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Weierstrass Fractal Drums - II

Towards a Fractal Cohomology

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Abstract

We explore the connections between the Complex Dimensions and the cohomological properties of a fractal object. In the case of the Weierstrass Curve, we define the corresponding fractal cohomology and show that the functions belonging to the cohomology groups associated to the Curve (and its prefractal approximations) are obtained, by induction, as (finite or infinite) sums indexed by the underlying Complex Dimensions. The functions that constitute the cohomology groups also satisfy the same discrete local Hölder conditions as the Weierstrass function \mathcal{W} itself. More precisely, for any natural integer m , the m^{th} cohomology group is obtained as the set of continuous functions f on the Curve such that, for any point M located in the m^{th} finite graph of the prefractal approximation to the Curve, $f(M)$ has an expansion which might be interpreted as a generalized Taylor expansion, with fractional derivatives of orders the underlying Complex Dimensions. Those expansions are then compared to the fractal expansion of the function which is the most naturally defined on the Curve, namely, the Weierstrass function \mathcal{W} itself. An important new result comes from the fact that, contrary to fractal tube formulas, which are obtained for small values of a positive parameter ε , the aforementioned fractal expansions are only valid for the value of the (multi-scales) *cohomology infinitesimal* ε associated to the scaling relationship obeyed by the Weierstrass Curve. As a consequence, it makes it possible to express, in a very precise way, the relations satisfied by the functions which belong to the cohomology groups, as well as to completely characterize the elements of these groups. We also obtain a suitable counterpart of Poincaré Duality in this context. Our results shed new light on the theory and the interpretation of Complex Fractal Dimensions.

MSC Classification: 11M36, 11M41, 28A75, 28A80, 35R02, 53A70, 55N10, 55N20.

Keywords: Weierstrass Curve, graph and polygonal prefractal approximations, Complex Dimensions of a fractal drum, Minkowski dimension, sharper Hölder exponent, discrete reverse-Hölder continu-

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ity, discrete differential operators, differentials, fractal cohomology, cohomology groups, topological invariants, fractal expansions, cohomology infinitesimal, fractal complex, Poincaré duality.

Contents

1	Introduction	2
2	Geometric Framework	5
3	Complex Dimensions, and Associated Series Expansion of the Complexified Weierstrass Function	18
4	Fractal Cohomology	24
4.1	Review and Preliminaries	24
4.2	General Considerations: h -Cohomology and Complex Dimensions	25
4.3	Differentials	27
4.4	Fractal Complex, and Cohomology Groups	29
4.5	Poincaré Duality	50
4.6	Total Fractal Cohomology of the Weierstrass Curve	53
5	Concluding Comments	57

1 Introduction

Thus far, the set up of a fractal cohomology theory appears as a very little explored field, where almost everything remains to be built. Many unanswered questions are involved, among which one may first retain the following one: what are the topological invariants of a fractal object?

In [DL23c], by using the concept of h -differentiation, where h denotes a very small real parameter, the first author and Gilles Lebeau have connected the associated h -cohomology to the classical de Rham cohomology. The results of that work go further than the existing ones on small scale parameter based cohomology (see the paper by Alain Connes and Henri Moscovici [CM90], then, the articles of Laurent Bartholdi, Thomas Schick, Stephen Smale, and Nathan Smale [BSSS12], along with the complement written by Stephen and Nathan Smale in [SS12]), in so far as, for the first time, we pass to the limit of the resolvent of the h -scale Laplacian, when the scale parameter h tends towards zero, along with the ad hoc Hodge decomposition. Among the many difficulties encountered in order to obtain the connections between the h -Laplacian and the Laplacian from fractal analysis, one had to define a proper differential, suitably adapted to fractals. This was done by means of discrete paths across prefractals (a sequence of finite graphs that converge towards the fractal).

Note that this approach is completely different from the one that can be found in the works of Fabio Cipriani and Jean-Luc Sauvageot in [CS09], followed up by that of Marius Ionescu, Luke G. Rogers and Alexander Teplyaev in [IRT12], based on the construction of Fredholm modules. We refer to the introduction of [DL23c] for detailed comments.

In [LvF00], [LvF06] and [LvF13], the second author and Machiel van Frankenhuysen have suggested that there should exist a fractal cohomology having direct links with the theory of Complex Dimensions, developed for many years now by Michel L. Lapidus and his collaborators, for example in [Lap91], [Lap92], [Lap93], [LP93], [LM95], [LP06], [Lap08], [LPW11], [LvF00], [LvF06], [LvF13], [LRŽ17a], [LRŽ17b], [LRŽ18], [Lap19], [HL21], [Lap24]. Recall that this theory of Fractal Complex

Dimensions makes the connection between the geometry of an object and its differentiability properties, which is done by means of *geometric (or fractal) zeta functions*. Those zeta functions stand for the trace of a differential operator at a complex order s . The Complex Dimensions are obtained as the poles of the meromorphic continuations of those fractal zeta functions. The hint is that to each Complex Dimension ω associated to a fractal, one could associate a cohomology group H^ω . See also [Lap08] (and the relevant references therein) for further discussion of the expected connections between this potential fractal cohomology theory and number theory, along with arithmetic geometry.

Substantial results on fractal cohomology have later been obtained by the second author and Tim Cobler in [CL17], where are studied the properties of the derivative operator $D = \frac{d}{dz}$ acting on a particular family of weighted Bergman space consisting of entire functions on \mathbb{C} . This operator has to be understood (upon suitable translations and direct sums involving the underlying Complex Dimensions) as an appropriate substitute for the Frobenius operator, and – via the spectrum of its action on the corresponding fractal cohomology spaces – the associated (generalized) Polya–Hilbert operator encodes all of the key information about a given meromorphic function, including especially its zeros and poles. The Frobenius operator – or a suitable analog – appears as being perfectly suited to fractals, when iterated function systems (ifs), and the associated prefractal approximations are involved. Somehow, one intuitively understands that points – vertices – at the m^{th} step of the approximation process – necessarily carry the information coming from the previous $(m - 1)^{\text{th}}$ step. In light of the prefractal sequence, composed of finite graphs where neighboring points are connected by edges, a shift operator also appears to be very natural. We note that the work in [CL17] is pursued in the second author’s book [Lap24], dedicated in large part to the subject of fractal cohomology and its motivations via the theory of Complex Dimensions and a suitably complexified version of quantized number theory [LvF13], [HL21]; see also the epilog of [Lap19] for a brief overview.

But how could one go further, and obtain the underlying connections between Complex Dimensions and cohomology groups? The idea that came to our minds was to study a fractal object which could also be associated with a function. A test case, in a way. Our choice fell on the (nowhere differentiable) Weierstrass Curve.

We first tackled the problem in [DL22], by determining the Complex Dimensions of the Curve – and establishing, in the process, a fractal tube formula expressing the volume of a small ε -neighborhood of the Weierstrass Curve as limits of finite sums indexed by the corresponding Complex Codimensions. As previously evoked, those Complex Dimensions are obtained as the poles of the tube (or, equivalently, the distance) zeta function associated to the Curve. As could have been expected, the Minkowski dimension (or box dimension) $D_{\mathcal{W}}$ is the Complex Dimension with maximal real part, and zero imaginary part. In [DL22], we also proved new geometric properties of the Curve and of the associated function, in relation with its discrete local Hölder and reverse Hölder continuity, with explicit estimates that had not been obtained before. In particular, we showed that the Codimension $2 - D_{\mathcal{W}}$ is the optimal Hölder exponent for the Weierstrass function \mathcal{W} . This, naturally, goes in the direction of the existence of fractional derivatives, of orders expressed in function of the corresponding Dimensions.

As a corollary of these results, we concluded, in [DL22] and [DL23b], that the Weierstrass Curve $\Gamma_{\mathcal{W}}$ is *fractal*, in the sense of the theory of Complex Dimensions ([LvF00], [LvF06], [LvF13], [LRŽ17b], [Lap19]), because it admits *nonreal* Complex Dimensions – and hence also, intrinsic oscillations in its geometry. See Theorem 3.1, on page 18 and Remark 4.7, on page 47 below for a brief overview of some of the relevant main results of [DL22], including a fractal tube formula for the expression of the volume of the ε -neighborhoods of the Weierstrass Curve, as a sum over its Complex Codimensions.

Now, a very interesting new question and feature arise: can one rewrite the series expansion of the Weierstrass function, in a form that directly yields a second one, indexed by the Complex Dimensions?

This echoes the Hölder properties of the function, with a direct connection between the value of the Hölder exponent and the Complex Dimensions. We will show here that it is, indeed, the case.

The natural question which then arises is the following one: are those Complex Dimensions connected to the cohomological properties of the Curve? The answer is yes, even though it was rather difficult to prove it and to properly formulate it. In order to solve this problem, we naturally used the same kind of differentiation (as well as a necessary generalization) as the one obtained in [DL23c], by means of discrete paths along prefractals; see Section 4.3. In the process, we also came across a very interesting and useful feature, in the context of our study, where the fractal object – the Weierstrass Curve $\Gamma_{\mathcal{W}}$ – is directly connected with a function: in addition to its discrete local Hölder and reverse-Hölder properties (see [DL22]), the Weierstrass function satisfies a new geometric condition which amounts to a uniform continuity condition in its argument part. In this light, by considering classes of functions which satisfy the same kind of properties, we prove that one can obtain, by induction, a complete characterization of all the elements of the cohomology groups associated to the Curve. And, as expected, we show that these cohomology groups consist of continuous functions (on the Weierstrass Curve) which are expressed in terms of (finite, or countably infinite) sums indexed by the underlying Complex Dimensions. More precisely, as obtained in Theorem 4.11, on page 53, one has an exact correspondance between the m^{th} cohomology group and the real terms in the sums. As for the complex terms, they can be understood as modes of vibrations of the Weierstrass fractal Curve.

As could perhaps also be expected, the sum that enables us to express any given function belonging to the m^{th} cohomology group, at a given vertex of the associated m^{th} prefractal graph, is in accordance with the expression of the Complexified Weierstrass function at the same point. In fact, we show, in Theorem 3.3, on page 20, that the Complexified Weierstrass function can exactly be expressed as an infinite sum indexed by the underlying Complex Dimensions. Going further, this might be interpreted as a kind of generalized Taylor expansion, with fractional derivatives of orders $k(2 - D_{\mathcal{W}}) + ik\ell_k \mathbf{p}$, where \mathbf{p} denotes the oscillatory period of the Weierstrass Curve, for $k \in \mathbb{N}$ arbitrary, and where $\ell_k \in \mathbb{Z}$ satisfies a specific condition governed by the underlying geometry of the Curve; see Theorem 4.3, on page 33.

The Weierstrass Curve has a natural symmetry with respect to the vertical line $x = \frac{1}{2}$. It is then natural to define the associated *left* and *right side* differentials and complexes, as well as a Complex Conjugation with respect to this vertical line. One then naturally obtains a suitable version of Poincaré Duality for the fractal cohomology of the Weierstrass Curve, in relation with our notion of *paths* (from Section 4.4) across the prefractal graphs; see Proposition 4.10, on page 52.

We point out that the fractal cohomology groups H^m associated with each of the m^{th} prefractal approximations of the Weierstrass Curve $\Gamma_{\mathcal{W}}$ (where $m \in \mathbb{N}$ is arbitrary) are characterized in Theorem 4.3, on page 33, while the total fractal cohomology group of $\Gamma_{\mathcal{W}}$, H^{\star} – interpreted and defined as an appropriate inductive limit of the groups H^m (where $m \in \mathbb{N}$) – is fully described in Theorem 4.11, on page 53.

The results of this paper and of [DL22] are announced in the survey article [DL24a], where the main results are presented in a summarized form. As is commented upon in several places throughout the present paper (and [DL22]), our results shed new light on the theory and interpretation of Complex Dimensions – particularly in connection with the vibrations of fractal drums (or strings), as well with the key notion of scales (including transition scales) in mathematical and theoretical physics.

2 Geometric Framework

Henceforth, we place ourselves in the Euclidean plane, equipped with a direct orthonormal frame. The usual Cartesian coordinates are denoted by (x, y) . The horizontal and vertical axes will be respectively referred to as $(x'x)$ and $(y'y)$.

Notation 1 (Set of all Natural Numbers, and Intervals).

As in Bourbaki [Bou04] (Appendix E. 143), we denote by $\mathbb{N} = \{0, 1, 2, \dots\}$ the set of all natural numbers, and set $\mathbb{N}^* = \mathbb{N} \setminus \{0\}$.

Given a, b with $-\infty \leq a \leq b \leq \infty$, $]a, b[= (a, b)$ denotes an open interval, while, for example, $]a, b] = (a, b]$ denotes a half-open, half-closed interval.

Notation 2 (Wave Inequality Symbol).

Given two positive-valued functions f and g , defined on a subset \mathcal{I} of \mathbb{R} , we use the following notation, for all $x \in \mathcal{I}$: $f(x) \lesssim g(x)$ when there exists a strictly positive constant C such that, for all $x \in \mathcal{I}$, $f(x) \leq C g(x)$.

Notation 3 (Weierstrass Parameters).

In the sequel, λ and N_b are two real numbers such that

$$0 < \lambda < 1 \quad , \quad N_b \in \mathbb{N}^* \quad \text{and} \quad \lambda N_b > 1. \quad (\clubsuit)$$

Note that this implies that $N_b > 1$ (i.e., $N_b \geq 2$).

As explained in [Dav19], we deliberately made the choice to introduce the notation N_b which replaces the initial number b , in so far as, in Hardy's paper [Har16] (in contrast to Weierstrass's original article [Wei75]), b is any positive real number satisfying $\lambda b > 1$, whereas we deal here with the specific case of a natural integer, which accounts for the natural notation N_b .

Definition 2.1 (Weierstrass Function, Weierstrass Curve).

We consider the *Weierstrass function* \mathcal{W} (also called, in short, the *W-function*) defined, for any real number x , by

$$\mathcal{W}(x) = \sum_{n=0}^{\infty} \lambda^n \cos(2\pi N_b^n x). \quad (1)$$

We call the associated graph the *Weierstrass Curve*, and denote it by $\Gamma_{\mathcal{W}}$.

Due to the one-periodicity of the \mathcal{W} -function, from now on, and without loss of generality, we restrict our study to the interval $[0, 1[= [0, 1)$.

Definition 2.2 (Complexified Weierstrass Function).

We introduce the *Complexified Weierstrass function* \mathcal{W}_{comp} , defined, for any real number x , by

$$\mathcal{W}_{comp}(x) = \sum_{n=0}^{\infty} \lambda^n e^{2i\pi N_b^n x}.$$

Notation 4 (Logarithm).

Given $y > 0$, $\ln y$ denotes the natural logarithm of y , while, given $a > 1$, $\ln_a y = \frac{\ln y}{\ln a}$ denotes the logarithm of y in base a ; so that, in particular, $\ln = \ln_e$.

Notation 5 (Minkowski Dimension and Hölder Exponent).

For the parameters λ and N_b satisfying condition (\clubsuit) (see Notation 3, on page 5), we denote by

$$D_{\mathcal{W}} = 2 + \frac{\ln \lambda}{\ln N_b} = 2 - \ln_{N_b} \frac{1}{\lambda} \in]1, 2[$$

the box-counting dimension (or Minkowski dimension) of the Weierstrass Curve $\Gamma_{\mathcal{W}}$, which happens to be equal to its Hausdorff dimension [KMPY84], [BBR14], [She18], [Kel17]. We point out that the results in our previous paper [DL22] and in our later paper [DL23b] also provide a direct geometric proof of the fact that $D_{\mathcal{W}}$, the Minkowski dimension (or box-counting dimension) of $\Gamma_{\mathcal{W}}$, exists and takes the above values, as well as of the fact that \mathcal{W} is Hölder continuous with *optimal* Hölder exponent

$$2 - D_{\mathcal{W}} = -\frac{\ln \lambda}{\ln N_b} = \ln_{N_b} \frac{1}{\lambda}.$$

Convention (The Weierstrass Curve as a Cyclic Curve).

In the sequel, we identify the points $(0, \mathcal{W}(0))$ and $(1, \mathcal{W}(1)) = (1, \mathcal{W}(0))$. This is justified by the fact that the Weierstrass function \mathcal{W} is 1-periodic, since N_b is an integer.

Remark 2.1. The above convention makes sense, because, in addition to the periodicity property of the \mathcal{W} -function, the points $(0, \mathcal{W}(0))$ and $(1, \mathcal{W}(1))$ have the same vertical coordinate.

Property 2.1 (Symmetry with Respect to the Vertical Line $x = \frac{1}{2}$).

Since, for any $x \in [0, 1]$,

$$\mathcal{W}(1-x) = \sum_{n=0}^{\infty} \lambda^n \cos(2\pi N_b^n - 2\pi N_b^n x) = \mathcal{W}(x),$$

the Weierstrass Curve is symmetric with respect to the vertical straight line $x = \frac{1}{2}$.

Proposition 2.2 (Nonlinear and Noncontractive Iterated Function System (IFS)).

Following our previous work [Dav18], we approximate the restriction $\Gamma_{\mathcal{W}}$ to $[0, 1[\times\mathbb{R}$, of the Weierstrass Curve, by a sequence of graphs, built via an iterative process. For this purpose, we use the nonlinear iterated function system (IFS) consisting in the family of C^∞ maps from \mathbb{R}^2 to \mathbb{R}^2 denoted by

$$\mathcal{T}_{\mathcal{W}} = \{T_0, \dots, T_{N_b-1}\},$$

where, for any integer i belonging to $\{0, \dots, N_b - 1\}$ and any point (x, y) of \mathbb{R}^2 ,

$$T_i(x, y) = \left(\frac{x+i}{N_b}, \lambda y + \cos\left(2\pi\left(\frac{x+i}{N_b}\right)\right) \right).$$

Property 2.3 (Attractor of the IFS [Dav18], [Dav19]).

The Weierstrass Curve $\Gamma_{\mathcal{W}}$ is the attractor of the IFS $\mathcal{T}_{\mathcal{W}}$, and hence, is the unique nonempty compact subset \mathcal{K} of \mathbb{R}^2 satisfying $\mathcal{K} = \bigcup_{i=0}^{N_b-1} T_i(\mathcal{K})$; in particular, we have that $\Gamma_{\mathcal{W}} = \bigcup_{i=0}^{N_b-1} T_i(\Gamma_{\mathcal{W}})$.

Notation 6 (Fixed Points).

For any integer i belonging to $\{0, \dots, N_b - 1\}$, we denote by

$$P_i = (x_i, y_i) = \left(\frac{i}{N_b-1}, \frac{1}{1-\lambda} \cos\left(\frac{2\pi i}{N_b-1}\right) \right)$$

the unique fixed point of the map T_i ; see [Dav19].

Definition 2.3 (Sets of Vertices, Prefractals).

We denote by V_0 the ordered set (according to increasing abscissae) of the points

$$\{P_0, \dots, P_{N_b-1}\}.$$

The set of points V_0 – where, for any integer i in $\{0, \dots, N_b - 2\}$, the point P_i is linked to the point P_{i+1} – constitutes an oriented finite graph, ordered according to increasing abscissae, which we will denote by $\Gamma_{\mathcal{W}_0}$. Then, V_0 is called *the set of vertices* of the graph $\Gamma_{\mathcal{W}_0}$.

For any positive integer m , i.e., for $m \in \mathbb{N}^*$, we set $V_m = \bigcup_{i=0}^{N_b-1} T_i(V_{m-1})$.

The set of points V_m , where two consecutive points are linked, is an oriented finite graph, ordered according to increasing abscissae, called the **m^{th} -order \mathcal{W} -prefractal**. Then, V_m is called *the set of vertices* of the prefractal $\Gamma_{\mathcal{W}_m}$; see Figure 2, on page 10.

Definition 2.4 (Adjacent Vertices, Edge Relation).

For any $m \in \mathbb{N}$, the prefractal graph $\Gamma_{\mathcal{W}_m}$ is equipped with an edge relation \sim_m , as follows: two vertices X and Y of $\Gamma_{\mathcal{W}_m}$ (i.e. two points belonging to V_m) are said to be *adjacent* (i.e., *neighboring* or *junction points*) if and only if the line segment $[X, Y]$ is an edge of $\Gamma_{\mathcal{W}_m}$; we then write $X \sim_m Y$. Note that this edge relation depends on m , which means that points adjacent in V_m might not remain adjacent in V_{m+1} .

Property 2.4. [Dav18] *For any $m \in \mathbb{N}$, the following statements hold:*

- i. $V_m \subset V_{m+1}$.
- ii. $\#V_m = (N_b - 1) N_b^m + 1$, where $\#V_m$ denotes the number of elements in the finite set V_m .
- iii. The prefractal graph $\Gamma_{\mathcal{W}_m}$ has exactly $(N_b - 1) N_b^m$ edges.
- iv. The consecutive vertices of the prefractal graph $\Gamma_{\mathcal{W}_m}$ are the vertices of N_b^m simple nonregular polygons $\mathcal{P}_{m,k}$ with N_b sides. For any strictly positive integer m , the junction point between two consecutive polygons is the point

$$\left(\frac{(N_b - 1)k}{(N_b - 1)N_b^m}, \mathcal{W} \left(\frac{(N_b - 1)k}{(N_b - 1)N_b^m} \right) \right), \quad 1 \leq k \leq N_b^m - 1.$$

Hence, the total number of junction points is $N_b^m - 1$. For instance, in the case $N_b = 3$, the polygons are all triangles; see Figure 1, on page 9.

In the sequel, we will denote by \mathcal{P}_0 **the initial polygon**, whose vertices are the fixed points of the maps T_i , $0 \leq i \leq N_b - 1$, introduced in Notation 6 and Definition 2.3, on page 7, i.e., $\{P_0, \dots, P_{N_b-1}\}$; see, again, Figure 1, on page 9.

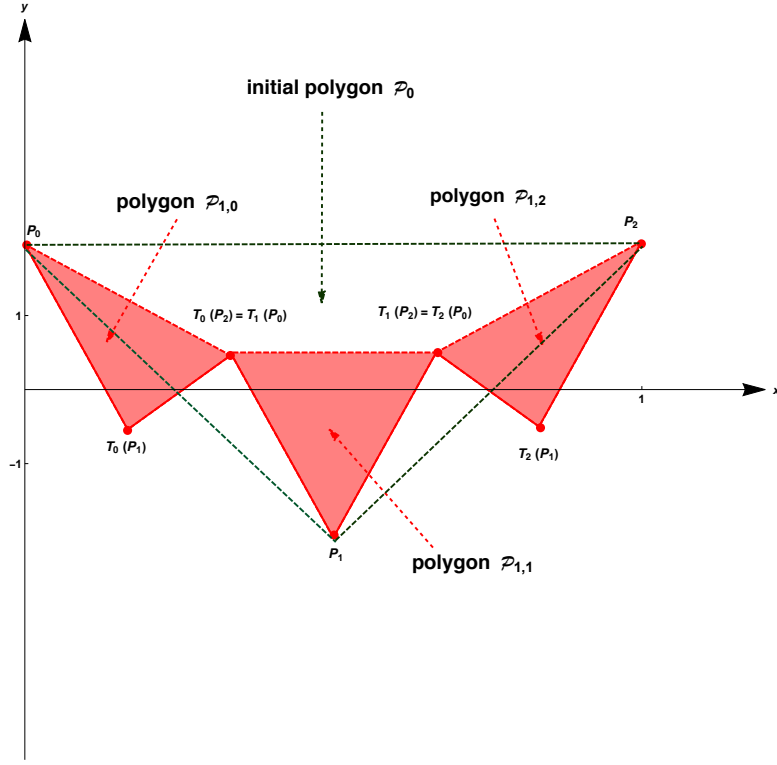


Figure 1: The initial polygon \mathcal{P}_0 , and the polygons $\mathcal{P}_{1,0}$, $\mathcal{P}_{1,1}$, $\mathcal{P}_{1,2}$, in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$. (See also Figure 2, on page 10.)

Definition 2.5 (Vertices of the Prefractals, Elementary Lengths, Heights and Angles).

