all axioms being theorems, the set of theorems of  $L^+$  must be different from the set of theorems of  $L$ .

8. Notice that  $\mathcal{A}$  is neither a tautology nor a contradiction. Therefore, neither  $\mathcal{A}$  nor  $(\sim \mathcal{A})$  are theorems of  $L$ . Therefore, by the previous exercise,  $L^+$ , the extension of  $L$  with  $\mathcal{A}$  as an axiom, has a larger set of theorems than  $L$ , in the sense that more *wfs* are theorems of  $L^+$ .

Now suppose that  $L^+$  is inconsistent. In an inconsistent system, every *wf* is a theorem, so  $(\sim \mathcal{A})$  must be a theorem of  $L^+$ . But since  $L^+$  is  $L$  with  $\mathcal{A}$  as an additional axiom, it follows that  $\{\mathcal{A}\} \vdash_L (\sim \mathcal{A})$ , and by the deduction theorem,  $(\mathcal{A} \rightarrow (\sim \mathcal{A}))$  is a theorem of  $L$ . But since  $(\mathcal{A} \rightarrow (\sim \mathcal{A}))$  is not a tautology, it cannot be a theorem of  $L$ . With this contradiction, it is seen that  $L^+$  must be consistent.

9. Suppose that  $\mathcal{B}$  is a contradiction as well as a theorem in  $L^+$ . For a contradiction, suppose that  $L^+$  is a consistent extension of  $L$ . Then by Proposition 2.22, there is a valuation  $v$  such that every theorem of  $L^+$  takes value  $T$ . So  $v(\mathcal{B}) = T$ , but this contradicts  $\mathcal{B}$  being a contradiction.

*Note.* See the note in Definition 2.13.

10.  $L^{++}$  must have the contradiction

$$(((\sim (p_1 \rightarrow p_1)) \rightarrow (p_1 \rightarrow p_1)) \rightarrow ((p_1 \rightarrow p_1) \rightarrow (\sim (p_1 \rightarrow p_1))))$$

as a theorem, since it is an instance of the given axiom scheme. By the previous exercise,  $L^{++}$  cannot be consistent.

11. Let  $J$  be a consistent complete extension of  $L$ , and let  $\mathcal{A}$  be a *wf* of  $L$ . Let  $J^+$  be the extension of  $J$  obtained by including  $\mathcal{A}$  as an additional axiom. It is to be proved that  $J^+$  is consistent if and only if  $\mathcal{A}$  is a theorem of  $J$ .

$\Rightarrow$  Suppose that  $J^+$  is consistent. For a contradiction, suppose that  $\mathcal{A}$  is not a theorem of  $J$ . Then  $(\sim \mathcal{A})$  must be a theorem of  $J$ , since  $J$  is consistent and complete. Since  $J^+$  is an extension of  $J$ ,  $(\sim \mathcal{A})$  must also be a theorem of  $J^+$ , which contradicts the consistency of  $J^+$ , since  $\mathcal{A}$  is an axiom and hence a theorem of  $J$ .

$\Leftarrow$  Suppose that  $\mathcal{A}$  is a theorem of  $J$  and let  $\mathcal{B}$  be any theorem in  $J^+$ . We will demonstrate that  $\mathcal{B}$  must be a theorem in  $J$ .

If the proof of  $\mathcal{B}$  in  $J^+$  does not rely on  $\mathcal{A}$ , then  $\mathcal{B}$  is a theorem of  $J$ , since  $J^+$  extends  $J$  with only  $\mathcal{A}$  as an additional axiom.

The other possibility is that the proof of  $\mathcal{B}$  does involve  $\mathcal{A}$ , which is to say that  $\{\mathcal{A}\} \vdash_J \mathcal{B}$ , and so by the deduction theorem  $\vdash_J (\mathcal{A} \rightarrow \mathcal{B})$ . By MP and  $\mathcal{A}$  being a theorem in  $J$ ,  $\mathcal{B}$  is a theorem in  $J$ . Therefore, any theorem in  $J^+$  is a theorem in  $J$ , and since  $J$  is consistent,  $J^+$  must be so as well.

12. We will prove this using strong induction on the number of *wfs* in the proof of  $\mathcal{A}$ .

Suppose as an induction hypothesis that for any theorem  $\mathcal{A}$  in  $L$  in which statement letters appear and in which its proof involves less than  $n$  *wfs*,  $\mathcal{B}$ , a *wf* with any *wfs* substituted for the statement letters, is also a theorem of  $L$ .

It may be the case that  $\mathcal{A}$  is an instance of an axiom, in which case  $\mathcal{B}$  is also an instance of axiom and hence a theorem of  $L$ .

Otherwise,  $\mathcal{A}$  proceeds from two prior *wfs* in the proof via MP. These two *wfs* have less than  $n$  *wfs* in their proof, and therefore by the induction hypothesis, there exist theorems in  $L$  with the same substitutions of *wfs* for the statement letters described above. By MP and these two statements,  $\mathcal{B}$  is a theorem of  $L$  as well.

*Note.* In other words,  $\mathcal{B}$  can be proved in an identical manner as  $\mathcal{A}$ , except by substituting the proper *wfs* for each *wf* in the proof of  $\mathcal{A}$ .

# Chapter 3

## Informal predicate calculus

### 3.1 Predicates and sequences

#### A warning

The reader of *Logic For Mathematicians* of course already has knowledge of formal mathematics regarding quantified statements. There is a common unspoken convention in math that statements are to quantified implicitly if quantifiers are absent. A statement like  $x < y$  might be written to be short for  $(\forall x)(\forall y)(x < y)$ , where  $x$  and  $y$  are integers.

But this assumption cannot be held while reading Chapter 3 of the textbook or when studying first-order logic in general. Some strings of symbols, which will later be called *wfs*, are neither true nor false, and the reason for this is the absence of quantifiers. For example, the string  $x < y$  is assumed to be indeterminate in the sense that it is neither true nor false, and likewise  $(\forall x)x < y$  is also indeterminate. The truth of these formulas depend on how  $x$  and  $y$  are evaluated ( $x = y = 3$  would yield a false evaluation, for example), which is an idea which will be formalized in the last chapter of this section.

We will see later that all *closed formulas*, which refer to formulas where all variables are quantified, are true or false, as expected. However, not all unquantified formulas are indeterminate. Consider  $x = x$ , which is true, despite the formula having no quantifiers.

#### Solutions to exercises

1. (a)  $\sim (\forall x)(F(x) \rightarrow D(x))$   
(b)  $(\exists x)(F(x) \wedge C(x) \wedge (\sim D(x)))$   
(c)  $(\exists x)(T(x) \wedge L(x)) \rightarrow (\forall x)(T(x) \rightarrow L(x))$   
(d)  $(\forall x)(E(x) \vee O(x))$   
(e)  $\sim (\exists x)(E(x) \wedge O(x))$   
(f)  $(\exists x)(P(x) \wedge (\forall y)(P(y) \rightarrow H(x, y)))$   
(g)  $(\forall x)(E(x) \rightarrow (\forall y)(M(y) \rightarrow H(x, y)))$
2. (a)  $\sim (\forall x)(C(x) \rightarrow T(x))$   
 $(\exists x)(C(x) \wedge \sim T(x))$

- (b)  $\sim (\forall x)(P(x) \rightarrow (\sim L(x) \wedge \sim S(x)))$   
 $(\exists x)(P(x) \wedge (L(x) \vee S(x)))$
- (c)  $(\forall x)(\forall y)((M(x) \wedge E(y)) \rightarrow \sim H(x, y))$   
 $\sim (\exists x)(\exists y)(M(x) \wedge E(y) \wedge H(x, y))$
- (d)  $(\forall x)(N(x) \vee S(x))$   
 $\sim (\exists x)((\sim N(x)) \wedge (\sim S(x)))$

3.

## 3.2 First order languages

Here we will define a mathematical structure which is not a formal system as it has no rules or deductions or axioms. It does have an alphabet, which is specified below. In fact, it may be thought of, structurally speaking, as only an alphabet, a set of symbols.

A *first order language*  $\mathcal{L}$  will have as its alphabet of symbols:

- the countably infinite list of *variables*  $x_1, x_2, \dots$
- some or none of the *constants*  $a_1, a_2, \dots$
- some or none of the *predicate letters*  $A_1^1, A_2^1, \dots; A_1^2, A_2^2, \dots; A_1^3, A_2^3, \dots; \dots$
- some or none of the *function letters*  $f_1^1, f_2^1, \dots; f_1^2, f_2^2, \dots; f_1^3, f_2^3, \dots; \dots$ 
  - the predicate and function letters are countably infinite lists of countably infinite lists
  - the subscripts are used to distinguish different functions of the same arity, while the superscript indicates the arity
  - the function letters are not strictly necessary, as they can be expressed as relations as well, but the redundancy is kept for purposes of intuitive clarity
- the left and right parentheses ( and ) and the comma , as *punctuation symbols*
- the *connectives*  $\sim$  and  $\rightarrow$
- the quantifier  $\forall$ 
  - the existential quantifier  $\exists$  can be expressed in terms of the universal quantifier along with the  $\sim$  connective, so it is not included

*Note.* Two first order languages differ only in the symbols which are in the alphabet, particularly which constants, predicate letters and function letters are included. For example, one first order language might only include  $a_1$  and  $f_1^1$ , and another might only include  $A_1^1$ .

The alphabet will be part of a formal system described in the next chapter which will make clear the logical rules in a first-order system. Since no rules of deduction or axioms have been specified, studying first order languages, which is the subject of this chapter, will be limited to studying not the valid rules of transformations of strings of symbols that correspond to valid deductions, but rather what the valid strings are and how they are to be interpreted.



**Definition 3.6.** A *term* in a first order language  $\mathcal{L}$  is defined as follows

- (i) Variables and individual constants are terms.
- (ii) If  $f_i^n$  is a function letter in  $\mathcal{L}$ , and  $t_1, \dots, t_n$  are terms in  $\mathcal{L}$ , then  $f_i^n(t_1, \dots, t_n)$  is a term in  $\mathcal{L}$ .
- (iii) The set of all terms is generated as in (i) and (ii).

An *atomic formula* in  $\mathcal{L}$  is defined by: if  $A_j^k$  is a predicate letter in  $\mathcal{L}$  and  $t_1, \dots, t_n$  are terms in  $L$ , then  $A_j^k(t_1, \dots, t_n)$  is an atomic formula of  $\mathcal{L}$ .

A *well-formed formula* of  $\mathcal{L}$  is defined by:

- (i) Every atomic formula of  $\mathcal{L}$  is a *wf* of  $\mathcal{L}$ .
- (ii) If  $\mathcal{A}$  and  $\mathcal{B}$  are *wfs*, so are  $(\sim \mathcal{A})$ ,  $(\mathcal{A} \rightarrow \mathcal{B})$  and  $(\forall x_i)\mathcal{A}$ , where  $x_i$  is any variable.
- (iii) The set of all *wfs* of  $\mathcal{L}$  is generated as in (i) and (ii)

Terms are to be considered as objects in the language, a *wf* as a statement, and an atomic formula as the most simple kind of statement.

The symbols  $\exists$ ,  $\wedge$  and  $\vee$  are treated as shorthand.

- $(\exists x_i)\mathcal{A}$  is an abbreviation for  $(\sim ((\forall x_i)(\sim \mathcal{A}))$
- $(\mathcal{A} \wedge \mathcal{B})$  is an abbreviation for  $(\sim (\mathcal{A} \rightarrow (\sim \mathcal{B})))$
- $(\mathcal{A} \vee \mathcal{B})$  is an abbreviation for  $((\sim \mathcal{A}) \rightarrow \mathcal{B})$

*Note.* Unlike in chapter 2, this manual will follow the book's style for omitting parentheses. That is, a  $\sim$  will be presumed to apply to the shortest possible subsequent *wf*. Also notice that this is how the  $\forall$  quantifier is treated, by definition.

**Definition 3.8.** In the *wf*  $(\forall x_i)\mathcal{A}$ , we say that  $\mathcal{A}$  is the *scope* of the quantifier. When  $(\forall x_i)\mathcal{A}$  occurs as a subformula of a *wf*  $\mathcal{B}$ , the scope of the quantifier  $(\forall x_i)$  is said to be  $\mathcal{A}$  in  $\mathcal{B}$ .

A variable  $x_i$  in a *wf* is said to be *bound* if it occurs within the scope of a  $(\forall x_i)$  in the *wf* or if it is the  $x_i$  in a  $(\forall x_i)$ . A variable which is not bound is said to be *free*.

*Note.* One point of confusion is that the meaning of a formula  $(\forall x_i)\mathcal{A}$  is reliant on its *free* variables, not its bound ones, which might be contrary to one's intuitions about the words *free* and *bound*.

From here on out, if  $\mathcal{A}(x_i)$  is a *wf* in which  $x_i$  occurs free, then  $\mathcal{A}(t)$  will refer to  $\mathcal{A}(x_i)$  with all *free* occurrences of  $x_i$  replaced with  $t$ . So if  $\mathcal{A}(x_i)$  is  $(\forall x_2)A_1^1(x_i) \rightarrow (\forall x_i)A_1^1(x_i)$ , then  $\mathcal{A}(t)$  is  $(\forall x_2)A_1^1(t) \rightarrow (\forall x_i)A_1^1(x_i)$ . We will want to only substitute  $t$  for  $x_i$  if it does not interact with quantifiers in  $\mathcal{A}(x_i)$ . In the previous example,  $x_2$  would be a different substitution than any other variable. For this reason, we need the next definition, which is as important as it is confusing. A few equivalent definitions will be provided.

**Definition 3.11.** Let  $\mathcal{A}$  be any *wf* of  $\mathcal{L}$ . A term  $t$  is *free for  $x_i$  in  $\mathcal{A}$*  if  $x_i$  does not occur free in  $\mathcal{A}$  within the scope of a  $(\forall x_j)$ , where  $x_j$  is any variable occurring in  $t$ .

Equivalently, a term  $t$  is *free for  $x_i$  in  $\mathcal{A}$*  if substituting  $t$  for any free instance of  $x_i$  in  $\mathcal{A}$  would not introduce any new bound variables.

Equivalently, a term  $t$  is *free for  $x_i$  in  $\mathcal{A}$*  if any variable in  $t$  is free in  $\mathcal{A}$  after substituting it for any free instance of  $x_i$ .

An algorithm for determining whether a term  $t$  is *free for  $x_i$  in  $\mathcal{A}$*  goes as follows:

1. Find all free instances of  $x_i$  in  $\mathcal{A}$ .
2. For each free instance  $x_j$ , repeat the following step:
  - (a) For each variable  $x_k$  in  $t$ , repeat the following steps:
    - i. Substitute  $x_k$  for  $x_j$ .
    - ii. If  $x_k$  is bound in  $\mathcal{A}$ , then  $t$  is not free for  $x_i$ , and terminate the algorithm.
3. Conclude that  $t$  is free for  $x_i$ .

*Note.* A term being free for a variable  $x_i$  does not necessarily indicate that it may be substituted for that variable, because the variable  $x_i$  may be bound. But if  $x_i$  only occurs free, then a term being free for it is equivalent to a term being substitutable for it. Therefore “ $t$  being free for  $x_i$ ” can be thought of as “ $t$  being substitutable for free instances of  $x_i$ .”

*Note.* It is easy to confirm that if  $x_i$  occurs only bound in  $\mathcal{A}$ , then any term is free for it. Also, for any *wf* and any variable  $x_i$ ,  $x_i$  is free for itself in  $\mathcal{A}$ .

## Solutions to exercises

4. The set of terms in a first order language with no function letters is just the set of the variables and the individual constants.
5. The set of terms is  $f_1^1(x_1), f_1^1(x_2), f_1^1(x_3), \dots$
6. The formulas that are well-formed formulas are (a), (d), (e), (g), and (h).

*Note.* The answer key in the book omits (d) as a well-formed formula, but this appears to be wrong.

7. (a) free  
 (b) bound, bound  
 (c) bound, bound, free  
 (d) free, free, free, free

Since all occurrences of  $x_2$  in the *wfs* are bound, the term  $f_1^2(x_1, x_3)$  (and any other term) is free for  $x_2$  in the *wfs*.

