Riemannian Geometries on Spaces of Plane Curves

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ABSTRACT. We study some Riemannian metrics on the space of regular smooth curves in the plane, viewed as the orbit space of maps from $S^1$ to the plane modulo the group of diffeomorphisms of $S^1$, acting as reparameterizations. In particular we investigate the metric for a constant $A > 0$:

$$G_c^A(h, k) := \int_{S^1} \left( 1 + A \kappa_c(\theta)^2 \right) \langle h(\theta), k(\theta) \rangle \nu(\theta) \, d\theta$$

where $\kappa_c$ is the curvature of the curve $c$ and $h, k$ are normal vector fields to $c$. The term $A \kappa^2$ is a sort of geometric Tikhonov regularization because, for $A = 0$, the geodesic distance between any 2 distinct curves is 0, while for $A > 0$ the distance is always positive. We give some lower bounds for the distance function, derive the geodesic equation and the sectional curvature, solve the geodesic equation with simple endpoints numerically, and pose some open questions. The space has an interesting split personality: among large smooth curves, all its sectional curvatures are $\geq 0$, while for curves with high curvature or perturbations of high frequency, the curvatures are $\leq 0$.

1. Introduction

This paper arose from the attempt to find the simplest Riemannian metric on the space of 2-dimensional ‘shapes’. By a shape we mean a compact simply connected region in the plane whose boundary is a simple closed curve. By requiring that the boundary curve has various degrees of smoothness, we get not just one space but a whole hierarchy of spaces. All these spaces will include, however, a core, namely the space of all shapes with $C^\infty$ boundary curves. We expect that the most natural shape spaces will arise as the completions of this core space in some metric hence we take this core as our basic space. Note that it is the orbit space

$$B_c(S^1, \mathbb{R}^2) = \text{Emb}(S^1, \mathbb{R}^2) / \text{Diff}(S^1)$$

of the space of all $C^\infty$ embeddings of $S^1$ in the plane, under the action by composition from the right by diffeomorphisms of the circle. The space $\text{Emb}(S^1, \mathbb{R}^2)$ is a smooth manifold, in fact an open subset of the Fréchet space $C^\infty(S^1, \mathbb{R}^2)$, and it is the total space of a smooth principal bundle with base $B_c(S^1, \mathbb{R}^2)$

In fact, most of our results carry over to the bigger orbit space of immersions mod diffeomorphisms:

$$B_i(S^1, \mathbb{R}^2) = \text{Imm}(S^1, \mathbb{R}^2) / \text{Diff}(S^1).$$

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This action is not quite free (see 2.4 and 2.5), hence this orbit space is an orbifold (see 2.5) and not quite a manifold. There is the slightly smaller space $\text{Imm}_f$ (see 2.1) of immersed curves where diffeomorphisms act freely, the total space of a principal fiber bundle with a natural connection admitting parallel transport. Existence of horizontal curves, however, holds also in the big space $\text{Imm}$ (see 2.5) which will be one of the weapons in our hunt for geodesics on $B_h$.

The second author was led to study the space $B_h$ from its relevance to computer vision. To understand an image of the world, one needs to identify the most salient objects present in this image. In addition to readily quantifiable properties like color and area, objects in the world and their projections depicted by 2D images possess a 'shape' which is readily used by human observers to distinguish, for example, cats from dogs, BMWs from Hondas, etc. In fact people are not puzzled by what it means to say two shapes are similar but rather find this a natural question. This suggests that we construct, on some crude level, a mental metric which can be used to recognize familiar objects by the similarity of their shapes and to cluster categories of related objects like cats. Incidentally, immersions also arise in vision when a 3D object partially occludes itself from some viewpoint, hence its full 2D contour has visible and invisible parts which, together, form an immersed curve in the image plane.

It is a central problem in computer vision to devise algorithms by which computers can similarly recognize and cluster shapes. Many types of metrics have been proposed for this purpose [7]. For example, there are $L^1$-type metrics such are the area of the symmetric difference of the interiors of two shapes. And there are $L^\infty$-type metrics such as the Hausdorff metric: the maximum distance of points on either shape from the points on the other or of points outside one shape from points outside the other. These metrics will come up below, but the starting point of this investigation was whether one could use the manifold structure on the space of shapes and define an $L^2$-type metric by introducing a Riemannian structure on the space.

Such questions have also arisen in Teichmüller theory and string theory, where the so-called Weil-Petersson metric on the space of shapes (also called the ‘universal Teichmüller space) has been much studied. In a second part of this paper, we will compare our metric to this remarkable (homogeneous!) metric.

In this paper, we sought the absolutely simplest Riemannian metric that the space $B_h$ supports. The most obvious $\text{Diff}(S^1)$-invariant weak Riemannian metric on the space of immersions is the $H^1$-metric:

$$G^1_c(h, k) = \int_{S^1} \langle h(\theta), k(\theta) \rangle |c'(\theta)| \, d\theta$$

where $c : S^1 \to \mathbb{R}^2$ is an embedding defining a point in $B_h$, and $h, k$ are vector fields along the image curve, defining two tangent vectors to $\text{Imm}(S^1, \mathbb{R}^2)$ at $c$. This induces a $\text{Diff}(S^1)$-invariant weak Riemannian metric on the space of all immersions and on $\text{Emb}(S^1, \mathbb{R}^2)$, and for the latter space it induces a weak Riemannian metric on the base manifold $B_h$.

Surprisingly, the Riemannian distance defined as the infimum of the arclength of paths connecting two points in $B_h (S^1, \mathbb{R}^2)$ turns out to be 0, see 3.10! This seems
to be one of the first examples where this purely infinite dimensional phenomenon actually appears.

Motivated by the proof of this result 3.10 we are led to consider the invariant Riemannian metric 3.2.1 for a constant $A > 0$:

$$G_A^A(h, k) := \int_{S^1} (1 + A\kappa_c(\theta)^2) |h(\theta), k(\theta)| e_c(\theta) |d\theta|$$

where $\kappa_c(\theta)$ is the curvature of $c$ at $c(\theta)$. We will argue that this induces a reasonable metric on $B_c(S^1, \mathbb{R}^2)$, as the infimum of arclengths of paths connecting distinct points is always positive. Another reason is that the length function $\ell : B_c(S^1, \mathbb{R}^2) \to \mathbb{R}_{\geq 0}$ has the following Lipschitz estimate 3.3.2 with respect to this Riemannian distance:

$$\sqrt{\ell(C_1)} - \sqrt{\ell(C_0)} \leq \frac{1}{2\sqrt{A}} \text{dist}_{G_A}^A(C_1, C_2).$$

In fact, one can bound the Fréchet distance between two curves in terms of this metric (see 3.5). The completion of the space of smooth curves in this metric contains all curves for whose curvature exists weakly as a finite signed measure (e.g. piecewise $C^2$ curves) and is contained in the space of Lipschitz maps from $S^1$ to $\mathbb{R}^2$ modulo a suitable equivalence relation, see 2.11.

The geodesic equation for the metric $G^A$ on $\text{Emb}(S^1, \mathbb{R}^2)$ and on $B_c(S^1, \mathbb{R}^2)$ can be found in 4.1.1: It is a highly non-linear partial differential equation of order 4 with degenerate symbol, but which nonetheless seems to have a hypoelliptic linearization. If $A = 0$, the equation reduces to a non-linear second order hyperbolic PDE, which gives a well defined local geodesic spray. For any $A$, the sectional curvature on $B_c(S^1, \mathbb{R}^2)$ has an elegant expression which can be found in 4.5.2 and 4.5.4. It is non-negative if $A = 0$ and, for general $A$, becomes strictly negative only if the curve has large curvature or the plane section has high frequency. Of course we would have liked to solve the problem of existence and uniqueness of geodesics for $A > 0$. We can, however, translate the minimization of path length in our metric into an anisotropic Plateau-like problem: In 3.12 we show that a curve projects onto a geodesic in $B_c(S^1, \mathbb{R}^2)$ if and only if its graph in $[0, 1] \times \mathbb{R}^2$ is a surface with given boundary at $\{0\} \times \mathbb{R}^2$ and $\{1\} \times \mathbb{R}^2$ which is critical for the anisotropic area functional 3.12.3.

In 5.1 we determine the geodesic running through concentric circles and the equation for Jacobi vector fields along this geodesic. The solution of the ordinary differential equation 5.1.1 describing this geodesic can be written in terms of elliptic functions. This geodesic is no longer globally minimizing when the radius of the circles is large compared to $\sqrt{A}$ and has conjugate points when it hits this positive curvature zone. In 5.2 we study geodesics connecting arbitrary distant curves, hence requiring long translations. The middle part of such geodesics appear to be approximated by a uniformly translating `cigar'-like curve with semi-circular ends of radius $\sqrt{A}$ connected by straight line segments parallel to the direction of translation. These figures were found by numerically minimizing a discrete form of the energy functional 3.12.1.

Finally, in 5.3 and 5.4, we have some further pictures of geodesics. First we examine the formation of singularities when a small perturbation is propagated
forward and \( A = 0 \). Then we look at some geodesic triangles in \( B \), whose vertices are ellipses with the same eccentricity and center but different orientations. For various values of \( A \), we find that these triangles have angle sums greater and less than \( \pi \).

2. The manifold of immersed closed curves

2.1. Conventions. It is often convenient to use the identification \( \mathbb{R}^2 \cong \mathbb{C} \), giving us:

\[
\tilde{x} \tilde{y} = \langle x, y \rangle + i \det(x, y), \quad \det(x, y) = \langle ix, y \rangle.
\]

We shall use the following spaces of \( C^\infty \) (smooth) diffeomorphisms and curves, and we give the shorthand and the full name:

\( \text{Diff}(S^1) \), the regular Lie group (\([6], 38.4\)) of all diffeomorphisms \( S^1 \to S^1 \) with its connected components \( \text{Diff}^+(S^1) \) of orientation preserving diffeomorphisms and \( \text{Diff}^-(S^1) \) of orientation reversing diffeomorphisms.

\( \text{Diff}_1(S^1) \), the subgroup of diffeomorphisms fixing \( 1 \in S^1 \). We have diffeomorphically \( \text{Diff}(S^1) = \text{Diff}_1(S^1) \times S^1 = \text{Diff}_1^+(S^1) \times (S^1 \times \mathbb{Z}_2) \).

\( \text{Emb} = \text{Emb}(S^1, \mathbb{R}^2) \), the manifold of all smooth embeddings \( S^1 \to \mathbb{R}^2 \). Its tangent bundle is given by \( T \text{Emb}(S^1, \mathbb{R}^2) = \text{Emb}(S^1, \mathbb{R}^2) \times C^\infty(S^1, \mathbb{R}^2) \).

\( \text{Imm} = \text{Imm}(S^1, \mathbb{R}^2) \), the manifold of all smooth immersions \( S^1 \to \mathbb{R}^2 \). Its tangent bundle is given by \( T \text{Imm}(S^1, \mathbb{R}^2) = \text{Imm}(S^1, \mathbb{R}^2) \times C^\infty(S^1, \mathbb{R}^2) \).

\( \text{Imm}_f = \text{Imm}_f(S^1, \mathbb{R}^2) \), the manifold of all smooth free immersions \( S^1 \to \mathbb{R}^2 \), i.e., those with trivial isotropy group for the right action of \( \text{Diff}(S^1) \) on \( \text{Imm}(S^1, \mathbb{R}^2) \).

\( B_\varepsilon = B_\varepsilon(S^1, \mathbb{R}^2) = \text{Emb}(S^1, \mathbb{R}^2) / \text{Diff}(S^1) \), the manifold of 1-dimensional connected submanifolds of \( \mathbb{R}^2 \), see 2.3.

\( B_i = B_i(S^1, \mathbb{R}^2) = \text{Imm}(S^1, \mathbb{R}^2) / \text{Diff}(S^1) \), an infinite dimensional ‘orbifold’, whose points are, roughly speaking, smooth curves with crossings and multiplicities, see 2.5.

\( B_{i,f} = B_{i,f}(S^1, \mathbb{R}^2) = \text{Imm}_f(S^1, \mathbb{R}^2) / \text{Diff}(S^1) \), a manifold, the base of a principal fiber bundle, see 2.4.3.

We want to avoid referring to a path in our infinite dimensional spaces like \( \text{Imm} \) or \( B_\varepsilon \) as a curve, because it is then a ‘curve of curves’ and confusion arises when you refer to a curve. So we will always talk of ‘paths’ in the infinite dimensional spaces, not curves. Curves will be in \( \mathbb{R}^2 \). Moreover, if \( t \mapsto (\theta \mapsto c(t, \theta)) \) is a path, its \( t \)-th curve will be denoted by \( c(t) = c(t, \theta) \). By \( c_t \) we shall denote the derivative \( \partial_t c \), and \( c_\theta = \partial_\theta c \).

2.2. Length and curvature on \( \text{Imm}(S^1, \mathbb{R}^2) \). The volume form on \( S^1 \) induced by \( c \) is given by

\[
(1) \quad \text{vol} : \text{Emb}(S^1, \mathbb{R}^2) \to \Omega^1(S^1), \quad \text{vol}(c) = |c_\theta| d\theta
\]
and its derivative is
\[ d \text{vol}(c)(h) = \frac{\langle h_\theta, c_\theta \rangle}{|c_\theta|} \, d\theta. \]

We shall also use the normal unit field
\[ n_c = \frac{c_\theta}{|c_\theta|}. \]

The length function is given by
\[ \ell : \text{Im}(S^1, \mathbb{R}^2) \to \mathbb{R}, \quad \ell(c) = \int_{S^1} |c_\theta| \, d\theta \]
and its differential is
\[ d\ell(c)(h) = \int_{S^1} \frac{\langle h_\theta, c_\theta \rangle}{|c_\theta|} \, d\theta = -\int_{S^1} \left( \frac{\langle c_\theta, c_\theta \rangle}{|c_\theta|^3} - \frac{\langle c_\theta, \kappa(c)_\theta \rangle}{|c_\theta|^2} \right) \, d\theta \]
\[ = -\int_{S^1} \langle h, \kappa(c)_\theta \rangle \, d\theta = -\int_{S^1} \langle h, n_c(c) \rangle \, d\theta \]
\[ = -\int_{S^1} \langle h, \kappa(c) \rangle \, d\theta. \]

The curvature mapping is given by
\[ \kappa : \text{Im}(S^1, \mathbb{R}^2) \to C^\infty(S^1, \mathbb{R}), \quad \kappa(c) = \frac{\text{det}(c_\theta, c_\theta \theta)}{|c_\theta|^3} = \frac{\langle ic_\theta, c_\theta \theta \rangle}{|c_\theta|^3} \]
and is equivariant so that \( \kappa(c \circ f) = \pm \kappa(c) \circ f \) for \( f \in \text{Diff}^+(S^1) \). Its derivative is given by
\[ d\kappa(c)(h) = \frac{\langle ih_\theta, c_\theta \theta \rangle}{|c_\theta|^3} + \frac{\langle ic_\theta, h_\theta \rangle}{|c_\theta|^3} - 3\kappa(c) \frac{\langle h_\theta, c_\theta \rangle}{|c_\theta|^2}. \]

With some work, this can be shown to equal:
\[ d\kappa(c)(h) = \frac{\langle h, c_\theta \rangle}{|c_\theta|^2} \kappa_\theta + \frac{\langle h, ic_\theta \rangle}{|c_\theta|} \kappa + \frac{1}{|c_\theta|} \left( \frac{\langle h, ic_\theta \rangle}{|c_\theta|} \right)_\theta. \]

To verify this, note that both the left and right hand side are equivariant with respect to \( \text{Diff}(S^1) \), hence it suffices to check it for constant speed parametrizations, i.e., \( |c_\theta| \) is constant and \( c_\theta \theta = \kappa |c_\theta| ic_\theta \). By linearity, it is enough to take the 2 cases \( h = ac_\theta \) and \( h = bc_\theta \). Substituting these into formulas (6) and (7), the result is straightforward.

2.3. The principal bundle of embeddings \( \text{Emb}(S^1, \mathbb{R}^2) \). We recall some basic results whose proof can be shown in [6]:

(A) The set \( \text{Emb}(S^1, \mathbb{R}^2) \) of all smooth embeddings \( S^1 \to \mathbb{R}^2 \) is an open subset of the Fréchet space \( C^\infty(S^1, \mathbb{R}^2) \) of all smooth mappings \( S^1 \to \mathbb{R}^2 \) with the \( C^\infty \)-topology. It is the total space of a smooth principal bundle \( \pi : \text{Emb}(S^1, \mathbb{R}^2) \to B_\tau(S^1, \mathbb{R}^2) \) with structure group \( \text{Diff}(S^1) \), the smooth regular Lie group group of all diffeomorphisms of \( S^1 \), whose base \( B_\tau(S^1, \mathbb{R}^2) \) is the smooth Fréchet manifold of all submanifolds of \( \mathbb{R}^2 \) of type \( S^1 \), i.e., the smooth manifold of all simple closed curves in \( \mathbb{R}^2 \). ([6], 44.1)

(B) This principal bundle admits a smooth principal connection described by the horizontal bundle whose fiber \( X_c \) over \( c \) consists of all vector fields \( h \) along \( c \) such that \( \langle h, c_\theta \rangle = 0 \). The parallel transport for this connection exists and is smooth. ([6], 38.1 and 43.1)
See 2.4.3 for a sketch of proof of the first part in a slightly more general situation. See also 3.2.2 and 3.2.3 for the horizontal bundle $\mathcal{N}_c$. Here we want to sketch the use of the second part. Suppose that \( t \mapsto (\theta \mapsto c(t, \theta)) \) is a path in \( \text{Emb}(S^1, \mathbb{R}^2) \). Then \( \pi \circ c \) is a smooth path in \( B_{s_1}(S^1, \mathbb{R}^2) \). Parallel transport over it with initial value \( c(0, \cdot) \) is a now a path \( f \) in \( \text{Emb}(S^1, \mathbb{R}^2) \) which is horizontal, i.e., we have \( \langle f_t, f_\theta \rangle = 0 \). This argument will play an important role below. In 2.5 we will prove this property for general immersions.

### 2.4. Free immersions

The manifold \( \text{Imm}(S^1, \mathbb{R}^2) \) of all immersions \( S^1 \to \mathbb{R}^2 \) is an open set in the manifold \( C^\infty(S^1, \mathbb{R}^2) \) and thus itself a smooth manifold. An immersion \( c : S^1 \to \mathbb{R}^2 \) is called free if \( \text{Diff}(S^1) \) acts freely on it, i.e., \( c \circ \varphi = c \) for \( \varphi \in \text{Diff}(S^1) \) implies \( \varphi = \text{Id} \). We have the following results:

1. If \( \varphi \in \text{Diff}(S^1) \) has a fixed point and if \( c \circ \varphi = c \) for any immersion \( c \) then \( \varphi = \text{Id} \). This is \([2], 1.3\).
2. If for \( c \in \text{Imm}(S^1, \mathbb{R}^2) \) there is a point \( x \in c(S^1) \) with only one preimage then \( c \) is a free immersion. This is \([2], 1.4\). There exist free immersions without such points: Consider a figure eight consisting of two touching ovals, and map \( S^1 \) to this by first transversing the upper oval 3 times and then the lower oval 2 times. This is a free immersion.

3. **The manifold** \( B_{s_1}(S^1, \mathbb{R}^2) \). \([2], 1.5\) The set \( \text{Imm}_f(S^1, \mathbb{R}^2) \) of all free immersions is open in \( C^\infty(S^1, \mathbb{R}^2) \) and thus a smooth submanifold. The projection

\[
\pi : \text{Imm}_f(S^1, \mathbb{R}^2) \to \text{Imm}_f(S^1, \mathbb{R}^2) / \text{Diff}(S^1)
\]

onto a Hausdorff smooth manifold is a smooth principal fibration with structure group \( \text{Diff}(S^1) \). By \([6], 39.1 \text{ and } 43.1\) this fibration admits a smooth principal connection described by the horizontal bundle with fiber \( \mathcal{N}_c \) consisting of all vector fields \( h \) along \( c \) such that \( \langle h, c_\theta \rangle = 0 \). This connection admits a smooth parallel transport over each smooth curve in the base manifold.

