



TECHNISCHE
UNIVERSITÄT
WIEN

B A C H E L O R A R B E I T

Growth, order and zeros of entire functions

ausgeführt am

Institut für
Analysis und Scientific Computing
TU Wien

unter der Anleitung von

Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Harald Woracek

durch

Ian Hornik

Matrikelnummer: 12115564

Haizingergasse 18/4

1180 Wien

Wien, am Datum

Contents

1	Introduction	1
2	Picard's Great Theorem	2
2.1	Bloch's Theorem	2
2.2	Schottky's Theorem	3
2.3	Picard's Great Theorem	4
3	Entire Functions	5
3.1	Order & Type	5
3.2	Hadamard's Theorem	6
3.3	Zeros	7
3.4	Composition	9
	Bibliography	11

1 Introduction

Some words why the subject is of interest.

A reference to the primary literature used.

Overview of used notation.

$$M_f(r) := \max_{|z|=r} |f(z)|$$

2 Picard's Great Theorem

2.1 Bloch's Theorem

Lemma 2.1. *Let $G \subset \mathbb{C}$ be a bounded domain, $f : \overline{G} \rightarrow \mathbb{C}$ continuous and $f|_G : G \rightarrow \mathbb{C}$ open. If there is a point $a \in G$ such that $s := \min_{z \in \partial G} |f(z) - f(a)| > 0$, then $B(f(a), s) \subseteq f(G)$.*

Proof. The function $z \mapsto |z - f(a)|$ is continuous on the compact set $\partial f(G)$, hence it attains its minimum m at some $w_* \in \partial f(G)$. Let $(z_n)_{n \in \mathbb{N}}$ be a sequence in G , such that $\lim_{n \rightarrow \infty} f(z_n) = w_*$. Since \overline{G} is compact, we can find a subsequence that converges to some $z_* \in \overline{G}$. Since f is continuous, we have $f(z_*) = w_* \in \partial f(G)$.

Assuming $z_* \in G$, since $f|_G$ is open, the image of any open set in G containing z_* under f must be an open set in $f(G)$ containing w_* , which is impossible since $w_* \in \partial G$.

Therefore $z_* \in \partial G$ and we have $m = |w_* - f(a)| = |f(z_*) - f(a)| \geq s$, from which it follows that $B(f(a), s) \subseteq f(G)$. ■

Lemma 2.2. *Let $a \in \mathbb{C}, r > 0$ and $B := B(a, r)$. Suppose further that f is analytic on \overline{B} such that $\|f'\|_B \leq 2|f'(a)|$. Then*

$$B(f(a), R) \subseteq f(B), \quad \text{where } R := (3 - 2\sqrt{2})r|f'(a)|. \quad (3 - 2\sqrt{2} > \tfrac{1}{6})$$

Proof. Without loss of generality we can assume $a = f(a) = 0$. Consider the function

$$\alpha_f : \begin{cases} B(0, r) \rightarrow \mathbb{C} \\ z \mapsto f(z) - f'(0)z \end{cases},$$

which satisfies, for the line γ connecting 0 to $z \in \mathbb{C}$,

$$|\alpha_f(z)| = \left| \int_{\gamma} f'(\zeta) - f'(0) d\zeta \right| \leq \int_0^1 |f'(tz) - f'(0)| |z| dt. \quad (2.1)$$

Let $w \in B$, then Cauchy's integral formula gives

$$\begin{aligned} |f'(w) - f'(0)| &= \frac{1}{2\pi} \left| \int_{\partial B} \frac{f'(\zeta)}{\zeta - w} - \frac{f'(\zeta)}{\zeta} d\zeta \right| = \frac{1}{2\pi} \left| \int_{\partial B} \frac{wf'(\zeta)}{\zeta(\zeta - w)} d\zeta \right| \leq \\ &\leq \frac{1}{2\pi} \int_{\partial B} \frac{|w| \|f'\|_B}{r(r - |w|)} d\zeta = \frac{|w|}{r - |w|} \|f'\|_B. \end{aligned}$$

Combining the above with eq. (2.1) and our estimate on $\|f'\|_B$ yields

$$|\alpha_f(z)| \leq \int_0^1 \frac{|zt| \|f'\|_B}{r - |zt|} |z| dt \leq \frac{|z|^2}{r - |z|} \|f'\|_B \int_0^1 t dt \leq \frac{|z|^2}{r - |z|} |f'(0)|.$$

Let $0 < \rho < r$, then for $|z| = \rho$ we have

$$\begin{aligned} |f'(0)|\rho - |f(z)| &\leq |\alpha_f(z)| \leq \frac{\rho^2}{r - \rho} |f'(0)| \\ \iff |f(z)| &\geq \left(\rho - \frac{\rho^2}{r - \rho} \right) |f'(0)|. \end{aligned}$$

