

# MATH 2305 Notes

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# 1 Logic and Proofs

## 1.1 Propositional Logic

A proposition is a declarative statement that is either true or false, but not both. We use letters to denote propositional variables. The conventional letters for propositional variables are  $p, q, r, s$ . True is notated as T and false is notated as F. An atomic proposition is a proposition that cannot be expressed in terms of simpler propositions.

### Definition

Let  $p$  be a proposition. The negation of  $p$ , denoted by  $\neg p$  (or  $\bar{p}$ ) means "It is not the case that  $p$ ".

The proposition  $\neg p$  is read as "not  $p$ ". The truth value of the negation of  $p$ ,  $\neg p$  is the opposite of the truth value of  $p$ .

The negation of a proposition can also be considered the result of the operation of the negation operator on a proposition.

The next operator is a connective and it is used to form new propositions from two or more existing propositions.

### Definition

Let  $p$  and  $q$  be propositions. The conjunction of  $p$  and  $q$ , denoted by  $p \wedge q$ , is the proposition of " $p$  and  $q$ ". The conjunction  $p \wedge q$  is true when both are true, and false when both are false.

### Definition

Let  $p$  and  $q$  be propositions. The disjunction of  $p$  and  $q$ , denoted by  $p \vee q$ , is the proposition " $p$  or  $q$ ". The disjunction  $p \vee q$  is false when both  $p$  and  $q$  are false, otherwise it is true.

### Definition

Let  $p$  and  $q$  be propositions. The exclusive or of  $p$  and  $q$ , denoted by  $p \oplus q$  is the proposition that is true when exactly one of  $p$  and  $q$  is true and is false otherwise.

There are other ways propositions can be combined.

### Definition

Let  $p$  and  $q$  be propositions. The conditional statement  $p \rightarrow q$ , is the proposition, "if  $p$ , then  $q$ ". The conditional statement  $p \rightarrow q$  is false when  $p$  is true and  $q$  is false, and true otherwise.  $p$  is called the hypothesis and  $q$  is called the conclusion.

A conditional statement is also called an implication.

With  $p \rightarrow q$ , we can form three related conditional statements.

The first is the proposition  $q \rightarrow p$ , which is the converse of  $p \rightarrow q$ .

The contrapositive of  $p \rightarrow q$  is  $\neg q \rightarrow \neg p$ .

The inverse of  $p \rightarrow q$  is  $\neg p \rightarrow \neg q$ .

The contrapositive of a conditional statement is equal to it. We all two compound propositions equivalent when they always have the same truth values. The converse and inverse of a conditional statement are equivalent as well.

There is another way to combine propositions that expresses that two propositions have the same truth value.

### Definition

Let  $p$  and  $q$  be propositions. The biconditional statement  $p \leftrightarrow q$  is the proposition " $p$  if and only  $q$ ". This statement is true if  $p$  and  $q$  have the same truth values, and is false otherwise.

The negation operator is applied before all logical operators. Another general rule is that the conjunction operator takes precedence over the disjunction operator. It is an accepted rule that conditional and biconditional operators have lower precedence than the conjunction and disjunction operators.

A bit is a symbol with two values, 0 and 1. 1 is true, and 0 is false.

## 1.2 Propositional Equivalences

### Definition

A compound proposition that is always true, no matter what the truth values of the propositional values that occur in it, is called a tautology. A compound proposition that is always false is called a contradiction. If it is neither a tautology or a contradiction, it is called a contingency.

Compound propositions that have the same truth values in all possible cases are called logically equivalent.

### Definition

The compound propositions  $p$  and  $q$  are called logically equivalent if  $p \leftrightarrow q$  is a tautology. The notation  $p \equiv q$  denotes that  $p$  and  $q$  are logically equivalent.

We can establish logical equivalence of more than two compound propositions. Generally  $2^n$  rows are required if a compound proposition involves  $n$  propositional variables.

TABLE 6 Logical Equivalences.	
Equivalence	Name
$p \wedge \mathbf{T} \equiv p$ $p \vee \mathbf{F} \equiv p$	Identity laws
$p \vee \mathbf{T} \equiv \mathbf{T}$ $p \wedge \mathbf{F} \equiv \mathbf{F}$	Domination laws
$p \vee p \equiv p$ $p \wedge p \equiv p$	Idempotent laws
$\neg(\neg p) \equiv p$	Double negation law
$p \vee q \equiv q \vee p$ $p \wedge q \equiv q \wedge p$	Commutative laws
$(p \vee q) \vee r \equiv p \vee (q \vee r)$ $(p \wedge q) \wedge r \equiv p \wedge (q \wedge r)$	Associative laws
$p \vee (q \wedge r) \equiv (p \vee q) \wedge (p \vee r)$ $p \wedge (q \vee r) \equiv (p \wedge q) \vee (p \wedge r)$	Distributive laws
$\neg(p \wedge q) \equiv \neg p \vee \neg q$ $\neg(p \vee q) \equiv \neg p \wedge \neg q$	De Morgan's laws
$p \vee (p \wedge q) \equiv p$ $p \wedge (p \vee q) \equiv p$	Absorption laws
$p \vee \neg p \equiv \mathbf{T}$ $p \wedge \neg p \equiv \mathbf{F}$	Negation laws

**TABLE 7** Logical Equivalences Involving Conditional Statements.

$p \rightarrow q \equiv \neg p \vee q$
$p \rightarrow q \equiv \neg q \rightarrow \neg p$
$p \vee q \equiv \neg p \rightarrow q$
$p \wedge q \equiv \neg(p \rightarrow \neg q)$
$\neg(p \rightarrow q) \equiv p \wedge \neg q$
$(p \rightarrow q) \wedge (p \rightarrow r) \equiv p \rightarrow (q \wedge r)$
$(p \rightarrow r) \wedge (q \rightarrow r) \equiv (p \vee q) \rightarrow r$
$(p \rightarrow q) \vee (p \rightarrow r) \equiv p \rightarrow (q \vee r)$
$(p \rightarrow r) \vee (q \rightarrow r) \equiv (p \wedge q) \rightarrow r$

**TABLE 8** Logical Equivalences Involving Biconditional Statements.

$p \leftrightarrow q \equiv (p \rightarrow q) \wedge (q \rightarrow p)$
$p \leftrightarrow q \equiv \neg p \leftrightarrow \neg q$
$p \leftrightarrow q \equiv (p \wedge q) \vee (\neg p \wedge \neg q)$
$\neg(p \leftrightarrow q) \equiv p \leftrightarrow \neg q$

Credit: Rosen's Discrete Mathematics 8e

When using De Morgan's Laws, remember to change the logical connective after you negate.

