Cryptography

Algebraic Structures

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Groups

Definition

A *group* G is a set together with a law of composition

$$\circ : G \times G \to G$$

such that the following properties are satisfied:

- For all $a, b, c \in G$ one has $(a \circ b) \circ c = a \circ (b \circ c)$ (*associative law*).
- There is an *identity* element $e \in G$ such that $e \circ g = g \circ e = g$ for all $g \in G$ (*identity element*).
- For every $g \in G$ there is an *inverse* element $x \in G$ with $g \circ x = x \circ g = e$ (*inverse elements*).

The group is called *abelian* or *commutative* if for all $a, b \in G$, one has $a \circ b = b \circ a$ (*commutative law*).

Examples of Groups

- $(\mathbb{Z}, +)$ is an additive abelian group.
- $(\mathbb{R} \setminus \{0\}, \cdot)$ is a multiplicative abelian group.
- $(\mathbb{Z}_n, +)$ (the residue classes modulo n) are an additive abelian group with n elements.
- $(\mathbb{Z}_n^*, \cdot)$ (the units modulo n) are a multiplicative abelian group with $\varphi(n)$ elements and

$$\mathbb{Z}_n^* = \{x \bmod n \mid x \in \mathbb{Z} \text{ and } \gcd(x, n) = 1\}.$$

- Let p be a prime. Then $(\mathbb{Z}_p^*, \cdot)$ is a multiplicative abelian group containing the $p-1$ residue classes $1, 2, \ldots, p-1 \bmod p$.
- The permutations of $\{1, 2, \ldots, n\}$ (with composition of mappings) from a non-commutative group with $n!$ elements.

Homomorphism and Isomorphism

Definition

Let $f : G_1 \to G_2$ be a map between two groups G_1, G_2. Then f is called a *group homomorphism* if $f(g \circ g') = f(g) \circ f(g')$ for all $g, g' \in G_1$. A bijective group homomorphism is called an *isomorphism*. If f is an isomorphism, then G_1 is *isomorphic* to G_2 and write $G_1 \cong G_2$.

Warning: A bijection between two groups does not necessarily imply that they are isomorphic! For example, $\mathbb{Z}_4 \not\cong \mathbb{Z}_2 \times \mathbb{Z}_2$.

Examples of Homomorphisms

- There is a bijection between $G_1 = \mathbb{Z}_2 \times \mathbb{Z}_2$ and $G_2 = \mathbb{Z}_4$ (since both groups have 4 elements), but they are not isomorphic.
- The projection map $f : \mathbb{Z} \to \mathbb{Z}_n$, defined by $f(k) = k \bmod n$, is a surjective homomorphism.
- Let $G_1 = (\mathbb{Z}_4, +) = \{\overline{0}, \overline{1}, \overline{2}, \overline{3}\}$ be the additive group of integers modulo 4 and $G_2 = (\mathbb{Z}_5^*, \cdot) = \{\overline{1}, \overline{2}, \overline{3}, \overline{4}\}$ the multiplicative group of units modulo 5. The map $f : G_1 \to G_2$, defined by

$$f(k \bmod 4) = 2^k \bmod 5,$$

  is a well defined homomorphism and bijective. Therefore, f is an isomorphism and $(\mathbb{Z}_4, +) \cong (\mathbb{Z}_5^*, \cdot)$.

Subgroups

Definition

Let G be a group. A *subgroup* H of G is a subset of G, which contains the identity element and is closed under the law of composition and inverse.

Example: Let $G = (\mathbb{Z}, +)$ and $H = 26\,\mathbb{Z}$ the set of all integer multiples of 26. Then H is an additive subgroup of G, since $0 \in H$ and H is closed under composition as well as inverse:

$$\begin{aligned} 26x + 26y &= 26(x+y) \in H \\ -26x &= 26(-x) \in H \end{aligned}$$

Subgroups generated by Elements

Each group element generates a subgroup:

Definition

Let G be a group and $g \in G$, then the set $< g > = \{g^k \mid k \in \mathbb{Z}\}$ is called the *subgroup generated by g*. Here we used the multiplicative notation. For an additive group, we write $< g > = \{k \cdot g \mid k \in \mathbb{Z}\}$.

The subgroups $< g >$ are in fact *cyclic* groups (see below).

