

# Topics in Analysis and Linear Algebra

Le Chen

le.chen@emory.edu

Emory University

Atlanta GA

Last updated on

July 22, 2021

Summer Bootcamp for  
Emory Biostatistics and Bioinformatics  
PhD Program

July 22 - 28, 2021



# Chapter 1. Mathematical Logics

This part is mostly based on Chapters 1, 3, 4 of

*Hamilton, A. G., **Logic for mathematicians**. 2<sup>nd</sup> ed., Cambridge Univ. Press, 1988.*

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability

This section is based on Chapter 1 of

*Hamilton, A. G., **Logic for mathematicians.** 2<sup>nd</sup> ed., Cambridge Univ. Press, 1988.*

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

### § 1.1.1 Statements and connectives

### § 1.1.2 Truth functions and truth tables

### § 1.1.3 Rules for manipulation and substitution

### § 1.1.4 Normal forms

### § 1.1.5 Adequate sets of connectives

### § 1.1.6 Arguments and validity

### § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

### § 1.2.1 Predicates and quantifiers

### § 1.2.2 First order languages

### § 1.2.3 Interpretations

### § 1.2.4 Operations on predicate calculus

### § 1.2.5 Prenex form

### § 1.2.6 One example – convergence in probability

► **Simple sentences** : subject + predicate

Napoleon is dead

John owes James two pounds

All eggs which are not square are round

► **Compound sentences** : subject + predicate with connectives

Napoleon is dead and the world is rejoicing

If all eggs are not square then all eggs are round

If the barometer falls then either it will rain or it will snow



Simple/compound sentences  $\rightarrow$  Simple/compound statements.

**Basic assumption:** All simple statements are either true (T) or false (F).

$A, B, C, \dots$  : simple statements.

$p, q, r, \dots$  : statements variables.

## Connectives

not $A$	$\neg A$	negation
$A$ and $B$	$A \wedge B$	conjunction
$A$ or $B$	$A \vee B$	disjunction
if $A$ then $B$	$A \rightarrow B$	conditional
$A$ if and only if $B$	$A \leftrightarrow B$	biconditional

Napoleon is dead and the world is rejoicing

If all eggs are not square then all eggs are round

If the barometer falls then either it will rain or it will snow

 $A \wedge B$  $C \rightarrow D$  $E \rightarrow (F \vee G)$

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability

# Negation

$p$	$\neg p$
T	F
F	T

# Conjunction

$p$	$q$	$p \wedge q$
T	T	T
T	F	F
F	T	F
F	F	F

# Disjunction

$p$	$q$	$p \vee q$
T	T	T
T	F	T
F	T	T
F	F	F

## Conditional

$p$	$q$	$p \rightarrow q$
T	T	T
T	F	F
F	T	T
F	F	T



## Biconditional

$p$	$q$	$p \leftrightarrow q$
T	T	T
T	F	F
F	T	F
F	F	T

Def. A **statement form** is an expression involving statement variables and connectives, which can be formed using the rules:

(i) Any statement variable is a statement form.

(ii) If  $\mathcal{A}$  and  $\mathcal{B}$  are statement forms, then  $(\neg \mathcal{A})$ ,  $(\mathcal{A} \vee \mathcal{B})$ ,  $(\mathcal{A} \wedge \mathcal{B})$ ,  $(\mathcal{A} \rightarrow \mathcal{B})$ ,  $(\mathcal{A} \leftrightarrow \mathcal{B})$  are statement forms.

E.g. Construct the truth table of the statement form  $p \rightarrow (q \vee r)$

Sol.

$p$	$q$	$r$	$p \vee q$	$p \rightarrow (q \vee r)$
T	T	T		
T	T	F		
T	F	T		
T	F	F		
F	T	T		
F	T	F		
F	F	T		
F	F	F		

□

Def. A statement form is a **tautology** if it only takes true value  $T$ .

A statement form is a **contradiction** if it only takes false value  $F$ .

E.g.  $p \vee (\neg p)$  is a tautology

$p \wedge (\neg p)$  is a contradiction

Sol.

$p$	$\neg p$	$p \vee (\neg p)$
T	F	<b>T</b>
F	T	<b>T</b>

$p$	$\neg p$	$p \wedge (\neg p)$
T	F	<b>F</b>
F	T	<b>F</b>

□

Def. If  $\mathcal{A}$  and  $\mathcal{B}$  are statement forms, then

$\mathcal{A}$  logically implies  $\mathcal{B}$ , denoted as  $\mathcal{A} \Rightarrow \mathcal{B}$ , if  $\mathcal{A} \rightarrow \mathcal{B}$  is a tautology.

$\mathcal{A}$  is logically equivalent to  $\mathcal{B}$ , denoted as  $\mathcal{A} \Leftrightarrow \mathcal{B}$ , if  $\mathcal{A} \leftrightarrow \mathcal{B}$  is a tautology.

