## Complex Analysis/Mathematical Physics

# Random curves by conformal welding ${ }^{\omega}$ 

## Courbes aléatoires par soudure conforme

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#### Abstract

We construct a conformally invariant random family of closed curves in the plane by welding of random homeomorphisms of the unit circle given in terms of the exponential of Gaussian Free Field. We conjecture that our curves are locally related to SLE $(\kappa)$ for $\kappa<4$. © 2010 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.


## R É S U M É

On construit une famille aléatoire conformément invariante de courbes fermées dans le plan par soudure d'un cercle unité donné en terme d'exponentielle d'un champ libre gaussien. On conjecture que nos courbes sont localement reliées à SLE $(\kappa)$ pour $\kappa<4$.
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## Version française abrégée

Dans cette Note, on résume une construction d'une famille de courbes aléatoires. Pour la construction on résout le problème de soudure pour un ensemble aléatoire d'homéomorphismes $h_{\omega}: \mathbb{T} \rightarrow \mathbb{T}$, localement invariant par changement d'échelle, obtenant ainsi un ensemble aléatoire de courbes de Jordan. Pour définir $h$, on identifie le cercle à $\mathbb{T}=\mathbb{R} / \mathbb{Z}=[0,1)$ et on écrit $h(t)=\tau([0, t)) / \tau([0,1))$ où $\tau=h^{\prime}$ est une mesure de Borel positive $\tau$ sans atomes. Notre choix de $\tau$ est

$$
\tau(\mathrm{d} t)=\lim _{\varepsilon \rightarrow 0} e^{\beta X_{\varepsilon}(t)} / \mathbb{E} e^{\beta X_{\varepsilon}(t)} \mathrm{d} t
$$

où $\beta \geqslant 0$ et $X_{\varepsilon}$ est une régularisation du Champ Gaussien Libre $X$ sur le cercle i.e. le champ aléatoire avec covariance

$$
\mathbb{E} X(t) X\left(t^{\prime}\right)=-\log \left|e^{2 \pi i t}-e^{2 \pi i t^{\prime}}\right|
$$

Notre résultat principal est alors :

[^0]Théorème 0.1. Pour $\beta^{2}<2$ et presque sûrement en $\omega$, la formule (4) définit un homéomorphisme du cercle höldérien, tel que le problème de soudure possède une solution $\gamma$, où $\gamma$ est une courbe de Jordan délimitant un domaine $\Omega=f_{+}(\mathbb{D})$ avec une application de Riemann hölderienne $f_{+}$. Pour un $\omega$ donné, la solution est unique à une transformation de Möbius du plan près.

La preuve de ce résultat est basée sur des techniques quasi-conformes. On recherche une solution homéomorphe à l'équation de Beltrami.

$$
\begin{equation*}
\frac{\partial F}{\partial \bar{z}}=\chi_{\mathbb{D}}(z) \mu(z) \frac{\partial F}{\partial z}, \quad \text { pour p.tout. } z \in \mathbb{C} \tag{B}
\end{equation*}
$$

où $\mu$ est la dilatation complexe de l'extension de Beurling-Ahlfors $f$ de $h$ à l'intérieur du disque unité. On vérifie que les applications de soudures sont alors obtenues avec $f_{-}:=\left.F\right|_{\mathbb{C} \backslash \overline{\mathbb{D}}}$ et $f_{+}:=F \circ f^{-1}$ sur $\mathbb{D}$. Dans ce cadre, on est très loin des situations couvertes par la théorie classique, où on suppose $\|\mu\|_{\infty}<1$. Par conséquent, il reste un problème non-trivial : dans notre situation non-dégénérée, comment prouve-t-on que l'équation auxilliaire (B) possède une solution homéomorphe, unique à une transformation conforme près ?

