Measuring the local non-convexity of real algebraic curves

by

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ABSTRACT

The goal of this paper is to measure the non-convexity of compact and smooth connected components of real algebraic plane curves. We study these curves first in a general setting and then in an asymptotic one. In particular, we consider sufficiently small levels of a real bivariate polynomial in a small enough neighbourhood of a strict local minimum at the origin of the real affine plane. We introduce and describe a new combinatorial object, called the Poincaré-Reeb graph, whose role is to encode the shape of such curves and allow us to quantify their non-convexity. Moreover, we prove that in this setting the Poincaré-Reeb graph is a plane tree and can be used as a tool to study the asymptotic behaviour of level curves near a strict local minimum. Finally, using the real polar curve, we show that locally the shape of the levels stabilises and that no spiralling phenomena occur near the origin.

INTRODUCTION

This work is situated at the crossroads between the geometry and topology of singularities and the study of real algebraic plane curves. The origins of this subject date back to the works of Harnack, Klein, and Hilbert ([Har76], [Kle73], [Hil91]). Continuous progress and recent interest on these subjects is shown for instance by Coste, de la Puente, Dutertre, Ghys, Itenberg, Sturmfels, and Viro ([CP01], [Dut16], [Ghy17], [IMR18],[Stu+17], [Vir08]).

Our goal is to measure how far from being convex a given algebraic curve is and what is its behaviour near a strict local minimum. Non-convexity plays an important role in many applications, such as optimisation theory or computational geometry (see for instance [JK17] or [Jut+19]). To this end, we construct and study a new combinatorial object called the Poincaré-Reeb tree, whose role is to encode the shape of a smooth compact connected component of a real algebraic plane curve. In particular, we will use this tool to quantify the non-convexity of the curve. The Poincaré-Reeb tree is adapted from the classical construction introduced by H. Poincaré (see [Poi10, 1904, Fifth supplement, page 221]), which was rediscovered by G. Reeb in 1946 (in [Ree46]). Both used it as a tool in Morse theory. Namely, given a Morse function on a closed manifold, they associated it a graph as a quotient of the manifold by the equivalence relation whose classes are the connected components of the levels of the function. We will perform an analogous construction for a special type of manifold with boundary. We prove that in our setting the Poincaré-Reeb graph is a plane tree, and show several other properties of this tree.
0 Introduction

Note that there exist results on graphs encoding the topology of real algebraic plane curves (see, for example, [Che+10] and the references therein). Those graphs are different from our novel Poincaré-Reeb construction.

We will now list the main contributions of this paper.

![Diagram](image)

**Figure 1.** The Poincaré-Reeb graph of a smooth and compact connected component of a real algebraic curve in $\mathbb{R}^2$.

**Measuring the non-convexity via the The Poincaré-Reeb tree.** Consider a compact and smooth connected component $\mathcal{C}$ of a real algebraic curve contained in the plane $\mathbb{R}^2$ (see Figure 1). Denote by $\mathcal{D}$ the disk bounded by $\mathcal{C}$. Endow the plane $\mathbb{R}^2$ with its canonical orientation and with its foliation by vertical lines. The curve $\mathcal{C}$, being a connected component of an algebraic curve, has only finitely many points of vertical tangency. The vertices of the Poincaré-Reeb graph are images of the points of the curve having vertical tangent by the projection $\Pi : \mathcal{D} \to \mathbb{R}, \Pi(x,y) := x$. For $x_0 \in \mathbb{R}$, if the fibre $\Pi^{-1}(x_0)$ is not the empty set, then it is a finite union of vertical segments. We define an equivalence relation that lets us contract each of these segments into a point. By the quotient map, the image of the initial disk becomes a one-dimensional connected topological subspace embedded in the real plane. More precisely, it is a connected plane graph. In addition to this construction, we prove the following result:

**Theorem 0.1** (see Corollary 4.21). The Poincaré-Reeb graph associated to a compact and smooth connected component of a real algebraic plane curve and to a direction of projection $x$ is a plane tree whose open edges are transverse to the foliation induced by the function $x$. Its vertices are endowed with a total preorder relation induced by the function $x$.

Note that the main tool used in the proof of Theorem 0.1 is the integration of constructible functions with respect to the Euler characteristic (see [Cos05, Chapter 3, page 22]).
Nested level curves of a real bivariate polynomial near a strict local minimum. Let us consider a polynomial function $f: \mathbb{R}^2 \rightarrow \mathbb{R}$, such that $f$ has a strict local minimum at the origin and $f(0) = 0$. We focus on the so-called real Milnor fibres at the origin of $f$, namely the small enough level curves $(f(x, y) = \varepsilon)$, for sufficiently small $0 < \varepsilon \ll 1$. We prove that they are smooth Jordan curves (see Lemma 5.3). The simplest example is the circle. Whenever the origin is a Morse strict local minimum, we show that the small enough levels become boundaries of convex topological disks. In the non-Morse case, these curves may fail to be convex, as was shown by a counterexample found by Michel Coste. Let us restrict the study of the Poincaré-Reeb trees to the asymptotic setting, namely let us study the trees associated to small enough level curves of a real bivariate polynomial function, near a strict local minimum at the origin of the plane. We show that the tree stabilises for sufficiently small level curves. We call it the asymptotic Poincaré-Reeb tree. Therefore the shape of the levels stabilises near the strict local minimum (see Figure 2).

![Figure 2. Stabilisation of the shape of the levels.](image)

We also prove the following result:

**Theorem 0.2** (see Theorem 5.31). The asymptotic Poincaré-Reeb tree is a rooted tree and the total preorder relation on its vertices, induced by the function $x$, is strictly monotone on each geodesic starting from the root.

The strict monotonicity on the geodesics starting from the root allows us to prove that the small enough level curves $C_\varepsilon$ have no turning back or spiralling phenomena.

In other words, near a strict local minimum, for $0 < \varepsilon \ll 1$ sufficiently small there are no level curves $(f = \varepsilon)$ like the one in Figure 3.

![Figure 3. Forbidden shape for small enough $0 < \varepsilon \ll 1$: there are no going backwards like this.](image)
The present paper is organised as follows. After introducing the necessary notations and hypotheses in Section 1, we show in Section 2 that topological disks bounded by the level curves of $f$ in a small enough neighbourhood of a *Morse* strict local minimum are convex sets (see Theorem 2.3). Section 3 is dedicated to Coste's counterexample (see Example 3.1) in the *non-Morse* case and our generalisations. In Section 4 we give the construction of a new combinatorial object, called the Poincaré-Reeb graph, whose role is to measure the non-convexity of a compact smooth connected component of a plane algebraic curve in $\mathbb{R}^2$. Using a Fubini-type theorem and integration with respect to the Euler characteristic, we show that the Poincaré-Reeb graph is in fact a plane tree (see Corollary 4.21). Section 5 focuses on the asymptotic case, where the real polar curve plays a key role. We prove that in a small enough neighbourhood of the origin the Poincaré-Reeb trees become equivalent, starting with a small enough level. In other words, the shape of the levels stabilises near the origin. In addition, the Poincaré-Reeb tree allows us to prove Theorem 5.31. Namely we show that asymptotically there is no spiralling phenomenon near the strict local minimum. This is due to the fact that the induced preorder endowing the set of vertices is strictly monotonous on each geodesic starting from the root of the tree.

**Figure 4.** An asymptotic Poincaré-Reeb tree.

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1 Notations and hypotheses

In this chapter, the expressions “sufficiently small $\varepsilon$” or “small enough $\varepsilon$” mean: “there exists $\varepsilon_0 > 0$ such that, for any $0 < \varepsilon < \varepsilon_0$, one has . . .”. We will often denote this by $0 < \varepsilon \ll 1$.

We will consider a polynomial function $f : \mathbb{R}^2 \to \mathbb{R}$ in two variables with $f(0, 0) = 0$. Let us **fix a neighbourhood** $V$ of $(0, 0)$ such that:

- the point $(0, 0)$ is the **only strict local minimum** of $f$ in $V$;
we have \( V \cap (f = 0) = \{(0, 0)\} \).

**Definition 1.1.** Let us consider a polynomial function \( f : \mathbb{R}^2 \to \mathbb{R} \) that vanishes at the origin \( O \), exhibiting a strict local minimum at this point. For \( \varepsilon > 0 \), consider the set \( f^{-1}([0, \varepsilon]) \) and denote its connected component that contains the origin by \( D_\varepsilon \). Denote by \( C_\varepsilon := D_\varepsilon \setminus \text{Int } D_\varepsilon \).

Later on (see Lemma 5.3), we shall prove that for \( 0 < \varepsilon \ll 1 \) sufficiently small, \( C_\varepsilon \) is diffeomorphic to a circle and that \( D_\varepsilon \) is diffeomorphic to a disk, completely included in \( V \).

**Example 1.2.** The surface \( \text{graph}(f) := \{(x, y, z) \in \mathbb{R}^3 \mid z = f(x, y)\} \) of the cubic \( f(x, y) := y^2 - x^3 + x^2 \) is shown in Figure 6 (see for instance [Wal78, page 57, Figure 2.2]).

We did not choose yet a sufficiently small neighbourhood \( V \) of the origin. An illustration of such a neighbourhood \( V \) that satisfies the hypotheses from Section 1 is shown in Figure 7 below. The zero locus of \( f \) has two connected components: a point and a curve. We take \( V \) small enough such that it does not intersect the curve, that is the connected component far from the origin.
2 Notations and hypotheses

Choose a small enough neighbourhood $V$ of the origin such that the point $(0,0)$ is the only strict local minimum of $f$ in $V$ and $V \cap \{ f = 0 \} = \{(0,0)\}$.

Examples of functions $f$ as in Section 1 are shown in Figure 8, Figure 10, Figure 12.

For the following classical definition see for instance [Mil68, page 10]:

Definition 1.3. Let $\varphi : \mathbb{R}^n \to \mathbb{R}^p$, with $n, p \in \mathbb{N}^*, n \geq p$, be a polynomial map.

Let $\rho := \max \{ \text{rank} \text{ Jac}(\varphi)(x) \mid x \in \mathbb{R}^n \}$ be the maximal rank of $\varphi$, where $\text{Jac}(\varphi)(x)$ is the Jacobian matrix of $\varphi$, evaluated at $x$.

Then the set of singular points (called also critical points) of $\varphi$ is by definition

$$\text{Sing}(\varphi) := \{ x \in \mathbb{R}^n \mid \text{rank} \text{ Jac}(\varphi)(x) < \rho \}.$$

The image of a singular point under $\varphi$ is called a singular value of $\varphi$.

