

Part II – Number Theory

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0 Introduction

Number theory is concerned with the (non-obvious, sometimes mysterious) properties of the integers, $\mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$ and the rationals, $\mathbb{Q} = \{\frac{m}{n} \mid m, n \in \mathbb{Z}, n \neq 0\}$. It has been around for thousands of years, and has always been an experimental science where one can conduct experiments with numbers to spot their properties. Experimental data leads to conjectures which can turn out to be very hard to prove, for instance:

1. Congruent number problem: Let $N \geq 1$ be an integer of the form $8n + 5$, $8n + 6$ or $8n + 7$. Does there exist a right-angled triangle with sides of rational length, and area equal to N ?
2. Twin prime conjecture: Does there exist infinitely many primes p such that $p + 2$ is also prime? Very recently, we know there are infinitely many primes p such that $\{p + 2, p + 4, \dots, p + 246\}$ contains a prime.
3. $\pi(x)$ refers to the prime counting function, the number of prime numbers $p \leq x$. The prime number theorem says that $\pi(x) \sim \text{li}(x) := \int_2^x \frac{dt}{\log t}$. It is not known whether or not $|\pi(x) - \text{li}(x)| \leq \sqrt{x} \log(x)$, which is equivalent to the Riemann hypothesis - a statement about a certain complex analytic function.

Problem 1 follows from the Birch-Swinnerton-Dyer conjecture, related to algebraic geometry. Often these proofs can require sophisticated theorems, well beyond the statement of the problem.

1 Euclid's algorithm and factoring

Definition (Division algorithm). Given $a, b \in \mathbb{Z}$, with $b > 0$, there are $q, r \in \mathbb{Z}$ with $0 \leq r < b$ and $a = bq + r$, that is, we can divide a by b to give a quotient q and remainder r .

Proof. Let $S = \{a - nb \mid n \in \mathbb{Z}\}$, which certainly contains some non-negative integers. Let r be the least of them which exists by the well ordering property of the non-negative integers. Claim $r < b$, since if not then $r - b \in S$, and $r - b \geq 0$, contradicting the choice of r . \square

Notation. If $r = 0$ (that is, $a = bq$ for some $q \in \mathbb{Z}$), write $b \mid a$ (read as ‘ b divides a ’), otherwise write $b \nmid a$.

Given $a_1, \dots, a_n \in \mathbb{Z}$ not all zero, let

$$I = \{\lambda_1 a_1 + \dots + \lambda_n a_n \mid \lambda_i \in \mathbb{Z}\}$$

We recognise this from GRM as the ideal generated by $\{a_1, \dots, a_n\}$. Note if $a, b \in I$, for any choice $l, m \in \mathbb{Z}$ then $la + mb \in I$.

Lemma 1.1. $I = d\mathbb{Z} = \{\lambda d \mid \lambda \in \mathbb{Z}\}$ for some $d \leq 1$, clearly unique.

Proof. As not all of a_i are 0, I contains some positive integer, let d be the least of them. So, $d \in I$, and hence $d\mathbb{Z} \subset I$. On the other hand, for $a \in I$ the division algorithm gives us $a = qd + r$ with $0 \leq r < d$. But then $r = a - dq \in I$ so by minimality of d we have $r = 0$, and so $a \in d\mathbb{Z}$, giving $I \subset d\mathbb{Z}$ as required. \square

Definition (Greatest common divisor). $a_i \in I = d\mathbb{Z}$ so $d \mid a_i$. If in addition, we have that $\forall i, e \mid a_i$, then e divides every element of I , so $e \mid d$. Write $d = \gcd(a_1, \dots, a_n) = (a_1, \dots, a_n)$, the **greatest common divisor** (alternatively the highest common factor).

The study of **Diophantine equations** involves solving equations with integer solutions, and may have more variables than equations. The simplest case is linear in two variables, and can be solved easily.

Corollary. Let $a, b, c \in \mathbb{Z}$ with not both a, b equal to 0. Then we can find $x, y \in \mathbb{Z}$ such that $ax + by = c \Leftrightarrow (a, b) \mid c$.

The definition of the greatest common divisor given here is non-constructive, but **Euclid's algorithm** is an efficient way to compute it.

Euclid's algorithm Assume $a > b > 0$. Apply successively the [division algorithm](#):

$$\begin{array}{ll} a = q_1 b + r_1 & 0 \leq r_1 < b \\ b = q_2 r_1 + r_2 & 0 \leq r_2 < b \\ r_1 = q_3 r_2 + r_3 & 0 \leq r_3 < b \\ \vdots & \\ r_{k-2} = q_k r_{k-1} + r_k & 0 \leq r_k < b \\ r_{k-1} = q_{k+1} r_k + 0 & \end{array}$$

for some k , so $r_k \mid r_{k-1}$. We claim $r_k = (a, b)$. Indeed, $(a, b) = (a - q_1 b, b) = (b, r_1) = (r_1, r_2) = \dots = (r_{k-1}, r_k) = r_k$.

Remark. By Lemma 1.1, $(a, b) = ra + sb$ for some integers r, s . Euclid's algorithm gives such r, s .

Recall that if $n > 1$ then n is **prime** if its only positive divisors are $\{1, \dots, n\}$, otherwise n is **composite**.

Lemma 1.2. Let p be prime, $a, b \in \mathbb{Z}$. Then $p \mid ab \implies p \mid a$ or $p \mid b$.

Proof. Suppose $p \mid ab$, $p \nmid a$. Then $\gcd(a, b) \neq p$, so it must be 1. So $\exists r, s \in \mathbb{Z}$ such that $ar + ps = 1$. Therefore, $b = (ab)r + p(bs)$, and hence $p \mid b$. \square

This lets us prove the fundamental theorem of arithmetic.

Theorem (Fundamental theorem of arithmetic). Every integer $n > 1$ can be written as a product of primes, and this representation is *unique* up to ordering.

Proof. Existence is trivial. Uniqueness: suppose $n = p_1 \dots p_r = q_1 \dots q_s$. $p_1 \mid n$, so p_1 divides some q_j . Hence $p_1 = q_j$ and so we can cancel p_1 and q_j from the relation, and repeat the process for $\frac{n}{p_1}$, eventually giving that the $\{p_1, \dots, p_r\}$ are the same as the $\{q_1, \dots, q_s\}$, up to ordering. \square

If we know $a = \prod_{i=1}^k p_i^{\alpha_i}$, $b = \prod_{i=1}^k p_i^{\beta_i}$ for $\alpha_i, \beta_i \geq 0$ and p_i are distinct primes, then by uniqueness of prime factorisation,

$$(a, b) = \prod_{i=1}^k p_i^{\gamma_i}, \quad \gamma_i = \min(\alpha_i, \beta_i)$$

However if a, b are large, this is an inefficient way to compute GCDs.

Definition. An algorithm with input an integer $N > 0$ is **polynomial time** if $\exists b, c > 0$ for which the algorithm completes after less than $c(\log N)^b$ 'elementary operations'. Examples of elementary operations include adding or multiplying digits in some fixed base.

If there are k integer inputs, we require less than $c(\max_k(\log N_i))^b$ operations.

Example.

- Adding, multiplying integers (usual method)
- Computing GCDs by Euclid's algorithm
- Testing if N is prime (recent discovery, 2002)

Factoring What about factoring N ? The obvious method is trial division by integers $\leq \sqrt{N}$. If $N = pq$, then $p, q \sim \sqrt{N}$ this will take \sqrt{N} divisions - asymptotically larger than any power of $\log N$. For instance, if N has 100 digits, and we can do 2^9 divisions every second, this will take around $10^{50}/2^9$ seconds, which is about 6×10^{39} years. However, Euclid's algorithm will compute the GCD of two such numbers in a few milliseconds. However, there are better algorithms for factoring which we will see later, but so far no polynomial-time algorithm is known (important for security of encryption algorithms like RSA). These are practical for numbers with fewer than 200 digits (for a large computer - the record is 232 digits using thousands of computers and several months)

We will study the distribution of primes and the counting function later. For now,

Theorem (Euclid). There are infinitely many primes

Proof. It is enough to show that given N , there is a prime $p > N$. Let q be the largest prime $\leq N$, and set $M = (2 \times 3 \times 5 \times \cdots \times q) + 1$. If p is any prime factor of M , then $p \notin \{2, 3, \dots, q\}$ so $p > N$. \square

Remark. This is constructive, in that it gives a way to find a prime greater than any N , but is not efficient. For instance, if $N = 1000$, M has over 400 digits.

Finding large primes For reasonable size numbers (fewer than 1000 digits), it is reasonable to pick numbers at random and test for primality. For very large primes, there are special (faster) tests for primality of numbers of the form $N = 2^q - 1$, called Mersenne numbers. Using these, it has been shown that $2^q - 1$ is prime when $q = 74207281$.

2 Congruences

Fix $n \geq 1$ (the modulus). Typically we will use $n > 1$.

Definition. $a \equiv b \pmod{n}$ if $n \mid a - b$, and we say ‘ a is congruent to $b \pmod{n}$ ’

This defines an equivalence relation on \mathbb{Z} . Write $\mathbb{Z}/n\mathbb{Z}$ for the set of equivalence classes $\{a + n\mathbb{Z}\}$, where $a + n\mathbb{Z} = b + n\mathbb{Z} \iff a \equiv b \pmod{n}$. It is easy to see that the operations of addition and multiplication in $\{a + n\mathbb{Z}\}$ are well defined. [In other words, $n\mathbb{Z}$ is an ideal in the ring \mathbb{Z} , and $\mathbb{Z}/n\mathbb{Z}$ is the quotient ring.]

Lemma 2.1. Let $a \in \mathbb{Z}$. The following are equivalent:

- i. $(a, n) = 1$
- ii. $\exists b \in \mathbb{Z}$ with $ab \equiv 1 \pmod{n}$
- iii. (The equivalence class of) a is a generator of the group $(\mathbb{Z}/n\mathbb{Z}, +)$.

Proof.

- i. \Rightarrow ii. If $(a, n) = 1$, $\exists b, c \in \mathbb{Z}$ with $ab + nc = 1$ so $ab \equiv 1 \pmod{n}$
- ii. \Rightarrow i. $ab \equiv 1 \pmod{n} \iff ab + kn = 1$, for some $k \in \mathbb{Z} \implies (a, n) = 1$
- ii. \Leftrightarrow iii. $ab \equiv 1 \pmod{n}$ for some $b \iff 1$ belongs to the subgroup of $\mathbb{Z}/n\mathbb{Z}$ generated by $a \iff$ the subgroup generated by a is $\mathbb{Z}/n\mathbb{Z}$

□

Notation. For $n > 1$, we write $(\mathbb{Z}/n\mathbb{Z})^*$ to denote the set of units (invertible elements) of $\mathbb{Z}/n\mathbb{Z}$. By [Lemma 2.1](#), this is the set of classes $a + n\mathbb{Z}$ where $(a, n) = 1$. We can then define $\phi(n) = \#(\mathbb{Z}/n\mathbb{Z})^* = \#\{a \in \mathbb{Z} \mid 1 \leq a \leq n, (a, n) = 1\}$, the **Euler ϕ -function**.

Remark. For $n > 1$, $\mathbb{Z}/n\mathbb{Z}$ is a field \iff every non-zero element has an inverse under $\times \iff n$ is prime $\iff \phi(n) = n - 1$.

Theorem (Euler-Fermat Theorem). If $(a, n) = 1$, then $a^{\phi(n)} \equiv 1 \pmod{n}$

Proof. ($n > 1$) Apply Lagrange’s theorem to the group $G = (\mathbb{Z}/n\mathbb{Z})^*$ which has order $\phi(n)$. Then $a \in \mathbb{Z}$ with $(a, n) = 1$ defines an element of G whose order divides $\phi(n)$. So $a^{\phi(n)} \equiv 1 \pmod{n}$. □

This has an important special case, called Fermat’s Little Theorem.

Theorem (Fermat’s Little Theorem). If p is prime and $a \in \mathbb{Z}$, then $a^p \equiv a \pmod{p}$.

Proof. Trivial if $p \mid a$. If not, $(a, p) = 1$ so $a^{\phi(p)} \equiv 1 \pmod{p} \implies a^p \equiv a \pmod{p}$ □

Lemma 2.2. Let G be a cyclic group of order $n \geq 1$. Then

$$\begin{aligned} \phi(n) &= \#\{g \in G \mid (\text{order of } g) = n\} \\ &= \# \text{ of generators of } G \end{aligned}$$

Proof. We may assume $G = \mathbb{Z}/n\mathbb{Z}$, in which case this is just [Lemma 2.1](#) □

2.1 Simultaneous Congruences

Example. We would like to find all $x \in \mathbb{Z}$ such that $x \equiv 7 \pmod{10}$ and $x \equiv 3 \pmod{13}$. One way might be to try $7, 17, 27, \dots$ in turn.

A better way: suppose we have $u, v \in \mathbb{Z}$ such that

$$\begin{aligned} u &\equiv 1 \pmod{10} & v &\equiv 0 \pmod{10} \\ u &\equiv 0 \pmod{13} & v &\equiv 1 \pmod{13} \end{aligned}$$

Then $x = 7u + 3v$ is a solution.

To find u, v : $(10, 13) = 1$ so $\exists r, s$ with $10r + 13s = 1$, so setting $u = 13s$ and $v = 10r$ ensures the above congruences are satisfied. From the Euclidean algorithm, we see $r = 4$ and $s = -3$ work, so $u = -39$ and $v = 40$.

We can confirm $x = 7(-39) + 3(40) \equiv 107 \pmod{130}$ is a solution. In fact, the set of all solutions is $\{x \mid x \equiv 107 \pmod{130}\}$.

This is a special case of

Theorem (Chinese Remainder Theorem). Let m_1, \dots, m_k be integers ≥ 1 with $(m_i, m_j) = 1$ if $i \neq j$ (they are pairwise coprime). Write $M = m_1 \cdots m_k$ for $k \geq 2$. Let $a_1, \dots, a_k \in \mathbb{Z}$. Then there exists a solution $x \in \mathbb{Z}$ of

$$\begin{cases} x \equiv a_1 \pmod{m_1} \\ \vdots \\ x \equiv a_k \pmod{m_k} \end{cases} \quad (1)$$

and x is unique mod M .

