1. Introduction

The topic of this lecture is arithmetic functions and Dirichlet series.

By way of introduction, consider Euclid’s proof that there exist infinitely many primes: If $p_1$ through $p_n$ are prime then the number

\[ q = 1 + \prod_{i=1}^{n} p_i \]

is not divisible by any $p_i$. According to this argument, the next prime after $p_1$ through $p_n$ could be as large as $q$. The overestimate is astronomical. Specifically, compute that for $n \geq 3$, because

\[ p_n \leq 1 + p_1 \cdots p_{n-1} \leq (7/6)p_1 \cdots p_{n-1}, \]

it follows that

\[
\begin{align*}
p_n &\leq (7/6)p_1 \cdots p_{n-1} \\
&\leq (7/6)^2(p_1 \cdots p_{n-2})^2 \\
&\leq (7/6)^4(p_1 \cdots p_{n-3})^4 \\
&\leq \cdots \\
&\leq (7/6)^{2^{n-3}}(p_1p_2)^{2^{n-3}} \\
&= 7^{2^{n-3}} \text{ (because } p_1p_2 = 6) \\
&< e^{2^{n-2}}.
\end{align*}
\]

So, for example, the tenth prime $p_{10}$ satisfies $p_{10} < 1.51143 \times 10^{11}$. Because in fact $p_{10} = 29$, we see how little Euclid’s argument tells us.

By contrast, Euler argued that

\[ \sum_{p \in P} \frac{1}{p} \text{ diverges,} \]

and in fact his argument shows more. The argument proceeds as follows. Define

\[ \zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \quad s > 1. \]

The basic estimate $\int_{1}^{\infty} x^{-s} \, dx < \zeta(s) < 1 + \int_{1}^{\infty} x^{-s} \, dx$ shows that as $s$ approaches 1 from the right, $\zeta(s)$ is asymptotic to $1/(s - 1)$ and so $\log \zeta(s)$ is asymptotic to $\log(1/(s - 1))$. (The logarithm is natural, of course.) Thus

\[ \lim_{s \to 1^+} \zeta(s) = \infty, \]

and also

\[ \lim_{s \to 1^+} \log \zeta(s) = \infty. \]
Now, summing over values of \( n \) with steadily more prime factors gives
\[
\sum_{n=2^{e_2}3^{e_3}} n^{-s} = \sum_{e_2=0}^{\infty} (2^{-s})^{e_2} \sum_{e_3=0}^{\infty} (3^{-s})^{e_3} = (1 - 2^{-s})^{-1}(1 - 3^{-s})^{-1},
\]
\[
\vdots
\]
\[
\sum_{n=2^{e_2}3^{e_3}p^s} n^{-s} = (1 - 2^{-s})^{-1} \cdots (1 - p^{-s})^{-1}.
\]
And so, being very casual about convergence, it is essentially a restatement of unique factorization that the zeta function also has an infinite product expression,
\[
\zeta(s) = \sum_{n \in \mathbb{Z}^+} n^{-s} = \prod_{p \in \mathcal{P}} (1 - p^{-s})^{-1}.
\]
From the general series
\[
\log(1 - X)^{-1} = \sum_{n=1}^{\infty} X^n / n, \quad |X| < 1,
\]
we have (again being very casual about convergence)
\[
\log \zeta(s) = \log \prod_{p \in \mathcal{P}} (1 - p^{-s})^{-1} = \sum_{p \in \mathcal{P}} \log(1 - p^{-s})^{-1} = \sum_{p \in \mathcal{P}} \sum_{n=1}^{\infty} \frac{p^{-ns}}{n}
\]
\[
= \sum_{p \in \mathcal{P}} p^{-s} + \sum_{p \in \mathcal{P}} \sum_{n=2}^{\infty} \frac{p^{-ns}}{n}.
\]
From above, we know that \( \lim_{s \to 1^+} \log \zeta(s) = \infty \), while one term at the end of the previous display is \( \sum_{p \in \mathcal{P}} p^{-s} \), which we want to understand as \( s \) tends to 1. As for the other term,
\[
\sum_{p \in \mathcal{P}} \frac{p^{-ns}}{n} < \sum_{p \in \mathcal{P}} p^{-n} = \sum_{p \in \mathcal{P}} \frac{1}{p^2(1 - p^{-1})} = \sum_{p \in \mathcal{P}} \frac{1}{p(p - 1)} < \sum_{n=2}^{\infty} \frac{1}{n(n - 1)} = 1.
\]
This shows that the quantity that we want to understand is close to a quantity that we do understand,
\[
\left| \sum_{p \in \mathcal{P}} p^{-s} - \log \zeta(s) \right| < 1.
\]
And so
\[
\lim_{s \to 1^+} \sum_{p \in \mathcal{P}} p^{-s} = \infty,
\]
and more specifically,
\[
\lim_{s \to 1^+} \frac{\sum_p p^{-s}}{\log \zeta(s)} = 1.
\]
Thus the sum of prime reciprocals grows asymptotically as the logarithm of the harmonic series. Recall that the partial sums of the harmonic series themselves
grow logarithmically, so that the sum of prime reciprocals grows very slowly. Euler’s result is much stronger than Euclid’s, and it illustrates analytic number theory.

