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Iterated convolutions and endless Riemann surfaces

Shingo Kamimoto and David Sauzin

Abstract

We discuss a version of Écalle’s definition of resurgence, based on the notion of endless continuability in the Borel plane. We relate this with the notion of Ω-continuability, where \( \Omega = (\Omega_L)_{L \in \mathbb{R}_{>0}} \) is a discrete filtered set, and show how to construct a universal Riemann surface \( X_\Omega \) whose holomorphic functions are in one-to-one correspondence with Ω-continuable functions. We then discuss the Ω-continuability of convolution products and give estimates for iterated convolutions of the form \( \hat{\phi}_1 \ast \cdots \ast \hat{\phi}_n \). This allows us to handle nonlinear operations with resurgent series, e.g. substitution into a convergent power series.

1 Introduction

In this article, we deal with the following version of Écalle’s definition of resurgence:

**Definition 1.1.** A convergent power series \( \hat{\phi} \in \mathbb{C}\{\zeta\} \) is said to be **endlessly continuable** if, for every real \( L > 0 \), there exists a finite subset \( F_L \) of \( \mathbb{C} \) such that the holomorphic germ at 0 defined by \( \hat{\phi} \) can be analytically continued along every Lipschitz path \( \gamma: [0, 1] \to \mathbb{C} \) of length smaller than \( L \) such that \( \gamma(0) = 0 \) and \( \gamma((0,1]) \subset \mathbb{C} \setminus F_L \). We denote by \( \hat{\mathbb{R}} \subset \mathbb{C}\{\zeta\} \) the space of endlessly continuable functions.

We will usually identify a convergent power series and the holomorphic germ that it defines at the origin of \( \mathbb{C} \), as well as the holomorphic function which is thus defined near 0. Holomorphic germs with meromorphic or algebraic analytic continuation are examples of endlessly continuable functions, but the functions in \( \hat{\mathbb{R}} \) can have a multiple-valued analytic continuation with a rich set of singularities.

**Definition 1.2.** A formal series \( \tilde{\phi}(z) = \sum_{j=0}^{\infty} \phi_j z^{-j} \in \mathbb{C}[[z^{-1}]] \) is said to be **resurgent** if \( \hat{\phi}(\zeta) = \sum_{j=1}^{\infty} \phi_j \frac{\zeta^{-1}(\zeta - 1)}{(j-1)!} \) is an endlessly continuable function.

In other words, the space of resurgent series is

\[
\hat{\mathbb{R}} := B^{-1}(\mathbb{C} \delta \oplus \hat{\mathbb{R}}) \subset \mathbb{C}[[z^{-1}]],
\]

where \( B: \mathbb{C}[[z^{-1}]] \to \mathbb{C} \delta \oplus \mathbb{C}[[\zeta]] \) is the formal Borel transform, defined as mapping \( \tilde{\phi}(z) \) to \( \phi_0 \delta + \tilde{\phi}(\zeta) \) in the notation of Definition 1.2. The **convolution product** is defined as the Borel image of multiplication and denoted by the symbol \( \ast \): for \( \tilde{\phi}, \tilde{\psi} \in \mathbb{C}[[\zeta]] \), \( \tilde{\phi} \ast \tilde{\psi} := B(B^{-1} \tilde{\phi} \cdot B^{-1} \tilde{\psi}) \), and \( \delta \) is the convolution unit (obtained from \( \mathbb{C}[[\zeta]], \ast \) by adjunction of unit). As is well known, for convergent power series, convolution admits the integral representation

\[
\phi \ast \psi(\zeta) = \int_0^\zeta \phi(\xi) \psi(\zeta - \xi) \, d\xi
\]
for \( \zeta \) in the intersection of the discs of convergence of \( \hat{\varphi} \) and \( \hat{\psi} \).

Our aim is to study the analytic continuation of the convolution product of an arbitrary number of endlessly continuable functions, to check its endless continuability, and also to provide bounds, so as to be able to deal with nonlinear operations on resurgent series. A typical example of nonlinear operation is the substitution of one or several series without constant term \( \tilde{\varphi}_1, \ldots, \tilde{\varphi}_r \) into a power series \( F(w_1, \ldots, w_r) \), defined as

\[
F(\tilde{\varphi}_1, \ldots, \tilde{\varphi}_r) := \sum_{k \in \mathbb{N}^r} c_k \tilde{\varphi}_1^{k_1} \cdots \tilde{\varphi}_r^{k_r}
\]

for \( F = \sum_{k \in \mathbb{N}^r} c_k w_1^{k_1} \cdots w_r^{k_r} \). One of our main results is

**Theorem 1.3.** Let \( r \geq 1 \) be integer. Then, for any convergent power series \( F(w_1, \ldots, w_r) \in \mathbb{C}\{w_1, \ldots, w_r\} \) and for any resurgent series \( \tilde{\varphi}_1, \ldots, \tilde{\varphi}_r \) without constant term, one has

\[
F(\tilde{\varphi}_1, \ldots, \tilde{\varphi}_r) \in \tilde{\mathcal{R}}.
\]

The proof of this result requires suitable bounds for the analytic continuation of the Borel transform of each term in the right-hand side of (1.2). Along the way, we will study the Riemann surfaces generated by endlessly continuable functions.

Resurgence theory was developed in the early 1980s, with [Eca81] and [Eca85], and has many mathematical applications in the study of holomorphic dynamical systems, analytic differential equations, WKB analysis, etc. (see the references e.g. in [Sau15]). More recently, there has been a burst of activity on the use of resurgence in Theoretical Physics, in the context of matrix models, string theory, quantum field theory and also quantum mechanics—see e.g. [AS15], [ASV12], [AU12], [CDU15], [CSSV15], [DU12], [DU14], [GGvS14], [Mar14]. In almost all these applications, it is an important fact that the space of resurgence series be stable under nonlinear operations: such stability properties are useful, and at the same time they account for the occurrence of resurgent series in concrete problems.

These stability properties were stated in a very general framework in [Eca85], but without detailed proofs, and the part of [CNP93] which tackles this issue contains obscurities and at least one mistake. It is thus our aim in this article to provide a rigorous treatment of this question, at least in the slightly narrower context of endless continuability. The definition of resurgence that we use, based on Definition [1.1] is indeed more restrictive than Écalle’s most general definition [Eca85]. (It is in fact a variant of the one used by Pham et al. in [CNP93]; besides, Definition [1.1] is more or less equivalent to the definition used in [OD15], but the latter preprint has flaws which induced us to develop the results of the present paper). The simplified version we are dealing with in this article is sufficient for a large class of applications, which virtually contains all the aforementioned ones—see for instance [Kam16] for the details concerning the case of nonlinear systems of differential or difference equations. The advantage of this definition, based on endless continuability, is that it allows for a description of the location of the singularities in the Borel plane by means of discrete filtered sets (defined in Section 2.1): the notion of discrete filtered set, adapted from [CNP93] and [OD15], is flexible enough to allow for a control of the singularity structure of convolution products.

An even more restrictive definition is used [Sau15] and [MS16] (see also [Eca81]), which can be phrased as
Definition 1.4. Let $\Sigma$ be a closed discrete subset of $\mathbb{C}$. A convergent power series $\hat{\phi}$ is said to be $\Sigma$-continuable if it can be analytically continued along any path which starts in its disc of convergence and stays in $\mathbb{C}\setminus \Sigma$. The space of $\Sigma$-continuable functions is denoted by $\mathcal{C}_\Sigma$.

This is clearly a particular case of Definition 1.1 whose requirement is satisfied by any $\Sigma$-continuable function with $F_\Sigma = \{ \omega \in \Sigma \mid |\omega| \leq L \}$. It is proved in [MS16] that, if $\Sigma'$ and $\Sigma''$ are closed discrete subsets of $\mathbb{C}$, and if also $\Sigma := \{ \omega' + \omega'' \mid \omega' \in \Sigma', \omega'' \in \Sigma'' \}$ is closed and discrete, then $\hat{\phi} \in \mathcal{C}_\Sigma$, $\hat{\psi} \in \mathcal{C}_{\Sigma''} \Rightarrow \hat{\phi} \ast \hat{\psi} \in \mathcal{C}_\Sigma$. This is because in formula (1.1), heuristically, singular points tend to add to create new singularities; so, the analytic continuation of $\hat{\phi} \ast \hat{\psi}$ along a path which does not stay close to the origin is possible provided the path avoids $\Sigma$. In particular, if a closed discrete set $\Sigma$ is closed under addition, then $\mathcal{C}_\Sigma$ is closed under convolution; moreover, in this case, bounds for the analytic continuation of iterated convolutions $\hat{\phi}_1 \ast \cdots \ast \hat{\phi}_n$ are given in [Sau15], where an analogue of Theorem 1.3 is proved for $\Sigma$-continuable functions.

The notion of $\Sigma$-continuability is sufficient to cover interesting applications, e.g. differential equations of the saddle-node singularity type or difference equations like Abel’s equation

\[
\frac{d\phi}{dz} - \lambda \phi = b(z),
\]

where $b(z)$ is given in $z^{-1} \mathbb{C}\{z^{-1}\}$ and $\lambda \in \mathbb{C}^*$, has a unique formal solution in $\mathbb{C}[\{z^{-1}\}]$, namely $\hat{\phi}(z) := -\lambda^{-1} \left( \text{Id} - \lambda^{-1} \frac{d}{dz} \right)^{-1} b$, whose Borel transform is $\hat{\phi}(\zeta) = -(\lambda + \zeta)^{-1} b(\zeta)$; here, the Borel transform $b(\zeta)$ of $b(z)$ is entire, hence $\hat{\phi}$ is meromorphic, with a pole at $\zeta = -\lambda$ and no other singularity. Therefore, heuristically, for a nonlinear equation

\[
\frac{d\phi}{dz} - \lambda \phi = b_0(z) + b_1(z) \phi + b_2(z) \phi^2 + \cdots
\]

with $b(z, w) = \sum b_m(z) w^m \in z^{-1} \mathbb{C}\{z^{-1}, w\}$ given, we may expect a formal solution whose Borel transform $\hat{\phi}$ has singularities at $\zeta = -n\lambda$, $n \in \mathbb{Z}_{\geq 0}$ (because, as an effect of the nonlinearity, the singular points tend to add), i.e. $\hat{\phi}$ will be $\Sigma$-continuable with $\Sigma = \{-\lambda, -2\lambda, \ldots\}$ (see [Sau09] for a rigorous proof of this), but in the multidimensional case, for a system of $r$ coupled equations with left-hand sides of the form $\frac{d\phi_j}{dz} - \lambda_j \phi_j$ with $\lambda_1, \ldots, \lambda_r \in \mathbb{C}^*$, we may expect that the Borel transforms $\hat{\phi}_j$ of the components of the formal solution have singularities at the points $\zeta = -(n_1\lambda_1 + \cdots + n_r\lambda_r)$, $n \in \mathbb{Z}^r_{\geq 0}$; this set of possible singular points may fail to be closed and discrete (depending on the arithmetical properties of $(\lambda_1, \ldots, \lambda_r)$), hence, in general, we cannot expect these Borel transforms to be $\Sigma$-continuable for any $\Sigma$. Still, this does not prevent them from being always endlessly continuaible, as proved in [Kam16].

Another illustration of the need to go beyond $\Sigma$-continuability stems from parametric resurgence [Pan84]. Suppose that we are given a holomorphic function $b(t)$ globally defined on $\mathbb{C}$, with isolated singularities $\omega \in S \subset \mathbb{C}$, e.g. a meromorphic function, and consider the differential equation

\[
\frac{d\phi}{dt} - z \lambda \phi = b(t),
\]
where \( \lambda \in \mathbb{C}^* \) is fixed and \( z \) is a large complex parameter with respect to which we consider perturbative expansions. It is easy to see that there is a unique solution which is formal in \( z \) and analytic in \( t \), namely \( \tilde{\varphi}(z,t) := -\sum_{k=0}^{\infty} \lambda^{-k-1} z^{-k-1} b(k)(t) \), and its Borel transform \( \hat{\varphi}(\zeta,t) = -\lambda^{-1} b(t + \lambda^{-1} \zeta) \) is singular at all points of the form \( \zeta_{t,\omega} := \lambda(-t + \omega), \omega \in S \). Now, if we add to the right-hand side of (1.3) a perturbation which is nonlinear in \( \varphi \), we can expect the Borel transform of the formal solution to have a rich set of singular points generated by the \( \zeta_{t,\omega} \)'s, which might easily be too rich to allow for \( \Sigma \)-continuability with any \( \Sigma \); however, we can still hope endless continuability.

These are good motivations to study endless continuable functions. As already alluded to, we will use discrete filtered sets to work with them. These are not sets, but families of sets of the form \( \Omega = (\Omega_L)_{L \in \mathbb{R}_{\geq 0}} \), where each \( \Omega_L \) is a finite set; we will define \( \Omega \)-continuability when \( \Omega \) is not a set but a discrete filtered set, and the space of endlessly continuable functions will appear as the totality of \( \Omega \)-continuible functions for all possible discrete filtered sets. This was already the approach of [CNP93], and it was used in [OD15] to prove that the convolution product of two endlessly continuable functions is endlessly continuable, hence \( \mathcal{R} \) is a subring of \( \mathbb{C}[[z^{-1}]] \). However, to reach the conclusions of Theorem 1.3 precise estimates on the convolution product of an arbitrary number of endlessly continuable functions are needed, so as to prove the convergence of the series of holomorphic functions \( \sum c_k \hat{\varphi}_1^{*k_1} \cdots \hat{\varphi}_r^{*k_r} \) (Borel transform of the right-hand side of (1.2)) and to check its endless continuability.

Moreover, having at one’s disposal explicit bounds for iterated convolutions may prove useful in itself; in the context of \( \Sigma \)-continuability, such bounds were obtained in [Sau15] and they were used in [K316] in a study in WKB analysis, where the authors track the analytic dependence upon parameters in the exponential of the Voros coefficient.

As another contribution to the study of endlessly continuable functions, we will show how to construct, for each discrete filtered set \( \Omega \), a universal Riemann surface \( X_\Omega \) whose holomorphic functions are in one-to-one correspondence with \( \Omega \)-continuable functions.

The plan of the paper is as follows.

- Section 2 introduces discrete filtered sets, the corresponding \( \Omega \)-continuible functions and their Borel images, the \( \Omega \)-resurgent series, and discusses their relation with Definitions 1.1 and 1.2.
- Section 3 discusses the notion of \( \Omega \)-endless Riemann surface and shows how to construct a universal object \( X_\Omega \) (Theorem 3.2).
- In Section 4 we state and prove Theorem 4.8 which gives precise estimates for the convolution product of an arbitrary number of endlessly continuable functions.
- Section 5 is devoted to applications of Theorem 4.8, the proof of Theorem 1.3 and even of a more general and more precise version, Theorem 5.2 and an implicit resurgent function theorem, Theorem 5.3.

Some of the results presented here have been announced in [KS16].
2 Discrete filtered sets and $\Omega$-continuability

In this section, we review the notions concerning discrete filtered sets (usually denoted by the letter $\Omega$), the corresponding $\Omega$-allowed paths and $\Omega$-continuable functions. The relation with endless continuability is established, and sums of discrete filtered sets are defined in order to handle convolution of endlessly continuable functions.

2.1 Discrete filtered sets

We first introduce the notion of discrete filtered sets which will be used to describe singularity structure of endlessly continuable functions (the first part of the definition is adapted from [CNP93] and [OD15]):

Definition 2.1. We use the notation $\mathbb{R}_{\geq 0} = \{ \lambda \in \mathbb{R} \mid \lambda \geq 0 \}$.

