

**4190.101**

# **Discrete Mathematics**

Chapter 2 Basic Structures: Sets, Functions,  
Sequences, Sums, and Matrices

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# Chapter Summary

- Sets
  - The Language of Sets
  - Set Operations
  - Set Identities
- Functions
  - Types of Functions
  - Operations on Functions
  - Computability
- Sequences and Summations
  - Types of Sequences
  - Summation Formulae
- Set Cardinality
  - Countable Sets
- Matrices
  - Matrix Arithmetic

# Sets

## Section 2.1

# Section Summary

- Definition of sets
- Describing Sets
  - Roster Method
  - Set-Builder Notation
- Some Important Sets in Mathematics
- Empty Set and Universal Set
- Subsets and Set Equality
- Cardinality of Sets
- Tuples
- Cartesian Product

# Introduction

- Sets are one of the basic building blocks for the types of objects considered in discrete mathematics.
  - Important for counting.
  - Programming languages have set operations.
- Set theory is an important branch of mathematics.
  - Many different systems of axioms have been used to develop set theory.
  - Here we are not concerned with a formal set of axioms for set theory. Instead, we will use what is called naïve set theory.

# Sets

- A *set* is an unordered collection of objects.
  - The students in this class
  - The chairs in this room
- The objects in a set are called the *elements*, or *members* of the set. A set is said to *contain* its elements.
- The notation  $a \in A$  denotes that  $a$  is an element of the set  $A$ .
- If  $a$  is not a member of  $A$ , write  $a \notin A$

# Describing a Set: Roster Method

- Order not important
  - $S = \{a, b, c, d\} = \{b, c, a, d\}$
- Each distinct object is either a member or not; listing more than once does not change the set.
  - $S = \{a, b, c, d\} = \{a, b, c, b, c, d\}$
- Ellipses (...) may be used to describe a set without listing all of the members when the pattern is clear.
  - $S = \{a, b, c, d, \dots, z\}$

# Roster Method

- Set of all vowels in the English alphabet:
  - $V = \{a, e, i, o, u\}$
- Set of all odd positive integers less than 10:
  - $O = \{1, 3, 5, 7, 9\}$
- Set of all positive integers less than 100:
  - $S = \{1, 2, 3, \dots, 99\}$
- Set of all integers less than 0:
  - $S = \{\dots, -3, -2, -1\}$



# Some Important Sets

- $\mathbf{N}$  = set of *natural numbers* =  $\{0,1,2,3,\dots\}$
- $\mathbf{Z}$  = set of *integers* =  $\{\dots,-3,-2,-1,0,1,2,3,\dots\}$
- $\mathbf{Z}^+$  = set of *positive integers* =  $\{1,2,3,\dots\}$
- $\mathbf{R}$  = set of *real numbers*
- $\mathbf{R}^+$  = set of *positive real numbers*
- $\mathbf{C}$  = set of *complex numbers*.
- $\mathbf{Q}$  = set of rational numbers

# Set-Builder Notation

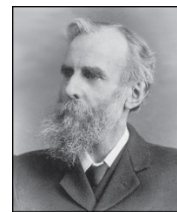
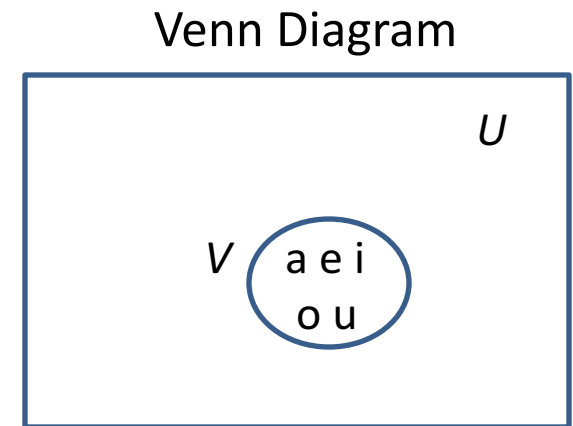
- Specify the property or properties that all members must satisfy:
  - $S = \{x \mid x \text{ is a positive integer less than } 100\}$
  - $O = \{x \mid x \text{ is an odd positive integer less than } 10\}$
  - $O = \{x \in \mathbf{Z}^+ \mid x \text{ is odd and } x < 10\}$
- A predicate may be used:  $S = \{x \mid P(x)\}$ 
  - Example:  $S = \{x \mid \text{Prime}(x)\}$
- Positive rational numbers:
  - $\mathbf{Q}^+ = \{x \in \mathbf{R} \mid x = p/q, \text{ for some positive integers } p, q\}$