De Morgan's Laws tell us how to negate conjunctions and how to negate disjunctions. The equivalence  $\neg(p \vee q) \equiv \neg p \wedge \neg q$  tells us that the negation of a disjunction is formed from the conjunction of the negations of the component propositions. The negation of a conjunction also gives you the disjunction of the negations of component propositions.

A compound proposition is satisfiable if there is an assignment of truth values to its variables that make it true. If no such assignments exist, then it is unsatisfiable.

### 1.3 Predicates and Quantifiers

We will introduce predicate logic now. For example in the statement  $x$  is greater than 3, the variable is  $x$  and the predicate is "is greater than 3".

In general a statement involving  $n$  variables  $x_1, x_2, \dots, x_n$  can be denoted as  $P(x_1, x_2, \dots, x_n)$ .

#### Definition

The universal quantification of  $P(x)$  is the statement:

" $P(x)$  for all values of  $x$  in the domain."

The notation  $\forall x P(x)$  denotes the universal quantification of  $P(x)$ . Here  $\forall$  is called the universal quantifier. An element for which  $P(x)$  is false is called a counterexample to  $\forall x P(x)$ .

#### Definition

The existential quantification of  $P(x)$  is the proposition:

"There exists an element in  $x$  in the domain such that  $P(x)$ "

We use the notation  $\exists x P(x)$  for the existential quantification of  $P(x)$ .

Remember the truth value for both  $\forall x P(x)$  and  $\exists x P(x)$  depends on the domain.

TABLE 2 De Morgan's Laws for Quantifiers.			
Negation	Equivalent Statement	When Is Negation True?	When False?
$\neg \exists x P(x)$	$\forall x \neg P(x)$	For every $x$ , $P(x)$ is false.	There is an $x$ for which $P(x)$ is true.
$\neg \forall x P(x)$	$\exists x \neg P(x)$	There is an $x$ for which $P(x)$ is false.	$P(x)$ is true for every $x$ .

Credit: Rosen's Discrete Mathematics 8e

## 1.4 Nested Quantifiers

A nested quantifier is when one quantifier is in the scope of another.

Here is table that summarizes different quantifications involving two variables.

TABLE 1 Quantifications of Two Variables.		
Statement	When True?	When False?
$\forall x \forall y P(x, y)$ $\forall y \forall x P(x, y)$	$P(x, y)$ is true for every pair $x, y$ .	There is a pair $x, y$ for which $P(x, y)$ is false.
$\forall x \exists y P(x, y)$	For every $x$ there is a $y$ for which $P(x, y)$ is true.	There is an $x$ such that $P(x, y)$ is false for every $y$ .
$\exists x \forall y P(x, y)$	There is an $x$ for which $P(x, y)$ is true for every $y$ .	For every $x$ there is a $y$ for which $P(x, y)$ is false.
$\exists x \exists y P(x, y)$ $\exists y \exists x P(x, y)$	There is a pair $x, y$ for which $P(x, y)$ is true.	$P(x, y)$ is false for every pair $x, y$ .

## 1.5 Rules of Inference

Rules of inference are our basic tools for establishing the truth of statements.

An argument in propositional logic is a sequence of propositions. All but the final proposition in the argument are called premises and the final proposition is called the conclusion. An argument is valid if the truth of all its premises implies the conclusion is true.

An argument form in propositional logic is a sequence of compound propositions involving propositional variables. An argument form is valid if no matter what particular propositions are substituted for the propositional variables in the premises, the conclusion is true if the premises are all true.

The tautology  $(p \wedge (p \rightarrow q)) \rightarrow q$  is the basis of the rule of inference modus ponens, or the law of detachment, basically: if  $p$  and  $p \rightarrow q$   $\therefore q$ .

Yet again another chart I took from Rosen.

**TABLE 1** Rules of Inference.

<i>Rule of Inference</i>	<i>Tautology</i>	<i>Name</i>
$\begin{array}{l} p \\ p \rightarrow q \\ \hline \therefore q \end{array}$	$(p \wedge (p \rightarrow q)) \rightarrow q$	Modus ponens
$\begin{array}{l} \neg q \\ p \rightarrow q \\ \hline \therefore \neg p \end{array}$	$(\neg q \wedge (p \rightarrow q)) \rightarrow \neg p$	Modus tollens
$\begin{array}{l} p \rightarrow q \\ q \rightarrow r \\ \hline \therefore p \rightarrow r \end{array}$	$((p \rightarrow q) \wedge (q \rightarrow r)) \rightarrow (p \rightarrow r)$	Hypothetical syllogism
$\begin{array}{l} p \vee q \\ \neg p \\ \hline \therefore q \end{array}$	$((p \vee q) \wedge \neg p) \rightarrow q$	Disjunctive syllogism
$\begin{array}{l} p \\ \hline \therefore p \vee q \end{array}$	$p \rightarrow (p \vee q)$	Addition
$\begin{array}{l} p \wedge q \\ \hline \therefore p \end{array}$	$(p \wedge q) \rightarrow p$	Simplification
$\begin{array}{l} p \\ q \\ \hline \therefore p \wedge q \end{array}$	$((p) \wedge (q)) \rightarrow (p \wedge q)$	Conjunction
$\begin{array}{l} p \vee q \\ \neg p \vee r \\ \hline \therefore q \vee r \end{array}$	$((p \vee q) \wedge (\neg p \vee r)) \rightarrow (q \vee r)$	Resolution

Fallacies resemble rules of inference, the difference lies in that they are based in contingencies rather than tautologies.

