Lyapunov 1-forms for flows

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Abstract

In this paper we find conditions which guarantee that a given flow \( \Phi \) on a compact metric space \( X \) admits a Lyapunov one-form \( \omega \) lying in a prescribed Čech cohomology class \( \xi \in H^1(X; \mathbb{R}) \). These conditions are formulated in terms of the restriction of \( \xi \) to the chain recurrent set of \( \Phi \). The result of the paper may be viewed as a generalization of a well-known theorem of C. Conley about the existence of Lyapunov functions.

1 Introduction

C. Conley proved in [1, 2] that any flow \( \Phi : X \times \mathbb{R} \to X \) on a compact metric space \( X \) decomposes into a chain recurrent flow and a gradient-like flow. More precisely, he proved the existence of a Lyapunov function for the flow, i.e. a continuous function \( L : X \to \mathbb{R} \), which decreases along any orbit of the flow lying in the complement \( X - R \) of the chain recurrent set \( R \subseteq X \) of \( \Phi \) and is constant on the connected components of \( R \).

**Theorem 1 (C. Conley, [1, 2])** Let \( \Phi : X \times \mathbb{R} \to X \), \( \Phi(x, t) = x \cdot t \), be a continuous flow on a compact metric space \( X \). Then there exists a continuous function \( L : X \to \mathbb{R} \), which is constant on the connected components of the chain recurrent set \( R = R(\Phi) \) of the flow \( \Phi \), and satisfies \( L(x \cdot t) < L(x) \) for any \( x \in X - R \) and \( t > 0 \).

This important result led Conley to his program of understanding very general flows as collections of isolated invariant sets linked by heteroclinic orbits.

Our aim in this paper is to go one step further and to analyze the flow within the chain-recurrent set \( R \), where it is typically complicated. As a new tool, we study the notion of a Lyapunov one-form for \( \Phi \), which is a natural generalization of the notion of a Lyapunov function and has been introduced in a different context in Farber’s papers [5, 6]. We prove that under some natural
assumptions, a given Čech cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \) can be represented by a continuous closed Lyapunov one-form for the flow \( \Phi \).

The notion of a continuous closed one-form on a topological space generalizes the notion of a continuous function. For convenience of the reader we recall the relevant definitions and the main properties of continuous closed one-forms in §2, referring for more details to the papers [5, 6], where they were originally introduced. For the purpose of this introduction, let us say that continuous closed one-forms are analogous of the familiar smooth closed one-forms on differentiable manifolds. Any continuous closed one-form \( \omega \) on a topological space \( X \) canonically determines a Čech cohomology class \( [\omega] \in \check{H}^1(X; \mathbb{R}) \), which plays a role analogous to the de Rham cohomology class of a smooth closed one-form.

For any continuous curve \( \gamma : [0, 1] \to X \), the line integral \( \int_\gamma \omega \in \mathbb{R} \) is defined and has the usual properties; in particular, it depends only on the homotopy class of the curve relative to the end-points.

**Definition 1** Consider a continuous flow \( \Phi : X \times \mathbb{R} \to X \) on a topological space \( X \). Let \( Y \subset X \) be a closed subset invariant under \( \Phi \). A continuous closed one-form \( \omega \) on \( X \) is called a Lyapunov one-form for the pair \((\Phi, Y)\) if it has the following two properties:

\[
\text{(L1) For every } x \in X - Y \text{ and every } t > 0, \quad \int_x^{x+it} \omega < 0,
\]

where the integral is calculated along the trajectory of the flow, and

\[
\text{(L2) } \omega|_Y = 0.
\]

Any continuous function \( L : X \to \mathbb{R} \) determines the closed one-form \( \omega = dL \) (see §2) and in this special case condition (L1) reduces to the requirement \( L(x \cdot t) < L(x) \) for any \( t > 0 \) and \( x \in X - Y \), while condition (L2) means that the restriction \( L|_Y \) is locally constant. Hence for \( \omega = dL \), the above definition reduces to the classical notion of a Lyapunov function, see [13].

The following remark illustrates Definition 1. Given a flow \( \Phi \) on \( X \) and a Lyapunov one-form \( \omega \) for \((\Phi, Y)\), representing a non-zero Čech cohomology class \( [\omega] = \xi \in \check{H}^1(X; \mathbb{R}) \), the homology class \( z \in H_1(X; \mathbb{Z}) \) of any periodic orbit of \( \Phi \) satisfies

\[
\langle \xi, z \rangle \leq 0,
\]

with equality if and only if the periodic orbit is contained in \( Y \). Using this fact one constructs flows such that no non-zero cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \) contains a Lyapunov 1-form.

