Discrete Mathematics

Propositions

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Licence

Topics

Proposition

Definition

proposition (or statement):
a declarative sentence that is either true or false

- law of the excluded middle:
  a proposition cannot be partially true or partially false
- law of contradiction:
  a proposition cannot be both true and false

Proposition Examples

Example (proposition)

- The Moon revolves around the Earth.
- Elephants can fly.
- $3 + 8 = 11$

Example (not proposition)

- What time is it?
- Ali, throw the ball!
- $x < 43$

Proposition Variable

Definition

proposition variable:
a name that represents the proposition

- can take on the values *True* (T) or *False* (F)

Example

- p_1: The Moon revolves around the Earth. (T)
- p_2: Elephants can fly. (F)
- p_3: $3 + 8 = 11$ (T)

Compound Propositions

- compound propositions are obtained by
  - negating a proposition, or
  - combining two or more propositions using logical connectives
- primitive propositions can not be decomposed into smaller units
- truth table: a table that lists the truth value of the compound proposition for all possible values of its primitive propositions

Negation (NOT)

Table: $\neg p$

p	$\neg p$
T	F
F	T

Example

- $\neg p_1$: The Moon does not revolve around the Earth.
  $\neg T$: *False*
- $\neg p_2$: Elephants cannot fly.
  $\neg F$: *True*

Conjunction (AND)

Table: $p \wedge q$

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

Example

- $p_1 \wedge p_2$: The Moon revolves around the Earth and elephants can fly.
  $T \wedge F$: *False*

Disjunction (OR)

Table: $p \vee q$

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

Example

- $p_1 \vee p_2$: The Moon revolves around the Earth or elephants can fly.
  $T \vee F$: *True*

Exclusive Disjunction (XOR)

Table: $p \veebar q$

p	q	$p \veebar q$
T	T	F
T	F	T
F	T	T
F	F	F

Example

- $p_1 \veebar p_2$: Either the Moon revolves around the Earth or elephants can fly.
  $T \veebar F$: *True*

Implication (IF)

Table: $p \rightarrow q$

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

- p: hypothesis
- q: conclusion
- read:
  - if p then q
  - p is sufficient for q
  - q is necessary for p
- $\neg p \vee q$

Implication Examples

Example

- p_4: $3 < 8$, p_5: $3 < 14$, p_6: $3 < 2$
- p_7: The Sun revolves around the Earth.

- $p_4 \rightarrow p_5$: If 3 is less than 8, then 3 is less than 14. $T \rightarrow T$: *True*
- $p_4 \rightarrow p_6$: If 3 is less than 8, then 3 is less than 2. $T \rightarrow F$: *False*
- $p_2 \rightarrow p_1$: If elephants can fly then the Moon revolves around the Earth. $F \rightarrow T$: *True*
- $p_2 \rightarrow p_7$: If elephants can fly then the Sun revolves around the Earth. $F \rightarrow F$: *True*

Implication Examples

Example

- "If I weigh over 70 kg, then I will exercise."

- p: I weigh over 70 kg.
- q: I exercise.
- when is this claim false?

Table: $p \rightarrow q$

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

Biconditional (IFF)

Table: $p \leftrightarrow q$

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

- read:
  - p if and only if q
  - p is necessary and sufficient for q
- $(p \rightarrow q) \wedge (q \rightarrow p)$
- $\neg(p \veebar q)$

Example

Example

- The parent tells the child: "If you do your homework, you can play computer games."
- s: The child does her homework.
- t: The child plays computer games.
- which one does the parent mean?
  - $s \rightarrow t$
  - $\neg s \rightarrow \neg t$
  - $s \leftrightarrow t$

Well-Formed Formula

syntax

- which rules will be used to form compound propositions?
- formula that obeys these rules: well-formed formula (WFF)

semantics

- *interpretation*: calculating the value of a compound proposition by assigning values to its primitive propositions
- truth table: all interpretations of a proposition

Formula Examples

Example (not well-formed)

- $\vee p$
- $p \wedge \neg$
- $p \neg \wedge q$

Precedence

1. $\neg$
2. $\wedge$
3. $\vee$
4. $\rightarrow$
5. $\leftrightarrow$

- parentheses are used to change precedence

Precedence Examples

Example

- s: Phyllis goes out for a walk.
- t: The Moon is out.
- u: It is snowing.

