

# Basic Structures: Sets, Functions, Sequences, Sums, and Matrices

Chapter 2

# 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
- 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

- $S = \{a,b,c,d\}$
- 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.

$$S = \{a,b,c,d\} = \{a,b,c,b,c,d\}$$

- Ellipsis (three-dots) 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

**N** = *natural numbers* = {0,1,2,3,...}

**Z** = *integers* = {...,-3,-2,-1,0,1,2,3,...}

**Z<sup>+</sup>** = *positive integers* = {1,2,3,.....}

**R** = set of *real numbers*

**R<sup>+</sup>** = set of *positive real numbers*

**C** = set of *complex numbers.*

**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

$$[a,b] = \{x \mid a \leq x \leq b\}$$

$$[a,b) = \{x \mid a \leq x < b\}$$

$$(a,b] = \{x \mid a < x \leq b\}$$

$$(a,b) = \{x \mid a < x < b\}$$

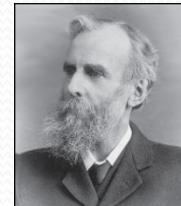
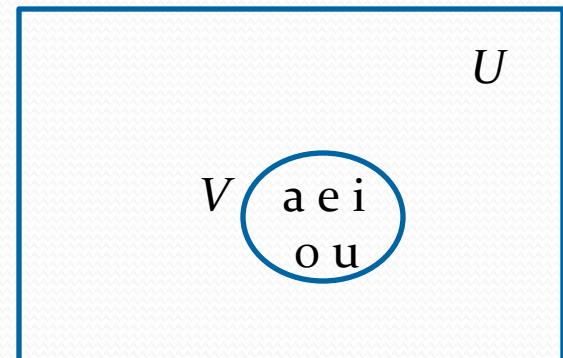
*closed interval* [a,b]

*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 by  $\emptyset$ .

Venn Diagram



John Venn (1834-1923)  
Cambridge, UK

# Russell's Paradox

- Let  $S$  be the set of all sets which are not members of themselves. A paradox results from trying to answer the question “Is  $S$  a member of itself?”
- Related Paradox:
  - Henry is a barber who shaves all people who do not shave themselves. A paradox results from trying to answer the question “Does Henry shave himself?”



Bertrand Russell (1872-1970)  
Cambridge, UK  
Nobel Prize Winner

# Some things to remember

- Sets can be elements of sets.

$$\{\{1,2,3\}, a, \{b,c\}\}$$

$$\{\mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{R}\}$$

- 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.

$$\{1,3,5\} = \{3, 5, 1\}$$

$$\{1,5,5,5,3,3,1\} = \{1,3,5\}$$

# Subsets

**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

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

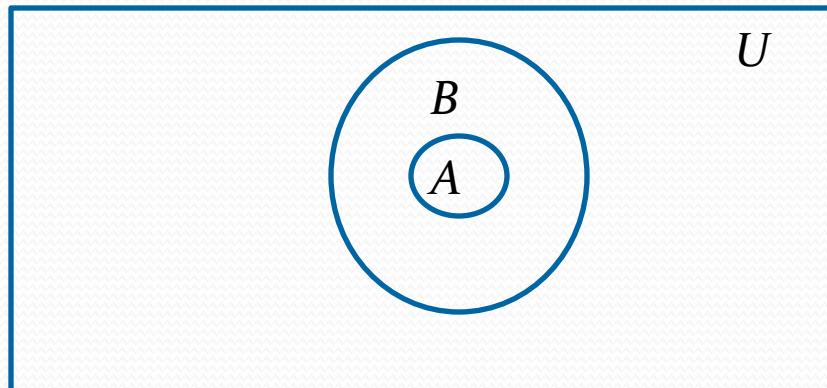
# Proper Subsets

**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  $P(A)$ , is called the *power set* of  $A$ .

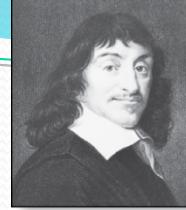
**Example:** If  $A = \{a,b\}$  then

$$\mathcal{P}(A) = \{\emptyset, \{a\}, \{b\}, \{a,b\}\}$$

- If a set has  $n$  elements, then the cardinality of the power set is  $2^n$ . (In Chapters 5 and 6, 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:**  $A \times B \times C = \{(0,1,0), (0,1,1), (0,1,2), (0,2,0), (0,2,1), (0,2,2), (1,1,0), (1,1,1), (1,1,2), (1,2,0), (1,2,1), (1,1,2)\}$

# 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 CS2209.
- 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

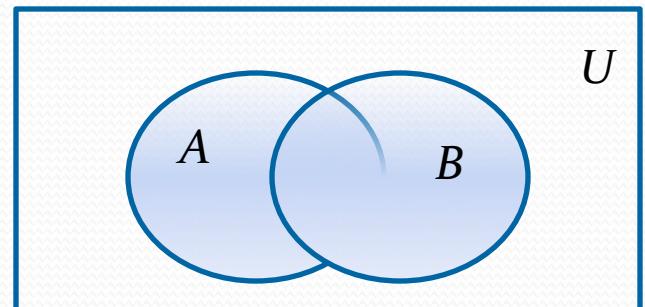
- **Definition:** Let  $A$  and  $B$  be sets. The *union* of the sets  $A$  and  $B$ , denoted by  $A \cup B$ , is the set:

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

- **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

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

- Note if the intersection is empty, then  $A$  and  $B$  are said to be *disjoint*.

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

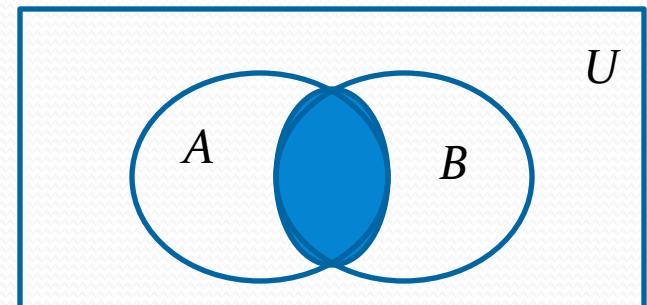
Solution: {3}

- **Example:** What is

$$\{1,2,3\} \cap \{4,5,6\} ?$$

Solution:  $\emptyset$

Venn Diagram for  $A \cap B$



# Complement

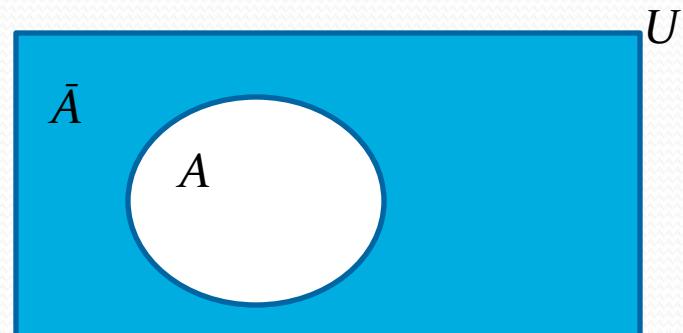
**Definition:** If  $A$  is a set, then the complement of the  $A$  (with respect to  $U$ ), denoted by  $\bar{A}$  is the set  $U - A$

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

(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  $\{x \mid x > 70\}$

Venn Diagram for Complement



# Complement

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

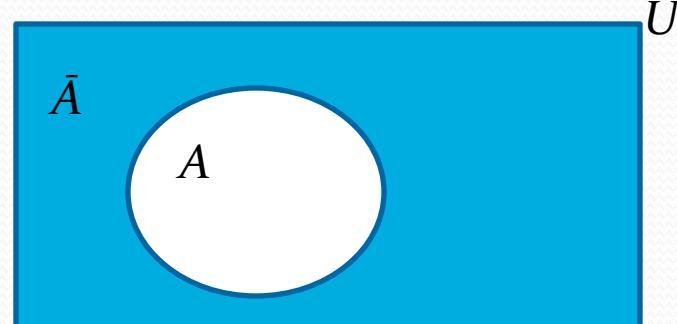
$$\bar{A} = \{x \in U \mid x \notin A\}$$

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

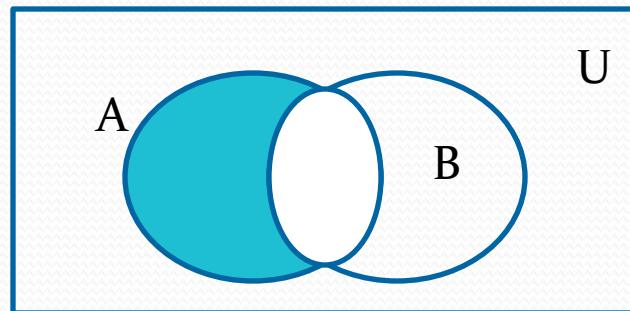
Venn Diagram for Complement



# 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  $A$ .

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

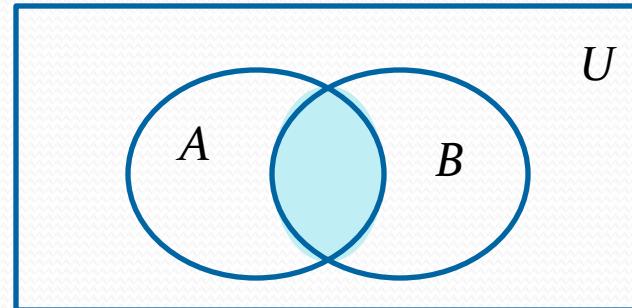


Venn Diagram for  $A - B$

# The Cardinality of the 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:**  $U = \{0,1,2,3,4,5,6,7,8,9,10\}$   $A = \{1,2,3,4,5\}$ ,  $B = \{4,5,6,7,8\}$

1.  $A \cup B$

2.  $A \cap B$

3.  $\bar{A}$

4.  $\bar{B}$

5.  $A - B$

6.  $B - A$

# Review Questions

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

1.  $A \cup B$

**Solution:**  $\{1,2,3,4,5,6,7,8\}$

2.  $A \cap B$

**Solution:**  $\{4,5\}$

3.  $\bar{A}$

**Solution:**  $\{0,6,7,8,9,10\}$

4.  $\bar{B}$

**Solution:**  $\{0,1,2,3,9,10\}$

5.  $A - B$

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

6.  $B - A$

**Solution:**  $\{6,7,8\}$

# 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

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

- 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

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

- Absorption laws

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

- Complement laws

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

# Proving Set Identities

- Prove that each set (side of the identity) is a subset of the other.
- Use definitions and propositional logic

# 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)  $\overline{A \cap B} \subseteq \overline{A} \cup \overline{B}$  and

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

*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:

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

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

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

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

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

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

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

$$\overline{A} \cup \overline{B} \subseteq \overline{A \cap B}$$

by assumption

defn. of union

defn. of complement

defn. of negation

by 1st De Morgan Law for Prop Logic

defn. of intersection

defn. of complement



# 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,

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

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

# Computer Representation of Sets

- Assume the universal set  $U$  is finite (not larger than the memory size of the computer being used)
- First specify an arbitrary ordering of the elements in  $U$ , for instance  $a_1, a_2, \dots, a_n$
- Represent a subset  $A$  of  $U$  with the bit string of length  $n$ , where the  $i$ th bit is 1 if  $a_i$  belongs to  $A$  and is 0 if  $a_i$  does not belong to  $A$
- Example: Let  $U = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$ , and the ordering of  $U$  has the elements in the increasing order.

What bit strings represent the subset of all odd integers?

What bit string represents the set of all even integers?

What bit string represents the subset of integers not exceeding 5 in  $U$ ?

What is the bit string that represents the complement of a subset?

What is the bit string that represents the union of two subsets?

What is the bit string that represents the intersection of two subsets?