We might view \( \text{Imm}_f(S^1, \mathbb{R}^2) \) as the nonlinear Stiefel manifold of parametrized curves in \( \mathbb{R}^2 \) and consequently \( B_{s_1}(S^1, \mathbb{R}^2) \) as the nonlinear Grassmannian of unparametrized simple closed curves.

**Sketch of proof.** See also \([2]\) for a slightly different proof with more details. For \( c \in \text{Imm}_f(S^1, \mathbb{R}^2) \) and \( s = (s_1, s_2) \in V(c) \subset C^\infty(S^1, \mathbb{R} \times S^1) \) consider

\[
\varphi_c(s) : S^1 \to \mathbb{R}^2, \quad \varphi_c(s)(\theta) = c(s_2(\theta)) + s_1(s_2(\theta))n_c(s_2(\theta))
\]

where \( V(c) \) is a \( C^\infty \)-open neighborhood of \((0, \text{Id}_{S^1}) \) in \( C^\infty(S^1, \mathbb{R} \times S^1) \) chosen in such a way that:

- \( s_2 \in \text{Diff}(S^1) \) for each \( s \in V(c) \).
- \( \varphi_c(s) \) is a free immersion for each \( s \in V(c) \).
- For \( (s_1, s_2) \in V(c) \) and \( \alpha \in \text{Diff}(S^1) \) we have \( (s_1, s_2 \circ \alpha) \in V(c) \).

Obviously \( \varphi_c(s_1, s_2) \circ \alpha = \varphi_c(s_1, s_2 \circ \alpha) \) and \( s_2 \) is uniquely determined by \( \varphi_c(s_1, s_2) \) since this is a free immersion. Thus the inverse of \( \varphi_c \) is a smooth chart for the manifold \( \text{Imm}_f(S^1, \mathbb{R}^2) \). Moreover, we consider the mapping (which will be important
in section 4 below)

\[ \psi_c : C^\infty(S^1, (-\varepsilon, \varepsilon)) \to \text{Im} f(S^1, \mathbb{R}^2), \quad \mathcal{Q}(c) := \psi_c(C^\infty(S^1, (-\varepsilon, \varepsilon))) \]

\[ \psi_c(f)(\theta) = c(\theta) + f(\theta) \eta_c(\theta) = \varphi_c(f, \text{Id}_{S^1})(\theta), \]

\[ \pi \circ \psi : C^\infty(S^1, (-\varepsilon, \varepsilon)) \to B_{k,f}(S^1, \mathbb{R}^2), \]

where \( \varepsilon \) is small. Then (an open subset of) \( \mathcal{V}(c) \) splits diffeomorphically into

\[ C^\infty(S^1, (-\varepsilon, \varepsilon)) \times \text{Diff} S^1 \]

and thus its image under \( \varphi_c \) splits into \( \mathcal{Q}(c) \times \text{Diff} (S^1) \). So the inverse of \( \pi \circ \psi_c \) is a smooth chart for \( B_{k,f}(S^1, \mathbb{R}^2) \). That the chart changes induced by the mappings \( \varphi_c \) and \( \psi_c \) contracted here are smooth is shown by writing them in terms of compositions and projections only and applying the setting of [6].

\[ \square \]

2.5. **Non free immersions.** Any immersion is proper since \( S^1 \) is compact and thus by ([2], 2.1) the orbit space \( B_i(S^1, \mathbb{R}^2) = \text{Im} f(S^1, \mathbb{R}^2)/\text{Diff}(S^1) \) is Hausdorff. Moreover, by ([2], 3.1 and 3.2) for any immersion \( c \) the isotropy group \( \text{Diff}(S^1)_c \) is a finite cyclic group which acts as group of covering transformations for a finite covering \( q_c : S^1 \to S^1 \) such that \( c \) factors over \( q_c \) to a free immersion \( \bar{c} : S^1 \to \mathbb{R}^2 \) with \( \bar{c} \circ q_c = c \). Thus the subgroup \( \text{Diff}(S^1) \) of all diffeomorphisms \( \varphi \) fixing \( 1 \in S^1 \) acts freely on \( \text{Im} f(S^1, \mathbb{R}^2) \). Moreover, for each \( c \in \text{Im} f \) the submanifold \( \mathcal{Q}(c) \) from the proof of 2.4.3 (dropping the freeness assumption) is a slice in a strong sense:

- \( \mathcal{Q}(c) \) is invariant under the isotropy group \( \text{Diff}(S^1)_c \).
- If \( \mathcal{Q}(c) \circ \varphi \cap \mathcal{Q}(c) \neq \emptyset \) for \( \varphi \in \text{Diff}(S^1) \) then \( \varphi \) is already in the isotropy group \( \varphi \in \text{Diff}(S^1)_c \).
- \( \mathcal{Q}(c) \circ \text{Diff}(S^1) \) is an invariant open neighbourhood of the orbit \( c \circ \text{Diff}(S^1) \) in \( \text{Im} f(S^1, \mathbb{R}^2) \) which admits a smooth retraction \( r \) onto the orbit. The fiber \( r^{-1}(c \circ \varphi) \) equals \( \mathcal{Q}(c \circ \varphi) \).

Note that also the action

\[ \text{Im} f(S^1, \mathbb{R}^2) \times \text{Diff}(S^1) \to \text{Im} f(S^1, \mathbb{R}^2) \times \text{Im} f(S^1, \mathbb{R}^2), \quad (c, \varphi) \mapsto (c, c \circ \varphi), \]

is proper so that all assumptions and conclusions of Palais’ slice theorem [8] hold. This results show that the orbit space \( B_i(S^1, \mathbb{R}^2) \) has only very simple singularities of the type of a cone \( \mathbb{C} / \{ e^{2\pi i k/n} : 0 \leq k < n \} \) times a Fréchet space. We may call the space \( B_i(S^1, \mathbb{R}^2) \) an infinite dimensional orbifold. The projection \( \pi : \text{Im} f(S^1, \mathbb{R}^2) \to B_i(S^1, \mathbb{R}^2) = \text{Im} f(S^1, \mathbb{R}^2)/\text{Diff}(S^1) \) is a submersion off the singular points and has only mild singularities at the singular strata. The normal bundle \( \mathcal{N}_c \) mentioned in 2.3 is well defined and is a smooth vector subbundle of the tangent bundle. We do not have a principal bundle and thus no principal connections, but we can prove the main consequence, the existence of horizontal paths, directly:

**Proposition.** For any smooth path \( c \) in \( \text{Im} f(S^1, \mathbb{R}^2) \) there exists a smooth path \( \varphi \) in \( \text{Diff}(S^1) \) with \( \varphi(t, \theta) = \text{Id}_{S^1} \) depending smoothly on \( c \) such that the path \( \varepsilon \) given by \( \varepsilon(t, \theta) = c(t, \varphi(t, \theta)) \) is horizontal: \( \varepsilon \perp \varepsilon \).

**Proof.** Let us write \( \varepsilon = c \circ \varphi \) for \( c(t, \theta) = c(t, \varphi(t, \theta)) \), etc. We look for \( \varphi \) as the integral curve of a time dependent vector field \( \xi(t, \theta) \) on \( S^1 \), given by \( \varphi_t = \xi \circ \varphi \).
We want the following expression to vanish:
\[
\langle \partial_t (c \circ \varphi), \partial_t (c \circ \varphi) \rangle = \langle \varphi_t \circ \varphi + (c_\theta \circ \varphi) \varphi_t, (c_\theta \circ \varphi) \varphi_t \rangle \\
= ((c_t, c_\theta) \circ \varphi) \varphi_t + ((c_\theta, c_\theta) \circ \varphi) \varphi_t \\
= ((c_t, c_\theta) + (c_\theta, c_\theta) \xi) \circ \varphi \varphi_t.
\]
Using the time dependent vector field \( \xi = -\frac{\langle c_\theta, c_\theta \rangle}{|c_\theta|^2} \) and its flow \( \varphi \) achieves this. \( \square \)

2.6. The manifold of immersions with constant speed. Let \( \text{Imm}_c(S^1, \mathbb{R}^2) \) be the space of all immersions \( c : S^1 \to \mathbb{R}^2 \) which are parametrized by scaled arc length, so that \( |c_\theta| \) is constant.

**Proposition.** The space \( \text{Imm}_c(S^1, \mathbb{R}^2) \) is a smooth manifold. There is a diffeomorphism \( \text{Imm}_c(S^1, \mathbb{R}^2) \cong \text{Imm}_c(S^1, \mathbb{R}^2) \times \text{Diff}_+^*(S^1) \) which respects the splitting \( \text{Diff}(S^1) = \text{Diff}_+^*(S^1) \times (S^1 \times \mathbb{Z}_2) \). There is a smooth action of the rotation and reflection group \( S^1 \times \mathbb{Z}_2 \) on \( \text{Imm}_c(S^1, \mathbb{R}^2) \) with orbit space \( \text{Imm}_c(S^1, \mathbb{R}^2)/(S^1 \times \mathbb{Z}_2) \cong B_c(S^1, \mathbb{R}^2) \).

**Proof.** For \( c \in \text{Imm}_c(S^1, \mathbb{R}^2) \) we put
\[
\sigma_c \in \text{Diff}_1(S^1), \quad \sigma_c(\theta) = \exp\left(\frac{2\pi i}{\int_{S^1} |c'(u)| \, du} \int_0^1 c'(u) \, du \right)
\]
\( \alpha : \text{Imm}(S^1, \mathbb{R}^2) \to \text{Imm}_c(S^1, \mathbb{R}^2), \quad \alpha(c)(\theta) := c(\sigma_c^{-1}(\theta)). \)

By the fundamentals of manifolds of mappings [6] the mapping \( \alpha \) is smooth from \( \text{Imm}(S^1, \mathbb{R}^2) \) into itself and we have \( \alpha \circ \alpha = \alpha \).

Now we show that \( \text{Imm}_c(S^1, \mathbb{R}^2) \) is a manifold. We use the notation from the proof of 2.4.3 with the freeness assumption dropped. For \( c \in \text{Imm}_c(S^1, \mathbb{R}^2) \) we use the following mapping as the inverse of a chart:
\[
C^\infty(S^1, (-\varepsilon, \varepsilon)) \xrightarrow{\phi_c} Q(c) \xrightarrow{\alpha} \text{Imm}_c(S^1, \mathbb{R}^2).
\]
The chart changes are smooth: \( \phi_c \) is a diffeomorphism, and if \( c_1 \in Q(c) \) then \( c_1 \circ \sigma_{c_1} = \alpha(c_1) = \alpha(c_2) = c_2 \circ \sigma_{c_2} \) and both curves are equally oriented, thus \( c_2 = c_1 \circ \varphi \) for a unique diffeomorphism \( \varphi \in \text{Diff}_+^*(S^1) \) (see 2.4.1) which depends smoothly on \( c_1 \) and \( c_2 \). For the latter assertion one has to show that a smooth path through \( c_1 \) in \( Q(c_1) \) is mapped to a smooth path in \( \text{Diff}_1(S^1) \). This follows from the finite dimensional implicit function theorem. The mapping \( \alpha \) is now smooth into \( \text{Imm}_c(S^1, \mathbb{R}^2) \) and the diffeomorphism \( \text{Imm}(S^1, \mathbb{R}^2) \to \text{Imm}_c(S^1, \mathbb{R}^2) \times \text{Diff}_1(S^1) \) is given by \( c \mapsto (\alpha(c), \sigma_c) \) with inverse \( (c, \varphi) \mapsto c \circ \varphi^{-1} \). Only the group \( S^1 \times \mathbb{Z}_2 \) of rotations and reflections of \( S^1 \) then still acts on \( \text{Imm}_c(S^1, \mathbb{R}^2) \) with orbit space \( B_c(S^1, \mathbb{R}^2) \). The rest is clear. \( \square \)

2.7. Tangent space, length, curvature, and Frenet-Serret formulas on \( \text{Imm}_c(S^1, \mathbb{R}^2) \). A smooth curve \( t \mapsto c(t) \in \text{Imm}(S^1, \mathbb{R}^2) \) lies in \( \text{Imm}_c(S^1, \mathbb{R}^2) \) if and only if \( |\partial_t c| = |c_\theta|^2 \) is constant in \( \theta \), i.e., \( |\partial_t c| |c_\theta|^2 = 2\langle c_\theta, c_\theta \rangle = 0 \). Thus \( h = \partial_t |c| \in T_c \text{Imm}(S^1, \mathbb{R}^2) = C^\infty(S^1, \mathbb{R}^2) \) is tangent to \( \text{Imm}_c(S^1, \mathbb{R}^2) \) at the foot point \( c \) if and only if \( \langle h_\theta, c_\theta \rangle + \langle h_\theta, c_\theta \rangle = \langle h_\theta, c_\theta \rangle = 0 \), i.e., \( \langle h_\theta, c_\theta \rangle \) is constant
in $\theta$. For $c \in \text{Imm}_e(S^1, \mathbb{R}^2)$ the volume form is constant in $\theta$ since $|c_{\theta}| = \ell(c)/2\pi$. Thus for the curvature we have

$$
\kappa : \text{Imm}_e(S^1, \mathbb{R}^2) \to C^\infty(S^1, \mathbb{R}), \quad \kappa(c) = \left(\frac{2\pi}{\ell(c)}\right)^3 \det(c_\theta, c_{\theta\theta}) = \left(\frac{2\pi}{\ell(c)}\right)^3 \langle ic_\theta, c_{\theta\theta}\rangle
$$

and for the derivative of the length function we get

$$
d\ell(c)(h) = \int_{S^1} \frac{\langle h, c_\theta \rangle}{|c_\theta|} d\theta = \frac{(2\pi)^2}{\ell(c)} \langle h(1), c_\theta(1) \rangle.
$$

Since $c_{\theta\theta}$ is orthogonal to $c_\theta$ we have (Frenet formulas)

$$
c_{\theta\theta} = \left(\frac{2\pi}{\ell(c)}\right)^2 \langle ic_\theta, c_{\theta\theta}\rangle ic_\theta = \left(\frac{2\pi}{\ell(c)}\right)^2 \kappa(c)ic_\theta,
$$

$$
c_{\theta\theta\theta} = \left(\frac{\ell(c)}{2\pi}\right) \kappa(c)_\theta ic_\theta + \left(\frac{\ell(c)}{2\pi}\right) \kappa(c)ic_{\theta\theta} = \frac{\ell(c)}{2\pi} \kappa(c)_\theta ic_\theta - \left(\frac{\ell(c)}{2\pi}\right)^2 \kappa(c)^2 c_\theta.
$$

The derivative of the curvature thus becomes:

$$
d\kappa(c)(h) = -2\left(\frac{2\pi}{\ell(c)}\right)^2 \langle h, c_\theta \rangle \kappa(c) + \left(\frac{2\pi}{\ell(c)}\right)^3 \langle ic_\theta, h_{\theta\theta}\rangle.
$$

### 2.8. Horizontality on $\text{Imm}_e(S^1, \mathbb{R}^2)$. Let us denote by $\text{Imm}_{e,f}(S^1, \mathbb{R}^2)$ the splitting submanifold of $\text{Imm}$ consisting of all constant speed free immersions. For $c \in S^1$, $\text{Imm}_{e,f}(S^1, \mathbb{R}^2)$ is the projection $\text{Imm}_{e,f}(S^1, \mathbb{R}^2) \to B_f(S^1, \mathbb{R}^2)$ is principal fiber bundle with structure group $S^1 \times \mathbb{Z}_2$, and it is a reduction of the principal fibration $\text{Imm}_f \to B_f$. The principal connection described in 2.4.3 is not compatible with this reduction. But we can easily find some principal connections. The one we will use is described by the horizontal bundle with fiber $N_c, c \in S^1$ of all vector fields $h$ along $c$ such that $\langle h, c_{\theta}\rangle_\theta = 0$ (tangent to $\text{Imm}_e$) and $\langle h(1), c_{\theta}(1) \rangle = 0$ for $1 \in S^1$ (horizontality). This connection admits a smooth parallel transport; but we can even do better, beyond the principal bundle, in the following proposition whose proof is similar and simpler than that of proposition 2.5.

**Proposition.** For any smooth path $c$ in $\text{Imm}_e(S^1, \mathbb{R}^2)$ there exists a smooth curve $\varphi_c$ in $S^1$ with $\varphi_c(t) = 1$ depending smoothly on $c$ such that the path $\varphi$ given by $\varphi(t, \theta) = c(t, \varphi_c(t)\theta)$ is horizontal: $c_t(1) \perp c_\theta(1)$. $\square$

### 2.9. The degree of immersions. Recall that the degree of an immersion $c : S^1 \to \mathbb{R}^2$ is the winding number with respect to $0$ of the tangent $c' : S^1 \to \mathbb{R}^2$. Since this is invariant under isotopies of immersions, the manifold $\text{Imm}(S^1, \mathbb{R}^2)$ decomposes into the disjoint union of the open submanifolds $\text{Imm}_k(S^1, \mathbb{R}^2)$ for $k \in \mathbb{Z}$ according to the degree $k$. We shall also need the space $\text{Imm}_e^k(S^1, \mathbb{R}^2)$ of all immersions of degree $k$ with constant speed.

### 2.10. Theorem.

1. The manifold $\text{Imm}_e^k(S^1, \mathbb{R}^2)$ of immersed curves of degree $k$ contains the subspace $\text{Imm}_e^k(S^1, \mathbb{R}^2)$ as smooth strong deformation retract.
(2) The manifold $\text{Imm}^k_k(S^1, \mathbb{R}^2)$ of immersed constant speed curves of degree $k$ contains $S^1$ as a strong smooth deformation retract.

(3) For $k \neq 0$ the manifold $B^k_k(S^1, \mathbb{R}^2) := \text{Imm}^k_k(S^1, \mathbb{R}^2)/\text{Diff}^+(S^1)$ is contractible.

Note that for $k \neq 0$ $\text{Imm}^k_k$ is invariant under the action of the group $\text{Diff}^+(S^1)$ of orientation preserving diffeomorphisms only, and that any orientation reversing diffeomorphism maps $\text{Imm}^k_k$ to $\text{Imm}^{-k}_k$.

The nontrivial $S^1$ in $\text{Imm}^k_k$ appears in 2 ways: (a) by rotating each curve around $c(0)$ so that $c'(0)$ rotates. And (b) also by acting $S^1 \ni \beta \mapsto (c(\beta) \mapsto c(\beta \theta))$. The two corresponding elements $a$ and $b$ in the fundamental group are then related by $a^k = b$ which explains our failure to describe the topological type of $B^k_k$.

**Proof.** (1) is a consequence of 2.6 since $\text{Diff}^+(S^1)$ is contractible.

The general proof is inspired by the proof of the Whitney-Graustein theorem, [9], [4], [3]. We shall view curves here as $2\pi$-periodic plane-valued functions. For any curve $c$ we consider its center of mass

$$\text{Center}(c) := \frac{1}{\ell(c)} \int_0^{2\pi} c(u) |c'(u)| \, du \in \mathbb{R}^2$$

which is invariant under $\text{Diff}(S^1)$. We shall also use $a(c) = c'(0) / |c'(0)|$.

**The case** $k \neq 0$. We first embed $S^1$ into $\text{Imm}(S^1, \mathbb{R}^2)$ in the following way. For $a \in S^1 \subset \mathbb{C} = \mathbb{R}^2$ and $k \neq 0$ we put $c_0(\theta) = a, e^{ik\theta} / |k|$, a circle of radius $1 / |k|$ transversed $k$-times in the direction indicated by the sign of $k$. Note that we have $\text{Center}(c_0) = 0$ and $c_0'(0) = a$.

Since the isotopies to be constructed later will destroy the property of having constant speed, we shall first construct a smooth deformation retraction $A : [0, 1] \times \text{Imm}^k_k \to \text{Imm}^k_k$ onto the subspace $\text{Imm}^k_k$ of unit speed degree $k \neq 0$ curves with center 0.