E.g.  $p \wedge q \Rightarrow p$

$$\neg(p \wedge q) \Leftrightarrow (\neg p) \vee (\neg q)$$

$$\neg(p \vee q) \Leftrightarrow (\neg p) \wedge (\neg q)$$

Sol. Check whether the truth tables of the following statement forms only produce  $T$ , i.e., tautology:

$$p \wedge q \rightarrow p$$

$$\neg(p \wedge q) \Leftrightarrow (\neg p) \vee (\neg q)$$

$$\neg(p \vee q) \Leftrightarrow (\neg p) \wedge (\neg q)$$

Sol. (continued) Let's check  $p \wedge q \rightarrow p$ :

$p$	$q$	$p \wedge q$	$p \wedge q \rightarrow p$
T	T	T	T
T	T	F	T
F	T	F	T
F	F	F	T

□

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

§ 1.1.1 Statements and connectives

§ 1.1.2 Truth functions and truth tables

§ 1.1.3 Rules for manipulation and substitution

§ 1.1.4 Normal forms

§ 1.1.5 Adequate sets of connectives

§ 1.1.6 Arguments and validity

§ 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

§ 1.2.1 Predicates and quantifiers

§ 1.2.2 First order languages

§ 1.2.3 Interpretations

§ 1.2.4 Operations on predicate calculus

§ 1.2.5 Prenex form

§ 1.2.6 One example – convergence in probability

►  $A \Leftrightarrow \neg\neg A$

►  $A \Leftrightarrow A \wedge A$

►  $A \Leftrightarrow A \vee A$

►  $A \wedge B \Leftrightarrow B \wedge A$

►  $A \vee B \Leftrightarrow B \vee A$

►  $(A \wedge B) \wedge C \Leftrightarrow A \wedge (B \wedge C)$

►  $(A \vee B) \vee C \Leftrightarrow A \vee (B \vee C)$



$$\blacktriangleright A \wedge (B \vee C) \Leftrightarrow (A \wedge C) \vee (A \wedge B)$$

$$\blacktriangleright A \vee (B \wedge C) \Leftrightarrow (A \vee C) \wedge (A \vee B)$$

$$\blacktriangleright \neg(A \wedge B) \Leftrightarrow (\neg A) \vee (\neg B)$$

$$\blacktriangleright \neg(A \vee B) \Leftrightarrow (\neg A) \wedge (\neg B)$$

$$\neg(\bigwedge_{i=1}^n A_i) = \bigvee_{i=1}^n (\neg A_i)$$

$$\neg(\bigvee_{i=1}^n A_i) = \bigwedge_{i=1}^n (\neg A_i)$$

$$\blacktriangleright A \vee (A \wedge B) \Leftrightarrow A$$

$$\blacktriangleright A \wedge (A \vee B) \Leftrightarrow A$$

$$\blacktriangleright A \vee T \Leftrightarrow T$$

$$\blacktriangleright A \wedge F \Leftrightarrow F$$

$$\blacktriangleright A \wedge T \Leftrightarrow A$$

$$\blacktriangleright A \vee F \Leftrightarrow A$$

►  $A \vee (\neg A) \Leftrightarrow T$

►  $A \wedge (\neg A) \Leftrightarrow F$

►  $A \rightarrow B \Leftrightarrow (\neg A) \vee B$

►  $A \leftrightarrow B \Leftrightarrow (A \rightarrow B) \vee (B \rightarrow A)$

►  $A \rightarrow B \Leftrightarrow (\neg B) \rightarrow (\neg A)$

►  $A \leftrightarrow B \Leftrightarrow (\neg B) \leftrightarrow (\neg A)$

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms**

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability

Def. Disjunctive normal form:  $\bigvee_{i=1}^m (\bigwedge_{j=1}^n O_{ij})$

Conjunctive normal form:  $\bigwedge_{i=1}^m (\bigvee_{j=1}^n O_{ij})$

where  $O_{ij}$  is either a statement variable or the negation of a statement variable.

Thm. Every statement form which is not a contradiction can be write as disjunctive normal form.

Every statement form which is not a tautology can be write as conjunctive normal form.

E.g. 1 Transform the following truth table to disjunctive normal form.

$p$	$q$	$r$	$f(p, q, r)$
T	T	T	T
T	T	F	T
T	F	T	F
T	F	F	F
F	T	T	F
F	T	F	F
F	F	T	F
F	F	F	T

Sol. Find the entries with “T” and combine them with  $\vee$ .

Sol. (Continued)

$p$	$q$	$r$	$f(p, q, r)$	
T	T	T	T	$p \wedge q \wedge r$
T	T	F	T	$p \wedge q \wedge \neg r$
T	F	T	F	
T	F	F	F	
F	T	T	F	
F	T	F	F	
F	F	T	F	
F	F	F	T	$\neg p \wedge \neg q \wedge \neg r$

Hence,

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

□

E.g.2 Find a conjunctive normal form for  $((\neg p) \vee q) \rightarrow r$ .

