POINT SHIFT DIFFERENTIALS AND EXTREMAL QUASICONFORMAL MAPPINGS

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Abstract. We consider quasiconformal selfmappings \( f \) of the disk with given boundary values. For fixed \( z_0 \) the set of image points \( \{ f_0(z_0) \} \) for all extremal mappings \( f_0 \) is called the variability set \( V[z_0] \) of \( z_0 \). Extremal mappings \( f_m \) which take \( z_0 \) into points \( w_m \notin V[z_0] \) are called point shift mappings. They are Teichmüller mappings associated with quadratic differentials \( \varphi_m \) of norm \( \| \varphi_m \| = 1 \), called point shift differentials. It is shown that the \( \varphi_m \) form Hamilton sequences for the extremal mappings which take \( z_0 \) into boundary points of \( V[z_0] \). From that it follows, using the frame mapping criterion, that the \( \varphi_m \) depend continuously in norm of the point \( w_m \). Their constant dilatation \( K[w_m] \) is called the dilatation function. Based on a variational method for point shift mappings, it is shown that the level lines of \( K[w_m] \) are Jordan curves separating \( V[z_0] \) from \( \partial D_w \). Thus, \( V[z_0] \) is a compact, connected set without holes.

1. Introduction

1. A holomorphic quadratic differential \( \varphi(z) dz^2 \) induces a conformally invariant metric \( |\varphi(z)|^{1/2} |dz| \). It is Euclidean in the neighborhood of the non critical points of \( \varphi \) (the critical points are the zeroes and poles): if we apply the conformal mapping

\[
\zeta = \Phi(z) = \int^z \sqrt{\varphi(z)} \, dz
\]

we find \( d\zeta^2 = \varphi(z) dz^2 \), which is the Euclidean line element in the \( \zeta \)-plane. This metric and its geodesics (for details see [12]) lead to certain inequalities which constitute a fundamental tool in the theory of extremal quasiconformal mappings.

2. The first of these inequalities is the so-called Main Inequality (see [6] for the disk, and [11] for arbitrary Riemann surfaces).

Let \( w = f(z) \) and \( \tilde{w} = \tilde{f}(z) \) be quasiconformal mappings of the unit disk \( D_z \) onto \( D_w \) which agree on the boundary of \( D_z \). Let \( dw = p(z) \, dz + q(z) \, d\bar{z} \) be the differential of \( f \), \( \varkappa = q/p \) its complex dilatation and \( K \) its maximal dilatation. The inverse of \( \tilde{f} \) is denoted by \( f_1 = \tilde{f}^{-1} \), its complex dilatation by \( \varkappa_1 \). Of course, its maximal dilatation \( K_1 \) is equal to the maximal dilatation \( \tilde{K} \) of \( \tilde{f} \). The combination \( f_1 \circ \tilde{f} = f^{-1} \circ f \) is a qc selfmapping of \( D_z \) which is equal to the identity on \( \partial D_z \).

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Let now $\varphi \not\equiv 0$ be any holomorphic quadratic differential in $D_z$ of norm $\|\varphi\| = \iint |\varphi(z)| \, dx \, dy = 1$. It serves as a test quantity. Let $\alpha$ be any non critical trajectory of $\varphi$. It has two different end points on $\partial D_z$, and the curve $\tilde{\alpha} = f_1 \circ f(\alpha)$ has the same end points as $\alpha$. Since $\alpha$ is a geodesic, we have the length inequality, in terms of the $\varphi$-metric, $|\tilde{\alpha}|_\varphi \geq |\alpha|_\varphi$. Using the conformal parameter $\Phi$ along the trajectories of $\varphi$ this length inequality can be integrated over the whole disk $D_z$, which leads to the “Main Inequality”

\begin{equation}
1 \leq \iint |\varphi(z)| \frac{1 - \kappa(\varphi/|\varphi|)}{1 - |\kappa|^2} \{ \cdots \} \, dx \, dy,
\end{equation}

with

\begin{equation}
\{ \cdots \} = \frac{1 - \frac{p}{\varphi} \frac{\varphi - \varphi(\varphi/|\varphi|)}{1 - \kappa(\varphi/|\varphi|)}}{1 - |\kappa|^2}
\end{equation}

(see [6], ineq. 1.5.1, and [11] for Riemann surfaces; the method first appears in [8].)

The term (3) in brackets has the upper bound $K_1 = \tilde{K}$. If we set $\tilde{f} = f_0$, where $f_0$ is an extremal quasiconformal mapping for the given boundary values, i.e. one with smallest maximal dilatation $K_0$, we have $\{ \cdots \} \leq K_0$. This turns (2) into the simpler form

\begin{equation}
\frac{1}{K_0} \leq \iint |\varphi(z)| \frac{1 - \kappa(\varphi/|\varphi|)}{1 - |\kappa|^2} \, dx \, dy,
\end{equation}

which we call the reduced form of the Main Inequality. Its contents is the following: Let $f$ be a qc selfmapping of $D$ and let $K_0$ be the smallest maximal dilatation in the class of all qc selfmappings of $D$ with the boundary values of $f$. Then, for every holomorphic quadratic differential $\varphi$ of norm one in $D$ we have (4). (See [6], and [11] for Riemann surfaces.)

3. The holomorphic quadratic differentials of finite norm give rise to a very interesting necessary and sufficient condition for the complex dilatation $\kappa$ of a qc mapping to be extremal. It reads as follows: Let $\kappa$ be the complex dilatation of a qc mapping $f$. Then, $f$ is extremal for its boundary values (and in its homotopy class) if and only if

\begin{equation}
\sup_{\|\varphi\|=1} \Re \iint \kappa \varphi \, dx \, dy = \|\kappa\|_\infty.
\end{equation}

The necessity was shown by R.S. Hamilton [1] and simultaneously (for complex dilatations of constant absolute value) by S. Krushkal [2]. The sufficiency is a consequence of the reduced form (4) of the main inequality and was shown, for

A sequence of holomorphic quadratic differentials $\varphi_n$ of norm one such that

$\text{(6)} \quad \text{Re} \int \int \kappa \varphi_n \, dx \, dy \to \| \kappa \|_\infty$

is called a Hamilton sequence. If there exists such a sequence which converges to a quadratic differential $\varphi$ in the sense that $\| \varphi_n - \varphi \| \to 0$, it is easily seen that

$\text{(7)} \quad \kappa = k \frac{\varphi}{|\varphi|}$

This is the complex dilatation of a Teichmüller mapping. The crucial situation is when there is no such sequence, i.e. every Hamilton sequence for $\kappa$ converges locally uniformly to zero (what we call a “degenerating Hamilton sequence”).

The Main Inequality provides a criterion to the effect that there is no degenerating Hamilton sequence for $\kappa$. It is called the Frame Mapping Criterion ([9], [10]) and reads as follows (we only formulate it for the disk here, but it is true in full generality): Let $K_0$ be the smallest maximal dilatation for all qc selfmappings of $D$ with a given quasisymmetric boundary homeomorphism $h$. Assume that $h$ can be continued quasiconformally into a neighborhood of $\partial D$ with a maximal dilatation $H < K_0$. Then, $\kappa$ does not admit a degenerating Hamilton sequence and thus has the Teichmüller form $\kappa = k|\varphi|/|\varphi| = 1$. Moreover, every Hamilton sequence $(\varphi_n)$ for $\kappa$ tends in norm to $\varphi$ ([10], Theorem 1). According to an earlier theorem (originally in [7], with a new proof in [6]) the mapping $f$ is then uniquely extremal.

4. The existence of a Hamilton sequence $(\varphi_n)$ for every extremal $\kappa$ was proved by R. Hamilton in an abstract way. It is however possible, for the disk, to give Hamilton sequences in a more concrete manner, namely as differentials of certain Teichmüller mappings.

