

# 1 Operators

$$a|b :\Leftrightarrow \exists c \ b = ac \text{ for } a \neq 0$$
$$a \equiv_m b :\Leftrightarrow m|(a - b) \text{ i.e. } \exists r \in \mathbb{Z} \ a = b + rm$$

# 2 Propositions

<b>Implication:</b>	$A \rightarrow B :\Leftrightarrow \neg A \vee B$
<b>Two-sided Implication:</b>	$A \leftrightarrow B :\Leftrightarrow A \equiv B$
<b>Associativity:</b>	$(F \wedge G) \wedge H \equiv F \wedge (G \wedge H)$
<b>Distributive Law:</b>	$(A \wedge B) \vee C \equiv (A \vee C) \wedge (B \vee C)$ $(A \vee B) \wedge (C \vee D) \equiv (A \wedge C) \vee (A \wedge D) \vee (B \wedge C) \vee (B \wedge D)$
<b>Idempotence:</b>	$F \wedge F \equiv F$
<b>Absorption:</b>	$F \wedge (F \vee G) \equiv F$
<b>de Morgan's Law:</b>	$\neg(A \wedge B) \equiv (\neg A \vee \neg B)$

# 3 Proofs

To prove a sentence (either true or false) means to show that it's a tautology. The following **proof patterns** may be used.

## 3.0.1 Direct Proof of an Implication

**Example:**  $F \rightarrow G$

A **direct proof of an implication** works by assuming  $F$  and then deriving  $G$  from  $F$ .

$$F \Rightarrow \dots \Rightarrow \dots \Rightarrow \dots \Rightarrow G$$

## 3.0.2 Indirect Proof of an Implication

**Example:**  $F \rightarrow G$

An **indirect proof of an implication** proceeds by assuming  $\neg G$  and deriving  $\neg F$  under this assumption.

$$\neg G \Rightarrow \dots \Rightarrow \dots \Rightarrow \dots \Rightarrow \neg F$$

## 3.0.3 Composition of Implications

**Example:**  $F \rightarrow G$  and  $G \rightarrow H$

1. Prove the statement  $F$
2. Prove the implications  $F \Rightarrow G$  and  $G \Rightarrow H$

## 3.0.4 Case Distinction

1. Define a complete list of cases
2. Prove the statement for each case separately

### 3.0.5 Proof by Contradiction

Assume that the sentence  $F$  is false and derive a false statement from it.

$$\neg F \Rightarrow \dots \Rightarrow \dots \Rightarrow \dots \Rightarrow \perp$$

### 3.0.6 Existence Proof

**Example:**  $\exists x P(x)$

Either find a variable which satisfies the sentence (**constructive**) or proof the existence of such a variable without exhibiting it (**non-constructive**).

### 3.0.7 Proof by Counterexample

**Example:**  $\neg \forall x P(x)$

Find a variable such that the sentence is wrong.

### 3.0.8 Proof by Induction

**Example:**  $\forall n P(n)$

1. **Basis step:** Prove  $P(0)$
2. Assume  $P(n)$
3. **Induction step:** Prove  $P(n+1)$

## 4 Predicate Logic

### 4.1 Rules

1.  $\forall x P(x) \wedge \forall x Q(x) \Leftrightarrow \forall x (P(x) \wedge Q(x))$
2.  $\exists x (P(x) \wedge Q(x)) \Rightarrow \exists x P(x) \wedge \exists x Q(x)$
3.  $\neg \forall x P(x) \Leftrightarrow \exists x \neg P(x)$
4.  $\neg \exists x P(x) \Leftrightarrow \forall x \neg P(x)$
5.  $\exists y \forall x P(x, y) \Rightarrow \forall x \exists y P(x, y)$
6.  $\forall x (\exists x P(x) \wedge P(x)) \vee P(\underline{x})$ , where  $\underline{x}$  is free