Examples: a) $26\mathbb{Z} = < 26 >$ is a subgroup of $\mathbb{Z}$.
b) Let $< \overline{4} >$ be the subgroup of the multiplicative group $\mathbb{Z}_5^*$ generated by 4 mod 5. Then $< \overline{4} > = \{\overline{1}, \overline{4}\}$, since $4^0 = 1$, $4^1 = 4$, $4^2 = 1 \bmod 5$, $4^3 = 4 \bmod 5$, $\ldots$, $4^{-1} = 4 \bmod 5$, $4^{-2} = 1 \bmod 5$, $4^{-3} = 4 \bmod 5$, $\ldots$

Order of Groups and Subgroups

Definition (Order)

Let G be a group, then $\text{ord}(G) = |G|$ (or infinity). Let $g \in G$. Then the order of the element g is $\text{ord}(g) = \text{ord}(< g >)$.

Theorem (Lagrange)

Let G be a finite group and $H \subset G$ a subgroup. Then the order of H divides the order of G:

$$ord(H) \mid ord(G)$$

In particular, we have for every $g \in G$: $ord(g) \mid ord(G)$.

Example: If $\text{ord}(G) = 26$ and $g \in G$, then $\text{ord}(g) \in \{1, 2, 13, 26\}$.

Euler's Theorem

Theorem (Euler)

Let G be a finite group and $g \in G$, then

$$g^{\mathrm{ord}(G)} = e.$$

This follows from $g^{\mathrm{ord}(g)} = e$ and $\mathrm{ord}(g) \mid \mathrm{ord}(G)$.

We apply Euler's Theorem to $G = \mathbb{Z}_n^*$. In this case, $\mathrm{ord}(G) = \varphi(n)$.
For all $x \in \mathbb{Z}$ with $\gcd(x, n) = 1$, i.e., for $x \bmod n \in \mathbb{Z}_n^*$, we have:

$$x^{\varphi(n)} \equiv 1 \bmod n.$$

For a prime modulus p, it follows that

$$x^{p-1} \equiv 1 \bmod p \quad \text{and} \quad x^p \equiv x \bmod p.$$

Cyclic Groups

Definition

Let G be a group and $g \in G$. If $< g > = G$ then G is called a *cyclic group* and we say g is a *generator* of G.

The elements of a cyclic group G with generator g are

$$G = \{\dots, g^{-2}, g^{-1}, e, g, g^2, g^3, \dots\}.$$

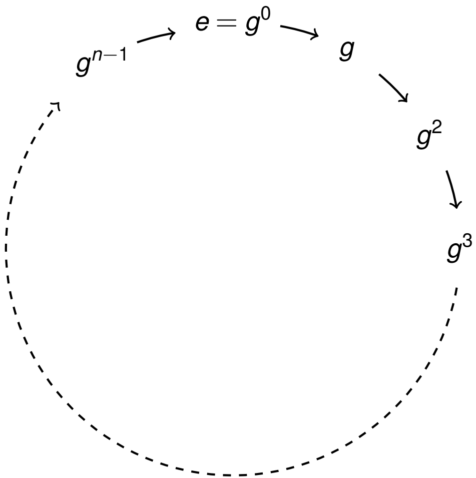
If $\operatorname{ord}(g) = n$ then $g^n = e$ and thus

$$G = \{e, g, g^2, g^3, \dots, g^{n-1}\}.$$

The map $f : \mathbb{Z}_n \to G$, $f(k \bmod n) = g^k$, is an isomorphism and hence

$$G \cong \mathbb{Z}_n.$$

Illustration of Cyclic Groups



Generators of the Integers modulo n

Finding generators of the *additive* group $G = (\mathbb{Z}_n, +)$ is easy: G is cyclic of order n and 1 mod n is a generator. In general, an integer x is a generator modulo n if and only if $\gcd(x, n) = 1$.

For the *multiplicative* group $G = (\mathbb{Z}_n^*, \cdot)$, finding generators is more difficult. It depends on n whether G is cyclic or not. If a generator exists, then we call it a *primitive root* modulo n.

Example: $G = (\mathbb{Z}_5^*, \cdot)$ is cyclic of order 4 and $< 2 > = \mathbb{Z}_5^*$. Hence 2 mod 5 is a primitive root modulo 5.