Les principaux ingrédients de notre preuve sont le résultat de Jones et Smirnov [10] pour ce qui est de l'unicité, et une variante quantitative de la méthode de Lehto pour ce qui est de l'existence et de la continuité höldérienne locale requise de notre solution de (B). Cela nous conduit à estimer des intégrales de Lehto :

$$
L_{K}(w, r, R):=\int_{r}^{R} \frac{1}{\int_{0}^{2 \pi} K\left(w+\rho e^{i \theta}\right) \mathrm{d} \theta} \frac{\mathrm{~d} \rho}{\rho}
$$

où $K$ est la distortion :

$$
K(z)=\frac{1+|\mu(z)|}{1-|\mu(z)|}
$$

Notre estimation probabiliste principale nous fournit exactement la borne nécessaire pour obtenir les estimations uniformes voulues pour la continuité Höldérienne de la solution de (B) : Soit $w \in \mathbb{T}$ et soit $\beta<\sqrt{2}$. Alors il existe $b>0$ et $\delta_{0}>0$ tels que pour $\delta<\delta_{0}$ l'intégrale de Lehto satisfait l'estimation

$$
\begin{equation*}
\mathbb{P}\left(L\left(w, 2^{-N}, 1\right)<N \delta\right) \leqslant 2^{-(1+b) N} \tag{E}
\end{equation*}
$$

## 1. Introduction

A major breakthrough in the study of conformally invariant random curves in the plane occurred when 0 . Schramm [14] introduced the Schramm-Loewner Evolution (SLE), a stochastic process which describes such curves growing in a fictitious time so that the curve of interest is obtained as time tends to infinity. In this note we summarize a different construction [3] of random curves which is stationary i.e. the probability measure on curves is directly defined without introducing an auxiliary time. We carry out this construction for closed curves, a case that is not naturally covered by SLE.

Our construction is based on the idea of conformal welding which provides a correspondence between Jordan curves on the extended plane $\widehat{\mathbb{C}}$ and a set of homeomorphisms of the circle $\mathbb{T}$. Given a Jordan curve $\Gamma \subset \widehat{\mathbb{C}}$, let

$$
f_{+}: \mathbb{D} \rightarrow \Omega_{+} \quad \text { and } \quad f_{-}: \mathbb{D}_{\infty} \rightarrow \Omega_{-}
$$

be a choice of Riemann mappings of the unit disk $\mathbb{D}$ and its complement onto the components of $\widehat{\mathbb{C}} \backslash \Gamma=\Omega_{+} \cup \Omega_{-}$. By Caratheodory's theorem $f_{-}$and $f_{+}$both extend continuously to $\mathbb{T}=\partial \mathbb{D}=\partial \mathbb{D}_{\infty}$, and thus

$$
\begin{equation*}
\phi=f_{+}^{-1} \circ f_{-} \tag{1}
\end{equation*}
$$

is a homeomorphism of $\mathbb{T}$. In the welding problem we are asked to invert this process; given a homeomorphism $\phi: \mathbb{T} \rightarrow \mathbb{T}$ we are to find a Jordan curve $\Gamma$ and conformal mappings $f_{ \pm}$onto the complementary domains $\Omega_{ \pm}$so that (1) holds. It is clear that the welding problem, when solvable, has natural conformal invariance attached to it; any image of the curve $\Gamma$ under a Möbius transformation of $\widehat{\mathbb{C}}$ is equally a welding curve. Similarly, if $\phi: \mathbb{T} \rightarrow \mathbb{T}$ admits a welding, then so do all its compositions with Möbius transformations of the disk.

We solve the welding problem for a random, locally scale invariant set of homeomorphisms $h_{\omega}: \mathbb{T} \rightarrow \mathbb{T}$, thereby obtaining a random set of Jordan curves. To define $h$, identify the circle as $\mathbb{T}=\mathbb{R} / \mathbb{Z}=[0,1)$. Given a positive Borel measure $\tau$ without atoms we get a homeomorphism $h:[0,1) \rightarrow[0,1)$ by:

$$
\begin{equation*}
h(t)=\tau([0, t)) / \tau([0,1)) \tag{2}
\end{equation*}
$$

It was proposed by the second author some years ago that a natural class of homeomorphisms $h$ is obtained by taking $\tau$ formally proportional to $e^{\beta X(t)} \mathrm{d} t$ where $\beta \geqslant 0$ and $X$ is the Gaussian Free Field on the circle i.e. the random field $X$ with covariance:

$$
\begin{equation*}
\mathbb{E} X(t) X\left(t^{\prime}\right)=-\log \left|e^{2 \pi i t}-e^{2 \pi i t^{\prime}}\right| \tag{3}
\end{equation*}
$$

