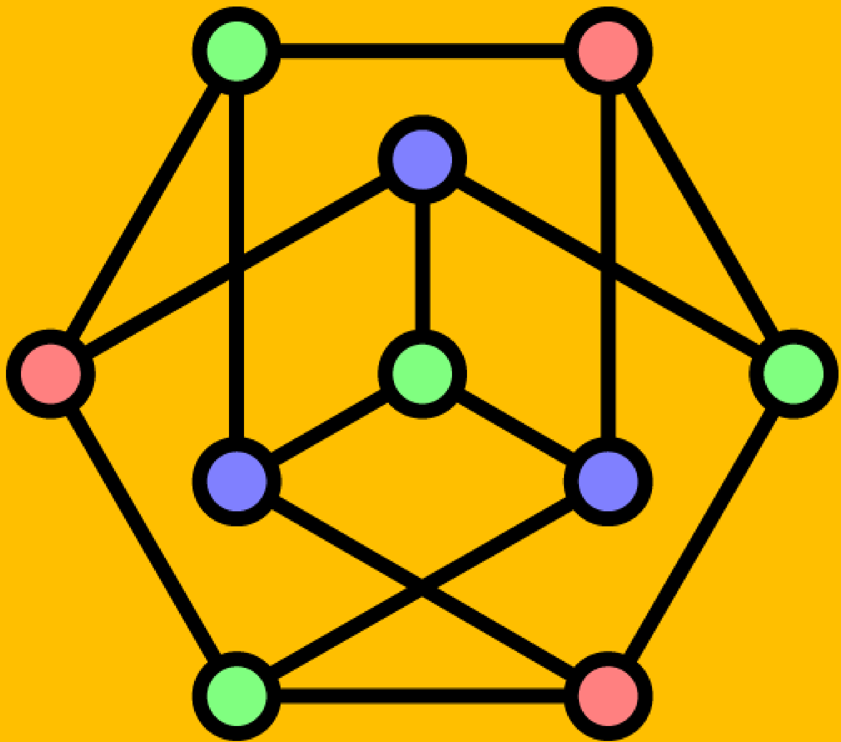
THEORETICAL COMPUTER SCIENCE

DISCRETE STRUCTURES FOR COMPUTER SCIENCE STUDENTS



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PREFACE

Those notes are supposed to be parsed together with explanations from the lectures. Any questions or found errors should be addressed to matjaz.krnc@upr.si, or raised as an issue in our public repository

https://github.com/mkrnc/TOR1-vaje---TCS1-exercises.git.

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CONTENTS

1 MATHEMATICAL LOGIC

1.1 BASIC EXERCISES

Problem 1. The following two propositions are given: A: "It is cold outside." B: "It is raining outside."

Write the following compound propositions in natural language:

- (a) $\neg A$
- (b) $A \wedge B$
- (c) $A \vee B$
- (d) $B \vee \neg A$

Problem 2. The following two propositions are given: A: "Janez is rich." B: "Janez is happy."

Write the following propositions symbolically:

- (a) If Janez is rich, then he is unhappy.
- (b) Janez is neither happy nor rich.
- (c) Janez is happy only if he is poor.
- (d) Janez is poor if and only if he is unhappy.

Problem 3. Find the truth tables for the examples from the previous task.

Problem 4. Is the following reasoning correct?

- Premise 1: "I think, therefore I am."
- Premise 2: "I think, therefore I reason."
- Conclusion: "I am, therefore I reason."

Solution: The logical implication is:

$$(A_1 \Rightarrow A_2) \wedge (A_1 \Rightarrow A_3) \Rightarrow (A_2 \Rightarrow A_3)$$

For $A_1(d) = 0$, $A_2(d) = 1$, $A_3(d) = 0$, this implication is false. Therefore, the reasoning is incorrect.