# Functions

Section 2.3

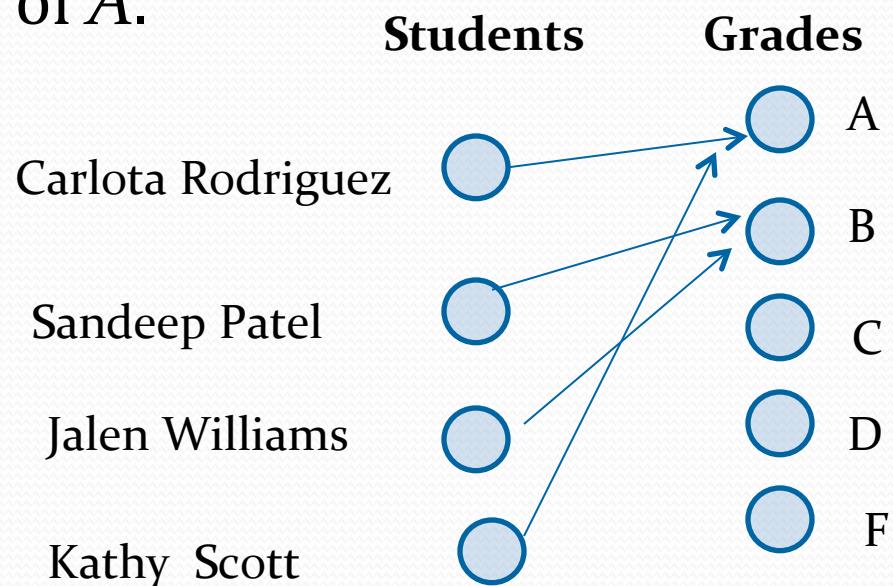
# Section Summary

- Definition of a Function.
  - Domain, Codomain
  - Image, Preimage
- Injection, Surjection, Bijection
- Inverse Function
- Function Composition
- Graphing Functions
- Floor, Ceiling, Factorial
- Partial functions

# Functions

**Definition:** Let  $A$  and  $B$  be nonempty sets. A *function*  $f$  from  $A$  to  $B$ , denoted  $f: A \rightarrow B$  is an assignment of each element of  $A$  to exactly one element of  $B$ . We write  $f(a) = b$  if  $b$  is the unique element of  $B$  assigned by the function  $f$  to the element  $a$  of  $A$ .

- Functions are sometimes called *mappings* or *transformations*.



# Functions

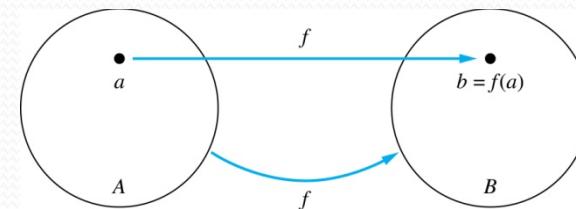
- A function  $f: A \rightarrow B$  can also be defined as a subset of  $A \times B$  (a relation). This subset is restricted to be a relation where no two elements of the relation have the same first element.
- Specifically, a function  $f$  from  $A$  to  $B$  contains one, and only one ordered pair  $(a, b)$  for every element  $a \in A$ .  
$$\forall x[x \in A \rightarrow \exists y[y \in B \wedge (x, y) \in f]]$$

and  $\forall x, y_1, y_2[((x, y_1) \in f \wedge (x, y_2)) \rightarrow y_1 = y_2]$

# Functions

Given a function  $f: A \rightarrow B$ :

- We say  $f$  maps  $A$  to  $B$  or  $f$  is a *mapping* from  $A$  to  $B$ .
- $A$  is called the *domain* of  $f$ .
- $B$  is called the *codomain* of  $f$ .
- If  $f(a) = b$ ,
  - then  $b$  is called the *image* of  $a$  under  $f$ .
  - $a$  is called the *preimage* of  $b$ .
- The range of  $f$  is the set of all images of points in  $A$  under  $f$ . We denote it by  $f(A)$ .
- Two functions are *equal* when they have the same domain, the same codomain and map each element of the domain to the same element of the codomain.



# Representing Functions

- Functions may be specified in different ways:
  - An explicit statement of the assignment.  
Students and grades example.
  - A formula.  
$$f(x) = x + 1$$
  - A computer program.
    - A Java program that when given an integer  $n$ , produces the  $n$ th Fibonacci Number (covered in the next section and also in Chapter 5).

# Questions

$f(a) = ?$

The image of d is ?

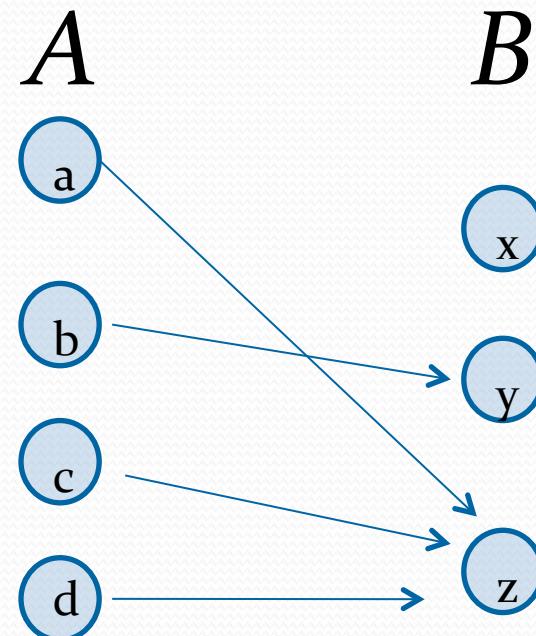
The domain of f is ?

The codomain of f is ?

The preimage of y is ?

$f(A) = ?$

The preimage(s) of z is (are) ?



# Questions

$f(a) = ? \quad z$

The image of d is ?  $z$

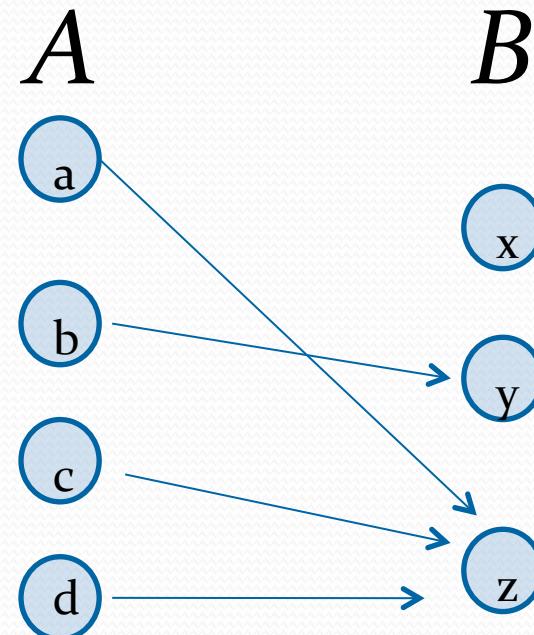
The domain of f is ?  $A$

The codomain of f is ?  $B$

The preimage of y is ?  $b$

$f(A) = ? \quad \{y, z\}$

The preimage(s) of z is (are) ?  $\{a,c,d\}$



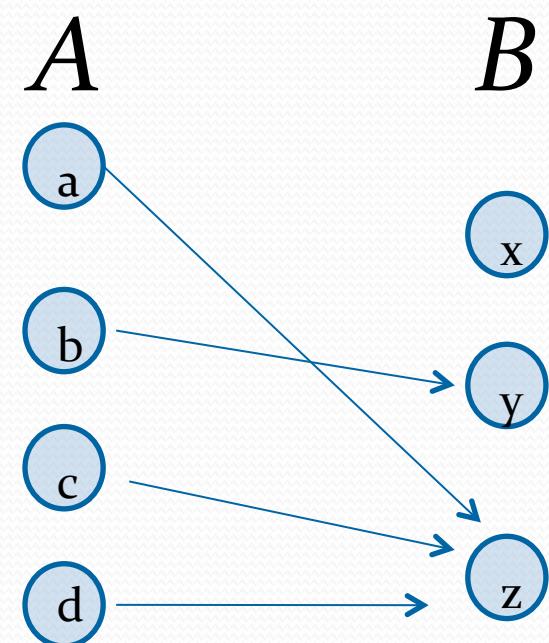
# Question on Functions and Sets

- If  $f : A \rightarrow B$  and  $S$  is a subset of  $A$ , then

$$f(S) = \{f(s) | s \in S\}$$

$f\{a,b,c,\}$  is ?

$f\{c,d\}$  is ?



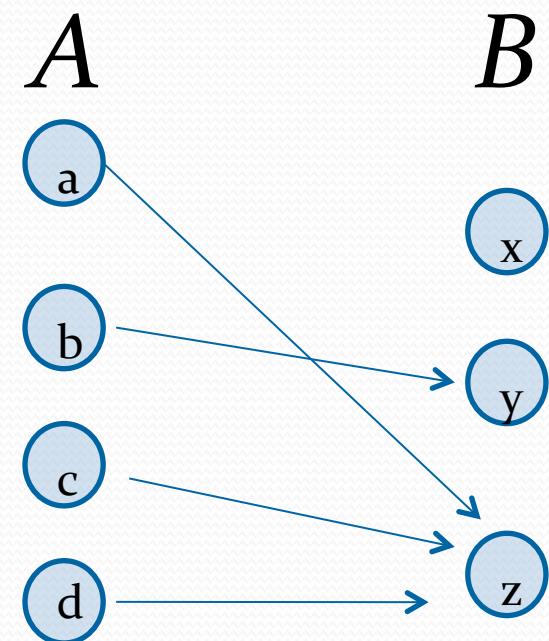
# Question on Functions and Sets

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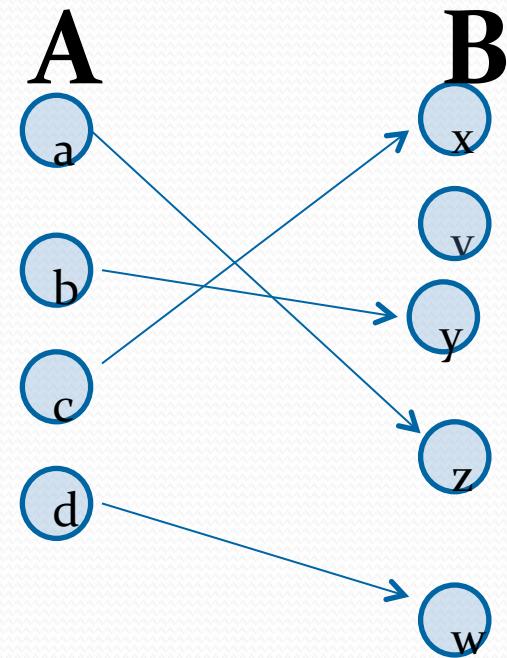
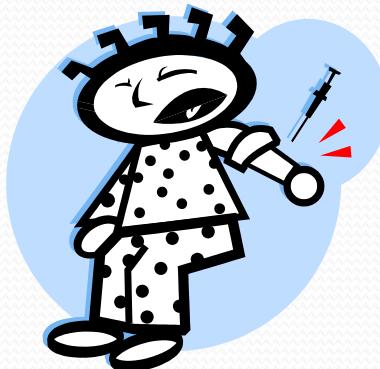
$f\{a,b,c,\}$  is ?     $\{y,z\}$

$f\{c,d\}$  is ?     $\{z\}$



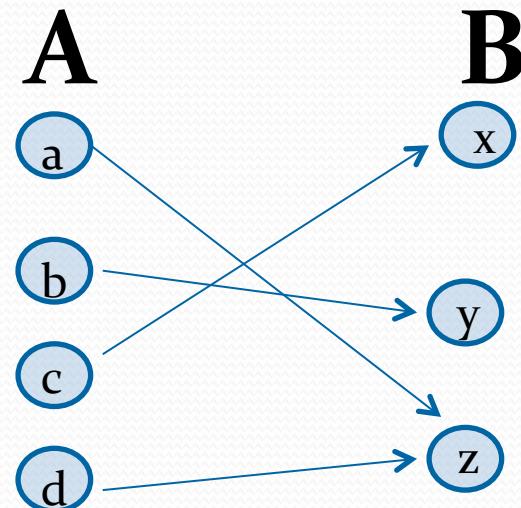
# Injections

**Definition:** A function  $f$  is said to be *one-to-one*, or *injective*, if and only if  $f(a) = f(b)$  implies that  $a = b$  for all  $a$  and  $b$  in the domain of  $f$ . A function is said to be an *injection* if it is one-to-one.



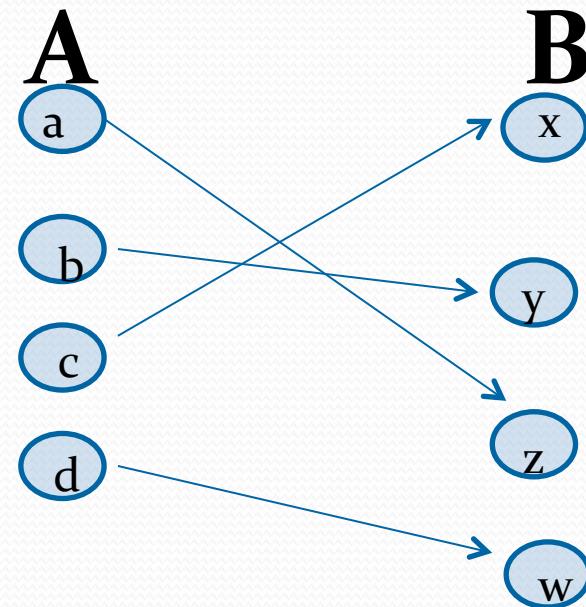
# Surjections

**Definition:** A function  $f$  from  $A$  to  $B$  is called *onto* or *surjective*, if and only if for every element  $b \in B$  there is an element  $a \in A$  with  $f(a) = b$ . A function  $f$  is called a *surjection* if it is onto.