2. Dirichlet Series

The zeta function is a particular instance of a Dirichlet series.

Definition 2.1. An arithmetic function is a complex-valued function of positive integers,

\[ f : \mathbb{Z}^+ \rightarrow \mathbb{C}. \]

Its associated Dirichlet series is a formal series that depends on a parameter \( s \),

\[ F(s) = \sum_{n=1}^{\infty} \frac{f(n)}{n^s}. \]

Using Dirichlet series to discuss arithmetic functions is not really necessary, but I think that the Dirichlet series clarify what is going on.

Let \( F \) and \( G \) be the Dirichlet series associated to the arithmetic functions \( f \) and \( g \). Compute that their product is

\[ F(s)G(s) = \sum_{d} \frac{f(d)}{d^s} \sum_{e} \frac{g(e)}{e^s} = \sum_{d,e} \frac{f(d)g(e)}{(de)^s} = \sum_{n} \frac{\sum_{de=n} f(d)g(e)}{n^s}. \]

Thus, if we define the convolution (or Dirichlet product) of \( f \) and \( g \) to be

\[ f * g : \mathbb{Z}^+ \rightarrow \mathbb{C}, \quad (f * g)(n) = \sum_{de=n} f(d)g(e), \]

then the corresponding product of Dirichlet series is

\[ F(s)G(s) = \sum_{n=1}^{\infty} \frac{(f * g)(n)}{n^s}. \]

That is, for arithmetic functions \( f, g, \) and \( h \), and for Dirichlet series \( F, G, \) and \( H \),

\[ h = f * g \iff H = FG. \]

Because Dirichlet series with nonzero leading term are invertible (\( \sum a_n n^{-s} \) has inverse \( \sum b_n n^{-s} \) where \( b_1 = a_1^{-1} \) and \( b_n = -a_1^{-1} \sum_{d|n} a_d b_{n/d} \) for \( n > 1 \)), it follows from the boxed equivalence that the arithmetic functions that do not vanish at 1 form a group under convolution.

3. Examples, Möbius Inversion

With the boxed equivalence in mind, we create a small catalogue of arithmetic functions and their Dirichlet series.

