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Paths of Rapid Growth of Entire Functions

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In 1957 A. HUBER published a paper in which he deduced the following theorem ([1], p. 52):

Theorem. Let f(z) be an entire function, not a polynomial. Let $\lambda > 0$. Then there exists a locally rectifiable path C_{λ} tending to infinity, such that

$$\int_{C_{\lambda}} |f(z)|^{-\lambda} |dz| < \infty.$$
(1)

HUBER'S proof depends on a deep study of subharmonic functions and is quite involved. Because of the simplicity of the result, I have been seeking a simple proof. This I have succeeded in obtaining only for special values of λ : $\lambda \ge 1$ or $\lambda = 1 - (1/n)$, n = 2, 3, ... In this note I present the proof for these values of λ .

As remarked by HUBER, there is no difficulty if f(z) has only a finite number of zeros, so that $f(z) = P(z) \exp[g(z)]$, where P is a polynomial and g is entire. The function

$$w = \Phi(z) = \int_{0}^{z} e^{-\lambda g(z)} dz$$

is then entire and without critical points. If the inverse function $\Phi^{-1}(w)$ has no singular points, then it is also entire, so that $\Phi(z)$ has form az + b and f(z) is a polynomial; hence $\Phi^{-1}(w)$ must have singularities. In particular there must be a functional element of $\Phi^{-1}(w)$ which can be continued from w = 0 along a finite segment ending at a singularity w_0 . The segment is mapped by $\Phi^{-1}(w)$ on a path C_{λ} in the z-plane, on which $z \to \infty$ as $w \to w_0$. Then

$$|w_0| = \int_{C_\lambda} \left| \frac{dw}{dz} \right| |dz| = \int_{C_\lambda} |e^{g(z)}|^{-\lambda} |dz|$$

Thus C_{λ} is the desired path if $P(z) \equiv 1$; by removing a finite portion of C_{λ} , one can ensure that $|P(z)| \geq 1$ on the remaining portion C'_{λ} , so that C'_{λ} is the desired path.

Now let us suppose that f has infinitely many zeros and let λ have form 1 - (1/n), $n = 2, 3, \ldots$ We can then assume without loss of generality that f(z) is expressible as $z^{2n}G(z)$, where G(z) is entire and $G(0) \neq 0$. For moving a zero of f from z_1 to the origin, or from the origin to z_1 , is equivalent to multiplying f by $z/(z - z_1)$, or by $(z - z_1)/z$, a factor which approaches 1

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as z approaches infinity and which has therefore no effect on the integral in (1). We select k such that $f(k) \neq 0$ and introduce

$$w = \Phi(z) = \int_{k}^{z} [f(z)]^{-\lambda} dz = \int_{k}^{z} z^{2-2n} [G(z)]^{\frac{1}{n}-1} dz \quad .$$
 (2)

This equation defines $\Phi(z)$ as a multiple-valued function of z. However, we remark that one branch (in fact, every branch) has a pole of order 2n - 3 at z = 0. The inverse function $\Phi^{-1}(w)$ can be considered as the solution of the differential equation

$$\frac{dz}{dw} = z^{2n-2} [G(z)]^{1-\frac{1}{n}} , \qquad (3)$$

such that z = k when w = 0. We consider the solution along rays arg w = const., starting with a given analytic branch at w = 0. By the theory of differential equations, the solution continues to exist as long as the value of z remains within the domain of analyticity of the right-hand member of (3). Trouble can arise as $w \to w_0$ ($w_0 \neq \infty$) only if, as $w \to w_0$, z approaches a zero of G or z approaches infinity. If $z \to z_0$, $G(z_0) = 0$, then z_0 must be a zero of first order of G, for by (2) at a multiple zero $w \to \infty$ as $z \to z_0$. Near a first order zero we obtain series expansions

$$w - w_0 = (z - z_0)^{1/n} [b_0 + b_1 (z - z_0) + \ldots], \ b_0 \neq 0,$$

$$z - z_0 = b_0^{-n} (w - w_0)^n + \ldots;$$

that is, $\Phi^{-1}(w)$ is a single-valued analytic function in a neighborhood of w_0 . [An illustration is provided by $z = \sin w$ as a solution of the differential equation $dz/dw = (1 - z^2)^{\frac{1}{2}}$].

Therefore continuation of $\Phi^{-1}(w)$ can be interrupted at a finite value w_0 only if, as $w \to w_0, z \to \infty$. If indefinite continuation were possible along all rays, then $\Phi^{-1}(w)$ would be an entire function of w. But we know that one branch of $\Phi^{-1}(w)$ approaches 0 as $w \to \infty$, because of the pole of $\Phi(z)$ at z = 0. Therefore $\Phi^{-1}(w) \to 0$ as $w \to \infty$. Accordingly, $\Phi^{-1}(w) \equiv 0$, and there is a contradiction. Hence continuation must be interrupted at at least one value w_0 , and we obtain the path C_{λ} as in the first part of the proof.