# Bijections

**Definition:** A function  $f$  is a *one-to-one correspondence*, or a *bijection*, if it is both one-to-one and onto (surjective and injective).



# Showing that $f$ is one-to-one or onto

Suppose that  $f : A \rightarrow B$ .

*To show that  $f$  is injective* Show that if  $f(x) = f(y)$  for arbitrary  $x, y \in A$  with  $x \neq y$ , then  $x = y$ .

*To show that  $f$  is not injective* Find particular elements  $x, y \in A$  such that  $x \neq y$  and  $f(x) = f(y)$ .

*To show that  $f$  is surjective* Consider an arbitrary element  $y \in B$  and find an element  $x \in A$  such that  $f(x) = y$ .

*To show that  $f$  is not surjective* Find a particular  $y \in B$  such that  $f(x) \neq y$  for all  $x \in A$ .

## Showing that $f$ is one-to-one or onto

**Example 1:** Let  $f$  be the function from  $\{a,b,c,d\}$  to  $\{1,2,3\}$  defined by  $f(a) = 3$ ,  $f(b) = 2$ ,  $f(c) = 1$ , and  $f(d) = 3$ . Is  $f$  an onto function?

**Example 2:** Is the function  $f(x) = x^2$  from the set of integers onto?

## Showing that $f$ is one-to-one or onto

**Example 1:** Let  $f$  be the function from  $\{a,b,c,d\}$  to  $\{1,2,3\}$  defined by  $f(a) = 3$ ,  $f(b) = 2$ ,  $f(c) = 1$ , and  $f(d) = 3$ . Is  $f$  an onto function?

**Solution:** Yes,  $f$  is onto since all three elements of the codomain are images of elements in the domain. If the codomain were changed to  $\{1,2,3,4\}$ ,  $f$  would not be onto.

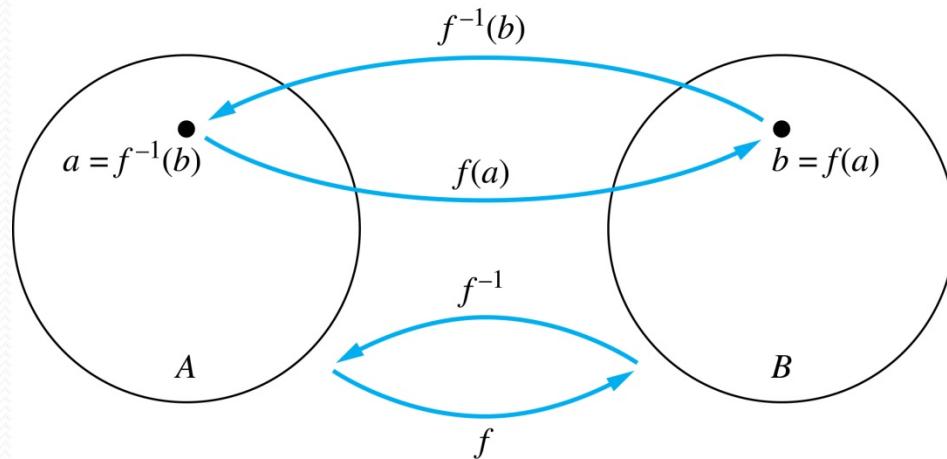
**Example 2:** Is the function  $f(x) = x^2$  from the set of integers onto?

**Solution:** No,  $f$  is not onto because there is no integer  $x$  with  $x^2 = -1$ , for example.

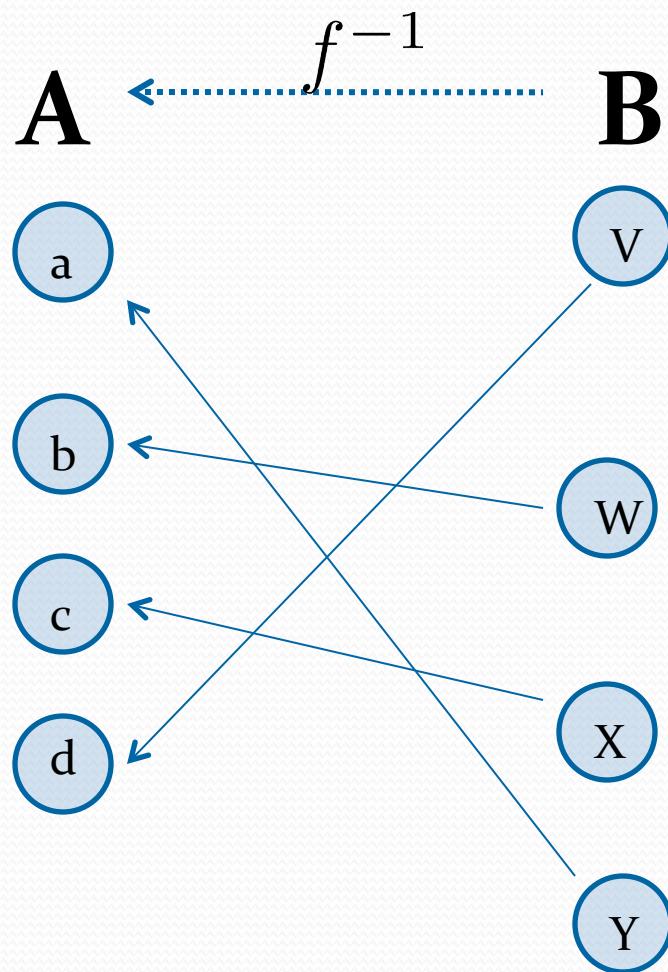
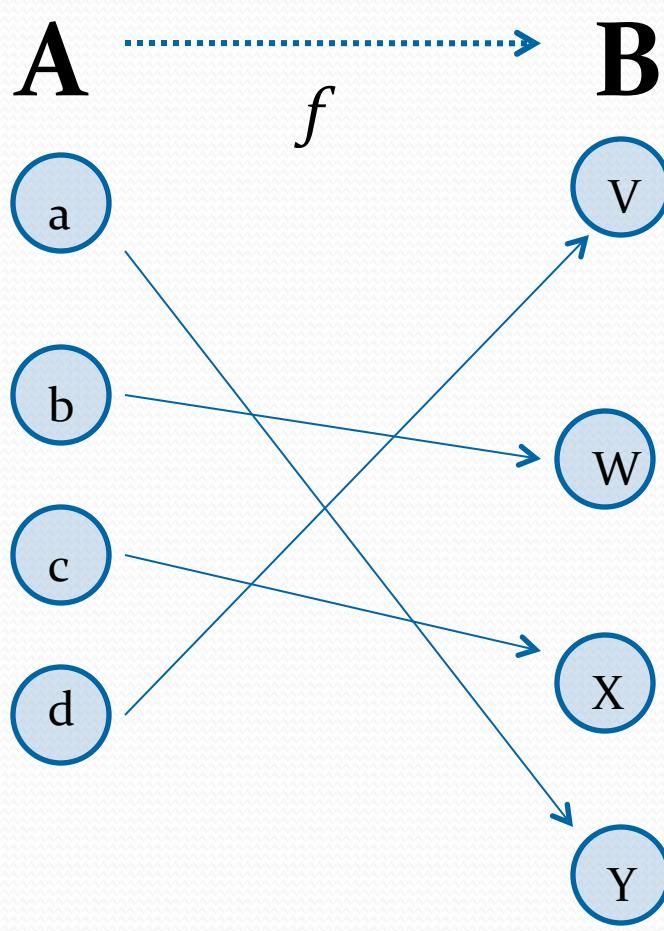
# Inverse Functions

**Definition:** Let  $f$  be a bijection from  $A$  to  $B$ . Then the *inverse* of  $f$ , denoted  $f^{-1}$ , is the function from  $B$  to  $A$  defined as  $f^{-1}(y) = x$  iff  $f(x) = y$

No inverse exists unless  $f$  is a bijection. Why?



# Inverse Functions



# Questions

**Example 1:** Let  $f$  be the function from  $\{a,b,c\}$  to  $\{1,2,3\}$  such that  $f(a) = 2$ ,  $f(b) = 3$ , and  $f(c) = 1$ . Is  $f$  invertible and if so what is its inverse?

# Questions

**Example 1:** Let  $f$  be the function from  $\{a,b,c\}$  to  $\{1,2,3\}$  such that  $f(a) = 2$ ,  $f(b) = 3$ , and  $f(c) = 1$ . Is  $f$  invertible and if so what is its inverse?

**Solution:** The function  $f$  is invertible because it is a one-to-one correspondence. The inverse function  $f^{-1}$  reverses the correspondence given by  $f$ , so  $f^{-1}(1) = c$ ,  $f^{-1}(2) = a$ , and  $f^{-1}(3) = b$ .

# Questions

**Example 2:** Let  $f: \mathbf{Z} \rightarrow \mathbf{Z}$  be such that  $f(x) = x + 1$ . Is  $f$  invertible, and if so, what is its inverse?

# Questions

**Example 2:** Let  $f: \mathbf{Z} \rightarrow \mathbf{Z}$  be such that  $f(x) = x + 1$ . Is  $f$  invertible, and if so, what is its inverse?

**Solution:** The function  $f$  is invertible because it is a one-to-one correspondence. The inverse function  $f^{-1}$  reverses the correspondence so  $f^{-1}(y) = y - 1$ .

# Questions

**Example 3:** Let  $f: \mathbf{R} \rightarrow \mathbf{R}$  be such that  $f(x) = x^2$ . Is  $f$  invertible, and if so, what is its inverse?

# Questions

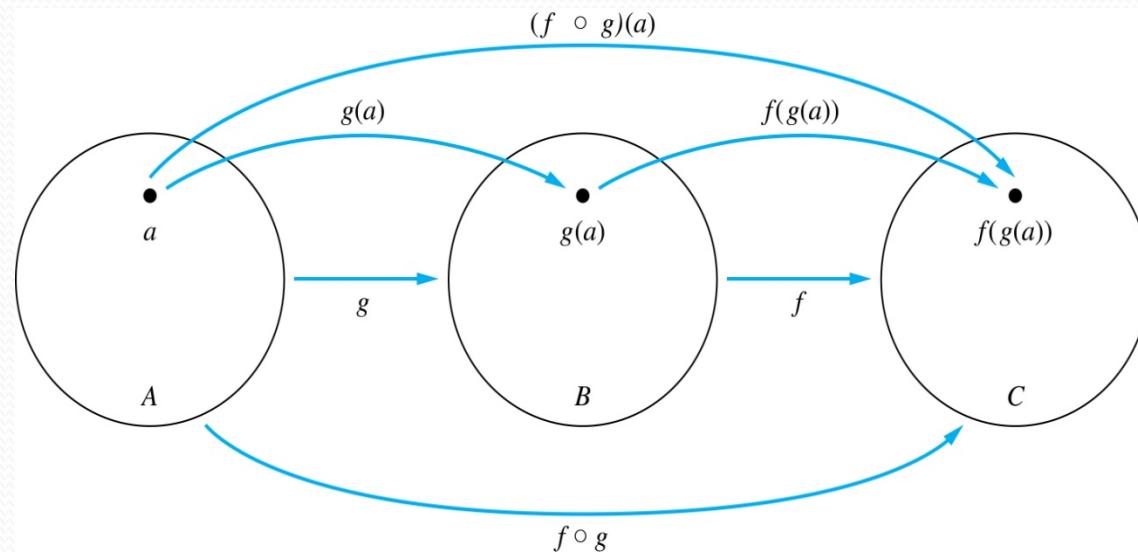
**Example 3:** Let  $f: \mathbf{R} \rightarrow \mathbf{R}$  be such that  $f(x) = x^2$ . Is  $f$  invertible, and if so, what is its inverse?