8. Suppose that  $x_j$  is free for  $x_i$  in  $\mathcal{A}(x_i)$ . Then  $x_i$  does not occur free in the scope of a  $(\forall x_j)$  in  $\mathcal{A}(x_i)$ . The goal is to show that  $x_j$  does not occur free in the scope of a  $(\forall x_i)$  in  $\mathcal{A}(x_j)$ .

Now consider an occurrence of an  $x_j$  in  $\mathcal{A}(x_j)$ , which is either (1) a substitution for an  $x_i$  in  $\mathcal{A}(x_i)$  or (2) not a substitution for an  $x_i$  in  $\mathcal{A}(x_i)$ . If (1), then since  $x_1$

was assumed to occur free in  $\mathcal{A}(x_i)$ , it must not be in the scope of a  $(\forall x_i)$ , and so the substituted  $x_j$  must also not be in the scope of a  $(\forall x_i)$ . If (2), then it must occur the same as it does in  $\mathcal{A}(x_i)$ , a *wf* in which it is assumed to occur bound, and therefore it does not occur free in the scope of a  $(\forall x_i)$ , or any quantifier for that matter.

Since in both (1) and (2),  $x_j$  does not occur free in the scope of a  $(\forall x_i)$  in  $\mathcal{A}(x_j)$ , it can be concluded that  $x_i$  is free for  $x_j$  in  $\mathcal{A}(x_j)$ .

*Note.* The hypothesis that  $x_j$  is free for  $x_i$  is never used in the proof. It seems that there is either a mistake in the proof or in the exercise. The hint/proof in the back of the book seems to agree with the proof given here.

9. (a) Since  $(\forall x_1)$  and  $(\forall x_3)$  never occur,  $t$  is free for  $x_1$ .  
 (b) Since  $x_1$  only occurs bound,  $t$  is free for  $x_1$ .  
 (c) Since  $x_1$  occurs free in the scope of a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .  
 (d) Since  $x_1$  occurs free in the scope of a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .
10. Here, the (a), (b), (c), and (d) refer to the *wfs* in the exercise 9 and not the terms in exercise 10.

*Note.* There is a mistake in the text, the exercise should read “Repeat Exercise 9...” instead of “Repeat Exercise 6...”.

Let  $t = x_2$ .

- (a) Since  $x_1$  occurs free in the scope of a  $(\forall x_2)$ ,  $t$  is not free for  $x_1$ .  
 (b) Since  $x_1$  only occurs bound,  $t$  is free for  $x_1$ .  
 (c) Since  $x_1$  does not occur in the scope of a  $(\forall x_2)$ , it does not occur free in it, so  $t$  is free for  $x_1$ .  
 (d) Since  $x_1$  occurs free in the scope of a  $(\forall x_2)$ ,  $t$  is not free for  $x_1$ .

Let  $t = x_3$ .

- (a) Since a  $(\forall x_3)$  never occurs,  $t$  is free for  $x_1$ .  
 (b) Since  $x_1$  only occurs bound,  $t$  is free for  $x_1$ .  
 (c) Since  $x_1$  occurs free in the scope of a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .  
 (d) Since  $x_1$  occurs free in the scope of a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .

Let  $t = f_1^2(a_1, x_1)$ .

- (a) Since a  $(\forall x_1)$  never occurs,  $t$  is free for  $x_1$ .  
 (b) Since  $x_1$  only occurs bound,  $t$  is free for  $x_1$ .  
 (c) Since a  $(\forall x_1)$  never occurs,  $t$  is free for  $x_1$ .  
 (d) Since a  $(\forall x_1)$  never occurs,  $t$  is free for  $x_1$ .

Let  $f_1^3(x_1, x_2, x_3)$ .

- (a) Since  $x_1$  occurs free in the scope of a  $(\forall x_2)$ ,  $t$  is not free for  $x_1$ .

- (b) Since  $x_1$  only occurs bound,  $t$  is free for  $x_1$ .
- (c) Since  $x_1$  occurs free in the scope of a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .
- (d) Since  $x_1$  occurs free in the scope of a  $(\forall x_2)$  and a  $(\forall x_3)$ ,  $t$  is not free for  $x_1$ .

### 3.3 Interpretations

**Definition 3.14.** An *interpretation*  $I$  of  $\mathcal{L}$  is

- a non-empty set  $D_I$  called the *domain* of  $I$  together with a collection
- a collection of distinguished elements  $(\bar{a}_1, \bar{a}_2, \dots)$  of  $D_I$
- a collection of functions from  $D_I$  to  $D_I$  denoted by  $(\bar{f}_1^n, i > 0, n > 0)$
- a collection of relations on  $D_I$  denoted by  $(\bar{A}_1^n, i > 0, n > 0)$

An interpretation allows a *wf* of a first order language to be interpreted as a statement with a truth value, analogous to how a valuation of  $L$  allowed a *wf* in  $L$  to have a truth value. This concept will be formalized in the coming sections.

#### Solutions to exercises

11. The interpretation of  $\mathcal{A}$  in  $I$  is the statement

$$(\forall x_1)(\forall x_2)(x_1 - x_2 < 0 \rightarrow x_1 < x_2)$$

which is a true statement in the integers. Consider the same interpretation  $I$  with  $\bar{f}_1^2(x, y)$  as  $x + y$ . The interpretation of  $\mathcal{A}$  in  $I$  is then

$$(\forall x_1)(\forall x_2)(x_1 + x_2 < 0 \rightarrow x_1 < x_2)$$

which is false.

12. Let  $I$  be the interpretation described above in the previous exercise with the addition of  $\bar{f}_1^1, \bar{A}_1^1$  defined by  $\bar{f}_1^1(x) = x - 1$  and  $\bar{A}_1^1(x)$  if and only if  $x > 0$ . Then the statement corresponding to the *wf* under  $I$  is

$$(\forall x_i)(x_1 > 0 \rightarrow x_1 - 1 > 0)$$

which is false.

13. Let  $I$  again be the interpretation described in Exercise 11 with  $\bar{A}_1^2(x, y)$  as  $x < y$ . Then the interpretation of the *wf* is

$$(\forall x_1)(x_1 < x_2 \rightarrow x_2 < x_1)$$

which is false, since it defies the law of trichotomy, a property of the integers.

### 3.4 Satisfaction, truth

In this chapter  $I$  will be an interpretation of the language  $\mathcal{L}$  with notation consistent with Definition 3.14.

In the previous chapter, values of true or false were informally assigned to various *wfs* of  $\mathcal{L}$  under some interpretation  $I$ . This chapter will formalize this process of evaluating the truth of a *wf*. The process will and must be similar to the informal process of determining the truth value of a *wf*. First, the terms must be assigned to values. A particular assignment is formally known as a *valuation*.

**Definition 3.17.** A *valuation* in  $I$  is a function  $v$  from the set of terms of  $\mathcal{L}$  to the set domain of  $I$ ,  $D_I$ , with the properties:

- (i)  $v(a_i) = \bar{a}_i$  for each constant  $a_i$  of  $\mathcal{L}$ .
- (ii)  $v(f_i^n(t_1, \dots, t_n)) = f_i^n(v(t_1), \dots, v(t_n))$ , where  $f_i^n$  is any function letter in  $\mathcal{L}$ , and  $t_1, \dots, t_n$  are any terms of  $\mathcal{L}$ .

*Note.* An interpretation will have as many different valuations as there are ways of assigning the variables in  $\mathcal{L}$  to elements of  $D_I$ .

*Note.* A term in  $\mathcal{L}$  may be a variable, a constant, or a function with terms as its arguments. The variables can be assigned to any elements in  $D_I$  and no property is needed to govern the valuation of a variable. By property (i), every valuation assigns constants of  $\mathcal{L}$  to its corresponding constant in  $D_I$ . Property (ii) guarantees that the valuation of functions in  $\mathcal{L}$  behave as expected.

**Definition 3.19.** Two valuations  $v$  and  $v'$  are *i-equivalent* if  $v(x_j) = v'(x_j)$  for every  $j \neq i$ .

*Note.* The purpose of this definition will be better understood after reading further on.

Continuing from where we left off before Definition 3.17, after the terms are assigned values, the *wfs* can be evaluated as true or false, depending on the particular values of the terms. If a particular *wf* is to be interpreted as a true statement when its terms take on some particular values specified by a valuation, the valuation is said to satisfy the *wf*. Since a *wf* in  $\mathcal{L}$  was defined recursively, and likewise the definition of satisfaction of a *wf* must also be defined recursively.

**Definition 3.20.** Let  $\mathcal{A}$  be a *wf* of  $\mathcal{L}$ , and let  $I$  be an interpretation of  $\mathcal{L}$ . A valuation  $v$  in  $I$  is said to satisfy...

- (i) the atomic formula  $A_j^n(t_1, \dots, t_n)$  if  $\bar{A}_j^n(v(t_1), \dots, v(t_n))$  is true in  $D_I$ ,
- (ii) the negation  $(\sim \mathcal{B})$  if  $v$  does not satisfy  $\mathcal{B}$ ,
- (iii) the implication  $(\mathcal{B} \rightarrow \mathcal{C})$  if either  $v$  satisfies  $(\sim \mathcal{B})$  or  $v$  satisfies  $\mathcal{C}$ ,
- (iv) the quantified *wf*  $(\forall x_i)\mathcal{B}$  if all valuations  $v'$  which are *i-equivalent* to  $v$  satisfy  $\mathcal{B}$ .

*Note.* The first three parts of the definition are straightforward. The last one should be explained further. It states that a valuation satisfies a quantified *wf* if any corresponding interpretation is true when the bound variable takes on any possible value.

**Proposition 3.23.** Let  $\mathcal{A}(x_i)$  be a wf of  $\mathcal{L}$  in which  $x_i$  appears free, and let  $t$  be a term free for  $x_i$ . Suppose that  $v$  is a valuation and  $v'$  is the valuation which is  $i$ -equivalent to  $v$  and has  $v'(x_i) = v(t)$ . Then  $v$  satisfies  $\mathcal{A}(t)$  if and only if  $v'$  satisfies  $\mathcal{A}(x_i)$ .

*Note.* The condition that  $x_i$  appears free in  $\mathcal{A}(x_i)$  can be relaxed if  $\mathcal{A}(t)$  is defined as replacing all bound instances of  $x_i$ .

*Proof.* We will first prove a lemma.

**Lemma.** Let  $u$  be a term in which  $x_i$  occurs. Let  $u'$  be the term obtained by substituting  $t$  for  $x_i$  in  $u$ . Then  $v(u') = v'(u)$ .

*Proof.* The proof is by strong induction on the number of sub-terms in  $u$ . Note that this number takes sub-terms of sub-terms into account, so  $f_1^2(f_1^2(x_1, x_1), f_1^2(x_1, x_1))$  has four, not two, sub-terms.

Suppose as a hypothesis of strong induction that if a term has fewer than  $n$  sub-terms in it, then  $v(u') = v'(u)$ , where  $u$  and  $u'$  are defined as above.

(base case) It may be that  $n = 1$ , in which case  $u = x_i$  and  $u' = t$ . Then  $v'(u) = v'(x_i) = v(t) = v(u')$  by construction of  $v'$  in the premise.

(inductive step) Otherwise,  $n > 1$ , and so  $u = f_i^k(u_1, \dots, u_k)$ , where  $u_1, \dots, u_k$  are sub-terms that necessarily have fewer than  $n$  sub-terms. In the same way that  $u'$  was defined for  $u$ , define  $u'_1, \dots, u'_k$  as the terms obtained by substituting  $t$  for  $x_i$  in  $u_1, \dots, u_k$ . Finally, notice that  $u' = f_i^k(u'_1, \dots, u'_k)$ , so

$$\begin{aligned}
 v(u') &= v(f_i^k(u'_1, \dots, u'_k)) && \text{definition of } u' \\
 &= \overline{f}_i^k(v(u'_1), \dots, v(u'_k)) && \text{Definition 3.17} \\
 &= \overline{f}_i^k(v'(u_1), \dots, v'(u_k)) && \text{Induction hypothesis} \\
 &= v'(f_i^k(u_1, \dots, u_k)) && \text{Definition 3.17} \\
 &= v'(u) && \text{Definition of } u
 \end{aligned}$$

With this induction complete, we may conclude that  $v'(u) = v(u')$  for any  $u$ . □

Now we prove the proposition by another strong induction on the number of connectives and quantifiers of  $\mathcal{A}(x_i)$ .

(base case) It may be that  $\mathcal{A}(x_i)$  has non quantifiers and connectives, and so it must be an atomic formula, say  $A_i^n(u_1, \dots, u_n)$ . Let  $u'_1, \dots, u'_n$  be the terms  $u_1, \dots, u_n$  with  $t$  substituted for  $x_i$ , so that  $\mathcal{A}(t)$  must then be  $\mathcal{A}(u'_1, \dots, u'_n)$ . Then the following are all equivalent.

- (a)  $v$  satisfies  $\mathcal{A}(t)$ , by assumption
- (b)  $v$  satisfies  $A_i^n(u'_1, \dots, u'_n)$ , by definition of  $\mathcal{A}(t)$
- (c)  $A_i^n(v(u'_1), \dots, v(u'_n))$  is true in  $I$ , by Definition 3.20
- (d)  $A_i^n(v'(u_1), \dots, v'(u_n))$  is true in  $I$ , by the lemma above
- (e)  $v'$  satisfies  $A_i^n(u_1, \dots, u_n)$ , by Definition 3.20
- (f)  $v'$  satisfies  $A_i^n(x_i)$ , by Definition 3.20

and the equivalence of (a) and (f) is what we desired to prove.

(inductive step) Otherwise,  $\mathcal{A}(x_i)$  has  $k$  quantifiers and connectives. Suppose that  $\mathcal{B}(x_i)$  has fewer than  $k$  quantifiers and connectives. Let  $w$  be a valuation and let  $w'$  be the valuation which is  $i$ -equivalent to  $w$  and has  $w'(x_i) = w(t)$ . Suppose, as an inductive hypothesis, that  $w$  satisfies  $\mathcal{A}(t)$  if and only if  $w'$  satisfies  $\mathcal{A}(x_i)$ .

There are three cases to check.

1. The  $wf \mathcal{A}(x_i)$  is  $\sim \mathcal{B}(x_i)$ , a  $wf$  with fewer than  $k$  quantifiers and connectives. Note that  $\mathcal{A}(t)$  is  $\sim \mathcal{B}(t)$ . The following are equivalent.

- (a)  $v$  satisfies  $\mathcal{A}(t)$ , by assumption
- (b)  $v$  satisfies  $\sim \mathcal{B}(t)$ , by definition of  $\mathcal{A}(t)$
- (c)  $v$  does not satisfy  $\mathcal{B}(t)$ , by Definition 3.20
- (d)  $v'$  does not satisfy  $\mathcal{B}(t)$ , by the induction hypothesis
- (e)  $v'$  satisfies  $\sim \mathcal{B}(t)$ , by definition of  $\mathcal{A}(t)$
- (f)  $v'$  satisfies  $\mathcal{A}(x_i)$ , by Definition 3.20

The equivalence between (a) and (f) is what we desired to prove. Note that in (d), we used the equivalent negative form of the inductive hypothesis.

2. The  $wf \mathcal{A}(x_i)$  is  $\mathcal{B}(x_i) \rightarrow \mathcal{C}(x_i)$ , where both  $\mathcal{B}(x_i)$  and  $\mathcal{C}(x_i)$  are  $wfs$  with fewer than  $k$  quantifiers and connectives. Note that  $\mathcal{B}(t)$  is  $\mathcal{B}(t) \rightarrow \mathcal{C}(t)$ . The following are equivalent.

- (a)  $v$  satisfies  $\mathcal{A}(t)$ , by assumption
- (b)  $v$  satisfies  $\mathcal{B}(t) \rightarrow \mathcal{C}(t)$ , by definition of  $\mathcal{A}(t)$
- (c)  $v$  satisfies  $\sim \mathcal{B}(t)$  or  $v$  satisfies  $\mathcal{C}(t)$ , by Definition 3.20
- (d)  $v'$  satisfies  $\sim \mathcal{B}(t)$  or  $v$  satisfies  $\mathcal{C}(t)$ , by the induction hypothesis
- (e)  $v'$  satisfies  $\sim \mathcal{B}(t) \rightarrow \mathcal{C}(t)$ , by Definition 3.20
- (f)  $v'$  satisfies  $\mathcal{A}(x_i)$ , by definition of  $\mathcal{A}(x_i)$

3. The  $wf \mathcal{A}(x_i)$  is  $(\forall x_j)\mathcal{B}(x_i)$ , where  $i \neq j$  because  $x_i$  is assumed to occur free in  $\mathcal{A}$ . Note that  $\mathcal{B}(x_i)$  has fewer than  $k$  quantifiers and that  $\mathcal{A}(t)$  is  $(\forall x_j)\mathcal{B}(t)$ . Then the following are all equivalent.