In this paper we will associate with any cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \) a subset \( R_\xi \subset R \) of the chain recurrent set \( R = \overline{R(\Phi)} \) of the flow \( \Phi \), see section §3 for details. The set \( R_\xi \) is closed and invariant under the flow and can be characterized as the projection of the chain recurrent set of the natural lift of the flow to the Abelian cover of \( X \) associated with the class \( \xi \).
A \((\delta, T)\)-cycle is a pair \((x, t) \in X \times \mathbb{R}\) satisfying \(t \geq T\) and \(d(x, x \cdot t) < \delta\). Here \(d\) denotes the distance function on \(X\). See Figure 1. If \(X\) is locally path-connected, any \((\delta, T)\)-cycle with small enough \(\delta\) determines a closed loop, which first follows the flow line from \(x\) to \(x \cdot t\) and then returns from \(x \cdot t\) to \(x\) by a path contained in a suitably small ball. This leads to the notion of a homology class \(z \in H_1(X; \mathbb{Z})\) associated to a \((\delta, T)\)-cycle; see Definition 4. The class \(z\) is uniquely defined if \(X\) is homologically locally 1-connected; without this assumption the homology class \(z\) associated with a \((\delta, T)\)-cycle might not be unique. The natural bilinear pairing \(\langle \cdot, \cdot \rangle : \tilde{H}^1(X; \mathbb{R}) \times H_1(X; \mathbb{Z}) \to \mathbb{R}\) can be understood as \(\langle \xi, z \rangle = \int_\gamma \omega\), where \(\omega\) is a representative closed one-form for \(\xi \in \tilde{H}^1(X; \mathbb{R})\) and \(\gamma : [0, 1] \to X\) is a loop representing the class \(z \in H_1(X; \mathbb{Z})\).

Despite the fact that the homology class \(z\) associated to a \((\delta, T)\)-cycle might depend (for wild \(X\)) on the choice of the connecting path between \(x \cdot t\) and \(x\), the construction is such that the value \(\langle \xi, z \rangle \in \mathbb{R}\) only depends (for small enough \(\delta > 0\)) on the \((\delta, T)\)-cycle itself; see §3 for details.

The following Theorem is our main result:

**Theorem 2** Let \(\Phi\) be a continuous flow on a compact, locally path connected, metric space \(X\) and \(\xi\) a cohomology class in \(\tilde{H}^1(X; \mathbb{R})\). Denote by \(C_\xi\) the subset

\[
C_\xi = R - R_\xi
\]

(1.1)

of the chain recurrent set \(R\) of the flow \(\Phi\). Assume that the following two conditions are satisfied

(A) \(\xi_{|R_\xi} = 0\);

(B) there exist constants \(\delta > 0\), \(T > 1\), such that every homology class \(z \in H_1(X; \mathbb{Z})\) associated to an arbitrary \((\delta, T)\)-cycle \((x, t)\) with \(x \in C_\xi\) satisfies

\[
\langle \xi, z \rangle \leq -1.
\]
Then there exists a Lyapunov one-form $\omega$ for $(\Phi, R_\xi)$ representing the cohomology class $\xi$. Moreover, the subset $C_\xi$ is closed.

Conversely, if for the given cohomology class $\xi$ there exists a Lyapunov one-form for the pair $(\Phi, R_\xi)$ in the class $\xi$ and if the set $C_\xi$ is closed then (A) and (B) hold true.

**Corollary 1** Let $\Phi : X \times \mathbb{R} \rightarrow X$ be a continuous flow on a compact, locally path connected metric space. Any Čech cohomology class $\xi \in \check{H}^1(X; \mathbb{R})$ satisfying $\xi|_R = 0$ (where $R = R(\Phi)$ denotes the chain recurrent set of the flow), contains a Lyapunov one-form $\omega$ for $(\Phi, R)$.

Corollary 1 follows directly from Theorem 2 since under the assumption $\xi|_R = 0$ the set $R_\xi$ coincides with $R$ (compare Definition 5) and so the set $C_\xi$ is empty. Corollary 1 also admits a simple, independent proof based on Conley’s Theorem 1.

**Corollary 2** Suppose $\Phi : X \times \mathbb{R} \rightarrow X$ is a flow on a compact locally path connected metric space, whose chain recurrent set consists of finitely many rest points and periodic orbits. Then a Lyapunov one-form for $(\Phi, Y)$, with suitable $Y \subset X$, exists in a nontrivial cohomology class $\xi \in \check{H}^1(X; \mathbb{R})$ if and only if the homology classes of the periodic orbits are contained in the half space

$$H_\xi := \{ z \in H_1(X; \mathbb{Z}) \mid \langle \xi, z \rangle \leq 0 \}.$$

If the above condition holds, then the set $Y$ coincides with the union of the rest points and of those periodic orbits, for which the corresponding homology classes $z \in H_1(X; \mathbb{Z})$ satisfy $\langle \xi, z \rangle = 0$.

This Corollary is a direct consequence of our main Theorem 2. The class of flows meeting its assumptions includes the Morse-Smale flows on closed manifolds.

