1. Theory

Recall that

Definition 1.1 (Dirichlet Series)**.** Let f be an arithmetic function. Then the corresponding Dirichlet series is defined, for $s \in \mathbb{C}$, by

$$D_f(s) = \sum_{n=1}^{\infty} \frac{f(n)}{n^s}.$$

Lemma 1.2.

$$0 \leq 3 + 4\cos\theta + \cos 2\theta = 2\left(1+\cos\theta\right)^2$$

Lemma 1.3. *Let $\sigma > 1$. Then*

$$\Re\left(-3\frac{\zeta'}{\zeta}(\sigma) - 4\frac{\zeta'}{\zeta}(\sigma+it) - \frac{\zeta'}{\zeta}(\sigma+2it)\right) \geq 0$$

For the proof of the lemma, one shows that

$$\Re\left(\frac{1}{n^s}\right) = \frac{1}{n^\sigma}\cos\left(t\log n\right), \quad s = \sigma + it \tag{A_1}$$

Proof.

$$\Re\left(-\frac{\zeta'}{\zeta}(s)\right) = \Re\sum_{n=1}^{\infty}\frac{\Lambda(n)}{n^s} = \sum_{n=1}^{\infty}\frac{\Lambda(n)}{n^\sigma}\cos\left(t\log n\right).$$

Hence

$$\Re\left(-3\frac{\zeta'}{\zeta}(\sigma) - 4\frac{\zeta'}{\zeta}(\sigma+it) - \frac{\zeta'}{\zeta}(\sigma+2it)\right) = \sum_{n=1}^{\infty}\frac{\Lambda(n)}{n^\sigma}\left[3 + 4\cos\left(t\log n\right) + \cos\left(2t\log n\right)\right] \overset{(1.2)}{\geq} 0$$

$\square$

2. Week 1

Exercise 2.1 (E1.1. Abel summation)**.** Let $\{a_n\}_{n\in\mathbb{N}} \subset \mathbb{C}$ and $f\colon [1,x] \to \mathbb{C}$ be C^1. Define $A(t) = \sum_{n\leq t} a_n$. Then for $x > 1$, we have

$$\sum_{n\leq x} a_n f(n) = A(x)f(x) - \int_1^x A(t)f'(t)dt.$$

3. Week 2

Let $\psi(x) := \sum_{n\leq x} \Lambda(n)$.

Exercise 3.1 (E2.6)**.** Show that

$$\theta(x) := \sum_{p\leq x} \log p = \psi(x) + O\left(x^{\frac{1}{2}} \log^2 x\right)$$

Proof.

$$\begin{aligned}\psi(x) - \sum_{p\leq x} \log p &= \sum_{\substack{n\leq x\\ n=p^k}} \log p - \sum_{p\leq x} \log p \\ &= \sum_{\substack{p^k\leq x\\ k\geq 2}} \log p\end{aligned}$$

For each prime p, we have some maximal N such that $p^N \leq x$ and $N = \left[\frac{\log x}{\log p}\right]$. If $p^k \leq x$ for $k \geq 2$ then $p \leq \sqrt{x}$ and if $p \leq \sqrt{x}$ then $p^2 \leq x$. So

$$\begin{aligned}\sum_{\substack{p^k\leq x\\ k\geq 2}} \log p &= \sum_{p\leq\sqrt{x}} \log p \left(\sum_{2\leq n\leq \frac{\log x}{\log p}} 1 \right) \\ &\leq \sum_{p\leq\sqrt{x}} \log p \frac{\log x}{\log p} \\ &\leq \sqrt{x}\log x.\end{aligned}$$

We have

$$\psi(x) = \sum_{n=1}^{\infty} \theta\left(x^{\frac{1}{n}}\right)$$

□

Exercise 3.2 (E2.7)**.** Show that

$$\pi(x) = \frac{\psi(x)}{\log x} + \int_2^x \frac{\psi(t)}{t\log^2 t}dt + O\left(x^{\frac{1}{2}}\log x\right).$$

Proof. By Abel summation, we first find that

$$\theta(x) := \sum_{p\leq x} \log p = \pi(x)\log x - \int_2^x \frac{\pi(t)}{t}dt$$

and from the previous exercise, we now find that

$$\pi(x) = \frac{\psi(x)}{\log x} + \frac{1}{\log x}\int_2^x \frac{\pi(t)}{t}dt + O\left(x^{\frac{1}{2}}\log x\right)$$

The result follows if we can show that
$$\frac{1}{\log x}\int_2^x \frac{\pi(t)}{t}dt = \int_2^x \frac{\psi(t)}{t\log^2 t}dt + O\left(x^{\frac{1}{2}}\log x\right).$$
Now $\psi(t) \leq \pi(t)\log t$, so
$$\begin{aligned}\left|\int_2^x \frac{\psi(t)}{t\log^2 t} - \frac{\pi(t)}{t\log x}dt\right| &\leq \left|\int_2^x \frac{\pi(t)}{t\log t} - \frac{\pi(t)}{t\log x}dt\right| \\ &= \left|\int_2^x \frac{\pi(t)}{t}\frac{\log\left(\frac{x}{t}\right)}{\log x\log t}dt\right|\end{aligned}$$

□

4. Week 3

Exercise 4.1 (E3.1)**.** Let $m \geq 0$. Show that
$$\sum_{n\leq x}\log^m n = x\log^m x + O\left(x\log^{m-1}x\right).$$

Proof. Let $a_n = 1$ for all n. Then $A(x) = \lfloor x\rfloor$, so
$$\begin{aligned}\sum_{n\leq x}\log^m n &= \lfloor x\rfloor\log^m x - \int_1^x m\lfloor t\rfloor\frac{1}{t}\log^{m-1}tdt \\ &= x\log^m x - (x-\lfloor x\rfloor)\log^m x - m\int_1^x\frac{\lfloor t\rfloor}{t}\log^{m-1}(t)dt\end{aligned}$$
Thus we must show that
$$\left|(x-\lfloor x\rfloor)\log^m x + m\int_1^x\frac{\lfloor t\rfloor}{t}\log^{m-1}(t)dt\right| \leq Cx\log^{m-1}x$$
But $\frac{\lfloor t\rfloor}{t}\log^{m-1}(t) \leq \log^{m-1}(x)$ giving that the right hand term is $O\left(x\log^{m-1}x\right)$. For the left hand term, it suffices to show that $(x-\lfloor x\rfloor)\log x \leq x$, but this is clear since $x - \lfloor x\rfloor \leq 1$ and $\log x \leq x$. □

Exercise 4.2 (E3.2)**.** Let $d(n) = \sum_{d|n}1$. Show $d(n) \leq 2\sqrt{n}$. If we consider the set $D \subset \mathbb{N}$ of positive divisors of n, then we can define a bijection $D \to D$ by $k \mapsto \frac{n}{k}$. Suppose now that $d(n) > 2\sqrt{n}$. Suppose $d \mid n$ and $d \geq \sqrt{n}$. Then since $\frac{d}{n}\cdot d = n$, we must have $\frac{d}{n} \leq \sqrt{n}$. This implies that under this bijection, either the source or target lies in $\{1,\ldots,\lfloor\sqrt{n}\rfloor\}$. Hence $d(n) = |D| \leq 2\left|\{1,\ldots,\lfloor\sqrt{n}\rfloor\}\right| \leq 2\sqrt{n}$.

Exercise 4.3 (E3.3)**.** Prove that for every $\varepsilon > 0$, there exists a constant C_ε such that $d(n) \leq C_\varepsilon n^\varepsilon$.
Hint:

(1) Show that $d(n_1n_2) = d(n_1)d(n_2)$ if $(n_1,n_2) = 1$.
(2) Show that
$$\frac{d(n)}{n^\varepsilon} = \prod_{p^\alpha||n}\frac{\alpha+1}{p^{\alpha\varepsilon}}$$
where $p^\alpha \mid\mid n$ means that α is a positive integer, $p^\alpha \mid n$ and $p^{\alpha+1} \not| n$.
(3) Split the product in 2. Into the product over those primes $p < 2^{\frac{1}{\varepsilon}}$ and the product over the rest. Show that the second product is bounded by 1.

(4) Show that the factors in the first product are less than $1 + (\varepsilon \log 2)^{-1}$.

Proof. We follow the hint:
(1) Suppose $(n_1, n_2) = 1$. Let D be the set of divisors of $n_1 n_2$, D_1 the set of divisors of n_1 and D_2 the set of divisors of n_2. Suppose $d_1 \in D_1, d_2 \in D_2$. Then $d_1 a = n_1, d_2 b = n_2$, so $d_1 d_2 ab = n_1 n_2$, hence $d_1 d_2 \in D$. We thus obtain a map $D_1 \times D_2 \to D$ sending $(d_1, d_2) \mapsto d_1 d_2$. We claim this is a bijection. Suppose $d_1 d_2 = d_1' d_2'$. If $d_1 \mid d_2'$, then $d_1 = 1$, in which case, $d_1' = 1$, and thus $d_2 = d_2'$. Suppose thus that $d_1 \neq 1$, so $d_1 \not| d_2'$. Then since $(d_1', d_2') = 1$, we have $d_1 \mid d_1'$. Similarly, $d_1' \mid d_1$. So $d_1 = d_1'$. And again $d_2 = d_2'$. This gives injectivity. For surjectivity, if $d \mid n_1 n_2$, then consider $d_1 := \frac{d}{(n_2, d)}$ and $d_2 := \frac{d}{(n_1, d)}$. Then $d_1 d_2 = d$ and $d_1 \in D_1, d_2 \in D_2$.
(2) Clearly, $n^\varepsilon = \prod_{p^\alpha || n} p^{\alpha\varepsilon}$. It thus suffices to show that $\prod_{p^\alpha || n} (\alpha + 1) = d(n)$. But if we factorize n as $n = p_1^{\alpha_1} \cdots p_m^{\alpha_m}$, then it is clear that the divisors corresponds precisely to tuples $(a_1, \ldots, a_m)$ with $0 \leq a_i \leq \alpha_i$. There are precisely $\alpha_1 + 1$ choices for each a_i, giving $(\alpha_1 + 1) \cdots (\alpha_m + 1) = d(n)$ which indeed is what we wanted to show.
(3) We can split the product as

$$\frac{d(n)}{n^\varepsilon} = \underbrace{\prod_{\substack{p^\alpha || n \\ p < 2^{\frac{1}{\varepsilon}}}} \frac{\alpha + 1}{p^{\alpha\varepsilon}}}_{A} \cdot \underbrace{\prod_{\substack{p^\alpha || n \\ p \geq 2^{\frac{1}{\varepsilon}}}} \frac{\alpha + 1}{p^{\alpha\varepsilon}}}_{B}$$

We claim that $B \leq 1$. Indeed

$$\prod_{\substack{p^\alpha || n \\ p \geq 2^{\frac{1}{\varepsilon}}}} \frac{\alpha + 1}{p^{\alpha\varepsilon}} \leq \prod_{\substack{p^\alpha || n \\ p \geq 2^{\frac{1}{\varepsilon}}}} \underbrace{\frac{\alpha + 1}{2^\alpha}}_{\leq 1} \leq 1$$

(4) For the factors in the first product, we have $\alpha = \left\lfloor \frac{\log n}{\log p} \right\rfloor$ and $\log p < \frac{1}{\varepsilon} \log 2$, and $\alpha \leq \frac{\log n}{\log p}$, so $\frac{\log p}{\log n} \leq \frac{1}{\alpha}$

$$\varepsilon^2 \log p < \varepsilon \log 2$$

$$\frac{\alpha + 1}{p^{\alpha\varepsilon}} \leq \frac{\log n + \log p}{p^{\alpha\varepsilon} \log p} \leq 1 + \frac{1}{\varepsilon \log 2} = \frac{\varepsilon \log 2 + 1}{\varepsilon \log 2}$$

What we want to bound is

$$\prod_{\substack{p^\alpha || n \\ p < 2^{\frac{1}{\varepsilon}}}} \frac{\alpha + 1}{p^{\alpha\varepsilon}}$$

Note here that p is bounded and as α increases, we should expect the denominator to take over. However, while α is small, we might have some large terms since p^ε might be large. All our terms are however bounded by p^ε by the looks of it? Then we would get that the product is the product is bounded by $\prod_{p < 2^{\frac{1}{\varepsilon}}} \frac{\log n}{\log p} \frac{1}{p^\varepsilon}$

$\square$

Exercise 4.4 (E3.4)**.** Show that

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

is absolutely convergent in $\Re(s) > 1$.

Proof. Fix some $s = \sigma + it \in \mathbb{C}$ with $\sigma > 1$. Then choosing an $\varepsilon > 0$ with $1+\varepsilon < \sigma$, we have that $d(n) \leq C_\varepsilon n^\varepsilon$, so

$$\sum \left| \frac{d(n)}{n^s} \right| \leq \sum C_\varepsilon \frac{n^\varepsilon}{n^\sigma} \leq C_\varepsilon \sum \frac{1}{n^{\sigma-\varepsilon}} < \infty.$$

$\square$

Exercise 4.5 (E3.5)**.** Show that the average order of $d(n)$ is $\log n$, i.e., that

$$\frac{1}{x} \sum_{n \leq x} d(n) = \log x + o(\log x).$$

Hint: Show that

$$\sum_{n \leq x} d(n) = \sum_{a \leq x} \left[\frac{x}{a} \right]$$

where $[b]$ is the integer part of b.

