

Selberg's Sieve - Bounding Twin Primes

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July 23rd, 2024



Recall Setup

Let us recall that

$$S(A, P, z) = \#\{a \in A : a \text{ is not divisible by any } p < z \text{ with } p \in \mathcal{P}\}$$

and Selberg's Sieve gives us

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

where

$$V(z) = \sum_{\substack{d \leq z \\ d | P_z}} \frac{\mu^2(d)}{f_1(d)} \quad f(n) = \sum_{d|n} f_1(d) \quad \text{and} \quad |A_d| = \frac{X}{f(d)} + R_d$$

Notice that in order to use Selberg's Sieve, we want to find an upper bound for $\frac{1}{V(z)}$, thus a lower bound for $V(z)$, which motivates the following lemma:

Lemma

Lemma

Let \tilde{f} be a completely multiplicative function with $\tilde{f}(p) := f(p)$ for all primes p . Then we have

$$V(z) \geq \sum_{\substack{e \leq z \\ p|e \Rightarrow p|P_z}} \frac{1}{\tilde{f}(e)} \quad \text{where} \quad P_z = \prod_{\substack{p \in \mathcal{P} \\ p \leq z}} p$$

Note: If \mathcal{P} is the set of all primes, then the second condition $p \mid e \Rightarrow p \mid P_z$ is trivial. However, we will keep our \mathcal{P} generic in this lemma.

Twin Primes

Definition

A prime p is called a twin prime if $p + 2$ is also a prime.

Let

$$\pi_2(x) := \# \text{ of twin primes } \leq x$$

We would like to use Selberg's Sieve to obtain an upper bound for $\pi_2(x)$ as $x \rightarrow \infty$. In the setting of this problem, we define

$$A = \{n(n+2) : n \leq x\} \quad \text{and} \quad \mathcal{P} = \text{set of all primes}$$

Each natural number n corresponds to a unique $a = n(n+2) \in A$, and vice versa; so we will sieve through A instead of the set $\{n \in \mathbb{N} : n \leq x\}$.

Understanding $S(A, \mathcal{P}, z)$

For $0 < z < x$, we have

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

and so

$$S(A, \mathcal{P}, z) := \#\{n(n+2) : n \leq x, p \nmid n \text{ and } p \nmid (n+2) \text{ for all } p \leq z\}$$

- If $n \leq z$, $n(n+2)$ is not counted in $S(A, \mathcal{P}, z)$, ie. n is not counted.
- All twin primes $z < p \leq x$ are counted.

$$\pi_2(x) = \sum_{\substack{p \leq x \\ p+2 \in \mathcal{P}}} 1 = \pi_2(z) + \sum_{\substack{z < p \leq x \\ p+2 \in \mathcal{P}}} 1$$

$$\leq \pi_2(z) + S(A, \mathcal{P}, z) \leq z + S(A, \mathcal{P}, z)$$

Outline of Steps

Once again, Selberg's Sieve gives us

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

To use Selberg's Sieve, we will need to

- Find X , estimation of the size of A (Clearly, $X = x$) ✓
- Estimate $|A_d|$ for $d \mid P_z$ to find our multiplicative function, f
- Find lower bound for $V(z)$
- Estimate error term

Estimating $|A_d|$

Let $d \mid P_z$, say $d = p_1 \cdots p_n$. Then we have

$$\begin{aligned}|A_d| &= \#\{n(n+2) : n \leq x \text{ and } d \mid n(n+2)\} \\ &= \#\{n(n+2) : n \leq x \text{ and } n(n+2) \equiv 0 \pmod{d}\}\end{aligned}$$

Let $N(q)$ be the number of solutions to $n(n+2) \equiv 0 \pmod{q}$. By the Chinese Remainder Theorem, $n(n+2) \equiv 0 \pmod{d}$ has the same number of solutions as

$$\begin{aligned}n(n+2) &\equiv 0 \pmod{p_1} \\ &\vdots \\ n(n+2) &\equiv 0 \pmod{p_k}\end{aligned}$$