There are also some rules of inference for statements involving quantifiers. This is what Rosen summarized:

**TABLE 2** Rules of Inference for Quantified Statements.

<i>Rule of Inference</i>	<i>Name</i>
$\begin{array}{l} \forall x P(x) \\ \hline \therefore P(c) \end{array}$	Universal instantiation
$\begin{array}{l} P(c) \text{ for an arbitrary } c \\ \hline \therefore \forall x P(x) \end{array}$	Universal generalization
$\begin{array}{l} \exists x P(x) \\ \hline \therefore P(c) \text{ for some element } c \end{array}$	Existential instantiation
$\begin{array}{l} P(c) \text{ for some element } c \\ \hline \therefore \exists x P(x) \end{array}$	Existential generalization

Because universal instantiation and modus ponens are so often used together, the combination of rules is called universal modus ponens. This rule tells us if  $\forall x(P(x) \rightarrow Q(x))$  is true, and if  $P(a)$  is true for a particular element  $a$  in the domain of the universal quantifier, then  $Q(a)$  must also be true. Note that by universal instantiation  $P(a) \rightarrow Q(a)$  is true. By modus ponens,  $Q(a)$  must also be true.

This is how it is described:

$$\frac{\forall x (P(x) \rightarrow Q(x))}{P(a), \text{ where } a \text{ is a particular element in the domain}} \\ \therefore Q(a)$$

There is also universal modus tollens:

$$\frac{\forall x (P(x) \rightarrow Q(x))}{\neg Q(a) \text{ where } a \text{ is a particular element in the domain}} \\ \therefore \neg P(a)$$

## 1.6 Introduction to Proofs

A proof is a valid argument that establishes the truth of a mathematical statement.

A theorem is a statement that can be shown to be true. We show the truth using a proof.

A less important theorem that is helpful in the proof of other results is called a lemma.

A corollary is a theorem that can be established directly from a theorem that has been proved.

A conjecture is a statement that is being proposed to be a true statement.

A direct proof of a conditional statement  $p \rightarrow q$  is constructed with the assumption that  $p$  is true with the goal for the combination of  $p$  being true and  $q$  being false to never happen.

### Definition

The integer  $n$  is even if there exists an integer  $k$  such that  $n = 2k$ , and  $n$  is odd if there exists an integer  $k$  such that  $n = 2k + 1$ . Two integers have the same parity when both are even or both are odd; they have opposite parity when one is even and the other is odd.

An indirect proof is a type of proof that is not direct. One example is proof by contraposition. Proofs by contraposition use the fact that  $p \rightarrow q$  is equal to  $\neg q \rightarrow \neg p$ . We have to show  $\neg q \rightarrow \neg p$  is true to show that  $p \rightarrow q$  is true as well.

We can prove that  $p \rightarrow q$  is true if  $p$  is false as well. This is called a vacuous proof.

If we show that  $q$  is true in  $p \rightarrow q$  this is called a trivial proof.

### Definition

The real number  $r$  is rational if there exist integers  $p$  and  $q$  with  $q \neq 0$  such that  $r = p/q$ . A real number that is not rational is irrational.

Suppose we want to prove a statement  $p$  is true. Suppose that we can find a contradiction  $q$  such that  $\neg p \rightarrow q$  is true. Because  $q$  is false, but  $\neg p \rightarrow q$  is true, we can conclude  $\neg p$  is false, meaning  $p$  is true.

To find a contradiction  $q$  that might help us find that  $p$  is true, we can show that  $\neg p \rightarrow (r \wedge \neg r)$  is true for some proposition  $r$ . This is called a proof by contradiction.

To prove a theorem in the form  $p \leftrightarrow q$ , we show that both  $p \rightarrow q$  and  $q \rightarrow p$  are both true.

Many incorrect arguments are based on a fallacy called begging the question or circular reasoning. This fallacy occurs when one or more steps of a proof are based on the truth of the statement being proved.

## 1.7 Proof Methods and Strategy

Suppose we have a conditional  $(p_1 \vee p_2 \vee \dots \vee p_n) \rightarrow q$ . We can separate the proof into different cases, called proof by cases by proving each of the  $n$  conditional statements.



Some theorems can be proved by examining a relatively small number of examples. This is called proof by exhaustion.

The phrase "without loss of generality" (WLOG) means that we assert by proving one case of a theorem, no additional argument is required to prove other specified cases.

Many theorems are assertions that objects of a particular type exist. A theorem of this type is a proposition in the form  $\exists xP(x)$ , where  $P$  is a predicate. A proof of a proposition in this form is called an existence proof. Sometimes an existence proof can be given by finding an element  $a$ , called a witness, such that  $P(a)$  is true. This existence proof is called constructive. If we prove  $\exists xP(x)$  is true in another way it can be nonconstructive.

For a uniqueness proof, we need two parts:

- Existence: We show that an element  $x$  with the desired property exists.
- Uniqueness: We show that if  $x$  and  $y$  both have the desired property,  $x = y$

Forward reasoning is a proof when you start with your premises. You construct a proof with steps leading to the conclusion. It may sometimes be helpful to use backwards reasoning, we find a statement  $p$  that we can prove  $p \rightarrow q$ .

# 2 Sets, Functions, Sequences, Sums, and Matrices

## 2.1 Sets

Sets are used to group objects together.

A set is an unordered collection of objects, called elements or members of the set. A set contains its elements. We write  $a \in A$  to denote  $a$  is in an element of set  $A$ . The notation  $a \notin A$  denotes  $a$  is not an element of set  $A$ .

Here are some sets to remember:

- $\mathbb{N}$  is the set of all natural numbers
- $\mathbb{Z}$  is the set of all integers
- $\mathbb{Z}^+$  is the set of all positive integers
- $\mathbb{Q}$  is the set of all rational numbers
- $\mathbb{R}$  is the set of all real numbers
- $\mathbb{R}^+$  is the set all positive real numbers
- $\mathbb{C}$  is the set of all complex numbers

Two sets are equal only if they contain the same elements.