Problem 5. The following two propositions are given: A: "Andrej speaks French." and B: "Andrej speaks Danish." Write the following compound propositions in natural language:

(a) $A \vee B$

(b) $A \wedge B$

(c) $A \wedge \neg B$

(d) $\neg A \vee \neg B$

(e) $\neg\neg A$

(f) $\neg(\neg A \wedge \neg B)$

Problem 6. Given the propositions:
A : "John reads The New York Times."
B : "John reads The Wall Street Journal."
C : "John reads The Daily Mail."

Transcribe the following statements into symbolic propositions:

a) John reads The New York Times, but not The Wall Street Journal.

b) Either John reads both The New York Times and The Wall Street Journal, or he does not read The New York Times and The Wall Street Journal.

c) It is not true that John reads The New York Times, and does not read The Daily Mail.

d) It is not true that John reads The Daily Mail or The Wall Street Journal, and not The New York Times.

Problem 7. Find the truth tables for the symbolic propositions from Exercise **Problem 6.**.

Problem 8. For three lines p, q, r we may construct also geometric propositions. Suppose that the following is true:

$$(p||q) \wedge (p \cap q \neq \emptyset) \wedge (q \cap r \neq \emptyset).$$

What can you say about the lines p, q, r?

Problem 9. Express the propositions below with connectives $\wedge$ and $\neg$ only!

a) $A \vee B$

b) $A \Rightarrow B$

c) $A \Leftrightarrow B$

1.2 KNIGHTS AND SERVANTS (KNEVES)

Knights always tell the truth, while servants always lie.

Problem 10. Artur: "It is not true that Cene is a servant."

Bine: "Cene is a knight or I am a knight."

Cene: "Bine is a servant."

For each of them, determine whether they are knights or servants!

Solution: Let us denote: A – Arthur is a knight, B – Bine is a knight, C – Cene is a knight.

(i) The following compound statement holds:

$$(A \iff C) \wedge (B \iff C \vee B) \wedge (C \iff \neg B)$$

With the help of the truth table, we see that the statement is true only for the set $A = C = 0$ and $B = 1$.

Problem 11. Artur: "Cene is a servant or Bine is a servant." Bine: "Cene is a knight and Artur is a knight."

For each of them, determine whether they are knights or servants!

Solution: Let us denote: A – Arthur is a knight, B – Bine is a knight, C – Cene is a knight.

The following compound statement holds:

$$(A \iff \neg C \vee \neg B) \wedge (B \iff C \wedge A)$$

With the help of the truth table, we see that the statement is true only for the set $A = 1$ and $B = C = 0$.

Problem 12. Let us analyze the statements made by A, B, C, and D:

- A: "D is a servant and C is a servant."
- B: "If A and D are servants, then C is a servant."
- C: "If B is a servant, then A is a knight."
- D: "If E is a servant, then both C and B are servants."

Problem 13. Solve the following exercises about knights and servants:

- Arthur: "It is not true that Bine is a servant."
- Bine: "We are not both of the same kind."

Problem 14. Now Arthur and Bine say the following:

- Arthur: "Me and Bine are not of the same kind."
- Bine: "Exactly one of us is a knight."

Problem 15. Knights and servants!

a) Arthur: Chloe or Bob are servants.

b) Bob: Cene and Arthur are knights.

1.3 CANONICAL FORMS

Problem 16. Find the canonical disjunctive normal form (DNF) and the canonical conjunctive normal form (CNF) for the following propositions:

(i) $\neg(A \wedge B) \Rightarrow (\neg B \Rightarrow A)$

(ii) $\neg(A \vee B) \wedge (A \Rightarrow B)$

Problem 17. For the following compound proposition find a truth table, determine DNF, CNF and draw the corresponding circuit.

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

1.4 SWITCHING CIRCUITS

Problem 18. For the circuits in Figure 1, find the corresponding compound propositions.