**Solution:** The function  $f$  is not invertible because it is not one-to-one .

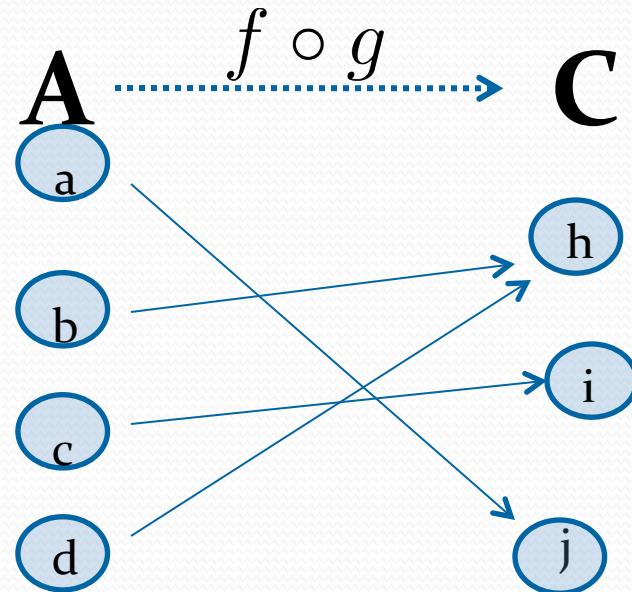
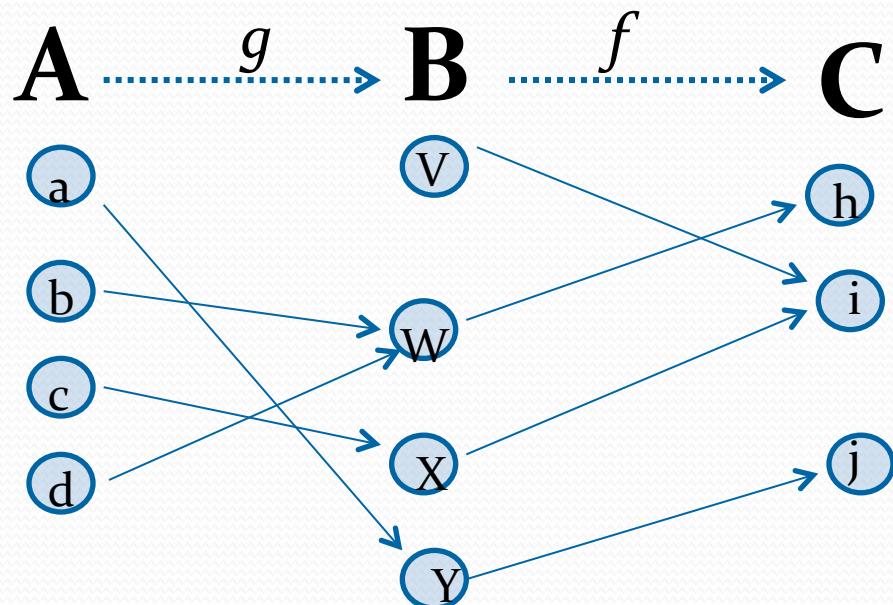
# Composition

- **Definition:** Let  $f: B \rightarrow C$ ,  $g: A \rightarrow B$ . The *composition of  $f$  with  $g$* , denoted  $f \circ g$  is the function from  $A$  to  $C$  defined by

$$f \circ g(x) = f(g(x))$$



# Composition



# Composition

**Example 1:** If  $f(x) = x^2$  and  $g(x) = 2x + 1$  ,  
then

$$f(g(x)) = (2x + 1)^2$$

and

$$g(f(x)) = 2x^2 + 1$$

# Composition Questions

**Example 2:** Let  $g$  be the function from the set  $\{a,b,c\}$  to itself such that  $g(a) = b$ ,  $g(b) = c$ , and  $g(c) = a$ . Let  $f$  be the function from the set  $\{a,b,c\}$  to the set  $\{1,2,3\}$  such that  $f(a) = 3$ ,  $f(b) = 2$ , and  $f(c) = 1$ .

What is the composition of  $f$  and  $g$ , and what is the composition of  $g$  and  $f$ .

# Composition Questions

**Example 2:** Let  $g$  be the function from the set  $\{a,b,c\}$  to itself such that  $g(a) = b$ ,  $g(b) = c$ , and  $g(c) = a$ . Let  $f$  be the function from the set  $\{a,b,c\}$  to the set  $\{1,2,3\}$  such that  $f(a) = 3$ ,  $f(b) = 2$ , and  $f(c) = 1$ .

What is the composition of  $f$  and  $g$ , and what is the composition of  $g$  and  $f$ .

**Solution:** The composition  $f \circ g$  is defined by

$$f \circ g (a) = f(g(a)) = f(b) = 2.$$

$$f \circ g (b) = f(g(b)) = f(c) = 1.$$

$$f \circ g (c) = f(g(c)) = f(a) = 3.$$

Note that  $g \circ f$  is not defined, because the range of  $f$  is not a subset of the domain of  $g$ .

# Composition Questions

**Example 2:** Let  $f$  and  $g$  be functions from the set of integers to the set of integers defined by  $f(x) = 2x + 3$  and  $g(x) = 3x + 2$ .

What is the composition of  $f$  and  $g$ , and also the composition of  $g$  and  $f$ ?

# Composition Questions

**Example 2:** Let  $f$  and  $g$  be functions from the set of integers to the set of integers defined by  $f(x) = 2x + 3$  and  $g(x) = 3x + 2$ .

What is the composition of  $f$  and  $g$ , and also the composition of  $g$  and  $f$ ?

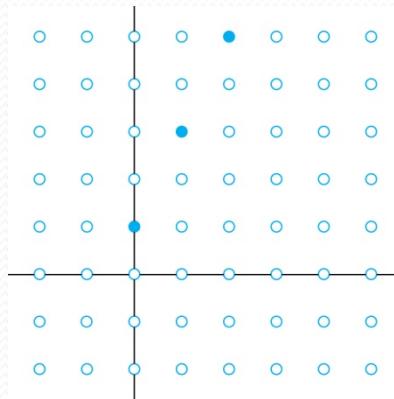
**Solution:**

$$f \circ g (x) = f(g(x)) = f(3x + 2) = 2(3x + 2) + 3 = 6x + 7$$

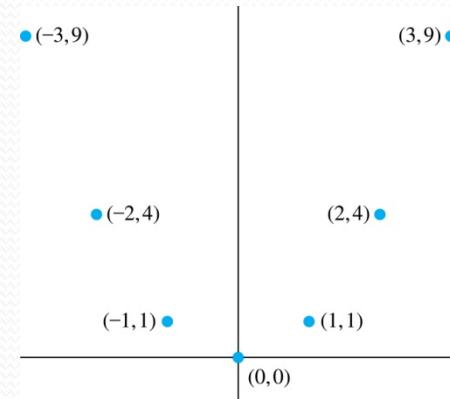
$$g \circ f (x) = g(f(x)) = g(2x + 3) = 3(2x + 3) + 2 = 6x + 11$$

# Graphs of Functions

- Let  $f$  be a function from the set  $A$  to the set  $B$ . The *graph* of the function  $f$  is the set of ordered pairs  $\{(a,b) \mid a \in A \text{ and } f(a) = b\}$ .



Graph of  $f(n) = 2n + 1$   
from  $\mathbb{Z}$  to  $\mathbb{Z}$



Graph of  $f(x) = x^2$   
from  $\mathbb{Z}$  to  $\mathbb{Z}$

# Some Important Functions

- The *floor* function, denoted

$$f(x) = \lfloor x \rfloor$$

is the largest integer less than or equal to  $x$ .

- The *ceiling* function, denoted

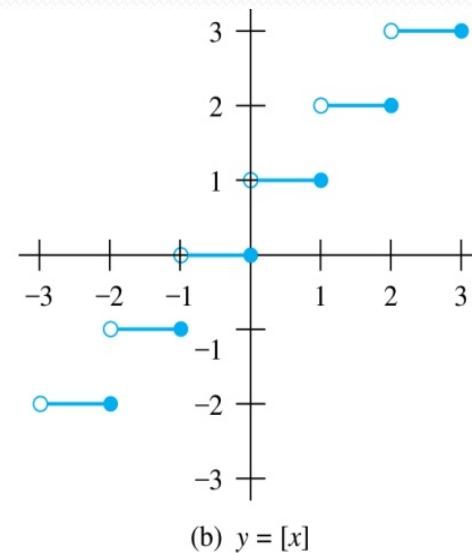
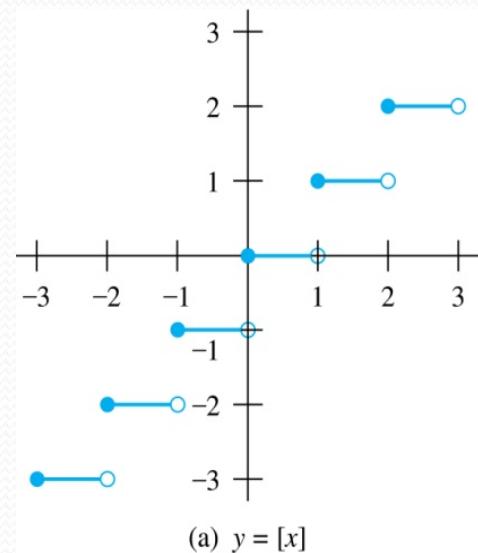
$$f(x) = \lceil x \rceil$$

is the smallest integer greater than or equal to  $x$

**Example:**  $\lceil 3.5 \rceil = 4$        $\lfloor 3.5 \rfloor = 3$

$$\lceil -1.5 \rceil = -1 \quad \lfloor -1.5 \rfloor = -2$$

# Floor and Ceiling Functions



Graph of (a) Floor and (b) Ceiling Functions

# Floor and Ceiling Functions

**TABLE 1** Useful Properties of the Floor and Ceiling Functions.

( $n$  is an integer,  $x$  is a real number)

(1a)  $\lfloor x \rfloor = n$  if and only if  $n \leq x < n + 1$

(1b)  $\lceil x \rceil = n$  if and only if  $n - 1 < x \leq n$

(1c)  $\lfloor x \rfloor = n$  if and only if  $x - 1 < n \leq x$

(1d)  $\lceil x \rceil = n$  if and only if  $x \leq n < x + 1$

(2)  $x - 1 < \lfloor x \rfloor \leq x \leq \lceil x \rceil < x + 1$

(3a)  $\lfloor -x \rfloor = -\lceil x \rceil$

(3b)  $\lceil -x \rceil = -\lfloor x \rfloor$

(4a)  $\lfloor x + n \rfloor = \lfloor x \rfloor + n$

(4b)  $\lceil x + n \rceil = \lceil x \rceil + n$

# Computer Applications of Floor and Ceiling Functions

- Example: Data stored on a computer or transmitted over a network are represented as a string of *bytes*. Each *byte* consists of *8 bits*. How many bytes are required to encode 100 bits of data?
- Example: In asynchronous transfer mode (ATM) (a communication protocol used in backbone networks), data are organized into *cells* of 53 bytes. How many *ATM cells* can be transmitted in 1 minute over a connection that transmits data at a rate of 500 kilobits per second?

# Proving Properties of Functions

**Example:** Prove that  $x$  is a real number, then

$$\lfloor 2x \rfloor = \lfloor x \rfloor + \lfloor x + \frac{1}{2} \rfloor$$

# Proving Properties of Functions

**Example:** Prove that  $x$  is a real number, then

$$\lfloor 2x \rfloor = \lfloor x \rfloor + \lfloor x + 1/2 \rfloor$$

**Solution:** Let  $x = n + \varepsilon$ , where  $n$  is an integer and  $0 \leq \varepsilon < 1$ .

*Case 1:*  $\varepsilon < 1/2$

- $2x = 2n + 2\varepsilon$  and  $\lfloor 2x \rfloor = 2n$ , since  $0 \leq 2\varepsilon < 1$ .
- $\lfloor x + 1/2 \rfloor = n$ , since  $x + 1/2 = n + (1/2 + \varepsilon)$  and  $0 \leq 1/2 + \varepsilon < 1$ .
- Hence,  $\lfloor 2x \rfloor = 2n$  and  $\lfloor x \rfloor + \lfloor x + 1/2 \rfloor = n + n = 2n$ .

*Case 2:*  $\varepsilon \geq 1/2$

- $2x = 2n + 2\varepsilon = (2n + 1) + (2\varepsilon - 1)$  and  $\lfloor 2x \rfloor = 2n + 1$ , since  $0 \leq 2\varepsilon - 1 < 1$ .
- $\lfloor x + 1/2 \rfloor = \lfloor n + (1/2 + \varepsilon) \rfloor = \lfloor n + 1 + (\varepsilon - 1/2) \rfloor = n + 1$  since  $0 \leq \varepsilon - 1/2 < 1$ .
- Hence,  $\lfloor 2x \rfloor = 2n + 1$  and  $\lfloor x \rfloor + \lfloor x + 1/2 \rfloor = n + (n + 1) = 2n + 1$ . ◀

# Factorial Function

**Definition:**  $f: \mathbf{N} \rightarrow \mathbf{Z}^+$ , denoted by  $f(n) = n!$  is the product of the first  $n$  positive integers when  $n$  is a nonnegative integer.

$$f(n) = 1 \cdot 2 \cdots (n - 1) \cdot n, \quad f(0) = 0! = 1$$

## Examples:

$$f(1) = 1! = 1$$

$$f(2) = 2! = 1 \cdot 2 = 2$$

$$f(6) = 6! = 1 \cdot 2 \cdot 3 \cdot 4 \cdot 5 \cdot 6 = 720$$

$$f(20) = 2,432,902,008,176,640,000.$$

Stirling's Formula:

$$n! \sim \sqrt{2\pi n}(n/e)^n$$

$$f(n) \sim g(n) \doteq \lim_{n \rightarrow \infty} f(n)/g(n) = 1$$

# Partial Functions

**Definition:** A *partial function*  $f$  from a set  $A$  to a set  $B$  is an assignment to each element  $a$  in a subset of  $A$ , called the *domain of definition* of  $f$ , of a unique element  $b$  in  $B$ .