A point $x \in \mathbb{R}^n$ is called regular of $\varphi$ if it is not singular.

Example 1.4. Let $f : \mathbb{R}^2 \to \mathbb{R}$ be a polynomial function. Then by Definition 1.3, the set of singular points of $f$ is

$$\text{Sing} f = \left\{ (x,y) \in \mathbb{R}^2 \mid \frac{\partial f}{\partial x}(x,y) = \frac{\partial f}{\partial y}(x,y) = 0 \right\}.$$

For more examples, see for instance [PP18] or [Wal78, page 57].

2 Morse extrema and convex level sets

The classical well-known statement that follows is meant to present equivalent characterisations of convex functions (see, for instance, [Rek+83, pages 640-650]).

Theorem 2.1. Let us consider a convex set $C \subset \mathbb{R}^2$ and a $C^2$ function $f : C \to \mathbb{R}$. The following properties are equivalent:

1. for any two points $x, y \in C$, for any $t \in [0,1]$, we have

   $$f(tx + (1-t)y) \leq tf(x) + (1-t)f(y);$$

2. the set $\text{epi}(f) := \{ (x,y,z) \in \mathbb{R}^3 \mid z \geq f(x,y) \}$ is convex;

3. the Hessian matrix of $f$, denoted by $\text{Hess}_f(x,y)$, is everywhere positive definite or positive semidefinite.

Definition 2.2. A $C^2$ function $f : \mathbb{R}^2 \to \mathbb{R}$ is convex if $f$ verifies one of the properties from Theorem 2.1.
Theorem 2.3. Let \( f : \mathbb{R}^2 \to \mathbb{R} \) be a polynomial function of the form \( f(x,y) = ax^2 + by^2 + h(x,y) \), where \( a, b \in \mathbb{R}, \ a > 0, \ b > 0, \ f(0,0) = 0 \) and \( h : \mathbb{R}^2 \to \mathbb{R} \) is a polynomial function of degree of each monomial at least 3. Then for a sufficiently small \( 0 < \varepsilon \ll 1 \), \( D_\varepsilon \) is a convex set in a small enough neighbourhood of the origin.

Proof. Note that we are situated in a small enough neighbourhood of the origin. We have \( a > 0, \ b > 0, \lim_{(x,y) \to (0,0)} \det H_f(x,y) = ab > 0 \), for any \( (x,y) \) in a small enough neighbourhood of \( (0,0) \). Thus the Hessian matrix is positive definite and we conclude that \( f \) is a convex function, since we are in dimension 2 and by Sylvester criterion if a symmetric matrix has all diagonal elements and all the leading principal determinants positive, then the matrix is a positive definite matrix (see [Gil91, page 45], or [Rek+83]). Recall the fact that positive definite forms form an open set in the space of all forms. Since the function \( f \) is \( \mathcal{C}^2 \), its Hessian form varies continuously.

Therefore, the epigraph of \( f \) restricted to a convex domain is a convex set. Let us consider \( 0 < \varepsilon \ll 1 \), sufficiently small. Since \( \mathcal{D}_\varepsilon := \text{epi}(f) \cap (z = \varepsilon) \), we obtain that \( \mathcal{D}_\varepsilon \) is a convex set, since it is the intersection of two convex sets. Thus, the projection of \( \mathcal{D}_\varepsilon \) on the plane \( xOy \) is also convex, in fact it is equal to \( \mathcal{D}_\varepsilon \).

Let us sketch a second proof. Since \( \lim_{(x,y) \to (0,0)} \det H_f(x,y) = ab \neq 0 \), for any \( (x,y) \) in a small enough neighbourhood of \( (0,0) \), the Hessian curve of \( f \) given by \( \{(x,y) \in \mathbb{R}^2 \mid \det H_f(x,y) = 0\} \), is empty. Thus (see [Wal04, page 71]) for a sufficiently small \( 0 < \varepsilon \ll 1 \), the level curve \( \mathcal{C}_\varepsilon \) has no inflexion points, hence it is convex.

\[ \square \]

Example 2.4. The circular paraboloid \( z = x^2 + y^2 \) (see in Figure 8 below): \( \mathcal{C}_\varepsilon \) are circles.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure8.png}
\caption{A non-degenerated (namely, Morse) critical point: we obtain convex disks.}
\end{figure}

3 Non-convex level sets

The starting point of this research is the following question:

Question (E. Giroux to P. Popescu-Pampu, 2004). Are the small enough level curves of \( f \) near strict local minima always boundaries of convex disks (even for non-Morse singularities)?

Answer: The answer to this question is negative, as the following counterexample by M. Coste shows.
Non-convex level sets

Example 3.1. Let us study the counterexample found by M. Coste:

\[ f(x, y) := x^2 + (y^2 - x)^2. \]

See Figure 9b for the family of its level sets. Figure 10 illustrates the graph of \( f \) and Figure 9a a single level \((f(x, y) = 0.1)\).

The idea used by M. Coste was that instead of taking the sum of squares of functions defining transverse curves like in \( x^2 + y^2 \) (i.e. the lines defined by \( x = 0 \) and \( y = 0 \) are transverse), to take the sum of squares of \( x \) and \( y^2 - x \), which define two curves that are tangent at the origin.

Note that the function \( f \) was also mentioned in [JK11], [Bol80].

![Figure 9](image1.png) ![Figure 10](image2.png)

(A) The level curve \((f(x, y) = 0.1)\) in \( \mathbb{R}^2 \), (B) A family of level curves in \( \mathbb{R}^2 \) of where the function \( f(x, y) := x^2 + (y^2 - x)^2. f(x, y) := x^2 + (y^2 - x)^2. \)

Figure 9. The counterexample provided by Coste.

**Proposition 3.2.** The topological disks \( D_\varepsilon \) from Example 3.1 are never convex for \( \varepsilon > 0 \).

**Proof.** Indeed, if we denote by \( M_\varepsilon := C_\varepsilon \cap \{x > 0 \mid y = 0\} \), by \( P_\varepsilon := C_\varepsilon \cap \{y > 0 \mid y^2 - x = 0\} \) and by \( N_\varepsilon := C_\varepsilon \cap \{y < 0 \mid y^2 - x = 0\} \), then we get \( x_{M_\varepsilon} = \sqrt{\frac{\varepsilon}{2}}, y_{M_\varepsilon} = 0, x_{P_\varepsilon} = \sqrt{\varepsilon}, y_{P_\varepsilon} = \sqrt{\varepsilon}, \) and \( x_{N_\varepsilon} = \sqrt{\varepsilon}, y_{N_\varepsilon} = -\sqrt{\varepsilon} \) (see Figure 11).
3.1 Generalisations

Figure 11. Coste’s example is non-convex.

Denote by $Q_{\varepsilon}$ the midpoint of $[N_{\varepsilon}P_{\varepsilon}]$. Then $x_{Q_{\varepsilon}} = \sqrt{\varepsilon} > x_{M_{\varepsilon}}$. Since $y_{M_{\varepsilon}} = y_{Q_{\varepsilon}} = 0$ and there is no other point to the right of $M_{\varepsilon}$, we conclude that $Q_{\varepsilon} \notin D_{\varepsilon}$. Hence there exist the points $N_{\varepsilon} \in D_{\varepsilon}$ and $P_{\varepsilon} \in D_{\varepsilon}$ such that the segment $[N_{\varepsilon}P_{\varepsilon}]$ is not included in $D_{\varepsilon}$. In conclusion, we proved that there exists at least a point outside the disk $D_{\varepsilon}$ on the segment $[N_{\varepsilon}P_{\varepsilon}]$. □

3.1 Generalisations

In the sequel we give some new examples of functions $f : \mathbb{R}^2 \to \mathbb{R}$ with a strict local minimum at the origin $(0,0)$, whose level sets $(f(x,y) = \varepsilon)$ are all boundaries of non-convex disks for a sufficiently small $0 < \varepsilon \ll 1$.

The shape of these level curves $C_{\varepsilon}$ stabilises for sufficiently small $0 < \varepsilon \ll 1$, as we shall prove in this paper.

Example 3.3. Let us take the following polynomial:

$$f(x,y) := x^{16} + (y^2 + x)^2(y^2 - x)^2.$$  

For a family of level curves of $f$, see Figure 12.

Figure 12. A family of level curves in $\mathbb{R}^2$ of $f(x,y) := x^{16} + (y^2 + x)^2(y^2 - x)^2$. 

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3 Non-convex level sets

Example 3.4. Let us consider the following polynomial:

\[ f(x, y) := x^6 + (y^4 + y^2 - x)(y^2 - x)^2. \]

The shape of its level curves is sketched in Figure 13.

![Figure 13. The sketch of a level curve (f = ε), f(x, y) := x^6 + (y^4 + y^2 - x)(y^2 - x)^2.](image)

3.2 Star domains The following definition is well-known:

Definition 3.5. [AB06, page 168] A set \( S \) in the Euclidean space \( \mathbb{R}^n \) is called a \textbf{star domain with respect to} \( x_0 \in S \) if for all \( x \in S \), the line segment from \( x_0 \) to \( x \) is in \( S \).

Proposition 3.6. The polynomial function \( f : \mathbb{R}^2 \to \mathbb{R} \)

\[ f(x, y) := x^{2p} + (y^2 - x)^2 \]

for \( p \geq 3 \), has the following properties: \( O \) is a strict local minimum and for sufficiently small \( 0 < \varepsilon \ll 1 \), the set \( D_\varepsilon := f^{-1}([0, \varepsilon]) \) is not a star domain with respect to any point \( P \in D_\varepsilon \).

Before the proof, let us first present the following Lemma:

Lemma 3.7. If a set \( D \subset \mathbb{R}^2 \) is a star domain with respect to a point and if \( D \) admits a symmetry axis, say \( \Delta \) (see Figure 14), then there exists a point \( P \in D \cap \Delta \) such that \( D \) is a star domain with respect to \( P \).

![Figure 14. A star domain \( D \) with a symmetry axis \( \Delta \).](image)

Proof. By hypothesis, the given set \( D \subset \mathbb{R}^2 \) is a star domain with respect to a point. Denote this point by \( P_1 \). If \( P_1 \in \Delta \), there is nothing to prove. Let us consider \( P_1 \notin \Delta \), as pictured in Figure 15.
3.2 Star domains

By hypothesis, $\Delta$ is a symmetry axis for $\mathcal{D}$. Let us denote by $P_2 \in \mathcal{D}$ the symmetric of $P_1$ with respect to $\Delta$. Denote by $P$ the midpoint of the segment $[P_1P_2]$. Hence, $P \in \Delta$ and by symmetry, $\mathcal{D}$ is a star domain also with respect to $P_2$. Let us now prove that $\mathcal{D}$ is a star domain with respect to any point $Q \in [P_1P_2]$, hence $\mathcal{D}$ is a star domain with respect to the point $P$.