For a rigorous definition one introduces a regularization $X_{\varepsilon}$ which is a.s. continuous if $\varepsilon>0$ and shows that almost surely the weak limit of Borel measures,

$$
\begin{equation*}
\tau(\mathrm{d} z)=\lim _{\varepsilon \rightarrow 0} e^{\beta X_{\varepsilon}(z)} / \mathbb{E} e^{\beta X_{\varepsilon}(z)} \mathrm{d} z \tag{4}
\end{equation*}
$$

exists and defines a non-atomic random Borel measure on $[0,1]$.
Our main result is then:
Theorem 1.1. For $\beta^{2}<2$ and almost surely in $\omega$, formulas (2), (4) define a Hölder continuous circle homeomorphism, such that the welding problem has a solution $\gamma$, where $\gamma$ is a Jordan curve bounding a domain $\Omega=f_{+}(\mathbb{D})$ with a Hölder continuous Riemann mapping $f_{+}$. For a given $\omega$, the solution is unique up to a Möbius map of the plane.

The "critical (inverse) temperature" $\beta_{c}=\sqrt{2}$ corresponds to loss of continuity of the maps $h$. For $\beta \geqslant \beta_{c}$ the limit (4) is zero almost surely. Based on theoretical physics [9] one may conjecture that a corresponding limit of the normalized measures $\tau_{\varepsilon} / \tau_{\varepsilon}([0,1])$ is nontrivial also for $\beta \geqslant \beta_{c}$ and atomic for $\beta>\beta_{c}$ thereby giving rise to a discontinuous map $h$. This phase transition is closely connected to the one observed in two dimensional Liouville Quantum Gravity [7] where a two dimensional version of our measure $\tau$ is considered.

We conjecture that the curves $\gamma$ locally resemble $\operatorname{SLE}\left(2 \beta^{2}\right)$ (see also [8] for arguments to this direction). The case $\beta=\beta_{c}$, presumably corresponding to $\operatorname{SLE}(4)$, is not covered by our analysis.

It would also be of interest to understand the connection of our weldings to those arising from stochastic flows studied in the interesting work [1]. In [1] a program was set up for studying weldings that correspond to Hölder continuous random homeomorphisms, but the boundary behaviour of the welding maps and hence the existence and uniqueness of the welding was left open.

## 2. Beltrami equation

A powerful way to solve the welding problem goes by using the Beltrami equation. Assume a homeomorphism $\phi: \mathbb{T} \rightarrow \mathbb{T}$ is extended to a locally quasiconformal map $f: \mathbb{D} \rightarrow \mathbb{D}$, i.e. $f \in C(\overline{\mathbb{D}})$ is a homeomorphism with $\nabla f$ locally integrable in $\mathbb{D}$ and satisfying,

$$
\begin{equation*}
\frac{\partial f}{\partial \bar{z}}=\mu(z) \frac{\partial f}{\partial z}, \quad \text { for a.e. } z \in \mathbb{D} \tag{5}
\end{equation*}
$$

with $\sup _{z \in K}|\mu(z)|<1$ for $K \subset \subset \mathbb{D}$. One then considers the modified equation:

$$
\begin{equation*}
\frac{\partial F}{\partial \bar{z}}=\chi_{\mathbb{D}}(z) \mu(z) \frac{\partial F}{\partial z}, \quad \text { for a.e. } z \in \mathbb{C} . \tag{6}
\end{equation*}
$$

Suppose we can find a solution $F$ to (6) which is a homeomorphism of $\widehat{\mathbb{C}}$. Then $\Gamma=F(\mathbb{T})$ is a Jordan curve. Moreover, as $\partial_{\bar{z}} F=0$ for $|z|>1$, we can set $f_{-}:=\left.F\right|_{\mathbb{D}_{\infty}}$ and $\Omega_{-}:=F\left(\mathbb{D}_{\infty}\right)$ to define a conformal mapping

$$
f_{-}: \mathbb{D}_{\infty} \rightarrow \Omega_{-}
$$

To get the mapping $f_{+}$note that both $f$ and $F$ solve the Beltrami equation (5) in the unit disk $\mathbb{D}$. By the uniqueness properties of Eq. (5) we conclude that