For a given extremal mapping $f$ with complex dilatation $\kappa$ pick a finite set of boundary points $\zeta_i$, $i = 1, \ldots, n$. The disk $D$ together with these points is called a polygon $\Pi_n$ with vertices $\zeta_i$. According to Teichmüller’s theorem there is a unique extremal selfmapping of $D$ which takes the vertices $\zeta_i$ into their images by $f$, $\zeta'_i = f(\zeta_i)$. It is a Teichmüller mapping associated with a holomorphic quadratic differential $\varphi$, $\| \varphi \| = 1$, which is real along the sides of the polygon, i.e. $\varphi(z) \, dz^2$ real for tangential $dz$ between the vertices. (The vertices themselves are at worst first order poles.)

Call the $\varphi$ “polygon differentials”. One can show that, if the vertices of the polygons $\Pi_n$ become more and more dense, the associated polygon differentials form a Hamilton sequence for $\kappa$ ([6], Theorem 6).
5. The basis of this article is a new kind of Hamilton sequences, namely point shift differentials. They were introduced in ([10], Theorem 7). Pick a point \( z_0 \in D \). Consider again the qc selfmappings \( f \) of \( D \) with boundary values \( h \). The set of image points of \( z_0 \) by the extremal mappings \( f_0 \) is called the set of variability of \( z_0 \) and denoted by \( V[z_0] \) (see [10], p. 479). Of course, if \( h \) has a unique extremal solution, \( V[z_0] \) consists of a single point for every \( z_0 \in D \). In general it is a compact subset of \( D \). Choose \( w_n \notin V[z_0] \). Then, the extremal qc mapping \( f_n \) with boundary values \( h \) on \( \partial D \) and taking \( z_0 \) into \( w_n \) is a Teichmüller mapping associated with a quadratic differential \( \varphi_n \) of norm one which has a first order pole at \( z_0 \). (This is an immediate consequence of the frame mapping criterion.) \( \varphi_n \) is called a point shift differential, \( f_n \) a point shift mapping.

Let now \( w_0 \) be a boundary point of \( V[z_0] \), and let \( f_0(z_0) = w_0 \). It will be shown that for \( w_n \to w_0 \) the point shift differentials \( \varphi_n \) form a Hamilton sequence for the complex dilatation \( \kappa_0 \) of \( f_0 \).

It should be noticed that the polygon differentials provide Hamilton sequences for every extremal mapping, i.e. also for extremal mappings which take \( z_0 \) into an interior point of \( V[z_0] \). This is not so for point shift differentials, because they only exist if the shifted point \( w_n \) is outside \( V[z_0] \). In the case of unique extremality this is of course no restriction. The obvious advantage of the point shift differentials is the fact that they only depend on one complex parameter, namely the shifted point \( w_n \). On the other hand the polygon differentials depend on an increasing number of parameters, namely the vertices of the polygons. This makes them geometrically extremely hard to control.

Clearly, point shift differentials exist in the most general case, in the same generality as the frame mapping criterion.

6. The simplest but quite formal definition of a Teichmüller mapping is by its complex dilatation, which is \( \kappa = k\overline{\varphi}/|\varphi| \), \( 0 < k < 1 \), where \( \varphi \) is a meromorphic quadratic differential. For our purposes it is however necessary to express this in geometric terms. It is done here for the disk (see [8]), but most generally true for arbitrary Riemann surfaces.

![Figure 1](image)

Let \( f: D_z \to D_w \) be a qc mapping with complex dilatation (7). Pick a
neighborhood $U \subset \mathbb{D}_z$ such that $\varphi$ is holomorphic in $U$ without zeroes (Figure 1). Let
\begin{equation}
\zeta = \xi + i\eta = \Phi(z) = \int^z \sqrt{\varphi(z)} \, dz
\end{equation}
in $U$. By restriction of $U$, if necessary, we may assume that $\Phi$ is schlicht in $U$. Set $U^* = \Phi(U)$ and let $F_K$ be the horizontal stretching of $U^*$ by $K = (1 + k)/(1 - k)$. We have
\begin{equation}
\zeta^* = F_K(\zeta) = K\xi + i\eta = \frac{1}{2}(K + 1)\zeta + \frac{1}{2}(K - 1)\bar{\zeta} = \frac{1}{2}(K + 1)(\Phi(z) + k\bar{\Phi}(z)).
\end{equation}
From this expression follows that the complex dilatation of the composition $F_K \circ \Phi$ is given by (7). Therefore the mappings $f$ and $F_K \circ \Phi$ are related by a conformal mapping $\Psi: V = f(U) \rightarrow V^* = F_K(U^*)$ such that
\begin{equation}
\Psi \circ f = F_K \circ \Phi.
\end{equation}
It is easy to see that $\psi = \Psi'^2$ is single valued in $\mathbb{D}_w$. It is the well defined quadratic differential which is associated to $\varphi$. We realize that the horizontal and the vertical trajectories of $\varphi$ through a point $z \in U$ go into the horizontal and vertical trajectories of $\psi$ through $w = f(z)$ respectively. Horizontal lengths are stretched by $K$, vertical lengths are preserved.

We will call $\varphi$ and $\psi$ the quadratic differentials associated with the Teichmüller mapping $f$. Clearly, if $\|\varphi\| = 1$, $\|\psi\| = K$.

II Point shift differentials

7. Let $T[w_1, w_2]$ be the extremal qc selfmapping of the unit disk $\mathbb{D}$ which takes $w_1$ into $w_2$ and is equal to the identity on $\partial\mathbb{D}$. The Frame Mapping Criterion assures that it is a Teichmüller mapping associated with a pair of quadratic differentials $\varphi$ and $\psi$ of finite norm. $\varphi$ has a first order pole at $w_1$, $\psi$ has one at $w_2$, and if we set $\|\varphi\| = 1$ and use the horizontal stretching version for Teichmüller mappings (as we always do) we have $\|\psi\| = K_T$ where $K_T$ is the dilatation of $T$. The mapping $T$ is conjugate, by a Möbius transformation of the disk, to the mapping in Teichmüller’s “Verschiebungssatz”, where $w_1 = 0$ and $w_2 = -\varrho$. It is not hard to see that $K_T \rightarrow 1$ for $w_2 \rightarrow w_1$. Because of this connection we call $T[w_1, w_2]$ the Teichmüller shift.

8. Denote the unit disks of the $z$- and the $w$-plane by $\mathbb{D}_z$ and $\mathbb{D}_w$ respectively. Let $h$ be a fixed quasisymmetric mapping of $\partial\mathbb{D}_z$ onto $\partial\mathbb{D}_w$. Choose a fixed point $z_0 \in \mathbb{D}_z$ and, for $w \in \mathbb{D}_w$, let $f$ be an extremal qc mapping of $\mathbb{D}_z$ onto $\mathbb{D}_w$ which is equal to $h$ on $\partial\mathbb{D}_z$ and takes $z_0$ into $w$. Let $K$ be its maximal dilatation.
Theorem 1. The maximal dilatation $K$ is, for fixed $z_0$, a continuous function of $w$ which tends to infinity for $|w| \to 1$. It is called the dilatation function and denoted by $K[w]$.

Proof. To prove the first statement, choose $\tilde{w} \neq w$ and let $\tilde{K}$ be the maximal dilatation of an extremal mapping $\tilde{f}$, $\tilde{f}(z_0) = \tilde{w}$, $\tilde{f} \mid \partial D_z = h$. The composition $T[w, \tilde{w}] \circ f$ takes $z_0$ into $\tilde{w}$ and has therefore a maximal dilatation which is at least equal to $\tilde{K}$. On the other hand it is smaller or equal to $K \cdot T$, thus $K \cdot T \geq \tilde{K}$, which gives

$$\lim_{\tilde{w} \to w} \tilde{K} \leq K.$$ 

On the other hand, since $f$ is extremal,

$$\lim_{\tilde{w} \to w} \tilde{K} \geq K,$$ 

which gives

$$\lim_{\tilde{w} \to w} \tilde{K} = K,$$ 

as claimed.