Let $M \in \mathcal{D}$. Since $\mathcal{D}$ is a star domain with respect to both $P_1$ and $P_2$, we have that $[MP_1]$, $[MP_2]$ and $[P_1P_2]$ are included in $\mathcal{D}$. Thus, both the triangle $\triangle MP_1P_2$ and its interior are included in $\mathcal{D}$, since the interior is the union of $]P_1X[ \setminus [P_2M[$. In particular, for any point $Q \in [P_1P_2]$, we obtain $[QM] \subset \mathcal{D}$. Namely, $\mathcal{D}$ is a star domain with respect to any point $Q \in [P_1P_2]$. In conclusion, $\mathcal{D}$ is a star domain with respect to $P$. \hfill $\square$

In the following let us present the proof of Proposition 3.6.

**Proof.** By Lemma 3.7, it is sufficient to prove that $\mathcal{D}_\varepsilon$ is not a star domain with respect to any point $B(x_B,0)$ on $(y = 0) \cap \mathcal{D}_\varepsilon$, such that $f(B) \leq \varepsilon$, because the line $\Delta := (y = 0)$ is a symmetry axis for $\mathcal{D}_\varepsilon$. 

---

**Figure 15.** There exists $P \in \mathcal{D} \cap \Delta$ such that $\mathcal{D}$ is a star domain with respect to $P$.

**Figure 16.** Example of a non-star domain.
4 Non-convex level sets

Consider the point \( A_\varepsilon \left( \varepsilon \frac{1}{2p}, \varepsilon \frac{1}{2p} \right) \) \( \in (y^2 - x = 0) \cap \{ f = \varepsilon \} \), see Figure 16. Then the midpoint of the segment \([BA_\varepsilon]\) (see Figure 16 below) is the point

\[
M_\varepsilon \left( \frac{\varepsilon \frac{1}{2p} + x_B}{2}, \frac{\varepsilon \frac{3}{2p}}{2} \right).
\]

We will prove that \( M_\varepsilon \not\in D_\varepsilon \).

Since \( f(B) \leq \varepsilon \), we have \( x_B^2 + x_B^2 \leq \varepsilon \). For sufficiently small \( 0 < \varepsilon \ll 1 \), we have \( x_B \) sufficiently small, thus \( x_B^2 < x_B^2 \). Hence \( |x_B| < \sqrt{\varepsilon} \).

We have \( f(M_\varepsilon) - \varepsilon > (\frac{1}{4} \varepsilon \frac{1}{2p} - \frac{1}{2} (\varepsilon \frac{3}{2p} + x_B))^2 - \varepsilon = \frac{1}{16} \varepsilon \frac{1}{p} + \frac{1}{2} \varepsilon \frac{1}{2p} x_B + \frac{1}{4} x_B^2 - \varepsilon \).

There are two cases to consider.

- First, if \( x_B \geq 0 \), then we have \( f(M_\varepsilon) - \varepsilon \geq \frac{1}{16} \varepsilon \frac{1}{p} - \varepsilon > 0 \) for a sufficiently small \( 0 < \varepsilon \ll 1 \).
- Secondly, if \( x_B < 0 \), then \( f(M_\varepsilon) - \varepsilon \geq \frac{1}{16} \varepsilon \frac{1}{p} + \frac{1}{2} \varepsilon \frac{1}{2p} x_B - \varepsilon \). Since \( |x_B| \leq \sqrt{\varepsilon} \) and \( \varepsilon \frac{1}{2p} < 1 \), we obtain \( |x_B| \varepsilon \frac{1}{2p} \leq \sqrt{\varepsilon} \). Thus, \( f(M_\varepsilon) - \varepsilon \geq \frac{1}{16} \varepsilon \frac{1}{p} - \frac{1}{2} \sqrt{\varepsilon} - \varepsilon > 0 \) for a sufficiently small \( 0 < \varepsilon \ll 1 \) and for \( p \geq 3 \).

In both cases, we get \( f(M_\varepsilon) > \varepsilon \), hence \( M \not\in D_\varepsilon \) and thus the segment \([BA_\varepsilon]\) is not included in \( D_\varepsilon \), even though \( A_\varepsilon, B \in D_\varepsilon \). In other words, \( D_\varepsilon \) is not a star domain with respect to any \( B \in D_\varepsilon \cap \Delta \).

4 The Poincaré-Reeb tree

4.1 The Poincaré-Reeb construction The main purpose of this section is to introduce a new combinatorial object that measures the non-convexity of a smooth and compact connected component of a real algebraic curve in \( \mathbb{R}^2 \). We will define the Poincaré-Reeb graph, associated to the given curve and to a direction of projection \( x \). It is adapted from the classical construction introduced by H. Poincaré (see [Poi10, 1904, Fifth supplement, page 221]), which was rediscovered by G. Reeb (in [Ree46]). Both used it as a tool in Morse theory (see [Mat02]). Namely, given a Morse function on a closed manifold, they associated it a graph as a quotient of the manifold by the equivalence relation whose classes are the connected components of the levels of the function. We will perform an analogous construction for a special type of manifold with boundary, namely for a topological disk \( D \) bounded by a smooth and compact connected component of a real algebraic curve. We prove that in our setting the Poincaré-Reeb graph is a plane tree.

- Let us consider a smooth and compact connected component of a real algebraic curve in \( \mathbb{R}^2 \), denoted by \( C \). Let \( D \) denote the topological disk bounded by \( C \) (see Figure 17 below). Moreover, let us define the projection \( \Pi : \mathbb{R}^2 \to \mathbb{R} \), \( \Pi(x, y) := x \).

**Definition 4.1.** For each \( x \in \mathbb{R} \), \( \Pi^{-1}(x) \cap D \) is a finite union of connected vertical segments. Let us define the equivalence relation \( \sim \) as follows: if \( (x, y) \) and \( (x, y') \) are two points in the real plane \( \mathbb{R}^2 \) then \( (x, y) \sim (x, y') \) if and only if they belong to the same vertical connected component of the fibre \( \Pi^{-1}(x) \cap D \).

Given the above equivalence relation, let us consider the canonical quotient map

\[
q : \mathbb{R}^2 \to \mathbb{R}^2 / \sim.
\]
4.1 The Poincaré-Reeb construction

Figure 17. A Poincaré-Reeb graph of a smooth and compact connected component of a real algebraic curve $C$.

Denote by $P := \mathbb{R}^2$ and by $\tilde{P} := \mathbb{R}^2/\sim$. The coordinates in $\tilde{P}$ are $(\tilde{x}, \tilde{y})$, with $\tilde{x} = x$.

The function $\Pi$ descends to the quotient in a function $\tilde{\Pi} : \tilde{P} \to \mathbb{R}$, $\tilde{\Pi}(x, \tilde{y}) := x$. The function $\tilde{\Pi}$ is continuous, since $\Pi$ is continuous.

We obtain the following commutative diagram (see Figure 18):

\[
\begin{array}{ccc}
D & \rightarrow & P \\
\downarrow \Pi & & \downarrow q \\
\mathbb{R} & \rightarrow & \tilde{P} \leftarrow \tilde{D} := q(D)
\end{array}
\]

Figure 18. The diagram is commutative: $\Pi = \tilde{\Pi} \circ q$.

Our next aim is to prove that $\tilde{P}$ is homeomorphic to $\mathbb{R}^2$. First we show that $\tilde{P}$, endowed with the function $\tilde{\Pi}$ is a fibre bundle, i.e. that satisfies a local triviality. We will prove that it is locally a cartesian product of two sub-spaces. Furthermore, we shall prove that the local trivialisation of the fibre bundle $\tilde{P}$ implies that $\tilde{P}$ is a trivial fibre bundle, i.e. it is not just locally a product of two spaces, but globally.

**Proposition 4.2.** The topological space $\tilde{P}$ endowed with the function $\tilde{\Pi}$ is a fibre bundle.
Proof. By the definition of the fibre bundle (see for instance [Frè13, page 51]), what we need to prove is that there exists a local trivalisation of $\tilde{P}$. Let us consider a point $x_0 \in \mathbb{R}$ in the base space, that is the $Ox$-axis. Take an open neighbourhood of $x_0$, called $U \subset \mathbb{R}$. We want to show that the set $\tilde{\Pi}^{-1}(U)$ is homeomorphic to $U \times \mathbb{R}$, here by $\mathbb{R}$ we mean a space that is homeomorphic to the real line $\mathbb{R}$. To this end, we have the following two arguments:

1. If on a vertical line we contract a finite number of segments into points (by the quotient map $q$ described above), we obtain a topological space that is homeomorphic to $\mathbb{R}$. Denote this space by $\mathbb{R}$.

2. The set $\mathcal{D} \cap \Pi^{-1}(x_0)$ is a finite union of intervals (some of them empty intervals), whose extremities depend continuously on $x$ (see Figure 19), except when $x_0$ is a critical point.

Hence we have the local triviality: $\tilde{\Pi}^{-1}(U)$ is homeomorphic to $U \times \mathbb{R}$. Thus the image $\tilde{P}$ of the plane $P$, by the quotient map $q$, is a fibre bundle.

![Diagram](image.png)

**Figure 19.** The extremities of the intervals in $\mathcal{D} \cap \Pi^{-1}(x_0)$ depend continuously on $x$. After the quotient, we obtain vertical lines homeomorphic to $\mathbb{R}$.

**Proposition 4.3.** The topological space $\tilde{P}$ endowed with the function $\tilde{\Pi}$ is a trivial fibre bundle.

**Proof.** The base space of the fibre bundle $\tilde{P}$ is the $Ox$-axis, namely $\mathbb{R}$, and $\mathbb{R}$ is contractible to a point. Thus we conclude that $\tilde{P}$ is a trivial fibre bundle, since by [Osb82, Proposition 3.5, page 75] a fibre bundle over a base space that is contractible to a point is trivial. To be more precise, we have $\tilde{P}$ homeomorphic to $\mathbb{R}^2$. □

**Corollary 4.4.** The topological subspace $\tilde{\mathcal{D}} := q(\mathcal{D})$ is embedded in a real plane.

**Theorem 4.5.** The topological subspace $\tilde{\mathcal{D}}$ is connected.
4.1 The Poincaré-Reeb construction

Proof. The image of a connected space by a continuous function is connected. Since \( \tilde{\mathcal{D}} := q(\mathcal{D}) \), the topological disk \( \mathcal{D} \) is connected and the quotient map \( q \) is continuous, the proof is complete. \( \square \)

Theorem 4.6. The topological subspace \( \tilde{\mathcal{D}} \) is a one-dimensional subspace of \( \tilde{\mathcal{P}} \). In each of the regular points of \( \mathcal{D} \), we have \( \mathcal{D} \) transverse to the foliation of the plane \( \mathcal{P} \) by vertical lines, induced by \( \Pi \).