# Interval Notation

- $[a,b] = \{x \mid a \leq x \leq b\}$
  - $[a,b) = \{x \mid a \leq x < b\}$
  - $(a,b] = \{x \mid a < x \leq b\}$
  - $(a,b) = \{x \mid a < x < b\}$
- 
- Closed interval  $[a,b]$
  - Open interval  $(a,b)$

# Universal Set and Empty Set

- The *universal set*  $U$  is the set containing everything currently under consideration.
  - Sometimes implicit
  - Sometimes explicitly stated.
  - Contents depend on the context.
- The empty set is the set with no elements. Symbolized  $\emptyset$ , but  $\{\}$  also used.



John Venn (1834-1923)  
Cambridge, UK

# Some things to remember

- Sets can be elements of sets.
  - $\{\{1,2,3\}, a, \{b,c\}\}$
  - $\{\mathbf{N}, \mathbf{Z}, \mathbf{Q}, \mathbf{R}\}$
- The empty set is different from a set containing the empty set.
  - $\emptyset \neq \{ \emptyset \}$

# Set Equality

- **Definition:** Two sets are *equal* if and only if they have the same elements.
  - Therefore if  $A$  and  $B$  are sets, then  $A$  and  $B$  are equal if and only if  $\forall x(x \in A \leftrightarrow x \in B)$ .
  - We write  $A = B$  if  $A$  and  $B$  are equal sets.
$$\{1,3,5\} = \{3, 5, 1\}$$
$$\{1,5,5,5,3,3,1\} = \{1,3,5\}$$

# Set Equality

- **Definition:** The set  $A$  is a *subset* of  $B$ , if and only if every element of  $A$  is also an element of  $B$ .
  - The notation  $A \subseteq B$  is used to indicate that  $A$  is a subset of the set  $B$ .
  - $A \subseteq B$  holds if and only if  $\forall x(x \in A \rightarrow x \in B)$  is true.
    1. Because  $a \in \emptyset$  is always false,  $\emptyset \subseteq S$  for every set  $S$ .
    2. Because  $a \in S \rightarrow a \in S$ ,  $S \subseteq S$ , for every set  $S$ .

# Showing a Set is or is not a Subset of Another Set

- **Showing that A is a Subset of B:** To show that  $A \subseteq B$ , show that if  $x$  belongs to  $A$ , then  $x$  also belongs to  $B$ .
- **Showing that A is not a Subset of B:** To show that  $A$  is not a subset of  $B$ ,  $A \not\subseteq B$ , find an element  $x \in A$  with  $x \notin B$ . (Such an  $x$  is a counterexample to the claim that  $x \in A$  implies  $x \in B$ .)
- **Examples:**
  1. The set of all computer science majors at your school is a subset of all students at your school.
  2. The set of integers with squares less than 100 is not a subset of the set of nonnegative integers.



