Discrete Mathematics Recitation Class

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Contents

The Natural Numbers (P8)

The set of natural numbers

$$\mathbb{N} := \{0, 1, 2, 3, \cdots\}$$

Addition & Multiplication

$$+ : \mathbb{N} \times \mathbb{N} \to \mathbb{N} \qquad \cdot : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$$

If $a, b, c \in \mathbb{N}$,

$$\begin{aligned} \text{Comutativity} &: a + b = b + a, a \cdot b = b \cdot a \\ \text{Associativity} &: a + b + c = a + (b + c), a \cdot b \cdot c = a \cdot (b \cdot c) \\ \text{Distributivity} &: a \cdot (b + c) = a \cdot c + b \cdot c \end{aligned}$$

The Natural Numbers (P9)

Definitions

1. *greater than (or equal to)*
2. *exact division*
3. *odd & even*
4. *prime*

Question

Prove that every natural number is either even or odd and not both.

Uniqueness of Odevity (P9)

Proof.
Suppose that $n \in \mathbb{N}$,

1. prove that
   if n is odd, n cannot be even
2. prove that
   if n is even, n cannot be odd
3. prove that *n cannot be neither odd nor even* (**Do not forget!**)

$\square$

Proof.
Suppose that $n \in \mathbb{N}$,

1. prove that
   if n isnot odd, n must be even
2. prove that
   if n isnot even, n must be odd
3. prove that *n cannot be both odd and even* (**Do not forget!**)

$\square$

Propositions

Definition (P11)

- Declarative
- One can tell true (T) or false (F) immediately

Compound Expressions (using connectives) (P12)

- unary connective: $\neg$(not)
- binary connectives: $\vee$(disjunction), $\wedge$(conjunction), $\Rightarrow$(implication), $\Leftrightarrow$(biconditonal)

Negation (P13)

Definition (by truth table)
Suppose A is a proposition:

A	¬A
T	F
F	T

Conjunction (P13)

Definition (by truth table)
Suppose A, B are propositions:

A	B	A∧B
T	T	T
T	F	F
F	T	F
F	F	F

Disjunction (P14)

Definition (by truth table)
Suppose A, B are propositions:

A	B	A∨B
T	T	T
T	F	T
F	T	T
F	F	F

Implication (P16)

Definition (by truth table)
Suppose A, B are propositions:

A	B	A⇒B
T	T	T
T	F	F
F	T	T
F	F	T

A: antecedent, B: consequence

Biconditional (P18)

Definition (by truth table)
Suppose A, B are propositions:

A	B	A⇔B
T	T	T
T	F	F
F	T	F
F	F	T

Logical Equivalence

Definitions

1. *tautology (P15)*
   A compound expression that is always true.
2. *contradiction (P15)*
   A compound expression that is always false.
3. *logical equivalence (P19)*
   The biconditional of two propositions is tautology.

Logical Equivalence Examples

1. De Morgan Rules (P19)

$$\neg(A \vee B) \equiv (\neg A) \wedge (\neg B) \qquad \neg(A \wedge B) \equiv (\neg A) \vee (\neg B)$$

2. Contraposition (P20)

A	B	¬A	¬B	A⇒B	¬B⇒¬A	A⇒B⇔¬B⇒¬A
T	T	F	F	T	T	T
T	F	F	T	F	F	T
F	T	T	F	T	T	T
F	F	T	T	T	T	T

3. Other Logical Equivalences (P21-P23)

Manipulating propositional expressions

Usages

1. Express some connectives with other connectives (P24)
   e.g. Prove that $\neg(A \Rightarrow B)$ is equivalent to $A \wedge \neg B$
2. Prove tautologies/contradictions without truth tables (P25)
   e.g. Prove that $(A \wedge B) \Rightarrow (A \vee B)$ is a tautology.

