Selberg's Sieve I

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Overview

1. Notations
2. Sieve of Eratosthenes
3. Selberg's Sieve

Notations

1. $\mathbb{N}$ = the set of natural numbers (positive integers).
2. $\mathbb{P}$ = the set of all prime numbers.
3. For $x > 0$, let:

$$\pi(x) = \# \text{ of prime numbers } \leq x$$

   to be the prime counting function.

4. For nonzero $a, b \in \mathbb{N}$, denote:

$$(a, b) := \gcd(a, b) \text{ and } [a, b] := \text{lcm}(a, b)$$

Sieve Method

Sieve Methods are techniques used to estimate the size of a set after elements with some undesirable property have been removed.

Sieve of Eratosthenes

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Using the language of sieve method, let $A = [1, x] \cap \mathbb{N}$. To find all primes, we want to estimate the size of A after removing 1 and all composite numbers.

Characterize composite numbers

Theorem (1.1)

Let $x \geq 2$ be a real number. Let $n \in \mathbb{N}$ with $2 \leq n \leq x$. If n is composite, then n has a prime factor p with $p \leq \sqrt{x}$.

Characterize composite numbers

Theorem (1.1)

Let $x \geq 2$ be a real number. Let $n \in \mathbb{N}$ with $2 \leq n \leq x$. If n is composite, then n has a prime factor p with $p \leq \sqrt{x}$.

Proof: Suppose the result is not true. Since n is composite, it must have at least two prime factors p, q (not necessarily distinct). Then $p, q > \sqrt{x}$, so:

$$n \geq pq > \sqrt{x}\sqrt{x} = x$$

which is a contradiction. $\square$

Sieve of Eratosthenes

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So, to remove all composite numbers, it suffices to remove all integers in A that do not satisfy the property in Lemma 1.1.

For $x \geq 2$, if we remove all the multiplies of primes $\leq \sqrt{x}$ in A, the numbers that remain are primes numbers in $(\sqrt{x}, x]$ and the number 1, thus:

$$\pi(x) - \pi(\sqrt{x}) + 1 = \pi(x, \sqrt{x}) \tag{1.1}$$

Here $\pi(x, \sqrt{x})$ denote the number of $n \leq x$ with no prime factors $\leq \sqrt{x}$.

Generalization

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Definition

Let $A \subseteq \mathbb{N}$ be a finite subset of $\mathbb{N}$. Let $P \subseteq \mathbb{P}$ be a set of prime numbers and let $z > 0$. Define:

$$S(A, P, z) = \# \text{ of } a \in A \text{ that is not divisible by any } p \leq z \text{ with } p \in P$$

Generalization

If we define:

$$P_z = \prod_{\substack{p \in P \\ p \leq z}} p$$

For $p \in P$ and $p \leq z$, we have $p \mid a$ if and only if $(a, P_z) > 1$.

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Therefore, we can rewrite $S(A, P, z)$ as:

$$S(A, P, z) = \sum_{\substack{a \in A \\ (a, P_z) = 1}} 1 = \sum_{a \in A} F(a)$$

where:

$$F(a) = \begin{cases} 1 & \text{if } (a, P_z) = 1 \\ 0 & \text{if } (a, P_z) > 1 \end{cases}$$

Generalization

Let $n \in \mathbb{N}$. Define the **Möbius function**:

$$\mu(n) = \begin{cases} 1 & \text{if } n = 1 \\ 0 & \text{if } n \text{ is not squarefree} \\ (-1)^r & \text{if } n = p_1 \cdots p_r \text{ is squarefree} \end{cases}$$

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Lemma (1.2)

Let μ denote the Möbius function, then:

$$I(n) := \sum_{d|n} \mu(d) = \begin{cases} 1 & \textit{if } n = 1 \\ 0 & \textit{if } n > 1 \end{cases}$$