# Another look at Equality of Sets

- Recall that two sets  $A$  and  $B$  are *equal*, denoted by  $A = B$ , iff

$$\forall x (x \in A \leftrightarrow x \in B)$$

- Using logical equivalences we have that  $A = B$  iff

$$\forall x [(x \in A \rightarrow x \in B) \wedge (x \in B \rightarrow x \in A)]$$

- This is equivalent to

$$A \subseteq B \quad \text{and} \quad B \subseteq A$$

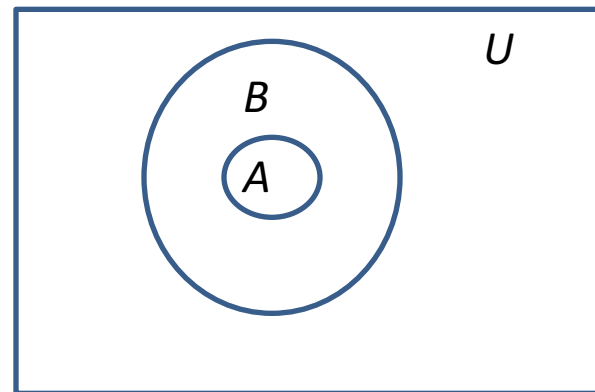
# Proper Subsets

- **Definition:** If  $A \subseteq B$ , but  $A \neq B$ , then we say  $A$  is a *proper subset* of  $B$ , denoted by  $A \subset B$ . If  $A \subset B$ , then

$$\forall x(x \in A \rightarrow x \in B) \wedge \exists x(x \in B \wedge x \notin A)$$

is true

- Venn Diagram



# Set Cardinality

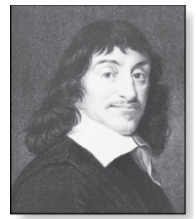
- **Definition:** If there are exactly  $n$  distinct elements in  $S$  where  $n$  is a nonnegative integer, we say that  $S$  is *finite*. Otherwise it is *infinite*.
- **Definition:** The *cardinality* of a finite set  $A$ , denoted by  $|A|$ , is the number of (distinct) elements of  $A$ .
- **Examples:**
  1.  $|\emptyset| = 0$
  2. Let  $S$  be the letters of the English alphabet. Then  $|S| = 26$
  3.  $|\{1,2,3\}| = 3$
  4.  $|\{\emptyset\}| = 1$
  5. The set of integers is infinite.

# Power Sets

- **Definition:** The set of all subsets of a set  $A$ , denoted  $\mathcal{P}(A)$ , is called the *power set* of  $A$ .
- **Example:** If  $A = \{a, b\}$  then
$$\mathcal{P}(A) = \{\emptyset, \{a\}, \{b\}, \{a, b\}\}$$
- If a set has  $n$  elements, then the cardinality of the power set is  $2^n$ . (In later chapters, we will discuss different ways to show this.)

# Tuples

- The *ordered n-tuple*  $(a_1, a_2, \dots, a_n)$  is the ordered collection that has  $a_1$  as its first element and  $a_2$  as its second element and so on until  $a_n$  as its last element.
- Two n-tuples are equal if and only if their corresponding elements are equal.
- 2-tuples are called *ordered pairs*.
- The ordered pairs  $(a, b)$  and  $(c, d)$  are equal if and only if  $a = c$  and  $b = d$ .



René Descartes  
(1596-1650)

# Cartesian Product

- **Definition:** The *Cartesian Product* of two sets  $A$  and  $B$ , denoted by  $A \times B$  is the set of ordered pairs  $(a,b)$  where  $a \in A$  and  $b \in B$ .

$$A \times B = \{(a, b) | a \in A \wedge b \in B\}$$

- **Example:**

$$A = \{a, b\} \quad B = \{1, 2, 3\}$$

$$A \times B = \{(a, 1), (a, 2), (a, 3), (b, 1), (b, 2), (b, 3)\}$$

- **Definition:** A subset  $R$  of the Cartesian product  $A \times B$  is called a *relation* from the set  $A$  to the set  $B$ . (Relations will be covered in depth in Chapter 9.)