Another interesting special case arises when $R_\xi = \emptyset$. From Theorem 2 we also deduce the following result:

**Corollary 3** Let $\Phi : X \times \mathbb{R} \rightarrow X$ be a continuous flow on a compact, locally path connected, metric space $X$ and let $\xi \in \check{H}^1(X; \mathbb{R})$ be a nonzero Čech cohomology class. The following two conditions are equivalent:

(i) $R_\xi = \emptyset$ and the flow satisfies condition (B) of Theorem 2;

(ii) there exists a Lyapunov one-form for $(\Phi, \emptyset)$ representing the class $\xi$.

If the class $\xi$ is integral, i.e. $\xi \in \check{H}^1(X; \mathbb{Z})$, then either of the above conditions is equivalent to the existence of a continuous locally trivial fibration $p : X \rightarrow S^1 \subset \mathbb{C}$ with the following properties. The function $t \mapsto \text{arg}(p(x \cdot t))$ is differentiable, the derivative

$$\frac{d}{dt} \text{arg}(p(x \cdot t)) < 0$$

4
is negative for all $x \in X$, $t \in \mathbb{R}$, and the cohomology class $p^*(\mu) \in \tilde{H}^1(X; \mathbb{Z})$ coincides with $\xi$, where $\mu \in \tilde{H}^1(S^1; \mathbb{Z})$ is the fundamental class of the circle $S^1$ oriented counterclockwise. In particular, for any angle $\theta \in S^1$ the set $K = p^{-1}(\theta)$ is a cross section of the flow $\Phi$.

Recall that a closed subset $K \subset X$ is a cross section of the flow $\Phi$ if the flow map $K \times \mathbb{R} \to X$ is a surjective local homeomorphism (see S. Schwartzman [11]). A cross section $K$ is transversal to the flow and the orbit of every point in $X$ intersects $K$ in forward and backward time.

We give a proof of Corollary 3 in section 5.

Under slightly stronger assumptions, S. Schwartzman [12] proved, among other results, the equivalence of the property of having a cross section and the existence of a fibration $p : X \to S^1$ as stated in the second part of Corollary 3. In subsequent work we will compare in detail our results with Schwartzman's beautiful paper [11].

The second part of Corollary 3 may be viewed as a generalization of Fried's results on the existence of cross sections to flows on manifolds [9, Theorem D]. The assumption of D. Fried to ensure the existence of cross sections is formulated in terms of the notion of homological directions of a flow, which we now recall. A sequence $(x_n, t_n) \in X \times (1, \infty)$ is a closing sequence based at $x \in X$ if the sequences $x_n$ and $x_n \cdot t_n$ tend to $x$. We will assume that $X$ is a compact polyhedron. Then any closing sequence determines uniquely a sequence of homology classes $z_n \in H_1(X; \mathbb{Z})$. Here $z_n$ denotes the homology class of a loop, which starts at $x_n$, follows the flow until $x_n \cdot t_n$, and then returns to $x_n$ along a "short" path. Let $D_X$ be the factorspace $D_X = H_1(X; \mathbb{R})/\mathbb{R}_+$, where this space is topologized as the disjoint union of the unit sphere with the origin. Any closing sequence as above determines a sequence of "homology directions" $\tilde{z}_n \in D_X$, the equivalence classes of $z_n$ in $D_X$. The set of homology directions $D_\Phi \subset D_X$ of the flow $\Phi$ is defined as the set of all accumulation points of all sequences $\tilde{z}_n$ corresponding to closing sequences in $X$. As noted by D. Fried [9] it is enough to consider closing sequences $(x_n, t_n)$ with $t_n \to \infty$.

**Proposition 1** Let $X$ be a finite polyhedron and let $\xi \in H^1(X; \mathbb{Z})$ be an integral cohomology class. Let $\Phi : X \times \mathbb{R} \to X$ be a continuous flow such that the chain recurrent set $R_\xi$ is isolated in $R$. Then condition (B) of Theorem 2 is equivalent to the Fried's condition that any homology direction $\tilde{z} = \lim z_n \in D_X$ of any closing sequence $(x_n, t_n) \in X \times (1, \infty)$ with $x_n \in C_\xi$ satisfies $(\xi, \tilde{z}) < 0$.


A comparison of the results of D. Fried [9] with the results of this paper shows that our setting is more general in two respects: we allow spaces $X$ of a more general nature and arbitrary real Čech cohomology classes $\xi$. In [9] $X$ is required to be a compact manifold, possibly with boundary, and the class $\xi$ has to be integral. The equivalence of our condition (B) with the condition of D. Fried (Proposition 1) holds only under these additional assumptions.