Given a strictly positive integer m , we denote by $(M_{j,m})_{0 \leq j \leq (N_b-1)N_b^m}$ the set of vertices of the prefractal graph $\Gamma_{\mathcal{W}_m}$. One thus has, for any integer j in $\{0, \dots, (N_b-1)N_b^m\}$:

$$M_{j,m} = \left(\frac{j}{(N_b-1)N_b^m}, \mathcal{W} \left(\frac{j}{(N_b-1)N_b^m} \right) \right).$$

We also introduce, for any integer j in $\{0, \dots, (N_b-1)N_b^m - 1\}$:

- i. the elementary horizontal lengths:

$$L_m = \frac{1}{(N_b-1)N_b^m};$$

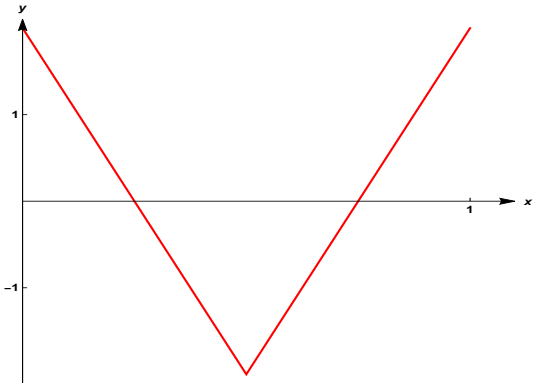
- ii. the elementary lengths:

$$l_{j,j+1,m} = d(M_{j,m}, M_{j+1,m}) = \sqrt{L_m^2 + h_{j,j+1,m}^2},$$

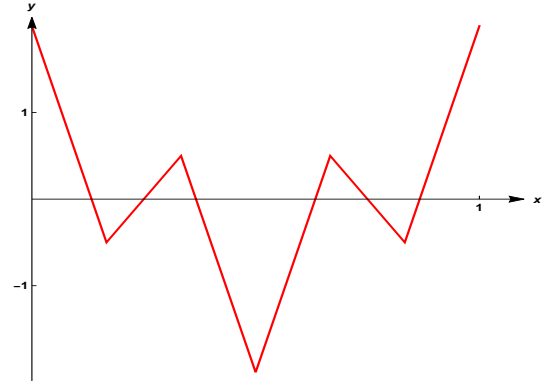
where $h_{j,j+1,m}$ is defined in *iii.* just below.

- iii. the elementary heights:

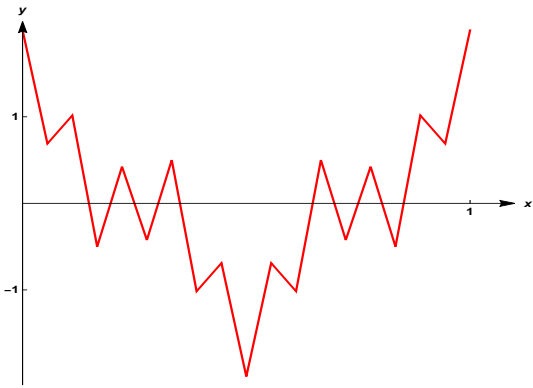
$$h_{j-1,j,m} = \left| \mathcal{W} \left(\frac{j}{(N_b-1)N_b^m} \right) - \mathcal{W} \left(\frac{j-1}{(N_b-1)N_b^m} \right) \right|, \quad h_{j,j+1,m} = \left| \mathcal{W} \left(\frac{j+1}{(N_b-1)N_b^m} \right) - \mathcal{W} \left(\frac{j}{(N_b-1)N_b^m} \right) \right|;$$



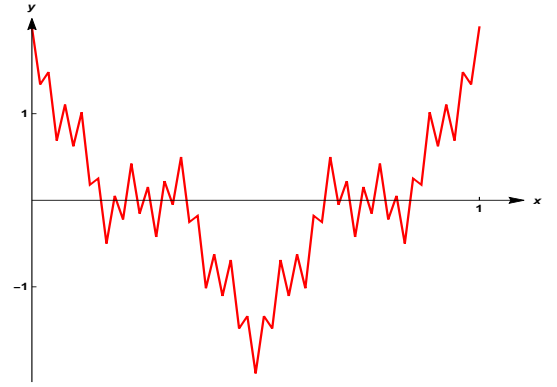
(a) The prefractal graph Γ_{W_0} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.



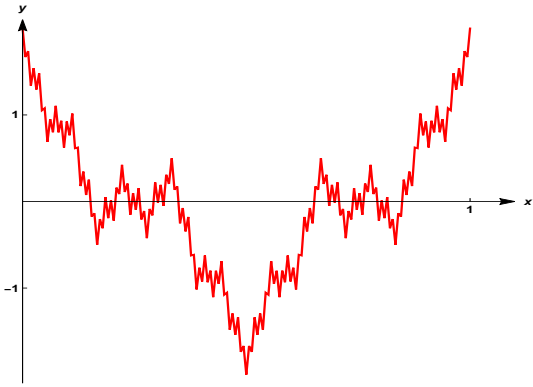
(b) The prefractal graph Γ_{W_1} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.



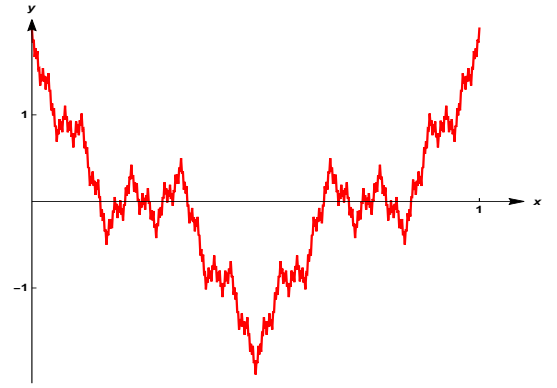
(c) The prefractal graph Γ_{W_2} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.



(d) The prefractal graph Γ_{W_3} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.



(e) The prefractal graph Γ_{W_4} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.



(f) The prefractal graph Γ_{W_5} , in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.

Figure 2: The prefractal graphs $\Gamma_{W_0}, \Gamma_{W_1}, \Gamma_{W_2}, \Gamma_{W_3}, \Gamma_{W_4}, \Gamma_{W_5}$, in the case when $\lambda = \frac{1}{2}$ and $N_b = 3$.

iv. the geometric angles:

$$\theta_{j-1,j,m} = ((y'y), (\widehat{M_{j-1,m}M_{j,m}})) \quad , \quad \theta_{j,j+1,m} = ((y'y), (\widehat{M_{j,m}M_{j+1,m}})),$$

where $(y'y)$ denotes the vertical axis, which yield **the following value of the geometric angle between consecutive edges**, namely, $[M_{j-1,m} M_{j,m}, M_{j,m} M_{j+1,m}]$, with $\arctan = \tan^{-1}$:

$$\theta_{j-1,j,m} + \theta_{j,j+1,m} = \arctan \frac{L_m}{h_{j-1,j,m}} + \arctan \frac{L_m}{h_{j,j+1,m}}.$$

(Note that, of course, $\theta_{j-1,j,m} = \arctan \frac{L_m}{h_{j-1,j,m}}$ and $\theta_{j,j+1,m} = \arctan \frac{L_m}{h_{j,j+1,m}}$.)

Property 2.5 (Density of the Set V^* in the Weierstrass Curve [DL22]).

The set $V^* = \bigcup_{n \in \mathbb{N}} V_n$ is dense in the Weierstrass Curve $\Gamma_{\mathcal{W}}$.

Proof.

Since the function \mathcal{W} is continuous, it suffices to remark that the set of the abscissae of the vertices is dense in $[0, 1]$.

Formally, as is given in Definition 2.5, on page 9, for all $m \in \mathbb{N}$, the set of consecutive vertices of V_m is given by

$$(M_{j,m})_{0 \leq j \leq \#V_m - 1} = \left(\left(\frac{j}{(N_b - 1) N_b^m}, \mathcal{W} \left(\frac{j}{(N_b - 1) N_b^m} \right) \right) \right)_{0 \leq j \leq \#V_m - 1},$$

with

$$[0, 1] = \bigcup_{j=0}^{\#V_m - 2} \left[\frac{j}{(N_b - 1) N_b^m}, \frac{j+1}{(N_b - 1) N_b^m} \right]. \quad (2)$$

Let us now consider a point $M = (x, \mathcal{W}(x))$ of the Weierstrass Curve $\Gamma_{\mathcal{W}}$, along with a strictly positive number ε . Since the Weierstrass function is continuous, there exists a nonnegative integer $m_0 \in \mathbb{N}^*$ such that, for all $m \geq m_0$, we have that

$$\forall x' \in [0, 1]: \quad |x - x'| \leq \frac{1}{(N_b - 1) N_b^m} \implies \left| \mathcal{W}(x) - \mathcal{W}(x') \right| \leq \varepsilon$$

By using relation (2), we obtain the existence of an integer $m_1 \geq m_0$ such that, for all $m \geq m_1$, there exists $j \in \{0, \dots, \#V_m - 2\}$ such that

$$\frac{j}{(N_b - 1) N_b^m} \leq x \leq \frac{j+1}{(N_b - 1) N_b^m},$$

from which we deduce that

$$\left| \mathcal{W}(x) - \mathcal{W} \left(\frac{j+1}{(N_b - 1) N_b^m} \right) \right| \leq \varepsilon;$$

this yields the expected density result. □

Property 2.6. For the geometric angle $\theta_{j-1,j,m}$, $0 \leq j \leq (N_b - 1) N_b^m$, $m \in \mathbb{N}$, we have the following relation:

$$\tan \theta_{j-1,j,m} = \frac{h_{j-1,j,m}}{L_m}.$$

At this point, it is interesting to use the scaling properties of the Weierstrass function, as obtained in [DL22].

Property 2.7 (Scaling Properties of the Weierstrass Function, and Consequences [DL22]).

Since, for any real number x , $\mathcal{W}(x) = \sum_{n=0}^{\infty} \lambda^n \cos(2\pi N_b^n x)$, one also has

$$\mathcal{W}(N_b x) = \sum_{n=0}^{\infty} \lambda^n \cos(2\pi N_b^{n+1} x) = \frac{1}{\lambda} \sum_{n=1}^{\infty} \lambda^n \cos(2\pi N_b^n x) = \frac{1}{\lambda} (\mathcal{W}(x) - \cos(2\pi x)),$$

which yields, for any strictly positive integer m and any j in $\{0, \dots, \#V_m\}$,

$$\mathcal{W}\left(\frac{j}{(N_b - 1) N_b^m}\right) = \lambda \mathcal{W}\left(\frac{j}{(N_b - 1) N_b^{m-1}}\right) + \cos\left(\frac{2\pi j}{(N_b - 1) N_b^m}\right).$$

By induction, one then obtains that

$$\mathcal{W}\left(\frac{j}{(N_b - 1) N_b^m}\right) = \lambda^m \mathcal{W}\left(\frac{j}{(N_b - 1)}\right) + \sum_{k=0}^{m-1} \lambda^k \cos\left(\frac{2\pi N_b^k j}{(N_b - 1) N_b^m}\right).$$

Property 2.8 (A Consequence of the Symmetry with Respect to the Vertical Line $x = \frac{1}{2}$).

For any strictly positive integer m and any j in $\{0, \dots, \#V_m\}$, we have that

$$\mathcal{W}\left(\frac{j}{(N_b - 1) N_b^m}\right) = \mathcal{W}\left(\frac{(N_b - 1) N_b^m - j}{(N_b - 1) N_b^m}\right),$$

which means that the points

$$\left(\frac{(N_b - 1) N_b^m - j}{(N_b - 1) N_b^m}, \mathcal{W}\left(\frac{(N_b - 1) N_b^m - j}{(N_b - 1) N_b^m}\right)\right) \quad \text{and} \quad \left(\frac{j}{(N_b - 1) N_b^m}, \mathcal{W}\left(\frac{j}{(N_b - 1) N_b^m}\right)\right)$$

are symmetric with respect to the vertical line $x = \frac{1}{2}$; see Figure 3, on page 13.

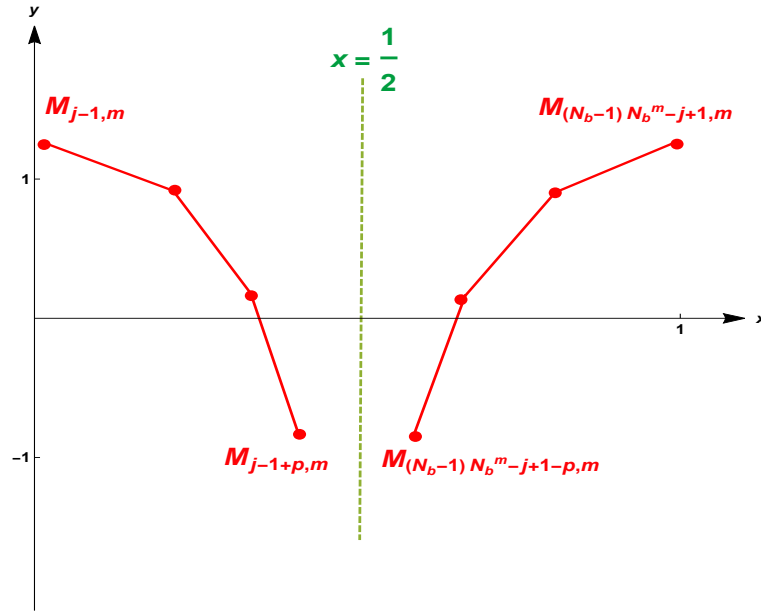


Figure 3: Symmetric points with respect to the vertical line $x = \frac{1}{2}$.

Definition 2.6 (Left-side and Right-side Vertices).

Given integers $(m, k) \in \mathbb{N}^2$ such that $0 \leq k \leq N_b^m - 1$, and a polygon $\mathcal{P}_{m,k}$, we define:

- i. The set of its *left-side vertices* as the set of the first $\left\lfloor \frac{N_b - 1}{2} \right\rfloor$ vertices, where $\lfloor y \rfloor$ denotes the integer part of the real number y .
- ii. The set of its *right-side vertices* as the set of the last $\left\lfloor \frac{N_b - 1}{2} \right\rfloor$ vertices.

When the integer N_b is odd, we define the bottom vertex as the $\left(\frac{N_b - 1}{2}\right)^{th}$ one; see Figure 4, on page 13.

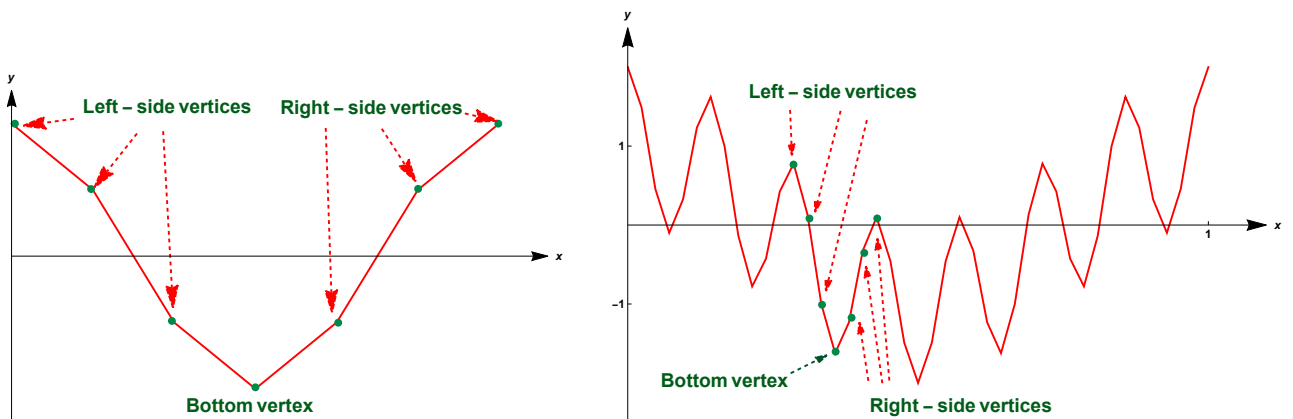


Figure 4: The Left and Right-Side Vertices.

Property 2.9 ([DL22]).

Since, for any $n \in \mathbb{N}$,

$$N_b^n = (1 + N_b - 1)^n = \sum_{k=0}^n \binom{n}{k} (N_b - 1)^k \equiv 1 \pmod{N_b - 1},$$

one obtains, for any integer j in $\{0, \dots, N_b - 1\}$:

$$\mathcal{W}\left(\frac{j}{N_b - 1}\right) = \sum_{n=0}^{\infty} \lambda^n \cos\left(2\pi N_b^n \frac{j}{N_b - 1}\right) = \sum_{n=0}^{\infty} \lambda^n \cos\left(\frac{2\pi j}{N_b - 1}\right) = \frac{1}{1 - \lambda} \cos\left(\frac{2\pi j}{N_b - 1}\right).$$

We observe that the point

$$\left(\frac{j}{N_b - 1}, \mathcal{W}\left(\frac{j}{N_b - 1}\right)\right) = \left(\frac{j}{N_b - 1}, \frac{1}{1 - \lambda} \cos\left(\frac{2\pi j}{N_b - 1}\right)\right)$$

is also **the fixed point** of the map T_j introduced in Proposition 2.2, on page 7, and Notation 6, on page 7 preceding it.

Property 2.10 ([DL22]).

For $0 \leq j \leq \frac{(N_b - 1)}{2}$ (resp., for $\frac{(N_b - 1)}{2} \leq j \leq N_b - 1$), we have that

$$\mathcal{W}\left(\frac{j+1}{N_b - 1}\right) - \mathcal{W}\left(\frac{j}{N_b - 1}\right) \leq 0 \quad \left(\text{resp., } \mathcal{W}\left(\frac{j+1}{N_b - 1}\right) - \mathcal{W}\left(\frac{j}{N_b - 1}\right) \geq 0\right).$$

Notation 7 (Signum Function).

The *signum function* of a real number x is defined by

$$\text{sgn}(x) = \begin{cases} -1, & \text{if } x < 0, \\ 0, & \text{if } x = 0, \\ +1, & \text{if } x > 0. \end{cases}$$

Property 2.11 ([DL22]).

Given any strictly positive integer m , we have the following properties:

i. For any j in $\{0, \dots, \#V_m\}$, the point

$$\left(\frac{j}{(N_b - 1)N_b^m}, \mathcal{W}\left(\frac{j}{(N_b - 1)N_b^m}\right)\right)$$

is the image under the map T_i , $0 \leq i \leq N_b - 1$, of the point

$$\left(\frac{j}{(N_b - 1)N_b^{m-1}} - i, \mathcal{W}\left(\frac{j}{(N_b - 1)N_b^{m-1}} - i\right)\right) = \left(\frac{j - i(N_b - 1)N_b^{m-1}}{(N_b - 1)N_b^{m-1}}, \mathcal{W}\left(\frac{j - i(N_b - 1)N_b^{m-1}}{(N_b - 1)N_b^{m-1}}\right)\right)$$

under the map T_i , $0 \leq i \leq N_b - 1$.

Consequently, for $0 \leq j \leq N_b - 1$, the j^{th} vertex of the polygon $\mathcal{P}_{m,k}$, $0 \leq k \leq N_b^m - 1$, i.e., the point

$$\left(\frac{(N_b - 1)k + j}{(N_b - 1)N_b^m}, \mathcal{W}\left(\frac{(N_b - 1)k + j}{(N_b - 1)N_b^m}\right) \right),$$

is the image under the map T_i of the point

$$\left(\frac{(N_b - 1)(k - i(N_b - 1)N_b^{m-1}) + j}{(N_b - 1)N_b^{m-1}}, \mathcal{W}\left(\frac{(N_b - 1)(k - i(N_b - 1)N_b^{m-1}) + j}{(N_b - 1)N_b^{m-1}}\right) \right),$$

which is also the j^{th} vertex of the polygon $\mathcal{P}_{m-1, k-i(N_b-1)N_b^{m-1}}$. Therefore, there is an exact correspondance between vertices of the polygons at consecutive steps $m-1$, m .

ii. Given j in $\{0, \dots, N_b - 2\}$ and k in $\{0, \dots, N_b^m - 1\}$, we have that

$$\text{sgn} \left(\mathcal{W}\left(\frac{k(N_b - 1) + j + 1}{(N_b - 1)N_b^m}\right) - \mathcal{W}\left(\frac{k(N_b - 1) + j}{(N_b - 1)N_b^m}\right) \right) = \text{sgn} \left(\mathcal{W}\left(\frac{j + 1}{N_b - 1}\right) - \mathcal{W}\left(\frac{j}{N_b - 1}\right) \right).$$

Property 2.12 (Lower Bound and Upper Bound for the Elementary Heights [DL22]).

For any strictly positive integer m and any j in $\{0, \dots, (N_b - 1)N_b^m\}$, we have the following estimates:

$$C_{inf} L_m^{2-D_W} \leq \underbrace{|\mathcal{W}((j+1)L_m) - \mathcal{W}(jL_m)|}_{h_{j,j+1,m}} \leq C_{sup} L_m^{2-D_W} \quad , \quad 0 \leq j \leq (N_b - 1)N_b^m, \quad (\spadesuit)$$

where the finite and positive constants C_{inf} and C_{sup} are given by

$$C_{inf} = (N_b - 1)^{2-D_W} \min_{0 \leq j \leq N_b - 1, \mathcal{W}\left(\frac{j+1}{N_b-1}\right) \neq \mathcal{W}\left(\frac{j}{N_b-1}\right)} \left| \mathcal{W}\left(\frac{j+1}{N_b-1}\right) - \mathcal{W}\left(\frac{j}{N_b-1}\right) \right|$$

and

$$C_{sup} = (N_b - 1)^{2-D_W} \left(\max_{0 \leq j \leq N_b - 1} \left| \mathcal{W}\left(\frac{j+1}{N_b-1}\right) - \mathcal{W}\left(\frac{j}{N_b-1}\right) \right| + \frac{2\pi}{(N_b - 1)(\lambda N_b - 1)} \right).$$

One should note, in addition, that these constants C_{inf} and C_{sup} are clearly indepeant of $m \in \mathbb{N}$, but depend on the initial polygon \mathcal{P}_0 .

Theorem 2.13 (Sharp Local Discrete Reverse Hölder Properties of the Weierstrass Function [DL22]).

For any $m \in \mathbb{N}^*$, let us consider a pair of real numbers (x, x') such that

$$x = \frac{(N_b - 1)k + j}{(N_b - 1)N_b^m} = ((N_b - 1)k + j) L_m \quad , \quad x' = \frac{(N_b - 1)k + j + \ell}{(N_b - 1)N_b^m} = ((N_b - 1)k + j + \ell) L_m \quad ,$$

where $0 \leq k \leq N_b^m - 1$, and

i. if the integer N_b is odd,

$$0 \leq j < \frac{N_b - 1}{2} \quad \text{and} \quad 0 < j + \ell \leq \frac{N_b - 1}{2}$$

or

$$\frac{N_b - 1}{2} \leq j < N_b - 1 \quad \text{and} \quad \frac{N_b - 1}{2} < j + \ell \leq N_b - 1 ;$$

ii. if the integer N_b is even,

$$0 \leq j < \frac{N_b}{2} \quad \text{and} \quad 0 < j + \ell \leq \frac{N_b}{2}$$

or

$$\frac{N_b}{2} + 1 \leq j < N_b - 1 \quad \text{and} \quad \frac{N_b}{2} + 1 < j + \ell \leq N_b - 1 .$$

This means that the points $(x, \mathcal{W}(x))$ and $(x', \mathcal{W}(x'))$ are vertices of the polygon $\mathcal{P}_{m,k}$ (see part iv. of Property 2.4, on page 8 above), both located on the left-side of the polygon, or both located on the right-side; see Figure 4, on page 13.

Then, one has the following (discrete, local) reverse-Hölder inequality, with sharp Hölder exponent $-\frac{\ln \lambda}{\ln N_b} = 2 - D_{\mathcal{W}}$,

$$C_{inf} |x' - x|^{2-D_{\mathcal{W}}} \leq |\mathcal{W}(x') - \mathcal{W}(x)| \quad ,$$

where $(x, \mathcal{W}(x))$ and $(x', \mathcal{W}(x'))$ are adjacent vertices of the same m^{th} prefractal approximation, $\Gamma_{\mathcal{W}_m}$, with $m \in \mathbb{N}$ arbitrary. Here, C_{inf} is given as in Property 2.12, on page 15 just above.

Remark 2.2. It is clear that, for any $m \in \mathbb{N}$, and any pair $((x, \mathcal{W}(x)), (x', \mathcal{W}(x')))$ of adjacent vertices of the finite prefractal graph $\Gamma_{\mathcal{W}_m}$, the same following (discrete, local) Hölder and reverse-Hölder inequality, with sharp Hölder exponent $-\frac{\ln \lambda}{\ln N_b} = 2 - D_{\mathcal{W}}$, holds (see [DL22]); i.e., still with C_{inf} and C_{sup} given as in Property 2.12, on page 15 above, we have that

$$C_{inf} |x' - x|^{2-D_{\mathcal{W}}} \leq |\mathcal{W}(x') - \mathcal{W}(x)| \leq C_{sup} |x' - x|^{2-D_{\mathcal{W}}} .$$

Corollary 2.14 (Optimal Hölder Exponent for the Weierstrass Function (see [DL22])).

The local reverse Hölder property of Theorem 2.13, on page 15 just above – in conjunction with the Hölder condition satisfied by the Weierstrass function (see also [Zyg02], Chapter II, Theorem 4.9, page 47) – shows that the Codimension $2 - D_{\mathcal{W}} = -\frac{\ln \lambda}{\ln N_b} \in]0, 1[$ is the best (i.e., optimal) Hölder

exponent for the Weierstrass function (as was originally shown, by a completely different method, by G. H. Hardy in [Har16]).