## 5 Sets

$$\begin{aligned} A \subseteq B &: \Leftrightarrow \forall x (x \in A \rightarrow x \in B) \\ A = B &\Leftrightarrow A \subseteq B \wedge B \subseteq A \\ P(A) &:= \{S \mid S \subseteq A\} \\ A \cap (B \cup C) &= (A \cap B) \cup (A \cap C) \\ A \times B &= \{(a, b) \mid a \in A \wedge b \in B\} \\ \mathcal{P}(\{a, b, c\}) &= \{\emptyset, \{a\}, \{b\}, \{c\}, \{a, b\}, \{a, c\}, \{b, c\}, \{a, b, c\}\} \end{aligned}$$

## 6 Relations

### 6.1 Reflexive

**Formula:**  $a \rho a$

**Set:**  $id \subseteq \rho$

**Matrix:** Diagonal is all 1

**Graph:** Every vertex has a loop

**Examples:**  $\leq, \geq, |, \equiv_m$  on  $\mathbb{Z}$

### 6.2 Transitive

**Formula:**  $a \rho b \wedge b \rho c \Rightarrow a \rho c$

**Set:**  $\rho^2 \subseteq \rho$

**Examples:**  $\leq, \geq, |, <, >, \equiv_m$  on  $\mathbb{Z}$

### 6.3 Symmetric

**Formula:**  $a \rho b \Leftrightarrow b \rho a$

**Set:**  $\rho = \hat{\rho}$

**Matrix:** Matrix is symmetric

**Graph:** Undirected graph, possibly with loops

**Examples:**  $\equiv_m$  on  $\mathbb{Z}$

### 6.4 Antisymmetric

**Formula:**  $a \rho b \wedge b \rho a \Rightarrow a = b$

**Set:**  $\rho \cap \hat{\rho} \subseteq id$

**Graph:** No cycle of length 2

**Examples:**  $\leq, \geq$  on  $\mathbb{Z}$  and  $|$  on  $\mathbb{N}$

#### 6.4.1 Relations as Sets

$a \rho \sigma b:$   $\exists b \in B : (a \rho b \wedge b \sigma c)$

$a (\rho \cup \sigma) b:$  Either  $a \rho b$  or  $a \sigma b$

$a (\rho \cap \sigma) b:$   $a \rho b$  and  $a \sigma b$

**The empty set  $\emptyset$ :** symmetric and transitive

#### 6.4.2 Equivalence Relation

**Example:**  $\equiv_m$  on  $\mathbb{Z}$

A relation that is reflexive, symmetric, and transitive.

The set of elements in  $A$  that equivalent to  $a \in A$  according to the equivalence relation  $\theta$  is called the **equivalence class** of  $a$ .

$$[a]_\theta := \{b \in A \mid b \theta a\}$$

The set  $A/\theta$  of equivalence classes of  $\theta$  on  $A$  is a **partition**.

*Hint:*

$$a \theta b \Rightarrow [a] = [b]$$

$$a \not\theta b \Rightarrow [a] \cap [b] = \emptyset$$

### 6.5 Partial Order

**Example:**  $\leq$  and  $\geq$  on  $\mathbb{Z}, \mathbb{Q}$  or  $\mathbb{R}$

A relation that is reflexive, antisymmetric, and transitive.

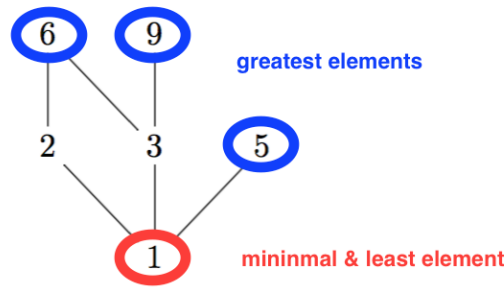
Special elements in a poset  $(A, \preceq)$  with a subset  $S \subseteq A$ :

**minimal (maximal) element:**  $a \in S$  if there exists no  $b \in S$  with  $b \prec a$  ( $b \succ a$ )

**least (greatest) element:**  $a \in S$  if  $a \preceq b$  ( $a \succeq b$ ) for all  $b \in S$

**lower (upper) bound:**  $a \in A$  if  $a \preceq b$  ( $a \succeq b$ ) for all  $b \in S$

**greatest lower (least upper) bound:**  $a \in A$  if  $a$  is the greatest (least) element of the set of all lower (upper) bounds of  $S$



