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- 1° Any two points of the set $E \cap \text{cl}U(z, r)$ can be joined by an arc lying in $E \cap \text{cl}U(z, br)$.
- 2° Any two points of the set $E - U(z, r)$ can be joined by an arc lying in $E - U(z, r/b)$.

The following result has recently been proved by Gehring [2]:

LEMMA 3.2. *Let the set C contain at least two points and bound a simply connected domain A . If A is b -locally connected, then C is a $c(b)$ -quasicircle, where $c(b)$ depends only on b .*

3.3 *Quasiconformal reflection.* Let C be a Jordan curve bounding the domains A and B . A sense-reversing K -quasiconformal mapping $\varphi: A \rightarrow B$ is a K -quasiconformal reflection in C if φ leaves every point of C invariant.

It is not difficult to prove that C admits a quasiconformal reflection if and only if C is a quasicircle. It follows that a quasiconformal mapping $f: A \rightarrow B$ between domains A and B bounded by quasicircles can be extended to a quasiconformal mapping of the plane. In fact, if φ and ψ are quasiconformal reflections in the boundaries ∂A and ∂B , such that φ is defined outside A and ψ in B , then $\psi \circ f \circ \varphi$ extends f quasiconformally.

A quasicircle always admits quasiconformal reflections which are continuously differentiable or even real-analytic. For a K -quasicircle passing through ∞ , a reflection φ exists such that $|d\varphi(z)|/|dz|$ is bounded by a constant depending only on K .

For more details of the properties of quasicircles we refer to [10].

4. DEVIATION OF A DOMAIN FROM A DISC

4.1 *Schwarzian derivative.* Let f be a locally injective meromorphic function in a simply connected domain A . At finite points of A which are not poles of f , the Schwarzian derivative S_f of f is defined by

$$S_f = (f''/f')' - \frac{1}{2}(f''/f')^2,$$

and the definition is extended to ∞ and to the poles of f by means of inversion.

The Schwarzian derivative is holomorphic in A . Conversely, every function which is holomorphic in A is the Schwarzian of some f . The Schwarzian vanishes identically if and only if f is a Möbius transformation.

More generally, the Schwarzian determines a function up to a Möbius transformation.

Suppose the boundary of A consists of more than one point; then a conformal mapping h of A onto the unit disc exists. Through h a conformally invariant metric $\rho(z) |dz|$ is defined in A , by the rule $\rho(z) |dz| = (1 - |w|^2)^{-1} |dw|$, $w = h(z)$. For functions φ holomorphic in A we introduce the norm

$$\|\varphi\|_A = \sup_{z \in A} |\varphi(z)| \rho(z)^{-2}.$$

The Schwarzian obeys the composition rule $S_{f \circ g} = (S_f \circ g) f'^2 + S_g$. We note certain of its immediate consequences. First, let f be meromorphic in A and $h: A \rightarrow B$ a conformal mapping. Then

$$(4.1) \quad |S_f(z) - S_h(z)| \rho_A(z)^{-2} = |S_{f \circ h^{-1}}(\zeta)| \rho_B(\zeta)^{-2}, \quad \zeta = h(z).$$

It follows that $\|S_f - S_h\|_A = \|S_{f \circ h^{-1}}\|_B$. In particular,

$$(4.2) \quad \|S_h\|_A = \|S_{h^{-1}}\|_B.$$

Secondly, let f and g be meromorphic in A and $h: G \rightarrow A$ a conformal mapping. Then

$$(4.3) \quad \|S_{f \circ h} - S_{g \circ h}\|_G = \|S_f - S_g\|_A.$$

Finally, we remark that the norm of the Schwarzian is completely invariant under Möbius transformations: If f is meromorphic in A and g and h are Möbius transformations, then $\|S_{h \circ f \circ g}\|_{g^{-1}(A)} = \|S_f\|_A$.

4.2 Constant σ_1 . We associate with the domain A the constant $\sigma_1 = \|S_f\|_A$, where f is a conformal map of A onto a disc. Here a disc means an ordinary disc or a half-plane. The number σ_1 is well defined, and equal to 0 if and only if A itself is a disc. It can be regarded as a measure of how much the domain A differs from a disc.

It is well known that $\sigma_1 \leq 6$ (Theorem of Kraus [6]). For the domain $A = \{z \mid 0 < \arg z < k\pi\}$, $1 \leq k \leq 2$, we have $\sigma_1 = 2(k^2 - 1)$. It follows that σ_1 can take any value in the closed interval $[0, 6]$.

4.3 Domains bounded by a quasicircle. In some cases, information about the boundary of A makes it possible to improve the estimate $\sigma_1 \leq 6$.

THEOREM 4.1. *For a domain A bounded by a K -quasicircle,*

$$(4.4) \quad \sigma_1 \leq 6 \frac{K^2 - 1}{K^2 + 1}.$$

Proof: By Lemma 3.1, there exists a K^2 -quasiconformal mapping w of the plane whose restriction to the upper half-plane H maps H conformally onto A . For the function $w|_H$ the Krauss estimate can be improved:

$$\|S_{w|_H}\|_H \leq 6 \frac{K^2 - 1}{K^2 + 1};$$

for the proof we refer to Kühnau [7], or to [8]. Hence (4.4) follows from (4.2).

4.4 Domains with bounded boundary rotation. Let A be a domain bounded by a continuously differentiable Jordan curve. The total variation of the direction angle of the boundary tangent under a complete circuit is called the boundary rotation of A . If the boundary is not so regular, boundary rotation is defined by means of approximations from inside.