Sol. Construct the form by the truth table:

$p$	$q$	$r$	$\neg p$	$\neg p \vee q$	$(\neg p \vee q) \rightarrow r$	
T	T	T	F	T	T	$p \vee q \vee r$
T	T	F	F	T	F	
T	F	T	F	F	T	$p \vee \neg q \vee r$
T	F	F	F	F	T	$p \vee \neg q \vee \neg r$
F	T	T	T	T	T	$\neg p \vee q \vee r$
F	T	F	T	T	F	
F	F	T	T	T	T	$\neg p \vee \neg q \vee r$
F	F	F	T	T	F	

Therefore,

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



# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

§ 1.1.1 Statements and connectives

§ 1.1.2 Truth functions and truth tables

§ 1.1.3 Rules for manipulation and substitution

§ 1.1.4 Normal forms

§ 1.1.5 Adequate sets of connectives

§ 1.1.6 Arguments and validity

§ 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

§ 1.2.1 Predicates and quantifiers

§ 1.2.2 First order languages

§ 1.2.3 Interpretations

§ 1.2.4 Operations on predicate calculus

§ 1.2.5 Prenex form

§ 1.2.6 One example – convergence in probability



Def. 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.

Remark  $\{\wedge, \vee, \neg\}$  is an adequate set.

For example,

$$\begin{aligned}A \rightarrow B &\Leftrightarrow \neg B \vee A \\A \leftrightarrow B &\Leftrightarrow (A \rightarrow B) \wedge (B \rightarrow A).\end{aligned}$$

Thm. The pairs

$$\{\neg, \wedge\}, \quad \{\neg, \vee\} \quad \text{and} \quad \{\neg, \rightarrow\}$$

are adequate sets of connectives.

**Proof** We only show the case  $\{\neg, \wedge\}$ . This is true because

$$A \vee B \quad \Leftrightarrow \quad \neg(\neg A \wedge \neg B).$$

□

**Nor**

$p$	$q$	$p \downarrow q$
T	T	F
T	F	F
F	T	F
F	F	T

**Nand**

$p$	$q$	$p q$
T	T	F
T	F	T
F	T	T
F	F	T

Thm. The singleton sets

$\{\downarrow\}$  and  $\{| \}$

are adequate sets of connectives.

Proof. Show this as an exercise.

□

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

§ 1.1.1 Statements and connectives

§ 1.1.2 Truth functions and truth tables

§ 1.1.3 Rules for manipulation and substitution

§ 1.1.4 Normal forms

§ 1.1.5 Adequate sets of connectives

**§ 1.1.6 Arguments and validity**

§ 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

§ 1.2.1 Predicates and quantifiers

§ 1.2.2 First order languages

§ 1.2.3 Interpretations

§ 1.2.4 Operations on predicate calculus

§ 1.2.5 Prenex form

§ 1.2.6 One example – convergence in probability

Simplest **argument forms**:

$$\begin{array}{l} p \rightarrow q \\ p \\ \therefore q \end{array}$$

In general, an argument form takes the following form:

$$A_1, A_2, \dots, A_n; \quad \therefore A$$

Premises

Conclusion

Sometimes, the above argument form is also written as

$$A_1 \wedge A_2 \wedge \dots \wedge A_n \Rightarrow A$$

Def. The argument form

$$A_1, A_2, \dots, A_n; \quad \therefore A$$

is **valid** if the statement form

$$(A_1 \wedge A_2 \wedge \dots \wedge A_n) \rightarrow A \quad \text{is tautology;}$$

otherwise, the argument form is **invalid**.

E.g.1 Check the validity of the argument form:

$$p \rightarrow q, \quad (\neg q) \rightarrow r, \quad r; \quad \therefore p.$$

Sol. Let's simplify the following expression:

$$\begin{aligned} & (p \rightarrow q) \wedge ((\neg q) \rightarrow r) \wedge r \rightarrow p \\ & \quad \Updownarrow \\ & \neg [(p \rightarrow q) \wedge ((\neg q) \rightarrow r) \wedge r] \vee p \\ & \quad \Updownarrow \\ & \neg [(\neg p \vee q) \wedge ((\neg \neg q) \vee r) \wedge r] \vee p \\ & \quad \Updownarrow \\ & (p \wedge \neg q) \vee (\neg q \wedge \neg r) \vee (\neg r) \vee p \\ & \quad \Updownarrow \\ & (\neg r) \vee p \end{aligned}$$

which is not a tautology. Hence, the argument form is invalid.

□

E.g.2 Check the validity of the following argument form:

$$p_1 \rightarrow (p_2 \rightarrow p_3), \quad p_2; \quad \therefore p_1 \rightarrow p_3$$