Generalization

Proof: If $n = 1$, trivial. Otherwise, write $n = p_1^{e_1} \cdots p_r^{e_r}$. Since $\mu(d) = 0$ if d is not squarefree, we have:

$$
\begin{aligned}
I(n) &= \sum_{\substack{d \mid n \\ d \text{ squarefree}}} \mu(d) \\
&= \sum_{(s_1, \cdots, s_r) \in \{0,1\}^r} \mu(p_1^{s_1} \cdots p_r^{s_r}) \\
&= \sum_{(s_1, \cdots, s_r) \in \{0,1\}^r} (-1)^{s_1 + \cdots + s_r} \\
&= \left(\sum_{s_1 \in \{0,1\}} (-1)^{s_1} \right) \cdots \left(\sum_{s_r \in \{0,1\}} (-1)^{s_r} \right) \\
&= 0
\end{aligned}
$$

As desired. $\square$

Generalization

By the lemma, we have:

$$I((a, P_z)) = \sum_{d|(a,P_z)} \mu(d) = \begin{cases} 1 & \text{if } (a, P_z) = 1 \\ 0 & \text{if } (a, P_z) > 1 \end{cases}$$

Hence, we have:

$$S(A, P, z) = \sum_{a \in A} \sum_{d|(a,P_z)} \mu(d) \tag{1.2}$$

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But this talk is not called the Legendre's Sieve, so by contrapositive we are not going to analyze the sum directly.

Selberg's trick

Look at the sum (1.2):

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Selberg's trick

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$$S(A, P, z) = \sum_{a \in A} \sum_{d|(a,P_z)} \mu(d)$$

Note that $\sum_{d|(a,P_z)} \mu(d)$ is either 1 or 0, so:

$$\sum_{d|(a,P_z)} \mu(d) \leq \left(\sum_{d|(a,P_z)} \lambda_d \right)^2 \tag{2.1}$$

for any sequence $(\lambda_d) \subseteq \mathbb{R}$ with $\lambda_1 = 1$.

Selberg's trick

But obviously, we cannot choose (λ_d) to be an arbitrary sequence. We need to choose it so that the quadratic form with indeterminates λ_d:

$$\left(\sum_{d|(a,P_z)} \lambda_d\right)^2 = \sum_{d_1,d_2|(a,P_z)} \lambda_{d_1}\lambda_{d_2}$$

is minimal. Otherwise, our upper bound is too big, then this trick is useless.

Selberg's Sieve

Now we can start the derivation for Selberg's Sieve.

$$
\begin{aligned}
S(A, P, z) = \sum_{\substack{a \in A \\ (a, P_z) = 1}} 1 &= \sum_{a \in A} \sum_{d \mid (a, P_z)} \mu(d) \\
&\leq \sum_{a \in A} \left(\sum_{d \mid (a, P_z)} \lambda_d \right)^2 \\
&= \sum_{a \in A} \sum_{d_1, d_2 \mid (a, P_z)} \lambda_{d_1} \lambda_{d_2}
\end{aligned}
$$

Selberg's Sieve

Note that:

$$
\begin{aligned}
d \mid (a,b) &\iff d \mid a \text{ and } d \mid b \\
[a,b] \mid \ell &\iff a \mid \ell \text{ and } b \mid \ell
\end{aligned}
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Selberg's Sieve

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$$d \mid (a,b) \iff d \mid a \text{ and } d \mid b$$
$$[a,b] \mid \ell \iff a \mid \ell \text{ and } b \mid \ell$$

Therefore:

$$\begin{aligned} S(A,P,z) &\leq \sum_{a \in A} \sum_{\substack{d_1,d_2 \mid a \\ d_1,d_2 \mid P_z}} \lambda_{d_1}\lambda_{d_2} \\ &= \sum_{d_1,d_2 \mid P_z} \lambda_{d_1}\lambda_{d_2} \sum_{\substack{a \in A \\ d_1,d_2 \mid a}} 1 \\ &= \sum_{d_1,d_2 \mid P_z} \lambda_{d_1}\lambda_{d_2} \sum_{\substack{a \in A \\ [d_1,d_2] \mid a}} 1 \end{aligned}$$

Selberg's Sieve

The last sum:

$$\sum_{\substack{a\in A\\ [d_1,d_2]|a}} 1$$

is exactly the number of $a \in A$ such that $[d_1, d_2] \mid a$.