Problem 19. For the following compound proposition, find a truth table, determine DNF, CNF, and draw the corresponding circuit.

$$(A \Rightarrow (B \Rightarrow C)) \Rightarrow ((A \Rightarrow B) \Rightarrow (A \Rightarrow C))$$

Problem 20. Find a compound proposition I such that

$$(A \Rightarrow (I \Rightarrow \neg B)) \Rightarrow (A \wedge B) \vee I$$

is a tautology.

1.5 LOGICAL IMPLICATIONS

Problem 21. Prove the following logical equivalences:

(1) $(A \Rightarrow B) \wedge (B \Rightarrow C) \Rightarrow (A \Rightarrow C)$

(2) $(A \Rightarrow B) \Rightarrow ((C \Rightarrow A) \Rightarrow (C \Rightarrow B))$

(3) $(A \Rightarrow B) \Rightarrow ((B \Rightarrow C) \Rightarrow (A \Rightarrow C))$

(4) $(A \Rightarrow B) \Rightarrow (A \wedge C \Rightarrow B \wedge C)$

(5) $(A \Rightarrow B) \Rightarrow (A \vee C \Rightarrow B \vee C)$

(6) $(A \Leftrightarrow B) \wedge (B \Leftrightarrow C) \Rightarrow (A \Leftrightarrow C)$

(7) $(A \Leftrightarrow B) \Rightarrow (A \Rightarrow B)$

(8) $(A \Leftrightarrow B) \Rightarrow (B \Rightarrow A)$

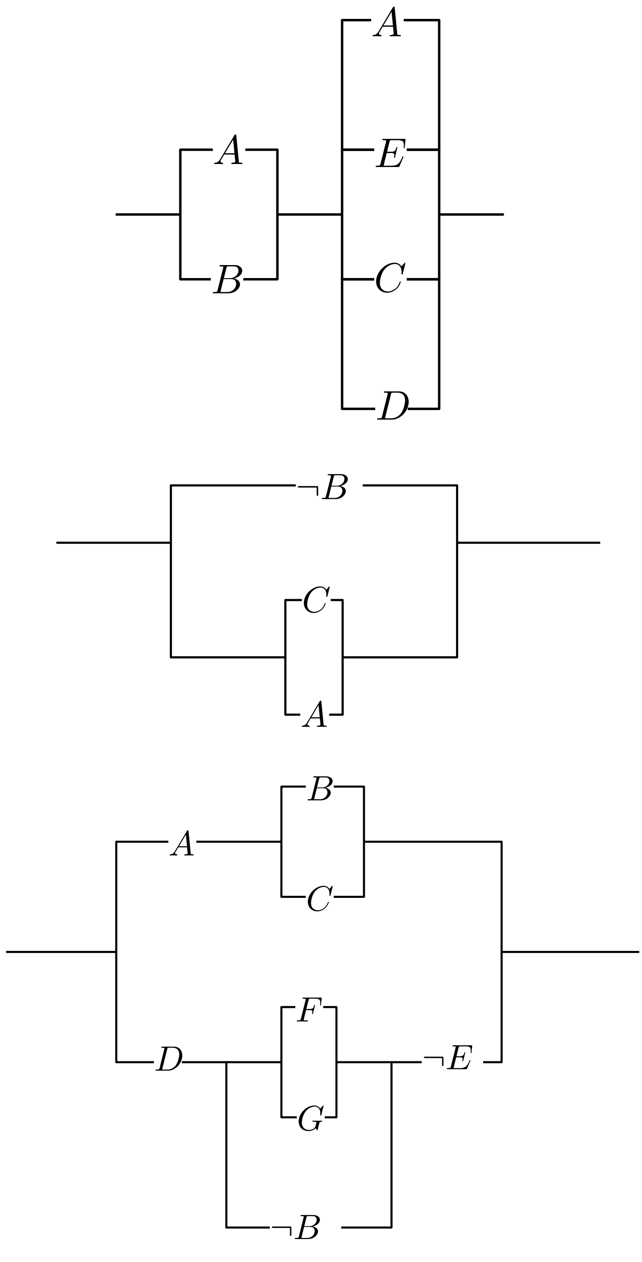

Figure 1: Switching circuits for **Problem 18.**

(9) $A \wedge (A \Leftrightarrow B) \Rightarrow B$

(10) $\neg A \wedge (A \Leftrightarrow B) \Rightarrow \neg B$

(11) $B \Rightarrow (A \Leftrightarrow A \wedge B)$

(12) $\neg B \Rightarrow (A \Leftrightarrow A \vee B)$

(13) $(A \Rightarrow (B \wedge \neg B)) \Rightarrow \neg A$

Problem 22. Simplify the following logical proposition:

$$(A \Rightarrow B) \vee (B \Rightarrow C)$$

Solution.

$$\begin{aligned}
(A \Rightarrow B) \vee (B \Rightarrow C) &\Leftrightarrow (\neg A \vee B) \vee (\neg B \vee C) \\
&\Leftrightarrow \neg A \vee B \vee \neg B \vee C \\
&\Leftrightarrow \neg A \vee (B \vee \neg B) \vee C \\
&\Leftrightarrow \neg A \vee 1 \vee C \\
&\Leftrightarrow 1.
\end{aligned}$$

1.6 PROOFS

Problem 23. Show that the following propositions are logical implications (i.e., tautologies where the main connective is implication):

(i) $A \wedge (A \Rightarrow B) \Rightarrow B$

(ii) $\neg B \wedge (A \Rightarrow B) \Rightarrow \neg A$

(iii) $\neg A \wedge (A \vee B) \Rightarrow B$

(iv) $(A \Rightarrow B) \wedge (B \Rightarrow C) \Rightarrow (A \Rightarrow C)$

(v) $A \wedge (A \Leftrightarrow B) \Rightarrow B$

Problem 24. Are the following propositions logical implications?

(i) $(A \Rightarrow B) \wedge (A \Rightarrow C) \wedge A \Rightarrow B \wedge C$

(ii) $\neg(A \vee B) \wedge (A \vee C) \wedge (D \Rightarrow C) \Rightarrow D$

(iii) $(A \Rightarrow B) \wedge (A \Rightarrow C) \wedge (D \wedge E \Rightarrow F) \wedge (C \Rightarrow E) \Rightarrow F$

Problem 25. Show that the following propositions are logical implications (a tautology where the main connective is implication).

(i) $A \wedge (A \Rightarrow B) \Rightarrow B$

(ii) $\neg B \wedge (A \Rightarrow B) \Rightarrow \neg A$

(iii) $\neg A \wedge (A \vee B) \Rightarrow B$

(iv) $(A \Rightarrow B) \wedge (B \Rightarrow C) \Rightarrow (A \Rightarrow C)$

(v) $A \wedge (A \Leftrightarrow B) \Rightarrow B$

Rešitev. (i) Recimo $A \wedge (A \Rightarrow B)$ pravilna, B pa nepravilna. Potem je A pravilna in $A \Rightarrow B$ pravilna. Sledi B pravilna. Protislovje.

Problem 26. Are the following propositions logical implications?

(i) $(A \Rightarrow B) \wedge (A \Rightarrow C) \wedge A \Rightarrow B \wedge C$

(ii) $\neg(A \vee B) \wedge (A \vee C) \wedge (D \Rightarrow C) \Rightarrow D$

(iii) $(A \Rightarrow B) \wedge (A \Rightarrow C) \wedge (D \wedge E \Rightarrow F) \wedge (C \Rightarrow E) \Rightarrow F$

Problem 27. With a direct proof show:

If n is even, then so is $n^2 + 3n$.

Is the converse also true?

Problem 28. Use a direct proof of the implication to show: If a real number x is non-negative, then the sum of the number x and its reciprocal is greater than or equal to 2.

Problem 29. Use contradiction to show that there are infinitely many prime numbers.

Problem 30. Find the error in the following proof.

Statement: 1 is the largest natural number.