An empty set is notated as  $\emptyset$ .

A set with one element is a singleton set.

Set  $A$  is a subset of set  $B$  and set  $B$  is the superset of set  $A$  if every element of  $A$  is also an element of  $B$ . To indicate  $A$  is a subset of  $B$  we write  $A \subseteq B$ . For the equivalent superset, we write  $B \supseteq A$ .

For every nonempty set  $S$ , there is a guarantee to have at least two subsets, the empty set and the set  $S$  itself.

When we want to say that  $A$  is a subset of  $B$ , but  $A \neq B$ , we can write  $A \subset B$ .

If there are  $n$  distinct elements in a set  $S$ , then the set is finite and  $n$  is the cardinality of  $S$ . The cardinality of  $S$  is denoted as  $|S|$ .

Otherwise, the set is infinite if it is not finite.

### Definition

Given a set  $S$ , the power set of  $S$  is the set of all subsets of the set  $S$ . The power set of  $S$  is defined as  $\mathcal{P}(S)$ .

The power set of a set has  $2^n$  elements. Because sets are unordered, we need to represent ordered collections using ordered  $n$ -tuples.

### Definition

The ordered  $n$ -tuple  $(a_1, a_2, \dots, a_n)$  is the ordered collection that has  $a_1$  as its first element,

## 2.2 Set Operations

If we let  $A$  and  $B$  be sets, the union of the sets,  $A \cup B$ , is the set that contains those elements that are either in  $A$  or  $B$ , or in both.

The intersection of the sets,  $A \cap B$ , is the set containing those elements in both  $A$  and  $B$ .

Two sets are called disjoint if the intersection of the sets is an empty set.

The difference of sets  $A$  and  $B$ , or  $A - B$  is the set containing those elements that are in  $A$  but not in  $B$ . It is also called the complement of  $B$  with respect to  $A$ .

### Definition

Let  $U$  be the universal set. The complement of set  $A$  denoted as  $\bar{A}$  is the complement of  $A$  with respect to  $U$ . Therefore the complement of the set  $A$  is  $U - A$ .

Much like the last chapter, there are some set identities and properties

TABLE 1 Set Identities.	
Identity	Name
$A \cap U = A$ $A \cup \emptyset = A$	Identity laws
$A \cup U = U$ $A \cap \emptyset = \emptyset$	Domination laws
$A \cup A = A$ $A \cap A = A$	Idempotent laws
$\overline{(\bar{A})} = A$	Complementation law
$A \cup B = B \cup A$ $A \cap B = B \cap A$	Commutative laws
$A \cup (B \cap C) = (A \cup B) \cap C$ $A \cap (B \cup C) = (A \cap B) \cup C$	Associative laws
$A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$ $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$	Distributive laws
$\overline{A \cap B} = \bar{A} \cup \bar{B}$ $\overline{A \cup B} = \bar{A} \cap \bar{B}$	De Morgan's laws
$A \cup (A \cap B) = A$ $A \cap (A \cup B) = A$	Absorption laws
$A \cup \bar{A} = U$ $A \cap \bar{A} = \emptyset$	Complement laws

Credits to Rosen again.

The union of a collection of sets is the set that contains those elements that are members of at least one set in the collection.

The intersection of a collection of sets is the set that contains those elements that are members of all sets in the collection.

## 2.3 Functions

### Definition

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

If  $f$  is a function from  $A$  to  $B$ , we say  $A$  is the domain of  $f$  and  $B$  is the codomain of  $f$ . Also if  $f(a) = b$ , we can say  $b$  is the image of  $a$  and  $a$  is a preimage of  $b$ . The range, or image, is the set of all images of elements of  $A$ . Also, if  $f$  is a function from  $A$  to  $B$ , we say that  $f$  maps from  $A$  to  $B$ .

A function is called real-valued if its codomain is the set of real numbers and integer-valued if the codomain is the set of integers.

Some functions never assign the same value to two different domain elements. These are called one-to-one functions, or injective functions.

A function is called surjective or onto when the range and codomain are equal.

If a function is both surjective and injective, then it is bijective.

Only a one-to-one function can be invertible because the inverse of a one-to-one function exists.

## 2.4 Sequences and Summations

Sequences are ordered lists of elements. The terms of a sequence can be specified by providing a formula for each term of the sequence.

A sequence is used to represent an ordered list. We use the notation  $a_n$  to denote the image of the integer  $n$ . We call  $a_n$  a term of the sequence.

A geometric progression is a sequence in the following form:

$$a, ar, ar^2, \dots, ar^n, \dots$$

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

An arithmetic progression is a sequence in the form:

$$a, a + d, a + 2d, \dots, a + nd, \dots$$

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

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 in the sequence.

A sequence is called a solution of a recurrence relation if its terms satisfy the recurrence relation.

### Definition

The Fibonacci sequence,  $f_0, f_1, f_2, \dots$ , is defined by the initial conditions  $f_0 = 0, f_1 = 1$ , and the recurrence relation:

$$f_n = f_{n-1} + f_{n-2}$$

for  $n = 2, 3, 4, \dots$ .

Now we introduce the summation notation.

We use the notation  $\sum_{j=m}^n a_j$  to represent  $a_m + a_{m+1} + \dots + a_n$ .

Here  $j$  is the index of summation and is arbitrary.

Sums of terms of geometric progressions commonly arise.

$$\sum_{j=0}^n ar^j = \frac{ar^{n+1} - a}{r - 1}$$

when  $r \neq 1$  and  $(n+1)a$  when  $r = 1$ .