Arguments

Definitions (P27)

1. *arguments*
2. *premises*
3. *conclusion*
4. *valid*

Rules of Inference (P29-P33)

1. Hypothetical Syllogisms
2. Disjunctive and Conjunctive Syllogisms
3. Simple Arguments

Validity & Soundness (P34)

Definitions

1. *validity*: True premises leads to true conclusion. (Conclusion does not need to be true if premises are not true.)
2. *soundness*: All premises are true. (Only deals with truth of premises.)

Predicate

Definitions (P38)

1. *predicate*: Declarative sentence involving variables.
2. *arity*: number of distinct variables in the predicate.

Difference between Predicates and Propositions:

e.g.

- "$x > 5$" is not a proposition. (we cannot tell the true or false immediately because the value of x is unknown)
- "$x < 5$" is a unary predicate.

Predicate

(P39)

$$\text{predicate logic}\begin{cases}\text{basic predicate variables}: A, B, P, Q, \cdots \\ \text{variables}: x, y, z, \cdots \\ \text{constants}: a, b, c, \cdots \\ \text{domain of discourse}\end{cases}$$

$$\text{Predicates/Formulaes} \xrightarrow[\text{replace variables by constants}]{\text{bound with quantifiers}} \text{Sentences}$$

Logical Quantifiers

Definitions (P41)

1. $\forall$: for all$\cdots$
2. $\exists$: there exists$\cdots$

Hanging Quantifiers (P42)

Appearing at the back is equivalent to appearing just before the expression.

Contraposition of Quantifiers (P43)

$$\neg((\exists x \in M)A(x)) \equiv (\forall x \in M)\neg A(x)$$

$$\neg((\forall x \in M)A(x)) \equiv (\exists x \in M)\neg A(x)$$

Passing negation symbol in quantifier statements
from the very left to the very right

Vacuous Truth (P44)

Definition

- Apply only for universal quantifier $\forall$
- Domain $M = \emptyset$
- Regardless of $A(x)$ being true or false

A universal statement is true unless there is a counterexample to prove it false.

Quantifier Order (P45)

e.g.

- $\forall x \exists y (x + y > 0)$ is a true statement.
  For each x, one needs to find a specific y to satisfy the statement, y can be different for different x.
- $\exists x \forall y (x + y > 0)$ is a false statement.
  Find a y first, then that specific y (value unchanged) needs to satisfy the statement for any value of x.

Tautology in Predicate Logic

Definition (P46)

- non-empty domain of discourse

Rules of Inference (P47)

- 1. Universal Instantiation
  2. Universal Generalization
  3. Existential Instantiation
  4. Existential Generalization
- All other rules of inference that are valid in propositional logic

Proof by Contradiction

Recall the definition of validity of arguments: If all premises are true, then the conclusion is also true.

Question

Prove that there are infinitely many prime numbers.

Proof.

Suppose that there are not infinitely many primes. Therefore there must be finitely many primes: $p_1 < p_2 < \cdots < p_n$ and hence a largest prime p_n. Let

$$m = \prod_{1 \leqslant i \leqslant n} p_i + 1$$

By our assumption, m is not prime. So there exists p_j such that $p_j | m$, i.e. $m = p_j k$ for some integer k. But now,

$$1 = p_j \left(k - \prod_{1 \leqslant i \leqslant n} p_i \right)$$

which shows that $p_j | 1$. This is a contradiction. Therefore, we can conclude that there are infinitely many primes. $\square$

Sets

Definition (P53)

- collection of objects
- ignore order
- ignore repetitions

Express Sets with Predicates: $X = \{x|P(x)\}$ $i.e.$ $x \in X$ iff $P(x)$

e.g.

Suppose $A = \{x|A(x)\}, B = \{x|B(x)\}, C$ are sets,

- $\forall x \in A(A(x) \wedge B(x)) \Leftrightarrow A \subseteq B \Leftrightarrow (A(x) \Rightarrow B(x))$
- $\exists x \in A(A(x) \wedge B(x)) \Leftrightarrow A \cap B \neq \emptyset$
- $C = \{x|\neg A(x)\} = A^c$

The examples above may help you understand the relation between sets and predicates better.