In the papers [5], [6] two different generalizations $\text{cat}(X, \xi)$ and $\text{Cat}(X, \xi)$ of the classical notion of Lusternik - Schnirelman category $\text{cat}(X)$ were introduced;
here $X$ is a finite polyhedron and $\xi \in H^1(X; \mathbb{R})$ a cohomology class. Using these new concepts, an extension of the Lusternik-Schnirelman theory for flows was constructed, see [5], [6]. The main results of [5], [6] allow to estimate the number of fixed points of a flow under the assumption that (1) the fixed points are isolated in the chain recurrent set, and (2) the flow admits a Lyapunov closed 1-form lying in the class $\xi$. The results of the present paper fit nicely in this program and explain the nature of the assumption (2). Note that (1) is similar in spirit (although formally not equivalent) to the property that the set $R_\xi$ is isolated in the chain recurrent set $R$ of the flow.

## 2 Closed one-forms on topological spaces

In this section we recall the notion of a continuous closed one-form on a topological space, which has been introduced in [5, 6].

**Definition 2** Let $X$ be a topological space. A continuous closed one-form on $X$ is defined by an open cover $\mathcal{U} = \{U\}$ of $X$ and by a collection $\{\varphi_U\}_{U \in \mathcal{U}}$ of continuous functions $\varphi_U : U \to \mathbb{R}$ with the following property: for any two subsets $U, V \in \mathcal{U}$ the difference

$$\varphi_U|_{U \cap V} - \varphi_V|_{U \cap V} : U \cap V \to \mathbb{R}$$

(2.1)

is a locally constant function (i.e., constant on each connected component of $U \cap V$). Two such collections $\{\varphi_U\}_{U \in \mathcal{U}}$ and $\{\psi_U\}_{V \in \mathcal{V}}$ are called equivalent if their union $\{\varphi_U, \psi_V\}_{U \in \mathcal{U}, V \in \mathcal{V}}$ satisfies condition (2.1). The equivalence classes are called continuous closed one-forms on $X$.

Any continuous function $f : X \to \mathbb{R}$ (viewed as a family consisting of a single element) determines a continuous closed one-form, which we denote by $df$ (the differential of $f$).

A continuous closed one-form $\omega$ vanishes, $\omega = 0$, if it is represented by a collection of locally constant functions.

The sum of two continuous closed one-forms determined by collections $\{\varphi_U\}_{U \in \mathcal{U}}$ and $\{\psi_V\}_{V \in \mathcal{V}}$ is the continuous closed one-form corresponding to the collection $\{\varphi_U|_{U \cap V} + \psi_V|_{U \cap V}\}_{U \in \mathcal{U}, V \in \mathcal{V}}$. Similarly, one can multiply continuous closed one-forms by real numbers $\lambda \in \mathbb{R}$ by multiplying the corresponding representatives with $\lambda$. With these operations, the set of continuous closed one-forms on $X$ is a real vector space.

Continuous closed one-forms behave naturally with respect to continuous maps: If $h : Y \to X$ is continuous and $\{\varphi_U\}_{U \in \mathcal{U}}$ determines a continuous closed one-form $\omega$ on $X$, then the collection of continuous functions $\phi_U \circ h : h^{-1}(U) \to \mathbb{R}$ determines a continuous closed one-form on $Y$ which will be denoted by $h^*\omega$. As a special case of this construction, we will often use the operation of restriction of a closed one-form $\omega$ to a given subset $A \subset X$; in this case $h$ is the inclusion map $A \to X$ and the form $h^*\omega$ is simply denoted as $\omega|_A$.

A continuous closed one-form $\omega$ on $X$ can be integrated along continuous paths in $X$. Namely, let $\omega$ be given by a collection $\{\varphi_U\}_{U \in \mathcal{U}}$, and $\gamma : [0, 1] \to X$
be a continuous path. We may find a finite subdivision \(0 = t_0 < t_1 < \cdots < t_N = 1\) of the interval \([0, 1]\) such that for each \(0 \leq i < N\) the image \(\gamma([t_{i-1}, t_i])\) is contained in a single open set \(U_i \in \mathcal{U}\). Then we define the line integral

\[
\int_\gamma \omega := \sum_{i=1}^{N} \varphi_{U_i}(\gamma(t_i)) - \varphi_{U_i}(\gamma(t_{i-1})).
\]  

(2.2)

The standard arguments show that the integral (2.2) is independent of all choices and in fact depends only on the homotopy class of \(\gamma\) relative to its endpoints.

Consider the following exact sequence of sheaves over \(X\)

\[
0 \to R_X \to C_X \to B_X \to 0,
\]

(2.3)

where \(R_X\) is the sheaf of locally constant functions, \(C_X\) is the sheaf of real-valued continuous functions, and \(B_X\) is the sheaf of germs of continuous functions modulo locally constant ones. More precisely, \(B_X\) is the sheaf corresponding to the presheaf \(U \mapsto C_X(U)/R_X(U)\). By the definitions above, the global sections of the sheaf \(B_X\) are in one-to-one correspondence with continuous closed 1-forms on \(X\). Hence the space of all closed 1-forms on \(X\) is \(H^0(X; B_X)\).