- The identity arithmetic function is

\[ \mathfrak{i}(n) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{otherwise}. \end{cases} \]

The corresponding Dirichlet series is simply

\[ \mathfrak{I}(s) = 1. \]

Because \( \mathfrak{I}(s) \) is the multiplicative identity, \( \mathfrak{i} \) is the convolution identity.
• The \textbf{unit} arithmetic function is
\[ u(n) = 1 \text{ for all } n. \]
(Ireland and Rosen call this function \( I \).) The corresponding Dirichlet series is the zeta function,
\[ U(s) = \zeta(s). \]

• The reciprocal of the zeta function is the Dirichlet series
\[ \zeta(s)^{-1} = \prod_p (1 - p^{-s}) = 1 - \sum_p p^{-s} + \sum_{p,q} (pq)^{-s} - \sum_{p,q,r} (pqr)^{-s} + \cdots. \]

The corresponding arithmetic function is the \textbf{Möbius function},
\[ \mu(n) = \begin{cases} (-1)^k & \text{if } n = p_1 \cdots p_k \text{ (distinct primes)}, \\ 0 & \text{if } n \text{ is divisible by a nontrivial square}. \end{cases} \]

The first case in the previous formula says in particular that \( \mu(1) = 1 \). Because \( \zeta(s) \) and \( \zeta(s)^{-1} \) are Dirichlet series inverses, \( u \) and \( \mu \) are convolution inverses,
\[ \mu * u = i. \]

That is, because \( u \) always returns the value 1,
\[ \sum_{d|n} \mu(d) = \begin{cases} 1 & \text{if } n = 1, \\ 0 & \text{if } n > 1. \end{cases} \]

The reader may enjoy verifying this directly, without reference to Dirichlet series.

More generally, for any arithmetic functions \( f \) and \( g \), because \( u \) and \( \mu \) are inverses, we have the \textbf{Möbius Inversion Principle},
\[ g = f * u \iff f = g * \mu. \]

Usually this equivalence is written as the \textbf{Möbius Inversion Formula},
\[ g(n) = \sum_{d|n} f(d) \iff f(n) = \sum_{d|n} g(d)\mu(n/d). \]

Often the idea is that \( f \) is interesting but we don’t immediately have a formula for it, while \( g = f * u \) is easy to compute, so that Möbius inversion gives a formula for \( f \). For example, consider two arithmetic functions,
\[ f(n) = \text{sum of the primitive } n\text{th roots of } 1, \]
\[ g(n) = \text{sum of all } n\text{th roots of } 1. \]

Here \( f \) is interesting while the finite geometric sum formula shows that \( g \) is simply the convolution identity function \( i \). The relation \( f * u = g = i \) says that \( f \) is the convolution inverse of \( u \), the Möbius function. That is,
\[ \text{sum of the primitive } n\text{th roots of } 1 = \mu(n). \]

The reader can enjoy verifying this for \( n = 1, 2, 3, \ldots \) through the first value of \( n \) where it is not easy.
4. The Euler Totient Function

The **Euler totient function** is an arithmetic function,

\[ \phi : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+, \quad \phi(n) = \# \{ x \in \{0, \ldots, n-1\} : \text{gcd}(x, n) = 1 \} = \#(\mathbb{Z}/n\mathbb{Z})^\times. \]

Thus \( \phi(1) = 1 \) and \( \phi(p) = p - 1 \) for \( p \) prime.

Now we set up Möbius inversion by counting that

\[ n = \sum_{d \mid n} \phi(d) \quad \text{for all} \quad n \in \mathbb{Z}^+. \]

Indeed, noting that \( (k(n/d), n) = (n/d)(k, d) \) for the second equality to follow,

\[ \{0, \ldots, n-1\} = \bigcup_{d \mid n} \{ x \in \{0, \ldots, n-1\} : (x, n) = n/d \} = \bigcup_{d \mid n} \{ k(n/d) : 0 \leq k < d, (k, d) = 1 \}, \]

and the desired counting formula follows immediately by definition of the totient function. (For example, if \( n = 20 \) then the disjoint union is

\[ \{0\} \sqcup \{10\} \sqcup \{5, 15\} \sqcup \{4, 8, 12, 16\} \]
\[ \sqcup \{2, 6, 14, 18\} \sqcup \{1, 3, 7, 9, 11, 13, 17, 19\}, \]

with \( \{2, 6, 14, 18\} \) being the multiples of 20/10 by factors coprime to 10, and so on.) Consequently, Möbius inversion gives

\[ \phi(n) = n \sum_{d \mid n} \mu(d) \frac{n}{d}. \]