Remark. If x satisfies Equation (1), then so does $x + Mn$ for $n \in \mathbb{Z}$, so the solution is just $x + M\mathbb{Z}$.

Proof.

- Uniqueness: If x, y satisfies Equation (1), then $m_i \mid (x - y)$ for every i . As no prime divides two of the m_i , it follows that $M = \prod m_i \mid (x - y)$, so $x \equiv y \pmod{M}$.
- Existence: Write $M_i = M/m_i = \prod_{j \neq i} m_j$. By the hypothesis, $(M_i, m_i) = 1$. So $\exists c_i \in \mathbb{Z}$ with $c_i M_i \equiv 1 \pmod{m_i}$. Obviously $c_i M_i \equiv 0 \pmod{m_j} \forall j \neq i$. Let $x = \sum_{i=1}^k a_i c_i M_i$, then x satisfies Equation (1), as required.

□

Note we find the c_i by Euclid's algorithm, so this is constructive.

Corollary. If $M = \prod_{i=1}^k m_i$, with m_i pairwise coprime, then

$$\varphi(M) = \varphi(m_1) \cdots \varphi(m_k)$$

Proof. $(a, M) = 1 \Leftrightarrow \forall i, (a, m_i) = 1$. So by the Chinese Remainder Theorem, we have a bijection

$$\{1 \leq x \leq M \mid (x, M) = 1\} \xrightarrow{\sim} \{(a_1, \dots, a_k \mid 1 \leq a_i \leq m_i, (a_i, m_i) = 1)\}$$

So

$$\#LHS = \varphi(M), \#RHS = \prod_i \varphi(m_i)$$

□

Algebraic aside: We can write thus in terms of the rings $R_i = \mathbb{Z}/m_i\mathbb{Z}$.

Definition (Product ring). The **product ring** is

$$R_1 \times \cdots \times R_k = \{ (r_1, \dots, r_k) \mid r_i \in R_i \}$$

with $+$, \times defined component-wise. This is a ring with 0 as the zero vector, and 1 as the vector of ones.

Theorem 2.3. Take $M = \prod m_i$, with m_i pairwise coprime. The map

$$\begin{aligned} \Theta : \mathbb{Z}/M\mathbb{Z} &\longrightarrow \mathbb{Z}/m_1\mathbb{Z} \times \cdots \times \mathbb{Z}/m_k\mathbb{Z} \\ a + M\mathbb{Z} &\longmapsto (a + m_1\mathbb{Z}, \dots, a + m_k\mathbb{Z}) \end{aligned}$$

is an isomorphism of rings.

Proof. $m_i \mid M \Rightarrow a + m_i\mathbb{Z}$ only depends on $a + M\mathbb{Z}$, so Θ is well-defined. It is a homomorphism (by definition of $+$, \times in the product ring), and the [Chinese Remainder Theorem](#) implies that it is bijective. □

Definition (Multiplicative function). A **multiplicative function** is a function $f : \mathbb{N} = \{1, 2, 3, \dots\} \rightarrow \mathbb{C}$ for which

$$(m, n) = 1 \implies f(mn) = f(m)f(n)$$

(This is the traditional terminology, although it is confusing we don't require $\forall m, n, f(mn) = f(m)f(n)$, which is sometimes called **totally multiplicative**)

Example. Examples of [multiplicative functions](#).

- $\varphi(n)$
- $\tau(n) = \#$ of positive divisors of n
- $\sigma(n) = \sum_{1 \leq d \mid n} d$
- More generally $\sigma_k(n) = \sum_{1 \leq d \mid n} d^k$, note $\sigma = \sigma_1, \tau = \sigma_0$

Lemma 2.4. Let f be a multiplicative function. Then so is g , defined by

$$g(n) = \sum_{d \mid n} f(d)$$

Proof. Let $(m, n) = 1$. Then $\{ \text{divisors } d \text{ of } mn \} = \{ d = d_1 d_2 \mid d_1 \mid m, d_2 \mid n \}$.

$$g(mn) = \sum_{d \mid mn} f(d) = \sum_{d_1 \mid m} \sum_{d_2 \mid n} f(d_1 d_2) = \sum_{d_1 \mid m} f(d_1) \sum_{d_2 \mid n} f(d_2) = g(m)g(n)$$

□

Example. $f(n) = n^k$ (obviously multiplicative). Then $g(n) = \sigma_k(n)$. Later we will see how to recover f from g .

Theorem 2.5.

$$(i) \ p \text{ prime}, k \leq 1 \implies \varphi(p^k) = p^{k-1}(p-1) = p^k \left(1 - \frac{1}{p}\right)$$

$$(ii) \ n \geq 1: \varphi(n) = n \prod_{p|n} \left(1 - \frac{1}{p}\right)$$

$$(iii) \ \sum_{d|n} \varphi(d) = n$$

Proof.

$$(i) \ \varphi(p^k) = \# \{ 1 \leq a \leq p^k \mid p \nmid a \} = p^k - p^{k-1}$$

(ii) Write

$$n = \prod_i p_i^{k_i}$$

with p_i distinct. Then,

$$\begin{aligned} \varphi(n) &= \prod_i \varphi(p_i^{k_i}) \\ &= \prod_i p_i^{k_i} \left(1 - \frac{1}{p_i}\right) \\ &= n \prod_i \left(1 - \frac{1}{p_i}\right) \end{aligned}$$

(iii) By [Lemma 2.4](#), the left hand side is multiplicative. The right hand side is obviously multiplicative, so it is enough to prove for $n = p^k$.

$$\begin{aligned} \sum_{d|n} \varphi(d) &= \varphi(1) + \varphi(p) + \cdots + \varphi(p^k) \\ &= 1 + (p-1) + (p^2-p) + \cdots + (p^k - p^{k-1}) \\ &= p^k \end{aligned}$$

□

2.2 Polynomial Congruences

We will take $R = \mathbb{Z}, \mathbb{Q}$ or $\mathbb{Z}/n\mathbb{Z}$ (or any commutative ring with 1)

Recall $R[X]$ refers to polynomials in X taking coefficients from R , formally:

$$\{ a_n X^n + a_{n-1} X^{n-1} + \cdots + a_0 \mid n \geq 0, a_i \in R \}$$

Two polynomials are equal if their coefficients are the same. Importantly, a polynomial $f \in R[X]$ determines a function $R \rightarrow R$, given by $\alpha \mapsto f(\alpha) = \sum a_i \alpha^i$. It can happen that different polynomials give the same function.

Example. For p a prime and $R = \mathbb{Z}/p\mathbb{Z}$, consider $f(X) = X^p - X$. Then $\forall a \in R$, $f(a) = 0$ in $\mathbb{Z}/p\mathbb{Z}$ by Fermat's Little Theorem. So f and the zero polynomial determine the same function.

Multiplication and addition of polynomials is defined in the obvious way: for $f = \sum_{i=0}^n a_i X^i$, $g = \sum_{i=0}^n b_i X^i$, we have

$$f + g = \sum_{i=0}^n (a_i + b_i) X^i$$

$$fg = \sum_{i=0}^{2n} \left(\sum_{j+k=i} a_j b_k \right) X^i$$

so $R[X]$ is a ring.

We also have a division algorithm for polynomials, where the measure of size is the degree.

Definition. $\deg(f)$ is the largest i for which the coefficient of X^i is non-zero, and $\deg(f) = \infty$ if f is the zero polynomial.

We also have $\deg(fg) \leq \deg(f) + \deg(g)$.

Definition (Division algorithm for polynomials). Let $f, g \in R[X]$. Assume that the leading coefficient of g is a unit in R (that is, has an inverse under multiplication) Then $\exists q, r \in R[X]$ with $\deg(r) < \deg(g)$ and $f = gq + r$.

Proof. Induction on $\deg f$. If $\deg f < \deg g$, then $q = 0$ and $r = f$ will do.

Otherwise $f = aX^m + \dots$, $a \neq 0$, $g = bX^n + \dots$, with $b = \frac{1}{c}$ invertible by assumption and $m \geq n$.

Then $f_1 = f - acX^{m-n}g \in R[X]$ has degree strictly less than m . So $f_1 = gq_1 + r$ say, $\deg(r) < \deg(g)$ and so $f = (q_1 + acX^{m-n})g + r$, as required. \square

Corollary 2.6 (Remainder theorem). Take $f \in R[X]$ and $\alpha \in R$. Then

$$f(X) = (X - \alpha)f_1(X) + f(\alpha)$$

Proof. Apply the division algorithm with $g = X - \alpha$, so $f = (X - \alpha)f_1 + c$. c has degree less than 1, so must be in R . Now, evaluate both sides at $X = \alpha$, so $c = f(\alpha)$. \square

In particular, if $f(\alpha) = 0$ then $f(X) = (X - \alpha)f_1(X)$.

However in general a polynomial can have more roots than its degree - consider $f(X) = X^2 - 1$ with $R = \mathbb{Z}/8\mathbb{Z}$

Definition. A nonzero ring R is an integral domain if $ab = 0$ implies $a = 0$ or $b = 0$.

Example. \mathbb{Q} and \mathbb{Z} are integral domains, and $\mathbb{Z}/n\mathbb{Z}$ is an integral domain if and only if n is prime.

Theorem 2.7. If R is an integral domain, and $f \in R[X]$ is a non-zero polynomial of degree $n \geq 0$, then f has $\leq n$ roots in R .

Corollary (Lagrange's Theorem). Take p prime, $f \in \mathbb{Z}[X]$ of degree n , and f not divisible by p . Then the congruence $f(x) \equiv 0 \pmod{p}$ has $\leq n$ solutions mod p .

Proof. The $n = 0$ case is trivial.

Suppose $n > 0$. If f has no roots in R , we have nothing to prove.

Otherwise $\exists \alpha \in R$, $f(\alpha) = 0$ so $f(X) = (X - \alpha)f_1(X)$, $f_1 \in R[X]$ with $\deg(f_1) = n - 1$. By induction, f_1 has $\leq n - 1$ roots in R . If β is a root of f , then $(\beta - \alpha)f_1(\beta) = 0$ so either $\beta = \alpha$ or $f_1(\beta) = 0$, as R is an integral domain. So, the roots of f are exactly α and the roots of f_1 , so f has $\leq n$ roots. \square

Example. Take p prime, and set

$$f(X) = X^{p-1} - 1 - \prod_{a=1}^{p-1} (X - a) \in \mathbb{Z}/p\mathbb{Z}[X]$$

Then, $\deg f \leq p - 2$. If $a = 1, \dots, p - 1$ then $a^{p-1} \equiv 1 \pmod{p}$ so $f(a) = 0 \in \mathbb{Z}/p\mathbb{Z}$. So as f has $\geq p - 1$ roots mod p , it must be identically zero mod p . So $f(0)$ is zero mod p , and

$$-1 - \prod_{a=1}^{p-1} (-a) \equiv 0 \pmod{p}$$

Giving us Wilson's Theorem, $(p - 1)! \equiv -1 \pmod{p}$.

The additive group $(\mathbb{Z}/n\mathbb{Z}, +)$ is cyclic. What about $((\mathbb{Z}/n\mathbb{Z})^*, \times)$?

Example. Consider $n = 7$, then we can check 3 is a generator of $(\mathbb{Z}/7\mathbb{Z})^*$ and hence the group is cyclic.

Theorem 2.8. If p is prime, then $G = (\mathbb{Z}/p\mathbb{Z})^*$ is cyclic of order $p - 1$.

Proof. $\#G = p - 1 = \sum_{d|p-1} \phi(d)$ by Theorem 2.5 part (iii).

Also, by Lagrange's Theorem in elementary group theory,

$$\#G = \sum_{d|p-1} \# \{g \in G \text{ of order } d\} = \sum_{d|p-1} N_d$$

Suppose G is not cyclic, so G has no element of order $p - 1$, then $N_{p-1} = 0 < \phi(p - 1)$. As $\sum \phi(d) = \sum N_d$, there exists some d for which $N_d > \phi(d) > 0$. Let $\alpha \in G$ be an element of order d . Then $\langle \alpha \rangle := \{1, \alpha, \alpha^2, \dots, \alpha^{d-1}\} \subset G$ is a cyclic subgroup of order d so has exactly $\phi(d)$ elements of order d by Lemma 2.2. So $\exists \beta \notin \langle \alpha \rangle$ where β has order d . Then $1, \alpha, \alpha^{d-1}, \beta$ are $(d + 1)$ roots of the polynomial $X^d - 1$, contradicting Theorem 2.7. So, G must be cyclic. \square

Definition (Primitive root). If g is a generator of $(\mathbb{Z}/p\mathbb{Z})^*$ then g is said to be a **primitive root mod p** .

By Theorem 2.8, primitive roots exist.

Example. Take $p = 19$, and let d be the order of 2 inside $(\mathbb{Z}/19\mathbb{Z})^*$, then $d \mid p - 1 = 18$. We have $2^6 \equiv 7 \not\equiv 1 \pmod{19}$, so $d \nmid 6$. Similarly, $2^9 \equiv -1 \pmod{19}$ so $d \nmid 9$. Hence, $d = 18$ and 2 is a primitive root mod 19.

There are many unsolved problems about primitive roots:

1. Artin's Primitive Root conjecture:

Fix $g \geq 2$. Then there exist infinitely many p for which g is a primitive root mod p (say g is prime). Even the case $g = 2$ is unknown. From analytic number theory, it is known there are infinitely many p for which one of $2, 3, 5$ is a primitive root.

2. How large is the smallest primitive root mod p ?

We can show that this goes to ∞ as p grows. It is known that it is bounded above by $cp^{1/4+\epsilon}$ for any $\epsilon > 0$, but expected to be smaller (bounded by $c(\log p)^2$).