Hasse Diagram of the Poset  $(\{1, 2, 3, 5, 6, 9\}; |)$

## 6.6 Function

- injective:** no collisions
- surjective:** every value in the codomain is taken on for some argument
- bijective:** one-to-one mapping (injective and surjective)

## 7 Combinatorics

	with repetition	without repetition
<b>ordered</b>	$n^k$	$\frac{n!}{(n-k)!}$
	A passcode of length $n$ with $k$ different digits	How many ways can $k$ places be awarded to $n$ people
<b>unordered</b>	$\binom{n+k-1}{k}$	$\binom{n}{k} = \frac{n!}{k!(n-k)!}$
	Choose $k$ scoops of ice cream from $n$ different flavours	Select $k$ from $n$ objects

*Hint:*  $\binom{n}{0} = \binom{n}{n} = 1$ ,  $\binom{n}{1} = \binom{n}{n-1} = n$

### 7.1 Countability

- same cardinality**  $A \sim B$ : There exists a bijection  $A \rightarrow B$
- B has at least the cardinality of A**  $A \preceq B$ :  $A \sim C$  for some subset  $C \subseteq B$
- B dominates A**  $A \prec B$ :  $A \preceq B \wedge A \not\sim B$
- countable:**  $A \preceq \mathbb{N}$

*Hint:*

The set  $\{0, 1\}^* := \{0, 1, 00, 01, \dots\}$  of **finite binary sequences** is countable.

The set  $\{0, 1\}^\infty$  is uncountable (Cantor's diagonalization argument).

The set  $A^n$  of  **$n$ -tuples** over  $A$  is countable.

The **union of a countable list** of countable sets is countable (can be considered as tuples).

### 7.2 Inclusion/Exclusion Principle

$$|A \cup B \cup C| = |A| + |B| + |C| - |A \cap B| - |A \cap C| - |B \cap C| + |A \cap B \cap C|$$

### 7.3 Binomial Theorem

$$(x + y)^n = \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k$$

## 8 Graph Theory

### 8.1 Traversals

<b>walk:</b>	sequence of vertices such that consecutive vertices are connected
<b>tour:</b>	a walk with distinct edges
<b>circuit:</b>	a tour that ends where it started
<b>Hamiltonian cycle:</b>	a circuit that visits all vertices

### 8.2 Planar Graphs

A **tree** is an *undirected, connected* graph with no cycles and  $n - 1$  edges.

For *connected, planar* graphs, the following equations hold:

$$\begin{aligned}\text{number of regions } r &= |E| - |V| + 2 \\ \text{sum of the degrees of the regions} &= \sum_{v \in V} \deg(v) = 2|E| \\ &\text{if } |V| \geq 3 \Rightarrow |E| \leq 3|V| - 6 \\ &\text{if } |V| \geq 3 \text{ and bipartite} \Rightarrow |E| \leq 2|V| - 4\end{aligned}$$

Rules to prove **non-planarity**

- deletion of edges
- deletion of singleton vertices
- merging neighboring vertices

### 8.3 Isomorphism

Two graphs are **isomorphic** if there exists a bijection  $\pi : V \mapsto V'$  such that

$$\{u, v\} \in E \Leftrightarrow \{\pi(u), \pi(v)\} \in E'$$

*Hint:* Look for cycles with vertices that have a distinct number of degrees. If the graph in question doesn't contain that specific cycle, it can't be isomorph.

## 9 Number Theory

### 9.1 Division

*Hint:* Every non-zero integer is a divisor of 0. 1 and -1 are divisors of every integer.

### 9.2 Greatest Common Divisor

For integers  $a$  and  $b$  (not both 0), an integer  $d$  is called a  $\gcd(a, b)$  if  $d$  divides both  $a$  and  $b$  and if every common divisor of  $a$  and  $b$  divides  $d$ .

$$\begin{aligned}d|a \text{ and } d|b \text{ and } c|a \wedge c|b &\Rightarrow c|d \\ \gcd(a, b) &:\Leftrightarrow \exists u, v \quad ua + vb\end{aligned}$$