That is,

\[ \phi(n) = n \sum_{d \mid n} \frac{\mu(d)}{d} = n \left( 1 - \sum_{p \mid n} \frac{1}{p} + \sum_{p, q \mid n} \frac{1}{pq} - \cdots \right). \]

The alternating sum-of-sums factors to give the formula for the totient function,

\[ \boxed{\phi(n) = n \prod_{p \mid n} \left( 1 - \frac{1}{p} \right).} \]

Alternatively one can obtain the formula \( \phi(n) = \sum_{d \mid n} \mu(d) \frac{n}{d} \) by inclusion–exclusion, leading to the boxed formula for \( \phi(n) \) and also giving \( n = \sum_{d \mid n} \phi(d) \) for all \( n \in \mathbb{Z}^+ \) by Möbius inversion. In functional language, introducing the function \( \text{id}(n) = n \), which is neither the convolution identity function nor the unit function from earlier, we have shown that \( \text{id} = \phi \ast u \), so that \( \phi = \text{id} \ast \mu \), but alternatively one can proceed from \( \phi = \text{id} \ast \mu \) to \( \text{id} = \phi \ast u \).

Some consequences of the totient function formula are

\[ \phi(p^e) = p^e - p^{e-1} \text{ for } e \geq 1 \text{ (this is even if } p > 2 \text{ or } e \geq 1), \]
\[ \phi(mn) = \phi(m)\phi(n) \text{ if } (m, n) = 1, \]
\[ a \mid b \implies \phi(a) \mid \phi(b), \]
\[ n \geq 3 \implies \phi(n) \text{ is even}, \]
\[ n = p_1^{e_1} \cdots p_k^{e_k} \implies 2^k \mid \phi(n) \text{ if all } p_i > 2 \text{ or } 4 \mid n. \]
5. Two More Arithmetic Functions

The **kth power function** is
\[ \pi_k : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+, \quad \pi_k(n) = n^k. \]

The function \( \text{id}(n) = n \) from earlier is \( \pi_1 \). The **sum of divisor kth powers function** is
\[ \sigma_k : \mathbb{Z}^+ \rightarrow \mathbb{Z}^+, \quad \sigma_k(n) = \sum_{d|n} d^k. \]
Especially, \( \sigma_0 \) counts the divisors of \( n \) and \( \sigma_1 \) sums them.

The Dirichlet series of \( \pi_k \) is
\[ \Pi_k(s) = \zeta(s-k), \]
whose multiplicative inverse is
\[ \zeta^{-1}(s-k) = \sum_{n \geq 1} \mu(n) n^{s-k} = \sum_{n \geq 1} \frac{(\pi_k \mu)(n)}{n^s}, \]
and so the convolution inverse of \( \pi_k \) is \( \pi_k \mu \). Because \( \sigma_k = \pi_k \ast u \) is a convolution, its convolution inverse is the convolution of the individual convolution inverses, \( \pi_k \mu \ast \mu \). Also, the Dirichlet series \( \Sigma_k(s) \) of \( \sigma_k \) is the product of the corresponding Dirichlet series,
\[ \Sigma_k(s) = \zeta(s-k) \zeta(s), \]
as can be checked directly for practice. Möbius inversion of the relation \( \sigma_k = \pi_k \ast u \) gives \( \pi_k = \sigma_k \ast \mu \), i.e.,
\[ n^k = \sum_{d|n} \sigma_k(d) \mu(n/d), \quad n \geq 1. \]

Altogether, we now have the convolution identity function \( i \) and the convolution inverse pairs \( (u, \mu), (\pi_k, \pi_k \mu), \) and \( (\sigma_k, \pi_k \mu \ast \mu) \), with \( \sigma_k = \pi_k \ast u \) by definition and \( \pi_k = \sigma_k \ast \mu \) in consequence, and Euler’s totient function is \( \phi = \pi_1 \ast \mu \).