Note that, as a consequence, since the Hölder exponent is strictly smaller than one, it follows that the Weierstrass function \mathcal{W} is nowhere differentiable.

Corollary 2.15 (of Property 2.12, given on page 15 (see [DL22])).

Thanks to Property 2.12, on page 15, one may now write, for any strictly positive integer m and any integer j in $\{0, \dots, (N_b - 1)N_b^m - 1\}$:

i. for the elementary heights:

$$h_{j-1,j,m} = L_m^{2-D_{\mathcal{W}}} \mathcal{O}(1) ;$$

ii. for the elementary quotients:

$$\frac{h_{j-1,j,m}}{L_m} = L_m^{1-D_{\mathcal{W}}} \mathcal{O}(1) ,$$

and where

$$0 < C_{inf} \leq \mathcal{O}(1) \leq C_{sup} < \infty .$$

As a result, $\mathcal{O}(1)$ stands for an expression which is bounded away from 0 and ∞ , independently of $m \in \mathbb{N}$.

Corollary 2.16 (Nonincreasing Sequence of Geometric Angles (Coming from Property 2.11; see [DL22])).

For the **geometric angles** $\theta_{j-1,j,m}$, $0 \leq j \leq (N_b - 1)N_b^m$, $m \in \mathbb{N}$, we have the following result:

$$\tan \theta_{j-1,j,m} = \frac{L_m}{h_{j-1,j,m}} (N_b - 1) > \tan \theta_{j-1,j,m+1} ,$$

which yields

$$\theta_{j-1,j,m} > \theta_{j-1,j,m+1} \quad \text{and} \quad \theta_{j-1,j,m+1} \lesssim L_m^{D_{\mathcal{W}}-1} .$$

Corollary 2.17 (Local Extrema (Coming from Property 2.11, given on page 14; see [DL22])).

i. The set of local maxima of the Weierstrass function on the interval $[0, 1]$ is given by

$$\left\{ \left(\frac{(N_b - 1)k}{N_b^m}, \mathcal{W} \left(\frac{(N_b - 1)k}{N_b^m} \right) \right) : 0 \leq k \leq N_b^m - 1, m \in \mathbb{N} \right\} ,$$

and corresponds to the extreme vertices of the polygons at a given step m (i.e., they are the vertices connecting consecutive polygons).

ii. For odd values of N_b , the set of local minima of the Weierstrass function on the interval $[0, 1]$ is given by

$$\left\{ \left(\frac{(N_b - 1)k + \frac{N_b - 1}{2}}{(N_b - 1)N_b^m}, \mathcal{W} \left(\frac{(N_b - 1)k + \frac{N_b - 1}{2}}{(N_b - 1)N_b^m} \right) \right) : 0 \leq k \leq N_b^m - 1, m \in \mathbb{N} \right\},$$

and corresponds to the bottom vertices of the polygons at a given step m .

3 Complex Dimensions, and Associated Series Expansion of the Complexified Weierstrass Function

The following results were obtained in [DL22], as a consequence of the very precise fractal tube formula also obtained in [DL22]. (See Remark 4.7, on page 47 below for an abbreviated version of this fractal tube formula.)

Theorem 3.1 (Complex Dimensions of the Weierstrass Curve [DL22]).

The possible Complex Dimensions of the Weierstrass Curve are all simple, exact, and given as follows:

$$D_{\mathcal{W}} - k(2 - D_{\mathcal{W}}) + im\mathbf{p} \quad , \quad \text{with } k \in \mathbb{N}, m \in \mathbb{Z},$$

$$1 - 2k + im\mathbf{p} \quad , \quad \text{with } k \in \mathbb{N}, m \in \mathbb{Z}, \text{ along with } -2 \text{ and } 0,$$

where $\mathbf{p} = \frac{2\pi}{\ln N_b}$ is the oscillatory period of the Weierstrass Curve; see Figure 5, on page 19.

Consequently, since it admits nonreal Complex Dimensions, the Weierstrass Curve is fractal, in the sense of the theory of Complex Dimensions developed in [LvF00], [LvF06], [LvF13], [LRŽ17b] and [Lap19].

Remark 3.1 (Genericity Hypothesis).

For the simplicity of the exposition, we assume implicitly that the values of the parameters λ and N_b are *in general position* – so that, for example, for any $(\ell, k) \in \mathbb{N}^2$, $D_{\mathcal{W}} - k(2 - D_{\mathcal{W}})$ and $1 - 2k$ be all distinct. For the exceptional cases, see the corresponding discussion in [DL22].

Definition 3.1 (Cohomological Vertex Integer [DL24c]).

Given $m \in \mathbb{N}$, and a vertex $M_{j,m} = M_{(N_b - 1)k' + k'', m} \in V_m$, of abscissa $\left((N_b - 1)k' + k'' \right) \varepsilon_m^m$, where $0 \leq k' \leq N_b^m - 1$ and $0 \leq k'' \leq N_b - 1$, we introduce the *cohomological vertex integer* $\ell_{j,m}$ associated to the vertex $M_{j,m}$ (which is also the $(k'')^{\text{th}}$ vertex of the polygon $\mathcal{P}_{m,k'}$; see part *iv.* of Property 2.4, on page 8), as

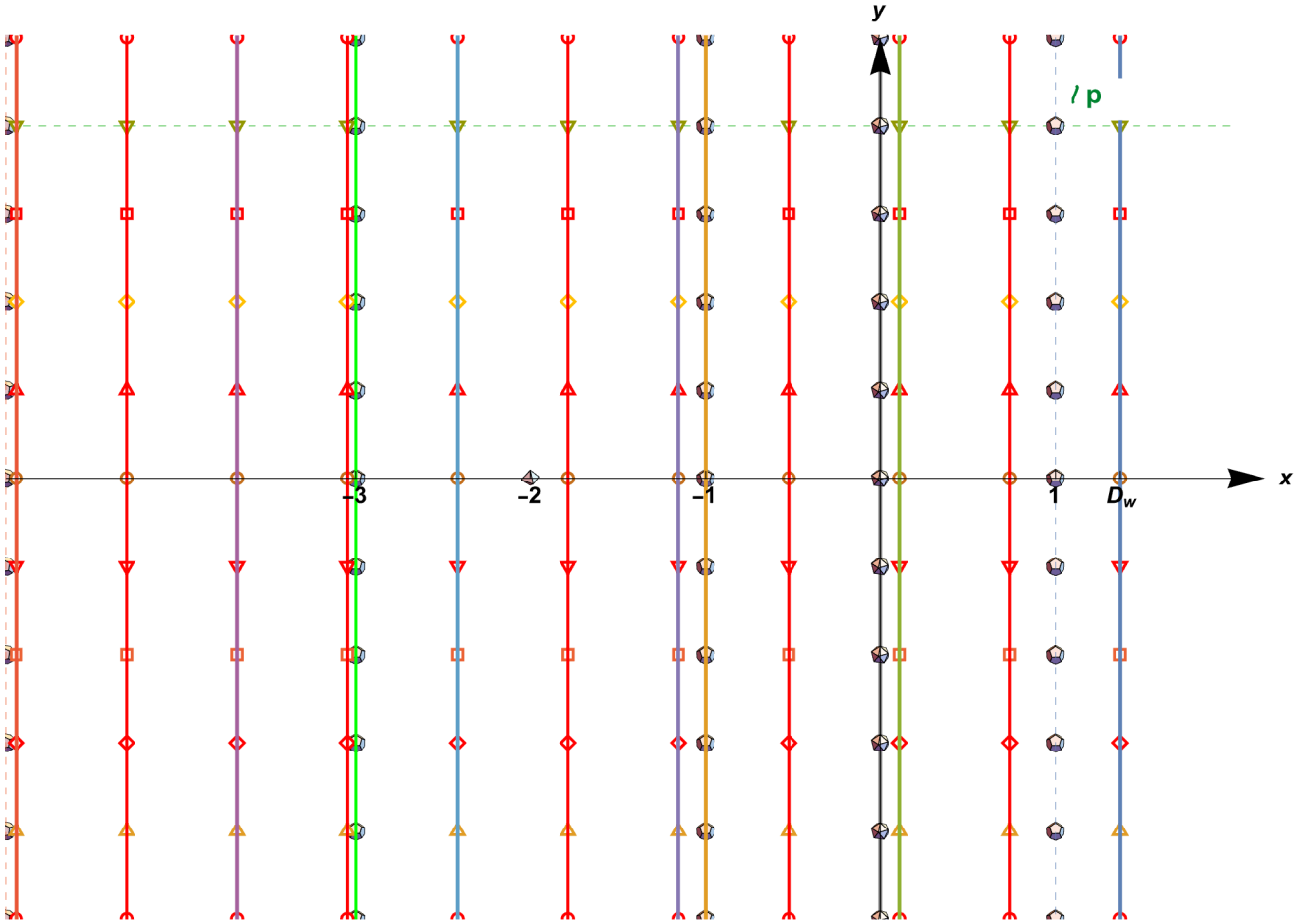


Figure 5: **The Complex Dimensions of the Weierstrass Curve.** The nonzero Complex Dimensions are periodically distributed (with the same period $p = \frac{2\pi}{\ln N_b}$, the oscillatory period of $\Gamma_{\mathcal{W}}$) along countably many vertical lines, with abscissae $D_{\mathcal{W}} - k(2 - D_{\mathcal{W}})$ and $1 - 2k$, where $k \in \mathbb{N}$ is arbitrary. In addition, 0 and -2 are Complex Dimensions of $\Gamma_{\mathcal{W}}$, but are not depicted here.

$$\ell_{j,m} = \ell_{k',k'',m} = (N_b - 1)k' + k'' . \quad (3)$$

$$\left((N_b - 1)k' + k'' \right) \varepsilon_m^m = \left((N_b - 1)k' \text{bis} + k'' \text{bis} \right) \varepsilon_{m+1}^{m+1} .$$

Depending on the context; that is,

- i.* when the cohomological vertex integer enables one to locate the vertex $M_{j,m}$.
- ii.* When it is used in a more general framework, i.e., in order to describe the generators of cohomology groups (see [DL24b]);

we will use the best suited notation between $\ell_{j,m}$, in case *i.*, or $\ell_{k',k'',m}$, in case *ii.*

Proposition 3.2 (Cross-Scales Paths, and Associated Sequence of Vertex Integers).

Given $m \in \mathbb{N}$, $0 \leq j \leq \#V_m - 1$ and a vertex $M_{j,m} = M_{(N_b-1)k'+k'',m}$ in V_m , with $0 \leq k' \leq N_b^m - 1$ and $0 \leq k'' \leq N_b - 1$, we introduce the cross-scales path $\mathcal{P}ath(P_{k'}, M_{j,m})$, where $P_{k'}$ is the (k') th fixed point of the map $T_{k'}$ (see Proposition 2.2, on page 7, along with Notation 6, on page 7), as the ordered set $(M_{j_{k,m},k})_{0 \leq k \leq m}$ such that:

i. For $0 \leq k \leq m$, each vertex $M_{j_{k,m},k}$ is in $V_k \setminus V_k \cap V_m$ (which means that $M_{j_{k,m},k}$ strictly belongs to V_k , i.e., it is in the k^{th} prefractal approximation $\Gamma_{\mathcal{W}_k}$, and not in $\Gamma_{\mathcal{W}_{k+1}}$).

ii. For $1 \leq k \leq m$, each vertex $M_{j_{k,m},k} = M_{(N_b-1)k'_{k,m}+k'',k}$, with $0 \leq k'_{k,m} \leq N_b^k - 1$, is the image of the point $M_{j_{k-1,m},k-1}$ under the map T_i (see again Proposition 2.2, on page 7), where $i \in \{0, \dots, N_b - 1\}$ is the smallest admissible value. We thus also have that

$$M_{j_{k-1,m},k-1} = \left(\frac{(N_b - 1) (k'_{k,m} - i(N_b - 1)N_b^{k-1}) + k''}{(N_b - 1)N_b^{k-1}}, \mathcal{W} \left(\frac{(N_b - 1) (k'_{k,m} - i(N_b - 1)N_b^{k-1}) + k''}{(N_b - 1)N_b^{k-1}} \right) \right).$$

This latter point is also **the (k'') th vertex of the polygon $k'_{k,m} - i(N_b - 1)N_b^{k-1}$** (see part iv. of Property 2.4, on page 8).

The sequence of vertex integers associated with the cross-scales path $\mathcal{P}ath(P_{k'}, M_{j,m})$ (or, in short, and equivalently, also referred to as the sequence of vertex integers associated with $M_{j,m}$) is the sequence $(\ell_{j_{k,m},k})_{0 \leq k \leq m}$, where, for $0 \leq k \leq m$, $\ell_{j_{k,m},k}$ is the cohomological vertex integer associated with the vertex $M_{j_{k,m},k}$ (see Definition 3.1, on page 18).

The next result is new and will play a key role in the rest of this paper (see, especially, Theorem 4.3, on page 33 below and its proof), as well as in one of its sequels, [DLO23]. We refer to Definition 2.2, on page 6 above for the definition of \mathcal{W}_{comp} .

Theorem 3.3 (Complex Dimensions Series Expansion of the Complexified Weierstrass function \mathcal{W}_{comp} and of the Weierstrass function \mathcal{W}).

For any sufficiently large positive integer m (i.e., for all $m \geq m_0$, with $m_0 \in \mathbb{N}^*$ optimal) and for any j in $\{0, \dots, \#V_m - 1\}$, we have the following fractal power series exact expansion, indexed by the Complex Codimensions $k(D_{\mathcal{W}} - 2) + i k \ell_{j_{k,m},k} \mathbf{P}$, with $0 \leq k \leq m$,

$$\begin{aligned} \mathcal{W}_{comp}(j \varepsilon_m^m) &= \mathcal{W}_{comp} \left(\frac{j \varepsilon^m}{N_b - 1} \right) \\ &= \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}_{comp} \left(\frac{j}{N_b - 1} \right) + \sum_{k=0}^{m-1} c_{k,j,m} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{i \ell_{k,j,m} \mathbf{P}} \\ &= \sum_{k=0}^m c_{k,j,m} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{i \ell_{k,j,m} \mathbf{P}}, \end{aligned} \tag{4}$$

where, for $0 \leq k \leq m$, ε^k is the k^{th} intrinsic cohomology infinitesimal, introduced in Definition 4.6, on page 32, with $\mathbf{p} = \frac{2\pi}{\ln N_b}$ denoting the oscillatory period of the Weierstrass Curve, as introduced in [DL22] and where:

i. $\ell_{j_k, m, k} \in \mathbb{Z}$ is the cohomological vertex integer associated with the vertex $M_{j_k, m, k}$ (see Definition 3.1, on page 18, along with Proposition 3.2, on page 20).

ii. $c_{m, j, m} = \mathcal{W}_{\text{comp}}\left(\frac{j}{N_b - 1}\right)$ and, for $0 \leq k \leq m - 1$, $c_{k, j, m} \in \mathbb{C}$ is given by

$$c_{k, j, m} = \exp\left(\frac{2i\pi}{N_b - 1} j \varepsilon^{m-k}\right); \quad (5)$$

for $0 \leq k \leq m$, the coefficient $c_{k, j, m}$ will also be referred to as the k^{th} Weierstrass coefficient associated with the vertex $M_{j_k, m, k} \in V_k$.

For any $m \in \mathbb{N}$, the complex numbers $\{c_{0, j, m+1}, \dots, c_{m+1, j, m+1}\}$ satisfy the following recurrence relations:

$$c_{m+1, j, m+1} = \mathcal{W}\left(\frac{j}{N_b - 1}\right) = c_{m, j, m} \quad (6)$$

and

$$\forall k \in \{1, \dots, m\} : \quad c_{k, j, m+1} = c_{k-1, j, m}. \quad (7)$$

In addition, since relation (4) is valid for any $m \in \mathbb{N}^*$ (and since, clearly, relation (5) implies that the coefficients $c_{k, j, m}$ are nonzero for $0 \leq k \leq m$), we deduce that the associated Complex Dimensions (i.e., in fact, the Complex Dimensions associated with the complexified Weierstrass function) are

$$D_{\mathcal{W}} - k(2 - D_{\mathcal{W}}) + i \ell_{j_k, m, k} \mathbf{p} \quad (8)$$

where $0 \leq j \leq \#V_m - 1$, $0 \leq k \leq m$ and $\ell_{j_k, m, k} \in \mathbb{Z}$ is the cohomological vertex integer associated with the vertex $M_{j_k, m, k}$ (see Definition 3.1, on page 18, along with Proposition 3.2, on page 20).

This immediately ensures, for the Weierstrass function (i.e., the real part of the Complexified Weierstrass function $\mathcal{W}_{\text{comp}}$), that, for any strictly positive integer m and for any j in $\{0, \dots, \#V_m - 1\}$,

$$\begin{aligned} \mathcal{W}(j \varepsilon_m^m) &= \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}_{\text{comp}}\left(\frac{j}{N_b - 1}\right) + \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \operatorname{Re}\left(c_{k, j, m} \varepsilon_k^{i \ell_{j_k, m, k} \mathbf{p}}\right) \\ &= \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}_{\text{comp}}\left(\frac{j}{N_b - 1}\right) + \frac{1}{2} \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \left(c_{k, j, m} \varepsilon^{i \ell_{j_k, m, k} \mathbf{p}} + \overline{c_{k, j, m}} \varepsilon^{-i \ell_{j_k, m, k} \mathbf{p}}\right) \\ &= \frac{1}{2} \sum_{k=0}^m \varepsilon^{k(2-D_{\mathcal{W}})} \left(c_{k, j, m} \varepsilon^{i \ell_{j_k, m, k} \mathbf{p}} + \overline{c_{k, j, m}} \varepsilon^{-i \ell_{j_k, m, k} \mathbf{p}}\right). \end{aligned} \quad (9)$$

More generally, for any strictly positive integer m and for any integer j ,

$$\mathcal{W}_{\text{comp}}(j \varepsilon^m) = \sum_{k=0}^{\infty} \varepsilon^{k(2-D_{\mathcal{W}})} c_{k, j, m} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{i \ell_{j_k, m, k} \mathbf{p}}, \quad (10)$$

where, for all $k \in \mathbb{N}$,

$$c_{k,j,m} = \varepsilon^{2i\pi N_b^k j \varepsilon^m}. \quad (11)$$

In addition, the Complex Dimensions associated with the (actual) Weierstrass function \mathcal{W} , are all exact and simple. Furthermore, they are given as in (8) above, on page 21, except for the fact that $i\ell_{j_k,m,k} \mathbf{p}$ should be replaced by $\pm i\ell_{j_k,m,k} \mathbf{p}$. Accordingly, as should be the case, the nonreal Complex Dimensions of the Weierstrass function come in complex conjugate pairs.

In particular, for any $k \in \mathbb{N}$, the only real Complex Dimension of \mathcal{W} with abscissa $d_k = D_{\mathcal{W}} - k (2 - D_{\mathcal{W}})$ is d_k itself, while the other Complex Dimensions of \mathcal{W} with abscissa d_k consist of countably many non-real complex conjugate pairs.

Proof. Thanks to Property 2.7, on page 12 (the Scaling Property of the Weierstrass function \mathcal{W}), for any strictly positive integer m and any j in $\{0, \dots, \#V_m - 1\}$, we then have that

$$\mathcal{W}\left(\frac{j}{(N_b - 1)N_b^m}\right) = \lambda^m \mathcal{W}\left(\frac{j}{N_b - 1}\right) + \sum_{k=0}^{m-1} \lambda^k \cos\left(\frac{2\pi N_b^k j}{(N_b - 1)N_b^m}\right).$$

By using the Minkowski Dimension $D_{\mathcal{W}}$ introduced in Notation 5, on page 6, this latter expression can be rewritten as

$$\begin{aligned} \mathcal{W}(j \varepsilon_m^m) &= N_b^{m(D_{\mathcal{W}}-2)} \mathcal{W}\left(\frac{j}{N_b - 1}\right) + \sum_{k=0}^{m-1} N_b^{k(D_{\mathcal{W}}-2)} \cos\left(\frac{2\pi}{N_b - 1} j \varepsilon^{m-k}\right) \\ &= \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b - 1}\right) + \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \cos\left(\frac{2\pi}{N_b - 1} j \varepsilon^{m-k}\right) \\ &= \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b - 1}\right) + \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \mathcal{R}e\left(\exp\left(\frac{2i\pi}{N_b - 1} j \varepsilon^{m-k}\right)\right). \end{aligned}$$

We must then show that there exist complex numbers $\{c_{0,j,m}, \dots, c_{m,j,m}\}$ such that, for any integer k in $\{0, \dots, m\}$,

$$\exp\left(\frac{2i\pi}{N_b - 1} j \varepsilon^{m-k}\right) = c_{k,j,m} \varepsilon^{i\ell_{j_k,m,k} \mathbf{p}} = c_{k,j,m} \exp(i\ell_{j_k,m,k} \mathbf{p} \ln \varepsilon) = c_{k,j,m} \exp(-2i\pi \ell_{j_k,m,k}),$$

where, for $0 \leq k \leq m$, $\ell_{j_k,m,k} \in \mathbb{Z}$ is the cohomological vertex integer associated with the vertex $M_{j_k,m,k}$ (see Definition 3.1, on page 18).

We obviously obtain that $c_{m,j,m} = \mathcal{W}_{comp}\left(\frac{j}{N_b - 1}\right)$ and that, for $0 \leq k \leq m - 1$,

$$c_{k,j,m} = \exp\left(\frac{2i\pi}{N_b - 1} j \varepsilon^{m-k}\right).$$

We note that, since, for any positive integer m and any j in $\{0, \dots, \#V_m - 1\}$ (see Property 2.7, on page 12),

$$\mathcal{W}_{comp}\left(\frac{j}{(N_b - 1)N_b^{m+1}}\right) = \lambda \mathcal{W}\left(\frac{j}{(N_b - 1)N_b^m}\right) + \exp\left(\frac{2\pi j}{(N_b - 1)N_b^{m+1}}\right),$$

this ensures that

$$\begin{aligned}
\mathcal{W}_{comp}\left(\frac{j}{(N_b-1)N_b^{m+1}}\right) &= \lambda \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b-1}\right) + \lambda \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \exp\left(\frac{2i\pi}{N_b-1} j \varepsilon^{m-k}\right) \\
&\quad + \exp\left(\frac{2\pi j}{(N_b-1)N_b^{m+1}}\right) \\
&= \varepsilon^{2-D_{\mathcal{W}}} \varepsilon^{m(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b-1}\right) + \varepsilon^{2-D_{\mathcal{W}}} \sum_{k=0}^{m-1} \varepsilon^{k(2-D_{\mathcal{W}})} \exp\left(\frac{2i\pi}{N_b-1} j \varepsilon^{m-k}\right) \\
&\quad + \exp\left(\frac{2\pi j}{(N_b-1)N_b^{m+1}}\right) \\
&= \varepsilon^{(m+1)(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b-1}\right) + \sum_{k=0}^{m-1} \varepsilon^{(k+1)(2-D_{\mathcal{W}})} \exp\left(\frac{2i\pi}{N_b-1} j \varepsilon^{m+1-k-1}\right) \\
&\quad + \exp\left(\frac{2\pi j}{(N_b-1)N_b^{m+1}}\right) \\
&= \varepsilon^{(m+1)(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b-1}\right) + \sum_{k=1}^m \varepsilon^{k(2-D_{\mathcal{W}})} \left(\exp\left(\frac{2i\pi}{N_b-1} j \varepsilon^{m+1-k}\right)\right) \\
&\quad + \exp\left(\frac{2\pi j}{(N_b-1)N_b^{m+1}}\right) \\
&= \varepsilon^{(m+1)(2-D_{\mathcal{W}})} \mathcal{W}\left(\frac{j}{N_b-1}\right) + \sum_{k=0}^m \varepsilon^{k(2-D_{\mathcal{W}})} \left(\exp\left(\frac{2i\pi}{N_b-1} j \varepsilon^{m+1-k}\right)\right).
\end{aligned}$$

At the same time, we have that

$$\mathcal{W}_{comp}\left(\frac{j}{(N_b-1)N_b^{m+1}}\right) = \sum_{k=0}^{m+1} c_{k,j,m+1} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{i\ell_{k,j,m+1}\mathbf{P}},$$

We thus deduce that the stated recurrence relations (6), on page 21, hold:

$$c_{m+1,j,m+1} = \mathcal{W}\left(\frac{j}{N_b-1}\right) = c_{m,j,m}$$

and that, for $1 \leq k \leq m+1$,

$$c_{k,j,m+1} = c_{k-1,j,m} \quad , \quad \varepsilon^{i\ell_{k,j,m+1,k}\mathbf{P}} = \varepsilon^{i\ell_{k,j,m,k}\mathbf{P}}.$$

Note that, by using the series expansion of the Weierstrass function, we also obtain that, since, for any positive integer m and any integer j ,

$$\mathcal{W}_{comp}(j \varepsilon^m) = \sum_{k=0}^{\infty} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{2i\pi N_b^k j \varepsilon^m},$$

which can be written in the following form,

$$\mathcal{W}_{comp}(j \varepsilon^m) = \sum_{k=0}^{\infty} \varepsilon^{k(2-D_{\mathcal{W}})} c_{k,j,m} \varepsilon^{k(2-D_{\mathcal{W}})} \varepsilon^{i \ell_{j,k,m,k} \mathbf{P}},$$

where, for all $k \in \mathbb{N}$,

$$c_{k,j,m} = \varepsilon^{2i\pi N_b^k j \varepsilon^m}.$$

This yields the identity (4), on page 20, in particular.