- what do the following WFFs mean?
  - $t \wedge \neg u \rightarrow s$
  - $t \rightarrow (\neg u \rightarrow s)$
  - $\neg(s \leftrightarrow (u \vee t))$
  - $\neg s \leftrightarrow u \vee t$

Formula Attributes

1. *tautology*: True for all interpretations
2. *contradiction*: False for all interpretations
3. *valid*: True for some interpretations

Tautology Example

Example

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

p	q	$p \rightarrow q$ (A)	$p \wedge A$ (B)	$B \rightarrow q$
T	T	T	T	T
T	F	F	F	T
F	T	T	F	T
F	F	T	F	T

Contradiction Example

Example

Table: $p \wedge (\neg p \wedge q)$

p	q	$\neg p$	$\neg p \wedge q$ (A)	$p \wedge A$
T	T	F	F	F
T	F	F	F	F
F	T	T	T	F
F	F	T	F	F

Metalanguage

Definition
target language:
the language being worked on

Definition
metalanguage:
the language used when talking about the properties of the target language

- validity, contradiction and tautology are defined in the metalanguage

Metalanguage Examples

Example (for a Turk who is learning English)

- target language: English
- metalanguage: Turkish

Example (in an introductory programming course)

- target language: C, Python, Java, ...
- metalanguage: English, Turkish, ...

Metalogic

- $P_1, P_2, \ldots, P_n \vdash Q$
  There is a proof which infers the conclusion Q from the assumptions $P_1, P_2, \ldots, P_n$.
- $P_1, P_2, \ldots, P_n \vDash Q$
  Q must be true if $P_1, P_2, \ldots, P_n$ are all true.

Formal Systems

Definition
consistent: for all well-formed formulas P and Q
if $P \vdash Q$ then $P \vDash Q$

- each provable proposition is actually true

Definition
complete: for all well-formed formulas P and Q
if $P \vDash Q$ then $P \vdash Q$

- every true proposition can be proven

Gödel's Theorem

- Propositional logic is consistent and complete.

Gödel's Theorem

- Any logical system that is powerful enough to express ordinary arithmetic must be either inconsistent or incomplete.

Approaches in Propositional Calculus

1. semantic approach: *truth tables*
   - too complicated when the number of primitive statements grow
2. syntactic approach: *rules of inference*
   - obtaining new propositions from existing propositions using logical implications
3. axiomatic approach: *Boolean algebra*
   - substituting equivalent formulas in equations

Truth Table Example

Example ($p \rightarrow q$)

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

- *contrapositive*: $\neg q \rightarrow \neg p$
- *converse*: $q \rightarrow p$
- *inverse*: $\neg p \rightarrow \neg q$

Logical Equivalence

Definition
if $P \leftrightarrow Q$ is a tautology, then P and Q are logically equivalent: $P \Leftrightarrow Q$

Logical Equivalence Example

Example

- $\neg p \Leftrightarrow p \rightarrow F$

Table: $\neg p \leftrightarrow p \rightarrow F$

p	$\neg p$	$p \rightarrow F$ (A)	$\neg p \leftrightarrow A$
T	F	F	T
F	T	T	T

Logical Equivalence Example

Example

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

Table: $(p \rightarrow q) \leftrightarrow (\neg p \vee q)$

p	q	$p \rightarrow q$ (A)	$\neg p$	$\neg p \vee q$ (B)	$A \leftrightarrow B$
T	T	T	F	T	T
T	F	F	F	F	T
F	T	T	T	T	T
F	F	T	T	T	T

Laws of Logic

Double Negation (DN)
$\neg(\neg p) \Leftrightarrow p$

Commutativity (Co)
$p \wedge q \Leftrightarrow q \wedge p$ $\quad$ $p \vee q \Leftrightarrow q \vee p$