Selberg's Sieve

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is exactly the number of $a \in A$ such that $[d_1, d_2] \mid a$.

This suggests that it is helpful to study the size of the set:

$$A_d = \{a \in A : d \mid a\}$$

for $d \mid P_z$.

Selberg's Sieve

Suppose there is a multiplicative function f with $f(p) > 1$ for all prime $p \in P$ such that:

$$|A_d| = \frac{X}{f(d)} + R_d \tag{2.2}$$

1. Think of X as an estimation of $|A|$.
2. Think of (2.2) as an estimation of $|A_d|$, with $1/f(d)$ the 'density' of A_d in A, and R_d as the error term to the estimation.

Selberg's Sieve

$$S(A, P, z) \leq \sum_{d_1, d_2 | P_z} \lambda_{d_1} \lambda_{d_2} |A_{[d_1, d_2]}|$$

Recall that:

$$|A_d| = \frac{X}{f(d)} + R_d$$

Selberg's Sieve

$$S(A,P,z) \le \sum_{d_1,d_2 | P_z} \lambda_{d_1}\lambda_{d_2} |A_{[d_1,d_2]}|$$

Recall that:

$$|A_d| = \frac{X}{f(d)} + R_d$$

We get:

$$\begin{aligned} S(A,P,z) &\le \sum_{d_1,d_2 | P_z} \lambda_{d_1}\lambda_{d_2} \left(\frac{X}{f([d_1,d_2])} + R_{[d_1,d_2]} \right) \\ &= X \underbrace{\sum_{d_1,d_2 | P_z} \frac{\lambda_{d_1}\lambda_{d_2}}{f([d_1,d_2])}}_{T} + \underbrace{\sum_{d_1,d_2 | P_z} \lambda_{d_1}\lambda_{d_2} R_{[d_1,d_2]}}_{R} \end{aligned}$$

Selberg's Sieve

Hence we get:

$$S(A, P, z) \leq XT + R$$

Remember, our goal is to minimize this upper bound by choosing (λ_d) optimally.

Let us analyze T first.

Möbius Inversion

Lemma (2.1)

Let $f, F : \mathbb{N} \to \mathbb{C}$. *Then:*

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

This is known as the **Möbius Inversion Formula**.

The Main Term

By Möbius Inversion, there is $f_1 : \mathbb{N} \to \mathbb{C}$ such that:

$$f(n) = \sum_{d|n} f_1(n)$$

Explicitly, we define:

$$f_1(n) = \sum_{d|n} f(d)\mu\left(\frac{n}{d}\right)$$

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For $n = p$ a prime, we get:

$$f_1(p) = \sum_{d|p} f(d)\mu\left(\frac{p}{d}\right) = f(1)\mu(p) + f(p)\mu(1) > 0$$

The Main Term

Lemma (2.2)

If f is multiplicative, then we have:

$$f([d_1, d_2])f((d_1, d_2)) = f(d_1)f(d_2)$$

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We have:

$$\begin{aligned} T &= \sum_{d_1,d_2 | P_z} \frac{\lambda_{d_1}\lambda_{d_2}}{f([d_1, d_2])} \\ &= \sum_{d_1,d_2 | P_z} \frac{\lambda_{d_1}\lambda_{d_2}}{f(d_1)f(d_2)} f((d_1, d_2)) \\ &= \sum_{d_1,d_2 | P_z} \frac{\lambda_{d_1}\lambda_{d_2}}{f(d_1)f(d_2)} \sum_{\delta | (d_1,d_2)} f_1(\delta) \end{aligned}$$

The Main Term

Now, we choose $\lambda_d = 0$ for $d > z$. We have:

$$
\begin{aligned}
T &= \sum_{\substack{d_1,d_2 \le z \\ d_1,d_2 | P_z}} \frac{\lambda_{d_1}\lambda_{d_2}}{f(d_1)f(d_2)} \sum_{\delta | (d_1,d_2)} f_1(\delta) \\
&= \sum_{\substack{\delta \le z \\ \delta | P_z}} f_1(\delta) \sum_{\substack{d_1,d_2 \le z \\ d_1,d_2 | P_z \\ \delta | (d_1,d_2)}} \frac{\lambda_{d_1}\lambda_{d_2}}{f(d_1)f(d_2)} \\
&= \sum_{\substack{\delta \le z \\ \delta | P_z}} f_1(\delta) \left(\sum_{\substack{d \le z \\ d | P_z \\ \delta | d}} \frac{\lambda_d}{f(d)} \right)^2
\end{aligned}
$$

