

Bernoulli Numbers

Emil Kerimov

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1 Bernoulli Numbers

Examining the Taylor expansion of $\frac{x}{e^x-1}$, this will be required for the evaluation of the even integer values of ζ .

Definition 1.1 *The Bernoulli numbers B_n are defined as the coefficients of the Taylor expansion of the following function*

$$\frac{x}{e^x - 1} = \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n$$

Theorem 1.1

$$\sum_k^n \binom{n+1}{k} B_k = 0 \quad \forall n > 0, \text{ with } B_0 = 1 \quad (1)$$

Proof

Starting from definition 1.1

$$\frac{x}{e^x - 1} = \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n$$

Using the Taylor expansion of e^x

$$\frac{x}{\sum_{k=1}^{\infty} \frac{x^k}{k!}} = \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n$$

Rearranging

$$\begin{aligned} x &= \sum_{k=1}^{\infty} \frac{x^k}{k!} \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n \\ 1 &= \sum_{k=1}^{\infty} \frac{x^{k-1}}{k!} \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n \end{aligned}$$

Adjusting the indicies

$$1 = \sum_{k=0}^{\infty} \frac{x^k}{(k+1)!} \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n$$

Using Cauchy's product formula for infinite sums ¹

$$1 = \sum_{n=0}^{\infty} \underbrace{\sum_{k=0}^n \underbrace{\left(\frac{B_k}{k!} x^k\right)}_{a_k} \underbrace{\left(\frac{x^{n-k}}{(n-k+1)!}\right)}_{b_{n-k}}}_{c_n}$$

Simplifying

$$\begin{aligned} 1 &= \sum_{n=0}^{\infty} \frac{1}{(n+1)!} \sum_{k=0}^n \binom{n+1}{k} B_k x^k x^{n-k} \\ 1 &= \sum_{n=0}^{\infty} \frac{x^n}{(n+1)!} \sum_{k=0}^n \binom{n+1}{k} B_k \end{aligned}$$

Comparing coefficients of powers of x of both sides we get

$$\begin{aligned} n = 0, \quad 1 &= B_0 \\ n \neq 0, \quad 0 &= \sum_{k=0}^n \binom{n+1}{k} B_k \end{aligned}$$

1.1 First few Bernoulli numbers

Using equation 1 with $n = 1$ implies $\binom{2}{0}B_0 + \binom{2}{1}B_1 = 0 = 1 + 2B_1$ which implies

$$B_1 = -\frac{1}{2} \quad (2)$$

Using equation 1 with $n = 2$ implies $\binom{3}{0}B_0 + \binom{3}{1}B_1 + \binom{3}{2}B_2 = 0 = 1 - \frac{3}{2} + 3B_2$ which implies

$$B_2 = \frac{1}{6} \quad (3)$$

Similarly when we apply this equation for increasing values of n

$$B_3 = 0, B_4 = -\frac{1}{30}, B_5 = 0, B_6 = \frac{1}{42}, \dots \quad (4)$$

Theorem 1.2 In fact we can show that all odd Bernoulli numbers after $n=1$ are 0

$$B_n = 0 \quad \forall \text{ odd } n > 1 \quad (5)$$

Proof

Starting from definition 1.1

$$\frac{x}{e^x - 1} = \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n$$

¹ $\left(\sum_{n=0}^{\infty} a_n\right)\left(\sum_{n=0}^{\infty} b_n\right) = \sum_{n=0}^{\infty} c_n$ where $c_n = \sum_{k=0}^n a_k b_{n-k}$. See proof: TODO ADD

Removing the first two terms of the sum

$$\frac{x}{e^x - 1} = B_0 + B_1x + \sum_{n=2}^{\infty} \frac{B_n}{n!} x^n$$

Rearranging

$$\begin{aligned} \frac{x}{e^x - 1} - 1 + \frac{x}{2} &= \sum_{n=2}^{\infty} \frac{B_n}{n!} x^n \\ \frac{x + xe^x}{2e^x - 2} - 1 &= \sum_{n=2}^{\infty} \frac{B_n}{n!} x^n \end{aligned}$$

If we can show that the RHS is an even function then we have established the proof

$$\begin{aligned} y(x) &= \frac{x + xe^x}{2e^x - 2} - 1 \\ y(-x) &= \frac{-x + -xe^{-x}}{2e^{-x} - 2} - 1 \end{aligned}$$

Simplifying

$$\begin{aligned} y(-x) &= \frac{-x - xe^{-x}}{2e^{-x} - 2} \cdot \frac{e^x}{e^x} - 1 \\ y(-x) &= \frac{-xe^x - x}{2 - 2e^x} - 1 \\ y(-x) &= \frac{x + xe^x}{2e^x - 2} - 1 \\ y(-x) &= y(x) \\ B_n &= 0 \quad \forall \text{ odd } n > 1 \end{aligned}$$

2 Bernoulli Polynomials

Definition 2.1 The Bernoulli polynomials $B_n(x)$ are defined as

$$B_n(x) = \sum_{k=0}^n \binom{n}{k} B_k x^{n-k}$$

2.1 Examples

$$B_0(x) = B_0 = 1$$

$$B_1(x) = B_0x + B_1 = x - \frac{1}{2}$$

$$B_2(x) = B_0x^2 + \binom{2}{1}B_1x + B_2 = x^2 - x + \frac{1}{6}$$

$$B_3(x) = B_0x^3 + \binom{3}{1}B_1x^2 + \binom{3}{2}B_2x + B_3 = x^3 - \frac{3}{2}x^2 + \frac{1}{2}x$$

Note that $B_n(x)$ is a polynomial of degree n .