Proof (by contradiction): Suppose the opposite. Let $n > 1$ be the largest natural number. Since n is positive, we can multiply the inequality $n > 1$ by n, giving

$$n > 1 \Leftrightarrow n^2 > n.$$

We have found that n^2 is greater than n, which contradicts the assumption that n is the largest natural number. Therefore, the assumption was incorrect, and 1 is the largest natural number.

Problem 31. Let x and y be real numbers such that $x < 2y$. By an indirect proof show:

If $7xy \leq 3x^2 + 2y^2$, then $3x \leq y$.

Problem 32. Prove the following equivalence in two parts: Let m and n be integers. Then m and n have different parities if and only if $m^2 - n^2$ is odd.

Problem 33. Using an "if and only if" proof, show that $ac \mid bc \Leftrightarrow a \mid b$.

Problem 34. Is the following inference correct?

(i) If today is Wednesday, I will have a tutorial. Today is Wednesday. Conclusion: I will have a tutorial.

(ii) If I study, I will pass the exam. I did not study. Conclusion: I will not pass the exam.

(iii) A student took the city bus to the exam. He thought, "If the next traffic light is green, I will pass the exam." When the bus reached the next light, it was not green, so the student said to himself, "Darn, I'll fail again."

(iv) An engineer who understands theory always designs a good circuit. A good circuit is economical. Therefore, an engineer who designs an uneconomical circuit does not understand theory.

Problem 35. Which of the following propositions are correct where the language of the conversation are real numbers?

(i) $(\forall x)(\exists y)(x + y = 0)$.

(ii) $(\exists x)(\forall y)(x + y = 0)$.

(iii) $(\exists x)(\exists y)(x^2 + y^2 = -1)$.

(iv) $(\forall x)[x > 0 \Rightarrow (\exists y)(y < 0 \wedge xy > 0)]$.

1.6.1 Proofs by Induction

Problem 36. Prove each using induction:

(a) $\sum_{i=1}^{n} i = \frac{n(n+1)}{2}$

(b) $\sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6}$

(c) $\sum_{i=1}^{n} 2^{i-1} = 2^n - 1$

(d) $\sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}$

(e) $\frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \cdots + \frac{1}{n(n+1)} = \frac{n}{n+1}$

(f) $\sum_{i=1}^{n} \frac{1}{i(i+1)} = \frac{n}{n+1}$

(g) $\sum_{i=1}^{n}(2i-1) = n^2$

(h) $n! > 2^n$ for $n \geq 4$.

(i) $2^{n+1} > n^2$ for all positive integers.

Problem 37. This exercise refers to the Fibonacci sequence:

$$1, 1, 2, 3, 5, 8, 13, 21, 34, \ldots$$

The sequence is defined recursively by $f_1 = 1$, $f_2 = 1$, then $f_{n+1} = f_n + f_{n-1}$ for each $n > 2$. As before, prove each of the following using induction. You might investigate each with several examples before you start.

(a) $f_1 + f_2 + \cdots + f_n = f_{n+2} - 1$

(b) $f_1^2 + f_2^2 + \cdots + f_n^2 = f_n f_{n+1}$

(c) $f_1 + f_3 + f_5 + \cdots + f_{2n-1} = f_{2n}$

2 | SET THEORY

1. Let $A = \{x \in \mathbb{N}; x < 7\}, B = \{x \in \mathbb{Z}; |x-2| < 4\}$ and $C = \{x \in \mathbb{R}; x^3 - 4x = 0\}$.
   (i) Write down the elements for all three sets.
   (ii) Find $A \cup C, B \cap C, B \setminus C, (A \setminus B) \setminus C$ and $A \setminus (B \setminus C)$.