1) A discrete filtered set, or d.f.s. for short, is a family $\Omega = (\Omega_L)_{L \in \mathbb{R}_{\geq 0}}$ where
   i) $\Omega_L$ is a finite subset of $\mathbb{C}$ for each $L$,
   ii) $\Omega_{L_1} \subseteq \Omega_{L_2}$ for $L_1 \leq L_2$,
   iii) there exists $\delta > 0$ such that $\Omega_{\delta} = \emptyset$.

2) Let $\Omega$ and $\Omega'$ be d.f.s. We write $\Omega \subset \Omega'$ if $\Omega_L \subset \Omega'_L$ for every $L$.

3) We call upper closure of a d.f.s. $\hat{\Omega}$ the family of sets $\hat{\Omega} = (\hat{\Omega}_L)_{L \in \mathbb{R}_{\geq 0}}$ defined by

$$\hat{\Omega}_L := \bigcap_{\varepsilon > 0} \Omega_{L+\varepsilon}$$

for $L \in \mathbb{R}_{\geq 0}$.

It is easy to check that $\hat{\Omega}$ is a d.f.s. and $\Omega \subset \hat{\Omega}$.

Example 2.2. Given a closed discrete subset $\Sigma$ of $\mathbb{C}$, the formula

$$\Omega(\Sigma)_L := \{ \omega \in \Sigma \mid |\omega| \leq L \}$$

for $L \in \mathbb{R}_{\geq 0}$

defines a d.f.s. $\Omega(\Sigma)$ which coincides with its upper closure.

From the definition of d.f.s., we find the following

Lemma 2.3. For any d.f.s. $\Omega$, there exists a real sequence $(L_n)_{n \geq 0}$ such that $0 = L_0 < L_1 < L_2 < \cdots$ and, for every integer $n \geq 0$,

$$L_n < L < L_{n+1} \Rightarrow \hat{\Omega}_{L_n} = \hat{\Omega}_L = \Omega_L.$$

Proof. First note that (2.1) entails

$$\hat{\Omega}_L := \bigcap_{\varepsilon > 0} \hat{\Omega}_{L+\varepsilon}$$

for every $L \in \mathbb{R}_{\geq 0}$

(because $\Omega_{L+\varepsilon} \subset \hat{\Omega}_{L+\varepsilon} \subset \hat{\Omega}_{L+2\varepsilon}$). Consider the weakly order-preserving integer-valued function $L \in \mathbb{R}_{\geq 0} \mapsto N(L) := \text{card} \hat{\Omega}_L$. For each $L$ the sequence $k \mapsto N(L + \frac{1}{k})$ must be eventually
constant, hence there exists $\varepsilon_L > 0$ such that, for all $L' \in (L, L + \varepsilon_L]$, $N(L') = N(L + \varepsilon_L)$, whence $\tilde{\Omega}_{L'} = \tilde{\Omega}_{L + \varepsilon_L}$, and in fact, by (2.2), this holds also for $L' = L$. The conclusion follows from the fact that $\mathbb{R}_{\geq 0} = \bigcup_{k \in \mathbb{Z}} N^{-1}(k)$ and each non-empty $N^{-1}(k)$ is convex, hence an interval, which by the above must be left-closed and right-open, hence of the form $[L, L')$ or $[L, \infty)$.

Given a d.f.s. $\Omega$, we set

$$S_{\Omega} := \{ (\lambda, \omega) \in \mathbb{R} \times \mathbb{C} \mid \lambda \geq 0 \text{ and } \omega \in \Omega_{\lambda} \}$$

and denote by $\overline{S}_{\Omega}$ the closure of $S_{\Omega}$ in $\mathbb{R} \times \mathbb{C}$. We then call

$$M_{\Omega} := (\mathbb{R} \times \mathbb{C}) \setminus \overline{S}_{\Omega}$$

the allowed open set associated with $\Omega$.

**Lemma 2.4.** One has

$$\overline{S}_{\Omega} = S_{\Omega} \quad \text{and} \quad M_{\Omega} = M_{\tilde{\Omega}}.$$

**Proof.** Suppose $(\lambda, \omega) \in S_{\tilde{\Omega}}$. Then $\omega \in \Omega_{\lambda+1/k}$ for each $k \geq 1$, hence $(\lambda + \frac{1}{k}, \omega) \in S_{\Omega}$, whence $(\lambda, \omega) \in \overline{S}_{\Omega}$.

Suppose $(\lambda, \omega) \in \overline{S}_{\Omega}$. Then there exists a sequence $(\lambda_k, \omega_k)_{k \geq 1}$ in $S_{\Omega}$ which converges to $(\lambda, \omega)$. If $\varepsilon > 0$, then $\lambda_k \leq \lambda + \varepsilon$ for $k$ large enough, hence $\omega_k \in \Omega_{\lambda+\varepsilon}$, whence $\omega \in \Omega_{\lambda+\varepsilon}$ (because a finite set is closed); therefore $(\lambda, \omega) \in \overline{S}_{\Omega}$.

Therefore, $S_{\Omega} = \overline{S}_{\Omega} = \overline{S}_{\tilde{\Omega}}$ and $M_{\Omega} = M_{\tilde{\Omega}}$. 

### 2.2 $\Omega$-allowed paths

When dealing with a Lipschitz path $\gamma: [a, b] \to \mathbb{C}$, we denote by $L(\gamma)$ its length.

We denote by $\Pi$ the set of all Lipschitz paths $\gamma: [0, t_\ast] \to \mathbb{C}$ such that $\gamma(0) = 0$, with some real $t_\ast \geq 0$ depending on $\gamma$. Given such a $\gamma \in \Pi$ and $t \in [0, t_\ast]$, we denote by

$$\gamma|_t := \gamma|_{[0, t]} \in \Pi$$

the restriction of $\gamma$ to the interval $[0, t]$.

**Definition 2.5.** Given a d.f.s. $\Omega$, we call $\Omega$-allowed path any $\gamma \in \Pi$ such that

$$\tilde{\gamma}(t) := (L(\gamma|_t), \gamma(t)) \in M_{\Omega} \quad \text{for all } t.$$ 

We denote by $\Pi_{\Omega}$ the set of all $\Omega$-allowed paths.

Notice that, given $t_\ast \geq 0$,

$$t \in [0, t_\ast] \mapsto \tilde{\gamma}(t) = (\lambda(t), \gamma(t)) \in M_{\Omega}$$

is a piecewise $C^1$ path such that

$$\tilde{\gamma}(0) = (0, 0) \quad \text{and} \quad \lambda'(t) = |\gamma'(t)| \quad \text{for a.e. } t,$$

then $\gamma \in \Pi_{\Omega}$.

In view of Lemmas 2.3 and 2.4, we have the following characterization of $\Omega$-allowed paths:
Lemma 2.6. Let $\Omega$ be a d.f.s. Then $\Pi_\Omega = \Pi_\Omega'$ and, given $\gamma \in \Pi$, the followings are equivalent:
1) $\gamma \in \Pi_\Omega$,
2) $\gamma(t) \in \mathbb{C} \setminus \Omega_L(\gamma)$ for every $t$,
3) for every $t$, there exists $n$ such that $L(\gamma) < L_{n+1}$ and $\gamma(t) \in \mathbb{C} \setminus \Omega_L$ (using the notation of Lemma 2.3).

Proof. Obvious. \hfill \Box

Notation 2.7. For $L, \delta > 0$, we set
\begin{equation}
\mathcal{M}_\Omega^{\delta,L} := \left\{ (\lambda, \zeta) \in \mathbb{R} \times \mathbb{C} \mid \text{dist}((\lambda, \zeta), S_\Omega) \geq \delta \text{ and } \lambda \leq L \right\},
\end{equation}
\begin{equation}
\Pi_\Omega^{\delta,L} := \left\{ \gamma \in \Pi_\Omega \mid (L(\gamma), \gamma(t)) \in \mathcal{M}_\Omega^{\delta,L} \text{ for all } t \right\},
\end{equation}
where \text{dist}(\cdot, \cdot) is the Euclidean distance in $\mathbb{R} \times \mathbb{C} \simeq \mathbb{R}^3$.

Note that
\begin{equation*}
\mathcal{M}_\Omega = \bigcup_{\delta,L > 0} \mathcal{M}_\Omega^{\delta,L}, \quad \Pi_\Omega = \bigcup_{\delta,L > 0} \Pi_\Omega^{\delta,L}.
\end{equation*}

2.3 $\Omega$-continuable functions and $\Omega$-resurgent series

Definition 2.8. Given a d.f.s. $\Omega$, we call $\Omega$-continuable function a holomorphic germ $\hat{\varphi} \in \mathbb{C}\{\zeta\}$ which can be analytically continued along any path $\gamma \in \Pi_\Omega$. We denote by $\hat{\mathcal{R}}_\Omega$ the set of all $\Omega$-continuable functions and define
\begin{equation*}
\hat{\mathcal{R}}_\Omega := \mathcal{B}^{-1}(\mathbb{C} \delta \oplus \hat{\mathcal{R}}_\Omega) \subset \mathbb{C}[[z^{-1}]]
\end{equation*}
to be the set of $\Omega$-resurgent series.

Remark 2.9. Given a closed discrete subset $\Sigma$ of $\mathbb{C}$, the $\Sigma$-continuability in the sense of Definition 1.4 is equivalent to the $\Omega(\Sigma)$-continuability in the sense of Definition 2.8 for the d.f.s. $\Omega(\Sigma)$ of Example 2.2.

Remark 2.10. Observe that, given d.f.s. $\Omega$ and $\Omega'$,
\begin{equation*}
\Omega \subset \Omega' \quad \Rightarrow \quad \hat{\mathcal{R}}_\Omega \subset \hat{\mathcal{R}}_{\Omega'}.
\end{equation*}
Indeed, $\Omega \subset \Omega'$ implies $\mathcal{S}_\Omega \subset \mathcal{S}_{\Omega'}$, hence $\mathcal{M}_{\Omega'} \subset \mathcal{M}_\Omega$ and $\Pi_{\Omega'} \subset \Pi_\Omega$.

Remark 2.11. Notice that, for the trivial d.f.s. $\Omega = \emptyset$, $\hat{\mathcal{R}}_\emptyset = \mathcal{O}(\mathbb{C})$, hence $\mathcal{O}(\mathbb{C}) \subset \hat{\mathcal{R}}_\Omega$ for every d.f.s. $\Omega$, i.e. entire functions are always $\Omega$-continuable. Consequently, convergent series are always $\Omega$-resurgent: $\mathbb{C}\{z^{-1}\} \subset \hat{\mathcal{R}}_\Omega$.

However, $\hat{\mathcal{R}}_\Omega = \mathcal{O}(\mathbb{C})$ does not imply $\Omega = \emptyset$. In fact, one can show that
\begin{equation*}
\hat{\mathcal{R}}_\Omega = \mathcal{O}(\mathbb{C}) \quad \iff \quad \forall L > 0, \exists L' > L \text{ such that } \Omega_{L'} \subset \{ \omega \in \mathbb{C} \mid |\omega| < L \}.
\end{equation*}
For example, consider the case of the d.f.s. $\Omega$ given by $\Omega_L = \emptyset$ for $0 \leq L < 2$ and $\Omega_L = \{1\}$ for $L \geq 2$. 7
Remark 2.12. In view of Lemma 2.6 we have \( \hat{\mathcal{R}}_{\Omega} = \hat{\mathcal{R}}_{\hat{\Omega}} \). Therefore, when dealing with \( \Omega \)-resurgence, we can always suppose that \( \Omega \) coincides with its upper closure (by replacing \( \Omega \) with \( \hat{\Omega} \)).

We now show the relation between resurgence in the sense of Definition 2.8 and \( \Omega \)-resurgence in the sense of Definition 2.13.

**Theorem 2.13.** A formal series \( \check{\varphi} \in \mathbb{C}[[z^{-1}]] \) is resurgent if and only if there exists a d.f.s. \( \Omega \) such that \( \check{\varphi} \) is \( \Omega \)-resurgent. In other words,

\[
\tilde{\mathcal{R}} = \bigcup_{\Omega \text{ d.f.s.}} \tilde{\mathcal{R}}_{\Omega}, \quad \hat{\mathcal{R}} = \bigcup_{\Omega \text{ d.f.s.}} \hat{\mathcal{R}}_{\Omega}.
\]

Before proving Theorem 2.13 we state a technical result.

**Lemma 2.14.** Suppose that we are given a germ \( \check{\varphi} \in \mathbb{C}\{\zeta\} \) that can be analytically continued along a path \( \gamma : [0, t_*] \to \mathbb{C} \) of \( \Pi \), and that \( F \) is a finite subset of \( \mathbb{C} \). Then, for each \( \varepsilon > 0 \), there exists a path \( \gamma^* : [0, t_*] \to \mathbb{C} \) of \( \Pi \) such that

- \( \gamma^*((0, t_*)) \subset \mathbb{C} \setminus F \),
- \( L(\gamma^*) < L(\gamma) + \varepsilon \),
- \( \gamma^*(t_*) = \gamma(t_*) \), the germ \( \check{\varphi} \) can be analytically continued along \( \gamma^* \) and the analytic continuations along \( \gamma \) and \( \gamma^* \) coincide.

**Proof of Lemma 2.14.** Without loss of generality, we can assume that \( \gamma([0, t_*]) \) is not reduced to \( \{0\} \) and that \( t \mapsto L(\gamma|_t) \) is strictly increasing.

The analytic continuation assumption allows us to find a finite subdivision \( 0 = t_0 < \cdots < t_m = t_* \) of \( [0, t_*] \) together with open discs \( \Delta_0, \ldots, \Delta_m \) so that, for each \( k \), \( \gamma(t_k) \in \Delta_k \), the analytic continuation of \( \check{\varphi} \) along \( \gamma|_{t_k} \) extends holomorphically to \( \Delta_k \), and \( \gamma([t_k, t_{k+1}]) \subset \Delta_k \) if \( k < m \).

For each \( k \geq 1 \), let us pick \( s_k \in (t_{k-1}, t_k) \) such that \( \gamma([s_k, t_k]) \subset \Delta_{k-1} \cap \Delta_k \); increasing the value of \( s_k \) if necessary, we can assume \( \gamma(s_k) \notin F \). Let us also set \( s_0 := 0 \) and \( s_{m+1} := t_* \), so that

\[
0 \leq k \leq m \quad \Rightarrow \quad \left\{ \begin{aligned}
\gamma([s_k, s_{k+1}]) &\subset \Delta_k, \\
\text{the analytic continuation of } \check{\varphi} \text{ along } \gamma|_{s_k} \text{ is holomorphic in } \Delta_k \\
\gamma(s_k) &\notin F \text{ except maybe if } k = 0, \\
\gamma(s_{k+1}) &\notin F \text{ except maybe if } k = m.
\end{aligned} \right.
\]

We now define \( \gamma^* \) by specifying its restriction \( \gamma^*|_{[s_k, s_{k+1}]} \) for each \( k \) so that it has the same endpoints as \( \gamma|_{[s_k, s_{k+1}]} \) and,

- if the open line segment \( S := (\gamma(s_k), \gamma(s_{k+1})) \) is contained in \( \mathbb{C} \setminus F \), then we let \( \gamma^*|_{[s_k, s_{k+1}]} \) start at \( \gamma(s_k) \) and end at \( \gamma(s_{k+1}) \) following \( S \); by setting

\[
\gamma^*(t) := \gamma(s_k) + \frac{t-s_k}{s_{k+1}-s_k} (\gamma(s_{k+1}) - \gamma(s_k)) \quad \text{for } t \in [s_k, s_{k+1}],
\]

and all the \( \gamma^*|_{[s_k, s_{k+1}]} \) are strictly increasing.