To prove the second statement, let $w_n \to \omega \in \partial D_w$. Let $\zeta = h^{-1}(\omega)$ and choose two disjoint closed intervals $\delta_1$ and $\delta_2$ on $\partial D_z$ none of which contains the point $\zeta$. The set of cross cuts $\gamma$ joining $\delta_1$ to $\delta_2$ in $D_z$ and separating $z_0$ from $\zeta$ goes over by $f_n$ into a set of curves $\gamma'$ connecting $\delta'_1 = h(\delta_1)$ and $\delta'_2 = h(\delta_2)$ and separating $w_n$ from $\omega$. Here, $f_n$ is an extremal mapping, with maximal dilatation $K_n$, taking $z_0$ into $w_n$. We have the extremal length inequality $\lambda{\gamma'} \leq K_n \lambda{\gamma}$, and since the left hand side evidently tends to infinity, we find $K_n \to \infty$, as claimed.

Corollary. The set of variability of $z_0$,

$$V[z_0] = \{w = f(z_0) ; f \text{ extremal for the boundary values } h\}$$

is compact.

This is so because all the extremal mappings $f_0$ for all points $w_0 \in V[z_0]$ have the same maximal dilatation $K_0$. Therefore $V[z_0]$ is bounded away from $\partial D_w$, and because of the continuity of the maximal dilatation it contains all its accumulation points.

9. Let $w_n$ be a point of $D_w$ outside the variability set $V[z_0]$. Then, any extremalqc mapping $f_n$ of $D_z$ onto $D_w$ with the boundary values $h$ and $f_n(z_0) = w_n$ has a maximal dilatation $K_n > K_0$, $K_0$ being the smallest maximal dilatation without the additional condition that $z_0 \to w_n$. We can therefore use any extremal mapping $f_0$ near $\partial D_z$ as a frame mapping (near $z_0$ we just use the translation $z_0 \to w_n$, which is of course conformal). The frame mapping condition applied
to the punctured disks tells us that $f_n$ is a Teichmüller mapping associated with a quadratic differential $\varphi_n$ of finite norm ($\|\varphi_n\| = 1$, say). $\varphi_n$ has a first order pole at $z_0$ and is otherwise holomorphic (without the pole, $f_n$ would be uniquely extremal for its boundary values $f_n \mid \partial D_z = h$, see [8] and [6]). We call $f_n$ a point shift mapping and $\varphi_n$ the associated point shift differential (see [10], p. 479).

The next result is basic for the whole paper.

10.

**Theorem 2.** Let $w_0$ be a boundary point of the variability set $V[z_0]$, and let $f_0$, with complex dilatation $\zeta_0$ and maximal dilatation $K_0$ be an extremal qc mapping which takes $z_0$ into $w_0$ (for brevity, we call such a mapping a “boundary element”, see also [5], p. 290). Let $w_n \in D_w \setminus V[z_0]$, and let $f_n$, $\varphi_n$ and $K_n$ be as in Section 9. Then, for $w_n \to w_0$ the sequence $(\varphi_n)$ is a Hamilton sequence for the complex dilatation $\zeta_0$ of $f_0$; i.e. $\Re\iint \varphi_n \, dx \, dy \to k_0 = \|\zeta_0\|_\infty$.

Proof. Let $T_n \equiv T[w_0, w_n]$ be the Teichmüller shift which takes $w_0$ into $w_n$. Let $\hat{f}_n = T_n \circ f_0$. This is a qc mapping of $D_z$ onto $D_w$, with the same boundary values as $f_n$, sending $z_0$ into $w_n$, and with a maximal dilatation $\hat{K}_n$ which tends to $K_0$ for $w_n \to w_0$.

Consider a regular trajectory $\alpha_n$ of $\varphi_n$, i.e. one which does not go to a zero or the simple pole of $\varphi_n$. It connects two different boundary points of the disk $D_z$. The image $\alpha'_n$ of $\alpha_n$ by $f_n$ is a well defined regular trajectory of the image differential $\tilde{\psi}_n$ connecting the images of the end points of $\alpha_n$. Let $\tilde{\alpha}_n$ be the image of $\alpha_n$ by $\hat{f}_n$; it has the same end points as $\alpha'_n$. Since $f_n(z_0) = \hat{f}_n(z_0) = w_n$, the two mappings $f_n$ and $\hat{f}_n$ are homotopic in $D_w \setminus \{w_n\}$ modulo the boundary. Therefore $\alpha_n$ and $\tilde{\alpha}_n$ are in the same homotopy class in $D_w \setminus \{w_n\}$ and thus satisfy the length inequality with respect to the $\tilde{\psi}_n$-metric, namely

$$|\tilde{\alpha}_n|_{\tilde{\psi}_n} \geq |\alpha'_n|_{\tilde{\psi}_n} = K_n|\alpha_n|_{\varphi_n}.$$  

(11) 

This inequality can now be integrated over the disk $D_z$ (see [8], or [6] p. 384–385 for polygon differentials). The image of $\alpha_n$ by $\zeta = \Phi_n(z)$ is an open horizontal interval $\alpha^*_n$ in the $\zeta = \xi + i\eta$-plane. We have, with $\tilde{w}_n = \hat{f}_n(z)$,

$$K_n|\alpha_n|_{\varphi_n} = K_n \int_{\alpha^*_n} d\xi \leq \int_{\alpha^*_n} |d\Psi_n(\tilde{w}_n)| = \int_{\alpha^*_n} \left| \frac{d\Psi_n(\tilde{w}_n)}{d\tilde{w}_n} \right| |d\tilde{w}_n|.  

(12)$$ 

With the notations $d\tilde{w}_n = \tilde{p}_n(z) \, dz + \tilde{q}_n(z) \, d\bar{z}$, $d\xi = \Phi_n'(z) \, dz$, we find along $\alpha^*_n$

$$d\tilde{w}_n = \left\{ \frac{\tilde{p}_n(z)}{\Phi_n(z)} + \frac{\tilde{q}_n(z)}{\Phi_n(z)} \right\} d\xi = \frac{1}{\Phi_n(z)} \left\{ \tilde{p}_n(z) + \tilde{q}_n(z) \frac{\varphi_n(z)}{|\varphi_n(z)|} \right\} d\xi.  

(13)$$

We put this expression into the equation (12) and integrate it over a short vertical interval in the $\zeta = \xi + i\eta$-plane. The domain of integration is a (Euclidean) horizontal strip $\Sigma$ in the $\zeta$-plane. Going back to the $z$-plane with
\[ d\xi \, d\eta = |\Phi_n'(z)|^2 \, dx \, dy = |\varphi_n(z)| \, dx \, dy \] the domain of integration is a strip \( S \) swept out by horizontal trajectories of \( \varphi_n \). Finally, summing up over a denumerable set of such strips forming an exhaustion of \( D_z \) (up to a set of measure zero) we get

\begin{equation}
K_n \|\varphi_n\| \leq \int\int_{|z| < 1} |\psi_n(\tilde{w}_n)|^{1/2} |\varphi_n(z)|^{1/2} \left| \tilde{p}_n(z) + \tilde{q}_n(z) \frac{\varphi_n(z)}{|\varphi_n(z)|} \right| \, dx \, dy.
\end{equation}

Before we apply the Schwarz inequality to this expression we insert the square root of the functional determinant

\begin{equation}
J(\tilde{w}_n \mid z) = |\tilde{p}_n(z)|^2 - |\tilde{q}_n(z)|^2
\end{equation}

and thus have

\begin{equation}
K_n \|\varphi_n\| \leq \int\int_{|z| < 1} |\psi_n(\tilde{w}_n)|^{1/2} J(\tilde{w}_n \mid z)^{1/2} \left| \frac{\varphi_n(z)^{1/2}}{J(\tilde{w}_n \mid z)^{1/2}} \tilde{p}_n + \tilde{q}_n(\varphi_n/|\varphi_n|) \right| \, dx \, dy.
\end{equation}

Finally, the Schwarz inequality yields

\begin{equation}
K_n^2 \|\varphi_n\|^2 \leq \int\int_{|z| < 1} |\psi_n(\tilde{w}_n)| \, J(\tilde{w}_n \mid z) \, dx \, dy \cdot \int\int_{|z| < 1} |\varphi_n| \left[ 1 + \frac{\tilde{\kappa}_n(\varphi_n/|\varphi_n|)}{1 - |\tilde{\kappa}_n|^2} \right]^2 \, dx \, dy,
\end{equation}

with \( \tilde{\kappa}_n = \tilde{q}_n(z)/\tilde{p}_n(z) \) the complex dilatation of \( \tilde{f}_n \).

