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DIRICHLET PRODUCT OF DERIVATIVE ARITHMETIC WITH AN ARITHMETIC FUNCTION MULTIPLICATIVE

A PREPRINT

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ABSTRACT

We define the derivative of an integer to be the map sending every prime to 1 and satisfying the Leibniz rule. The aim of this article is to calculate the Dirichlet product of this map with a function arithmetic multiplicative.

1 Introduction

Barbeau [1] defined the arithmetic derivative as the function $\delta : \mathbb{N} \rightarrow \mathbb{N}$, defined by the rules :

1. $\delta(p) = 1$ for any prime $p \in \mathbb{P} := \{2, 3, 5, 7, \dots, p_i, \dots\}$.
2. $\delta(ab) = \delta(a)b + a\delta(b)$ for any $a, b \in \mathbb{N}$ (the Leibnitz rule).

Let n a positive integer, if $n = \prod_{i=1}^s p_i^{\alpha_i}$ is the prime factorization of n , then the formula for computing the arithmetic derivative of n is (see, e.g., [1, 3]) giving by :

$$\delta(n) = n \sum_{i=1}^s \frac{\alpha_i}{p_i} = n \sum_{p^\alpha || n} \frac{\alpha}{p} \quad (1)$$

A brief summary on the history of arithmetic derivative and its generalizations to other number sets can be found, e.g., in [4].

First of all, to cultivate analytic number theory one must acquire a considerable skill for operating with arithmetic functions. We begin with a few elementary considerations.

Definition 1 (arithmetic function). An **arithmetic function** is a function $f : \mathbb{N} \rightarrow \mathbb{C}$ with domain of definition the set of natural numbers \mathbb{N} and range a subset of the set of complex numbers \mathbb{C} .

Definition 2 (multiplicative function). A function f is called an **multiplicative function** if and only if :

$$f(nm) = f(n)f(m) \quad (2)$$

for every pair of coprime integers n, m . In case (2) is satisfied for every pair of integers n and m , which are not necessarily coprime, then the function f is called **completely multiplicative**.

Clearly, if f are a multiplicative function, then $f(n) = f(p_1^{\alpha_1}) \dots f(p_s^{\alpha_s})$, for any positive integer n such that $n = p_1^{\alpha_1} \dots p_s^{\alpha_s}$, and if f is completely multiplicative, so we have : $f(n) = f(p_1)^{\alpha_1} \dots f(p_s)^{\alpha_s}$.

Example 3. Let $n \in \mathbb{N}^*$, This is the same classical arithmetic functions used in this article :

1. **Identity function** : The function defined by $Id(n) = n$ for all positive integer n .

$$2. \text{ The Euler phi function : } \varphi(n) = \sum_{\substack{k=1 \\ \gcd(k,n)=1}}^n 1.$$

$$3. \text{ The number of distinct prime divisors of } n : \omega(n) = \sum_{p|n} 1.$$

$$4. \text{ The Mobius function : } \mu(n) = \begin{cases} 1 & \text{if } n = 1 \\ 0 & \text{if } p^2 | n \text{ for some prime } p \\ (-1)^{\omega(n)} & \text{otherwise} \end{cases}$$

$$5. \text{ number of positive divisors of } n \text{ defined by : } \tau(n) = \sum_{d|n} 1.$$

$$6. \text{ sum of divisors function of } n \text{ defined by : } \sigma(n) = \sum_{d|n} d.$$

Now ,if $f, g : \mathbb{N} \rightarrow \mathbb{C}$ are two arithmetic functions from the positive integers to the complex numbers, the Dirichlet convolution $f * g$ is a new arithmetic function defined by:

$$(f * g)(n) = \sum_{d|n} f(d)g\left(\frac{n}{d}\right) = \sum_{ab=n} f(a)g(b) \quad (3)$$

where the sum extends over all positive divisors d of n , or equivalently over all distinct pairs (a, b) of positive integers whose product is n .

In particular, we have $(f * g)(1) = f(1)g(1)$, $(f * g)(p) = f(1)g(p) + f(p)g(1)$ for any prime p and for any power prime p^m we have :

$$(f * g)(p^m) = \sum_{j=0}^m f(p^j)g(p^{m-j}) \quad (4)$$

This product occurs naturally in the study of Dirichlet series such as the Riemann zeta function. It describes the multiplication of two Dirichlet series in terms of their coefficients:

$$\left(\sum_{n \geq 1} \frac{(f * g)(n)}{n^s} \right) = \left(\sum_{n \geq 1} \frac{f(n)}{n^s} \right) \left(\sum_{n \geq 1} \frac{g(n)}{n^s} \right) \quad (5)$$

with Riemann zeta function or is defined by :

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

These functions are widely studied in the literature (see, e.g., [5, 6, 7]).

Now before to past to main result we need this propriety , if f and g are multiplicative function , then $f * g$ is multiplicative.