Let us check by induction on $t$ that  $\hat{\gamma}$ meets the requirement of Definition 1.1 with $\Omega = \{0\}$. Suppose first that $\Omega$ is a d.f.s. and $\hat{\gamma} \in \hat{\Omega}$. Then, for every $L > 0$, $\hat{\gamma}$ meets the requirement of Definition 1.1 with $F_L = \Omega_L$, hence $\hat{\gamma} \in \hat{\Omega}$. Thus $\hat{\Omega} \subset \hat{\Omega}$, which yields one inclusion in (2.9).

Suppose now $\hat{\gamma} \in \hat{\Omega}$. In view of Definition 1.1 the radius of convergence $\delta$ of $\hat{\gamma}$ is positive and, for each positive integer $n$, we can choose a finite set $F_n$ such that

$$
\Omega_L := \bigcup_{k=0}^{n} F_k \quad \text{with } n := \lfloor L/\delta \rfloor.
$$

One can check that $\Omega := (\Omega_L)_{L \in \mathbb{R}_{\geq 0}}$ is a d.f.s. which coincides with its upper closure. We will show that $\hat{\gamma} \in \hat{\Omega}$.

Pick an arbitrary $\gamma : [0,1] \to \mathbb{C}$ such that $\gamma \in \Pi_\Omega$. It is sufficient to prove that $\hat{\gamma}$ can be analytically continued along $\gamma$. Our assumption amounts to $\gamma(t) \in \mathbb{C} \setminus \Omega_L(\gamma|_t)$ for each $t \in [0,1]$. Without loss of generality, we can assume that $\gamma([0,1])$ is not reduced to $\{0\}$ and that $t \mapsto L(\gamma|_t)$ is strictly increasing. Let

$$
N := \lfloor L(\gamma)/\delta \rfloor.
$$

We define a subdivision $0 = t_0 < t_1 < \cdots < t_N \leq 1$ by the requirement $L(\gamma|_{t_n}) = n\delta$ and set

$$
I_n := [t_n,t_{n+1}) \quad \text{for } 0 \leq n < N, \quad I_N := [t_N,1].
$$

For each integer $n$ such that $0 \leq n \leq N$,

$$
(2.11) \quad t \in I_n \quad \Rightarrow \quad n\delta \leq L(\gamma|_t) < (n+1)\delta,
$$

thus $\Omega_L(\gamma|_t) = \bigcup_{k=0}^{n} F_k$, in particular

$$
(2.12) \quad t \in I_n \quad \Rightarrow \quad \gamma(t) \in \mathbb{C} \setminus F_n.
$$

Let us check by induction on $n$ that $\hat{\gamma}$ can be analytically continued along $\gamma|_t$ for any $t \in I_n$.

If $t \in I_0$, then $\gamma|_t$ has length $< \delta$ and the conclusion follows from (2.10).

Suppose now that $1 \leq n \leq N$ and that the property holds for $n - 1$. Let $t \in I_n$. By (2.11)–(2.12), we have $L(\gamma|_t) < (n+1)\delta$ and $\gamma([t_n,t]) \subset \mathbb{C} \setminus F_n$. 

9
– If $\gamma([0, t_n]) \cap F_n$ is empty, then the conclusion follows from (2.10).

– If not, then, since $\mathbb{C} \setminus F_n$ is open, we can pick $t_* < t_n$ so that $\gamma([t_*, t]) \subset \mathbb{C} \setminus F_n$, and the induction hypothesis shows that $\hat{\varphi}$ can be analytically continued along $\gamma_{t_*}$. We then apply Lemma 2.14 to $\gamma_{t_*}$ with $F = F_n$ and $\varepsilon = (n+1)\delta - L(\gamma_{t_*})$: we get a path $\gamma^* : [0, t_*] \to \mathbb{C}$ which defines the same analytic continuation for $\hat{\varphi}$ as $\gamma_{t_*}$, avoids $F_n$ and has length $< L(\gamma_{t_*}) + \varepsilon$.

The concatenation of $\gamma^*$ with $\gamma|_{[t_*, t]}$ is a path $\gamma^*$ of length $< (n+1)\delta$ which avoids $F_n$, so it is a path of analytic continuation for $\hat{\varphi}$ because of (2.10), and so is $\gamma$ itself.

\[ \square \]

2.4 Sums of discrete filtered sets

It is easy to see that, if $\varOmega$ and $\varOmega'$ are d.f.s., then the formula

\[ (\varOmega \ast \varOmega')_L := \{ \omega_1 + \omega_2 \mid \omega_1 \in \varOmega_{L_1}, \omega_2 \in \varOmega'_{L_2}, L_1 + L_2 = L \} \cup \varOmega_L \cup \varOmega'_L \quad \text{for } L \in \mathbb{R}_{\geq 0} \]

defines a d.f.s. $\varOmega \ast \varOmega'$. We call it the sum of $\varOmega$ and $\varOmega'$.

The proof of the following lemma is left to the reader.

**Lemma 2.15.** The law $\ast$ on the set of all d.f.s. is commutative and associative. The formula $\varOmega^* := \underbrace{\varOmega \ast \ldots \ast \varOmega}_{n \text{ times}}$ (for $n \geq 1$) defines an inductive system, which gives rise to a d.f.s.

\[ \varOmega^{*\infty} := \lim_{n \to \infty} \varOmega^* \]

As shown in [CNP93] and [OD15], the sum of d.f.s. is useful to study the convolution product:

**Theorem 2.16 ([OD15]).** Assume that $\varOmega$ and $\varOmega'$ are d.f.s. and $\hat{\varphi} \in \hat{\mathcal{R}}_{\varOmega}$, $\hat{\psi} \in \hat{\mathcal{R}}_{\varOmega'}$. Then the convolution product $\hat{\varphi} \ast \hat{\psi}$ is $\varOmega \ast \varOmega'$-continuable.

**Remark 2.17.** Note that the notion of $\Sigma$-continuability in the sense of Definition 1.4 does not give such flexibility, because there are closed discrete sets $\Sigma$ and $\Sigma'$ such that $\varOmega(\Sigma) \ast \varOmega(\Sigma') \neq \varOmega(\Sigma'')$ for any closed discrete $\Sigma''$ (take e.g. $\Sigma = \Sigma' = (\mathbb{Z}_{>0} \cup \mathbb{Z}_{<0})$, and in fact there are $\Sigma$-continuable functions $\hat{\varphi}$ such that $\hat{\varphi} \ast \hat{\psi}$ is not $\Sigma''$-continuable for any $\Sigma''$.

In view of Theorem 2.13, a direct consequence of Theorem 2.16 is that the space of endlessly
continuable functions $\hat{\mathcal{R}}$ is stable under convolution, and the space of resurgent formal series $\hat{\mathcal{R}}$ is a subring of the ring of formal series $\mathbb{C}[[z^{-1}]]$.

Given $\hat{\varphi} \in \hat{\mathcal{R}}_{\varOmega} \cap z^{-1} \mathbb{C}[[z^{-1}]]$, Theorem 2.16 guarantees the $\varOmega^{*k}$-resurgence of $\hat{\varphi}^k$ for every integer $k$, hence its $\varOmega^{*\infty}$-resurgence. This is a first step towards the proof of the resurgence of $F(\hat{\varphi})$ for $F(w) = \sum c_k w^k \in \mathbb{C}\{w\}$, i.e. Theorem 1.3 in the case $r = 1$, however some analysis is needed to prove the convergence of $\sum c_k \hat{\varphi}^k$ in some appropriate topology. What we need is a precise estimate for the convolution product of an arbitrary number of endlessly
continuable functions, and this will be the content of Theorem 4.8. In Section 5 the substitution problem will be discussed in a more general setting, resulting in Theorem 5.2 which is more general and more precise than Theorem 1.3.
3 Ω-endless Riemann surfaces

We introduce the notion of Ω-endless Riemann surfaces for a d.f.s. Ω as follows:

Definition 3.1. We call Ω-endless Riemann surface any triple (X, p, 0) such that X is a connected Riemann surface, p : X → C is a local biholomorphism, 0 ∈ p⁻¹(0), and any path γ : [0, 1] → C of ΠΩ has a lift γ : [0, 1] → X such that γ(0) = 0. A morphism of Ω-endless Riemann surfaces is a local biholomorphism q : (X, p, 0) → (X', p', 0') that makes the following diagram commutative:

\[ (X, 0) \xrightarrow{q} (X', 0') \]
\[ \xrightarrow{p}\hspace{1cm} \xrightarrow{p'} \]
\[ (C, 0) \]

In this section, we prove the existence of an initial object (XΩ, pΩ, 0Ω) in the category of Ω-endless Riemann surfaces:

Theorem 3.2. There exists an Ω-endless Riemann surface (XΩ, pΩ, 0Ω) such that, for any Ω-endless Riemann surface (X, p, 0), there is a unique morphism q : (XΩ, pΩ, 0Ω) → (X, p, 0).

The Ω-endless Riemann surface (XΩ, pΩ, 0Ω) is unique up to isomorphism and XΩ is simply connected.

3.1 Construction of XΩ

We first define “skeleton” of Ω:

Definition 3.3. Let VΩ ⊂ ∪n=1∞(C × Z)n be the set of vertices

\[ v := ((ω_1, σ_1), · · · , (ω_n, σ_n)) ∈ (C × Z)^n \]

that satisfy the following conditions:

1) (ω1, σ1) = (0, 0) and (ωj, σj) ∈ C × (Z \{0}) for j ≥ 2,
2) ωj ≠ ωj+1 for j = 1, · · · , n − 1,
3) ωj ∈ ˆΩLj(v) with \[ L_j(v) := \sum_{i=1}^{j-1} |ω_{i+1} - ω_i| \]
for j = 2, · · · , n.

Let EΩ ⊂ VΩ × VΩ be the set of edges e = (v', v) that satisfy one of the following conditions:

i) v = ((ω1, σ1), · · · , (ωn, σn)) and v' = ((ω1, σ1), · · · , (ωn, σn), (ωn+1, ±1)),
ii) v = ((ω1, σ1), · · · , (ωn, σn)) and v' = ((ω1, σ1), · · · , (ωn, σn + 1)) with σn ≥ 1,
iii) v = ((ω1, σ1), · · · , (ωn, σn)) and v' = ((ω1, σ1), · · · , (ωn, σn - 1)) with σn ≤ -1.
We denote the directed tree diagram \((V_\Omega, E_\Omega)\) by \(Sk_\Omega\) and call it skeleton of \(\Omega\).

**Notation 3.4.** For \(v \in V_\Omega \cap (\mathbb{C} \times \mathbb{Z})^n\), we set \(\omega(v) := \omega_n\) and \(L(v) := L_n(v)\).

From the definition of \(Sk_\Omega\), we find the following

**Lemma 3.5.** For each \(v \in V_\Omega \setminus \{ (0,0) \}\), there exists a unique vertex \(v^\uparrow \in V_\Omega\) such that \((v,v^\uparrow) \in E_\Omega\).

To each \(v \in V_\Omega\) we assign a cut plane \(U_v\), defined as the open set

\[
U_v := \mathbb{C} \setminus \left( C_v \cup \bigcup_{v' \rightarrow v} C_{v' \rightarrow v} \right),
\]

where \(\bigcup\) is the union over all the vertices \(v' \in V_\Omega\) that have an edge \((v',v) \in E_\Omega\) of type \(i\),

\[
C_v := \left\{ \begin{array}{ll}
\emptyset & \text{when } v = (0,0), \\
\{ \omega_n - s(\omega_n - \omega_{n-1}) \mid s \in \mathbb{R}_{\geq 0} \} & \text{when } v \neq (0,0),
\end{array} \right.
\]

\[
C_{v' \rightarrow v} := \{ \omega_{n+1} + s(\omega_{n+1} - \omega_n) \mid s \in \mathbb{R}_{\geq 0} \}.
\]

We patch the \(U_v\)'s along the cuts according to the following rules:

Suppose first that \((v',v)\) is an edge of type \(i\), with \(v' = (v,(\omega_{n+1},\sigma_{n+1})) \in V_\Omega\). To it, we assign a line segment or a half-line \(\ell_{v' \rightarrow v}\) as follows: If there exists \(u = (v,(\omega_{n+1}',\pm 1)) \in V_\Omega\) such that \(\omega_{n+1}' \in C_{v' \rightarrow v} \setminus \{ \omega_{n+1} \}\), take \(u^{(0)} = (v,(\omega_{n+1}^{(0)},\pm 1)) \in V_\Omega\) so that \(|\omega_{n+1}^{(0)} - \omega_{n+1}|\)
gives the minimum of $|\omega'_{n+1} - \omega_{n+1}|$ for such vertices and assign an open line segment $\ell_{v' \to v} := \{\omega_{n+1} + s(\omega_{n+1}^{(0)} - \omega_{n+1}) \mid s \in (0, 1)\}$ to $(v', v)$. Otherwise, we assign the open half-line $\ell_{v' \to v} := C_{v' \to v} \setminus \{\omega_{n+1}\}$ to $(v', v)$. Since each $\Omega_L$ ($L \geq 0$) is finite, we can take a connected neighborhood $U_{v' \to v}$ of $\ell_{v' \to v}$ so that

$$U_{v' \to v} \setminus \ell_{v' \to v} = U_{v' \to v}^+ \cup U_{v' \to v}^- \quad \text{and} \quad U_{v' \to v}^\pm \subset U_v \cap U_{v'},$$

where

$$U_{v' \to v}^\pm := \{\zeta \in U_{v' \to v} \mid \pm \text{Im}(\zeta \cdot \overline{\zeta'}) > 0 \quad \text{for} \quad \zeta' \in \ell_{v' \to v}\}.$$  

Then, if $\sigma_{n+1} = 1$, we glue $U_v$ and $U_{v'}$ along $U_{v' \to v}$, whereas if $\sigma_{n+1} = -1$ we glue them along $U_{v' \to v}^-$. Suppose now that $(v', v)$ is an edge of type ii) and iii). As in the case of i), if there exists $u = (v, (\omega_{n+1}, \pm 1)) \in V_\Omega$ such that $\omega_{n+1} \in C_v \setminus \{\omega_n\}$, then we take $u^{(0)} = (v, (\omega_{n+1}^{(0)}, \pm 1)) \in V_\Omega$ so that $|\omega_{n+1}^{(0)} - \omega_n|$ is minimum and assign $\ell_{v' \to v} := \{\omega_n + s(\omega_{n+1} - \omega_n) \mid s \in (0, 1)\}$ to $(v', v)$. Otherwise, we assign $\ell_{v' \to v} := C_v \setminus \{\omega_n\}$ to $(v', v)$. Then, we take a connected neighborhood $U_{v' \to v}$ of $\ell_{v' \to v}$ satisfying (3.1), and glue $U_v$ and $U_{v'}$ along $U_{v' \to v}$ in case ii), and along $U_{v' \to v}^-$ in case iii).

Patching the $U_v$’s and the $U_{v' \to v}$’s according to the above rules, we obtain a Riemann surface $X_\Omega$, in which we denote by $\overline{\Omega}$ the point corresponding to $0 \in U_{(0,0)}$. The map $p_\Omega: X_\Omega \to \mathbb{C}$ is naturally defined using local coordinates $U_v$ and $U_{v' \to v}$.