Theorem

Let p be a prime; then $(\mathbb{Z}_p^*, \cdot)$ *is a cyclic group of order* $p - 1$*. The number of primitive roots is* $\varphi(p-1)$*.*

Finding Generators

Suppose G is cyclic of order n. How can we check whether a given element $g \in G$ is a generator? Using the definition, i.e., computing $g^0, g^1, g^2, \ldots, g^{n-1}$ and verifying if the sequence contains all elements in G, is inefficient. However, we know that $\operatorname{ord}(g) \mid G$. If $\operatorname{ord}(g) < n$ then $\operatorname{ord}(g) \mid \frac{n}{q}$ for a prime divisor q of n. Therefore, if $g^{n/q} \neq e$ for all prime factors q of n, then $ord(g)$ cannot divide any $\frac{n}{q}$, and so $\operatorname{ord}(g) = n$.

Example: Let $G = \mathbb{Z}_{53}^*$. Since 53 is a prime, G is a cyclic group of order 52. We want to check whether $g = 2 \bmod 53$ is a generator of G. The factorization $52 = 2^2 \cdot 13$ yields the prime factors 2 and 13. One computes $g^{52/13} = 2^4 = 16 \not\equiv 1$ and $g^{52/2} = 2^{26} \equiv 52 \not\equiv 1$. We conclude that $g = 2$ is a generator of G.

It also follows that $g^2 = 4$ has order 26 and the order of $g^4 = 16$ is 13.

Chinese Remainder Theorem

Theorem (Chinese Remainder Theorem)

Let $a, b \in \mathbb{N}$ be relatively prime, i.e., $\gcd(a, b) = 1$. Let $n = ab$, then the natural map $f : \mathbb{Z}_n \to \mathbb{Z}_a \times \mathbb{Z}_b$, $f(k \bmod n) = (k \bmod a,\ k \bmod b)$ is well defined and gives an isomorphism of additive groups:

$$\mathbb{Z}_n \cong \mathbb{Z}_a \times \mathbb{Z}_b$$

How is f^{-1} defined? Let $(k_1 \bmod a,\ k_2 \bmod b) \in \mathbb{Z}_a \times \mathbb{Z}_b$. We need to find $k \in \mathbb{Z}$ with $k \equiv k_1 \bmod a$ and $k \equiv k_2 \bmod b$. Since $\gcd(a, b) = 1$, the Extended Euclidean Algorithm gives $x, y \in \mathbb{Z}$ such that $ax + by = 1$. This implies $ax \equiv 1 \bmod b$ and $by \equiv 1 \bmod a$. Now set

$$k = k_1 by + k_2 ax.$$

Then $k \equiv k_1 by \equiv k_1 \bmod a$ and $k \equiv k_2 ax \equiv k_2 \bmod b$, as desired.

Example

The Chinese Remainder Theorem (CRT) also gives an isomorphism of the multiplicative groups:

$$\mathbb{Z}_n^* \cong \mathbb{Z}_a^* \times \mathbb{Z}_b^*.$$

The CRT also holds true for more than two factors if the factors are pairwise relatively prime.

Example: Let $n = 60 = 2^2 \cdot 3 \cdot 5$. Then the Chinese Remainder Theorem gives the following decomposition:

$$\mathbb{Z}_{60} \cong \mathbb{Z}_4 \times \mathbb{Z}_{15} \cong \mathbb{Z}_4 \times \mathbb{Z}_3 \times \mathbb{Z}_5$$

However, $\mathbb{Z}_4$ is not isomorphic to $\mathbb{Z}_2 \times \mathbb{Z}_2$. Both groups have order 4, but the first group is cyclic while the second is not.

Fundamental Theorem of Abelian Groups

Theorem

Let G be a finite abelian group, then G is isomorphic to a direct product of cyclic groups $\mathbb{Z}_{p^k}$ of order p^k, where p is a prime number and $k \in \mathbb{N}$. The same prime p can appear in several factors.