The Main Term

Define:

$$u_\delta = \sum_{\substack{d \leq z \\ d | P_z \\ \delta | d}} \frac{\lambda_d}{f(d)}$$

Hence we get:

$$T = \sum_{\substack{\delta \leq z \\ \delta | P_z}} f_1(\delta) u_\delta^2$$

Also, from the sum we see $u_\delta = 0$ for $\delta > z$.

The Main Term

It turns out, by another Inversion formula, we have:

$$\frac{\lambda_d}{f(d)} = \sum_{\substack{\delta | P_z \\ d | \delta}} \mu\left(\frac{\delta}{d}\right) u_\delta \tag{2.3}$$

Plug in $d = 1$ yields:

$$1 = \frac{\lambda_1}{f(1)} = \sum_{\delta | P_z} \mu\left(\delta\right) u_\delta = \sum_{\substack{\delta \le z \\ \delta | P_z}} \mu\left(\delta\right) u_\delta$$

To choose λ_d, it suffices to choose u_δ.

The Main Term

Define:

$$V(z) = \sum_{\substack{\delta \leq z \\ d | P_z}} \frac{\mu^2(\delta)}{f_1(\delta)}$$

Then we get:

$$\begin{aligned}
&\sum_{\substack{\delta \leq z \\ \delta | P_z}} f_1(\delta) \left(u_\delta - \frac{\mu(\delta)}{f_1(\delta) V(z)} \right)^2 + \frac{1}{V(z)} \\
&= \sum_{\substack{\delta \leq z \\ \delta | P_z}} f_1(\delta) u_\delta^2 - \frac{2}{V(z)} \sum_{\substack{\delta \leq z \\ \delta | P_z}} u_\delta \mu(\delta) + \frac{1}{V(z)^2} \sum_{\substack{\delta \leq z \\ \delta | P_z}} \frac{\mu^2(\delta)}{f_1(\delta)} + \frac{1}{V(z)} \\
&= T - \frac{2}{V(z)} + \frac{1}{V(z)} + \frac{1}{V(z)}
\end{aligned}$$

The Main Term

Hence we have:

$$T = \sum_{\substack{\delta \le z \\ \delta | P_z}} f_1(\delta) \left(u_\delta - \frac{\mu(\delta)}{f_1(\delta) V(z)} \right)^2 + \frac{1}{V(z)}$$

The Main Term

The first sum is non-negative as $f_1(p) > 1$ for all p.

So, T is minimized when:

$$u_\delta = \frac{\mu(\delta)}{f_1(\delta)V(z)}$$

So we can choose:

$$\lambda_d = f(d) \sum_{\substack{\delta | P_z \\ d | \delta}} \mu\left(\frac{\delta}{d}\right) u_\delta \tag{2.4}$$

Therefore, we have:

$$T = \frac{1}{V(z)}$$

The Error Term

The error term depends on λ_d. It turns out that, given:

$$\lambda_d = f(d) \sum_{\substack{\delta | P_z \\ d | \delta}} \mu\left(\frac{\delta}{d}\right) u_\delta$$

we must have $|\lambda_d| \leq 1$ for all d. Hence:

$$R \leq \left| \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} \lambda_{d_1} \lambda_{d_2} R_{[d_1, d_2]} \right| \leq \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} |R_{[d_1, d_2]}|$$

The final result

$$S(A, P, z) \leq \frac{X}{V(z)} + \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} |R_{[d_1, d_2]}| \tag{2.5}$$

Given a problem, if we want to apply Selberg's Sieve, we need to:

1. Find suitable A, P, z.
2. Estimate $|A_d|$ for $d \mid P_z$.
3. Find a lower bound for $V(z)$.