Proof. Since the curve \( \mathcal{C} \) is a connected component of a real algebraic curve, that is, it is an analytic curve, it has finitely many points of vertical tangency. In other words, there are finitely many critical levels of the projection \( \Pi|_{\mathcal{C}} : \mathcal{C} \to \mathbb{R} \). Locally near a critical point, one may have a tangency point of even order (see Figure 20a) or of odd order (see Figure 20b):

![Figure 20. Vertical tangents.](image)

Between any two critical levels, we have only what we call “bands” of the initial disk \( \mathcal{D} \). See, for a better comprehension, Figure 21 below. After taking the quotient, each band contracts into an arc of dimension one, transverse to the vertical foliation of the real plane \( \tilde{\mathcal{P}} \). Therefore, the topological space \( \tilde{\mathcal{D}} \) is a graph, being a finite union of transverse arcs.

Definition 4.7. [Vic89, pages 13-14] A preorder on a set is a binary relation that is reflexive and transitive.

Definition 4.8. Given the projection \( \Pi : \mathbb{R}^2 \to \mathbb{R} \), let us consider the image \( \tilde{\mathcal{D}} := q(\mathcal{D}) \), of the topological disk \( \mathcal{D} \) bounded by the smooth and compact connected component of a real algebraic curve \( \mathcal{C} \), where \( q \) the quotient map introduced before. The image \( \mathcal{D} \), endowed with special vertices, namely the finitely many points corresponding to the critical points of \( \Pi \) on \( \mathcal{C} \) is called the Poincaré-Reeb graph associated to the curve \( \mathcal{C} \) and to \( \Pi \). Endow the real plane with the trivial fibre bundle \( \tilde{\mathcal{P}} \), then endow the vertices of the graph with the induced preorder.
4 The Poincaré-Reeb tree

Figure 21. “Bands” of the disk $D$, between two consecutive critical levels of the vertical projection $\Pi$. The bands contract into one-dimensional transverse arcs.

In conclusion, the Poincaré-Reeb construction that we introduce in this paper gives us a plane connected graph, embedded in a surface that is homeomorphic to $\mathbb{R}^2$. We will prove in the next section that it is in fact a tree.

4.2 Constructible functions and a Fubini type theorem

In this section we will recall the integration of constructible functions with respect to the Euler characteristic and a Fubini-type theorem for it. Then we will apply it to the proof of Proposition 4.20.

We will first introduce the necessary tools: constructible functions. We shall follow the definitions and results from [Cos05, Chapter 3, pages 21-22]. For more details, the reader should refer to [Wal04, page 162]. Constructible functions have applications in the study of the topology of singular real algebraic sets (see for instance [Dut16]). The main tool is the integration against the Euler characteristic, which was first described in Viro’s paper [Vir88].

Definition 4.9. [Cos02, page 25] A basic semialgebraic set is a subset of $\mathbb{R}^n$ satisfying a finite number of polynomial equations and inequalities with real coefficients.

Example 4.10.
- All algebraic sets are basic semialgebraic.
- Unions of finitely many points and open intervals in $\mathbb{R}$ are basic semialgebraic sets.

Definition 4.11. [Cos02, page 29] Let us consider two basic semialgebraic sets $M \subset \mathbb{R}^m$ and $N \subset \mathbb{R}^n$. We say that a continuous map $s : M \to N$ is a semialgebraic map if its graph $\{(x, y) \in M \times N \mid y = s(x)\}$ is a semialgebraic subset of $\mathbb{R}^m \times \mathbb{R}^n$. 


4.2 Constructible functions and a Fubini type theorem

**Definition 4.12.** [Cos05, Chapter 3, page 21] A **constructible function** on a semialgebraic set \( A \) is a function \( \varphi : A \to \mathbb{Z} \) which takes finitely many values and such that, for every \( n \in \mathbb{Z} \), \( \varphi^{-1}(n) \) is a semialgebraic subset of \( A \).

**Remark 4.13.** [Wal04, page 162] Each constructible function is an integer linear combination of characteristic functions of constructible sets \( X_i \), i.e. of semialgebraic subsets of \( A \):

\[
\varphi = \sum_{i \in I} m_i 1_{X_i},
\]

where \( m_i \in \mathbb{Z} \) and \( 1_{X_i} \) is the characteristic function of \( X_i \).

**Definition 4.14.** [Cos05, Chapter 3, page 22] Let \( \varphi \) be a constructible function on a semialgebraic set \( X \). The **integral** of \( \varphi \) with respect to the Euler characteristic \( \chi \) is by definition:

\[
\int_X \varphi \, d\chi := \sum_{n \in \mathbb{Z}} n\chi(\varphi^{-1}(n) \cap X),
\]

where \( \chi \) denotes the Euler characteristic.

**Definition 4.15.** [Cos05, Chapter 3, page 22] Let us consider a continuous semialgebraic map \( f : A \to B \) and let \( \varphi \) be a constructible function on \( A \). The **pushforward** of \( \varphi \) along \( f \) (see Figure 22) is the function \( f_*\varphi : B \to \mathbb{Z} \),

\[
f_*\varphi(y) := \int_{f^{-1}(y)} \varphi \, d\chi.
\]

![Figure 22. The pushforward \( f_*\varphi \) of \( \varphi \) along \( f \).](image)

**Remark 4.16.** If we apply the definition of push-forward to the application from a set \( A \) towards a point, we obtain the function that associates at this point the integral with respect to the Euler characteristic of the starting function on \( A \).

**Remark 4.17.** The diagram from Figure 22 is not commutative. If, for example, \( A := \{a, b\} \), \( B := \{c\} \), where \( a, b, c \) are points in \( \mathbb{R}^2 \), \( f : A \to B \) a semialgebraic map such that \( f(a) = f(b) := c \) and \( \varphi \) a constructible function on \( A \) such that \( \varphi(a) := -1 \), \( \varphi(b) := 1 \), then by definition we compute \( f_*\varphi(b) = \int_{f^{-1}(c)} \varphi \, d\chi = -1 + 1 = 0 \). Thus \( f_*\varphi \circ f(a) = 0 \) while \( \varphi(a) = -1 \). Therefore \( f_*\varphi \circ f \neq \varphi \).

**Remark 4.18.** The following proofs can be extended to semianalytic sets, with the more general hypothesis that \( f \) is analytic.
Theorem 4.19. [Cos05, Chapter 3, page 22] **Fubini Type Theorem:** Let \( f : A \to B \) be a semialgebraic map and \( \varphi \) a constructible function on \( A \). Then

\[
\int_B f_\ast \varphi d\chi = \int_A \varphi d\chi.
\]

We are ready now to prove the main result of this section, namely Proposition 4.20.

**Proposition 4.20.** The Poincaré-Reeb graph of a topological disk \( \mathcal{D} \) bounded by a smooth and compact connected component of a real algebraic curve in \( \mathbb{R}^2 \) is a tree.

**Proof.** In Definition 4.15 let us replace \( A \) with the disk \( \mathcal{D} \), \( B \) with the graph \( G \) obtained after the Poincaré-Reeb contraction \( \pi \), the function \( f \) with the Poincaré-Reeb contraction \( \pi \) and \( \varphi \) with the characteristic function \( 1_\mathcal{D} \), as in Figure 23:

![Figure 23](image)

**Figure 23.** The pushforward \( \pi_\ast 1_\mathcal{D} \) of \( 1_\mathcal{D} \) along \( \pi \).

In other words, we apply the Fubini Type Theorem 4.19 for the pushforward of the constructible function \( 1_\mathcal{D} \).

Now for \( g \in G \), we obtain:

\[
\pi_\ast 1_\mathcal{D}(g) = \int_{\pi^{-1}(g)} 1_\mathcal{D} d\chi = \sum_{n \in \mathbb{Z}} n \chi(1_\mathcal{D}^{-1}(n) \cap \pi^{-1}(g)) = \chi(\pi^{-1}(g)) = 1,
\]

since \( \pi^{-1}(g) \) is a connected component of the fibre, i.e. a segment. Thus

\[
\pi_\ast 1_\mathcal{D} = 1_G.
\]

By Theorem 4.19, we have now

\[
\int_\mathcal{D} 1_\mathcal{D} d\chi = \int_G \pi_\ast 1_\mathcal{D} d\chi.
\]

Since \( \pi_\ast 1_\mathcal{D} = 1_G \), we obtain:

\[
\int_\mathcal{D} 1_\mathcal{D} d\chi = \int_G 1_G d\chi.
\]

Therefore, \( \chi(\mathcal{D}) = \chi(G) \). Since \( \mathcal{D} \) is a disk, we have \( \chi(\mathcal{D}) = 1 \). In Section 4 we proved that \( G \) is a connected graph, thus the Betti number \( b_0 = 1 \). We have \( \chi(G) = b_0 - b_1 \). Since we proved that its Euler characteristic is \( \chi(G) = 1 \), we get that the Betti number \( b_1 = 0 \). Thus we conclude that \( G \) has no cycles, hence \( G \) is a tree.

\[\square\]
Corollary 4.21. The Poincaré-Reeb graph associated to a compact and smooth connected component of a real algebraic plane curve and to a direction of projection $x$ is a plane tree whose open edges are transverse to the foliation induced by the function $x$. Its vertices are endowed with a total preorder relation induced by the function $x$.

Definition 4.22.

- A **transversal tree** is a finite tree embedded in a real oriented plane $P$ endowed with a trivialisable fibre bundle $\Pi : P \rightarrow \mathbb{R}$, such that each one of its edges is transversal to the fibres of $\Pi$.

- Two transversal trees $(P_1, T_1)$ and $(P_2, T_2)$ are considered to be **equivalent** if there exists an orientation preserving homeomorphism $\psi$ sending one pair into the other one and one fibre bundle into the other one (in the sense that there exists an orientation-preserving homeomorphism $\lambda : \mathbb{R} \rightarrow \mathbb{R}$ such that $\Pi_2 \circ \psi = \lambda \circ \Pi_1$).