2.2 Useful Properties

Theorem 2.1 $B_n(0)$

$$B_n(0) = B_n \tag{6}$$

Proof

$$B_n(x) = \sum_{k=0}^n \binom{n}{k} B_k x^{n-k}$$

$$B_n(x) = \sum_{k=0}^{n-1} \binom{n}{k} B_k x^{n-k} + B_n$$

$$B_n(0) = \sum_{k=0}^{n-1} \binom{n}{k} B_k \cdot 0 + B_n = B_n$$

Theorem 2.2 $B_n(1)$

$$B_n(1) = B_n \quad n \neq 1 \quad B_1(1) = -B_1 \tag{7}$$

Proof

$$B_n(x) = \sum_{k=0}^n \binom{n}{k} B_k x^{n-k}$$

$$B_n(1) = \sum_{k=0}^n \binom{n}{k} B_k$$

Using equation 1, $\sum_k^n \binom{n+1}{k} B_k = 0$

$$\sum_k^{n-1} \binom{n}{k} B_k = 0$$

Adding B_n to both sides

$$\sum_k^n \binom{n}{k} B_k = B_n$$

Theorem 2.3 *Derivative*

$$\boxed{B'_n(x) = nB_{n-1}(x)} \quad (8)$$

Proof

$$B_n(x) = \sum_{k=0}^n \binom{n}{k} B_k x^{n-k}$$

Taking derivatives of both sides

$$\begin{aligned} B'_n(x) &= \sum_{k=0}^{n-1} \binom{n}{k} B_k (n-k) x^{n-k-1} \\ B'_n(x) &= \sum_{k=0}^{n-1} \frac{n!(n-k)}{k!(n-k)!} B_k x^{n-1-k} \\ B'_n(x) &= \sum_{k=0}^{n-1} \frac{(n-1)! \cdot n}{k!(n-k-1)!} B_k x^{n-1-k} \\ B'_n(x) &= n \sum_{k=0}^{n-1} \binom{n-1}{k} B_k x^{n-1-k} \\ B'_n(x) &= nB_{n-1}(x) \end{aligned}$$

Theorem 2.4 *Integral*

$$\boxed{\int_{x=0}^1 B_n(x) dx = 0} \quad (9)$$

Proof

Starting from the derivative equation, using $m = n - 1$

$$B'_{m+1}(x) = (m+1) \cdot B_m(x)$$

Integrating both sides

$$\int_{x=0}^1 B'_{m+1}(x) dx = B_{m+1}(1) - B_{m+1}(0) = (m+1) \cdot \int_{x=0}^1 B_m(x) dx$$

Using the Bernoulli polynomial properties

$$B_{m+1}(1) - B_{m+1}(0) = B_{m+1} - B_{m+1} = 0$$

Therefore for $m \neq -1$

$$\int_{x=0}^1 B_m(x) dx = 0$$

3 Euler-Maclaurin formula

Let $\{x\} = x - \lfloor x \rfloor$ then

Theorem 3.1

$$\sum_{k=1}^{n-1} f(k) = \int_{x=1}^n f(x)dx - \sum_{k=1}^m \frac{B_k}{k!} \cdot (f^{(k-1)}(n) - f^{(k-1)}(1)) + R_{mn} \quad (10a)$$

$$R_{mn} = \frac{(-1)^{m+1}}{m!} \cdot \int_{x=1}^n B_m(\{x\}) f^{(m)}(x)dx \quad (10b)$$

Proof

See the Darboux Formula paper for proof

3.1 Stirling's Approximation

Theorem 3.2

$$n! = \left(\frac{n}{e}\right)^n \sqrt{2\pi n} \cdot \exp\left(\sum_{k=1}^{\lfloor m/2 \rfloor} \frac{B_{2k}}{2k \cdot (2k-1)} \frac{1}{n^{2k-1}} + O\left(\frac{1}{n^m}\right)\right) \quad (11)$$

Proof

See the Gamma function paper for proof

4 Connection to $\zeta(2n)$

See the Zeta function document.

Theorem 4.1 *We can express all even integer values of ζ using Bernoulli numbers*

$$\zeta(2n) = (-1)^{n+1} \frac{(2\pi)^{2n} B_{2n}}{2 \cdot (2n)!} \quad (12)$$

Proof: See the Zeta function document.

4.1 The first few even integer values of ζ

$$\begin{aligned} \zeta(2) &= \frac{\pi^2}{6}, \zeta(4) = \frac{\pi^4}{90}, \zeta(6) = \frac{\pi^6}{945}, \zeta(8) = \frac{\pi^8}{9450}, \zeta(10) = \frac{\pi^{10}}{93555}, \\ \zeta(12) &= \frac{691}{638512875} \pi^{12}, \zeta(14) = \frac{2}{18243225} \pi^{14}, \zeta(16) = \frac{3617}{325641566250} \pi^{16}, \\ \zeta(18) &= \frac{43867}{38979295480125} \pi^{18}, \zeta(20) = \frac{174611}{1531329465290625} \pi^{20}, \zeta(22) = \frac{155366}{13447856940643125} \pi^{22}, \\ \zeta(24) &= \frac{236364091}{201919571963756521875} \pi^{24}, \dots \end{aligned}$$