### 9.3 Chinese Remainder Theorem

$$\text{given} \quad z \equiv_{b_1} c_1$$

$$z \equiv_{b_2} c_2$$

$$z \equiv_{b_3} c_3$$

$$\text{then} \quad z = B_1x_1c_1 + B_2x_2c_2 + B_3x_3c_3$$

$$\text{where} \quad B_i = \frac{B}{b_i} \text{ with } B = b_1b_2b_3 \text{ and } B_ix_i \equiv_{b_i} 1$$

$$\text{To find different } z \text{ to satisfy certain constraints} \quad z' = z \pm n \cdot B, \quad n \in \mathbb{N}$$

### 9.4 Extended Euclidean Algorithm

$$\text{given} \quad x = \gcd(888, 54)$$

$$\text{then} \quad 888 = 54(16) + 24$$

$$54 = 24(2) + \underline{6}$$

$$24 = 6(4) + 0$$

$$\begin{aligned} \text{to find } 6 = u(888) + v(54): \quad 6 &= 54 - 24(2) \\ &= 54 + 24(-2) \\ &= 54 + (888 - 54(16))(-2) \\ &= 54 + (888 + 54(-16))(-2) \\ &= 54 + 888(-2) + 54(32) \\ &= (-2)888 + (33)54 \end{aligned}$$

### 9.5 Ideal

$$(a, b) := \{ua + vb | u, v \in \mathbb{Z}\}$$

$$(a) := \{ua | u \in \mathbb{Z}\}$$

For  $a, b \in \mathbb{Z}$  there exists  $d \in \mathbb{Z}$  such that  $(a, b) = (d)$ . This implies that  $d$  is the **gcd** of  $a$  and  $b$ .

### 9.6 Least Common Multiple

$l = \text{lcm}(a, b)$  is the common multiple of  $a$  and  $b$  which divides every common multiple of  $a$  and  $b$ .

$$a|l' \text{ and } b|l' \Rightarrow l|l'$$

It follows:

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

### 9.7 Modular Arithmetic

$$R_m(a + b) = R_m(R_m(a) + R_m(b))$$

$$R_m(ab) = R_m(R_m(a) \cdot R_m(b))$$

### 9.8 Multiplicative Inverses

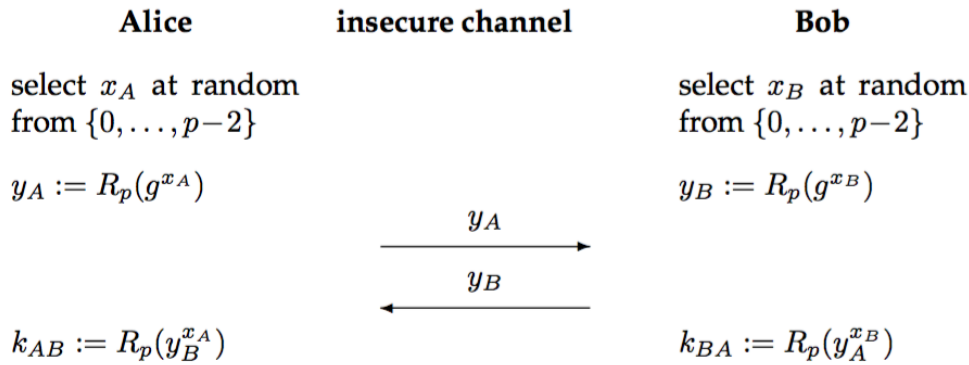
The **congruence equation** has a solution  $x \in \mathbb{Z}_m$  if and only if  $\gcd(a, m) = 1$ . The solution is unique.