Proof. We follow the hint. For each $n \in \mathbb{N}$, let D_n denote the set of positive divisors of n. Then we want to find $\left| D_1 \cup \ldots \cup D_{[x]} \right|$. Now, $\left[\frac{x}{a} \right]$ is precisely the amount of multiples of a smaller than or equal to x, i.e., the amount of numbers in between 1 and x which have a as a divisor. Hence the right hand side indeed counts the number of divisors of the numbers less than or equal to x which is precisely the left hand side. Now, recall also the bound

$$\log x + \frac{1}{x} \leq \sum_{a \leq x} \frac{1}{a} \leq \log x + 1$$

so

$$1 + \frac{1}{x \log x} \leq \frac{1}{\log x} \sum_{a \leq x} \frac{1}{a} \leq 1 + \frac{1}{\log x}.$$

In particular, taking the limit as $x \mapsto \infty$, the outer functions tend to 1, so

$$\lim_{x \to \infty} \frac{1}{\log x} \sum_{a \leq x} \frac{1}{x} = 1.$$

In particular,

$$\frac{1}{x \log x} \sum_{n \leq x} d(n) \leq \frac{1}{\log x} \sum_{a \leq x} \frac{1}{a} \to 1, \quad x \to \infty.$$

For a lower bound, we have

$$\frac{1}{\log x} \sum_{a \leq x} \frac{1}{a} - \frac{1}{x \log x} \sum_{a \leq x} \frac{1}{a} = \frac{1}{\log x} \sum_{a \leq x} \frac{x-1}{ax} \leq \frac{1}{\log x} \sum_{a \leq x} \left[\frac{x}{a} \right]$$

But

$$\frac{1}{x} + \frac{1}{x^2 \log x} \leq \frac{1}{x \log x} \sum_{a \leq x} \frac{1}{a} \leq \frac{1}{x} + \frac{1}{x \log x}$$

so letting $x \to \infty$,

$$\lim_{x \to \infty} \frac{1}{x \log x} \sum_{a \leq x} \frac{1}{a} = 0$$

Hence also

$$1 \leq \lim_{x \to \infty} \frac{1}{x \log x} \sum_{n \leq x} d(n) \leq 1$$

giving the desired result. $\square$

Exercise 4.6 (E3.6)**.** Let

$$\chi_4(n) = \begin{cases} (-1)^{\frac{n-1}{2}}, & n \text{ odd} \\ 0, & n \text{ even} \end{cases}.$$

Show that χ_4 is a Dirichlet character modulo 4 and find $L(1, \chi_4)$. Use the value to give (yet another) proof- based on the irrationality of π - that there are infinitely many primes. Hint: Remember (or prove by playing around with arctan(1)) that

$$\pi = 4 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{2n-1}.$$

Proof. We must check 3 criteria for χ_4 to be a Dirichlet character mod 4.
(i) It must be 4-periodic. Now if n is even, then $n+4$ is even, so then $\chi_4(n+4) = 0 = \chi_4(n)$.
If n is odd, then so is $n+4$, so

$$\chi_4(n+4) = (-1)^{\frac{n+4-1}{2}} = (-1)^{\frac{n-1}{2}+2} = (-1)^{\frac{n-1}{2}} = \chi_4(n).$$

So χ_4 is 4-periodic.
(ii) We must check that $\chi_4(n) = 0$ if and only if $(n, 4) \neq 1$. Now, $\chi_4(n) = 0$ if and only if n is even if and only if $(n, 4) \in \{2, 4\}$ if and only if $(n, 4) \neq 1$.
(iii) We must check that χ_4 is multiplicative. Indeed, if either n or m is even, then

$$\chi_4(nm) = 0 = \chi(n)\chi(m).$$

If both n, m are odd, then

$$\chi_4(nm) = (-1)^{\frac{nm-1}{2}} = \begin{cases} -1, & nm \equiv 3 \pmod 4 \\ 1, & nm \equiv 1 \pmod 4 \end{cases}$$

Now, if n and m are both equivalent to 3 mod 4, then their product is equivalent to 1 mod 4, which works out. If only one is equivalent to 3 mod 4, then nm is also, so it checks out, and similarly, if both are equivalent to 1 mod 4, then so is their product. Now, by definition,

$$L(1, \chi_4) := \sum_{n=1}^{\infty} \frac{\chi_4(n)}{n} = \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} = \arctan(1) = \frac{\pi}{4}$$

Now, since $\chi_4 \neq \chi_0^4$, we know that $L(s, \chi_4)$ is convergent and analytic for $\Re(s) > 0$. In particular, it is continuous at $s = 1$. But for $\Re(s) > 1$, we know that $L(s, \chi_4) = \prod_p (1 - \chi_4(p)p^{-s})^{-1}$, so by continuity,

$$\frac{\pi}{4} = L(1, \chi_4) = \prod_p \left(1 - \chi_4(p)p^{-1}\right)^{-1}$$

Now, all the terms in the product are rational, so by irrationality of π, this forces there to be infinitely many primes. $\square$

Exercise 4.7 (E3.7)**.** Let $\{a_n\}$ be a sequence of complex numbers satisfying that $\sum_{n \le x} a_n = O\left(x^{\delta}\right)$ for some $\delta > 0$. Prove that

$$\sum_{n=1}^{\infty} \frac{a_n}{n^s} = s \int_1^{\infty} \sum_{n \le t} a_n \frac{1}{t^{s+1}} dt$$

for $\Re(s) > \delta$, and that the sum converges to an analytic function in this region.

Proof. Let $f(x) = x^s$. Then

$$\sum_{n \le x} \frac{a_n}{n^s} = \sum_{n \le x} a_n \frac{1}{x^s} + s \int_1^x \sum_{n \le t} a_n \frac{1}{t^{s-1}} dt$$

when $s \neq 1$. But $\left|\sum_{n \le x} a_n\right| \le C x^\delta$, so

$$\left|\sum_{n \le x} a_n \frac{1}{x^s}\right| \le C x^{\delta - \sigma} \to 0, \quad x \to \infty$$

as $\delta - \sigma < 0$. Thus

$$\sum_{n=1}^{\infty} \frac{a_n}{n^s} = s \int_1^\infty \sum_{n \le t} a_n \frac{1}{t^{s+1}} dt.$$

□

5. Week 4

Exercise 5.1 (E4.1)**.** Let $K \ge 0$. Prove that

$$\log (K |t| + 4) = O (\log (|t| + 4))$$

for $t \in \mathbb{R}$. Let $c_1, c_2, c_3 > 0$. Prove that there exists a constant c_4 such that for all $t \in \mathbb{R}$,

$$c_1 + c_2 \log (|t| + 4) + c_3 \log (|2t| + 4) \le c_4 \log (|t| + 4).$$

Proof. If $0 \le K \le 1$, then $\log (K |t| + 4) \le \log (|t| + 4)$ by monotonicity of log. So assume $K > 1$. Then $\log (K |t| + 4) = \log K + \log \left(|t| + \frac{4}{K}\right) \le \log K + \log (|t| + 4)$. Now $\log (|t| + 4) > 1$, so there exists some C such that $C \log (|t| + 4) \ge \log K$. Hence $\log (K |t| + 4) = O (\log (|t| + 4))$. Since $c_1 + c_2 \log (|t| + 4) + c_3 \log (|2t| + 4)$ is a sum of terms that are all $O (\log (|t| + 4))$, so is their sum, so the conclusion holds. □

Exercise 5.2 (E4.2)**.** Let $f(s)$ be a complex polynomial of degree n with complex zeroes $z_1, z_2, \ldots, z_n$. Show that

$$\frac{f'}{f}(z) = \sum_{i=1}^{n} \frac{1}{z - z_i}.$$

Consider how Lemma 6.3 is a generalization of this.

Proof. Firstly, f' is entire, so $\frac{f'}{f}$ is holomorphic on $\mathbb{C} - \{z_1, \ldots, z_n\}$. Now, by Theorem 6.1 in KomAn, there exist unique functions g_i holomorphic on $\mathbb{C} - \{z_1, \ldots, z_n\}$ such that $g_i(z_i) \neq 0$ and

$$f(z) = (z - z_i)^{n_i} g_i(z)$$

where n_i is the multiplicity of z_i. In particular, $f'(z) = n_i(z - z_i)^{n_i - 1} g_i(z) + (z - z_i)^{n_i} g_i'(z)$ which has z_i a zero of order $n_i - 1$. Hence $\frac{f'}{f}$ has z_i as a simple pole. Applying the partial fraction decomposition to $\frac{f'}{f}$ (theorem 6.12 in KomAn), we get that

$$\frac{f'}{f}(z) = \sum_{i=1}^{n} \frac{c_i}{z - z_i}$$

for certain constants c_i. Now $\lim_{z\to z_i}(z-z_i)\frac{f'}{f}(z) = n_i$. Now, f is of degree n with n distinct zeroes, so n_i must be 1 for each i.

Now let us recall Lemma 6.3:

Lemma 5.3 (6.3)**.** *Let $f\colon B \to \mathbb{C}$ be analytic, $B \subset \mathbb{C}$ open, and assume*

(1) $\{z \mid |z| \le 1\} \subset B$
(2) $|f(z)| \le M$ *when* $|z| \le 1$
(3) $f(0) \neq 0$.

Let $0 < r < R < 1$. Then for $|z| < r$,

$$\frac{f'}{f}(z) = \sum_{\substack{f(z_k)=0 \\ |z_k|\le R}} \frac{1}{z-z_k} + O\left(\log\frac{M}{|f(0)|}\right)$$

Note here that f is not required to be a polynomial. However, since f is holomorphic in B, it has an analytic representation on B, so essentially, Lemma 6.3 generalizes the representation to analytic functions. $\square$

Exercise 5.4 (E4.3)**.** Show that the Riemann zeta function $\zeta(s)$ has no zeroes for $\frac{1}{2} \le s < 1$.

Proof. Recall that for $\sigma > 0$ and $s \neq 1$, we have

$$\zeta(s) = \frac{s}{s-1} - s\int_1^\infty (u-[u])\,u^{-s-1}du.$$

For $s \in [\frac{1}{2}, 1)$, $\frac{s}{s-1} \le -1$. So we wish to show that

$$s\int_1^\infty (u-[u])\,u^{-s-1}du > -1$$

But

$$s\int_1^\infty (u-[u])\,u^{-s-1}du$$

is positive since the inner function and s are both positive on $[1,\infty)$.

$\square$

Exercise 5.5 (E4.4)**.** Let χ be a Dirichlet character modulo q. Find the Dirichlet series representation for $L'(s,\chi)/L(s,\chi)$. Let χ_0 be the trivial Dirichlet character modulo q. Prove that for $\sigma > 1, t \in \mathbb{R}$,

$$R := \Re\left(-3\frac{L'(\sigma,\chi_0)}{L(\sigma,\chi_0)} - 4\frac{L'(\sigma+it,\chi)}{L(\sigma+it,\chi)} - \frac{L'(\sigma+i2t,\chi^2)}{L(\sigma+i2t,\chi^2)}\right) \ge 0.$$

Proof. We want to represent $\frac{L'(s,\chi)}{L(s,\chi)}$ as a Dirichlet series. We imitate the idea for $\frac{\zeta'}{\zeta}$.

$$\begin{aligned}
\frac{L'(s,\chi)}{L(s,\chi)} &= \frac{d}{ds}\log\left(L(s,\chi)\right) \\
&= -\sum_p \frac{d}{ds}\log\left(1-\frac{\chi(p)}{p^s}\right) \\
&= -\sum_p \frac{d}{ds}\sum_{k=1}^{\infty}(-1)^{k+1}\left(-\frac{\chi(p)}{p^s}\right)^k \\
&= \sum_p\sum_{k=1}^{\infty}\frac{d}{ds}\left(\frac{\chi(p)}{p^s}\right)^k \\
&= \sum_p\sum_{k=1}^{\infty}\chi(p)^k(-k\log p)p^{-sk} \\
&= -\sum_p\sum_{k=1}^{\infty}k\log p\left(\frac{\chi(p)}{p^s}\right)^k
\end{aligned}$$

Thus We want to find $\Re\left(\left(\frac{\chi(p)}{p^s}\right)^k\right)$. We have

$$\begin{aligned}
\Re\left(\left(\frac{\chi(p)}{p^s}\right)^k\right) &= \frac{1}{2}\left[\left(\frac{\chi(p)}{p^s}\right)^k+\left(\frac{\overline{\chi(p)}}{\overline{p^s}}\right)^k\right] \\
&=
\end{aligned}$$

$$\Re\left(-\frac{L'(s,\chi)}{L(s,\chi)}\right) = \sum_p\sum_{k=1}^{\infty}k\log p\cos\left(tk\log p\right).$$

So

$\square$

Exercise 5.6 (E4.5)**.** Let $\zeta(s)$ be the Riemann zeta function. Let K be a compact subset of $\{s\in\mathbb{C}\mid \Re(s)>0\}$. Assume that $1\in K$ and that K does not contain any zeroes of ζ. Show that

$$-\frac{\zeta'}{\zeta}(s) = \frac{1}{s-1}+O(1)$$

for $s\in K-\{1\}$. Show that there exists a constant $c>0$ such that for $0<\delta<1$,

$$-\frac{\zeta'}{\zeta}(1+\delta) < \frac{1}{\delta}+c.$$

Proof. Since 1 is a simple pole of $\frac{\zeta'}{\zeta}$ and K has no other zeroes of ζ and hence neither of ζ', we have that

$$-(s-1)\frac{\zeta'}{\zeta}(s)$$

is holomorphic on K, hence bounded as K is compact. Thus

$$-\frac{\zeta'}{\zeta}(s) = \frac{1}{s-1}+O(1)$$

for $s \in K - \{1\}$. Thus for small $0 < \delta < 1$ such that $1 + \delta \in K - \{1\}$,

$$-\frac{\zeta'}{\zeta}(1+\delta) < \frac{1}{\delta} + c$$

for some $c > 0$. $\square$

Exercise 5.7 (E4.6)**.** Use partial summation (Abel summation) to show that for $\sigma > 1$,

$$-\frac{\zeta'}{\zeta}(s) = s\int_1^\infty \frac{\psi(x)}{x^{s+1}}dx$$

where $\psi(x) = \sum_{n \le x} \Lambda(n)$, and Λ is the von Mangoldt function.