2. Let $\mathbb{Z}$ be a universal set and let P denote the set of all prime numbers, and S the set of all even integers. Write the following propositions in terms of set theory:
   (i) There exists an even prime number. $[P \cap S \neq \emptyset]$
   (ii) 0 is an integer, but it is not natural number. $[0 \in \mathbb{Z} \setminus \mathbb{N}]$
   (iii) Every natural number is an integer. $[\mathbb{N} \subseteq \mathbb{Z}]$
   (iv) Not every integer is a natural number. $[\mathbb{Z} \nsubseteq \mathbb{N}]$
   (v) Every prime number except 2 is odd. $[P \setminus \{2\} \subseteq \overline{S}]$
   (vi) 2 is an even prime number. $[2 \in S \cap P]$

3. Let A, B, C and D be subsets of some universal set U. Simplify the following expression
$$\overline{(\overline{(A \cup B)} \cap \overline{(\overline{A} \cup C)})} \setminus \overline{D}.$$

4. Show that $(A \cup C) \cap (B \setminus C) = (A \cap B) \setminus C$.

   Rešitev.
$$\begin{aligned}
x \in (A \cup C) \cap (B \setminus C) &\Leftrightarrow (x \in A \vee x \in C) \wedge (x \in B \wedge x \notin C)\\
&\Leftrightarrow ((x \in A \vee x \in C) \wedge (x \notin C)) \wedge x \notin B\\
&\Leftrightarrow ((x \in A \wedge x \notin C) \vee (x \in C \wedge x \notin C)) \wedge x \in B\\
&\Leftrightarrow x \in A \wedge x \notin C \wedge x \in B\\
&\Leftrightarrow x \in A \wedge x \in B \wedge x \notin C\\
&\Leftrightarrow x \in (A \cap B) \setminus C.
\end{aligned}$$

5. (Zadnja lastnost pri uniji) Prove that $A \subseteq C \land B \subseteq C \Rightarrow A \cup B \subseteq C$.

   Rešitev. Direktno.

6. (Predzadnja lastnost pri preseku) Prove that $A \subseteq B \Leftrightarrow A \cap B = A$.

   Rešitev. V dveh delih.

7. (Predzadnja lastnost pri kartezičnemu produktu) Prove that $A \times (B \cap C) = (A \times B) \cap (A \times C)$.

   Rešitev.

$$\begin{aligned}
(x,y) \in A \times (B \cap C) &\Leftrightarrow x \in A \land y \in B \cap C \\
&\Leftrightarrow x \in A \land y \in B \land y \in C \\
&\Leftrightarrow x \in A \land x \in A \land y \in B \land y \in C \\
&\Leftrightarrow x \in A \land y \in B \land x \in A \land y \in C \\
&\Leftrightarrow (x,y) \in A \times B \land (x,y) \in A \times C \\
&\Leftrightarrow (x,y) \in (A \times B) \cap (A \times C).
\end{aligned}$$

8. (Predzadnja lastnost pri razliki) Prove that $(A \cap B) \setminus B = \emptyset$. *Rešitev.*

$$\begin{aligned}
x \in (A \cap B) \setminus B &\Leftrightarrow x \in (A \cap B) \land x \notin B \\
&\Leftrightarrow (x \in A \land x \in B) \land x \notin B \\
&\Leftrightarrow x \in A \land (x \in B \land x \notin B) \\
&\Leftrightarrow x \in \emptyset.
\end{aligned}$$

9. Determine the following sets:
   (i) $\{\emptyset, \{\emptyset\}\} \setminus \emptyset \quad [\{\emptyset, \{\emptyset\}\}]$
   (ii) $\{\emptyset, \{\emptyset\}\} \setminus \{\emptyset\}$
   (iii) $\{\emptyset, \{\emptyset\}\} \setminus \{\}\emptyset\}\}$
   (iv) $\{1, 2, 3, \{1\}, \{5\}\} \setminus \{2, \{3\}, 5\}$

10. Which of the following propositions are correct for arbitrary sets A, B and C:
    a) If $A \in B$ and $B \in C$, then $A \in C$.
    b) If $A \subseteq B$ and $B \in C$, then $A \in C$.

c) If $A \cap B \subseteq \overline{C}$ and $A \cup C \subseteq B$, then $A \cap C = \emptyset$.

d) If $A \neq B$ and $B \neq C$, then $A \neq C$.

e) If $A \subseteq \overline{(B \cup C)}$ and $B \subseteq \overline{(A \cup C)}$, then $B = \emptyset$.