Let $U_e$, $\ell_e$ $(e \in E_\Omega)$ and $U_v$ $(v \in V_\Omega)$ respectively denote the subsets of $X_\Omega$ defined by $U_e$, $\ell_e$ and $U_v$. Notice that each $\zeta \in X_\Omega$ belongs to one of the $U_e$’s or $U_v$’s $(e \in E_\Omega$ or $v \in V_\Omega$). Therefore, we have the following decomposition of $X_\Omega$:

$$X_\Omega = \bigcup_{v \in V_\Omega} U_v \cup \bigcup_{e \in E_\Omega} \ell_e.$$

**Definition 3.6.** We define a function $L: X_\Omega \to \mathbb{R}_{\geq 0}$ by the following formula:

$$L(\zeta) := L(v) + |p(\zeta) - \omega(v)| \quad \text{when} \quad \zeta \in U_v \cup \ell_{v' \to v}. $$

We call $L(\zeta)$ the canonical distance of $\zeta$ from $\overline{\Omega}$.

We obtain from the construction of $L$ the following

**Lemma 3.7.** The function $L: X_\Omega \to \mathbb{R}_{\geq 0}$ is continuous and satisfies the following inequality for every $\gamma \in \Pi_\Omega$:

$$L(\gamma(t)) \leq L(\gamma|_0) \quad \text{for} \quad t \in [0, 1].$$
We now show the fundamental properties of $X_\Omega$.

**Lemma 3.8.** The Riemann surface $X_\Omega$ constructed above is simply connected.

**Proof.** We first note that, since $S\Omega$ is connected, $X_\Omega$ is path-connected. Let $\gamma : [0, 1] \to X_\Omega$ be a path such that $\gamma(0) = \gamma(1)$. Since the image of $\gamma$ is compact set in $X_\Omega$, we can take finite number of vertices $\{v_j\}_{j=1}^p \subset V_\Omega$ and $\{e_j\}_{j=1}^q \subset E_\Omega$ so that $v_1 = (0, 0)$ and the image of $\gamma$ is covered by $\{\cup v_j\}_{j=1}^p$ and $\{\cup e_j\}_{j=1}^q$. Since each of $\{v_j\}_{j=2}^p$ and $\{e_j\}_{j=2}^q$ has a path to $v_1$ that contains it, interpolating finite number of the vertices and the edges if necessary, we may assume that the diagram $\tilde{\delta k}$ defined by $\{v_j\}_{j=1}^p$ and $\{e_j\}_{j=1}^q$ are connected in $S\Omega$. Now, let $\mathcal{U}$ be the union of $\{\cup v_j\}_{j=1}^p$ and $\{\cup e_j\}_{j=1}^q$. Since all of the open sets are simply connected and $\tilde{\delta k}$ is acyclic, we can inductively confirm using the van Kampen’s theorem that $\mathcal{U}$ is simply connected. Therefore, the path $\gamma$ is contracted to the point $0_\Omega$. It proves the simply connectedness of $X_\Omega$. □

**Lemma 3.9.** The Riemann surface $X_\Omega$ constructed above is $\Omega$-endless.

**Proof.** Take an arbitrary $\Omega$-allowed path $\gamma$ and $\delta, L > 0$ so that $\gamma \in \Pi_\Omega^{\delta,L}$. Let $V^{\delta,L}_\Omega$ denote the set of vertices $v = ((\omega_1, \sigma_1), \cdots, (\omega_n, \sigma_n)) \in V_\Omega$ that satisfy

$$L^{\delta}(v) := L_n(v) + \sum_{j=2}^n (|\sigma_j| - 1)\delta \leq L$$

and set $E^{\delta,L}_\Omega := \{(v, v_\uparrow) \in E_\Omega | v \in V^{\delta,L}_\Omega\}$. Notice that $V^{\delta,L}_\Omega$ and $E^{\delta,L}_\Omega$ are finite. We set for $\varepsilon > 0$ and $v \in V^{\delta,L}_\Omega$

$$U^{\delta,L,\varepsilon}_v := \{\zeta \in U_v | \inf_{(v', v_\uparrow) \in E_\Omega} |\zeta - \omega(v')| \geq \delta, D^\zeta_v \subset U_{v_\uparrow} \cap D^{L-L^\delta(v)}_\omega(v),$$

where $D^\zeta := \{\zeta \in \mathbb{C} | |\zeta - \zeta'| \leq r\}$ for $\zeta \in \mathbb{C}, r > 0$. We also set for $\varepsilon > 0$ and $(v, v_\uparrow) \in E^{\delta,L}_\Omega$

$$U^{\delta,L,\varepsilon}_{v \to v_\uparrow} := \{\zeta \in U_{v \to v_\uparrow} | \min_{j=1,2} |\zeta - \tilde{\omega}_j| \geq \delta, \inf_{\zeta \in \omega_{v \to v_\uparrow}} |\zeta - \tilde{\zeta}| \leq \varepsilon\} \cap D^{L-L^\delta}_{\omega(v)}(v_\uparrow),$$

where $\tilde{\omega}_1 := \omega(v)$ and $\tilde{\omega}_2$ is the other endpoint of $\ell_{v \to v_\uparrow}$ if it exists and $\tilde{\omega}_2 := \omega(v)$ otherwise. Since $E^{\delta,L}_\Omega$ are finite set, we can take $\varepsilon > 0$ sufficiently small so that $D^\zeta_v \subset U_{v \to v_\uparrow}$ for all $\zeta \in U^{\delta,L,\varepsilon}_{v \to v_\uparrow}$ and $(v, v_\uparrow) \in E^{\delta,L}_\Omega$. We fix such a number $\varepsilon > 0$.

Now, let $I$ be the maximal interval such that the restriction of $\gamma$ to $I$ has a lift $\gamma'$ on $X_\Omega$. Obviously, $I \neq \emptyset$ and $I$ is open. Assume that $I = [0, a)$ for $a \in (0, 1]$. We take $b \in (0, a]$ so that $L(\gamma|_{[0,a)}) - L(\gamma|_{[a,1]}) < \varepsilon$. Then, notice that, since $\gamma \in \Pi_\Omega^{\delta,L}$ and $\gamma|_{[a,1]}$ has a lift on $X_\Omega$, $\gamma(b)$ is in $U^{\delta,L,\varepsilon}_v$ for $v \in V^{\delta,L}_\Omega$ or $U^{\delta,L,\varepsilon}_{e \to v}$ for $e \in E^{\delta,L}_\Omega$. Since $D^{e}_{\gamma(b)} \subset U_{v}$ (resp., $D^{e}_{\gamma(e)} \subset U_{v}$) when $\gamma(b) \in U^{\delta,L,\varepsilon}_v$ (resp., $\gamma(e) \in U^{\delta,L,\varepsilon}_{e \to v}$), we obtain a lift of $\gamma|_{[0,a]}$ by concatenating $\gamma|_{[0,a]}$ and $\gamma|_{[a,1]}$ in the coordinate. It contradicts the maximality of $I$, and hence, $I = [0, 1]$.

### 3.2 Proof of Theorem 3.2

We first show the following:

We fix such a number $\varepsilon > 0$. □
Lemma 3.10. For all \( \varepsilon > 0 \) and \( \zeta \in X_\Omega \), there exists an \( \Omega \)-allowed path \( \gamma \) such that \( L(\gamma) < L(\zeta) + \varepsilon \) and its lift \( \tilde{\gamma} \) on \( X_\Omega \) satisfies \( \tilde{\gamma}(0) = \tilde{\Omega} \) and \( \tilde{\gamma}(1) = \tilde{\zeta} \).

Proof. Let \( \zeta \in U_v \) for \( v = ((\omega_1, \sigma_1), \ldots, (\omega_n, \sigma_n)) \). We consider a polygonal curve \( P^0_\zeta \) obtained by connecting line segments \( [\omega_j, \omega_{j+1}] \) \( (j = 1, \ldots, n) \), where we set \( \omega_{n+1} := p_\Omega(\zeta) \) for the sake of notational simplicity. Now, collect all the points \( \omega_{j,k} \) on \( (\omega_j, \omega_{j+1}) \) such that \( (L_{j,k}, \omega) \in \overline{\Sigma}_\Omega \), where \( L_{j,k} := L_j(v) + |\omega_{j,k} - \omega_j| \). Since

\[
\overline{\Sigma}_\Omega \cap \{ \lambda \in \mathbb{R}_{\geq 0} \mid |\lambda| \leq L \} \times \mathbb{C} \text{ is written for each } L > 0 \text{ by the union of finite number of line segments of the form } \{ \lambda \in \mathbb{R}_{\geq 0} \mid L \leq \lambda \leq L \} \times \{ \omega \} \text{ (} L > 0, \omega \in \mathbb{C}, \text{)} \]

such points are finite. We order \( \omega_j \) and \( \omega_{j,k} \) so that \( L_j(v) \) and \( L_{j,k} \) increase along the order and denote the sequence by \( (\omega'_1, \omega'_2, \ldots, \omega'_n) \). We set \( L'_j := \sum_{i=1}^{j-1} |\omega'_{i+1} - \omega'_i| \). We extend \( v \) to \( v' = ((\omega'_1, \sigma'_1), \ldots, (\omega'_n, \sigma'_n)) \) by setting \( \sigma'_j = 1 \) (resp., \( \sigma'_j = -1 \)) when \( (\omega'_j, L'_j) = (\omega_{i,k}, L_{i,k}) \) for some \( i, k \) and \( \sigma_{i+1} \geq 1 \) (resp., \( \sigma_{i+1} \leq -1 \)). Then, in view of (3.2), we can take \( \delta > 0 \) so that

\[
\{ (L' + |\delta' - \omega'_j| + \delta, \omega'_j') \mid \omega'_j' \in (\omega'_j, \omega'_{j+1}) \} \cap \overline{\Sigma}_\Omega = \emptyset,
\]

\[
\{ (L'_j + \delta, \omega'_j) \mid 0 < |\omega'_j - \omega'_j'| < \delta \} \cap \overline{\Sigma}_\Omega = \emptyset
\]

hold for \( j = 1, \ldots, n' \). Let \( \omega'_{j,-} \) (resp., \( \omega'_{j,+} \)) be the intersection point of \( [\omega'_{j-1}, \omega'_j] \) (resp., \( [\omega'_j, \omega'_{j+1}] \)) and \( C'_{\omega_j} := \{ \omega' \in \mathbb{C} \mid |\omega'_j - \omega'_j'| = \varepsilon' \} \) for sufficiently small \( \varepsilon' > 0 \). We replace the part \( [\omega'_{j-1}, \omega'_j] \cup [\omega'_j, \omega'_{j+1}] \) of \( \ell \) with a path that goes anti-clockwise (resp., clockwise) along \( C'_{\omega_j} \) from \( \omega'_{j-} \) to \( \omega'_{j,+} \) and turns around \( \omega'_j \) (\(|\sigma'_j| - 1\)-times) when \( \sigma'_j \geq 1 \) (resp., when \( \sigma'_j \leq -1 \)). Let \( P^\varepsilon' \) denote a path obtained from \( P^0_\zeta \) by the modification. Then, \( P^\varepsilon' \) defines an \( \Omega \)-allowed path and its lift \( P^\varepsilon' \) on \( X_\Omega \) satisfies the conditions. Further, by taking \( \varepsilon' \) sufficiently small so that

\[
2\pi \varepsilon' \sum_{j=2}^{n'} |\sigma'_j| < \varepsilon,
\]

we find \( L(P^\varepsilon') < L(\zeta) + \varepsilon \). When \( \zeta \in \ell \) for an edge \( e = (v, v') \in E_\Omega \), we can construct such a path \( P^\varepsilon' \) in \( \Pi_\Omega \) by totally the same discussion.

Notice that, since the sequence \( v' \) in the proof of Lemma 3.10 is uniquely determined by \( \zeta \in X_\Omega \), the choice of the path \( P^\varepsilon' \) depends only on the radius \( \varepsilon' \) of the circles \( C'_{\omega'_j} \). Further, from the construction of the path \( P^\varepsilon' \), we can extend Lemma 3.10 as follows:

Lemma 3.11. For all \( \varepsilon > 0 \) and \( \zeta \in X_\Omega \), there exist a neighborhood \( U_{\zeta'} \) of \( \zeta \) and a continuous deformation \( Q^\varepsilon_\zeta \in \Pi_\Omega \) (\( \zeta' \in U_{\zeta'} \)) of the path \( P^\varepsilon' \) such that \( L(Q^\varepsilon_\zeta) < L(\zeta') + 2\varepsilon \) for each \( \zeta' \in U_{\zeta'} \) and the lift \( Q^\varepsilon_\zeta \) on \( X_\Omega \) satisfies \( Q^\varepsilon_\zeta(0) = 0 \) and \( Q^\varepsilon_\zeta(1) = \zeta' \).

Indeed, the deformation of \( P^\varepsilon' \) is concretely given as follows:

- When \( \zeta \in U_v \) for \( v \in V_\Omega \), taking a neighborhood \( U_{\zeta'} \subset U_v \) of \( \zeta \) sufficiently small, we find that the family of the paths \( P^\varepsilon' (\zeta' \in U_{\zeta'}) \) constructed in the proof of Lemma 3.10 gives such a deformation.
- When $\zeta \in \mathcal{L}$, for $e \in E$, we can take a neighborhood $U_{\zeta} \subset U_e$ of $\zeta$ so that $[\omega_{n',+}(\zeta'), p_{\Omega}(\zeta')] \subset U_e$ for all $\zeta' \in U_{\zeta}$, where $\omega_{n',+}(\zeta')$ is the intersection point of $[\omega_{n'}, p_{\Omega}(\zeta')]$ and $C_{\omega_{n'}}$. Define a deformation $Q_{\zeta,\zeta'}'$ by continuously varying the arc of $C_{\omega_{n'}}$ from $\omega_{n',-}(\zeta')$ to $\omega_{n',+}(\zeta')$ and the line segment $[\omega_{n',+}(\zeta'), p_{\Omega}(\zeta')]$ and fixing the other part of $P_{\zeta}'$. Then, shrinking $U_{\zeta}$ if necessary, we find that $Q_{\zeta,\zeta'}'$ satisfies $Q_{\zeta,\zeta'}' \in \Pi$ and $L(Q_{\zeta,\zeta'}') < L(\zeta') + 2\varepsilon$ for each $\zeta' \in U_{\zeta}$.

Beware that, when the edge $(v, v_{\uparrow})$ is the type i), $Q_{\zeta,\zeta'}'$ is different from $P_{\zeta}'$ for $\zeta \in \mathcal{L}_{v \rightarrow v_{\uparrow}}$ and $\zeta' \in U_{\zeta} \cap U_{v_{\uparrow}}$. On the other hand, $Q_{\zeta,\zeta'}' = P_{\zeta}'$ holds for $\zeta' \in U_{\zeta} \cap U_{v_{\uparrow}}$. When the edge $(v, v_{\uparrow})$ is the type ii) or iii), $Q_{\zeta,\zeta'}'$ is $P_{\zeta}'$ holds for $\zeta \in \mathcal{L}_{v \rightarrow v_{\uparrow}}$ and $\zeta' \in U_{\zeta}$.

Let $(X, p, 0)$ be an $\Omega$-endless Riemann surface. For each $\zeta \in X$, take $\gamma \in \Pi$ such that $\gamma(1) = \zeta$ and let $\gamma_{\zeta}$ be its lift on $X$. Then, define a map $q : X \Omega \rightarrow X$ by $q(\zeta) = \gamma_{\zeta}(1)$. We now show the well-definedness of $q$. For that purpose, it suffices to prove the following

**Proposition 3.12.** Let $\gamma_0, \gamma_1 \in \Pi$ such that $\gamma_0(1) = \gamma_1(1)$. Then, there exists a continuous family $(H_s)_{s \in [0, 1]}$ of $\Omega$-allowed paths satisfying the conditions

1. $H_s(0) = 0$ and $H_s(1) = \gamma_0(1)$ for all $s \in [0, 1]$,
2. $H_j = \gamma_j$ for $j = 0, 1$.