Examples:

1. Let G be an abelian group of order 77. Then $G \cong \mathbb{Z}_7 \times \mathbb{Z}_{11}$. G is isomorphic to $\mathbb{Z}_{77}$ and cyclic.
2. Let G be an abelian group of order 18. Then G is either isomorphic to $\mathbb{Z}_2 \times \mathbb{Z}_9$ or to $\mathbb{Z}_2 \times \mathbb{Z}_3 \times \mathbb{Z}_3$. Note that these two groups are not isomorphic. The first group is cyclic, while the second group is not cyclic.

Ring

Definition

A *ring* (or more precisely, a commutative ring with unity) is a set R with two operations (addition $+$ and multiplication $\cdot$) such that:

- $(R, +)$ is an abelian group with the additive identity element 0.
- $(R, \cdot)$ satisfies the associative law, is commutative and has an identity element denoted by 1. The existence of an inverse element is not required.
- $x \cdot (y + z) = (x \cdot y) + (x \cdot z)$ for all $x, y, z \in R$ (distributivity).

Example: $\mathbb{Z}$ and $\mathbb{Z}_n$ are rings with respect to addition and multiplication of integers and residue classes, respectively.

Ring Homomorphism

Ring homomorphisms are compatible with addition and multiplication.

Definition

Let $f : R_1 \to R_2$ be a map between the rings R_1 and R_2. Then f is called a *ring homomorphism* if

1. $f(x+y) = f(x) + f(y)$ for all $x, y \in R_1$, and
2. $f(x \cdot y) = f(x) \cdot f(y)$ for all $x, y \in R_1$, and
3. $f(1) = 1$.

A bijective ring homomorphism is called an *isomorphism*: $R_1 \cong R_2$.

Example: Let a, $b \in \mathbb{N}$ be relatively prime and $n = ab$, then the Chinese Remainder Theorem gives a *ring isomorphism*

$$\mathbb{Z}_n \cong \mathbb{Z}_a \times \mathbb{Z}_b.$$

Units

Definition

Let R be a ring, then the subset of invertible elements with respect to multiplication is called the *units* of R and denoted by R^*. The units form an abelian group.

Examples:

$$\mathbb{Z}^* = \{1, -1\}$$

$$\mathbb{Z}_n^* = \{x \bmod n \mid x \in \mathbb{Z} \text{ and } gcd(x, n) = 1\}$$

$$\mathbb{Q}^* = \mathbb{Q} \setminus \{0\}$$

Field

Definition

A *field* K is a ring if all nonzero elements are invertible, i.e., if $K^* = K \setminus \{0\}$.

Examples: $\mathbb{Q}$, $\mathbb{R}$ and $\mathbb{C}$ are fields, but $\mathbb{Z}$ is not a field.
$\mathbb{Z}_n$ is a field if and only if n is a prime.

Definition

Let p be a prime. Then the field $(\mathbb{Z}_p, +, \cdot)$ with p elements is called the Galois Field $GF(p)$.

Example: The smallest field is $GF(2)$.

Orders of Finite Fields

$GF(p)$ is a field of prime order. Can we construct finite fields of other orders?

Proposition

Let K be a finite field. Then $ord(K) = p^n$, where p is a prime number and $n \in \mathbb{N}$.

However, the obvious candidates are not necessarily fields. In fact, $\mathbb{Z}_{p^n}$ is a ring with p^n elements, but not a field if $n \geq 2$. For example, $p \bmod p^n$ is nonzero and not invertible modulo p^n.

The construction of a field $GF(p^n)$ of order p^n is a bit more involved and requires polynomial rings.

Polynomial Rings

Definition

Let K be a field, then $K[x]$ is called the *set (or ring) of polynomials* over K and consists of all formal expressions

$$f(x) = \sum_{i=0}^{n} a_i x^i = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n$$

where $a_i \in K$ and $n \geq 0$ is an integer. The *degree* $\deg(f)$ of f is equal to n if $a_n \neq 0$. The degree of constant polynomials is 0. A polynomial is called *monic* if $a_n = 1$.

Polynomials can be added and multiplied in the obvious way.

Proposition

The polynomials $(K[x], +, \cdot)$ *over* K *form a ring.*

Division of Polynomials

Obviously, $K[x]$ *is not a field* since polynomials of degree ≥ 1 cannot be inverted multiplicatively. But we have a *division with remainder*. Let $f(x), g(x) \in K[x]$ with $g(x) \neq 0$. Then the division $f(x) : g(x)$ gives a quotient $q(x) \in K[x]$ and a remainder $r(x) \in K[x]$ such that

$$f(x) = q(x)g(x) + r(x) \text{ where } \deg(r) < \deg(g).$$

Obviously, $g(x)$ divides $f(x)$ if and only if the remainder is 0.