- The sets  $A$  and  $B$  are called the *domain* and *codomain* of  $f$ , respectively.
- We say that  $f$  is *undefined* for elements in  $A$  that are not in the domain of definition of  $f$ .
- When the domain of definition of  $f$  equals  $A$ , we say that  $f$  is a *total function*.

**Example:**  $f: \mathbf{N} \rightarrow \mathbf{R}$  where  $f(n) = \sqrt{n}$  is a partial function from  $\mathbf{Z}$  to  $\mathbf{R}$  where the domain of definition is the set of nonnegative integers. Note that  $f$  is undefined for negative integers.

# Sequences and Summations

Section 2.4

# Section Summary

- Sequences.
  - Examples: Geometric Progression, Arithmetic Progression
- Recurrence Relations
  - Example: Fibonacci Sequence
- Summations

# Introduction

- Sequences are ordered lists of elements.
  - 1, 2, 3, 5, 8
  - 1, 3, 9, 27, 81, .....
- Sequences arise throughout mathematics, computer science, and in many other disciplines, ranging from botany to music.
- We will introduce the terminology to represent sequences and sums of the terms in the sequences.

# Sequences

**Definition:** A *sequence* is a function from a subset of the integers (usually either the set  $\{0, 1, 2, 3, 4, \dots\}$  or  $\{1, 2, 3, 4, \dots\}$ ) to a set  $S$ .

- The notation  $a_n$  is used to denote the image of the integer  $n$ . We can think of  $a_n$  as the equivalent of  $f(n)$  where  $f$  is a function from  $\{0, 1, 2, \dots\}$  to  $S$ . We call  $a_n$  a *term* of the sequence.

# Sequences

**Example:** Consider the sequence  $\{a_n\}$  where

$$a_n = \frac{1}{n} \quad \{a_n\} = \{a_1, a_2, a_3, \dots\}$$

$$1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots$$

# Geometric Progression

**Definition:** A *geometric progression* is a sequence of the form:  $a, ar, ar^2, \dots, ar^n, \dots$

where the *initial term*  $a$  and the *common ratio*  $r$  are real numbers.

## Examples:

1. Let  $a = 1$  and  $r = -1$ . Then:

$$\{b_n\} = \{b_0, b_1, b_2, b_3, b_4, \dots\} = \{1, -1, 1, -1, 1, \dots\}$$

2. Let  $a = 2$  and  $r = 5$ . Then:

$$\{c_n\} = \{c_0, c_1, c_2, c_3, c_4, \dots\} = \{2, 10, 50, 250, 1250, \dots\}$$

3. Let  $a = 6$  and  $r = 1/3$ . Then:

$$\{d_n\} = \{d_0, d_1, d_2, d_3, d_4, \dots\} = \{6, 2, \frac{2}{3}, \frac{2}{9}, \frac{2}{27}, \dots\}$$

# Arithmetic Progression

**Definition:** A *arithmetic progression* is a sequence of the form:  $a, a + d, a + 2d, \dots, a + nd, \dots$

where the *initial term*  $a$  and the *common difference*  $d$  are real numbers.

**Examples:**

1. Let  $a = -1$  and  $d = 4$ :

$$\{s_n\} = \{s_0, s_1, s_2, s_3, s_4, \dots\} = \{-1, 3, 7, 11, 15, \dots\}$$

2. Let  $a = 7$  and  $d = -3$ :

$$\{t_n\} = \{t_0, t_1, t_2, t_3, t_4, \dots\} = \{7, 4, 1, -2, -5, \dots\}$$

3. Let  $a = 1$  and  $d = 2$ :

$$\{u_n\} = \{u_0, u_1, u_2, u_3, u_4, \dots\} = \{1, 3, 5, 7, 9, \dots\}$$

# Sequences Used in Computer Science: Strings

**Definition:** A *string* is a finite sequence of characters from a finite set (an alphabet).

- Sequences of characters or bits are important in computer science.
- The *empty string* is represented by  $\lambda$ .
- The string *abcde* has *length* 5.
- The (bit) string 0011 1100 has length 8.

# Recurrence Relations

**Definition:** A *recurrence relation* for the sequence  $\{a_n\}$  is an equation that expresses  $a_n$  in terms of one or more of the previous terms of the sequence, namely,  $a_0, a_1, \dots, a_{n-1}$ , for all integers  $n$  with  $n \geq n_0$ , where  $n_0$  is a nonnegative integer.

- A sequence is called a *solution* of a recurrence relation if its terms satisfy the recurrence relation.
- The *initial conditions* for a sequence specify the terms that precede the first term where the recurrence relation takes effect.

# Questions about Recurrence Relations

**Example 1:** Let  $\{a_n\}$  be a sequence that satisfies the recurrence relation  $a_n = a_{n-1} + 3$  for  $n = 1, 2, 3, 4, \dots$  and suppose that  $a_0 = 2$ . What are  $a_1$ ,  $a_2$  and  $a_3$ ?  
[Here  $a_0 = 2$  is the initial condition.]

**Solution:** We see from the recurrence relation that

$$a_1 = a_0 + 3 = 2 + 3 = 5$$

$$a_2 = 5 + 3 = 8$$

$$a_3 = 8 + 3 = 11$$

# Questions about Recurrence Relations

**Example 2:** Let  $\{a_n\}$  be a sequence that satisfies the recurrence relation  $a_n = a_{n-1} - a_{n-2}$  for  $n = 2,3,4,\dots$  and suppose that  $a_0 = 3$  and  $a_1 = 5$ . What are  $a_2$  and  $a_3$ ?  
[Here the initial conditions are  $a_0 = 3$  and  $a_1 = 5$ . ]

# Questions about Recurrence Relations

**Example 2:** Let  $\{a_n\}$  be a sequence that satisfies the recurrence relation  $a_n = a_{n-1} - a_{n-2}$  for  $n = 2, 3, 4, \dots$  and suppose that  $a_0 = 3$  and  $a_1 = 5$ . What are  $a_2$  and  $a_3$ ?  
[Here the initial conditions are  $a_0 = 3$  and  $a_1 = 5$ . ]

**Solution:** We see from the recurrence relation that

$$a_2 = a_1 - a_0 = 5 - 3 = 2$$

$$a_3 = a_2 - a_1 = 2 - 5 = -3$$

# Fibonacci Sequence

**Definition:** Define the *Fibonacci sequence*,  $f_0, f_1, f_2, \dots$ , by:

- Initial Conditions:  $f_0 = 0, f_1 = 1$
- Recurrence Relation:  $f_n = f_{n-1} + f_{n-2}$

**Example:** Find  $f_2, f_3, f_4, f_5$  and  $f_6$ .

# Fibonacci Sequence

**Definition:** Define the *Fibonacci sequence*,  $f_0, f_1, f_2, \dots$ , by:

- Initial Conditions:  $f_0 = 0, f_1 = 1$
- Recurrence Relation:  $f_n = f_{n-1} + f_{n-2}$

**Example:** Find  $f_2, f_3, f_4, f_5$  and  $f_6$ .

**Answer:**

$$f_2 = f_1 + f_0 = 1 + 0 = 1,$$

$$f_3 = f_2 + f_1 = 1 + 1 = 2,$$

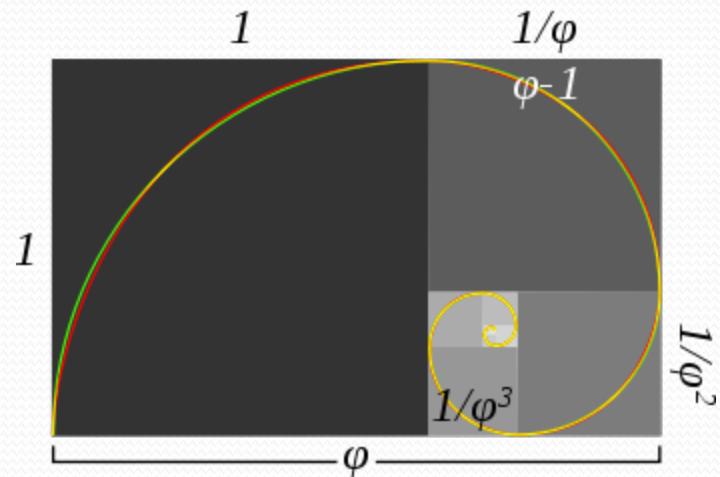
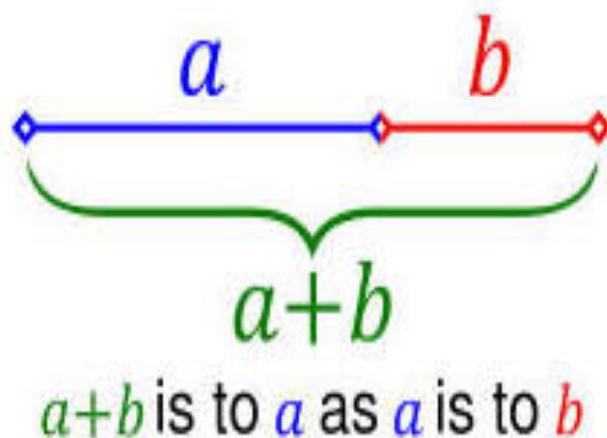
$$f_4 = f_3 + f_2 = 2 + 1 = 3,$$

$$f_5 = f_4 + f_3 = 3 + 2 = 5,$$

$$f_6 = f_5 + f_4 = 5 + 3 = 8.$$

# Fibonacci Sequence and the Golden Ratio

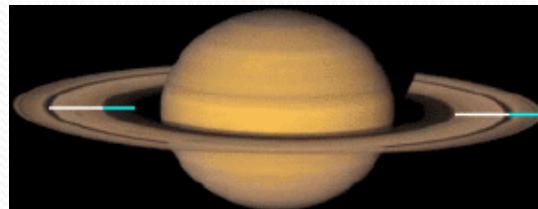
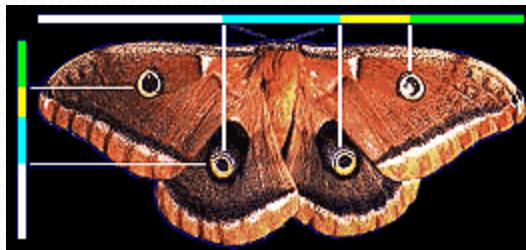
- Golden Ratio :  $(a+b)/a = a/b = \phi$
- Solution  $\phi = (1+ \sqrt{5})/2 = 1.61\dots$
- $\lim_{n \rightarrow \infty} (f_{n+1}/f_n) = \phi$