$$
\begin{equation*}
F(z)=f_{+} \circ f(z), \quad z \in \mathbb{D} \tag{7}
\end{equation*}
$$

for some conformal mapping $f_{+}: \mathbb{D}=f(\mathbb{D}) \rightarrow \Omega_{+}:=F(\mathbb{D})$. Then, on the unit circle,

$$
\begin{equation*}
\phi(z)=\left.f\right|_{\mathbb{T}}(z)=f_{+}^{-1} \circ f_{-}(z), \quad z \in \mathbb{T} \tag{8}
\end{equation*}
$$

and we have found a solution to the welding problem.
To carry out this set of ideas we observe first that any homeomorphic self map $\phi$ of the circle can be extended to a locally quasiconformal map $f: \mathbb{D} \rightarrow \mathbb{D}$ via the Beurling-Ahlfors extension. However, a highly nontrivial problem remains: when does the auxiliary equation (6) have a locally quasiconformal solution and when is this unique up to a conformal map?

A classical case where this question can be answered positively is the uniformly elliptic one where there is an extension with $\|\mu\|_{\infty}<1$. This in turn will be true if $\phi$ is quasisymmetric. In our case these conditions do not hold, and we are forced outside the uniformly elliptic PDE's and need to study (6) with strongly degenerate coefficients with only $|\mu(z)|<1$ almost everywhere.

## 3. Existence: Lehto method

We use the method due to Lehto [12] to show the existence of homeomorphic solutions to (6). This approach is based on controlling the conformal moduli of images of annular regions. To recall his result, define the distortion function,

$$
K(z)=\frac{1+|\mu(z)|}{1-|\mu(z)|}
$$

corresponding to the complex dilatation $\mu=\mu(z)$. Given an annulus $A(w, r, R):=\{z \in \mathbb{C}: r<|z-w|<R\}$ define the Lehto integral:

$$
\begin{equation*}
L(w, r, R):=\int_{r}^{R} \frac{1}{\int_{0}^{2 \pi} K\left(w+\rho e^{i \theta}\right) \mathrm{d} \theta} \frac{\mathrm{~d} \rho}{\rho} \tag{9}
\end{equation*}
$$

Lehto's theorem (see [2, p. 584]) states then that if $K(z)$ is locally integrable, and if for some $R_{0}>0$ the Lehto integral satisfies

$$
\begin{equation*}
L\left(z, 0, R_{0}\right)=\infty, \quad \text { for all } z \in \mathbb{C} \tag{10}
\end{equation*}
$$

then the Beltrami equation (6) admits a homeomorphic $W_{\text {loc }}^{1,1}$-solution $F: \mathbb{C} \rightarrow \mathbb{C}$.
We need actually a stronger result on the Lehto integrals to obtain Hölder continuity of the solution. The Lehto integral controls the geometric distortion of an annulus under a locally quasiconformal map. Indeed, for a quasiconformal map $f$ :

$$
\operatorname{diam}(f(B(w, r))) \leqslant 16 \exp \left(-2 \pi^{2} L(w, r, R)\right) \operatorname{diam}(f(B(w, R)))
$$

Eq. (6) is solved by considering a regularized uniformly elliptic equation where $\mu$ is replaced by $(1-\varepsilon) \mu$. Since the corresponding solutions $F_{\varepsilon}$ are conformal in $\mathbb{D}_{\infty}$ the diameters $\operatorname{diam}\left(F_{\varepsilon}(B(w, 1))\right)$ for $w \in \mathbb{D}$ are uniformly bounded by Koebe. Thus an estimate,

$$
L(w, r, 1) \geqslant a \log 1 / r
$$

leads to $\operatorname{diam}\left(F_{\varepsilon}(B(w, r))\right) \leqslant C r^{2 \pi^{2} a}$ i.e. to Hölder continuity of $F_{\varepsilon}$ uniformly in $\varepsilon$. Our main probabilistic estimate then is:
Theorem 3.1. Let $w \in \mathbb{T}$ and let $\beta<\sqrt{2}$. Then there exists $b>0$ and $\delta_{0}>0$ such that for $\delta<\delta_{0}$ the Lehto integral satisfies the estimate

$$
\begin{equation*}
\mathbb{P}\left(L\left(w, 2^{-N}, 1\right)<N \delta\right) \leqslant 2^{-(1+b) N} \tag{11}
\end{equation*}
$$