2 Main results

In this section we give the new result of Dirichlet product between derivative arithmetic and an arithmetic function multiplicative f , and we will give the relation between τ and the derivative arithmetic .

Theorem 4. *Given a multiplicative function f , and lets n and m two positive integers such that $\gcd(n, m) = 1$, Then we have :*

$$(f * \delta)(nm) = (Id * f)(n) \cdot (f * \delta)(m) + (Id * f)(m) \cdot (f * \delta)(n) \quad (6)$$

Proof. Lets n and m two positive integers such that $gcd(n, m) = 1$, and let f an arithmetic function multiplicative , then we have :

$$\begin{aligned}
(f * \delta)(nm) &= \sum_{d|nm} f\left(\frac{nm}{d}\right)\delta(d) = \sum_{\substack{d_1|n \\ d_2|m}} f\left(\frac{nm}{d_1 d_2}\right)\delta(d_1 d_2) = \sum_{\substack{d_1|n \\ d_2|m}} f\left(\frac{n}{d_1}\right)f\left(\frac{m}{d_2}\right)\left(d_1\delta(d_2) + d_2\delta(d_1)\right) \\
&= \sum_{\substack{d_1|n \\ d_2|m}} \left(d_1 f\left(\frac{n}{d_1}\right)f\left(\frac{m}{d_2}\right)\delta(d_2) + d_2 f\left(\frac{m}{d_2}\right)f\left(\frac{n}{d_1}\right)\delta(d_1)\right) \\
&= \left(\sum_{d_1|n} d_1 f\left(\frac{n}{d_1}\right)\right)\left(\sum_{d_2|m} f\left(\frac{m}{d_2}\right)\delta(d_2)\right) + \left(\sum_{d_2|m} d_2 f\left(\frac{m}{d_2}\right)\right)\left(\sum_{d_1|n} f\left(\frac{n}{d_1}\right)\delta(d_1)\right) \\
&= (Id * f)(n).(f * \delta)(m) + (Id * f)(m).(f * \delta)(n)
\end{aligned}$$

□

Lemma 5. For any natural number n , if $n = \prod_{i=1}^s p_i^{\alpha_i}$ is the prime factorization of n , then :

$$(f * \delta)(n) = (Id * f)(n) \sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})} \quad (7)$$

Proof. Let n a positive integer such that $n = p_1^{\alpha_1} \dots p_s^{\alpha_s}$ and let f an arithmetic function , Then :

$$\begin{aligned}
(f * \delta)(n) &= (f * \delta)(p_1^{\alpha_1} \dots p_s^{\alpha_s}) \\
&= (Id * f)(p_2^{\alpha_2} \dots p_s^{\alpha_s}).(f * \delta)(p_1^{\alpha_1}) + (Id * f)(p_1^{\alpha_1}).(f * \delta)(p_2^{\alpha_2} \dots p_s^{\alpha_s}) \\
&= (Id * f)(n) \cdot \frac{(f * \delta)(p_1^{\alpha_1})}{(Id * f)(p_1^{\alpha_1})} + (Id * f)(p_1^{\alpha_1}) \cdot \left[(Id * f)(p_3^{\alpha_3} \dots p_s^{\alpha_s}).(f * \delta)(p_2^{\alpha_2}) + \right. \\
&\quad \left. + (Id * f)(p_2^{\alpha_2}).(f * \delta)(p_3^{\alpha_3} \dots p_s^{\alpha_s}) \right] \\
&= (Id * f)(n) \frac{(f * \delta)(p_1^{\alpha_1})}{(Id * f)(p_1^{\alpha_1})} + (Id * f)(n) \frac{(f * \delta)(p_2^{\alpha_2})}{(Id * f)(p_2^{\alpha_2})} + \\
&\quad + (Id * f)(p_1^{\alpha_1})(Id * f)(p_2^{\alpha_2})(f * \delta)(p_3^{\alpha_3} \dots p_s^{\alpha_s}) \\
&\vdots \\
&= (Id * f)(n) \frac{(f * \delta)(p_1^{\alpha_1})}{(Id * f)(p_1^{\alpha_1})} + (Id * f)(n) \frac{(f * \delta)(p_2^{\alpha_2})}{(Id * f)(p_2^{\alpha_2})} + \dots + (Id * f)(n) \frac{(f * \delta)(p_s^{\alpha_s})}{(Id * f)(p_s^{\alpha_s})} \\
&= (Id * f)(n) \left[\frac{(f * \delta)(p_1^{\alpha_1})}{(Id * f)(p_1^{\alpha_1})} + \dots + \frac{(f * \delta)(p_s^{\alpha_s})}{(Id * f)(p_s^{\alpha_s})} \right] \\
&= (Id * f)(n) \sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})}
\end{aligned}$$

□

an other prof by induction on s that if $n = \prod_{i=1}^s p_i^{\alpha_i}$ then $(f * \delta)(n) = (Id * f)(n) \sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})}$.