Rešitev.

a) Napačna. Vzemi $A = \emptyset$, $B = \{\emptyset\}$, $B = \{\{\emptyset\}\}$.

b) Napačna. Vzemi isti primer kot v (a).

c) Pravilna. Dokaz s protislovjem. Recimo, da trditev ni pravilna. Naj bo $A \cap B \subseteq \overline{C}$, $A \cup C \subseteq B$ in naj obstaja $x \in A \cap C$. Torej je $x \in A$ in $x \in C$. Ker je po drugi predpostavki $A \cup C \subseteq B$, je $x \in B$. Sledi $x \in A \cap B$. Ker je po prvi predpostavki $A \cap B \subseteq \overline{C}$, je $x \in \overline{C}$. Protislovje, saj $x \in C$.

d) Napačna. Vzemi $A = C \neq B$.

e) Napačna. Vzemi tri paroma disjunktne neprazne množice.

11. Find $\mathcal{P}(A)$, where $A = \{a, b, c, d\}$.

12. Let $A = \{\{1, 2, 3\}, \{4, 5\}, \{6, 7, 8\}\}$.

(i) Write down the elements of A.

(ii) Is it true?
(a) $1 \in A$ (b) $\{1, 2, 3\} \subseteq A$ (c) $\{6, 7, 8\} \in A$ (d) $\{\{4, 5\}\} \subseteq A$
(e) $\emptyset \in A$ (f) $\emptyset \subseteq A$

13. Show that $A \times (B \cap C) = (A \times B) \cap (A \times C)$.

14. Let A, B in C be arbitrary subsets of the universal set $U = A \cup B \cup C$. Show the following propositions:

a) $A \setminus B \subseteq \overline{B}$.

b) $(A \setminus B) \cap B = \emptyset$.

c) $A \cap B \subseteq C \Leftrightarrow A \subseteq \overline{B} \cup C$.

d) $(A \setminus B) \cup B = A \Leftrightarrow B \subseteq A$.

e) If $B \subseteq A$, then$B \times B = (B \times A) \cap (A \times B)$.

f) Let A be a nonempty set. Which of the following sets

$$\emptyset, \{\emptyset\}, A, \{A\}, \{A, \emptyset\}$$

are elements and which are subsets of (i) $\mathcal{P}(A)$ and (ii) $\mathcal{P}(\mathcal{P}(A))$?

g) Is it true that $\mathcal{P}(A \times B) = \mathcal{P}(A) \times \mathcal{P}(B)$?

3 RELATIONS

1. Let $S = \{1,2,3,4,5\}$.
   a) Is $R = \{(1,2),(2,3),(3,5),(2,4),(5,1)\}$ a binary relation?
   b) Find the domain $\mathcal{D}R$ and the range $\mathcal{Z}R$ of R.
   c) Determine the inverse relation R^{-1} and $\mathcal{D}R^{-1}$ and $\mathcal{Z}R^{-1}$.

2. Let $R = \{(1,1),(2,1),(3,3),(1,5)\}$ and $T = \{(1,4),(2,1),(2,2),(2,5)\}$ be binary relations.
   a) Determine the compositions $R \circ T$ and $T \circ R$.
   b) Is it true that $R \circ T = T \circ R$?

3. Let $S = \{1,2,3,4,5,6,7\}$. Define

   $$R = \{(x,y) \mid x - y \text{ is divisible by } 3\} \quad \text{in} \quad T = \{(x,y) \mid x - y \geq 3\}.$$

   Determine $R, T, R \circ R$.