5 Asymptotic behaviour of curves near a strict local minimum

Let us consider a polynomial function $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ with a strict local minimum at the origin (see Section 1). The aim of this section is to study the asymptotic shape of the Poincaré-Reeb trees of sufficiently small levels. We will prove that their shapes stabilise to a limit shape which we shall call the “asymptotic Poincaré-Reeb tree of the strict minimum with respect to the function $x$”.

5.1 Nested smooth Jordan curves

The following definition and theorem are well-known:

Definition 5.1. [Kra99, page 19] A **Jordan curve** is the image of a continuous application $\gamma : [a, b] \rightarrow \mathbb{R}^2$, where $a, b \in \mathbb{R}$ are distinct real numbers, such that $\gamma(a) = \gamma(b)$ and $\gamma|[a,b]$ is injective.

Theorem 5.2. The complement in $\mathbb{R}^2$ of a Jordan curve $J$ consists of two connected components, each of which has $J$ as its boundary (see Figure 24). Both components are path-connected and open and exactly one is unbounded.

Proofs of Theorem 5.2 can be found in [Wal72, pages 119, 133].

![Figure 24. A Jordan Curve $J$: the bounded component of the real plane is $B$, while the unbounded component is $U$.](image)
Lemma 5.3. Under the notations and hypotheses listed in Section 1, for all sufficiently small \( \varepsilon > 0 \), the curve \( C_\varepsilon \) is a Jordan curve; more precisely, \( C_\varepsilon \) is diffeomorphic to \( S^1 \) and \( D_\varepsilon \) is diffeomorphic to a disk. If one denotes by \( \operatorname{Int} C_\varepsilon \) the bounded connected component of \( \mathbb{R}^2 \setminus C_\varepsilon \), then \((0,0) \in \operatorname{Int} C_\varepsilon \).

**Proof.** Let us start by giving a slightly different definition of \( C_\varepsilon \). At the end of this proof, we will have justified Definition 1.1.

Suppose that \( C_\varepsilon \) is the union of connected components of \( f^{-1}(\varepsilon) \), near the origin.

**First step: let us prove that \( C_\varepsilon \) is a one-dimensional manifold.**

By hypothesis (Section 1), \( C_0 = \{(0,0)\} \) is an isolated local minimum of \( f \), thus for a sufficiently small \( \varepsilon \), the level curve \( C_\varepsilon \) has no critical points. Therefore, \( C_\varepsilon \) is a one-dimensional manifold. By [Mil65, Appendix “Classifying 1-manifolds”, page 65], the manifold \( C_\varepsilon \) is diffeomorphic to a disjoint union of circles \( S^1 \), or of some intervals of real numbers: the real line \( \mathbb{R} \), the half-line \( \mathbb{R}_+ \) or the closed interval \([0,1]\).

**Second step: we prove that one cannot obtain components of \( C_\varepsilon \) which are diffeomorphic to closed or semiclosed segments in \( \mathbb{R} \).**

Let us show that \( C_\varepsilon \) has no connected components diffeomorphic to \([0,1]\) or \([0,\infty[\). The reader should recall that \( 0 < \varepsilon \ll 1 \) is a regular value of \( f \), thus (see [GP74, Preimage Theorem, page 21]) the set \( C_\varepsilon = f^{-1}(\varepsilon) \) is a submanifold of \( \mathbb{R}^2 \) of dimension 1. Let \( P \in C_\varepsilon \) be a point. If \( B_P \) is an open disk centered at \( P \), then \( C_\varepsilon \cap B_P \) is diffeomorphic to an open interval \([a,b[\), where the image of \( P \) is in \([a,b[\). Since the point \( P \) was chosen arbitrarily, we conclude that one cannot obtain connected components of \( C_\varepsilon \) diffeomorphic to either closed or semiclosed segments in \( \mathbb{R} \).

**Third step: let us prove that \( C_\varepsilon \) is a disjoint union of connected components which are all diffeomorphic to the circle \( S^1 \).**

We fix \( r \in \mathbb{R} \) small enough, \( r > 0 \) and we fix the neighbourhood \( V \) to be \( D_r := \{(x,y) \in \mathbb{R}^2 \mid ||(x,y)|| \leq r\} \) such that \((0,0)\) is the only critical point of \( f \) in the disk \( D_r \). Firstly, we have \( C_\varepsilon \) is a closed set, since the preimage of a closed set by the continuous function \( f \) is closed. Since \( C_\varepsilon \) is also bounded, it is compact.

Secondly, we will show that \( C_\varepsilon \cap \partial D_r = \emptyset \). Since for \( \varepsilon \) sufficiently small, the curve \( f = \varepsilon \) lies sufficiently close to the origin \((0,0)\), there exists \( 0 < \varepsilon_1 \ll 1 \) such that \( C_\varepsilon \cap D_{\varepsilon_1} \neq \emptyset \) for all \( \varepsilon < \varepsilon_1 \). We want to prove that there exists \( 0 < \varepsilon_2 \ll \varepsilon_1 \) such that \( C_\varepsilon \subset D_{\varepsilon_2} \) for all \( \varepsilon < \varepsilon_2 \). We argue by contradiction. Suppose there exists a sequence \( \varepsilon_n \to 0 \) such that \( C_{\varepsilon_n} \not\subset D_{\varepsilon_2} \), namely \( C_{\varepsilon_n} \cap D_r \setminus D_{\varepsilon_2} \neq \emptyset \). Hence, for any \( \varepsilon_n \), there exists a point \((x_{\varepsilon_n}, y_{\varepsilon_n}) \in C_{\varepsilon_n} \), namely \( f(x_{\varepsilon_n}, y_{\varepsilon_n}) = \varepsilon_n \), such that \((x_{\varepsilon_n}, y_{\varepsilon_n}) \in D_r \setminus D_{\varepsilon_2} \). If \( \varepsilon := \frac{1}{n} \), then one obtains a sequence \((x_n, y_n)\) with the following properties:

(a) \((x_n, y_n) \in D_r \setminus D_{\varepsilon_2} \);

(b) \( f(x_n, y_n) = \frac{1}{n} \).

Since \( D_r \setminus D_{\varepsilon_2} \) is a compact, there exists a convergent subsequence \((x_{\phi(n)}, y_{\phi(n)})\) of \((x_n, y_n)\). More precisely, \( \phi(n) \) is a strictly increasing and unbounded sequence of natural numbers. Let us denote by \( \lim_{n \to \infty} (x_{\phi(n)}, y_{\phi(n)}) = (x_\infty, y_\infty) \in \overline{D_r \setminus D_{\varepsilon_2}} \). One obtains \( f(x_{\phi(n)}, y_{\phi(n)}) = \frac{1}{\phi(n)} \) and by the continuity of \( f \), \( f(x_\infty, y_\infty) = \lim_{n \to \infty} f(x_{\phi(n)}, y_{\phi(n)}) = \lim_{n \to \infty} \frac{1}{\phi(n)} = 0 \).

Therefore, there exists \((x_\infty, y_\infty) \neq (0,0), (x_\infty, y_\infty) \in D_r \), such that \( f(x_\infty, y_\infty) = 0 \). This gives a contradiction with our hypothesis that \((0,0)\) is the isolated local minimum of \( f \) in \( D_r \). Hence, \( C_\varepsilon \) is bounded.
In conclusion, we proved that \( C_{\varepsilon} \cap \partial D_r = \emptyset \). Hence we conclude that the level set \( C_{\varepsilon} \) could be a disjoint union of connected components which are either diffeomorphic to the segment \([0, 1]\), or to the circle \( S^1 \). Since we have excluded the closed segments at the first step of our proof, \( C_{\varepsilon} \) is a disjoint union of connected components which are all diffeomorphic to the circle \( S^1 \).

Fourth and last step: we prove that \( C_{\varepsilon} \text{ diffeo} \simeq S^1 \).

We argue by contradiction. Let us suppose that \( C_{\varepsilon} \) is a disjoint union of at least two distinct connected components, say \( S_1 \) and \( S_2 \), which are both diffeomorphic to the circle \( S^1 \). By the Extreme Value Theorem, in the interiors of both these two connected components there is a local extremum of \( f \). Since locally the origin is the only critical point in \( V \) that \( f \) admits by hypothesis, we obtain \((0, 0) \in \text{Int } S_1 \) and \((0, 0) \in \text{Int } S_2 \). Since \( C_{\varepsilon} \) is not self-intersecting, the configuration from Figure 25(a) below is impossible.

![Impossible configuration for \( C_{\varepsilon} \).](image)

![The annulus \( A_{\varepsilon} \) in pink.](image)

Figure 25. Configurations for \( S_1 \) and \( S_2 \).

Hence the only two possible situations would be either \( S_1 \subset \text{Int } S_2 \) or \( S_2 \subset \text{Int } S_1 \). Without any loss of generality, let us choose \( S_2 \subset \text{Int } S_1 \). We have \((0, 0) \in \text{Int } S_2 \). Let us consider the closed annulus bounded by the two circles, namely \( A_{\varepsilon} := S_1 \cup (\text{Int } S_1 \setminus \text{Int } S_2) \). See Figure 25(b) above.

Since \( A_{\varepsilon} \) is compact, by the Extreme Value Theorem, the function \( f \) must attain a maximum value and a minimum value on \( A_{\varepsilon} \). We recall that \( f \) is not constant, since \((0, 0) = f^{-1}(0) \) is a strict local minimum of \( f \). If one extremum value is attained by \( f \) on \( S_1 \) and on \( S_2 \) \( (f = \varepsilon \) both on \( S_1 \) and on \( S_2 \) \), then the other extremum value will necessarily be attained in \( \text{Int } A_{\varepsilon} \). Hence we obtain a contradiction with the hypothesis of the unique singularity of \( f \) in a neighbourhood of the origin. Therefore, we conclude that \( C_{\varepsilon} \) cannot have more than one connected component diffeomorphic to the circle \( S^1 \), thus \( C_{\varepsilon} \text{ diffeo} \simeq S^1 \) and \((0, 0) \in C_{\varepsilon} \).

5.2 The polar curve

The notion of a polar curve goes back to the XIXth century, appearing in the work of J.-V. Poncelet ([Pon17]) and M. Plücker ([Plü37]) in the period of 1813-1830 (see for instance [Tei90], [Tei77], [TF16]). Starting with the 1970s, the theory of polar curves (see [BK86, page 589]) was renewed by important investigations and contributions due to Lê ([LMW89]), Teissier, Merle, Eggers, Delgado, García Barroso ([GB00], [GB98], [GB96]), Płoski, Gwoździewicz, Casas-Alvero, Michel, Weber, Maugendre ([Mau99]),
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Hefez among others. Considerable research on the polar curves has been carried out in the complex setting. However, less is known about the real polar curves.