Considering $\rho - \rho^2/(r - \rho)$ as a function of ρ , it attains its maximum value, $(3 - 2\sqrt{2})r$, at $\rho_* := (1 - \sqrt{2}/2)r < r$. Therefore,

$$|f(z)| \geq (3 - 2\sqrt{2})r |f'(0)| = R, \quad \text{for all } |z| = \rho_*.$$

Invoking Lemma 2.1 with $G := B(0, \rho_*)$ thus yields $B(0, R) \subseteq f(G) \subseteq f(B)$. ■

Theorem 2.3. *Let f be non-constant and analytic on $\overline{\mathbb{D}}$. Then there is a point $p \in \mathbb{D}$ and a constant $C_f > 0$ such that $B(f(p), R) \subseteq f(\mathbb{D})$, where $R := (\frac{3}{2} - \sqrt{2})C_f > \frac{1}{12}|f'(p)|$.*

Proof. The function

$$\alpha_f : \begin{cases} \mathbb{D} \rightarrow \mathbb{R} \\ z \mapsto |f'(z)|(1 - |z|) \end{cases}$$

is continuous and attains its maximum $C_f > 0$ at some point $p \in \mathbb{D}$.

Set $t := \frac{1}{2}(1 - |p|) > 0$, then for $z \in B(p, t)$ we have $B(p, t) \subseteq \mathbb{D}$ and $1 - |z| \geq t$. Since $|f'(z)|(1 - |z|) \leq M = 2t|f'(p)|$, this implies $|f'(z)| \leq 2|f'(p)|$. By Lemma 2.2, we obtain

$$B(f(p), R) \subseteq f(\mathbb{D}), \quad \text{where } R := (3 - 2\sqrt{2})t|f'(p)| = (\tfrac{3}{2} - \sqrt{2})C_f,$$

concluding the claim. ■

Theorem 2.4 (Bloch). *Let f be analytic on $\overline{\mathbb{D}}$ with $f'(0) = 1$. Then there is a point $p \in \mathbb{C}$ such that $B(f(p), R) \subseteq f(\mathbb{D})$ where $R := \frac{3}{2} - \sqrt{2} > \frac{1}{12}$.*

Proof. Need to figure out how to properly modify f to apply Theorem 2.3. ■

2.2 Schottky's Theorem

Theorem 2.5 (Schottky). *Let f be analytic on $\overline{\mathbb{D}}$ such that it does not attain 0 or 1 as values in $\overline{\mathbb{D}}$. Then there is a function $\psi(\omega, \theta) : \mathbb{C} \times (0, 1) \rightarrow \mathbb{R}_{\geq 0}$ such that if $|f(0)| \leq \omega$, then*

$$|f(z)| \leq \psi(\omega, \theta), \quad |z| \leq \theta. \tag{2.2}$$

Proof. Ref: Classical Topics p237. ■

2.3 Picard's Great Theorem

Theorem 2.6 (Picard's Great Theorem). *Let $c \in \mathbb{C}$ be an isolated singularity of f . Then, in every punctured neighbourhood of c , f assumes every complex number as a value infinitely many times, with at most one exception.*

Proof. Ref: Classical Topics p240. ■

Corollary 2.7. *Let f be a transcendental entire function. Then f attains every value in \mathbb{C} infinitely often, with at most one exception.*

Proof. If $f(z) = \sum_{n \in \mathbb{Z}_{\geq 0}} a_n z^n$, then $f(z^{-1}) = \sum_{n \in \mathbb{Z}_{\leq 0}} a_{-n} z^n$, thus f has an essential singularity at ∞ and Picard's Great Theorem (2.6) concludes the claim. ■

Corollary 2.8 (Picard's Little Theorem). *Every nonconstant entire function omits at most one value.*

Proof. A non-constant entire function f is either a non-constant polynomial or a transcendental function. In the latter case, the claim follows from Corollary 2.7.

Otherwise let $w \in \mathbb{C}$, then $f(z) - w$ is a non-constant polynomial. By the Fundamental Theorem of Algebra it has a zero at some $z_0 \in \mathbb{C}$. Therefore $f(z_0) = w$ and f attains all values. ■

3 Entire Functions

3.1 Order & Type

Definition 3.1. Let f be an entire function. The *order* of f is defined by

$$\rho_f := \limsup_{r \rightarrow \infty} \frac{\log \log M_f(r)}{\log r}. \quad (3.1)$$

Constant functions, by convention, have order 0.