Let $\omega(d) = k$ be the number of prime factors of d . Since for each $1 \leq i \leq k$, $N(p_i) \leq 2$, we have that

$$N(d) = N(p_1) \cdots N(p_k) \leq 2^k = 2^{\omega(d)}$$

Estimating $|A_d|$ Cont'n

Further, since $N(d)$ is only the number of solutions modulo d and we want all solutions $\leq x$, we can estimate the total number of solutions, ie. the size of A_d by

$$|A_d| = \frac{x}{d} \cdot N(d) + R_d, \quad \text{where } R_d \leq N(d) \leq 2^{\omega(d)}$$

Thus, we have our multiplicative function

$$f(d) = \frac{d}{N(d)}$$

which satisfies the conditions of Selberg's Sieve. And a simple fact for later:

$$f(p) = \frac{d}{N(d)} = \begin{cases} p & \text{if } p = 2 \\ p/2 & \text{if } p > 2 \end{cases}$$

Next Step

- Find X , estimation of the size of A (Clearly, $X = x$) ✓
- Estimate $|A_d|$ for $d \mid P_z$ to find our multiplicative function, f ✓
- Find lower bound for $V(z)$
- Estimate error term

Bounding $V(z)$ - Notations

First, let us define some notations

Definition

For $n \in \mathbb{N}$, define

$$\tau_1(n) := \# \text{ odd divisors of } n$$

And so for $n = 2^s p_1^{e_1} \cdots p_m^{e_m}$, we have $\tau_1(n) = (e_1 + 1) \cdots (e_m + 1)$

Definition

For $n \in \mathbb{N}$, define

$$\tau(n) := \# \text{ divisors of } n$$

Note that if d is square free, then $\tau(d) = 2^{\omega(d)}$.

Bounding $V(z)$

Let \tilde{f} be a completely multiplicative function with $\tilde{f}(p) = f(p)$ for all primes p , as defined in our lemma. Then the lemma tells us that

$$\begin{aligned} V(z) &\geq \sum_{\substack{n \leq z \\ p|n \Rightarrow p|P_z}} \frac{1}{\tilde{f}(n)} = \sum_{n \leq z} \frac{1}{\tilde{f}(2)^s \tilde{f}(p_1)^{e_1} \cdots \tilde{f}(p_m)^{e_m}} \\ &= \sum_{n \leq z} \frac{1}{2^s (p_1/2)^{e_1} \cdots (p_m/2)^{e_m}} \\ &= \sum_{n \leq z} \frac{2^{e_1} \cdots 2^{e_m}}{n} \\ &\geq \sum_{n \leq z} \frac{(e_1 + 1) \cdots (e_m + 1)}{n} \\ &= \sum_{n \leq z} \frac{\tau_1(n)}{n} \end{aligned}$$

Bounding $V(z)$ Cont'd

Next, we have

$$\sum_{n \leq z} \tau_1(n) = \sum_{n \leq z} \sum_{\substack{d|n \\ (d,2)=1}} 1 = \sum_{\substack{d \leq z \\ (d,2)=1}} \sum_{\substack{n \leq z \\ d|n}} 1 = \sum_{\substack{d \leq z \\ (d,2)=1}} \left[\frac{z}{d} \right]$$

Bounding $V(z)$ Cont'd

Next, we have

$$\begin{aligned}\sum_{n \leq z} \tau_1(n) &= \sum_{n \leq z} \sum_{\substack{d|n \\ (d,2)=1}} 1 = \sum_{\substack{d \leq z \\ (d,2)=1}} \sum_{\substack{n \leq z \\ d \nmid n}} 1 = \sum_{\substack{d \leq z \\ (d,2)=1}} \left[\frac{z}{d} \right] \\ &= \sum_{\substack{d \leq z \\ (d,2)=1}} \frac{z}{d} - \sum_{\substack{d \leq z \\ (d,2)=1}} \left\{ \frac{z}{d} \right\} \geq \sum_{\substack{d \leq z \\ (d,2)=1}} \frac{z}{d} - \sum_{\substack{d \leq z \\ (d,2)=1}} 1\end{aligned}$$