Now let's consider the more general case of $(\mathbb{Z}/p^n\mathbb{Z})^*$ for $n > 1$, and ask if it is cyclic. $(\mathbb{Z}/8\mathbb{Z})^* = \{\pm 1, \pm 3\}$, which all have order 1 or 2, so the group is not cyclic. If $n \geq 3$, the map $(\mathbb{Z}/2^n\mathbb{Z})^* \rightarrow (\mathbb{Z}/8\mathbb{Z})^*$ is surjective:

$$\forall n \geq 1, \quad (x, 8) = 1 \iff x \text{ odd} \iff (x, 2^n) = 1$$

So, $(\mathbb{Z}/2^n\mathbb{Z})^*$ is not cyclic for $n \geq 3$ since a generator would map to a generator of $(\mathbb{Z}/8\mathbb{Z})^*$.

Theorem 2.9. If $p > 2$ and $n \geq 1$ then $(\mathbb{Z}/p^n\mathbb{Z})^*$ is cyclic.

Proof. The proof is deferred until [Page 13](#). □

Lemma 2.10. Take p an odd prime, and let $y \in \mathbb{Z}$ and $k \geq 1$. Then,

- (i) If $x \equiv 1 + p^k y \pmod{p^{k+1}}$ then $x^p \equiv 1 + p^{k+1} y \pmod{p^{k+2}}$
- (ii) $(1 + py)^{p^k} \equiv 1 + p^{k+1} y \pmod{p^{k+2}}$

Proof.

- (i) We may as well assume (by replacing y with $y + pz$) that $x = 1 + p^k y$. Then,

$$\begin{aligned} x^p &= \sum_{j=0}^p \binom{p}{j} (p^k y)^j \\ &= 1 + p^{k+1} y + \sum_{j=2}^{p-1} \binom{p}{j} p^{kj} y^j + p^{p^k} y^p. \end{aligned}$$

For $2 \leq j \leq p-1$, we have $\binom{p}{j} \equiv 0 \pmod{p}$ and hence $\binom{p}{j} p^{kj} \equiv 0 \pmod{p^{2k+1}}$ and $2k+1 \geq k+2$. Since $p > 2$, we have $p^k \geq k+2$ so the last term is also $\equiv 0 \pmod{p^{k+2}}$, hence we are done.

- (ii) Apply part (i) k times to $1 + py$. □

Lemma 2.11. If $g \in \mathbb{Z}$, $(g, p) = 1$, g is a primitive root mod p , and $g^{p-1} \not\equiv 1 \pmod{p^2}$, then g is a generator of $(\mathbb{Z}/p^n\mathbb{Z})^* = G$.

Proof. Let d be the order of g in G . We know $d \mid \#G = p^{n-1}(p-1)$, so if g is not a generator, one of the following two cases must hold:

(i) $d \mid p^{n-2}(p-1)$, so $g^{p^{n-2}(p-1)} \equiv 1 \pmod{p^n}$.

(ii) $d = p^{n-1}e$, with $1 \leq e < p-1$ and $e \mid p-1$, and so $g^{p^{n-1}e} \equiv 1 \pmod{p^n}$.

Deal with these cases in turn:

(i) Let $x = g^{p-1} = 1 + py$ with $y \not\equiv 0 \pmod{p}$, because $g^{p-1} \not\equiv 1 \pmod{p^2}$. Then by [Lemma 2.10](#) part (ii), we have $x^{p^{n-2}} \equiv 1 + p^{n-1}y \pmod{p^n}$, so $g^{p^{n-2}(p-1)} \not\equiv 1 \pmod{p^n}$.

(ii) $g^{p^{n-1}e} \equiv g^e \pmod{p}$ by Fermat-Euler, and this is not congruent to 1 \pmod{p} as g is a primitive root mod p .

So neither (i) nor (ii) can hold, and hence g has order $p^{n-1}(p-1)$. \square

We can return and prove [Theorem 2.9](#).

Proof of Theorem 2.9. Let $g \in \mathbb{Z}$ be a primitive root mod p . If $g^{p-1} \not\equiv 1 \pmod{p^2}$, then by [Lemma 2.11](#), g generates $(\mathbb{Z}/p^n\mathbb{Z})^*$. If not, $g^p \equiv g \pmod{p^2}$. Let $g_1 = g(1+p)$. Then, $g_1^p = g^p(1+p)^p$ and $(1+p)^p \equiv 1 \pmod{p^2}$ by [Lemma 2.10](#).

So, $g_1^p \equiv g^p \pmod{p^2} \equiv g \pmod{p^2} \not\equiv g_1 \pmod{p^2}$, so by [Lemma 2.11](#), g_1 generates $(\mathbb{Z}/p^n\mathbb{Z})^*$. \square

Remark.

1. Our proof gives an easy way to find a generator for $(\mathbb{Z}/p^n\mathbb{Z})^*$, independent of $n \geq 2$.
2. What happens when $p = 2$? [Lemma 2.10\(i\)](#) fails to hold for $p = 2$, $k = 1$: $(1+2)^2 \equiv 1 \pmod{8}$. It does hold for $p = 2$ and $k \geq 2$ however. Part (ii) becomes $(1+4)^{k-1} \equiv 1 + 2^{k+1} \pmod{2^{k+2}}$. We can then show (following the argument for p odd), that $(\mathbb{Z}/2^n\mathbb{Z})^*$ for $n \geq 3$ is generated by -1 and 5 which have orders 2 and 2^{n-2} respectively. So, we have that

$$(\mathbb{Z}/2^n\mathbb{Z})^* \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2^{n-2}\mathbb{Z}$$

3. If $N = \prod_{1 \leq i \leq r} p_i^{k_i}$, then

$$(\mathbb{Z}/N\mathbb{Z})^* \cong (\mathbb{Z}/p_1^{k_1}\mathbb{Z})^* \times \cdots \times (\mathbb{Z}/p_r^{k_r}\mathbb{Z})^*$$

by the [Chinese Remainder Theorem](#).

3 Quadratic residues

Take $p > 2$ an odd prime. If $a \in \mathbb{Z}$, we know $x^2 \equiv a \pmod{p}$ has ≤ 2 solutions mod p .

For $a \equiv 0 \pmod{p}$, then there is one solution, $x \equiv 0 \pmod{p}$.

For $a \not\equiv 0 \pmod{p}$, if x is a solution then so is $-x$, and $-x \equiv x \pmod{p} \Leftrightarrow 2x \equiv 0 \pmod{p}$ but $a \not\equiv 0 \Rightarrow x \not\equiv 0 \pmod{p}$ so we have either 0 or 2 solutions.

Definition. $a \equiv 0 \pmod{p}$ is a **quadratic residue** mod p if $x^2 \equiv a \pmod{p}$ is soluble, and a **quadratic non-residue** if not.

So a is a quadratic residue mod p iff its class in $(\mathbb{Z}/p\mathbb{Z})^*$ is a square.

We can check directly that the quadratic residues mod 7 are $\{1, 2, 4\}$.

Lemma 3.1. Let p be an odd prime. There are exactly $\frac{p-1}{2}$ quadratic residues mod p .

Proof 1. Consider

$$\begin{aligned} (\mathbb{Z}/p\mathbb{Z})^* &\xrightarrow{\sigma} (\mathbb{Z}/p\mathbb{Z})^* \\ x &\mapsto x^2 \pmod{p} \end{aligned}$$

$\sigma(x) = \sigma(y) \Leftrightarrow x^2 \equiv y^2 \pmod{p} \Leftrightarrow (x-y)(x+y) \equiv 0 \pmod{p} \Leftrightarrow x \equiv \pm y \pmod{p}$. Since p is odd, if $(x, p) = 1$ then $x \not\equiv -x \pmod{p}$. So, σ is 2-to-1, hence the image of σ has $\frac{p-1}{2}$ elements. \square

Proof 2. Let g be a primitive root mod p . Then $(\mathbb{Z}/p\mathbb{Z})^* = \{1, g, g^2, \dots, g^{p-2}\}$ as $g^{p-1} = 1$. So,

$$\begin{aligned} \{x^2 \mid x \in (\mathbb{Z}/p\mathbb{Z})^*\} &= \{1, g^2, g^4, \dots, g^{p-3}, g^{p-1}, g^{p+1}, \dots, g^{2p-4}\} \\ &= \{1, g^2, g^4, \dots, g^{p-3}\} \end{aligned}$$

since $g^{p-1} = 1$ and $g^{p+1} = g^2$, and so on, hence there are $\frac{p-1}{2}$ elements. \square

Definition. The **Legendre symbol** of $a \pmod{p}$ (p an odd prime, $a \in \mathbb{Z}$) is

$$\left(\frac{a}{p}\right) = \begin{cases} 0 & \text{if } p \mid a \\ +1 & \text{if } a \text{ is a quadratic residue mod } p \\ -1 & \text{if } a \text{ is a quadratic non-residue mod } p \end{cases}$$

Lemma (Euler's Criterion).

$$\left(\frac{a}{p}\right) \equiv a^{\frac{p-1}{2}} \pmod{p}$$

Remark. $\left(\frac{a}{p}\right) \in \{0, \pm 1\}$ which is a set of 3 distinct integers mod p as $p > 2$. So the congruence in the lemma determines $\left(\frac{a}{p}\right)$ completely.

Proof. If $p \mid a$, obvious. Suppose $(a, p) = 1$. Then $a^{p-1} = \left(a^{\frac{p-1}{2}}\right)^2 \equiv 1 \pmod{p}$. Hence $a^{\frac{p-1}{2}} \equiv \pm 1 \pmod{p}$. If $a \equiv x^2 \pmod{p}$, then $a^{\frac{p-1}{2}} \equiv x^{p-1} \equiv +1 \pmod{p}$. By [Lemma 3.1](#), this gives $\frac{p-1}{2}$ solutions of $a^{\frac{p-1}{2}} \equiv 1 \pmod{p}$. So there are no more solutions, that is if $\left(\frac{a}{p}\right) = -1$, then $a^{\frac{p-1}{2}} \equiv -1 \pmod{p}$. \square

Corollary 3.2. Take $a, b \in \mathbb{Z}$ where p is an odd prime. Then

$$\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right) \left(\frac{b}{p}\right)$$

Proof.

$$\left(\frac{ab}{p}\right) \equiv (ab)^{\frac{p-1}{2}} \equiv a^{\frac{p-1}{2}} b^{\frac{p-1}{2}} \equiv \left(\frac{a}{p}\right) \left(\frac{b}{p}\right) \pmod{p}$$

By the previous remark, we have $\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right) \left(\frac{b}{p}\right)$. □

Remark. We have the following equivalent statements

- The map $(\mathbb{Z}/p\mathbb{Z})^* \rightarrow \{+1\}$ given by $a \mapsto \left(\frac{a}{p}\right)$ is a homomorphism of groups.
- The product of residues is a residue; the product of a residue and non-residue is a non-residue, and the product of non-residues is a residue.

Another consequence of [Euler's Criterion](#) allows equivalent computation of $\left(\frac{a}{p}\right)$ because there is a polynomial time algorithm to compute $a^n \pmod{N}$.

- write $n = n_0 + 2n_1 + 4n_2 + \dots + 2^k n_k$ in binary, $n_i \in \{0, 1\}$
- compute $a^2, a^4 = (a^2)^2, a^8 = (a^4)^2, \dots, a^{2^k} \pmod{N}$.
- $a^n \equiv \prod_{i: n_i=1} a^{2^i} \pmod{N}$

Corollary 3.3. For p an odd prime,

$$\left(\frac{-1}{p}\right) = \begin{cases} +1 & p \equiv 1 \pmod{4} \\ -1 & p \equiv 3 \pmod{4} \end{cases}$$

Proof. By [Euler's criterion](#), if $p = 4k + l$, with $l = 1$ or 3 ,

$$\left(\frac{-1}{p}\right) = (-1)^{\frac{p-1}{2}} = (-1)^{2k + \frac{l-1}{2}} = \begin{cases} +1 & l = 1 \\ -1 & l = 3 \end{cases}$$

□

What about $\left(\frac{2}{p}\right)$? So what is $2^{\frac{p-1}{2}} \pmod{p}$? Recall the proof of [Fermat's Little Theorem](#), and imitate this using $\left(\frac{p-1}{2}\right)!$ instead. This will prove

Lemma (Gauss's Lemma). Take p an odd prime and $(a, p) = 1$. Then $\left(\frac{a}{p}\right) = (-1)^\mu$ where μ is the number of $j \in \{1, \dots, \frac{p-1}{2}\}$ such that $aj \equiv k \pmod{p}$ where $\frac{p+1}{2} \leq k \leq p-1$.

Proof. $1 \leq j \leq \frac{p-1}{2}$. Write $aj \equiv \epsilon_j c_j \pmod{p}$ with $1 \leq c_j \leq \frac{p-1}{2}$ and $\epsilon_j \in \{\pm 1\}$ (by reducing $aj \pmod{p}$ into the interval $(-\frac{p}{2}, \frac{p}{2})$).

Now claim that if $j \neq k$ with $1 \leq j, k \leq \frac{p-1}{2}$ then $c_j \neq c_k$. Indeed if $c_j = c_k$ then $\epsilon_j a j \equiv \epsilon_k a k \pmod{p}$, that is, $j \equiv \pm k \pmod{p}$. As $1 \leq j, k \leq \frac{p-1}{2}$, $j + k \not\equiv 0 \pmod{p}$ so $j = k$.

So, $\{c_1, \dots, c_{\frac{p-1}{2}}\} = \{1, 2, \dots, \frac{p-1}{2}\}$ in some order.

Now, $\mu = \#\{j \in \{1, \dots, \frac{p-1}{2}\} \mid aj \equiv k \pmod{p}, \frac{p+1}{2} \leq k \leq p-1\} = \#\{j \mid \epsilon_j = -1\}$
 So,

$$a^{\frac{p-1}{2}} \cdot \left(\frac{p-1}{2}\right)! = \prod_{j=1}^{\frac{p-1}{2}} (aj) \equiv \prod_{j=1}^{\frac{p-1}{2}} \epsilon_j c_j \equiv \left(\prod_{j=1}^{\frac{p-1}{2}} \epsilon_j\right) \left(\prod_{j=1}^{\frac{p-1}{2}} c_j\right) \equiv (-1)^\mu \cdot \frac{p-1}{2}!$$

This gives

$$\left(\frac{a}{p}\right) \equiv a^{\frac{p-1}{2}} \equiv (-1)^\mu$$

□

Example. Take the (trivial) special case of $a = -1$, then $-j \in (-\frac{p}{2}, 0)$ so $\epsilon_j = -1$ and $c_j = j$ for any j . So, $\mu = \frac{p-1}{2}$ and $\left(\frac{-1}{p}\right) = (-1)^{\frac{p-1}{2}}$.