Sol. Let's simplify the following expression:

$$\begin{aligned} & [p_1 \rightarrow (p_2 \rightarrow p_3)] \wedge p_2 \rightarrow (p_1 \rightarrow p_3) \\ & \quad \Downarrow \\ & \neg[p_1 \rightarrow (p_2 \rightarrow p_3)] \vee \neg p_2 \vee (p_1 \rightarrow p_3) \\ & \quad \Downarrow \\ & \neg[\neg p_1 \vee (\neg p_2 \vee p_3)] \vee \neg p_2 \vee (\neg p_1 \vee p_3) \\ & \quad \Downarrow \\ & [p_1 \wedge p_2 \wedge \neg p_3] \vee \neg p_2 \vee \neg p_1 \vee p_3 \\ & \quad \Downarrow \\ & [p_1 \wedge p_2 \wedge \neg p_3] \vee \neg(p_1 \wedge p_2 \wedge \neg p_3) \\ & \quad \Downarrow \\ & T, \end{aligned}$$

which is a tautology. Hence, the argument form is valid. □



# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

§ 1.1.1 Statements and connectives

§ 1.1.2 Truth functions and truth tables

§ 1.1.3 Rules for manipulation and substitution

§ 1.1.4 Normal forms

§ 1.1.5 Adequate sets of connectives

§ 1.1.6 Arguments and validity

§ 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

§ 1.2.1 Predicates and quantifiers

§ 1.2.2 First order languages

§ 1.2.3 Interpretations

§ 1.2.4 Operations on predicate calculus

§ 1.2.5 Prenex form

§ 1.2.6 One example – convergence in probability

Method 1. Proof by contradiction

$$A \rightarrow B \Leftrightarrow (\neg B) \rightarrow (\neg A)$$

Proof.

$$\begin{aligned} A \rightarrow B &\Leftrightarrow (\neg A) \vee B \\ &\Leftrightarrow (\neg \neg B) \vee (\neg A) \\ &\Leftrightarrow (\neg B) \rightarrow (\neg A). \end{aligned}$$

□

Method 2. Proof by cases

$$(A_1 \vee A_2 \vee \cdots \vee A_n) \rightarrow B \quad \Leftrightarrow \quad (A_1 \rightarrow B) \wedge (A_2 \rightarrow B) \wedge \cdots \wedge (A_n \rightarrow B).$$

Proof.

$$\begin{aligned} \text{LHS} &\Leftrightarrow \neg(A_1 \vee A_2 \vee \cdots \vee A_n) \vee B \\ &\Leftrightarrow (\neg A_1 \wedge \neg A_2 \wedge \cdots \wedge \neg A_n) \vee B \\ &\Leftrightarrow (\neg A_1 \vee B) \wedge (\neg A_2 \vee B) \wedge \cdots \wedge (\neg A_n \vee B) \\ &\Leftrightarrow \text{RHS.} \end{aligned}$$



### Method 3. Proof by exportation/importation

$$(A_1 \wedge A_2 \wedge \cdots \wedge A_n) \rightarrow (A \rightarrow B) \quad \Leftrightarrow \quad (A_1 \wedge A_2 \wedge \cdots \wedge A_n \wedge A) \rightarrow B.$$

Proof.

$$\begin{aligned} \text{LHS} &\Leftrightarrow \neg(A_1 \wedge A_2 \wedge \cdots \wedge A_n) \vee (\neg A \vee B) \\ &\Leftrightarrow (\neg A_1 \vee \neg A_2 \vee \cdots \vee \neg A_n) \vee (\neg A \vee B) \\ &\Leftrightarrow (\neg A_1 \vee \neg A_2 \vee \cdots \vee \neg A_n \vee \neg A) \vee B \\ &\Leftrightarrow \neg(A_1 \wedge A_2 \wedge \cdots \wedge A_n \wedge A) \vee B \\ &\Leftrightarrow \text{RHS.} \end{aligned}$$

□

#### Method 4. Proof by chain argument

$$(A \rightarrow B) \wedge (B \rightarrow C) \Rightarrow A \rightarrow C.$$

Proof.

$[(A \rightarrow B) \wedge (B \rightarrow C)] \rightarrow (A \rightarrow C)$										
T	T	T	T	T	T	T	T	T	T	T
T	T	T	F	T	F	F	T	T	F	F
T	F	F	F	F	T	T	T	T	T	T
T	F	F	F	F	T	F	T	T	F	F
F	T	T	T	T	T	T	T	F	T	T
F	T	T	F	T	F	F	T	F	T	F
F	T	F	T	F	T	T	T	F	T	T
F	T	F	T	F	T	F	T	F	T	F

□

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

### § 1.1.1 Statements and connectives

### § 1.1.2 Truth functions and truth tables

### § 1.1.3 Rules for manipulation and substitution

### § 1.1.4 Normal forms

### § 1.1.5 Adequate sets of connectives

### § 1.1.6 Arguments and validity

### § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

### § 1.2.1 Predicates and quantifiers

### § 1.2.2 First order languages

### § 1.2.3 Interpretations

### § 1.2.4 Operations on predicate calculus

### § 1.2.5 Prenex form

### § 1.2.6 One example – convergence in probability

This section is based on Chapters 3 and 4 of

*Hamilton, A. G., **Logic for mathematicians.** 2<sup>nd</sup> ed., Cambridge Univ. Press, 1988.*

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

### § 1.1.1 Statements and connectives

### § 1.1.2 Truth functions and truth tables

### § 1.1.3 Rules for manipulation and substitution

### § 1.1.4 Normal forms

### § 1.1.5 Adequate sets of connectives

### § 1.1.6 Arguments and validity

### § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

### § 1.2.1 Predicates and quantifiers

### § 1.2.2 First order languages

### § 1.2.3 Interpretations

### § 1.2.4 Operations on predicate calculus

### § 1.2.5 Prenex form

### § 1.2.6 One example – convergence in probability



	All men are mortal		A
	You are a man		B
∴	You are mortal	∴	C

We need **quantifiers** to make sense of the above arguments.