The exact sequence of sheaves (2.3) generates the cohomological exact sequence

\[
0 \to H^0(X; R_X) \to H^0(X; C_X) \xrightarrow{d} H^0(X; B_X) \xrightarrow{\delta} H^1(X; R_X) \to 0
\]

(2.4)

In this exact sequence, \(H^0(X; C_X) = C(X)\) is the space of all continuous functions \(f : X \to \mathbb{R}\) and the map \(d\) assigns to any continuous function \(f\) its differential \(df \in H^0(X; B_X)\). The group \(H^1(X; R_X)\) is the Čech cohomology \(\check{H}^1(X; R)\) (see [14], chapter 6); the map \([\ ]\) assigns to any closed one-form \(\omega\) its Čech cohomology class \([\omega]\) \(\in \check{H}^1(X; \mathbb{R})\). This proves:

**Lemma 1** A continuous closed 1-form \(\omega \in H^0(X; B_X)\) equals \(d\) for some continuous function \(f : X \to \mathbb{R}\) if and only if its Čech cohomology class \([\omega]\) \(\in \check{H}^1(X; \mathbb{R})\) vanishes, \([\omega] = 0\). Any Čech cohomology class \(\xi \in \check{H}^1(X; \mathbb{R})\) can be realized by a continuous closed 1-form on \(X\).

Note also that there is a natural homomorphism \(\check{H}^1(X; \mathbb{R}) \to H^1(X; \mathbb{R})\) from Čech cohomology to singular cohomology. Using Lemma 1 and the well-known identification \(H^1(X; \mathbb{R}) \cong \text{Hom}(H_1(X); \mathbb{R})\), it can be described as a pairing

\[
\langle \cdot, \cdot \rangle : \check{H}^1(X; \mathbb{R}) \times H_1(X; \mathbb{Z}) \to \mathbb{R}, \quad \langle [\omega], [\gamma] \rangle = \int_\gamma \omega.
\]

(2.5)

In other words, choosing a representative closed 1-form \(\omega\) for a cohomology class \(\xi \in \check{H}^1(X; \mathbb{R})\) and a closed loop \(\gamma\) in \(X\) representing a homology class \(z \in H_1(X; \mathbb{Z})\), the number \(\langle \xi, z \rangle \in \mathbb{R}\) equals the line integral \(\int_\gamma \omega\), which is independent of the choices.

Here is a generalization of the well-known Tietze extension theorem:
Proposition 2 Let \( X \) be a metric space and \( A \subset X \) a closed subset. Let \( \omega \) be a continuous closed one-form on \( A \), and let \( \xi \in \check{H}^1(A; \mathbb{R}) \) denote the Čech cohomology class of \( \omega \). Then for any cohomology class \( \xi' \in \check{H}^1(X; \mathbb{R}) \), satisfying \( \xi'|_A = \xi \), there exists a continuous closed one-form \( \omega' \) on \( X \) representing the cohomology class \( \xi' \), such that \( \omega'|_A = \omega \).

Proof. Choose an arbitrary continuous closed one-form \( \Omega' \) representing the class \( \xi' \). Then \( \Omega'|_A \) is cohomologous to \( \omega \), i.e. \( \Omega'|_A - \omega = df \), where \( f : A \to \mathbb{R} \) is a continuous function. By the Tietze Extension Theorem for functions, we find a continuous function \( f' : X \to \mathbb{R} \) extending \( f \). Then \( \omega' = \Omega' - df' \) is a closed one-form in the class \( \xi' \) satisfying \( \omega'|_A = \omega \). \( \square \)

The statement of Proposition 2 can be expressed as follows: a continuous closed 1-form \( \omega \) on a closed subset \( A \subset X \) can be extended to a continuous closed 1-form on \( X \) if and only if the cohomology class [\( \omega \)] \( \in \check{H}^1(A; \mathbb{R}) \) can be extended to a cohomology class lying in \( \check{H}^1(X; \mathbb{R}) \).

3 The chain recurrent set \( R_\xi \)

The goal of this section is to introduce a new chain recurrent set \( R_\xi = R_\xi(\Phi) \subset X \), which is associated with a flow \( \Phi \) on \( X \) together with a Čech cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \). The set \( R_\xi \) appears in the statement of our main Theorem 2.

Throughout this section we will assume that \( X \) is a locally path connected compact metric space.

Recall that a space \( X \) is locally path connected if for every open set \( U \subset X \) and for every point \( x \in U \) there exists an open set \( V \subset U \) with \( x \in V \) such that any two points in \( V \) can be connected by a path in \( U \). Equivalently, \( X \) is locally path connected if the connected components of open subsets are open (see [14], page 65).