Associativity (As)
$(p \wedge q) \wedge r \Leftrightarrow p \wedge (q \wedge r)$ $\quad$ $(p \vee q) \vee r \Leftrightarrow p \vee (q \vee r)$

Idempotence (Ip)
$p \wedge p \Leftrightarrow p$ $\quad$ $p \vee p \Leftrightarrow p$

Inverse (In)
$p \wedge \neg p \Leftrightarrow F$ $\quad$ $p \vee \neg p \Leftrightarrow T$

Laws of Logic

Identity (Id)
$p \wedge T \Leftrightarrow p$ $\quad$ $p \vee F \Leftrightarrow p$

Domination (Do)
$p \wedge F \Leftrightarrow F$ $\quad$ $p \vee T \Leftrightarrow T$

Distributivity (Di)
$p \wedge (q \vee r) \Leftrightarrow (p \wedge q) \vee (p \wedge r)$ $\quad$ $p \vee (q \wedge r) \Leftrightarrow (p \vee q) \wedge (p \vee r)$

Absorption (Ab)
$p \wedge (p \vee q) \Leftrightarrow p$ $\quad$ $p \vee (p \wedge q) \Leftrightarrow p$

DeMorgan's Laws (DM)
$\neg(p \wedge q) \Leftrightarrow \neg p \vee \neg q$ $\quad$ $\neg(p \vee q) \Leftrightarrow \neg p \wedge \neg q$

Equivalence Example

Example

$$
\begin{array}{lll}
 & p \rightarrow q & \\
\Leftrightarrow & \neg p \vee q & \\
\Leftrightarrow & q \vee \neg p & Co \\
\Leftrightarrow & \neg\neg q \vee \neg p & DN \\
\Leftrightarrow & \neg q \rightarrow \neg p &
\end{array}
$$

Equivalence Example

Example

$$\begin{array}{lll} & \neg(\neg((p \vee q) \wedge r) \vee \neg q) & \\ \Leftrightarrow & \neg\neg((p \vee q) \wedge r) \wedge \neg\neg q & DM \\ \Leftrightarrow & ((p \vee q) \wedge r) \wedge q & DN \\ \Leftrightarrow & (p \vee q) \wedge (r \wedge q) & As \\ \Leftrightarrow & (p \vee q) \wedge (q \wedge r) & Co \\ \Leftrightarrow & ((p \vee q) \wedge q) \wedge r & As \\ \Leftrightarrow & q \wedge r & Ab \end{array}$$

Duality

Definition

If s contains no logical connectives other than $\wedge$ and $\vee$, then the dual of s, denoted s^d, is the statement obtained from s by replacing each occurrence of $\wedge$ by $\vee$, $\vee$ by $\wedge$, T by F, and F by T.

Example (dual proposition)

$$\begin{array}{rl} s: & (p \wedge \neg q) \vee (r \wedge T) \\ s^d: & (p \vee \neg q) \wedge (r \vee F) \end{array}$$

Principle of Duality

principle of duality

Let s and t be statements that contain no logical connectives other than $\wedge$ and $\vee$.
If $s \Leftrightarrow t$ then $s^d \Leftrightarrow t^d$.

Rules of Inference

Definition

if $P \rightarrow Q$ is a tautology, then P logically implies Q:
$P \Rightarrow Q$

Logical Implication Example

Example

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

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

p	q	$p \rightarrow q$ (A)	$p \wedge A$ (B)	$B \rightarrow q$
T	T	T	T	T
T	F	F	F	T
F	T	T	F	T
F	F	T	F	T

Inference

- establishing the validity of an argument, starting from a set of propositions which are assumed or proven to be true

notation

$$\begin{array}{c} p_1 \\ p_2 \\ \dots \\ \underline{p_n} \\ \therefore q \end{array} \qquad p_1 \wedge p_2 \wedge \cdots \wedge p_n \Rightarrow q$$