Definition 5.4. [GB00, Section 4] Let \( f : \mathbb{R}^2 \to \mathbb{R} \) be a polynomial function. The set

\[
\Gamma(f, x) = \left\{ (x, y) \in \mathbb{R}^2 \mid \frac{\partial f}{\partial y}(x, y) = 0 \right\}
\]

is called the polar curve of \( f \) with respect to \( x \).

Remark 5.5. The polar curve \( \Gamma(f, x) \) consists of the points \( (x, y) \in \mathbb{R}^2 \) where the level curves of \( f \) have a vertical tangent. Note that the vertices of the Poincaré-Reeb tree roughly speaking correspond to points on the level curve with vertical tangent lines. When we study the family of level curves, the points of vertical tangency move along the branches of the polar curve \( \Gamma(f, x) \).

However, if \( f \) has a strict local minimum, then the polar curve does not contain the projection direction (see Proposition 5.6).

Proposition 5.6. If \( f : \mathbb{R}^2 \to \mathbb{R} \) has a strict local minimum at the origin and \( f(0, 0) = 0 \), then the polar curve \( \Gamma(f, x) \) does not contain the line \( x = 0 \).

Proof. We argue by contradiction. If the line \( x = 0 \) is contained in \( \Gamma(f, x) \), then we may write \( \frac{\partial f}{\partial y}(x, y) = xg(x, y) \), where \( g \in \mathbb{R}[x, y] \). Then \( f(x, y) = f(x, 0) + \int_0^y xg(x, t)dt = x\varphi(x, y) \), since \( f(0, 0) = 0 \). Hence \( f \) does not have a strict local minimum at the origin, because it vanishes on \( x = 0 \). Contradiction.

Example 5.7. In Figure 2.22 is represented the polar curve \( \Gamma(f, x) \) of Coste’s example (see Example 3.1: \( f(x, y) := x^2 + (y^2 - x)^2 \)). It has two irreducible components, with equations \( (y = 0) \cup (y^2 - x = 0) \).

![Figure 26. The polar curve \((y = 0) \cup (y^2 - x = 0)\) for Example 3.1, namely Coste’s example](image)

Example 5.8. Recall our Example 3.3: \( f(x, y) := x^{16} + (y^2 + x)(y^2 - x)^2 \). In Figure 27, the polar curve \( \Gamma(f, x) \) has three components \( (y = 0) \cup (y^2 + x = 0) \cup (y^2 - x = 0) \).
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Figure 27. The polar curve \((y = 0) \cup (y^2 + x = 0) \cup (y^2 - x = 0)\) for Example 3.3.

Example 5.9. We can create new examples starting from Coste’s example by taking the parametrisation of a branch \(\gamma\) of the polar curve \(\Gamma(f, x)\), namely \(t \mapsto (t^2, t)\), and modify it, as follows.

Consider the new parametrisation \((t \mapsto p(t), q(t))\), where \(p(t) = t^2 + t^3\) and \(q(t) := t\). Let us compute the resultant of the polynomials \(g(t) := x - p(t)\) and \(h(t) := y - q(t)\), in order to find the implicit polynomial whose zero locus is \(\gamma\). We have the resultant (see for instance [BK86, page 178])

\[
\text{Res}_t(x, y) = \begin{vmatrix}
-1 & -1 & 0 & x \\
-1 & y & 0 & 0 \\
0 & -1 & y & 0 \\
0 & 0 & -1 & y \\
\end{vmatrix} = x - y^3 - y^2.
\]

Thus, (see [BK86, page 181]) we have a new algebraic branch \(\tilde{\gamma} := \{(x, y) \in \mathbb{R}^2 \mid x - y^3 - y^2 = 0\}\).

Take now \(\tilde{f}(x, y) := x^2 + (x - y^3 - y^2)^2(x - y^2)^2\) and obtain the local situation of the polar curve in a small enough neighbourhood of the origin as presented in Figure 28 below.

Figure 28. We modified the initial parabola \(\gamma\) (in red) into \(\tilde{\gamma}\) (in green), both branches of the polar curve \(\Gamma(\tilde{f}, x)\), to obtain a different local shape of \(C_\epsilon\) when compared to the initial one in Coste’s example.

Example 5.10. Recall our Example 3.4: \(f(x, y) := x^6 + (y^4 + y^2 - x)^2(y^2 - x)^2\). In Figure 29, the polar curve \(\Gamma(f, x)\) has four components.
For more details about Lemma 5.11 below, we refer to [Ghy17, page 105].

**Lemma 5.11.** [Mil68] Let $\Gamma$ be a real algebraic curve. Firstly, there exists a Milnor disk for $\Gamma$ at the origin: a Euclidean disk such that the boundaries of all the concentric disks inside the Milnor disk are transverse to the curve. Secondly, if the curve is analytically irreducible at the origin, then in such a disk the curve is homeomorphic to a segment.

A proof can be found in [Mil68, Lemma 3.3, page 28] and [Ghy17, page 105]. For recent progress in the complex setting on the intersection between plane curves and Milnor disks, see the very recent work of Bodin and Borodzik ([BB18]).

**Definition 5.12.** [Ghy17, page 2] A real branch is the germ at the origin of an analytically irreducible curve at this point.

A definition similar to Definition 5.13 can be found, for instance, in [Cas15, page 97].

**Definition 5.13.** A half-branch (see Figure 30 below) is the germ at the origin of the closure of one of the connected components of the complementary of the origin in a Milnor representative of a branch.

**Remark 5.14.** We can choose to denote one half-branch by $\gamma^+_i$ and the other one by $\gamma^-_i$.

Definition 5.15 is inspired by [CP01, Section 2].

**Definition 5.15.** We call polar half-branches the half-branches of the polar curve $\Gamma := \Gamma(f, x)$, in the sense of Definition 5.13. Let $\gamma^* \subset \Gamma$ be a polar half-branch and let $V$ be a good neighbourhood of the origin, as in Definition 5.28. We say that $\gamma^*$ in $V$ is a **right polar half-branch** if $x_{|\gamma^*} \geq 0$. If $x_{|\gamma^*} \leq 0$, we say that $\gamma^*$ in $V$ is a **left polar half-branch**.

**Remark 5.16.** By Corollary 5.23, in a sufficiently small $V$ we always have that $x$ is strictly increasing when restricted to the right polar half-branches and strictly decreasing when restricted to the left polar half-branches.

**Remark 5.17.** We sometimes call the union of the right polar half-branches the **positive** polar curve.
5.2 The polar curve

Figure 30. A branch $\gamma_i$ of $\Gamma$ has exactly two half-branches: $\gamma_i^-$ and $\gamma_i^+$.

A result similar to the following lemma can be found in [FCP96, Lemma 1.1].

**Lemma 5.18.** Let $g : \mathbb{R}^2 \to \mathbb{R}$ be a polynomial function with a strict local minimum at the origin $O = (0, 0)$ and let $\Gamma$ be an algebraic curve passing through the origin. In a small enough neighbourhood $V$ of the origin, for any half-branch $\gamma^* \subset \Gamma$, the restriction $g|_{\gamma^*}$ is strictly monotone. In particular, in the sufficiently small neighbourhood $V$, for a small enough $0 < \varepsilon \ll 1$, the intersection $(g = \varepsilon) \cap \gamma^*$ consists of exactly one point, for each half-branch $\gamma^*$ (see Figure 31). Here the symbol $* \in \{+, -\}$.

**Proof.** Let us choose, without loss of generality, to study the behaviour of $g$ on $\gamma^+$. Suppose that $g|_{\gamma^+}$ is not constant. Since $\Gamma$ is an algebraic curve, it has only a finite number of critical points. Therefore one can assume that in a small enough neighbourhood $V$ of the origin $O = (0, 0)$, the half-branch $\gamma^+$ has no critical points except maybe the origin $O = (0, 0)$. By [Mil68, Lemma 2.7], applied to the polynomial function $g$ and to the one-dimensional manifold $\gamma^+$, which is a subset of the algebraic curve $\Gamma$, in the sufficiently small neighbourhood of $O = (0, 0)$, the set of the local extrema of $g|_{\gamma^+}$ is an algebraic set of dimension zero. Thus, by [Eis95, Corollary 9.1, page 227], the set of local extrema is finite. Now let us choose $V$ sufficiently small such that in $V$ there are no local extrema of the function $g|_{\gamma^+ \setminus \{(0,0)\}}$. Thus, in $V$, $g|_{\gamma^+}$ is strictly monotone. \hfill $\Box$

**Corollary 5.19.** Given a polynomial function $f$ with a strict local minimum at the origin and its polar curve $\Gamma(f, x)$, if $\gamma^+$ is a right polar half-branch, then $f|_{\gamma^+}$ is always strictly increasing in $V$, when going further from the origin.
Asymptotic behaviour of curves near a strict local minimum

Proof. Apply Lemma 5.18 for the function \( f \) and the polar curve \( \Gamma(f, x) \), taking into account that \((0, 0)\) is a strict local minimum.

Example 5.20. Let us present in Figure 32 a configuration which is impossible asymptotically (i.e. for \( 0 < \varepsilon \ll 1 \) sufficiently small) in \( V \): even if \( x_{\gamma^+} \) is strictly increasing, we have \( f_{\gamma^+} \) not strictly increasing.

![Figure 32. Locally impossible configuration in \( V \): \( f_{\gamma^+} \) not strictly increasing.](image)

Corollary 5.21. In particular, the shape of \( C_\varepsilon \) in a sufficiently small enough \( V \) cannot go backwards or be spiral shaped.

Corollary 5.22. We can choose a sufficiently small neighbourhood \( V \) such that the intersection \( \gamma^* \cap C_\varepsilon \) consists of exactly one point, where \( C_\varepsilon := (f = \varepsilon) \cap V \).

Proof. By Corollary 5.19, for any polar half-branch \( \gamma^* \) one has \( f_{\gamma^*} \) is locally strictly increasing, thus for sufficiently small \( \varepsilon \), the intersection \( (f = \varepsilon) \cap \gamma^* \) consists of at most one point.

A consequence of Lemma 5.18, applied to the polar curve \( \Gamma(f, x) \) of \( f \) and for the function \( g : \mathbb{R}^2 \to \mathbb{R}, g(x, y) := x \) is the following result.

Corollary 5.23. Let \( f \) be a polynomial function with a strict local minimum at the origin and let \( \Gamma(f, x) := \{(x, y) \in \mathbb{R}^2 \mid \frac{\partial f}{\partial y}(x, y) = 0\} \) be its polar curve with respect to \( x \). In a small enough neighbourhood \( V \) of the origin, for any polar half-branch \( \gamma^* \subset \Gamma \), the restriction \( x_{\gamma^*} \) is strictly monotone. Here the symbol \(* \in \{+, -\} \) is.