The statements concerning the Complex Dimensions of the complexified and of the ordinary Weierstrass function follow at once (in the latter case, by taking the real part of identity (4), on page 20, in order to obtain (8), on page 21). □

Remark 3.2. One may note that only the Complex Dimensions $D_{\mathcal{W}} - k(2 - D_{\mathcal{W}}) + i \ell_{j,k,m,k} \mathbf{P}$ (resp., $D_{\mathcal{W}} - k(2 - D_{\mathcal{W}}) \pm i \ell_{j,k,m,k} \mathbf{P}$), where $m \in \mathbb{N}$ is arbitrary, are involved in the expansion obtained in Theorem 3.3, on page 20, in the case of the complexified (resp., ordinary) Weierstrass function \mathcal{W}_{comp} (resp., \mathcal{W}). This calls for the existence, among the set of Complex Dimensions of the ordinary Weierstrass Curve $\Gamma_{\mathcal{W}}$, of a subset of Complex Dimensions only associated with the Weierstrass function \mathcal{W} (as opposed to the Curve $\Gamma_{\mathcal{W}}$). Such a result seems natural, in light of the possible interpretation of the Complex Dimensions given in [DL22]: the vertical line $x = 0$ (i.e., the Complex Dimensions of $\Gamma_{\mathcal{W}}$ with real part 0) corresponds to oscillations coming from *points* – indeed, at any step m of the prefractal graph approximation, the prefractal graph $\Gamma_{\mathcal{W}_m}$ is, at first, constituted of points; as for the vertical line $x = 1$ (i.e., the Complex Dimensions of $\Gamma_{\mathcal{W}}$ with real part 1), it corresponds to oscillations coming from *lines* (or, rather, line segments): indeed, at any step m of the prefractal graph approximation, the polygonal curve $\Gamma_{\mathcal{W}_m}$ is constituted of line segments, in an Euclidean space of dimension two.

4 Fractal Cohomology

4.1 Review and Preliminaries

For the benefit of the reader who may not be familiar with mathematical notions pertaining to cohomology, we shall first recall several relevant definitions. For a comprehensive and accessible introduction to standard cohomology theory, we refer the interested reader to [GQ22].

Definition 4.1 (\mathcal{A} -Module of p -Fermions on a General Topological Space [DL23c]).

Given a ring \mathcal{A} of characteristic different from 2, a general topological space X , along with a nonnegative integer p , we call p -fermion on X , with values in \mathcal{A} , any antisymmetric map f from X^{p+1} to \mathcal{A} , i.e., such that, for any transposition τ of $\{0, \dots, p\}$ and any (x_0, \dots, x_p) in X^{p+1} ,

$$f(x_0, \dots, x_p) = -f(x_{\tau(0)}, \dots, x_{\tau(p)}).$$

A 0-fermion on X is simply a map f from X to \mathcal{A} . We will henceforth adopt the convention according to which a 0-fermion on X is a 0-antisymmetric map on X .

We then denote by $\mathcal{F}^p(X, \mathcal{A})$ the \mathcal{A} -module of p -fermions on X with values in \mathcal{A} , which makes it an abelian group with respect to the addition, with an external law from $\mathcal{A} \times \mathcal{F}^p(X, \mathcal{A})$ to $\mathcal{F}^p(X, \mathcal{A})$, where

$$\forall (a, b) \in \mathcal{A}^2, \forall (f, g) \in (\mathcal{F}^p(X, \mathcal{A}))^2 : \begin{cases} a(f + g) &= a f + a g, \\ (a + b)f &= a f + b f. \end{cases}$$

Definition 4.2 (*p -differential, Complex of Fermions, and Associated Cohomology [DL23c]*).

Given a ring \mathcal{A} of characteristic different from 2, a general topological space X and a nonnegative integer p , we define the *p -differentials* δ^p from $\mathcal{F}^p(X, \mathcal{A})$ to $\mathcal{F}^{p+1}(X, \mathcal{A})$, for any f in $\mathcal{F}^p(X, \mathcal{A})$, by

$$\forall (x_0, \dots, x_{p+1}) \in X^{p+2} : \delta^p(f)(x_0, \dots, x_{p+1}) = c_p \left(\sum_{q=0}^p (-1)^q f(\dots, x_{q-1}, x_{q+1}, \dots) \right),$$

where $c_p \in \mathcal{A}$ denotes a positive constant, the value of which is defined only when necessary. In the present paper, the precise value of $c_p \in \mathcal{A}$ is not important.

Note that the 0-differential δ^0 , from $\mathcal{F}^0(X, \mathcal{A})$ to $\mathcal{F}^1(X, \mathcal{A})$, is defined, for any f in $\mathcal{F}^0(X, \mathcal{A})$, by

$$\forall (x_0, x_1) \in X^2 : \delta^0(f)(x_0, x_1) = c_0 (f(x_1) - f(x_0)).$$

A key property is that

$$\forall p \in \mathbb{N} : \delta^{p+1} \circ \delta^p = 0.$$

The so-called (cochain) *Complex* $(\mathcal{F}^\bullet(X, \mathcal{A}), \delta^\bullet)$ is the following algebraic structure, which consists in a sequence of abelian groups (or, here, \mathcal{A} -modules) $(\mathcal{F}^p(X, \mathcal{A}))_{p \in \mathbb{N}}$, where, for each integer $p \in \mathbb{N}$, the group $\mathcal{F}^p(X, \mathcal{A})$ is connected to the group $\mathcal{F}^{p+1}(X, \mathcal{A})$ by means of the p -differential δ^p ; namely,

$$\mathcal{F}^0 \xrightarrow{\delta^0} \dots \mathcal{F}^p \xrightarrow{\delta^p} \mathcal{F}^{p+1} \xrightarrow{\delta^{p+1}} \dots$$

We then set

$$\mathcal{F}^\bullet(X, \mathcal{A}) = \bigoplus_{p=0}^{\infty} \mathcal{F}^p(X, \mathcal{A}).$$

The associated group cohomology, i.e., the set consisting of $\ker \delta^0$ and of the p -cohomology groups $\ker \delta^{p+1} / \text{Im } \delta^p$, $p \in \mathbb{N}^\star$, is denoted by

$$H^\bullet(\mathcal{F}^\bullet(X, \mathcal{A}), \delta^\bullet).$$

4.2 General Considerations: h -Cohomology and Complex Dimensions

In [DL23c], we evoked a prefractal cohomology where the cohomology groups were of the form

$$\ker \delta^{\#V_m} / \text{Im } \delta^{\#V_{m-1}}, \quad m \in \mathbb{N}^\star.$$

In doing so, we joined the approach developed by Michel L. Lapidus and Machiel van Franken-
huisjen in [LvF13], [LvF06] and [LvF00], where the authors suggest that there should exist a fractal
cohomology having direct links with the theory of Complex Dimensions. Recall from the introduc-
tion that further results along these lines have been obtained by Michel L. Lapidus and Tim Cobler
in [CL17]; see also [Lap19] and, especially, the second author's forthcoming book, [Lap24].

Undoubtedly, in our present setting, such a cohomology exists, as will be shown in this section.
However, it is interesting to look at Figure 5, on page 19, not *vertically*, but *horizontally*, i.e., along
a line $y = m \mathbf{p}$, $m \in \mathbb{Z}$. And then, things look rather different: this horizontal line travels across all
the vertical lines

$$x = D_{\mathcal{W}} - k (2 - D_{\mathcal{W}}) \quad , \text{ for } k \in \mathbb{N} .$$

As explained just above, one may infer that topological invariants, as the intrinsic objects of any
cohomology theory, have to be searched along the aforementioned horizontal line, $y = m \mathbf{p}$ ($m \in \mathbb{N}$);
which means, for a given purely imaginary mode, their *conservation* when switching from the m^{th}
prefractal graph, to the $(m + 1)^{\text{th}}$ one. From a physical point of view, this makes sense. So, one could
think of a cohomology as being indexed by the purely imaginary modes.

With regard to the real parts of the Complex Dimensions, one must bear in mind that they
are nothing but the values of the maximal orders of differentiation. Differentiation, through the
Dirac operator, is directly connected to the maximal length between adjacent vertices of a given m^{th}
prefractal graph approximation, which decreases proportionally to $N_b^{-m(2-D_{\mathcal{W}})}$ when one switches
from the m^{th} prefractal graph, to the $(m + 1)^{\text{th}}$ one. This point will next be taken into account
through our concept of *generalized fermions*. Henceforth, the ring \mathcal{A} discussed above is chosen to
be $\mathcal{A} = \mathbb{C}$, the field of complex numbers.

We point out that, in the present paper (and by contrast with [DL22]), the aforementioned vertical
lines will be replaced by the vertical lines

$$x = -k (2 - D_{\mathcal{W}}) \quad , \text{ for } k \in \mathbb{N} ,$$

while the above horizontal lines will be replaced by the horizontal lines $y = \ell_m \mathbf{p}$, for $m \in \mathbb{N}$ and some
suitable choice of $\ell_m \in \mathbb{Z}$; see, especially, Theorem 4.3, on page 33 and Theorem 4.11, on page 53,
along with Definition 4.8, on page 44, and Proposition 4.5, on page 44 below.

Definition 4.3 ((m, p)-Fermion (Generalization of Definition 4.1, given on page 24)).

By analogy with particle physics, given a pair of integers (m, p) , with $m \in \mathbb{N}$ and $p \in \mathbb{N}^*$, we will
call (m, p) -fermion on V_m , with values in \mathbb{C} , any antisymmetric map f from V_m^{p+1} to \mathbb{C} . Note that
these maps are not assumed to be multilinear (which would be meaningless here, anyway).

For any $m \in \mathbb{N}$, an $(m, 0)$ -fermion on V_m (or a 0-fermion, in short) is simply a map f from V_m
to \mathbb{C} . As in Definition 4.1, on page 24, we adopt the convention according to which a 0-fermion on V_m
is a 0-antisymmetric map on V_m .

In the sequel, for any $(m, p) \in \mathbb{N}^2$, we will denote by $\mathcal{F}^p(V_m, \mathbb{C})$ the \mathbb{C} -module (i.e., the complex
vector space) of (m, p) -fermions on V_m , with values in \mathbb{C} , which makes it an abelian group with
respect to the addition, with an external law from $\mathbb{C} \times \mathcal{F}^p(V_m, \mathbb{C})$ to $\mathcal{F}^p(V_m, \mathbb{C})$, given at the end of
Definition 4.1, on page 24 (with $\mathcal{A} = \mathbb{C}$).

4.3 Differentials

One now has to define a proper notion of differential. The problem is a bit more complicated than in our previous work [DL23c], since one does not deal with a fixed space: at stake are the prefractals $\Gamma_{\mathcal{W}_m}$, $m \in \mathbb{N}$.

We now adapt and expand the theory in order to be able to apply it to suitable fractals – and, in particular, in this paper, to the Weierstrass Curve $\Gamma_{\mathcal{W}}$ and its sequence of prefractal approximations.

In order to understand how things go, one may look at the initial polygon \mathcal{P}_0 : this polygon has exactly N_b vertices, which mean, in terms of potential topological invariants (under the form of a complex-valued function f defined on the whole set of vertices $\{M_{j,m}, 0 \leq j \leq \#V_m - 1, m \in \mathbb{N}\}$ of the m^{th} prefractal approximation $\Gamma_{\mathcal{W}_m}$), a number which will – or not – be conserved when switching to $\Gamma_{\mathcal{W}_1}$.

This can be achieved by examining the following quantities (see Figure 6, on page 28):

$$f(P_j) - f(M_{1,1}) + f(M_{2,1}) \dots + (-1)^{N_b-1} f(P_{j+1}), \text{ with } 0 \leq j \leq N_b,$$

where the points P_j , for $0 \leq j \leq N_b - 1$, are the vertices of \mathcal{P}_0 ; namely, they are the fixed points of the underlying maps T_j in the i.f.s. $\mathcal{T}_{\mathcal{W}} = \{T_0, \dots, T_{N_b-1}\}$; see Notation 6, on page 7, and Definition 2.3, on page 7.

One thus deals with alternate (i.e., antisymmetric) expressions with $N_b + 1$ terms.

When reaching the m^{th} prefractal graph, with $m \geq 1$, one will also have to examine quantities of the following form (see Figure 7, on page 28):

$$f(M_{i,m-1}) - f(M_{j,m}) + f(M_{j+1,m}) \dots + (-1)^{N_b-1} f(M_{i+1,m-1}),$$

for $0 \leq i \leq \#V_{m-1} - 1$, and where (with the notation of Definition 2.4, on page 8 above)

$$M_{i,m-1} \underset{m}{\sim} M_{i+1,m-1},$$

while, at the same time,

$$M_{i,m-1} \underset{m-1}{\sim} M_{j,m} \quad , \quad M_{j,m} \underset{m-1}{\sim} M_{j+1,m} \quad , \quad \dots ,$$

which means that the points $M_{i,m-1}$ and $M_{i+1,m-1}$ are consecutive vertices of V_{m-1} , and that the set of consecutive vertices of V_m located strictly between $M_{i,m-1}$ and $M_{i+1,m-1}$ consists of the points $M_{j,m}, M_{j+1,m}, \dots$; and so on.

Definition 4.4 (($m - 1, m$)-Path).

Given a strictly positive integer m , and two adjacent vertices $X_{m-1,k}, X_{m-1,k+1}$ in V_{m-1} , for $0 \leq k \leq \#V_{m-1} - 2$, we call ($m - 1, m$)-path between $X_{m-1,k}, X_{m-1,k+1}$ the ordered set of vertices

$$\mathcal{P}_{m-1,m}(X_{m-1,k}, X_{m-1,k+1}) = \{X_{m,\ell}, 0 \leq \ell \leq N_b\},$$

where

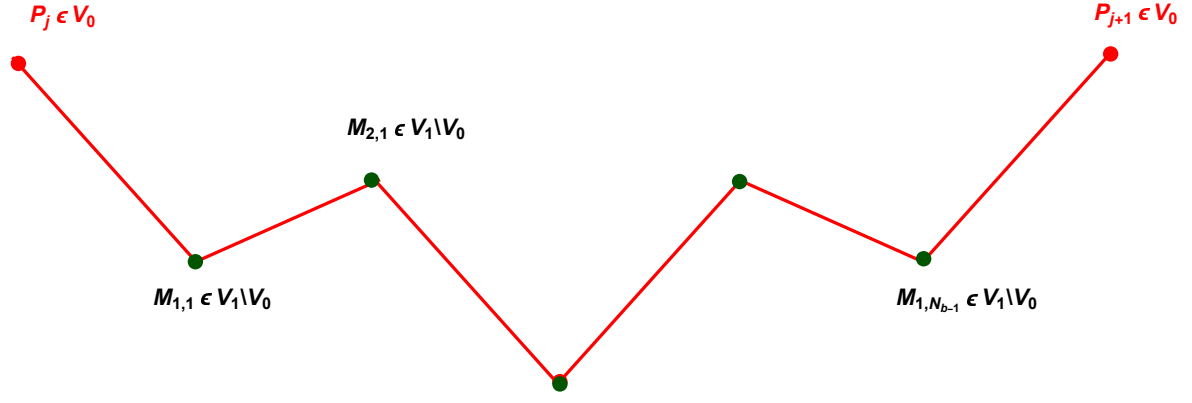


Figure 6: In search of invariants, when switching from the initial prefractal graph, to the first one.

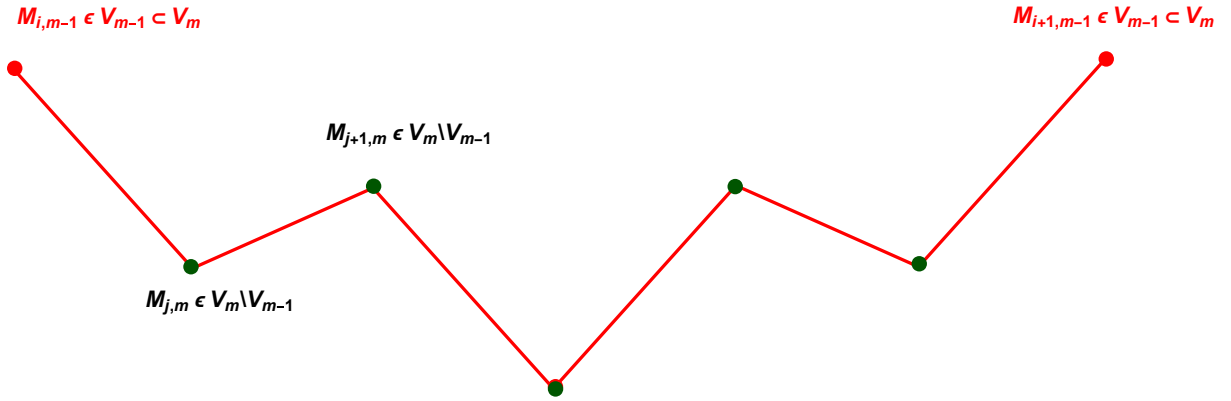


Figure 7: In search of invariants, when switching from the $(m - 1)^{th}$ prefractal graph, to the m^{th} one.

$$X_{m,\ell} = X_{m-1,k} \quad \text{and} \quad X_{m,\ell+N_b} = X_{m-1,k+1};$$

see Figure 7, on page 28.

Definition 4.5 ($(m - 1, m)$ and $(m - k, m)$ -Differentials).

Given a strictly positive integer m , we define the $(m - 1, m)$ -differential $\delta_{m-1,m}$ from $\mathcal{F}^0(V_m, \mathbb{C})$ to $\mathcal{F}^{N_b+1}(V_m, \mathbb{C})$, for any f in $\mathcal{F}^0(\Gamma_{\mathcal{W}}, \mathbb{C})$ and any (ordered set of consecutive vertices)

$$(M_{i,m-1}, M_{i+1,m-1}, M_{j+1,m}, \dots, M_{j+N_b-2,m}) \in V_m^{N_b+1}$$

such that

$$M_{i,m-1} = M_{j,m} \quad \text{and} \quad M_{i+1,m-1} = M_{j+N_b,m},$$

by

$$\delta_{m-1,m}(f)(M_{i,m-1}, M_{i+1,m-1}, M_{j+1,m}, \dots, M_{j+N_b-1,m}) = c_{m-1,m} \left(\sum_{q=0}^{N_b} (-1)^q f(M_{j+q,m}) \right),$$

where $c_{m-1,m}$ denotes a suitable positive constant. Note that as one deals with these differentials in the present paper, one does not need to know – or fix – the value of this constant. It becomes important, however, when operators involving the differentials, such as the Laplacian, are involved; see, for instance, Section 6 of [DL23c].

For $k < m$, we define the $(m-k, m)$ -differential $\delta_{m-k,m}$ from $\mathcal{F}^0(V_m, \mathbb{C})$ to $\mathcal{F}^{N_b^k+1}(V_m, \mathbb{C})$, for any f in $\mathcal{F}^0(V_m, \mathbb{C})$ and any $(M_{i,m-k}, M_{i+1,m-k}, M_{j+1,m}, \dots, M_{j+k(N_b-1)-1,m}) \in V_m^{N_b^k+1}$ such that

$$M_{i,m-k} = M_{j,m} \quad \text{and} \quad M_{i+1,m-k} = M_{j+N_b^k,m},$$

by

$$\delta_{m-k,m}(f) \left(M_{i,m-k}, M_{i+1,m-k}, M_{j+1,m}, \dots, M_{j+N_b^k-1,m} \right) = c_{m-k,m} \left(\sum_{q=0}^{N_b^k} (-1)^q f(M_{j+q,m}) \right),$$

where $c_{m-k,m}$ denotes a suitable positive constant. Again, we will not need to specify its value here.

By induction, we can, equivalently, consider the $(0, 1)$ -differential $\delta_{0,1}$ from $\mathcal{F}^0(V_0, \mathbb{C})$ to $\mathcal{F}^{N_b+1}(V_1, \mathbb{C})$, then, the $(1, 2)$ -differential $\delta_{1,2}$ from $\mathcal{F}^{N_b+1}(V_1, \mathbb{C})$ to $\mathcal{F}^{N_b^2+1}(V_2, \mathbb{C})$; and so on, which means that the $(m-1, m)$ -differential $\delta_{m-1,m}$ is defined from $\mathcal{F}^{N_b^{m-1}+1}(V_{m-1}, \mathbb{C})$ to $\mathcal{F}^{N_b^m+1}(V_m, \mathbb{C})$, for any $m \in \mathbb{N}^*$. In fact, at a given step $m \geq 0$, between two adjacent vertices of V_m , there are $N_b - 1$ consecutive vertices of $V_{m+1} \setminus V_m$. Hence, this results in $N_b - 1 + 2 = N_b + 1$ consecutive vertices of $V_{m+1} \supset V_m$. Among those $N_b + 1$ vertices, there are then N_b pairs of consecutive vertices of $V_{m+1} \supset V_m$, which themselves involve N_b^2 pairs of consecutive vertices of $V_{m+2} \supset V_{m+1}$, i.e., $N_b^2 + 1$ consecutive vertices of $V_{m+2} \supset V_{m+1} \supset V_m$; and so on, by induction.

Remark 4.1. Note that because of the density of the set $V^* = \bigcup_{n \in \mathbb{N}} V_n$ in the Weierstrass Curve $\Gamma_{\mathcal{W}}$ (see Property 2.5, on page 11), and since $\Gamma_{\mathcal{W}}$ is compact, a continuous – and hence, also, uniformly continuous – function defined on the Weierstrass Curve is obviously uniquely defined by its restriction to each set V_m , for $m \in \mathbb{N}$ (i.e., by its restriction to V^*). This topological property will be crucial in the formulation of the forthcoming prefractal cohomology to be introduced in Section 4.4 just below.

Conversely, any (uniformly) continuous function on V^* can be uniquely extended to a necessarily uniformly continuous function on the compact set $\Gamma_{\mathcal{W}} \subset \mathbb{R}^2$.

4.4 Fractal Complex, and Cohomology Groups

Proposition 4.1 (Fractal Complex).

Hereafter, the (cochain) Complex involved, denoted by $(\mathcal{F}^\bullet(\Gamma_{\mathcal{W}}, \mathbb{C}), \delta^\bullet)$ is the algebraic structure, which consists in the sequence of abelian groups (of (m, p) fermions, see Definition 4.3, on page 26) $(\mathcal{F}^{N_b^m+1}(V_m, \mathbb{C}))_{m \in \mathbb{N}}$, where, for each integer $m \geq 2$, the group $\mathcal{F}^{N_b^{m-1}+1}(V_{m-1}, \mathbb{C})$ is connected to the group $\mathcal{F}^{N_b^m+1}(V_m, \mathbb{C})$ by means of the $(m-1, m)$ -differentials $\delta_{m-1,m}$ introduced in Definition 4.5, on page 28, and viewed as group homomorphisms; namely,

$$\mathcal{F}^0(V_0, \mathbb{C}) \xrightarrow{\delta_{0,1}} \dots \mathcal{F}^{N_b^m+1}(V_m, \mathbb{C}) \xrightarrow{\delta_{m-1,m}} \mathcal{F}^{N_b^{m+1}+1}(V_{m+1}, \mathbb{C}) \xrightarrow{\delta_{m,m+1}} \dots$$

Because of the density of the set $V^\star = \bigcup_{n \in \mathbb{N}} V_n$ in the Weierstrass Curve $\Gamma_{\mathcal{W}}$ (see Remark 4.1 just above, on page 29), and due to the definition of the differentials in Definition 4.5, on page 28, this complex can also be written in the following form:

$$\mathcal{F}^0(\Gamma_{\mathcal{W}}, \mathbb{C}) \xrightarrow{\delta_{0,1}} \dots \mathcal{F}^{N_b^m+1}(\Gamma_{\mathcal{W}}, \mathbb{C}) \xrightarrow{\delta_{m-1,m}} \mathcal{F}^{N_b^{m+1}+1}(\Gamma_{\mathcal{W}}, \mathbb{C}) \xrightarrow{\delta_{m,m+1}} \dots$$

Proposition 4.2 (Prefractal Cohomology Groups).

