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Complex Analysis

Universal Taylor series for non-simply connected domains ☆

Séries universelles de Taylor pour les domaines non-simplement connexes

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ABSTRACT

It is known that, for any simply connected proper subdomain Ω of the complex plane and any point ζ in Ω, there are holomorphic functions on Ω that have "universal" Taylor series expansions about ζ; that is, partial sums of the Taylor series approximate arbitrary polynomials on arbitrary compacta in $\mathbb{C}\backslash\Omega$ that have connected complement. This note shows that this phenomenon can break down for non-simply connected domains Ω, even when $\mathbb{C}\backslash\Omega$ is compact. This answers a question of Melas and disproves a conjecture of Müller, Vlachou and Yavrian.

RÉSUMÉ

Il est connu que, pour un sous-domaine propre simplement connexe Ω du plan complexe et un point quelconque ζ de Ω, il y a des fonctions holomorphes sur Ω qui possèdent des séries de Taylor « universelles » autour de ζ; c'est-à-dire tout polynôme peut être approximé, sur tout compact de $\mathbb{C}\backslash\Omega$ ayant un complémentaire connexe, par les sommes partielles de la série de Taylor. Cette note montre que ce résultat n'est plus vrai en général pour les domaines non-simplement connexes Ω, même lorsque $\mathbb{C}\backslash\Omega$ est compact. Cela répond à une question de Melas et réfute une conjecture de Müller, Vlachou et Yavrian.

1. Introduction

Let Ω be a proper subdomain of the complex plane $\mathbb{C}$ and let $\zeta \in \Omega$. A function f on Ω is said to belong to the collection $U(\Omega, \zeta)$, of holomorphic functions on Ω with universal Taylor series expansions about ζ, if the partial sums

$$S_N(f,\zeta)(z) = \sum_{n=0}^{N} \frac{f^{(n)}(\zeta)}{n!}(z-\zeta)^n$$

of the Taylor series have the following property:

For every compact set $K \subset \mathbb{C}\backslash\Omega$ with connected complement and every function g which is continuous on K and holomorphic on K°, there is a subsequence $(S_{N_k}(f,\zeta))$ that converges to g uniformly on K.

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Nestoridis [17,18] has shown that $U(\Omega,\zeta)\neq\emptyset$ for any simply connected domain Ω and any $\zeta\in\Omega$. (The corresponding result, where K is required to be disjoint from $\overline{\Omega}$, had previously been established by Luh [12] and Chui and Parnes [4].) In fact, Nestoridis showed that possession of such universal Taylor series expansions is a generic property of holomorphic functions on simply connected domains Ω, in the sense that $U(\Omega,\zeta)$ is a dense G_δ subset of the space of all holomorphic functions on Ω endowed with the topology of local uniform convergence (see also Melas and Nestoridis [14] and the survey of Kahane [11]).

The situation when Ω is non-simply connected is much less well understood, despite much recent research: see, for example [2,3,5–7,9,13,15,19,22–25]. Melas [13] (see also Costakis [5]) has shown that $U(\Omega,\zeta)\neq\emptyset$ for any $\zeta\in\Omega$ whenever $\mathbb{C}\backslash\Omega$ is compact and connected, and has asked if $U(\Omega,\zeta)$ can be empty when $\mathbb{C}\backslash\Omega$ is compact but disconnected. On the other hand, Müller, Vlachou and Yavrian [15] have shown, for non-simply connected domains Ω, that thinness of the set $\mathbb{C}\backslash\Omega$ at infinity is necessary for $U(\Omega,\zeta)$ to be non-empty, and have conjectured that this condition is also sufficient. There is clearly a large gap between the results of [13] and [15]. Also there has been no known example of a domain Ω and points $\zeta_1,\zeta_2\in\Omega$ such that $U(\Omega,\zeta_1)\neq\emptyset$ and $U(\Omega,\zeta_2)=\emptyset$.

The purpose of this Note is to establish the following result. We denote by $D(a,r)$ the open disc of centre a and radius r, and write $\mathbb{D}=D(0,1)$. By a *non-degenerate continuum* we mean a connected compact set containing more than one element.