Proof. Recall that

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

for $\sigma = \Re(s) > 1$.
Let $f(x) = \frac{1}{x^s}$ and $a_n = \Lambda(n)$. Partial summation gives

$$\sum_{n \le x} \frac{\Lambda(n)}{n^s} = \underbrace{\sum_{n \le x} \Lambda(n)}_{\psi(x)} \frac{1}{x^s} + s\int_1^x \underbrace{\sum_{n \le t} \Lambda(n)}_{\psi(t)} \frac{1}{t^{s+1}}dt$$

By the prime number theorem,

$$\psi(x) = x + O\left(\frac{x}{e^{c'\sqrt{\log x}}}\right)$$

so

$$\frac{\psi(x)}{x^s} \to 0, \quad x \to \infty$$

Thus

$$-\frac{\zeta'}{\zeta}(s) = s\int_1^\infty \frac{\psi(t)}{t^{s+1}}dt$$

for $\sigma > 1$. $\square$

6. Week 5

Exercise 6.1 (E5.1)**.** Show that

$$x\exp\left(-c\sqrt{\log x}\right) = O_m\left(\frac{x}{\log^m x}\right)$$

for every m, and that

$$x^{1-\varepsilon} = O_\varepsilon\left(x\exp\left(-c\sqrt{\log x}\right)\right)$$

for every $\varepsilon > 0$. Discuss what this means for the quality of the error-term in the prime number theorem.

Proof.

$$\frac{\log^m x}{e^{c\sqrt{\log x}}} = \frac{\sqrt{\log x}^{2m}}{e^{c\sqrt{\log x}}}$$

Now

Lemma 6.2. *For any $a > 0$ and any $b > 1$,*

$$\frac{x^a}{b^x} \to 0, \quad x \to \infty.$$

Let $v = \sqrt{\log x}$. Then the above reads $\frac{v^{2m}}{e^{cv}}$. Assuming $c > 0$, we find that for $v \to \infty$, $\frac{v^{2m}}{e^{cv}} \to 0$. So in fact,

$$x \exp\left(-c\sqrt{\log x}\right) = o\left(\frac{x}{\log^m x}\right)$$

Now

$$x^{1-\varepsilon} = xx^{-\varepsilon} = xe^{-\log(x)\varepsilon} \leq xe^{-c\sqrt{\log x}}.$$

Recall that we proved the following version of the prime number theorem:

Theorem 6.3 (Prime number theorem)**.** *There exists a $c' > 0$ such that*

$$\psi(x) = x + O\left(x \exp\left(-c'\sqrt{\log x}\right)\right)$$

So by the above,

$$\psi(x) = x + O_m\left(\frac{x}{\log^m(x)}\right)$$

So essentially, the error term is smaller than $\frac{x}{\log^m(x)}$ for any x but still larger than $x^{1-\varepsilon}$ for any $\varepsilon > 0$. $\square$

Exercise 6.4 (E5.2)**.** Prove that the following two statements are equivalent:

(1) There exists a $c > 0$ such that

$$\psi(x) = x + O\left(x \exp\left(-c\sqrt{\log x}\right)\right)$$

(2) There exists a $c > 0$ such that

$$\pi(x) = li(x) + O\left(x \exp\left(-c\sqrt{\log x}\right)\right)$$

where $li(x) = \int_2^x \frac{1}{\log t} dt$.

Proof. Suppose (1) is true. Then

$$\begin{aligned}\pi(x) &= \frac{\psi(x)}{\log x} + \int_2^x \frac{\psi(t)}{t \log^2 t} dt + O\left(x^{\frac{1}{2}} \log x\right) \\ &= \frac{x}{\log x} + O\left(\frac{x}{\log x} \exp\left(-c\sqrt{\log x}\right)\right) + \int_2^x \frac{1}{\log^2 t} + O\left(\frac{1}{\log^2 t \exp\left(c\sqrt{\log t}\right)}\right) dt + O\left(x^{\frac{1}{2}} \log x\right)\end{aligned}$$

Now

$$\int_2^x \frac{1}{\log^2 t} dt = -\frac{t}{\log t}\bigg|_2^x + li(x)$$

giving

$$\pi(x) = li(x) + \frac{2}{\log 2} + O\left(\frac{x}{\log x} e^{-c\sqrt{\log x}}\right) + \int_2^x O\left(\frac{e^{-c\sqrt{\log t}}}{\log^2 t}\right) dt + O\left(x^{\frac{1}{2}} \log x\right)$$

All the middle terms apart from the last two are clearly $O\left(xe^{-c\sqrt{\log x}}\right)$. To take care of the last term, we use the lemma:

Lemma 6.5. *For any $a > 0$,*

$$\frac{\log x}{x^a} \to 0, \quad x \to \infty$$

Hence $x^{\frac{1}{2}} \log x = O\left(x^{\frac{3}{4}}\right) = O\left(xe^{-c'\sqrt{\log x}}\right)$.

For the last part

$$\int_2^x O\left(\frac{e^{-c\sqrt{\log t}}}{\log^2 t}\right) dt \leq$$

Note that the derivative of $xe^{-c\sqrt{\log x}}$ is

$$e^{-c\sqrt{\log x}} - c\frac{d}{dx}\left[\sqrt{\log x}\right] e^{-c\sqrt{\log x}} = e^{-c\sqrt{\log x}} - c\frac{1}{2}\frac{1}{x}\frac{1}{\sqrt{\log x}}e^{-c\sqrt{\log x}}$$

But as $x \to \infty$, this grows faster than $\frac{e^{-c\sqrt{\log x}}}{\log^2 x}$, which is what we wanted.

Now we want to show that (2) implies (1). So assume there exists a $c > 0$ such that

$$\pi(x) = li(x) + O\left(x \exp\left(-c\sqrt{\log x}\right)\right).$$

Then recall that

$$\psi(x) = \pi(x)\log x - \int_2^x \frac{\pi(t)}{t} dt - O\left(x^{\frac{1}{2}} \log^2 x\right)$$

So

$$\psi(x) = li(x)\log x + \log x O\left(xe^{-c\sqrt{\log x}}\right) - \int_2^x \frac{li(t)}{t} dt - \int_2^x O\left(e^{-c\sqrt{\log t}}\right) dt - O\left(x^{\frac{1}{2}} \log^2 x\right)$$

Now, by repeated integration by parts, we get

$$\begin{aligned} li(x) &= \left.\frac{t}{\log t}\right|_2^x + \int_2^x \frac{1}{\log^2 t} dt \\ &= \left.\frac{t}{\log t}\right|_2^x + \left[\left.\frac{t}{\log^2 t}\right|_2^x + 2\int_2^x \frac{1}{\log^3 t} dt\right] \\ &= \frac{t}{\log t} + \left.\frac{t}{\log^2 t}\right|_2^x + 2\left[\left.\frac{t}{\log^3 t}\right|_2^x + 3\int_2^x \frac{1}{\log^4 t} dt\right] \\ &= x\sum_{r=1}^{k-1} \frac{(r-1)!}{\log^r x} + (k-1)!\int_2^x \frac{1}{\log^k t} dt \end{aligned}$$

□

Exercise 6.6 (E5.3)**.** Let f be a Schwartz function on the real line, and let $\hat{f}$ be its Fourier transform. Show that

$$\sum_{n\in\mathbb{Z}} f\left(\frac{v+n}{t}\right) = \sum_{n\in\mathbb{Z}} |t|\,\hat{f}\,(nt)\,e^{2\pi i n v}.$$

Proof. For a Schwartz function f, we know from the Poisson summation formula that

$$\sum_{n\in\mathbb{Z}} f(n) = \sum_{n\in\mathbb{Z}} \hat{f}(n),$$

where

$$\hat{f}(y) = \int_{-\infty}^{\infty} e^{-2\pi ixy} f(x)dx$$

Define $g(x) = f\left(\frac{v+x}{t}\right)$. Then g is also a Schwartz function, so

$$\sum_{n\in\mathbb{Z}} g(n) = \sum_{n\in\mathbb{Z}} \int_{-\infty}^{\infty} e^{-2\pi inx} f\left(\frac{v+x}{t}\right) dx$$

Let $z = \frac{v+x}{t}$. Then $dz = \frac{1}{|t|}dx$, so

$$\sum_{n\in\mathbb{Z}} f\left(\frac{v+n}{t}\right) = \sum_{n\in\mathbb{Z}} g(n) = \sum_{n\in\mathbb{Z}} |t|\, e^{-2\pi in(tz-v)} f(z)dz = \sum_{n\in\mathbb{Z}} |t|\, \hat{f}(nt)e^{2\pi inv}$$

□

Exercise 6.7 (E5.4)**.** Let $\theta > \frac{1}{2}$. Prove that if for every $\varepsilon > 0$, $\psi(x) = x + O\left(x^{\theta+\varepsilon}\right)$, then the Riemann zeta function has no zeroes in $\Re(s) > \theta$. (It turns out that this is in fact an 'if and only if statement'). Think about what this implies for the Riemann hypothesis. Compare with the zerofree region provided by Theorem 6.6.

Proof. By the explicit formula, if we simply let x range among $\mathbb{R} - \mathbb{Z}$, then we have

$$O\left(x^{\theta+\varepsilon}\right) = \lim_{T\to\infty} \sum_{\substack{\zeta(\rho)=0 \\ |\operatorname{im}\rho|\le T}} \frac{x^\rho}{\rho} + \frac{\zeta'}{\zeta}(0) + \frac{1}{2}\log\left(1 - \frac{1}{x^2}\right),$$

however, if there is a ρ with $\Re(\rho) > \theta$, then choosing ε such that $\theta < \varepsilon < \Re(\rho)$, we get that the right hand side grows faster, giving a contradiction.

Hence the Riemann hypothesis can be reformulated as saying that for any $\varepsilon > 0$,

$$\psi(x) = x + O\left(x^{\frac{1}{2}+\varepsilon}\right).$$

Now, any θ would, of course, be a very strong improvement combined with the zero-free region. This is because the zero-free region tapers off as the imaginary part grows in size, while finding a θ such that the above holds would imply, as shown, that we can shrink the critical strip to a narrower strip. □

Exercise 6.8 (E5.5)**.** Let p_n be the n th prime. Show that

$$\frac{1}{N}\sum_{n=1}^{N} \frac{p_{n+1}-p_n}{\log p_n} \to 1$$

as $N \to \infty$, and discuss how to interpret this as a statement about the average spacing between adjacent primes.

Proof. By Abel summation, we have

$$\sum_{n\le x} \frac{p_{n+1}-p_n}{\log p_n} = \frac{p_{[x]+1}-2}{\log x} - \int_1^x \frac{p_{[t]+1}-2}{\log t} dt$$

$$\sum_{n\le x}\frac{p_n}{\log p_n}=\sum_{n\le x}p_n\frac{1}{\log x}-\int_1^x\sum_{n\le t}p_n\frac{1}{\log t}dt$$

And similarly

$$\sum_{n\le x}\frac{p_{n+1}}{\log p_n}=\sum_{n\le x}p_{n+1}\frac{1}{\log x}-\int_1^x\sum_{n\le t}p_{n+1}\frac{1}{\log t}dt$$

Hence

$$\begin{aligned}\sum_{n\le x}\frac{p_{n+1}-p_n}{\log p_n}&=\frac{1}{\log x}\sum_{n\le x}p_{n+1}-p_n-\int_1^x\frac{1}{\log t}\sum_{n\le t}(p_{n+1}-p_n)dt\\&=\frac{p_{[x]+1}-2}{\log x}-\int_1^x\frac{p_{[t]+1}-2}{\log t}dt\end{aligned}$$

Now $\frac{p_n}{n\log n}\to 1$ as $n\to\infty$, so $\frac{p_{n+1}}{n\log n}=\frac{p_{n+1}}{(n+1)\log(n+1)}\frac{(n+1)\log(n+1)}{n\log n}\to 1$ as $n\to\infty$. So we will get the result if we can show that

$$\lim_{n\to\infty}\frac{1}{n}\int_1^n\frac{p_{[t]+1}-2}{\log t}dt=0.$$

By the PNT, we have

$$p_n\sim n\log n.$$

So

$$\lim_{N\to\infty}\frac{1}{n}\sum_{n\ge N}\frac{p_{n+1}-p_n}{\log p_n}=\lim_{N\to\infty}\sum_{n\ge N}\frac{(1+\frac{1}{n})\log(n+1)-\log n}{\log n+\log\log n}=$$

□

7. Week 6

Exercise 7.1 (E6.1)**.** Show, using Corollary 10.3, that $\zeta(s)$ admits meromorphic continuation to $s\in\mathbb{C}$. Show that $\zeta(-2n)=0$ for $n\in\mathbb{N}$ (we call these zeroes *trivial*), and that all the non-trivial zeroes of $\zeta(s)$ lie in $0<\Re(s)<1$.