Now consider the case of $n = 2$. Then

$$\{2j \mid 1 \leq j \leq \frac{p-1}{2}\} = \{2, 4, \dots, p-3, p-1\}$$

If $0 < j < \frac{p}{4}$ then $2j \in \{1, \dots, \frac{p-1}{2}\}$ while if $\frac{p}{4} < j < \frac{p}{2}$ then $\frac{p}{2} < 2j < p$. So,

$$\begin{aligned} \mu &= \#\{j \in \mathbb{Z} \mid \frac{p}{4} < j < \frac{p}{2}\} \\ &= \left\lfloor \frac{p}{2} \right\rfloor - \left\lfloor \frac{p}{4} \right\rfloor \end{aligned}$$

Split into cases:

$$\begin{array}{llll} p = 8k + 1 & \implies & \mu = 4k - 2k = 2k & \implies (-1)^\mu = 1 \\ p = 8k + 3 & \implies & \mu = (4k + 1) - 2k = 2k + 1 & \implies (-1)^\mu = -1 \\ p = 8k + 5 & \implies & \mu = (4k + 2) - (2k + 1) = 2k + 1 & \implies (-1)^\mu = -1 \\ p = 8k + 7 & \implies & \mu = (4k + 3) - (2k + 1) = 2k + 2 & \implies (-1)^\mu = 1 \end{array}$$

Note that $8 \mid p^2 - 1$ and that $16 \mid p^2 - 1 \iff p = 8k \pm 1$, both easy to check.

Corollary 3.4.

$$\left(\frac{2}{p}\right) = \begin{cases} +1 & p \equiv \pm 1 \pmod{8} \\ -1 & p \equiv \pm 3 \pmod{8} \end{cases} = (-1)^{\frac{p^2-1}{8}}$$

What about $a = 3, 5, \dots$? For $p > 3$, consider $\{3j \mid 1 \leq j \leq \frac{p-1}{2}\}$.

$$0 < j < \frac{p}{6} \implies 0 < 3j < \frac{p}{2}$$

$$\frac{p}{6} < j < \frac{p}{3} \implies \frac{p}{2} < 3j < p$$

$$\frac{p}{3} < j < \frac{p}{2} \implies 0 < 3j - p < \frac{p}{2}$$

So, $\mu = \#\{j \mid \frac{p}{6} < j < \frac{p}{3}\}$ which we can work out from looking at $p \bmod 12$.

For general $1 \leq a \leq p-1$, look at $\{aj \mid 1 \leq j \leq \frac{p-1}{2}\}$. Then for $k \in \mathbb{Z}$,

$$kp < aj < \left(k + \frac{1}{2}\right)p \implies 0 < aj - kp < \frac{p}{2} \quad \text{does not contribute to } \mu$$

$$\left(k - \frac{1}{2}\right)p < aj < kp \implies -\frac{p}{2} < aj - kp < 0 \quad \text{contributes to } \mu$$

So $\mu = \sum_{k \in \mathbb{Z}} \#\{j \mid 1 \leq j \leq \frac{p-1}{2}, (k - \frac{1}{2})\frac{p}{a} < j < \frac{kp}{a}\}$, that is $\frac{p}{2} < aj - kp < 0$. Note also that $0 < k < \frac{1}{2} + \frac{aj}{p} < \frac{a+1}{2}$.

Theorem (Quadratic Reciprocity). For (p, q) distinct odd primes,

$$\left(\frac{p}{q}\right)\left(\frac{q}{p}\right) = (-1)^{\frac{p-1}{2} \frac{q-1}{2}}$$

$$\left(\frac{q}{p}\right) = \begin{cases} -\left(\frac{p}{q}\right) & \text{if } p \equiv q \equiv 3 \pmod{4} \\ \left(\frac{p}{q}\right) & \text{otherwise} \end{cases}$$

Example.

(i) $\left(\frac{3}{p}\right) = (-1)^{\frac{p-1}{2}} \left(\frac{p}{3}\right)$, but

$$(-1)^{\frac{p-1}{2}} = \begin{cases} +1 & p \equiv 1 \pmod{4} \\ -1 & p \equiv 3 \pmod{4} \end{cases}$$

$$\left(\frac{p}{3}\right) = \begin{cases} +1 & p \equiv 1 \pmod{3} \\ -1 & p \equiv 2 \pmod{3} \end{cases}$$

$$\therefore \left(\frac{3}{p}\right) = \begin{cases} +1 & p \equiv \pm 1 \pmod{12} \\ -1 & p \equiv \pm 5 \pmod{12} \end{cases}$$

(ii)

$$\left(\frac{19}{73}\right) = \left(\frac{73}{19}\right) = \left(\frac{16}{19}\right) = \left(\frac{4^2}{19}\right) = 1$$

(iii)

$$\left(\frac{34}{97}\right) = \left(\frac{2}{97}\right)\left(\frac{17}{97}\right) = (+1) \times \left(\frac{97}{17}\right) = \left(\frac{12}{17}\right) = \left(\frac{3}{17}\right)\left(\frac{2^2}{17}\right) \equiv -1$$

since $17 \equiv 5 \pmod{12}$.

Proof of Quadratic Reciprocity. By the previous calculation from Gauss' Lemma, $\left(\frac{q}{p}\right) = (-1)^\mu$ where

$$\mu = \#\left\{(j, k) \in S \mid 0 < kp - jq < \frac{p}{2}\right\}$$

and

$$S = \left\{(j, k) \mid 1 \leq j \leq \frac{p-1}{2}, 1 \leq k \leq \frac{q-1}{2}\right\}$$

By symmetry, $\left(\frac{p}{q}\right) = (-1)^\nu$ where

$$\nu = \# \left\{ (j, k) \in S \mid 0 < jp - kq < \frac{p}{2} \right\}$$

Now, $\#S = \frac{p-1}{2} \frac{q-1}{2} = \mu + \nu + \#A + \#B$ where

$$A = \left\{ (j, k) \in S \mid kp - jq > \frac{p}{2} \right\}$$

$$B = \left\{ (j, k) \in S \mid jp - kq > \frac{p}{2} \right\}$$

If $(j, k) \in S$, write $j' = \frac{p+1}{2} - j$, $k' = \frac{q+1}{2} - k$. Then $(j', k') \in S$, and

$$j'q - k'p = \left(\frac{p+1}{2} - j\right)q - \left(\frac{q+1}{2} - k\right)p = \left(kp - jq - \frac{p}{2}\right) + \frac{q}{2}$$

So $(j, k) \in A \iff (j', k') \in B$, so $\#A = \#B$. Hence $\frac{p-1}{2} \frac{q-1}{2} = \mu + \nu + 2\#A$ and

$$(-1)^{\frac{p-1}{2} \frac{q-1}{2}} = (-1)^{\mu+\nu} = \left(\frac{q}{p}\right) \left(\frac{p}{q}\right) \quad \square$$

Example.

$$\begin{aligned} \left(\frac{7411}{9283}\right) &= -\left(\frac{9283}{7411}\right) \\ &= -\left(\frac{1872}{7411}\right) \\ &= -\left(\frac{2^4 \cdot 3^2 \cdot 13}{7411}\right) \\ &= -\left(\frac{13}{7411}\right) \\ &= -\left(\frac{7411}{13}\right) \\ &= -\left(\frac{1}{13}\right) = -1 \end{aligned}$$

The problem here is that we needed to know that 7411 was prime and factor 1872. To avoid this, we will generalise the Legendre symbol to the Jacobi symbol.

Definition (Jacobi symbol). Let $n \geq 1$ be odd, and $n = p_1 \cdots p_k$ with p_i primes, not necessarily distinct. The **Jacobi symbol** is

$$\left(\frac{a}{n}\right) = \prod_{j=1}^k \left(\frac{a}{p_j}\right) \quad \text{for } a \in \mathbb{Z}$$

Note if $(a, n) > 1$ then $\left(\frac{a}{n}\right) = 0$, and if $n = 1$ then $\left(\frac{a}{1}\right) = 1$.

Proposition 3.5. (i)

$$\left(\frac{a}{n}\right) = \left(\frac{b}{n}\right) \text{ if } a \equiv b \pmod{n}$$

(ii)

$$\left(\frac{ab}{n}\right) = \left(\frac{a}{n}\right)\left(\frac{b}{n}\right), \quad \left(\frac{a}{mn}\right) = \left(\frac{a}{m}\right)\left(\frac{a}{n}\right)$$

(iii)

$$\left(\frac{-1}{n}\right) = (-1)^{\frac{n-1}{2}}$$

(iv)

$$\left(\frac{2}{n}\right) = (-1)^{\frac{n^2-1}{8}}$$

Proof. (i)

$$a \equiv b \pmod{n} \implies a \equiv b \pmod{p_j} \forall j \implies \left(\frac{a}{p_j}\right)\left(\frac{b}{p_j}\right)$$

(ii)

$$\left(\frac{ab}{p_j}\right) = \left(\frac{a}{p_j}\right)\left(\frac{b}{p_j}\right) \forall j$$

This proves the first equation, while the second follows by definition.

(iii) This is true if n is prime, so by part (ii) it is enough to show that if $m, n \geq 1$ are odd then

$$(-1)^{\frac{m-1}{2}} \cdot (-1)^{\frac{n-1}{2}} = (-1)^{\frac{mn-1}{2}}.$$

Indeed, $(m-1)(n-1) \equiv 0 \pmod{4}$, so $mn-1 \equiv m+n-2 \pmod{4}$ and hence

$$\frac{mn-1}{2} \equiv \frac{m-1}{2} + \frac{n-1}{2} \pmod{2}$$

(iv) Similarly to (iii), only need to show that for $m, n \geq 1$ odd

$$(-1)^{\frac{m-1}{2}} \cdot (-1)^{\frac{n-1}{2}} = (-1)^{\frac{m^2n^2-1}{2}}.$$

Indeed, $(m^2-1)(n^2-1) \equiv 0 \pmod{16}$ so $m^2n^2-1 \equiv m^2+n^2-2 \pmod{16}$, hence

$$\frac{m^2n^2-1}{8} \equiv \frac{m^2-1}{8} + \frac{n^2-1}{8} \pmod{2}$$

□

Theorem 3.6 (Quadratic Reciprocity for Jacobi symbol). Let $m, n \geq 1$ odd. Then

$$\left(\frac{m}{n}\right) = (-1)^{\frac{m-1}{2} \frac{n-1}{2}} \left(\frac{n}{m}\right)$$

and if $(m, n) = 1$,

$$\left(\frac{m}{n}\right)\left(\frac{n}{m}\right) = (-1)^{\frac{m-1}{2} \frac{n-1}{2}}$$

Proof. If $(m, n) > 1$, trivial since both sides are 0.

Assume that $(m, n) = 1$, with

$$m = \prod_{i=1}^k p_i, \quad n = \prod_{j=1}^l q_j \quad \text{no } p_i = q_j$$

Let

$$r = \# \{ i \mid p_i \equiv 3 \pmod{4} \}$$

$$s = \# \{ j \mid q_j \equiv 3 \pmod{4} \}$$

(rest of the proof coming soon) □

For p prime and $(a, p) = 1$, $\left(\frac{a}{p}\right) = 1 \iff a$ is a square mod p .

Generalising to the Jacobi symbol, for $n \geq 1$ odd and $(a, n) = 1$, if $a \equiv x^2 \pmod{n}$, then

$$\left(\frac{a}{n}\right) = \left(\frac{x^2}{n}\right) = \left(\frac{x}{n}\right)^2 = +1$$

but the converse does not hold! For instance

$$\left(\frac{2}{15}\right) = \left(\frac{2}{3}\right)\left(\frac{2}{5}\right) = (-1)(-1) = +1.$$

But 2 is not a square mod 15 as it is not a square mod 3 or mod 5.

Let $n = pq$, $p \neq q$ odd primes. Then by the CRT for $(a, pq) = 1$,

$$a \text{ is square mod } pq \iff a \text{ is a square mod } p \text{ and mod } q \iff \left(\frac{a}{p}\right) = \left(\frac{a}{q}\right) = 1$$

but of course

$$\left(\frac{a}{pq}\right) = 1 \iff \text{either } \left(\frac{a}{p}\right) = \left(\frac{a}{q}\right) = +1$$

$$\text{or } \left(\frac{a}{p}\right) = \left(\frac{a}{q}\right) = -1$$

If we know $\left(\frac{a}{pq}\right) = 1$, to determine whether or not a is a square mod pq , it is at least plausible that we need to know p and q , i.e. we need to factor n . (This is generally believed to be true - there are cryptographic protocols which rely on the difficulty of finding out whether a is a square mod $pq = n$, without knowing the factorisation of n .)

In computing Legendre symbols, need to factor the numerator to apply Section. Using Theorem, this can be avoided. For instance,

$$\left(\frac{33}{73}\right) = \left(\frac{73}{33}\right) = \left(\frac{7}{33}\right) = \left(\frac{33}{7}\right) = \left(\frac{5}{7}\right) = -1$$

where the fact that $33 \equiv 1 \pmod{4}$ was used.

At worst, we have to take out factors of 2 (since Quadratic Reciprocity requires m, n odd):

$$\left(\frac{66}{73}\right) = \left(\frac{2}{73}\right)\left(\frac{33}{73}\right) = -1.$$

So, it is very similar to Euclid's algorithm.

What about higher reciprocity laws?

- Higher powers, for instance cubes mod p . If $p \equiv 2 \pmod{3}$ then $3 \nmid p-1$, and we can easily see that everything is a cube mod p , since $x \mapsto x^3$ is a bijection $(\mathbb{Z}/p\mathbb{Z})^* \rightarrow (\mathbb{Z}/p\mathbb{Z})^*$. For $p \equiv 1 \pmod{3}$, we can define a ‘cubic Legendre symbol’ taking values in $\{0\} \cup \{1, \omega, \omega^2\}$ where ω is a cube root of unity. There is a cubic reciprocity law. A big success of 19th century number theory was a proof of a reciprocity law for n^{th} , for any $n \geq 2$.
- A highlight of the (early) 20th century: Recall that for p odd,

$$\begin{aligned} \left(\frac{-1}{p}\right) = 1 &\iff p \equiv 1 \pmod{4} \iff p = x^2 + y^2 \text{ for some } x, y \in \mathbb{Z} \\ &\iff p = (x + iy)(x - iy) \in \mathbb{Z}[i] \end{aligned}$$

This was hugely generalised to Artin’s Reciprocity Law (in Algebraic Number Theory), and tells us how primes factor in more general number fields.