# Cartesian Product

- **Definition:** The Cartesian products of the sets  $A_1, A_2, \dots, A_n$ , denoted by  $A_1 \times A_2 \times \dots \times A_n$ , is the set of ordered  $n$ -tuples  $(a_1, a_2, \dots, a_n)$  where  $a_i$  belongs to  $A_i$  for  $i = 1, \dots, n$ .

$$A_1 \times A_2 \times \dots \times A_n = \{(a_1, a_2, \dots, a_n) | a_i \in A_i \text{ for } i = 1, 2, \dots, n\}$$

- **Example:** What is  $A \times B \times C$  where  $A = \{0, 1\}$ ,  $B = \{1, 2\}$  and  $C = \{0, 1, 2\}$
- **Solution:**  $A \times B \times C = \{(0, 1, 0), (0, 1, 1), (0, 1, 2), (0, 2, 0), (0, 2, 1), (0, 2, 2), (1, 1, 0), (1, 1, 1), (1, 1, 2), (1, 2, 0), (1, 2, 1), (1, 2, 2)\}$

# Truth Sets of Quantifiers

- Given a predicate  $P$  and a domain  $D$ , we define the *truth set* of  $P$  to be the set of elements in  $D$  for which  $P(x)$  is true. The truth set of  $P(x)$  is denoted by

$$\{x \in D \mid P(x)\}$$

- Example:** The truth set of  $P(x)$  where the domain is the integers and  $P(x)$  is “ $|x| = 1$ ” is the set  $\{-1, 1\}$



# Set Operations

## Section 2.2

# Section Summary

- Set Operations
  - Union
  - Intersection
  - Complementation
  - Difference
- More on Set Cardinality
- Set Identities
- Proving Identities
- Membership Tables

# Boolean Algebra

- Propositional calculus and set theory are both instances of an algebraic system called a *Boolean Algebra*. This is discussed in Chapter 12.
- The operators in set theory are analogous to the corresponding operator in propositional calculus.
- As always there must be a universal set  $U$ . All sets are assumed to be subsets of  $U$ .

# Union

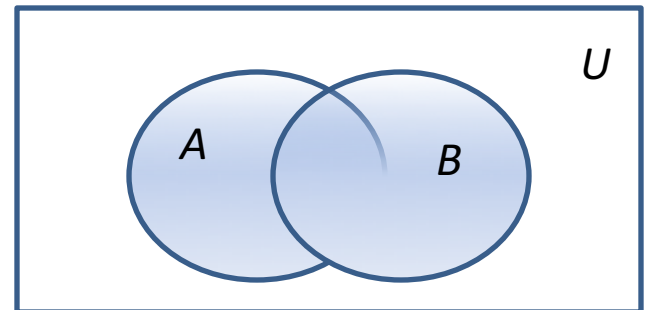
- **Definition:** Let  $A$  and  $B$  be sets. The *union* of the sets  $A$  and  $B$ , denoted by  $A \cup B$ , is the set:

$$\{x | x \in A \vee x \in B\}$$

- **Example:** What is  $\{1,2,3\} \cup \{3, 4, 5\}$ ?

**Solution:**  $\{1,2,3,4,5\}$

Venn Diagram for  $A \cup B$



# Intersection

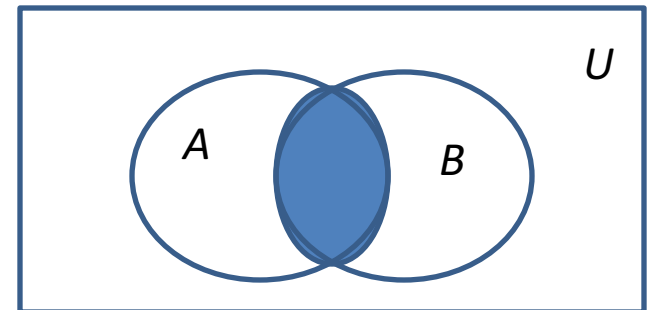
- **Definition:** The *intersection* of sets  $A$  and  $B$ , denoted by  $A \cap B$ , is
$$\{x \mid x \in A \wedge x \in B\}$$
- Note if the intersection is empty, then  $A$  and  $B$  are said to be *disjoint*.
- **Example:** What is?  $\{1,2,3\} \cap \{3,4,5\}$  ?