$$ax \equiv_m 1$$

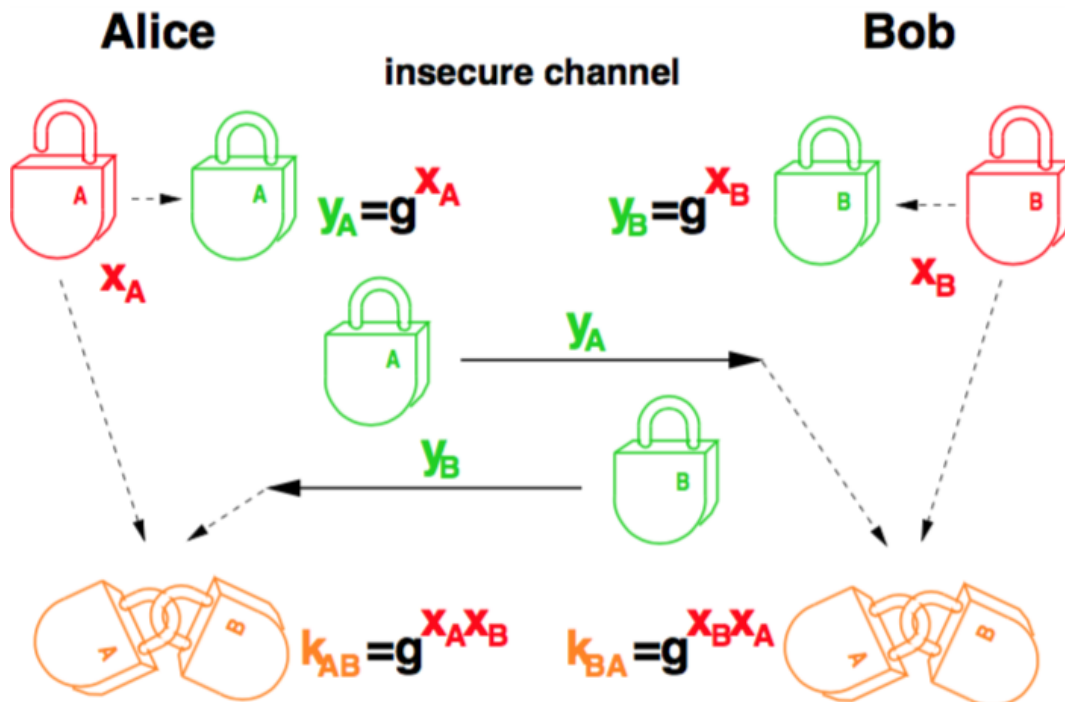
The  $x$  satisfying the equation is called the **multiplicative inverse of  $a$  modulo  $m$**  ( $x \equiv_m a^{-1}$  or  $x \equiv_m \frac{1}{a}$ ).

## 9.9 Diffie-Hellman Key-Agreement Protocol

The Diffie-Hellman protocol is based on the **discrete logarithm problem**. Basically, while  $y = R_p(g^x)$  can be computed efficiently, it can't be solved for  $x$ .



$$k_{AB} \equiv_p y_B^{x_A} \equiv_p (g^{x_B})^{x_A} \equiv_p g^{x_A x_B} \equiv_p k_{BA}$$

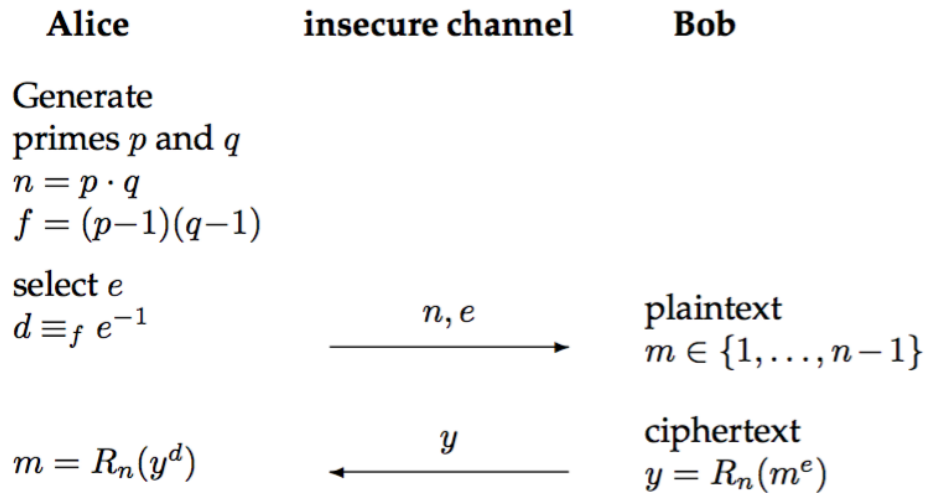


## 9.10 RSA

A finite group needs  $G$  needs to be chosen. Usually, the group  $\mathbb{Z}_n^*$  where  $n = pq$  is the product of two secret prime numbers. Then  $d$  is equal to

$$d \equiv_{|G|} e^{-1} \equiv_{(p-1)(q-1)} e^{-1}$$

where  $d$  is the **private key** and the tuple  $(n, e)$  is the **public key**.  
*Hint:* It's not possible to calculate  $d$  without knowing  $G$ 's order.