Another proof of infinitude of $p \equiv 3 \pmod{4}$.

$$\left(\frac{-1}{n}\right) = \begin{cases} 0 & n \text{ even} \\ 1 & n \equiv 1 \pmod{4} \\ -1 & n \equiv 3 \pmod{4} \end{cases}$$

and we know

$$\left(\frac{-1}{n}\right) = \prod_i \left(\frac{-1}{p_i}\right) \text{ if } n = \prod_i p_i$$

The series

$$\sum_{n \geq 1} \left(\frac{-1}{n}\right) \frac{1}{n} = \frac{1}{1} - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} \dots$$

is convergent as it is an alternating series.

Suppose $p \equiv 3 \pmod{4}$. Then

$$\begin{aligned} \left(1 + \frac{1}{p}\right) \sum_{n \geq 1} \left(\frac{-1}{n}\right) \frac{1}{n} &= \sum_{n \geq 1} \left(\frac{-1}{n}\right) \frac{1}{n} + \sum_{m \geq 1} \left(\frac{-1}{m}\right) \frac{1}{mp} \\ &= \sum_{n \geq 1} \left(\frac{-1}{n}\right) \frac{1}{n} - \sum_{m \geq 1} \left(\frac{-1}{mp}\right) \frac{1}{mp} \\ &= \sum_{\substack{(n,p)=1 \\ n \geq 1}} \left(\frac{-1}{n}\right) \frac{1}{n} \end{aligned}$$

must also be convergent.

If there are only a finite set $\{p_1, \dots, p_k\}$ of primes $\equiv 3 \pmod{4}$, then

$$\left(1 + \frac{1}{p_1}\right) \left(1 + \frac{1}{p_2}\right) \dots \left(1 + \frac{1}{p_k}\right) = \sum_{(n, p_1 \dots p_k) = 1} \left(\frac{-1}{n}\right) \frac{1}{n} \quad (*)$$

is also convergent.

But $(n, p_1 \dots p_k) = 1$ means that every odd prime dividing n is $\equiv 1 \pmod{4}$ so

$$\begin{aligned} \left(\frac{-1}{n}\right) &= \begin{cases} 0 & n \text{ even} \\ 1 & n \text{ odd} \end{cases} \\ \Rightarrow (*) &= \sum_{(n, 2p_1 \dots p_k)=1} \frac{1}{n} \end{aligned}$$

but this is divergent.

□

4 Binary quadratic forms

Motivating problem: Which $n \geq 1$ can be written as a sum of 2 integer squares?

Theorem 4.1. Take $N \geq 1$ an integer. Then N is a sum of two integer squares \iff every prime factor $p \equiv 3 \pmod{4}$ if N divides it to an even power.

Proof. (\implies) Suppose $N = x^2 + y^2$. Let $p \mid N$, $p \equiv 3 \pmod{4}$. Then $x^2 \equiv -y^2 \pmod{p}$, so $x \equiv 0 \equiv y \pmod{p}$, since otherwise $\exists z \in \mathbb{Z}$ with $yz \equiv 1 \pmod{p}$ and $(xz)^1 \equiv 1 \pmod{p}$, but $\left(\frac{-1}{p}\right) = -1$. So $p^2 \mid N$ and $N/p^2 = (x/p)^2 + (y/p)^2$, then repeat until no prime factor $p \equiv 3 \pmod{4}$ remains.

(\impliedby) Write $N = M^2 N_1$, where N_1 is a product of distinct primes, each either 2 or $\equiv 1 \pmod{4}$. It suffices to show $N_1 = x^2 + y^2$.

As $(x^2 + y^2)(z^2 + t^2) = (xz - yt)^2 + (xt + yz)^2$ and $2 = 1^2 + 1^2$, it's enough to show if $p \equiv 1 \pmod{4}$ then $p = x^2 + y^2$, which is done later (in lecture 11). \square

There are similar results (Euler) for $x^2 + 2y^2$ and $x^2 + 3y^2$. Meanwhile, $x^2 + 6y^2$ is complicated, we'll see why.

The general problem is to consider **binary quadratic forms** with integer coefficients

$$f(x, y) = ax^2 + bxy + cy^2 \quad a, b, c \in \mathbb{Z}$$

What are possible sets $\{f(x, y) \mid x, y \in \mathbb{Z}\}$? Say f **represents** $n \in \mathbb{Z}$ if $\exists x, y \in \mathbb{Z}$ with $f(x, y) = n$.

We use the convenient shorthand (a, b, c) for the form $ax^2 + bxy + cy^2$. Define a BQF as a binary quadratic form with coefficients in \mathbb{Z} . f can be written in matrix form:

$$ax^2 + bxy + cy^2 = \begin{pmatrix} x & y \end{pmatrix} \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2} & c \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

Example.

- $f(x, y) = x^2 + y^2$ or $(1, 0, 1)$ has matrix $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$.
- $g(x, y) = 4x^2 + 12xy + 10y^2$ or $(4, 12, 10)$ has matrix $\begin{pmatrix} 4 & 6 \\ 6 & 10 \end{pmatrix}$.

Note $g(x, y) = (2x + 3y)^2 + y^2 = X^2 + Y^2 = f(X, Y)$, so f, g are related by an integer change of variables. But they don't represent the same set of integers - g only represents even integers.

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} 2 & 3 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \iff \begin{pmatrix} x \\ y \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & -3 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix}.$$

Definition.

- (1) A **unimodular substitution** is one of the form

$$X = \alpha x + \gamma y, \quad Y = \beta x + \delta y, \quad \alpha, \beta, \gamma, \delta \in \mathbb{Z}, \quad \alpha\delta - \beta\gamma = 1$$

$$\text{so } \begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = A^T \begin{pmatrix} x \\ y \end{pmatrix}, \quad A = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$$

(2) BQFs f, g are **equivalent** if $f(X, Y) = g(x, y)$ for a unimodular substitution.

Remark.

(1) As A^{-1} has integer entries, if f, g are equivalent then they represent the same integers.

(2) (Exercise) This is an equivalence relation

More formally,

$$\left\{ A = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \mid \alpha, \beta, \gamma, \delta \in \mathbb{Z}, \alpha\delta - \gamma\beta = 1 \right\} = \mathrm{SL}_2(\mathbb{Z})$$

is a group under matrix multiplication ($\det A = 1 \implies A^{-1} \in \mathrm{SL}_2(\mathbb{Z})$) which acts on the set of BQFs by

$$A : f(x, y) \longmapsto f(\alpha x + \gamma y, \beta x + \delta y)$$

and the equivalence classes of BQFs are the orbits of this action.

We can check this is a group action:

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \implies Af = f$$

We must also check $(AB)f = (A(Bf))$.

If $f = (a, b, c)$, $g = Af = (a', b', c')$ for $A = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$ then

$$\begin{aligned} g(x, y) = f(X, Y) &= \begin{pmatrix} X & Y \end{pmatrix} \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} \\ &= \begin{pmatrix} x & y \end{pmatrix} A \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix} A^T \begin{pmatrix} x \\ y \end{pmatrix} \end{aligned}$$

and

$$A \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix} A^T = \begin{pmatrix} a' & \frac{b'}{2} \\ \frac{b'}{2}c' & c' \end{pmatrix} \quad (*)$$

So to see that $A(Bf) = (AB)f$, write in matrix form

$$A[B \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix} B^T]A^T = (AB) \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix} B^T A^T$$

and $B^T A^T = (AB)^T$.

Definition (Discriminant). The **discriminant** of $f = ax^2 + bxy + cy^2$ is $\mathrm{disc}(f) = b^2 - 4ac$.

Observe $\mathrm{disc}(f) = -4 \times \det \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2}c & c \end{pmatrix}$.

Example.

$$\begin{aligned} \mathrm{disc}(1, 0, 1) &= -4 \\ \mathrm{disc}(4, 12, 10) &= -16 \end{aligned}$$

Lemma 4.2. Equivalent forms have the same discriminant (so the discriminant is an invariant of BQFs under equivalence).

Proof. Take identity (*):

$$\begin{aligned} \begin{pmatrix} a' & \frac{b'}{2} \\ \frac{b'}{2} & c' \end{pmatrix} &= A \begin{pmatrix} a & \frac{b}{2} \\ \frac{b}{2} & c \end{pmatrix} A^T \\ \implies \text{disc}(a', b', c') &= \text{disc}(a, b, c) \det A \det A^T \\ &= \text{disc}(a, b, c) \end{aligned} \quad \square$$

Remark. The converse is false: forms of the same discriminant need not be equivalent:

$$f = (1, 0, 6) = x^2 + 6y^2, \quad g = (2, 0, 3) = 2x^2 + 3y^2$$

and $\text{disc}(f) = -24 = \text{disc}(g)$, but f represents 1 and g doesn't.

Lemma 4.3. \exists BQF f with $\text{disc}(f) = d \iff d \equiv 0 \text{ or } 1 \pmod{4}$.

Proof. $\implies d = \text{disc}(a, b, c) = b^2 - 4ac \equiv b^2 \pmod{4} \implies d \equiv 0 \text{ or } 1 \pmod{4}$

$$\begin{aligned} \Leftarrow \quad & \text{if } d \equiv 0 \pmod{4} & \text{then} & \quad \text{disc} \left(1, 0, -\frac{d}{4} \right) = d \\ & \text{if } d \equiv 1 \pmod{4} & \text{then} & \quad \text{disc} \left(1, 1, \frac{1-d}{4} \right) = d \end{aligned}$$

\square

Definition. A real quadratic form

$$f(\mathbf{x}) = \sum_{1 \leq i \leq j \leq n} a_{ij} x_i x_j \quad (a_{ij} \in \mathbb{R})$$

is

- **positive definite** if $\forall 0 \neq x \in \mathbb{R}^n, f(\mathbf{x}) > 0$
- **negative definite** if $\forall 0 \neq x \in \mathbb{R}^n, f(\mathbf{x}) < 0$
- **indefinite** if $\exists \mathbf{x}, \mathbf{x}' \in \mathbb{R}^n$ with $f(\mathbf{x}) > 0 > f(\mathbf{x}')$

Consider the case $n = 2$:

Lemma 4.4. Take $f = (a, b, c)$ a BQF with $d = b^2 - 4ac$.

- (i) $d < 0, a > 0 \implies f$ is **positive definite**
- (ii) $d < 0, a < 0 \implies f$ is **negative definite**
- (iii) $d > 0 \implies f$ is **indefinite**
- (iv) $d = 0 \implies f = l(mx + ny)^2 \quad l, m, n \in \mathbb{Z}$

Proof. (i) , (ii) $d < 0$, so $ac > 0$ and a, c have the same sign.

$$4af(x, y) = 4a^2x^2 + 4abxy + 4acy^2 = (2ax + by)^2 - dy^2$$

so $\forall x, y \in \mathbb{R}$, $4af(x, y) \geq 0$ (as $d < 0$) with equality if and only if $x = y = 0$. f is positive definite if $a > 0$ and negative definite if $a < 0$.

(iii) Assume $d > 0$ and $a > 0$. Consider $f(x, 1) = ax^2 + bx + c = a(x - \alpha)(x - \beta)$ with real $\alpha < \beta$ and

$$\alpha, \beta = \frac{-b \pm \sqrt{d}}{2a} \quad (2)$$

If $\frac{r}{s} \in \mathbb{Q}$,

$$f(r, s) = s^2 f\left(\frac{r}{s}, 1\right) = as^2 \left(\frac{r}{s} - \alpha\right) \left(\frac{r}{s} - \beta\right)$$

$$\text{so } \frac{r}{s} > \beta \quad f(r, s) > 0$$

$$\alpha < \frac{r'}{s'} < \beta \quad f(r', s') < 0.$$

so f is indefinite. Indeed \exists integer pairs $(r, s), (r', s')$ with $f(r, s) > 0 > f(r', s')$.

If $a > 0$ consider $-f$. If $a = 0$, $c \neq 0$ consider $f(1, y)$ instead. If $a = c = 0$ then $f = bxy$ and $b = \pm\sqrt{d} \neq 0$, so obviously indefinite.

(iv) $\alpha = \beta$, left as an exercise. □

Note. We can have $a, b, c > 0$ but f **indefinite**, for instance $(1, 3, 1)$ which has $d > 0$. We can also have $b < 0$ but f **positive definite**, for example $(1, -1, 2)$ which has $d < 0$.

From now on, we restrict to positive definite BQFs (a, b, c) with $a, c > 0$ and $d = b^2 - 4ac < 0$. The first aim is to identify the ‘simplest’ or ‘smallest’ form in each equivalence class.

Example. Take $(10, 34, 29)$ and we look for equivalent forms with smaller coefficients (this has $d = -4$)

First try to reduce $b = 45$ by replacing x with $x + \lambda y$ for suitable λ .

$$f(x, y) = ax^2 + bxy + cy^2 \implies f(x + \lambda y, y) = x^2 + (b + 2\lambda a)xy + (\lambda^2 a + \lambda b + c)y^2$$

Take $\lambda = \pm 1$, so

$$(a, b, c) \sim (a, b \pm 2a, a \pm b + c) \quad (*)$$

and in our example $(10, 34, 29) \sim (10, 14, 5) \sim (10, -6, 1)$.

To reduce the size of a , apply $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ so $X = y$, $Y = -x$ and

$$(a, b, c) \sim (c, -b, a) \quad (**)$$

In the example,

$$\begin{aligned}
(10, -6, 1) &\stackrel{(**)}{\sim} (1, 6, 10) \\
&\stackrel{(*)}{\sim} (1, 4, 5) \\
&\stackrel{(*)}{\sim} (1, 2, 2) \\
&\stackrel{(*)}{\sim} (1, 0, 1)
\end{aligned}$$

Remark. • Applying $(*)$ repeatedly, we can replace f by an equivalent form with the same a and $|b| \leq a$.