Let $c : \mathbb{R} \to \mathbb{R}^2$ be an arbitrary constant speed immersion of degree $k$, period $2\pi$, and length $\ell(c)$. Let $s_c(u) = \int_0^u |c'(u)| \, du$ be the arc-length function of $c$ and put

$$A(c, t, u) = \left(1 - t + \frac{1}{2\pi} \ell(c) \right) \left( c((1 - t)u + ts_{c}^{-1}(\frac{3\pi}{\ell(c)}u)) - t \cdot C(c) \right).$$

Then $A_t$ is an isotopy between $c$ and $c_1 := A(c, 1, \cdot)$ depending smoothly on $c$. The immersion $c_1$ has unit speed, length $2\pi$, and $\text{Center}(c_1) = 0$. Moreover, for the winding number $w_0$ around 0 we have:

$$w_0(c_1' |_{[0, 2\pi]}) = \deg(c_1) = \deg(c) = k = \deg(c_0(c)) = w_0(c_0(c) |_{[0, 2\pi]}).$$

Thus $\text{Imm}^k_k$ contains the subspace $\text{Imm}^k_k$ of unit speed immersions with center of mass 0 and degree $k$ as smooth strong deformation retract.

For $c \in \text{Imm}^k_k$ a unit speed immersion with center 0 we now construct an isotopy $t \mapsto H^1(c, t, \cdot)$ between $c$ and a suitable curve $c_0$. It will destroy the unit speed
property, however. For \( d \arg = \frac{-u \, dy + v \, dx}{\sqrt{x^2 + y^2}} \) we put:

\[
\varphi_c(u) := \int_{c_1[[0,u]]} d \arg, \quad \text{so that } c'(u) = c'(0) e^{i \varphi_c(u)},
\]

\[
a(c) := \frac{1}{2\pi} \int_0^{2\pi} (\varphi_\alpha(v) - k v) \, dv,
\]

\[
\psi_c(t, u) := (1 - t) \varphi_c(u) + t (k u + a(c)),
\]

\[
h(c, t, u) := \int_0^u e^{i \psi_c(t,v)} \, dv = \frac{u}{2\pi} \int_0^{2\pi} e^{i \psi_c(t,v)} \, dv,
\]

\[
H^1(c, t, u) := c'(0) \left( h(c, t, u) - \text{Center}(h(c, t, \cdot)) \right)
\]

Then \( H^1(c, t, u) \) is smooth in all variables, \( 2\pi \)-periodic in \( u \), with center of mass at \( 0 \), \( H^1(1, c, u) \) equals one the \( e_\alpha \)'s, and \( H^1(0, c, u) = c(u) \). But \( H^1(c, t, \cdot) \) is, however, no longer of unit speed in general. And we still have to show that \( t \mapsto h(c, t, \cdot) \) (and consequently \( H^1 \)) is an isotopy.

\[
\partial_u h(c, t, u) = e^{i \psi_c(t,u)} - \frac{1}{2\pi} \int_0^{2\pi} e^{i \psi_c(t,v)} \, dv,
\]

\[
\left| \frac{1}{2\pi} \int_0^{2\pi} e^{i \psi_c(t,v)} \, dv \right| \leq 1.
\]

If the last inequality is strict we have \( \partial_u h(t, u) \neq 0 \) so that \( h \) is an isotopy. If we have equality then \( \psi_c(t, v) \) is constant in \( v \) which leads to a contradiction as follows: If \( k \neq 0 \) then \( \psi_c(t, 2\pi) - \psi_c(t, 0) = 2\pi k \) so it cannot be constant for any \( t \).

Let us finally check how this construction depends on the choice of the base point \( c(0) \). We have:

\[
\varphi_{c(\beta+)}(u) = \varphi_c(\beta + u) - \varphi_c(\beta),
\]

\[
a(c(\beta+)) = a(c) + k \beta - \varphi_c(\beta),
\]

\[
\psi_{c(\beta+)}(t, u) = \psi_c(t, u + \beta) - \varphi_c(\beta),
\]

\[
h(c(\beta+), t, u) = e^{-i \varphi_c(\beta)}(h(c, t, \beta + u) - h(c, t, \beta)),
\]

\[
H^1(c(\beta+), t, u) = H^1(c, t, \beta + u).
\]

Let us now deform \( H^1 \) back into \( \text{Imm}^k_{1,0} \). For \( c \in \text{Imm}^k_{1,0} \) we consider

\[
H^2(c, t, u) := A(1, H^1(c, t, \cdot), u),
\]

\[
H^3(c, t, u) := H^3(c, t, u + \varphi_{H^2(c)}(t)),
\]

where the \( \varphi_f \) for a unit speed path \( f \) is from proposition 2.8, so that \( H^3(c) \) is a horizontal path of unit speed curves of length \( 2\pi \), (i.e., \( \partial_\alpha H^3(c, t, 0) \perp \partial_u H^3(c, t, u) \)).

The isotopy \( A \) reacts in a complicated way to rotations of the parameter, but we have \( A(c(\beta+), 1, u) = A(c, 1, \frac{k \beta}{2\pi} + c(\beta) + u) \). Thus \( H^3(c(\beta+), t, u) = H^3(c, t, u + \beta) \), so \( H^3 \) is equivariant under the rotation group \( S^1 \subset \text{Diff}(S^1) \). For \( k \neq 0 \) we get an equivariant smooth strong deformation retract within \( \text{Imm}^k_{1,0} \) onto the subset \( \{ e_\alpha : \alpha \in S^1 \} \subset \text{Imm}^k_{1,0} \) which is invariant under the rotation group \( S^1 \subset \text{Diff}(S^1) \). It factors to a smooth contraction on \( B^k_{\gamma} \). This proves assertions (2) and (3) for \( k \neq 0 \).
The case $k = 0$. For $k = 0$ we let $c$ be a smooth figure eight parametrized by arclength of length $2\pi$ with $0(0) = 0$ and $\dot{c}(0) = \left(\frac{1}{2}\right)$ whose image consists of two ovals symmetric under $y \mapsto -y$ and meeting $\{y = 0\}$ precisely at $0$. Note that $\dot{c}$ is nullhomotopic. We put $e_\alpha(\theta) = \alpha \cdot c(\theta)$ for $\alpha \in S^1$.

Now the proof for the case $k \neq 0$ carries over with the following change: For $c \in \text{Imm}^0$,

$$\psi_c(t, u) := (1 - t) \varphi_{c, t}(u) + t \varphi_{e, \psi_{c, t}(u)}$$

The argument that $h(c, t, \cdot)$ is an isotopy is finished as follows: If we have equality in (5), we note that $\varphi_{c, t}$ and $\varphi_{e, \psi_{c, t}(u)}$ are both periodic, so we may translate their parameterizations such that both have a minimum at $v = 0$. Then $\varphi_{c, t}(t, v) = t \varphi_{c, t}(v) + (1 - t) \varphi_{e, \psi_{c, t}(u)}(v)$ constant in $v$ implies that both $\varphi_{c_1}(v)$ are constant in $v$, so that both $c_1$ and $c$ with shifted parameterizations were straight lines, thus also in the unshifted parameterization.

Then $H^2$ is again a smooth strong deformation retract of $\text{Imm}^0$ onto the set $\{e_\alpha : \alpha \in S^1\}$, so assertion (2) holds in case $k = 0$. But the latter set does not project to a single shape in $B_1$, and $H^2$ is not $S^1$-equivariant.  

2.11 Bigger spaces of ‘immersed’ curves. We want to introduce a larger space containing $B_1(S^1, \mathbb{R}^2)$, which is complete in a suitable metric. This will serve as an ambient space which will contain the completion of $B_1(S^1, \mathbb{R}^2)$. Let $\text{Cont}(S^1, \mathbb{R}^2)$ be the space of all continuous functions $c : S^1 \to \mathbb{R}^2$. Instead of a group operation and its associated orbit space, we introduce an equivalence relation on $\text{Cont}(S^1, \mathbb{R}^2)$. Define a subset $R \subset S^1 \times S^1$ to be a monotone correspondence if it is the image of a map

$$x \to (h(x) \mod 2\pi, k(x) \mod 2\pi), \quad \text{where}$$

$$h, k : \mathbb{R} \to \mathbb{R}$$

are monotone non-decreasing continuous functions such that

$$h(x + 2\pi) = h(x) + 2\pi, \quad k(x + 2\pi) = k(x) + 2\pi.$$ 

In words, this is an orientation preserving homeomorphism from $S^1$ to $S^1$ which is allowed to have intervals where one or the other variable remains constant while the other continues to increase. (These correspondences arise naturally in computer vision in comparing the images seen by the right and left eyes, see [1].) Then we define the equivalence relation on $\text{Cont}(S^1, \mathbb{R}^2)$ by $c \sim d$ if and only if there is a monotone correspondence $R$ such that for all $\theta, \varphi \in R$, $c(\theta) = d(\varphi)$. It is easily seen that any non-constant $c \in \text{Cont}(S^1, \mathbb{R}^2)$ is equivalent to an $c_1$ which is not constant on any intervals in $S^1$ and that for such $c_1$’s and $d_1$’s, the equivalence relation amounts to $c_1 \circ h \equiv d_1$ for some homeomorphism $h$ of $S^1$. Let $B_1^{\text{enc}}(S^1, \mathbb{R}^2)$ be the quotient space by this equivalence relation. We call these Fréchet curves.

The quotient metric on $B_1^{\text{enc}}(S^1, \mathbb{R}^2)$ is called the Fréchet metric, a variant of the Hausdorff metric mentioned in the Introduction, both being $L^\infty$ type metrics. Namely, define

$$d_\infty(c, d) = \inf_{\text{monotone corr.} R} \left( \sup_{\theta, \varphi \in R} |c(\theta) - d(\varphi)| \right)$$

$$= \inf_{\text{homeomorph} h : S^1 \to S^1} \|c \circ h - d\|_\infty.$$
It is straightforward to check that this makes \( B^C_{\alpha_0}(S^1, \mathbb{R}^2) \) into a complete metric space.

Another very natural space is the subset \( B^L_{\alpha_0}(S^1, \mathbb{R}^2) \subset B^C_{\alpha_0}(S^1, \mathbb{R}^2) \) given by the non-constant \textit{Lipschitz} maps \( c : S^1 \to \mathbb{R}^2 \). The great virtue of Lipschitz maps is that their images are rectifiable curves and thus each of them is equivalent to a map \( d \) in which \( \theta \) is proportional to arclength, as in the previous section. More precisely, if \( c \) is Lipschitz, then \( c_\theta \) exists almost everywhere and is bounded and we can reparametrize by:

\[
h(\theta) = \int_0^\theta |c_\theta|d\theta / \int_0^{2\pi} |c_\theta|d\theta,
\]

obtaining an equivalent \( d \) for which \( |d_\theta| \equiv L/2\pi \). This \( d \) will be unique up to rotations, i.e. the action of \( S^1 \) in the previous section.

This subspace of rectifiable Fréchet curves is the subject of a nice compactness theorem due to Hilbert, namely that the set of all such curves in a closed bounded subset of \( \mathbb{R}^2 \) and whose length is bounded is compact in the Fréchet metric. This can be seen as follows: we can lift all such curves to specific Lipschitz maps \( c \) whose Lipschitz constants are bounded. This set is an equicontinuous set of functions by the bound on the Lipschitz constant. By the Ascoli-Arzelà theorem the topology of pointwise convergence equals then the topology of uniform convergence on \( S^1 \). So this set is a closed subset in a product of \( S^1 \) copies of a large ball in \( \mathbb{R}^2 \); this product is compact. The Fréchet metric is coarser than the uniform metric, so our set is also compact.

3. Metrics on spaces of curves

3.1 Need for invariance under reparametrization. The pointwise metric on the space of immersions \( \text{Imm}(S^1, \mathbb{R}^2) \) is given by

\[
G_c(h, k) := \int_{S^1} \langle h(\theta), k(\theta) \rangle d\theta.
\]

This Riemannian metric is not invariant under reparameterizations of the variable \( \theta \) and thus does not induce a sensible metric on the quotient space \( B_i(S^1, \mathbb{R}^2) \). Indeed, it induces the zero metric since for any two curves \( C_0, C_1 \in B_i(S^1, \mathbb{R}^2) \) the infimum of the arc lengths of curves in \( \text{Imm}(S^1, \mathbb{R}^2) \) which connect embeddings \( c_0, c_1 \in \text{Imm}(S^1, \mathbb{R}^2) \) with \( \pi(c_1) = C_1 \) turns out to be zero. To see this, take any \( c_0 \) in the \( \text{Diff}(S^1) \)-orbit over \( C_0 \). Take the following variation \( c(\cdot, t) \) of \( c_0 \): for \( \theta \) outside a small neighborhood \( U \) of length \( \varepsilon \) of 1 in \( S^1 \), \( c(\theta, t) = c_0(\theta) \). If \( \theta \in U \), then the variation for \( t \in [0, 1/2] \) moves the small part of \( c_0 \) so that \( c(\theta, 1/2) \) for \( \theta \in U \) takes off \( C_0 \), goes to \( C_1 \), traverses nearly all of \( C_1 \), and returns to \( C_0 \). Now in the orbit through \( c(\cdot, 1/2) \), reparameterize in such a way that the new curve is diligently traversing \( C_1 \) for \( \theta \notin U \), and for \( \theta \in U \) it travels back to \( C_0 \), runs along \( C_0 \), and comes back to \( C_1 \). This reparametrized curve is then varied for \( t \in [1/2, 1] \) in such a way, that the part for \( \theta \in U \) is moved towards \( C_2 \). It is clear that the length of both variations is bounded by a constant (depending on the distance between \( C_0 \) and \( C_1 \) and the lengths of both \( C_0 \) and \( C_1 \)) times \( \varepsilon \).
3.2. The $H^A_2$ and the $H^A$-metric. Let $h, k \in C^\infty(S^1, \mathbb{R}^2)$ be two tangent vectors with foot point $c \in \text{Im}(S^1, \mathbb{R}^2)$. The induced volume form is $\text{vol}(c) = \langle \partial_\theta c, \partial_\theta e \rangle^{1/2} d\theta = |c_e| d\theta$. We consider the following weak Riemannian metric on $\text{Im}(S^1, \mathbb{R}^2)$, for a constant $A \geq 0$:

$$G^A_2(h, k) := \int_{S^1} (1 + A\kappa_e(\theta)^2 \langle h(\theta), k(\theta) \rangle |c'(\theta)|) d\theta$$

which is invariant under $\text{Diff}(S^1)$. This makes the map $\pi : C^\infty(S^1, \mathbb{R}^2) \to B_k(S^1, \mathbb{R}^2)$ into a Riemannian submersion (off the singularities of $B_k(S^1, \mathbb{R}^2)$) which is very convenient. We call this the $H^A_2$-metric with curvature weight $A$. If $A = 0$ we get the $H^A$-metric.

Now we can determine the bundle $\mathcal{N} \to C^\infty(S^1, \mathbb{R}^2)$ of tangent vectors which are normal to the $\text{Diff}(S^1)$-orbits. The tangent vectors to the orbits are $T_c(c \circ \text{Diff}(S^1)) = \{g, c_\theta : g \in C^\infty(S^1, \mathbb{R})\}$. Inserting this for $k$ into the expression (1) of the metric we see that

$$\mathcal{N}_c = \{h \in C^\infty(S^1, \mathbb{R}^2) : \langle h, c_\theta \rangle = 0\}$$

$$= \{a ic_\theta \in C^\infty(S^1, \mathbb{R}^2) : a \in C^\infty(S^1, \mathbb{R})\}$$

$$= \{bn_c \in C^\infty(S^1, \mathbb{R}^2) : b \in C^\infty(S^1, \mathbb{R})\},$$

where $n_c$ is the normal unit field along $c$. Note that the bundle $\mathcal{N} \subset T \text{Im}(S^1, \mathbb{R}^2)$ is independent of $A$.

A tangent vector $h \in T_c \text{Im}(S^1, \mathbb{R}^2) = C^\infty(S^1, \mathbb{R}^2)$ has an orthonormal decomposition

$$h = h^T + h^\perp \in T_c(c \circ \text{Diff}(S^1)) \oplus \mathcal{N}_c$$

where

$$h^T = \frac{\langle h, c_\theta \rangle}{|c_\theta|^2} c_\theta \in T_c(c \circ \text{Diff}(S^1)),$$

$$h^\perp = \frac{\langle h, ic_\theta \rangle}{|c_\theta|^2} ic_\theta \in \mathcal{N}_c,$$

into smooth tangential and normal components, independent of $A$.

Since the Riemannian metric $G^A_2$ on $\text{Im}(S^1, \mathbb{R}^2)$ is invariant under the action of $\text{Diff}(S^1)$ it induces a metric on the quotient $B_k(S^1, \mathbb{R}^2)$ as follows. For any $C_0, C_1 \in B_k$, consider all liftings $c_0, c_1 \in \text{Im}(S^1, \mathbb{R}^2)$ such that $\pi(c_0) = C_0, \pi(c_1) = C_1$ and all smooth curves $t \mapsto \{t \mapsto c(t, \theta)\}$ in $\text{Im}(S^1, \mathbb{R}^2)$ with $c(0, \cdot) = c_0$ and $c(1, \cdot) = c_1$. Since the metric $G$ is invariant under the action of $\text{Diff}(S^1)$ the arc-length of the curve $t \mapsto \pi(c(t, \cdot))$ in $B_k(S^1, \mathbb{R}^2)$ is given by

$$I^\text{cor}_{G_2,A}(c) := L_{G_2}(\pi(c(t, \cdot))) = \int_0^1 \sqrt{G^A_2(\pi(c(t, \cdot)))} dt = \int_0^1 \sqrt{G^A(c^T_t, c^T_t)} dt$$

$$= \int_0^1 \left( \int_{S^1} (1 + A\kappa_e^2) \frac{\langle \partial_\theta c_\theta, \partial_\theta c_e \rangle \langle \partial_\theta c_\theta, \partial_\theta c_e \rangle |c_e| d\theta \right)^{1/2} dt$$

$$= \int_0^1 \left( \int_{S^1} (1 + A\kappa_e^2) \langle c_\theta, c_e \rangle^2 \frac{|c_e| d\theta}{|c_e|^2} \right)^{1/2} dt$$

(4) $$= \int_0^1 \left( \int_{S^1} (1 + A\kappa_e^2) \langle c_\theta, c_e \rangle^2 \frac{|c_e| d\theta}{|c_e|^2} \right)^{1/2} dt$$

$$= \int_0^1 \left( \int_{S^1} (1 + A\kappa_e^2) \langle c_\theta, ic_e \rangle^2 d\theta \right)^{1/2} dt$$
The metric on $B_t(S^1,\mathbb{R}^2)$ is defined by taking the infimum of this over all paths $c$ (and all lifts $c_\theta, c_1$):

$$\text{dist}_{G^4}^t (C_1, C_2) = \inf_c L_{G^4}^t(c).$$

Note that if a path $\pi(c)$ in $B_t(S^1,\mathbb{R}^2)$ is given, then one can choose its lift to a path $c$ in $\text{Im}(S^1,\mathbb{R}^2)$ to have various good properties. Firstly, we can choose the lift $c(0,\cdot)$ of the initial curve to have a parametrization of constant speed, i.e. if its length is $\ell$, then $|c_\theta(\theta,0)| = \ell/2\pi$ for all $\theta \in S^1$. Secondly, we can make the tangent vector to $c$ everywhere horizontal, i.e. $<c_t,c_\theta> \equiv 0$, by 2.5. Thirdly, we can reparametrize the coordinate $t$ on the path of length $L$ so that the path is traversed at constant speed, i.e.

$$\int_{S^1} (1 + A\kappa_\theta^2) <c_t, ic_\theta>^2 \ d\theta/|c_\theta| \equiv L^2, \text{ for all } 0 \leq t \leq 1.$$