We mention the not-at-all-obvious fact that, letting \( r(n, 4) \) denote the number of representations of \( n \) as a sum of 4 squares,
\[ r(n, 4) = 8 \sigma_1(n) \quad \text{if } 4 \nmid n \]
For example, one can check directly that \( r(3, 4) = 32 \) and also \( 8 \sigma_1(3) = 32 \), but \( r(4, 4) = 24 \) while \( 8 \sigma_1(4) = 56 \).

6. Multiplicative and Totally Multiplicative Functions

**Definition 6.1.** Let \( f : \mathbb{Z}^+ \rightarrow \mathbb{C} \) be an arithmetic function. Then \( f \) is **multiplicative** if
\[ f(nm) = f(n)f(m) \quad \text{for all } n \text{ and } m \text{ such that } (n,m) = 1, \]
and \( f \) is **totally multiplicative** if
\[ f(nm) = f(n)f(m) \quad \text{for all } n \text{ and } m. \]

Thus:
For nonzero multiplicative functions, \( f(1) = 1 \) and \( f\left( \prod_p p^{r_p} \right) = \prod_p f(p^{r_p}) \).
And:

*For totally multiplicative functions, furthermore* $f(\prod p^{r_p}) = \prod f(p)^{r_p}.$

The corresponding Dirichlet series conditions are

\[ f \text{ is multiplicative } \iff F(s) = \prod_p \sum_{e=0}^\infty \frac{f(p^e)}{p^{es}} \]

and

\[ f \text{ is totally multiplicative } \iff F(s) = \prod_p (1 - f(p)p^{-s})^{-1}. \]

The first equivalence follows from the formal identity that for any arithmetic function $f$,

\[ \prod_p \sum_{e=0}^\infty \frac{f(p^e)}{p^{es}} = \sum_{n=1}^\infty \frac{\prod_{p^e\mid n} f(p^e)}{n^s}, \]

because the right side is the Dirichlet series of $f$ exactly when $f$ is multiplicative. Here the notation $p^e\mid n$ means that $p^e$ is the highest power of $p$ that divides $n$.

The second equivalence follows from the first and from the geometric series formula.

Some further facts that are straightforward to check, either directly or by using Dirichlet series, are

- If $f$ and $g$ are multiplicative then so is $f * g$.
- If $f$ is multiplicative and nonzero then so is the convolution inverse of $f$.
- If $f$ is totally multiplicative and nonzero then its convolution inverse is $f\mu$.

We have seen the third bullet for $f = \pi_k$.

To establish the first bullet using Dirichlet series, compute that because $f$ and $g$ are multiplicative, their Dirichlet series are

\[ F(s) = \prod_p \sum_{e=0}^\infty \frac{f(p^e)}{p^{es}} \quad \text{and} \quad G(s) = \prod_p \sum_{e=0}^\infty \frac{g(p^e)}{p^{es}}, \]

and then it follows quickly that

\[ F(s)G(s) = \prod_p \sum_{e=0}^\infty \frac{(f*g)(p^e)}{p^{es}}, \]

so that $f * g$ is again multiplicative.

The second bullet says that if $f$ is multiplicative and nonzero then so is the convolution inverse of $f$. To establish this using Dirichlet series, let $g$ be the convolution inverse of $f$, and consider the Dirichlet series

\[ H(s) = \prod_p \sum_{e=0}^\infty \frac{g(p^e)}{p^{es}}. \]

As above, $F(s)H(s)$ multiplies out to $\prod_p \sum_{e=0}^\infty (f*g)(p^e)/p^{es}$, and because $g$ is the convolution inverse of $f$, this is 1. That is, $H(s)$ inverts $F(s)$, showing that $H(s)$ is the Dirichlet series of $g$, and now the form of $H$ shows that $g$ is multiplicative.