Here is some formulae for commonly occurring sums:

<b>TABLE 2</b> Some Useful Summation Formulae.	
<i>Sum</i>	<i>Closed Form</i>
$\sum_{k=0}^n ar^k \ (r \neq 0)$	$\frac{ar^{n+1} - a}{r - 1}, r \neq 1$
$\sum_{k=1}^n k$	$\frac{n(n+1)}{2}$
$\sum_{k=1}^n k^2$	$\frac{n(n+1)(2n+1)}{6}$
$\sum_{k=1}^n k^3$	$\frac{n^2(n+1)^2}{4}$
$\sum_{k=0}^{\infty} x^k,  x  < 1$	$\frac{1}{1-x}$
$\sum_{k=1}^{\infty} kx^{k-1},  x  < 1$	$\frac{1}{(1-x)^2}$

Credits to Rosen again.

# 3 Algorithms

An algorithm is a finite sequence of precise instructions for performing a computation or for solving a problem.

There are many properties of algorithms to keep in mind:

- Input - input values from a specified set
- Output - from each set of input values an algorithm produces output values
- Definiteness - the steps of an algorithm must be defined precisely
- Correctness - an algorithm should produce correct output values for each set of input values
- Finiteness - an algorithm should produce the desired output after a finite number of steps for any input
- Effectiveness - it must be possible to perform each step of an algorithm exactly and in a finite amount of time
- Generality - the procedure should be applicable for all problems of the desired form

The first algorithm to present is the linear search, or sequential search. This search begins by comparing a  $x$  and  $a_1$  and continues with each  $a_n$  until a match is found.

The binary search works when the list is sorted. We first split the list into two smaller sublists of the same size, and keep splitting it up based on the comparison to the term to be found the middle term.

The bubble sort is one of the simplest sorting algorithms. It puts a list into increasing order by successively comparing adjacent elements.

The insertion sort begins with the second element and compares it with the the first element. Then the third element is compared with the first and then the second if it is larger than the first.

Many algorithms are designed to solve optimization problems. This means they want to maximize or minimize some parameter. Algorithms that make what seems to be the "best" choice at each step are called greedy algorithms.

An example would be the cashier's algorithm which makes changes using the fewest coins possible when change is made from quarters, dimes, nickels, and pennies.

The halting problem is a interesting problem. It asks whether there is a procedure that can input a computer program and determine whether the program will eventually stop.

The reason there isn't one is because you do not know if it will never halt or you haven't waited long enough for it to terminate.

# 4 Number Theory and Cryptography

## 4.1 Divisibility and Modular Arithmetic

### Definition

If  $a$  and  $b$  are integers with  $a \neq 0$ , we say that  $a$  divides  $b$  if there is an integer  $c$  such that  $b = ac$  (or equivalently, if  $\frac{b}{a}$  is an integer). When  $a$  divides  $b$  we say that  $a$  is a factor or divisor of  $b$ , and that  $b$  is a multiple of  $a$ . The notation  $a \mid b$  denotes that  $a$  divides  $b$ . We write  $a \nmid b$  when  $a$  does not divide  $b$ .

We can express  $a \mid b$  using quantifiers as  $\exists c(ac = b)$ .

There are some basic properties of divisibility of integers:

- If  $a \mid b$  and  $a \mid c$ , then  $a \mid (b + c)$
- If  $a \mid b$ , then  $a \mid bc$  for all integers  $c$
- If  $a \mid b$  and  $b \mid c$ , then  $a \mid c$

### Corollary 4.1

If  $a$ ,  $b$ , and  $c$  are integers, where  $a \neq 0$ , such that  $a \mid b$  and  $a \mid c$ , then  $a \mid mb + nc$  whenever  $m$  and  $n$  are integers.

When an integer is divided by a positive integer, there is a quotient and a remainder, as the division algorithm shows.

### Theorem 4.2: The Division Algorithm

Let  $a$  be an integer and  $d$  a positive integer. Then there are unique integers  $q$  and  $r$ , with  $0 \leq r < d$ , such that  $a = dq + r$ .

In the equality given in the division algorithm,  $d$  is called the divisor,  $a$  is called the divided,  $q$  is called the quotient, and  $r$  is called the remainder. The notation  $q = a \text{ div } d$  is used to denote quotient, and  $r = a \bmod d$  is used to denote the remainder.

When  $a$  is an integer and  $d$  is a positive integer,  $a \text{ div } d = \lfloor a/d \rfloor$  and  $a \bmod d = a - d \cdot \lfloor a/d \rfloor$ .

### Definition

If  $a$  and  $b$  are integers and  $m$  is a positive integer, then  $a$  is congruent to  $b$  modulo  $m$  if  $m$  divides  $a - b$ . We use the notation  $a \equiv b \pmod{m}$  to indicate that  $a$  is congruent to  $b$  modulo  $m$ . We say that  $a \equiv b \pmod{m}$  is a congruence and that  $m$  is its modulus. If  $a$  and  $b$  are not congruent modulo  $m$ , we write  $a \not\equiv b \pmod{m}$ .

### Theorem 4.3

Let  $a$  and  $b$  be integers, and let  $m$  be a positive integer. Then  $a \equiv b \pmod{m}$  if and only if  $a \bmod m = b \bmod m$ .

### Theorem 4.4

Let  $m$  be a positive integer. The integers  $a$  and  $b$  are congruent modulo  $m$  if and only if there is an integer  $k$  such that  $a = b + km$ .