3.3. A Lipschitz bound for arc length in $G^4$. We apply the Cauchy-Schwarz inequality to the derivative 2.2.4 of the length function along this curve:

$$\partial_t \ell(c) = d\ell(c)(c_\theta) = - \int_{S^1} \kappa(c) \langle c_t, n_c \rangle |c_\theta| \ d\theta \leq \left| \int_{S^1} \kappa(c) \langle c_t, n_c \rangle |c_\theta| \ d\theta \right|$$

$$\leq \left( \int_{S^1} 1^2 |c_\theta| \ d\theta \right)^\frac{1}{2} \left( \int_{S^1} \kappa(c)^2 \langle c_t, n_c \rangle^2 |c_\theta| \ d\theta \right)^\frac{1}{2}$$

$$\leq \ell(c)^\frac{1}{2} \frac{1}{\sqrt{A}} \left( \int_{S^1} (1 + A\kappa(c)^2) |\langle c_t, n_c \rangle |^2 |c_\theta| \ d\theta \right)^\frac{1}{2}$$

Thus

$$\partial_t \left( \sqrt{\ell(c)} \right) = \frac{\partial_t \ell(c)}{2\sqrt{\ell(c)}} \leq \frac{1}{2\sqrt{A}} \left( \int_{S^1} (1 + A\kappa(c)^2) |\langle c_t, n_c \rangle |^2 |c_\theta| \ d\theta \right)^\frac{1}{2}$$

and by using (3.2.4) we get

$$\sqrt{\ell(c_1)} - \sqrt{\ell(c_0)} = \int_0^1 \partial_t (\sqrt{\ell(c)}) \ dt$$

$$\leq \frac{1}{2\sqrt{A}} \int_0^1 \left( \int_{S^1} (1 + A\kappa(c)^2) |\langle c_t, n_c \rangle |^2 |c_\theta| \ d\theta \right)^\frac{1}{2} \ dt$$

$$= \frac{1}{2\sqrt{A}} L_{G^4}^t(c).$$

(1)

If we take the infimum over all curves connecting $c_0$ with the $\text{Diff}(S^1)$-orbit through $c_1$ we get:

**Lipschitz continuity of $\sqrt{\ell}$** $B_t(S^1,\mathbb{R}^2) \to \mathbb{R}_{\geq 0}$. For $C_0$ and $C_1$ in $B_t(S^1,\mathbb{R}^2) = \text{Im}(S^1,\mathbb{R}^2)/\text{Diff}(S^1)$ we have for $A > 0$:

$$\sqrt{\ell(C_1)} - \sqrt{\ell(C_0)} \leq \frac{1}{2\sqrt{A}} \text{dist}_{G^4}^t(C_1, C_2).$$

(2)
3.4. **Bounding the area swept by a path in** $B_k$. Secondly, we want to bound the area swept out by a curve $C_0$ to reach any curve $C_1$ nearby in our metric. First we use the Cauchy-Schwarz inequality in the Hilbert space $L^2(S^1, |c_\theta(t, \theta)| \, d\theta)$ to get

$$\int_{S^1} 1 \cdot |c_t(t, \theta)||c_\theta(t, \theta)| \, d\theta = \langle 1, |c_t| \rangle_{L^2} \leq \left( \int_{S^1} |c_t(t, \theta)| \, d\theta \right)^{\frac{1}{2}} \left( \int_{S^1} |c_\theta(t, \theta)| \, d\theta \right)^{\frac{1}{2}}.$$

Now we assume that the variation $c(t, \theta)$ is horizontal, so that $\langle c_t, c_\theta \rangle = 0$. Then $L_{G_A}(c) = L_{G_A}^\text{hor}(c)$. We use this inequality and then the intermediate value theorem of integral calculus to obtain

$$L_{G_A}^\text{hor}(c) = L_{G_A}(c) = \int_0^1 \sqrt{G_{c_t}^A(c_t, c_t)} \, dt$$

$$= \int_0^1 \left( \int_{S^1} (1 + A_{\kappa}(c)^2) |c_t(t, \theta)|^2 |c_\theta(t, \theta)| \, d\theta \right)^{\frac{1}{2}} \, dt$$

$$\geq \int_0^1 \left( \int_{S^1} |c_t(t, \theta)|^2 |c_\theta(t, \theta)| \, d\theta \right)^{\frac{1}{2}} \, dt$$

$$\geq \int_0^1 \left( \int_{S^1} |c_\theta(t, \theta)| \, d\theta \right)^{-\frac{1}{2}} \int_{S^1} |c_t(t, \theta)| \, d\theta \, dt$$

$$= \left( \int_{S^1} |c_\theta(t_0, \theta)| \, d\theta \right)^{-\frac{1}{2}} \int_0^1 \int_{S^1} |c_t(t, \theta)| \, d\theta \, dt$$

$$\geq \frac{1}{\sqrt{\ell(c(t_0, \cdot)) \int_{[0,1] \times S^1} |\det dc(t, \theta)| \, d\theta \, dt}}.$$

**Area swept out bound.** If $c$ is any path from $C_0$ to $C_1$, then

$$\left( \text{area of the region swept out by the variation } c \right) \leq \max_t \sqrt{\ell(c(t, \cdot))} \cdot L_{G_A}^\text{hor}(c).$$

This result enables us to compare the double cover $B^\text{or}_k(S^1, \mathbb{R}^2)$ of our metric space $B_k(S^1, \mathbb{R}^2)$ consisting of oriented unparametrized curves to the fundamental space of geometric measure theory. Note that there is a map $h_1$ from $B^\text{or}_k$ to the space of 1-currents $\mathcal{D}_1$ given by:

$$\langle h_1(c \mod \text{Diff}^+(S^1)), \omega \rangle = \int_{S^1} c^* \omega \, d\theta, \quad c \in \text{Imm}(S^1, \mathbb{R}^2).$$

The image $h_1(C)$ is, in fact, closed. For any $C$, define the integer-valued measurable function $w_C$ on $\mathbb{R}^2$ by:

$$w_C([x, y]) = \text{winding number of } C \text{ around } (x, y).$$

Then it is easy to see that, as currents, $h_1(C) = \partial(w_C \, dx \wedge dy)$, hence $\partial h_1(C) = 0$. 


Although $h_1$ is obviously injective on the space $B_e$, it is not injective on $B_l$ as illustrated in Figure 1 below. The image of this mapping lies in the basic subset $\mathcal{I}_{1,e} \subset \mathcal{D}_1$ of closed integral currents, namely those which are both closed and countable sums of currents defined by Lipschitz mappings $c : [0, 1] \to \mathbb{R}^2$ of finite total length. Integral currents carry what is called the flat metric, which, for closed 1-currents, reduces (by the isoperimetric inequality) to the area distance

\[ d^*(C_1, C_2) = \int_{\mathbb{R}^2} |w_{C_1} - w_{C_2}| \, dx \, dy. \]

To connect this with our ‘area swept out bound’, note that if we have any path $c$ in $\text{Imm}(S^1, \mathbb{R}^2)$ joining $C_1$ and $C_2$, this path defines a 2-current $u(c)$ such that $\partial u(c) = h_1(C_1) - h_1(C_2)$ and

\[ \int_{\mathbb{R}^2} |u(c)| \, dx \, dy \leq \int_1^1 \int_{S^1} |\det c| \, dt \, d\theta, \]

which is what we are calling the area swept out. But $\partial(u_{C_1} - u_{C_2}) = h_1(C_1) - h_1(C_2)$ too, so $u(c) = u_{C_1} - u_{C_2}$. Thus

\[ d^*(C_1, C_2) \leq \min_{\text{all paths } c \text{ joining } C_1, C_2} \text{[area swept out by } c]\]

Finally, we recall the fundamental compactness result of geometric measure theory in this simple case: the space of integral 1-currents of bounded length is compact in the flat metric. This implies that our ‘area swept out bound’ above has the Corollary:

Corollary.

\begin{enumerate}
\item If $\{C_n\}$ is any Cauchy sequence in $B_l$ for the metric $\text{dist}_{G^A}$, then $\{h_1(C_n)\}$ is a Cauchy sequence in $\mathcal{I}_{1,e}$ on which length is bounded.
\item Hence $h_1$ extends to a continuous map from the completion $\overline{B}_l$ of $B_l$ in the metric $G^A$ to $\mathcal{I}_{1,e}$.
\end{enumerate}

3.5. Bounding how far curves move in small paths in $B_l$. We want to bound the maximum distance a curve $C_0$ can move on any path whose length is small in $G^A$ metric. Fix the initial curve $C_0$ and let $\ell$ be its length. The result is:

\textbf{Maximum distance bound.} Consider $\epsilon < \min\{2\sqrt{A}, l^{3/2}\}/8$ and let $\eta = 4(l^{3/4}A^{-1/4} + l^{1/4})\sqrt{\epsilon}$. Then for any path $c$ starting at $C_0$ whose length is $\epsilon$, the
final curve lies in the tubular neighborhood of \( C_0 \) of width \( \eta \). More precisely, if we choose the path \( c(t, \theta) \) to be horizontal, then \( \max_{\theta_0} |c(0, \theta_0) - c(1, \theta_0)| < \eta \).

**Proof.** For all of this proof, we assume the path in \( B_t \) has been lifted to a horizontal path \( c \in \text{Imm}(S^1, \mathbb{R}^2) \) with \( |c_\theta(\theta, 0)| \equiv \ell/2\pi \), so that \( \langle c_t, c_\theta \rangle \equiv 0 \), and also \( \int_{S^1} (1 + A \kappa^2) |c_\theta|^2 \, d\theta \equiv \epsilon^2 \). The first step in the proof is to refine the Lipschitz bound on the length of a curve to a local estimate. Note that by horizontality

\[
\frac{d}{dt} \sqrt{|c_\theta|} = \frac{c_{\theta t} + c_{tt} \theta}{2c_{\theta \theta}^{3/2}} = -\frac{c_{\theta t}^2 + c_{tt}^2}{2|c_{\theta \theta}|^{3/2}} = -\frac{c_{\theta t}^2}{2|\kappa|^{3/2}} = -\frac{1}{2\kappa} |c_t||c_\theta|^{1/2}
\]

hence

\[
\int_{S^1} \left( \frac{d}{dt} \sqrt{|c_\theta|} \right)^2 \, ds \leq \frac{\epsilon^2}{4A^2}.
\]

Now we make the key definition:

\[
\widetilde{c}_\theta(t, \theta) = \min_{0 \leq t_1 \leq t} |c_\theta(t_1, \theta)|.
\]

Note that the \( t \)-derivative of \(|\widetilde{c}_\theta|\) is either 0 or equal to that of \(|c_\theta|\) and is \( \leq 0 \). Thus we have:

\[
\int_{S^1} \left( \frac{\ell}{2\pi} - \sqrt{|\widetilde{c}_\theta|}(\theta, 1) \right) d\theta \leq \int_0^1 \int_{S^1} \frac{d}{dt} \sqrt{|c_\theta|} \, d\theta \, dt
\]

\[
\leq \int_0^1 \int_{S^1} \left| \frac{d}{dt} \sqrt{|c_\theta|} \right| \, d\theta \, dt
\]

\[
\leq \int_0^1 \left( \int_{S^1} d\theta \right)^{1/2} \cdot \left( \int_{S^1} \left| \frac{d}{dt} \sqrt{|c_\theta|} \right|^2 \, d\theta \right)^{1/2} \, dt
\]

\[
\leq \frac{\sqrt{2\pi}}{2\sqrt{A}} \cdot \frac{\epsilon}{2\sqrt{A}}
\]

To make use of this inequality, let \( E = \{ \theta, |\widetilde{c}_\theta| \leq (1 - (A\ell)^{-1/4} \sqrt{\epsilon}/2\pi) \} \). Our assumption on \( \epsilon \) gives \( (A\ell)^{-1/4} \sqrt{\epsilon} < 1/2 \), hence on \( S^1 \setminus E \) we have \( |c_\theta| > \ell/4\pi \). On \( E \) we have also \( (|c_\theta|)^{1/2} \leq (1 - (A\ell)^{-1/4} \sqrt{\epsilon}/2\pi)\sqrt{\ell}/2\pi \). Combining this with the previous inequality, we get (where \( \mu(E) \) is the measure of \( E \)):

\[
\mu(E) \cdot \frac{1}{2\sqrt{2\pi}} \left( \frac{\ell}{A} \right)^{1/4} \sqrt{\epsilon} \leq 2\pi \cdot \frac{\epsilon}{2\sqrt{A}}, \quad \text{hence} \quad \mu(E) \leq 2\pi \frac{\sqrt{\epsilon}}{(A\ell)^{1/4}} < \pi.
\]

We now use the lower bound on \(|c_\theta|\) on \( S^1 - E \) to control \( c(\theta, 1) - c(\theta, 0) \):

\[
\int_{S^1 - E} |c(\theta, 1) - c(\theta, 0)| \, d\theta \leq \int_0^1 \int_{S^1 - E} |c_t| \, d\theta \, dt
\]

\[
\leq \sqrt{2\pi} \cdot \int_0^1 \left( \int_{S^1 - E} |c_t|^2 \, d\theta \right)^{1/2} \, dt
\]

\[
\leq \sqrt{2\pi} \int_0^1 \left( \int_{S^1 - E} |c_t|^2 \, d\theta \right)^{1/2} \, dt \leq \frac{2\sqrt{2\pi}}{\sqrt{\ell}} \cdot \epsilon
\]
Again, introduce a small exceptional set \( F = \{ \theta \mid \theta \in E \text{ and } |c(\theta, 1) - c(\theta, 0)| \geq \ell^{1/4}\sqrt{\varepsilon} \} \). By the inequality above, we get:
\[
\mu(F) \cdot \ell^{1/4}\sqrt{\varepsilon} \leq \frac{2\sqrt{\varepsilon} \pi \lambda}{\sqrt{\ell}}, \quad \text{hence } \mu(F) \leq \frac{2\sqrt{\varepsilon} \pi \sqrt{\varepsilon}}{\ell^{3/4}} < \pi.
\]

The last inequality follows from the second assumption on \( \varepsilon \). Knowing \( \mu(E) \) and \( \mu(F) \) gives us the lengths \( |c(E, 0)| \) and \( |c(F, 0)| \) in \( \mathbb{R}^2 \). But we need the lengths \( |c(E, 1)| \) and \( |c(F, 1)| \) too. We get these using the fact that the whole length of \( C_1 \) can’t be too large, by 3.3:

\[
\sqrt{|C_1|} \leq \sqrt{\ell} + \frac{\varepsilon}{2\sqrt{A}}, \quad \text{hence}

|C_1| \leq \ell + 2\varepsilon \sqrt{\frac{\ell}{A}} \leq \ell + \varepsilon \cdot \frac{\ell^{3/4}}{A^{1/4}}.
\]

On \( S^1 \setminus E \) we have \( \tilde{c}_{\theta} > (1 - (AL)^{-1/4}\sqrt{\varepsilon})\ell/2\pi \), thus we get
\[
|c(E \cup F, 1)| = |C_1| = |c(S^1 \setminus (E \cup F), 1)|
\]
\[
\leq \ell + \varepsilon \cdot \frac{\ell^{3/4}}{A^{1/4}} - \left( 1 - \frac{\varepsilon}{(AL)^{1/4}} \right) \frac{\ell}{2\pi} \left( 2\pi - \mu(E \cup F) \right)
\]
\[
\leq \varepsilon \cdot \left( 3 \frac{\ell^{3/4}}{A^{1/4}} + \varepsilon \right)
\]

Finally, we can get from \( c(\theta, 0) \) to \( c(\theta, 1) \) by going via \( c(\theta', 0) \) and \( c(\theta', 1) \) where \( \theta' \in S^1 \setminus (E \cup F) \neq \emptyset \). Thus
\[
\max_{\theta} |c(\theta, 0) - c(\theta, 1)| \leq |c(E \cup F, 0)| + \ell^{1/4}\sqrt{\varepsilon} + |c(E \cup F, 1)|
\]
\[
\leq 4\left( \varepsilon^{3/4} A^{-1/4} + \ell^{1/4} \right) \sqrt{\varepsilon} \quad \square
\]

Combining this bound with the Lipschitz continuity of the square root of arc length, we get:

3.6. **Corollary.** For any \( A > 0 \), the map from \( B_{\ell}(S^1, \mathbb{R}^2) \) in the \( \text{dist}_{G, A} \) metric to the space \( \text{dist}_{G, A}^* (S^1, \mathbb{R}^2) \) in the Fréchet metric is continuous, and, in fact, uniformly continuous on every subset where the length \( \ell \) is bounded. In particular, \( \text{dist}_{G, A} \) is a separating metric on \( B_{\ell}(S^1, \mathbb{R}^2) \). Moreover, the completion \( \overline{B}_{\ell}(S^1, \mathbb{R}^2) \) of \( B_{\ell}(S^1, \mathbb{R}^2) \) in this metric can be identified with a subset of \( B_{\ell}^{1/2}(S^1, \mathbb{R}^2) \).

If we iterate this bound, then we get the following:

3.7. **Corollary.** Consider all paths in \( B_{\ell} \) joining curves \( C_0 \) and \( C_1 \). Let \( L \) be the length of this path in the \( \text{dist}_{G, A} \) metric and let \( \ell_{\min}, \ell_{\max} \) be the minimum and maximum of the arc lengths of the curves in this path. Then there are parametrizations \( c_0, c_1 \) of \( C_0 \) and \( C_1 \) such that:

\[
\max_{\theta} |c_0(\theta) - c_1(\theta)| \leq 50 \max(L F^*, \sqrt{\ell_{\max} L F^*}), \quad \text{where}
\]
\[
F^* = \max \left( \frac{1}{\sqrt{\ell_{\min}}}, \sqrt{\frac{\ell_{\max}}{A}} \right).
\]
To prove this, you need only break up the path into a minimum number of pieces for which the maximum distance bound 3.5 holds and add together the estimates for each piece. We will only sketch this proof which is straightforward. The constant 50 is just what comes out without attempting to optimize the bound. The second option for bound, $50\sqrt{\kappa/\ell_{\text{max}}L^2F^*}$ is just a rephrasing of the bound already in the theorem for short paths. If the path is too long to satisfy the condition of the theorem, we break the path at intermediate curves $C_i$ of length $\ell_i$ such that each begins a subpath with length $\varepsilon_i = \min(\sqrt{\kappa/\ell_i}, \varepsilon_i^{5/2})/8$ and which don’t overlap for more than 2:1. Thus $\sum \varepsilon_i \leq 2L$. Then apply the theorem to each piece, letting $\eta_i$ be the bound on how far points move in this subpath or any parts thereof and verify:

$$\eta_i \leq 2\sqrt{2\ell_i} \leq 16\sqrt{2\varepsilon_i F^*},$$

from which we get what we need by summing over $i$.

3.8. A final Corollary shows that if we parametrize any path appropriately, we get explicit equicontinuous continuity bounds on the parametrization depending only on $L$, $\ell_{\text{max}}$ and $\ell_{\text{min}}$. This is a step towards establishing the existence of weak geodesics. The idea is this: instead of the horizontal parametrization $\langle \varepsilon_0, i\varepsilon_0 \rangle \equiv 0$, we parametrize each curve at constant speed $|\varepsilon_0| = \ell(t)/2\pi$ where $\ell(t)$ is the length of the $t^{th}$ curve and ask only that $\langle \varepsilon_0, i\varepsilon_0 \rangle(0,1) \equiv 0$ for some base point 0. Then we get:

Corollary. If a path $c(\theta,t), 0 \leq t \leq 1$ satisfies

$$|c_\theta(\theta,t)| = \ell(t)/2\pi \quad \text{for all } \theta, t$$

$$\langle c_\theta, i\varepsilon_\theta \rangle(0,t) \equiv 0 \quad \text{for all } t \text{ and}$$

$$\int_{c_\theta} (1 + A\kappa G_\theta)^2 |(c_\theta, i\varepsilon_\theta)|^2 d\theta/|c_\theta| \equiv L^2 \text{ for all } t,$$

then

$$|c(\theta_1,t_1) - c(\theta_2,t_2)| \leq \frac{\ell_{\text{max}}}{2\pi} |\theta_1 - \theta_2| + 7(\ell_{\text{max}}^{3/4}/A^{1/4} + \ell_{\text{max}}^{1/4})\sqrt{L(t_1 - t_2)}$$

whenever $|t_1 - t_2| \leq \min(2\sqrt{\ell_{\text{min}}}, \varepsilon_i^{5/2})/(8L)$.