Basic Rules

Identity (ID)

$$\frac{p}{\therefore p}$$

Contradiction (CTR)

$$\frac{F}{\therefore p}$$

Basic Rules

Implication Introduction (ImpI)

$$\frac{p \vdash q}{\therefore \; \vdash p \rightarrow q}$$

- if it can be shown that q is true assuming p is true, then $p \rightarrow q$ is true *without assuming p is true*
- p is a provisional assumption (PA)
- provisional assumptions have to be discharged at some point

Basic Rules

AND Introduction (AndI)

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

AND Elimination (AndE)

$$\frac{p \wedge q}{\therefore p}$$

Basic Rules

OR Introduction (OrI)

$$\frac{p}{\therefore p \vee q}$$

OR Elimination (OrE)

$$\frac{\begin{array}{c} p \vee q \\ p \vdash r \\ q \vdash r \end{array}}{\therefore \; \vdash r}$$

Basic Rules

Modus Ponens (Implication Elimination - ImpE)

$$\frac{\begin{array}{c} p \rightarrow q \\ p \end{array}}{\therefore q}$$

Modus Tollens (MT)

$$\frac{\begin{array}{c} p \rightarrow q \\ \neg q \end{array}}{\therefore \neg p}$$

Modus Tollens

Example

$$\frac{\begin{array}{c} p \rightarrow q \\ \neg q \end{array}}{\therefore \neg p}$$

1.	$p \rightarrow q$	A
2.	$\neg q \rightarrow \neg p$	1
3.	$\neg q$	A
4.	$\neg p$	$ImpE : 2, 3$

Modus Ponens Example

Example

- If Ali wins the lottery, he will buy a car.
- Ali has won the lottery.
- Therefore, Ali will buy a car.

Modus Tollens Example

Example

- If Ali wins the lottery, he will buy a car.
- Ali did not buy a car.
- Therefore, Ali did not win the lottery.

Fallacies

fallacy of affirming the conclusion

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

- $(p \rightarrow q) \wedge q \rightarrow p$ is not a tautology:
  if $p = F, q = T$: $(F \rightarrow T) \wedge T \rightarrow F$

Example of Affirming the Conclusion

Example

- If Ali wins the lottery, he will buy a car.
- Ali has bought a car.
- Therefore, Ali has won the lottery.

Fallacies

fallacy of denying the hypothesis

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

- $(p \rightarrow q) \wedge \neg p \rightarrow \neg q$ is not a tautology:
  if $p = F, q = T$: $(F \rightarrow T) \wedge T \rightarrow F$

Example of Denying the Hyphothesis

Example

- If Ali wins the lottery, he will buy a car.
- Ali has not won the lottery.
- Therefore, Ali will not buy a car.

Disjunctive Syllogism

Disjunctive Syllogism (DS)

$$\frac{p \lor q \quad \neg p}{\therefore q}$$

1.	$p \lor q$	A
2.	$\neg p$	A
3.	$p \rightarrow F$	2
$4a1.$	p	PA
$4a2.$	F	$ImpE : 3, 4a1$
$4a.$	q	$CTR : 4a2$
$4b1.$	q	PA
$4b.$	q	$ID : 4b1$
5.	q	$OrE : 1, 4a, 4b$

Disjunctive Syllogism Example

Example

- Ali's wallet is either in his pocket or on his desk.
- Ali's wallet is not in his pocket.
- Therefore, Ali's wallet is on his desk.

Hypothetical Syllogism

Hypothetical Syllogism (HS)

$$\frac{p \rightarrow q \quad q \rightarrow r}{\therefore p \rightarrow r}$$

1.	p	PA
2.	$p \rightarrow q$	A
3.	q	$ImpE : 2, 1$
4.	$q \rightarrow r$	A
5.	r	$ImpE : 4, 3$
6.	$p \rightarrow r$	$ImpI : 1, 5$

Hypotetical Syllogism Example

Example (Star Trek)

Spock to Lieutenant Decker:

> *It would be a suicide to attack the enemy ship now.*
> *Someone who attempts suicide is not psychologically fit to command the Enterprise.*
> *Therefore, I am obliged to relieve you from duty.*

Hypotetical Syllogism Example

Example (Star Trek)

- p: Decker attacks the enemy ship.
- q: Decker attempts suicide.
- r: Decker is not psychologically fit to command the Enterprise.
- s: Spock relieves Decker from duty.