Chapters 1-2	Chapters 3-4
Statement logic	Predicate logic
Statement calculus	Predicate calculus
Propositional logic	Quantification logic
zero-order logic	first-order logic
zero-order language	first-order language

First-order logic is the extension of the zero-order logic

by including

quantifiers

Def. **Universal quantifier**: "for all  $x$ ", denoted as  $\forall x$ ,

**Existential quantifier**: "there exists a  $x$ ", denoted as  $\exists x$ ,

where  $x$  is called the **bound variable**.

## Examples:

1. Not all birds can fly:

$$\neg(\forall x) (B(x) \rightarrow F(x))$$

2. Some people are stupid:

$$(\exists y)(P(y) \wedge S(y))$$

3. There is an integer which is greater than every other integer:

$$(\exists x) \left( I(x) \wedge [(\forall y) (I(y) \rightarrow \{x \geq y\})] \right)$$

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability

The alphabet of symbols of a first order language  $\mathcal{L}$

1. variables  $x_1, x_2, \dots$ ,
2. some (possibly none) of the individual constants  $a_1, a_2, \dots$ ,
3. some (possibly none) of the predicate letters  $A_i^n$ ,
4. some (possibly none) of the function letters  $f_i^n$ ,
5. the punctuation symbols: “(”, “)”, “,”,
6. the connectives:  $\neg$  and  $\rightarrow$ ,
7. the quantifier:  $\forall$ .

## Remarks

- Recall that  $\{\neg, \rightarrow\}$  is an adequate set of connectives because

$$A \wedge B \quad \Leftrightarrow \quad \neg(A \rightarrow \neg B)$$

$$A \vee B \quad \Leftrightarrow \quad (\neg A) \rightarrow \neg B$$

- Existential quantifier  $\exists$  can be represented using universal quantifier  $\forall$  because

$$(\exists x)A(x) \quad \Leftrightarrow \quad \neg(\forall x)(\neg A(x))$$

- $A_i^n$  is the  $i$ -th predicate that takes  $n$  arguments.

$f_i^n$  is the  $i$ -th function that takes  $n$  arguments.

E.g. Let  $\mathcal{L}$  be the language for the arithmetic of natural numbers. Let

symbols	stands for
$a_1$	0
$A_1^2$	=
$f_1^2$	+
$f_2^2$	×

Then, the following statement:

For any integer  $x$  there exists  
an integer  $y$  such that  $x + y = xy$

can be stated as

$$(\forall x)(\exists y) A_1^2(f_1^2(x, y), f_2^2(x, y))$$



Def. Let  $\mathcal{L}$  be a first order language. A *term* in  $\mathcal{L}$  is defined as follows:

- (i) Variables and individual constants are terms.
- (ii) If  $t_1, \dots, t_n$  are terms, then  $f_i^n(t_1, \dots, t_n)$  is a term.
- (iii) All possible terms are generated as in (i) and (ii).

E.g.  $x_1, f_4^1(x_3), f_2^3(x_3, x_5, f_2^1(x_2))$  are terms.

Def. If  $t_1, \dots, t_n$  are terms in  $\mathcal{L}$ , then  $A_i^n(t_1, \dots, t_n)$  is an *atomic formula* in  $\mathcal{L}$ .

E.g.  $A_1^2(x_3, x_5)$  and  $A_2^3(x_2, f_2^1(x_4), f_3^2(x_1, x_4, x_5))$  are atomic formulas.

Def. A *well-formed formula*, or *wf.*, of  $\mathcal{L}$  is defined by

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

E.g. Here are some *wfs.*:

$$\forall x_1 A_1^1(x_1) \quad \text{and} \quad \forall x_1 (A_2^1(x_1) \rightarrow \neg \forall x_2 A_1^2(x_1, x_2)) .$$

Def. In the *wf.*  $(\forall x_i)A$ , we say that  $A$  is the *scope* of the quantifier.

More generally, when  $((\forall x_i)A)$  occurs as a subformula in a bigger *wf.*  $B$ , we say that the scope of this quantifier in  $B$  is  $A$ .

An occurrence of the variable  $x_i$  in the *wf.* is said to be *bound* if it occurs within the scope of a  $(\forall x_i)$  in the *wf.* or it is the  $x_i$  in a  $(\forall x_i)$ . Otherwise, it is called *free*.

E.g.