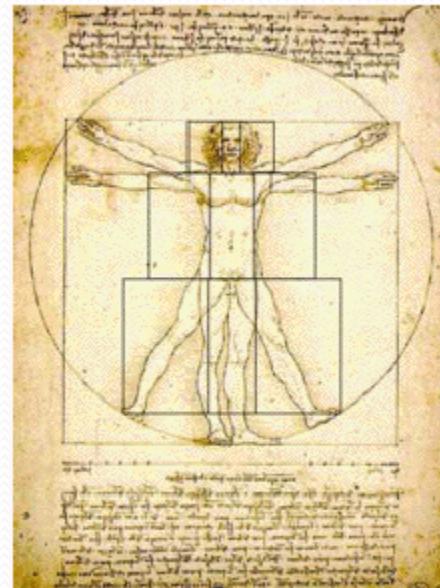
# Golden Ratio in Nature



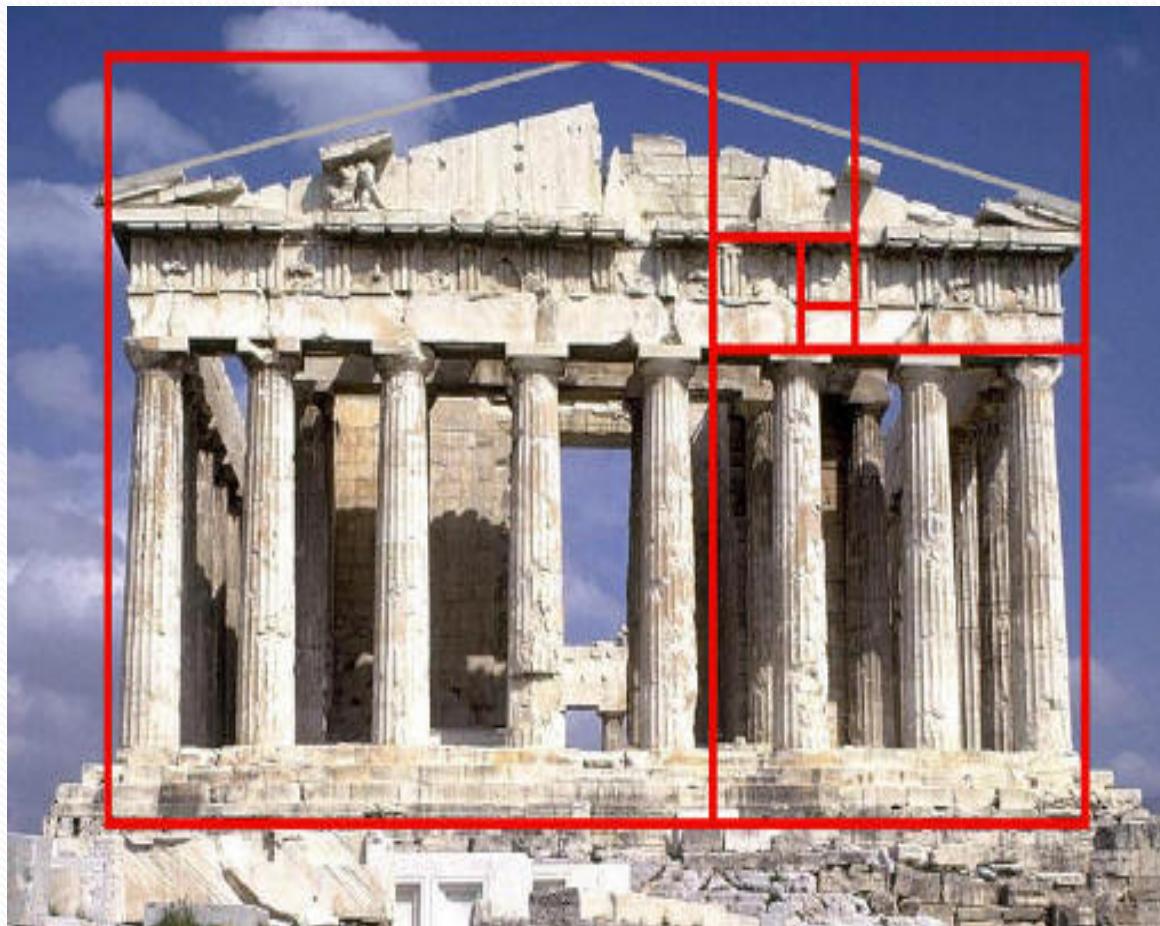
# Golden Ratio in Nature



# Golden Ratio in Art



# Golden Ratio in Architecture



# Solving Recurrence Relations

- Finding a formula for the  $n$ th term of the sequence generated by a recurrence relation is called *solving the recurrence relation*.
- Such a formula is called a *closed formula*.
- Various methods for solving recurrence relations are covered in Chapter 8 where recurrence relations are studied in greater depth.
- Here we illustrate by example the method of iteration in which we need to guess the formula. The guess can be proved correct by the method of induction (Chapter 5).

# Iterative Solution Example

**Method 1:** Working upward, forward substitution

Let  $\{a_n\}$  be a sequence that satisfies the recurrence relation  $a_n = a_{n-1} + 3$  for  $n = 2, 3, 4, \dots$  and suppose that  $a_1 = 2$ .

$$a_2 = 2 + 3$$

$$a_3 = (2 + 3) + 3 = 2 + 3 \cdot 2$$

$$a_4 = (2 + 2 \cdot 3) + 3 = 2 + 3 \cdot 3$$

.

.

.

$$a_n = a_{n-1} + 3 = (2 + 3 \cdot (n - 2)) + 3 = 2 + 3(n - 1)$$

# Iterative Solution Example

**Method 2:** Working downward, backward substitution

Let  $\{a_n\}$  be a sequence that satisfies the recurrence relation  $a_n = a_{n-1} + 3$  for  $n = 2, 3, 4, \dots$  and suppose that  $a_1 = 2$ .

$$a_n = a_{n-1} + 3$$

$$= (a_{n-2} + 3) + 3 = a_{n-2} + 3 \cdot 2$$

$$= (a_{n-3} + 3) + 3 \cdot 2 = a_{n-3} + 3 \cdot 3$$

.

.

.

$$= a_2 + 3(n-2) = (a_1 + 3) + 3(n-2) = 2 + 3(n-1)$$

# Financial Application

**Example:** Suppose that a person deposits \$10,000.00 in a savings account at a bank yielding 11% per year with interest compounded annually. How much will be in the account after 30 years?

Let  $P_n$  denote the amount in the account after  $n$  years.  
 $P_n$  satisfies the following recurrence relation:

$$P_n = P_{n-1} + 0.11P_{n-1} = (1.11) P_{n-1}$$

with the initial condition  $P_0 = 10,000$

*Continued on next slide →*

# Financial Application

$$P_n = P_{n-1} + 0.11P_{n-1} = (1.11)P_{n-1}$$

with the initial condition  $P_0 = 10,000$

**Solution:** Forward Substitution

$$P_1 = (1.11)P_0$$

$$P_2 = (1.11)P_1 = (1.11)^2P_0$$

$$P_3 = (1.11)P_2 = (1.11)^3P_0$$

:

$$P_n = (1.11)P_{n-1} = (1.11)^n P_0 = (1.11)^n 10,000$$

$P_n = (1.11)^n 10,000$  (Can prove by induction, covered in Chapter 5)

$$P_{30} = (1.11)^{30} 10,000 = \$228,992.97$$

# Useful Sequences

**TABLE 1** Some Useful Sequences.

<i><b><math>n</math>th Term</b></i>	<i><b>First 10 Terms</b></i>
$n^2$	1, 4, 9, 16, 25, 36, 49, 64, 81, 100, ...
$n^3$	1, 8, 27, 64, 125, 216, 343, 512, 729, 1000, ...
$n^4$	1, 16, 81, 256, 625, 1296, 2401, 4096, 6561, 10000, ...
$2^n$	2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, ...
$3^n$	3, 9, 27, 81, 243, 729, 2187, 6561, 19683, 59049, ...
$n!$	1, 2, 6, 24, 120, 720, 5040, 40320, 362880, 3628800, ...
$f_n$	1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, ...

# Summations

- Sum of the terms from the sequence  $a_m, a_{m+1}, \dots, a_n$
- The notation:  $\{a_n\}$

$$\sum_{j=m}^n a_j \quad \sum_{j=m}^n a_j \quad \sum_{m \leq j \leq n} a_j$$

represents

$$a_m + a_{m+1} + \cdots + a_n$$

- The variable  $j$  is called the *index of summation*. It runs through all the integers starting with its *lower limit*  $m$  and ending with its *upper limit*  $n$ .

# Summations

- More generally for a set  $S$ :

$$\sum_{j \in S} a_j$$

- Examples:**  $r^0 + r^1 + r^2 + r^3 + \cdots + r^n = \sum_0^n r^j$

$$1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots = \sum_1^\infty \frac{1}{i}$$

If  $S = \{2, 5, 7, 10\}$  then  $\sum_{j \in S} a_j = a_2 + a_5 + a_7 + a_{10}$

# Product Notation

- Product of the terms  $a_m, a_{m+1}, \dots, a_n$  from the sequence  $\{a_n\}$
- The notation:

$$\prod_{j=m}^n a_j \quad \prod_{j=m}^n a_j \quad \prod_{m \leq j \leq n} a_j$$

represents  $a_m \times a_{m+1} \times \cdots \times a_n$

# Geometric Series

**Sums of terms of geometric progressions**

$$\sum_{j=0}^n ar^j = \begin{cases} \frac{ar^{n+1}-a}{r-1} & r \neq 1 \\ (n+1)a & r = 1 \end{cases}$$

*Continued on next slide →*

# Geometric Series

**Sums of terms of geometric progressions**

$$\sum_{j=0}^n ar^j = \begin{cases} \frac{ar^{n+1}-a}{r-1} & r \neq 1 \\ (n+1)a & r = 1 \end{cases}$$

**Proof:** Let  $S_n = \sum_{j=0}^n ar^j$

To compute  $S_n$ , first multiply both sides of the equality by  $r$  and then manipulate the resulting sum as follows:

$$rS_n = r \sum_{j=0}^n ar^j$$

$$= \sum_{j=0}^n ar^{j+1}$$

*Continued on next slide →*

# Geometric Series

$$= \sum_{j=0}^n ar^{j+1} \quad \text{From previous slide.}$$

$$= \sum_{k=1}^{n+1} ar^k \quad \text{Shifting the index of summation with } k = j + 1.$$

$$= \left( \sum_{k=0}^n ar^k \right) + (ar^{n+1} - a) \quad \begin{matrix} \text{Removing } k = n + 1 \text{ term and} \\ \text{adding } k = 0 \text{ term.} \end{matrix}$$

$$= S_n + (ar^{n+1} - a) \quad \text{Substituting } S \text{ for summation formula}$$

$$\therefore rS_n = S_n + (ar^{n+1} - a)$$

$$S_n = \frac{ar^{n+1} - a}{r - 1} \quad \text{if } r \neq 1$$

$$S_n = \sum_{j=0}^n ar^j = \sum_{j=0}^n a = (n + 1)a \quad \text{if } r = 1$$

# Some Useful Summation Formulae

TABLE 2 Some Useful Summation Formulae.

Sum	Closed Form
$\sum_{k=0}^n ar^k (r \neq 0)$	$\frac{ar^{n+1} - a}{r - 1}, r \neq 1$
$\sum_{k=1}^n k$	$\frac{n(n + 1)}{2}$
$\sum_{k=1}^n k^2$	$\frac{n(n + 1)(2n + 1)}{6}$
$\sum_{k=1}^n k^3$	$\frac{n^2(n + 1)^2}{4}$
$\sum_{k=0}^{\infty} x^k,  x  < 1$	$\frac{1}{1 - x}$
$\sum_{k=1}^{\infty} kx^{k-1},  x  < 1$	$\frac{1}{(1 - x)^2}$

Geometric Series: We just proved this.

Later we will prove some of these by induction.

Proof in text (requires calculus)

# Cardinality of Sets

Section 2.5

# Section Summary

- Cardinality
- Countable Sets
- Computability

# Cardinality

**Definition:** The *cardinality* of a set  $A$  is equal to the cardinality of a set  $B$ , denoted

$$|A| = |B|,$$

if and only if there is a one-to-one correspondence (*i.e.*, a bijection) from  $A$  to  $B$ .

- If there is a one-to-one function (*i.e.*, an injection) from  $A$  to  $B$ , the cardinality of  $A$  is less than or the same as the cardinality of  $B$  and we write  $|A| \leq |B|$ .
- When  $|A| \leq |B|$  and  $A$  and  $B$  have different cardinality, we say that the cardinality of  $A$  is less than the cardinality of  $B$  and write  $|A| < |B|$ .

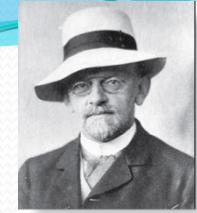
# Cardinality

- **Definition:** A set that is either finite or has the same cardinality as the set of positive integers ( $\mathbb{Z}^+$ ) is called *countable*. A set that is not countable is *uncountable*.
- The set of real numbers  $\mathbb{R}$  is an uncountable set.
- When an infinite set is countable (*countably infinite*) its cardinality is  $\aleph_0$  (where  $\aleph$  is aleph, the 1<sup>st</sup> letter of the Hebrew alphabet). We write  $|S| = \aleph_0$  and say that  $S$  has cardinality “aleph null.”

# Showing that a Set is Countable

- An infinite set is countable if and only if it is possible to list the elements of the set in a sequence (indexed by the positive integers).
- The reason for this is that a one-to-one correspondence  $f$  from the set of positive integers to a set  $S$  can be expressed in terms of a sequence  $a_1, a_2, \dots, a_n, \dots$  where  $a_1 = f(1)$ ,  $a_2 = f(2), \dots, a_n = f(n), \dots$

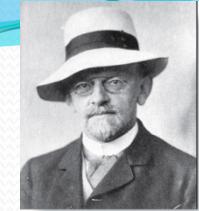
# Hilbert's Grand Hotel



David Hilbert

The Grand Hotel (example due to David Hilbert) has countably infinite number of rooms, each occupied by a guest. We can always accommodate a new guest at this hotel. How is this possible?