- Applying $(**)$ repeatedly, we can replace f by an equivalent form with $a \leq c$ and $|b|$ unchanged.

Definition. A positive definite BQF is reduced if either

$$-a < b \leq a < c \text{ or } 0 \leq b \leq a = c.$$

Note that in both cases $|b| \leq a \leq c$.

In the example, $(10, 34, 29)$ is not reduced as $|b| \not\leq a$, but $(1, 0, 1)$ is.

Lemma 4.5. Every positive definite BQF is equivalent to a reduced form.

Proof. Consider the unimodular substitutions

$$\begin{aligned}
T_{\pm} &= \begin{pmatrix} 1 & 0 \\ \pm 1 & 1 \end{pmatrix} : (a, b, c) \mapsto (a, b \pm 2a, a \pm b + c) \\
S &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} : (a, b, c) \mapsto (c, -b, a)
\end{aligned}$$

If $a > c$, apply S to replace f with an equivalent form with smaller a but $|b|$ unchanged.

If $a \geq c$ and $|b| > a$, use one of T_{\pm} to decrease $|b|$ (as $|b \pm 2a| < |b|$ for some \pm since $a < |b|$) leaving a unchanged.

Repeat. At each step, $a + |b|$ is decreased, and $a + |b| > 0$. So the process must terminate; after a finite number of substitutions, we reach a form (a, b, c) with $|b| \leq a \leq c$. There are two cases:

- a) $a < c$: then (a, b, c) will be reduced unless $b = -a$ and then

$$(a, b, c) = (a, -a, c) \sim (a, a, c)$$

which is reduced since $-a < b = a < c$.

- b) $a = c$, then (a, b, c) will be reduced provided $0 \leq b \leq a$. Otherwise, $-a \leq b < 0$ and then $(a, b, c) = (a, b, c) \sim (a, -b, a)$ which is reduced. \square

Remark. We showed that our form was equivalent to a reduced form using only the substitutions S, T_{\pm} . With a bit more work, this shows that any unimodular substitution may be written as a product of S s and T_{\pm} s, so $SL_2(Z)$ is generated by S and T_+ .

Lemma 4.6. Let $f = (a, b, c)$ be a reduced positive definite BQF, $d = b^2 - 4ac < 0$. Then $|b| \leq a \leq \sqrt{\frac{|d|}{3}}$ and $b \equiv d \pmod{2}$.

Remark. For fixed d , there are only finitely many possible (a, b) , and $c = \frac{b^2 - d}{4a}$, so there is only a finite number of reduced forms of discriminant d .

Proof. $b^2 \equiv d \pmod{4}$ so $b \equiv d \pmod{2}$. f is reduced $\implies |b| \leq a \leq c$, and $d = b^2 - 4ac \leq ac - 4ac = -3ac \leq -3a^2$, so $a^2 \leq \frac{1}{3}|d|$. \square

Example. Take $d = -4$. Then $|b| \leq a \leq 1$, and $b \equiv 0 \pmod{2}$ so $a = 1, b = 0 \implies c = 1$. So the only reduced BQF of discriminant -4 (positive definite) is $x^2 + y^2$.

Use this to prove the ‘serious’ part of [Theorem 4.1](#): if $p \equiv 1 \pmod{4}$ then $p = x^2 + y^2$, $x, y \in \mathbb{Z}$.

Proof. $p \equiv 1 \pmod{4} \implies \left(\frac{-1}{p}\right) = 1$, so $\exists u, k \in \mathbb{Z}$ such that $u^2 = -1 + pk$. Let $f = (p, 2u, k)$. Then $f(1, 0) = p$, $\text{disc}(f) = 4u^2 - 4pk = -4$.

But by [Lemma 4.5](#) and the last calculation, f is equivalent to $x^2 + y^2$. So $\exists x, y \in \mathbb{Z}$ such that $x^2 + y^2 = p$. \square

This method can be applied more generally. Note if $f(x, y) = n$ then $f(kx, ky) = k^2n$. Recall f represents n if $\exists x, y \in \mathbb{Z}$ such that $f(x, y) = 1$.

Definition (Proper representation). f **properly represents** n if $\exists x, y \in \mathbb{Z}$ such that $f(x, y) = n$ and $(x, y) = 1$ (in particular $(x, y) \neq (0, 0)$.)

Remark. Suppose $f(x, y) = g(X, Y)$ with $\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$ and $\alpha\delta - \beta\gamma = 1$, so $\begin{pmatrix} \delta & -\gamma \\ -\beta & \alpha \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix}$. For $x, y \in \mathbb{Z}$, $\gcd(x, y) = \gcd(X, Y)$, so f, g properly represent the same integers.

Lemma 4.7. The least integers properly represented by a reduced positive definite BQF $f = (a, b, c)$ are a, c and $a - |b| + c$ in that order.

A number in this list is repeated \iff it is (properly) represented by f in more than one way – excluding $f(x, y) = f(-x, -y)$. For example, take $f = x^2 + y^2 = (1, 0, 1)$. $f(1, 0) = a = f(0, 1) = c < f(1, 1) = 2 = a - |b| + c$.

Proof. If $f(x, 0) = n$ properly, then $(x, y) = 1 \implies x = \pm 1 \implies n = f(1, 0) = a$. If $f(0, y) = n$ properly, then $y = \pm 1 \implies n = f(0, 1) = c$.

Suppose $n = f(x, y)$, $|x| \geq |y| > 0$, $\gcd(x, y) = 1$.

Then

$$\begin{aligned} n = ax^2 + bxy + cy^2 &\geq ax^2 - |b| |x| |y| + cy^2 \\ &\geq ax^2 - |b| x^2 + cy^2 \\ &\geq (a - |b|) + c \geq c \end{aligned}$$

For a choice of sign, $f(1, \pm 1) = a \pm b + c = a - |b| + c$. So $a \leq c \leq a - |b| + c$ are the least values properly represented by f . \square

Theorem 4.8. Every positive definite BQF is equivalent to a *unique* reduced form.

Proof. By Lemma 4.5, every positive definite BQF is equivalent to some reduced form, so have to show that if $f \sim g$ and f, g are reduced, then $f = g$. Say $f = (a, b, c) \sim g = (a', b', c')$ are both reduced.

By Lemma 4.7, the least n properly represented by f is a , and by g is a' , so $a = a'$. The next least integer properly represented by f is c , and by g is c' , so $c = c'$. (The $a = c$ case needs to be taken care of, and is left as an exercise). So, $b^2 = d + 4ac = d + 4a'c' = b'^2$, so $g = (a, b, c)$ or $g = (a, -b, c)$.

If $a = c$ then (a, b', a) is reduced $\iff 0 \leq b' \leq a$, so $(a, -b, a)$ is excluded and $f = g$.

Otherwise $a < c$, $-a < b \leq a$. If $(a, -b, c)$ is reduced then $-a < b < a$. Then $a < c < a - |b| + c$ (no repeats). By the proof of Lemma 4.7

$$f(x, y) = \begin{cases} a & \iff (x, y) = (\pm 1, 0) \\ c & \iff (x, y) = (0, \pm 1) \end{cases}$$

and same for g .

As $g(x, y) = f(X, Y)$, $\begin{pmatrix} X \\ Y \end{pmatrix} = \begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$ so $(x, y) = (\pm 1, 0) \iff f = a = g \iff (X, Y) = (\pm 1, 0)$. Similarly, $(x, y) = (0, \pm 1) \iff (X, Y) = (0, \pm 1)$ so $\begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} = \begin{pmatrix} \pm 1 & 0 \\ 0 & \pm 1 \end{pmatrix}$. As $\alpha\delta - \beta\gamma = 1$, $\begin{pmatrix} \alpha & \gamma \\ \beta & \delta \end{pmatrix} = \pm \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, hence $g(x, y) = f(\epsilon x, \epsilon y) = f(x, y)$. \square

Remark. The definition of ‘reduced’ was cooked up precisely to ensure that this Theorem holds.

Example. For $d = -24$, $x^2 + 6y^2$ and $2x^2 + 3y^2$ are reduced and inequivalent, with disc = -24 . Are there others? $\|b\| \leq a \leq \sqrt{8}$ so $|b| \leq a \leq 2$, and $b = d = 0 \pmod{2}$.

For $a = 1$, we have $b = 0$ so $c = 6$, giving $(1, 0, 6)$. For $a = 2$, $b \in \{0, \pm 2\}$ and $c = \frac{b^2 + 24}{8}$. $b = \pm 2 \implies c \notin \mathbb{Z}$, so $b = 0$ and $c = 3$ giving $(2, 0, 3)$. So there are no others.

So every positive definite BQF is equivalent to a unique reduced form, and \exists only a finite number of reduced forms of discriminant d .

Definition (Class number). The number of positive definite reduced forms of discriminant d is called the **class number** $h(d)$.

Example. $h(-4) = 1 = h(-7)$, and $h(-24) = 2$.

We saw that for given d , we can easily work out what the reduced forms are. How does $h(d)$ behave as a function of d ? How many d are there with $h(d) = 1$? Some results (beyond the scope of this course), mostly using analytic number theory:

1. $h(d) \rightarrow \infty$ as $d \rightarrow -\infty$ (1934 Heilbronn), so $\#\{d \mid h(d) \leq X\}$ is finite. First Siegel showed $h(d) \rightarrow \infty$ assuming the generalized Riemann hypothesis in analytic number theory. Then Heilbronn proved $h(d) \rightarrow \infty$ assuming GRH false by a completely different method.
2. ‘On average $h(d) \approx \sqrt{|d|}$ ’:

$$\frac{1}{2X} \sum_{\substack{0 \leq d \leq -x \\ d \equiv 0,1 \pmod{4}}} h(d) \sim c\sqrt{X} \text{ for some } c > 0. \quad ((1874, \text{Mertens}))$$

3. $h(d) = 1 \iff -d = 3, 4, 7, 8, 11, 19, 43, 67, 163$ and $12, 16, 27, 28$. It was known since around 1900 that this was true, except for possibly one other d with $-d$ very large. (1967 Baker, Stark showed the list was complete, but was actually proved 10 years earlier by Heeger).
4. $\{d \mid h(d) \leq 100\}$ is known. In fact \exists explicit bound for the largest $|d|$ with $h(d) = N$, but it is not very practical, for $N = 1$ is e^{5000} . This is nevertheless a very hard result using analytic number theory, algebraic geometry and elliptic curves.

Now study the problem: if f is a BQF and $n \in \mathbb{Z}$, when does f represent n ? We've seen the answer for $x^2 + y^2$. Now partially generalise this to positive definite BQFs. For indefinite forms look at the section on continued fractions the method is very different.

Lemma 4.9. Let f be a BQF, $n \in \mathbb{Z}$. Then f properly represents $n \iff f \sim g = (a, b, c)$ with $a = n$.

Proof. (\Leftarrow). $g(n, b, c) \implies g(1, 0) = n$, so g represents n properly. Hence if $f \sim g$, so does g .

(\Rightarrow) f properly represents n means $\exists \gamma, \delta \in \mathbb{Z}$ with $f(\gamma, \delta) = n$ and $(\gamma, \delta) = 1$. Then $\exists \alpha, \beta \in \mathbb{Z}$ such that $\alpha\delta - \beta\gamma = 1$ by Euclid. Let $g(x) = f(\gamma x + \alpha y, \delta x + \beta y) \sim f$. Then $g(1, 0) = f(\gamma, \delta) = n$, i.e. $g = (n, b, c)$. \square

Recall $p = x^2 + y^2 \iff p = 2$ or $\left(\frac{-1}{p}\right) = 1$. Generalise:

Theorem 4.10. Let $d < 0$ be a discriminant (i.e. $d \equiv 0$ or $1 \pmod{4}$), $n \geq 1$. Then (n is properly represented by some BQF of discriminant d) $\iff (x^2 \equiv d \pmod{4n})$ is soluble).

Proof. (\Rightarrow) Suppose $n = f(x, y)$ properly, and $\text{disc}(f) = d$. Then Lemma 4.9 $\implies f \sim g = (n, b, c)$ with $b, c \in \mathbb{Z}$ and $d = \text{disc}(g) = b^2 - 4cn \implies b^2 \equiv d \pmod{4n}$.

(\Leftarrow) Suppose soluble. $\exists b, c \in \mathbb{Z}$ with $b^2 = d + 4nc$. Then (n, b, c) has discriminant d , and properly represents n . \square

Example. What integers are represented (properly) by $f = x^2 + xy + 2y^2$. $\text{disc}(f) = -7$. f is reduced. If (a, b, c) is any reduced form of $\text{disc}(f)$ then $|b| \leq a \leq \sqrt{\frac{7}{3}}$ and $b \equiv d \pmod{2}$ is odd, so $a = 1$, $b = \pm 1$, $c = 2$ and (a, b, c) reduced $\implies (a, b, c) = (1, 1, 2)$ so $h(-7) = 1$.

Let's first consider $f(x, y) = p$, p prime, $p \neq 2, 7$. By Theorem 4.10, p is properly represented by $f \iff x^2 \equiv -7 \pmod{4p}$ is soluble

$$\iff \begin{cases} x^2 \equiv -7 \pmod{4} \\ x^2 \equiv -7 \pmod{p} \end{cases} \text{ are soluble.} \iff \left(\frac{-7}{p}\right) = 1.$$

But

$$\left(\frac{-7}{p}\right) = \left(\frac{-1}{p}\right)(-1)^{\frac{p-1}{2}}\left(\frac{p}{7}\right) = \left(\frac{p}{7}\right) = \begin{cases} 1 & p \equiv 1, 2, 4 \pmod{7} \\ -1 & p \equiv 3, 5, 6 \pmod{7} \end{cases}.$$

Also $f(0, 1) = 2$ and $f(1, -2) = 7$.

So, a prime p is properly represented $\iff p = 7$ or $p \equiv 1, 2, 4 \pmod{7}$.