Taking into account that

\begin{equation}
\int\int_{|z| < 1} |\psi_n(\tilde{w}_n)| \, J(\tilde{w}_n \mid z) \, dx \, dy = \|\psi_n\| = K_n \|\varphi_n\|
\end{equation}

and normalizing \( \|\varphi_n\| = 1 \) we get

\begin{equation}
K_n \leq \int\int_{|z| < 1} |\varphi_n(z)| \left[ 1 + \frac{\tilde{\kappa}_n(\varphi_n/|\varphi_n|)}{1 - |\tilde{\kappa}_n|^2} \right]^2 \, dx \, dy.
\end{equation}

We call this the “point shift inequality”. It resembles very much the “polygon inequality” (see [6, p. 385]).

11. To evaluate the point shift inequality, we write

\begin{equation}
\left| 1 + \frac{\varphi_n}{\tilde{\kappa}_n} \right|^2 = (1 + |\tilde{\kappa}_n|)^2 - 2 \left\{ |\tilde{\kappa}_n| - \text{Re} \, \frac{\varphi_n}{\tilde{\kappa}_n} \left| \frac{\varphi_n}{\tilde{\kappa}_n} \right| \right\}.
\end{equation}

Since

\begin{equation}
\frac{1 + |\tilde{\kappa}_n|}{1 - |\tilde{\kappa}_n|} \leq \frac{1 + \tilde{K}_n}{1 - \tilde{K}_n} = \tilde{K}_n \quad \text{a.e.}
\end{equation}
the point shift inequality (19) gives

\begin{equation}
K_n \leq \int \int_{|z|<1} |\varphi_n(z)| \frac{1 + |\bar{\zeta}_n|}{1 - |\bar{\zeta}_n|} dx \, dy - 2 \int \int_{|z|<1} \frac{|\bar{\zeta}_n| |\varphi_n| - \Re \bar{\zeta}_n \varphi_n}{1 - |\bar{\zeta}_n|^2} dx \, dy
\end{equation}

(22)

\begin{equation}
\leq \int \int_{|z|<1} |\varphi_n| \frac{1 + |\bar{\zeta}_n|}{1 - |\bar{\zeta}_n|} dx \, dy \leq \tilde{K}_n.
\end{equation}

Let now \( w_n \to w_0 \in \partial V[z_0] \). Then, because of the continuity of \( K[w_n] \) and since \( K[w_0] = K_0 \) we have \( K_n \to K_0 \). On the other hand, we have \( \tilde{K}_n \leq K_{T_n} \cdot K_0 \) and thus

\[ \lim_{w_n \to w_0} \tilde{K}_n \leq K_0. \]

From (22) we conclude that \( \tilde{K}_n \to K_0 \) for \( w_n \to w_0 \).

Another use of (22) shows that for \( w_n \to w_0 \)

\begin{equation}
\int \int_{|z|<1} |\varphi_n(z)| \frac{1 + |\bar{\zeta}_n|}{1 - |\bar{\zeta}_n|} dx \, dy \to K_0
\end{equation}

(23)

and

\begin{equation}
\int \int_{|z|<1} \frac{|\bar{\zeta}_n| |\varphi_n| - \Re \bar{\zeta}_n \varphi_n}{1 - |\bar{\zeta}_n|^2} dx \, dy \to 0.
\end{equation}

(24)

Therefore necessarily

\begin{equation}
\int \int_{|z|<1} \{ |\bar{\zeta}_n| |\varphi_n| - \Re \bar{\zeta}_n \varphi_n \} dx \, dy \to 0.
\end{equation}

(25)

The quantity \( \bar{\zeta}_n \) is the complex dilatation of the composition \( \tilde{f}_n = T_n \circ f_0 \), with \( T_n = T[w_0, w_n] \). Denote the complex dilatation of \( T_n \) by \( \zeta_{T_n} \); since it is a Teichmüller mapping, its absolute value is constant, \( |\zeta_{T_n}| = k_{T_n} \). The formula for the complex dilatation of the composition gives

\begin{equation}
\bar{\zeta}_n = \frac{\bar{\zeta}_0 + \bar{\zeta}_{T_n} \tau_0}{1 + \bar{\zeta}_{T_n} \bar{\zeta}_0 \tau_0}, \quad \tau_0 = \frac{\bar{p}_0}{p_0},
\end{equation}

(26)

(the differential of the extremal mapping \( w = f_0(z) \) is \( dw = p_0(z) \, dz + q_0(z) \, d\bar{z} \)). From this is follows that

\begin{equation}
\bar{\zeta}_n - \zeta_0 = \zeta_{T_n} \frac{\tau_0 \{ 1 - |\zeta_0|^2 \}}{1 + \zeta_{T_n} \bar{\zeta}_0 \tau_0}.
\end{equation}

(27)

Since \( |\zeta_{T_n}(z)| \equiv k_{T_n} \to 0, \ |\zeta_0(z)| \leq k_0 < 1 \) and \( |\tau_0| = 1 \) we conclude that

\begin{equation}
|\bar{\zeta}_n| - |\zeta_0| \leq |\bar{\zeta}_n - \zeta_0| \leq k_{T_n} \frac{1}{1 - k_{T_n} k_0} \to 0
\end{equation}

(28)
uniformly in $z$ with $n \to \infty$. We can therefore replace $\tilde{\kappa}_n$ by $\kappa_0$ in relations (23) and (25) and get

$$(23') \quad \int \int_{|z|<1} |\varphi_n(z)| \frac{1+|\kappa_0(z)|}{1-|\kappa_0(z)|} \, dx \, dy \to K_0$$

and

$$(25') \quad \int \int_{|z|<1} \{ |\kappa_0(z)||\varphi_n(z)| - \text{Re} \, \kappa_0(z) \varphi_n(z) \} \, dx \, dy \to 0$$

for $w_n \to w_0$.

If $|\kappa_0(z)| = k_0$ a.e., relation (25') gives

$$(29) \quad \text{Re} \int \int \kappa_0(z) \varphi_n(z) \, dx \, dy \to k_0,$$

which is the Hamilton relation (6) for $\kappa_0$.

If, however, $|\kappa_0(z)|$ is not equal to $k_0$ a.e., it follows from relation (23') that $\int \int_E |\varphi_n(z)| \, dx \, dy \to 0$ on every measurable set $E$ on which $|\kappa_0(z)| \leq k_0 - \varepsilon$, for every $\varepsilon > 0$. Since the $\varphi_n$ are analytic and the sequence $(\varphi_n)$ is locally bounded in $D_z$, it must be degenerating. Writing

$$(30) \quad \int \int_{|z|<1} |\kappa_0(z)||\varphi_n(z)| \, dx \, dy = \int \int_E + \int \int_{D_z \setminus E}$$

and considering that on $D_z \setminus E$ we have $k_0 - \varepsilon < |\kappa_0(z)| \leq k_0$ we get

$$\int \int_{|z|<1} |\kappa_0(z)||\varphi_n(z)| \, dx \, dy \to k_0$$

as before. (25') thus leads to (29) again, which proves the Theorem.

12. Summing up, we have considered the following situation. The qc mapping $f_0$ has the boundary values $h$ on $\partial D_z$ and takes $z_0$ into $w_0$. Its maximal dilatation is $K_0$, and it is extremal for the above data. Moreover there is a sequence of points $w_n \in D_z$, $w_n \to w_0$, such that the corresponding extremal mappings $f_n$, $f_n(z_0) = w_n$, are Teichmüller mappings associated with quadratic differentials $\varphi_n$ of norm one. The $\varphi_n$ are defined and holomorphic in $D_z \setminus \{ z_0 \}$. They have a first order pole at $z_0$, because otherwise the mapping $f_n$ would be uniquely extremal for its boundary values on $\partial D_z$, without any further condition. Then, we have shown that these $\varphi_n$ form a Hamilton sequence for the complex dilatation $\kappa_0$ of $f_0$.