The proof of Proposition 3.12 is reduced to the following

**Lemma 3.13.** For each $\gamma \in \Pi$ and $\varepsilon' > 0$ sufficiently small, there exists a continuous family $(H_s)_{s \in [0, 1]}$ of $\Omega$-allowed paths satisfying the following conditions:
1. \( L(\tilde{H}_s) \leq L(\gamma|_{s}) \) and \( \tilde{H}_s(1) = \gamma(s) \) for all \( s \in [0, 1] \),

2. \( \tilde{H}_s = P_{\gamma|_{s}}^{\varepsilon'} \) for \( s = 0, 1 \).

Notice that, since \( \gamma(0) = 0 \), \( P_{\gamma|_{s}}^{\varepsilon'} \) is the constant map \( P_{\gamma|_{s}}^{\varepsilon'} = 0 \).

**Reduction of Proposition 3.12 to Lemma 3.13.** For each \( \gamma \in \Pi_{\Omega} \) and \( s \in (0, 1) \), define \( H_s \) using \( \tilde{H}_s \) constructed in Lemma 3.13 as follows:

\[
H_s(t) = \begin{cases} 
\tilde{H}_s(t/s) & \text{when } t \in [0, s], \\
\gamma(t) & \text{when } t \in [s, 1].
\end{cases}
\]

It extends continuously to \( s = 0 \) and gives a continuous family \( \{H_s\}_{s \in [0, 1]} \) of \( \Omega \)-allowed paths satisfying the assumption of Proposition 3.12.

Now, let \( \gamma_0 \) and \( \gamma_1 \) be the \( \Omega \)-allowed paths satisfying the assumption of Proposition 3.12. Applying the above discussion to each of \( \gamma_0 \) and \( \gamma_1 \), we obtain two families of \( \Omega \)-allowed paths connecting them to \( P_{\gamma|_{s}}^{\varepsilon'} \) and, concatenating the deformations at \( \gamma|_{s}^{\varepsilon'} \), we obtain a deformation \( \{H_s\}_{s \in [0, 1]} \) satisfying the conditions in Proposition 3.12.

**Proof of Lemma 3.13.** Take \( \delta, L > 0 \) so that \( \gamma \in \Pi_{\Omega}^{\delta, L} \). We first show the following:

\[
(3.3) \quad \text{When } \gamma(t_0) \in U_{(0,0)} \text{ for } t_0 \in (0, 1) \text{ and } v = ((0,0), (\omega_2, \sigma_2)), \text{ the following estimate holds for } t \in [t_0, 1]:
\]

\[
L(\gamma(t)) + \sqrt{|\omega_2|^2 + \delta^2} - |\omega_2| \leq L(\gamma|_{t_0}).
\]

Notice that, since \( \gamma \in \Pi_{\Omega}^{\delta, L} \), the length \( L(\gamma|_{t_0}) \) of \( \gamma|_{t_0} \) must be longer than that of the polygonal curve \( C \) obtained by concatenating the line segments \([0, \omega_2 + \delta e^{i \theta}]\) and \([\omega_2 + \delta e^{i \theta}, \gamma(t_0)]\), where \( \theta = \text{arg}(\omega_2) - \sigma_2 \pi/2 \). Then, we find that, for an arbitrary \( \varepsilon > 0 \), taking \( \varepsilon' > 0 \) sufficiently small, the path \( \tilde{\gamma}^{\varepsilon'} \) obtained by concatenating the paths \( P_{\gamma|_{s}}^{\varepsilon'} \) and \( \gamma|_{t_0} \) satisfies \( \tilde{\gamma}^{\varepsilon'} \in \Pi_{\Omega} \), \( \tilde{\gamma}^{\varepsilon'}(t) = \gamma(t) \) and \( L(\tilde{\gamma}^{\varepsilon'}|_{t_0}) \leq L(\gamma|_{t_0}) + \varepsilon \) for \( t \in [t_0, 1] \). Therefore, we have

\[
L(\gamma(t)) \leq L(\tilde{\gamma}^{\varepsilon'}|_{t_0}) \quad \text{for } t \in [t_0, 1]
\]

Since \( L(C) \geq \sqrt{|\omega_2|^2 + \delta^2} + |\gamma(t_0)| - \omega_2 | \), we find

\[
L(\gamma|_{t_0}) = L(\tilde{\gamma}^{\varepsilon'}|_{t_0}) + L(\gamma|_{t_0}) - L([0, \gamma(t_0)]) \geq L(\gamma(t)) + \sqrt{|\omega_2|^2 + \delta^2} - |\omega_2|
\]

holds for \( t \in [t_0, 1] \), and hence, we obtain (3.3).

Now, we shall construct \( \{H_s\}_{s \in [0, 1]} \). Let \( \varepsilon > 0 \) be given. We assign the path \( P_{\gamma|_{s}}^{\varepsilon'} \) \( (\varepsilon' > 0) \) to each \( t \in [0, 1] \) and take a neighborhood \( U_{\gamma|_{s}}^{(0)} \) of \( \gamma(t) \) and the deformation \( Q_{\gamma|_{s}}^{\varepsilon'}=(\varepsilon' \in U_{\gamma|_{s}}^{(0)} \) of \( P_{\gamma|_{s}}^{\varepsilon'} \) constructed in Lemma 3.11. Then, we can cover \([0, 1]\) by a finite number of intervals \( I_j = [a_j, b_j] \) \( (j = 1, 2, \cdots, k) \) satisfying the following conditions:

- The interior \( I_j \) of \( I_j \) satisfies \( I_{j_1} \cap I_{j_2} \neq \emptyset \) when \( |j_1 - j_2| \leq 1 \) and \( I_{j_1} \cap I_{j_2} = \emptyset \) otherwise.
There exists $t_j \in I_j$ such that $t_j < t_{j+1}$ for $j = 1, \cdots, k - 1$ and $\gamma(I_j) \subset U_{\epsilon}(t_j)$.

Notice that, since $U_{\epsilon}(t_j)$ is taken for each $t \in [0, 1]$ so that it is contained in one of the charts $U_v$ ($v \in V_\Omega$) or $U_e$ ($e \in E_\Omega$), one of the followings holds:

- $\gamma(t_j) \in U_v$, and $\gamma(I_j) \subset U_v$ ($v \in V_\Omega$).
- $\gamma(t_j) \in U_e$ and $\gamma(I_j) \subset U_e$ ($e \in E_\Omega$).

We set $\epsilon' = \min\{\epsilon'_{t_j} \mid \gamma(t_j) \notin U_{(0,0)}\}$. Then, $P^e_{\gamma(t_j)}$ and its deformation $Q^e_{\omega_{\gamma(t_j)}(t)}$ ($\zeta' \in U_{\gamma(t_j)}$) also satisfy the conditions in Lemma 3.10 and Lemma 3.11. Let $J_E \subset \{1, \cdots, k\}$ denote the set of suffixes satisfying the condition that there exists $e \in E_\Omega$ such that $\gamma(t_j) \in U_e$ and let $j_0$ be the minimum of $J_E$. Shrinking the neighborhood $U_{\epsilon}(t)$ for each $t \in [0, 1]$ at the first, we may assume without loss of generality that,

- $|\gamma(t) - \gamma(t_j)| \leq \epsilon$ for $t \in I_j$ and $j = 1, \cdots, k$,
- if $j, j + 1 \in J_E$, there exists an edge $e \in E_\Omega$ such that $\gamma(t_j), \gamma(t_{j+1}) \in U_e$.

Recall that, from the construction of $Q^e_{\omega_{\gamma(t)}}$,

$$Q^e_{\omega_{\gamma(t)}} = Q^e_{\gamma(t), \gamma(t)} \text{ for } t \in I_j \cap I_{j+1}$$

except for the cases where there exists an edge $e = (v, v_1) \in E_\Omega$ of the type i) such that

- $\gamma(t_j) \in U_v$ and $\gamma(t_{j+1}) \in U_{v_1}$,
- $\gamma(t_j) \in U_{v_1}$ and $\gamma(t_{j+1}) \in U_v$.

In the first case, the difference between $Q^e_{\omega_{\gamma(t)}}$ and $Q^e_{\gamma(t), \gamma(t)}$ is the part from $\omega^e(v_1)$ to $\gamma(t)$, where $\omega^e(v_1)$ is the intersection point of $C^e_{\omega(v_1)}$ and $[\omega(v_1), \gamma(t)]$. Let $e_i, i = 0, \cdots, m + 1$ be the points on the line segment $[\omega(v_1), \omega(v)]$ satisfying the conditions $(L_{e_i,i}, e_{e_i,i}) \in \gamma(t)$ and $L_{e_i,i} < L_{e,i+1}$, where $L_{e,i} := L(v_1) + |\omega(e_i) - \omega(v_1)|$. Then, the part of $Q^e_{\omega_{\gamma(t)}}$ from $\omega^e(v_1)$ to $\gamma(t)$ is given by concatenating the arcs of $C^e_{\omega(v_1)}$, $(i = 0, \cdots, m + 1)$, the intervals of the line segment $[\omega(v_1), \omega(v)]$ and $[\omega^e(v_1), \gamma(t)]$, where $\omega^e(v_1)$ is the intersection point of $C^e_{\omega(v_1)}$ and $[\omega(v_1), \gamma(t)]$. (See Figure 3(a).) On the other hand, $Q^e_{\gamma(t), \gamma(t)}$ goes directly from $\omega^e(v_1)$ to $\gamma(t)$. (See Figure 3(d).)

Now, let $\omega^e_i$ be the intersection point of $C^e_{\omega_{\gamma(t)}}$ and $[\omega^e(v_1), \omega^e(v)]$ that is the closer to $\omega^e(v)$ (resp. $\omega^e(v_1)$). While $t$ moves on $I_j \cap I_{j+1}$, we first deform the part of $Q^e_{\omega_{\gamma(t)}}$ from $\omega^e(v_1)$ to $\omega^e(v)$ to the line segment $[\omega^e(v_1), \omega^e(v)]$ by shrinking the part of $Q^e_{\omega_{\gamma(t)}}$ from $\omega^e_{i-}$ to $\omega^e_{i+}$ (resp. from $\omega^e_{i-}$ to $\omega^e_{i+}$) to the line segment $[\omega^e_i, \omega^e_i]$ (resp. $[\omega^e_i, \omega^e_i]$) for each $i$. (See Figure 3(b) and (c).) Then, further shrinking the polygonal line given by concatenating $[\omega^e(v_1), \omega^e(v)]$ and $[\omega^e(v), \gamma(t)]$ to the line segment $[\omega^e(v), \gamma(t)]$, we obtain a continuous family of $\Omega$-allowed paths $(H_\delta)_{\delta \in [\delta, t_{j+1}]}$ satisfying the following conditions:
\[ \tilde{H}_s = Q_{\tilde{\gamma}(t_j)}^{\varepsilon'}(s) \] when \( s \in [t_j, t_{j+1}] \setminus I_{j+1} \),
\[ \tilde{H}_s = Q_{\gamma^{\varepsilon'}(t_{j+1})}^{\varepsilon'}(s) \] when \( s \in [t_j, t_{j+1}] \setminus I_j \),
\[ L(\tilde{H}_s) \leq L(Q_{\tilde{\gamma}(t_j), \gamma^{\varepsilon'}(t_{j+1})}^{\varepsilon'}(s)) \] and \( \tilde{H}_s(1) = \gamma(s) \) when \( s \in I_j \cap I_{j+1} \).

Figure 4:

For the second case, we can also construct a continuous family of \( \Omega \)-allowed paths \( (\tilde{H}_s)_{s \in [t_j, t_{j+1}]} \) satisfying the first and the second conditions above and

\[ L(\tilde{H}_s) \leq L(Q_{\tilde{\gamma}(t_{j+1}), \gamma^{\varepsilon'}(t_{j+1})}^{\varepsilon'}(s)) \text{ and } \tilde{H}_s(1) = \gamma(s) \text{ when } s \in I_j \cap I_{j+1}. \]

Then, we can continuously extend \( \tilde{H}_s \) to \([0, 1]\) by interpolating it by \( Q_{\tilde{\gamma}(t_j), \gamma^{\varepsilon'}(t_j)}^{\varepsilon'}(s) \) so that it satisfies

\[ L(\tilde{H}_s) \leq \max_j \{ L(Q_{\tilde{\gamma}(t_j), \gamma^{\varepsilon'}(t_j)}^{\varepsilon'}(s)) \mid s \in I_j \} \text{ and } \tilde{H}_s(1) = \gamma(s) \text{ for all } s \in [0, 1]. \]

Since \( I_{j_0} \) is taken so that \( |\gamma(t) - \gamma(t_{j_0})| \leq \varepsilon \) holds on \( I_{j_0} \), applying (3.3) with \( t_0 = t_{j_0} \), we have the following estimates:

\[ L(\gamma(t)) + \sqrt{\omega_2^2 + \delta^2} - |\omega_2| - \varepsilon \leq L(\gamma(t)) \quad \text{for } t \in [a_{j_0}, 1]. \]

On the other hand, since \( \gamma(t) \in U_{(0, 0)} \) for \( t \in [0, a_{j_0}] \), we find \( L(Q_{\tilde{\gamma}(t_{j}), \gamma^{\varepsilon'}(t_{j})}^{\varepsilon'}(s)) = L(\gamma(t)) \) holds for \( t \in I_j \) and \( j < j_0 \) from the construction of \( Q_{\tilde{\gamma}(t_{j}), \gamma^{\varepsilon'}}(s) \). Therefore, taking \( \varepsilon > 0 \) sufficiently small so that

\[ 3\varepsilon \leq \sqrt{\omega_2^2 + \delta^2} - |\omega_2|, \]

we obtain the following estimates from Lemma 3.10 and (3.4):

\[ L(\tilde{H}_s) \leq L(\gamma(s)) \quad \text{for } s \in [0, 1]. \]

Finally, from the construction of \( \tilde{H}_s \), we find that \( \tilde{H}_s \) satisfies \( \tilde{H}_s = P_{\gamma^{\varepsilon'}(s)}^{\varepsilon'}(s) \) for \( s = 0, 1. \)
Since \( p_\Omega = p \circ q \) and \( p \) is isomorphic near \( 0 \), all the maps \( q : X_\Omega \to X \) must coincide near \( 0 \), and hence, uniqueness of \( q \) follows from the uniqueness of the analytical continuation of \( q \). Finally, \( X_\Omega \) is unique up to isomorphism because \( X_\Omega \) is an initial object in the category of \( \Omega \)-endless Riemann surfaces.

### 3.3 Supplement to the properties of \( X_\Omega \)

Let \( \mathcal{O}_X \) denote the sheaf of holomorphic functions on a Riemann surface \( X \) and consider the natural morphism \( p^*_\Omega : p_\Omega^{-1} \mathcal{O}_C \to \mathcal{O}_{X_\Omega} \) induced by \( p_\Omega : X_\Omega \to C \). Since \( X_\Omega \) is simply connected, we obtain the following:

**Proposition 3.14.** Let \( \hat{\varphi} \in \mathcal{O}_{C,0} \). Then the followings are equivalent:

1. \( \hat{\varphi} \in \mathcal{O}_{C,0} \) is \( \Omega \)-continuable,
2. \( p^*_\Omega \hat{\varphi} \in \mathcal{O}_{X_\Omega,0} \) can be analytically continued along any path on \( X_\Omega \),
3. \( p^*_\Omega \hat{\varphi} \in \mathcal{O}_{X_\Omega,0} \) can be extended to \( \Gamma(X_\Omega, \mathcal{O}_{X_\Omega}) \).

Therefore, we find \( p^*_\Omega : \hat{\mathcal{R}}_\Omega \sim \to \Gamma(X_\Omega, \mathcal{O}_{X_\Omega}) \).