Proof. Here is Corollary 10.3:

Corollary 7.2 (10.3)**.** *The function*

$$\xi(s)=\frac{1}{2}s(s-1)\zeta(s)\Gamma\left(\frac{s}{2}\right)\pi^{-\frac{s}{2}}$$

is entire, and $\xi(s)=\xi(1-s)$ for all s.

Hence we can define ζ as

$$\zeta(s)=\frac{2\pi^{\frac{s}{2}}\xi(s)}{s(s-1)\Gamma(\frac{s}{2})}$$

But using this, we see that as a product and quotient of meromorphic functions, ζ is also meromorphic. In particular, we know that $\Gamma(s)$ has poles at $0,-1,-2,-3,\ldots$, which implies that ζ has zeroes at $-2,-4,-6,\ldots$ (to see this formally, use Theorem 6.1 in KomAn). These are the trivial zeroes. Now, by the Euler product of ζ, it has no zeroes in $\Re(s)>1$. We also claim that ζ has no other zeroes apart from the nontrivial zeroes on $\Re(s)<0$. Indeed, the poles from Γ has already been accounted for, and note that ξ has no zeroes in $\Re(s)<0$ since then it would, by its functional equation, have zeroes in $\Re(s)>0$, thus giving a zero in $\Re(s)>0$ to

ζ also. Furthermore, it has no zeroes on $\Re(s)=1$ by the zero-free region, and by symmetry of the functional equation stemming from the symmetry of ξ, it also has no zeroes on $\Re(s)=0$. $\square$

Exercise 7.3 (E6.2)**.** Find all poles of $\zeta(s)$, and show that if ρ is a non-trivial zero of $\zeta(s)$ then $1-\rho$ and $\overline{\rho}$ are zeros of $\zeta(s)$.

Proof. Since ξ is analytic, all poles must stem from zeroes of $s(s-1)\Gamma(\frac{s}{2})$. Now, Γ has no zeroes by a theorem, hence it does not give rise to any poles, so the only possible poles are 0 and 1. We know that it has a pole at 1 by its series representation/Landau's lemma, and thus by the functional equation of ξ, since $\xi(1)=\xi(0)$ and $\xi(1)\neq 0$ since $(s-1)$ cancels with the pole from ξ, then also $\xi(0)\neq 0$, so s must cancel. Now, Γ has a simple pole at 0, hence this cancels with s. Since ξ has no zeroes, ζ can therefore not have a pole at 0.
Concluding, ζ only has a single pole at 1 which is simple.

Now, if ρ is a non-trivial zero, then it lies in $0<\Re(s)<1$, so also $1-\rho\in 0<\Re(s)<1$. In particular, since ρ lies in the critical strip, it does not arise from a pole of Γ, hence it must arise from a zero of $\xi(s)$, and thus also $\xi(1-\rho)=\xi(\rho)=0$ by the functional equation. This shows that $1-\rho$ is then also a zero. Now, note that on ζ is at least real valued on $(0,1)$ since on here, ζ has the representation

$$\zeta(s)=\frac{s}{s-1}+s\int_1^\infty([t]-t)\,t^{-s-1}dt$$

which in particular, is real valued on $(0,1)$. Thus ζ is reflection invariant everywhere by exercise 6.3 in KomAn. I.e., $\overline{\zeta(s)}=\zeta(\overline{s})$. So if ρ is a zero, then so is $\overline{\rho}$. $\square$

Recall that $\theta(u)=\sum_{n\in\mathbb{Z}}e^{-\pi n^2 u}$ for $\Re(u)>0$.

Exercise 7.4 (E6.3)**.** Show that $\theta(u)=1+O\left(e^{-\pi u}\right)$ for $u\in(1,\infty)$.

Proof. We have $\theta(u)-1=2\sum_{n=1}^\infty e^{-\pi n^2 u}\leq 2\sum_{n=1}^\infty \frac{1}{2^{n-1}}e^{-\pi u}=4e^{-\pi u}$ since $\frac{1}{e^{\pi u(n^2-1)}}\leq\frac{1}{2^{n-1}}$ for $u>1$ and $n>1$. $\square$

Exercise 7.5 (E6.4)**.** Show that for u real, $\theta(u)\sim\sqrt{u}^{-1}$ when $u\to 0$.

Proof. Saying that $\theta(u)\sim\sqrt{u}^{-1}$ as $u\to 0$ is the statement that $\sqrt{u}\theta(u)\to 1$ as $u\to 0$. But recall that $\theta(\frac{1}{u})=\sqrt{u}\theta(u)$. So the statement is precisely that $\theta\left(\frac{1}{u}\right)\to 1$ as $u\to 0$. Now

$$\theta\left(\frac{1}{u}\right)=1+2\sum_{n=1}^\infty e^{-\pi n^2\frac{1}{u}}$$

and

$$\lim_{u\to 0}\theta\left(\frac{1}{u}\right)=1+2\sum_{n=1}^\infty\lim_{u\to 0}e^{-\pi n^2\frac{1}{u}}=1.$$

Interchange of limit with sum here is possible because of the dominated convergence theorem (note that sums are just integrals with respect to the counting measure on $\mathbb{N}$). $\square$

Exercise 7.6 (E6.5)**.** Show that if $\Re(s)>1$, then $\int_0^\infty(\theta(u)-1)\,u^{\frac{s}{2}-1}du$ is convergent.

Proof. As a function of s, $(\theta(u)-1)\,u^{\frac{s}{2}-1}$ is holomorphic for $\Re(s)>1$, so by theorem 4.20 in KomAn,

$$\int_a^b (\theta(u)-1)\,u^{\frac{s}{2}-1}du$$

is convergent and holomorphic for $a,b\geq 1$. Now, since $\theta(\frac{1}{u})=\sqrt{u}\theta(u)$, it follows that θ is also convergent on $(0,1]$. It remains to show that the integral is convergent when we take $a\to 0+$ and $b\to\infty$. Let $a>1$. Then

$$\int_a^b (\theta(u)-1)\,u^{\frac{s}{2}-1}du=\int_a^b O\left(e^{-\pi u}u^{\frac{s}{2}-1}\right)du$$

But $O\left(e^{-\pi u}u^{\frac{s}{2}-1}\right)=O\left(\frac{1}{u^2}\right)$, so

$$\int_a^b O\left(e^{-\pi u}u^{\frac{s}{2}-1}\right)du\leq -\frac{1}{u}\bigg|_a^b=\frac{1}{a}-\frac{1}{b}\to\frac{1}{a},\quad \text{as } b\to\infty$$

Since the integral is also a monotone function, it converges. Secondly, we must show that

$$\lim_{a\to 0+}\int_a^\infty (\theta(u)-1)\,u^{\frac{s}{2}-1}du$$

exists.
But $\theta(u)\sim\sqrt{u}^{-1}$ as $u\to 0$, so for some $\delta>0$, we have

$$\left|\int_0^\delta (\theta(u)-1)\,u^{\frac{s}{2}-1}du\right|\leq\left|\int_0^\delta\left(\frac{1}{\sqrt{u}}-1\right)u^{\frac{s}{2}-1}du\right|+\varepsilon<\infty$$

because $\Re(s)>1$. Hence the integral converges. □

Exercise 7.7 (E6.6)**.** Find the value $\zeta(0)$.

Solution. We have

$$\zeta(0)=\frac{\xi(s)}{-\frac{1}{2}s(1-s)\pi^{-\frac{s}{2}}\Gamma(\frac{s}{2})}\bigg|_{s=0}$$

Now, the pole at 0 for Γ cancels with s, so since $s\Gamma(s)=\Gamma(s+1)$, we have $\Gamma\left(\frac{s}{2}\right)=\Gamma\left(\frac{s}{2}+1\right)\frac{2}{s}$, so we find

$$\zeta(0)=\frac{\xi(0)}{-\frac{1}{2}\Gamma(1)2}=-\frac{\xi(0)}{\Gamma(1)}=-\xi(0)=-\xi(1)=\frac{1}{2}s(1-s)\pi^{-\frac{s}{2}}\Gamma(\frac{s}{2})\zeta(s)\bigg|_{s=1}$$

Now in this case, $(1-s)$ cancels with the pole of ζ at 1. Now, around 1, we have

$$(1-s)\zeta(s)=-s+s(1-s)\int_1^\infty([t]-t)\,t^{-s-1}dt$$

so $(1-s)\zeta(s)\Big|_{s=1}=-1$. Hence

$$\zeta(0)=-\frac{1}{2}\pi^{-\frac{1}{2}}\Gamma(\frac{1}{2})$$

But $\Gamma(\frac{1}{2})=\pi^{\frac{1}{2}}$, so

$$\zeta(0)=-\frac{1}{2}.$$

□

Exercise 7.8 (E6.7)**.** The table defines a Dirichlet character χ mod 14. Find the conductor d of χ and find a primitive χ_1 mod d such that $\chi=\chi_1\chi_0^{14}$.

TABLE 1. caption

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$\chi(n)$	1	0	-1	0	-1	0	0	0	1	0	1	0	-1	0

Solution. The conductor is the smallest pseudo-period. Recall that the conductor must divide the period, so $d \mid 14$. Hence there are 4 possibilities for the value of d: $1, 2, 7, 14$. However, since χ takes both the values 1 and -1, it cannot be 1. Now, also $1 \equiv 3 \pmod 2$ and $(3, 14) = 1$, however, $\chi(1) = 1 \neq -1 = \chi(3)$, so also 2 is not a pseudo-period. Now, for any two numbers equivalent modulo 7 in the list, one is even while the other is odd, hence the product cannot be relatively prime to 14. This implies that the condition for being a pseudo-prime is trivially satisfied, so 7 is the conductor. Next, we must find a primitive χ_1 mod 7 such that $\chi = \chi_1\chi_0^{14}$. Recall that the definition of χ_1 is essentially forced to be $\chi_1(n) = \chi(n)$ whenever $(n, 14) = 1$ which is for $1, 3$ and 5 modulo 7. For $0, 2, 4, 6$ modulo 7, we let $\chi_1(n) = \chi(n + 7k)$ such that $(n + 7k, 14) = 1$, so either $k = 0$ or $k = 1$. Hence $\chi_1(0) = 0, \chi_1(2) = \chi(9) = 1, \chi_1(4) = \chi(11) = 1, \chi_1(6) = \chi(13) = -1$, and then extend this 7-periodically. Then $\chi = \chi_1\chi_0^{14}$. $\square$

Exercise 7.9 (E6.9)**.** Show that a character χ mod q is real, i.e., has real values, if and only if $\chi^2 = \chi_0^q$. We call a character *quadratic* if $\chi^2 = \chi_0^q$, but $\chi \neq \chi_0^q$. Show that if χ mod q is real and $\chi(-1) = 1$, then the Gauss symbol $\tau(\chi)$ is also real. What happens if $\chi(-1) = -1$?

Solution. We have $\chi\overline{\chi} = \chi_0^q$ since $\overline{\chi}$ forms the inverse of χ in the group of Dirichlet characters modulo q. If χ is real, then clearly $\chi^2 = \chi\overline{\chi} = \chi_0^q$. Conversely, if $\chi^2 = \chi_0^q = \chi\overline{\chi}$, then since these form a group, taking the inverse on both sides, we get $\chi = \overline{\chi}$, hence χ is real-valued.
Now, recall that

$$\overline{\tau(\chi)} = \chi(-1)\tau\left(\overline{\chi}\right),$$

so if χ is real and $\chi(-1) = 1$, then we simply get $\overline{\tau(\chi)} = \tau(\chi)$, so $\tau(\chi)$ is real. If $\chi(-1) = -1$, we get $\overline{\tau(\chi)} = -\tau(\chi)$ which means that $\tau(\chi)$ is purely imaginary.

8. WEEK 7

Exercise 8.1 (E7.1)**.** Let $\chi \mod q$ be the Legende symbol. I.e.,

$$\chi(m) = \begin{cases} 0, & \text{if } 5 \mid m \\ 1, & \text{if } m \equiv a^2 \mod 5 \\ -1, & \text{if } m \not\equiv a^2 \mod 5 \end{cases}$$

Show that χ is primitive and calculate the Gauss sum $\tau(\chi)$.

Solution. A character is primitive if and only if its conductor is its period. Here the period of χ is 5. Since the conductor is a divisor of the period, the conductor is either 1 or 5. Since χ takes both values 1 and -1, its conductor must be 5, hence χ is primitive.