<i>wfs.</i>	$(\forall x_1)A_1^1(x_2)$	$(\forall x_1)(\forall x_2)(A_1^2(x_1, x_2) \rightarrow A_1^1(x_2))$
$x_1$ free or bound	bound	bound
$x_1$ scope	$A_1^1(x_2)$	$(\forall x_2)(A_1^2(x_1, x_2) \rightarrow A_1^1(x_2))$
$x_2$ free or bound	free	bound
$x_2$ scope	—	$A_1^2(x_1, x_2) \rightarrow A_1^1(x_2)$

□

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

§ 1.1.1 Statements and connectives

§ 1.1.2 Truth functions and truth tables

§ 1.1.3 Rules for manipulation and substitution

§ 1.1.4 Normal forms

§ 1.1.5 Adequate sets of connectives

§ 1.1.6 Arguments and validity

§ 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

§ 1.2.1 Predicates and quantifiers

§ 1.2.2 First order languages

**§ 1.2.3 Interpretations**

§ 1.2.4 Operations on predicate calculus

§ 1.2.5 Prenex form

§ 1.2.6 One example – convergence in probability

Def. An *interpretation*  $I$  of  $\mathcal{L}$  consists of four parts:

- (1) A non-empty set  $D_I$  — the domain of the interpretation  $I$ ;
- (2) A collection of distinguished elements:  $\{\bar{a}_1, \bar{a}_2, \dots\}$ ;
- (3) A collection of functions on  $D_I$ :  $\{\bar{f}_i^n : i, n \geq 1\}$ ;
- (4) A collection of relations on  $D_I$ :  $\{\bar{A}_i^n : i, n \geq 1\}$ .

Remark The meaning of a *wf.* is given by the interpretation.

Truth or falsity of a particular *wf.* depends on the interpretation.

E.g.1 Interpret the following *wf*.

$$\forall x_1 \forall x_2 \neg \forall x_3 \left( \neg A_1^2 \left( f_1^2(x_1, x_3), x_2 \right) \right)$$

with

$$D_N = \{0, 1, 2, \dots\}$$

$$\bar{a}_1 = 0$$

$$\bar{f}_1^2(x, y) = x + y, \quad \bar{f}_2^2(x, y) = xy$$

$$\bar{A}_1^2(x, y) : \quad x = y, \quad x, y \in D_N.$$

Sol. For all integers  $x$  and  $y$ , it is not true that all integer  $z$  satisfies that  $x + z \neq y$ .

Or equivalently

For all integers  $x$  and  $y$ , there is some integer  $z$  such that  $x + z = y$ .  $\square$

Remark Apparently, this is a false statement.

E.g.2 Interpret the following *wf*.

$$\forall x_1 \forall x_2 \neg \forall x_3 \left( \neg A_1^2 \left( f_1^2(x_1, x_3), x_2 \right) \right)$$

with

$D_N$  = the set of positive rational nubmers

$$\bar{a}_1 = 1$$

$$\bar{f}_1^2(x, y) = xy, \quad \bar{f}_2^2(x, y) = x/y$$

$$\bar{A}_1^2(x, y) : \quad x = y, \quad x, y \in D_N.$$

Sol. For all positive rationals  $x$  and  $y$ , it is not true that all positive rational  $z$  satisfies that  $xz \neq y$ .

Or equivalently

For all positive rationals  $x$  and  $y$ , there is some positive rational  $z$  such that  $xz = y$ .  $\square$

Remark Apparently, this is a true statement.



# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

### § 1.1.1 Statements and connectives

### § 1.1.2 Truth functions and truth tables

### § 1.1.3 Rules for manipulation and substitution

### § 1.1.4 Normal forms

### § 1.1.5 Adequate sets of connectives

### § 1.1.6 Arguments and validity

### § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

### § 1.2.1 Predicates and quantifiers

### § 1.2.2 First order languages

### § 1.2.3 Interpretations

### § 1.2.4 Operations on predicate calculus

### § 1.2.5 Prenex form

### § 1.2.6 One example – convergence in probability

Def. For any two *wfs.*  $A$  and  $B$  in  $\mathcal{L}$ ,

$A \Rightarrow B$  if and only if  $A \rightarrow B$  is logically valid.

Thm. *Distribution of quantifiers*

Suppose that  $x_i$  occurs free in both  $A(x_i)$  and  $B(x_i)$ . Then

$$\forall x_i A(x_i) \vee \forall x_i B(x_i) \Rightarrow \forall x_i [A(x_i) \vee B(x_i)]$$

$$\forall x_i A(x_i) \wedge \forall x_i B(x_i) \Rightarrow \forall x_i [A(x_i) \wedge B(x_i)]$$

and

$$\forall x_i A(x_i) \rightarrow \forall x_i B(x_i) \Rightarrow \forall x_i A(x_i) \rightarrow \forall x_i B(x_i)$$

$$\forall x_i A(x_i) \rightarrow \forall x_i B(x_i) \Rightarrow \exists x_i A(x_i) \rightarrow \exists x_i B(x_i)$$

Thm. *Increasing, decreasing and switching quantifiers*

$$\forall x \forall y A(x, y) \Rightarrow \forall x A(x, x)$$

$$\exists x A(x, x) \Rightarrow \exists x \exists y A(x, y)$$

$$\exists x \forall y A(x, y) \Rightarrow \forall y \exists x A(x, y)$$

Def. Let  $A$  and  $B$  be two *wfs.*. We say  $A$  and  $B$  are *provably equivalent* if

$A \leftrightarrow B$  is logically valid,

which is denoted as  $A \Leftrightarrow B$ .