This estimate suffices to prove the existence and Hölder continuity of the solution to (6). First, only annuli centered at $w \in \partial \mathbb{D}$ need to be considered. Second, the $b>0$ allows us to cover, for each integer $N, \partial \mathbb{D}$ by balls $B_{i}$ of radii $2^{-\left(1+\frac{1}{2} b\right) N}$ such that for $\alpha>0$

$$
\operatorname{diam}\left(F\left(B_{i}\right)\right) \leqslant C 2^{-\alpha N}
$$

for all $i$, with probability $1-\mathcal{O}\left(2^{-\frac{1}{2} b N}\right)$. A Borel-Cantelli argument then gives an a.s. Hölder continuity of $F$.

## 4. Uniqueness of the welding

An important issue of the welding is its uniqueness, that the curve $\Gamma$ is unique up to composing with a Möbius transformation of $\widehat{\mathbb{C}}$. This would follow from the uniqueness of solutions to the Beltrami equation (6), up to a Möbius transformation. Unfortunately the condition (10) in Lehto's theorem is much too weak to imply this. However, in our case the uniqueness of solutions to the Beltrami equation (6) is equivalent to the conformal removability of the curve $F(\mathbb{T})$. Indeed, suppose that we have two pairs $f_{ \pm}$and $g_{ \pm}$of solutions to Eq. (1). Then the formula

$$
\Psi(z)= \begin{cases}g_{+} \circ\left(f_{+}\right)^{-1}(z) & \text { if } z \in f_{+}(\mathbb{D}) \\ g_{-} \circ\left(f_{-}\right)^{-1}(z) & \text { if } z \in f_{-}\left(\mathbb{D}_{\infty}\right)\end{cases}
$$

defines a homeomorphism of $\widehat{\mathbb{C}}$ that is conformal outside $\Gamma=f_{ \pm}(\mathbb{T})$. Since $\Gamma$ is a Hölder curve by Theorem 3.1 we can invoke the result of Jones and Smirnov in [10] that Hölder curves are conformally removable i.e. that $\Psi$ extends conformally to the entire sphere. Thus it is a Möbius transformation and uniqueness of the welding follows.

## 5. A large deviation estimate

Theorem 3.1 follows from a large deviation estimate for weakly correlated random variables. Let $\rho=2^{-p}$ where we choose $p$ large. Let $L_{k}=L\left(w, \rho^{k}, 2 \rho^{k}\right)$ so that

$$
L\left(w, 2^{-N p}, 1\right) \geqslant \sum_{k=1}^{N} L_{k}
$$

For $p$ large $L_{k}$ are Lehto integrals in well separated annuli (in logarithmic scale). Estimate (11) follows then from the inequality

$$
\begin{equation*}
\mathbb{P}\left(\sum_{k=1}^{N} L_{k}<N \delta\right)<\rho^{(1+b) N} \tag{12}
\end{equation*}
$$

The bound (12) is a large deviation estimate and to prove it we establish two facts: that (i) the random variables $L_{k}$ are (exponentially) weakly correlated and (ii) uniformly in $k, \mathbb{P}\left(L_{k}<\varepsilon\right) \leqslant C \varepsilon$. These facts in turn rely on three ingredients: (a) an extension of $\phi$ to $f: \mathbb{D} \rightarrow \mathbb{D}$ with good local distortion bounds in terms of the random measure $\tau$, (b) sharp probabilistic bounds for $\tau$ and (c) a decomposition of the free field in terms of random fields localized in scale space.