Let us now consider a point $w_m$ in $D_w$ outside the variability set $V[z_0]$. The mapping $f_m: z_0 \to w_m$, with boundary values $h$ on $\partial D_z$ is a uniquely extremal
Teichmüller mapping with a (constant) dilatation \( K_m > K_0 \). Let \( w_n \to w_m \). Then, the mappings \( f_n, f_n(z_0) = w_n \), tend to \( f_m \) uniformly in \( D_z \) (because \( f_m \) is uniquely extremal) and the associated normalized quadratic differentials \( \varphi_n \), all defined and holomorphic in \( D_z \setminus \{z_0\} \), form a Hamilton sequence for the complex dilatation \( \kappa_m = k_m(\varphi_m/|\varphi_m|) \) of \( f_m \). But now the frame mapping criterion says: there is no degenerating Hamilton sequence for \( \kappa_m \) (as a frame mapping we can use any extremal mapping \( f_0 \) near \( \partial D_z \) and the translation \( z \to w_m + z - z_0 \) near \( z_0 \), since \( K_m > K_0 \)). Therefore the \( \varphi_n \) tend to \( \varphi_m \) in norm. We thus have proved the

**Theorem 3.** Let \( w_m \in D_z \setminus V[z_0] \), and let \( w_n \to w_m \). Then, the normalized point shift differentials \( \varphi_n \) tend in norm to the Teichmüller differential \( \varphi_m \) of \( f_m \), i.e. \( \|\varphi_n - \varphi_m\| \to 0 \).

13. Actually, every Teichmüller mapping is associated with a pair of quadratic differentials, \( \varphi \) on the original domain and \( \psi \) on the image domain, and the mapping sends the trajectories and orthogonal trajectories of \( \varphi \) into the trajectories and orthogonal trajectories respectively of \( \psi \). We have seen, that, for \( w_n \to w_m \), \( \varphi_n \to \varphi_m \) in norm, and hence, because of analyticity, locally uniformly; we will need the analogue for the \( \psi_n \).

To fix the ideas, take, for a given \( w_m \), a closed, regular \( \varphi_m \)-rectangle \( S_m \) and the corresponding \( \psi_m \)-rectangle \( S_m' \). \( S_m \) is bounded by two opposite horizontal and two opposite vertical intervals, and there are no zeroes of \( \varphi_m \) on \( S_m \). The same holds for \( S_m' \) with respect to \( \psi_m \). \( \zeta = \Phi_m(z) \), \( \zeta^* = \Psi_m(w) \) take \( S_m \) and \( S_m' \) into horizontal Euclidean rectangles \( R_m, R_m' \) respectively. By a proper choice of the additive constants we can achieve that \( \zeta = \zeta^* = 0 \) in the lower left corners of the rectangles. We express everything in terms of these parameters \( \zeta \) and \( \zeta^* \) respectively. Since \( d\zeta^2 = \varphi_m(z)dz^2 \), we have \( \varphi_m(\zeta) \equiv 1 \), and analogously \( \psi_m(\zeta^* \equiv 1 \). Moreover, \( \Phi_m(\zeta) \equiv \zeta \), \( \Psi_m(\zeta^* \equiv \zeta^* \), and the Teichmüller mapping \( f_m \) is

\[
\zeta^* = f_m(\zeta) = K_m \zeta + i\eta \equiv F_{K_m}(\zeta), \quad \zeta = \xi + i\eta.
\]

\( F_{K_m} \) denotes the horizontal stretching of \( R_m \) onto \( R_m' \) by \( K_m \).

We have seen, in the preceding section, that, with \( w_n \to w_m \) and the normalization \( \|\varphi_n\| = \|\varphi_m\| = 1 \), we have \( \|\varphi_n - \varphi_m\| \to 0 \). In terms of the parameter \( \zeta \) we therefore have \( \varphi_n(\zeta) \to 1 \) uniformly in \( R_m \). Therefore \( \Phi_n(\zeta) \to \zeta \), also uniformly in \( R_m \), and clearly \( f_n(\zeta) \to f_m(\zeta) \), also uniformly.

The mapping \( f_n \) has the representation, locally

\[
f_n = \Psi_n^{-1} \circ F_K \circ \Phi_n,
\]

and thus

\[
\Psi_n(\zeta^*) = F_{K_n}(\Phi_n(f_n^{-1}(\zeta^*))).
\]

Taking into account that, with \( w_n \to w_m \), \( f_n^{-1}(\zeta^*) \to \zeta \), \( \Phi_n(\zeta) \to \zeta \), \( K_n \to K_m \), hence \( F_{K_n}(\zeta) \to \zeta^* \) uniformly, we find

\[
\Psi_n(\zeta^*) \to \zeta^*
\]
uniformly in $R'_m$. This gives, because of the analyticity, $\psi_n(\zeta^*) \to 1$ uniformly in $R'_m$.

The natural normalization of the $\psi$-differentials is, according to the Euclidean geometry of the $\Psi$-planes and the horizontal stretching by the dilatation $K$, $\|\psi_m\| = K_m$, $\|\psi_n\| = K_n$. With this we have, in any finite collection $B = \bigcup_j S^j_m$ of $\psi_m$-rectangles,

$$\|\psi_n - \psi_m\|_B \to 0.$$  

On the other hand we can clearly approximate $D_w$, for any positive $\varepsilon$, by a finite system $B$ of non-overlapping $\psi_m$-rectangles, such that $\|\psi_m\|_{D_w \setminus B} < \varepsilon$ and $\|\psi_n\|_{D_w \setminus B} < \varepsilon$ for all $w_n$ which are lying sufficiently close to $w_m$. This gives the result $\|\psi_n - \psi_m\| \to 0$. We have proved the following

**Theorem 4.** Let $w_m \notin V[z_0]$, $w_n \to w_m$, and let $f_n$, $f_m$ be a corresponding point shift mappings. Let $\psi_n$, $\psi_m$ be the image differentials of the $\varphi_n$, $\varphi_m$ in the normalization $\|\psi_n\| = K_n$, $\|\psi_m\| = K_m$. Then, $\|\psi_n - \psi_m\| \to 0$.

We can interpret that as continuity of the $\psi_n$ with respect to the norm topology. By the mean value theorem we get $\psi_n \to \psi_m$ locally uniformly in $D_w \setminus \{w_m\}$.

**III A method of variation for point shift mappings**

14. The quadratic differential

$$\varphi(z) \, dz^2 = \frac{1}{z} \, dz^2$$  

is basic in the following considerations. Its regular (horizontal) trajectories are the parabolas with focus $z_0 = 0$ and with vertex on the negative real axis: this is geometrically evident, since the field of line element $(1/z) \, dz^2 > 0$, i.e. $\arg dz = \frac{1}{2} \arg z \mod \pi$, is equal to the field of tangential elements of the parabolas. The only critical trajectory is the positive real half line. The vertical trajectories are the orthogonal parabolas and the negative real half line. Clearly, the field of line elements as well as the trajectories and orthogonal trajectories are invariant with respect to homotheties with center $z_0$. 


Let $\alpha$ be one of the parabolas. The interior of it is denoted by $\Pi_\alpha = \Pi$. It is mapped by $\zeta = \Phi(z) = \int \sqrt{\varphi(z)} \, dz = 2z^{1/2}$ onto a horizontal parallel half strip (Figure 2). The interval between the vertex $z_1$ and the focus $z_0$ is opened up into a vertical interval with center $\zeta_0 = 0 = \Phi(0)$, whereas the two branches of $\alpha$ go over into the two horizontal half lines which bound the strip. This again is geometrically evident because the tangential elements of the parabolas are turned into horizontal position by $\Phi$. A Teichmüller mapping $f$ of $\Pi_\alpha$ associated with the quadratic differential $\varphi$ and any constant dilatation $K > 1$ is represented by the horizontal stretching $\zeta = \xi + i\eta \rightarrow K\xi + i\eta$ of the half strip. It is therefore a self-mapping of $\Pi_\alpha$ with fixed point $z_0$. Actually all the points of the horizontal interval $[z_1, z_0]$ are fixed points of $f$. Each trajectory of $\varphi$ is mapped onto itself, whereas every vertical trajectory is transformed into another one, further away from $z_0$.