Given $m \in \mathbb{N}^\star$, we define the image $Im \delta_{m-2,m-1}$ as the set of antisymmetric maps acting on consecutive vertices $(M_{j,m-1}, \dots, M_{j+N_b^m,m-1})$, with extreme vertices $M_{j,m-1}$ and $M_{j+N_b^m,m-1}$ in V_0 , while the intermediate ones are in $V_{m-1} \setminus V_0$.

In our present setting, with the differential introduced in Definition 4.5, on page 28, the cohomology groups are therefore the quotient groups

$$H^m = \ker \delta_{m-1,m} / Im \delta_{m-2,m-1} \quad , \quad \text{for } m \geq 0 \quad ,$$

which consist in maps the expression of which is obtained as the difference of an antisymmetric map with respect to the set of vertices $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m})$ and of an antisymmetric map with respect to the set of vertices $(M_{i,0}, M_{i+1,0}, M_{j+1,m-1}, \dots, M_{j+N_b^{m-1}-1,m-1})$.

Hereafter, we will use the additional convention that $\delta_{-2,-1} = 0$ and $\delta_{-1,0} = 0$, which ensures that $H^0 = \{0\}$.

Remark 4.2. For any $k \in \mathbb{N}$ and $m \in \mathbb{N}^\star$, the quotient of the Complex Dimensions

$$\frac{k(2 - D_{\mathcal{W}})}{m \mathbf{p}}$$

is also a quotient of frequencies, for oscillatory maps defined on the countable set of vertices $V^\star = \bigcup_{n \in \mathbb{N}} V_n$.

The fundamental frequencies

$$\frac{2 - D_{\mathcal{W}}}{\mathbf{p}}, \frac{1}{\mathbf{p}},$$

respectively associated to oscillations in the vertical and horizontal directions, happen to be proportional to each other.

Proof. The search for invariants amounts in finding oscillatory maps f that are preserved either when switching from the m^{th} prefractal graph to the $(m+1)^{th}$ one, or, alternatively, from the initial prefractal graph to the m^{th} prefractal graph.

Also, because applying the map T_j , for any $j \in \{0, \dots, N_b - 1\}$, corresponds, in the argument of f , to a multiplication by $\frac{1}{N_b}$ in the horizontal direction, and by $\lambda = \left(\frac{1}{N_b}\right)^{2-D_{\mathcal{W}}}$ in the vertical direction, it makes sense to observe that, given a complex number $s = r + it$ (with $(r, t) \in \mathbb{R}^2$), we have that

$$\left(\frac{\lambda}{N_b}\right)^s = e^{m(r+it)(\ln \lambda - \ln N_b)} = \frac{\lambda^r}{N_b^r} e^{-it(2-D_{\mathcal{W}}) \ln N_b} e^{-it \ln N_b}.$$

Note that the frequencies

$$\frac{1}{\mathbf{p}} = \frac{\ln N_b}{2\pi} \quad \text{and} \quad \frac{2 - D_{\mathcal{W}}}{\mathbf{p}}$$

are proportional to each other. □

As a search for topological invariants, a fractal cohomological approach must take into account the specific geometric properties of an object. For our present Fractal Curve $\Gamma_{\mathcal{W}}$, the symmetry with respect to the vertical line $x = \frac{1}{2}$ plays an important role in this setting. Indeed, not only is it present at the initial step of the prefractal graph construction, but it also continues to hold, at a given integer step $m \geq 1$, with the associated polygons $\mathcal{P}_{m,k}$, for $0 \leq k \leq N_b^m - 1$, in the following precise sense:

- i. When the integer N_b is odd, for $0 \leq k \leq \frac{N_b^m - 1}{2}$, the polygons $\mathcal{P}_{m,k}$ and $\mathcal{P}_{m, N_b^m - k}$ are symmetrical ones.
The line $x = \frac{1}{2}$ is also a symmetry axis for the middle polygon $\mathcal{P}_{m, \frac{N_b^m + 1}{2}}$.
- ii. When the integer N_b is even, for $0 \leq k \leq \frac{N_b^m}{2}$, the polygons $\mathcal{P}_{m,k}$ and $\mathcal{P}_{m, N_b^m - k}$ are symmetrical ones.

Another interesting point is that, for $0 \leq k \leq N_b^m - 1$, the *extreme vertices* of $\mathcal{P}_{m,k}$, i.e., the points

$$M_{(N_b-1)k,m} \quad \text{and} \quad M_{(N_b-1)(k+1),m},$$

are also *adjacent points of the prefractal graph of level $m - 1$* :

$$M_{(N_b-1)k+j,m} = M_{(N_b-1)k'+j',m-1} \quad \text{and} \quad M_{(N_b-1)(k+1),m} = M_{(N_b-1)k'+j'+1,m-1},$$

for $0 \leq k' \leq N_b^{m-1} - 1$ and $0 \leq j' \leq N_b - 1$.

Hence, the consecutive edges of $\mathcal{P}_{m,k}$ are nothing but a *path* between $M_{(N_b-1)k+j,m}$ and $M_{(N_b-1)(k+1)+j,m}$. This *deformed path*, in a sense, is the image of the direct one

$$M_{(N_b-1)k'+j',m-1} \rightsquigarrow M_{(N_b-1)k'+j'+1,m-1}.$$

One can go as far as saying that, in some sense, these two paths are *homotopic*.

In this light, it thus seems natural to encode this symmetry in the cohomological approach.

Our forthcoming results (see Theorems 4.3, on page 33, and Theorem 4.11, on page 53 below) highlight the part played, at each step $m \in \mathbb{N}$ of the prefractal graph approximation, by a characteristic

number called the m^{th} *cohomology infinitesimal* (see Definition 4.6, on page 32 just below), in relation with *local scaling zeta functions*; see Definition 4.8, on page 44, and Proposition 4.5, on page 44 below.

Definition 4.6 (m^{th} **Cohomology Infinitesimal and m^{th} Intrinsic Cohomology Infinitesimal [DL23b]).**

From now on, given any $m \in \mathbb{N}$, we will call m^{th} *cohomology infinitesimal* the number $\varepsilon_m^m > 0$ which also corresponds to the elementary horizontal length introduced in part *i.* of Definition 2.5, on page 9; i.e., $\varepsilon_m^m = (\varepsilon_m)^m = \frac{1}{N_b - 1} \frac{1}{N_b^m}$.

Observe that, clearly, ε_m itself – and not just ε_m^m – depends on m .

In addition, since $N_b > 1$, ε_m^m satisfies the following asymptotic behavior,

$$\varepsilon_m^m \rightarrow 0, \text{ as } m \rightarrow \infty,$$

which, naturally, results in the fact that the larger m , the smaller ε_m^m . It is for this reason that we call ε_m^m – or rather, the *sequence* $(\varepsilon_m^m)_{m=0}^\infty$ of positive numbers tending to zero as $m \rightarrow \infty$, with $\varepsilon_m^m = (\varepsilon_m)^m$, for each $m \in \mathbb{N}$ – an *infinitesimal*, called *the cohomology infinitesimal*. Note that this cohomology infinitesimal is the one naturally associated to the scaling relation of Proposition 2.7, on page 12.

In the sequel, it is also useful to keep in mind that the sequence of positive numbers $(\varepsilon_m)_{m=0}^\infty$ itself satisfies

$$\varepsilon_m \sim \frac{1}{N_b}, \text{ as } m \rightarrow \infty ;$$

i.e., $\varepsilon_m \rightarrow \frac{1}{N_b}$, as $m \rightarrow \infty$. In particular, $\varepsilon_m \not\rightarrow 0$, as $m \rightarrow \infty$, but, instead, ε_m tends to a strictly positive and finite limit.

We also introduce, given any $m \in \mathbb{N}$, the m^{th} *intrinsic cohomology infinitesimal*, denoted by $\varepsilon^m > 0$, such that

$$\varepsilon^m = \frac{1}{N_b^m},$$

where

$$\varepsilon = \frac{1}{N_b}.$$

We call ε *the intrinsic scale*, or *intrinsic subdivision scale*.

Note that

$$\varepsilon_m^m = \frac{\varepsilon^m}{N_b - 1}$$

and that the m^{th} *intrinsic cohomology infinitesimal* ε^m is asymptotic (when m tends to ∞) to the m^{th} *cohomology infinitesimal* ε_m^m (up to the positive multiplicative constant $(N_b - 1)$).

Also, $\varepsilon_m \rightarrow \varepsilon$, as $m \rightarrow \infty$.

Remark 4.3. Henceforth, it is useful to view $V^\star = \bigcup_{n \in \mathbb{N}} V_n$ as being densely embedded into the Weierstrass Curve $\Gamma_{\mathcal{W}} \supset V^\star$; see Remark 4.1, on page 29 above for the relevance of this comment to Theorem 4.3, on page 33 just below, as well as to Theorem 4.11, on page 53 further on.

Notation 8 (Argument of a Complex Number).

Given a nonzero complex number z , we denote by $\arg(z)$ the *argument* of z ; i.e., the angle between the positive real axis and the line joining the origin and the point M with affix z . Implicitly, we always choose the same convention (e.g., $\arg(z) \in]-\pi, \pi]$) whenever evaluating $\arg(z)$ – and hence also, $\arg(z) - \arg(z')$, for $(z, z') \in \mathbb{C}^\star \times \mathbb{C}^\star$.

Definition 4.7 (Set of Functions of the Same Nature as the Weierstrass Function \mathcal{W}).

i. We say that a continuous, complex-valued function f , defined on $\Gamma_{\mathcal{W}} \supset V^\star$, is *of the same nature as the Weierstrass function \mathcal{W}* , if it satisfies local Hölder and reverse-Hölder properties analogous to those satisfied by the Weierstrass function \mathcal{W} ; i.e., for any pair of adjacent vertices (M, M') of respective affixes $(z, z') \in \mathbb{C}^2$ of the prefractal graph $\Gamma_{\mathcal{W}_m}$, with $m \in \mathbb{N}$ arbitrary (see Remark 2.2, on page 16),

$$\tilde{C}_{inf} |z' - z|^{2-D_{\mathcal{W}}} \leq |f(z') - f(z)| \leq \tilde{C}_{sup} |z' - z|^{2-D_{\mathcal{W}}},$$

where \tilde{C}_{inf} and \tilde{C}_{sup} denote positive and finite constants (but not necessarily the same ones as for the Weierstrass function \mathcal{W} itself, in Property 2.12, on page 15). This can be written, equivalently, as

$$|z - z'|^{2-D_{\mathcal{W}}} \leq |f(z) - f(z')| \leq |z - z'|^{2-D_{\mathcal{W}}}. \quad (\blacklozenge) \tag{12}$$

Hereafter, we will denote by $\mathcal{H}öld(\Gamma_{\mathcal{W}})$ the set consisting of the continuous, complex-valued functions f , defined on $\Gamma_{\mathcal{W}} \supset V^\star$ and satisfying relation (12); see the discussion just above.

ii. Moreover, we will denote by $\mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}}) \subset \mathcal{H}öld(\Gamma_{\mathcal{W}})$ the subset of $\mathcal{H}öld(\Gamma_{\mathcal{W}})$ consisting of the functions f of $\mathcal{H}öld(\Gamma_{\mathcal{W}})$ which satisfy the following *additional geometric condition* (13), again, for any pair of adjacent vertices (M, M') with respective affixes $(z, z') \in \mathbb{C}^2$ of the prefractal graph V_m , with $m \in \mathbb{N}$ arbitrary; we have that,

$$\left| \arg(f(z)) - \arg(f(z')) \right| \leq |z - z'|^{D_{\mathcal{W}}-1}. \quad (\blackspade) \tag{13}$$

We can now state the following key result.

Theorem 4.3 (Complex Dimensions Series Expansion and Characterization of the Prefractal Cohomology Groups H^m).

Let $m \in \mathbb{N}$ be arbitrary. Then:

i. *Within the set $\mathcal{H}öld(\Gamma_{\mathcal{W}})$ (see part i. of Definition 4.7, on page 33 just above), then, for any integer $m \geq 1$, and with the convention $H^0 = \text{Im } \delta_{-1,0} = \{0\}$, the cohomology groups*

$$H^m = \ker \delta_{m-1,m} / \text{Im } \delta_{m-2,m-1}$$

are comprised of the restrictions to V_m of $(m, N_b^m + 1)$ -fermions, i.e., the restrictions to (the Cartesian product space) $V_m^{N_b^m + 1}$ of antisymmetric maps on $\Gamma_{\mathcal{W}}$, with $N_b^m + 1$ variables (corresponding to the vertices of V_m), involving the restrictions to V_m of continuous functions f on $\Gamma_{\mathcal{W}}$, such that, for any vertex $M_{j,m} \in V_m$, the following Taylor-like expansion is satisfied,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \quad , \quad M_{\star,m} \in V_m, c_k(f, M_{\star,m}) \in \mathbb{C}, \quad (\blacklozenge\blacklozenge) \quad (14)$$

where, for each integer k such that $0 \leq k \leq m$, the number $\varepsilon_k^k > 0$ is the k^{th} cohomology infinitesimal introduced in Definition 4.6, on page 32 above.

The coefficients $c_k(f, M_{\star})$ are complex quantities, which only depend on the function f involved, and on the point M_{\star} at which they are evaluated. As will follow from an obvious modification of Definition 4.8 below, on page 44, these coefficients $c_k(f, M_{\star})$ are the residues (at the possible Complex Dimensions $-k(2 - D_{\mathcal{W}})$) of a suitable global scaling zeta function.

Note that, insofar as the functions f involved are, in a sense, determined, at any vertex $M_{j,m} \in V_m$, by the expansion given in relation (14), it is natural to identify the cohomology groups H^m with those functions also belonging to $\mathcal{H}\ddot{o}ld(\Gamma_{\mathcal{W}})$.

ii. If the functions f of part i. belong to $\mathcal{H}\ddot{o}ld_{geom}(\Gamma_{\mathcal{W}})$ (see part ii. of Definition 4.7, on page 33 above), then, for any strictly positive integer m , and again with the convention $H^0 = \text{Im } \delta_{-1,0} = \{0\}$, the cohomology groups

$$H^m = \ker \delta_{m-1,m} / \text{Im } \delta_{m-2,m-1}$$

are comprised of the restrictions to V_m of $(m, N_b^m + 1)$ -fermions, i.e., the restrictions to $V_m^{N_b^m + 1}$ of antisymmetric maps on $\Gamma_{\mathcal{W}}$, with $N_b^m + 1$ variables (corresponding to the vertices of V_m), involving the restrictions to V_m of continuous functions f on $\Gamma_{\mathcal{W}}$, such that, for any vertex $M_{j,m} \in V_m$,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,m} \mathbf{p}} = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}}) + ik \ell_{k,j,m} \mathbf{p}} \quad , \quad M_{\star,m} \in V_m \quad (15)$$

where \mathbf{p} denotes the oscillatory period introduced in [DL22],

$$\mathbf{p} = \frac{2\pi}{\ln N_b},$$

and where the coefficients $c_k(\star, \star)$ are complex numbers which still depend on the function f involved, and on the point at which they are evaluated. Here, in relation (15), for each integer k such that $0 \leq k \leq m$, $\ell_{k,j,m}$ denotes an integer (in \mathbb{Z}) satisfying the estimate

$$\left| \left\{ k \ell_{k,j,m} \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}. \quad (\heartsuit) \quad (16)$$

The proof of Theorem 4.3, on page 33, will be given on page 37, just after Remark 4.5.

Remark 4.4 (A Few Important Comments About Theorem 4.3).

i. Note that since, the fractional part map is one-periodic, this results (in part *ii.*) can be interpreted in a kind of *periodicity* with respect to the integers $\ell_{k,j,m}$: the set $\{\ell_{k,j,m}, k \in \mathbb{N}\}$ is infinite and equal to \mathbb{Z} . In particular, $|\ell_{k,j,m}| \rightarrow \infty$ as $k \rightarrow \infty$. We thus recover completely analogous results to those obtained in Theorem 3.1, on page 18 above (from [DL22]).

ii. In part *ii.*, much as in part *i.* of Theorem 4.3, the coefficients $c_k(f, M_\star)$, for $0 \leq k \leq m$, depend only on the function f and on the point M_\star of V_m at which they are evaluated. Note that, obviously, the values of the constants c_k in part *ii.* are different from those obtained in part *i.*

Furthermore, as will follow from Definition 4.8, on page 44, and Proposition 4.5, on page 44, these coefficients $c_k(f, M_\star)$ are the residues (at the possible Complex Dimensions $-(k(2 - D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{p}))$ of a suitable global scaling zeta function; see relation (19) of Proposition 4.5, on page 44.

iii. In both expansions (14) and (15), the coefficients $c_k(f, M_\star)$, for $0 \leq k \leq m$, reflect the dependence of the value taken by the map f at the vertex $M_{j,m}$ on the values taken by f at previous steps – vertices – of the m^{th} prefractal graph approximation, in conjunction with values taken by f at neighboring vertices of $M_{j,m}$ at the same level (m) of the prefractal sequence and with vertices which, in addition, strictly belong to the same polygon $\mathcal{P}_{m,k}$ introduced in Property 2.4, on page 8, with $1 \leq k \leq N_b^m - 1$ (by “strictly” here, we mean that the junction vertices are not included).

iv. The expansion in part *ii.* (namely, (15)) might be interpreted as a kind of generalized Taylor expansion with corresponding complex derivatives of orders $-\omega_k = k(2 - D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{p}$, where $k \in \mathbb{N}$ is arbitrary, the coefficients $c_k(f, M_\star)$ can thus be interpreted as (discrete) derivatives of complex order $-\omega_k$ of the function f , evaluated at the point M_\star of $V^\star \subset \Gamma_{\mathcal{W}}$. A similar comment can be made about the expansion in part *i.* (namely, (14)), but now with the above value of $-\omega_k$ replaced by $k(2 - D_{\mathcal{W}})$.

Again, as in part *i.*, it is natural to identify the cohomology groups H^m with the sets of functions satisfying, at any vertex $M_{j,m} \in V_m$, the expansion given in relation (15).

v. Note that the result given in part *ii.* above is significantly stronger than the one given in part *i.* of this theorem. Indeed, the expansion (14) in part *i.* only involves (modulo a translation by $-D_{\mathcal{W}}$) the real parts of some of the Complex Dimensions listed in Theorem 3.1, on page 18, and Remark 3.2, on page 24; namely, it does not include the real parts of the Complex Dimensions different from 0 and -2 , as well as of the possible Complex Dimensions with real part 1. By contrast, in part *ii.*, we can also recover some of the imaginary parts of those same Complex Dimensions; note that this is possible only because the functions involved satisfy the geometric condition (13) introduced in Definition 4.7 above, on page 33.

vi. It immediately follows from the expansion given in (15) of part *ii.* above, as well as from the fact that the sequence of sets of vertices $(V_m)_{m \in \mathbb{N}}$ is increasing (see part *i.* of Property 2.4, on page 8), that the sequence of cohomology groups $(H^m)_{m \in \mathbb{N}}$ is increasing; i.e.,

$$\forall m \in \mathbb{N} : H^m \subset H^{m+1}.$$

vii. Finally, in both expansions (14) and (15), the number ε is not an arbitrary one. It is directly connected to the scaling properties of the Weierstrass Curve, and enables us to express the exact form of the associated scaling relationship (see Property 2.7, on page 12, along with Theorem 3.3, on page 20). In other words, the number ε – or, rather, the corresponding m^{th} cohomology infinitesimal ε_m^m , in the sense of Definition 4.6, on page 32 above – depends on the geometry of the Curve. In light of our

expansions, it can be interpreted as a (geometric) coefficient connecting the Weierstrass Curve and the appropriate complex-valued functions defined on the set $V^\star = \bigcup_{n \in \mathbb{N}} V_n$.

Corollary 4.4 (The Cohomology Groups are Nontrivial).

Let us set, for any real number t in $[0, 1]$,

$$\gamma_{\mathcal{W}}(t) = (t, \mathcal{W}(t)) .$$

For any positive integer m , we then have that the identity function on the Weierstrass Curve, $\mathbb{1}_{\Gamma_{\mathcal{W}}}$, restricted to the set of vertices V_m , namely, $\mathbb{1}_{\Gamma_{\mathcal{W}}}|_{V_m}$, obviously belongs to H^m . Hence, $H^m \neq \{0\}$, and is nontrivial.

Similarly, it will follow from Theorem 4.11, on page 53 below that the identity function on $\Gamma_{\mathcal{W}}$, namely, $\mathbb{1}_{\Gamma_{\mathcal{W}}}$, belongs to the total cohomology group H^\star , a fact which we condense as follows: the Weierstrass function itself belongs to its own fractal cohomology.

Remark 4.5. The above geometric condition (13), introduced in Definition 4.7, on page 33, and used in part *ii.* of Theorem 4.3, on page 33, in an essential manner – a kind of Hölder (or even Lipschitz) condition in the argument of the functions – is satisfied by the most natural function on the Weierstrass Curve, namely, the Weierstrass function itself. We came across this property in our previous work [DL22], where we proved that, for the **geometric angles** $\theta_{j-1,j,m}$, with $0 \leq j \leq (N_b - 1) N_b^k$, $m \in \mathbb{N}$ (see part *iv.* of Definition 2.5, on page 9):

$$\theta_{j-1,j,m+1} \lesssim \varepsilon_m^{m(D_{\mathcal{W}}-1)} .$$

One then has, for vertices $M_{j_{m+1},m+1} \in V_{m+1}$ and $M_{j_m,m} \in V_m \subset V_{m+1}$ such that $M_{j_{m+1},m+1} \underset{m+1}{\sim} M_{j_m,m}$,

$$|\arg (M_{j_{m+1},m+1}) - \arg (M_{j_m,m})| \lesssim \varepsilon_m^{m(D_{\mathcal{W}}-1)} ,$$

or, equivalently,

$$\arg (M_{j_m,m}) = \arg (M_{j_{m-1},m-1}) + C_m \varepsilon_m^{m(D_{\mathcal{W}}-1)} \quad , \quad \text{for some nonnegative constant } C_m \in \mathbb{R} .$$

Let us now denote by k_m an integer (in \mathbb{Z}) such that

$$\left\{ k_m \frac{\ln \varepsilon}{\ln N_b} \right\} = C_m \frac{\varepsilon_m^{m(D_{\mathcal{W}}-1)}}{2\pi} ,$$

with $\{y\} \in [0, 1[$ denoting the fractional part of $y \in \mathbb{R}$. It then follows that

$$\varepsilon_m^{i m k_m \mathbf{p}} = e^{i m k_m \mathbf{p} \ln \varepsilon_m} = e^{i 2\pi m k_m \frac{\ln \varepsilon_m}{\ln N_b}} = e^{i 2\pi \left[m k_m \frac{\ln \varepsilon_m}{\ln N_b} \right] + 2\pi i \left\{ m k_m \frac{\ln \varepsilon_m}{\ln N_b} \right\}} = e^{i 2\pi \left\{ m k_m \frac{\ln \varepsilon_m}{\ln N_b} \right\}} = e^{i C_m \varepsilon_m^{m(D_{\mathcal{W}}-1)}} .$$

Note that, for practical reasons, it is more convenient to write

$$\left| \left\{ m k_m \frac{\ln \varepsilon_m}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_m^{m(D_{\mathcal{W}}-1)}}{2\pi} .$$

This key condition is the one that enables us to obtain the expansion (15) in part *ii.* of Theorem 4.3 above, on page 33: indeed, without this condition, it is impossible to obtain the terms $\varepsilon_k^{i k \ell_{k,j,m} \mathbf{P}}$, for some suitable values of $\ell_{k,j,m} \in \mathbb{Z}$.

More precisely, this condition results, for the argument of the involved function f , in *an arithmetic growth* proportional to $\varepsilon_m^{m(D_{\mathcal{W}}-1)}$ when switching from the m^{th} prefractal graph to the $(m+1)^{\text{th}}$ one, which is in perfect agreement with the interpretation given in [DL22]. At the same time, it goes further than [DL22] with regard to the imaginary parts of the Complex Dimensions, since it enables us to show that the m^{th} prefractal graph bears, in a sense, the oscillations of its predecessors.

We are now ready to provide the proof of Theorem 4.3, on page 33, along with some preliminary discussion.

Proof. (of Theorem 4.3, given on page 33)

Notation 9. In this proof, for the sake of simplicity, we will often write $M_{\star,m}$, $m \in \mathbb{N}$, for the points $M_{j,m}$, with $0 \leq j \leq \#V_m - 1$, of the prefractal graph $\Gamma_{\mathcal{W}_m}$. In the same way, we will also use \star as a dummy expression in order to denote the relevant quantities involved at the different levels of our forthcoming induction.