To calculate the Gauss sum, we have

$$\begin{aligned}\tau(\chi) = \sum_{a=1}^{5} \chi(a) e\left(\frac{a}{5}\right) &= e(\frac{1}{5}) - e(\frac{2}{5}) - e\left(\frac{3}{5}\right) + e\left(\frac{4}{5}\right) \\ &= -1 - 2\left[e^{2\pi i \frac{2}{5}} + e^{2\pi i \frac{3}{5}}\right] \\ &= -1 - 4\cos\left(\frac{4\pi}{5}\right) \\ &= \sqrt{5}\end{aligned}$$

Exercise 8.2 (E7.2)**.** Let χ be a primitive Dirichlet character modulo $q > 1$. Show that

$$L\left(\frac{1}{2}, \chi\right) = O\left(q^{\frac{1}{4}} \sqrt{\log q}\right).$$

Proof. We have

$$\begin{aligned}L\left(\frac{1}{2}, \chi\right) &= \sum_{n=1}^{\infty} \frac{\chi(n)}{\sqrt{n}} \\ &= \sum_{n \le x} \frac{\chi(n)}{\sqrt{n}} + \sum_{n > x} \frac{\chi(n)}{\sqrt{n}}\end{aligned}$$

Using partial summation,

$$\begin{aligned}\sum_{n > x} \frac{\chi(n)}{\sqrt{n}} &= \sum_{n \le z} \chi(n) \frac{1}{\sqrt{z}}\Bigg|_{z=x}^{z=\infty} + \frac{1}{2}\int_x^{\infty} \sum_{n \le t} \chi(n) t^{-\frac{3}{2}}\, dt \\ &= -\frac{1}{\sqrt{x}} O\left(\sqrt{q}\log q\right) + \frac{1}{2}\int_x^{\infty} O\left(\sqrt{q}\log q\right) t^{-\frac{3}{2}}\, dt\end{aligned}$$

Thus by the triangle inequality, we have

$$\left|\sum_{n > x} \frac{\chi(n)}{\sqrt{n}}\right| \le C_1 \frac{\sqrt{q}\log q}{\sqrt{x}} + C_2 \frac{\sqrt{q}\log q}{2} \frac{1}{\sqrt{x}}$$

Letting $x = \sqrt{q}\log q$, we get

$$\sum_{n > x} \frac{\chi(n)}{\sqrt{n}} = O\left(q^{\frac{1}{4}} \sqrt{\log q}\right)$$

Now, for the first sum, we have

$$\sum_{n \le x} \frac{\chi(n)}{\sqrt{n}} = \underbrace{\underbrace{\sum_{n \le x} \chi(n)}_{O(x)} \frac{1}{\sqrt{x}}}_{O(\sqrt{x})} + \frac{1}{2}\int_1^{x} \underbrace{\sum_{n \le t} \chi(n) t^{-\frac{3}{2}}}_{O(t^{-\frac{1}{2}})}\, dt$$

Hence

$$\left|\sum_{n \le x} \frac{\chi(n)}{\sqrt{n}}\right| \le \sqrt{x} + \left[\sqrt{x} - 1\right]$$

so with our choice of x, we find that also

$$\sum_{n\leq x}\frac{\chi(n)}{\sqrt{n}}=O\left(q^{\frac{1}{4}}\sqrt{\log q}\right).$$

□

Exercise 8.3 (E7.3)**.** Let f be a sufficiently nice real function on $\mathbb{R}$, e.g., a Schwartz function. Show that the Fourier transform of f' is $2\pi iy\hat{f}(y)$. Let $u>0$. Show that the Fourier transform of $xe^{-\pi u(qx)^2}$ is

$$-\frac{iy}{\left(u^{\frac{1}{2}}q\right)^3}e^{-\pi u^{-1}\left(\frac{y}{q}\right)^2}.$$

Proof.

$$\begin{aligned}\hat{f'}(y)&=\int_{-\infty}^{\infty}e^{-2\pi ixy}f'(x)dx\\&=\underbrace{e^{-2\pi ixy}}_{\text{modulus 1}}f(x)\Big|_{-\infty}^{\infty}+(2\pi iy)\underbrace{\int_{-\infty}^{\infty}e^{-2\pi ixy}f(x)dx}_{=\hat{f}(y)}.\end{aligned}$$

Now, let $f(x)=-\frac{1}{2\pi uq^2}e^{-\pi u(qx)^2}$. Then $f'(x)=xe^{-\pi u(qx)^2}$. So by the above $\hat{f'}(y)=2\pi iy\hat{f}(y)$. Now

$$\begin{aligned}\hat{f'}(y)&=-\frac{2\pi iy}{2\pi uq^2}\int_{-\infty}^{\infty}e^{-2\pi ixy}e^{-\pi u(qx)^2}dx\\&=-\frac{iy}{uq^2}e^{-\pi\left(\frac{y}{q\sqrt{u}}\right)^2}\int_{-\infty}^{\infty}e^{-\pi\left[u(qx)^2+2ixy-\left(\frac{y}{q\sqrt{u}}\right)^2\right]}dx\end{aligned}$$

Let $w=\left(\sqrt{u}qx+\frac{iy}{q\sqrt{u}}\right)$. Then $dw=\sqrt{u}qdx$, so

$$\begin{aligned}-\frac{iy}{uq^2}e^{-\pi\left(\frac{y}{q\sqrt{u}}\right)^2}\int_{-\infty}^{\infty}e^{-\pi\left[u(qx)^2+2ixy-\left(\frac{y}{q\sqrt{u}}\right)^2\right]}dx&=-\frac{iy}{u^{\frac{3}{2}}q^3}e^{-\pi\left(\frac{y}{q\sqrt{u}}\right)^2}\underbrace{\int_{-\infty}^{\infty}e^{-\pi w^2}dw}_{=1}\\&=\frac{-iy}{\left(u^{\frac{1}{2}}q\right)^3}e^{-\pi u^{-1}\left(\frac{y}{q}\right)^2}\end{aligned}$$

□

Exercise 8.4 (E7.4)**.** Let χ be an odd primitive character (meaning $\chi(-1)=-1$). Define

$$\vartheta_\chi(u):=\sum_{n\in\mathbb{Z}}n\chi(n)e^{-\pi n^2u}.$$

Show that

$$\vartheta_\chi(u)=\frac{\tau(\chi)}{iq^2u^{\frac{3}{2}}}\vartheta_{\overline{\chi}}\left(\frac{1}{q^2u}\right)$$

Proof. Recall from Theorem 12.2 that

$$\sum_{n\in\mathbb{Z}} \chi(n) f\left(\frac{n}{q}\right) = \tau(\chi)\sum_{n\in\mathbb{Z}} \overline{\chi(n)}\hat{f}(n).$$

Letting $f(x) = qxe^{-\pi(qx)^2 u}$, we find that

$$\begin{aligned}
\vartheta_\chi(u) = \sum_{n\in\mathbb{Z}} \chi(n) f\left(\frac{n}{q}\right) &= \tau(\chi)\sum_{n\in\mathbb{Z}} \overline{\chi(n)}\left(-\frac{inq}{\left(u^{\frac{1}{2}}q\right)^3} e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2}\right) \\
&= \frac{\tau(\chi)}{iq^2u^{\frac{3}{2}}}\sum_{n\in\mathbb{Z}} \overline{\chi(n)} n e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2} \\
&= \frac{\tau(\chi)}{iq^2u^{\frac{3}{2}}}\vartheta_{\overline{\chi}}\left(\frac{1}{q^2u}\right)
\end{aligned}$$

□

Exercise 8.5 (E7.5)**.** Show that for $\Re(s) > 1$, we have

$$2\pi^{\frac{-(s+1)}{2}}\Gamma\left(\frac{s+1}{2}\right) L(s,\chi) = \int_0^\infty \vartheta_\chi(u) u^{\frac{s+1}{2}}\frac{du}{u}.$$

Proof. Recall that

$$\Gamma\left(\frac{s+1}{2}\right) = \int_0^\infty e^{-u}u^{\frac{s+1}{2}}\frac{du}{u}$$

and

$$L(s,\chi) = \sum_{n=1}^\infty \frac{\chi(n)}{n^s}.$$

Now

$$\begin{aligned}
\int_0^\infty \theta_\chi(u) u^{\frac{s+1}{2}}\frac{du}{u} &= \int_0^\infty \sum_{n\in\mathbb{Z}} n\chi(n) e^{-\pi n^2 u} u^{\frac{s+1}{2}}\frac{du}{u} \\
&= \sum_{n\in\mathbb{Z}} n\chi(n)\int_0^\infty e^{-\pi n^2 u} u^{\frac{s+1}{2}}\frac{du}{u} \\
&= 2\sum_{n=1}^\infty n\chi(n)\int_0^\infty e^{-\pi n^2 u} u^{\frac{s+1}{2}}\frac{du}{u}
\end{aligned}$$

Where we can change the summation to be over $\mathbb{N}$ instead since $\chi(-1) = -1$ forces $\chi(-n) = -\chi(n)$, hence since the integrand is symmetric (i.e., invariant under $n \mapsto -n$), and $n\chi(n)$ is also invariant, it follows that the sum is the same as 2 times the sum over $\mathbb{N}$. Here 0 does not matter since n and $\chi(n)$ are both 0 then.

Let $w = \pi n^2 u$. Then $dw = \pi n^2 du$, so

$$
\begin{aligned}
2\sum_{n=1}^{\infty} n\chi(n)\int_0^{\infty} e^{-\pi n^2 u} u^{\frac{s+1}{2}}\frac{du}{u} &= 2\sum_{n=1}^{\infty}\frac{1}{n\pi}\chi(n)\int_0^{\infty} e^{-w}\left(\frac{w}{\pi n^2}\right)^{\frac{s-1}{2}} dw \\
&= 2\sum_{n=1}^{\infty}\frac{\chi(n)}{n^s}\pi^{\frac{-(s+1)}{2}}\Gamma\left(\frac{s+1}{2}\right)
\end{aligned}
$$

□

Exercise 8.6 (E7.6)**.** Show that the integral on the right in E7.5 defines an analytic function for all $s \in \mathbb{C}$.

Proof. The integrand is holomorphic with respect to s and continuous with respect to u, so by theorem 4.20 in KomAn, $\int_0^a \vartheta_\chi(u)u^{\frac{s+1}{2}}\frac{du}{u}$ is holomorphic for all $a > 0$. Now, we have

$$
\begin{aligned}
\left|\int_0^{\infty}\vartheta_\chi(u)u^{\frac{s+1}{2}}\frac{du}{u}\right| &\leq 2\int_0^{\infty}\sum_{n=1}^{\infty} n e^{-\pi n^2 u}u^{\frac{\sigma-1}{2}} du \\
&\leq 2\sum_{n=1}^{\infty} n\int_0^{\infty} e^{-\pi n^2 u}u^{\frac{\sigma-1}{2}} du
\end{aligned}
$$

uniformly for $\Re(s) > 1$ on compact sets. Hence it follows as the uniformly compact limit of a sequence of holomorphic functions is holomorphic. □

Exercise 8.7 (E7.7)**.** Let for $\Re(s) > 1, \xi(s,\chi) = \left(\frac{q}{\pi}\right)^{\frac{s+1}{2}}\Gamma\left(\frac{s+1}{2}\right)L(s,\chi)$. Show that $\xi(s,\chi)$ admits analytic continuation to $s \in \mathbb{C}$ and show that

$$
\xi(s,\chi) = \frac{\tau(\chi)}{i\sqrt{q}}\xi(1-s,\overline{\chi}).
$$

Proof. Notice that by definition and E7.5, we have

$$
\xi(s,\chi) = \frac{q^{\frac{s+1}{2}}}{2}\int_0^{\infty}\vartheta_\chi(u)u^{\frac{s+1}{2}}\frac{du}{u},
$$

which in particular shows that it admits an analytic continuation to all of $\mathbb{C}$. Next we have

$$
\begin{aligned}
\xi(s,\chi) &= \frac{\tau(\chi)q^{\frac{s+1}{2}}}{i2q^2}\int_0^{\infty} u^{-\frac{3}{2}}\vartheta_{\overline{\chi}}\left(\frac{1}{q^2u}\right)u^{\frac{-(1-s)}{2}} du \\
&= \frac{\tau(\chi)q^{\frac{s+1}{2}}}{i2q^2}\int_0^{\infty}\vartheta_{\overline{\chi}}\left(\frac{1}{q^2u}\right)u^{\frac{-(4-s)}{2}} du.
\end{aligned}
$$

Let $w = \frac{1}{q^2u}$. Then $dw = -\frac{1}{(qu)^2}du$, so

$$\begin{aligned}
\xi(s,\chi) &= \frac{\tau(\chi) q^{\frac{s+1}{2}}}{i2q^2} \int_0^\infty \vartheta_{\overline{\chi}}\left(\frac{1}{q^2 u}\right) u^{\frac{-(4-s)}{2}} du \\
&= \frac{\tau(\chi) q^{\frac{s-3}{2}}}{2i} \int_0^\infty \vartheta_{\overline{\chi}}(w)(wq^2)^{\frac{4-s}{2}} (\frac{1}{qw})^2 dw \\
&= \frac{\tau(\chi) q^{\frac{s-3}{2}}}{2i} q^{2-s} \int_0^\infty w^{\frac{2-s}{2}} \vartheta_{\overline{\chi}}(w) \frac{dw}{w} \\
&= \frac{\tau(\chi)}{i} q^{\frac{s-3+4-2s}{2}} \int_0^\infty w^{\frac{2-s}{2}} \vartheta_{\overline{\chi}}(w) \frac{dw}{w} \\
&= \frac{\tau(\chi)}{i\sqrt{q}} \underbrace{q^{\frac{2-s}{2}} \int_0^\infty w^{\frac{2-s}{2}} \vartheta_{\overline{\chi}}(w) \frac{dw}{w}}_{\xi(1-s,\overline{\chi})} \\
&= \frac{\tau(\chi)}{i\sqrt{q}} \xi\left(1-s,\overline{\chi}\right).
\end{aligned}$$

□

9. Assignment 1

Exercise 9.1 (H1.1)**.** *Proof.*

$$f * e(n) = \sum_{d|n} f(d) e(\frac{n}{d}) = \sum_{d|n} f(d) \delta_{\frac{n}{d},1} = f(n)$$

and since the sets $\{d\colon d \mid n\}$ and $\left\{\frac{n}{d}\colon d \mid n\right\}$ are equal, we have

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

□

Exercise 9.2 (H1.2)**.** *Proof.*

$$\mu * 1(n) = \sum_{d|n} \mu(d) 1\left(\frac{n}{d}\right) = \sum_{d|n} \mu(d)$$

If $n = p$ is a prime, we trivially have $\{d\colon d \mid n\} = \{1, p\}$, so $\sum_{d|n} \mu(d) = 1 - 1 = 0 = e(p)$, so it is true for n a prime.

