

SFU MACM-101-D3 2004-2 week 12

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Logic Statements

Definition 1 (Statement) A *declarative sentence* which –when uttered– is either *true* or *false*, cannot be *both true and false* or *neither true nor false* is a statement (also called a *proposition*).

Observation 1 Statements have *truth value*: true or false.

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Logic Statements

Examples of statements:

- Glass is brittle.
- Water is liquid at room temperature.
- The price of oil is decreasing.
- Today is Tuesday.

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Logic Statements

Examples of non-statements:

- You should go to school.
- You are fired!
- Great fries!
- What is the height of Mt. Everest?
- $x + 3 > 8$
- The King of France is bald.

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Observation 2 Utterances in natural language are inherently *ambiguous*. This justifies the use of a mathematical apparatus to deal with truth values of complex statements.

Note 1 *Propositional logic* is the systematic study of the truth values of statements.

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Combining Statements

Definition 2 (Primitive Statement) A statement that cannot be broken into simpler statements is a *primitive statement*.

Definition 3 (Compound Statements; Connectives) Statements can be transformed through *negation*. Statements can be combined into *compound statements* using *connectives*.

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Negation and Connectives

Consider p and q logical statements.

- **Negation:** $\neg p$ read “Not p ”.
- **Conjunction:** $p \wedge q$ read “ p and q ”
- **Disjunction:** $p \vee q$ read “ p or q ”
- **Exclusive or:** $p \underline{\vee} q$ read “Exactly one of p and q is true”
- **Implication:** $p \rightarrow q$ read “ p implies q ”
- **Biconditional:** $p \leftrightarrow q$ read “ p if and only if q ”

The Definition of Negation

Consider p a logical statement.

p	$\neg p$
0	1
1	0

The Definitions of Connectives

Consider p and q logical statements.

p	q	$p \wedge q$	$p \vee q$	$p \underline{\vee} q$	$p \rightarrow q$	$p \leftrightarrow q$
0	0	0	0	0	1	1
0	1	0	1	1	1	0
1	0	0	1	1	0	0
1	1	1	1	0	1	1

Definition 4 (Tautology) A compound statement is called a **tautology** (noted T_0) if it is **true** for all truth values of its primitive statements.

Definition 5 (Contradiction) A compound statement is called a **contradiction** (noted F_0) if it is **false** for all truth values of its primitive statements.

Logical Equivalence

Definition 6 Two statements s_1 and s_2 are said to be **logically equivalent** (written $s_1 \Leftrightarrow s_2$) when the statement s_1 is true (respectively false) whenever the statement s_2 is true (respectively false).

Observation 3 Logically equivalent statements have identical truth tables.

Observation 4 For p and q logically equivalent statements $p \Leftrightarrow q$, the biconditional $p \leftrightarrow q$ is a tautology.

Logical Equivalence: Example

p	$\neg p$	q	$p \rightarrow q$	$\neg p \vee q$
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	1	1

$$p \rightarrow q \Leftrightarrow \neg p \vee q$$

Logical Equivalence: Example 2

p	q	$p \rightarrow q$	$q \rightarrow p$	$(p \rightarrow q) \wedge (q \rightarrow p)$	$p \leftrightarrow q$
0	0	1	1	1	1
0	1	1	0	0	0
1	0	0	1	0	0
1	1	1	1	1	1

$$p \leftrightarrow q \Leftrightarrow (p \rightarrow q) \wedge (q \rightarrow p)$$

The problem with truth tables

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Observation 6 A truth table for a compound statement with n primitive statements has 2^n truth values (*exponential* in n).

Writing truth tables

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Observation 8 Choose truth values for n primitive statements in a compound statement:

1. Write all numbers with n digits in base 2, in order.
2. For each such binary number, for each k from 1 to n , assign to the k -th primitive statement the value of the k -th digit in the binary number.

The problem with truth tables

Observation 9 Exponentials grow *very, very quickly*.

- $2^1 = 2$
- $2^2 = 4$
- $2^3 = 8$
- ...
- $2^{10} = 1024$
- ...
- $2^{20} \approx 10^6$
- ...
- $2^{30} \approx 10^9$

The Laws of Logic

Observation 10 All laws of logic (below) are defined for [primitive statements](#).