- (a)  $v$  satisfies  $\mathcal{A}(t)$ , by assumption
- (b)  $v$  satisfies  $(\forall x_j)\mathcal{B}(t)$ , by definition of  $\mathcal{A}(t)$
- (c) any  $j$ -equivalent valuation to  $v$  satisfies  $\mathcal{B}(t)$ , by Definition 3.20
- (d) any  $j$ -equivalent valuation to  $v'$  satisfies  $\mathcal{B}(x_i)$ , by the induction hypothesis, and the note below
- (e)  $v'$  satisfies  $(\forall x_j)\mathcal{B}(x_i)$ , by Definition 3.20
- (f)  $v'$  satisfies  $\mathcal{A}(x_i)$ , by definition of  $\mathcal{A}(x_i)$

Additional detail must be given to show that (c) and (d) are equivalent.

$\Rightarrow$  Suppose that any  $j$ -equivalent valuation to  $v$  satisfies  $\mathcal{B}(t)$ . Then let  $w'$  be a valuation  $j$ -equivalent to  $v'$ . Let  $w$  be a valuation  $j$ -equivalent to  $v$  with  $w(x_j) = w'(x_j)$  that necessarily satisfies  $\mathcal{B}(t)$ . By construction, we have that  $w$  is  $i$ -equivalent to  $w'$ . Notice that  $v'(x_i) = v'(t)$ , so  $w'(x_i) = w'(t)$ , since  $w'$  is  $j$ -equivalent to  $v'$ , and so we may apply the inductive hypothesis. Therefore,  $w'$  satisfies  $\mathcal{B}(x_i)$ .

$\Leftarrow$  Suppose that any  $j$ -equivalent valuation to  $v'$  satisfies  $\mathcal{B}(x_i)$ . Then let  $w$  be a valuation  $j$ -equivalent to  $v$ . Let  $w'$  be a valuation  $j$ -equivalent to  $v'$  with  $w'(x_j) = w(x_j)$  that necessarily satisfies  $\mathcal{B}(x_i)$ . By construction, we have that  $w'$  is  $i$ -equivalent to  $w$ . Notice that  $v'(x_i) = v'(t)$ , so  $w'(x_i) = w'(t)$ , since  $w'$  is  $j$ -equivalent to  $w$ , and so we may apply the inductive hypothesis. Therefore,  $w$  satisfies  $\mathcal{B}(t)$ .

By verifying all three cases, we have completed the induction.  $\square$

*Note.* In the proof in the book, there is a mistake in Case 1, it should instead read: " $\mathcal{A}(x_i)$  is  $\sim \mathcal{B}(x_i)$ ".

**Definition 3.24.** A wf  $\mathcal{A}$  is true in an interpretation  $I$  if every valuation in  $I$  satisfies  $\mathcal{A}$ . It is false if there is no valuation in  $I$  which satisfies  $\mathcal{A}$ . If  $\mathcal{A}$  is true in  $I$ , we write  $I \models \mathcal{A}$ .

*Note.* By part (ii) of Definition 3.20, if a given wf is satisfied by all valuations, then its negation is not satisfied by all valuations and vice versa. So no wf can be both true and false.

*Note.* Some wfs can be neither true nor false if there exists a valuation satisfying it and another one satisfying its negation.

**Proposition 3.26.** If, in an interpretation  $I$ , the wf  $\mathcal{A}$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  are true, then  $\mathcal{B}$  is also true.

*Proof.* Let  $v$  be a valuation in  $I$ . The wfs  $\mathcal{A}$  and  $(\mathcal{A} \rightarrow \mathcal{B})$  are true in  $I$ , which is to say that they are true for any valuation, and thus true for  $v$ . Since  $v$  satisfies  $(\mathcal{A} \rightarrow \mathcal{B})$ , it either satisfies  $\mathcal{B}$  or  $(\sim \mathcal{A})$ . But it cannot satisfy  $(\sim \mathcal{A})$ , or else it would not satisfy  $\mathcal{A}$ . Therefore, it satisfies  $\mathcal{B}$ . Since  $v$  was chosen as an arbitrary valuation, every valuation satisfies  $\mathcal{B}$ , and so it is true in  $I$ .  $\square$

**Proposition 3.27.** Let  $\mathcal{A}$  be a wf of  $\mathcal{L}$ , and let  $I$  be an interpretation of  $\mathcal{L}$ . Then  $I \models \mathcal{A}$  if and only if  $I \models (\forall x_i)\mathcal{A}$ , where  $x_i$  is any variable.

*Proof.*  $\Rightarrow$  Suppose that  $I \models \mathcal{A}$ . Let  $v$  be any valuation in  $I$  and let  $v'$  be any  $i$ -equivalent valuation to  $v$ . Since all valuations satisfy  $\mathcal{A}$ ,  $v'$  satisfies  $\mathcal{A}$ . Therefore,  $v$ , which was chosen to be an arbitrary valuation, satisfies  $(\forall x_i)\mathcal{A}$ , and so all valuations in  $I$  satisfy  $(\forall x_i)\mathcal{A}$ .

$\Leftarrow$  Suppose that  $I \models (\forall x_i)\mathcal{A}$ . Let  $v$  be any valuation in  $I$ . Since  $v$  is  $i$ -equivalent to  $v$ , it must satisfy  $\mathcal{A}$ . Since  $v$  was chosen as an arbitrary valuation, all valuations in  $I$  satisfy  $\mathcal{A}$ .  $\square$

**Corollary 3.28.** Let  $y_1, \dots, y_n$  be variables in  $\mathcal{L}$ , let  $\mathcal{A}$  be a wf of  $\mathcal{L}$ , and let  $I$  be an interpretation. Then  $I \models \mathcal{A}$  if and only if  $I \models (\forall y_1) \dots (\forall y_n)\mathcal{A}$ .

*Proof.* By repeated application of Proposition 3.27.  $\square$



The above corollary is significant because it states that implicit quantification of variables is legitimate when a statement of an interpretation is known to be true. For example,  $x = x$  as a statement about the integers does not need be quantified because it is known that the statement alone is true. Similarly, if a true statement already has all of its variables quantified, then the quantifiers can be omitted with no loss of meaning. It also implies that adding quantifiers to a false or indeterminate *wf* cannot “upgrade” its truth value so that the new quantified *wf* is true. However, adding quantifiers can turn an indeterminate *wf* into one which is false (there are many examples of this).

**Proposition 3.29.** In an interpretation  $I$ , a valuation  $v$  satisfies the formula  $(\exists x_i)\mathcal{A}$  if and only if there is at least one valuation  $v'$  which is  $i$ -equivalent to  $v$  and which satisfies  $\mathcal{A}$ .

*Proof.* This proof is done by mechanically applying the definitions. Let  $v$  be a valuation in an interpretation  $I$ .

$\Rightarrow$  Suppose  $v$  satisfies the formula  $(\exists x_i)\mathcal{A}$ , which is to say that  $v$  satisfies  $\sim (\forall x_i)(\sim \mathcal{A})$ , and therefore  $v$  does not satisfy  $(\forall x_i)(\sim \mathcal{A})$ . Therefore there must exist some  $v'$  which  $i$ -equivalent to  $v$  which does not satisfy  $\sim \mathcal{A}$ , and so this  $v'$  must satisfy  $\mathcal{A}$ .

$\Leftarrow$  Suppose that  $v'$  is an  $i$ -equivalent valuation to  $v$  that satisfies  $\mathcal{A}$ . Then this  $v'$  does not satisfy  $(\sim \mathcal{A})$ , and so  $v$  does not satisfy  $(\forall x_i)(\sim \mathcal{A})$ , and so  $v$  must satisfy  $\sim (\forall x_i)(\sim \mathcal{A})$ , i.e.,  $v$  satisfies  $(\exists x_i)\mathcal{A}$ .  $\square$

A *wf* of  $L$  and a *wf* of  $\mathcal{L}$  are both formed by possibly using the connectives  $\sim$  and  $\rightarrow$ . If we take a *wf*  $\mathcal{A}$  in  $L$  and replace all of its statement letters by the same *wf* in  $\mathcal{L}$ , the new formula is now a *wf* in  $\mathcal{L}$ , and we call it a *substitution instance* of  $\mathcal{A}$  in  $\mathcal{L}$ .

Note that a *wf* in  $\mathcal{L}$  can be a substitution instance of more than one *wf* in  $L$ , depending on how its sub-formulas are replaced. For instance,

$$\underbrace{((\forall x_i)A_1^1(x_1))}_{p_1} \rightarrow \underbrace{((\forall x_i)A_1^2(x_1))}_{p_2} \rightarrow \underbrace{(\forall x_i)A_1^2(x_1))}_{p_3}$$

may be considered as a substitution instance of  $(p_1 \rightarrow (p_2 \rightarrow p_3))$ . Also,

$$\underbrace{((\forall x_i)A_1^1(x_1))}_{p_1} \rightarrow \underbrace{((\forall x_i)A_1^2(x_1) \rightarrow (\forall x_i)A_1^2(x_1))}_{p_2}$$

may be considered as a substitution instance of  $(p_1 \rightarrow p_2)$ .

The use of the term tautology may be expanded to  $\mathcal{L}$ , and it has the expected property of being true regardless of its valuation in any interpretation.

**Definition 3.30.** A *wf*  $\mathcal{A}$  of  $\mathcal{L}$  is a *tautology* if it is a substitution instance in  $\mathcal{L}$  of a tautology in  $L$ .

**Proposition 3.31.** A *wf* of  $\mathcal{L}$  which is a tautology is true in any interpretation of  $\mathcal{L}$ .

*Proof.* Let  $\mathcal{A}_{\mathcal{L}}$  be a tautology in  $\mathcal{L}$  and let  $\mathcal{A}_L$  be its corresponding tautology in  $L$ . Then  $\mathcal{A}_L$  consists of the statement letters  $p_1, \dots, p_n$  whose replacements in  $L$  are the *wfs* that we shall label  $\mathcal{A}_1, \dots, \mathcal{A}_n$ .

Now let  $v_{\mathcal{L}}$  be a valuation in any interpretation  $I$ . The goal is to prove that  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$ .

First notice that  $\mathcal{A}_L$  can only be evaluated as true or false if its statement letters have values, and to this end. So let  $v_L$  be the valuation in  $L$  defined on the statement letters  $p_1, \dots, p_n$  in an expected way:

$$v_L(p_i) = \begin{cases} T & \text{if } v_{\mathcal{L}} \text{ satisfies } \mathcal{A}_i \\ F & \text{if } v_{\mathcal{L}} \text{ does not satisfy } \mathcal{A}_i \end{cases}$$

The values of  $v_L$  for all other statement letters not appearing in  $\mathcal{A}_L$  are arbitrarily set to  $T$  so that  $v_L$  is indeed a valuation.

Now we will prove that  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$  if and only if  $v_L(\mathcal{A}_L) = T$ . From this result, the proof of the proposition will immediately follow. We proceed by strong induction on the number of connectives  $\sim$  and  $\rightarrow$  in  $\mathcal{A}_L$ :

Suppose as a hypothesis of string induction that if a *wf* in  $L$  has fewer than  $k$  connectives, then  $v_{\mathcal{L}}$  satisfies the *wf* if and only if the value of  $v_L$  when applied to the substitution instance in  $\mathcal{L}$  is  $T$ .

Now let the number of connectives of  $\mathcal{A}_L$  be  $j$ . If  $j = 0$ , then  $\mathcal{A}$  consists of a statement letter only, say  $p$ . By the definition of  $v_L$ ,  $v_L(p) = T$  if and only if  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$ , as desired. If  $j > 0$ , then there are two cases two consider:

1. The *wf*  $\mathcal{A}_L$  is of the form  $\sim \mathcal{B}_L$ . Then  $\mathcal{A}_{\mathcal{L}}$  is of the form  $\sim \mathcal{B}_{\mathcal{L}}$ , where  $\mathcal{B}_{\mathcal{L}}$  is the substitution instance of  $\mathcal{B}_L$ . Since  $\mathcal{B}_L$  has fewer than  $j$  connectives, by the induction hypothesis,  $v$  satisfies  $\mathcal{B}$  if and only if  $v'(\mathcal{B}_{\mathcal{L}}) = T$ , which is equivalent to saying that  $v$  does not satisfy  $\mathcal{B}$  if and only if  $v'(\mathcal{B}_{\mathcal{L}}) = F$ , which is once again equivalent, by Definition 3.20 (ii) and 2.12 (i) to saying that  $v$  satisfies  $\mathcal{A}_{\mathcal{L}}$  if and only if  $v(\mathcal{A}_L) = T$ .
2. The *wf*  $\mathcal{A}_L$  of the form  $\mathcal{B}_L \rightarrow \mathcal{C}_L$ , and so  $\mathcal{A}$  is of the form  $\mathcal{B}_{\mathcal{L}} \rightarrow \mathcal{C}_{\mathcal{L}}$ , where  $\mathcal{B}_{\mathcal{L}}$  and  $\mathcal{C}_{\mathcal{L}}$  are the substitution instances of  $\mathcal{B}_L$  and  $\mathcal{C}_L$  respectively. Note that  $\mathcal{B}_L$  and  $\mathcal{C}_L$  both have fewer than  $j$  connectives. The following assertions are all equivalent:
  - (a)  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$
  - (b)  $v_{\mathcal{L}}$  satisfies  $\mathcal{B}_{\mathcal{L}} \rightarrow \mathcal{C}_{\mathcal{L}}$
  - (c) either  $v_{\mathcal{L}}$  satisfies  $\sim \mathcal{B}_{\mathcal{L}}$  or  $\mathcal{C}_{\mathcal{L}}$  (by Definition 3.20 (iii))
  - (d) either  $v$  does not satisfy  $\mathcal{B}_{\mathcal{L}}$  or satisfies  $\mathcal{C}_{\mathcal{L}}$  (by Definition 3.20 (ii))
  - (e) either  $v_L(\mathcal{B}_L) = F$  or  $v_L(\mathcal{C}_L) = T$  (by the strong induction hypothesis)
  - (f)  $v_L(\mathcal{B}_L \rightarrow \mathcal{C}_L) = T$  (by Definition 2.12)
  - (g)  $v_L(\mathcal{A}_L) = T$

and the equivalence of (a) and (g) is what we desired to prove for this case.

Now with the induction complete, we can prove the original proposition. Recall that  $\mathcal{A}_{\mathcal{L}}$  is a tautology in  $\mathcal{L}$ ,  $\mathcal{A}_L$  is a tautology in  $L$ , and  $v_{\mathcal{L}}$  is an arbitrary valuation in an arbitrary interpretation  $I$ . From the above, we know that  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$  if and only if  $v_L(\mathcal{A}_L) = T$ . But  $\mathcal{A}_L$  is a tautology in  $L$ , so indeed  $v_L(\mathcal{A}_L) = T$ , and so  $v_{\mathcal{L}}$  satisfies  $\mathcal{A}_{\mathcal{L}}$ . Thus  $\mathcal{A}_{\mathcal{L}}$  is true in any interpretation  $I$ .  $\square$

*Note.* This proof is long, but also is mostly just straightforward applications of definition. Its length comes from having to define  $v_L$

*Note.* The need for strong induction comes from case 2. Normal induction would not be sufficient because both of the *wfs* in  $L$  might have fewer than  $j - 1$  connectives.

As stated in the warning at the beginning of this chapter (in the manual, not the textbook), if a *wf* has all of its variables quantified, then it must be either true or false. We will prove this shortly, but first we introduce a short definition and a proposition.

**Definition 3.32.** A *wf*  $\mathcal{A}$  of  $\mathcal{L}$  is said to be *closed* if all variables in  $\mathcal{A}$  occurs bound.

**Proposition 3.33.** Let  $I$  be an interpretation of  $\mathcal{L}$  and let  $\mathcal{A}$  be a *wf* of  $\mathcal{L}$ . If  $v$  and  $w$  are valuations such that  $v(x_i) = w(x_i)$  for every free variable  $x_i$  of  $\mathcal{A}$ , then  $v$  satisfies  $\mathcal{A}$  if and only if  $w$  satisfies  $\mathcal{A}$ .

