A Proof from THE BOOK: The Partial Fraction Expansion of the Cotangent

Manuel Eberl

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Abstract

In this article, I formalise a proof from THE BOOK [1, Chapter 23]; namely a formula that was called 'one of the most beautiful formulas involving elementary functions':

$$\pi \cot(\pi z) = \frac{1}{z} + \sum_{n=1}^{\infty} \left(\frac{1}{z+n} + \frac{1}{z-n} \right)$$

The proof uses Herglotz's trick to show the real case and analytic continuation for the complex case.

Contents

1 The Partial-Fraction Formula for the Cotangent Function

theory *Cotangent-PFD-Formula*
imports *HOL−Complex-Analysis.Complex-Analysis HOL−Real-Asymp.Real-Asymp*

begin

1.1 Auxiliary lemmas

The following variant of the comparison test for showing summability allows us to use a 'Big-O' estimate, which works well together with Isabelle's automation for real asymptotics.

lemma *summable-comparison-test-bigo*:
fixes $f :: nat \Rightarrow real$
assumes $summable\ (\lambda n.\ norm\ (g\ n))\ f \in O(g)$
shows $summable\ f$
$\langle proof \rangle$

lemma *uniformly-on-image*:
$uniformly\text{-}on\ (f\ `\ A)\ g = filtercomap\ (\lambda h.\ h \circ f)\ (uniformly\text{-}on\ A\ (g \circ f))$
$\langle proof \rangle$

lemma *uniform-limit-image*:
$uniform\text{-}limit\ (f\ `\ A)\ g\ h\ F \longleftrightarrow uniform\text{-}limit\ A\ (\lambda x\ y.\ g\ x\ (f\ y))\ (\lambda x.\ h\ (f\ x))\ F$
$\langle proof \rangle$

lemma *Ints-add-iff1* [*simp*]: $x \in \mathbb{Z} \Longrightarrow x + y \in \mathbb{Z} \longleftrightarrow y \in \mathbb{Z}$
$\langle proof \rangle$

lemma *Ints-add-iff2* [*simp*]: $y \in \mathbb{Z} \Longrightarrow x + y \in \mathbb{Z} \longleftrightarrow x \in \mathbb{Z}$
$\langle proof \rangle$

If a set is discrete (i.e. the difference between any two points is bounded from below), it has no limit points:

lemma *discrete-imp-not-islimpt*:
assumes e: $0 < e$
and d: $\forall x \in S.\ \forall y \in S.\ dist\ y\ x < e \longrightarrow y = x$
shows $\neg x\ islimpt\ S$
$\langle proof \rangle$

In particular, the integers have no limit point:

lemma *Ints-not-limpt*: $\neg((x :: 'a :: real\text{-}normed\text{-}algebra\text{-}1)\ islimpt\ \mathbb{Z})$
$\langle proof \rangle$

The following lemma allows evaluating telescoping sums of the form

$$\sum_{n=0}^{\infty} (f(n) - f(n+k))$$

where $f(n) \longrightarrow 0$, i.e. where all terms except for the first k are cancelled by later summands.

lemma *sums-long-telescope*:
fixes f :: *nat* ⇒ *'a* :: {*topological-group-add*, *topological-comm-monoid-add*, *ab-group-add*}
assumes *lim*: $f \longrightarrow 0$
shows $(\lambda n.\ f\ n - f\ (n + c))$ *sums* $(\sum k<c.\ f\ k)$ (**is** - *sums ?S*)
⟨*proof*⟩

1.2 Definition of auxiliary function

The following function is the infinite sum appearing on the right-hand side of the cotangent formula. It can be written either as

$$\sum_{n=1}^{\infty} \left(\frac{1}{x+n} + \frac{1}{x-n} \right)$$

or as

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

definition *cot-pfd* :: *'a* :: {*real-normed-field*, *banach*} ⇒ *'a* **where**
cot-pfd $x = (\sum n.\ 2 * x\ /\ (x\ \hat{}\ 2 - \textit{of-nat}\ (\textit{Suc}\ n)\ \hat{}\ 2))$

The sum in the definition of *cot-pfd* converges uniformly on compact sets. This implies, in particular, that *cot-pfd* is holomorphic (and thus also continuous).

lemma *uniform-limit-cot-pfd-complex*:
assumes $R \geq 0$
shows *uniform-limit* (*cball 0 R* :: *complex set*)
$(\lambda N\ x.\ \sum n<N.\ 2 * x\ /\ (x\ \hat{}\ 2 - \textit{of-nat}\ (\textit{Suc}\ n)\ \hat{}\ 2))$ *cot-pfd sequentially*
⟨*proof*⟩

lemma *sums-cot-pfd-complex*:
fixes x :: *complex*
shows $(\lambda n.\ 2 * x\ /\ (x\ \hat{}\ 2 - \textit{of-nat}\ (\textit{Suc}\ n)\ \hat{}\ 2))$ *sums cot-pfd* x
⟨*proof*⟩

lemma *sums-cot-pfd-complex'*:
fixes x :: *complex*
assumes $x \notin \mathbb{Z}$
shows $(\lambda n.\ 1\ /\ (x + \textit{of-nat}\ (\textit{Suc}\ n)) + 1\ /\ (x - \textit{of-nat}\ (\textit{Suc}\ n)))$ *sums cot-pfd* x