**Notation 3.15.** For \( L, \delta > 0 \), we define compact subsets \( K^\delta_{\Omega,L} \) of \( X_\Omega \) by

\[
K^\delta_{\Omega,L} := \{ \zeta \in X_\Omega \mid \exists \gamma \in \Pi^\delta_{\Omega,L} \text{ such that } \zeta = \gamma(1) \}
\]

(with \( \Pi^\delta_{\Omega,L} \) defined by (2.8)).

Notice that \( X_\Omega \) is exhausted by \( (K^\delta_{\Omega,L})_{\delta,L>0} \). Therefore, the family of seminorms \( \| \cdot \|_{\delta,L} \) \((\delta, L > 0)\) defined by

\[
\| \hat{f} \|_{\delta,L} := \sup_{\zeta \in K^\delta_{\Omega,L}} |\hat{f}(\zeta)| \quad \text{for } \hat{f} \in \Gamma(X_\Omega, \mathcal{O}_{X_\Omega})
\]

induces a structure of Fréchet space on \( \Gamma(X_\Omega, \mathcal{O}_{X_\Omega}) \).

**Definition 3.16.** We introduce a structure of Fréchet space on \( \hat{\mathcal{R}}_\Omega \) by a family of seminorms \( \| \cdot \|_{\delta,L} \) \((\delta, L > 0)\) defined by

\[
\| \varphi \|_{\delta,L} := |\varphi_0| + \| p^*_\Omega \varphi \|_{\delta,L} \quad \text{for } \varphi \in \hat{\mathcal{R}}_\Omega,
\]

where \( \mathcal{B}(\tilde{\varphi}) = \varphi_0 \delta + \tilde{\varphi} \in \mathbb{C} \delta \oplus \hat{\mathcal{R}}_\Omega \).

Let \( \Omega' \) be a d.f.s. such that \( \Omega \subset \Omega' \). Since \( \Pi_{\Omega'} \subset \Pi_{\Omega} \), \( X_\Omega \) is \( \Omega' \)-endless. Therefore, Theorem 3.1 yields a morphism

\[
q : (X_{\Omega'}, p_{\Omega'}, 0_{\Omega'}) \to (X_\Omega, p_\Omega, 0_\Omega),
\]

which induces a morphism \( q^* : q^{-1} \mathcal{O}_{X_\Omega} \to \mathcal{O}_{X_{\Omega'}} \). Since \( q(K^\delta_{\Omega,L}) \subset K^\delta_{\Omega_{\Omega'}} \), we have

\[
\| q^* \hat{f} \|_{\delta,L} \leq \| \hat{f} \|_{\delta,L} \quad \text{for } \hat{f} \in \Gamma(X_\Omega, \mathcal{O}_{X_\Omega}),
\]

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and hence,
\[ \| \tilde{\varphi} \|_{\Omega}^{\delta,L} \leq \| \tilde{\varphi} \|_{\Omega}^{\delta,L} \text{ for } \tilde{\varphi} \in \tilde{R}_\Omega. \]

In view of Theorem 4.8 below, the product map
\[ \tilde{R}_\Omega \times \tilde{R}_\Omega' \to \tilde{R}_{\Omega \ast \Omega'} \]
is continuous and hence, when \( \Omega \ast \Omega = \Omega \), \( \tilde{R}_\Omega \) is a Fréchet algebra.

4 Estimates for the analytic continuation of iterated convolutions

In this section, our aim is to prove the following theorem, which is the analytical core of our study of the convolution product of endlessly continuable functions.

**Theorem 4.1.** Let \( \delta, L > 0 \) be reals. Then there exist \( c, \delta' > 0 \) such that, for every d.f.s. \( \Omega \) such that \( \Omega_{4\delta} = \emptyset \), for every integer \( n \geq 1 \) and for every \( \hat{f}_1, \ldots, \hat{f}_n \in \hat{R}_\Omega \), the function \( 1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n \) (which is known to belong to \( \hat{R}_{\Omega^n} \)) satisfies
\[ (4.1) \quad \| \hat{p}_{\Omega^n}^n (1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n) (\zeta) \| \leq \frac{c^n}{n!} \sup_{L_1 + \cdots + L_n = L} \| \hat{p}_{\Omega}^n \hat{f}_1 \|_{\Omega}^{\delta',L_1} \cdots \| \hat{p}_{\Omega}^n \hat{f}_n \|_{\Omega}^{\delta',L_n} \text{ for } \zeta \in K_{\Omega^n}. \]

Using the Cauchy inequality, the identity
\[ \frac{d}{d\zeta} (1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n) = \hat{f}_1 \ast \cdots \ast \hat{f}_n \]
and the inverse Borel transform, one easily deduce the following

**Corollary 4.2.** Let \( \delta, L > 0 \) be reals. Then there exist \( c, \delta', L' > 0 \) such that, for every d.f.s. \( \Omega \) such that \( \Omega_{4\delta} = \emptyset \), for every integer \( n \geq 1 \) and for every \( \hat{f}_1, \ldots, \hat{f}_n \in \hat{R}_\Omega \) without constant term, the formal series \( \hat{f}_1 \cdots \hat{f}_n \) (which is known to belong to \( \hat{R}_{\Omega^n} \)) satisfies
\[ \| \hat{f}_1 \cdots \hat{f}_n \|_{\Omega^n}^{\delta,L} \leq \frac{c^{n+1}}{n!} \| \hat{f}_1 \|_{\Omega}^{\delta',L'} \cdots \| \hat{f}_n \|_{\Omega}^{\delta',L'}. \]

In fact, one can cover the case \( \hat{f}_1 \in \hat{R}_{\Omega_1}, \ldots, \hat{f}_n \in \hat{R}_{\Omega_n} \) with different d.f.s.’s \( \Omega_1, \ldots, \Omega_n \) as well—see Theorem 4.8—, but we only give details for the case of one d.f.s. so as to lighten the presentation.

4.1 Notations and preliminaries

We fix an integer \( n \geq 1 \) and a d.f.s. \( \Omega \). In view of Remark 2.12 without loss of generality, we can suppose that \( \Omega \) coincides with its upper closure:
\[ (4.2) \quad \Omega = \tilde{\Omega}. \]

Let \( \rho > 0 \) be such that \( \Omega_{3\rho} = \emptyset \). We set
\[ U := \{ \zeta \in \mathbb{C} \mid |\zeta| < 3\rho \}. \]
For each \( \zeta \in U \), the path \( \gamma_\zeta : t \in [0, 1] \mapsto t \zeta \) is \( \Omega \)-allowed and hence has a lift \( \gamma_{\zeta} \) on \( X_\Omega \) starting at \( \Omega \). Then \( \mathcal{L}(\zeta) := \gamma_{\zeta}(1) \) defines a holomorphic function on \( U \) and induces an isomorphism
\[
\mathcal{L} : U \xrightarrow{\sim} U, \quad \text{where } U := \mathcal{L}(U) \subset X_\Omega,
\]
such that \( p_\Omega \circ \mathcal{L} = \text{Id} \).

Let us denote by \( \Delta_n \) the \( n \)-dimensional simplex
\[
\Delta_n := \{ (s_1, \ldots, s_n) \in \mathbb{R}^{n} \geq 0 \mid s_1 + \cdots + s_n \leq 1 \}
\]
with the standard orientation, and by \([\Delta_n] \in \mathcal{E}_n(\mathbb{R}^n)\) the corresponding integration current. For \( \zeta \in U \), we define a map \( \tilde{\mathcal{G}}(\zeta) \) on a neighbourhood of \( \Delta_n \) in \( \mathbb{R}^n \) by
\[
\tilde{\mathcal{G}}(\zeta) : \bar{s} = (s_1, \ldots, s_n) \mapsto \tilde{\mathcal{G}}(\zeta, \bar{s}) := (\mathcal{L}(s_1 \zeta), \ldots, \mathcal{L}(s_n \zeta)) \in U^n \subset X^n_\Omega
\]
and denote by \( \tilde{\mathcal{G}}(\zeta)_#|\Delta_n| \in \mathcal{E}_n(X^n_\Omega) \) the push-forward of \([\Delta_n]\) by \( \tilde{\mathcal{G}}(\zeta) \). (See [Sau15] for the notations and notions related to integration currents.)

As in [Sau15], our starting point will be

**Lemma 4.3.** Let \( \hat{f}_1, \ldots, \hat{f}_n \in \hat{\mathbb{R}}_\Omega \) and
\[
\beta := (p_\Omega \hat{f}_1)(\zeta_1) \cdots (p_\Omega \hat{f}_n)(\zeta_n) \, d\zeta_1 \wedge \cdots \wedge d\zeta_n,
\]
where we denote by \( d\zeta_1 \wedge \cdots \wedge d\zeta_n \) the pullback by \( p_\Omega^n : X^n_\Omega \to \mathbb{C}^n \) of the \( n \)-form \( d\zeta_1 \wedge \cdots \wedge d\zeta_n \).

Then
\[
1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n(\zeta) = \tilde{\mathcal{G}}(\zeta)_#|\Delta_n|(\beta) \quad \text{for } \zeta \in U.
\]

**Proof.** This is just another way of writing the formula
\[
1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n(\zeta) = \zeta^n \int_{\Delta_n} \hat{f}_1(\zeta s_1) \cdots \hat{f}_n(\zeta s_n) \, ds_1 \cdots ds_n.
\]
See [Sau15] for the details. \( \square \)

**Notation 4.4.** We set
\[
\mathcal{N}(\zeta) := \{ (\zeta_1, \ldots, \zeta_n) \in X^n_\Omega \mid p_\Omega(\zeta_1) + \cdots + p_\Omega(\zeta_n) = \zeta \} \quad \text{for } \zeta \in \mathbb{C},
\]
\[
\mathcal{N}_j := \{ (\zeta_1, \ldots, \zeta_n) \in X^n_\Omega \mid \zeta_j = 0_\Omega \} \quad \text{for } 1 \leq j \leq n.
\]

### 4.2 \( \gamma \)-adapted deformations of the identity

Let us consider a path \( \gamma : [0, 1] \to \mathbb{C} \) in \( \Pi_{\Omega^n} \) for which there exists \( a \in (0, 1) \) such that
\[
\gamma(t) = \frac{a}{t} \zeta(a) \quad \text{for } t \in [0, a], \quad |\zeta(a)| = \rho, \quad \gamma|_{[a, 1]} \text{ is } C^1.
\]

We now introduce the notion of \( \gamma \)-adapted deformation of the identity, which is a slight generalization of the \( \gamma \)-adapted origin-fixing isotopies which appear in [Sau15, Def. 5.1].
Definition 4.5. A $\gamma$-adapted deformation of the identity is a family $(\Psi_t)_{t \in [a,1]}$ of maps

$$\Psi_t : V \rightarrow X^n, \quad t \in [a,1],$$

where $V := \mathcal{G}(\gamma(a))(\Delta_n) \subset X^n_{\Omega}$, such that $\Psi_a = \text{Id}$, the map $(t, \zeta) \in [a,1] \times V \mapsto \Psi_t(\zeta) \in X^n_{\Omega}$ is locally Lipschitz, and for any $t \in [a,1]$ and $j = 1, \ldots, n$,

$$(4.8) \quad \Psi_t(V \cap N(\gamma(a))) \subset N(\gamma(t)), \quad \Psi_t(V \cap N_j) \subset N_j$$

(with the notations (4.5)–(4.6)).

Let $\gamma$ denote the lift of $\gamma$ in $X_{\Omega}$ starting at $\Omega_{\gamma}$. The analytical continuation along $\gamma$ of a convolution product can be obtained as follows:

Proposition 4.6 ([Sau15]). If $(\Psi_t)_{t \in [a,1]}$ is a $\gamma$-adapted deformation of the identity, then

$$(4.9) \quad \rho_t^\ast (1 * \hat{f}_1 * \cdots * \hat{f}_n)(\gamma(t)) = \left( \Psi_t \circ \mathcal{G}(\gamma(a)) \right)(\ast_t^{\#}[\Delta_n])(\beta) \quad \text{for } t \in [a,1]$$

for any $\hat{f}_1, \ldots, \hat{f}_n \in \mathcal{R}_{\Omega}$, with $\beta$ as in Lemma 4.3.

Proof. See the proof of [Sau15] Prop. 5.2. □

Note that the right-hand side of (4.9) must be interpreted as

$$(4.10) \quad \int_{\Delta_n} \left( \rho_t^\ast \hat{f}_1 \right)(\zeta^t_1) \cdots \left( \rho_t^\ast \hat{f}_n \right)(\zeta^t_n) \det \left[ \frac{\partial \zeta^t_i}{\partial s_j} \right]_{1 \leq i,j \leq n} ds_1 \cdots ds_n$$

with the notation

$$(4.11) \quad (\zeta^t_1, \ldots, \zeta^t_n) := \Psi_t \circ \mathcal{G}(\gamma(a)), \quad \zeta^t_i := \rho_t^\ast \zeta^t_i \quad \text{for } 1 \leq i \leq n$$

(each function $\zeta^t_i$ is Lipschitz on $\Delta_n$ and Rademacher’s theorem ensures that it is differentiable almost everywhere on $\Delta_n$, with bounded partial derivatives).

The following is the key estimate:

Theorem 4.7. Let $\delta \in (0,\rho)$ and $L > 0$. Let $\gamma \in \Pi^{\delta,L}_{\Omega\times\Omega}$ satisfy (4.7) and let

$$(4.12) \quad \delta^\ast := \rho e^{-2\sqrt{2\delta^{-1}L(\gamma|_{(a,1)}),} \quad c(t) := \rho e^{3\delta^{-1}L(\gamma|_{(a,1)})} \quad \text{for } t \in [a,1].$$

Then there exists a $\gamma$-adapted deformation of the identity $(\Psi_t)_{t \in [a,1]}$ such that

$$(4.13) \quad \Psi_t \circ \mathcal{G}(\gamma(a))(\Delta_n) \subset \bigcup_{L_1+\cdots+L_n=L(\gamma|_{(a,1)})} K^{\delta^\ast,L_1}_{\Omega} \times \cdots \times K^{\delta^\ast,L_n}_{\Omega} \quad \text{for } t \in [a,1].$$

Further, with the notation (4.11), the partial derivatives $\partial \zeta^t_i / \partial s_j$ satisfy

$$(4.14) \quad \left| \det \left[ \frac{\partial \zeta^t_i}{\partial s_j} \right]_{1 \leq i,j \leq n} \right| \leq (c(t))^n \quad \text{a.e. on } \Delta_n$$

for each $t \in [a,1]$.  

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Proof that Theorem 4.7 implies Theorem 4.1. Let \( \delta, L > 0 \). We will show that (4.1) holds with
\[
\delta' := \min \{ \delta, \rho e^{-4\sqrt{2}(1+\delta^{-1}L)} \}, \quad c := \max \{ 2\rho, \rho e^{6(1+\delta^{-1}L)} \}, \quad \text{where} \quad \rho := \frac{4}{3}\delta.
\]

Let \( \Omega \) be a d.f.s. such that \( \Omega_{4\delta} = \emptyset \). Without loss of generality we may suppose that \( \Omega = \tilde{\Omega} \).

In view of formula (4.4), the inequality (4.1) holds for \( \zeta \in K_{\Omega}^{\delta,L} \cap \mathcal{L} \), where \( \mathcal{L} \) is defined by (4.7), because the Lebesgue measure of \( \Delta_n \) is \( 1/n! \).