For more general n , let $n = 2^{e_2} 3^{e_3} = \prod_p p^{e_p}$, $e_p \geq 0$ and $e_p = 0$ for all but finitely many p . Then

$$x^2 \equiv d \pmod{4n} \text{ is soluble} \iff \begin{cases} \forall p \neq 2 & x^2 \equiv d \pmod{p^{e_p}} \\ \text{and} & x^2 \equiv d \pmod{2^{e_2+2}} \end{cases} \text{ are soluble}$$

The next goal is to show if $x^2 \equiv d \pmod{p}$ soluble ($p \nmid d$), then soluble mod $p^e \forall e \geq 1$ for p odd, i.e. that the Legendre symbol determines solubility.

Lemma 4.11. (i) Take p an odd prime, $a \in \mathbb{Z}$ with $\left(\frac{a}{p}\right) = 1$. Then $\forall n \geq 1$, $x^2 \equiv a \pmod{p^n}$ is soluble.

(ii) $a \equiv 1 \pmod{8} \implies x^2 \equiv a \pmod{2^n}$ soluble $\forall n \geq 1$.

Proof. (i) $\left(\frac{a}{p}\right) = 1 \implies$ there is a solution to $x^2 \equiv 0 \pmod{p}$. So, by induction assume that for some $n \geq 1$, $x^2 = a + kp^n$ for some $k \in \mathbb{Z}$. Consider $t \in \mathbb{Z}$, so

$$\begin{aligned} (x + tp^n)^2 &= x^2 + 2xtp^n + t^2p^{2n} \\ &\equiv a + (k + 2xt)p^n \pmod{p^{n+1}}. \end{aligned}$$

Since $\left(\frac{a}{p}\right) \neq 0$, $(a, p) = 1 = (x, p)$. So, $\exists t \in \mathbb{Z}$ such that $k + 2xt \equiv 0 \pmod{p}$. For this t , $(x + p^n t)^2 \equiv a \pmod{p^{n+1}}$.

(ii) $n \geq 3$ is easy, take $x = 1$. So again by induction, assume $x^2 = a + 2^n k$ for $n \geq 3$. If k even, then $x^2 \equiv a \pmod{2^{n+1}}$. Otherwise,

$$\begin{aligned} (x + 2^{n-1})^2 &= x^2 + x2^n + 2^{2n-2} \equiv a + (x + k)2^n \pmod{2^{n+1}} \\ &\equiv a \pmod{2^{n+1}}. \end{aligned}$$

□

Example. Continuing the example of $f = (1, 1, 2)$ with $d = -7$, $-7 \equiv 1 \pmod{8} \implies x^2 \equiv -7 \pmod{2^n}$ is soluble $\forall n$. For p odd and $p \equiv 1, 2, 4 \pmod{7}$, $\left(\frac{-7}{p}\right) = 1 \implies x^2 \equiv -7 \pmod{p^n}$ is soluble $\forall n \geq 1$. For $p = 7$: $x^2 \equiv -7 \pmod{7}$ is soluble, but $x^2 \equiv -7 \pmod{49}$ is insoluble, hence insoluble mod $7^n \forall n \geq 2$. Conclusion: $f = (1, 1, 2)$ properly represents $n \geq 1$ if and only if

$$n = 2^{e_2} 7^{e_7} \prod_{p \equiv 1, 2, 4 \pmod{7}} p^{e_p} \quad e_p \geq 0, e_7 \in \{0, 1\}$$

The numbers represented (not necessarily properly) by f are $k^2 n$, $k \geq 1$ with n as above. That is, $n = x^2 + xy + 2y^2$ for some $x, y \in \mathbb{Z}$ if and only if $n = 0$ or every prime $p \not\equiv 1, 2, 4 \pmod{7}$ dividing n divides it to an even power.

This method completely describes the integers represented by f of discriminant $d < 0$ when $h(d) = 1$. For $h(d) > 1$, all this tells us is which n are represented by *some* equivalence class of BQFs of discriminant d .

Sometimes (as on the example sheet), you can figure out which just by congruence conditions, but usually not. For example, $x^2 + 23y^2$ - the representability of n by $x^2 + 23y^2$ cannot be described using congruence conditions on $p \mid n$. (Why? Deep algebraic number theory related to ‘non-abelian reciprocity laws’)

Definition (Fundamental discriminant). $d \equiv 0$ or $1 \pmod{4}$ is a **fundamental discriminant** if $d \equiv k^2 d'$, where $k \geq 2$ and $d' \equiv 0$ or $1 \pmod{4}$.

For fundamental discriminant $d < 0$, Gauss defined composition of 2 BQFs of discriminant d to get a third, turning {equivalence classes of positive definite BQFs of discriminant d } into an abelian group, the class group. This turns out to be the ideal class group of the quadratic field $\mathbb{Q}(\sqrt{d})$ (see Number Fields).

Negative definite forms now provide nothing new, but what about indefinite forms?

The key difference between definite and indefinite forms is that for a definite form f , $\#\{(x, y) \in \mathbb{Z}^2 \mid f(x, y) = n\}$ is always finite. For instance, $x^2 + y^2 = n \implies |x|, |y| \leq \sqrt{n}$. In general, $f(x, y) = n$ is the equation of an ellipse in \mathbb{R}^2 , so integer points (x, y) on it have bounded size. On the other hand, if f is indefinite, then there can be infinitely many solutions. For example, $x^2 - 2y^2$ is indefinite. Consider $x^2 - 2y^2 = 1$. We have solutions $(x, y) = (1, 0)$ and also $(3, 2)$. If (x, y) is a solution, then $(x^2 + 2y^2)^2 - 2(2xy)^2 = (x^2 - 2y^2)^2 = 1$ as well. So starting with $(3, 2)$ and repeating gets solutions of arbitrarily large size. We study $x^2 - dy^2 = 1$ later.

What about more variables? For instance, what integer values does $x_1^2 + x_2^2 + \cdots + x_k^2$ take?

Theorem (1770, Lagrange). Every positive integer n is a sum of 4 squares. So for $k \geq 4$, we are done.

Proof. Not in the scope of this course, but there is a formula for the number of representations involving 'modular forms'. \square

Harder is

Theorem (1797, Legendre).

$$n = x^2 + y^2 + z^2 \iff n \neq 4^a(8b+7)$$

Proof. The \implies direction is easy, and the usual proof of \impliedby is hard and uses quadratic reciprocity, and Dirichlet's theorem on existence of primes in arithmetic progressions. Again, this is out of scope. \square

5 Distribution of the primes

2, 3, 5, 7, 11, 13, 17, ..., 691, ..., 144169, ...

an infinite sequence (Euclid).

Two natural questions are:

1. How rapidly does the sequence grow?
2. How (ir)regular e.g. how big are the gaps?

(i) is partially answered by the

Theorem (Prime Number Theorem).

$$\begin{aligned}\pi(X) = \#\{\text{primes } p \leq X\} &\sim \frac{X}{\log X} \text{ as } X \rightarrow \infty \\ &\sim \int_2^X \frac{dt}{\log t} \text{ logarithmic integral}\end{aligned}$$

The proof uses complex analysis.

We'll eventually prove

Theorem (Tchebyshev's Theorem). $\exists c_2 > c_1 > 0$ such that

$$c_1 \frac{x}{\log x} < \pi(x) < c_2 \frac{x}{\log x}$$

For the moment, we'll prove some weaker results:

Lemma 5.1.

$$\pi(x) \geq \frac{\log x}{2 \log 2} \quad \forall \text{ integers } x \geq 1$$

Proof. Let $\{p_1, \dots, p_r\} = \{\text{primes} \leq x\}$ (so $\pi(x) = r$). If $n \leq x$, $n = k^2 = p_1^{\alpha_1} \cdots p_r^{\alpha_r}$, $1 \leq K \leq \sqrt{x}$, $\alpha_i \in \{0, 1\}$ (so K is the largest square dividing n).

$$\left. \begin{array}{l} \leq \sqrt{x} \quad \text{possibilities for } k \\ \leq 2^r \quad \text{possibilities for } \alpha_i\text{'s} \end{array} \right\} \implies x = \#\{1 \leq n \leq x\} \leq \sqrt{x} 2^r$$

$$2^r = 2^{\pi(x)} \geq \sqrt{x} \implies \pi(x) \geq \frac{\log x}{2 \log 2}.$$

□

Say p_n is the n th prime. On average, by the prime number theorem, $p_{n+1} - p_n$ is around $\log X$. But the gap oscillates wildly.

Small gaps An old conjecture ('twin prime problem') $\exists \infty$ many n with $p_{n+1} = p_n + 2$. Quite recently: there is a constant C such that for infinitely many n , $p_{n+1} \leq p_n + C$. The best known such constant is $C = 246$, from the Polymath project.

Big gaps By the PNT, at least $\log p_n$ infinitely often.

We will prove:

Theorem (Bertrand's postulate). $p_{n+1} \leq 2p_n$, there is always a prime between N and $2N$.

Analytic number theory in fact shows that for n sufficiently large, $p_{n+1} - p_n \leq p_n^{0.525}$.

In the other direction, $\exists \infty$ many n such that

$$p_{n+1} - p_n > c \frac{\log p_n \log \log p_n \log \log \log p_n}{\log \log \log p_n}$$

(and $(\log p_n)^2$ is conjectured).

Theorem 5.2.

(i) $\sum_{p \text{ prime}} \frac{1}{p}$ is divergent

(ii) $\prod_{p \text{ prime}} \left(1 - \frac{1}{p}\right)^{-1}$ is divergent i.e. $\prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1} \rightarrow \infty$ as $x \rightarrow \infty$.

Proof. First prove (ii)

$$\prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1} = \prod_{p \leq x} \left(1 + \frac{1}{p} + \frac{1}{p^2} + \dots\right) \geq \sum_{n \leq x} \frac{1}{n}.$$

If $n = p_1^{e_1} \dots p_k^{e_k}$, all $p_i \leq x$ then $\frac{1}{n} = \frac{1}{p_1^{e_1}} \dots \frac{1}{p_k^{e_k}}$ occurs in the product and all terms > 0 .

So as $\sum \frac{1}{n} \rightarrow \infty$, the product $\rightarrow \infty$ as $x \rightarrow \infty$.

For (i) take logarithms

$$\begin{aligned} \log \prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1} &= \sum_{p \leq x} -\log\left(1 - \frac{1}{p}\right) \\ &= \sum_{p \leq x} \left(\frac{1}{p} + \frac{1}{2p^2} + \frac{1}{3p^3} + \dots\right) \\ &= \sum_{p \leq x} \frac{1}{p} + R_x \\ R_x &= \sum_{p \leq x} \left(\frac{1}{2p^2} + \frac{1}{3p^3} + \dots\right) \leq \sum_{p \leq x} \left(\frac{1}{p^2} + \frac{1}{p^3} + \dots\right) \\ &= \sum_{p \leq x} \frac{1}{p(p-1)} \\ &\leq \sum_{m \geq 2} \frac{1}{m(m-1)} = 1. \end{aligned}$$

As $\prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1} \rightarrow \infty$, so does $\log(\prod_{p \leq x} \left(1 - \frac{1}{p}\right)^{-1})$ and so does $\sum_{p \leq x} \frac{1}{p}$. \square

To take these ideas further, Riemann introduced the Riemann ζ -function for complex variables

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}$$

(previously considered by Euler for real $s > 1$).

Proposition 5.3. The series converges absolutely iff $\text{Re}(s) > 1$.

Proof. Let $s = \sigma + it$, $\sigma, t \in \mathbb{R}$. Then

$$\left| \frac{1}{n^s} \right| = \left| \frac{1}{e^{\log n(\sigma + it)}} \right| = \frac{1}{n^\sigma}.$$

So the series is absolutely convergent $\iff \sum_{n \geq 1} \frac{1}{n^\sigma}$ converges $\iff \sigma > 1$. \square

By complex analysis and uniform convergence $\implies \zeta(s)$ is an analytic function of s for $\text{Re}(s) > 1$. What has ζ got to do with primes?

Theorem 5.4.

(i) $\zeta(s) = \prod_{p \text{ prime}} (1 - \frac{1}{p^s})^{-1}$ - the ‘Euler product’ ($\text{Re}(s) > 1$).

(ii) $\zeta(s) \neq 0$ if $\text{Re}(s) > 1$.

Proof. (i) The aim is to show

$$\prod_{p \leq x} \left(1 - \frac{1}{p^s}\right)^{-1} \rightarrow \zeta(s) \text{ as } x \rightarrow \infty$$

$$\begin{aligned} \zeta(s) - \prod_{p \leq x} \left(1 - \frac{1}{p^s}\right)^{-1} &= \sum_{n \geq 1} n^{-s} - \prod_{p \leq x} (1 + p^{-s} + p^{-2s} + \dots) \\ &= \sum_{n \in \eta_x} n^{-s}, \quad \eta_x = \{n \geq 1 \mid \text{at least one prime factor of } n \text{ is } > x\} \end{aligned}$$

because

$$\prod_{p \leq x} (1 + p^{-s} + p^{-2s} + \dots) = \sum_{\substack{n \text{ product} \\ \text{of primes} \\ \leq x}} n^{-s}$$

by unique factorisation. So

$$\begin{aligned} \left| \zeta(s) - \prod_{p \leq x} \left(1 - \frac{1}{p^s}\right)^{-1} \right| &\leq \sum_{n \leq \eta_x} n^{-\sigma} \quad (\sigma = \text{Re}(s) > 1) \\ &\leq \sum_{n > x} n^{-\sigma} \rightarrow 0 \text{ as } x \rightarrow \infty \text{ as } \sigma > 1. \end{aligned}$$

(ii)

$$\begin{aligned} \prod_{p \leq x} \left(1 - \frac{1}{p^s}\right) \cdot \zeta(s) &= \prod_{p > x} \left(1 - \frac{1}{p^s}\right)^{-1} \text{ by part (i)} \\ &= 1 + \sum_{\substack{n \text{ s.t.} \\ \text{all } p \mid n \\ \text{satisfy } p > x}} n^{-s} \rightarrow 1 \text{ as } x \rightarrow \infty \end{aligned}$$

so

$$\left| \prod_{p \leq x} \left(1 - \frac{1}{p^s}\right) \zeta(s) \right| \geq 1 - \sum_{n > x} n^{-\sigma} > 0 \text{ if } x \text{ is large enough}$$

$$\implies \zeta(s) \neq 0. \quad \square$$

Theorem 5.5. $\zeta(s) - \frac{1}{s-1}$ extends to an analytic function on $\{Re(s) > 0\}$ by analytic continuation.