Let f be a conformal mapping of the unit disc D onto a domain A with boundary rotation $k\pi$, $2 \leq k < \infty$. A real-valued function ψ with the properties

$$\int_0^{2\pi} d\psi(\theta) = 2, \quad \int_0^{2\pi} |d\psi(\theta)| = k,$$

can be associated with f , such that

$$(4.5) \quad f'(z) = f'(0) \exp \left(- \int_0^{2\pi} \log(1 - ze^{-i\theta}) d\psi(\theta) \right).$$

The domain A is convex if and only if $k = 2$. This is equivalent to ψ being an increasing function. A function f whose derivative admits the representation (4.5) is always univalent if the total variation of ψ is ≤ 4 .

Domains with bounded boundary rotation were introduced by Löwner and their basic properties established by Paatero [14].

THEOREM 4.2. *For a domain A with boundary rotation $\leq k\pi$, $2 \leq k \leq 4$,*

$$(4.6) \quad \sigma_1 \leq \frac{2k + 4}{6 - k}.$$

The bound is sharp.

Proof: Let $f: D \rightarrow A$ be a conformal mapping, z_0 an arbitrary point of D , and h a conformal self-mapping of D , such that $h(0) = z_0$. Since $\rho_D(0) = 1$, it follows from (4.1) that

$$(4.7) \quad |S_f(z_0)| \rho_D(z_0)^{-2} = |S_{f \circ h}(0)|.$$

Hence, (4.6) follows if we prove that $|S_f(0)| \leq (2k+4)/(6-k)$. Since we may replace f by the function $z \rightarrow cf(ze^{i\varphi})$, c complex, φ real, there is no loss of generality in assuming that $S_f(0) \geq 0$ and that $f'(0) = 1$. From the representation formula (4.5) we then deduce that

$$(4.8) \quad S_f(0) = \int_0^{2\pi} \cos 2\theta d\psi(\theta) - \frac{1}{2} \left(\int_0^{2\pi} \cos \theta d\psi(\theta) \right)^2 + \frac{1}{2} \left(\int_0^{2\pi} \sin \theta d\psi(\theta) \right)^2.$$

If $k = 2$, we have $d\psi(\theta) \geq 0$. In this case we get the inequality $\sigma_1 \leq 2$ for convex domains from (4.8) quite easily, just by use of Schwarz's inequality. Extremal functions can also be determined. These computations have been carried out in [9]. Nehari [13] proved the result $\sigma_1 \leq 2$ by means of variational methods.

If $2 < k \leq 4$, establishing (4.6) requires a more careful handling of formula (4.8). These computations will be published in a joint paper with O. Tammi.

Matti Lehtinen has let me know that for functions f whose derivative satisfies (4.5) with a ψ whose total variation is $\leq k$, $k \geq 4$, the sharp upper bound for $\|S_f\|$ is equal to $(k^2 - 4)/2$. The extremal functions are not univalent.

4.5 Constant σ_2 . The domain constant

$$\sigma_2 = \sup \{ \|S_f\|_A \mid f \text{ univalent in } A \}$$

is in simple relation with σ_1 ([9]):

THEOREM 4.3. *In every domain A , $\sigma_2 = \sigma_1 + 6$.*

Proof: Let f be univalent in A and $h: D \rightarrow A$ conformal. By (4.3),

$$\|S_f\|_A = \|S_{f \circ h} - S_f\|_D \leq 6 + \|S_h\|_D = 6 + \sigma_1.$$

In order to derive an estimate in the opposite direction, let an $\varepsilon > 0$ be given. In view of formula (4.7), we can choose $h: D \rightarrow A$ so that $|S_h(0)|$

$> \sigma_1 - \varepsilon$. If w is defined by $w(z) = z + e^{i\theta}/z$ and $f = w \circ h^{-1}$, then f is univalent in A and

$$\|S_f\|_A = \|S_w - S_h\|_D \geq |S_w(0) - S_h(0)| = |6e^{i\theta} + S_h(0)|.$$

By choosing φ suitably we obtain $\|S_f\|_A > 6 + \sigma_1 - \varepsilon$.

5. SCHWARZIAN DERIVATIVE AND UNIVALENCE

5.1 *Constant σ_3 .* Let A again be a simply connected domain with more than one boundary point. As a kind of opposite to the constant σ_2 we define

$$\sigma_3 = \sup \{a \mid \|S_f\| \leq a \text{ implies } f \text{ univalent in } A\}.$$

Note that the number $a = 0$ is always in the above set. In this definition, sup can be replaced by max, as can be shown by a standard normal family argument.

Nehari [12] proved that in a disc, the condition $\|S_f\| \leq 2$ implies the univalence of f , and Hille [5] showed that the bound 2 is best possible. In other words, $\sigma_3 = 2$ for a disc.

A closer study of σ_3 leads to the universal Teichmüller space and reveals an intrinsic significance of quasiconformal mappings in the theory of univalent functions. The gist is the following result.

THEOREM 5.1. *The constant σ_3 is positive if and only if A is bounded by a quasicircle.*

Proof: The sufficiency of the condition was established by Ahlfors [1] who actually proved more: If A is bounded by a K -quasicircle, there is an $\varepsilon > 0$ depending only on K , such that whenever $\|S_f\|_A < \varepsilon$, then f is univalent and can be continued to a quasiconformal mapping of the plane. In the proof, the extension of the given meromorphic f is explicitly constructed by means of a continuously differentiable quasiconformal reflection φ in ∂A with bounded $|d\varphi|/|dz|$ (cf. 3.3).

The necessity was proved by Gehring [2]. His proof was in two steps. It was first shown, by aid of an example, that if A is not b -locally connected for any b , then $\sigma_3 = 0$. After this, the desired conclusion was drawn from the result we stated above as Lemma 3.2.

5.2 *Universal Teichmüller space.* Henceforth, we assume that the domain A is bounded by a quasicircle. Let $Q(A)$ be the Banach space