Law 1 (Double negation)

$$\neg p \Leftrightarrow p$$

Proof:

p	$\neg p$	$\neg \neg p$
0	1	0
1	0	1

The Laws of Logic

Law 2 (DeMorgan's)

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

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

Proof:

p	q	$\neg(p \vee q)$	$(\neg p \wedge \neg q)$
0	0	1	1
0	1	0	0
1	0	0	0
1	1	0	0

The Laws of Logic

Law 3 (Commutative)

$$p \vee q \Leftrightarrow q \vee p$$

$$p \wedge q \Leftrightarrow q \wedge p$$

Law 4 (Associative)

$$(p \vee q) \vee r \Leftrightarrow p \vee (q \vee r)$$

$$(p \wedge q) \wedge r \Leftrightarrow p \wedge (q \wedge r)$$

Law 5 (Distributive)

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

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

The Laws of Logic

Law 6 (Idempotent)

$$p \vee p \Leftrightarrow p$$

$$p \wedge p \Leftrightarrow p$$

Law 7 (Identity)

$$p \vee F_0 \Leftrightarrow p$$

$$p \wedge T_0 \Leftrightarrow p$$

Law 8 (Inverse)

$$p \vee \neg p \Leftrightarrow T_0$$

$$p \wedge \neg p \Leftrightarrow F_0$$

The Laws of Logic

Law 9 (Domination)

$$p \vee T_0 \Leftrightarrow T_0$$

$$p \wedge F_0 \Leftrightarrow F_0$$

Law 10 (Absorption)

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

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

Logic Duality

Observation 11 All laws of logic, with the exception of the first law (double negation) [come in pairs](#).

Definition 7 Let s be a statement [which contains no other connectives than \$\wedge\$ and \$\vee\$](#) , the [dual](#) of s , written s^d is a statement where every $\wedge$ symbol in s is replaced with a $\vee$ and every $\vee$ is replaced with a $\wedge$.

Example:

$$s = (\neg p \vee q) \wedge (\neg q \vee p)$$

$$s^d = (\neg p \wedge q) \vee (\neg q \wedge p)$$

Logic Duality

Theorem 1 (The Principle of Duality) Let s and t be statements which contain no other connectives than $\wedge$ and $\vee$. If $s \Leftrightarrow t$ then $s^d \Leftrightarrow t^d$

Proof : in Chapter 15 of the textbook (not required).

Observation 12 For a statement s which contains no other connectives than $\wedge$ and $\vee$, $(s^d)^d \Leftrightarrow s$.

Observation 13 Any statement is equivalent to a statement which contains no other connectives than $\wedge$ and $\vee$.

Substitution rules

Axiom 1 For a compound statement P , which is a tautology, for a primitive statement p , if each occurrence of p is replaced with another statement q (not necessarily primitive) the resulting statement P_1 will also be a tautology.

Axiom 2 For a compound statement P , which is a tautology, for an arbitrary statement p that appears in P , if $q \Leftrightarrow p$, then for the statement P_1 obtained from P where each occurrence of p is replaced with q , $P \Leftrightarrow P_1$.

Applications: programming

The SFU student registration system.

- If a student is registered for a course, they have paid to SFU more than the \$100 deposit.
- Do you apply to a student a late course drop penalty?
- Does a student have the prerequisites for taking a given course?
- Does a student qualify for graduation?

Build a calendar application that displays the number of days in a month (including for leap years).

Logical implication

Definition 8 (Logical implication) For p and q statements so that $p \rightarrow q$ is a tautology, $p \Rightarrow q$ (read p implies q)

$$(p \Rightarrow q) \Leftrightarrow ((p \rightarrow q) \Leftrightarrow T_0)$$

Observation 14 Logical equivalence is stronger than implication.

Rules of inference

Rule 1 (Modus Ponens)

$$[p \wedge (p \rightarrow q)] \rightarrow q$$

Rule 2 (Law of the Syllogism)

$$[(p \rightarrow q) \wedge (q \rightarrow r)] \rightarrow (p \rightarrow r)$$

Rule 3 (Modus Tollens)

$$[(p \rightarrow q) \wedge \neg q] \rightarrow \neg p$$

Rules of inference

Rule 4 (Rule of Conjunction)

$$\begin{array}{c} p \\ q \\ \hline \therefore p \wedge q \end{array}$$

Rule 5 (Rule of Disjunctive Syllogism)

$$[(p \vee q) \wedge \neg p] \rightarrow q$$

Rule 6 (Rule of Contradiction)

$$(p \rightarrow F_0) \rightarrow \neg p$$

Rules of inference**Rule 7 (Rule of Conjunctive Simplification)**

$$(p \wedge q) \rightarrow p$$

Rule 8 (Rule of Disjunctive Amplification)

$$p \rightarrow (p \vee q)$$

Rules of inference**Rule 9 (Rule of Conditional Proof)**

$$[(p \wedge q) \wedge [p \rightarrow (q \rightarrow r)]] \rightarrow r$$

Rule 10 (Rule of Conditional Proof)

$$[(p \rightarrow r) \wedge (q \rightarrow r)] \rightarrow [(p \vee q) \rightarrow r]$$