Proof. Consider $n \in \mathbb{N}$ and express $n = \prod_{i=1}^s p_i^{\alpha_i}$ where all p_i are distinct .

where $s = 1$, it is clear that $(f * \delta)(n) = (Id * f)(n) \sum_{i=1}^1 \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})} = (Id * f)(p_1^{\alpha_1}) \frac{(f * \delta)(p_1^{\alpha_1})}{(Id * f)(p_1^{\alpha_1})} = (f * \delta)(p_1^{\alpha_1})$.

Assume that $n = \prod_{i=1}^s p_i^{\alpha_i}$, then we have :

$$\begin{aligned}
(id * \delta)(n.p_{s+1}^{\alpha_{s+1}}) &= (Id * f)(p_{s+1}^{\alpha_{s+1}}) \cdot (f * \delta)(n) + (Id * f)(n) \cdot (f * \delta)(p_{s+1}^{\alpha_{s+1}}) \\
&= (Id * f)(p_{s+1}^{\alpha_{s+1}}) \cdot (Id * f)(n) \sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})} + (Id * f)(p_{s+1}^{\alpha_{s+1}}) \cdot (Id * f)(n) \frac{(f * \delta)(p_{s+1}^{\alpha_{s+1}})}{(Id * f)(p_{s+1}^{\alpha_{s+1}})} \\
&= (Id * f)(n.p_{s+1}^{\alpha_{s+1}}) \sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})} + (Id * f)(n.p_{s+1}^{\alpha_{s+1}}) \frac{(f * \delta)(p_{s+1}^{\alpha_{s+1}})}{(Id * f)(p_{s+1}^{\alpha_{s+1}})} \\
&= (Id * f)(n.p_{s+1}^{\alpha_{s+1}}) \left[\sum_{i=1}^s \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})} + \frac{(f * \delta)(p_{s+1}^{\alpha_{s+1}})}{(Id * f)(p_{s+1}^{\alpha_{s+1}})} \right] \\
&= (Id * f)(n.p_{s+1}^{\alpha_{s+1}}) \sum_{i=1}^{s+1} \frac{(f * \delta)(p_i^{\alpha_i})}{(Id * f)(p_i^{\alpha_i})}
\end{aligned}$$

□

Proposition 6. Let f a function arithmetic multiplicative, and δ the derivative arithmetic, then we have :

$$(Id * \delta)(n) = \frac{1}{2} \tau(n) \delta(n) \quad (8)$$

Proof. Since $(Id * Id)(n) = \sum_{d|n} \frac{n}{d} = n \sum_{d|n} 1 = n\tau(n)$.

and : $(Id * \delta)(p^\alpha) = \sum_{j=1}^{\alpha} \delta(p^j) Id(p^{\alpha-j}) = \sum_{j=1}^{\alpha} j p^{j-1} p^{\alpha-j} = \frac{1}{2} \alpha(\alpha+1) p^{\alpha-1}$.

Then for every a positive integer n such that $n = p_1^{\alpha_1} \dots p_s^{\alpha_s}$, we have :

$$\begin{aligned}
(Id * \delta)(n) &= (Id * Id)(n) \sum_{i=1}^s \frac{(Id * \delta)(p_i^{\alpha_i})}{(Id * Id)(p_i^{\alpha_i})} \\
&= n\tau(n) \sum_{i=1}^s \frac{\frac{1}{2} \alpha_i (\alpha_i + 1) p_i^{\alpha_i - 1}}{p_i^{\alpha_i} \tau(p_i^{\alpha_i})} \\
&= n\tau(n) \sum_{i=1}^s \frac{\frac{1}{2} \alpha_i (\alpha_i + 1) p_i^{\alpha_i - 1}}{p_i^{\alpha_i} (\alpha_i + 1)} \\
&= \frac{1}{2} n\tau(n) \sum_{i=1}^s \frac{\alpha_i}{p_i} = \frac{1}{2} \tau(n) \delta(n)
\end{aligned}$$

□

So by the proposition 6, and the equality 5 we have this relation between arithmetic derivative and the function τ :

$$2\zeta(s-1) \sum_{n \geq 1} \frac{\delta(n)}{n^s} = \sum_{n \geq 1} \frac{\delta(n) \tau(n)}{n^s} \quad (9)$$

Let defined the new function arithmetic called **En-naoui** function, by :

$$\Phi_\varphi(n) = n \sum_{p|n} \left(1 - \frac{1}{p} \right) \quad (10)$$

Then we have this equality related between 8 arithmetic function :

$$(\mu * \delta)(n) = \varphi(n) \left(\delta(n) - 2\omega(n) + B(n) + \frac{\Phi_\varphi(n)}{n} + \frac{(B * Id)(n)}{\sigma(n)} \right). \quad (11)$$

with B is the arithmetic function defined by : $B(n) = \sum_{p^\alpha || n} \alpha p$. In next article i will prove this equality, just I need to submit an article about this new function .

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