#### Theorem 4.5

Let  $m$  be a positive integer. If  $a \equiv b \pmod{m}$  and  $c \equiv d \pmod{m}$ , then

$$a + c \equiv b + d \pmod{m}$$

and

$$ac \equiv bd \pmod{m}$$

#### Corollary 4.6

Let  $m$  be a positive integer and let  $a$  and  $b$  be integers. Then:

$$(a + b) \pmod{m} = ((a \pmod{m}) + (b \pmod{m})) \pmod{m}$$

and

$$ab \pmod{m} = ((a \pmod{m})(b \pmod{m})) \pmod{m}$$

We can define arithmetic operations on  $Z_m$ , the set of nonnegative integers less than  $m$ , that is, the set  $0, 1, \dots, m-1$ . We define the addition of these integers as:

$$a +_m b = (a + b) \pmod{m}$$

We can define the multiplication of these integers as

$$a \cdot_m b = (a \cdot b) \pmod{m}$$

Here are some properties of these:

- Closure - If  $a$  and  $b$  belong to  $Z_m$ , then  $a +_m b$  and  $a \cdot_m b$  belong to  $Z_m$ .
- Associativity - If  $a$ ,  $b$ , and  $c$ , belong to  $Z_m$ , then  $(a +_m b) +_m c = a +_m (b +_m c)$  and  $(a \cdot_m b) \cdot_m c = a \cdot_m (b \cdot_m c)$ .
- Commutativity - If  $a$  and  $b$  belong to  $Z_m$ , then  $a +_m b = b +_m a$  and  $a \cdot_m b = b \cdot_m a$ .
- Identity elements - The elements 0 and 1 are identity elements for addition and multiplication modulo  $m$ , respectively.
- Additive Inverses - If  $a \neq 0$  belongs to  $Z_m$ , then  $m - a$  is an additive inverse of  $a$  modulo  $m$  and 0 is its own additive inverse. That is,  $a +_m (m - a) = 0$  and  $0 +_m 0 = 0$ .
- Distributivity - If  $a$ ,  $b$ , and  $c$  belong to  $Z_m$ , then  $a \cdot_m (b +_m c) = (a \cdot_m b) +_m (a \cdot_m c)$  and  $(a +_m b) \cdot_m c = (a \cdot_m c) +_m (b \cdot_m c)$ .

## 4.2 Integer Representation and Algorithms

#### Theorem 4.7

Let  $b$  be an integer greater than 1. Then if  $n$  is a positive integer, it can be expressed uniquely in the form:

$$n = a_k b^k + a_{k-1} b^{k-1} + \dots + a_1 b + a_0$$

where  $k$  is a nonnegative integer,  $a_0, a_1, \dots, a_k$  are nonnegative integers less than  $b$ , and  $a_k \neq 0$ .

Choosing 2 as the base gives binary expansions of integers. In binary notation each digit is either a 0 or a 1. In other words, the binary expansion of an integer is just a bit string.



Base 8 expansions are called octal expansions and base 16 expansions are hexadecimal expansions.

We can describe an algorithm for constructing the base  $b$  expansion of an integer  $n$ .

First divide  $n$  by  $b$  to obtain a quotient and remainder:

$$n = bq_0 + a_0$$

assuming  $a_0$  is positive and less than  $b$ .

The remainder,  $a_0$ , is the rightmost digit in the base  $b$  expansion of  $n$ . Next, divide  $q_0$  by  $b$  to obtain:

$$q_0 = bq_1 + a_1 \quad 0 \leq a_1 < b$$

Continue this process, successively dividing the quotients by  $b$ , obtaining additional base  $b$  digits as the remainders.

The algorithms for performing operations with integers using their binary expansions is important.

Throughout the following, let's suppose that the binary expansions of  $a$  and  $b$  are:

$$a = (a_{n-1}a_{n-2} \dots a_1a_0)_2, b = (b_{n-1}b_{n-2} \dots b_1b_0)_2$$

so that  $a$  and  $b$  each have  $n$  bits.

Let's first consider the adding two integers in binary notation. The procedure is as follows:

First add their rightmost bits:

$$a_0 + b_0 = c_0 \cdot 2 + s_0$$

where  $s_0$  is the rightmost bit in the binary expansion of  $a + b$  and  $c_0$  is the carry, either a 0 or 1.

Continue this:

$$a_1 + b_1 + c_0 = c_1 \cdot 2 + s_1$$

This procedure produces the binary expansion of the sum:

$$a + b = (s_ns_{n-1}s_{n-2} \dots s_1s_0)_2$$

Now we consider multiplication. Using the distributive law it is easy to see that

$$\begin{aligned} ab &= a(b_02^0 + b_12^1 + \dots + b_{n-1}2^{n-1}) \\ &= a(b_02^0) + a(b_12^1) + \dots + a(b_{n-1}2^{n-1}) \end{aligned}$$

There is an algorithm for div and mod as well. Given integers  $a$  and  $d$ , where  $d > 0$ , we can find  $q = a \text{div} d$  and  $r = a \bmod d$  using the algorithm below.

We can show that this algorithm uses  $O(q \log a)$  bit operations when  $a > d$ .

Given  $a$  as an integer, and  $d$  as a positive integer, we can make  $q$  equal to 0 and  $r = |a|$ .

While  $r \geq d$ ,  $r$  gets assigned to  $r - d$  and  $q$  gets assigned  $q + 1$ .

If  $a < 0$  and  $r > 0$  then  $r$  gets assigned  $d - r$  and  $q$  gets assigned  $-(q + 1)$ .

We return the quotient as  $q$  and the remainder as  $r$ .

When  $a$  is divided by  $b$ , we need  $O(n^2)$  bit operations to find the quotient and remainder.

In cryptography it is important to be able to find  $b^n \bmod m$  efficiently without using an excessive amount of memory.

First observe that we can avoid using a large amount of memory if we compute  $b^n \bmod m$  by successively computing  $b^k \bmod m$  for  $k = 1, 2, \dots, n$  using that fact that  $b^{k+1} \bmod m = b(b^k \bmod m) \bmod m$ .

To motivate the fast modular exponentiation algorithm, we can first explain how to use the binary expansion of  $n$ .

Say that  $n = (a_{k-1} \dots a_1 a_0)_2$  to compute  $b^n$ . Firstly, note that:

$$b^n = b^{a_{k-1} \cdot 2^{k-1} + \dots + a_1 \cdot 2 + a_0} = b^{a_{k-1} \cdot 2^{k-1}} \dots b^{a_1 \cdot 2} \cdot b^{a_0}$$

This shows that to compute  $b^n$  we only have to compute  $b, b^2, b^4, \dots, b^{2^k}$ .

Note that  $(b^{2^n})^2 = b^{2^{n+1}}$  when  $n$  is a nonnegative integer.