3.1 Definition of \( R_\xi \)

Recall the definition of the chain-recurrent set \( R = R(\Phi) \) of the flow \( \Phi \). Given any \( \delta > 0 \), \( T > 0 \), a \((\delta, T)\)-chain from \( x \in X \) to \( y \in X \) is a finite sequence \( x_0 = x, x_1, \ldots, x_N = y \) of points in \( X \) and numbers \( t_1, \ldots, t_N \in \mathbb{R} \) satisfying \( t_i \geq T \) and \( d(x_{i-1}, t_i, x_i) < \delta \) for all \( 1 \leq i \leq N \). Note that a \((\delta, T)\)-cycle (see §1) is a \((\delta, T)\)-chain of a special kind (with \( n = 1 \)).

The chain recurrent set \( R = R(\Phi) \) of the flow \( \Phi \) is defined as the set of all points \( x \in X \) such that for any \( \delta > 0 \) and \( T \geq 1 \) there exists a \((\delta, T)\)-chain starting and ending at \( x \). It is immediate from this definition that the chain recurrent set is closed and invariant under the flow; \( R \) contains all fixed points and periodic orbits. The chain recurrent set \( R \) contains the set of all nonwandering points and, in particular, the positive and negative limit sets of any orbit [1, §II.6].
Lemma 2 Given a locally path connected compact metric space $X$ and a number $\varepsilon > 0$, there exists $\delta = \delta(\varepsilon) > 0$ such that any two points $x, y \in X$ with $d(x, y) < \delta$ can be connected by a continuous path $\gamma : [0, 1] \to X$ contained in some open $\varepsilon$-ball.

Proof. By the definition of local path-connectedness, each point $x \in X$ has a neighborhood $V_x$ contained in the $\varepsilon$-ball $B_x$ around $x$ such that any two points in $V_x$ can be connected by a path in $B_x$. Choose a finite subcover of the covering $\{V_x\}_{x \in X}$ of $X$ and choose $\delta(\varepsilon)$ as the Lebesgue number of this finite cover. \[ \square \]

Definition 3 A pair $(\varepsilon, \delta)$ of real numbers $\varepsilon = \varepsilon(\xi) > 0$ and $\delta = \delta(\xi) > 0$ is called a scale of a non-zero cohomology class $\xi \in \check{H}^1(X; \mathbb{R})$ if (1) $\xi|_B = 0$ for any ball $B \subset X$ of radius $2\varepsilon$ and (2) any two points $x,y \in X$ with $d(x,y) < \delta$ can be connected by a path in $X$ contained in a ball of radius $\varepsilon$.

Such a scale always exists. In fact, since we may realize the class $\xi$ by a continuous closed 1-form $\omega = \{\phi_U\}_{U \in \mathcal{U}}$ with a finite open cover $\mathcal{U}$ and then take for $\varepsilon$ half of the Lebesgue number of $\mathcal{U}$. Using Lemma 2 we may then find $\delta = \delta(\xi) > 0$ satisfying condition (2) in Definition 3.

We want to evaluate Čech cohomology classes on broken chains of trajectories of the flow which start and end at the same point. This can be done as follows. Let $\varepsilon = \varepsilon(\xi)$, $\delta = \delta(\xi)$ be a scale for $\xi \in \check{H}^1(X; \mathbb{R})$ (see Definition 3). Suppose we are given a closed $(\delta, T)$-chain, i.e. a $(\delta, T)$-chain from a point $x$ to itself. We have a sequence of points $x_0 = x, x_1, \ldots, x_{N-1}, x_N = x$ of $X$ and a sequence of numbers $t_1, \ldots, t_N \in \mathbb{R}$ with $t_i \geq T$, such that $d(x_{i-1}, t_i, i) < \delta$ for any $1 \leq i \leq N$. We want to associate with such a chain a homology class $z \in H_1(X; \mathbb{Z})$. Choose continuous paths $\gamma_i : [0, 1] \to X$, where $1 \leq i \leq N$, connecting $x_{i-1}$ with $x_i$ and lying in a ball $B_i$ of radius $\varepsilon$. We obtain a singular cycle which is a combination of the parts of the trajectories from $x_{i-1}$ to $x_i$ and the paths $\gamma_i$.

Definition 4 The homology class $z \in H_1(X; \mathbb{Z})$ of this singular cycle is said to be associated with the given closed $(\delta, T)$-chain.

Note that the obtained class $z$ may depend on the choice of paths $\gamma_i$ (if the
space $X$ is wild, i.e. not locally contractible). However the value

$$\langle \xi, z \rangle \in \mathbb{R}, \quad \text{where} \quad \langle \xi, z \rangle = \sum_{i=1}^{N} \int_{\sigma_{i-1}}^{\sigma_{i}} \omega + \sum_{i=1}^{N} \int_{\sigma_{i}} \omega, \quad (3.1)$$

is independent of the paths $\sigma_i$. Indeed, if we use two different sets of curves $\sigma_i$ and $\sigma'_i$ then the difference of the corresponding expressions in (3.1) will be the integral over the sum of singular cycles $\sum_{i=1}^{N}(\sigma_i - \sigma'_i)$, each cycle $\sigma_i - \sigma'_i$ being contained in a ball of radius $2\varepsilon$. Since we know that the restriction of the cohomology class $\xi$ on any such ball vanishes, we see that the right side of (3.1) is independent of the choice of the curves $\sigma_1, \ldots, \sigma_N$.