Example: Let $f(x) = x^6 + x^5 + x^3 + x^2 + x + 1$ and $g(x) = x^4 + x^3 + 1$ be polynomials in $GF(2)[x]$. The quotient of $f(x) : g(x)$ is $q(x) = x^2$, the remainder is $r(x) = x^3 + x + 1$ and we have an equation

$$x^6 + x^5 + x^3 + x^2 + x + 1 = x^2(x^4 + x^3 + 1) + (x^3 + x + 1).$$

Greatest Common Divisor

Polynomials behave similar to the integers: they form a ring, there is a division with remainder, a greatest common divisor, there are prime elements and residue classes.

Definition

Let $f(x), g(x) \in K[x]$ be nonzero polynomials, then the *greatest common divisor* $gcd(f, g)$ is the monic polynomial of highest possible degree that divides $f(x)$ and $g(x)$.

The greatest common divisor (gcd) of two polynomials can be efficiently computed using the *Extended Euclidean Algorithm*. The algorithm takes two polynomials f and g as input and outputs $gcd(f, g)$ along with two polynomials $a(x)$ and $b(x)$ such that

$$gcd(f, g) = a(x)f(x) + b(x)g(x).$$

Residue Classes

We define *residue classes* of polynomials:

Definition

Let $g \in K[x]$ be a polynomial with $\deg(g) \geq 1$, then $g(x)$ defines an equivalence relation on $K[x]$:

$$f_1(x) \sim f_2(x) \text{ if } f_1(x) - f_2(x) = q(x)g(x) \text{ for some } q(x) \in K[x]$$

Equivalent polynomials f_1 and f_2 are called *congruent modulo* $g(x)$ and we write $f_1(x) \equiv f_2(x) \bmod g(x)$. The set of equivalence classes or *residue classes modulo* $g(x)$ is denoted by $K[x]/(g(x))$.

Example (see above):
$x^6 + x^5 + x^3 + x^2 + x + 1 \equiv x^3 + x + 1 \bmod (x^4 + x^3 + 1)$, since $x^3 + x + 1$ is the remainder of the division of $x^6 + x^5 + x^3 + x^2 + x + 1$ by $x^4 + x^3 + 1$.

Quotient Ring

Proposition

Let $g \in K[x]$ and $n = \deg(g) \geq 1$, then $K[x]/(g(x))$ is again a ring called quotient ring, factor ring or residue class ring, with the operations induced by $K[x]$. Each residue class has a unique standard representative of degree less than n.

The ring structure can be easily verified. The standard representative can be found by division with remainder. Let $f(x) \in K[x]$ be any representative of a residue class. We divide $f(x)$ by $g(x)$ and obtain polynomials $q(x)$, $r(x)$ such that

$$f(x) = q(x)g(x) + r(x),$$

where $\deg(r) < n$. The equation implies $f(x) \equiv r(x) \bmod g(x)$ and $r(x)$ is the standard representative of the class $f(x) \bmod g(x)$.

Polynomial Rings over $GF(p)$ and their Quotient Rings

Proposition

Let p be a prime and $g \in GF(p)[x]$ a polynomial of degree n, then the quotient ring $GF(p)[x]/(g(x))$ has p^n elements.

Our objective is to construct a *field* with p^n elements. We have to factor out an *irreducible* polynomial $g(x)$.

Definition

A polynomial $g(x) \in K[x]$ is called *irreducible*, if it cannot be factored into two polynomials of smaller degree. Otherwise, the polynomial is called *reducible*.

Irreducible polynomials can be viewed as the prime elements of the polynomial ring.

Irreducible Polynomials

Irreducible polynomials in $K[x]$ do not possess any zeros $a \in K$, since otherwise a linear factor $(x - a)$ can be split off. However, for polynomials of degree ≥ 4, irreducibility is a stronger condition! For example, $g(x) = x^4 + x^2 + 1$ has no zeros over $GF(2)$, but $g(x) = (x^2 + x + 1)^2$ in $GF(2)[x]$. Hence $g(x)$ is reducible.