## 10 Algebra

### 10.1 Special Properties

Some special properties of an algebra  $\langle S; *, e \rangle$  are

<b>neutral element:</b>	$e \in S$ such that $e * a = a * e = a$
<b>associativity:</b>	$*$ is associative if $a * (b * c) = (a * b) * c$ for all $a, b, c \in S$
<b>inverse element:</b>	$b$ is the inverse of $a$ if $b * a = a * b = e$
<b>commutative/abelian:</b>	$a * b = b * a$ for all $a, b \in S$

The **neutral** and **inverse element** can have a left and right version. E.g.  $e * a = a$  is the left neutral element. However, there is *always only one* neutral/inverse element.



## 10.2 Special Algebras

	Notation	Axioms	Examples
<b>Semigroup</b>	$\langle S; * \rangle$	$*$ is associative	
<b>Monoid</b>	$\langle M; *, e \rangle$	$*$ is associative	
		$e$ is the neutral element	
<b>Group</b>	$\langle G; *, \hat{\cdot}, e \rangle$	$*$ is associative	$\langle \mathbb{Z}; +, -, 0 \rangle,$ $\langle \mathbb{Q} - \{0\}; \cdot, ^{-1}, 1 \rangle,$ $\langle \mathbb{R}; +, -, 0 \rangle$
		$e$ is the neutral element	
		every $a \in G$ has an inverse element	
<b>Ring</b>	$\langle R; +, -, 0, \cdot, 1 \rangle$	$\langle R; +, -, 0 \rangle$ is a commutative group	$\mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C}$ (commutative)
		$\langle R; \cdot, 1 \rangle$ is a monoid	
		$a(b + c) = ab + ac$ and $(b + c)a = ba + ca$ for all $a, b, c \in R$	
<b>Integral Domain</b>		commutative	$\mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C}$
		no zerodividers $ab = 0 \Rightarrow a = 0 \vee b = 0$	
<b>Field</b>	$GF(p) \equiv \mathbb{Z}_p$	$\langle F - \{0\}; \cdot, ^{-1}, 1 \rangle$ is a commutative ring	$\mathbb{Q}, \mathbb{R}, \mathbb{C}$
		every nonzero element is a unit (has an inverse)	

*Hint:* In order to prove a specific algebra, prove its axioms and that the set is closed in correspondence to its operations.

## 10.3 Groups

### 10.3.1 Direct Product

The **direct product of  $n$  groups**  $\langle G_1; *_1 \rangle, \dots, \langle G_n; *_n \rangle$  is the group

$$\langle G_1 \times \dots \times G_n, \star \rangle$$

where the operation  $\star$  is component-wise:

$$(a_1, \dots, a_n) \star (b_1, \dots, b_n) = (a_1 *_1 b_1, \dots, a_n *_n b_n)$$

### 10.3.2 Homomorphism

A function  $\psi$  from a group  $\langle G; *, \hat{\cdot}, e \rangle$  to a group  $\langle H; \star, \hat{\cdot}, e' \rangle$  is a group homomorphism if, for all  $a$  and  $b$

$$\psi(a * b) = \psi(a) \star \psi(b)$$

Furthermore,  $\psi$  is an **isomorphism** if it's a bijection.

A group homomorphism satisfies:

$$\begin{aligned} \psi(e) &= e' \\ \psi(\hat{a}) &= \widehat{\psi(a)} \end{aligned}$$

## 10.4 Subgroup

A subset  $H \subseteq G$  of a group  $\langle G; *, \hat{\cdot}, e \rangle$  is called a subgroup if  $\langle H; *, \hat{\cdot}, e \rangle$  is *closed* with respect to all operations.

$$a * b \in H \text{ for all } a, b \in H$$

$$e \in H$$

$$\hat{a} \in H \text{ for all } a \in H$$

The smallest subgroup of a group  $G$  containing the element  $g \in G$  is the **group generated** by  $g$ :

$$\langle g \rangle := \{g^n | n \in \mathbb{Z}\}$$

where the resulting group is called **cyclic**.