We will also make use of complex coefficients of the form $c_{\star}(\star)$ (resp., $\ell_{k,\star,m}$ integers). When $c_0(\star)$ coefficients (resp., $\ell_{k,\star,m}$) are involved, they denote constants depending on the argument (resp., integers associated with the vertex $M_{k,\star,m} \in V_m$); for instance, a coefficient $c_0(f, \star)$ (resp., $\ell_{k,0,m}$) refers to values of the function f at vertices \star of the Curve (resp., integers associated with the vertex $M_{k,0,m} \in V_m$).

Preliminaries. We hereafter place ourselves within the set $\mathcal{H}\ddot{o}ld(\Gamma_{\mathcal{W}})$ introduced in part *i.* of Definition 4.7, on page 33.

i. Henceforth, we aim at proving, by induction, that, for any integer $m \geq 1$, and with the convention $H^0 = \text{Im } \delta_{-1,0} = \{0\}$, the cohomology groups $H^m = \ker \delta_{m-1,m} / \text{Im } \delta_{m-2,m-1}$ consist of the restrictions to V_m of $(m, N_b^m + 1)$ -fermions, involving the restrictions of continuous, complex-valued functions f defined on the set $\Gamma_{\mathcal{W}} \supset V^{\star} = \bigcup_{n \in \mathbb{N}} V_n$, such that, for any vertex $M_{j,m} \in V_m$,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m,k}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \quad , \quad c_k(f, M_{\star}, k) \in \mathbb{C} \quad ,$$

where $\varepsilon_k^k > 0$ is the k^{th} cohomology infinitesimal introduced in Definition 4.6, on page 32, so that

$$\varepsilon_k^k = \frac{1}{(N_b - 1) N_b^k} \quad ,$$

and where, for $0 \leq k \leq m$, the complex coefficients $c_k(f, M_{\star}, k)$ are such that

$$0 \leq \tilde{C}_{inf} \lesssim |c_k(f, M_{\star}, k)| \lesssim \tilde{C}_{sup} < \infty \quad . \quad (\star\star) \quad (17)$$

Note that, accordingly, some of the coefficients c_k could vanish.

↪ Initialization:

Let us thus consider a continuous, complex-valued function f in $\mathcal{H}öld(\Gamma_{\mathcal{W}})$. The values of the function on the set of vertices V_0 can then be considered as constant ones (i.e., independent of ε_m^m). For any vertex $M_{j,0} \in V_0$, $0 \leq j \leq \#V_0 - 1$, we therefore set

$$f(M_{j,0}) = c_0(f, M_{j,0}) \quad , \quad c_0(f, M_{j,0}) \in \mathbb{C}.$$

Let us suppose that

$$f \in \ker \delta_{0,1} / \text{Im } \delta_{-1,0}; \text{ i.e., } f \in \ker \delta_{0,1}.$$

One thus has, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,1}, \dots, M_{j+N_b-1,1}) \in V_1^{N_b+1}$ such that $M_{i,0} = M_{j,1}$ and $M_{i+1,0} = M_{j+N_b,1}$,

$$\begin{aligned} & \delta_{0,1}(f)(M_{i,0}, M_{i+1,0}, M_{j+1,1}, \dots, M_{j+N_b-1,1}) = \\ & = c_{0,1} \left(c_0(f, M_{i,0}) + (-1)^{N_b} c_0(f, M_{i+1,0}) + \sum_{q=1}^{N_b-1} (-1)^q f(M_{j+q,1}) \right) = 0, \end{aligned}$$

where the positive constant $c_{0,1}$ is the one associated to the differential $\delta_{0,1}$ (see Definition 4.5, on page 28).

Each value $f(M_{j+1,1})$ can then be expressed as

$$f(M_{j+1,1}) = \sum_{0 \leq q \leq N_b-2} (-1)^{q+1} f(M_{j+q+1,1}) + c_1(f, M_{i,0}) + c_0(f, M_{i+1,0}),$$

where the coefficients $c_{\star}(f, \star)$ belong to \mathbb{C} and depend on the points $M_{\star,0}$.

The discrete local Hölder and reverse-Hölder property of the function then yields, for $0 \leq q \leq N_b - 2$,

$$\varepsilon_1^{2-D_{\mathcal{W}}} \lesssim |f(M_{j+q,1}) - f(M_{j+q+1,1})| \lesssim \varepsilon_1^{2-D_{\mathcal{W}}},$$

(where $\varepsilon_1 = (\varepsilon_1)^1 = \varepsilon_1^1$) which enables us to express the sum $\sum_{0 \leq q \leq N_b-2} (-1)^{q+1} f(M_{j+q+1,1})$ in the form

$$\sum_{0 \leq k \leq N_b-2} (-1)^{q+1} f(M_{j+q+1,1}) = c_0(f, M_{\star,1}) + c_1(f, M_{\star,1}) \varepsilon_1^{2-D_{\mathcal{W}}},$$

where the coefficients $c_{\star}(f, \star)$ belong to \mathbb{C} , and with

$$\tilde{C}_{inf} \lesssim |c_1(f, \star)| \lesssim (N_b - 1) \tilde{C}_{sup}.$$

We thus obtain the sought for expression, i.e.,

$$f(M_{j+1,1}) = \sum_{0 \leq k \leq 1} c_k(f, M_{j+1,1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \quad , \quad c_k(f, M_{\star,1}) \in \mathbb{C}.$$

↪ At a given strictly positive step m :

Our induction hypothesis consists in the following assumptions:

- a. the $(m, N_b^m + 1)$ -fermions, denoted by φ_m , belonging to H^m (or, equivalently, the restrictions to $V_m^{N_b^m + 1}$ of antisymmetric maps, with $N_b^m + 1$ variables, belonging to H^m), involve the restrictions to V_m of functions $f \in \mathcal{H}öld(\Gamma_{\mathcal{W}})$ such that, for any vertex $M_{j,m} \in V_m$,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \quad , \quad c_k(f, M_{\star,k}) \in \mathbb{C}.$$

- b. Given $\delta_{m-2,m-1}(\varphi_{m-2})$ in $Im \delta_{m-2,m-1}$, and involving the restrictions to V_{m-1} of functions $g_f \in \mathcal{H}öld(\Gamma_{\mathcal{W}})$ such that, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^{m-1}-1,m-1}) \in V_{m-1}^{N_b^{m-1}+1}$ satisfying

$$M_{i,0} = M_{j,-1} \quad \text{and} \quad M_{i+1,0} = M_{j+N_b^{m-1}-1,m},$$

we have that

$$\delta_{m-2,m-1}(\varphi_{m-2})(M_{i,0}, M_{i+1,0}, M_{j+1,m-1}, \dots, M_{j+N_b^{m-1}-1,m-1}) = \sum_{k=0}^{m-1} c_k(g_f, M_{\star,m-1}) \varepsilon_k^{k(2-D_{\mathcal{W}})},$$

where the coefficients $c_{\star}(g_f, \star)$ belong to \mathbb{C} .

Let us then consider an $(m, N_b^{m+1} + 1)$ -fermion, denoted by φ_{m+1} , belonging to the $(m+1)^{th}$ cohomology group H^{m+1} . It involves the restrictions to V_{m+1} of functions $f \in \mathcal{H}öld(\Gamma_{\mathcal{W}})$, such that, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b-2,m}) \in V_{m+1}^{N_b+1}$ satisfying

$$M_{i,0} = M_{j,m+1} \quad \text{and} \quad M_{i+1,0} = M_{j+N_b^{m+1},m+1},$$

we have that

$$\delta_{m,m+1}(\varphi_{m+1})(M_{i,0}, M_{i+1,0}, M_{j+1,m+1}, \dots, M_{j+N_b^{m+1}-1,m+1}) = 0,$$

with

$$\begin{aligned} \delta_{m,m+1}(\varphi_{m+1})(M_{i,0}, M_{i+1,0}, M_{j+1,m+1}, \dots, M_{j+N_b^{m+1}-1,m+1}) &= c_{m,m+1} \left(\sum_{q=0}^{N_b^{m+1}} (-1)^q f(M_{j+q,m+1}) \right) \\ &= c_{m,m+1} \left(f(M_{i,0}) + (-1)^{N_b^{m+1}} f(M_{i+1,0}) + \sum_{q=1}^{N_b^{m+1}-1} (-1)^q f(M_{j+q,m+1}) \right). \end{aligned} \quad (18)$$

At the same time, given $\delta_{m-1,m}(\varphi_{m-1})$ in $Im \delta_{m-1,m}$, and involving the restrictions to V_m of continuous functions g_f on $\Gamma_{\mathcal{W}}$, such that, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}) \in V_m^{N_b^m+1}$ satisfying

$$M_{i,0} = M_{j,m} \quad \text{and} \quad M_{i+1,0} = M_{j+N_b^m,m},$$

we have that

$$\begin{aligned} \delta_{m-1,m}(\varphi_{m-1})(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}) &= \\ &= c_{0,1} \left(c_0(g_f, M_{i,0}) + (-1)^{N_b^m} c_0(g_f, M_{i+1,0}) + \sum_{q=1}^{N_b^m-1} (-1)^q g_f(M_{j+q,m}) \right). \end{aligned}$$

Since the sequence of sets of vertices $(V_m)_{m \in \mathbb{N}}$ is increasing, the sum

$$\sum_{q=1}^{N_b^m - 1} (-1)^q g_f(M_{j+q,m})$$

can also be written in the form

$$\sum_{q=1}^{N_b^{m-1} - 1} (-1)^q g_f(M_{j'+q,m-1}) + \sum_{q=1}^{N_b^m - N_b^{m-1}} (-1)^q g_f(M_{j+q,m}),$$

where the vertices $M_{j'+q,m-1} \in V_{m-1}$ are the intersection points between V_{m-1} and V_m , for $1 \leq j' + q \leq \#V_{m-1} - 1$.

We can then make use of part *b.* of the induction hypothesis, and obtain that

$$\begin{aligned} & \delta_{m-1,m}(\varphi_{m-1})(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}) = \\ & = c_{m-1,m} \left(\sum_{k=0}^{m-1} c_k(g_f, M_{\star,m-1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} + \sum_{q=1}^{N_b^m - N_b^{m-1}} (-1)^q g_f(M_{j+q,m}) \right), \end{aligned}$$

where the coefficients $c_{\star}(g_f, \star)$ belong to \mathbb{C} .

The discrete, local, Hölder and reverse-Hölder properties of the function g_f then yields, for $1 \leq j + q \leq N_b^m - N_b^{m-1}$,

$$\varepsilon_m^{m(2-D_{\mathcal{W}})} \leq |g_f(M_{j+q,m}) - g_f(M_{j+q+1,m})| \leq \varepsilon_m^{m(2-D_{\mathcal{W}})},$$

which enables us to express the sum $\sum_{q=1}^{N_b^m - N_b^{m-1}} (-1)^q g_f(M_{j+q,m})$ in the following form:

$$\sum_{q=1}^{N_b^m - N_b^{m-1}} (-1)^q g_f(M_{j+q,m}) = c_0(g_f, M_{\star,m}) + c_m(g_f, M_{\star,m}) \varepsilon_m^{m(2-D_{\mathcal{W}})},$$

where the coefficients $c_{\star}(g_f, \star)$ belong to \mathbb{C} . Bearing in mind that the sequence of sets of vertices $(V_m)_{m \in \mathbb{N}}$ is increasing, we thus obtain that

$$\begin{aligned} & \delta_{m-1,m}(\varphi_{m-1})(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}) = \\ & = \sum_{k=0}^{m-1} c_k(g_f, M_{\star,m-1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} + c_m(g_f, M_{\star,m}) \varepsilon_m^{m(2-D_{\mathcal{W}})} = \sum_{k=0}^m c_k(g_f, M_{\star,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})}, \end{aligned}$$

where the coefficients $c_{\star}(f, \star)$ belong to \mathbb{C} .

Back to relation (18), on page 39, i.e., the relation translating the fact that the $(m, N_b^{m+1} + 1)$ -fermion φ_{m+1} belongs to the $(m+1)^{th}$ cohomology group H^{m+1} , we can then deduce that each value $f(M_{j+1,m+1})$ can be expressed in the following form:

$$f(M_{j+1,m+1}) = c_0(M_{j+1,m+1}) + \sum_{q=2}^{N_b^{m+1} - 1} (-1)^{q+1} f(M_{j+q,m+1}) + \sum_{k=0}^m c_k(g_f, M_{\star,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})}.$$

In light of the discrete local Hölder and reverse-Hölder properties of the function f , we have that, for $2 \leq q \leq N_b^{m+1} - 2$,

$$\varepsilon_{m+1}^{(m+1)(2-D_{\mathcal{W}})} \lesssim |f(M_{j+q,m+1}) - f(M_{j+q+1,m+1})| \lesssim \varepsilon_{m+1}^{(m+1)(2-D_{\mathcal{W}})},$$

which enables us to express the sum $\sum_{q=2}^{N_b^{m+1}-1} (-1)^{q+1} f(M_{j+q,m+1})$ as

$$\sum_{q=2}^{N_b^{m+1}-1} (-1)^{q+1} f(M_{j+q,m+1}) = \tilde{c}_0(M_{j+q,m+1}) + c_{m+1}(f, M_{j,m+1}) \varepsilon_{m+1}^{(m+1)(2-D_{\mathcal{W}})},$$

where the coefficients $\tilde{c}_0(f, \star)$ and $c_{\star}(f, \star)$ belong to \mathbb{C} .

In the end, and because, implicitly, the function g_f itself depends on f , we obtain the sought for expression,

$$f(M_{j+1,m+1}) = \sum_{0 \leq k \leq m+1} c_k(f, M_{j+1,m+1}) \varepsilon_k^{k(2-D_{\mathcal{W}})}, \quad c_k(f, M_{\star,k}) \in \mathbb{C}.$$

This completes the proof by induction of part *i.* of the theorem.

ii. If the functions f of part *i.* belong to $\mathcal{Höld}_{geom}(\Gamma_{\mathcal{W}})$; i.e., if they satisfy the following additional geometric condition (13) in Definition 4.7, on page 33, again, for any pair of adjacent vertices (M, M') of respective affixes $(z, z') \in \mathbb{C}^2$ of the prefractal graph $\Gamma_{\mathcal{W}_m}$, with $m \in \mathbb{N}$ arbitrary, we have that

$$|\arg(f(z)) - \arg(f(z'))| \lesssim |z - z'|; \quad (\spadesuit)$$

then the expected result is obtained in the manner explained in Remark 4.5, on page 36 above. For the sake of simplicity, we will only rewrite the additional points in the induction.

↪ Initialization:

It is the same as in *i.*. We simply set $\ell_{k,j,0} = 0$. As a result, we do not repeat the argument here.

↪ At a given strictly positive step m :

Our induction hypothesis now consists in the following assumptions:

a. the $(m, N_b^m + 1)$ -fermions, denoted by φ_m , belonging to H^m (or, equivalently, the restrictions to $V_m^{N_b^m+1}$ of antisymmetric maps, with $N_b^m + 1$ variables, belonging to H^m), involve the restrictions to V_m of functions $f \in \mathcal{Höld}_{geom}(\Gamma_{\mathcal{W}})$ such that, for any vertex $M_{j,m} \in V_m$,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{i k \ell_{k,j,m} \mathcal{P}}, \quad c_k(f, M_{\star,k}) \in \mathbb{C},$$

and where, for $0 \leq k \leq m$, $\ell_{k,j,m}$ denotes an integer (in \mathbb{Z}) satisfying the estimate (still with ε_k^k denoting the k^{th} cohomology infinitesimal, introduced in Definition 4.6, on page 32 above)

$$\left| \left\{ \ell_{k,j,m} \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}.$$

b' . Given $\delta_{m-2,m-1}(\varphi_{m-2})$ in $Im \delta_{m-2,m-1}$, and involving the restrictions to V_{m-1} of functions $g_f \in \mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$ such that, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^{m-1}-1,m-1}) \in V_{m-1}^{N_b^{m-1}+1}$ satisfying

$$M_{i,0} = M_{j,-1} \quad \text{and} \quad M_{i+1,0} = M_{j+N_b^{m-1},-1m},$$

we have that

$$\delta_{m-2,m-1}(\varphi_{m-2})\left(M_{i,0}, M_{i+1,0}, M_{j+1,m-1}, \dots, M_{j+N_b^{m-1}-1,m-1}\right) = \sum_{k=0}^{m-1} c_k(g_f, M_{\star,m-1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,\star,m-1} p},$$

where the coefficients $c_{\star}(g_f, \star)$ belong to \mathbb{C} , and where, for $0 \leq k \leq m-1$, $\ell_{k,j,m}$ denotes an integer (in \mathbb{Z}) satisfying the same estimate as in $a.$, i.e.,

$$\left| \left\{ \ell_{k,j,m} \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \leq \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}.$$

Let us then consider an $(m, N_b^{m+1} + 1)$ -fermion, denoted by φ_{m+1} , belonging to the $(m+1)^{th}$ cohomology group H^{m+1} , which involves the restrictions to V_{m+1} of functions $f \in \mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$.

We then proceed as in $b.$ above. For the sake of simplicity, we will only give details for the additional changes. We start by considering $\delta_{m-1,m}(\varphi_{m-1})$ in $Im \delta_{m-1,m}$, and involving the restrictions to V_m of functions $g_f \in \mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$ such that, for any $(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}) \in V_m^{N_b^m+1}$, satisfying

$$M_{i,0} = M_{j,m} \quad \text{and} \quad M_{i+1,0} = M_{j+N_b^m,m},$$

we have that

$$\begin{aligned} & \delta_{m-1,m}(\varphi_{m-1})\left(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}\right) = \\ & = c_{m-1,m} \left(c_0(g_f, M_{i,0}) + (-1)^{N_b^m} c_0(g_f, M_{i+1,1}) + \sum_{q=1}^{N_b^m-1} (-1)^q g_f(M_{j+q,m}) \right). \end{aligned}$$

As was explained in Remark 4.5, on page 36, by reasoning through a chain of adjacent vertices (i.e., a path in the corresponding, oriented finite graph), the geometric condition yields, for $1 \leq q \leq N_b^m - N_b^{m-1} - 1$,

$$\arg(M_{j+q,m}) = \arg(M_{j',m}) + C_m \varepsilon_m^{m(D_{\mathcal{W}}-1)} \quad , \quad 0 \leq j+q \leq \#V_m - 1 \quad , \quad C_m \in \mathbb{R}.$$

We thus obtain that

$$\begin{aligned} & \delta_{m-1,m}(\varphi_{m-1})\left(M_{i,0}, M_{i+1,0}, M_{j+1,m}, \dots, M_{j+N_b^m-1,m}\right) = \\ & = c_{m-1,m} \left(\sum_{k=0}^{m-1} c_k(g_f, M_{\star,m-1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,\star,m-1} p} + c_m(g_f, M_{j+q,m}) \varepsilon_m^{m(2-D_{\mathcal{W}})} \varepsilon_m^{im \ell_{m,j+q,m} p} \right), \end{aligned}$$

where the coefficients $c_{\star}(g, \star)$ belong to \mathbb{C} , $\ell_{k,\star,m-1}$ are integers (we use Notation 9, on page 37) and where, for $0 \leq k \leq m$, $\ell_{k,j,m}$ denotes an integer (in \mathbb{Z}) satisfying the estimate

$$\left| \left\{ \ell_{k,j,m} \frac{\ln \varepsilon_k}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}.$$

Back to the fact that the $(m, N_b^{m+1} + 1)$ -fermion φ_{m+1} belongs to the $(m+1)^{th}$ cohomology group H^{m+1} , we can then deduce that each value $f(M_{j+1,m+1})$ can then be expressed in the following form:

$$f(M_{j+1,m+1}) = c_0(M_{j+1,m+1}) + \sum_{q=2}^{N_b^{m+1}-1} (-1)^{q+1} f(M_{j+q,m+1}) + \sum_{k=0}^m c_k(g_f, M_{\star,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{i k \ell_{k,\star,m} \mathbf{P}}.$$

The geometric condition (13), on page 33, in conjunction with the discrete local Hölder and reverse-Hölder properties of the function f , enables us this time to express the sum $\sum_{q=2}^{N_b^{m+1}-1} (-1)^{q+1} f(M_{j+q,m+1})$ as

$$\sum_{q=2}^{N_b^{m+1}-1} (-1)^{q+1} f(M_{j+q,m+1}) = \tilde{c}_0(f, M_{j+q,m+1}) + c_{m+1}(f, M_{j,m+1}) \varepsilon_{m+1}^{(m+1)(2-D_{\mathcal{W}})} \varepsilon_{m+1}^{i(m+1)\ell_{m+1,j,m+1} \mathbf{P}},$$

where the coefficients $\tilde{c}_0(f, \star)$ and $c_{\star}(f, \star)$ belong to \mathbb{C} , and where $\ell_{m+1,j,m+1}$ denotes an integer (in \mathbb{Z}) satisfying the estimate

$$\left| \left\{ \ell_{m+1,j,m+1} \frac{\ln \varepsilon_{m+1}}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_{m+1}^{(m+1)(D_{\mathcal{W}}-1)}}{2\pi}.$$

We therefore obtain the desired result and complete the (strong) induction.

Note that, given $m \in \mathbb{N}$, this proof thus gives the value of f at any vertex $M_{j,m} \in V_m$, for $1 \leq j \leq \#V_m - 1$. In fact, the expressions associated to the extreme vertices $M_{0,m}$ and $M_{\#V_m}$, which are, also, the extreme vertices (i.e., the endpoints) of the Curve $\Gamma_{\mathcal{W}}$, are still valid, with zero coefficients in factor of the terms $\varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{i k \ell_{k,\star,m} \mathbf{P}}$, for $k \geq 1$.

Two other comments about our proof are warranted:

- \rightsquigarrow In both parts *i.* and *ii.*, the first induction hypothesis *a.* simply states that the desired result – namely, the Taylor-like expansion – is true at the considered step $m \in \mathbb{N}$.
- \rightsquigarrow In both parts *i.* and *ii.*, the second induction hypothesis *b.* (resp. *b'.*) is the one that is required in order to carry out the strong induction.

This completes the proof of Theorem 4.3, stated on page 33. □

We note that, in light (and with the notation) of Theorem 4.3, on page 33 above, and Theorem 4.11, on page 53 below, Definition 4.8, on page 44 and Proposition 4.5, on page 44 just below can be applied to any $f \in H^m$, for $m \in \mathbb{N}$, and to any $f \in H^{\star}$, respectively.

Definition 4.8 (Local Scaling Zeta Function).

Given $m \in \mathbb{N}$, and a function f in $\mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$ (see part *ii.* of Definition 4.7, on page 33 above), possessing, by Theorem 4.3, on page 33, for any vertex $M_{j,m} \in V_m$, an expansion of the form (15) obtained in part *ii.* of Theorem 4.3, on page 33; i.e.,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})+i k \ell_{k,j,m} \mathbf{P}} \quad , \quad M_{\star,k} \in V_k, c_k(f, M_{j,m}) \in \mathbb{C},$$

where, for $0 \leq k \leq m$, ε_k^k has been introduced in Definition 4.6, on page 32, and where the coefficients $c_k(f, M_{\star,m})$ are uniformly bounded complex numbers, we define the *local scaling zeta function* $\zeta_{f, M_{j,m}, loc}$ associated to f at the vertex $M_{j,m}$, as the following truncated Mellin transform, initially given, for any complex number s such that $\mathcal{R}e(s) > 0$, by

$$\zeta_{f, M_{j,m}, loc}(s) = \sum_{k=0}^m c_k(f, M_{\star,m}) \int_0^\varepsilon t^{s-1} t^{k(2-D_{\mathcal{W}})+i k \ell_{k,j,m} \mathbf{P}} dt.$$

By meromorphic continuation to all of \mathbb{C} , one then obtains the local scaling zeta function $\zeta_{f, M_{j,m}, loc}$ for all $s \in \mathbb{C}$, as given by the equality just above. More precisely, we have that, for all $s \in \mathbb{C}$,

$$\zeta_{f, M_{j,m}, loc}(s) = \sum_{k=0}^m c_k(f, M_{j,m}) \frac{\varepsilon^{s+k(2-D_{\mathcal{W}})+i k \ell_{k,j,m} \mathbf{P}}}{s + k(2 - D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{P}},$$

where $\varepsilon = \frac{1}{N_b}$ is the intrinsic scale, introduced in Definition 4.6, on page 32. (For further details about the definition of fractal zeta functions in our context, see [DL23b].)

Note that, similarly, for any $k \in \mathbb{N}$, $\varepsilon_k^k = (\varepsilon_k)^k$ denotes the k^{th} cohomology infinitesimal introduced in Definition 4.6, on page 32; the same comment applies to Proposition 4.5, on page 44 just below.

Proposition 4.5 (Global Scaling Zeta Function).