**Solution:**  $\{3\}$

- **Example:** What is?  
 $\{1,2,3\} \cap \{4,5,6\}$  ?

**Solution:**  $\emptyset$

Venn Diagram for  $A \cap B$



# Complement

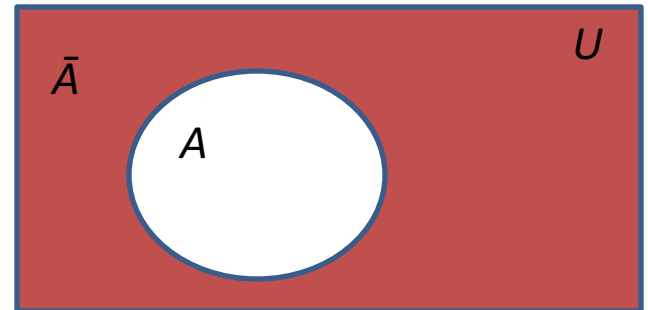
- **Definition:** If  $A$  is a set, then the complement of  $A$  (with respect to  $U$ ), denoted by  $\bar{A}$  is the set  $U - A$

$$\bar{A} = \{x \in U \mid x \notin A\}$$

- The complement of  $A$  is sometimes denoted by  $A^c$ .
- **Example:** If  $U$  is the positive integers less than 100, what is the complement of  $\{x \mid x > 70\}$

Solution:  $\{x \mid x \leq 70\}$

Venn Diagram for Complement

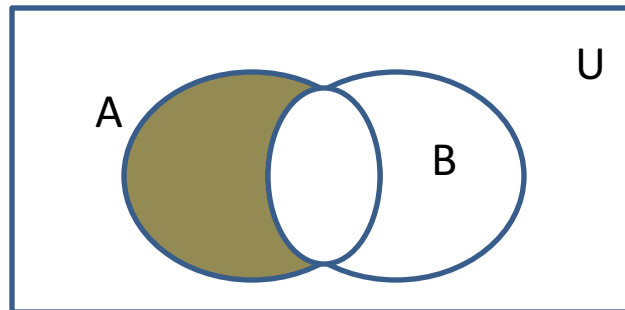


# Difference

- **Definition:** Let  $A$  and  $B$  be sets. The *difference* of  $A$  and  $B$ , denoted by  $A - B$ , is the set containing the elements of  $A$  that are not in  $B$ . The difference of  $A$  and  $B$  is also called the complement of  $B$  with respect to  $A$ .

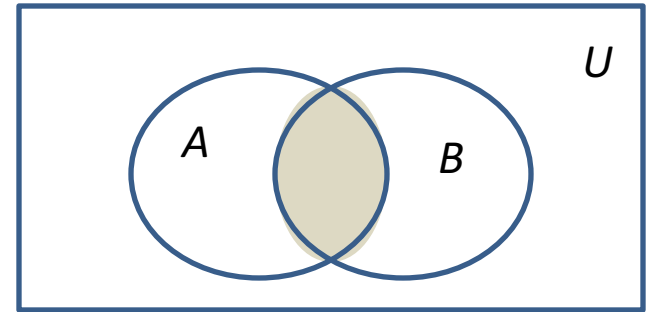
$$A - B = \{x \mid x \in A \wedge x \notin B\} = A \cap \bar{B}$$

Venn Diagram for  $A - B$



# Cardinality of Union of Two Sets

- Inclusion-Exclusion  
 $|A \cup B| = |A| + |B| - |A \cap B|$



Venn Diagram for  $A$ ,  $B$ ,  $A \cap B$ ,  $A \cup B$

- **Example:** Let  $A$  be the math majors in your class and  $B$  be the CS majors. To count the number of students who are either math majors or CS majors, add the number of math majors and the number of CS majors, and subtract the number of joint CS/math majors.
- We will return to this principle in Chapter 6 and Chapter 8 where we will derive a formula for the cardinality of the union of  $n$  sets, where  $n$  is a positive integer.