# Hilbert's Grand Hotel



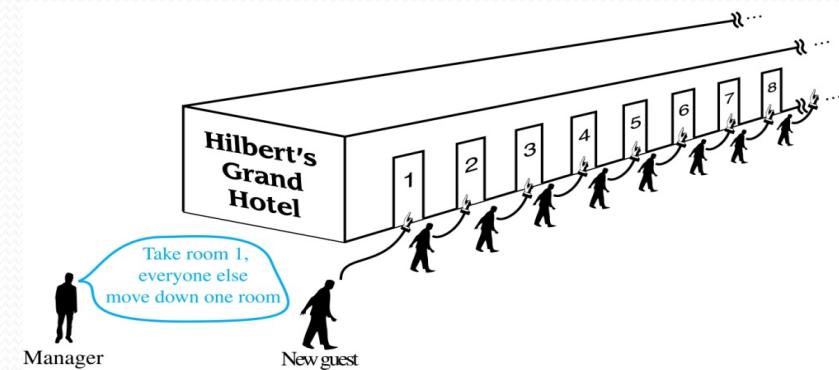
David Hilbert

The Grand Hotel (example due to David Hilbert) has countably infinite number of rooms, each occupied by a guest. We can always accommodate a new guest at this hotel. How is this possible?

**Explanation:** Because the number of rooms of Grand Hotel is countable, we can list them as Room 1, Room 2, Room 3, and so on.

When a new guest arrives, we move the guest in Room 1 to Room 2, the guest in Room 2 to Room 3, and in general the guest in Room  $n$  to Room  $n + 1$ , for all positive integers  $n$ .

This frees up Room 1, which we assign to the new guest, and all the current guests still have rooms.



The hotel can also accommodate a countable number of new guests, all the guests on a countable number of buses where each bus contains a countable number of guests (see exercises).

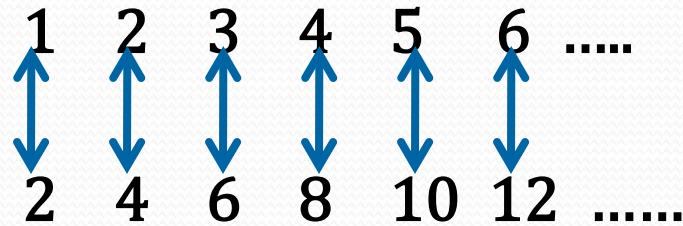
# Showing that a Set is Countable

**Example 1:** Show that the set of positive even integers  $E$  is countable set.

# Showing that a Set is Countable

**Example 1:** Show that the set of positive even integers  $E$  is countable set.

**Solution:** Let  $f(x) = 2x$ .



Then  $f$  is a bijection from  $\mathbf{N}$  to  $E$  since  $f$  is both one-to-one and onto. To show that it is one-to-one, suppose that  $f(n) = f(m)$ . Then  $2n = 2m$ , and so  $n = m$ . To see that it is onto, suppose that  $t$  is an even positive integer. Then  $t = 2k$  for some positive integer  $k$  and  $f(k) = t$ .



# Showing that a Set is Countable

**Example 2:** Show that the set of integers  $\mathbb{Z}$  is countable.

# Showing that a Set is Countable

**Example 2:** Show that the set of integers  $\mathbf{Z}$  is countable.

**Solution:** Can list in a sequence:

0, 1, -1, 2, -2, 3, -3 ,.....

Or can define a bijection from  $\mathbf{N}$  to  $\mathbf{Z}$ :

- When  $n$  is even:  $f(n) = n/2$
- When  $n$  is odd:  $f(n) = -(n-1)/2$



# The Set of Positive Rational Numbers is Countable

- **Definition:** A *rational number* can be expressed as the ratio of two integers  $p$  and  $q$  such that  $q \neq 0$ .
  - $\frac{3}{4}$  is a rational number
  - $\sqrt{2}$  is not a rational number.

**Example 3:** Show that the set of positive rational numbers is countable.

# The Set of Positive Rational Numbers is Countable

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  - $\frac{3}{4}$  is a rational number
  - $\sqrt{2}$  is not a rational number.

**Example 3:** Show that the set of positive rational numbers is countable.

**Solution:** The set of positive rational numbers is countable since they can be arranged in a sequence:

$$r_1, r_2, r_3, \dots$$

The next slide shows how this is done.



# The Set of Positive Rational Numbers is Countable

First row  $q = 1$ .

Second row  $q = 2$ .

etc.

## Constructing the List

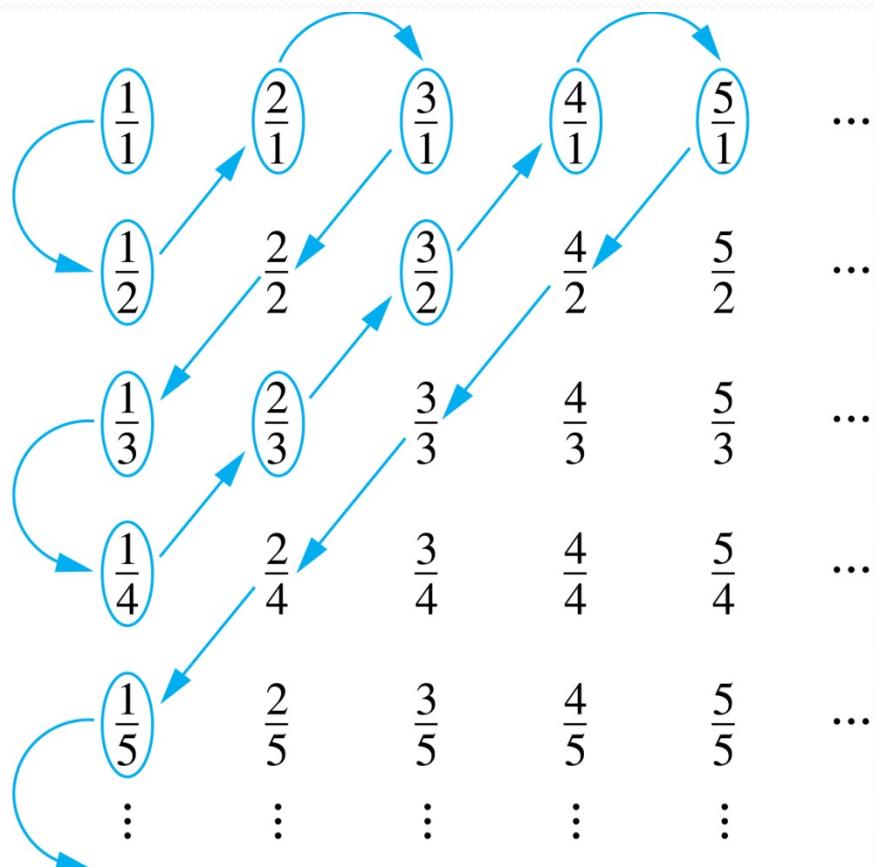
First list  $p/q$  with  $p + q = 2$ .

Next list  $p/q$  with  $p + q = 3$

And so on.

1,  $\frac{1}{2}$ , 2, 3,  $\frac{1}{3}$ ,  $\frac{1}{4}$ ,  $\frac{2}{3}$ , ...

Terms not circled  
are not listed  
because they  
repeat previously  
listed terms



# Strings

**Example 4:** Show that the set of finite strings  $S$  over a finite alphabet  $A$  is countably infinite.

Assume an alphabetical ordering of symbols in  $A$

# Strings

**Example 4:** Show that the set of finite strings  $S$  over a finite alphabet  $A$  is countably infinite.

Assume an alphabetical ordering of symbols in  $A$

**Solution:** Show that the strings can be listed in a sequence. First list

1. All the strings of length 0 in alphabetical order.
2. Then all the strings of length 1 in lexicographic (as in a dictionary) order.
3. Then all the strings of length 2 in lexicographic order.
4. And so on.

This implies a bijection from  $\mathbf{N}$  to  $S$ , hence  $S$  is a countably infinite set. 

# The set of all Java programs is countable

**Example 5:** Show that the set of all Java programs is countable.

# The set of all Java programs is countable.

**Example 5:** Show that the set of all Java programs is countable.

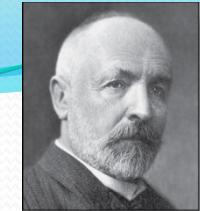
**Solution:** Let  $S$  be the set of strings constructed from the characters which can appear in a Java program. Use the ordering from the previous example. Take each string in turn:

- Feed the string into a Java compiler. (A Java compiler will determine if the input program is a syntactically correct Java program.)
- If the compiler says YES, this is a syntactically correct Java program, we add the program to the list.
- We move on to the next string.

In this way we construct an implied bijection from  $\mathbb{N}$  to the set of Java programs. Hence, the set of Java programs is countable.



# The Set of Real Numbers is Uncountable



Georg Cantor  
(1845-1918)

**Example:** Show that the set of real numbers is uncountable.

**Solution:** The method is called the Cantor diagonalization argument, and is a proof by contradiction.

1. Suppose  $\mathbf{R}$  is countable. Then the real numbers between 0 and 1 are also countable (any subset of a countable set is countable - an exercise in the text).
2. The real numbers between 0 and 1 can be listed in order  $r_1, r_2, r_3, \dots$ .
3. Let the decimal representation of this listing be  $r_1 = 0.d_{11}d_{12}d_{13}d_{14}d_{15}d_{16} \dots$   
 $r_2 = 0.d_{21}d_{22}d_{23}d_{24}d_{25}d_{26} \dots$   
 $r_3 = 0.d_{31}d_{32}d_{33}d_{34}d_{35}d_{36} \dots$   
 $\vdots$
4. Form a new real number with the decimal expansion  $r = .r_1r_2r_3r_4 \dots$   
where  $r_i = 3$  if  $d_{ii} \neq 3$  and  $r_i = 4$  if  $d_{ii} = 3$
5.  $r$  is not equal to any of the  $r_1, r_2, r_3, \dots$ . Because it differs from  $r_i$  in its  $i$ th position after the decimal point. Therefore there is a real number between 0 and 1 that is not on the list since every real number has a unique decimal expansion. Hence, all the real numbers between 0 and 1 cannot be listed, so the set of real numbers between 0 and 1 is uncountable.
6. Since a set with an uncountable subset is uncountable (an exercise), the set of real numbers is uncountable.

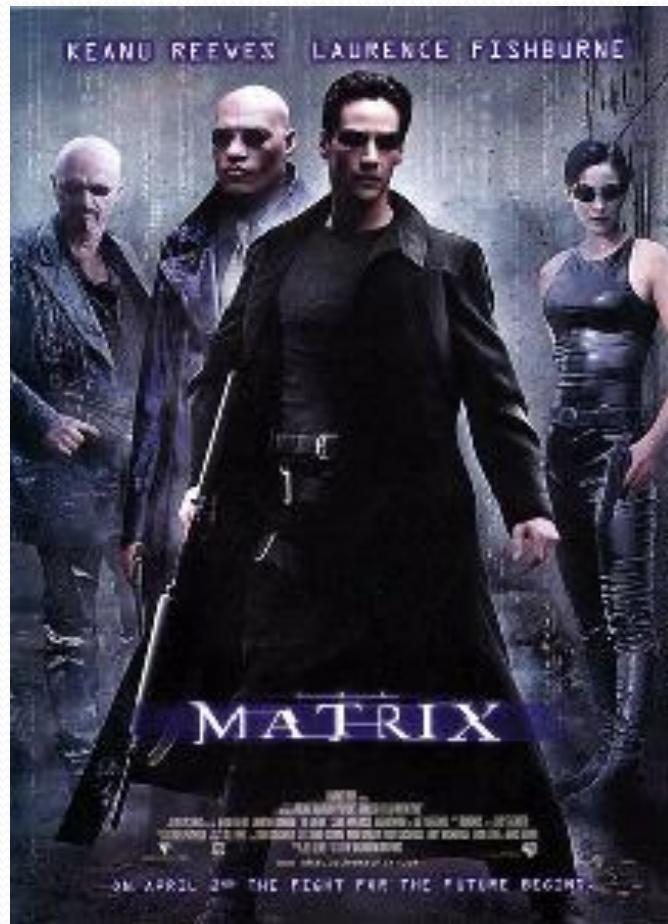


# Computability

- **Definition:** We say that a function is **computable** if there is a computer program in some programming language that finds the values of this function. If a function is not computable we say it is **uncomputable**.
- There are uncomputable functions. We have shown that the set of Java programs is countable. Exercise 38 in the text shows that there are uncountably many different functions from a particular countably infinite set (i.e., the positive integers) to itself. Therefore (Exercise 39) there must be uncomputable functions.

# Matrices

Section 2.6



# Section Summary

- Definition of a Matrix
- Matrix Arithmetic
- Transposes and Powers
- Zero-One matrices

# Matrices

- Matrices are useful discrete structures that can be used in many ways. For example, they are used to:
  - Describe certain types of functions known as linear transformations.
  - Express which vertices of a graph are connected by edges (see Chapter 10).
- Here we cover the aspect of matrix arithmetic that will be needed later.