The homology class $z \in H_1(X; \mathbb{Z})$ associated with a closed $(\delta, T)$-chain is uniquely defined if $X$ is homologically locally connected in dimension 1 (see [14], chapter 6, page 340 for the definition) and $\delta > 0$ is sufficiently small.

Now we are ready to define the subset $R_\xi$ of the chain recurrent set $R$.

**Definition 5** Let $\varepsilon = \varepsilon(\xi)$ and $\delta = \delta(\xi)$ be a scale of a cohomology class $\xi \in H^1(X; \mathbb{R})$. Then $R_\xi = R_\xi(\Phi)$ denotes the set of all points $x \in X$ with the following property: for any $0 < \delta' < \delta$ and $T > 1$ there exists a $(\delta', T)$-chain from $x$ to $x$ such that $\langle \xi, z \rangle = 0$ for any homology class $z \in H_1(X; \mathbb{Z})$ associated with this chain.

Roughly, the set $R_\xi$ can be characterized as the part of the chain recurrent set of the flow in which the cohomology class $\xi$ does not detect the motion.

It is easy to see that $R_\xi$ is closed and invariant with respect to the flow.

Note also that $R_\xi = R_{\xi'}$ whenever $\xi' = \lambda \xi$, with $\lambda \in \mathbb{R}$, $\lambda \neq 0$. Thus, $R_\xi$ depends only on the line through $\xi$ in the real vector space $H^1(X; \mathbb{R})$.

Any fixed point of the flow belongs to $R_\xi$. The points of a periodic orbit belong to $R_\xi$ if the homology class $z \in H_1(X; \mathbb{Z})$ of this orbit satisfies $\langle \xi, z \rangle = 0$.

**Example.** It may happen that the points of a periodic orbit belong to $R_\xi$ although $\langle \xi, z \rangle \neq 0$ for the homology class $z$ of the orbit. This possibility is illustrated by the following example.

![Figure 3: The flow on the planar ring Y.](image-url)
Consider the flow on the planar ring \( Y \subset \mathbb{C} \) shown on Figure 3. In the polar coordinates \((r, \phi)\) the ring \( Y \) is given by the inequalities \( 1 \leq r \leq 3 \) and the flow is given by the differential equations

\[
r = (r - 1)^2(r - 3)^2(r - 5)^2, \quad \phi = \sin \left( r \cdot \frac{\pi}{2} \right).
\]

Let \( C_k \), where \( k = 1, 2, 3 \), denote the circle \( r = 2k - 1 \). The circles \( C_1, C_2, C_3 \) are invariant under the flow. The motion along the circles \( C_1 \) and \( C_3 \) has constant angular velocity 1. Identifying any point \((r, \phi) \in C_1 \) with \((5r, \phi) \in C_3 \) we obtain a torus \( X = Y / \sim \) and a flow \( \Phi : X \times \mathbb{R} \rightarrow X \). The images of the circles \( C_1, C_2, C_3 \subset Y \) represent two circles \( C_1' = C_3' \) and \( C_2' \) on the torus \( X \).

Let \( \xi \in H^1(X; \mathbb{R}) \) be a nonzero cohomology class which is the pullback of a cohomology class of \( Y \). One verifies that in this example the set \( R_\xi(\Phi) \) coincides with the whole torus \( X \). In particular, \( R_\xi(\Phi) \) contains the periodic orbits \( C_1' = C_3' \) and \( C_2' \) although clearly \( \langle \xi, [C_4'] \rangle \neq 0 \).

### 3.2 \( R_\xi \) and dynamics in the free Abelian cover

Now we will give a different characterization of \( R_\xi \) using the dynamics in the covering space associated to the class \( \xi \). We will use chapter 2 in [14] as a reference for notions related to the theory of covering spaces.

Recall our standing assumption that \( X \) is a locally path connected compact metric space. For simplicity of exposition we will additionally assume that \( X \) is connected.

Any Čech cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \) determines a homomorphism

\[
h_\xi : \pi_1(X, x_0) \to \mathbb{R}, \quad h_\xi([\alpha]) = \langle \xi, [\alpha] \rangle = \int_\alpha \omega \in \mathbb{R},
\]

where \( \alpha : [0, 1] \to X \) is a continuous loop \( \alpha(0) = \alpha(1) = x_0, [\alpha] \in \pi_1(X, x_0) \) denotes its homotopy class, and \( \omega \) is a continuous closed one-form in the class \( \xi \). The map \( h_\xi \) is called homomorphism of periods.