Proof. Since \( x \) is not constant on \( \Gamma(f, x) \) by Proposition 5.6, we can apply Lemma 5.18.

Example 5.24. Let us present in Figure 33 a locally impossible configuration in \( V \) of \( C_\varepsilon \) with a polar half-branch \( \gamma^+ \): even if \( f_{\gamma^+} \) is strictly increasing, we have \( x_{\gamma^+} \) not strictly increasing.

![Figure 33. Impossible asymptotic configuration in \( V \), since \( x_{\gamma^+} \) is not strictly increasing.](image)
Remark 5.25. In particular, the shape of $C_\varepsilon$ in a sufficiently small $V$ cannot “go backwards”. More rigorously, if we choose $V$ small enough, then the polar curve $\Gamma(f, x)$ has no vertical tangents in $V$. A vertical tangent of a polar half-branch $\gamma^*$ would correspond to a local extremum of the function $x|_{\gamma^*}$, which is impossible.

A consequence of Lemma 5.18, applied to the polar curve $\Gamma(f, x)$ of a polynomial function $f$ with a strict local minimum at the origin and to the function square of the distance to the origin, namely $x^2 + y^2$ is the following result.

Corollary 5.26. Let $f$ be a polynomial function $f$ with a strict local minimum at the origin and let $\Gamma(f, x)$ be its polar curve with respect to $x$. In a small enough neighbourhood $V$ of the origin, for any polar half-branch $\gamma^* \subset \Gamma$, the restriction $x^2 + y^2|_{\gamma^*}$ is strictly monotone. Here the symbol $* \in \{+, -\}$.

Corollary 5.27. We can choose a sufficiently small neighbourhood $V$ such that for any polar half-branch $\gamma^*$, the intersection $\gamma^* \cap \partial V$ consists of exactly one point.

5.3 Stabilisation. No spiralling

Definition 5.28. Let us consider a polynomial function $f : \mathbb{R}^2 \to \mathbb{R}$ with a strict local minimum at the origin, such that $f(0, 0) = 0$. Denote by $\Gamma(f, x)$ the polar curve of $f$ with respect to the direction $x$. Let $V$ be a neighbourhood of the origin $O(0, 0)$. We say that the neighbourhood $V$ is a good neighbourhood of the origin for the couple $(f, x)$ if $V$ satisfies:

(i) the point $(0, 0)$ is the only strict local minimum of $f$ in $V$;
(ii) we have $V \cap (f = 0) = \{(0, 0)\}$;
(iii) $\text{Sing}(\Gamma(f, x)) \cap V \subseteq \{(0, 0)\}$;
(iv) $V$ is small enough such that on each polar half-branch $\gamma^*$ of $\Gamma(f, x)$ we have $f|_{\gamma^*}$ is strictly monotone;
(v) $V$ is small enough such that on each polar half-branch $\gamma^*$ of $\Gamma(f, x)$ we have $x|_{\gamma^*}$ is strictly monotone.

Remark 5.29. Condition (i) implies that for any two distinct polar half-branches $\gamma^*_i$ and $\gamma^*_j$, we have

$$(\gamma^*_i \cap \gamma^*_j) \cap V = \{(0, 0)\}.$$  

Definition 5.30. Consider a polynomial function $f$ with a strict local minimum at the origin, such that $f(0, 0) = 0$. The asymptotic Poincaré-Reeb tree of $f$ relative to $x$ is the “limit” Poincaré-Reeb tree of its sufficiently small levels near the origin with respect to $x$. Here by “limit” we mean: for a sufficiently small $\varepsilon > 0$.

Theorem 5.31. Besides the properties of the Poincaré-Reeb tree (see Corollary 4.21), the asymptotic Poincaré-Reeb tree stabilises up to equivalence (see Definition 4.22) when the level gets small enough. It is a rooted plane tree, the root being the image of the origin. The total preorder relation on its vertices, induced by the function $x$, is strictly monotone on each geodesic starting from the root. In addition, the asymptotic Poincaré-Reeb tree is a union of a positive tree (at the right of the origin) and a negative tree (at the left of the origin), the latter two having a common root, that is the image of the origin.
5 Asymptotic behaviour of curves near a strict local minimum

Proof. Let us first prove the stabilisation. Take two right polar half-branches $\gamma_i$ and $\gamma_j$. Denote by $(x_i(t), y_i(t))$, respectively $(x_j(t), y_j(t))$ their corresponding Newton-Puiseux parametrisations (see [Wal04, Theorem 2.1.1]). Here $x_1(t), y_1(t), x_2(t), y_2(t) \in \mathbb{R}\{t\}$ are convergent analytic parametrisations. Now denote by $g(t) := x_i(t) - x_j(t)$. We have two possibilities: either $g(t) \equiv 0$, i.e. we have a vertical bitangent, or $g(t) \not\equiv 0$. In the second case, by taking a sufficiently small $t$, the sign of the analytic function $g$ does not change. Since there are finitely many polar half-branches, we can choose a sufficiently small $t$ such that the total preorder stabilises.

In the asymptotic setting, if we consider a polynomial function $f : \mathbb{R}^2 \to \mathbb{R}$ with a strict local minimum at the origin such that $f(0,0) = 0$, then the root of the Poincaré-Reeb tree is the image of the origin by the quotient map (see Section 4). By Lemma 5.3, the origin is in the interior of the disk $D_\varepsilon$. Since the real plane is cooriented, we distinguish without ambiguity between the positive tree (at the right of the origin) and the negative tree (at the left of the origin), the latter two having the common root, that is the image of the origin.

Moreover, we have the induced application $\tilde{x} := x$ of the projection function $x : \mathbb{R}^2 \to \mathbb{R}$ to the embedded Poincaré-Reeb tree. By Corollary 5.23: for any polar half-branch $\gamma^* \subset \Gamma(f, x)$, the restriction $x_{|\gamma^*}$ is strictly monotone. Thus, $\tilde{x}$ has no internal local extremum on an edge of $\mathcal{R}(f, x)$. To the right, $\tilde{x}$ only attains its local maxima on the leaves of the Poincaré-Reeb tree. Similarly, to the left, $\tilde{x}$ only attains its local minima on the leaves. In other words, there are no edges which “go backwards” towards the root.

\[\square\]

Remark 5.32. The strict monotonicity on the geodesics starting from the root implies that the small enough level curves $C_\varepsilon$ have no turning back or spiralling phenomena. In particular, for $0 < \varepsilon \ll 1$ sufficiently small, there are no shapes $C_\varepsilon$ like the one in Figure 34.

![Figure 34](image)

**Figure 34.** Impossible shape for small enough $0 < \varepsilon \ll 1$. 28
References

[AB06] Charalambos Dionisios Aliprantis and Kim Christian Border. *Infinite dimensional analysis*. Third. A hitchhiker’s guide. Springer, Berlin, 2006, pp. xxii+703 (cit. on p. 10).

[BB18] Arnaud Bodin and Maciej Borodzik. “Intermediate links of plane curves”. In: *Israel J. Math.* 227.1 (2018), pp. 63–111. ISSN: 0021-2172. DOI: 10.1007/s11856-018-1716-y. URL: https://doi.org/10.1007/s11856-018-1716-y (cit. on p. 24).

[BK86] Egbert Brieskorn and Horst Knörrer. *Plane algebraic curves*. Translated from the German by John Stillwell. Birkhäuser Verlag, Basel, 1986, pp. vi+721. DOI: 10.1007/978-3-0348-5097-1. URL: https://doi.org/10.1007/978-3-0348-5097-1 (cit. on pp. 21, 23).

[Bol80] Theodore S. Bolis. “Degenerate critical points”. In: *Math. Mag.* 53.5 (1980), pp. 294–299. DOI: 10.2307/2689393. URL: https://doi.org/10.2307/2689393 (cit. on p. 8).

[Cas15] Roberto Castellini. “The topology of A’Campo deformations of singularities: an approach through the lotus.” PhD thesis. Université de Lille 1, 2015. URL: https://www.theses.fr/2015LIL10062 (cit. on p. 24).

[Che+10] Jinsan Cheng et al. “On the topology of real algebraic plane curves”. In: *Math. Comput. Sci.* 4.1 (2010), pp. 113–137. ISSN: 1661-8270. URL: https://doi.org/10.1007/s11786-010-0044-3 (cit. on p. 2).

[Cos02] Michel Coste. “An introduction to semialgebraic geometry”. In: *RAAG network school* 145 (2002), p. 30 (cit. on p. 16).

[Cos05] Michel Coste. “Real algebraic sets”. In: *Notes de cours* (2005) (cit. on pp. 2, 16–18).

[CP01] Michel Coste and María Jesús de la Puente. “Atypical values at infinity of a polynomial function on the real plane: an erratum, and an algorithmic criterion”. In: *J. Pure Appl. Algebra* 162.1 (2001), pp. 23–35. DOI: 10.1016/S0022-4049(00)00111-0. URL: https://doi.org/10.1016/S0022-4049(00)00111-0 (cit. on pp. 1, 24).

[Dut16] Nicolas Dutertre. “Topology and geometry of real singularities”. In: *School on real and complex singularities in São Carlos, 2012*. Vol. 68. Adv. Stud. Pure Math. Math. Soc. Japan, [Tokyo], 2016, pp. 1–40. URL: https://doi.org/10.2969/aspm/06810001 (cit. on pp. 1, 16).

[Eis95] David Eisenbud. *Commutative algebra*. Vol. 150. Graduate Texts in Mathematics. With a view toward algebraic geometry. Springer-Verlag, New York, 1995, pp. xvii+785. DOI: 10.1007/978-1-4612-5350-1. URL: https://doi.org/10.1007/978-1-4612-5350-1 (cit. on p. 25).

[FCP96] Juan Ferrera Cuesta and María Jesús de la Puente. “The asymptotic values of a polynomial function on the real plane”. In: *J. Pure Appl. Algebra* 106.3 (1996), pp. 263–273. DOI: 10.1016/0022-4049(95)00025-9. URL: https://doi.org/10.1016/0022-4049(95)00025-9 (cit. on p. 25).

[Frè13] Pietro Giuseppe Frè. *Gravity, a geometrical course. Volume 1*. Development of the theory and basic physical applications. Springer, Dordrecht, 2013, pp. xviii+336 (cit. on p. 14).
References

[GB00] Evelia R. García Barroso. “Sur les courbes polaires d’une courbe plane réduite”. In: Proc. London Math. Soc. (3) 81.1 (2000), pp. 1–28. DOI: 10.1112/S0024611500012430. URL: https://doi.org/10.1112/S0024611500012430 (cit. on pp. 21, 22).