The algorithm successively finds  $b \bmod m, b^2 \bmod m, b^4 \bmod m, \dots, b^{2^{k-1}} \bmod m$  and multiplies together those terms  $b^{2^{a_j}} \bmod m$  where  $a_j = 1$ , finding the remainder of the product when divided by  $m$  after each multiplication. We only need to perform  $O(\log_2(n))$  multiplications.

We can also show the most efficient algorithm as seen:

Let  $b$  be an integer and  $n = (a_{k-1} a_{k-2} \dots a_1 a_0)_2$  and  $m$  be positive integers.

Let  $x$  be 1 and power be  $b \bmod m$ .

For all values 0 to  $k-1$ , if  $a_i = 1$ , then  $x$  becomes  $(x \cdot \text{power}) \bmod m$  and power becomes  $\text{power} \cdot \text{power} \bmod m$ .

The return value for this algorithm is  $x$ , which is  $b^n \bmod m$ .

This algorithm only uses  $O((\log m)^2 \log n)$  bit operations to find  $b^n \bmod m$ .

### 4.3 Primes and Greatest Common Divisors

Positive integers that have exactly two different positive integer factors are called prime.

#### Definition

An integer  $p$  greater than 1 is called prime if the only positive factors of  $p$  are 1 and  $p$ . A positive integer that is greater than 1 and is not prime is called composite.

Remember that 1 is not prime, and that an integer  $n$  is composite if and only if there exists an integer  $a$  such that  $a \mid n$  and  $1 < a < n$ .

#### Theorem 4.8: The Fundamental Theorem of Arithmetic

Every integer greater than 1 can be written uniquely as a prime or as the product of two or more primes, where the prime factors are written in order of nondecreasing size.

#### Theorem 4.9

If  $n$  is a composite number, then  $n$  has a prime divisor less than or equal to  $\sqrt{n}$ .

From this theorem above, it follows that an integer is prime if it is not divisible by any prime less than or equal to its square root. This leads to the brute-force algorithm known as trial division. To use trial division, we divide  $n$  by all primes not exceeding  $\sqrt{n}$  and conclude that  $n$  is prime if it is not divisible by any of these primes.

Because every integer has a prime factorization, it would be useful to have a procedure for finding the prime factorization. Start with the theorem above, and find if there is a prime factor not exceeding  $\sqrt{n}$ . If there is none found, then continue by factoring  $n/p$ . Note that  $n/p$  will have no prime factors less than  $p$ . If  $n/q$  has a prime factor  $q$ , then continue by factoring  $n/(pq)$ . There are infinitely many primes.

#### Theorem 4.10: The Prime Number Theorem

The ratio of  $\pi(x)$ , the number of primes not exceeding  $x$ , and  $x/\ln x$  approaches 1 as  $x$  grows without bound.

Every odd integer is in one of the two arithmetic progressions  $4k + 1$  or  $4k + 3$ , where  $k = 1, 2, \dots$ .

The largest integer that divides two integers is called the greatest common divisor of these integers.

#### Definition

Let  $a$  and  $b$  be integers, not both zero. The largest integer  $d$  such that  $d \mid a$  and  $d \mid b$  is called the greatest common divisor of  $a$  and  $b$ . The greatest common divisor of  $a$  and  $b$  is denoted by  $\gcd(a, b)$ .

#### Definition

The integers  $a$  and  $b$  are relatively prime if their greatest common divisor is 1.

#### Definition

The integers  $a_1, a_2, \dots, a_n$  are pairwise relatively prime if  $\gcd(a_i, a_k) = 1$  whenever  $1 \leq i < j \leq n$ .

Prime factorizations can be used to find the least common multiple of the integers.

#### Definition

The least common multiple of the positive integers  $a$  and  $b$  is the smallest positive integer that is divisible by both  $a$  and  $b$ . The least common multiple of  $a$  and  $b$  is denoted by  $\text{lcm}(a, b)$ .

#### Theorem 4.11

Let  $a$  and  $b$  be positive integers. Then

$$ab = \gcd(a, b) \cdot \text{lcm}(a, b)$$

There is a more efficient way of finding the greatest common divisor using the Euclidean algorithm.

#### Lemma 4.12

Let  $a = bq + r$ , where  $a, b, q$ , and  $r$  are integers. Then  $\gcd(a, b) = \gcd(b, r)$ .

*Proof.* If we can show that the common divisors of  $a$  and  $b$  are the same as the common divisors of  $b$  and  $r$ , we will have shown that  $\gcd(a, b) = \gcd(b, r)$ , because both pairs must have the same greatest common divisors.

So suppose that  $d$  divides both  $a$  and  $b$ . Then it follows that  $d$  also divides  $a - bq = r$ . Hence, any common divisor of  $a$  and  $b$  is also a common divisor of  $b$  and  $r$ .

Likewise, suppose that  $d$  divides both  $b$  and  $r$ . Then  $d$  also divides  $bq + r = a$ . Hence, any common divisor of  $b$  and  $r$  is also a common divisor of  $a$  and  $b$ .

Consequently,  $\gcd(a, b) = \gcd(b, r)$ .  $\square$

An important result is that the greatest common divisor of two integers  $a$  and  $b$  can be expressed in the form:

$$sa + tb$$

where  $s$  and  $t$  are integers. In other words,  $\gcd(a, b)$  can be expressed as a linear combination with integer coefficients of  $a$  and  $b$ .

#### Theorem 4.13: Bezout's Theorem

If  $a$  and  $b$  are positive integers, then there exist integers  $s$  and  $t$  such that  $\gcd(a, b) = sa + tb$ .

**Lemma 4.14**

If  $a$ ,  $b$ , and  $c$  are positive integers such that  $\gcd(a, b) = 1$  and  $a \mid bc$ , then  $a \mid c$ .

**Lemma 4.15**

If  $p$  is a prime and  $p \mid a_1 a_2 \cdots a_n$ , where each  $a_i$  is an integer, then  $p \mid a_i$  for some  $i$ .