Proof. We need to compare the constant speed parametrization here with the horizontal parametrization - call it $c^*$ - used in the Theorem. Under the horizontal parametrization, let the point $(\theta_1, t_1)$ on $C_{\theta_1}$ correspond to $(\theta^*_1, t_2)$ on $C_{\theta_1^*}$, i.e. $c(\theta_1^*, t_2) = c^*(\theta_1, t_2)$. Let $C = (\ell_{\text{max}}^{3/4}/A^{1/4} + \ell_{\text{max}}^{1/4})$. Then we know from the Theorem that

$$|c(\theta_1, t_1) - c(\theta_1^*, t_2)| \leq 4C \sqrt{L(t_1 - t_2)}.$$
To compare \( \theta_1 \) and \( \theta_1' \), we use the properties of the set \( E \) in the Theorem to estimate:

\[
\frac{(\theta_1' - \theta_1) \ell_2}{2\pi} = \int_0^{\theta_1} |c^*_1(\varphi, t_2)| d\varphi - \frac{\theta_1 \ell_2}{2\pi} \\
\geq \left( 1 - \frac{\sqrt{L(t_1 - t_2)}}{(At_1)^{1/4}} \right) (\theta_1 - \mu(E)) \frac{\ell_1}{2\pi} - \frac{\theta_1 \ell_2}{2\pi} \\
\geq -2\ell_1 \frac{\sqrt{L(t_1 - t_2)}}{(At_1)^{1/4}} - |\ell_1 - \ell_2| \quad \text{and similarly} \\
\frac{(2\pi - \theta_1') - (2\pi - \theta_1) \ell_2}{2\pi} = \int_{\theta_1}^{2\pi} |c^*_1(\varphi, t_2)| d\varphi - \frac{(2\pi - \theta_1) \ell_2}{2\pi} \\
\geq -2\ell_1 \frac{\sqrt{L(t_1 - t_2)}}{(At_1)^{1/4}} - |\ell_1 - \ell_2| \]

Combining these and using the Lipschitz property of length, we get:

\[
\frac{\theta_1' - \theta_1 \ell_2}{2\pi} \leq 2C \sqrt{L(t_1 - t_2)} + 2|\ell_1 - \sqrt{\ell_2}| \sqrt{\ell_{\max}} \\
\leq 2C \sqrt{L(t_1 - t_2)} + \sqrt{\ell_{\max} \frac{L(t_1 - t_2)}{\sqrt{A}}} \leq \frac{5}{2} C \sqrt{L(t_1 - t_2)}
\]

Thus, finally:

\[
|c(\theta_1, t_1) - c(\theta_2, t_2)| \leq |c(\theta_1, t_1) - c(\theta_1, t_2)| + \\
+ |c(\theta_1, t_2) - c(\theta_1, t_2)| + |c(\theta_1, t_2) - c(\theta_2, t_2)| \\
\leq 4C \sqrt{L(t_1 - t_2)} + \frac{5}{2} C \sqrt{L(t_1 - t_2)} + \frac{\ell_{\max}}{2\pi} |\ell_1 - \ell_2|. \quad \Box
\]

3.9. One might also ask whether the maximum distance bound 3.5 can be strengthened to assert that the 1-jets of such curves \( C \) must be close to the 1-jets of \( C_0 \). The answer is NO, as is easily seen from looking a small wavelet-type perturbations of \( C_0 \). Specifically, calculate the length of the path: \( c(t, \theta) = c_0(\theta) + t \cdot a f(\theta / a) \cdot i(c_0)(\theta), 0 \leq t \leq 1 \) where \( f(x) \) is an arbitrary \( C^3 \) function with compact support and \( a \) is very small. We claim the length of this path is \( O(\sqrt{a}) \), while the 1-jet at the point \( \theta = 0 \) of the final curve of the path approaches \( (1 + i f'(0))(c_0)(0) \).

We sketch the proof, which is straightforward. Let \( C_{a, b} \) be the curves on this path. Then \( \sup |c_0| = O(a), \sup |c_0(\theta)| = O(1/a), A \leq c_0| \leq B \) for suitable \( A, B > 0 \) and \( \ell(\text{support}(c_0)) = O(a) \). Then the integral \( \int_{c_0}(1 + A r^2)(c_1, i c_0)^2 \frac{d\theta}{|c_0|} \) breaks up into 2 pieces, the first being \( O(a^2) \), the second being \( O(1) \) and the integral vanishing outside an interval of length \( O(a) \). Thus the total distance is \( O(\sqrt{a}) \).

3.10. The \( H^2 \)-distance on \( B_1(S^1, \mathbb{R}^2) \) vanishes. Let \( c_0, c_1 \in \text{Imm}_1(S^1, \mathbb{R}^2) \) be two immersions, and suppose that \( t \mapsto (\theta \mapsto c(t, \theta)) \) is a smooth curve in \( \text{Imm}(S^1, \mathbb{R}^2) \) with \( c(0, \cdot) = c_0 \) and \( c(1, \cdot) = c_1 \).

The arc-length for the \( H^2 \)-metric of the curve \( t \mapsto \pi(c(t, \cdot)) \) in \( B_1(S^1, \mathbb{R}^2) \) is given by 3.2.4 as

\[
L_{\text{arc}}^2(c) = \int_0^1 \left( \int_{S^1} \langle c_2, \text{ic}_3 \rangle^2 |c_4| \right)^{1/2} dt
\]
Theorem. For \( c_0, c_1 \in \text{Imm}(S^1, \mathbb{R}^2) \) there exists always a path \( t \mapsto c(t, \cdot) \) with \( c(0, \cdot) = c_0 \) and \( \pi(c(1, \cdot)) = \pi(c_1) \) such that \( L^\text{hor}_{\tau} (c) \) is arbitrarily small.

Heuristically, the reason for this is that if the curve is made to zig-zag wildly, say with teeth at an angle \( \alpha \), then the length of the curve goes up by a factor \( \frac{1}{\cos(\beta)} \) but the normal component of the motion of the curve goes down by the factor \( \cos(\beta) \) and this normal component is squared, hence it dominates.

Proof. Take a path \( c(t, \theta) \) in \( \text{Imm}(S^1, \mathbb{R}^2) \) from \( c_0 \) to \( c_1 \) and make it horizontal using 2.5 so that that \( \langle c_t, c_\theta \rangle = 0 \); this forces a reparameterization on \( c_1 \).

Now let us view \( c \) as a smooth mapping \( c : [0, 1] \times [0, 1] \rightarrow \mathbb{R}^2 \). We shall use the piecewise linear reparameterization \( (\varphi(t, \theta), \theta) \) of the square shown above, which for \( 0 \leq t \leq 1/2 \) deforms the straight line into a zig-zag of height 1 and period \( n/2 \) connecting the two end-curves, and then removes the teeth for \( 1/2 \leq t \leq 1 \). In detail: Let \( \tilde{c}(t, \theta) = c(\varphi(t, \theta), \theta) \) where

\[
\varphi(t, \theta) = \begin{cases} 
2t(2n\theta - 2k) & \text{for } 0 \leq t \leq 1/2, \frac{2k}{2n} \leq \theta \leq \frac{2k+1}{2n} \\
2t(2k + 2 - 2n\theta) & \text{for } 0 \leq t \leq 1/2, \frac{2k+1}{2n} \leq \theta \leq \frac{2k+2}{2n} \\
2t - 1 + 2(1 - t)(2n\theta - 2k) & \text{for } 1/2 \leq t \leq 1, \frac{2k}{2n} \leq \theta \leq \frac{2k+1}{2n} \\
2t - 1 + 2(1 - t)(2k + 2 - 2n\theta) & \text{for } 1/2 \leq t \leq 1, \frac{2k+1}{2n} \leq \theta \leq \frac{2k+2}{2n}.
\end{cases}
\]

Then we get \( \tilde{c}_\theta = \varphi_{\theta_t} c_t + c_\theta \) and \( \tilde{c}_t = \varphi_t c_t \) where

\[
\varphi_\theta = \begin{pmatrix} +4nt \\ -4nt \\ +4n(1-t) \\ -4n(1-t) \end{pmatrix}, \quad \varphi_t = \begin{pmatrix} 4n\theta - 4k \\ 4k + 4 - 4n\theta \\ 2 - 4n\theta + 4k \\ -(2 - 4n\theta + 4k) \end{pmatrix},
\]
Also, \( \langle c_t, c_\phi \rangle = 0 \) implies \( \langle \hat{c}_t, i\hat{c}_\delta \rangle = \varphi_t \langle c_t, |c_\phi| \rangle \) and \( |\hat{c}_\delta| = |c_\delta| \sqrt{1 + \varphi_\delta^2 (c_t/|c_\phi|)^2} \). Thus

\[
L_{\text{cor}}^\phi (\hat{c}) = \int_0^1 \left( \int_0^1 \langle \hat{c}_t, i\hat{c}_\delta \rangle^2 \frac{d\delta}{|\hat{c}_\delta|} \right)^{\frac{1}{2}} dt = \int_0^1 \left( \int_0^1 \frac{\varphi_t^2 |c_t|^2 |c_\phi|}{\sqrt{1 + \varphi_\delta^2 (c_t/|c_\phi|)^2}} \frac{d\delta}{|\hat{c}_\delta|} \right)^{\frac{1}{2}} dt =
\]

\[
= \int_0^1 \left( \sum_{k=0}^{n-1} \left( \int_0^{\frac{2\pi}{2n}} \frac{(4n\theta - 4k)^2 |c_t (\varphi, \theta)|^2 |c_\phi (\varphi, \theta)|}{\sqrt{1 + (4n)^2 (1 - t)^2 (\varphi_\delta (\varphi, \theta))^2}} \frac{d\theta}{\varphi_\delta (\varphi, \theta)} \right)^{\frac{1}{2}} dt + \right. \]
\]

\[
+ \int_0^1 \left( \sum_{k=0}^{n-1} \left( \int_0^{\frac{2\pi}{2n}} \frac{2 - 4n\theta + 4k)^2 |c_t (\varphi, \theta)|^2 |c_\phi (\varphi, \theta)|}{\sqrt{1 + (4n)^2 (1 - t)^2 (\varphi_\delta (\varphi, \theta))^2}} \frac{d\theta}{\varphi_\delta (\varphi, \theta)} \right)^{\frac{1}{2}} dt + \right. \]
\]

The function \( |c_\phi (\varphi, \theta)| \) is uniformly bounded above and away from 0, and \( |c_t (\varphi, \theta)| \) is uniformly bounded. Thus we may estimate

\[
\sum_{k=0}^{n-1} \left( \int_0^{\frac{2\pi}{2n}} \frac{(4n\theta - 4k)^2 |c_t (\varphi, \theta)|^2 |c_\phi (\varphi, \theta)|}{\sqrt{1 + (4n)^2 (1 - t)^2 (\varphi_\delta (\varphi, \theta))^2}} \frac{d\theta}{\varphi_\delta (\varphi, \theta)} \right)^{\frac{1}{2}} dt \leq O(1) \sum_{k=0}^{n-1} \int_0^{\frac{1}{2n}} \frac{4n^2 \theta^2 |c_t (\varphi (t, \frac{2k}{2n} + \theta), \frac{2k}{2n} + \theta)|^2}{\sqrt{1 + (4n)^2 (\varphi (t, \frac{2k}{2n} + \theta), \frac{2k}{2n} + \theta))^2}} \frac{d\theta}{\varphi (t, \frac{2k}{2n} + \theta), \frac{2k}{2n} + \theta}) \right)^{\frac{1}{2}}
\]

We estimate this sum of integrals as follows: Fix \( \varepsilon > 0 \). Consider first the set of all \( \theta \) such that \( |c_t (\varphi (t, \frac{2k}{2n} + \theta), \frac{2k}{2n} + \theta)| < \varepsilon \) which is a countable disjoint union of open intervals. There we get the estimate \( O(1, n, 4n^2 \varepsilon^2 (\theta^2/3)^{d=1/2n}) = O(\varepsilon) \), uniformly in \( n \). On the set where \( c_t (\varphi (t, \frac{2k}{2n} + \theta), \frac{2k}{2n} + \theta)| \geq \varepsilon \) we estimate by \( O(1, n, 4n^2 \varepsilon^2 \theta^2 (\theta^2/3)^{d=1/2n}) = O(1, n, \varepsilon) \). The other sums of integrals can be estimated similarly, thus \( L_{\text{cor}}^\phi (\hat{c}) \) goes to 0 for \( n \to \infty \). It is clear that one can approximate \( \varphi \) by a smooth function without changing the estimates essentially.

3.11. Non-smooth curves in the completion of \( B_t \). We have seen in 3.6 that the completion of \( B_t \) in the metric \( G^\delta \) lies in the space of Lipschitz maps \( c : S^1 \to \mathbb{R}^2 \) mod monotone correspondences, that is, rectifiable Fréchet immersed curves. But how big is it really? We cannot answer this, but we show, in this section, that certain non-smooth curves are in the completion. To be precise, if \( c \) is rectifiable, then we can assume \( c \) is parametrized at constant speed \( \varphi_\delta \equiv L/2\pi \) where \( L \) is the length of the curve. Therefore \( c_\phi = (L/2\pi) e^{i\alpha (\theta)} \) for some measurable function \( \alpha (\theta) \) giving the orientation of the tangent line at almost every point. We will say that a rectifiable curve \( c \) is \( L-BV \) if the function \( \alpha \) is of bounded variation. Note that this means that the derivative of \( \alpha \) exists as a finite signed measure, hence the curvature of \( c \) -- which is \((2\pi/L)\alpha'\) is also a finite signed measure. In
particular, there are a countable set of ‘vertices’ on such a curve, points where \( \alpha \) has a discontinuity and the measure giving its curvature has an atomic component. Note that \( \alpha \) has left and right limits everywhere and vertices can be assigned angles, namely \( \alpha_+ (\theta) = \alpha_- (\theta) \).

**Theorem.** All 1-BV rectifiable curves are in the completion of \( B_t \) with respect to the metric \( G^A \).

**Proof.** This is proven using the following lemma:

**Lemma.** Let \( c(t, \theta), 0 < t \leq 1 \) be an open path of smooth curves \( c(t) \) and let \( \alpha(t, \theta) = \arg(c_t(\theta, t)) \). Assume that

1. The length of all curves \( c(t) \) is bounded by \( C_1 \),
2. \( |\alpha| \leq C_2 \), for all \( (t, \theta) \),
3. For all \( t \), the total variation in \( \theta \) of \( \alpha(\theta, t) \) is bounded by \( C_3 \) and
4. The curvature of \( c(t) \) satisfies \( |\kappa_{c(t)}(\theta, t)| \leq \frac{C_4}{t} \) for all \( \theta \).

Then the length of this path is bounded by \( C_2 (\sqrt{C_1} + 2\sqrt{AC_3 C_4}) \).

To prove the lemma, let \( s_t \) be arc length on \( c(t) \) and estimate the integral:

\[
\int_{s(t)} (1 + \kappa_{c(t)}(\theta, t)) (\dot{\theta}^2 + \dot{\psi}^2) d\theta \leq \int_{s(t)} \frac{i\dot{\psi}}{|\dot{\psi}|} \frac{|\alpha|}{|\dot{\psi}|} d\psi \leq C_2 (C_1 + A \int_{s(t)} \kappa_{c(t)} d\theta)
\]

\[
= C_2 (C_1 + A \int_{s(t)} \kappa_{c(t)} ds_t)
\]

\[
\leq C_2 (C_1 + A \frac{C_4}{t} C_3).
\]

Taking the square root of both sides and integrating from 0 to 1, we get the result.

We apply this lemma to the simplest possible smoothing of a 1-BV rectifiable curve \( c_0 \):

\[
c(t, \theta) = \frac{1}{\sqrt{2\pi t}} \int_{\mathbb{R}} c_0(t, \psi) e^{-\psi^2/2t^2} d\psi = \frac{1}{\sqrt{2\pi t}} \int_{\mathbb{R}} c_0(\psi) e^{-t(\theta - \psi)^2/2t^2} d\psi, 0 < t \leq 1.
\]

Note that \( t \) is the standard deviation of the Gaussian, not the variance. We assume \( c_0 \) has a constant speed parametrization and \( c'_0 = (L/2\pi)e^{i\alpha} \) as above, where \( \alpha' \) is a finite signed measure. Thus:

\[
c_{\theta} = \frac{L}{(2\pi)^{3/2} t} \int_{\mathbb{R}} e^{i\alpha (\theta - \psi)^2/2t^2} d\phi
\]

\[
c_{\theta \theta} = \frac{iL}{(2\pi)^{3/2} t} \int_{\mathbb{R}} e^{i\alpha (\theta - \psi)^2/2t^2} \alpha' (d\phi)
\]
Moreover, using the second expression for the convolution and the heat equation for the Gaussian, we see that $c_t = t c_{\theta}$. We now estimate:

\[
|c_t| \leq L/2\pi, \quad \text{hence length}(C_t) \leq L
\]

\[
|c_{\theta}| \leq \frac{L}{(2\pi)^3/2 |t|} \int_{S^1} \sum_{n} e^{-(x-nL)^2/2t^2} |\alpha'(d\varphi)|
\]

\[
\leq \sup_{x} \left( \sum_{n} e^{-(x-nL)^2/2t^2} \right) \frac{L \cdot \operatorname{Var}(\arg(c_{\theta}))}{(2\pi)^3/2 |t|} = O(1/t),
\]

\[
\int_{S^1} |c_{\theta}|\,d\theta \leq \frac{L}{2\pi} \left( \int_{\mathbb{R}} \frac{1}{\sqrt{2\pi t}} e^{-\theta^2/2t^2} \,d\theta \right) \left( \int_{S^1} \alpha'(d\varphi) \right) = \frac{L}{2\pi} \operatorname{Var}(\arg(c_{\theta}))
\]

\[
|c_t| = t |c_{\theta}| = O(1).
\]

To finish the proof, all we need to do is get a lower bound on $|c_{\theta}|$. However, $|c_{\theta}|$ can be very small if the curve $c_0$ has corners with small angles. In fact, $c_0$ can even double back on itself, giving a 'corner' with angle $\pi$. We need to treat this as a special case. When all the vertex angles of $c_0$ are less than $\pi$, we can get a lower bound for $|c_{\theta}|$ as follows. We start with the estimate:

\[
|c_{\theta}(\theta)| = \frac{1}{\sqrt{2\pi t}} \int_{\mathbb{R}} e^{i\alpha(\theta - \varphi) - \varphi^2/2t^2} e^{i\alpha(\theta)} \,d\varphi
\]

\[
\geq \frac{1}{\sqrt{2\pi t}} \int_{\mathbb{R}} \cos(\alpha(\theta - \varphi) - \alpha(\theta)) e^{-\varphi^2/2t^2} \,d\varphi
\]

We break up the integral over $\mathbb{R}$ into 3 intervals $(-\infty, -\delta/2], [-\delta/2, \delta/2], [\delta/2, +\infty)$ for a suitable $\delta$. If $t$ is sufficiently small, the integral of the Gaussian over the first and third intervals goes uniformly to 0 and, on the middle interval, goes to 1. Thus it suffices to estimate the cos in the middle interval. We use a remark on BV functions:

**Lemma.** For any BV function $f(x)$ and any $C > 0$, there is a $\delta > 0$ such that on every interval $I$ of length less than $\delta$, either $f|_I$ has a simple jump of size $\geq C$ or $\max(f|_I) - \min(f|_I) \leq C$.