[GB96] Evelia R. García Barroso. “Invariants des singularités de courbes planes et courbure des fibres de Milnor”. PhD thesis. Universidad de La Laguna, 1996. URL: http://ergarcia.webs.ull.es/tesis.pdf (cit. on p. 21).

[GB98] Evelia R. García Barroso. “Un théorème de décomposition pour les polaires génériques d’une courbe plane”. In: C. R. Acad. Sci. Paris Sér. I Math. 326.1 (1998), pp. 59–62. DOI: 10.1016/S0764-4442(97)82713-9. URL: https://doi.org/10.1016/S0764-4442(97)82713-9 (cit. on p. 21).

[Ghy17] Étienne Ghys. A singular mathematical promenade. ENS Éditions, Lyon, 2017, pp. viii+302. URL: http://ghys.perso.math.cnrs.fr/bricabrac/promenade.pdf (cit. on pp. 1, 24).

[Gil91] George Thomas Gilbert. “Positive definite matrices and Sylvester’s criterion”. In: Amer. Math. Monthly 98.1 (1991), pp. 44–46. DOI: 10.2307/2324036. URL: https://doi.org/10.2307/2324036 (cit. on p. 7).

[GP74] Victor Guillemin and Alan Pollack. Differential topology. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1974, pp. xvi+222 (cit. on p. 20).

[Har76] Axel Harnack. “Über die Vieltheiligkeit der ebenen algebraischen Curven”. In: Math. Ann. 10.2 (1876), pp. 189–198. ISSN: 0025-5831. URL: https://doi.org/10.1007/BF01442458 (cit. on p. 1).

[Hil91] David Hilbert. “Über die reellen Züge algebraischer Curven”. In: Math. Ann. 38.1 (1891), pp. 115–138. ISSN: 0025-5831. URL: https://doi.org/10.1007/BF01212696 (cit. on p. 1).

[IMR18] Ilia Itenberg, Grigory Mikhalkin, and Johannes Rau. “Rational quintics in the real plane”. In: Trans. Amer. Math. Soc. 370.1 (2018), pp. 131–196. ISSN: 0002-9947. DOI: 10.1090/tran/6938. URL: https://doi.org/10.1090/tran/6938 (cit. on p. 1).

[JK11] Jennifer M. Johnson and János Kollár. “How small can a polynomial be near infinity?” In: Amer. Math. Monthly 118.1 (2011), pp. 22–40. DOI: 10.4169/amer.math.monthly.118.01.022. URL: https://doi.org/10.4169/amer.math.monthly.118.01.022 (cit. on p. 8).

[JK17] Prateek Jain and Purushottam Kar. “Non-convex Optimization for Machine Learning”. In: Found. Trends Mach. Learn. 10.3-4 (Dec. 2017), pp. 142–336. ISSN: 1935-8237. DOI: 10.1561/2200000058. URL: https://doi.org/10.1561/2200000058 (cit. on p. 1).

[Jut+19] Bert Juttler et al. “Arc fibrations of planar domains”. In: Comput. Aided Geom. Design 71 (2019), pp. 105–118. DOI: 10.1016/j.cagd.2019.04.010. URL: https://doi.org/10.1016/j.cagd.2019.04.010 (cit. on p. 1).

[Kle73] Felix Klein. Gesammelte mathematische Abhandlungen. Zweiter Band: Anschauliche Geometrie, Substitutionsgruppen und Gleichungstheorie, zur mathematischen Physik, Herausgegeben von R. Fricke und H. Vermeil (von F. Klein mit ergänzenden Zusätzen versehen), Reprint der Erstauflagen [Verlag von Julius Springer, Berlin, 1922]. Springer-Verlag, Berlin-New York, 1973, pp. ii+vi+713 (cit. on p. 1).
References

[Kra99] Steven George Krantz. *Handbook of complex variables*. Birkhäuser Boston, Inc., Boston, MA, 1999, pp. xxiv+290. DOI: 10.1007/978-1-4612-1588-2. URL: https://doi.org/10.1007/978-1-4612-1588-2 (cit. on p. 19).

[LMW89] Dúng-Tráng Lê, Françoise Michel, and Claude Weber. “Sur le comportement des polaires associées aux germes de courbes planes”. In: *Compositio Math.* 72.1 (1989), pp. 87–113. URL: http://www.numdam.org/item?id=CM_1989__72_1_87_0 (cit. on p. 21).

[Mat02] Yukio Matsumoto. *An introduction to Morse theory*. Vol. 208. Translations of Mathematical Monographs. Translated from the 1997 Japanese original by Kiki Hudson and Masahico Saito, Iwanami Series in Modern Mathematics. American Mathematical Society, Providence, RI, 2002, pp. xiv+219 (cit. on p. 12).

[Mau99] Hélène Maugendre. “Topologie comparée d’une courbe polaire et de sa courbe discriminante”. In: *Rev. Mat. Complut.* 12.2 (1999), pp. 439–450. DOI: 10.5209/rev_REMA.1999.v12.n2.17149. URL: https://doi.org/10.5209/rev_REMA. 1999.v12.n2.17149 (cit. on p. 21).

[Mil65] John Willard Milnor. *Topology from the differentiable viewpoint*. Based on notes by David W. Weaver. The University Press of Virginia, Charlottesville, Va, 1965 (cit. on p. 20).

[Mil68] John Willard Milnor. *Singular points of complex hypersurfaces*. Annals of Mathematics Studies, No. 61. Princeton University Press, Princeton, N.J.; University of Tokyo Press, Tokyo, 1968, pp. iii+122 (cit. on pp. 6, 24, 25).

[Osb82] Howard Osborn. *Vector bundles*. Vol. 1. Vol. 101. Pure and Applied Mathematics. Foundations and Stiefel Whitney classes. Academic Press, Inc. [Harcourt Brace Jovanovich, Publishers], New York, 1982, pp. xii+371 (cit. on p. 14).

[Plü37] Julius Plücker. “Sur les points singuliers des courbes”. In: *Journal de Mathématiques pures et appliquées (Journal de Liouville)* 2 (1837), pp. 11–15 (cit. on p. 21).

[Poi10] Henri Poincaré. *Papers on topology, Cinquième complément à l’analysis situs*. Vol. 37. History of Mathematics. Rendiconti del Circolo Matematico di Palermo (1884-1940), 45–110, Springer, translated and with an introduction by John Stillwell, 1904. American Mathematical Society, Providence, RI; London Mathematical Society, London, 2010, pp. xx+228 (cit. on pp. 1, 12).

[Pon17] Jean-Victor Poncelet. “Théorie des polaires réciproques”. In: *Annales de Mathématiques pures et appliquées* 8 (1817), pp. 201–232 (cit. on p. 21).

[PP18] Patrick Popescu-Pampu. “From singularities to graphs”. In: (2018). URL: https://arxiv.org/abs/1808.00378 (cit. on p. 6).

[Ree46] Georges Reeb. “Sur les points singuliers d’une forme de Pfaff complètement intégrable ou d’une fonction numérique”. In: *C. R. Acad. Sci. Paris* 222 (1946), pp. 847–849 (cit. on pp. 1, 12).

[Rek+83] Gintaras Victor Reklaitis et al. *Engineering optimization*. A Wiley-Interscience Publication. Methods and applications. John Wiley & Sons, Inc., New York, 1983, pp. xviii+684 (cit. on pp. 6, 7).

[Sor18] Miruna-Ştefana Sorea. “The shapes of level curves of real polynomials near strict local minima”. PhD thesis. Université de Lille, 2018. URL: https://hal.archives-ouvertes.fr/tel-01909028v1 (cit. on p. 4).

[Stu+17] Bernd Sturmfels et al. “Sixty-Four Curves of Degree Six”. In: arXiv:1703.01660v2 (2017). URL: https://arxiv.org/abs/1703.01660 (cit. on p. 1).
References

[Tei77] Bernard Teissier. “Variétés polaires. I. Invariants polaires des singularités d’hypersurfaces”. In: *Invent. Math.* 40.3 (1977), pp. 267–292. DOI: 10.1007/BF01425742. URL: https://doi.org/10.1007/BF01425742 (cit. on p. 21).

[Tei90] Bernard Teissier. “Quelques points de l’histoire des variétés polaires, de Poncelet à nos jours”. In: *Séminaire d’Analyse, 1987–1988 (Clermont-Ferrand, 1987–1988)*. Univ. Clermont-Ferrand II, Clermont-Ferrand, 1990, Exp. No. 4, 12 (cit. on p. 21).

[TF16] Bernard Teissier and Arturo Giles Flores. “Local polar varieties in the geometric study of singularities”. In: *arXiv preprint arXiv:1607.07979* (2016) (cit. on p. 21).

[Vic89] Steven Vickers. *Topology via logic*. Vol. 5. Cambridge Tracts in Theoretical Computer Science. Cambridge University Press, Cambridge, 1989, pp. xvi+200 (cit. on p. 15).

[Vir08] Oleg Viro. “From the sixteenth Hilbert problem to tropical geometry”. In: *Jpn. J. Math.* 3.2 (2008), pp. 185–214. ISSN: 0289-2316. URL: https://doi.org/10.1007/s11537-008-0832-6 (cit. on p. 1).

[Vir88] Oleg Yanovich Viro. “Some integral calculus based on Euler characteristic”. In: *Topology and geometry—Rohlin Seminar*. Vol. 1346. Lecture Notes in Math. Springer, Berlin, 1988, pp. 127–138. DOI: 10.1007/BFb0082775. URL: https://doi.org/10.1007/BFb0082775 (cit. on p. 16).

[Wal04] Charles Terence Clegg Wall. *Singular points of plane curves*. Vol. 63. London Mathematical Society Student Texts. Cambridge University Press, Cambridge, 2004, pp. xii+370. DOI: 10.1017/CBO9780511617560. URL: https://doi.org/10.1017/CBO9780511617560 (cit. on pp. 7, 16, 17, 28).

[Wal72] Charles Terence Clegg Wall. *A geometric introduction to topology*. Addison-Wesley Publishing Co., Reading, Mass.-London-Don Mills, Ont., 1972, pp. vii+168 (cit. on p. 19).

[Wal78] Robert John Walker. *Algebraic curves*. Reprint of the 1950 edition. Springer-Verlag, New York-Heidelberg, 1978, pp. x+201 (cit. on pp. 5, 6).