(As $s \rightarrow 1$, the series representing $\zeta(s)$ becomes divergent, and we would like to subtract off the divergence. $\int_1^\infty \frac{dx}{x^{s-1}} = \frac{1}{s-1}$.)

Proof. Suppose $Re(s) > 2$ for the moment.

$$\begin{aligned} \zeta(s) &= \sum_{n \geq 1} \frac{1}{n^s} = \sum_{n \geq 1} \left(\frac{n}{n^s} - \frac{n-1}{n^s} \right) = \sum_{n \geq 1} \frac{n}{n^s} - \sum_{n \geq 2} \frac{n-1}{n^s} \\ &= \sum_{n \geq 1} \frac{n}{n^s} = \sum_{n \geq 1} \frac{n}{(n+1)^s} = \sum_{n \geq 1} n \left(\frac{1}{n^s} - \frac{1}{(n+1)^s} \right) \\ &= \sum_{n \geq 1} n \int_n^{n+1} s \frac{dx}{x^{s+1}} \end{aligned}$$

since

$$\begin{aligned} \int_a^b \frac{dx}{x^s} &= \left[-\frac{x^{1-s}}{s-1} \right]_a^b \\ &= \frac{1}{s-1} \left(\frac{1}{a^{s-1}} - \frac{1}{b^{s-1}} \right) \end{aligned}$$

If $n \leq x < n+1$ then $n = \lfloor x \rfloor$.

$$\begin{aligned} &= s \sum_{n \geq 1} \int_n^{n+1} \frac{\lfloor x \rfloor}{x^{s+1}} dx = s \int_1^\infty \frac{\lfloor x \rfloor}{x^{s+1}} dx = s \int_1^\infty \frac{x}{x^{s+1}} - \frac{x - \lfloor x \rfloor}{x^{s+1}} dx \\ &= \frac{s}{\underbrace{s-1}_{=\frac{1}{s-1}+1}} - s \int_1^\infty \frac{x - \lfloor x \rfloor}{x^{s+1}} dx \end{aligned}$$

So $\sigma(s) - \frac{1}{s-1} = 1 - s \int_1^\infty \frac{x - \lfloor x \rfloor}{x^{s+1}} dx$. As $0 \leq x - \lfloor x \rfloor < 1$, the integral converges for $Re(s+1) > 1$, i.e. $Re(s) > 0$ and by complex analysis represents an analytic function there. \square

Remark. (i) In fact (using a more subtle integral) can show that $\zeta(s) - \frac{1}{s-1}$ is analytic $\forall s \in \mathbb{C}$ and $\zeta(s)$ satisfies an interesting identity

$$\begin{aligned} \xi(s) &:= \pi^{-\frac{s}{2}} \Gamma\left(\frac{s}{2}\right) \zeta(s) \\ &\quad \xi(1-s) \end{aligned}$$

where Γ is the function which interpolates factorial $\Gamma(s) = \int_0^\infty e^{-y} y^{s-1} dy$.

- (ii) A key ingredient in the prime number theorem is that $\zeta(s) \neq 0$ if $s = 1 + it$, $t \neq 0$, (can't get this from the infinite product).

We will say a little more about series of the form $\sum_{n \geq 1} a_n n^{-s}$ (Dirichlet series). A useful tool for manipulating these (and for other purposes) is the Möbius function.

Recall [Lemma 2.4](#):

Lemma 2.4. Let f be a multiplicative function. Then so is g , defined by

$$g(n) = \sum_{d|n} f(d)$$

How can we recover f from g ?

Example. Try an example:

$$\begin{aligned} g(6) &= f(1) + f(2) + f(3) + f(6) \\ g(3) &= f(1) + f(3) \\ g(2) &= f(1) + f(2) \\ g(1) &= f(1) \\ \implies f(6) &= g(6) - g(2) - g(3) + g(1) \end{aligned}$$

This obviously works in general!

Definition (Möbius function). The **Möbius function** $\mu : \mathbb{N} \rightarrow \{0, \pm 1\}$ is given by

$$\mu(n) = \begin{cases} 1 & n = 1 \\ (-1)^k & n = p_1 \cdots p_k \text{ is a product of } k \text{ distinct primes} \\ 0 & \text{otherwise (divisible by a square } \neq 1) \end{cases}$$

Exercise. μ is a multiplicative function.

Apply [Lemma 2.4](#) to μ , let $\nu(n) = \sum_{d|n} \mu(d)$. Then ν is a multiplicative function. Now

$$\begin{aligned} \nu(p^k) &= \mu(1) + \mu(p) + \cdots + \mu(p^k) \\ &= \begin{cases} \mu(1) = 1 & \text{if } k = 0 \\ \mu(1) + \mu(p) = 0 & \text{if } k = 1 \\ 0 & \text{if } k > 1. \end{cases} \end{aligned}$$

So by multiplicativity

$$\nu(n) = \begin{cases} 1 & \text{if } n = 1 \\ 0 & \text{if } n > 1 \end{cases}$$

Proposition 5.6 (Möbius inversion formula). Let $f : \mathbb{N} \rightarrow \mathbb{C}$ be any function, and $g(n) = \sum_{d|n} f(d)$. Then

$$f(n) = \sum_{d|n} \mu(d) g\left(\frac{n}{d}\right) = \sum_{d|n} \mu\left(\frac{n}{d}\right) g(d).$$

Proof.

$$\begin{aligned}\sum_{d|n} \mu(d) g\left(\frac{n}{d}\right) &= \sum_{d|n} \mu(d) \sum_{e|\frac{n}{d}} f(e) \\ &= \sum_{e|n} f(e) \underbrace{\sum_{d|\frac{n}{e}} \mu(d)}_{\nu(\frac{n}{e})} = f(n).\end{aligned}$$

□

Definition (Dirichlet series). The series

$$\sum_{n \geq 1} \frac{a_n}{n^s}$$

for s a (complex) variable is called a **Dirichlet series**.

This is absolutely convergent if $|a_n| \leq An^k$ for some k and $\operatorname{Re}(s) > k + 1$.

We can take products of Dirichlet series

$$\begin{aligned}\sum_{m \geq 1} \frac{a_m}{m^s} \sum_{n \geq 1} \frac{b_n}{n^s} &= \sum_{m, n \geq 1} \frac{a_m b_n}{(mn)^s} = \sum_{N \geq 1} \frac{c_N}{N^s} \quad N = mn \\ &\text{where } c_N = \sum_{d|N} a_d b_{\frac{N}{d}}\end{aligned}$$

Example.

$$\zeta(s-1)\zeta(s) = \left(\sum_{n \geq 1} \frac{n}{n^s}\right) \left(\sum_{n \geq 1} \frac{1}{n^s}\right) = \sum_{n \geq 1} \left(\sum_{d|n} d\right) \frac{1}{n^s} = \sum_{n \geq 1} \frac{\sigma(n)}{n^s}$$

where $\sigma(n) = \sum_{d|n} d$.

A Dirichlet series related to primes:

Theorem 5.7.

$$\begin{aligned}-\frac{\zeta'(s)}{\zeta(s)} &= \sum_{n \geq 1} \Lambda(n) n^{-s} = \frac{\log 2}{2^s} + \frac{\log 3}{3^s} + \frac{\log 2}{4^s} + \frac{\log 5}{5^s} + \frac{\log 7}{7^s} \\ \text{where } \Lambda(n) &= \begin{cases} \log p & n = p^k, p \text{ prime} \\ 0 & \text{otherwise} \end{cases} \quad \text{von Mangoldt function}\end{aligned}$$

Proof. Assume $s > 1$ is real (for complex s , same follows by analytic continuation).

$$\begin{aligned}-\frac{\zeta'(s)}{\zeta(s)} &= -\frac{d}{ds} \log \zeta(s) = -\frac{d}{ds} \sum_{p \text{ prime}} \log \left(\frac{1}{1-p^{-s}} \right) \quad (\text{by Euler product}) \\ &= \sum_{p \text{ prime}} \frac{(\log p) p^{-s}}{1-p^{-s}} \\ &= \sum_{p \text{ prime}} \log p (p^{-s} + p^{-2s} + \dots) \\ &= \sum_{n \geq 1} \Lambda(n) n^{-s}.\end{aligned}$$

(Exchange of $\frac{d}{ds}$ and \sum is justified by uniform convergence.) □

Define $\Psi(x) = \sum_{n \leq x} \Lambda(n)$. It is not hard to show that

$$\pi(x) \sim \frac{\Psi(x)}{\log x}$$

so the prime number theorem is equivalent to $\Psi(x) \sim x$. This is proved by integrating $\frac{x^{s+1}}{s(s+1)} \frac{\zeta'(s)}{\zeta(s)}$ over suitable contours (the non-vanishing of $\zeta(s)$ for $\operatorname{Re} s = 1$ enters here).

Theorem (Dirichlet's theorem). Let $a, N \in \mathbb{Z}$, $N > 1$, $(a, N) = 1$. There are infinitely many primes $\equiv a \pmod{N}$ (we have seen this already for $N = 4$, $a = 1$ and $a = -1$) i.e. the arithmetic progression $\{a, a + N, a + 2N, \dots\}$ contains ∞ many primes.

In fact, the proportion of primes in such an arithmetic progression is $\frac{1}{\varphi(N)}$.

Sketch. The proof involves Dirichlet series. Take this series

$$F_{a,N}(s) = \sum_{p \equiv a \pmod{N}} \frac{1}{p^s}$$

and show it has infinitely many terms. It is enough to show that the series diverges for $s = 1$. To get a handle on $F_{a,N}(s)$, write it as a linear combination of Dirichlet series of the form $\sum_p \frac{\chi(p)}{p^s}$, where $\chi(p)$ is a multiplicative function. □

Definition (Dirichlet character). A **Dirichlet character** mod N is a function $\chi : \mathbb{N} \rightarrow \mathbb{C}$ such that

- (i) $\chi(1) = 1$, $\chi(n) = 0$ if $(N, n) > 1$.
- (ii) $\chi(n + N) = \chi(n)$ periodic mod N .
- (iii) $\chi(mn) = \chi(m)\chi(n) \forall m, n$.

So χ is just a homomorphism $(\mathbb{Z}/N\mathbb{Z})^\times \rightarrow C^*$ extended to all n by $\chi(n) = 0$ if $(n, N) > 1$. An example is given by the Legendre/Jacobi symbol.

Fact. The function

$$f(n) = \begin{cases} 1 & \text{if } n \equiv a \pmod{N} \\ 0 & \text{if } n \not\equiv a \pmod{N} \end{cases}$$

for $(a, N) = 1$ is a linear combination of Dirichlet characters mod N .

Example. For $N = 3$, $\chi_p : \mathbb{N} \rightarrow \mathbb{C}$:

$$\begin{aligned} \chi_0(n) &= \begin{cases} 1 & \text{if } (n, 3) = 1 \\ 0 & \text{otherwise} \end{cases} \\ \chi_1(n) &= \begin{cases} 1 & n \equiv 1 \pmod{3} \\ -1 & n \equiv -1 \pmod{3} \\ 0 & (n, 3) \neq 1 \end{cases} \\ \frac{\chi_0(n) \pm \chi_1(n)}{2} &= \begin{cases} 1 & n \equiv \pm 1 \pmod{3} \\ 0 & \text{otherwise} \end{cases} \end{aligned}$$

Analytic facts about $L(\chi, s) = \sum_{n \geq 1} \chi(n) n^{-s}$ then can be used to prove Dirichlet's theorem.

5.1 Elementary methods for primes

Sieve of Eratosthenes: if you delete from $\{2, 3, \dots, X\}$ all multiples of primes $\leq \sqrt{X}$, left with $\{p \text{ primes} \mid \sqrt{X} \leq p \leq X\}$.

Proposition 5.8 (Legendre's formula). Let $x \geq 1$. $P = \prod_{p \leq \sqrt{X}} p$ product of all primes $\leq \sqrt{X}$. Then $\pi(X) - \pi(\sqrt{X}) + 1 = \#\{1 \leq n \leq X \mid (n, P) = 1\} = \sum_{d \mid P} \mu(d) \left\lfloor \frac{X}{d} \right\rfloor$.

Proof.

$$\{1 \leq n \leq X \mid (n, P) = 1\} = \{1\} \cup \{p \mid \sqrt{X} \leq p \leq X\}$$

hence first equality. Recall

$$\sum_{d \mid n} \mu(d) = \begin{cases} 1 & \text{if } n = 1 \\ 0 & \text{if } n > 1 \end{cases}$$

so

$$\begin{aligned} \#\{1 \leq n \leq X \mid (n, P) = 1\} &= \sum_{1 \leq n \leq X} \left[\sum_{d \mid (n, P)} \mu(d) \right] \\ &= \sum_{d \mid P} \mu(d) \sum_{\substack{1 \leq n \leq X \\ n \equiv 0 \pmod{d}}} 1 \\ &= \sum_{d \mid P} \mu(d) \left\lfloor \frac{X}{d} \right\rfloor. \end{aligned}$$

□

5.2 Divisibility of special numbers

Definition. Let $n \geq 1$, p prime. Let $\nu_p(n)$ = exponent of p in factorisation of n (p -adic valuation of n).

So $n = p^{\nu_p(n)} n_0$ where $(n_0, p) = 1$. In addition, $\nu_p(mn) = \nu_p(m) + \nu_p(n)$.

Example.

$$\binom{2n}{n} = N = \frac{2n(2n-1) \cdots (n+1)}{n(n-1) \cdots 1}$$

If $n < p \leq 2n$, p exactly divides numerator, and doesn't divide the denominator. $\nu_p(n) = 1 \forall p \in (n, 2n]$.

On the other hand $N \leq \sum_r \binom{2n}{r} = 2^{2n}$, so $\prod_{n < p \leq 2n} p \leq N \leq 2^{2n}$, giving an estimate and upper bound for $\pi(x)$. A similar argument also gives a lower bound if more careful.