⟨*proof*⟩

lemma *summable-cot-pfd-complex*:
  fixes x :: *complex*
  shows *summable* ($\lambda n.\ 2 * x$ / (x ^ 2 − *of-nat* (*Suc* n) ^ 2))
  ⟨*proof*⟩

lemma *summable-cot-pfd-real*:
  fixes x :: *real*
  shows *summable* ($\lambda n.\ 2 * x$ / (x ^ 2 − *of-nat* (*Suc* n) ^ 2))
⟨*proof*⟩

lemma *sums-cot-pfd-real*:
  fixes x :: *real*
  shows ($\lambda n.\ 2 * x$ / (x ^ 2 − *of-nat* (*Suc* n) ^ 2)) *sums cot-pfd* x
  ⟨*proof*⟩

lemma *cot-pfd-complex-of-real* [*simp*]: *cot-pfd* (*complex-of-real* x) = *of-real* (*cot-pfd* x)
  ⟨*proof*⟩

lemma *uniform-limit-cot-pfd-real*:
  assumes $R \geq 0$
  shows *uniform-limit* (*cball* 0 R :: *real set*)
    ($\lambda N\ x.\ \sum n<N.\ 2 * x$ / (x ^ 2 − *of-nat* (*Suc* n) ^ 2)) *cot-pfd sequentially*
⟨*proof*⟩

1.3 Holomorphicity and continuity

lemma *holomorphic-on-cot-pfd* [*holomorphic-intros*]:
  assumes $A \subseteq -(\mathbb{Z}-\{0\})$
  shows *cot-pfd holomorphic-on* A
⟨*proof*⟩

lemma *continuous-on-cot-pfd-complex* [*continuous-intros*]:
  assumes $A \subseteq -(\mathbb{Z}-\{0\})$
  shows *continuous-on* A (*cot-pfd* :: *complex* ⇒ *complex*)
  ⟨*proof*⟩

lemma *continuous-on-cot-pfd-real* [*continuous-intros*]:
  assumes $A \subseteq -(\mathbb{Z}-\{0\})$
  shows *continuous-on* A (*cot-pfd* :: *real* ⇒ *real*)
⟨*proof*⟩

1.4 Functional equations

In this section, we will show three few functional equations for the function *cot-pfd*. The first one is trivial; the other two are a bit tedious and not very insightful, so I will not comment on them.

cot-pfd is an odd function:

lemma *cot-pfd-complex-minus* [*simp*]: *cot-pfd* $(-x :: complex) = -cot\text{-}pfd\ x$
⟨*proof*⟩

lemma *cot-pfd-real-minus* [*simp*]: *cot-pfd* $(-x :: real) = -cot\text{-}pfd\ x$
⟨*proof*⟩

cot-pfd is periodic with period 1:

lemma *cot-pfd-plus-1-complex*:
assumes $x \notin \mathbb{Z}$
shows *cot-pfd* $(x + 1 :: complex) = cot\text{-}pfd\ x - 1\ /\ (x + 1) + 1\ /\ x$
⟨*proof*⟩

lemma *cot-pfd-plus-1-real*:
assumes $x \notin \mathbb{Z}$
shows *cot-pfd* $(x + 1 :: real) = cot\text{-}pfd\ x - 1\ /\ (x + 1) + 1\ /\ x$
⟨*proof*⟩

cot-pfd satisfies the following functional equation:

$$2f(x) = f\left(\frac{x}{2}\right) + f\left(\frac{x+1}{2}\right) + \frac{2}{x+1}$$

lemma *cot-pfd-funeq-complex*:
fixes x :: *complex*
assumes $x \notin \mathbb{Z}$
shows $2 * cot\text{-}pfd\ x = cot\text{-}pfd\ (x\ /\ 2) + cot\text{-}pfd\ ((x + 1)\ /\ 2) + 2\ /\ (x + 1)$
⟨*proof*⟩

lemma *cot-pfd-funeq-real*:
fixes x :: *real*
assumes $x \notin \mathbb{Z}$
shows $2 * cot\text{-}pfd\ x = cot\text{-}pfd\ (x\ /\ 2) + cot\text{-}pfd\ ((x + 1)\ /\ 2) + 2\ /\ (x + 1)$
⟨*proof*⟩

1.5 The limit at 0

lemma *cot-pfd-real-tendsto-0*: *cot-pfd* $-0\rightarrow$ $(0 :: real)$
⟨*proof*⟩

1.6 Final result

To show the final result, we first prove the real case using Herglotz's trick, following the presentation in 'Proofs from THE BOOK'. [1, Chapter 23].

lemma *cot-pfd-formula-real*:
assumes $x \notin \mathbb{Z}$
shows $pi * cot\ (pi * x) = 1\ /\ x + cot\text{-}pfd\ x$
⟨*proof*⟩

We now lift the result from the domain $\mathbb{R}\backslash\mathbb{Z}$ to $\mathbb{C}\backslash\mathbb{Z}$. We do this by noting that $\mathbb{C}\backslash\mathbb{Z}$ is connected and the point $\frac{1}{2}$ is both in $\mathbb{C}\backslash\mathbb{Z}$ and a limit point of $\mathbb{R}\backslash\mathbb{Z}$.

lemma *one-half-limit-point-Reals-minus-Ints*: $(1\ /\ 2 :: complex)$ *islimpt* $\mathbb{R} - \mathbb{Z}$
⟨*proof*⟩

theorem *cot-pfd-formula-complex*:
  fixes z :: *complex*
  assumes $z \notin \mathbb{Z}$
  shows $pi * cot\ (pi * z) = 1\ /\ z + \textit{cot-pfd}\ z$
⟨*proof*⟩

end

References

[1] M. Aigner and G. M. Ziegler. *Proofs from THE BOOK*. Springer, 4th edition, 2009.