# Matrix

**Definition:** A *matrix* is a rectangular array of numbers. A matrix with  $m$  rows and  $n$  columns is called an  $m \times n$  matrix.

- The plural of matrix is *matrices*.
- A matrix with the same number of rows as columns is called *square*.
- Two matrices are *equal* if they have the same number of rows and the same number of columns and the corresponding entries in every position are equal.

$3 \times 2$  matrix

$$\begin{bmatrix} 1 & 1 \\ 0 & 2 \\ 1 & 3 \end{bmatrix}$$

# Notation

- Let  $m$  and  $n$  be positive integers and let

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

- The  $i$ th row of  $\mathbf{A}$  is the  $1 \times n$  matrix  $[a_{i1}, a_{i2}, \dots, a_{in}]$ . The  $j$ th column of  $\mathbf{A}$  is the  $m \times 1$  matrix:
- The  $(i,j)$ th *element* or *entry* of  $\mathbf{A}$  is the element  $a_{ij}$ . We can use  $\mathbf{A} = [a_{ij}]$  to denote the matrix with its  $(i,j)$ th element equal to  $a_{ij}$ .

$$\begin{bmatrix} a_{1j} \\ a_{2j} \\ \cdot \\ \cdot \\ a_{mj} \end{bmatrix}$$

# Matrix Arithmetic: Addition

**Defintion:** Let  $A = [a_{ij}]$  and  $B = [b_{ij}]$  be  $m \times n$  matrices. The sum of  $A$  and  $B$ , denoted by  $A + B$ , is the  $m \times n$  matrix that has  $a_{ij} + b_{ij}$  as its  $(i,j)$ th element. In other words,  $A + B = [a_{ij} + b_{ij}]$ .

**Example:**

$$\begin{bmatrix} 1 & 0 & -1 \\ 2 & 2 & -3 \\ 3 & 4 & 0 \end{bmatrix} + \begin{bmatrix} 3 & 4 & -1 \\ 1 & -3 & 0 \\ -1 & 1 & 2 \end{bmatrix} = \begin{bmatrix} 4 & 4 & -2 \\ 3 & -1 & -3 \\ 2 & 5 & 2 \end{bmatrix}$$

Note that matrices of different sizes can not be added.

# Matrix Multiplication

**Definition:** Let  $\mathbf{A}$  be an  $m \times k$  matrix and  $\mathbf{B}$  be a  $k \times n$  matrix. The *product* of  $\mathbf{A}$  and  $\mathbf{B}$ , denoted by  $\mathbf{AB}$ , is the  $m \times n$  matrix that has its  $(i,j)$ th element equal to the sum of the products of the corresponding elements from the  $i$ th row of  $\mathbf{A}$  and the  $j$ th column of  $\mathbf{B}$ . In other words, if  $\mathbf{AB} = [c_{ij}]$  then  $c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{ik}b_{kj}$ .

**Example:**

$$\begin{bmatrix} 1 & 0 & 4 \\ 2 & 1 & 1 \\ 3 & 1 & 0 \\ 0 & 2 & 2 \end{bmatrix} \begin{bmatrix} 2 & 4 \\ 1 & 1 \\ 3 & 0 \end{bmatrix} = \begin{bmatrix} 14 & 4 \\ 8 & 9 \\ 7 & 13 \\ 8 & 2 \end{bmatrix}$$

The product of two matrices is undefined when the number of columns in the first matrix is not the same as the number of rows in the second.

# Illustration of Matrix Multiplication

- The Product of  $\mathbf{A} = [a_{ij}]$  and  $\mathbf{B} = [b_{ij}]$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1k} \\ a_{21} & a_{22} & \dots & a_{2k} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \textcolor{red}{a_{i1}} & \textcolor{red}{a_{i2}} & \dots & \textcolor{red}{a_{ik}} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ a_{m1} & a_{m2} & \dots & a_{mk} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} b_{11} & a_{12} & \dots & \textcolor{red}{b_{1j}} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & \textcolor{red}{b_{2j}} & \dots & b_{2n} \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ b_{k1} & b_{k2} & \dots & \textcolor{red}{b_{kj}} & \dots & b_{kn} \end{bmatrix}$$

$$\mathbf{AB} = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \textcolor{red}{c_{ij}} \\ \cdot & \cdot & & \cdot \\ c_{m1} & c_{m2} & \dots & c_{mn} \end{bmatrix}$$

$$c_{ij} = a_{i1}b_{1j} + a_{i2}b_{2j} + \dots + a_{ik}b_{kj}$$

# Matrix Multiplication is not Commutative

**Example:** Let

$$A = \begin{bmatrix} 1 & 1 \\ 2 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$$

Does  $AB = BA$ ?

# Matrix Multiplication is not Commutative

**Example:** Let

$$A = \begin{bmatrix} 1 & 1 \\ 2 & 1 \end{bmatrix}$$

$$B = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$$

Does  $AB = BA$ ?

**Solution:**

$$AB = \begin{bmatrix} 2 & 2 \\ 5 & 3 \end{bmatrix}$$

$$BA = \begin{bmatrix} 4 & 3 \\ 3 & 2 \end{bmatrix}$$

$AB \neq BA$

# Identity Matrix and Powers of Matrices

**Definition:** The *identity matrix of order n* is the  $n \times n$  matrix  $\mathbf{I}_n = [\delta_{ij}]$ , where  $\delta_{ij} = 1$  if  $i = j$  and  $\delta_{ij} = 0$  if  $i \neq j$ .

$$\mathbf{I}_n = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \ddots & & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} \quad \mathbf{AI}_n = \mathbf{I}_m \mathbf{A} = \mathbf{A}$$

when  $\mathbf{A}$  is an  $m \times n$  matrix

Powers of square matrices can be defined. When  $\mathbf{A}$  is an  $n \times n$  matrix, we have:

$$\mathbf{A}^0 = \mathbf{I}_n \quad \mathbf{A}^r = \underbrace{\mathbf{AAA}\cdots\mathbf{A}}_{r \text{ times}}$$

# Transposes of Matrices

**Definition:** Let  $\mathbf{A} = [a_{ij}]$  be an  $m \times n$  matrix. The *transpose* of  $\mathbf{A}$ , denoted by  $\mathbf{A}^t$ , is the  $n \times m$  matrix obtained by interchanging the rows and columns of  $\mathbf{A}$ .

If  $\mathbf{A}^t = [b_{ij}]$ , then  $b_{ij} = a_{ji}$  for  $i = 1, 2, \dots, n$   
and  $j = 1, 2, \dots, m$ .

The transpose of the matrix  $\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}$  is the matrix  $\begin{bmatrix} 1 & 4 \\ 2 & 5 \\ 3 & 6 \end{bmatrix}$ .

# Transposes of Matrices

**Definition:** A square matrix  $A$  is called symmetric if  $A = A^t$ . Thus  $A = [a_{ij}]$  is symmetric if  $a_{ij} = a_{ji}$  for  $i$  and  $j$  with  $1 \leq i \leq n$  and  $1 \leq j \leq n$ .

The matrix  $\begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$  is square.

Square matrices do not change when their rows and columns are interchanged.

# Zero-One Matrices

**Definition:** A matrix all of whose entries are either 0 or 1 is called a *zero-one matrix*. (These will be used in Chapters 9 and 10.)

Algorithms operating on discrete structures represented by zero-one matrices are based on Boolean arithmetic defined by the following Boolean operations:

$$b_1 \wedge b_2 = \begin{cases} 1 & \text{if } b_1 = b_2 = 1 \\ 0 & \text{otherwise} \end{cases} \quad b_1 \vee b_2 = \begin{cases} 1 & \text{if } b_1 = 1 \text{ or } b_2 = 1 \\ 0 & \text{otherwise} \end{cases}$$

# Zero-One Matrices

**Definition:** Let  $\mathbf{A} = [a_{ij}]$  and  $\mathbf{B} = [b_{ij}]$  be an  $m \times n$  zero-one matrices.

- The *join* of  $\mathbf{A}$  and  $\mathbf{B}$  is the zero-one matrix with  $(i,j)$ th entry  $a_{ij} \vee b_{ij}$ . The *join* of  $\mathbf{A}$  and  $\mathbf{B}$  is denoted by  $\mathbf{A} \vee \mathbf{B}$ .
- The *meet* of  $\mathbf{A}$  and  $\mathbf{B}$  is the zero-one matrix with  $(i,j)$ th entry  $a_{ij} \wedge b_{ij}$ . The *meet* of  $\mathbf{A}$  and  $\mathbf{B}$  is denoted by  $\mathbf{A} \wedge \mathbf{B}$ .

# Joins and Meets of Zero-One Matrices

**Example:** Find the join and meet of the zero-one matrices

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \end{bmatrix}.$$

# Joins and Meets of Zero-One Matrices

**Example:** Find the join and meet of the zero-one matrices

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \end{bmatrix}.$$

**Solution:** The join of  $\mathbf{A}$  and  $\mathbf{B}$  is

$$\mathbf{A} \vee \mathbf{B} = \begin{bmatrix} 1 \vee 0 & 0 \vee 1 & 1 \vee 0 \\ 0 \vee 1 & 1 \vee 1 & 0 \vee 0 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix}.$$

The meet of  $\mathbf{A}$  and  $\mathbf{B}$  is

$$\mathbf{A} \wedge \mathbf{B} = \begin{bmatrix} 1 \wedge 0 & 0 \wedge 1 & 1 \wedge 0 \\ 0 \wedge 1 & 1 \wedge 1 & 0 \wedge 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}.$$

# Boolean Product of Zero-One Matrices

**Definition:** Let  $\mathbf{A} = [a_{ij}]$  be an  $m \times k$  zero-one matrix and  $\mathbf{B} = [b_{ij}]$  be a  $k \times n$  zero-one matrix. The *Boolean product* of  $\mathbf{A}$  and  $\mathbf{B}$ , denoted by  $\mathbf{A} \odot \mathbf{B}$ , is the  $m \times n$  zero-one matrix with  $(i,j)$ th entry

$$c_{ij} = (a_{i1} \wedge b_{1j}) \vee (a_{i2} \wedge b_{2j}) \vee \dots \vee (a_{ik} \wedge b_{kj}).$$

**Example:** Find the Boolean product of  $\mathbf{A}$  and  $\mathbf{B}$ , where

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix}.$$

*Continued on next slide →*

# Boolean Product of Zero-One Matrices

**Solution:** The Boolean product  $\mathbf{A} \odot \mathbf{B}$  is given by

$$\mathbf{A} \odot \mathbf{B} = \begin{bmatrix} (1 \wedge 1) \vee (0 \wedge 0) & (1 \wedge 1) \vee (0 \wedge 1) & (1 \wedge 0) \vee (0 \wedge 1) \\ (0 \wedge 1) \vee (1 \wedge 0) & (0 \wedge 1) \vee (1 \wedge 1) & (0 \wedge 0) \vee (1 \wedge 1) \\ (1 \wedge 1) \vee (0 \wedge 0) & (1 \wedge 1) \vee (0 \wedge 1) & (1 \wedge 0) \vee (0 \wedge 1) \end{bmatrix}$$

$$= \begin{bmatrix} 1 \vee 0 & 1 \vee 0 & 0 \vee 0 \\ 0 \vee 0 & 0 \vee 1 & 0 \vee 1 \\ 1 \vee 0 & 1 \vee 0 & 0 \vee 0 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix}.$$

# Boolean Powers of Zero-One Matrices

**Definition:** Let  $A$  be a square zero-one matrix and let  $r$  be a positive integer. The  $r$ th Boolean power of  $A$  is the Boolean product of  $r$  factors of  $A$ , denoted by  $A^{[r]}$ . Hence,

$$A^{[r]} = \underbrace{A \odot A \odot \dots \odot A}_{r \text{ times}}.$$

We define  $A^{[r]}$  to be  $I_n$ .

(The Boolean product is well defined because the Boolean product of matrices is associative.)

# Boolean Powers of Zero-One Matrices

**Example:** Let  $A = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$ .

Find  $A^n$  for all positive integers  $n$ .

# Boolean Powers of Zero-One Matrices

**Example:** Let  $A = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{bmatrix}$ .

Find  $A^n$  for all positive integers  $n$ .

**Solution:**

$$A^{[2]} = A \odot A = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix}$$

$$A^{[3]} = A^{[2]} \odot A = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix}$$

$$A^{[4]} = A^{[3]} \odot A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$A^{[5]} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad A^{[n]} = A^5 \quad \text{for all positive integers } n \text{ with } n \geq 5.$$