Theorem 1. *Let Ω be a domain of the form $\mathbb{C}\backslash(L\cup\{1\})$, where L is a non-degenerate continuum in $\mathbb{C}\backslash\overline{\mathbb{D}}$. Then $U(\Omega,0)=\emptyset$.*

The conjecture of Müller, Vlachou and Yavrian is thus disproved. Also, if we take L to be $\overline{D}(-5/3,1/3)$, then $U(\Omega,0)=\emptyset$ by Theorem 1 and yet a result of the second author [22] tells us that $U(\Omega,-1/2)\neq\emptyset$ (see also Costakis and Vlachou [7]). Thus we now have an example of a domain where the existence of functions with universal Taylor series depends on the chosen centre for expansion. The result of Melas, that $U(\Omega,0)\neq\emptyset$ if $\mathbb{C}\backslash\Omega$ is compact and connected, is now seen to be sharp in the sense that, by Theorem 1, it can fail with the removal of one additional point from the domain. Theorem 1 fails if L is allowed to be a singleton [13].

2. Proof

Let Ω be as in the statement of Theorem 1, and suppose, for the sake of contradiction, that there exists a function f in $U(\Omega,0)$. We can write $f=g+h$, where g is the singular part of the Laurent expansion of f associated with the singularity at 1, and h is holomorphic on $\mathbb{C}\backslash L$. We denote the Taylor coefficients of g and h about 0 by (a_n) and (b_n), respectively. Since $(S_N(f,0)(1))$ is dense in $\mathbb{C}$ and $(S_N(h,0)(1))$ converges, we see that g is non-zero.

Let $\rho=\inf\{|z|:\ z\in L\}$ and $0<\delta<\varepsilon<\rho-1$. The Taylor series for g and h about 0 converge absolutely in $\mathbb{D}$ and $D(0,\rho)$, respectively, so we can define the finite quantities

$$\alpha_\delta=\sum_{n=0}^{\infty}\frac{|a_n|}{(1+\delta)^n}\quad\text{and}\quad\beta_\delta=\sum_{n=0}^{\infty}|b_n|\left(\frac{\rho}{1+\delta}\right)^n.$$

Since $f\in U(\Omega,0)$, we can choose a strictly increasing sequence (N_k) of natural numbers such that

$$S_{N_k}(g,0)(z)+S_{N_k}(h,0)(z)\to 0\quad\text{as } k\to\infty,\ \text{uniformly on } L. \tag{1}$$

On $\overline{D}(0,\rho(1+\varepsilon))$ we have

$$\left|S_{N_k}(h,0)(z)\right|\leqslant\sum_{n=0}^{N_k}|b_n|\rho^n(1+\varepsilon)^n\leqslant\left\{(1+\varepsilon)(1+\delta)\right\}^{N_k}\beta_\delta,$$

so by (1) we can choose k_0 such that

$$\left|S_{N_k}(g,0)(z)\right|\leqslant\left\{(1+\varepsilon)(1+\delta)\right\}^{N_k}(\beta_\delta+1)\quad\left(z\in L\cap\overline{D}\big(0,\rho(1+\varepsilon)\big);\,k\geqslant k_0\right).$$

We also have

$$\left|S_{N_k}(g,0)(z)\right|\leqslant\sum_{n=0}^{N_k}|a_n|(1+\varepsilon)^n\leqslant\left\{(1+\varepsilon)(1+\delta)\right\}^{N_k}\alpha_\delta\quad\left(z\in\overline{D}(0,1+\varepsilon)\right),$$

so

$$\left|S_{N_k}(g,0)(z)\right|\leqslant\left\{(1+\varepsilon)(1+\delta)\right\}^{N_k}\gamma_\delta\quad(z\in A_\varepsilon;\,k\geqslant k_0), \tag{2}$$

where $\gamma_\delta=\max\{\alpha_\delta,\beta_\delta+1\}$ and

$$A_\varepsilon=\overline{D}(0,1+\varepsilon)\cup\left[L\cap\overline{D}\big(0,\rho(1+\varepsilon)\big)\right].$$

Let G_ε denote the Green function for the domain $D_\varepsilon=(\mathbb{C}\cup\{\infty\})\backslash A_\varepsilon$ with pole at infinity. Then

$$G_\varepsilon(z)-\log|z|\to-\log\mathcal{C}(A_\varepsilon)\quad\big(|z|\to\infty\big),$$

where $\mathcal{C}(A)$ denotes the logarithmic capacity of a set A (see Section 5.8 of [1], or Section 5.2 of [21]). Thus we can choose $r_{\delta,\varepsilon} > \max\{|z|: z \in L\}$ such that

$$G_\varepsilon(z) \leqslant \log|z| - \log\mathcal{C}(A_\varepsilon) + \delta \quad \big(|z| \geqslant r_{\delta,\varepsilon}\big). \tag{3}$$