*Note.* This is stating the obvious fact that if two valuations “plug in” the same values for variables, then the resulting truth values will be the same.

*Proof.* The proof follows from strong induction on the numbers of connectives and quantifiers in  $\mathcal{A}$ .

As a hypothesis of strong induction, suppose that for any *wf*  $\mathcal{A}$  of  $\mathcal{L}$  with fewer than  $n$  connectives,  $v$  satisfies  $\mathcal{A}$  if and only if  $w$  satisfies  $\mathcal{A}$ , where  $v$  and  $w$  are valuations such that  $v(x_i) = w(x_i)$  for any  $x_i$  of  $\mathcal{A}$ .

It may be the case that  $n = 0$ , in which case the *wf* is an atomic formula with  $j$  terms of the general form  $A_i^j(t_1, \dots, t_j)$ . A term  $t$  can either be a constant, in which case  $v(t) = w(t)$ , since all are defined to have the same values for constants, or the term can be a variable or a function which takes terms. Since  $v$  and  $w$  agree for variables, since any variable in the atomic formula occurs free, they must also agree for functions (this can be formalized via another induction, but that is tedious). Therefore, for any atomic formula  $\mathcal{A}$ ,  $v$  satisfies  $\mathcal{A}$  if and only if  $w$  satisfies  $\mathcal{A}$ .

It may be the case that  $n > 0$ , in which case the inductive hypothesis must be employed to prove the three distinct cases which may occur.

1. The *wf*  $\mathcal{A}$  is of the form  $\sim \mathcal{B}$ . Notice that  $\mathcal{B}$  has fewer than  $n$  connectives, so  $v$  satisfies  $\mathcal{B}$  if and only if  $w$  satisfies  $\mathcal{B}$ , which is to say that  $v$  does not satisfy  $\mathcal{B}$  if and only if  $w$  does not satisfy  $\mathcal{B}$ , which is once again equivalent to stating that  $v$  satisfies  $\sim \mathcal{B}$  if and only if  $w$  satisfies  $\sim \mathcal{B}$ , by Definition 3.20 (ii). And since  $\sim \mathcal{B}$  is  $\mathcal{A}$ , we have proved the desired property for this case.
2. The *wf*  $\mathcal{A}$  is of the form  $\mathcal{B} \rightarrow \mathcal{C}$ . The following are all equivalent:
  - (a)  $v$  satisfies  $\mathcal{A}$
  - (b)  $v$  satisfies  $\mathcal{B} \rightarrow \mathcal{C}$
  - (c)  $v$  satisfies  $\sim \mathcal{B}$  or  $v$  satisfies  $\mathcal{C}$ , by Definition 3.20 (iii)
  - (d)  $w$  satisfies  $\sim \mathcal{B}$  or  $w$  satisfies  $\mathcal{C}$ , by the induction hypothesis, and the fact that both  $\sim \mathcal{B}$  and  $\mathcal{C}$  have fewer than  $n$  connectives
  - (e)  $w$  satisfies  $\mathcal{B} \rightarrow \mathcal{C}$ , again by definition 3.20 (ii)
  - (f)  $w$  satisfies  $\mathcal{A}$

and the equivalence between (a) and (f) is what we desired to prove for this case.

3. The wf  $\mathcal{A}$  is of the form  $(\forall x_i)\mathcal{B}$ . We are to prove that  $v$  satisfies  $\mathcal{A}$  if and only if  $w$  satisfies  $\mathcal{A}$ .

$\Rightarrow$  Suppose that  $v$  satisfies  $\mathcal{A}$ . Then for any  $i$ -equivalent valuation to  $v$ ,  $v'$  satisfies  $\mathcal{B}$ . To show that  $w$  satisfies  $\mathcal{A}$ , which is  $(\forall x_i)\mathcal{B}$ , we must show that any  $i$ -equivalent valuation to  $w$  satisfies  $\mathcal{B}$ . So let  $w'$  be  $i$ -equivalent to  $w$ , and let  $v'$  be the particular valuation  $i$ -equivalent to  $v$  which satisfies  $v'(x_i) = w'(x_i)$ . Now let  $y$  be a free variable of  $\mathcal{B}$ . There are two cases to consider.

- (a) If  $y = x_i$ , then  $v'(x_i) = w'(x_i)$ , since  $v'$  was chosen in this way.
- (b) If  $y \neq x_i$ , then it is a free variable of  $\mathcal{A}$ , since  $\mathcal{B}$  differs from  $\mathcal{A}$  in that only  $x_i$  may potentially be free in  $\mathcal{B}$ , and so

$$\begin{array}{ll} v'(y) = v(y) & v' \text{ and } v \text{ are } i\text{-equivalent} \\ v(y) = w(y) & v(x) = w(x) \text{ for any free variable } x \text{ in } \mathcal{A} \\ w(y) = w'(y) & w' \text{ and } w \text{ are } i\text{-equivalent} \end{array}$$

with the conclusion in this case being that  $v'(y) = w'(y)$ .

Therefore, whenever  $y$  is a free variable of  $\mathcal{B}$ , a wf with fewer than  $n$  connectives,  $v'(y) = w'(y)$ , and so by the induction hypothesis and since  $v'$  satisfies  $\mathcal{B}$ ,  $w'$  satisfies  $\mathcal{B}$ . Since  $w'$  was chosen to be an arbitrary  $i$ -equivalent valuation to  $w$ , it follows that  $w$  satisfies  $(\forall x_i)\mathcal{B}$ , i.e.,  $w$  satisfies  $\mathcal{A}$ .

$\Leftarrow$  This direction is proved in precisely the same way as the above direction except with the occurrences of  $v$  and  $w$  switched.

With the induction complete, we have proved the proposition.  $\square$

*Note.* In case 3,  $x_i$  need not be free in  $\mathcal{B}$ , in which the quantifier  $(\forall x_i)$  appears in  $\mathcal{B}$ , but in that case  $x_i$  would not be considered as a possible free variable  $y$  in  $\mathcal{B}$ , so it would be disregarded.

*Note.* In case 1, the free variables of  $\mathcal{A}$  were the same as the free variables of  $\mathcal{B}$ . Similarly, in case 2, the free variables of  $\mathcal{B}$  and  $\mathcal{C}$  were the same as  $\mathcal{A}$ . Therefore, in both cases,  $v$  and  $w$  could be applied to the inductive hypothesis regarding  $\mathcal{B}$  in case 2 or  $\mathcal{B}$  and  $\mathcal{C}$  in case 3. In case 3, on the other hand, the free variables of  $\mathcal{A}$  and  $\mathcal{B}$  differed in that  $x_i$  need not have been free in  $\mathcal{B}$ . Instead,  $i$ -equivalent valuations of  $v$  and  $w$  were shown to agree for any free variable in  $\mathcal{B}$  so that the inductive hypothesis could be applied.

**Corollary 3.34.** If  $\mathcal{A}$  is a closed wf of  $\mathcal{L}$  and  $I$  is an interpretation of  $\mathcal{L}$ , then either  $I \models \mathcal{A}$  or  $I \models (\sim \mathcal{A})$ .

*Proof.* Let  $v$  and  $w$  be any valuations. Since  $\mathcal{A}$  has no free variables,  $v(y) = w(y)$  for any free variable  $y$ , vacuously. So  $v$  satisfies  $\mathcal{A}$  if and only if  $w$  satisfies  $\mathcal{A}$ , by Proposition 3.33. So, either every valuation satisfies  $\mathcal{A}$  or every valuation does not satisfy  $\mathcal{A}$ , which is to say that  $\mathcal{A}$  is either true or false in  $I$ . So either  $I \models \mathcal{A}$  or  $I \models (\sim \mathcal{A})$ .  $\square$

**Definition 3.35.** A wf  $\mathcal{A}$  of  $\mathcal{L}$  is *logically valid* if  $\mathcal{A}$  is true in every interpretation of  $\mathcal{L}$  and is *contradictory* if  $\mathcal{A}$  is false in every interpretation of  $\mathcal{L}$ .

These terms are the analogues of tautology and contradiction in  $L$ . However, there are more logically valid *wfs* in  $\mathcal{L}$  than there are tautologies in  $\mathcal{L}$  in the sense that all tautologies in  $\mathcal{L}$  are logically valid (Proposition 3.31), but there are some logically valid *wfs* that are not tautologies, i.e., their logical validity comes not from their form involving  $\sim$  and  $\rightarrow$  but rather from the relationship between quantifiers and terms. The goal of the next chapter is to find all of these logically valid *wfs*.

## Solutions to exercises

14. (a) The corresponding statement in  $N$  is  $x_1 + x_1 = x_2 \times x_3$ . Any valuation  $v$  with  $v(x_1) = v(x_2) = v(x_3) = 0$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = v(x_2) = v(x_3) = 1$  will not satisfy the *wf*.
- (b) The corresponding statement in  $N$  is  $x_1 + 0 = x_2 \rightarrow x_1 + x_2 = x_3$ . Any valuation  $v$  with  $v(x_1) = v(x_2) = v(x_3) = 0$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = v(x_2) = v(x_3) = 1$  will not satisfy the *wf*.
- (c) The corresponding statement in  $N$  is  $\sim (x_1 x_2 = x_2 x_3)$ . Any valuation  $v$  with  $v(x_1) = 0, v(x_2) = v(x_3) = 1$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = v(x_2) = v(x_3) = 1$  will not satisfy the *wf*.
- (d) The corresponding statement in  $N$  is  $(\forall x_1) x_1 x_2 = x_3$ . Any valuation  $v$  with  $v(x_2) = v(x_3) = 0$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_2) = v(x_3) = 1$  will not satisfy the *wf*.
- (e) The corresponding statement in  $N$  is  $((\forall x_1) x_1 \times 0 = x_1) \rightarrow x_1 = x_2$ . Since  $(\forall x_1) x_1 \times 0 = x_1$  is false in  $N$ , any valuation will vacuously satisfy the *wf*, and so no valuation will not satisfy the *wf*.
15. (a) The corresponding statement is  $x_1 < 0$ . Any valuation  $v$  with  $v(x_1) = -1$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = 1$  will not satisfy the *wf*.
- (b) The corresponding statement is  $x_1 - x_2 < x_1 \rightarrow 0 < x_1 - x_2$ . Any valuation  $v$  with  $v(x_1) = v(x_2) = 0$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = v(x_2) = 1$  will not satisfy the *wf*.
- (c) The corresponding statement is  $\sim (x_1 < x_1 - (x_1 - x_2))$ . Any valuation  $v$  with  $v(x_1) = v(x_2) = 0$  will satisfy the *wf*, and any valuation  $v$  with  $v(x_1) = 0, v(x_2) = 1$  will not satisfy the *wf*.
- (d) The corresponding statement is  $(\forall x_1) x_1 - x_2 < x_3$ , which is false, so no valuation will satisfy the *wf*, and any valuation will not satisfy the *wf*.
- (e) The corresponding statement is  $((\forall x_1) x_1 - 0 < x_1) \rightarrow x_1 < x_2$ . Since  $((\forall x_1) x_1 - 0 < x_1)$  is false, any valuation will vacuously satisfy the *wf*, and no valuation will not satisfy the *wf*.
16. Only the *wfs* (b), (c), and (d) are true in the interpretation.
17. Only the *wfs* (c) and (d) are true in the interpretation.
18. We are to prove that in an interpretation  $I$ , a *wf*  $(\mathcal{A} \rightarrow \mathcal{B})$  is false if and only if  $\mathcal{A}$  is true and  $\mathcal{B}$  is false. Let  $v$  be a valuation in  $I$ . The following are all equivalent statements.

- (a)  $(\mathcal{A} \rightarrow \mathcal{B})$  is false
- (b)  $v$  does not satisfy  $(\mathcal{A} \rightarrow \mathcal{B})$ , by (a)
- (c)  $v$  does not satisfy  $(\sim \mathcal{A})$  and  $v$  does not satisfy  $\mathcal{B}$ , by Definition 3.20 (iii)
- (d)  $v$  satisfies  $\mathcal{A}$  and  $v$  does not satisfy  $\mathcal{B}$ , by Definition 3.20 (ii)
- (e)  $\mathcal{A}$  is true and  $\mathcal{B}$  is false, by Definition 3.24

Note that (e) is true since  $v$  is an arbitrary valuation. The equivalence between (a) and (e) is what we set out to prove.

19. In the following lemma and sub-exercises, let  $I$  be any interpretation and let  $v$  be any valuation in  $I$ .

**Lemma.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be wfs of  $\mathcal{L}$ . Let  $\star$  be the implication “if  $v$  satisfies  $\mathcal{A}$ , then  $v$  satisfies  $\mathcal{B}$ ”. If  $\star$  is true, then  $\mathcal{A} \rightarrow \mathcal{B}$  is logically valid.

*Proof.* Suppose that the implication  $\star$  is true. Then there are two cases to consider.

- (i) The valuation  $v$  satisfies  $\mathcal{A}$ . By  $\star$ ,  $v$  satisfies  $\mathcal{B}$ , and therefore by Definition 3.20 (iii),  $v$  satisfies  $\mathcal{A} \rightarrow \mathcal{B}$ .
- (ii) The valuation  $v$  does not satisfy  $\mathcal{A}$ . By Definition 3.20 (ii),  $v$  satisfies  $\sim \mathcal{A}$ . By Definition 3.20 (iii),  $v$  satisfies  $\mathcal{A} \rightarrow \mathcal{B}$ .

We have proved that  $v$ , an arbitrary valuation in an arbitrary interpretation, always satisfies  $\mathcal{A} \rightarrow \mathcal{B}$ . Therefore,  $\mathcal{A} \rightarrow \mathcal{B}$  is logically valid.  $\square$

*Note.* This lemma can be more succinctly stated as “if  $\mathcal{A}$  being true in any  $I$  implies that  $\mathcal{B}$  is true in any  $I$ , then  $\mathcal{A} \rightarrow \mathcal{B}$  is logically valid.” Also notice that the relationship is an “if and only if”, and a little more work could be done to prove the other direction.

This lemma confirms that the logical validity of a wf of the form  $\mathcal{A} \rightarrow \mathcal{B}$  can be proved in the expected way. Using this lemma, we now prove that the wfs in (a), (b), (c) and (d) are logically valid.

- (a) Suppose that  $v$  satisfies  $(\exists x_1)(\forall x_2)A_1^2(x_1, x_2)$ . By Proposition 3.29, there is a valuation  $v'$  which is 1-equivalent to  $v$  which satisfies  $(\forall x_2)A_1^2(x_1, x_2)$ . By Definition 3.20 (iv), any 2-equivalent valuation to  $v'$  satisfies  $A_1^2(x_1, x_2)$  (\*). Now, let  $w$  be 2-equivalent to  $v$ . The goal is to show the existence of a valuation which is 1-equivalent to  $w$  and satisfies  $A_1^2(x_1, x_2)$ . So let  $w'$  be the valuation which is 2-equivalent to  $v'$  with  $w'(x_2) = w(x_2)$ . By (\*),  $w'$  satisfies  $A_1^2(x_1, x_2)$ . Now let  $x$  be any element in the domain of  $w'$  which is not  $x_1$ . There are two cases to consider.
  - i. It may be that  $x = x_2$ , in which case, by construction of  $w'$ ,  $w'(x) = w(x)$ .
  - ii. Otherwise,  $x \neq x_2$ . Since  $w'$  is 2-equivalent to  $v'$ ,  $w'(x) = v'(x)$ . Since  $v'$  is 1-equivalent to  $v$ , and since  $x$  is assumed not to be  $x_1$ , we have  $v'(x) = v(x)$ . Since  $w$  is 2-equivalent to  $v$ , we have  $v(x) = w(x)$ . Finally, by the chaining the equalities,  $w'(x) = v'(x) = v(x) = w(x)$ .

Therefore,  $w'$  is 1-equivalent to  $w$  and satisfies  $A_1^2(x_1, x_2)$ , and by Proposition 3.29,  $(\forall x_2)(\exists x_1)A_1^2(x_1, x_2)$ . By the lemma above, we may conclude that  $((\exists x_1)(\forall x_2)A_1^2(x_1, x_2) \rightarrow (\forall x_2)(\exists x_1)A_1^2(x_1, x_2))$ .

*Note.* In the following sub-exercises for the sake of brevity, the lemma, Definition 3.20, and Proposition 3.29 will not be explicitly referenced when they are used.