For (a) we use the classical Beurling-Ahlfors extension [6]. We pave $\mathbb{D}$ by Whitney cubes $\left\{C_{I}\right\}_{I \in \mathcal{D}}$ indexed by dyadic intervals $I \subset \partial \mathbb{D}$ with $\operatorname{diam}\left(C_{I}\right)$ and $\operatorname{dist}\left(C_{I}, I\right)$ comparable to $|I|$. Then, extending results by Reed on the Beurling-Ahlfors extension [13], for $z \in C_{I}$ we have the local distortion bound,

$$
\begin{equation*}
K(z) \leqslant C \sum_{J, J^{\prime}} \frac{\tau(J)}{\tau\left(J^{\prime}\right)} \tag{13}
\end{equation*}
$$

where $J, J^{\prime}$ run through dyadic intervals of size $2^{-4}|I|$ lying in $I$ and its dyadic neighbours. The virtue of this bound is that the resulting lower bound for Lehto integral $L_{k}$ depends mostly on the ratios $\frac{\tau(J)}{\tau\left(J^{\prime}\right)}$ for $J, J^{\prime}$ dyadic intervals of size $\mathcal{O}\left(2^{-k p}\right)$ and of distance $\mathcal{O}\left(2^{-k p}\right)$ from $w$. Thus we need to understand the sizes and mutual correlations of such ratios.

For (b) we use results by Bacry and Muzy [4] and Kahane [11] on multiplicative cascades (we refer the reader to [5] for an extensive discussion of random multifractal measures). The most crucial facts are that for $\beta<\sqrt{2}$ the measure $\tau$ is non-atomic and for any interval $I$,

$$
\begin{equation*}
\tau(I) \in L^{p}(\omega), \quad p \in\left(-\infty, 2 / \beta^{2}\right) \tag{14}
\end{equation*}
$$

Hence in particular the ratios in (13) are in $L^{p}(\omega)$ for $p \in\left[1,2 / \beta^{2}\right.$ ). These facts are used in the proof of statement (ii) above. The fact that we may choose $p>1$ is crucial for our analysis and is the source for the restriction to $\beta<\sqrt{2}$.

Finally for (c), to understand the correlations between the $L_{k}$ i.e. between the ratios $\frac{\tau(J)}{\tau\left(J^{\prime}\right)}$ on scale $2^{-k p}$ we use a representation due to Bacry and Muzy [4] of the free field $X$. It allows to decompose $X$ as

$$
\begin{equation*}
X=\sum_{k=0}^{\infty} \zeta_{k} \tag{15}
\end{equation*}
$$

where $\zeta_{k}$ are mutually independent a.s. continuous fields with $\zeta_{k}(x)$ independent from $\zeta_{k}(y)$ for $|x-y|>\mathcal{O}\left(2^{-k p}\right)$. This decomposition leads to the following lower bound,

$$
\begin{equation*}
L_{n} \geqslant m_{n} \exp \left(\sum_{k=0}^{n-1} 2^{-a p(n-k)} t_{n, k}\right)\left(1+\sum_{k=n+1}^{\infty} 2^{-a p(k-n)} \ell_{n, k}\right)^{-1} \tag{16}
\end{equation*}
$$

for $a>0$. The main contribution here is the scale $2^{-n p}$ contribution $m_{n}$. The positive random variables $m_{n}$ are i.i.d. and satisfy the condition $\mathbb{P}\left(m_{n}<\varepsilon\right) \leqslant C \varepsilon$. Thus their sum $\sum m_{n}$ satisfies the estimate (12).

The corrections $t_{n, k} \geqslant 0$ and $\ell_{n, k} \geqslant 0$ represent correlations between scale $2^{-n p}$ and scale $2^{-k p}$ and are multiplied with weights exponentially small in $|n-k|$. Further, $t_{n, k}$ has Gaussian tails:

$$
\mathbb{P}\left(t_{n, k}>u\right) \leqslant c e^{-u^{2} / c}
$$

and the $\ell_{n, k}$ has a power law tail:

$$
\mathbb{P}\left(\ell_{n, m}>\lambda\right) \leqslant C \lambda^{-q}
$$

for $q>1$. Moreover, $t_{n, k}$ and $t_{n, k^{\prime}}$ are independent if $k \neq k^{\prime}$ and $\ell_{n, m}$ and $\ell_{n^{\prime}, m^{\prime}}$ are independent if $n>m^{\prime}$ or $n^{\prime}>m$. These properties suffice to show that the estimate (12) extends from the $m_{n}$ to the $L_{n}$.

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