Let \( \zeta \in K_{\Omega}^{\delta,L} \setminus \mathcal{L} \). We can write \( \zeta = \gamma(1) \) with \( \gamma \in \Pi_{\Omega}^{\delta,\infty} \), assuming without loss of generality that the first two conditions in (4.7) hold. If the third condition in (4.7) does not hold, i.e. if \( \gamma_{[a,1]} \) is not \( C^1 \), then we use a sequence of paths \( \gamma_k \in \Pi_{\Omega}^{\delta/2,\infty} \) such that \( \gamma_k|[0,a] = \gamma|[0,a] \), \( \gamma_k(1) = \gamma(1) \), \( \gamma_k|[a,1] \) is \( C^1 \) and \( \sup_{t \in [a,1]} |\gamma(t) - \gamma_k(t)| \to 0 \) as \( k \to \infty \); for \( k \) large enough one has \( \gamma_k(1) = \zeta \), thus one then can replace \( \gamma \) by \( \gamma_k \). Hence we can assume that (4.7) holds.

Let \( \tilde{(\mathcal{P}_t)}_{t \in [a,1]} \) denote the \( \gamma \)-adapted deformation of the identity provided by Theorem 4.7, possibly with \( (\delta, L) \) replaced by \( (\delta/2, L + \delta) \). Proposition 4.6 shows that, for \( \hat{f}_1, \ldots, \hat{f}_n \in \hat{\mathcal{P}}_{\Omega} \), \( p_{\Omega}^{n}(1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n)(\zeta) \) can be written as (4.10) with \( t = 1 \), and (4.13)–(4.14) then show that (4.1) holds because \( \delta^* \geq \delta' \) and \( c(1) \leq c \). Therefore, (4.1) holds on \( K_{\Omega}^{\delta,L} \setminus \mathcal{L} \) too. \( \square \)

In fact, in view of the proof of Theorem 4.7 given below, one can give the following generalization of Theorem 4.1:

**Theorem 4.8.** Let \( \delta, L \) be positive real numbers. Then there exist positive constants \( c \) and \( \delta' \) such that, for every integer \( n \geq 1 \) and for all d.f.s. \( \Omega_1, \ldots, \Omega_n \) with \( \Omega_{j\delta} = \emptyset \) \( (j = 1, \ldots, n) \) and \( \hat{f}_1, \ldots, \hat{f}_n \in \hat{\mathcal{P}}_{\Omega} \), the function \( 1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n \) belongs to \( \hat{\mathcal{P}}_{\Omega} \), where \( \Omega := \Omega_1 \ast \cdots \ast \Omega_n \), and satisfies
\[
|p_{\Omega}^{n}(1 \ast \hat{f}_1 \ast \cdots \ast \hat{f}_n)(\zeta)| \leq \frac{C^n}{n!} \sup_{L_1 + \cdots + L_n = L} \| p_{\Omega}^{*} \hat{f}_1 \|_{\Omega_1}^{\delta_{L_1}} \cdots \| p_{\Omega_1}^{*} \hat{f}_n \|_{\Omega_n}^{\delta_{L_n}} \quad \text{for} \quad \zeta \in K_{\Omega}^{\delta,L}.
\]

### 4.3 Proof of Theorem 4.7

We suppose that we are given \( n \geq 1 \), \( \rho > 0 \), a d.f.s. \( \Omega \) such that \( \Omega = \tilde{\Omega} \) and \( \Omega_{2\rho} = \emptyset \), and \( \gamma \in \Pi_{\Omega}^{\delta,\infty} \) satisfying (4.7) with \( \delta \in (0, \rho) \) and \( L > 0 \).

We set \( \tilde{\gamma}(t) := (L(\gamma_{[t]}), \gamma(t)) \) and define functions
\[
\eta : \mathbb{R} \times \mathbb{C} \to \mathbb{R}_{\geq 0}, \quad D : [a, 1] \times (\mathbb{R} \times \mathbb{C})^n \to \mathbb{R}_{\geq 0}
\]
by the formulas
\[
\eta(v) := \text{dist} (v, \{(0,0) \} \cup \mathcal{S}_{\Omega}), \quad D(t, \bar{v}) := \eta(v_1) + \cdots + \eta(v_n) + |\tilde{\gamma}(t) - (v_1 + \cdots + v_n)|,
\]
where \(| \cdot |\) is the Euclidean norm in \( \mathbb{R} \times \mathbb{C} \simeq \mathbb{R}^3 \). The assumptions \( \Omega = \tilde{\Omega} \) and \( \gamma \in \Pi_{\Omega}^{\delta,\infty} \) yield

**Lemma 4.9.** The function \( D \) satisfies
\[
D \geq \delta \quad \text{on} \quad [a, 1] \times (\mathbb{R} \times \mathbb{C})^n.
\]
We construct a \( \gamma_t \) by the formulas
\[
\eta(v_j) = |v_j - u_j|, \\
\text{and let } u := u_1 + \cdots + u_n. 
\]
Either all of the \( u_j \)'s equal \((0,0)\), in which case \( u = (0,0) \) too, or \( u = (\lambda, \omega) \) is a non-trivial sum of at most \( n \) points of the form \( u_j = (\lambda_j, \omega_j) \in \mathcal{S}^n_{\Omega} \), in which case we have in fact \( \omega_j \in \Omega_{\lambda_j} \) because of Lemma 2.4 and the assumption \( \hat{\Omega} = \Omega \), hence \( 2.13 \) then yields \( \omega \in \Omega_{\lambda} \). We thus find
\[
(4.18) \quad D(t, \bar{v}) = |v_1 - u_1| + \cdots + |v_n - u_n| + |\gamma(t) - (v_1 + \cdots + v_n)| \geq |\bar{\gamma}(t) - u| 
\]
with \( u \in \{(0,0)\} \cup \mathcal{S}_{\Omega^n} \).

If \( u = (0,0) \), then \( D(t, \bar{v}) \geq |\gamma(t)| \geq L|\gamma| \geq \rho \geq \delta \) because \( t \geq a \).

Otherwise, \( u \in \mathcal{S}_{\Omega^n} \) and (4.18) shows that \( D(t, \bar{v}) \geq \delta \) because \( \gamma \in \Pi_{\Omega^n}^{L,\delta} \).

Since \( D \) never vanishes, we can define a non-autonomous vector field
\[
(t, \bar{v}) \in [a,1] \times (\mathbb{R} \times \mathbb{C})^n \mapsto \bar{X}(t, \bar{v}) \in T_{\bar{v}}((\mathbb{R} \times \mathbb{C})^n) \simeq (\mathbb{R} \times \mathbb{C})^n
\]
bys the formulas
\[
(4.19) \quad \bar{X}(t, \bar{v}) = \begin{cases} 
X_1(t, \bar{v}) := \frac{\eta(v_1)}{D(t, \bar{v})} \gamma'(t) \\
\vdots \\
X_n(t, \bar{v}) := \frac{\eta(v_n)}{D(t, \bar{v})} \gamma'(t) 
\end{cases}
\]
Note that \( \bar{\gamma}'(t) = (|\gamma'(t)|, \gamma'(t)) \).

The functions \( X_j : [a,1] \times (\mathbb{R} \times \mathbb{C})^n \rightarrow \mathbb{R} \times \mathbb{C} \) are locally Lipschitz, thus we can apply the Cauchy-Lipschitz theorem on the existence and uniqueness of solutions to differential equations and get a locally Lipschitz flow map
\[
(4.20) \quad (t^*, t, \bar{v}) \in [a,1] \times [a,1] \times (\mathbb{R} \times \mathbb{C})^n \mapsto \Phi^{t-t^*}_{t^*}(\bar{v}) \in (\mathbb{R} \times \mathbb{C})^n
\]
(value at time \( t \) of the unique maximal solution to \( d\bar{v}/dt = \bar{X}(t, \bar{v}) \)) whose value at time \( t^* \) is \( \bar{v} \).

We construct a \( \gamma \)-adapted deformation of the identity out of the flow map as follows:

**Proposition 4.10.** Let \( \bar{\zeta} = (\mathcal{L}(\zeta_1), \ldots, \mathcal{L}(\zeta_n)) \in \dot{\mathcal{L}}^n \), i.e. \( \zeta_j = s_j \gamma(a) \) with \( (s_1, \ldots, s_n) \in \Delta_n \).

We define \( \bar{v} := (|\zeta_1|, \zeta_1), \ldots, (|\zeta_n|, \zeta_n) \in (\mathbb{R} \times \mathbb{C})^n \) and \( \Gamma = (\bar{\gamma}_1, \ldots, \bar{\gamma}_n) : [0,1] \rightarrow (\mathbb{R} \times \mathbb{C})^n \) by
\[
t \in [0,a] \Rightarrow \Gamma(t) := (\frac{t}{a}(\zeta_1, \zeta_1), \ldots, \frac{t}{a}(\zeta_n, \zeta_n)), \\
t \in [a,1] \Rightarrow \Gamma(t) := \Phi^{a-t}_{t^*}(\bar{v}).
\]

Then, for each \( j \in \{1, \ldots, n\} \), \( \bar{\gamma}_j \) is a path \([0,1] \rightarrow \mathbb{R} \times \mathbb{C} \) whose \( \mathbb{C} \)-projection \( \gamma_j \) belongs to \( \Pi_{\Omega} \), and the formula
\[
(4.21) \quad \Psi_t(\bar{\zeta}) := (\bar{\gamma}_1(t), \ldots, \bar{\gamma}_n(t)) \in X^n_{\Pi} \textrm{ for } t \in [a,1].
\]
defines a \( \gamma \)-adapted deformation of the identity.
Proof. We first prove that $\gamma_1, \ldots, \gamma_n \in \Pi_\Omega$. In view of (4.19), we just need to check that, for each $j \in \{1, \ldots, n\}$, the path $\tilde{\gamma}_j = (\lambda_j, \gamma_j)$ satisfies

$$\tilde{\gamma}_j(t) \in \mathcal{M}_\Omega$$

and $d\lambda_j/dt = |d\gamma_j/dt|$. Since $\zeta_j \in U$ and $\gamma_j(t) = \zeta_j$ for $t \in [0, a]$, the property (4.22) holds for $t \in [0, a]$. For $t \in [a, 1]$, the second property in (4.22) follows from the fact that the $\mathbb{R}$-projection of $X_j(t, \vec{v}) \in \mathbb{R} \times \mathbb{C}$ coincides with the modulus of its $\mathbb{C}$-projection. Since $(\tilde{\gamma}_1(t), \ldots, \tilde{\gamma}_n(t)) = \Phi^{a,t}(\tilde{\gamma}_1(a), \ldots, \tilde{\gamma}_n(a))$ and the first property in (4.22) holds at $t = a$, the first property in (4.22) for $t \in [a, 1]$ is a consequence of the inclusion

$$(4.23) \quad \Phi^{a,t}(\mathcal{M}_\Omega^n) \subset \mathcal{M}_\Omega^n,$$

which can itself be checked as follows: suppose $\vec{v}^* \in (\mathbb{R} \times \mathbb{C})^n \setminus \mathcal{M}_\Omega^n$, then it has at least one component $v_j^*$ in $\mathcal{S}_\Omega$ and, in view of the form of the vector field (4.19), the submanifold $\{v \in (\mathbb{R} \times \mathbb{C})^n \mid v_j = v_j^*\}$ is invariant by the maps $\Phi^{1,t}$ (because $\eta(v_j) = 0$ implies that $X_j = 0$ on this submanifold), in particular $\Phi^{1,a}((\mathbb{R} \times \mathbb{C})^n \setminus \mathcal{M}_\Omega^n) \subset (\mathbb{R} \times \mathbb{C})^n \setminus \mathcal{M}_\Omega^n$, whence (4.23) follows because $\Phi^{a,t}$ and $\Phi^{t,a}$ are mutually inverse bijections.

Therefore the paths $\gamma_1, \ldots, \gamma_n$ are $\Omega$-allowed and have lifts in $X_\Omega$ starting at $Q_\Omega$, which allow us to define the maps $\Psi_t$ by (4.21) on $\mathcal{V}$. We now prove that $(\Psi_t)_{t \in [a, 1]}$ is a $\gamma$-adapted deformation of the identity. The map $(t, \vec{v}) \mapsto \Psi_t(\vec{v})$ is locally Lipschitz because the flow map (4.20) is locally Lipschitz, and $\Psi_a = \text{Id}$ because $\Phi^{a,a}$ is the identity map of $(\mathbb{R} \times \mathbb{C})^n$; hence, we just need to prove (4.8).

We set

$$\tilde{N}(w) := \{(v_1, \ldots, v_n) \in (\mathbb{R} \times \mathbb{C})^n \mid v_1 + \cdots + v_n = w\} \quad \text{for } w \in \mathbb{R} \times \mathbb{C},$$

$$\tilde{N}_j := \{(v_1, \ldots, v_n) \in (\mathbb{R} \times \mathbb{C})^n \mid v_j = (0, 0)\} \quad \text{for } 1 \leq j \leq n.$$

Let $j \in \{1, \ldots, n\}$. The second part of (4.8) follows from the inclusion

$$\Phi^{a,t}(\tilde{N}_j) \subset \tilde{N}_j \quad \text{for } t \in [a, 1],$$

which stems from the fact that the $j$th component of the vector field (4.19) vanishes on $\tilde{N}_j$ (because $\gamma_j((0, 0)) = 0$).

Since $\zeta_1 + \cdots + \zeta_n = \gamma(a) \Rightarrow |\zeta_1| + \cdots + |\zeta_n| = |\gamma(a)|$ for any $(\zeta_1, \ldots, \zeta_n) \in \mathcal{V}$, the first part of (4.8) follows from the inclusion

$$\Phi^{a,t}(\tilde{N}(\tilde{\gamma}(a))) \subset \tilde{N}(\tilde{\gamma}(t)) \quad \text{for } t \in [a, 1],$$

which can be itself checked as follows: consider first an arbitrary initial condition $\vec{v} \in (\mathbb{R} \times \mathbb{C})^n$ and the corresponding solution $\vec{v}(t) := \Phi^{a,t}(\vec{v})$, and let $v_0(t) := v_1(t) + \cdots + v_n(t)$; then (4.19) shows that

$$\frac{d}{dt}(\tilde{\gamma}(t) - v_0(t)) = \frac{|\gamma(t) - v_0(t)|}{D(t, \vec{v}(t))} |\gamma(t)|,$$

hence the Lipschitz function $h(t) := |\gamma(t) - v_0(t)|$ has an almost everywhere defined derivative which satisfies $|h'(t)| \leq \frac{1}{D(t, \vec{v}(t))} |\gamma(t)| h(t)$, which is $\leq \delta^{-1} \sqrt{2} |\gamma(t)| h(t)$ by (4.17), whence

$$|\gamma(t) - v_0(t)| \leq |\gamma(a) - v_0(a)| \exp \left(\delta^{-1} \sqrt{2} L(\gamma)_{a,a} \right).$$
for all $t$; now, if $\tilde{v} \in \tilde{N}(\tilde{\gamma}(a))$, we find $v_0(a) = \tilde{\gamma}(a)$, whence $v_0(t) = \tilde{\gamma}(t)$ for all $t$. \qed

We now show that $\gamma$-adapted deformation of the identity that we have constructed in Proposition 4.10 meets the requirements of Theorem 4.7.

In view of (2.7)–(2.8) and (3.5), the inclusion (4.13) follows from Lemma 4.11.

**Lemma 4.11.** Let $\hat{\mathcal{V}} := \{ (s_1, \ldots, s_n) \mid (s_1, \ldots, s_n) \in \Delta_n \} \subset (\mathbb{R} \times \mathbb{C})^n$. Then

\begin{align}
\Phi^{a,t}(\hat{\mathcal{V}}) \subset \bigcup_{L_1+\cdots+L_n=L(\gamma(t))} \mathcal{M}^{L_1,\delta^*} \times \cdots \times \mathcal{M}^{L_n,\delta^*}
\end{align}

for all $t \in [a, b]$, with $\delta^*$ as in (4.12).