- (b) We will first demonstrate that if  $(\forall x_1)A_1^1(x_1)$  is true in  $I$ , then  $(\forall x_2)A_1^1(x_2)$  is true in  $I$ .

Suppose that  $v$  satisfies  $(\forall x_1)A_1^1(x_1)$ . Then any 1-equivalent valuation to  $v$  satisfies  $A_1^1(x_1)$ . Let  $v_2$  be a 2-equivalent valuation to  $v$ . Let  $v_1$  be the 1-equivalent valuation with  $v_1(x_1) = v_2(x_2)$ , which must necessarily satisfy  $A_1^1(x_1)$ , which is a *wf* in which  $x_2$  is free for  $x_1$ . By Proposition 3.23,  $v_2$  satisfies  $A_1^1(x_2)$  if and only if  $v_1$  satisfies  $A_1^1(x_1)$ . Since  $v_1$  does indeed satisfy  $A_1^1(x_1)$ ,  $v_2$  must satisfy  $A_1^1(x_2)$ . Therefore,  $v$  satisfies  $(\forall x_2)A_1^1(x_2)$ , as desired. Now, we will prove that the original *wf* is logically valid. Suppose that  $v$  satisfies  $(\forall x_1)A_1^1(x_1)$ . By the above, we know that  $v$  satisfies  $(\forall x_2)A_1^1(x_2)$ , and therefore it satisfies  $((\forall x_1)A_1^1(x_1) \rightarrow (\forall x_2)A_1^1(x_2))$ , and so we may conclude that  $(\forall x_1)A_1^1(x_1) \rightarrow ((\forall x_1)A_1^1(x_1) \rightarrow (\forall x_2)A_1^1(x_2))$  is logically valid.

- (c) Suppose that  $v$  satisfies  $(\forall x_1)(\mathcal{A} \rightarrow \mathcal{B})$ . There are two cases to consider.
- i. It may be that  $v$  satisfies  $\sim (\forall x_i)\mathcal{A}$ . Then  $v$  satisfies  $(\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}$ .
  - ii. Otherwise,  $v$  satisfies  $(\forall x_i)\mathcal{A}$ . Now let  $v'$  be 1-equivalent to  $v$ . It must satisfy  $\mathcal{A}$ , and therefore it cannot satisfy  $\sim \mathcal{A}$ . But since  $v$  also satisfies  $(\forall x_1)(\mathcal{A} \rightarrow \mathcal{B})$ ,  $v'$  must satisfy  $\mathcal{B}$  if it does not satisfy  $\sim \mathcal{A}$ . Therefore,  $v$  must satisfy  $(\forall x_i)\mathcal{B}$ , and so  $v$  must satisfy  $(\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}$ .

In both cases,  $(\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}$ , and so we may conclude that

$$(\forall x_1)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\forall x_1)\mathcal{A} \rightarrow (\forall x_1)\mathcal{B}).$$

*Note.* This proof relies on applying Definition 3.20 (iii) repeatedly.

- (d) Suppose that  $v$  satisfies  $(\forall x_1)(\forall x_2)\mathcal{A}$ . Then
- (i) any valuation  $v'$  which is 1-equivalent to  $v$  satisfies  $(\forall x_2)\mathcal{A}$  and...
  - (ii) any valuation which is 2-equivalent to  $v'$  satisfies  $\mathcal{A}$ .

Now let  $w$  be a valuation which is 2-equivalent to  $v$  and let  $w'$  be a valuation that is 1-equivalent to  $w$ . The goal is to show that  $w'$  satisfies  $\mathcal{A}$ , from which we may deduce that  $w$  satisfies  $(\forall x_1)\mathcal{A}$  and hence  $v$  satisfies  $(\forall x_2)(\forall x_1)\mathcal{A}$ .

Let  $v'$  be a valuation which is 1-equivalent to  $v$  with  $v'(x_1) = w'(x_1)$ . Then by (i),  $v'$  satisfies  $(\forall x_2)\mathcal{A}$ . Now let  $x$  be any element in the domain of  $w'$  that is not  $x_2$ . There are two cases to consider.

- (1) It may be that  $x = x_1$ , in which case, by construction of  $v'$ ,  $v'(x) = w'(x)$ .
- (2) Otherwise,  $x \neq x_1$ , so

$$\begin{array}{ll} v'(x) = v(x), & \text{since } v' \text{ is 1-equivalent to } v \\ v(x) = w(x), & \text{since } w \text{ is 2-equivalent to } v \\ w(x) = w'(x), & \text{since } w' \text{ is 1-equivalent to } w \end{array}$$

and thus,  $v'(x) = w'(x)$  in this case as well.

In both cases, we can see that  $v'(x) = w'(x)$ , and therefore  $w'$  is 2-equivalent to  $v'$ . By (ii), we may conclude that  $w'$  satisfies  $\mathcal{A}$ , as desired.

20. One example is  $A_1^1(x_1) \rightarrow A_1^1(x_1)$ . It is not closed, but it is a tautology since it is a substitution instance of  $p_1 \rightarrow p_1$ . Therefore, it is logically valid.
21. Suppose that  $v$  is a valuation in an interpretation  $I$  that satisfies  $\mathcal{A}(t)$ . Let  $v'$  be  $i$ -equivalent to  $v$  with  $v'(x_i) = v(t)$ . By Proposition 3.23,  $v'$  must satisfy  $\mathcal{A}(x_i)$ . By Proposition 3.29,  $v$  must satisfy  $(\exists x_i)\mathcal{A}(x_i)$ . By the lemma in Exercise 19,  $\mathcal{A}(t) \rightarrow (\exists x_i)\mathcal{A}(x_i)$  is logically valid.
22. Let  $I$  be the interpretation with the integers as the domain,  $\bar{a}_0 = 0$ , the relation  $\leq$  as  $A_1^2$ , and the relation  $=$  as  $A_1^1$ . Note that  $A_1^1$  does not involve  $\bar{a}_0 = 0$ , since the relation is just the set  $\{(0, 0)\}$ . Then the given wfs (a) - (d) correspond to the following wfs.
  - (a)  $((\forall x_1)(\exists x_2) x_1 \leq x_2) \rightarrow ((\exists x_2)(\forall x_1) x_1 \leq x_2)$
  - (b)  $(\forall x_1)(\forall x_2)(x_1 \leq x_2 \rightarrow x_2 \leq x_1)$
  - (c)  $(\forall x_1)(\sim (x_1 = 0)) \rightarrow (\sim (x_1 = 0))$
  - (d)  $(\forall x_1)(x_1 \leq x_1) \rightarrow ((\exists x_2)(\forall x_1) x_1 \leq x_2)$

These statements in  $I$  are all easily seen to be false, and therefore, none of the wfs are logically valid.

23. This follows immediately from Proposition 3.23, since if  $v$  satisfies  $v(x_i) = v(t)$ , then it itself is an  $i$ -equivalent valuation  $v'$  to  $v$  with  $v'(x_i) = v(t)$ .

*Note.* In the textbook, Proposition 3.23 is not proved fully, and the remainder is left as an exercise, but in this manual it is proved fully, so there is no need to elaborate more on it here.



# Chapter 4

## Formal predicate calculus

### 4.1 The formal system $K_{\mathcal{L}}$

In the previous chapter, we discussed various *wfs* which were valid in all first-order languages. Depending on the interpretations of the language, the *wfs* could be true or false. Some *wfs* were seen to be true regardless of the interpretation, and these *wfs* were said to be logically valid. In this chapter, we will construct a formal system which will allow deduction of other *wfs* from certain *wfs*. The fundamental property of this system that will be proved is that its theorems are precisely the *wfs* which are logically valid.

Let  $\mathcal{L}$  be a first order language. The formal system  $K_{\mathcal{L}}$  has, as its alphabet of symbols, the same alphabet of symbols as  $\mathcal{L}$ .

Let  $\mathcal{A}$  and  $\mathcal{B}$  be *wfs* of  $\mathcal{L}$ . The axioms of  $K_{\mathcal{L}}$  are given by the following schemes.

- (K1)  $(\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{A}))$ .
- (K2)  $((\mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow \mathcal{C})))$ .
- (K3)  $((\sim \mathcal{A}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{A})$ .
- (K4)  $((\forall x_i)\mathcal{A} \rightarrow \mathcal{A})$ , if  $x_i$  does not occur free in  $\mathcal{A}$ .
- (K5)  $((\forall x_i)\mathcal{A}(x_i) \rightarrow \mathcal{A}(t))$ , if  $t$  is free for  $x_i$  in  $\mathcal{A}(x_i)$ .
- (K6)  $((\forall x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}))$ , if  $\mathcal{A}$  contains no free occurrences of  $x_i$ .

*Note.* (K1) - (K3) are analogous to the axioms of  $L$ .

*Note.* In (K4) and (K6), it may aid understanding to note that a variable does not occur free in a *wf* if it occurs bound, in which case it can either not occur at all in a *wf*, or it occurs bound already. In both cases, the quantifier is redundant or meaningless. Therefore, (K4) allows the removal of an unnecessary quantifier while (K6) allows the quantifier in an implication to be moved to only the consequent of the implication if the quantifier is unnecessary in the hypothesis.

*Note.* We may immediately deduce that  $((\forall x_i)\mathcal{A} \rightarrow \mathcal{A})$  for any *wf*  $\mathcal{A}$ , regardless of whether  $x_i$  occurs free in  $\mathcal{A}$  or not. For if  $x_i$  does not occur free in  $\mathcal{A}$ , then  $((\forall x_i)\mathcal{A} \rightarrow \mathcal{A})$  is true by (K4). If  $x_i$  occurs free in  $\mathcal{A}$ , then we may write  $\mathcal{A}(x_i)$ , and since  $x_i$  is free for  $x_i$  in  $\mathcal{A}(x_i)$ , by (K6), we may deduce  $((\forall x_i)\mathcal{A}(x_i) \rightarrow \mathcal{A}(x_i))$ .

The rules of deduction of  $K_{\mathcal{L}}$  are:

1. *Modus ponens*, from  $\mathcal{A}$  and  $(\mathcal{A} \rightarrow \mathcal{B})$ , deduce  $\mathcal{B}$ .
2. *Generalization*, from  $\mathcal{A}$ , deduce  $(\forall x_i)\mathcal{A}$ , where  $x_i$  is any variable.

The second rule may be curious. It states that a quantifier may be added to a *wf* with no consequences in terms of logical deduction. Indeed, if the quantified variable is bound already in  $\mathcal{A}$ , then the addition of the quantifier will be redundant. But if the variable is free in  $\mathcal{A}$ , then  $\mathcal{A}$  may be neither true nor false in some interpretation, so there may be a valuation in which  $\mathcal{A}$  is true but  $(\forall x_i)\mathcal{A}$  is false (a concrete example of this will be provided shortly). The consequence of this is that the Deduction Theorem for  $\mathcal{L}$  must be restricted slightly, as we will see. However, the theorems of  $K_{\mathcal{L}}$  will be shown to be the logically valid *wfs* of  $\mathcal{L}$ , so this issue will not arise as long as generalization is applied to a *wf* which is theorem of  $K_{\mathcal{L}}$ .

**Definition 4.2.** A *proof* in  $K_{\mathcal{L}}$  is a sequence of *wfs* such that each *wf* is an axiom of  $K_{\mathcal{L}}$  or a deduction from one or more of the previous *wfs* by one of the rules of deduction. A *theorem* of  $K_{\mathcal{L}}$  is any *wf* which is the last member of a sequence of a proof in  $K_{\mathcal{L}}$ .

Let  $\Gamma$  be a set of *wfs* of  $K_{\mathcal{L}}$ . A *deduction from  $\Gamma$*  is a proof in  $K_{\mathcal{L}}$  with any *wf* of  $\Gamma$  permitted as a *wf* in the sequence or proof. A *consequence* of  $\Gamma$  in  $K_{\mathcal{L}}$  is the last member of a deduction from  $\Gamma$ .

We write  $\Gamma \vdash_{K_{\mathcal{L}}} \mathcal{A}$  to denote that  $\mathcal{A}$  is a consequence of  $\Gamma$ , and if  $\Gamma$  is empty, then  $\mathcal{A}$  is just a theorem of  $K_{\mathcal{L}}$ , in which case we write  $\vdash_{K_{\mathcal{L}}} \mathcal{A}$ .

For the sake of convenience, we will abbreviate  $K_{\mathcal{L}}$  to  $K$  unless there is reason to specify  $\mathcal{L}$ . Writing that a *wf* is a *wf* of  $K$  is to say that it is a *wf* of the unspecified first-order language associated with  $K$ .

**Proposition 4.3.** If  $\mathcal{A}$  is a tautology (see Definition 3.30), then  $\mathcal{A}$  is a theorem of  $K$ .

*Proof.* Recall that  $\mathcal{A}$  must be a *wf* of  $\mathcal{L}$  which is a substitution instance of a tautology in  $L$ , which is to say that there must be a  $\mathcal{A}_L$  in  $L$  which is a tautology such that  $\mathcal{A}$  is obtained by substituting the statement variables of  $L$  with *wfs* of  $\mathcal{L}$ . By Proposition 2.23,  $\mathcal{A}_L$  must be a theorem of  $L$ . Therefore, there exists a proof in  $L$  of  $\mathcal{A}_L$ . In the proof, substitute each statement variable in  $L$  with the *wf* which was substituted for that statement variable to obtain  $\mathcal{A}$  to obtain a sequence of *wfs* of  $K$ .

Consider a *wf* after this substitution. It could have been an axiom in  $L$ , in which case the substituted *wf* is an axiom of  $K$  since the axioms of  $L$  are given in (K1), (K2) and (K3). Otherwise, the *wf* was a result of MP and since MP is a rule of deduction in  $K$ , the substituted *wf* could be obtained from two previous *wfs* in the sequence after the substitution. Therefore, the sequence is a valid proof in  $K$ , and so  $\mathcal{A}$  is a theorem of  $K$ .  $\square$

*Note.* As usual, this proof could be done via induction. In particular, the last paragraph could be verified in this way.

The converse of this proposition can easily be seen to be false. For example, the *wf*  $((\forall x_i)\mathcal{A} \rightarrow (\exists x_i)\mathcal{A})$  was seen to be logically valid in Example 3.37 for any first-order language  $\mathcal{L}$ . This *wf* in  $K_{\mathcal{L}}$  is a substitution instance of the *wf*  $(p_1 \rightarrow p_2)$  in  $L$ , which is not a tautology of  $L$ , and therefore the *wf* in  $\mathcal{L}$  is not a tautology in  $\mathcal{L}$ . Later, we shall see that the theorems of  $K_{\mathcal{L}}$  are the logically valid *wfs* of  $\mathcal{L}$ , and so the given *wf* disproves the converse of the proposition.

We will now prove that  $K$  has the basic property of being sound. That is, every theorem is logically valid. We start by proving the property for the axioms.

**Proposition 4.4.** All axioms of  $K_{\mathcal{L}}$  are logically valid.

*Proof.* Let  $\mathcal{C}$  be an axiom of  $K_{\mathcal{L}}$ . It may be the case that it is an instance of axioms (K1), (K2), or (K3). In this case,  $\mathcal{C}$  must be a tautology, as it is a substitution instance of a tautology in  $L$ , and by Proposition 4.3,  $\mathcal{C}$  must be logically valid. The other possibility is that  $\mathcal{C}$  is an instance of the axiom schemes (K4), (K5), or (K6).

We implicitly use the lemma in exercise 19 of Section 3.4 to prove implications. Let  $v$  be a valuation in any interpretation of  $\mathcal{L}$ .