**Proof.** In fact, let $C - \varepsilon$ be the size of the largest jump in $f$ less than $C$ and break up the domain of $f$ into intervals $J_i$ on each of which the variation of $f$ is less than $\varepsilon/2$, big jumps being on their boundaries. If $\delta$ is less than the minimum of the lengths of the $J_i$, we get what we want.

Now let $\pi - \beta$ be the largest vertex angle of the curve $c_0$. Using the lemma, choose a $\delta$ so that on every interval $I$ in the $\beta$-line of length less than $\delta$, either $I$ contains a single vertex with exterior angle $\geq \beta/3$ or $\max(f|_I) - \min(f|_I) \leq \beta/3$. Now if there is no vertex in $[\theta - \delta/2, \theta + \delta/2]$, then $|\alpha(\theta - \varphi) - \alpha(\theta)| \leq \beta/3$ on this interval and our lower bound is:

\[
|c_{\theta}(\theta)| \geq \cos(\beta/3) - o(t).
\]

On the other hand, if there is such a vertex, say at $\tilde{\theta}$, then $\alpha$ varies by at most $\beta/3$ in $[\theta - \delta/2, \tilde{\theta}]$, jumps by at most $\pi - \beta$ at $\tilde{\theta}$ and then varies by at most $\beta/3$ on
\((\tilde{\theta}, \theta + \delta/2]\). Assume \(\theta < \tilde{\theta}\) (the case \(\theta > \tilde{\theta}\) is similar). Then:

\[
\cos(\alpha |\theta - \varphi| - \alpha(\theta)) \geq \begin{cases} 
\cos(\beta/3), & \text{if } \varphi \in (\theta - \tilde{\theta}, \theta + \delta/2] \\
\cos(\pi - \beta + \beta/3) = -\cos(2\beta/3), & \text{if } \varphi \in [\theta - \delta/2, \theta - \tilde{\theta})
\end{cases}
\]

Thus:

\[
|c_\theta(t)| \geq \frac{1}{2}(\cos(\beta/3) - \cos(2\beta/3)) - o(t).
\]

hence, if \(t\) is sufficiently small, we get a uniform lower bound on \(|c_\theta|\). Since \(|\kappa_{C_i}| \leq |c_\theta| / |c_\theta|^2\), we get the required upper bound both on \(|\kappa_{C_i}|\) and on the variation of \(\alpha_{C_i}\), i.e. \(\int_{S^1} |\kappa_{C_i}|\) and all the requirements of the lemma are satisfied.

\[\text{Figure 3. Approximating } 1 - BV \text{ curves with zero angle vertices by curves with positive angle vertices.}\]

If \(c_0\) has a vertex with angle \(\pi\), we need to add an extra argument. \(c_0\) certainly has at most a finite number of such vertices and we can construct a new curve by drawing a circle of radius \(t\) around each of these vertices and letting \(c_0^{(t)}\) be the curve which follows \(c_0\) until it hits one of these circles and then replaces the vertex with a circle around the circle; see Figure 3. Each of the curves \(c_0^{(t)}\) is in the completion of \(B_i\) by the previous argument and the path formed by the \(c_0^{(t)}\)'s also has finite length, hence \(c_0\) is in the completion. We omit the details which are straightforward.

### 3.12. The energy of a path as ‘anisotropic area’ of its graph in \(\mathbb{R}^2\).

Consider a path \(t \mapsto c(\cdot, t)\) in the manifold \(\text{Emb}(S^1, \mathbb{R}^2)\). It projects to a path \(\pi \circ c\) in \(\text{Emb}(S^1, \mathbb{R}^2)\) whose energy is

\[
E_{G, \pi}(\pi \circ c) = \frac{1}{2} \int_0^T G_{\pi(c)}(T_{c, \pi(c).T_{c, \pi(c)}}) \, dt
\]

\[
= \frac{1}{2} \int_0^T G_{\pi}(c(\cdot, t), c(\cdot, t)) \, dt = \frac{1}{2} \int_0^T \int_{S^1} (1 + A\kappa(c)^2) \langle c(\cdot, t) \rangle |c(\cdot, t)| \, dt \, dt
\]

\[
= \frac{1}{2} \int_0^T \int_{S^1} (1 + A\kappa(c)^2) \left( \frac{\langle c(\cdot, t) \rangle}{|c(\cdot, t)|} \cdot ic(\cdot, t) \cdot ic(\cdot, t) \right) c(\cdot, t) \, dt \, dt
\]

\[
= \frac{1}{2} \int_0^T \int_{S^1} (1 + A\kappa(c)^2) \langle c(\cdot, t) \rangle \left( \frac{\langle c(\cdot, t) \rangle}{|c(\cdot, t)|} \cdot ic(\cdot, t) \right)^2 \, dt \, dt
\]

\[
(1)
\]
If the curve $c$ is horizontal, i.e., it satisfies $\langle c_t, c_\theta \rangle = 0$. Then $\langle c_t, ic_\theta \rangle = |c_t| |c_\theta|$ and we have

$$E_{G}\xi (c) = \frac{1}{4} \int_a^b \int_{S^1} (1 + A K(c)^2) |c_t|^2 |c_\theta| d\theta dt, \quad \langle c_t, c_\theta \rangle = 0$$

which is just the usual energy of $c$.

Let $c(t, \theta) = (x(t, \theta), y(t, \theta))$ be still horizontal and consider the graph

$$\Phi (t, \theta) = (t, x(t, \theta), y(t, \theta)) \in \mathbb{R}^3.$$  

We also have $|x_t y_\theta - x_\theta y_t| = |\det (c_t, c_\theta)| = |c_t| |c_\theta|$ and for the vector product $\Phi_t \times \Phi_\theta = (x_t y_\theta - x_\theta y_t, -x_t y_\theta, x_\theta y_t)$, so we get

$$|\Phi_t \times \Phi_\theta|^2 = (x_t y_\theta - x_\theta y_t)^2 + y_\theta^2 + x_\theta^2 = (x_t^2 + y_\theta^2)(x_\theta^2 + y_t^2) + 1 = |c_t|^2(|c_t|^2 + 1).$$

We express now $E_{G}\xi (c)$ as an integral over the surface $S \subset \mathbb{R}^3$ parametrized by $\Phi$ in terms of the surface area $d\mu_S = |\Phi_t \times \Phi_\theta| d\theta dt$ as follows:

$$E_{G}\xi (c) = \frac{1}{4} \int_a^b \int_{S^1} (1 + A K(c)^2) \frac{|c_t|^2 |c_\theta|}{|\Phi_t \times \Phi_\theta|} |\Phi_t \times \Phi_\theta| d\theta dt$$

$$= \frac{1}{4} \int_{[a,b] \times S^1} (1 + A K(c)^2) \frac{|c_t|^2}{|c_t|^2 + 1} d\mu_S$$

Next we want to express the integrand as a function $\gamma$ of the unit normal $n_S = (\Phi_t \times \Phi_\theta)/|\Phi_t \times \Phi_\theta|$. Let $c_\theta = (1, 0, 0)$, then the absolute value of the $t$-component $n^o_S$ of the unit normal $n_S$ is

$$|n^o_S| := |\langle c_\theta, n_S \rangle| = \frac{|c_t|}{\sqrt{|c_t|^2 + 1}},$$

and

$$\frac{|c_t|^2}{\sqrt{|c_t|^2 + 1}} = \frac{|n^o_S|^2}{\sqrt{1 - |n^o_S|^2}}.$$

Thus for horizontal $c$ (i.e., with $c_t \perp c_\theta$) we have

**Horizontal energy as anisotropic area.**

$$E_{G}\xi^\mathbb{H} (c) = \frac{1}{4} \int_{[a,b] \times S^1} (1 + A K(c)^2) \frac{|n^o_S|^2}{\sqrt{1 - |n^o_S|^2}} d\mu_S$$

Here the final expression is only in terms of the surface $S$ and does not depend on the curve $c$ being horizontal. This anisotropic area functional has to be minimized in order to prove that geodesics exist between arbitrary curves (of the same degree) in $B_1(f)(S^1, \mathbb{R}^2)$. Thus we are led to the

**Question.** For free immersions $c_\theta, c_1 : S^1 \to \mathbb{R}^2$ does there exist an immersed surface $S \equiv (\text{ins}_p, [1], c) : [0, 1] \times S^1 \to \mathbb{R} \times \mathbb{R}^2$ such that the functional (3) is critical at $S$?

A first step is:

**Bounding the area.** For any path $[a, b] \ni t \mapsto c(t, \cdot)$ the area of the graph surface $S = S(c)$ is bounded as follows:

$$\text{Area}(S) = \int_{[a,b] \times S^1} d\mu_S \leq 2E_{G}\xi^\mathbb{H} (c) + \max_t \ell(c(t, \cdot))(b - a)$$
Proof. Writing the unit normal \( n_s = (n_s^1, n_s^2, n_s^3) \in S^2 \) according to the coordinates \((t, x, y)\) we have

\[
|n_s^1| + |n_s^2| + \frac{|n_s^3|^2}{\sqrt{1 - |n_s^1|^2}} \geq |n_s^1|^2 + |n_s^2|^2 + |n_s^3|^2 = 1
\]

Since \(|n_s^3|d\mu_s\) is the area element of the projection of \( S \) onto the \((t, y)\)-plane we have

\[
\text{Area}(S) = \int_{[0,\beta] \times S^1} d\mu_s \leq \int_{[0,\beta] \times S^1} (1 + A\kappa(c)^2) \left( |n_s^1| + |n_s^2| + \frac{|n_s^3|^2}{\sqrt{1 - |n_s^1|^2}} \right) d\mu_s
\]

\[
\leq 2E_{G^2}(c) + \max \{\ell(c(t, ), ())|t-b-a\}. \quad \square
\]

4. Geodesic equations and sectional curvatures

4.1. Geodesics on \( \text{Imm}(S^1, \mathbb{R}^2) \). The energy of a curve \( t \mapsto c(t, ) \) in the space \( \text{Imm}(S^1, \mathbb{R}^2) \) is

\[
E_{G^2}(c) = \frac{1}{2} \int_a^b \int_{S^1} (1 + A\kappa(c)^2) \langle c_t, c_t \rangle d\theta \, dt.
\]

By calculating its first variation, we get the equation for a geodesic:

Geodesic Equation.

\[
(1 + A\kappa^2) c_{\theta} \cdot c_t = \left( \frac{1 + A\kappa^2}{2} \cdot \frac{c_t}{|c_t|^2} \cdot c_t + A \frac{\kappa |c_t|^2}{|c_t|^2} \cdot i c_t \right) \cdot c_{\theta}.
\]

Proof. From 2.2 we have

\[
\kappa(c) = \frac{\langle ic_{\theta}, c_{\theta\theta} \rangle}{|c_t|^2} + \frac{\langle ic_{\theta}, c_{\theta\theta} \rangle}{|c_t|^2} - 3\kappa \frac{\langle c_{\theta\theta}, c_{\theta} \rangle}{|c_t|^2}
\]

and

\[
c_{\theta\theta} = \frac{\langle c_{\theta\theta}, c_{\theta} \rangle}{|c_t|^2} c_{\theta} + \frac{\langle c_{\theta\theta}, ic_{\theta} \rangle}{|c_t|^2} ic_{\theta} = \frac{|c_t|}{|c_t|^2} c_{\theta} + \kappa(c)|c_t|ic_{\theta}.
\]

Now we compute

\[
\partial_t |E(c) = \frac{1}{2} \partial_t |\int_a^b \int_{S^1} (1 + A\kappa^2) \langle c_t, c_t \rangle |c_{\theta}| \, d\theta \, dt
\]

\[
= \int_a^b \int_{S^1} (A\kappa^2 |c_{\theta}|^2 + (1 + A\kappa^2) \langle c_{tt}, c_t \rangle |c_{\theta}| + \frac{1 + A\kappa^2}{2} \frac{|c_t|^2 \langle c_{\theta\theta}, c_{\theta} \rangle}{|c_t|^2}) \, d\theta \, dt
\]

\[
= \int_a^b \int_{S^1} (A\kappa \langle ic_{\theta}, c_{\theta\theta} \rangle \frac{|c_t|^2}{|c_t|^2} + A\kappa \langle ic_{\theta}, c_{\theta\theta} \rangle \frac{|c_t|^2}{|c_t|^2} - 3A\kappa^2 \langle c_{\theta\theta}, c_{\theta} \rangle \frac{|c_t|^2}{|c_t|^2}
\]

\[
- \langle c_t, ((1 + A\kappa^2) |c_t| c_t + \frac{1 + A\kappa^2}{2} \frac{|c_t|^2}{|c_t|^2} c_{\theta} \rangle) \, d\theta \, dt
\]
\[
\int_0^\theta \int_{S^1} \left( \left\langle c_\theta, A \left( \kappa \frac{|c_\theta|^2}{|c_\theta|} i c_\theta \right) \right\rangle + \left\langle c_\theta, A \left( \kappa \frac{|c_\theta|^2}{|c_\theta|} i c_\theta \right) \right\rangle + \left\langle c_\theta, 3 A \left( \kappa^2 \frac{|c_\theta|^2}{|c_\theta|} i c_\theta \right) \right\rangle - \left\langle c_\theta, (1 + \kappa \kappa^2) |c_\theta| c_{\theta \theta} + \left( \frac{1 + \kappa \kappa^2}{2} \frac{|c_\theta|^2}{|c_\theta|} \right) \right\rangle \right) \, d\theta \, dt
\]

where

\[
F = A\kappa \frac{|c_\theta|^2}{|c_\theta|} i c_\theta + A(\kappa |c_\theta|^2) e^{i \kappa^2 |c_\theta|^2} - 2 A\kappa |c_\theta|^2 \left( \frac{c_\theta \theta^2 i c_\theta}{|c_\theta|^3} + A \kappa \frac{|c_\theta|^2}{|c_\theta|} i c_\theta \right) + 3 A\kappa^2 \frac{|c_\theta|^2}{|c_\theta|} c_\theta - \frac{1 + \kappa \kappa^2}{2} \frac{|c_\theta|^2}{|c_\theta|} c_\theta
\]

Substituting the expression for \( c_\theta \) and simplifying, this reduces to

\[
F = \frac{-1 + \kappa \kappa^2}{2} \frac{|c_\theta|^2}{|c_\theta|} c_\theta + A(\kappa |c_\theta|^2) e^{i \kappa^2 |c_\theta|^2}
\]

which gives the required formula for geodesics.

Putting \( A = 0 \) in 4.1.1 we get the geodesic equation for the \( H^k \)-metric on \( \text{Imm}(S^1, \mathbb{R}^2) \)

\[
(\kappa |c_\theta|^2)_{\theta \theta} - \frac{1}{2} \left( \frac{|c_\theta|^2 c_\theta}{|c_\theta|} \right)_{\theta} = 0
\]

### 4.2 Geodesics on \( B_t(S^1, \mathbb{R}^2) \)

We may also restrict to geodesics which are perpendicular to the orbits of \( \text{Diff}(S^1) \), i.e. \( \langle c_t, c_\theta \rangle = 0 \), obtaining the geodesics in the quotient space \( B_t(S^1, \mathbb{R}^2) \). To write this in the simplest way, we introduce the ‘velocity’ \( a \) by setting \( c_\theta = i a c_\theta / |c_\theta| \) (so that \( |c_\theta|^2 = a^2 \)). When we substitute this into the above geodesic equation, the equation splits into a multiple of \( c_\theta \) and a multiple of \( ic_\theta \). The former vanishes identically and the latter gives:

\[
\left( (1 + \kappa \kappa^2) c_\theta \right)_{\theta} = \frac{-1 + \kappa \kappa^2}{2} a^2 \left( \frac{c_\theta \theta^2}{|c_\theta|} + A \left( \frac{\kappa a^2}{|c_\theta|} \right) \right) e^{i \kappa^2 |c_\theta|^2}
\]

or

\[
\left( (1 + \kappa \kappa^2) c_\theta \right)_{\theta} = \frac{-1 + \kappa \kappa^2}{2} \kappa |c_\theta| a^2 + A \left( \frac{\kappa a^2}{|c_\theta|} \right) e^{i \kappa^2 |c_\theta|^2}
\]

If we use derivatives with respect to arclength instead of \( \theta \) and write these with the subscript \( s \), so that \( f_s = f_{\theta / |c_\theta|} \) this simplifies. We need:

\[
|c_\theta| = \frac{\langle c_\theta, c_{\theta \theta} \rangle}{|c_\theta|} = - \frac{\langle c_{\theta \theta}, c_\theta \rangle}{|c_\theta|^2} = -a \frac{\langle c_{\theta \theta}, i c_\theta \rangle}{|c_\theta|^2} = -a \kappa \kappa^2 |c_\theta|
\]

which gives us a simple form for the equation for geodesics on \( B_t(S^1, \mathbb{R}^2) \):

\[
\left( (1 + \kappa \kappa^2) a \right)_s = \left( 1 + 3 \kappa \kappa^2 \right) \kappa a^2 + A(\kappa \kappa^2) a_s.
\]

Finally, we may expand the \( t \)-derivatives on the left hand side, using the formula \( \kappa_t = a \kappa + a_s \), noted in 2.2.7; we also collect all constraint equations that we chose
along the way:

$$\begin{align*}
0 &= \langle e_z, e_z \rangle, \quad e_z = a i e_z, \quad \kappa = \langle e_z, i e_z \rangle \\
\dot{a}_1 &= \kappa a^2 + A (a^2 (\kappa e_z - \frac{1}{2} \kappa^2) + 4\kappa a a_z + 2\kappa a_z^2) \\
1 + A \kappa^2
\end{align*}$$

Handle this with care: Going to unit speed parametrization (so that \( f_z \) is really a holonomic partial derivative) destroys the first constraint 'horizontality'. This should be seen as a gauge fixing. If we set \( A = 0 \), the equation becomes simply

$$\dot{a}_1 = \kappa a^2.$$

### 4.3. The induced metric on \( B_{i,f}(S^1, \R^2) \) in a chart.

We also want to compute the curvature of \( B_{i,f}(S^1, \R^2) \) in this metric. For this, we need second derivatives and the most convenient way to calculate these seems to be to use a local chart. Consider the smooth principal bundle \( \pi : \text{Imm}_f(S^1, \R^2) \to B_{i,f}(S^1, \R^2) \) with structure group \( \text{Diff}(S^1) \) described in 2.4.3. We shall describe the metric in the following chart near \( C \in B_{i,f}(S^1, \R^2) \): Let \( e \in \text{Imm}_f(S^1, \R^2) \) be parametrized by arclength with \( \pi(e) = C \) of length \( L \), with unit normal \( n_e \). We assume that the parameter \( \theta \) runs in the scaled circle \( S^1 \) below. As in the proof of 2.4.3 we consider the mapping

$$
\begin{align*}
\psi : C^\infty(S^1, (-\varepsilon, \varepsilon)) &\to \text{Imm}_f(S^1, \R^2), \quad Q(e) := \psi(C^\infty(S^1, (-\varepsilon, \varepsilon))) \\
\psi(f)(\theta) &= c(\theta) + f(\theta) n_e(\theta) = c(\theta) + f(\theta) i e'(	heta), \\
\pi \circ \psi : C^\infty(S^1, (-\varepsilon, \varepsilon)) &\to B_{i,f}(S^1, \R^2),
\end{align*}
$$

where \( \varepsilon \) is so small that \( \psi(f) \) is an embedding for each \( f \). By 2.4.3 the mapping \( (\pi \circ \psi)^{-1} \) is a smooth chart on \( B_{i,f}(S^1, \R^2) \). Note that:

$$
\begin{align*}
\dot{\psi}(f)' &= e' + f' i e' + f i e'' = (1 - f \kappa) e' + f' i e' \\
\dot{\psi}(f)'' &= e'' + f'' i e' + 2 f' i e'' + f i e''' = -(2 f' \kappa + f \kappa') e' + (\kappa_e + f'' - f \kappa_e^2) i e'
\end{align*}
$$

$$
n_{\psi(f)} = \frac{1}{\sqrt{(1 - f \kappa_e)^2 + f'^2}} \left( (1 - f \kappa_e) i e' - f' e' \right),
$$

$$
T_{\psi(f),h} = h. i e' \quad \in C^\infty(S^1, \R^2) = T_{\psi(f)} \text{Imm}_f(S^1, \R^2)
$$

$$
= \frac{h(1 - f \kappa)}{\sqrt{(1 - f \kappa_e)^2 + f'^2}} n_{\psi(f)} + \frac{h f'}{(1 - f \kappa_e)^2 + f'^2} \dot{\psi}(f)' ,
$$

$$
(T_{\psi(f),h})^\perp = \frac{h(1 - f \kappa)}{\sqrt{(1 - f \kappa_e)^2 + f'^2}} n_{\psi(f)} \in N_{\psi(f)}
$$

$$
\kappa_{\psi(f)} = \frac{1}{\sqrt{(1 - f \kappa_e)^2 + f'^2}} \langle \dot{\psi}(f)', \dot{\psi}(f)'' \rangle
$$

$$
= \kappa_e + f'' - f \kappa_e^2 - f f'' \kappa_e + f^2 \kappa_e^2 + 2 f' \kappa_e + 2 f' \kappa_e' \frac{1}{(1 - f \kappa_e)^2 + f'^2}
$$

Let \( G^A \) denote also the induced metric on \( B_{i,f}(S^1, \R^2) \). Since \( \pi \) is a Riemannian submersion, \( T_{\psi(f)} \pi : (N_{\psi(f)}, G_{\psi(f)}^A) \to (B_{i,f}(S^1, \R^2), G_{\psi(f)}^A) \) is an isometry. Then we compute for \( f \in C^\infty(S^1, (-\varepsilon, \varepsilon)) \) and \( h, k \in C^\infty(S^1, \R) \):

$$
((\pi \circ \psi)^* G^A)_f(h, k) = G^A_{\psi(f)} \left( T_f(\pi \circ \psi) h, T_f(\pi \circ \psi) k \right)
$$
\[
G^A_{\psi(f)} \left( (T_f \psi, h)^\perp, (T_f \psi, k)^\perp \right) \\
= \int_{s_2^1} \left( 1 + A \kappa^2_{\psi(f)} \right) \left( (T_f \psi, h)^\perp, (T_f \psi, k)^\perp \right) |\psi(f)'| \, d\theta \\
= \int_{s_2^1} \left( 1 + A \kappa^2_{\psi(f)} \right) \frac{hk (1 - f \kappa_c)^2}{\sqrt{(1 - f \kappa_c)^2 + f^2}} \, d\theta
\]

This is the expression from which we have to compute the geodesic equation in the chart on \( B_{i,f}(S^2_k, \mathbb{R}^2) \).