**15.** Let $S$ be a segment of the parabola domain $\Pi_\alpha$, bounded by a symmetric interval of $\alpha$ and a symmetric interval of an orthogonal parabola $\beta$. For short, we call these intervals $\alpha$ and $\beta$ again. Let us denote the restriction of $f$ to $S$ by $f_0$, its dilatation by $K_0$. $S' = f_0(S)$ is a segment of the same parabola domain $\Pi_\alpha$. In the $\zeta$-plane the corresponding quantities are rectangles $R$ and $R'$ and a horizontal stretching of $R$ onto $R'$ by $K_0$ (Figure 2). The mapping $f_0: S \rightarrow S'$ is uniquely extremal for its boundary values on $\partial S$ and with $z_0$ as fixed point. This follows from the fact that it is a Teichmüller mapping associated with a holomorphic quadratic differential of finite norm, namely the restriction of $\varphi$ to $S \setminus \{z_0\}$.
We now look at the extremal mapping \( \tilde{f}_0: S \to S' \) with the boundary values of \( f_0 \) but without the assumption that \( z_0 \) be fixed. The boundary dilatation of \( f_0 \) on \( \partial S \) is determined by the local boundary dilatation at the two points \( z_2 \) and \( z_3 \) on \( \partial S \), because \( f_0 \) is analytic on the boundary intervals in-between these two points. However, at these two points the local boundary dilatation is smaller than \( K_0 \) (see [7]). Therefore, \( H < K_0 \) (see [10], p. 475). If the maximal dilatation \( \tilde{K}_0 \) of \( \tilde{f}_0 \) were known to be greater than \( H \), an application of the frame mapping condition would tell us that \( \tilde{f}_0 \) is a uniquely extremal Teichmüller mapping associated with a holomorphic quadratic differential \( \tilde{\varphi}_0 \) of finite norm. However, the only thing which is known is \( \tilde{K}_0 \leq K_0 \). This is the reason for an additional step in the argument.

Move the vertical interval \( \beta \) to the right. Then, the segment \( S \) tends to \( \Pi_\alpha \). In the \( \zeta \)-plane again, this corresponds to a shift of the right hand vertical boundary interval of \( R \) to the right. \( \tilde{f}_0 \) goes over into a \( \tilde{K}_0 \)-qc mapping of a half strip, equal to the stretching by \( K_0 \) on its horizontal boundaries. It is then well known (see [7]) that the maximal dilatation \( \tilde{K}_0 \) tends to \( K_0 \). Therefore there is a segment \( S \) such that \( \tilde{K}_0 > H \), and for this \( S \) the above conclusion holds. Also, because of the unique extremality of \( f_0 \) and the symmetry of the boundary values, the point \( \tilde{z}_0 = \tilde{f}_0(z_0) \) lies on the real axis. Again because of the unique extremality and since \( \tilde{\varphi} \neq \varphi \), \( \tilde{f}_0(z_0) \neq z_0 \) and \( \tilde{K}_0 < K_0 \).

An extremal length argument shows that \( \tilde{z}_0 \) cannot lie between \( z_0 \) and the vertex \( z_1 \) of \( \alpha \). To this end, look at the upper half of the parabola segment \( S \). It is mapped by \( \tilde{f}_0 \) onto the upper half of \( S' \). The extremal distance of the interval \( (z_1, z_0) \) from the upper half of the orthogonal parabola segment \( \beta \) is \( 2a/b \), \( a \) being the length of the rectangle \( R \) and \( b \) its height. The analogous quantity in \( S' \) is \( K_0 \cdot 2a/b \). Assume that \( \tilde{z}_0 \in (z_1, z_0) \). Then, the extremal distance of \( (z_1, \tilde{z}_0) \) from the upper half of \( \beta' \) is \( > K_02a/b \). On the other hand, since \( \tilde{f}_0 \) is \( \tilde{K}_0 \)-qc, it is \( \leq \tilde{K}_02a/b \) which is smaller than \( K_02a/b \), a contradiction.

16. Next, we claim that for all points \( \xi \in (z_0, \tilde{z}_0) \) on the real axis the extremal mapping \( \tilde{f}: z_0 \to \xi \), \( f: S \to S' \) is a Teichmüller mapping with a dilatation \( \tilde{K} \), \( \tilde{K}_0 < \tilde{K} < K_0 \). Its quadratic differential has finite norm and a first order pole at \( z_0 \).

To this end we use a homothety with center \( z_0 \), retracting the segments \( S, S' \) into inner parabola segments \( \tilde{S}, \tilde{S}' \). The extremal mapping \( \tilde{f}_0: S \to S' \) goes over into the extremal mapping of \( \tilde{S} \) onto \( \tilde{S}' \), with the boundary values of \( f_0 \) on \( \partial \tilde{S} \). It takes \( z_0 \) into the point \( \tilde{\xi} \in (z_0, \tilde{z}_0) \) which is the image of \( \tilde{z}_0 \) by the homothety. Of course, its dilatation is again \( \tilde{K}_0 \). This retracted mapping can be continued, by the orginal mapping \( f_0 \), to a qc mapping of \( S \) onto \( S' \). Its dilatation is \( \tilde{K}_0 \) in \( \tilde{S} \) and \( K_0 \) in \( S \setminus \tilde{S} \), and it takes \( z_0 \) into \( \tilde{z}_0 \). The extremal mapping \( \tilde{f} \) with these conditions must have a dilatation \( \tilde{K} > \tilde{K}_0 \), because it is subject to the additional condition \( z_0 \to \xi \), whereas \( f_0 \) was free on \( z_0 \). It is therefore a uniquely extremal Teichmüller mapping. Because of that, clearly \( \tilde{K} < K_0 \), because the latter is the
maximal dilatation of a competing mapping.

The construction with the homothety is possible for all \( \tilde{z} \in (z_0, \tilde{z}_0) \), just by changing the homothety factor. We have thus shown the claim.

The final step is the following. The parabola segment \( S \) we were forced to take in the first step and in which we have constructed the variations of \( f_0 \) could be quite long. However, by means of a homothety of \( S \) we can make it as small as we want. We have thus proved the following

**Parabola Lemma.** Consider the quadratic differential \( \varphi(z) dz^2 = (1/z) dz^2 \) and a number \( K_0 > 1 \). Let \( f_0 \) be the corresponding Teichmüller mapping of the plane. Then, in any neighborhood of \( z_0 = 0 \) there are parabola segments \( S, S' \), associated with \( \varphi \), and mappings \( \tilde{f} : S \to S' \) with maximal dilatations \( \tilde{K} < K_0 \), \( \tilde{f}(z_0) = \tilde{z}, \tilde{f} | \partial S = f_0 | \partial S \). The points \( \tilde{z} \) fill out an interval \( (z_0, \tilde{z}_0) \) of positive length \( \delta \). The extremal mappings satisfying the above boundary conditions are actually Teichmüller mappings, the quadratic differentials of which have finite norm and, if \( \tilde{z} \neq \tilde{z}_0 \), a first order pole at \( z_0 \).

17. Application to the point shift mappings.

**Theorem 5.** Let \( f_m : D_z \to D_w \) be extremal for its boundary values, with \( f_m(z_0) = w_m \notin V[z_0] \). Let the associated quadratic differentials be \( \varphi_m \) in \( D_z \) and \( \psi_m \) in \( D_w \), and let \( K_m \) be the dilatation of \( f_m \). Denote the critical trajectory of \( \psi_m \) emanating from \( w_m \) by \( \gamma_m \). Then, there exists a closed subinterval \( \Delta \gamma_m \) of \( \gamma_m \) with \( w_m \) one of its endpoints such that for every \( w_n \in \Delta \gamma_m \), \( w_n \neq w_m \), the point shift mapping \( f_n, f_n(z_0) = w_n \), has a dilatation \( K_n < K_m \) (Figure 3).