- For (K4),  $((\forall x_i)\mathcal{A} \rightarrow \mathcal{A})$ , suppose that  $v$  satisfies  $(\forall x_i)\mathcal{A}$ . Then any  $i$ -equivalent valuation to  $v$  satisfies  $\mathcal{A}$ , so, in particular,  $v$  satisfies  $\mathcal{A}$ . Therefore, (K4),  $((\forall x_i)\mathcal{A} \rightarrow \mathcal{A})$  is logically valid.
- For (K5),  $((\forall x_i)\mathcal{A}(x_i) \rightarrow \mathcal{A}(t))$  if  $t$  is free for  $x_i$ , suppose that  $v$  satisfies  $(\forall x_i)\mathcal{A}(x_i)$  and that  $t$  is a term free for  $x_i$ . Then any  $i$ -equivalent valuation to  $v$  satisfies  $\mathcal{A}(x_i)$ . In particular, the  $i$ -equivalent valuation  $v'$  with  $v'(x_i) = v(t)$  satisfies  $\mathcal{A}(x_i)$ , so by Proposition 3.23,  $v$  satisfies  $\mathcal{A}(t)$ . Therefore, (K5),  $((\forall x_i)\mathcal{A}(x_i) \rightarrow \mathcal{A}(t))$ , is logically valid.
- For (K6),  $((\forall x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}))$  if  $\mathcal{A}$  contains no free occurrence of the variable  $x_i$ , suppose that  $v$  satisfies  $(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$  and that  $x_i$  does not occur free in  $\mathcal{A}$ . Then every  $i$ -equivalent valuation to  $v$  satisfies  $(\mathcal{A} \rightarrow \mathcal{B})$ , which is to say that it must either not satisfy  $\mathcal{A}$  or satisfy  $\mathcal{B}$ , by Definition 3.20, and we label this statement as  $\star$ .

The goal is to show that  $v$  satisfies  $(\mathcal{A} \rightarrow (\forall x_i)\mathcal{B})$ , as doing this will demonstrate the logical validity of (K6), so suppose that  $v$  satisfies  $\mathcal{A}$ . Now, let  $w$  be an  $i$ -equivalent valuation to  $v$ . Notice that  $v$  satisfies  $\mathcal{A}$  by assumption, so by Proposition 3.33 and the fact that  $x_i$  does not occur free in  $\mathcal{A}$ ,  $w$  must also satisfy  $\mathcal{A}$ , and so by  $\star$ ,  $w$  must satisfy  $\mathcal{B}$ , which allows us to say that  $v$  satisfies  $(\forall x_i)\mathcal{B}$ . We may conclude that  $v$  satisfies  $(\mathcal{A} \rightarrow (\forall x_i)\mathcal{B})$ , as desired.

We have shown that any instance of the axiom schemes of  $K_{\mathcal{L}}$  are logically valid, i.e., any axiom of  $K_{\mathcal{L}}$  is logically valid.  $\square$

**Proposition 4.5** (The Soundness Theorem for  $K$ ). If  $\mathcal{A}$  is a theorem of  $K$ , then  $\mathcal{A}$  is logically valid.

*Proof.* The proof is by strong induction on  $n$ , the number of  $wfs$  in the sequence consisting of the proof of  $\mathcal{A}$ . As a hypothesis of strong induction, suppose that any theorem of  $K$  with fewer than  $n$   $wfs$  in its proof is logically valid.

(base case) It may be the case that  $n = 1$ , which is to say that  $\mathcal{A}$  is an axiom of  $K$ , and so by the previous proposition,  $\mathcal{A}$  is logically valid.

(induction step) Alternatively,  $n > 1$ . It may still be the case that  $\mathcal{A}$  is an axiom of  $K$ , in which case it is logically valid. If it is not an axiom, then it follows from one of the two rules of deduction.

1. In the case that  $\mathcal{A}$  follows from MP and two  $wfs$ , one  $wf$  must necessarily be of the form  $\mathcal{B}$  and the other of the form  $(\mathcal{B} \rightarrow \mathcal{A})$ . By the induction hypothesis, both of these  $wfs$  are logically valid, and so by Remark 3.36(a) (which, in turn, is a consequence of Proposition 3.26),  $\mathcal{A}$  must be logically valid.

2. In the case that  $\mathcal{A}$  follows from Generalization from a previous *wf*  $\mathcal{B}$ ,  $\mathcal{A}$  must necessarily be of the form  $(\forall x_i)\mathcal{B}$ . Since, by the induction hypothesis,  $\mathcal{B}$  is logically valid,  $\mathcal{A}$  must be logically valid by Remark 3.36(b) (which, in turn, is a consequence of Proposition 3.26).

We have shown that in both cases when  $\mathcal{A}$  follows from a rule of deduction,  $\mathcal{A}$  is logically valid, as desired.  $\square$

**Corollary 4.6.**  $K$  is consistent (for no *wf*  $\mathcal{A}$  are both  $\mathcal{A}$  and  $(\sim \mathcal{A})$  both theorems of  $K$ ).

*Proof.* For a contradiction, suppose that both  $\mathcal{A}$  and  $(\sim \mathcal{A})$  are both theorems of  $K$  for some *wf*  $\mathcal{A}$  of  $K$ . Then  $\mathcal{A}$  and  $(\sim \mathcal{A})$  are both logically valid, by the above proposition. Hence, in any interpretation, both  $\mathcal{A}$  and  $(\sim \mathcal{A})$  are true, which contradicts Remark 3.25(c).  $\square$

In  $L$ , we saw that if we could prove  $\mathcal{A} \vdash_L \mathcal{B}$ , then  $\vdash_L (\mathcal{A} \rightarrow \mathcal{B})$ . This is almost true in  $\mathcal{L}$  in the sense that we must restrict the relationship between  $\mathcal{A}$  and  $\mathcal{B}$  to apply a similar theorem for  $K$ . In particular, in the deduction of  $\mathcal{B}$  from  $\mathcal{A}$  must not involve the deduction rule of Generalization. The reason for this is best seen with an example.

Consider  $x = 0$  in the integers. It is neither true nor false, since its truth value is dependent on what a valuation assigns to  $x$ . Now consider  $(\forall x)x = 0$ . It is certainly false, since any valuation that does not assign  $x$  to 0 will not satisfy  $x = 0$ . So the implication  $x = 0 \rightarrow (\forall x)x = 0$  must be false in the interpretation.

Now, notice that  $x = 0$  is an interpretation of  $A_1^1(x)$ , where  $x$  is just any variable of some appropriate first order language, and likewise  $(\forall x)x = 0$  is an interpretation of  $(\forall x)A_1^1(x)$ . We know that by Generalization,  $A_1^1(x) \vdash_{K\mathcal{L}} (\forall x)A_1^1(x)$ , but we have just seen an interpretation where  $A_1^1(x) \rightarrow (\forall x)A_1^1(x)$  is false, and hence the *wf* is not logically valid, and so it cannot be a theorem of  $K$ , by Proposition 4.5.

This example shows the issue that can arise when generalizing a statement that is neither true nor false in an interpretation<sup>1</sup>. However, with careful restriction on the *wfs*, we may still use the Deduction Theorem of  $L$  in an analogous way in  $K$ .

**Proposition 4.8** (The Deduction Theorem for  $K$ ). Let  $\mathcal{A}$  and  $\mathcal{B}$  be *wfs* of  $K$  and let  $\Gamma$  be a set of *wfs* of  $\mathcal{L}$ . If  $\Gamma \cup \{\mathcal{A}\} \vdash_K \mathcal{B}$ , and this deduction contains no application of Generalization involving a variable free in  $\mathcal{A}$ , then  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$ .

*Proof.* The proof is by induction on the number of *wfs*,  $n$ , in the deduction of  $\mathcal{B}$ . Let  $\mathcal{A}'$  and  $\mathcal{B}'$  be *wfs* and let  $\Gamma'$  be a set of *wfs*. Suppose, as an induction hypothesis, that whenever  $\Gamma' \cup \{\mathcal{A}'\} \vdash_K \mathcal{B}'$ , and this deduction has fewer than  $n$  *wfs* and has no occurrence of Generalization involving a variables free in  $\mathcal{A}'$ , it follows that  $\Gamma' \vdash_K (\mathcal{A}' \rightarrow \mathcal{B}')$ .

(base case) The verification of the base case proceeds in an identical manner as that of the proof of the Deduction Theorem for  $L$ . It may be that  $n = 1$ , in which  $\mathcal{B}$  is either an axiom of  $K$ , a member of  $\Gamma$ , or  $\mathcal{A}$  itself. If  $\mathcal{B}$  is an axiom of  $K$ , then:

1	$\mathcal{B}$	axiom of $K$
2	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	(K1)
3	$(\mathcal{A} \rightarrow \mathcal{B})$	1, 2, MP

<sup>1</sup>If the statement is not indeterminate in this sense, then generalization is fine (see the additional exercises section in the appendix of the manual)

If  $\mathcal{B}$  is a member of  $\Gamma$ :

1	$\mathcal{B}$	member of $\Gamma$
2	$(\mathcal{B} \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	(K1)
3	$(\mathcal{A} \rightarrow \mathcal{B})$	1, 2, MP

If  $\mathcal{B}$  is  $\mathcal{A}$ , then  $(\mathcal{A} \rightarrow \mathcal{B})$  is  $(\mathcal{A} \rightarrow \mathcal{A})$ .

1	$((\mathcal{A} \rightarrow ((\mathcal{A} \rightarrow \mathcal{A}) \rightarrow \mathcal{A})) \rightarrow ((\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{A})))$	(L2)
2	$(\mathcal{A} \rightarrow ((\mathcal{A} \rightarrow \mathcal{A}) \rightarrow \mathcal{A}))$	(L1)
3	$((\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A})) \rightarrow (\mathcal{A} \rightarrow \mathcal{A}))$	1, 2, MP
4	$(\mathcal{A} \rightarrow (\mathcal{A} \rightarrow \mathcal{A}))$	(L1)
5	$(\mathcal{A} \rightarrow \mathcal{A})$	3, 4, MP

The above is a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  (which is  $(\mathcal{A} \rightarrow \mathcal{A})$ ) from  $\Gamma$ . Note that it is also a general theorem of  $K$ .

And so in all three cases, we have formed a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$ , as desired.

(inductive step) Now it may be that  $n > 1$ . There are a number of cases to verify.

1. It may be that  $\mathcal{B}$  is an axiom of  $K$  or a member of  $\Gamma \cup \{\mathcal{A}\}$ , in which case the deductions in the base case serve as the desired deductions.
2. It may be that  $\mathcal{B}$  proceeds from MP and two prior *wfs* in the deduction. The two *wfs* must necessarily be of the form  $\mathcal{C}$  and  $(\mathcal{C} \rightarrow \mathcal{B})$ , and the subsequences of the deduction of  $\mathcal{B}$  that are deductions of  $\mathcal{C}$  and  $(\mathcal{C} \rightarrow \mathcal{B})$  must necessarily have fewer than  $n$  *wfs*, in which case, by the induction hypothesis, there exist deductions from  $\Gamma$  of  $(\mathcal{A} \rightarrow \mathcal{C})$  and  $(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$ .

1	$(\mathcal{A} \rightarrow \mathcal{C})$	Induction hypothesis
2	$(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$	Induction hypothesis
3	$((\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B})) \rightarrow ((\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})))$	(K2)
4	$((\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B}))$	2, 3, MP
5	$(\mathcal{A} \rightarrow \mathcal{B})$	1, 4, MP

The above is deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$ , as desired. The first two lines were shortened ways of expressing that deductions from  $\Gamma$  of  $(\mathcal{A} \rightarrow \mathcal{C})$  and  $(\mathcal{A} \rightarrow (\mathcal{C} \rightarrow \mathcal{B}))$  exist.

3. The only possible remaining is that  $\mathcal{B}$  follows from generalization from some *wf*,  $\mathcal{C}$ , and so  $\mathcal{B}$  is  $(\forall x_i)\mathcal{C}$ , where  $x_i$  is a variable that must necessarily not be free in  $\mathcal{A}$ . The induction hypothesis may be applied to the deduction of  $\mathcal{C}$ , so there exists a deduction from  $\Gamma$  of  $(\mathcal{A} \rightarrow \mathcal{C})$ .

1	$(\mathcal{A} \rightarrow \mathcal{C})$	Induction hypothesis
2	$(\forall x_i)(\mathcal{A} \rightarrow \mathcal{C})$	1, Generalization
3	$((\forall x_i)(\mathcal{A} \rightarrow \mathcal{C}) \rightarrow (\mathcal{A} \rightarrow (\forall x_i)\mathcal{C}))$	(K6)
4	$(\mathcal{A} \rightarrow (\forall x_i)\mathcal{C})$	1, 3, MP

Just as in the previous case, the first line is an abbreviation of the deduction of  $(\mathcal{A} \rightarrow \mathcal{C})$  from  $\Gamma$ . We have constructed a deduction of  $\mathcal{A} \rightarrow \mathcal{B}$  from  $\Gamma$ , since  $(\mathcal{A} \rightarrow (\forall x_i)\mathcal{C})$  is  $(\mathcal{A} \rightarrow \mathcal{B})$ .

In all possible cases, we have constructed a deduction of  $(\mathcal{A} \rightarrow \mathcal{B})$  from  $\Gamma$ , as desired.  $\square$

**Corollary 4.9.** If  $\Gamma \cup \{\mathcal{A}\} \vdash_K \mathcal{B}$  and  $\mathcal{A}$  is a closed *wf*, then  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$ .

*Proof.* Since  $\mathcal{A}$  is closed, it contains no free variables, so by the previous proposition,  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$ .  $\square$

**Corollary 4.10.** For any *wfs*  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  of  $K$ ,

$$\{(\mathcal{A} \rightarrow \mathcal{B}), (\mathcal{B} \rightarrow \mathcal{C})\} \vdash_K (\mathcal{A} \rightarrow \mathcal{C})$$

*Proof.* The proof relies only on the Deduction Theorem above and is identical to that of Corollary 2.10.  $\square$

Just as in  $L$ , the corollary of the Deduction Theorem holds in  $K$ .

**Proposition 4.11.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be *wfs* of  $K$ , and let  $\Gamma$  be a set of *wfs* of  $K$ . Then if  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$ , then  $\Gamma \cup \{\mathcal{A}\} \vdash_K \mathcal{B}$ .

*Proof.* The proof is identical to the proof of Proposition 2.9.  $\square$

It will often be the case that we would like to apply the deduction theorem to a deduction obtained from the Deduction Theorem. The following corollary will be useful.

**Corollary.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be *wfs* of  $K$  and let  $\Gamma$  be a set of *wfs* of  $\mathcal{L}$ . Suppose that  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  is obtained from the fact that  $\Gamma \cup \{\mathcal{A}\} \vdash_K \mathcal{B}$  and the Deduction Theorem. The deduction of  $\mathcal{A} \rightarrow \mathcal{B}$  contains no application of Generalization involving a variable free in  $\mathcal{A}$ .

*Proof.* Since the Deduction Theorem was applied to  $\Gamma \cup \{\mathcal{A}\}$ , we must assume that the deduction obtained contains no instances of Generalization involving a variable free in  $\mathcal{A}$ . Now consider the deduction  $\Gamma \vdash_K \mathcal{A}$ . The proof of the Deduction Theorem contains a construction of it. All lines in all deductions do not invoke Generalization except for in Case 3 of the proof in the inductive step or possibly lines obtained from the induction hypothesis. If the line was obtained by the induction hypothesis, we may use similarly use induction to demonstrate that those lines only involved instances of Generalization occurring free in  $\mathcal{A}$ , although we will not write this out fully. Now it might be the case that a line of the deduction was obtained by Generalization. In particular, line 2 of case 3 of the inductive step was justified by Generalization involving a variable not assumed to be free in  $\mathcal{A}$ .

Therefore, the deduction of  $\Gamma \vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  obtained from  $\Gamma \cup \{\mathcal{A}\} \vdash_K \mathcal{B}$  contains no instances of Generalization involving a variable free in  $\mathcal{A}$ .  $\square$

The next corollary is used implicitly in the textbook. We will state it clearly here.

**Corollary.** Let  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  be *wfs* of  $K$  and let  $\Gamma$  be a set of *wfs* of  $\mathcal{L}$ . Suppose that  $\Gamma \cup \{\mathcal{A}\} \vdash_K (\mathcal{B} \rightarrow \mathcal{C})$  is obtained from the fact  $\Gamma \cup \{\mathcal{A}, \mathcal{B}\} \vdash_K \mathcal{C}$  using the Deduction Theorem. If  $\mathcal{B}$  contains no variables occurring free in  $\mathcal{A}$ , then  $\Gamma \vdash_K \mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})$ .

*Proof.* The deduction of  $\mathcal{B} \rightarrow \mathcal{C}$  obtained from the Deduction Theorem contains no applications of Generalization involving a variable occurring free in  $\mathcal{B}$ , by the above lemma. Therefore, if  $\mathcal{B}$  contains no variables occurring free in  $\mathcal{A}$ , then the deduction of  $\mathcal{B} \rightarrow \mathcal{C}$  contains no applications of Generalization involving a variable occurring free in  $\mathcal{A}$ . By the Deduction Theorem, we may conclude that  $\Gamma \vdash_K \mathcal{A} \rightarrow (\mathcal{B} \rightarrow \mathcal{C})$ .  $\square$

Just as in the textbook, we will not explicitly reference these corollaries when they are used.