Note that, for any entire function f , we have $0 \leq \rho_f \leq \infty$. Furthermore, $\rho_f < \infty$ if and only if $M_f(r) = O(\exp(r^{\rho_f + \varepsilon}))$ for every $\varepsilon > 0$ and no $\varepsilon < 0$, as $r \rightarrow \infty$ [2].

An elementary fact regarding the order of the sum or product of two entire functions of finite order can immediately be obtained by naively estimating their respective maximum modulus:

Proposition 3.2. *Let f, g be entire functions of finite order. Then it holds that:*

- i. $\rho_{f+g} \leq \max\{\rho_f, \rho_g\}$
- ii. $\rho_{fg} \leq \max\{\rho_f, \rho_g\}$

I could remark that if $\rho_f \neq \rho_g$ we can actually achieve equality in the above, but the proof for the multiplication case is tedious.

Proposition 3.3. *Let f be an entire function of finite order, then $\rho_{f'} = \rho_f$.*

Proof. **TODO.** ■

For functions of finite and positive order, we can obtain a natural refinement of the concept of order:

Definition 3.4. Let f be an entire function of finite and positive order. The *type* of f is defined by

$$\tau_f := \limsup_{r \rightarrow \infty} \frac{\log M_f(r)}{r^{\rho_f}} \quad (3.2)$$

For any entire function f with $0 < \rho_f < \infty$, we have $0 < \tau_f \leq \infty$. Additionally, we have $0 < \rho_f < \infty$ and $\tau_f < \infty$ if and only if $M_f(r) = O(\exp((\tau_f + \varepsilon)r^{\rho_f}))$ for every $\varepsilon > 0$ and no $\varepsilon < 0$, as $r \rightarrow \infty$ [2].

Imitating the proof of Proposition 3.3, we immediately get:

Proposition 3.5. *Let f be an entire function of finite type, then $\tau_{f'} = \tau_f$.*

Definition 3.6. Let f be an entire function. Then f is said to be of *growth* (a, b) if

- $\rho_f < a$, or
- $\rho_f = a$ and $\tau_f \leq b$.

Example 3.7. Maybe give some functions together with their order and type?

3.2 Hadamard's Theorem

Theorem 3.8 (Weierstrass [1, 3]). *Let $(z_j)_{j \in \mathbb{N}}$ be a sequence in \mathbb{C} without accumulation points. Then there exists an entire function E (called the Weierstrass canonical product formed from said sequence) that has zeros precisely at $(z_j)_{j \in \mathbb{N}}$, with multiplicities equal to how often z_j occurs in the sequence.*

In particular, we have

$$E(z) = z^k \prod_{n=1}^{\infty} \left(1 - \frac{z}{z_n}\right) e^{R_n(z/z_n)}, \quad (3.3)$$

where k is the order of the zero at $z = 0$ and R_n is a polynomial, namely a truncation of the power series for $-\log(1 - \frac{z}{z_n})$ chosen of smallest degree to ensure convergence of the product [2].

Weierstrass' Theorem (3.8) is also known as the *Weierstrass Factorization Theorem*, due to the following corollary:

Corollary 3.9. *Let f be an entire function with zeros $(z_j)_{j \in \mathbb{N}}$. Then there exists an entire function g , such that*

$$f(z) = e^{g(z)} E(z),$$

where E is a Weierstrass canonical product formed from the zeros of f .

Proof. Since f/E has removable singularities at all $(z_j)_{j \in \mathbb{N}}$, we have that f/E is entire and nowhere 0. Thus there exists an entire function g with $f/E = e^g$, which yields $f = e^g E$. ■

Hadamard's Theorem will show that, for functions of finite order ρ , the function g in Corollary 3.9 can be taken to be a polynomial of degree less than ρ and the degree of the polynomials R_n in eq. (3.3) can be taken to be independent of n . To prove this we require the following lemma, which can be interpreted as a version of the maximum modulus theorem applied to the real part of an analytic function.

Lemma 3.10 (Borel-Carathéodory). *Let f be analytic in $\overline{\mathbb{D}}$ and let*

$$A_f(r) = \max_{|z|=r} \Re f(z).$$

Then, for $0 < r < R$,

$$M_f(r) \leq \frac{2r}{R-r} A_f(R) + \frac{R+r}{R-r} |f(0)|$$

and, if additionally $A_f(R) \geq 0$, then for $n \in \mathbb{N}$

$$\max_{|z|=r} |f^{(n)}(z)| \leq \frac{2^{n+2} n! R}{(R-r)^{n+1}} (A_f(R) + |f(0)|).$$

Proof. **TODO.** ■

Theorem 3.11 (Hadamard). *Let f be an entire function of finite order with zeros $(z_j)_{j \in \mathbb{N}}$. Then there exists a polynomial Q with $\deg Q \leq \rho_f$, such that*

$$f(z) = e^{Q(z)} E(z),$$

where E is a Weierstrass canonical product formed from the zeros of f .