Hypotetical Syllogism Example

Example

$$\frac{p \quad p \rightarrow q \quad q \rightarrow r \quad r \rightarrow s}{\therefore s}$$

1.	$p \rightarrow q$	A
2.	$q \rightarrow r$	A
3.	$p \rightarrow r$	$HS : 1, 2$
4.	$r \rightarrow s$	A
5.	$p \rightarrow s$	$HS : 3, 4$
6.	p	A
7.	s	$ImpE : 5, 6$

Inference Examples

Example

$$\begin{array}{c} p \to r \\ r \to s \\ x \vee \neg s \\ u \vee \neg x \\ \neg u \\ \hline \therefore \neg p \end{array}$$

1.	$u \vee \neg x$	A	6.	$r \to s$	A
2.	$\neg u$	A	7.	$\neg r$	$MT : 6, 5$
3.	$\neg x$	$DS : 1, 2$	8.	$p \to r$	A
4.	$x \vee \neg s$	A	9.	$\neg p$	$MT : 8, 7$
5.	$\neg s$	$DS : 4, 3$			

Inference Examples

Example

$$\begin{array}{c} (\neg p \vee \neg q) \to (r \wedge s) \\ r \to x \\ \neg x \\ \hline \therefore p \end{array}$$

1.	$r \to x$	A	6.	$(\neg p \vee \neg q) \to (r \wedge s)$	A
2.	$\neg x$	A	7.	$\neg(\neg p \vee \neg q)$	$MT : 6, 5$
3.	$\neg r$	$MT : 1, 2$	8.	$p \wedge q$	$DM : 7$
4.	$\neg r \vee \neg s$	$OrI : 3$	9.	p	$AndE : 8$
5.	$\neg(r \wedge s)$	$DM : 4$			

Inference Examples

Example

$$\begin{array}{c} p \to (q \vee r) \\ s \to \neg r \\ q \to \neg p \\ p \\ s \\ \hline \therefore F \end{array}$$

1.	$q \to \neg p$	A
2.	p	A
3.	$\neg q$	$MT : 1, 2$
4.	s	A
5.	$s \to \neg r$	A
6.	$\neg r$	$ImpE : 5, 4$
7.	$p \to (q \vee r)$	A
8.	$q \vee r$	$ImpE : 7, 2$
9.	q	$DS : 8, 6$
10.	$q \wedge \neg q : F$	$AndI : 9, 3$

Inference Examples

Example

If there is a chance of rain or her red headband is missing, then Lois will not mow her lawn. Whenever the temperature is over 20℃, there is no chance for rain. Today the temperature is 22℃ and Lois is wearing her red headband. Therefore, Lois will mow her lawn.

Inference Examples

Example

- p: There is a chance of rain.
- q: Lois' red headband is lost.
- r: Lois mows her lawn.
- s: The temperature is over 20℃.

Inference Examples

Example

$$\begin{array}{c} (p \vee q) \to \neg r \\ s \to \neg p \\ s \wedge \neg q \\ \hline \therefore r \end{array}$$

1.	$s \wedge \neg q$	A
2.	s	$AndE : 1$
3.	$s \to \neg p$	A
4.	$\neg p$	$ImpE : 3, 2$
5.	$\neg q$	$AndE : 1$
6.	$\neg p \wedge \neg q$	$AndI : 4, 5$
7.	$\neg(p \vee q)$	$DM : 6$
8.	$(p \vee q) \to \neg r$	A
9.	?	7, 8

References

Required Text: Grimaldi

- Chapter 2: Fundamentals of Logic
  - 2.1. Basic Connectives and Truth Tables
  - 2.2. Logical Equivalence: The Laws of Logic
  - 2.3. Logical Implication: Rules of Inference

Supplementary Text: O'Donnell, Hall, Page

- Chapter 6: Propositional Logic