That is,

$A \Leftrightarrow B$  if and only if  $A \leftrightarrow B$  is logically valid.

Thm. *Negation of quantifiers*

$$\neg \forall x A \Leftrightarrow \exists x \neg A$$

$$\neg \exists x A \Leftrightarrow \forall x \neg A$$

E.g.

$$\neg \forall x \exists y \forall z F(x, y, z) \Leftrightarrow \exists x \forall y \exists z \neg F(x, y, z)$$

Thm. *Enlarging and shrinking the scope of quantifiers*

Let  $A$  and  $B$  be two *wfs*. Suppose  $x_i$  occurs free in  $A(x_i)$  but not in  $B$ .

Then

$$\forall x_i (A(x_i) \vee B) \Leftrightarrow (\forall x_i A(x_i)) \vee B$$

$$\forall x_i (A(x_i) \wedge B) \Leftrightarrow (\forall x_i A(x_i)) \wedge B$$

$$\forall x_i (A(x_i) \rightarrow B) \Leftrightarrow (\exists x_i A(x_i)) \rightarrow B$$

$$\forall x_i (B \rightarrow A(x_i)) \Leftrightarrow B \rightarrow \forall x_i A(x_i)$$

and

$$\exists x_i (A(x_i) \vee B) \Leftrightarrow (\exists x_i A(x_i)) \vee B$$

$$\exists x_i (A(x_i) \wedge B) \Leftrightarrow (\exists x_i A(x_i)) \wedge B$$

$$\exists x_i (A(x_i) \rightarrow B) \Leftrightarrow (\forall x_i A(x_i)) \rightarrow B$$

$$\exists x_i (B \rightarrow A(x_i)) \Leftrightarrow B \rightarrow \exists x_i A(x_i)$$

Thm. *Distribution of quantifiers*

$$\forall x [A(x) \wedge B(x)] \Leftrightarrow \forall x A(x) \wedge \forall x B(x)$$

$$\exists x [A(x) \vee B(x)] \Leftrightarrow \exists x A(x) \vee \exists x B(x)$$



Thm. *Substitution*

If  $x_i$  occurs free in  $A(x_i)$  and  $x_j$  is a variable which does not occur, free or bound, in  $A(x_i)$ , then

$$\forall x_i A(x_i) \Leftrightarrow \forall x_j A(x_j).$$

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

### § 1.1.1 Statements and connectives

### § 1.1.2 Truth functions and truth tables

### § 1.1.3 Rules for manipulation and substitution

### § 1.1.4 Normal forms

### § 1.1.5 Adequate sets of connectives

### § 1.1.6 Arguments and validity

### § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

### § 1.2.1 Predicates and quantifiers

### § 1.2.2 First order languages

### § 1.2.3 Interpretations

### § 1.2.4 Operations on predicate calculus

### § 1.2.5 Prenex form

### § 1.2.6 One example – convergence in probability

Recall that the normal forms for the statement calculus are

Disjunctive normal form:  $\bigvee_{i=1}^m \bigwedge_{j=1}^n O_{ij}$

Conjunctive normal form:  $\bigwedge_{i=1}^m \bigvee_{j=1}^n O_{ij}$

What about the predicate calculus?

Def. A *wf.* of  $\mathcal{L}$  is said to be in *prenex form* if it is of the form

$$Q_1 x_1 Q_2 x_2 \cdots Q_k x_k B$$

where  $Q_i$  ( $1 \leq i \leq k$ ) is either  $\forall$  or  $\exists$ , and  $B$  is a *wf.* with no quantifiers.

E.g. Find the prenex form for

$$(\forall x_1 A_1^2(x_1, x_2) \rightarrow \exists x_2 A_1^1(x_2)) \rightarrow \neg \forall x_1 \forall x_2 A_2^2(x_1, x_2) \quad (\star)$$

Sol.

$$\begin{aligned} (\star) &\Leftrightarrow (\forall x_1 A_1^2(x_1, x_2) \rightarrow \exists x_3 A_1^1(x_3)) \rightarrow \neg \forall x_4 \forall x_5 A_2^2(x_4, x_5) \\ &\Leftrightarrow (\forall x_1 A_1^2(x_1, x_2) \rightarrow \exists x_3 A_1^1(x_3)) \rightarrow \exists x_4 \exists x_5 \neg A_2^2(x_4, x_5) \\ &\Leftrightarrow \exists x_1 \exists x_3 (A_1^2(x_1, x_2) \rightarrow A_1^1(x_3)) \rightarrow \exists x_4 \exists x_5 \neg A_2^2(x_4, x_5) \\ &\Leftrightarrow \forall x_1 \forall x_3 (A_1^2(x_1, x_2) \rightarrow A_1^1(x_3)) \rightarrow \exists x_4 \exists x_5 \neg A_2^2(x_4, x_5) \\ &\Leftrightarrow \forall x_1 \forall x_3 \exists x_4 \exists x_5 [(A_1^2(x_1, x_2) \rightarrow A_1^1(x_3)) \rightarrow \neg A_2^2(x_4, x_5)] \end{aligned}$$

□

Remark The prenex form is not unique.

$$(\star) \Leftrightarrow \exists x_4 \exists x_5 \forall x_1 \forall x_3 [(A_1^2(x_1, x_2) \rightarrow A_1^1(x_3)) \rightarrow \neg A_2^2(x_4, x_5)] .$$

Prenex form gives a way to measure the complexity of *wfs*.