Proof. **TODO.** ■

3.3 Zeros

We recall a rather explicit connection between the moduli of the zeros of an analytic function and the modulus of the function itself:

Theorem 3.12 (Jensen [3]). *Let f be analytic on $B(0, R)$ with $f(0) \neq 0$ and let r_1, r_2, \dots denote the moduli of the zeros of f in $B(0, R)$ arranged in a non-decreasing sequence. Then, for $r_n < r < r_{n+1}$, we have*

$$\frac{1}{2\pi} \int_0^{2\pi} \log |f(re^{i\vartheta})| d\vartheta = \log |f(0)| + \log \frac{r^n}{r_1 \dots r_n}.$$

Definition 3.13. Let f be analytic on $B(0, R)$. Then, for $0 < r < R$, we denote by $n_f(r)$ the number of zeros of f in $\overline{B(0, r)}$.

Corollary 3.14. *Let f be analytic on $B(0, R)$ with $f(0) \neq 0$. Then, for $0 < r < R$, we have*

$$\frac{1}{2\pi} \int_0^{2\pi} \log |f(re^{i\vartheta})| d\vartheta = \log |f(0)| + \int_0^r \frac{n_f(s)}{s} ds$$

Proof. Let r_1, r_2, \dots denote the moduli of the zeros of f in $B(0, R)$ arranged in a non-decreasing sequence. Then, for any $r_n < r < r_{n+1}$, we obtain

$$\begin{aligned} \log \frac{r^n}{r_1 \dots r_n} &= \sum_{k=1}^n \log \frac{r}{r_k} = \sum_{k=1}^n \int_{r_k}^r \frac{1}{s} ds = \\ &= \sum_{k=1}^n \int_0^r \mathbb{1}_{(r_k, \infty)}(s) \frac{1}{s} ds = \int_0^r \left(\sum_{k=1}^n \mathbb{1}_{(r_k, \infty)}(s) \right) \frac{1}{s} ds = \\ &= \int_0^r \frac{n_f(s)}{s} ds \end{aligned}$$

and Theorem 3.12 concludes the claim. ■

In particular, we observe that the more zeros a function $f(z)$ has, the faster its modulus must grow as $|z| \rightarrow \infty$. The converse is naturally false, as seen by iterated exponentials [2].

Definition 3.15. Let f be an entire function and let $(r_j)_{j \in \mathbb{N}}$ denote the non-zero moduli of its zeros (if any) arranged in non-decreasing order. Then

$$\lambda_f := \inf \left\{ \lambda > 0 : \sum_{n=1}^{\infty} \frac{1}{r_n^\lambda} < \infty \right\}$$

is called the *exponent of convergence of the zeros of f* . If f has finitely many zeros, then we set $\lambda_f = 0$ by convention.

Furthermore, the *exponent of convergence of the a -points of f* is defined as exponent of convergence of zeros of $f(z) - a$.

Theorem 3.16. Let f be an entire function of finite order. Then $\lambda_f \leq \rho_f$.

Proof. TODO. ■

Example 3.17. Consider the entire function $f(z) := \sin(z)$, which has zeros at $(n\pi)_{n \in \mathbb{Z}}$, and let $\lambda > 0$. Since

$$\sum_{n \in \mathbb{Z} \setminus \{0\}} \frac{1}{|n\pi|^\lambda} = \frac{2}{\pi^\lambda} \sum_{n=1}^{\infty} \frac{1}{|n|^\lambda}$$

is finite if and only if $\lambda > 1$, we obtain $\lambda_f = 1$. Furthermore, we have $|\sin(z)| \leq e^{|\Im z|}$ and therefore

$$M_f(r) \leq \max_{|z|=r} |e^z|.$$

Since e^z is of order 1, this implies $\rho_f \leq 1$. Finally, Theorem 3.16 concludes $\rho_f = 1$.

Theorem 3.18. Let E be a Weierstrass canonical product of finite order. Then $\lambda_E = \rho_E$.