The third bullet says that if $f$ is totally multiplicative and nonzero then its convolution inverse is $f\mu$. To establish this using Dirichlet series, we need to show that
the inverse $F(s)^{-1}$ of the Dirichlet series of $f$ is the Dirichlet series $\sum_n (f\mu)(n)/n^s$ of $f\mu$. Compute that indeed because $F(s) = \prod_p (1 - f(p)p^{-s})^{-1}$,

$$F(s)^{-1} = \prod_p (1 - f(p)p^{-s})$$

$$= 1 - \sum_p f(p)p^{-s} + \sum_{p,q} f(q)p^{-s} - \sum_{p,q,r} f(qr)p^{-s} + \cdots$$

$$= \sum_{n=1}^{\infty} \frac{f(n)\mu(n)}{n^s},$$

as desired. Also, we can establish the third bullet very quickly without Dirichlet series, by recalling from section 3 that

$$\sum_{d \mid n} \mu(d) = 1 \text{ for } n = 1 \text{ and is 0 for } n > 1,$$

and computing that

$$(f \ast f\mu)(n) = \sum_{d \mid n} f(n/d)f(d)\mu(d) = f(n)\sum_{d \mid n} \mu(d) = i(n).$$

As an example of the first bullet, the observation from earlier that $\sigma_k = \pi_k \ast u$ now says that $\sigma_k$ is multiplicative because $\pi_k$ and $u$ are, and indeed the verification of the Dirichlet series $\Sigma_k(s) = \zeta(s-k)\zeta(s)$, earlier left as an exercise, shows that $\sigma_k$ is determined completely by the values $\sigma_k(p^e)$. By the finite geometric sum formula, these are

$$\sigma_k(p^e) = \frac{p^{(e+1)k} - 1}{p^k - 1}.$$  

For another example, because Euler’s totient function is the convolution $\phi = \pi_1 \ast \mu$, where $\pi_1(n) = n$ and $\mu$ is the Möbius function, its Dirichlet series is the corresponding product

$$\Phi(s) = \zeta(s-1)\zeta(s)^{-1} = \prod_p (1 - p^{1-s})^{-1}(1 - p^{-s}).$$

Here the Euler factor $1 - p^{-s}$ of $\zeta(s)^{-1}$ is $\sum_{c \geq 0} \mu(p^c)p^{-cs}$, the general Euler factor formula for a multiplicative function specialized to $\mu$. Because $\pi_1$ and $\mu$ are multiplicative, so is $\phi$, and so its Dirichlet series is

$$\Phi(s) = \prod_p \sum_{c \geq 0} \frac{\phi(p^c)}{p^{cs}}.$$  

Match Euler factors to show that for every prime $p$,

$$\sum_{c \geq 0} \frac{\phi(p^c)}{p^{cs}} = (1 - p^{1-s})^{-1}(1 - p^{-s}).$$

Of course this can be verified directly, noting that $\phi(p^e)$ is 1 for $e = 0$ and is $p^e(1 - p^{-1})$ for $e \geq 1$.

7. Abelian Group Möbius Inversion and Cyclotomic Polynomials

The arithmetic functions in this writeup have been complex-valued, but more generally we may take arithmetic functions from the positive integers to any abelian group, and Möbius inversion still holds.

To see this, note that any abelian group $G$ carries not only addition but also scalar multiplication by $\mathbb{Z}$; e.g., $3g$ means $g + g + g$ and $(-5)g$ means $-(5g)$, taking
the latter inverse in $G$. Now, for any functions $f : \mathbb{Z}^+ \rightarrow G$ and $v : \mathbb{Z}^+ \rightarrow \mathbb{Z}$, define

$$f \star v : \mathbb{Z}^+ \rightarrow G, \quad (f \star v)(n) = \sum_{d \mid n} v(n/d)f(d) \quad \text{(adding and scaling in $G$)}.$$ 