## Solutions to exercises

1. The following is a proof of  $(\forall x_1)(A_1^1(x_1) \rightarrow A_1^1(x_1))$ .

1	$(A_1^1(x_1) \rightarrow A_1^1(x_1))$	tautology
2	$(\forall x_1)(A_1^1(x_1) \rightarrow A_1^1(x_1))$	Generalization

2. In (a) of the exercise,  $x_i$  must not occur free in  $\mathcal{B}$ . This is ambiguous in the presentation of the exercise, since the condition is only stated in (b) and the assumption is that the *wf*  $\mathcal{B}$  is the same one in  $\mathcal{A}$ .

(a) We will first prove a simple lemma.

**Lemma.** Let  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  be *wfs* of some first order language  $\mathcal{L}$ . If  $\mathcal{A} \vdash_{K_{\mathcal{L}}} ((\sim \mathcal{C}) \rightarrow (\sim \mathcal{B}))$ , then  $\mathcal{A} \vdash_{K_{\mathcal{L}}} (\mathcal{B} \rightarrow \mathcal{C})$ .

*Proof.* Suppose that  $\mathcal{A} \vdash_{K_{\mathcal{L}}} ((\sim \mathcal{C}) \rightarrow (\sim \mathcal{B}))$ . The deduction can be extended in the following way.

		$\vdots$	
k	$((\sim \mathcal{C}) \rightarrow (\sim \mathcal{B}))$		deduction from $\mathcal{A}$
k+1	$((\sim \mathcal{C}) \rightarrow (\sim \mathcal{B})) \rightarrow (\mathcal{B} \rightarrow \mathcal{C})$		(K3)
k+2	$(\mathcal{B} \rightarrow \mathcal{C})$		k, k+1, MP

The above is a deduction of  $(\mathcal{B} \rightarrow \mathcal{C})$  from  $\mathcal{A}$ .  $\square$

Now we begin the proof. First we show that  $\{(\sim \mathcal{B}), (\forall x_i)\mathcal{A}\} \vdash_{K_{\mathcal{L}}} (\forall x_i)(\sim (\mathcal{A} \rightarrow \mathcal{B}))$ .

1	$(\sim \mathcal{B})$	assumption
2	$(\forall x_i)\mathcal{A}$	assumption
3	$\mathcal{A}$	Remark 4.1(b)
4	$((\sim \mathcal{B}) \rightarrow (\mathcal{A} \rightarrow (\sim (\mathcal{A} \rightarrow \mathcal{B}))))$	tautology
5	$(\mathcal{A} \rightarrow (\sim (\mathcal{A} \rightarrow \mathcal{B})))$	1, 4, MP
6	$(\sim (\mathcal{A} \rightarrow \mathcal{B}))$	2, 5, MP
7	$(\forall x_i)(\sim (\mathcal{A} \rightarrow \mathcal{B}))$	Generalization

By the deduction theorem and the fact that the only instance of generalization in the above deduction involved  $x_i$ , a variable not free in  $(\sim \mathcal{B})$ , we have

$$(\sim \mathcal{B}) \vdash_{K_{\mathcal{L}}} ((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)(\sim (\mathcal{A} \rightarrow \mathcal{B}))),$$

and by the lemma,

$$(\sim \mathcal{B}) \vdash_{K_{\mathcal{L}}} ((\sim (\forall x_i)(\sim (\mathcal{A} \rightarrow \mathcal{B}))) \rightarrow (\sim (\forall x_i)\mathcal{A})),$$

which is, by the definition of the  $\exists$  quantifier,

$$(\sim \mathcal{B}) \vdash_{K_{\mathcal{L}}} ((\exists x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\sim (\forall x_i)\mathcal{A})),$$

and by the converse of the Deduction Theorem, Proposition 4.11,

$$\{(\exists x_i)(\mathcal{A} \rightarrow \mathcal{B}), (\sim \mathcal{B})\} \vdash_{K_{\mathcal{L}}} (\sim (\forall x_i)\mathcal{A}),$$

and by the Deduction theorem once again and the fact that  $x_i$  does not occur free in  $\mathcal{B}$ ,

$$\{(\exists x_i)(\mathcal{A} \rightarrow \mathcal{B})\} \vdash_{K_{\mathcal{L}}} ((\sim \mathcal{B}) \rightarrow (\sim (\forall x_i)\mathcal{A})),$$

By the lemma,

$$\{(\exists x_i)(\mathcal{A} \rightarrow \mathcal{B})\} \vdash_{K_{\mathcal{L}}} ((\forall x_i)\mathcal{A} \rightarrow \mathcal{B}),$$

Finally, by the deduction theorem once again,

$$\vdash_{K_{\mathcal{L}}} ((\exists x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\forall x_i)\mathcal{A} \rightarrow \mathcal{B})).$$

(b) Observe the following deduction.

1	$(\sim (\forall x_i) \sim \mathcal{A} \rightarrow \mathcal{B})$	assumption
2	$\sim \mathcal{B}$	assumption
3	$(\sim (\forall x_i) \sim \mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\sim \mathcal{B} \rightarrow \sim \sim (\forall x_i) \sim \mathcal{A})$	tautology
4	$(\sim \mathcal{B} \rightarrow \sim \sim (\forall x_i) \sim \mathcal{A})$	1, 2, MP
5	$\sim \sim (\forall x_i) \sim \mathcal{A}$	2, 4, MP
6	$\sim \sim (\forall x_i) \sim \mathcal{A} \rightarrow (\forall x_i) \sim \mathcal{A}$	tautology
7	$(\forall x_i) \sim \mathcal{A}$	5, 6, MP
8	$\sim \mathcal{A}$	Remark 4.1(b)

The above deduction did not invoke Generalization. Therefore, by the Deduction Theorem,

$$((\exists x_i)\mathcal{A} \rightarrow \mathcal{B}) \vdash_{K_{\mathcal{L}}} (\sim \mathcal{B} \rightarrow \sim \mathcal{A}).$$

Note that we used the existential quantifier abbreviation above. Therefore, there exists a deduction from  $((\exists x_i)\mathcal{A} \rightarrow \mathcal{B})$  of  $(\sim \mathcal{B} \rightarrow \sim \mathcal{A})$  that may be extended in the following way.

	$\vdots$	
k	$(\sim \mathcal{B} \rightarrow \sim \mathcal{A})$	deduction from $((\exists x_i)\mathcal{A} \rightarrow \mathcal{B})$
k+1	$(\sim \mathcal{B} \rightarrow \sim \mathcal{A}) \rightarrow (\mathcal{A} \rightarrow \mathcal{B})$	(K3)
k+2	$(\mathcal{A} \rightarrow \mathcal{B})$	k, k+1, MP
k+3	$(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$	Generalization

The above deduction does not involve Generalization involving a variable occurring free in  $((\exists x_i)\mathcal{A} \rightarrow \mathcal{B})$ , since  $x_i$  does not occur free in  $\mathcal{B}$ . Therefore, by the Deduction Theorem,

$$((\exists x_i)\mathcal{A} \rightarrow \mathcal{B}) \rightarrow (\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$$

is a theorem of  $K_{\mathcal{L}}$ .



(c) Observe the following deduction.

1	$(\forall x_i) \sim\sim \mathcal{A}$	assumption
2	$\sim\sim \mathcal{A}$	Remark 4.1(b)
3	$(\sim\sim \mathcal{A} \rightarrow \mathcal{A})$	tautology
4	$\mathcal{A}$	2, 3, MP
5	$(\forall x_i)\mathcal{A}$	Generalization

The only instance of Generalization in the above deduction involves  $x_i$ , which is free in  $(\forall x_i) \sim\sim \mathcal{A}$ . Therefore, by the Deduction Theorem,

$$((\forall x_i) \sim\sim \mathcal{A} \rightarrow (\forall x_i)\mathcal{A})$$

is a theorem of  $K_{\mathcal{L}}$ , so the proof of the above can be extended in the following way.

	$\vdots$	
k	$((\forall x_i) \sim\sim \mathcal{A} \rightarrow (\forall x_i)\mathcal{A})$	theorem of $K_{\mathcal{L}}$
k+1	$((\forall x_i) \sim\sim \mathcal{A} \rightarrow (\forall x_i)\mathcal{A}) \rightarrow$ $(\sim (\forall x_i)\mathcal{A} \rightarrow \sim (\forall x_i) \sim\sim \mathcal{A}))$	tautology
k+2	$(\sim (\forall x_i)\mathcal{A} \rightarrow \sim (\forall x_i) \sim\sim \mathcal{A})$	k, k+1, MP

and therefore, the last line is a theorem of  $K_{\mathcal{L}}$ , and it is, by definition of  $\exists$ ,

$$(\sim (\forall x_i)\mathcal{A} \rightarrow (\exists x_i) \sim \mathcal{A}),$$

as desired.

3. (a) In line 2, Generalization involving  $x_1$  appears, but the variable  $x_1$  occurs free in  $(\exists x_2)A_1^2(x_1, x_2)$ , so the application of the Deduction Theorem later is invalid. Additionally, in line 3,  $x_2$  is not free for  $x_1$  in  $(\exists x_2)A_1^2(x_1, x_2)$ , so the instance of axiom scheme (K5) is invalid.
- (b) Consider an interpretation with the domain being the integers and  $A_1^2(x_i, x_j)$  indicating that  $x_i \neq x_j$ . Then the interpretation of the formula given in the exercise is  $((\exists x_2)x_1 \neq x_2 \rightarrow (\exists x_2)x_2 \neq x_2)$ . Let  $v$  be any valuation such that  $v(x_1) \neq v(x_2)$ . This valuation will not satisfy the  $wf$ , and hence the given formula is not logically valid.

## 4.2 Equivalence, substitution

Let  $\mathcal{A}, \mathcal{B}$  be  $wfs$  of  $\mathcal{L}$ . The connective is defined such that  $(\mathcal{A} \leftrightarrow \mathcal{B})$  is to stand for

$$\sim ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \sim (\mathcal{B} \rightarrow \mathcal{A})).$$

**Proposition 4.15.** For any  $wfs$   $\mathcal{A}, \mathcal{B}$  of  $\mathcal{L}$ ,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$  if and only if  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{A})$ .

*Proof.*  $\Rightarrow$  Suppose that  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$ , i.e.  $\vdash_K \star$ , where  $\star$  is

$$\sim ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \sim (\mathcal{B} \rightarrow \mathcal{A})).$$

Then  $\star \rightarrow (\mathcal{A} \rightarrow \mathcal{B})$  and  $\star \rightarrow (\mathcal{B} \rightarrow \mathcal{A})$  are both tautologies (their truth tables will verify this), and so, by MP, both  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{A})$ .

$\Leftarrow$  Suppose that  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{A})$ . The *wf*

$$(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\mathcal{B} \rightarrow \mathcal{A}) \rightarrow \sim ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \sim (\mathcal{B} \rightarrow \mathcal{A})))$$

is a tautology (by its truth table), and by MP,  $\vdash_K \sim ((\mathcal{A} \rightarrow \mathcal{B}) \rightarrow \sim (\mathcal{B} \rightarrow \mathcal{A}))$ .  $\square$

**Definition 4.16.** If  $(\mathcal{A} \leftrightarrow \mathcal{B})$  is a theorem of  $K$ , then we say that the *wfs*  $\mathcal{A}$  and  $\mathcal{B}$  are *provably equivalent*.

**Corollary 4.17.** Let  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  be *wfs* of  $\mathcal{L}$ . If  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \leftrightarrow \mathcal{C})$ , then  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{C})$ .

*Proof.* By Proposition 4.15,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$  if and only if  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{A})$ . Similarly,  $\vdash_K (\mathcal{B} \leftrightarrow \mathcal{C})$  if and only if  $\vdash_K (\mathcal{B} \rightarrow \mathcal{C})$  and  $\vdash_K (\mathcal{C} \rightarrow \mathcal{B})$ . Since both  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{C})$ , by HP,  $\vdash_K (\mathcal{A} \rightarrow \mathcal{C})$ . Since both  $\vdash_K (\mathcal{C} \rightarrow \mathcal{B})$  and  $\vdash_K (\mathcal{B} \rightarrow \mathcal{A})$ , by HP,  $\vdash_K (\mathcal{C} \rightarrow \mathcal{A})$ . By Proposition 4.15,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{C})$ .  $\square$

Recall that  $\mathcal{A}(x_i)$  denotes a *wf* in which  $x_i$  occurs free, and  $\mathcal{A}(x_j)$  denotes  $\mathcal{A}(x_i)$  with every *free* occurrence of  $x_i$  substituted with  $x_j$ .

**Proposition 4.18.** If  $x_i$  occurs *only free and never bound*<sup>2</sup> in  $\mathcal{A}(x_i)$  and  $x_j$  is a variable which does not occur, free or bound, in  $\mathcal{A}(x_i)$ , then

$$\vdash_K ((\forall x_i)\mathcal{A}(x_i) \leftrightarrow (\forall x_j)\mathcal{A}(x_j)).$$

*Proof.* First,  $x_j$  is free for  $x_i$  in  $\mathcal{A}(x_i)$ , therefore line 2 in the following deduction is valid.

1	$(\forall x_i)\mathcal{A}(x_i)$	assumption
2	$((\forall x_i)\mathcal{A}(x_i) \rightarrow \mathcal{A}(x_j))$	(K5)
3	$\mathcal{A}(x_j)$	1, 2, MP
4	$(\forall x_j)\mathcal{A}(x_j)$	Generalization

Hence, since the instance of Generalization in line 4 involved  $x_j$ , a variable not free in  $(\forall x_i)\mathcal{A}(x_i)$ , we may use the Deduction Theorem to obtain

$$\vdash_K ((\forall x_i)\mathcal{A}(x_i) \rightarrow (\forall x_j)\mathcal{A}(x_j)).$$

Now, since  $x_i$  is free for  $x_j$  in  $\mathcal{A}(x_j)$ , we may use an identical deduction as the one above with  $x_j$  and  $x_i$  switched.

1	$(\forall x_j)\mathcal{A}(x_j)$	assumption
2	$((\forall x_j)\mathcal{A}(x_j) \rightarrow \mathcal{A}(x_i))$	(K5)
3	$\mathcal{A}(x_i)$	1, 2, MP
4	$(\forall x_i)\mathcal{A}(x_i)$	Generalization

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<sup>2</sup>We add this additional restriction to handle the “edge case” in which  $x_i$  occurs redundantly bound within  $\mathcal{A}(x_i)$ .

By the Deduction Theorem, we obtain the converse of the implication above,

$$\vdash_K ((\forall x_j)\mathcal{A}(x_j) \rightarrow (\forall x_i)\mathcal{A}(x_i)),$$

so by Proposition 4.15,

$$\vdash_K ((\forall x_j)\mathcal{A}(x_j) \leftrightarrow (\forall x_i)\mathcal{A}(x_i)),$$

as desired. □

The above proposition makes clear that the name of a bound variable in a *wf* is of no importance to the meaning of the *wf*. The meaning of the *wf* is dependent on its free variables.

**Proposition 4.19.** Let  $\mathcal{A}$  be a *wf* of  $\mathcal{L}$  whose  $n$  free variables are  $x_1, \dots, x_n$ . The *wf*  $\mathcal{A}$  is a theorem of  $K$  if and only if  $(\forall x_1) \dots (\forall x_n)\mathcal{A}$  is a theorem of  $K$ .

*Proof.*  $\Rightarrow$  Suppose that  $\vdash_K \mathcal{A}$ . We proceed by induction on  $n$ . As a hypothesis of induction, suppose that if  $\mathcal{B}$  is a *wf* of  $\mathcal{L}$  with fewer than  $n$  free variables, then if  $\mathcal{B}$  is a theorem of  $K$ , then  $(\forall y_1) \dots (\forall y_k)\mathcal{B}$  is a theorem of  $K$ , where  $y_1, \dots, y_k$  are the free variables of  $\mathcal{B}$ .

(base case) It may be that  $n = 0$ , which is to say that  $\mathcal{A}$  has no free variables. In this case,  $\mathcal{A}$  itself has all of its free variables vacuously quantified.