Suppose now that $n = p_1 \cdots p_s$, so $\mu(n) = (-1)^s$. We need to find out how many elements the set $D_k = \{d \mid n\colon d \text{ is a product of k distinct primes}\}$ has. But this is simply the same as choosing an unordered set of k elements from a set of s elements. There are precisely $\binom{s}{k}$ ways to do so. Since for each $d \in D_k$, we have $\mu(d) = (-1)^k$, we find that

$$\sum_{d|n} \mu(d) = \sum_{k=1}^{s} \binom{s}{k} (-1)^k = (1-1)^s = 0.$$

Then, in particular,

$$\sum_{d|n} \mu(d)$$

Lastly, for $n = p_1^{\alpha_1} \cdots p_k^{\alpha_k}$, it reduces to the previous case because μ is only non-zero on squarefree integers, so

$$\mu * 1(n) = \sum_{d|\frac{n}{p_1^{\alpha_1 - 1} \cdots p_k^{\alpha_k - 1}}} \mu(d) = 0$$

since the sets $\left\{d \colon d \mid \frac{n}{p_1^{\alpha_1-1} \cdots p_k^{\alpha_k-1}}\right\}$ and $\{d \colon d \mid p_1 \cdots p_k\}$ are equal.
Thus, indeed, $\mu * 1 = e$. $\square$

Exercise 9.3 (H1.3)**.** We claim that the set of arithmetic functions with Dirichlet convolution as a binary operation is an abelian semigroup. For this, if $f, g \colon \mathbb{N} \to \mathbb{C}$, then clearly $f * g \colon \mathbb{N} \to \mathbb{C}$ too. Also, $f * g(n) = \sum_{ab=n} f(a)g(b) = \sum_{ba=n} g(b)f(a) = g * f(n)$ by commutativity of multiplication in $\mathbb{C}$. Lastly,

$$(f * g) * h(n) = \sum_{ab=n} f * g(a)h(b) = \sum_{ab=n} \sum_{cd=a} f(c)g(d)h(b) = \sum_{cdb=n} f(c)g(d)h(b)$$

and

$$f * (g * h)(n) = \sum_{ab=n} f(a)g * h(b) = \sum_{ab=n} \sum_{cd=b} f(a)g(c)h(d) = \sum_{acd=n} f(a)g(c)h(d)$$

(all of this is just Theorem 5.1.4 in the book for Introduction to Number Theory by Risager).
Now, if $f = 1 * g$ then $\mu * f = \mu * (1 * g) = (\mu * 1) * g = e * g = g * e = g$ by the above together with H1.1. Likewise, if $g = \mu * f$, then $1 * g = 1 * (\mu * f) = (1 * \mu) * f = (\mu * 1) * f = e * f = f * e = f$ again.

Exercise 9.4 (H1.4)**.** We have

$$\begin{aligned} \sum_{n=1}^{\infty} \left| \frac{f(n)}{n^s} \right| &\leq \sum_{n=1}^{\infty} \frac{Cn^k}{n^\sigma} \\ &\leq \sum_{n=1}^{\infty} \frac{C}{n^{\sigma-k}} \\ &< \infty \end{aligned}$$

as $\sigma - k > 1$. Thus the series converges absolutely.

Exercise 9.5 (H1.5)**.** *Proof.* We know that L_f converges absolutely for $\sigma > 1 + k_f$ and L_g converges absolutely for $\sigma > 1 + k_g$. Assume without loss of generality that $k_g > k_f$. Now,

$$\begin{aligned} \sum_{n=1}^{\infty} \left| \frac{\sum_{d|n} f(d)g(\frac{n}{d})}{n^s} \right| &\leq \sum_{n=1}^{\infty} \sum_{d|n} \frac{C_f C_g d^{k_f} \left(\frac{n}{d}\right)^{k_g}}{n^\sigma} \\ &= \sum_{n=1}^{\infty} C_f C_g \sum_{d|n} d^{k_f - k_g} \frac{1}{n^{\sigma - k_g}} \end{aligned}$$

Now, by E3.2, we have $d(n) \leq 2\sqrt{n}$, so since $\sum_{d|n} d^{k_f - k_g} \leq \sum_{d|n} 1 = d(n) \leq 2\sqrt{n}$, we have

$$\begin{aligned}\sum_{n=1}^{\infty} C_f C_g \sum_{d|n} d^{k_f-k_g} \frac{1}{n^{\sigma-k_g}} &\leq \sum_{n=1}^{\infty} C_f C_g 2\sqrt{n} \frac{1}{n^{\sigma-k_g}} \\ &= 2C_f C_g \sum_{n=1}^{\infty} \frac{1}{n^{\sigma-\left(k_g+\frac{1}{2}\right)}}\end{aligned}$$

Hence the sum defining $L_{f*g}(s)$ is absolutely convergent for $\sigma > k_g + \frac{3}{2}$, and in this half-plane,

$$L_f(s)L_g(s) = \sum_{k=1}^{\infty}\sum_{t=1}^{\infty} \frac{f(k)}{k^s}\frac{g(t)}{t^s} = \sum_{r=1}^{\infty}\sum_{d|r} \frac{f(d)g(\frac{n}{d})}{r^s} = L_{f*g}(s)$$

□

Exercise 9.6 (H1.6)**.** We have that when L_1 and L_μ are absolutely convergent, and satisfy the bounds from H1.5, we can use Cauchy summation to get $L_1(s)L_\mu(s) = L_{1*\mu}(s) = L_e(s) = 1$ which is absolutely convergent everywhere; but $L_1(s) = \zeta(s)$ and $L_\mu(s) = \sum_{n=1}^{\infty} \frac{\mu(n)}{n^s}$, so the result follows in whenever all sums are absolutely convergent. Hence the desired equality extends (by the identity theorem) to all of $\Re(s) > 1$ since $\sum_{n=1}^{\infty} \frac{\mu(n)}{n^s}$ converges to a holomorphic function in this half-plane (being the uniform limit of a series of holomorphic functions).

Exercise 9.7 (H 1.7)**.** *Proof.* For $f(n) = n^w$, we have $\sigma_w(n) = f * 1(n)$. The abscissa of convergence for 1 is 1 and for f it is $1 + \Re(w)$. In some halfplane, we have $\sum_{n=1}^{\infty} \frac{\sigma_w(n)}{n^s} = L_{\sigma_w}(s) = L_f(s)L_1(s)$. Now $L_1(s) = \zeta(s)$, and

$$L_f(s) = \sum_{n=1}^{\infty} \frac{n^w}{n^s} = \sum_{n=1}^{\infty} \frac{1}{n^{s-w}} = \zeta(s-w).$$

Thus $\sum_{n=1}^{\infty} \frac{\sigma_w(n)}{n^s} = \zeta(s-w)\zeta(s)$ in some right half-plane. □

10. Assignment 2

Exercise 10.1 (H2.1)**.** Show that

$$\sum_{p \leq x} \frac{1}{p} = \log\log(x) + O(1),$$

where the sum is over primes less than x.

Proof. As is the custom, we of course start by Abel summation:

$$\sum_{p \leq x} \frac{1}{p} = \pi(x)\frac{1}{x} + \int_1^x \frac{\pi(t)}{t^2} dt$$

Now applying the PNT, we get

$$\pi(x)\frac{1}{x} + \int_1^x \frac{\pi(t)}{t^2} dt = \frac{1}{\log x} + O\left(e^{-c\sqrt{\log x}}\right) + \int_1^x \frac{1}{t\log t} dt + \int_1^x O\left(t^2 e^{-c\sqrt{\log t}}\right) dt$$

Since

$$\int_1^x \frac{1}{t\log t} dt = \log\log t\Big|_1^x$$

we have what we needed.

$\square$

Exercise 10.2 (H2.2)**.** This exercise gives a different proof that $\zeta(s)$ has no zeros on $\Re(s) = 1$.

(1) Prove that for $\sigma > 1, t \in \mathbb{R}$,
$$\Re := \Re\left(3\log\zeta(\sigma) + 4\log\zeta\left(\sigma + it\right) + \log\zeta\left(\sigma + 2it\right)\right) \geq 0.$$
(2) Prove that $\left|\zeta(\sigma)^3\zeta\left(\sigma + it\right)^4\zeta\left(\sigma + 2it\right)\right| \geq 1$.
(3) Prove that if $\zeta\left(1 + it_0\right) = 0$, then $\left|\zeta(\sigma)^3\zeta\left(\sigma + it_0\right)^4\zeta\left(\sigma + 2it_0\right)\right| \to 0$ as $\sigma \to 1$.
(4) Conclude that $\zeta\left(1 + it\right) \neq 0$ for every $t \neq 0$.

Proof. (1) We want to make use of Lemma 1.2 or Lemma 1.3.
We have
$$\log\zeta\left(s\right) = \sum_{n=1}^{\infty}\frac{\Lambda(n)}{\log n}n^{-s}$$
for $\sigma = \Re(s) > 1$. Thus $\Re\left(\log\zeta(s)\right) = \sum_{n=1}^{\infty}\frac{\Lambda(n)}{\log n}\frac{1}{n^{\sigma}}\cos\left(t\log n\right)$ by (A_1). Hence
$$\Re = \sum_{n=1}^{\infty}\frac{\Lambda(n)}{n^{\sigma}\log n}\left[3 + 4\cos(t\log n) + \cos(2t\log n)\right] \geq 0$$
since all the terms are positive.

(2) Let
$$X := \zeta(\sigma)^3\zeta\left(\sigma + it\right)^4\zeta\left(\sigma + 2it\right)$$
Then $\Re\log X \geq 0$, hence $|X| = \left|e^{\log X}\right| = \left|e^{\Re\log X}\right| \geq 1$.

(3) Suppose $\zeta\left(1 + it_0\right) = 0$. Since X is continuous as a function of σ with fixed t_0 for $\sigma > 1$, we find that if
$$X_{t_0}(\sigma) = \zeta(\sigma)^3\zeta\left(\sigma + it_0\right)^4\zeta\left(\sigma + 2it_0\right)$$
then the claim is $\lim_{\sigma\to1+}X_{t_0}(\sigma) = 0$. Recall that ζ is meromorphic on $\mathbb{C}$ and has only one pole which is at 1 and is simply. So in particular, $(s-1)\zeta(s)$ is holomorphic around 1, so let $g(s) = (s-1)\zeta(s)$. In particular then, if $t_0 \neq 0$, we then $1 + it_0$ is not a pole, so if we write $\zeta\left(s\right) = (s - (1 + it_0))h(s)$ near $1 + it_0$, then we get that for σ close to 1, we have
$$\begin{aligned}X_{t_0}(\sigma) &= \frac{g(\sigma)^3}{(\sigma-1)^3}\left((\sigma + it_0) - (1 + it_0)\right)^4 h(\sigma + it_0)\zeta\left(\sigma + 2it_0\right)\\ &= \left(\sigma - 1\right)g(\sigma)^3 h\left(\sigma + it_0\right)\zeta\left(\sigma + 2it_0\right) \to 0, \quad \sigma \to 1+\end{aligned}$$

(4) Since $X\left(\sigma + it\right) \geq 1$ for all $\sigma > 1$, we thus cannot have that $X\left(1 + it\right) = 0$ since continuity would break.

$\square$

11. Assignment 3

Definition 11.1 (k-almost prime)**.** For a number $n = p_1^{a_1} \cdots p_m^{a_m}$, let $\Omega(n) = \sum_{i=1}^m a_i$. Then n is called a k-almost prime if $\Omega(n) = k$. Let P_k denote the set of k-almost primes. Then define $\pi_k(x) = \#\left(\{1, \ldots, [x]\} \cap P_k\right)$, i.e., the number of k-almost primes less than or equal to x.

Exercise 11.2 (H3.1)**.** (1) Show that

$$\pi_2(x) = \sum_{p \leq \sqrt{x}} \pi\left(\frac{x}{p}\right) + O\left(\frac{x}{\log^2 x}\right)$$

(2) Show that the sum in (1) is

$$\sum_{p \leq \sqrt{x}} \frac{x}{p \log\left(\frac{x}{p}\right)} + O\left(\frac{x \log\log x}{\log^2 x}\right)$$

(3) Use PNT and summation by parts to show that the above sum is

$$x \int_2^{\sqrt{x}} \frac{1}{u \log\left(\frac{x}{u}\right) \log u} du + O\left(\frac{x}{\log x}\right).$$

(4) Show that

$$\pi_2(x) = x \frac{\log\log x}{\log x} + O\left(\frac{x}{\log x}\right).$$

Proof. (1) Suppose $n \in \{1, \ldots, [x]\} \cap P_2$, so $n = p_1 p_2$ where we don't necessarily have that $p_1 \neq p_2$. Suppose without loss of generaliy that $p_2 \geq p_1$. Then, in particular, $\frac{n}{p_2} = p_1 \leq \sqrt{x}$. For suppose for the contrary that $p_1 > \sqrt{x}$. Then $p_2 > \sqrt{x}$, so $x < p_1 p_2 = n \leq x$, contradiction.
Using this, we see that

$$\pi_2(x) = \sum_{p_1 \leq \sqrt{x}} \sum_{p_1 < p_2 \leq \frac{x}{p_1}} 1 = \sum_{p \leq \sqrt{x}} \pi\left(\frac{x}{p}\right) - \pi(p) \leq \sum_{p \leq \sqrt{x}} \pi\left(\frac{x}{p}\right) + O\left(\sum_{p \leq \sqrt{x}} \pi(p)\right)$$

And

$$\sum_{p \leq \sqrt{x}} \pi(p) \leq \pi\left(\sqrt{x}\right)^2 = O\left(\frac{x}{\log^2\left(\sqrt{x}\right)}\right) = O\left(\frac{x}{\log^2 x}\right)$$

since $\log^2\left(x^{\frac{1}{2}}\right) = \frac{1}{4} \log^2 x$, where we also used $\pi(x) = O\left(\frac{x}{\log x}\right)$.