Bernstein's lemma (Theorem 5.5.7 in [21]) tells us that any polynomial q of degree $n \geqslant 1$ satisfies

$$\left(\frac{|q(z)|}{\max_{A_\varepsilon}|q|}\right)^{1/n} \leqslant e^{G_\varepsilon(z)} \quad \big(z \in D_\varepsilon \backslash \{\infty\}\big).$$

Applying this inequality to the polynomial $S_{N_k}(g,0)$, and using (2) and then (3), we obtain

$$\begin{aligned}\big|S_{N_k}(g,0)(z)\big| &\leqslant \big\{(1+\varepsilon)(1+\delta)\big\}^{N_k}\gamma_\delta e^{N_k G_\varepsilon(z)} \\ &\leqslant \left\{\frac{(1+\varepsilon)(1+\delta)e^\delta|z|}{\mathcal{C}(A_\varepsilon)}\right\}^{N_k}\gamma_\delta \quad \big(|z| \geqslant r_{\delta,\varepsilon};\, k \geqslant k_0\big).\end{aligned}$$

We next adapt an argument from pp. 498, 499 of Gehlen [8]. Let $\nu \in (0,1)$. Since

$$\begin{aligned}|a_n|^{1/n} &= \left|\frac{1}{2\pi i}\int_{\{|z|=r_{\delta,\varepsilon}\}} \frac{S_{N_k}(g,0)(z)}{z^{n+1}}\,dz\right|^{1/n} \\ &\leqslant \left\{\frac{(1+\varepsilon)(1+\delta)e^\delta}{\mathcal{C}(A_\varepsilon)}\right\}^{N_k/n}\gamma_\delta^{1/n} r_{\delta,\varepsilon}^{N_k/n-1} \quad (n \leqslant N_k;\, k \geqslant k_0),\end{aligned}$$

we obtain

$$\limsup_{k\to\infty}\max_{\nu N_k \leqslant n \leqslant N_k}|a_n|^{1/n} \leqslant \frac{\{(1+\varepsilon)(1+\delta)e^\delta\}^{1/\nu} r_{\delta,\varepsilon}^{1/\nu-1}}{\mathcal{C}(A_\varepsilon)} = \lambda, \quad \text{say}. \tag{4}$$

Since L is a non-degenerate continuum that intersects $\{|z| = \rho\}$, we have

$$\mathcal{C}\big(L \cap \overline{D}\big(0, \rho(1+\varepsilon)\big)\big) > 0$$

and so

$$\mathcal{C}(A_\varepsilon) > \mathcal{C}\big(\overline{D}(0, 1+\varepsilon)\big) = 1+\varepsilon.$$

We can thus choose δ sufficiently small that $(1+\varepsilon)(1+\delta)e^\delta < \mathcal{C}(A_\varepsilon)$, and then choose ν sufficiently close to 1 to ensure that $\lambda < 1$.

Finally, we will apply an observation of Müller (see Remark 2 in [16]). Since the function g has its only singularity at 1 and vanishes at ∞, Wigert's theorem (Theorem 11.2.2 in Hille [10]) tells us that there is an entire function F of exponential type 0 such that $F(n) = a_n$ for all $n \geqslant 0$. However, Theorem V of Pólya [20] says that, for any $\mu > 0$, however small, such a function F has the property that the sequence $\{n \in \mathbb{N}: |F(n)| > e^{-\mu n}\}$ is of density 1. This contradicts (4) with $\lambda < 1$. Thus our original assumption, that there exists f in $U(\Omega, 0)$, must be false, and the proof of the theorem is complete. □

Remarks.

(1) The assumption that L is a continuum can be relaxed. It is enough to suppose that L is a compact subset of $\mathbb{C}\backslash\overline{\mathbb{D}}$ such that $\mathcal{C}(D(0,\rho^2) \cap L) > 0$ where $\rho = \inf\{|z|: z \in L\}$.

(2) The proof actually shows that there is no holomorphic function f on Ω such that $(S_N(f,0))$ is divergent at $z = 1$ and has a subsequence that is uniformly bounded on L.

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