Alternatively, it may be that  $n = 1$ , in which case since  $\mathcal{A}$  is a theorem of  $K$ , by Generalization,  $(\forall y_1)\mathcal{A}$  must be a theorem of  $K$  as well, where  $y_1$  is the only free variable occurring in  $\mathcal{A}$ .

(inductive step) It may be that  $n > 1$ . Since  $\mathcal{A}$  is a theorem of  $K$ , by Generalization,  $(\forall y_n)\mathcal{A}$  is a theorem of  $K$ . Notice this *wf* has  $y_1, \dots, y_{n-1}$  as its free variables, so by the induction hypothesis

$$(\forall y_1) \dots (\forall y_{n-1})(\forall y_n)\mathcal{A}$$

must be a theorem of  $K$ , as desired.

$\Leftarrow$  By Remark 4.1(b) or repeated applications of (K5), if  $(\forall y_1) \dots (\forall y_n)\mathcal{A}$  is a theorem of  $K$ , then  $\mathcal{A}$  must be a theorem of  $K$ <sup>3</sup> □

**Definition 4.20.** Let  $\mathcal{A}$  be a *wf* of  $\mathcal{L}$  with  $y_1, \dots, y_n$  as the only variables occurring free in  $\mathcal{A}$ . The *wf*  $(\forall y_1) \dots (\forall y_n)\mathcal{A}$  is the *universal closure* of  $\mathcal{A}$  and is denoted by  $\mathcal{A}'$ .

It is true that  $\vdash_K \mathcal{A}' \rightarrow \mathcal{A}$ , but  $\mathcal{A}$  and  $\mathcal{A}'$  are in general not provably equivalent. A counterexample can be found in the example in this manual used to motivate the Deduction Theorem.

**Proposition 4.22.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be *wfs* of  $\mathcal{L}$ , and let  $\mathcal{A}_0$  be a *wf* of  $\mathcal{L}$  with occurrences of  $\mathcal{A}$ , and let  $\mathcal{B}_0$  be the *wf*  $\mathcal{A}_0$  in which all occurrences of  $\mathcal{A}$  are replaced with  $\mathcal{B}$ .

If  $\vdash_K (\mathcal{A} \rightarrow \mathcal{B})'$ , then  $\vdash_K (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ .

*Proof.* Let  $n$  denote the number of connectives and quantifiers in  $\mathcal{A}_0$ . We proceed by induction on  $n$ .

(hypothesis) Suppose that for any *wf* containing instances of  $\mathcal{A}$  and having fewer  $n$  connectives and quantifiers, the property above holds for it.

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<sup>3</sup>A more complete proof would involve induction in the proof of the other direction of the equivalence.

(base case) It may be that  $n = 0$ , i.e.,  $\mathcal{A}_0$  has no connectives or quantifiers. Then  $\mathcal{A}_0$  is just  $\mathcal{A}$ , and  $\mathcal{B}_0$  is just  $\mathcal{B}$ . Therefore,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A} \leftrightarrow \mathcal{B})$ , by repeated applications of Remark 4.1(b), i.e.  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ , as desired.

(induction step) It may be that  $n > 1$ , which is to say that more than one connective or quantifier occurs in  $\mathcal{A}_0$ . There are three cases to consider, each one corresponding to one of the three possible forms that  $\mathcal{A}_0$  can take.

1. The *wf*  $\mathcal{A}_0$  is  $(\sim \mathcal{C}_0)$  and  $\mathcal{B}_0$  is  $(\sim \mathcal{D}_0)$ , where  $\mathcal{D}_0$  is the *wf* in which instances of  $\mathcal{B}$  in  $\mathcal{C}_0$  are substituted for  $\mathcal{A}$ . The induction hypothesis may be applied to  $\mathcal{C}_0$ , so

$$\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{D}_0)).$$

Since  $(\mathcal{C}_0 \leftrightarrow \mathcal{D}_0) \rightarrow (\sim \mathcal{C}_0 \leftrightarrow \sim \mathcal{D}_0)$  is a tautology, it is a theorem of  $K$ . By HS,

$$\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\sim \mathcal{C}_0 \leftrightarrow \sim \mathcal{D}_0)), \text{ i.e., } \vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)),$$

as desired.

2. The *wf*  $\mathcal{A}_0$  is  $(\sim \mathcal{C}_0 \rightarrow \sim \mathcal{D}_0)$  and  $\mathcal{B}_0$  is  $(\sim \mathcal{E}_0 \rightarrow \sim \mathcal{F}_0)$ , where  $\mathcal{E}_0$  and  $\mathcal{F}_0$  are the *wfs* in which instances of  $\mathcal{B}$  are substituted for  $\mathcal{A}$  in  $\mathcal{C}_0$  and  $\mathcal{D}_0$ , respectively. The induction hypothesis may be applied to both  $\mathcal{C}_0$  and  $\mathcal{D}_0$ , so

$$\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{E}_0)) \text{ and } \vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{D}_0 \leftrightarrow \mathcal{F}_0)).$$

The statement form

$$(a \rightarrow (c \leftrightarrow e)) \rightarrow ((a \rightarrow (d \leftrightarrow f)) \rightarrow (a \rightarrow ((c \rightarrow d) \leftrightarrow (e \rightarrow f)))),$$

is a tautology. Therefore, (treat  $a$  as  $(\mathcal{A} \leftrightarrow \mathcal{B})'$ ) by two applications of MP,

$$\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow ((\mathcal{C}_0 \rightarrow \mathcal{D}_0) \leftrightarrow (\mathcal{E}_0 \rightarrow \mathcal{F}_0))),$$

which is to say that

$$\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)),$$

as desired.

3. The *wf*  $\mathcal{A}_0$  is  $(\forall x_i)\mathcal{C}_0$ , and  $\mathcal{B}_0$  is  $(\forall x_i)\mathcal{D}_0$ , where  $\mathcal{D}_0$  is the *wf* obtained by replacing all instances of  $\mathcal{A}$  in  $\mathcal{C}_0$  with  $\mathcal{B}$ . The induction hypothesis may be applied to  $\mathcal{C}_0$  to obtain  $\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$ . We may continue this deduction in the following way.

		$\vdots$	
k	$((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$		Induction hypothesis
k+1	$(\forall x_i)((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$		Generalization
k+2	$(\forall x_i)((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$		
	$\rightarrow ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\forall x_i)(\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$		(K6)
k+3	$((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\forall x_i)(\mathcal{C}_0 \leftrightarrow \mathcal{D}_0))$		k+1, k+2, MP
k+4	$((\forall x_i)(\mathcal{C}_0 \leftrightarrow \mathcal{D}_0) \rightarrow ((\forall x_i)\mathcal{C}_0 \leftrightarrow (\forall x_i)\mathcal{D}_0))$		Lemma
k+5	$((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow ((\forall x_i)\mathcal{C}_0 \leftrightarrow (\forall x_i)\mathcal{D}_0))$		k+3, k+4, HS

Note that line k+2 is possible by since  $x_i$  does not occur free in  $(\mathcal{A} \leftrightarrow \mathcal{B})'$ , since it is a universal closure, and this is also the reason that proving  $\mathcal{A}$  to be provably equivalent to  $\mathcal{B}$  is not enough for the proposition. Line k+1 is justified by the following lemma.

**Lemma.** Let  $\mathcal{A}$  and  $\mathcal{B}$  be wfs of  $\mathcal{L}$ . Then

$$(\forall x_i)(\mathcal{A} \leftrightarrow \mathcal{B}) \rightarrow ((\forall x_i)\mathcal{A} \leftrightarrow (\forall x_i)\mathcal{B})$$

is a theorem of  $K$ .

*Proof.* We claim that

$$\vdash_K (\forall x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}),$$

and we will prove this in Exercise 4. Additionally, the deduction above contains no instances of generalization involving a variable other than  $x_i$ .

1	$(\forall x_i)(\mathcal{A} \leftrightarrow \mathcal{B})$	assumption
2	$(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$	1, Proposition 4.15
3	$(\forall x_i)(\mathcal{B} \rightarrow \mathcal{A})$	1, Proposition 4.15
4	$(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B})$	above theorem
5	$(\forall x_i)(\mathcal{B} \rightarrow \mathcal{A}) \rightarrow ((\forall x_i)\mathcal{B} \rightarrow (\forall x_i)\mathcal{A})$	above theorem
6	$((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B})$	2, 4, MP
7	$((\forall x_i)\mathcal{B} \rightarrow (\forall x_i)\mathcal{A})$	3, 5, MP
8	$((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}) \rightarrow$ $((\forall x_i)\mathcal{B} \rightarrow (\forall x_i)\mathcal{A}) \rightarrow ((\forall x_i)\mathcal{A} \leftrightarrow (\forall x_i)\mathcal{B})$	tautology
9	$((\forall x_i)\mathcal{B} \rightarrow (\forall x_i)\mathcal{A}) \rightarrow ((\forall x_i)\mathcal{A} \leftrightarrow (\forall x_i)\mathcal{B})$	6, 8, MP
10	$((\forall x_i)\mathcal{A} \leftrightarrow (\forall x_i)\mathcal{B})$	7, 9, MP

By the Deduction Theorem,

$$(\forall x_i)(\mathcal{A} \leftrightarrow \mathcal{B}) \leftrightarrow ((\forall x_i)\mathcal{A} \leftrightarrow (\forall x_i)\mathcal{B}),$$

as desired.  $\square$

To conclude the induction and the proof, we have shown that for any value of  $n$ ,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ , as desired.  $\square$

Now, for the wfs  $\mathcal{A}, \mathcal{B}$  described above, if  $(\mathcal{A} \leftrightarrow \mathcal{B})$  is logically valid, i.e., it is a theorem of  $K$ , then its universal closure is also a theorem, so we may freely use the above Proposition. We will refer to this property in the below corollary.

**Corollary 4.23.** Let  $\mathcal{A}, \mathcal{B}, \mathcal{A}_0, \mathcal{B}_0$  be as in Proposition 4.22 above. If  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$ , then  $\vdash_K (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ .

*Proof.* Suppose that  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})$ . Then, by Proposition 4.19,  $\vdash_K (\mathcal{A} \leftrightarrow \mathcal{B})'$ . By Proposition 4.22,  $\vdash_K ((\mathcal{A} \leftrightarrow \mathcal{B})' \rightarrow (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0))$ . By MP,  $\vdash_K (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ .  $\square$

**Corollary 4.24.** Let  $x_i$  occur free in the wf  $\mathcal{A}(x_i)$ . Let  $\mathcal{A}_0$  be a wf containing instances of  $(\forall x_i)\mathcal{A}(x_i)$  as a subformula. Let  $\mathcal{B}_0$  be the wf obtained by replacing in  $\mathcal{A}_0$  one or more instances of  $(\forall x_i)\mathcal{A}(x_i)$  with  $(\forall x_j)\mathcal{A}(x_j)$ .

If  $x_j$  does not occur, free or bound, in  $\mathcal{A}(x_i)$ , then  $\vdash_K (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ .

*Proof.* Since  $x_j$  does not occur, free or bound, in  $\mathcal{A}(x_i)$ , by Proposition 4.18,

$$\vdash_K ((\forall x_i)\mathcal{A}(x_i) \leftrightarrow (\forall x_j)\mathcal{A}(x_j))$$

Therefore, by Corollary 4.23,  $\vdash_K (\mathcal{A}_0 \leftrightarrow \mathcal{B}_0)$ .  $\square$

### Solutions to exercises

4. Observe the following deduction.

1	$(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$	assumption
2	$(\forall x_i)\mathcal{A}$	assumption
3	$\mathcal{A} \rightarrow \mathcal{B}$	1, Remark 4.1(b)
4	$\mathcal{A}$	2, Remark 4.1(b)
5	$\mathcal{B}$	3, 4, MP
6	$(\forall x_i)\mathcal{B}$	5, Generalization

Notice that the only instance of Generalization involves  $x_i$ , which does not occur free in  $(\forall x_i)(\mathcal{A} \rightarrow \mathcal{B})$  and  $(\forall x_i)\mathcal{A}$ . By applying the Deduction Theorem twice, we conclude that

$$\vdash_K (\forall x_i)(\mathcal{A} \rightarrow \mathcal{B}) \rightarrow ((\forall x_i)\mathcal{A} \rightarrow (\forall x_i)\mathcal{B}),$$

as desired.

5. The *wf*  $(\sim\sim (\forall x_i) \sim \mathcal{A}) \leftrightarrow (\forall x_i)(\sim \mathcal{A})$  is a tautology, hence it is a theorem of  $K$ . Notice that by the definition of  $\exists$ , the left-hand side of the  $\leftrightarrow$  is  $\sim (\exists x_i)\mathcal{A}$ , so

$$\vdash_K (\sim (\exists x_i)\mathcal{A}) \leftrightarrow (\forall x_i)(\sim \mathcal{A}),$$

i.e.,  $(\sim (\exists x_i)\mathcal{A})$  and  $(\forall x_i)(\sim \mathcal{A})$  are provably equivalent.

6. (a) Observe the following deduction.

1	$(\forall x_1)(\forall x_2)A_1^2(x_1, x_2)$	assumption
2	$((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \leftrightarrow (\forall x_1)(\forall x_3)A_1^2(x_1, x_3))$	Proposition 4.18
3	$((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \leftrightarrow (\forall x_1)(\forall x_3)A_1^2(x_1, x_3)) \rightarrow$ $((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \rightarrow (\forall x_1)(\forall x_3)A_1^2(x_1, x_3))$	tautology
4	$((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \rightarrow (\forall x_1)(\forall x_3)A_1^2(x_1, x_3))$	2, 3, MP
5	$(\forall x_1)(\forall x_3)A_1^2(x_1, x_3)$	1, 4, MP

We could continue this deduction in the same way to deduce

$$(\forall x_2)(\forall x_3)A_1^2(x_2, x_3),$$

as desired.

(b) The following is a satisfactory deduction.

1	$(\forall x_1)(\forall x_2)A_1^2(x_1, x_2)$	assumption
2	$((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \rightarrow (\forall x_2)A_1^2(x_1, x_2))$	Remark 4.1(b)
3	$((\forall x_2)A_1^2(x_1, x_2) \rightarrow A_1^2(x_1, x_1))$	(K5)
4	$((\forall x_1)(\forall x_2)A_1^2(x_1, x_2) \rightarrow A_1^2(x_1, x_1))$	2, 3, HS
5	$A_1^2(x_1, x_1)$	1, 4, MP
6	$(\forall x_1)A_1^2(x_1, x_1)$	5, Generalization

Note that in line 3, we used the fact that  $x_1$  is free for  $x_2$  in  $A_1^2(x_1, x_2)$ .

7. Since  $x_j$  does not occur, free or bound, in  $\sim \mathcal{A}(x_i)$ , by Proposition 4.18,

$$\vdash_K (\forall x_i)(\sim \mathcal{A}(x_i)) \leftrightarrow (\forall x_j)(\sim \mathcal{A}(x_j)),$$

and since  $(\mathcal{C} \leftrightarrow \mathcal{D}) \rightarrow ((\sim \mathcal{D}) \leftrightarrow (\sim \mathcal{C}))$  is a tautology, then by MP and the previously obtained theorem,

$$\vdash_K (\sim (\forall x_i)(\sim \mathcal{A}(x_i))) \leftrightarrow (\sim (\forall x_j)(\sim \mathcal{A}(x_j))), \text{ i.e., } \vdash_K (\exists x_i)\mathcal{A}(x_i) \leftrightarrow (\exists x_j)\mathcal{A}(x_j),$$

as desired.

## 4.3 Prenex Form

### Solutions to exercises

- 8. (a)
- (b)
- (c)
- (d)
- 9.
- 10.

## 4.4 The Adequacy Theorem for $K$

### Solutions to exercises

- 11.
- 12.
- 13.
- 14.

## 4.5 Models

### Solutions to exercises

- 15.
- 16.
- 17.
- 18.
- 19.

# **Chapter 5**

## **Mathematical systems**



## **Chapter 6**

# **The Gödel Incompleteness Theorem**

## **Chapter 7**

### **Computability, unsolvability, undecidability**

# Appendix A

## Additional propositions

This chapter contains proofs of exercises left to the reader in the textbook or otherwise useful propositions.

**Proposition A.1.** The set of *wfs* of  $L$  is countable.

## **Appendix B**

### **Additional exercises**