For $\lambda \geq 1$ we consider two cases: λ rational, equal to m/n; λ irrational. In the rational case the proof for the case $\lambda = 1 - (1/n)$ can be repeated with the simplification that, at each zero of G(z), $w \to \infty$ as $z \to z_0$.

If λ is irrational, we do not need to normalize f at z = 0. The previous argument can be repeated with slight modification; the differential equation (3) is replaced by the equation $dz/dw = [f(z)]^{\lambda}$ and a solution z(w) can be continued along a ray arg w = const. unless z approaches the boundary of

the domain of analyticity of $[f(z)]^{\lambda}$, a RIEMANN surface over the z-plane. Since $|f(z)|^{\lambda}$ has the same value on all sheets of this surface, we conclude that continuation can be interrupted for finite w_0 only if, as $w \to w_0$, z approaches ∞ or a zero of f. But since $\lambda > 1$, $w \to \infty$ as z approaches a zero of f. Hence, if $\Phi^{-1}(w)$ has no singularity at which $z \to \infty$, then $\Phi^{-1}(w)$ is single-valued, an entire function $\psi(w)$, and

$$\frac{dz}{dw} = \frac{d\psi}{dw} = [f(z)]^{\lambda} = [f(\psi(w))]^{\lambda} = [g(w)]^{\lambda},$$

where g(w) is entire. Therefore $[g(w)]^{\lambda}$ is also entire. This is possible with λ irrational only if g(w) has no zeros—hence only if f(z) has at most one zero. Again we have a contradiction. Therefore HUBER's theorem is proved for $\lambda \geq 1$ and for $\lambda = 1 - (1/n)$ (n = 2, 3, ...).

Remark 1. The theorem can be strengthened for functions having no zeros. For then $\log f(z)$ can be defined as an entire function; if $\log f(z)$ is not a polynomial, there exists a path C_{λ} on which

$$\int_{C_{\lambda}} |\log f(z)|^{-1} |dz| < \infty .$$

Remark 2. In his paper ([1], p. 52) HUBER raises the question: Suppose f(z) is entire and that there exists $\lambda > 0$ such that

$$\int_{1}^{\infty} |f(re^{i\theta})|^{-\lambda} dr = \infty$$

for all θ , $0 \leq \theta < 2\pi$; does this imply that f(z) is a polynomial? In other words, in the preceding theorem, can C_{λ} be chosen to be a ray?

This question we answer negatively as follows. A theorem of KELDYS and MERGELYAN ([2], p. 37) implies that, if g(z) is continuous on a closed set E and analytic on the interior of E, then for each $\epsilon > 0$ there exists an entire function f(z) such that $|f(z) - g(z)| < \epsilon$ on E, provided the complement E' of E is locally connected at infinity. In particular, E can be chosen to be the closure of a domain bounded by a simple path γ which approaches infinity in both directions. On such a set E we can easily construct g(z), not identically constant, such that $|g(z)| < \frac{1}{2}$ on E (for example, g(z) can be obtained with the aid of conformal mapping from the function $\frac{1}{4}e^{z}$ in the left half-plane). Let $g(z_0) = a$, $g(z_1) = b \neq a$. We choose $\epsilon = |b - a|/2$ and f(z) entire, so that $|f - g| < \epsilon$ on E. Then f is not identically constant and |f| < 1 on E. Since f is bounded on such a set, f cannot be a polynomial. By proper choice of γ , we can force every ray $C_{\theta}: \theta = \text{const.}$ to meet E in a set of infinite length; for example, γ can be formed of two spirals which approach

each other as $|z| \rightarrow \infty$, and E' as the set between the spirals. Then

$$\int_{C_{\theta}} |f(z)|^{-\lambda} |dz| \ge \int_{C_{\theta} \cap E} |dz| = \infty.$$

For such a function f(z) it is clear that the path C_{λ} of HUBER's theorem must either lie between the spirals (that is, in E') or be asymptotic to E' in the sense that the length of the part of C_{λ} outside of E' must be finite; hence effectively there is only one path.

Remark 3. Although the paths $\arg z = \text{const.}$ are not generally allowable as a choice of C_{λ} , it appears reasonable that the paths $\arg w = \text{const.}$ can serve. For on such a path, not passing through a zero of f, |f(z)| grows steadily in one direction. I conjecture that, for each f(z), a path $\arg f(z) = c$ can serve as C_{λ} for almost all values of c. For a similar reason, it appears probable that the paths $\operatorname{Re}[f(z)] = c$, $\operatorname{Im}[f(z)] = c$ can also serve as C_{λ} for almost all c.

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