Proof. **TODO.** ■

Theorem 3.19. *Let f be an entire function of finite, non-integer order. Then $\rho_f = \lambda_f$.*

Proof. By Theorem 3.16 we have $\lambda_f \leq \rho_f$. Invoking Hadamard's Theorem we can write $f = e^Q E$ for a polynomial Q with $\deg Q \leq \rho_f$. Since ρ_f is not an integer, this implies $\deg Q \leq \lfloor \rho_f \rfloor < \rho_f$. Now, again by Hadamard's Theorem, e^Q has order $\deg Q$ and by Theorem 3.18 E has order λ_f . Using Proposition 3.2 we obtain

$$\rho_f \leq \max\{\deg Q, \lambda_f\} = \lambda_f \leq \rho_f,$$

implying $\rho_f = \lambda_f$. ■

Theorem 3.20. *Let f be an entire function of finite, non-integer order. Then f has infinitely many zeros.*

Proof. By Theorem 3.19 we have $\rho_f = \lambda_f$. Since ρ_f is not an integer, $\lambda_f > 0$, which implies that f has infinitely many zeros. ■

Maybe introduce Borel exceptional values as a definition? But then again, I will never need them again. Maybe also add a remark on the relation to lacunary values (Picard).

Theorem 3.21 (Borel). *Existence of Borel exceptional values.*

Proof. **TODO.** ■

3.4 Composition

As seen by Proposition 3.2, the order of the sum or product of two entire functions is reasonably bounded by the order of the functions involved. This is not the case when composition is involved. Indeed, consider e^{e^z} , which has infinite order, yet is the composition of two functions of order 1. Necessary conditions for the order of a composition to be finite will be illustrated by Pólya's Theorem, the proof of which relies on the following result:

Lemma 3.22 (Bohr). *Let $0 < R < 1$ and suppose f is analytic on $\overline{\mathbb{D}}$, such that $f(0) = 0$ and $M_f(R) = 1$. Let r_f denote the largest $r \geq 0$ such that $C_r \subseteq f(\overline{\mathbb{D}})$. Then we have $r_f > C > 0$, where C is a constant depending only on R .*

Proof. **TODO.** Note that the proof relies on the strong form of Schottky's Theorem. ■

Theorem 3.23 (Pólya). *Let g, h be entire. For the order of $g \circ h$ to be finite, it must hold that either*

- i. h is a polynomial and g of finite order, or*

ii. h is of finite order, not a polynomial, and g is of order zero.

Proof. **TODO.** ■

Theorem 3.24 (Thron). *Let g be an entire function of finite order, not a polynomial, which takes some value w only finitely often. Suppose further that there exists some function f such that $f \circ f = g$. Then f is not entire.*

Proof. Seeking contradiction, suppose f were entire. Since g is not a polynomial, Theorem 3.23 implies that f is of order 0 and not a polynomial. Let $(z_j)_{j \in J}$ denote the points where f equals w . For each $m \in J$ we additionally denote by $(z_{j,m})_{j \in J_m}$ the points where f equals z_m . Thus, for each $m \in J$ and $n \in J_m$ we have

$$g(z_{n,m}) = f(f(z_{n,m})) = f(z_m) = w.$$

Our assumption on g assures that there must only be finitely many distinct points among the $(z_{n,m})_{m \in J, n \in J_m}$. Thus, each point in $(z_j)_{j \in J}$ is only taken on by f finitely often.

By Corollary 2.7, f attains all values in the complex plane infinitely often, with at most one exception. This implies that there is at most one z_0 in $(z_j)_{j \in J}$ that is only taken on finitely often by f .

If there is no such z_0 , then $h(z) := f(z) - w$ is entire, of order 0 and nowhere 0. Thus, by Hadamard's Theorem (3.11), h must be constant, and therefore f as well, a contradiction.

If such a z_0 exists, then $h(z) := f(z) - w$ has a zero of finite order $n \in \mathbb{N}$ at z_0 . Therefore we can write $h(z) = (z - z_0)^n p(z)$, where p is entire, of order 0 and nowhere 0. Again, this implies that p is constant, and therefore f a polynomial, a contradiction. ■

Example 3.25. A natural application of Theorem 3.24 is taking g to be e^z , which never takes on 0 as a value. Indeed, this implies that there is no entire function f satisfying

$$f(f(z)) = e^z.$$

On the other hand, there does exist a real-analytic function satisfying the above, as demonstrated by H. Kneser. **I probably still need a citation here.**

Bibliography

- [1] M. Blümlinger. Komplexe Analysis, 2021.
- [2] S. L. Segal. *Nine introductions in complex analysis*, volume 208 of *North-Holland Mathematics Studies*. Elsevier Science B.V., Amsterdam, revised edition, 2008.
- [3] E. M. Stein and R. Shakarchi. *Complex analysis*, volume 2 of *Princeton Lectures in Analysis*. Princeton University Press, Princeton, NJ, 2003.