Given a point $M_{\star,m} \in V_m$, for some arbitrary $m \in \mathbb{N}$, and a function f in $\mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$, possessing, by Theorem 4.3, on page 33, for any vertex $M_{j,m} \in V_m$, an expansion of the form (15) in part *ii.* of Theorem 4.3 (see also Definition 4.8 just above, on page 44), we introduce the *global scaling zeta function* $\zeta_{f, M_{\star,m}, gl}$ associated to f at the point $M_{\star,m}$, as the following convergent (and, even, absolutely convergent) series. Namely, $\zeta_{f, M_{\star,m}, gl}$ is the meromorphic function on \mathbb{C} given, for all $s \in \mathbb{C}$, by

$$\zeta_{f, M_{\star,m}, gl}(s) = \sum_{k=0}^{\infty} c_k(f, M_{\star,m}) \frac{\varepsilon^{s+k(2-D_{\mathcal{W}})+i k \ell_{k,j,m} \mathbf{P}}}{s + k(2 - D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{P}}, \quad (19)$$

where, as in Definition 4.8 just above, on page 44, $\varepsilon = \frac{1}{N_b}$ is the intrinsic scale, introduced in Definition 4.6, on page 32.

Accordingly, in light of Definition 4.8, on page 44 just above, $\zeta_{f, M_{\star,m}, gl}$ is a countably infinite linear combination (with coefficients $c_k(f, M_{\star,m})$, for all $k \in \mathbb{N}$) of truncated Mellin transforms determined by the k^{th} cohomology infinitesimal ε_k^k (for all $k \in \mathbb{N}$).

Note that the set of local Complex Dimensions (i.e., the set of poles of $\zeta_{f, M_{\star,m}, gl}$),

$$\mathcal{CD}_{f, M_{\star, m}} = \{-k(2 - D_{\mathcal{W}}) - i\ell_{k, j, m} \mathbf{p}, c_k(f, M_{\star, m}) \neq 0, k \in \mathbb{N}\},$$

depends on the function f and on the point $M_{\star, m}$.

By contrast, naturally, the set of possible local Complex Dimensions,

$$\mathcal{CD}_{f, M_{\star, m}}^{\text{possible}} = \{-k(2 - D_{\mathcal{W}}) - i\ell_{k, j, m} \mathbf{p}, k \in \mathbb{N}\}, \quad (20)$$

does not depend on f or $M_{\star, m}$.

More precisely, the poles of $\zeta_{f, M_{\star, m}, gl}$ are all simple, and are the complex numbers $\omega_k = -k(2 - D_{\mathcal{W}}) - i\ell_{k, j, m} \mathbf{p}$, for each $k \in \mathbb{N}$ such that $c_k(f, M_{\star, m}) \neq 0$.

Furthermore, for all $k \in \mathbb{N}$, the residue of $\zeta_{f, M_{\star, m}, gl}$ at ω_k is given by

$$\text{res} \left(\zeta_{f, M_{\star, m}, gl}(s), \omega_k \right) = c_k(f, M_{\star, m}) .$$

Proof. (Of Proposition 4.5, given on page 44)

The (local) uniform convergence on \mathbb{C} , of the series involved just above in the expression (19) of the global scaling zeta function $\zeta_{f, M_{\star, m}, gl}$ is ensured by the fact that the coefficients $c_k(f, M_{\star, m})$ are uniformly bounded complex numbers (with respect to $k \in \mathbb{N}$); see the inequalities in relation (17) of the proof of Theorem 4.3, on page 33 above.

Indeed, by placing ourselves in a compact set $\mathcal{K} \subset \mathbb{C}$ contained in the open set $\mathcal{U} \subset \mathbb{C}$ which is the complement of the discrete set of possible poles $\mathcal{CD}_{f, M_{\star, m}}^{\text{possible}}$ (see relation (20), on page 45), we have that, for each $k \in \mathbb{N}$,

$$\begin{aligned} \left| c_k(f, M_{\star, m}) \frac{\varepsilon^{s+k(2-D_{\mathcal{W}})+i\ell_{k, j, m} \mathbf{p}}}{s+k(2-D_{\mathcal{W}})+i\ell_{k, j, m} \mathbf{p}} \right| &\lesssim \frac{\varepsilon^{\text{Re}(s)+k(2-D_{\mathcal{W}})}}{\sqrt{(\text{Re}(s)+k(2-D_{\mathcal{W}}))^2 + (\text{Im}(s)+\ell_{k, j, m} \mathbf{p})^2}} \\ &\lesssim \frac{\varepsilon^{\text{Re}(s)+k(2-D_{\mathcal{W}})}}{k(2-D_{\mathcal{W}})} \\ &= \frac{\varepsilon^{\text{Re}(s)}}{k(2-D_{\mathcal{W}})} \left(\varepsilon^k \right)^k \\ &\lesssim \frac{1}{k(2-D_{\mathcal{W}})} \frac{1}{N_b^{\text{Re}(s)}} \left(\frac{1}{N_b^{2-D_{\mathcal{W}}}} \right)^k \\ &\lesssim \frac{1}{k(2-D_{\mathcal{W}})} \frac{1}{\min_{z \in \mathcal{K}} N_b^{\text{Re}(z)}} \left(\frac{1}{N_b^{2-D_{\mathcal{W}}}} \right)^k, \end{aligned} \quad (21)$$

where $\sum_{k \in \mathbb{N}} \frac{1}{k} \left(\frac{1}{N_b^{k(2-D_{\mathcal{W}})}} \right) < \infty$, which can be checked, for example, via the ratio test for series. This ensures the (local) normal convergence – and hence, the (local) uniform convergence – of the series

involved just above in the expression of the global scaling zeta function $\zeta_{f, M_{\star, m}, gl}$ given in (19), on page 19. (Note that, since \mathcal{K} is compact, a moment's reflection shows that

$$\min_{z \in \mathcal{K}} N_b^{\operatorname{Re}(z)} \geq \min \left(N_b^{\min(\operatorname{Re}(\mathcal{K}))}, N_b^{\max(\operatorname{Re}(\mathcal{K}))} \right) > 0.)$$

The remainder of our proof – in the case when we place ourselves in a compact set $\mathcal{K} \subset \mathbb{C}$ containing some of the potential poles (necessarily, finitely namely, since \mathcal{K} is compact and the poles are isolated) of $\tilde{\zeta}_m^e$ – can be obtained by using the chordal metric, as we next explain.

For this purpose, a (complex-valued) meromorphic function f is viewed as a continuous function with values in $\mathbb{P}^1(\mathbb{C})$, equipped with the chordal metric, and such that, for any pole ω of f , $f(\omega)$ takes the value ∞ (for instance, as in [LvF13], Section 3.4 and Appendix C).

More precisely, if $\mathbb{P}^1(\mathbb{C}) = \mathbb{C} \cup \infty$ denotes the Riemann sphere (or complex projective line), we can show that, for *the chordal metric* (as, e.g., in [LvF13], [LRŽ17b], [HL21], defined, for all $(z_1, z_2) \in (\mathbb{P}^1(\mathbb{C}))^2$ by

$$\|z_1, z_2\| = \frac{|z_1 - z_2|}{\sqrt{1 + |z_1^2|} \sqrt{1 + |z_2^2|}}, \text{ if } z_1 \neq \infty \text{ and } z_2 \neq \infty, \quad (22)$$

and

$$\|z_1, \infty\| = \frac{1}{\sqrt{1 + |z_1^2|}}, \text{ if } z_1 \neq \infty. \quad (23)$$

Since the discrete set of possible poles $\mathcal{CD}_{f, M_{\star, m}}^{\text{possible}}$ (see relation (20), on page 45), intersects each compact set $\mathcal{K} \subset \mathbb{C}$ at a countably finite number of points, we can restrict ourselves to the case when \mathcal{K} contains one single pole of the scaling zeta function $\zeta_{f, M_{j, m}, loc}$.

The only difference with the first case, when the compact set $\mathcal{K} \subset \mathbb{C}$ does not intersect $\mathcal{CD}_{f, M_{\star, m}}^{\text{possible}}$, is that $\frac{1}{|s + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}|}$ has to be replaced by

$$\frac{1}{\sqrt{1 + |s - 2 + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}|^2}}.$$

The convergence – of the series involved just above in the expression of the global scaling zeta function $\zeta_{f, M_{\star, m}, gl}$ given in (19), on page 44, implies that the (uniform) limit fractal zeta function $\zeta_{f, M_{\star, m}, gl}$, is holomorphic on \mathcal{U} , as the (locally) uniform limit of a sequence of holomorphic functions on \mathcal{U} . By applying Weierstrass' Theorem, we conclude that, for all $s \in \mathbb{C} \setminus \{-k(2 - D_{\mathcal{W}}) - i \ell_{k, j, m} \mathbf{P}, k \in \mathbb{N}\}$,

the series of meromorphic – and even, holomorphic – functions $s \mapsto c_k(f, M_{\star, m}) \frac{\varepsilon_k^{s + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}}}{s + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}}$, for $k \in \mathbb{N}$, is itself holomorphic.

For $k_0 \in \mathbb{N}$, and $s = \omega_{k_0} = -k_0(2 - D_{\mathcal{W}}) - i \ell_{k_0} \mathbf{P}$, the same computation as above, in conjunction with the local uniform convergence (in $s \in \mathbb{C}$, on every compact subset of \mathbb{C}) of the series of functions $s \mapsto c_k(f, M_{\star, m}) \frac{\varepsilon_k^{s + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}}}{s + k(2 - D_{\mathcal{W}}) + i \ell_{k, j, m} \mathbf{P}}$, shows that

$$\begin{aligned}
\lim_{s \rightarrow \omega_{k_0}} (s - \omega_{k_0}) \zeta_{f, M_{\star, m}, gl}(s) &= \sum_{k \in \mathbb{N}} \lim_{s \rightarrow \omega_{k_0}} (s - \omega_{k_0}) \zeta_{f, M_{\star, m}, gl}(s) \\
&= c_{k_0}(f, M_{\star, m}) + \sum_{k \in \mathbb{N}, k \neq k_0} \lim_{s \rightarrow \omega_{k_0}} \frac{s - \omega_{k_0}}{s - \omega_k} c_k(f, M_{\star, m}) \varepsilon_k^{k s - \omega_k} \\
&= c_{k_0}(f, M_{\star, m}) \varepsilon^0 = c_{k_0}(f, M_{\star, m}) ;
\end{aligned}$$

i.e., the residue of $\zeta_{f, M_{\star, m}, gl}$ exists and is given (still for any $k_0 \in \mathbb{N}$) by

$$\text{res} \left(\zeta_{f, M_{\star, m}, gl}(s), \omega_{k_0} \right) = c_{k_0}(f, M_{\star, m}) .$$

Note that $\zeta_{f, M_{\star, m}, gl}$ is initially defined by an infinite sum of truncated Mellin transforms – exactly as in Definition 4.8, on page 44, for $\zeta_{f, M_{j, m}, loc}$, except for m now replaced by ∞ in the summation. □

Remark 4.6. The result of Theorem 4.3, on page 33, is in perfect agreement with the one obtained, in the specific case of the Complexified Weierstrass function \mathcal{W}_{comp} , studied in detail in Proposition 3.3, on page 20 above.

We may also note that those results (in Proposition 3.3, on page 20, and Proposition 4.5, on page 44, as well as in Theorem 4.3 above and 4.11 below) enable us to distinguish between the set of Complex Dimensions associated to the Weierstrass function \mathcal{W} , and the set of Complex Dimensions associated to the Weierstrass Curve $\Gamma_{\mathcal{W}}$, restricted here to their imaginary parts in $\{0, \dots, m \mathbf{p}\}$. We plan to further discuss this issue in a later work.

Remark 4.7 (A Consequence for the Interpretation of the Complex Dimensions).

In [DL22], the Complex Dimensions of the Weierstrass Curve $\Gamma_{\mathcal{W}}$ have been obtained by means of a fractal tube formula; i.e., in our case, for any $m \in \mathbb{N}$ sufficiently large, the area of a two-sided ε -neighborhood of $\Gamma_{\mathcal{W}_m}$, the m^{th} prefractal approximation of $\Gamma_{\mathcal{W}}$, which (apart from two terms associated with the Complex Dimensions 0 and -2) consists of an expansion of the form

$$\sum_{\alpha \text{ real part of a Complex Dimension}} \varepsilon_m^{m(2-\alpha)} G_{\alpha} \left(\ln_{N_b} \left(\frac{1}{\varepsilon^m} \right) \right), \quad (\star)$$

where, for any real part α of a Complex Dimension, G_{α} denotes a continuous and one-periodic function – and where, for $\alpha = D_{\mathcal{W}} - k (2 - D_{\mathcal{W}})$, with $k \in \mathbb{N}$ arbitrary, so that if $k = 0$, $2 - D_{\mathcal{W}}$ is the optimal Hölder exponent for the Weierstrass function, as shown in Corollary 2.14, on page 16; in this case, the function G_{α} is nonconstant, for any $k \in \mathbb{N}$ – as well as, if $k = 0$, bounded away from zero and infinity. It is, therefore, important to note that, similarly, the expansions of Theorem 4.3, on page 33 above (as well as those of Theorem 4.11, on page 53 below) are also only valid for the values of the cohomology infinitesimal introduced in Definition 4.6, on page 32, i.e., the infinitesimal $(\varepsilon_k^k)_{k \in \mathbb{N}}$ associated to the scaling law of the Weierstrass Curve $\Gamma_{\mathcal{W}}$.

As a consequence, it makes it possible to express, in an extremely precise way, the relations satisfied by the functions which belong to the cohomology groups.

Remark 4.8 (The Case of Junction Vertices).

In the case of junction vertices, i.e., points $M_{j,m} = M_{j',m+1}$ belonging to consecutive prefractal graphs $\Gamma_{\mathcal{W}_m}$ and $\Gamma_{\mathcal{W}_{m+1}}$, for $m \in \mathbb{N}$, $0 \leq j \leq \#V_m$, $0 \leq j' \leq \#V_{m+1} - 1$, the expansion (15) given in part *ii.* of Theorem 4.3, on page 33, is of the form

$$f(M_{j,m}) = f(M_{j',m+1}) = \sum_{k=0}^{m+1} c_k(f, M_{j',m+1}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,m+1} \mathbf{P}} \quad , \quad M_{\star,k} \in V_k, c_k(f, M_{j,m,k}) \in \mathbb{C},$$

with $c_{m+1}(f, M_{j',m+1}) = 0$ and

$$\forall k \in \{0, \dots, m\} : \quad c_k(f, M_{j',m+1}) = c_k(f, M_{j,m}) \quad ,$$

as well as for some suitable sequence $(\ell_{k,j,m+1})_{0 \leq k \leq m+1} \in \mathbb{Z}^{m+2}$, as specified in the statement of part *ii.* of Theorem 4.3, on page 33.

Note that it is in perfect agreement with the fact that the sequence of cohomology groups $(H^m)_{m \in \mathbb{N}}$ is increasing, as seen at the end of Theorem 4.3, on page 33.

Corollary 4.6 ((of Theorem 4.3, on page 33) Recursive Method for Obtaining the Coefficients of the Fractal Expansions).

*Given a function $f \in \mathcal{H}\ddot{o}l d_{geom}(\Gamma_{\mathcal{W}})$ (see part *ii.* of Definition 4.7, on page 33), a natural question consists in asking how one can determine, for any integer $m \geq 0$ and any integer $j \in \{0, \dots, \#V_m - 1\}$, the explicit expression of the coefficients $c_k(f, M_{\star,k})$ involved in the expansion (15).*

In fact, things present themselves as follows:

\rightsquigarrow At step $m = 0$:

One simply determines the values of the complex coefficients $c_0(f, M_{j,0})$, for $0 \leq j \leq \#V_0 - 1$, such that

$$\forall j \in \{0, \dots, \#V_0 - 1\} : \quad f(M_{j,0}) = c_1(f, M_{j,0}) \quad .$$

\rightsquigarrow At step $m = 1$:

The point is to determine the values of the complex coefficients $c_k(f, M_{j,2})$, for $1 \leq j \leq \#V_1 - 1$, such that

$$f(M_{j,1}) = \sum_{k=0}^1 c_k(f, M_{j,2}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,1} \mathbf{P}} \quad .$$

\rightsquigarrow At step $m = 2$:

The point is to determine the values of the complex coefficients $c_k(f, M_{j,2})$, for $1 \leq j \leq \#V_2 - 1$, such that

$$f(M_{j,2}) = \sum_{k=0}^2 c_k(f, M_{j,2}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,2} \mathbf{P}} \quad .$$

As is shown in the proof of Theorem 4.3, given on page 33, we have that

$$\sum_{0 \leq k \leq N_b - 2} (-1)^{k+1} f(M_{j+k+1,2}) = c_2(f, M_{j+1,2}) \varepsilon_2^{2(2-D_{\mathcal{W}})} \varepsilon_2^{i2\ell_{2,j+1,2}\mathbf{P}}.$$

Consequently, for all integers j in $\{0, \dots, \#V_2 - 1\}$ such that $f(M_{j+1,2}) \neq 0$, one immediately obtains that

$$c_2(f, M_{j+1,2}) = \sum_{0 \leq k \leq N_b - 2} (-1)^{k+1} f(M_{j+k+1,2}) \varepsilon_2^{-2(2-D_{\mathcal{W}})} \varepsilon_2^{-i2\ell_{2,j+1,2}\mathbf{P}}.$$

One could proceed likewise at every step m . Therefore, the difficulty seems to determine, at a given step $m \geq 1$, the values of the coefficients $c_k(f, M_{j+1,m})$, for $0 \leq k \leq m - 1$.

The result obtained in Proposition 3.3, on page 20, yields the exact expression for those coefficients, in the case of the Complexified Weierstrass function $\mathcal{W}_{\text{comp}}$. One possible approach is to test whether analogous expressions, adapted to functions satisfying the hypotheses of Theorem 4.3, on page 33, are suitable and can be obtained (i.e., they belong to the cohomology groups). This will be the object of our forthcoming work [DLO23].

Proposition 4.7 (Generators of the Cohomology Groups).

For any integer $m \geq 1$, and with the convention $H^0 = \text{Im } \delta_{-1,0} = \{0\}$, the generators of the (additive) cohomology groups

$$H^m = \ker \delta_{m-1,m} / \text{Im } \delta_{m-2,m-1}$$

are to be understood in the sense of the k^{th} cohomology infinitesimals ε_k^k , for $0 \leq k \leq m$ (see Definition 4.6, on page 32). Note that by generators we do not refer to the notion of group generators in group theory, but in a broader sense, instead. In our present context, indeed, we express the values, at the vertices of V_m , of the continuous, complex-valued maps defined on the Weierstrass Curve $\Gamma_{\mathcal{W}} \supset \bigcup_{n \in \mathbb{N}} V_n$,

which constitute the quotient groups H^m , by means of Taylor-like expansions involving fractional powers of the k^{th} cohomology infinitesimals ε_k^k , for $0 \leq k \leq m$. So, in a sense, one could think of those generators as generalized (fractional) polynomial variables. Those generators are thus of the following form:

$$\varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik\ell_{k,j,m}\mathbf{P}} = \varepsilon_k^{k((2-D_{\mathcal{W}})+i\ell_{k,j,m}\mathbf{P})},$$

with $0 \leq k \leq m$ and $\ell_{k,j,m} \in \mathbb{Z}$ such that $\left| \left\{ \ell_k \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \leq \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}$; see also Proposition 4.5, on page 44 above.

Proof. This follows at once from the statement of part *ii.* of Theorem 4.3, on page 33. □

4.5 Poincaré Duality

The goal of this section is to obtain an appropriate analog, in the present context, of Poincaré Duality (from algebraic topology and geometry). Very useful references on Poincaré Duality can be found in the book of Jean Gallier and Jocelyn Quaintance [GQ22] (Chapter 7), and in the Lecture notes of Weiyi Zhang [Zha13].

In our context, where we lay the foundations of prefractal cohomology, we also have in mind to obtain, in a future work, an appropriate fractal homology theory of which the present existing fractal cohomology theory (or a suitable modification therein) would be, in some sense, the dual theory. At the same time, we have at our disposal this natural symmetry (with respect to the vertical line $x = \frac{1}{2}$ (see Property 2.1, on page 6)). In this light, we could not bypass defining the associated *left* and *right side* differentials and complexes, as well as a Complex Conjugation with respect to this vertical line, as is done below.

Also, our prefractal graphs enable us to obtain a polyhedral neighborhood of the Weierstrass Curve $\Gamma_{\mathcal{W}}$, see [DL24c], [DL23b]. As is discussed in *loc. cit.*, an immediate consequence of Property 4.8 below, on page 50, is that we have a natural correspondence between the polygons located on either side of the vertical line $x = \frac{1}{2}$, directly connected to Poincaré Duality.

Proposition 4.8 (Conjugation).

In light of the symmetry of $\Gamma_{\mathcal{W}}$ with respect to the vertical line $x = \frac{1}{2}$ (see Property 2.1, on page 6), it seems natural to consider the following change of variables from real to complex coordinates (with an obvious relabelling of the axes):

$$Z = y + i \left(x - \frac{1}{2} \right), \text{ where } (x, y) \in \mathbb{R}^2.$$

We then define the corresponding complex conjugation, which, to any point M of the complex plane, associates its symmetric point M' with respect to the vertical line $x = \frac{1}{2}$,

$$\overline{M} = M',$$

with affix the complex number \bar{Z} defined by $\bar{Z} = y - i \left(x - \frac{1}{2} \right)$.

This yields, for any $m \in \mathbb{N}$ and any j in $\left\{ 0, \dots, \frac{(N_b - 1) N_b^m}{2} \right\}$,

$$\overline{M_{(N_b - 1) N_b^m - j, m}} = M_{j, m},$$

or

$$\overline{\left(\frac{j}{(N_b - 1) N_b^m}, \mathcal{W} \left(\frac{j}{(N_b - 1) N_b^m} \right) \right)} = \left(\frac{(N_b - 1) N_b^m - j}{(N_b - 1) N_b^m}, \mathcal{W} \left(\frac{(N_b - 1) N_b^m - j}{(N_b - 1) N_b^m} \right) \right).$$

In the following definitions and results (i.e., Definition 4.9, on page 51, and Definition 4.10, on page 51, along with Proposition 4.10, on page 52), it is helpful to remember that, in light of part *ii.* of Property 2.4, on page 8, we have that, for any integer $m \geq 0$,

$$\#V_m - 1 = (N_b - 1) N_b^m .$$

Definition 4.9 (Left and Right Side of the Prefractal Sequence and Curve).

We define *the Left Side* of the Prefractal Sequence $(\Gamma_{\mathcal{W}_m})_{m \in \mathbb{N}}$ as the following sequence of sets:

$$(\mathcal{L}_m)_{m \in \mathbb{N}} = \left\{ M_{j,m}, 0 \leq j \leq \frac{(N_b - 1) N_b^m}{2} \right\}_{m \in \mathbb{N}} .$$

In the same way, we define *the Right Side* of the Prefractal Sequence $(\Gamma_{\mathcal{W}_m})_{m \in \mathbb{N}}$ as the following sequence of sets:

$$(\mathcal{R}_m)_{m \in \mathbb{N}} = \left\{ M_{j,m}, \frac{(N_b - 1) N_b^m}{2} \leq j \leq (N_b - 1) N_b^m \right\}_{m \in \mathbb{N}} = (\overline{\mathcal{L}_m})_{m \in \mathbb{N}} .$$

Thus, for any $m \in \mathbb{N}$, \mathcal{L}_m represents the Left Side of the prefractal graph $\Gamma_{\mathcal{W}_m}$, while \mathcal{R}_m stands for its Right Side.

Proposition 4.9 (Complex Differentials).

Under the prism of the symmetry with respect to the vertical line $x = \frac{1}{2}$ (see Property 2.1, on page 6), it seems natural to consider, for any strictly positive integer m , instead of the differentials introduced in Definition 4.5, on page 28:

- i. **The Left Side Differential**, $\delta_{z,m-1,m}$, as the restriction of the differential $\delta_{m-1,m}$ to the Left Side of the Prefractal graph \mathcal{L}_m ; i.e.,

$$\delta_{Z,m-1,m} = \delta_{m-1,m}|_{\mathcal{L}_m} .$$

- ii. **The Right Side Differential**, $\delta_{\bar{z},m-1,m}$, as the restriction of the differential $\delta_{m-1,m}$ to the Right Side of the Prefractal graph \mathcal{R}_m ; i.e.,

$$\delta_{\bar{Z},m-1,m} = \delta_{m-1,m}|_{\mathcal{R}_m} .$$

Then, the Complex Conjugation defined in Proposition 4.8, on page 50, exactly yields the following identity:

$$\delta_{\bar{Z},m-1,m} = \overline{\delta_{Z,m-1,m}} .$$

We can similarly define the left-side and right-side complexes, in the obvious manner.

Definition 4.10 (Left and Right Side Cohomology Groups).