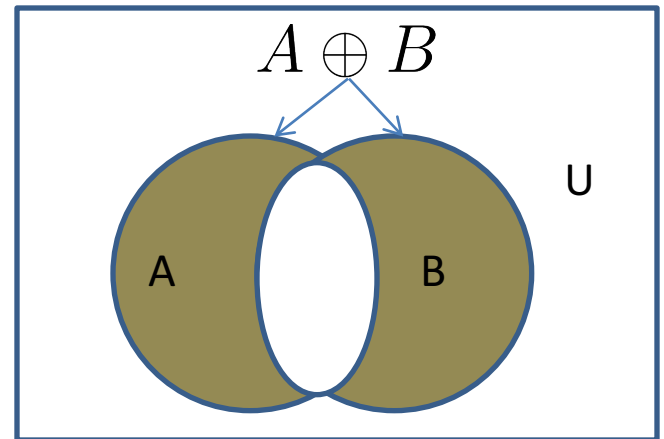


# Review Questions

- **Example:**  $U = \{0,1,2,3,4,5,6,7,8,9,10\}$ ,  
 $A = \{1,2,3,4,5\}$ ,  $B = \{4,5,6,7,8\}$ 
  - $A \cup B$ :                      **Solution:**  $\{1,2,3,4,5,6,7,8\}$
  - $A \cap B$ :                      **Solution:**  $\{4,5\}$
  - $\bar{A}$ :                              **Solution:**  $\{0,1,2,3,9,10\}$
  - $A - B$ :                        **Solution:**  $\{1,2,3\}$
  - $B - A$ :                        **Solution:**  $\{6,7,8\}$

# Symmetric Difference (*optional*)

- **Definition:** The *symmetric difference* of **A** and **B**, denoted by  $A \oplus B$  is the set.
- **Example:**
  - $U = \{0,1,2,3,4,5,6,7,8,9,10\}$
  - $A = \{1,2,3,4,5\}$     $B = \{4,5,6,7,8\}$
  - What is  $A \oplus B$  :
  - **Solution:**  $\{1,2,3,6,7,8\}$



Venn Diagram

# Set Identities

- Identity laws

$$A \cup \emptyset = A \quad A \cap U = A$$

- Domination laws

$$A \cup U = U \quad A \cap \emptyset = \emptyset$$

- Idempotent laws

$$A \cup A = A \quad A \cap A = A$$

- Complementation law

$$\overline{(\overline{A})} = A$$

*Continued on next slide →*

# Set Identities

- Commutative laws

$$A \cup B = B \cup A \quad A \cap B = B \cap A$$

- Associative laws

$$A \cup (B \cup C) = (A \cup B) \cup C$$

$$A \cap (B \cap C) = (A \cap B) \cap C$$

- Distributive laws

$$A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$$

$$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$$

*Continued on next slide →*

# Set Identities

- De Morgan's laws

$$\overline{A \cup B} = \overline{A} \cap \overline{B} \qquad \overline{A \cap B} = \overline{A} \cup \overline{B}$$

- Absorption laws

$$A \cup (A \cap B) = A \qquad A \cap (A \cup B) = A$$

- Complement laws

$$A \cup \overline{A} = U \qquad A \cap \overline{A} = \emptyset$$

# Proving Set Identities

- Different ways to prove set identities:
  1. Prove that each set (side of the identity) is a subset of the other.
  2. Use set builder notation and propositional logic.
  3. Membership tables: Verify that elements in the same combination of sets always either belong or do not belong to the same side of the identity. Use 1 to indicate it is in the set and a 0 to indicate that it is not.