4.4. Computing the Christoffel symbols in \( B_{i,f}(S^2_k, \mathbb{R}^2) \) at \( C = \pi(c) \). We have to compute second derivatives in \( f \) of the expression of the metric in 4.2. For that we expand the two main contributing expressions in \( f \) to order 2, where we put \( \kappa = \kappa_c \).

\[
\kappa_{\psi(f)} = (1 - 2f \kappa + f^2 \kappa^2 + f'^2)^{-3/2} (\kappa + f'' - 2f \kappa^2 - f f'' \kappa + f^2 \kappa^3 + 2f'^2 \kappa + f f' \kappa') \\
= \kappa + (f'' + f \kappa') + (f^2 \kappa^3 + \frac{1}{2} f'^2 \kappa + f f' \kappa' + 2 f f'' \kappa) + O(f^3) \\
(1 - f \kappa_c)^3 (1 - 2f \kappa + f^2 \kappa^2 + f'^2)^{-1/2} = 1 - f \kappa - \frac{1}{2} f'^2 + O(f^3)
\]

Thus

\[
(1 + A \kappa^2_{\psi(f)}) \frac{(1 - f \kappa_c)^2}{\sqrt{(1 - f \kappa_c)^2 + f^2}} = 1 + A \kappa^2 + 2Af'' \kappa + Af \kappa^3 - f \kappa - \frac{1}{2} f'^2 + A f^2 \kappa^4 + A f f' \kappa' + 2Af f' \kappa' + A f'^2 + 4Af f'' \kappa^2
\]

and finally

\[
(1) \quad G^A_f(h, k) = \left( (\pi \circ \psi)^* G^A \right)_f(h, k) = \\
= \int_{s_2^1} hk \left( (1 + A \kappa^2) + (2Af'' \kappa + Af \kappa^3 - f \kappa) + \frac{1}{2} f'^2 \\
+ A(f f'' \kappa^2 + f^2 \kappa^2 + \frac{1}{2} f'^2 \kappa^2 + 2f f' \kappa' + f'' \kappa') + O(f^3) \right) \, d\theta.
\]

We differentiate the metric

\[
dG^A_f(l)(h, k) = \int_{s_2^1} hk \left( 2f'' \kappa + (A \kappa^3 - \kappa) l + 4Af f'' \kappa^2 + 4Af f'' \kappa^2 + \\
+ 2Af \kappa^4 + (A \kappa^2 - 1) f'' l + 2Af f' \kappa' + 2Af f' \kappa' + 2Af'' \kappa' + O(f^2) \right) \, d\theta
\]

and compute the Christoffel symbol

\[
-2G^A_f(T_f(h, k), l) = -dG^A_f(l)(h, k) + dG^A_f(f)(h)(k, l) + dG^A_f(f)(k)(l, h)
\]

\[
= \int_{s_2^1} l \left( (A \kappa^3 - \kappa + 2 \kappa \kappa' f' + 4 \kappa^2 f'' + 2 \kappa^2 f) k \kappa h \\
+ (2 \kappa + 4 \kappa \kappa' f + 2A f'' (h'' k + h k'') \\
+ (A \kappa^2 f' - f' + 2 \kappa \kappa' f)(h' k + h k') + O(f^2) \right) \, d\theta
\]
\[-\int_{s^l_1} l^{(f}(Ak^2 f'hk - f'hk + 2Akk' fhk)
+ l^{(f}(2Akhk + 4Ak^2 fhk + 2Af''hk) + O(f^3)) \, d\theta
\]
\[
\int_{s^l_1} l \left( (Ak^3 - \kappa - 2Ak''h) + 4 Ak'(h'k + hh') - 4 Ak h'k' \\
+ (-2Af^{(4)}f' - 2Ak^2 f - 6Ak^2 f - 6Akk''f - 10Ak'f' + Ak^2 f'')hk \\
- (2f' + 4Af'' + 4Ak'f + 6Ak^2 f')(h'k + hh') \\
- 2(4Ak^2 f + 2Af''h'k' + O(f^3)) \right) \, d\theta.
\]
Thus
\[G^3_0 (\Gamma_f(h, k), l) = \]
\[
\int_{s^l_1} l \left( (Ak^3 - \kappa - 2Ak''h) + 4 Ak'(h'k + hh') + 2 Ak'h'k' \\
- (-2Af^{(4)}f' - 2Ak^2 f - 3Ak^2 f - 3Akk''f - 5Ak'f' + \frac{1}{2}Ak^2 f'')hk \\
+ (f' + 2Af'' + 6Akk'f + 3Ak^2 f')(h'k + hh') \\
+ (4Ak^2 f + 2Af''h'k' + O(f^3)) \right) \, d\theta.
\]
At the center of the chart, for \( f = 0 \), we get
\[G^3_0 (\Gamma_0(h, k), l) = \]
\[
\int_{s^l_1} l \left( \left( \frac{1}{2}Ak^3 - \kappa + Ak''h \right) + 2 Ak'(h'k + hh') + 2 Ak'h'k' \right) \, d\theta
\]
\[
\int_{s^l_1} l \left( \left( \frac{1}{2}Ak^3 - \kappa + Ak''h \right) + 2 Ak'(h'k + hh') + 2 Ak'h'k' \right) \, d\theta
\]
\[= G^3_0 \left( \left( \frac{1}{2}Ak^3 - \kappa + Ak''h \right) + 2 Ak'(h'k + hh') + 2 Ak'h'k' \right)
\]
so that
\[\Gamma_0(h, k) = \left( \frac{1}{2}Ak^3 - \kappa + Ak''h \right) + 2 Ak'(h'k + hh') + 2 Ak'h'k'.
\]
Letting \( h = k = f' \), this leads to the geodesic equation, valid at \( f = 0 \):
\[f' = \left( \frac{1}{2}Ak^3 - \kappa + Ak''h \right) f^2 + 4 Ak'(f'_f + 2Akk') f^2.
\]
If we substitute \( a \) for \( f \) and \( a_t \) for \( f' \), this is the same as the previous geodesic equation derived in 4.2 by variational methods. There is a subtle point here, however: why is it ok to identify the second derivatives \( a_t \) and \( f' \) with each other? To check this let \( c(\theta) + (a_1(\theta) + \frac{t^2}{2}a_2(\theta))i\theta(\theta) \) be a 2-jet in our chart. Then if we reparametrize the nearby curves by substituting \( \theta = \frac{1}{2}t^2a_1a_1' \) for \( \theta \), letting
\[c(\theta, t) = c(\theta - \frac{t^2}{2}a_1a_1') + (a_1(\theta - \frac{t^2}{2}a_1a_1') + \frac{t^2}{2}a_2(\theta - \frac{t^2}{2}a_1a_1'))i\theta(\theta - \frac{t^2}{2}a_1a_1')f'
\]
\[\equiv c(\theta) - (\frac{t^2}{2}a_1a_1')c'(\theta) + (a_1(\theta) + \frac{t^2}{2}a_2(\theta))i\theta(\theta) \mod t^3.
\]
then \( c'_t \equiv 0 \mod t^2 \), hence this 2-jet is horizontal and \( \langle c_{tt}, ic' \rangle \equiv a_2 \mod t \) as required.

4.5. **Computation of the sectional curvature in** \( B_{k,f}(\mathbb{S}^2_1, \mathbb{R}^2) \) **at** \( C \). We now go further. We use the following formula which is valid in a chart:

\[
(1) \quad 2R_f(m, h, m, h) = 2G^A_f(R_f(m, h)m, h) =
\]

\[
= -2d^3G^A_f(h)(m, h)m(m, h) + \dot{d}^3G^A_f(h)(m, h)m(m, h) + \ddot{d}G^A_f(h)(m, h)m(m, h)
\]

\[
- 2G^A_f(\Gamma(h, m), \Gamma(h, m)) + 2G^A_f(\Gamma(h, m), \Gamma(h, m))
\]

The sectional curvature at the two-dimensional subspace \( P_f(m, h) \) of the tangent space which is spanned by \( m \) and \( h \) is then given by:

\[
(2) \quad k_f(P(m, h)) = -\frac{G^A_f(\Gamma(h, m), \Gamma(h, m))}{||m||^2 ||h||^2 - G^A_f(\Gamma(h, m), \Gamma(h, m))^2}.
\]

We compute this directly for \( f = 0 \). From the expansion up to order 2 of \( G^A_f(h, k) \) in 4.4.1 we get:

\[
(3) \quad \frac{1}{2!}d^2G^A_f(0)(m, l)(h, k) = \int_{s^1_\perp} \frac{hk}{2} \left( \frac{1}{2}m't' + A \left( \begin{array}{l}
(2m'' + m'l')k^2 + mk^4 + \frac{1}{2}m' l' k^2 + (m'l' + m'')k' + m''l''
\end{array} \right) \right) d\theta
\]

Thus we have:

\[
- d^2G^A_f(0)(m, l)(h, m) = \frac{1}{2}d^2G^A_f(0)(m, l)(h, m) + \frac{1}{2}d^2G^A_f(0)(h, h)(m, m) =
\]

\[
= -2 \int_{s^1_\perp} hm \left( \frac{1}{2}m'h' + A \left( \begin{array}{l}
2(mh'' + mL'h)k^2 + mk^4 + \frac{1}{2}m'l'k^2 + (mh' + mL'h)k' + mL''
\end{array} \right) \right) d\theta
\]

\[
+ \int_{s^1_\perp} hh \left( \frac{1}{2}m'^2 + A \left( 4mm''k^2 + m^2k^4 + \frac{1}{2}m'^2k^2 + 2mm'k' + mL'' \right) \right) d\theta
\]

\[
+ \int_{s^1_\perp} mm \left( \frac{1}{2}h'k' + A \left( 4hh''k^2 + hhk^4 + \frac{1}{2}h'k'k^2 + 2hh'k' + k''h' \right) \right) d\theta
\]

\[
= \int_{s^1_\perp} \frac{1}{2}(Ak^2 - 1)(mh' - mL'h)^2 + A(mh'' - mL''h) \right) d\theta.
\]

For the second part of the curvature we have:

\[
- G_0(\Gamma(h, m), \Gamma(h, m)) + G_0(\Gamma(h, m), \Gamma(h, h)) =
\]

\[
= \int_{s^1_\perp} \left( \frac{1}{2}k - \frac{1}{2}Ak^3 + Ak' \right)hm + 2Ak'(h'm + mL'h) + 2Ak'm^2 
\]

\[
+ \int_{s^1_\perp} \left( \frac{1}{2}k - \frac{1}{2}Ak^3 + Ak'm^2 + 4Ak'm^2 + 2Ak'm^2 
\]

\[
= \int_{s^1_\perp} \left( AK^2 - A^2k^3 + 2A^2k'k' + 4A^2k'^2 \right)(mh' - mL'h)^2 d\theta.
\]
Thus we get
\[
R_0(m, h, m, h) = G^0_{\phi}(R_0(m, h)m, h) = \\
\int_{S^1_{\phi}} \left( \frac{1}{4} (Ak^2 - 1)(mh' - m'h)^2 + A(mh'' - m''h)^2 \right) d\theta \\
+ \int_{S^1_{\phi}} \left( (Ak^2 - A^2k^2 + 2A^2k^2) - 4A^2k^2 (mh' - m'h)^2 \right) \frac{d\theta}{1 + Ak^2}
\]

Letting \( W = mh' - hm' \) be the Wronskian of \( m \) and \( h \) and simplifying, we have:

\[
R_0(m, h, m, h) = \\
\int_{S^1_{\phi}} \left( -\frac{(Ak^2 - 1)^2 + 4A^2k^2 - 8A^2k^2}{2(1 + Ak^2)} \right) W^2 d\theta + \int_{S^1_{\phi}} AW'^2 d\theta
\]

What does this formula say? First of all, if \( \text{supp}(m) \cap \text{supp}(h) = \emptyset \), the sectional curvature in the plane spanned by \( m \) and \( h \) is 0. Secondly, we can divide the curve \( c \) into two parts:

\[
\begin{align*}
 c^+_A & = \text{set of points where } kk'' < 2(k')^2 + \left( \frac{A^2 - 1}{2} \right)^2 \\
 c^-_A & = \text{set of points where } kk'' > 2(k')^2 + \left( \frac{A^2 - 1}{2} \right)^2.
\end{align*}
\]

Note that if \( A \) is sufficiently small, \( c^-_A = \emptyset \) and even if \( A \) is large, \( c^-_A \) need not be non-empty. But if \( \text{supp}(m), \text{supp}(h) \subset c^+_A \), the sectional curvature is always negative. The interesting case is when \( \text{supp}(m), \text{supp}(h) \subset c^+_A \). We may introduce the self-adjoint differential operator on \( L^2(S^1) \):

\[
Sf = f'' + \frac{(Ak^2 - 1)^2 - 4A^2k^2}{2A(1 + Ak^2)} f
\]

so that \( R = -A(SW, W) \). The eigenvalues of \( S \) tend to \(-\infty \), hence \( S \) has a finite number of positive eigenvalues. If we take, for example, \( m = 1 \) and \( h \) such that \( h' \) is in the span of the positive eigenvalues, the corresponding sectional curvature will be positive. In general, the condition that the sectional curvature be positive is that the Wronskian \( W \) have a sufficiently large component in the positive eigenspace of \( S \). The special case where \( c \) is the unit circle may clarify the picture: then

\[
Sf = f'' + \frac{(A - 1)^2}{2A(1 + A)} f
\]

and the eigenfunctions are linear combinations of sines and cosines. It is easy to see that for any \( A \), a plane spanned by \( m \) and \( h \) of pure frequencies \( k \) and \( l \) will have positive curvature if and only if \( k \) and \( l \) are sufficiently near each other (asymptotically \( |k - l| < |A - 1|/\sqrt{A + a^2} \)), hence ‘beat’ at a low frequency.

4.6. The sectional curvature for the induced \( H^0 \)-metric on \( R_{i, f}(S^1_L, \mathbb{R}^3) \) in a chart. In the setting of 4.2 we have for \( f \in C^\infty(S^1_L, (-\varepsilon, \varepsilon)) \) and \( h, k \in C^\infty(S^1_L, \mathbb{R}) \)

\[
G^0_{\phi}(h, k) = \langle (\pi \circ \psi)^* G^0_{\phi} \rangle_f (h, k) = G^0_{\phi(\psi(f))} \left( T_f (\pi \circ \psi) h, T_f (\pi \circ \psi) k \right)
\]

\[
= G^0_{\phi(f)} \left( (T_f \psi, h)^\perp, (T_f \psi, k)^\perp \right)
\]
\[
= \int_{S^1} \frac{h^2(1 - f^2)}{\sqrt{(1 - f^2)^2 + f^2}} \, d\theta
\]

At the center of the chart described in 4.3, i.e., for \( f = 0 \), the Christoffel symbol 4.4.2 for \( A = 0 \) becomes

(2) \[ \Gamma_0(h, k) = \frac{1}{2} \kappa_c h k \]

The curvature 4.5.4 at \( f = 0 \) for \( A = 0 \) becomes

\[
R_0(m, h, m, h) = G_0(R_0(m, h) m, h) = \frac{1}{2} \int_{S^1} \left( k^2 m - h m' \right)^2 \, d\theta = \frac{1}{2} \int_{S^1} W(m, h)^2 \, d\theta
\]

and the sectional curvature \( k_0(P(m, h)) \) from 4.4.2 for \( A = 0 \) and \( f = 0 \) is non-negative.

In the full chart 4.2, starting from the metric 4.5.1, we managed to compute the full geodesic equation not just for \( f = 0 \) but for general \( f \), so long as \( A = 0 \). The outcome is

(4) \[
\Gamma_f(h, h) = \frac{\kappa_c h^2}{1 - f^2} + \frac{1}{2} \frac{\kappa_c (1 - f^2)}{(1 - f^2)^2 + f^2} \frac{f^2}{f_\theta^2} + \frac{3}{2} \frac{\kappa_c (1 - f^2) f^2 - \frac{3}{2} f^2 f' f''}{((1 - f^2)^2 + f^2)^2}.
\]

The geodesic equation is thus

(5) \[
f_{\theta\theta} = -\frac{\kappa_c f_{\theta}^2}{1 - f^2} + \frac{1}{2} \frac{\kappa_c (1 - f^2) f_{\theta}^2 + (\frac{3}{2} f_\theta^2 f_\theta + 2 f_\theta f_{\phi} f_{\phi})}{((1 - f^2)^2 + f_\theta^2)} + \frac{\kappa_c f_{\theta}^2 f_{\theta}^2}{((1 - f^2)^2 + f_\theta^2)} + \frac{3}{2} \frac{\kappa_c (1 - f^2) f_{\theta}^2 f_{\theta} - \frac{3}{2} f_\theta^2 f_{\theta} f_{\phi} f_{\phi}}{((1 - f^2)^2 + f_\theta^2)^2}.
\]

For \( A > 0 \) we were unable to get the analogous result.