**Proof of Lemma 4.11.** Let us consider an initial condition $\tilde{v} \in \tilde{\mathcal{V}}$ and the corresponding solution $\bar{v}(t) := \Phi^{a,t}(\tilde{v})$, whose components we write as $v_j(t) = (\lambda_j(t), \zeta_j(t))$ for $j = 1, \ldots, n$. We also have $v_j(a) = s_j \tilde{\gamma}(a)$ for some $(s_1, \ldots, s_n) \in \Delta_n$, whence $\lambda_1(a) + \cdots + \lambda_n(a) = \rho$ and $|v_j(a)| = \rho$ for $j = 1, \ldots, n$.

We first notice that

\begin{align}
\sum_{j=1}^n |\lambda_j'(t)| = \sum_{j=1}^n \frac{\eta(v_j(t))}{D(t, \bar{v}(t))} |\gamma'(t)| \leq |\gamma'(t)|,
\end{align}

hence $\lambda_1(t) + \cdots + \lambda_n(t) \leq \lambda_1(a) + \cdots + \lambda_n(a) + \int_a^t |\gamma'| \leq L(\gamma(t))$. Therefore, we just need to show that

\begin{align}
\text{dist} (v_j(t), \mathcal{S}_\Omega) \geq \delta^* \quad \text{for } j = 1, \ldots, n.
\end{align}

Let $j \in \{1, \ldots, n\}$. Since $\eta$ is 1-Lipschitz, we can define a Lipschitz function on $[a, b]$ by the formula $h_j(t) := \eta(v_j(t))$, and its almost everywhere defined derivative satisfies

\begin{align}
|h_j'(t)| \leq |v_j'(t)| = \frac{h_j(t)}{D(t, \bar{v}(t))} |\gamma'(t)| \leq g(t)h_j(t), \quad \text{where } g(t) := \delta^{-1}\sqrt{2} |\gamma'(t)|.
\end{align}

Since $\int_a^t g(\tau) \text{d}\tau = \delta^{-1}\sqrt{2} L(\gamma|_{[a,b]})$, we deduce that

\begin{align}
\eta(v_j(t)) e^{-\delta^{-1}\sqrt{2} L(\gamma|_{[a,b]})} \leq \eta(v_j(t)) \leq \eta(v_j(a)) e^{\delta^{-1}\sqrt{2} L(\gamma|_{[a,b]})} \quad \text{for all } t \in [a, b].
\end{align}

We conclude by distinguishing two cases.

Suppose first that $\eta(v_j(a)) \geq \rho e^{-\sqrt{T} \delta^{-1} L(\gamma|_{[a,b]})}$. Then the first inequality in (4.26) yields $\eta(v_j(t)) \geq \delta^*$, and since dist $(v_j(t), \mathcal{S}_\Omega) \geq \eta(v_j(t))$ we get (4.25).

Suppose now that $\eta(v_j(a)) < \rho e^{-\sqrt{T} \delta^{-1} L(\gamma|_{[a,b]})}$. Then the second inequality in (4.26) yields $\eta(v_j(t)) < \rho$ for all $t \in [a, b]$. This implies that $v_j([a, b]) \subset B := \{ v \in \mathbb{R} \times \mathbb{C} \mid |v| < 3\rho/2 \}$; indeed, if not, since $v_j(a) \in B$, there would exist $t' \in (a, b]$ such that $v_j(t') \in \partial B$, but using $\Omega_{3\rho} = 0$ it is easy to check that $v \in \overline{B} \Rightarrow \text{dist}(v, \mathcal{S}_\Omega) \geq 3\rho/2$.

hence we would have $\text{dist}(v_j(t'), \mathcal{S}_\Omega) \geq 3\rho/2 > \eta(v_j(t'))$, whence $\eta(v_j(t')) = \text{dist}(v_j(t'), (0,0)) = 3\rho/2$, which is a contradiction. Therefore, for each $t$, $v_j(t) \in B$, whence $\text{dist}(v_j(t), \mathcal{S}_\Omega) \geq 3\rho/2 > \delta^*$ and we are done. \qed

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Lemma 4.12. For any \( t \in [a, 1] \) and \( \bar{u}, \bar{v} \in (\mathbb{R} \times \mathbb{C})^n \), the vector field \((4.19)\) satisfies
\[
(4.27) \quad \sum_{j=1}^n |X_j(t, \bar{u}) - X_j(t, \bar{v})| \leq \frac{3 |\tilde{\gamma}(t)|}{D(t, \bar{u})} \sum_{j=1}^n |u_j - v_j|.
\]

Proof of Lemma 4.12. We rewrite \( X_j(t, \bar{u}) - X_j(t, \bar{v}) \) as follows:
\[
X_j(t, \bar{u}) - X_j(t, \bar{v}) = \left( \eta(u_j) - \eta(v_j) + (D(t, \bar{v}) - D(t, \bar{u})) \frac{\eta(v_j)}{D(t, \bar{v})} \right) \frac{\tilde{\gamma}(t)}{D(t, \bar{u})}.
\]
Since \(|\eta(u_j) - \eta(v_j)| \leq |u_j - v_j|\) holds for \( j = 1, \ldots, n \), we have
\[
|D(t, \bar{u}) - D(t, \bar{v})| \leq \sum_{j=1}^n |\eta(u_j) - \eta(v_j)| + \left| \tilde{\gamma}(t) - \sum_{j=1}^n u_j \right| - \left| \tilde{\gamma}(t) - \sum_{j=1}^n v_j \right| \\
\leq 2 \sum_{j=1}^n |u_j - v_j|.
\]

Then, summing up \( |X_j(t, \bar{u}) - X_j(t, \bar{v})| \) in \( j \), we obtain \( (4.27) \) from the inequality \( \sum_{j=1}^n \eta(v_j) \leq D(t, \bar{u}) \).

We conclude by deriving the inequality \((4.14)\) from Lemma 4.12. We use the notation \((4.11)\) to define \( \zeta_1', \ldots, \zeta_n' : \Delta_n \to \mathbb{C} \), and we now define \( v_j^a : \Delta_n \to \mathbb{R} \times \mathbb{C} \) for \( t \in [a, 1] \) by the formulas
\[
v_j^a(s) := s_j \tilde{\gamma}(a) \quad \text{and} \quad \bar{v}^t := (v_1^t, \ldots, v_n^t) := \Phi^{a,t} \circ (v_1^a, \ldots, v_n^a).
\]
Let
\[
V(t) := \sum_{j=1}^n |\zeta_j'(s) - \zeta_j'(s')| \quad \text{for} \quad s, s' \in \Delta_n.
\]
We obtain from \((4.17)\) and \((4.27)\) the following estimate:
\[
V(t) \leq V(a) + \frac{1}{\sqrt{2}} \sum_{j=1}^n \int_a^t \left| X_j(\tau, \bar{v}^\tau(s)) - X_j(\tau, \bar{v}^\tau(s')) \right| d\tau \\
\leq V(a) + \frac{3}{\delta} \int_a^t |\gamma(\tau)| V(\tau) d\tau.
\]
Therefore, Gronwall’s lemma yields \( V(t) \leq V(a) e^{3\delta - L(|\gamma|_{[a, 1]})} \), and hence, since \( V(a) = \rho \sum_{j=1}^n |s_j - s_j'| \), we have
\[
(4.28) \quad V(t) \leq \rho e^{3\delta - L(|\gamma|_{[a, 1]})} \sum_{j=1}^n |s_j - s_j'|.
\]

Then, \((4.28)\) entails via Rademacher’s theorem that the following estimate holds a.e. on \( \Delta_n \):
\[
\sum_{i=1}^n \left| \frac{\partial \zeta_i'}{\partial s_j} \right| \leq \rho e^{3\delta - L(|\gamma|_{[a, 1]})}.
\]
Finally, (4.14) follows from the inequality
\[
\left| \det \left[ \frac{\partial c^i}{\partial s^j} \right]_{1 \leq i,j \leq n} \right| \leq n \prod_{j=1}^{n} \left( \sum_{i=1}^{n} \left| \frac{\partial c^i}{\partial s^j} \right| \right).
\]

Remark 4.13. Theorem 4.8 is verified by replacing the vector field (4.19) by
\[
\vec{X}(t,\vec{v}) = \begin{vmatrix}
X_1 := \frac{\eta_1(v_1)}{D(t,\vec{v})} \tilde{\gamma}'(t) \\
\vdots \\
X_n := \frac{\eta_n(v_n)}{D(t,\vec{v})} \tilde{\gamma}'(t),
\end{vmatrix}
\]
where
\[
\eta_j(v) := \text{dist}(v,\{(0,0)\} \cup S_{\Omega_j}),
\]
\[
D(t,\vec{v}) := \eta_1(v_1) + \cdots + \eta_n(v_n) + |\tilde{\gamma}(t) - (v_1 + \cdots + v_n)|.
\]

5 Applications

In this section, we display some applications of our results of Section 4. We first introduce convergent power series with coefficients in \(\bar{R}_{\Omega}\):

Definition 5.1. Let \(\Omega\) be a d.f.s. We define \(\bar{R}_{\Omega} \{w_1,\ldots,w_r\}\) \((r \geq 1)\) as the subspace of \(\bar{R}_{\Omega}[[w_1,\ldots,w_r]]\) consisting of formal series
\[
\tilde{F}(z,w_1,\ldots,w_r) = \sum_{k \in \mathbb{Z}_{\geq 0}^r} \tilde{F}_k(z)w_1^{k_1}\cdots w_r^{k_r}
\]
such that, for every \(\delta,L > 0\), there exists a positive constant \(C\) satisfying
\[
\|\tilde{F}_k\|_{\Omega}^{\delta,L} \leq C^{|k|+1} \quad \text{for every} \quad k = (k_1,\ldots,k_r) \in \mathbb{Z}_{\geq 0}^r,
\]
where \(|k| := k_1 + \cdots + k_r\) (with the notation of Definition 3.16 for \(\| \cdot \|_{\Omega}^{\delta,L}\)).

We can now deal with the substitution of resurgent formal series in a context more general than in Theorem 1.3.

Theorem 5.2. Let \(r \geq 1\) be integer and let \(\Omega_0, \ldots, \Omega_r\) be d.f.s. Then for any \(\tilde{F}(w_1,\ldots,w_r) \in \bar{R}_{\Omega_0} \{w_1,\ldots,w_r\}\) and for any \(\tilde{\varphi}_1,\ldots,\tilde{\varphi}_r \in \mathbb{C}[|z|^{-1}]\) without constant term, one has
\[
\tilde{\varphi}_1 \in \bar{R}_{\Omega_1},\ldots,\tilde{\varphi}_r \in \bar{R}_{\Omega_r} \Rightarrow \tilde{F}(\tilde{\varphi}_1,\ldots,\tilde{\varphi}_r) \in \bar{R}_{\Omega_0^{*} \Omega^{*\infty}},
\]
where \(\Omega := \Omega_1 \ast \cdots \ast \Omega_r\).
Proof. Since the family \( \{ \Omega_0 \ast \Omega^{k} \} := \Omega_0 \ast \Omega^{k_1} \ast \cdots \ast \Omega^{k_r} \mid k = (k_1, \cdots, k_r) \in \mathbb{Z}_+^r \) of d.f.s. satisfies the conditions in Theorem 4.8 for sufficiently small \( \delta > 0 \), for every \( L > 0 \), there exist \( \delta', L', C > 0 \) such that

\[
\| \bar{F}_0 \bar{D}^{k_1} \cdots \bar{D}^{k_r} \|_{\Omega_0 \ast \Omega^{\infty}} \leq \frac{\mathcal{C}(k+2)}{\mathcal{C}(k+1)!} \| \bar{F}_0 \|_{\Omega_0} \| \bar{D}^{k_1} \|_{\Omega_0} \cdots \| \bar{D}^{k_r} \|_{\Omega_0}.
\]

Therefore, since \( \bar{F}(w_1, \ldots, w_r) \in \mathcal{R}_{\Omega_0 \ast \Omega^{\infty}} \), we find that \( \bar{F}(\bar{\varphi}_1, \ldots, \bar{\varphi}_r) \) converges in \( \mathcal{R}_{\Omega_0 \ast \Omega^{\infty}} \) and defines an \( \Omega_0 \ast \Omega^{\infty} \)-resurgent formal series.

Notice that, in view of Theorem 2.13 Theorem 1.3 is a direct consequence of Theorem 5.2.

Next, we show the following implicit function theorem for resurgent formal series:

**Theorem 5.3.** Let \( \bar{F}(z, w) \in \mathcal{R}_{\Omega_0 \ast \Omega^{\infty}} \) and assume that \( F(x, w) := \bar{F}(x^{-1}, w) \) satisfies \( F(0, 0) = 0 \) and \( \partial_w F(0, 0) \neq 0 \). Then, the unique solution \( \bar{\varphi} \in z \mathbb{C}[[z]] \) of

\[
(5.1) \quad \bar{F}(z; \bar{\varphi}(z)) = 0
\]

satisfies \( \bar{\varphi} \in \mathcal{R}_{\Omega^{\infty}} \).

**Proof.** We rewrite \( \bar{F}(z, w) \) into the form

\[
\bar{F}(z, w) = \bar{F}_0(z) + \partial_w F(0, 0)w + \sum_{k=1}^{\infty} \bar{F}_k(z)w^k.
\]

Considering \( (5.1) \) as the equation for \( \bar{\psi} = z^{-1}(\bar{\varphi}(z) - \bar{\varphi}_1 z) \), we can assume that \( \bar{F}_k \) has no constant term for \( k = 0, 1, \ldots \). Further, we can assume without loss of generality that \( \partial_w F(0, 0) = -1 \). Then, the unique solution \( \bar{\varphi} \in z \mathbb{C}[[z]] \) of \((5.1)\) can be written as \( \bar{\varphi} = \bar{H}(z, \bar{F}_0) \), where

\[
\bar{H}(z, w) = \sum_{m \geq 1} \bar{H}_m(z)w^m, \quad \bar{H}_m := \sum_{k \geq 1} \frac{(m + k - 1)!}{m!k!} \sum_{n_1 + \cdots + n_k = m + k - 1} \frac{1}{n_1 \cdots n_k} \bar{F}_1 \cdots \bar{F}_k.
\]

(see proof of Theorem 4 in [Sau15] for the detail). Since \( \bar{F}(z, w) \in \mathcal{R}_{\Omega_0 \ast \Omega^{\infty}} \), we obtain from Corollary 4.2 the following estimates: For every \( \delta, L > 0 \), there exist \( \delta', L', C > 0 \) such that

\[
\| \bar{H}_m \|_{\Omega^{\infty}} \leq \sum_{k \geq 1} \frac{(m + k - 1)!}{m!k!} \sum_{n_1 + \cdots + n_k = m + k - 1} \frac{C^{k+1}}{k!} \| \bar{F}_1 \|_{\Omega_0} \cdots \| \bar{F}_k \|_{\Omega_0} \| \bar{F}_n \|_{\Omega_0} \| \bar{D}^{k'} \|_{\Omega_0} \| \bar{D}^{L'} \|_{\Omega_0}.
\]

\[
\leq \sum_{k \geq 1} \frac{C^{m+k}}{k!} \sum_{n_1 + \cdots + n_k = m + k - 1} \frac{C^{m+3k}}{k!} \leq \sum_{k \geq 1} e^{6C^3(4C)^m}.
\]

This yields \( \bar{H}(z, w) \in \mathcal{R}_{\Omega^{\infty}} \), whence, \( \bar{H}(z, \bar{F}_0(z)) \in \mathcal{R}_{\Omega^{\infty}} \).

\[\square\]
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