4. Let $S = \mathbb{R}$. On S we define the relation R as follows

   $$(\forall x)(\forall y)(xRy \Leftrightarrow y \geq x + 3).$$

   Is R reflexive, symmetric, transitive or strict total?

5. Let $S = \{1,2,3,4\}$. We have the following relations
   (i) $R_1 = \{(1,1),(1,2),(2,3),(1,3),(4,4)\}$,
   (ii) $R_2 = \{(1,1),(1,2),(2,1),(2,2),(3,3),(4,4)\}$,
   (iii) $R_3 = \{(1,3),(2,1)\}$,
   (iv) $R_4 = \emptyset$,
   (v) $R_5 = S \times S$.

   Which of the following properties hold for each relation: reflexive, symmetric, antisymmetric, transitive?

6. Let R and S be symmetric relations. Show: $R \circ S$ symmetric $\Leftrightarrow$ $R \circ S = S \circ R$.
7. Let $S = \{m \in \mathbb{N} \,|\, 1 \le n \le 10\}$ in $R = \{(m,n) \in S \times S \,|\, 3|m-n\}$. Is R an equivalence relation? If yes, determine the corresponding equivalence classes and the factor set.

3.1 EQUIVALENCES

8. Let $S = \mathbb{Z} \times \mathbb{Z}$ and define the relation R as follows
$$(a,b)R(c,d) \Leftrightarrow ad = bc.$$
Show that R is an equivalence relation and find the corresponding equivalence classes.
9. Let $S = \mathbb{R}^2$ and define the relation R as follows
$$(x_1,y_1)R(x_2,y_2) \Leftrightarrow x_1^2 + y_1^2 = x_2^2 + y_2^2.$$
Show that R is an equivalence relation and find the equivalenec class $R[(7,1)]$.

3.2 FUNCTIONS

1. Let $A = \{1,2,3,4\}$, $B = \{x,y,z\}$, $C = \{a,b\}$. You are given functions $f : A \to B$ and $g : B \to C$.
$$f = \{(1,x),(2,y),(3,y),(4,x)\}$$
$$g = \{(x,a),(y,b),(z,b)\}$$
(a) Is f injective?
(b) Is f surjective?

(c) Is g injective?

(d) Is g surjective?

(e) Is $g \circ f$ surjective?

2. Let $A = \{a, b, c\}$, $B = \{1, 2, 3\}$, $C = \{x, y\}$. You are given functions $f : A \to B$ and $g : B \to C$.

$$f = \{(a, 1), (b, 3), (c, 2)\}$$

$$g = \{(1, x), (2, y), (3, x)\}$$

(a) Is f injective?

(b) Is f surjective?

(c) Is g injective?

(d) Is g surjective?

(e) Is $g \circ f$ surjective?

3. Let $A = \{x, y, z\}$, $B = \{1, 2, 3\}$, $C = \{a, b, c\}$. You are given functions $f : A \to B$ and $g : B \to C$.

$$f = \{(x, 2), (y, 1), (z, 3)\}$$

$$g = \{(1, a), (2, b), (3, c)\}$$

(a) Is f injective?

(b) Is f surjective?

(c) Is g injective?

(d) Is g surjective?

(e) Is $g \circ f$ surjective?

3.3 GRAPH THEORY

1. Let $n \geq 3$. Recall the definition of cycles and complete graphs:

$$C_n = \{[n], E_1\}$$

$$K_n = \{[n], E_2\}$$

and define

$$G_n = \{[n], E_2 \setminus E_1\}$$

- Draw $H, G_4, G_5, G_6, C_5, C_6, \overline{C_i}$
- For all the above graphs, determine $\Delta(G_i), \delta(G_i), \alpha(G_i), \omega(G_i), \chi(G_i), g(G_i)$
- Prove $(\forall i \geq 3)(G_i \simeq \overline{C_i})$

2. Let $G = ([n], E)$ be a graph.

- Prove: $\chi(G) \geq \omega(G)$
- Prove: $\chi(G) \geq \frac{n}{\alpha(G)}$