If the point \( w_m \) varies on a compact set \( C \subset D_w, C \cap V[z_0] = \emptyset \), the Euclidean length of the intervals \( \Delta \gamma_m \) has a positive lower bound.

![Figure 3.](image-url)

**Proof.** We introduce the normal parameter for \( \varphi_m \) near \( z_0 \) and for \( \psi_m \) near \( w_m \). That means that we apply local conformal mappings \( z \leftrightarrow \zeta \) and \( w \leftrightarrow \zeta \).
such that \( \varphi_m \) and \( \psi_m \) both have the representation, in terms of \( \zeta \), \( \varphi_m(z) \, dz^2 = (1/\zeta) \, d\zeta^2 \) and \( \psi_m(w) \, dw^2 = (1/\zeta) \, d\zeta^2 \) (see [12]).

The mapping \( f_m \) is locally represented in the \( \zeta \)-plane, by a parabola mapping \( f_m^{\ast} \), taking a parabola segment \( S^{\ast} \) into a parabola segment \( S^{\ast'} \) and with fixed point \( \zeta_0 = 0 \). The segments are bounded by subintervals of the same parabola \( \alpha^{\ast} \) and two different vertical parabola segments \( \beta^{\ast} \) and \( \beta^{\ast'} \) respectively.

The corresponding domains in the \( z \)- and \( w \)-planes are denoted by \( S_m \) and \( S'_m \) respectively. The points \( z_0 \) and \( w_m \) go over, by the parameter transformations, into \( \zeta_0 = 0 \).

The Parabola Lemma tells us that there exists a closed interval \([\zeta_0, \tilde{\zeta}_0]\) on the positive real axis of the \( \zeta \)-plane such that for every \( \tilde{\zeta} \in (\zeta_0, \tilde{\zeta}_0) \) the extremal mapping \( \tilde{f}: S^{\ast} \to S^{\ast'} \), with the induced boundary values and with \( \tilde{f}(\tilde{\zeta}_0) = \tilde{\zeta} \) has a dilatation \( \tilde{K} < K_m \). The mapping \( f_m: S_m \to S'_m \) can now be replaced by the mapping \( \tilde{f} \) composed with the parameter transformations \( z \to \zeta \) and \( \zeta \to w \). This local mapping can be continued to the whole disks \( D_z, D_w \) outside \( S_m, S'_m \) by \( f_m \). Its maximal dilatation is \( K_m \) but it takes \( z_0 \) into a point \( w_n \in \Delta \gamma_m \) which corresponds to \( \tilde{\zeta} \). The extremal mapping with this property is \( f_n \). Because of the unique extremality of \( f_n \) we have \( K_n < K_m \). Taking into account that the interval \([\zeta_0, \tilde{\zeta}_0]\) corresponds to a subinterval \( \Delta \gamma_m \) of \( \gamma_m \) of positive length, we have proved the theorem. The last statement follows because, due to the locally uniform convergence \( \varphi_n \to \varphi_m, \psi_n \to \psi_m \) for \( w_n \to w_m \) we can use the same parabola segments \( S^{\ast}, S^{\ast'} \) in the natural parameter plane for all \( n \) and \( m \).

18. Whereas in the previous section we have found points \( w_n \) with \( K[w_n] < K[w_m] \) we are now going to show the existence of points \( w_n \), in every neighborhood of \( w_m \), with \( K[w_n] > K[w_m] \).

**Theorem 6.** Let \( w_n \notin V[z_0] \) and let \( K[w_m] \) be the dilatation of the point shift mapping \( f_m: f_m(z_0) = w_m \). Then, in every neighborhood of \( w_m \) there is a point \( w_n \) such that the point shift mapping \( f_n: f_n(z_0) = w_n \), has a dilatation \( K[w_n] > K[w_m] \).

**Proof.** The proof consists in finding points \( w_n \neq w_m \) such that \( w_m \in \Delta \gamma_n \). We can then apply the previous result to get the desired inequality.
We start with a fixed parabola segment $S$ in the $\zeta$-plane (Figure 4). Let $g_m$ be the inverse of the parameter mapping for $\psi_m$, with $g_m(S) = S'_m$, and $g_m([\zeta_0, \tilde{\zeta}_0]) = \Delta \gamma_m$ the distinguished critical trajectory interval of $\psi_m$, with end points $w_m, \tilde{w}_m$. Likewise, let $g_n$ be the inverse of the parameter mapping for $\psi_n$, $g_n(S) = S'_n$, $g_n(\zeta_0) = w_n$, $g_n([\zeta_0, \tilde{\zeta}_0]) = \Delta \gamma_n$ the distinguished critical parameter interval of $\psi_n$. Because of the convergence $\|\psi_n - \psi_m\| \to 0$ for $w_n \to w_m$ the mappings $g_n$ tend to $g_m$ uniformly in $S$. In particular, the images $g_n(\zeta)$ and $g_m(\zeta)$, $\zeta \in [\zeta_0, \tilde{\zeta}_0]$, have a distance $|g_n(\zeta) - g_m(\zeta)|$ which is arbitrarily small, and the directions, in which the critical trajectories $\gamma_n$ and $\gamma_m$ leave the points $w_n$ and $w_m$ respectively are arbitrarily close. This is so because this direction is the same as minus the arg of the residue, and the residues are arbitrarily close by the locally uniform convergence $\psi_n \to \psi_m$ away from the pole $w_m$ and the Cauchy representation of the residue.

Choose now $\rho > 0$ small enough and let $w_n$ turn around $w_m$ on the circle $|w_n - w_m| = \rho$. Then, it is evident that the interval $\Delta \gamma_n$ must pass through the point $w_m$ at least once, and its origin is the point $w_n$ we are looking for.

IV The level sets of $K[w]$

19. Given a quasisymmetric boundary homeomorphism $h: \partial D_z \to \partial D_w$ and a fixed point $z_0 \in D_z$. Recall that for every $w \in D_w$ we define $K[w]$ to be the smallest maximal dilatation of all quasiconformal mappings $f: D_z \to D_w$ which agree with $h$ on $\partial D_z$ and satisfy $f(z_0) = w$. The smallest maximal dilatation of all qc mappings $f$ with $f \mid \partial D_z = h$ but without a given value at a fixed point is called $K_0$. Every extremal qc mapping $f_0: D_z \to D_w$, $f_0 \mid \partial D_z = h$, has maximal dilatation $K_0$, and the set of images of $z_0$ by all extremal qc mappings $f_0$ is called the variability set of $z_0$ and denoted by $V[z_0]$. Clearly, if the boundary homeomorphism $h$ admits a unique extremal solution, $V[z_0]$ consists of a single point for every $z_0$. In general, this is however not the case, but for every $w_0 \in V[z_0]$ there exists at least one extremal mapping $f_0$ with $f_0(z_0) = w_0$, by definition.

If $w_m \not\in V[z_0]$ the value $K[w_m]$ is realized as the (constant) dilatation of a unique extremal Teichmüller mapping $f_m$ associated with a pair of quadratic differentials $\varphi_m, \psi_m$ of norm $\|\varphi_m\| = 1$, $\|\psi_m\| = K[w_m]$. $\varphi_m$ has a first order pole at $z_0$, while $\psi_m$ has one at $w_m$; both differentials are holomorphic otherwise.

We already know that $V[z_0]$ is compact. But in addition to that we can now prove the following

Theorem 7. The variability set $V[z_0]$ is simply connected, i.e. connected and without holes.

The proof of the second statement is immediate. For, let $G$ be a component of $D_w \setminus V[z_0]$ which is bounded away from $\partial D_w$. Then, the boundary $\partial G$ lies in $V[z_0]$ and the continuous function $K[w]$ must attain its maximum in a point $w_m \in G$, $K[w_m] > K_0$. But by Theorem 6 there is a point $w$ in every neighborhood of $w_m$. 
with $K[w] > K[w_m]$, contradicting that $K[w_m]$ is the maximum value of $K[w]$ in $G$.

The first statement will follow from the theorem in the next section.

