

Chapter 15: Bernoulli Numbers

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Supplement. *Prove that*

$$x \cot x = 1 - 2 \sum_{n=1}^{\infty} \frac{x^2}{n^2 \pi^2 - x^2}.$$

Proof.

(1) *Show that*

$$\cot x = \frac{1}{2^n} \sum_{k=0}^{2^n-1} \cot \frac{x + k\pi}{2^n}$$

for all integers $n \geq 1$. Notice that

$$\begin{aligned} \cot(x + \pi) &= \cot x, \\ \cot\left(x + \frac{\pi}{2}\right) &= -\tan x, \\ \cot x &= \frac{1}{2} \left(\cot \frac{x}{2} - \tan \frac{x}{2} \right). \end{aligned}$$

Use mathematical induction. The case $n = 1$ is the same as the note. Assume the case $n = m$ holds. For $n = m + 1$,

$$\begin{aligned} \sum_{k=0}^{2^{m+1}-1} \cot \frac{x + k\pi}{2^{m+1}} &= \sum_{k=0}^{2^m-1} \cot \frac{x + k\pi}{2^{m+1}} + \sum_{k=2^m}^{2^{m+1}-1} \cot \frac{x + k\pi}{2^{m+1}} \\ &= \sum_{k=0}^{2^m-1} \cot \frac{x + k\pi}{2^{m+1}} + \sum_{k=0}^{2^m-1} \cot \frac{x + (2^m + k)\pi}{2^{m+1}} \\ &= \sum_{k=0}^{2^m-1} \cot \frac{x + k\pi}{2^{m+1}} + \sum_{k=0}^{2^m-1} \cot \left(\frac{x + k\pi}{2^{m+1}} + \frac{\pi}{2} \right) \\ &= \sum_{k=0}^{2^m-1} \left(\cot \frac{x + k\pi}{2^{m+1}} - \tan \frac{x + k\pi}{2^{m+1}} \right) \\ &= \sum_{k=0}^{2^m-1} \left(\cot \frac{x + k\pi}{2^{m+1}} - \tan \frac{x + k\pi}{2^{m+1}} \right) \\ &= 2 \sum_{k=0}^{2^m-1} \cot \frac{x + k\pi}{2^m}. \end{aligned}$$

Therefore,

$$\begin{aligned}
\frac{1}{2^{m+1}} \sum_{k=0}^{2^{m+1}-1} \cot \frac{x+k\pi}{2^{m+1}} &= \frac{1}{2^{m+1}} \cdot 2 \sum_{k=0}^{2^m-1} \cot \frac{x+k\pi}{2^m} \\
&= \frac{1}{2^m} \sum_{k=0}^{2^m-1} \cot \frac{x+k\pi}{2^m} \\
&= \cot x.
\end{aligned}$$

(2) By rearranging the index of summation of the identity in (1), we have

$$x \cot x = \frac{x}{2^n} \cot \frac{x}{2^n} - \frac{x}{2^n} \tan \frac{x}{2^n} + \sum_{k=1}^{2^{n-1}-1} \frac{x}{2^n} \left(\cot \frac{x+k\pi}{2^n} + \cot \frac{x-k\pi}{2^n} \right)$$

for all integers $n \geq 1$.

(3) Notice that $\lim_{x \rightarrow 0} x \cot x = 1$. Let $n \rightarrow \infty$, the result is established.

□