Given a strictly positive integer m , we respectively define:

i. *the Left and Right Side cohomology groups*, for each integer $m \geq 1$, as

$$H^m = \ker \delta_{Z,m-1,m} / \text{Im } \delta_{Z,m-2,m-1} \quad , \quad \overline{H}^m = \ker \delta_{\overline{Z},m-1,m} / \text{Im } \delta_{\overline{Z},m-2,m-1} ,$$

with the additional convention

$$H^0 = \text{Im } \delta_{Z,-1,0} = \{0\} \quad , \quad \overline{H}_0 = \text{Im } \delta_{\overline{Z},-1,0} = \{0\} .$$

ii. For each integer $m \geq 1$ and for $0 \leq j \leq \frac{(N_b - 1) N_b^m}{2}$, *the j^{th} Left and Right Side cohomology groups*, respectively denoted by $H_{m,j}$ and $\overline{H}_{m, \#V_{m-1-j}}$, as consisting of the respective restrictions to the left or right part of V_m of continuous, complex-valued functions f on the Weierstrass Curve $\Gamma_{\mathcal{W}}$ such that $f \in \mathcal{H}\ddot{o}l d_{geom}(\Gamma_{\mathcal{W}}) \subset \mathcal{H}\ddot{o}l d(\Gamma_{\mathcal{W}})$ and satisfying, for each any pair of conjugate vertices $(M_{j,m}, M_{\#V_{m-1-j},m}) \in V_m^2$,

$$f(M_{j,m}) = \sum_{k=0}^m c_k(f, M_{j,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,m} \mathbf{P}} \quad , \quad M_{\star,k} \in V_k, c_k(f, M_{j,m}) \in \mathbb{C} ,$$

and

$$f(M_{\#V_{m-1-j},m}) = \sum_{k=0}^m c_k(f, M_{\#V_{m-1-j},m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{ik \ell_{k,j,m} \mathbf{P}} \quad , \quad M_{\star,k} \in V_k, c_k(f, M_{\#V_{m-1-j},m}) \in \mathbb{C} ,$$

we have that

$$f(M_{j,m}) = \overline{f(M_{\#V_{m-1-j},m})} .$$

Proposition 4.10 (Poincaré Duality).

Given a strictly positive integer m , the conjugation property obtained in Proposition 4.9, on page 51, results in the isomorphism of the kernels

$$\ker \delta_{\overline{Z},m-1,m} \simeq \overline{\ker \delta_{Z,m-1,m}} ,$$

as well as of the images,

$$\text{Im } \delta_{Z,m-2,m-1} \simeq \text{Im } \delta_{\overline{Z},m-2,m-1} ,$$

and therefore immediately leads to the Duality

$$\ker \delta_{m-1,m} |_{\mathcal{L}_m} / \text{Im } \delta_{m-2,m-1} |_{\mathcal{L}_m} \simeq \ker \delta_{m-1,m} |_{\mathcal{R}_m} / \text{Im } \delta_{m-2,m-1} |_{\mathcal{R}_m}$$

and, for $0 \leq j \leq \frac{(N_b - 1) N_b^m}{2}$, to the following Poincaré duality (expressed as a group isomorphism):

$$H_{m,j} \simeq \overline{H}_{m, \#V_{m-1-j}} .$$

Remark 4.9. The above duality in Proposition 4.10, on page 52, simply states the natural isomorphism between a path connecting two vertices located on the Left Side and the path connecting the corresponding two vertices located on the Right Side of the m^{th} prefractal graph, symmetrically. In terms of the functions f , which comprise the left and right-side cohomology groups, it simply translates into the idempotent map $M \mapsto f(\overline{M})$.

4.6 Total Fractal Cohomology of the Weierstrass Curve

Regarding our final and main theorem just below, we refer the reader to Section 4.4 above for the definition of the fractal complex and of the cohomology groups associated to the Weierstrass Curve $\Gamma_{\mathcal{W}}$; we also refer to Remark 4.1, on page 29, and Remark 4.3, on page 33.

Theorem 4.11 (Fractal Cohomology of the Weierstrass Curve).

Within the set $\mathcal{H}öld_{geom}(\Gamma_{\mathcal{W}})$ of continuous, complex-valued functions f , defined on the Weierstrass Curve $\Gamma_{\mathcal{W}} \supset V^{\star} = \bigcup_{m \in \mathbb{N}} V_m$ (see part ii. of Definition 4.7 above, on page 33), let us consider the Complex (which can be called the Fractal Complex of $\Gamma_{\mathcal{W}}$),

$$H^{\star} = H^{\bullet}(\mathcal{F}^{\bullet}(\Gamma_{\mathcal{W}}, \mathbb{C}), \delta^{\bullet}) = \bigoplus_{m=0}^{\infty} H^m,$$

where, for any integer $m \geq 1$, and with the convention $H^0 = \text{Im } \delta_{-1,0} = \{0\}$, H^m is the cohomology group

$$H^m = \ker \delta_{m-1,m} / \text{Im } \delta_{m-2,m-1}.$$

Then, H^{\star} is the set consisting of functions f on $\Gamma_{\mathcal{W}}$, viewed as 0-fermions (in the sense of Definition 4.3, on page 26), and, for any integer $m \geq 1$, of the restrictions to V_m of $(m, N_b^m + 1)$ -fermions, i.e., the restrictions to (the Cartesian product space) $V_m^{N_b^m + 1}$ of antisymmetric maps on $\Gamma_{\mathcal{W}}$, with $N_b^m + 1$ variables (corresponding to the vertices of V_m), involving the restrictions to V_m of the continuous, complex-valued functions f on $\Gamma_{\mathcal{W}}$ – as, naturally, the aforementioned 0-fermions – satisfying the following convergent (and even, absolutely convergent) Taylor-like expansions (with $V^{\star} = \bigcup_{n \in \mathbb{N}} V_n$),

$$\forall M_{\star, \star} \in V^{\star} : \quad f(M_{\star, \star}) = \sum_{k=0}^{\infty} c_k(f, M_{\star, \star}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{i k \ell_{k,j,m} \mathbf{P}} = \sum_{k=0}^{\infty} c_k(f, M_{\star, \star}) \varepsilon_k^{k(2-D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{P}}, \quad (24)$$

where, for each integer $k \geq 0$, the coefficient $c_k(\star, \star) = c_k(f, \star) \in \mathbb{C}$ is the same as in part ii. of Theorem 4.3, on page 33, the number $\varepsilon_k^k > 0$ is the k^{th} cohomology infinitesimal introduced in Definition 4.6, on page 32, and where $\ell_{k,j,m}$ denotes an integer (in \mathbb{Z}) such that

$$\left| \left\{ \ell_{k,j,m} \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \lesssim \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}.$$

Note that since the functions f involved are uniformly continuous on the Weierstrass Curve $\Gamma_{\mathcal{W}} \supset V^{\star}$, and since the set V^{\star} is dense in $\Gamma_{\mathcal{W}}$, they are uniquely determined by their restriction to V^{\star} , as given by (24). We caution the reader, however, that at this stage of our investigations, we do not know whether $f(M)$ is given by an expansion analogous to the one in (24), for every $M \in \Gamma_{\mathcal{W}}$, rather than just for all $M \in V^{\star}$.

The convergence (or even, the absolute convergence) of the series $\sum_{k=0}^{\infty} c_k(f, M_{\star, \star}) \varepsilon_k^{k(2-D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{P}}$ directly comes from the fact that the coefficients $c_k(\star, \star)$ are uniformly bounded (see the inequalities (17) in the proof of Theorem 4.3, on page 33), and that, for any $k \in \mathbb{N}^{\star}$,

$$\left| \varepsilon_k^{k(2-D_{\mathcal{W}}) + i k \ell_{k,j,m} \mathbf{P}} \right| = \varepsilon_k^{k(2-D_{\mathcal{W}})} \lesssim (\varepsilon^{2-D_{\mathcal{W}}})^k, \quad \text{with } 0 < \varepsilon = \frac{1}{N_b} < 1 \text{ and } 2 - D_{\mathcal{W}} > 0.$$

Finally, for each $M_\star = M_{\star,m} \in V^\star$, as was shown in Proposition 4.5, on page 44 (of Section 4.4), the coefficients $c_k(\star, \star)$ (for any $k \in \mathbb{N}$) are the residues at the possible Complex Dimensions $-(k(2 - D_{\mathcal{W}}) + ik \ell_{k,j,m} \mathbf{p})$ of a suitable global scaling zeta function $\zeta_{f, M_{\star,m}, gl}$, also introduced in Proposition 4.5, on page 44.

The group $H^\star = \bigoplus_{m=0}^{\infty} H^m$ is called the total fractal cohomology group of the Weierstrass Curve $\Gamma_{\mathcal{W}}$ (or else, of the Weierstrass function \mathcal{W}).

Note that H^\star is to be understood in the sense of the inductive limit of the sequence of cohomology groups $(H^m)_{m \in \mathbb{N}}$; namely, for each fermion $\varphi \in H^\star$, and each $m \in \mathbb{N}$, the restriction $\varphi|_{V_m}$ of φ to the set of vertices V_m belongs to H^m ; the restriction $(\varphi|_{V_{m+1}})|_{V_m}$ to V_m of the restriction $\varphi|_{V_{m+1}}$ of φ to the set of vertices V_{m+1} (which is itself in H^{m+1}), coincides with the restriction $\varphi|_{V_m}$ of φ to V_m ; i.e.,

$$\forall m \in \mathbb{N} : \quad \varphi|_{V_m} \in H^m \quad \text{and} \quad (\varphi|_{V_{m+1}})|_{V_m} = \varphi|_{V_m} .$$

This amounts, for each $\varphi \in H^\star$, to

$$\varphi = (\varphi_m)_{m \in \mathbb{N}} ,$$

where, for each $m \in \mathbb{N}$, $\varphi_m \in H^m$, while, if we denote by $\pi : H^{m+1} \rightarrow H^m$ the natural projection from H^{m+1} onto H^m , we have that $\pi(\varphi_{m+1}) \in H^m$ coincides with φ_m . In other words, H^\star coincides with the corresponding inductive limit of the sequence of prefractal cohomology groups H^m , with $m \in \mathbb{N}$.

Proof. In light of Theorem 4.3, on page 33, and Proposition 4.7, on page 49, let us consider a complex-valued function f , which satisfies the same discrete local Hölder and reverse-Hölder property as the Weierstrass function \mathcal{W} , i.e., for any pair of adjacent vertices (M, M') , of respective affixes (z, z') ,

$$|z - z'|^{2-D_{\mathcal{W}}} \lesssim |f(z) - f(z')| \lesssim |z - z'|^{2-D_{\mathcal{W}}} , \quad (\blacklozenge) \quad (25)$$

along with the geometric condition

$$|\arg(f(z)) - \arg(f(z'))| \lesssim |z - z'| . \quad (\blackspade) \quad (26)$$

Now, given a point $M_{\star,\star} \in V^\star = \bigcup_{n \in \mathbb{N}} V_n$, there exists a (smallest) nonnegative integer m_0 such that $M_{\star,\star} = M_{j_{m_0}, m_0} \in V_{m_0}$, with $0 \leq j_{m_0} \leq \#V_{m_0} - 1$.

Then, since the sequence of sets of vertices $(V_m)_{m \in \mathbb{N}}$ is increasing (see part *i.* of Property 2.4, on page 8), we must have that

$$\forall m \geq m_0 : \quad M_{\star,\star} \in V_m .$$

In fact, this amounts, for each $m \geq m_0$, to $M_{\star,\star} = M_{j_m, m} \in V_m$, with $0 \leq j_m \leq \#V_m - 1$.

For the sake of simplicity, we will write $M_{\star,m}$, $m \in \mathbb{N}$, for such points $M_{j_m, m}$, with $0 \leq j_m \leq \#V_m - 1$.

In conjunction with the series expansion (15) obtained in part *ii.* of Theorem 4.3, on page 33, we have that

$$f(M_{\star,\star}) = \lim_{m \rightarrow \infty} f(M_{\star,m}) = \lim_{m \rightarrow \infty} \sum_{k=0}^m c_k(f, M_{\star,m}) \varepsilon_k^{k(2-D_{\mathcal{W}})} \varepsilon_k^{i k \ell_{k,j,m} \mathbf{P}} = \sum_{k=0}^{\infty} c_k(f, M_{\star,\star}) \varepsilon_k^{k((2-D_{\mathcal{W}})+i \ell_{k,j,m} \mathbf{P})},$$

where, for each integer $k \geq 0$, $c_k(f, M_{\star,\star})$ denotes a complex coefficient which depends on the function f and on the vertex $M_{\star,\star}$ involved, and where, for $k \geq 0$, $\ell_{k,j,m}$ denotes an integer such that

$$\left| \left\{ \ell_{k,j,m} \frac{\ln \varepsilon_k^k}{\ln N_b} \right\} \right| \approx \frac{\varepsilon_k^{k(D_{\mathcal{W}}-1)}}{2\pi}.$$

In our present setting, where we deal with an inductive limit, this immediately yields the desired result. □

Remark 4.10 (Interpretation).

The cohomology infinitesimal (or, equivalently, the elementary length) – which obviously depends on the magnification scale (i.e., the chosen prefractal approximation) – can be seen as a transition scale between the fractal domain and the classical one. In fact, we could say that the system is fractal below this scale, and classical above (for the level of magnification considered). In the limit when the integer m associated with the prefractal approximation tends to infinity, the system is fractal below the cohomological infinitesimal (which is really an infinitesimal, in this case), i.e., at small scales, and is classical beyond, i.e., on a large scale.

This is in perfect agreement with what is described by the French physicist Laurent Nottale in [Not98] about scale-relativity, and fractal-type objects in nature, pages 306-307: “La plupart des objets fractals qu’on rencontre dans la nature (...) sont également caractérisés géométriquement par l’existence d’une échelle de transition inférieure et/ou supérieure au-delà de laquelle ils redeviennent des objets standards” – “Most fractal objects encountered in nature (...) are also characterized geometrically by the existence of a lower and/or upper transition scale beyond which they become standard objects again”. In fact, and as explained again by Nottale, “the transition between fractal (at small relative scales) and non-fractal (at larger scales) behavior is identified with the quantum/classical transition”. This latter point appears to us to be of the greatest interest in the present context, and warrants much further exploration in the future.

Recall that in the standard mathematical theory of Complex Dimensions (see, e.g., [LvF13], [LRŽ17b], [Lap19]), a geometric object is said to be *fractal* if it admits at least one *nonreal* Complex Dimension (defined as a pole of the associated geometric or fractal zeta function). In our present context, indeed, the Weierstrass Curve $\Gamma_{\mathcal{W}}$ is fractal, since it has infinitely (and countably) many Complex Dimensions; see [DL24a], [DL23b]. In particular, it is both principally fractal (since it has infinitely many Complex Dimensions with real part $D_{\mathcal{W}}$, the Minkowski dimension of $\Gamma_{\mathcal{W}}$) and is fractal in infinitely (and countably) many values of d (namely, $d = D_{\mathcal{W}} - k(2 - D_{\mathcal{W}})$, with $k \in \mathbb{N}$ arbitrary).

At the same time, as is also proved in [DL23b], for all sufficiently large positive integers m (i.e., for all $m \geq m_0$, for some $m_0 \in \mathbb{N}$), the m^{th} prefractal approximation $\Gamma_{\mathcal{W}_m}$ to the Weierstrass Curve $\Gamma_{\mathcal{W}}$ is fractal and even, principally fractal. More specifically, it is fractal in dimension d , for precisely the following values of $d = d_k \in \mathbb{R}$:

$$d = d_k = D_{\mathcal{W}} - k(2 - D_{\mathcal{W}}),$$

with the integer k satisfying $0 \leq k \leq m$.

This latter point – as surprising as it may seem, at first sight – therefore corresponds to a *transition* when the integer m reaches m_0 (i.e., when ε_m^m is sufficiently small, namely, $\varepsilon_m^m \leq \varepsilon_{m_0}^{m_0}$). Our m^{th} cohomology infinitesimal ε_m^m (see Definition 4.6, on page 32), is directly connected to the *intrinsic (subdivision) scale* $\varepsilon = \frac{1}{N_b}$, also introduced in Definition 4.6, since

$$\varepsilon_m^m = \frac{\varepsilon^m}{N_b - 1}.$$

When the *resolution* (in L. Nottale’s words) improves (i.e., when m increases), fractality arises. Then, classical tools, for instance, usual differential operators, cannot be applied. We are therefore looking for their *fractal counterpart*, which make it possible to express, in a natural way, the evolution equations associated with the morpho-biological and physical phenomena involved, taking into account the underlying fractal nature.

We can also interpret the cohomology H^\star of the Weierstrass Curve $\Gamma_{\mathcal{W}}$ (or of \mathcal{W}) by means of the following rules:

- i.* Rule 1 – Self-Awareness: The geometry itself belongs to the (total) cohomology; i.e., the Weierstrass function \mathcal{W} belongs to the total cohomology space H^\star ; see Corollary 4.4, on page 36 above and Remark 4.11, on page 57 just below.
- ii.* Rule 2 – Optimality: The “restriction” (or rather, the truncation involving the expansion in terms of the allowed Complex Dimensions, up to order $m \in \mathbb{N}^\star$) of the geometry (say, the given function f) to H^m (the m^{th} cohomology quotient group) satisfies a certain *optimality* condition. In fact, it coincides with the projection of the geometry from the total cohomology space H^\star onto H^m .
- iii.* Rule 3 – Naturality: The total cohomology space H^\star is the space of objects “of the same nature” (see Definition 4.7, on page 33), whose Complex Dimensions form a subset – or rather, are in direct correspondence with a subset – of the set of Complex Dimensions of the Weierstrass Curve $\Gamma_{\mathcal{W}}$; see Theorem 3.1 from [DL22] and Remark 3.2, on page 24 (now revisited in the light of Theorems 4.3, on page 33, and 4.11, on page 53).

Note that, contrary to the classical cases of arithmetic or differentiable varieties, for which the decomposition of the total cohomology is indexed by integers, the total (fractal) cohomology H^\star is a sum of spaces indexed by the complex dimensions (as is expected in [LvF00], [LvF06], [LvF13] and [Lap08], and discussed in detail in [CL17], [Lap19] and [Lap24]), with an underlying quasiperiodicity property, induced by the estimate (on the imaginary parts of the complex dimensions) (16) in part *ii.* of Theorem 4.3, on page 33. This quasiperiodic geometric property (reminiscent of, but not identical to, that established in Chapter 3 of [LvF13] for the Complex Dimensions of nonlattice self-similar strings) can possibly be connected to the structure of a (generalized) quasicrystal (see [LvF13], Problem 3.22, page 89, and [Lap08], especially, Chapter 5 and Appendix F), especially in the case not considered in the present paper when N_b is not an integer. The aforementioned quasiperiodic geometric property suggests the existence of a natural *transfer operator* (Frobenius operator), under the action of which the the Weierstrass Curve $\Gamma_{\mathcal{W}}$ remains invariant. More precisely, given $m \in \mathbb{N}$, this transfer operator enables us to switch from each m^{th} graph approximation $\Gamma_{\mathcal{W}_m}$ to the $(m + 1)^{\text{th}}$ graph approximation $\Gamma_{\mathcal{W}_{m+1}}$. This transfer operator also acts on the (total) cohomology. This operator, that we have now identified, is described in detail in our forthcoming work [DL24b].

Of course, this goes hand in hand with Nottale’s perception concerning a characteristic feature of fractality in [Not98]: “l’apparition de nouvelles structures quand la résolution s’améliore” – “the appearance of new structures when the resolution improves.”

Remark 4.11 (About the Functions Defined on the Weierstrass Curve).

Continuous, complex-valued maps f defined on the Weierstrass Curve $\Gamma_{\mathcal{W}}$ can also be viewed as continuous parametrized plane curves γ . As was done in Corollary 4.4, on pag 36, if, for any real number t in $[0, 1]$,

$$\gamma_{\mathcal{W}}(t) = (t, \mathcal{W}(t)) ,$$

we then have that

$$\gamma = f \circ \gamma_{\mathcal{W}} ;$$

i.e.,

$$\forall t \in [0, 1] : \quad \gamma(t) = f(\gamma_{\mathcal{W}}(t)) = f(t, \mathcal{W}(t)) .$$

Hence, in particular, when we say that the Weierstrass function \mathcal{W} belongs to H^* , we really mean that the identity function on the Weierstrass Curve, $\mathbb{1}_{\Gamma_{\mathcal{W}}}$, itself belongs to H^* , which is obviously true.

Therefore, because of the properties of the Weierstrass function \mathcal{W} , the choice of $f = \mathbb{1}_{\Gamma_{\mathcal{W}}}$ (or, equivalently, $\gamma = \gamma_{\mathcal{W}}$) is valid, and proves that $H^* \neq \{0\}$, which is nontrivial, is in perfect agreement with Corollary 4.4, on page 36.

5 Concluding Comments

Our above results aim at providing a better understanding of Fractal Cohomology. As was mentioned in the introduction, the Weierstrass Curve stands as a *test case*, since it constitutes a fractal object which is, also, associated to a function. For the sake of consistency, in addition to the original function, we also choose to consider the Complexified Weierstrass function, in the spirit of the fractal explicit formulas obtained in [LvF00], [LvF06], [LvF13] and [LRŽ17b]. This function possesses an exact fractal expansion, consisting in a countably infinite sum indexed by the Complex Dimensions. This feature is all the more interesting that the generators of the cohomology groups are the building blocks of such fractal expansions; see Proposition 4.7, on page 49.

Going further, those expansions might be interpreted as generalized Taylor expansions, with fractional derivatives of underlying orders the corresponding Complex Dimensions. The conditions of existence of such Taylor-like expansions, as well as the explicit expressions of the corresponding (local) fractional derivatives, are the building blocks of a future work, [DLO23]. See also [DL24b] for new cohomological interpretations of such fractal expansions in terms of fractal analogs of Kähler geometry and Hodge theory.

A natural conjecture is that the coefficients $c_k(f, M)$, for $k \in \mathbb{N}$, involved in the expansions of Theorem 4.11, on page 53, can not only be interpreted as (local) fractional derivatives of the function f (in the cohomology space of the Weierstrass Curve) in question, evaluated at the point M and expressed using the derivative of the corresponding complex, but also – at least in the case when the function f is the Weierstrass function \mathcal{W} – as *local curvatures*, evaluated at a given point M of the

curve, and depending, of course, on the Complex Dimension $-(k(2 - D_{\mathcal{W}}) + i \ell_{k,j,m} \mathbf{p})$.

Moreover, when f is not necessarily equal to the Weierstrass function \mathcal{W} , the coefficients $c_k(f, M)$ could again be interpreted as local *curvatures*, still depending on the function f , but now seen by means of an ε -*microscope*, still depending on the Complex Dimension $-(k(2 - D_{\mathcal{W}}) + i \ell_{k,j,m} \mathbf{p})$ mentioned above. When $(\varepsilon_m^m)_{m=0}^{\infty} \rightarrow 0$ (i.e., when $m \rightarrow \infty$), we could thus obtain the *transition microscope*; i.e., the transition of optimal scales determined only by the geometry of the underlying fractal curve (here, the elementary lengths L_k). In the case of a fractal surface, for each scale $k \in \mathbb{N}$, we would have two elementary parameters – degrees of freedom – perhaps two radii of curvature in the sense of Gauss, and for a fractal manifold of dimension $n \geq 3$, we would have n such values, associated for example with the underlying *local* curvature tensor, in the sense of Riemann, again for each scale $k \in \mathbb{N}$ and evaluated at a given point M of the fractal surface (or, more generally, of the fractal manifold).

This is not all. Indeed, in the case of the Weierstrass Curve, our differentials δ and $\bar{\delta}$ (see Section 4.5) enable us to define the associated Laplacian $\delta \bar{\delta} + \bar{\delta} \delta$, which needs to be further explored in this context – especially, in conjunction with a corresponding fractal version of Hodge theory (see [DL24b]). Moreover, naturally, we intend to establish general results – concerning, in particular, both the Complex Dimensions and the cohomology groups – valid for a large class of (typically nowhere differentiable) fractal curves and functions, which will also be the subject of a future work, [DL23a]. Building on the present fractal cohomology theory, we also intend to develop an appropriate extension of Morse theory dedicated to fractal sets, where, in addition to the height function, Complex Dimensions should enable us to essentially characterize them; see [DL24c] for the beginning of such a development.

At a later stage, we envision extending the present theory to fractal surfaces and higher-dimensional fractal manifolds, as was alluded to just above. Moreover, an interesting and challenging problem (see [Lap19], [Lap24]) consists in constructing an appropriate fractal homology theory of which the present fractal cohomology theory (or a suitable modification therein) would be, in some sense, the dual theory.

Finally, in the long term, we would like to obtain a fruitful synthesis between the pure analytical and number-theoretic approach (and program) developed in ([LvF00], [Lap08], [LvF06], [LvF13], [CL17], [Lap19], [Lap24]) and the present geometric approach to fractal cohomology, relying, in part, on [CL17], [DL23c] and [DL22], in addition to the aforementioned work. Some progress in this direction has recently been made by the authors in [?].

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