Bounding $V(z)$ Cont'd

Next, we have

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Bounding $V(z)$ Cont'd

For the summation

$$\sum_{\substack{d \leq z \\ (d,2)=1}} \frac{1}{d}, \text{ we choose } c_d = \begin{cases} 1 & \text{if } (d,2) = 1 \\ 0 & \text{otherwise} \end{cases} \text{ and } f(d) = \frac{1}{d}$$

Then by the partial summation technique, we have

$$\sum_{\substack{d \leq z \\ (d,2)=1}} \frac{1}{d} = \frac{1}{z} \sum_{\substack{d \leq z \\ (d,2)=1}} 1 + \int_1^z \left(\frac{1}{t^2} \sum_{\substack{d \leq t \\ (d,2)=1}} 1 \right) dt$$

Bounding $V(z)$ Cont'd

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Bounding $V(z)$ Cont'd

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Bounding $V(z)$ Cont'd

Hence we have that

$$\sum_{n \leq z} \tau_1(n) \geq z \sum_{\substack{d \leq z \\ (d,2)=1}} \frac{1}{d} - z \geq \frac{1}{2} z \log z - \underbrace{(c+1)}_D z$$

Now, for

$$\sum_{n \leq z} \frac{\tau_1(n)}{n}, \quad \text{we choose } c_n = \tau_1(n) \quad \text{and } f(n) = \frac{1}{n}$$

Apply partial summation again, and we get

$$V(z) \geq \sum_{n \leq z} \frac{\tau_1(n)}{n} \geq \frac{1}{4} \log^2(z) + \left(\frac{1}{2} - D \right) \log z - D \gg \log^2(z)$$

Next Step

- Find X , estimation of the size of A (Clearly, $X = x$) ✓
- Estimate $|A_d|$ for $d \mid P_z$ to find our multiplicative function, f ✓
- Find lower bound for $V(z)$ ✓
- Estimate error term

Estimate Error Term

First, let us note that

$$\sum_{n \leq x} \tau(n) = \sum_{n \leq x} \sum_{\substack{d \leq x \\ d|n}} 1 = \sum_{d \leq x} \sum_{\substack{n \leq x \\ d|n}} 1 = \sum_{d \leq x} \left\lfloor \frac{x}{d} \right\rfloor \leq x \sum_{d \leq x} \frac{1}{d}$$

Taking $c_n = 1$ and $f(t) = \frac{1}{t}$, we can use partial summation to get that

$$x \sum_{d \leq x} \frac{1}{d} = x \left(\frac{1}{x} \cdot [x] + \int_1^x \frac{[t]}{t^2} dt \right) \leq x(1 + \log x) \ll x \log x$$

Hence,

$$\sum_{n \leq x} \tau(n) \ll x \log x$$

Estimate Error Term Cont'd

Note that our error term when estimating $|A_d|$ satisfies

$$R(d) \leq N(d) \leq 2^{\omega(d)}$$

Thus, we have for the error term from Selberg's Sieve,

$$\sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} R([d_1, d_2]) \leq \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} 2^{\omega([d_1, d_2])} \leq \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} 2^{\omega(d_1)} 2^{\omega(d_2)}$$

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Next Step

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- Find lower bound for $V(z)$ ✓
- Estimate error term ✓

Finalé

We shall recall our bound on $\pi_2(x)$ from before:

$$\pi_2(x) \leq x + S(A, \mathcal{P}, z)$$

As well, from Selberg and all the work we've done, we have

$$S(A, \mathcal{P}, z) \leq \frac{X}{V(z)} + \sum_{\substack{d_1, d_2 \leq z \\ d_1, d_2 | P_z}} |R_{[d_1, d_2]}| \ll \frac{x}{\log^2(z)} + (z \log z)^2$$

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And so

$$\pi_2(x) \ll z + \frac{x}{\log^2(z)} + (z \log z)^2$$

Now, if we pick $z = x^{1/4}$, we have

$$\pi_2(x) \ll x^{1/4} + 16 \cdot \frac{x}{\log^2(x)} + \frac{1}{16} \sqrt{x} \log^2(x) \ll \frac{x}{\log^2(x)}$$

The End

Thank You!