Sets

Definitions

1. *equality of two sets (P54)*
2. *empty set (P55)*
3. *(proper) subset (P56)*
4. *cardinality (P58)*
5. *powerset (P58)*

- Empty set ($\emptyset$) is subset of any set.
- $A \subseteq X \equiv A \in \mathcal{P}(X)$
- $|\mathcal{P}(X)| = 2^{|X|}$

e.g. (P57)
Let $A = \{\emptyset, \{\{\emptyset\}\}\}, B = \{\emptyset\}$ and $C = \{\{\emptyset\}\}. B \subseteq A$, but $B \notin A$, and $C \in A$, but $C \nsubseteq A$.

Operations on Sets (P59-P60)

Definitions

1. *union*
2. *intersection*
3. *difference*
4. *complement*
5. *disjoint*

Complex Operations on Sets

Suppose A, B, C are sets,

- $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$
- $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$
- $(A \cup B) \setminus C = (A \setminus C) \cup (B \setminus C)$
- $(A \cap B) \setminus C = (A \setminus C) \cap (B \setminus C)$
- $A \setminus (B \cup C) = (A \setminus C) \cap (B \setminus C)$
- $A \setminus (B \cap C) = (A \setminus C) \cup (B \setminus C)$
- $A \setminus B = B^c \cap A$
- $(A \setminus B)^c = A^c \cup B$

Use Wenn Diagrams to help understand.

Operations on Sets (P61-P62)

e.g. For a finite number $n \in \mathbb{N}$ of sets $A_0, A_1, \cdots, A_n$:

$$\bigcup_{k=0}^{n} A_k := A_0 \cup A_1 \cup \cdots \cup A_n \qquad \bigcap_{k=0}^{n} A_k := A_0 \cap A_1 \cap \cdots \cap A_n$$

If n extends to ∞,

$$x \in \bigcup_{k=0}^{\infty} A_k :\Leftrightarrow \underset{k \in \mathbb{N}}{\exists}\, x \in A_k \qquad x \in \bigcap_{k=0}^{\infty} A_k :\Leftrightarrow \underset{k \in \mathbb{N}}{\exists}\, x \in A_k$$

Operations on Sets (P63)

If A is an set and $X \subseteq \mathcal{P}(A)$, then

$$\bigcup X = \{x \in A | (\exists y \in X)(x \in y)\}$$

and

$$\bigcap X = \{x \in A | (\forall y \in X)(x \in y)\}$$

e.g. Let $A = \{1, 2\}, \mathcal{P}(A) = \{\emptyset, \{1\}, \{2\}, \{1, 2\}\}$. Suppose $X = \{\{1\}, \{1, 2\}\}$, then

$$\bigcap X = \{1\}, \bigcup X = \{1, 2\}$$

Here $\bigcup X$ indicates the union of all objects (sets) in X, while $\bigcap X$ indicates the intersection of all objects (set) in X.

e.g. Let

$$X = \{A \in \mathcal{P}(\mathbb{N}) | (\exists k \in \mathbb{N})(\forall n \in \mathbb{N})(n \in A \vee n = k)\}$$

Then

$$\bigcup X = \mathbb{N} \textit{ and } \bigcap X = \emptyset$$

Ordered Pairs & Cartesian Products (P64-P65)

Definitions

1. $(a, b) := \{\{a\}, \{a, b\}\}$
2. $(a, b) = (c, d) \Leftrightarrow (a = c) \wedge (b = d)$
3. Cartesian product of two sets
   $A \times B := \{(a, b) | a \in A \wedge b \in B\}$.
4. ordered $n-$tuple & $n-$fold Cartesian product

Paradoxes (P67-P69)

- Epimenides Paradox
- Barber Paradox (Russell's Paradox)

Russell's Paradox:

Theorem

The set of all sets that are not members of themselves is not a set. i.e.

$$R := \{x | x \notin x\} \text{ is not a set.}$$

Proof.

The proof is by contradiction. Suppose that R is a set. If $R \in R$, then $R \notin R$ by the definition of R, which is a contradiction. If $R \notin R$, then $R \in R$ by the definition of R, which is also a contradiction. $\square$