# Proof of Second De Morgan Law

- **Example:** Prove that  $\overline{A \cap B} = \overline{A} \cup \overline{B}$
- **Solution:** We prove this identity by showing that:

$$1) \quad \overline{A \cap B} \subseteq \overline{A} \cup \overline{B} \quad \text{and}$$

$$2) \quad \overline{A} \cup \overline{B} \subseteq \overline{A \cap B}$$

*Continued on next slide →*

# Proof of Second De Morgan Law

- These steps show that:  $\overline{A \cap B} \subseteq \overline{A} \cup \overline{B}$

$$x \in \overline{A \cap B}$$

by assumption

$$x \notin A \cap B$$

defn. of complement

$$\neg((x \in A) \wedge (x \in B))$$

defn. of intersection

$$\neg(x \in A) \vee \neg(x \in B)$$

1st De Morgan Law for Prop Logic

$$x \notin A \vee x \notin B$$

defn. of negation

$$x \in \overline{A} \vee x \in \overline{B}$$

defn. of complement

$$x \in \overline{A} \cup \overline{B}$$

defn. of union

*Continued on next slide →*



# Proof of Second De Morgan Law

- These steps show that:  $\overline{A} \cup \overline{B} \subseteq \overline{A \cap B}$

$$x \in \overline{A} \cup \overline{B}$$

by assumption

$$(x \in \overline{A}) \vee (x \in \overline{B})$$

defn. of union

$$(x \notin A) \vee (x \notin B)$$

defn. of complement

$$\neg(x \in A) \vee \neg(x \in B)$$

defn. of negation

$$\neg((x \in A) \wedge (x \in B))$$

by 1st De Morgan Law for Prop Logic

$$\neg(x \in A \cap B)$$

defn. of intersection

$$x \in \overline{A \cap B}$$

defn. of complement



# Set-Builder Notation: Second De Morgan Law

$$\begin{aligned}\overline{A \cap B} &= \{x | x \notin A \cap B\} && \text{by defn. of complement} \\ &= \{x | \neg(x \in (A \cap B))\} && \text{by defn. of does not belong symbol} \\ &= \{x | \neg(x \in A \wedge x \in B)\} && \text{by defn. of intersection} \\ &= \{x | \neg(x \in A) \vee \neg(x \in B)\} && \text{by 1st De Morgan law} \\ &&& \text{for Prop Logic} \\ &= \{x | x \notin A \vee x \notin B\} && \text{by defn. of not belong symbol} \\ &= \{x | x \in \overline{A} \vee x \in \overline{B}\} && \text{by defn. of complement} \\ &= \{x | x \in \overline{A} \cup \overline{B}\} && \text{by defn. of union} \\ &= \overline{A} \cup \overline{B} && \text{by meaning of notation}\end{aligned}$$



# Membership Table

- **Example:** Construct a membership table to show that the distributive law holds.

$$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$$

- **Solution:**

A	B	C	$B \cap C$	$A \cup (B \cap C)$	$A \cup B$	$A \cup C$	$(A \cup B) \cap (A \cup C)$
1	1	1	1	1	1	1	1
1	1	0	0	1	1	1	1
1	0	1	0	1	1	1	1
1	0	0	0	1	1	1	1
0	1	1	1	1	1	1	1
0	1	0	0	0	1	0	0
0	0	1	0	0	0	1	0
0	0	0	0	0	0	0	0

# Generalized Unions and Intersections

- Let  $A_1, A_2, \dots, A_n$  be an indexed collection of sets.

We define:

$$\bigcup_{i=1}^n A_i = A_1 \cup A_2 \cup \dots \cup A_n$$
$$\bigcap_{i=1}^n A_i = A_1 \cap A_2 \cap \dots \cap A_n$$

These are well defined, since union and intersection are associative.

- For  $i = 1, 2, \dots$ , let  $A_i = \{i, i + 1, i + 2, \dots\}$ . Then,

$$\bigcup_{i=1}^n A_i = \bigcup_{i=1}^n \{i, i + 1, i + 2, \dots\} = \{1, 2, 3, \dots\}$$

$$\bigcap_{i=1}^n A_i = \bigcap_{i=1}^n \{i, i + 1, i + 2, \dots\} = \{n, n + 1, n + 2, \dots\} = A_n$$