(2) By the PNT, $\pi(x) = \frac{x}{\log x} + O\left(\frac{x}{\log^2 x}\right)$, so

$$\sum_{p \leq \sqrt{x}} \pi\left(\frac{x}{p}\right) = \sum_{p \leq \sqrt{x}} \frac{\frac{x}{p}}{\log\left(\frac{x}{p}\right)} + O\left(\frac{\frac{x}{p}}{\log^2\left(\frac{x}{p}\right)}\right)$$

Now

$$\sum_{p \leq \sqrt{x}} \frac{x}{p \log^2\left(\frac{x}{p}\right)} \leq \sum_{p \leq \sqrt{x}} \frac{x}{p \log^2\left(\sqrt{x}\right)} \leq \frac{x}{4 \log^2 x} O\left(\log\log\sqrt{x}\right) = O\left(\frac{x \log\log x}{\log^2 x}\right),$$

giving

$$\sum_{p\le\sqrt{x}} \pi\left(\frac{x}{p}\right) = \sum_{p\le\sqrt{x}} \frac{x}{p\log\left(\frac{x}{p}\right)} + O\left(\frac{x\log\log x}{\log^2 x}\right).$$

(3) Let $f(y) = \frac{1}{y\log(\frac{x}{y})}$ and $a_n = \delta_{n,\text{ prime}}$. Then

$$f'(y) = -\frac{1}{y^2\log\left(\frac{x}{y}\right)} - \frac{y}{xy\log^2\left(\frac{x}{y}\right)} = -\frac{1}{y^2\log\left(\frac{x}{y}\right)} - \frac{1}{x\log^2\left(\frac{x}{y}\right)}.$$

$$\sum_{p\le\sqrt{x}} \frac{x}{p\log\left(\frac{x}{p}\right)} = \frac{\pi\left(\sqrt{x}\right)x}{\sqrt{x}\log\left(\sqrt{x}\right)} - x\int_1^{\sqrt{x}} \pi(t)\left[\frac{-1}{t^2\log\left(\frac{x}{t}\right)} - \frac{1}{x\log^2\left(\frac{x}{t}\right)}\right]dt$$

Firstly,

$$\frac{\pi\left(\sqrt{x}\right)x}{\sqrt{x}\log\left(\sqrt{x}\right)} = \frac{x}{4\log^2 x} + O\left(\frac{x}{\log^3 x}\right) = O\left(\frac{x}{\log x}\right).$$

Secondly,

$$x\int_1^{\sqrt{x}} \frac{\pi(t)}{t^2\log\left(\frac{x}{t}\right)}dt = x\int_1^{\sqrt{x}} \frac{1}{t\log t\log\left(\frac{x}{t}\right)}dt$$

which is precisely the term we want. It only remains to show that

$$x\int_1^{\sqrt{x}} \frac{\pi(t)}{x\log^2\left(\frac{x}{t}\right)}dt = O\left(\frac{x}{\log x}\right).$$

I.e.

$$\int_1^{\sqrt{x}} \frac{\pi(t)}{x\log^2\left(\frac{x}{t}\right)}dt = O\left(\frac{1}{\log x}\right).$$

Now

$$\int_2^{\sqrt{x}} \frac{\pi(t)}{x\log^2\left(\frac{x}{t}\right)}dt = \int_2^{\sqrt{x}} \frac{t}{x\log t\log^2\left(\frac{x}{t}\right)}dt + \int_2^{\sqrt{x}} O\left(\frac{t}{x\log^2(t)\log^2\left(\frac{x}{t}\right)}\right)dt$$

The derivative of $\frac{1}{\log x}$ is $-\frac{1}{x\log^2 x}$. Now

$$\left|\int_2^{\sqrt{x}} \frac{t}{x\log t\log^2\left(\frac{x}{t}\right)}dt\right| \le \left|\int_2^{\sqrt{x}} \frac{1}{t\log^3 t}dt\right| \le \left|\int_2^{\sqrt{x}} \frac{1}{t\log^2 t}dt\right| \le \left|\frac{1}{\log t}\Big|_2^{\sqrt{x}}\right| = O\left(\frac{1}{\log x}\right)$$

Furthermore, the second term is even smaller in size, hence also $O\left(\frac{1}{\log x}\right)$.

(4) Putting the above together, we find that

$$\begin{aligned}
\pi_2(x) &= \sum_{p\le\sqrt{x}} \pi\left(\frac{x}{p}\right) + O\left(\frac{x}{\log^2 x}\right) \\
&= \sum_{p\le\sqrt{x}} \frac{x}{p\log\left(\frac{x}{p}\right)} + O\left(\frac{x\log\log x}{\log^2 x}\right) + O\left(\frac{x}{\log^2 x}\right) \\
&= x\int_2^{\sqrt{x}} \frac{1}{t\log\left(\frac{x}{t}\right)\log t}dt + O\left(\frac{x}{\log x}\right) + O\left(\frac{x\log\log x}{\log^2 x}\right) + O\left(\frac{x}{\log^2 x}\right) \\
&= x\int_2^{\sqrt{x}} \frac{1}{t\log\left(\frac{x}{t}\right)\log t}dt + O\left(\frac{x}{\log x}\right).
\end{aligned}$$

Now, setting $\log t = v$, we get $dv = \frac{1}{t}dt$, so

$$\begin{aligned}
x\int_2^{\sqrt{x}} \frac{1}{t\log\left(\frac{x}{t}\right)\log t}dt &= x\int_{\log 2}^{\log\sqrt{x}} \frac{1}{v\left(\log x - v\right)}dv \\
&= \frac{x}{\log x}\int_{\log 2}^{\log\sqrt{x}} \frac{1}{v} + \frac{1}{\log x - v}dv \\
&= \frac{x}{\log x}\left[\log\log\sqrt{x} - \log\log 2\right] - \frac{x}{\log x}\left[\log\left(\log x - \log\sqrt{x}\right) - \log\left(\log x - \log 2\right)\right] \\
&= \frac{x}{\log x}\left[\log\log\frac{x}{2} - \log\log 2\right] = x\frac{\log\log x}{\log x} + O\left(\frac{x}{\log x}\right).
\end{aligned}$$

This completes the proof. □

Exercise 11.3 (H3.2)**.** Show that for x sufficiently large, there are more primes in the interval $(1, x]$ than in the interval $(x, 2x]$.

Proof. What this is saying is essentially that for x sufficiently large, $\pi(x) > \pi(2x) - \pi(x)$, i.e., $2\pi(x) > \pi(2x)$. By the prime number theorem, we have

$$\pi(x) = li(x) + O\left(\frac{x}{e^{c\sqrt{\log x}}}\right)$$

So

$$2\pi(x) - \pi(2x) = 2li(x) - li(2x) + O\left(\frac{x}{e^{c'\sqrt{\log x}}}\right)$$

Now

$$2li(x) - li(2x) = 2\int_2^x \frac{1}{\log t}dt - \int_2^{2x}\frac{1}{\log t}dt = \int_2^x \frac{1}{\log t}dt - \int_x^{2x}\frac{1}{\log t}dt$$

Now, $\log t \le t$, so $\int_2^x \frac{1}{\log t}dt \ge \int_2^x \frac{1}{t}dt = \log x - \log 2$.
In a weaker form, the prime number theorem says that

$$\pi(x) = \frac{x}{\log x} + O\left(\frac{x}{\log^2 x}\right).$$

Using this, we obtain

$$\begin{aligned}
2\pi(x) - \pi(2x) &= 2x\left[\frac{1}{\log x} - \frac{1}{\log 2x}\right] + 2x\left[O\left(\frac{1}{\log^2 x}\right) - O\left(\frac{1}{\log^2 2x}\right)\right] \\
&= 2\log 2\frac{x}{\log 2x\log x} + \ldots
\end{aligned}$$

Now

$$\frac{1}{\log x} - \frac{1}{\log 2x} = \frac{\log 2}{\log x \log 2x}$$

So $\frac{1}{\log 2x} = \frac{1}{\log x} + O\left(\frac{1}{\log^2 x}\right)$. Thus

$$2\log 2 \frac{x}{\log 2x \log x} = 2\log 2 \frac{x}{\log^2 x} + O\left(\frac{x}{\log^3 x}\right).$$

Now

$$\left|\left|\frac{1}{\log^2 2x}\right| - \left|\frac{1}{\log^2 x}\right|\right| \leq \left|\frac{1}{\log^2 x} - \frac{1}{\log^2 2x}\right| = \left|\frac{2\log 2 \log x + \log^2 2}{\log^2 x \log^2 2x}\right| \leq \left|\frac{2\log 2 \log x + \log^2 2}{\log^4 x}\right|$$

Hence also the last term is $O\left(\frac{x}{\log^3 x}\right)$, so we get

$$2\pi(x) - 2\pi(x) = 2\log 2 \frac{x}{\log^2 x} + O\left(\frac{x}{\log^3 x}\right).$$

Now, both $\frac{x}{\log^2 x}$ and $\frac{x}{\log^3 x}$ go to ∞ as $x \to \infty$, however, $\frac{x}{\log^2 x}$ grows faster, so we can find a $N \in \mathbb{N}$ such that $2\log 2 \frac{N}{\log^2 N} > \frac{N}{\log^3 N} + 1$. In particular, this implies that there is at least one more prime in $(x, 2x]$ than in $(1, x]$. $\square$

12. Assignment 4

Exercise 12.1 (H4.1)**.** Let $f \in \mathcal{S}(\mathbb{R})$ be a Schwartz-function on the real axis and let $\hat{f}(y) = \int_{\mathbb{R}} f(t)e^{-2\pi i t y}dt$ be its Fourier transform. Let $F(x) = \sum_{m\in\mathbb{Z}} f(x+m)$.

(1) Show that the sum defining $F(x)$ is convergent and that

$$F(x) = \sum_{m\in\mathbb{Z}} \hat{f}(m)e^{2\pi i m x}.$$

Let now χ be a primitive Dirichlet character modulo q.

(2) Show that

$$\sum_{m\in\mathbb{Z}} \chi(m) f\left(\frac{m}{q}\right) = \sum_{a=1}^{q} \chi(a) F\left(\frac{a}{q}\right).$$

(3) Show that

$$\sum_{a=1}^{q} \chi(a) F(\frac{a}{q}) = \tau(\chi) \sum_{m\in\mathbb{Z}} \overline{\chi(m)} \hat{f}(m).$$

(4) Wrap up 2) and 3) by stating in full a theorem that can be considered a character version of the Poisson summation formula.

Let $\theta_\chi(u) = \sum_{n\in\mathbb{Z}} \chi(n)e^{-\pi n^2 u}$.