E.g. Which one of the following two *wfs*. is more complicated?

$$\forall x_1 \forall x_2 \forall x_3 \forall x_4 A_1^2 (f_1^2(x_1, x_2), f_1^2(x_3, x_4))$$

$$\forall x_1 \exists x_2 \forall x_3 \exists x_4 A_1^2 (f_1^2(x_1, x_2), f_1^2(x_3, x_4))$$

Def. Let  $n \geq 1$ .

A *wf.* in prenex form is a  $\Pi_n$ -*form* if it starts with a **universal** quantifier and has  $n - 1$  alternations of quantifiers.

A *wf.* in prenex form is a  $\Sigma_n$ -*form* if it starts with an **existential** quantifier and has  $n - 1$  alternations of quantifiers.

E.g.

$$\begin{array}{l|l} \forall x_1 \forall x_2 \forall x_3 \forall x_4 A_1^4(x_1, x_2, x_3, x_4) & \Pi_1 \\ \forall x_1 \exists x_2 \forall x_3 \exists x_4 A_1^4(x_1, x_2, x_3, x_4) & \Pi_4 \\ \exists x_1 \forall x_2 \forall x_3 \exists x_4 A_1^4(x_1, x_2, x_3, x_4) & \Sigma_3 \end{array}$$

# Chapter 1. Mathematical Logics

## § 1.1 Statement calculus

- § 1.1.1 Statements and connectives

- § 1.1.2 Truth functions and truth tables

- § 1.1.3 Rules for manipulation and substitution

- § 1.1.4 Normal forms

- § 1.1.5 Adequate sets of connectives

- § 1.1.6 Arguments and validity

- § 1.1.7 Some proof techniques

## § 1.2 Predicate calculus

- § 1.2.1 Predicates and quantifiers

- § 1.2.2 First order languages

- § 1.2.3 Interpretations

- § 1.2.4 Operations on predicate calculus

- § 1.2.5 Prenex form

- § 1.2.6 One example – convergence in probability



E.g. *Convergence in probability*

$X_n$  converges to  $X$  in probability if for all  $\epsilon > 0$

$$\mathbb{P}(|X_n - X| > \epsilon) \rightarrow 0, \quad \text{as } n \rightarrow \infty.$$

Translate this definition into a *wf.* in the prenex form.

Sol. We first translate the limit  $\lim_{n \rightarrow \infty} \mathbb{P}(\dots) = 0$  as follows:

$$\forall \epsilon' \exists N \forall n [( \epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N) \rightarrow (\mathbb{P}(\dots) \leq \epsilon')].$$

Then put back the quantifier  $\forall \epsilon$  to see that

$X_n \rightarrow X$  in probability

$\Updownarrow$

$$\forall \epsilon \forall \epsilon' \exists N \forall n [(\epsilon > 0) \wedge (\epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N) \rightarrow (\mathbb{P}(|X_n - X| > \epsilon) \leq \epsilon')],$$

which is  $\Pi_3$ -form.

□

**Problem** How to show that  $X_n$  does not converge to  $X$  in probability?

**Sol.** We only need to make the negation of the above *wf.*:

$$\neg \forall \epsilon \forall \epsilon' \exists N \forall n [(\epsilon > 0) \wedge (\epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N) \rightarrow (\mathbb{P}(|X_n - X| > \epsilon) \leq \epsilon')]$$

$$\Updownarrow$$

$$\exists \epsilon \exists \epsilon' \forall N \exists n \neg [\neg \{(\epsilon > 0) \wedge (\epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N)\} \vee (\mathbb{P}(\dots) \leq \epsilon')]$$

$$\Updownarrow$$

$$\exists \epsilon \exists \epsilon' \forall N \exists n [\{(\epsilon > 0) \wedge (\epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N)\} \wedge \neg (\mathbb{P}(\dots) \leq \epsilon')]$$

$$\Updownarrow$$

$$\exists \epsilon \exists \epsilon' \forall N \exists n [(\epsilon > 0) \wedge (\epsilon' > 0) \wedge (N \geq 1) \wedge (n \geq N) \wedge (\mathbb{P}(|X_n - X| > \epsilon) > \epsilon')]$$

□

Ex. Suppose that  $Y_1, \dots, Y_n$  is a random sample from the exponential pdf,  $f_Y(y) = \lambda e^{-\lambda y}$ ,  $\lambda > 0, y > 0$ .

Show that  $\Lambda_n := \sum_{i=1}^n Y_i$  does not converges to  $\mathbb{E}(\Lambda)$  in probability.

(i.e.,  $\Lambda$  is not a consistent estimator for  $\lambda$ .)