20. For every $w_m \in D_w \setminus V[z_0]$ we consider the following three disjoint subsets of $D_w$. We set $K[w_m] = K_m$.

$$\Gamma^-_{K_m} := \{ w; K[w] < K_m \}$$
$$\Gamma^-_{K_m} := \{ w; K[w] = K_m \}$$
$$\Gamma^+_{K_m} := \{ w; K[w] > K_m \}$$

**Theorem 8.** The level set $\Gamma_{K_m}$ is a Jordan curve, $\Gamma^-_{K_m}$ its interior and $\Gamma^+_{K_m}$ its exterior (in $D_w$). The sets $\Gamma^-_{K_m}$ are decreasing with $K_m \setminus K_0$ and $V[z_0] = \bigcap_{K_m > K_0} \Gamma^-_{K_m}$.

**Proof.** (1) Since $K[w] \to \infty$ for $|w| \to 1$ the set $\Gamma^+_{K_m}$ contains an annulus $r < |w| < 1$ for sufficiently large $r$. As an open set, $\Gamma^+_{K_m}$ decomposes into domains, i.e. maximal connected open subsets. Let $G$ be such a domain and assume that it is bounded away from $\partial D_w$. Then, its boundary consists of points $w$ with $K[w] = K_m$, whereas for $w \in G$ $K[w] > K_m$. Therefore the function $K[w]$ assumes its maximum at a point $\hat{w} \in G$. But this is impossible, since in every neighborhood of $\hat{w}$ there are points $w$ with $K[w] > K[\hat{w}]$. We conclude that every component of $\Gamma^+_{K_m}$ contains points arbitrarily close to $\partial D_w$. This means that all components contain the annulus $r < |w| < 1$ and are thus connected themselves, hence $\Gamma^-_{K_m}$ is a domain.

(2) Let $C$ be a component of its complement. It consists of points $w$ with $K[w] \leq K_m$. Every boundary point of $C$ is a point $w_m \in \Gamma_{K_m}$. The trajectory interval $\Delta \gamma_m$ lies in $\Gamma^+_{K_m}$, except for its initial point $w_m$. On the other hand, as $\Delta \gamma_m$ is connected, it is contained in $C$. We conclude that $C$ has interior points, and in fact that every boundary point of $C$ is a boundary point of its interior.

Let $G^\nu$ be a component of its interior, hence a subdomain of $C$. For every point $w \in G^\nu K[w] < K_m$, whereas on $\partial G^\nu K[w] = K_m$. Therefore $K[w]$ must assume its minimum at a point $\hat{w} \in G^\nu$, and by the same reason as above $K[\hat{w}] = K_0$. We conclude that every component $G^\nu$ of int $C$ contains points of $V[z_0]$. From this it follows, because of the uniform continuity of $K[w]$ in $C$, that int $C$ consists of finitely many components $G^\nu$ only. Otherwise, we could pick a point $w_0^\nu \in V[z_0]$ out of every component $G^\nu$. An accumulation point $w_0$ of these points would lie in $V[z_0]$ and in $\partial C$, an impossibility. Every $G^\nu$ is clearly simply connected.

(3) The next step is to show that there can indeed be only one component of int $C$. For, let $G^0$ be a maximal subdomain of int $C$ and assume there is more than one. The boundary $\partial G^0$ is a subset of the connected set $\partial C$. It is now easy to see that there exists a point $w_m \in \partial G^0$ which is also a boundary point of at
least one other subdomain of int $C$, because otherwise we could find a point in $\partial C$ which is not a boundary point of int $C$. Assume that the points $w \in \Delta \gamma_m \setminus \{w_m\}$ lie in $G^0$, and let $G^1$ be another subdomain of int $C$ which has $w_m$ as boundary point. For $w^1 \in G^1$, sufficiently close to $w_m$, the interval $\Delta \gamma^1$ with initial point $w^1$ would be arbitrarily close to $\Delta \gamma_m$, and it would thus have to cut $\partial G^0$. But since $K[w^1] < K_m$ and hence $K[w] < K_m$ for every $w \in \Delta \gamma^1$ this would give a contradiction. We conclude that int $C$ consists of a single simply connected domain $G$.

(4) We now proceed to show that $G$ is a Jordan domain. Consider a boundary point $w_m$ of $G$. The interval $\Delta \gamma_m$ with initial point $w_m$ lies in $G$, except for $w_m$. This means that every boundary point of $G$ is the end point of an end-cut (the same as “erreichbarer Randpunkt”, see [3], pp. 357–363). Consider two end-cuts with the same end point $w_m$. Their initial points, which lie in $G$, can be joined by an arc in $G$. We thus have a Jordan curve which lies in $G$, except for the point $w_m$ itself. If the two end-cuts were not equivalent, the domain interior to this Jordan curve would contain boundary points of $G$, i.e. points of $\Gamma_{K_m}$. But in every neighborhood of such a point there is a point of $\Gamma_{K_m}^+$, which is impossible.

Therefore the equivalence classes of end-cuts are in one-to-one correspondence with the boundary points of $G$. By standard arguments the Riemann mapping of $G$ onto the disk has a homeomorphic extension to $\partial G$, which shows that $\partial G$ is a Jordan curve.

(5) The last step is to show that $\Gamma_{K_m}^-$ consists of only one Jordan domain and hence the level set $\Gamma_{K_m}$ is a single Jordan curve for every $K_m > K_0$. We have seen that the set $\Gamma_{K_m}^-$ consists of finitely many Jordan domains each of which contains points of $V[z_0]$, and the boundary curves of these Jordan domains are the components of $\Gamma_{K_m}$. For $K_n > K_m$ the set $\Gamma_{K_m}^-$ contains $\Gamma_{K_n}^-$ and therefore $\Gamma_{K_m}$ has at least as many components as $\Gamma_{K_n}$. Choose $r < 1$ such that the set $V[z_0]$ is contained in the disk $|w| < r$. For $K_m > \min\{K[w]; |w| = r\}$ the circle $|w| = r$ lies in $\Gamma_{K_m}^-$ and hence in one of its components. This component contains all of $V[z_0]$ and is hence the only one. We conclude that $\Gamma_{K_m}$ consists of a single Jordan curve for all sufficiently large $K_m$.

Let $K > K_m$, and denote the finitely many components of $\Gamma_{K_m}$ by $\Gamma_{K_m}^\nu$, hence $\Gamma_{K_m} = \bigcup_{\nu=1}^{N} \Gamma_{K_m}^\nu$, $\nu = 1, \ldots, N$. The level set $\Gamma_K$ is composed of finitely many Jordan curves $\Gamma_K^\mu$, $\mu = 1, \ldots, M$, $M \leq N$. They contain the curves $\Gamma_{K_m}^\nu$ in their interior, and it is easy to see, by contradiction, that for $K \setminus K_m$ the level set $\Gamma_K$ tends to $\Gamma_{K_m}$. Therefore there cannot be fewer curves, one $\Gamma_K^\mu$ for each $\Gamma_{K_m}^\nu$, thus $M = N$, as soon as $K$ is sufficiently close to $K_m$.

Assume now that $K < K_m$. Again, for $K \not\supseteq K_m$ the limit set of $\Gamma_K$ is $\Gamma_{K_m} = \bigcup K_{K_m}$. The Jordan curves $\Gamma_K^\mu$ tend to the Jordan curves $\Gamma_{K_m}^\mu$, and eventually in a neighborhood of each $\Gamma_{K_m}^\nu$ there can be only one $\Gamma_{K_m}^\mu$, $\mu = 1, \ldots, M$. We conclude that $M = N$ for all $K < K_m$ which are sufficiently close to $K_m$.

The number of components of $\Gamma_{K_m}$ is thus a continuous function of $K_m$, and being entire, it is constant, q.e.d.
The set $V[z_0]$ is evidently equal to the intersection $V[z_0] = \bigcap_{K_m > K_0} \Gamma_{K_m}$. This proves the theorem.

Added in proof. In a forthcoming paper, Clifford Earle and Nikola Lakic are going to generalize most of the theorems of this article to the case of Riemann surfaces, using Teichmüller space methods.

References


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