(5) Show that

$$\theta_\chi(u) = \frac{\tau(\chi)}{q u^{\frac{1}{2}}} \theta_{\overline{\chi}}\left(\frac{1}{q^2 u}\right).$$

Proof. (1) If $f \in \mathcal{S}(\mathbb{R})$, then also $f(x+m) \in \mathcal{S}(\mathbb{R})$, so letting $g(m) := f(x+m)$, we get by Poisson's summation formula that

$$\sum_{m\in\mathbb{Z}} g(x) = \sum_{m\in\mathbb{Z}} \hat{g}(x)$$

where $\hat{g}(y) = \int_{-\infty}^{\infty} e^{-2\pi i x y} g(x)dx$. Thus

$$F(x) = \sum_{m\in\mathbb{Z}} f(x+m) = \sum_{m\in\mathbb{Z}} g(m) = \sum_{m\in\mathbb{Z}} \hat{g}(m) = \sum_{m\in\mathbb{Z}} \int_{-\infty}^{\infty} e^{-2\pi i t m} f(x+t)dt$$

Let now $w = x+t$. Then $dw = dt$, so

$$\sum_{m\in\mathbb{Z}} \int_{-\infty}^{\infty} e^{-2\pi i t m} f(x+t)dt = \sum_{m\in\mathbb{Z}} \int_{-\infty}^{\infty} e^{-2\pi i (w-x) m} f(w)dw = \sum_{m\in\mathbb{Z}} \hat{f}(m) e^{2\pi i m x}.$$

(2) Since χ is q-periodic, we have

$$\begin{aligned}\sum_{m\in\mathbb{Z}} \chi(m) f\left(\frac{m}{q}\right) &= \sum_{a=1}^{q} \chi(a) \sum_{k\in\mathbb{Z}} f\left(\frac{a}{q}+k\right) \\ &= \sum_{a=1}^{q} \chi(a) F\left(\frac{a}{q}\right).\end{aligned}$$

(3) Since χ is primitive, we know that

$$\chi(n)\tau(\overline{\chi}) = c_{\overline{\chi}}(n) \tag{$\mathcal{A}_1$}$$

$$\begin{aligned}\sum_{a=1}^{q} \chi(a) F\left(\frac{a}{q}\right) &= \sum_{a=1}^{q} \chi(a) \sum_{m\in\mathbb{Z}} \hat{f}(m) e^{2\pi i m \frac{a}{q}} \\ &= \sum_{m\in\mathbb{Z}} \hat{f}(m) \sum_{a=1}^{q} \chi(a) e^{2\pi i m \frac{a}{q}} \\ &= \sum_{m\in\mathbb{Z}} \hat{f}(m) c_{\chi}(m) \\ &\overset{(\mathcal{A}_1)}{=} \tau(\chi) \sum_{m\in\mathbb{Z}} \overline{\chi}(m) \hat{f}(m)\end{aligned}$$

(4)

Theorem 12.2 (Poisson summation formula, character version)**.** *If $f \in \mathcal{S}(\mathbb{R})$, then*

$$\sum_{m\in\mathbb{Z}} \chi(m) f\left(\frac{m}{q}\right) = \tau(\chi) \sum_{m\in\mathbb{Z}} \overline{\chi(m)} \hat{f}(m).$$

(5) Let $f_u = e^{-\pi u(qx)^2}$. Then we have

$$\begin{aligned}
\theta_\chi(u) &= \sum_{n\in\mathbb{Z}} \chi(n) e^{-\pi n^2 u} \\
&= \sum_{n\in\mathbb{Z}} \chi(n) f\left(\frac{n}{q}\right) \\
&= \tau(\chi) \sum_{n\in\mathbb{Z}} \overline{\chi(n)} \hat{f}(n) \\
&= \tau(\chi) \sum_{n\in\mathbb{Z}} \overline{\chi(n)} \int_{-\infty}^{\infty} e^{-2\pi i x n} e^{-\pi u(qx)^2} dx \\
&= \tau(\chi) \sum_{n\in\mathbb{Z}} \overline{\chi(n)} e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2} \int_{-\infty}^{\infty} e^{-\pi\left[u(qx)^2 + 2ixn + \left(i\frac{n}{\sqrt{u}q}\right)^2\right]} dx \\
&= \tau(\chi) \sum_{n\in\mathbb{Z}} \overline{\chi(n)} e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2} \int_{-\infty}^{\infty} e^{-\pi\left[\sqrt{u}qx + \frac{in}{\sqrt{u}q}\right]^2} dx
\end{aligned}$$

Let $w = \sqrt{u}qx + \frac{in}{\sqrt{u}q}$. Then $dw = \sqrt{u}q dx$.

$$\begin{aligned}
\tau(\chi) \sum_{n\in\mathbb{Z}} \overline{\chi(n)} e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2} \int_{-\infty}^{\infty} e^{-\pi\left[\sqrt{u}qx + \frac{in}{\sqrt{u}q}\right]^2} dx &= \tau(\chi) u^{-\frac{1}{2}} \sum_{n\in\mathbb{Z}} \overline{\chi(n)} e^{-\pi u^{-1}\left(\frac{n}{q}\right)^2} \frac{1}{q} \int_{-\infty}^{\infty} e^{-\pi w^2} dw \\
&= \frac{\tau(\chi)}{q u^{\frac{1}{2}}} \theta_{\overline{\chi}}\left(\frac{1}{q^2 u}\right)
\end{aligned}$$

□

Exercise 12.3 (H4.2)**.** Assume that a sequence of complex numbers $\{a_n\}_{n=1}^{\infty}$ satisfies $a_n = O\left(n^c\right)$ for some $c > 0$. Let $f(y) = \sum_{n=1}^{\infty} a_n e^{-2\pi n y}$.

(1) Show that the sum defining $f(y)$ converges absolutely and uniformly for $y \geq \varepsilon > 0$.
Assume there are two sequences of complex numbers $\left\{a_n^i\right\}_{n=1}^{\infty}$ as above, $i = 1, 2$. Form the corresponding functions f_1, f_2 as above and assume that for some $r > 0, a > 0$, they satisfy

$$f_1\left(\frac{1}{y}\right) = y^r f_2\left(\frac{y}{a}\right).$$

Let $L_{f_i}(s) = \sum_{n=1}^{\infty} \frac{a_n^i}{n^s}$ which is convergent for $\Re(s) > 1 + c$.

(2) Show that $(2\pi)^{-s}\Gamma(s) L_{f_i}(s)$ admits analytic continuation to $s \in \mathbb{C}$ and that it satisfies a functional equation

$$(2\pi)^{-s}\Gamma(s) L_{f_1}(s) = a^{r-s}(2\pi)^{-(r-s)}\Gamma(r-s) L_{f_2}(r-s).$$

(3) Let χ be a primitive Dirichlet character modulo $q > 1$ which is even (i.e. $\chi(-1) = 1$). Show that if $L(s,\chi) = \sum_{n=1}^{\infty} \frac{\chi(n)}{n^s}$, then $\xi(s,\chi) =$

$\left(\frac{q}{\pi}\right)^{\frac{s}{2}}\Gamma\left(\frac{s}{2}\right)L\left(s,\chi\right)$ admits analytic continuation to $s\in\mathbb{C}$ and that it satisfies a functional equation

$$\xi\left(s,\chi\right)=\varepsilon(\chi)\xi\left(1-s,\overline{\chi}\right)$$

where $\varepsilon(\chi)=\frac{\tau(\chi)}{\sqrt{q}}$.

Proof. (1) Fix $\varepsilon>0$ and assume $y\geq\varepsilon$. Then, in particular, $e^{-2\pi ny}\leq e^{-2\pi n\varepsilon}<1$ for all $n\in\mathbb{N}$. Now, $a_n=o\left(\left(e^{-2\pi\varepsilon}\right)^n\right)$, so there exists some N such that $|a_n|\,e^{-2\pi n\varepsilon}<\frac{1}{n^2}$ for all $n\geq N$. But then the sum splits as

$$|f(y)|\leq\sum_{n=1}^{\infty}|a_n|\,e^{-2\pi ny}\leq\sum_{n=1}^{\infty}|a_n|\,e^{-2\pi n\varepsilon}\leq\sum_{n=1}^{N}|a_n|\,e^{-2\pi n\varepsilon}+\frac{\pi^2}{6}<\infty$$

and since this does not depend on y, we find that f converges absolutely and uniformly for $y\geq\varepsilon>0$.

(2) Define

$$\xi_i(s)=\int_0^{\infty}f_i(y)y^{s-1}dy.$$

Then

$$\begin{aligned}\xi_i(s)&=\int_0^{\infty}\sum_{n=1}^{\infty}a_n^ie^{-2\pi ny}y^{s-1}dy\\&=\sum_{n=1}^{\infty}a_n^i\int_0^{\infty}e^{-2\pi ny}y^{s-1}dy\end{aligned}$$

Let $w=2\pi ny$. Then $dw=2\pi ndy$, so

$$\begin{aligned}\sum_{n=1}^{\infty}a_n^i\int_0^{\infty}e^{-2\pi ny}y^{s-1}dy&=\sum_{n=1}^{\infty}a_n^i\frac{1}{2\pi n}\int_0^{\infty}e^{-w}\left(\frac{w}{2\pi n}\right)^{s-1}dw\\&=\frac{1}{(2\pi)^s}\sum_{n=1}^{\infty}\frac{a_n^i}{n^s}\Gamma(s)\\&=(2\pi)^{-s}\Gamma(s)L_{f_i}(s).\end{aligned}$$

Now in the same way as usual, we can argue that $\xi_i(s)$ is analytic, so in particular we get a meromorphic continuation to all of $\mathbb{C}$ for L_{f_i}. Now

$$(2\pi)^{-s}\,\Gamma(s)L_{f_1}(s)=\int_0^{\infty}f_1(y)y^{s-1}dy$$

Let $w=\frac{1}{y}$, so $dw=-\frac{1}{y^2}dy$. Then

$$(2\pi)^{-s}\,\Gamma(s)L_{f_1}(s) = \int_0^\infty f_1(y)y^{s-1}dy$$
$$= \int_0^\infty f_1(\frac{1}{w})(\frac{1}{w})^{s+1}dw$$
$$= \int_0^\infty w^{r-(s+1)}f_2\left(\frac{w}{a}\right)dw$$

Now let $z = \frac{w}{a}$, so $dz = \frac{1}{a}dw$. Hence

$$\int_0^\infty w^{r-(s+1)}f_2\left(\frac{w}{a}\right)dw = a\int_0^\infty (az)^{r-(s+1)}f_2(z)dz$$
$$= a^{r-s}\int_0^\infty z^{r-s-1}f_2(z)dz$$
$$= a^{r-s}\xi_2\left(r-s\right)$$

giving the functional equation that we wanted.

(3) Define a sequene a_m^1 by $a_m^1 = \chi(n)$ if $m = n^2$ and $a_m^1 = 0$ otherwise. We want to find a sequence a_n^2 such that for the corresponding functions f_1, f_2, we have

$$f_1\left(\frac{1}{y}\right) = y^{\frac{1}{2}}f_2\left(\frac{y}{4q^2}\right).$$

where, recall,

$$f_i(y) = \sum_{n=1}^{\infty} a_n^i e^{-2\pi n y}.$$

Now, we have that

$$f_i(y) = \sum_{n=1}^{\infty} a_n^i e^{-2\pi n y} = \sum_{n=1}^{\infty} \chi(n)e^{-2\pi n^2 y}$$

Since χ is assumed to be odd, we have $\chi(-n) = \chi(n)$, so

$$\sum_{n=1}^{\infty} \chi(n)e^{-2\pi n^2 y} = \frac{1}{2}\sum_{n\in\mathbb{Z}} \chi(n)e^{-2\pi n^2 y} = \frac{1}{2}\theta_\chi(2y)$$

By H4.1.(5), we have

$$f_i(\frac{1}{y}) = \frac{1}{2}\theta_\chi(\frac{2}{y}) = \frac{1}{2}\frac{\tau(\chi)}{q(\frac{2}{y})^{\frac{1}{2}}}\theta_{\overline{\chi}}\left(\frac{y}{q^2 2}\right) = y^{\frac{1}{2}}\sum_{n\in\mathbb{Z}}\overline{\chi}(n)\frac{1}{2}\frac{\tau(\chi)}{q\sqrt{2}}e^{-\pi n^2\left(\frac{y}{q^2}\right)}$$

Again since χ is odd, so is $\overline{\chi}$, so we similarly, get

$$f_i\left(\frac{1}{y}\right) = y^{\frac{1}{2}}\frac{1}{2}\sum_{n=1}^{\infty}\overline{\chi}(n)\frac{\tau(\chi)}{q\sqrt{2}}e^{-\pi n^2\left(\frac{y}{q^2}\right)}$$

Define $a_m^2 = \overline{\chi}(n)\frac{\tau(\chi)}{q\sqrt{2}}$ when $m = n^2$ and 0 otherwise. Then we precisely get

$$f_1\left(\frac{1}{y}\right) = y^{\frac{1}{2}}f_2\left(\frac{y}{4q^2}\right).$$

So in particular, $r=\frac{1}{2}$ and $a=4q^2$. Hence by the functional equation,

$$(2\pi)^{-s}\,\Gamma(s)L_{f_1}(s)=(4q^2)^{\frac{1}{2}-s}(2\pi)^{-\left(\frac{1}{2}-s\right)}\Gamma\left(\frac{1}{2}-s\right)L_{f_2}\left(\frac{1}{2}-s\right).$$

Now

$$L_{f_1}(s)=\sum_{n=1}^{\infty}\frac{a_n^1}{n^s}=\sum_{n=1}^{\infty}\frac{\chi(n)}{n^{2s}}=L\left(2s,\chi\right)$$

So $L\left(s,\chi\right)=L_{f_1}\left(\frac{s}{2}\right)$. But then

$$\begin{aligned}
\xi(s,\chi)=\left(\frac{q}{\pi}\right)^{\frac{s}{2}}\Gamma(\frac{s}{2})L\left(s,\chi\right)&=q^{\frac{s}{2}}2^{\frac{s}{2}}\left(4q^2\right)^{\frac{1-s}{2}}(2\pi)^{-\left(\frac{1-s}{2}\right)}\Gamma\left(\frac{1-s}{2}\right)L_{f_2}\left(\frac{1-s}{2}\right)\\
&=2^{\frac{s-(1-s)+2(1-s)}{2}}q^{1-\frac{s}{2}}\pi^{-\frac{1-s}{2}}\Gamma\left(\frac{1-s}{2}\right)L_{f_2}\left(\frac{1-s}{2}\right)\\
&=\sqrt{2}q^{1-\frac{s}{2}}\pi^{-\frac{1-s}{2}}\Gamma\left(\frac{1-s}{2}\right)\sum_{n=1}^{\infty}\frac{1}{n^{1-s}}\overline{\chi(n)}\frac{\tau(\chi)}{q\sqrt{2}}\\
&=\varepsilon(\chi)q^{\frac{1-s}{2}}\pi^{-\frac{1-s}{2}}\Gamma\left(\frac{1-s}{2}\right)\sum_{n=1}^{\infty}\frac{\overline{\chi}(n)}{n^{1-s}}\\
&=\varepsilon(\chi)\xi\left(1-s,\overline{\chi}\right).
\end{aligned}$$

□