**Theorem 4.16**

Let  $m$  be a positive integer and let  $a$ ,  $b$ , and  $c$  be integers. If  $ac \equiv bc \pmod{m}$  and  $\gcd(c, m) = 1$ , then  $a \equiv b \pmod{m}$ .

## 4.4 Solving Congruences

A congruence of the form

$$ax \equiv b \pmod{m}$$

where  $m$  is a positive integer,  $a$  and  $b$  are integers, and  $x$  is a variable, is called a linear congruence.

Our goal is to solve the linear congruence  $ax \equiv b \pmod{m}$ .

One method is to use an integer  $\bar{a}$  such that  $\bar{a}a \equiv 1 \pmod{m}$ , if such an integer exists. Such an integer  $\bar{a}$  is to be an inverse of  $a$  modulo  $m$ .

**Theorem 4.17**

If  $a$  and  $m$  are relatively prime integers and  $m > 1$ , then an inverse of  $a$  modulo  $m$  exists. Furthermore, this inverse is unique modulo  $m$ . (That is there is a unique positive integer  $\bar{a}$  less than  $m$  that is an inverse of  $a$  modulo  $m$  and every other inverse of  $a$  modulo  $m$  is congruent to  $\bar{a}$  modulo  $m$ .)

We can design a more efficient algorithm than brute force to find an inverse of  $a$  modulo  $m$  when  $\gcd(a, m) = 1$  using the steps of the Euclidean algorithm.

Once we have an inverse  $\bar{a}$  of  $a$  modulo  $m$ , we can solve the congruence  $ax \equiv b \pmod{m}$  by multiplying both sides of the linear congruence by  $\bar{a}$ .

The Chinese remainder theory states that when the moduli of a system of linear congruences are pairwise relatively prime, there is a unique solution of the system modulo of the product of the moduli.

**Theorem 4.18: The Chinese Remainder Theorem**

Let  $m_1, m_2, \dots, m_n$  be pairwise relatively prime positive integers greater than one and  $a_1, a_2, \dots, a_n$  arbitrary integers. Then the system

$$x \equiv a_1 \pmod{m_1}$$

$$x \equiv a_2 \pmod{m_2}$$

...

$$x \equiv a_n \pmod{m_n}$$

has a unique solution modulo  $m = m_1 m_2 \cdots m_n$ . (That is, there is a solution  $x$  with  $0 \leq x < m$ , and all other solutions are congruent modulo  $m$  to this solution.)

Suppose that  $m_1, m_2, \dots, m_n$  are pairwise relatively prime moduli and let  $m$  be their product. By the Chinese remainder theorem, we can show that an integer  $a$  with  $0 \leq a < m$  can be uniquely represented by the  $n$ -tuple consisting of its remainders upon division by  $m_i$ ,  $i = 1, 2, \dots, n$ . That is, we can uniquely represent  $a$  by

$$(a \bmod m_1, a \bmod m_2, \dots, a \bmod m_n)$$

#### Theorem 4.19: Fermat's Little Theorem

If  $p$  is prime and  $a$  is an integer not divisible by  $p$ , then

$$a^{p-1} \equiv 1 \pmod{p}$$

Furthermore, for every integer  $a$  we have

$$a^p \equiv a \pmod{p}$$

Fermat's little theorem tells us that if  $a \in \mathbb{Z}_p$ , then  $a^{p-1} = 1$  in  $\mathbb{Z}_p$ .

#### Definition

Let  $b$  be a positive integer. If  $n$  is a composite positive integer, and  $b^{n-1} \equiv 1 \pmod{n}$ , then  $n$  is called a pseudoprime to the base  $b$ .

#### Definition

A composite integer  $n$  that satisfies the congruence  $b^{n-1} \equiv 1 \pmod{n}$  for all positive integers  $b$  with  $\gcd(b, n) = 1$  is called a Carmichael number.

In the set of positive real numbers, if  $b > 1$  and  $x = b^y$ , we say that  $y$  is the logarithm of  $x$  to the base  $b$ . Here, we will show that we can also define the concept of logarithms modulo  $p$  of positive integers, where  $p$  is a prime.

#### Definition

A primitive root modulo of prime  $p$  is an integer  $r$  in  $\mathbb{Z}_p$  such that every nonzero element of  $\mathbb{Z}_p$  is a power of  $r$ .

An important fact in number theory is that there is a primitive root modulo  $p$  for every prime  $p$ .

Suppose that  $p$  is prime and  $r$  is a primitive root modulo  $p$ . If  $a$  is an integer between 1 and  $p - 1$ , that is, a nonzero element of  $\mathbb{Z}_p$ , we know that there is a unique exponent  $e$  such that  $r^e = a$  in  $\mathbb{Z}_p$ , that is,  $r^e \bmod p = a$ .

#### Definition

Suppose that  $p$  is a prime,  $r$  is a primitive root modulo  $p$ , and  $a$  is an integer between 1 and  $p - 1$  inclusive. If  $r^e \bmod p = a$  and  $0 \leq e \leq p - 1$ , we say that  $e$  is the discrete logarithm of  $a$  modulo  $p$  to the base  $r$  and we write  $\log_r a = e$  (where the prime  $p$  is understood).

# **5 Induction and Recursion**

## **5.1 Mathematical Induction**

## **5.2 Strong Induction and Well-Ordering**

## **5.3 Recursive Definitions and Structural Induction**

## **5.4 Recursive Algorithms**

# 6 Counting

6.1 The Basics of Counting

6.2 The Pigeonhole Principle

6.3 Permutations and Combinations

6.4 Binomial Coefficients and Identities

6.5 Generalized Permutations and Combinations

## **7 Discrete Probability**



# **8    Advanced Counting Techniques**

## **8.1   Applications of Recurrence Relations**

## **8.2   Inclusion-Exclusion**

## 9 Relations

# **10    Graphs**

## **10.1    Graphs and Graph Models**

## **10.2    Graph Terminology and Special Types of Graphs**

# 11 Trees