If also $w : \mathbb{Z}^+ \rightarrow \mathbb{Z}$ is integer-valued on $\mathbb{Z}^+$ then for any $n \in \mathbb{Z}^+$,

$$(f \star v) \star w(n) = \sum_{d \mid n} (f \star v)(n/d)w(d) = \sum_{d \mid n} \sum_{c \mid n/d} f(n/(cd))v(c)w(d) = \sum_{e \mid n} \sum_{d \mid e} f(n/e)v(e/d)w(d) = \sum_{e \mid n} f(n/e)(v \star w)(e) = (f \star (v \star w))(n).$$

Thus associativity still holds, $(f \star v) \star w = f \star (v \star w)$, with $v \star w$ the usual convolution of integer-valued functions. Especially, $(f \star \mu) \star u = (f \star u) \star \mu = f$ by associativity and because $\mu \star u = u \star \mu = \mathbb{1}$ is still the convolution identity. Abelian group Möbius inversion follows: For functions $f, g : \mathbb{Z}^+ \rightarrow G$,

$$g = f \star u \iff f = g \star \mu.$$ 

The **cyclotomic polynomials** $\Phi_n(X)$ for $n \geq 1$ are defined by the condition

$$X^n - 1 = \prod_{d \mid n} \Phi_d(X) \quad \text{for } n \geq 1, \quad \text{each } \Phi_d \text{ monic.}$$ 

For example, $\Phi_1(X) = X - 1$ and $X^p - 1 = (X - 1)\Phi_p(X)$ for $p$ prime, so that $\Phi_p(X) = X^{p-1} + X^{p-2} + \cdots + X + 1$. We state some facts about the cyclotomic polynomials without proof.

- The cyclotomic polynomials have integer coefficients.
- The degree of $\Phi_n$ is $\phi(n)$, and the complex roots of $\Phi_n$ are the primitive $n$th complex roots of unity, $e^{2\pi i k/n}$ where $0 \leq k < n$ and $\gcd(k, n) = 1$.
- The cyclotomic polynomials are irreducible as polynomials over $\mathbb{Q}$.

Now, let our abelian group $G$ be $\mathbb{Q}(X)^\times$, the multiplicative group of nonzero quotients of polynomials having rational coefficients. The “addition” operation of this group is multiplication, and the “scaling” operation is exponentiation,

$$r(X) \oplus \tilde{r}(X) = r(X)\tilde{r}(X), \quad c \odot r(X) = r(X)^c \text{ for } c \in \mathbb{Z}.$$ 

In this context, the condition $X^n - 1 = \prod_{d \mid n} \Phi_d(X)$ for $n \geq 1$ gives by Möbius inversion in $G$

$$\Phi_n(X) = \prod_{d \mid n} (X^d - 1)^{\mu(n/d)}, \quad n \geq 1.$$ 

For example,

$$\Phi_{pq}(X) = \frac{(X^{pq} - 1)(X - 1)}{(X^p - 1)(X^q - 1)}, \quad p, q \text{ distinct primes,}$$

and this is a monic polynomial with integer coefficients.
8. A Comment on Ireland and Rosen 2.4

Define a prime-counting function,
\[ \pi : \mathbb{R} \rightarrow \mathbb{R}, \quad \pi(x) = \# \{ p \in \mathcal{P} : p \leq x \}. \]

The **Prime Number Theorem** says that
\[ \lim_{x \to \infty} \frac{\pi(x)}{x/\log x} = 1. \]

Section 2.4 of Ireland and Rosen shows that easy analytic estimates give for some constants \( c_1 \) and \( c_2 \),
\[ c_1 x/\log x < \pi(x) < c_2 x/\log x. \]

The Prime Number Theorem was first proved in 1899 by Hadamard and (independently) Poussin. Elementary proofs were given in the 1940s by Erdős and Selberg. For students with background in complex analysis, see the writeup for this course that gives a short proof of the Prime Number Theorem.