Degree	Irreducible Polynomials
2	$x^2 + x + 1$
3	$x^3 + x + 1,\ x^3 + x^2 + 1$
4	$x^4 + x + 1,\ x^4 + x^3 + x^2 + x + 1,$ $x^4 + x^3 + 1$
5	$x^5 + x^2 + 1,\ x^5 + x^3 + x^2 + x + 1,$ $x^5 + x^3 + 1,\ x^5 + x^4 + x^3 + x + 1,$ $x^5 + x^4 + x^3 + x^2 + 1,\ x^5 + x^4 + x^2 + x + 1$

Construction of $GF(p^n)$

Proposition

Let $g(x) \in K[x]$ be an irreducible polynomial. Then the quotient ring $K[x]/(g(x))$ is a field.

Why is this true? Obviously, $K[x]$ is not a field. We use the *Extended Euclidean Algorithm for polynomials* to invert a nonzero polynomial f of degree less than $\deg(g)$. Since $gcd(f, g) = 1$, there are polynomials h_1 and h_2 such that

$$1 = h_1(x)f(x) + h_2(x)g(x) \Rightarrow h_1(x)f(x) \equiv 1 \bmod g.$$

Definition

Let $g(x) \in GF(p)[x]$ be an *irreducible polynomial* of degree n, then the residue field $GF(p)[x]/(g(x))$ defines the *Galois Field* $GF(p^n)$ of order p^n.

Example $GF(4)$

The polynomial $g(x) = x^2 + x + 1 \in GF(2)[x]$ has no zeros and is irreducible, and so $GF(2)[x]/(x^2 + x + 1) \cong GF(4)$.

$+$	0	1	x	$x+1$
0	0	1	x	$x+1$
1	1	0	$x+1$	x
x	x	$x+1$	0	1
$x+1$	$x+1$	x	1	0

$\cdot$				
0	0	0	0	0
1	0	1	x	$x+1$
x	0	x	$x+1$	1
$x+1$	0	$x+1$	1	x

Addition and multiplication table for $GF(4)$.

Example $GF(256)$

Let $g(x) = x^8 + x^4 + x^3 + x + 1 \in GF(2)[x]$. One can show that $g(x)$ is irreducible. Hence $GF(2)[x]/(x^8 + x^4 + x^3 + x + 1) \cong GF(256)$ defines a field of order 256.

This field is used in the block cipher AES. The elements in $GF(2^8)$ are in bijection to polynomials of degree less than 8, which in turn correspond the 8-bit words. The first bit (most significant bit, MSB) corresponds to the coefficient of x^7, the second bit to x^6 etc., and the last bit (least significant bit, LSB) to $x^0 = 1$, i.e., the byte $b_7 b_6 \dots b_1 b_0$ corresponds to the polynomial $b_7 x^7 + b_6 x^6 + \cdots + b_1 x + b_0$.

Addition of polynomials corresponds to a simple XOR operation of 8-bit words. However, multiplication is less obvious and defined by a multiplication of polynomials, followed by a reduction modulo $g(x)$.

Computations in $GF(256)$

Let $g(x) = x^8 + x^4 + x^3 + x + 1 \in GF(2)[x]$. Suppose we want to multiply x^7 and $(x+1)$ mod $g(x)$. This gives

$$x^7(x+1) = x^8 + x^7 \bmod g(x) \equiv x^7 + x^4 + x^3 + x + 1.$$

In hexadecimal notation, this can be written as $\texttt{80} \cdot \texttt{03} = \texttt{9B}$.

```
sage:   R.<x> = PolynomialRing(GF(2),x)
sage:   g=x^8+x^4+x^3+x+1
sage:   K.<a>=R.quotient_ring(g)
sage:   a^7 * (a+1) ; 1/(a+1)
a^7 + a^4 + a^3 + a + 1
```

Now we compute the inverse of $x+1$ mod $g(x)$:

```
sage:   1/(a+1)
a^7 + a^6 + a^5 + a^4 + a^2 + a
```

In fact, $(x+1)(x^7 + x^6 + x^5 + x^4 + x^2 + x) \equiv 1 \bmod g(x)$ and we can write $\texttt{03}^{-1} = \texttt{F6}$.