*Hint:* The order of a subgroup of a finite group divides its enclosing group's order  $|H|$  divides  $|G|$ .

### 10.4.1 Cyclic Group

A **cyclic group** of order  $n$  is isomorphic with  $\langle \mathbb{Z}_n; \oplus \rangle$ .

*Hint:* Every group of prime order is cyclic, and in such a group every element except the neutral element is a generator.

*Hint:*  $\mathbb{Z}_p^*$  is cyclic if and only if  $m = 2$ ,  $m = 4$ ,  $m = p^e$  or  $m = 2p^e$ , where  $p$  is a prime and  $e \geq 1$

### 10.4.2 Order

**of a finite group:**  $|G|$  is the order of  $G$

**of an element of  $G$ :** The order of  $a \in G$  is the least  $m \geq 1$  such that  $a^m = e$  if such an  $m$  exists, and  $\text{ord}(a) = \infty$  otherwise.

*Hint:*  $\text{ord}(e) = 1$ . If  $\text{ord}(a) = 2$ , then  $a^{-1} = a$ .

## 10.5 Group $\mathbb{Z}_m^*$ and Euler's Function

$\langle \mathbb{Z}_m^*; \odot, ^{-1}, 1 \rangle$  is a group with the set

$$\mathbb{Z}_m^* := \{a \in \mathbb{Z}_m \mid \gcd(a, m) = 1\}$$

The **Euler function** is defined as follows:

$$\varphi(m) = |\mathbb{Z}_m^*|$$

*Hint:* If  $p$  is a prime, then  $\mathbb{Z}_p^* = \{1, \dots, p-1\} = \mathbb{Z}_p - \{0\}$

## 10.6 Polynomials over Fields

$R[x]$  denotes a **polynomial ring**, a set of polynomials over  $R$ .

A polynomial is called **monic**, if its first coefficient is 1.

The polynomial  $a(x) \in F[x]$  is called **irreducible** if it is divisible only by constants and by constant multiples of  $a(x)$ . Moreover,  $\alpha \in F$  is a **root**  $\Leftrightarrow (x - \alpha)$  divides  $a(x)$ .

*Hint:* Every polynomial of degree 2 except  $x^2 + x + 1$  is reducible. Every irreducible polynomial of degree  $\geq 2$  has no roots.

**Example:** Polynomial Division on  $GF(2)$ :

$$\begin{array}{r}
 (x^4 + x + 1) : (x^2 + x + 1) = x + 2 \\
 \underline{-(x^3 + 2x)} \\
 -2x^2 - 2x + 5 \\
 \underline{-(2x^2 + 4)} \\
 -2x + 1
 \end{array}$$

**Example:** Polynomial Interpolation

$$\begin{array}{ll}
 \text{given} & a(x) \text{ with } a(3) = 2, a(4) = 6, a(5) = 7 \\
 \text{then} & a(x) = 2 \frac{(x-4)(x-5)}{(3-4)(3-5)} + 6 \frac{(x-3)(x-5)}{(4-3)(4-5)} + 7 \frac{(x-3)(x-4)}{(5-3)(5-4)}
 \end{array}$$

## 10.7 Error-Correcting Codes

A **(k,n)-error-correcting code**  $\mathcal{C}$  over the alphabet  $\mathcal{A}$  with  $|\mathcal{A}| = q$  is a subset of cardinality  $q^k$  of  $\mathcal{A}^n$  i.e. one element is of length  $n$ , with  $q^k$  different elements.

*Hint:* Usually,  $\mathcal{A} = \{0, 1\}$  with  $q = 2$  is being considered

The **Hamming distance** between two codewords is the number of positions at which the two codewords differ.

The **minimum distance** of an error-correcting code  $\mathcal{C}$  is the minimal Hamming distance between any two codewords.

A code  $\mathcal{C}$  with minimum distance  $d$  can correct  $t$  errors if and only if  $d \geq 2t + 1$ .