5. Examples and numerical results

5.1. The geodesics running through concentric circles. The simplest possible geodesic in \( B_2 \) is given by the set of all circles with common center. Let \( C_r \) be the circle of radius \( r \) with center the origin. Consider the path of such circles \( C_r(t) \)
given by the parametrization \( c(t, \theta) = r(t) e^{i\theta} \), where \( r(t) \) is a smooth increasing function \( r : [0, 1] \to \mathbb{R}_{>0} \). Then \( \kappa_c(t, \theta) = 1/r(t) \). If we vary \( r \) then the horizontal energy and the variation of this curve are

\[
E^{\text{hor}}_{G^A}(c) = \frac{1}{2} \int_0^1 \int_{S^1} (1 + A/r^2) r^2 \, d\theta \, dt
\]

\[
\partial_s |_{s=0} E^{\text{hor}}_{G^A}(c) = \int_0^1 \int_{S^1} \left( 1 + \frac{A}{r^2} \right) r_s \left( -r_{tt} - \frac{(1 - A/r^2)}{2(r + A/r)} r_t^2 \right) \, d\theta \, dt
\]

so that \( c \) is a geodesic if and only if

(1) \[ r_{tt} + \frac{(1 - A/r^2)}{2(r + A/r)} r_t^2 = 0. \]
Also the geodesic equation 4.1.1 reduces to (1) for \( c \) of this form.

The solution of (1) can be written in terms of the inverse of a complete elliptic integral of the second kind. More important is to look at what happens for small and large \( r \). As \( r \to 0 \), the ODE reduces to:

\[
\frac{r_{tt}}{2r} = 0
\]

whose general solution is \( r(t) = C(t - t_0)^2 \) for some constants \( C, t_0 \). In other words, at one end, the path ends in finite time with the circles imploding at their common center. Note that \( r' \to 0 \) as \( r \to 0 \) but not fast enough to prevent the collapse. On the other hand, as \( r \to \infty \), the ODE becomes:

\[
\frac{r_{tt}}{2r} = 0
\]

whose general solution is \( r(t) = C(t - t_0)^{2/3} \) for some constants \( C, t_0 \). Thus at the other end of the geodesic, the circles expand forever but with decreasing speed.

An interesting point is that this geodesic has conjugate points on it, so that it is a extremal path but not a local minimum for length over all intervals. This is a concrete reflection of the collapse of the metric when \( A = 0 \). To work this out, take any \( f(\theta) \) such that \( \int_0^{2\pi} f(\theta) \, d\theta = 0 \) and any function \( a(t) \). Then \( X = f(\theta)a(t) \frac{\partial}{\partial \theta} \) is a vector field along the geodesic, i.e. a family of tangent vectors to \( B_c \) at each circle \( C_r(t) \) normal to the tangent to the geodesic. Its length is easily seen to be:

\[
\|X\|^2_{C_r(t)} = \left( r(t) + \frac{A}{r(t)} \right) a(t)^2 \int_0^{2\pi} f(\theta)^2 \, d\theta.
\]

We need to work out its covariant derivative:

\[
\nabla^\parallel_{\theta}(X) = f(\theta) a_t \frac{\partial}{\partial r} + \Gamma_{c_r} \left( r_t \frac{\partial}{\partial r}, f(\theta) a_t \frac{\partial}{\partial r} \right).
\]

Using a formula for the Christoffel symbol which we get from 4.2.2 by polarizing, and noting that \( \kappa \equiv 1/r, \kappa_r \equiv 0 \), we get:

\[
\nabla^\parallel_{\theta}(X) = f(\theta) a_t \frac{\partial}{\partial r} + f(\theta) a_r \left( \frac{1 - A/r^2}{2(r + A/r)} \right) \frac{\partial}{\partial r}
\]

\[
= f(\theta) \left( r + A/r \right)^{-1/2} \left( (r + A/r)^{1/2} a_t \right) \frac{\partial}{\partial r}.
\]

(This formula also follows from the fact that the vectors \( (r + A/r)^{-1/2} \frac{\partial}{\partial r} \) have length independent of \( t \), hence covariant derivative zero.) Jacobi's equation is therefore:

\[
(2) \quad f(\theta) \left( r + A/r \right)^{-1/2} \left( (r + A/r)^{1/2} a_t \right) \frac{\partial}{\partial r} + R(X, r_t \frac{\partial}{\partial r}, r_t \frac{\partial}{\partial r}) = 0,
\]

where \( R \) is the curvature tensor. For later purposes, it is convenient to write this equation using \( r \) as the independent variable along the geodesic rather than \( t \) and think of \( a \) as a function of \( r \). Note that for any function \( b \) along the geodesic, \( b_t = b_r r_t \) and

\[
b_{tt} = b_{rr} r_t^2 + b_r r_{tt} = \left( b_{rr} - \frac{(1 - A/r^2)}{2(r + A/r)} b_r \right) r_t^2.
\]
Then a somewhat lengthy bit of algebra shows that:

\[
(r + A/r)^{-\frac{1}{2}} \left( (r + A/r)^{\frac{1}{2}} a \right)_{rr} = \left( (r + A/r)^{-\frac{1}{2}} \right)^{2} \left( (r + A/r) \frac{1}{r^2} a \right)_{rr} + F(r) a r^2,
\]

where

\[
F(r) = -\frac{5}{16} \left( \frac{1 - A/r^2}{r + A/r} \right)^2 + \frac{A}{2 r^3 (r + A/r)}.
\]

To work out the structure of \( R \) in this case, use the fact that the circles \( C_r \) and the vector field \( \partial/\partial r \) are invariant under rotations. This means that the map \( f \mapsto R(\partial/\partial r, f\partial/\partial r) (\partial/\partial r) \) has the two properties: it commutes with rotations and it is symmetric. The only such maps are diagonal in the Fourier basis, i.e. there are real constants \( \lambda_n \) such that

\[
R(\partial/\partial r, \begin{pmatrix} \cos(n\theta) \partial/\partial r \\ \sin(n\theta) \partial/\partial r \end{pmatrix}) (\partial/\partial r) = \lambda_n \begin{pmatrix} \cos(n\theta) \partial/\partial r \\ \sin(n\theta) \partial/\partial r \end{pmatrix}.
\]

To evaluate \( \lambda_n \), we take the inner product with \( \cos(n\theta) \) (or \( \sin(n\theta) \)) and use our calculation of \( R_0(m, k, m, k) \) in section 4.5 to show:

\[
\left\langle R(\partial/\partial r, \begin{pmatrix} \cos(n\theta) \partial/\partial r \\ \sin(n\theta) \partial/\partial r \end{pmatrix}), \cos(n\theta) \partial/\partial r \right\rangle = R_0 \begin{pmatrix} \frac{\partial}{\partial r} \cos(n\theta) \partial/\partial r, \frac{\partial}{\partial r} \cos(n\theta) \partial/\partial r \end{pmatrix} = \int_0^{2\pi} -\frac{(1 - A/r^2)^2}{2 (1 + A/r^2)} W^2 + AW n^2 \, r \, d\theta
\]

where

\[
W = 1. \frac{d}{ds}(\cos(n\theta)) = -n \frac{\sin(n\theta)}{r} \quad \text{and} \quad W' = \frac{d}{ds} W = -n^2 \frac{\cos(n\theta)}{r^2}.
\]

Simplifying, this gives:

\[
\lambda_n \left| \cos(n\theta) \frac{\partial}{\partial r} \right|^2 = \int_0^{2\pi} \left( -\frac{(1 - A/r^2)^2}{2 (r + A/r)} n^2 \sin^2(n\theta) + \frac{A}{r^3} n^4 \cos^2(n\theta) \right) d\theta
\]

\[
= \frac{(1 - A/r^2)^2}{2 (r + A/r)} n^2 \pi + \frac{A}{r^3} n^4 \pi
\]

hence

\[
\lambda_n = \frac{(1 - A/r^2)^2}{2 (r + A/r)^2} n^2 + \frac{A}{r^3 (r + A/r)} n^4.
\]

Thus for \( X = \cos(n\theta) a_n (t) \partial/\partial r \), if we combine everything, Jacobi’s equation reads:

\[
(r + A/r)^{-\frac{1}{2}} \left( (r + A/r)^{\frac{1}{2}} a_n \right)_{rr} = \left( -\frac{(1 - A/r^2)^2}{2 (r + A/r)^2} (n^2 - \frac{5}{8}) + \frac{A}{r^3 (r + A/r)} (n^4 - \frac{1}{4}) \right) a_n.
\]

Calling the right hand side the potential of Jacobi’s equation, we can check that for each \( n \), the potential is positive for small \( r \), negative for large \( r \) and it has one zero, approximately at \( \sqrt{2A}n \) for large \( n \). Thus, for small \( r \), these perturbations diverge from the geodesic of circles. For large \( r \), if we write \( b_n = (r + A/r)^{1/4} a_n \), then Jacobi’s equation approaches:

\[
(b_n)_{rr} \approx -\frac{n^2 - 0.625}{2 r^2} b_n.
\]
This is solved by $b_n = cx^\lambda + cx'^{\lambda'}$ where $\lambda, \lambda'$ are solutions of $\lambda^2 - \lambda = -(n^2 - 0.625)/2$. For $n = 1$, $\lambda, \lambda'$ are real and $b_n$ has no zeros; but for $n > 1$, $\lambda, \lambda'$ have an imaginary part, say $i\gamma_n$, and

$$b_n \approx \sqrt{n(c\cos(\gamma_n \log(r)) + e^\lambda \sin(\gamma \log(r)))}$$

with infinitely many zeros.

Figure 4 shows the solution for $n = 3$ which approaches 0 as $r \to 0$. The first zero of this solution is about $10.77\sqrt{\lambda}$, making it a conjugate point of $r = 0$. For other $n$, the first such conjugate point appears to be bigger, so we conclude: on any segment $0 < r_1 < r_2 < 10.77\sqrt{\lambda}$, the geodesic of circles is locally (and presumably globally) minimizing.

5.2. The geodesic connecting two distant curves. For any two distant curves $C_1, C_2$, one can construct paths from one to the other by (a) changing $C_1$ to some auxiliary curve $D$ near $C_1$, (b) translating $D$ without modifying it to a point near $C_2$ and (c) changing the translated curve $D$ to $C_2$. If $C_1$ and $C_2$ are very far from each other, the energy of the translation will dominate the energy required to modify them both to $D$. Thus we expect that a geodesic between distant curves will asymptotically utilize a curve $D$ which is optimized for least energy translation. To find such curves $D$, heuristically we may argue that it should be a curve such that the path given by all its translates in a fixed direction is a geodesic.

Such geodesics can be found as special cases of the general geodesic. We fix $\epsilon = (1,0)$ as the direction of translation and assume that the path $\{D + t\epsilon\}$ is a
geodesic. We need to express this geodesic up to order $O(t^2)$ in the chart used in section 4.3. Let $c(s)$ be arc length parametrization of $D$ and $\theta(s)$ be the orientation of $D$ at point $c(s)$, i.e. $c_s = \cos(\theta) + is\sin(\theta)$. Then a little calculation shows that if we reparametrize nearby curves via $\tilde{s} = s - \langle \epsilon, c_s \rangle t$, then the path of translates in direction $\epsilon$ is just:

$$c(\tilde{s}) + t\epsilon = c(s) + \langle t\langle \epsilon, c_s \rangle + \frac{t^2}{2}(\epsilon, c_s)^2 \kappa + O(t^3)\rangle i\epsilon,$$

Thus, in the notation of 4.2, $a = -\sin(\theta)$, hence $a_s = -\cos(\theta)\kappa$ and, moreover, $a_t = \cos^2(\theta)\kappa$. Substituting this in the geodesic formula 4.2.1, we get

$$(1 + A\kappa^2)\cos^2(\theta)\kappa =$$

$$= \frac{\kappa \sin^2(\theta)}{2} + A((\kappa_{ss} - \frac{\kappa^3}{2})\sin^2(\theta) + 4\cos(\theta)\sin(\theta)\kappa_{s} + 2\kappa^3 \cos^2(\theta)).$$

Since $\kappa = \theta_s$, this becomes, after some manipulation, a singular third order equation for $\theta(s)$:

$$\theta_{sss} = 4\cot(\theta)\theta_s + \frac{1}{2} - \cos^2(\theta)\theta_{s} + \frac{1}{\sqrt{A}}.$$

One solution of this equation is $\theta(s) \equiv \frac{1}{\sqrt{A}}$, i.e. a circle of radius $\sqrt{A}$. In fact, this seems to be the only simple closed curve which solves this equation. However, if we drop smoothness, a weak solution of this equation is given by the $C^1$, piecwise $C^3$-curve made up of 2 semi-circles of radius $\sqrt{A}$ joined by 2 straight line segments parallel to the vector $\epsilon$ and separated by the distance $2\sqrt{A}$ (as in figure 5). Note that such ‘cigar’-shaped curves can be made with line segments of any length.

A numerical approach to minimize $E_{\alpha}^{\gamma}(c)$ for variations $\epsilon$ with initial and end curves circles at a certain distance produced the two such geodesics shown in Figure 5. Note that the middle curve is indeed close to such a ‘cigar’-shape. However, the width of this shape is somewhat greater than $2\sqrt{A}$: this is presumably because the endcurves of this path are not sufficiently far apart. Thus experiments as well as the theory suggest strongly that geodesics joining any two curves sufficiently far apart compared to their size asymptotically approach a constant ‘cigar’-shaped $C^1$, intermediate curve made up of 2 semi-circles of radius $\sqrt{A}$ and 2 parallel line segments. We conjecture that this is true.

5.3 The growth of a ‘bump’ on a straight line, when $A = 0$. We have seen above that the geodesic spray is locally well-defined when $A = 0$. To understand this spray and see whether it appears to have global solutions, we take that the initial curve contains a segment with curvature identically zero, i.e. contains a line segment, and that the initial velocity $a$ is set to a smooth function with compact support contained in this segment. For simplicity, we take the velocity $a$ to be a cubic B-spline, i.e. a piecewise cubic which is $C^3$ with 5 non-$C^3$ knots approximating a Gaussian bfp. The result of integrating is shown in Figure 6. Note several things: first, where the curvature is zero, the curve moves with constant velocity if we follow the orthogonal trajectories. Secondly, where the curve is moving opposite to its curvature (like an expanding circle, the part in the middle), it is decelerating; but where it is moving with its curvature (like a contracting circle, the parts on
the 2 ends), it is accelerating. This acceleration in the 2 ends, creates higher and higher curvature until a corner forms. In the figure, the simulation is stopped just before the curvature explodes. In the middle, the curve appears to be getting more and more circular. As the corners form, the curve is approaching the boundary of our space. Perhaps, with the right entropy condition, one can prolong the solution past the corners with a suitable piecewise $C^1$-curve.

Although this calculation assumes $A = 0$, one will find very similar geodesics when $A$ is much smaller than $1/\kappa^2, 1/(\kappa, \log(a)\kappa)$ and $\kappa/\kappa_\kappa$, so that the dominant terms in the geodesic equation are those without an $A$. In other words, geodesics between large smooth curves are basically the same as those with $A = 0$.

5.4 Several geodesic triangles in $B_\kappa$. We have examined dilations, translations and the evolution of blips. We look next at rotations. To get a pure rotational situation, we consider ellipses centered at $(0,0)$ with the same eccentricity $3$ and maximum radius $1$, but differently oriented. We take $3$ such ellipses, with orientations differing by $60^\circ$ and $120^\circ$ degrees. Joining each pair by a geodesic, we get a triangle in $B_\kappa$. 

Figure 5. On the top, the geodesic joining circles of radius $1$ at distance $3$ apart with $A = 1$ (using 20 time samples and a 46-gon for the circle). On the bottom, the geodesic joining 2 ‘random’ shapes of size about 1 at distance 5 apart with $A = 25$ (using 20 time samples and a 48-gon approximation for all curves). In both cases the middle curve which is highlighted.
Figure 6. The forward integration of the geodesic equation when $A = 0$, starting from a straight line in the direction given by a smooth bump-like vector field. Note that two corner-like singularities with curvature going to $\infty$ are about to form.

We wanted to examine whether along the geodesic joining 2 such ellipses (a) one ellipse rotates into the other or (b) the initial ellipse shrinks towards a circle, while the final ellipse grows, independently of one another. It turns out that, depending on the value of $A$, both can happen. Note that we get similar geodesics by either changing $A$ or making the ellipses smaller or larger with $A$ held fixed. For each $A$, we get an absolute distance scale with unit $1/\sqrt{A}$ and, if the ellipses are bigger than this, (b) dominates, while, if smaller, (a) dominates.

The results are shown in Figure 7. We have taken the three values $A = 1, 0.1$ and 0.01. For each value, on the top, we show the geodesic joining 2 of the ellipses as a sequence of curves in their common ambient $\mathbb{R}^2$. Below this, we show the triple of geodesics as a triangle, by displaying the intermediate curves as small shapes along lines joining the ellipses. This Euclidean triangle is being used purely for display, to indicate that the computed structure is a triangle in $B_r$. Note that for $A = 1$, the intermediate shapes are very close to ellipses, whose axes are rotating; while for $A = 0.01$, the bulges in one ellipse shrink while those of the other grow.

We can also compute the angles in $B_r$ between the sides of this triangle. They work out to be $34^\circ$ when $A = 1$, i.e. the angle sum for the triangle is $162^\circ$, much less than $\pi$ radians, showing strong negative sectional curvature in the plane containing this triangle. But if $A = 0.1$ or 0.01, the angle is $77^\circ$ and $69^\circ$ respectively, giving more than $\pi$ radians in the triangle. Thus the sectional curvature is positive for such small values of $A$.

5.5 Notes on the numerical simulations. All simulations in this paper were carried out in MatLab. The forward integration for the geodesic equation for $A = 0$ was carried out by the simplest possible finite difference scheme. This seems very stable and reliable. Solving for the geodesics was done using the MatLab minimization routine $\text{fminunc}$ using both its medium and large scale modes. This, however, was quite unstable due to discretization artifacts. A general path between two curves was represented by a matrix of points in $\mathbb{R}^2$, approximating each curve by a polygon and sampling the path discretely. The difficulty is that when the polygons have very acute angles, the discretization tends to be highly inaccurate because of the high curvature localized at one vertex. Initially, in order to minimize the number of variables in the problem, we tried to use small numbers of samples.
and higher order accurate discrete approximations to the derivatives. In all these attempts, the discrete approximation “cheated” by finding minima to the energy of the path with polygons with very small angles. The only way we got around this was to use first order accurate expressions for the derivatives and relatively large numbers of samples (e.g. 48 points on each curve, 20 samples along the geodesic, hence $2 \times 20 \times 48 = 1920$ variables in the expression for the energy.

Another problem is that the energy only depends on the path of unparametrized curves and is independent of the parametrization. To solve this, we added a term to the energy which is minimized by constant speed parametrizations. This still leaves a possibly wandering basepoint, and we added $\epsilon$ times another term which asked that all points on each curve should move as normally as possible. In practice, if the initialization was reasonable, this term was not needed. The final discrete energy that was minimized was this. Let $x_{i,j}$ be the $i^{th}$ sample point on the $j^{th}$ curve $C_j$. For each $(i,j)$, estimate the sum of the squared curvature of $C_j$ plus the squared acceleration of the parametrization by:

$$k(i,j) = \frac{1}{2} \left( \frac{1}{\|x_{i-1,j} - x_{i,j}\|^4} + \frac{1}{\|x_{i,j} - x_{i+1,j}\|^4} \right) \cdot \|x_{i-1,j} - 2x_{i,j} + x_{i+1,j}\|^2.$$  

(The harmonic mean of the segment lengths is used here to further force the parametrization to be uniform.) Then, for each $(i,j)$, the four triangles $t = \{a = (i,j), b = (i \pm 1, j), c = (i, j \pm 1)\}$ around $(i,j)$ are considered and the energy is
taken to be:
\[
\sum_{i,j} \left( \frac{\left( x_{a} - x_{b} \right) \cdot (x_{a} - x_{c})}{\|x_{a} - x_{b}\|} + \varepsilon \left( (x_{a} - x_{b}) \cdot (x_{a} - x_{c}) \right) \right) (1 + A k(a)).
\]

We make no guarantees about the accuracy of this simulation! The results, however, seem to be stable and reasonable.

References