## 11 Logic

### 11.1 Proof System

A **proof system** is a quadruple  $\Pi = (\mathcal{S}, \mathcal{P}, \tau, \phi)$  with the following components:

- set of statements  $\mathcal{S}$ :** every  $s \in \mathcal{S}$  is either *true* or *false*
- set of proofs  $\mathcal{P}$ :** e.g. strings over some alphabet
- truth function  $\tau$ :** defines the meaning (*semantics*) of objects in  $\mathcal{S}$
- verification function  $\phi$ :**  $\phi(s, p) = 1$  means that  $p$  is a valid proof for the statement  $s$

The proof system  $\Pi = (\mathcal{S}, \mathcal{P}, \tau, \phi)$  is

- sound** if no false statement has a proof  
 $\phi(s, p) = 1 \Rightarrow \tau(s) = 1$
- complete** if every true statement has a proof  
 $\tau(s) = 1 \Rightarrow \exists p \in (\mathcal{P}) \phi(s, p) = 1$

## 11.2 Syntax and Semantics

	Description	Notation
<b>Syntax</b>	alphabet of allowed symbols and which strings are valid	
<b>Interpretation</b>	an assignment to all variable symbols	$\mathcal{A}(A) = \{0, 1\}$
<b>Semantics</b>	a function $\sigma$ assigning to each formula $F$ and each suitable interpretation $\mathcal{A}$ a truth value	$\sigma(F, \mathcal{A}) = \{0, 1\}, \mathcal{A}(F)$
<b>Model</b>	an interpretation $\mathcal{A}$ for which $F$ is true	$\mathcal{A} \models F$

*Hint:*  $F \models G$  means that every model for  $F$  is also a model for  $G$ .

### 11.2.1 Structure

A **structure** is a tuple  $\mathcal{A} = (U, \phi, \psi, \xi)$  with the following components:

**universe  $U$ :** nonempty set

**function  $\phi$ :** assigns to each function symbol a function  $U^k \mapsto U$

**function  $\psi$ :** assigns to each predicate symbol a function  $U^k \mapsto \{0, 1\}$

**function  $\xi$ :** assigns to each variable symbol a value in  $U$

## 11.3 Calculi

A **derivation rule** is a rule for deriving a formula from a set of formulas.  $G$  can be derived from the set  $\{F_1, \dots, F_k\}$  by rule  $R$ :

$$\{F_1, \dots, F_k\} \vdash_R G$$

A **calculus  $K$**  is a finite set of derivation rules  $K = \{R_1, \dots, R_m\}$ . It is

**sound/correct** if and only if every derivation rule is correct

**complete** if  $F$  is a logical consequence of  $M$ , then  $F$  can be derived from  $M$  using  $K$

## 11.4 Normal Forms

### 11.4.1 Conjunctive Normal Form (CNF)

$$F = (L_{11} \vee \dots \vee L_{1m_1}) \wedge \dots \wedge (L_{n1} \vee \dots \vee L_{nm_n})$$

### 11.4.2 Disjunctive Normal Form (DNF)

$$F = (L_{11} \wedge \dots \wedge L_{1m_1}) \vee \dots \vee (L_{n1} \wedge \dots \wedge L_{nm_n})$$

*Hint:* Every formula is equivalent to a formula in **CNF** and **DNF**.

## 11.5 Resolution Calculus

Given a Formula  $F$  in  $CNF$ , one can transform it into a set of clauses:

$$\mathcal{K}(F) = \{\{L_{11}, \dots, L_{1m_1}\}, \dots, \{L_{n1}, \dots, L_{nm_1}\}\}$$

A clause  $K$  is then a **resolvent** of clauses  $K_1$  and  $K_2$  if there is a literal  $L$  such that  $L \in K_1$  and  $\neg L \in K_2$

$$K = (K_1 - \{L\}) \cup (K_2 - \{\neg L\})$$

This derivation is denoted as follows:

$$\{K_1, K_2\} \vdash_{res} K$$

*Hint:* A set  $M$  of formulas is unsatisfiable if and only if  $\mathcal{K}(M) \vdash_{res} \emptyset$

### 11.5.1 Prenex Form

In order to bring a formula into prenex form

1. Resolve all name collisions
2. Pull the quantifiers to the front by inverting them every time they surpass a  $\neg$ .