The kernel of \( h_\xi \) is a normal subgroup \( H = \text{Ker}(h_\xi) \subset \pi_1(X, x_0) \). We want to construct a covering projection map \( p_\xi : \tilde{X}_\xi \to X \), corresponding to \( H \), i.e. \( p_\xi \circ \pi_1(\tilde{X}_\xi, \tilde{x}_0) = H \). The uniqueness of such a covering projection map follows from [14], chapter 2, Corollary 3. To show the existence we may use [14], chapter 2, Theorem 13; according to this Theorem (see also Lemma 11 in [14], chapter 2) we have to show that for some open cover \( \mathcal{U} \) of \( X \) the subgroup \( \pi_1(\mathcal{U}, x_0) \subset \pi_1(X, x_0) \) is contained in \( H \). Here \( \pi_1(\mathcal{U}, x_0) \subset \pi_1(X, x_0) \) denotes the subgroup generated by homotopy classes of the loops of the form \( \alpha = (\gamma \ast \gamma') \ast \gamma^{-1} \) where \( \gamma' \) is a closed loop lying in some element of \( \mathcal{U} \) and \( \gamma \) is a path from \( x_0 \) to \( \gamma'(0) \). To show that this condition really holds in our situation, let us realize \( \xi \) by a closed one-form \( \omega = \{ f_U \}_{U \in \mathcal{U}}, \mathcal{U} \) being an open cover of \( X \). We claim that \( \pi_1(\mathcal{U}, x_0) \subset H \) for this cover \( \mathcal{U} \). Indeed, for any loop of the form \( \alpha = (\gamma \ast \gamma') \ast \gamma^{-1} \) where \( \gamma' \) lies in some \( U \in \mathcal{U} \),

\[
\langle \xi, [\alpha] \rangle = \int_\alpha \omega = \int_{\gamma'} \omega = 0.
\]
since \( \gamma' \) lies in \( U \) and \( \xi|_U = 0 \). Thus: Any Čech cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \) uniquely determines a covering projection map \( p : \tilde{X}_\xi \rightarrow X \) with connected total space \( \tilde{X}_\xi \), such that \( (p_\xi)_* \pi_1(\tilde{X}_\xi, z_0) = \text{Ker}(h_\xi) \).

**Lemma 3** Let \( X \) be a connected and locally path connected compact metric space and let \( \xi \in \check{H}^1(X; \mathbb{R}) \) be a Čech cohomology class. The group of covering transformations of the covering map \( \tilde{X}_\xi \rightarrow X \) is a finitely generated free Abelian group.

**Proof.** The group of covering transformations of \( \tilde{X}_\xi \rightarrow X \) can be identified with \( \pi_1(X, x_0)/H \), which is isomorphic to the image of the homomorphism of periods \( h_\xi(\pi_1(X, x_0)) \subset \mathbb{R} \). It is a subgroup of \( \mathbb{R} \) and hence it is Abelian and has no torsion. Therefore it is enough to show that the image of the homomorphism of periods \( h_\xi(\pi_1(X, x_0)) \subset \mathbb{R} \) is finitely generated.

Let \( \omega = \{ f\xi \}_{\xi \in U} \) be a continuous closed 1-form with respect to an open cover \( U \) representing \( \xi \). Find an open cover \( V \) of \( X \) and a function \( \kappa : V \rightarrow U \) such that for any \( V \in \mathcal{V} \), the set \( U = \kappa(V) \in \mathcal{U} \) satisfies \( \mathcal{V} \subset U \). We may realize \( \omega \) with respect to the open cover \( \mathcal{V} \) as \( \omega = (g\xi)_V \), where \( g\xi = f\xi |_V \) for \( U = \kappa(V) \). The path connected components of open subsets of \( X \) are open (since \( X \) is locally path connected) and hence the family of path connected components of the sets \( V \in \mathcal{V} \) form an open cover of \( X \). Using compactness, we may pass to a finite subcover; therefore, without loss of generality we may assume that \( \mathcal{V} \) is finite and the sets \( V \in \mathcal{V} \) are path connected.

For any \( V_1, V_2 \in \mathcal{V} \) the function \( g_{V_1} - g_{V_2} : V_1 \cap V_2 \rightarrow \mathbb{R} \) is locally constant. We claim that the set \( S_{V_1, V_2} \subset \mathbb{R} \) of real numbers \( g_{V_1}(x) - g_{V_2}(x) \in \mathbb{R} \), where \( x \) varies in \( V_1 \cap V_2 \), is finite. Assume the contrary, i.e. there exists an infinite sequence \( x_n \in V_1 \cap V_2 \), where \( n = 1, 2, \ldots \), such that

\[
g_{V_1}(x_n) - g_{V_2}(x_n) \neq g_{V_1}(x_m) - g_{V_2}(x_m) \quad \text{for} \quad n \neq m.
\]

By compactness we may assume that \( x_n \) converges to a point \( x_\infty \in X \). Denote \( U_1 = \kappa(V_1), U_2 = \kappa(V_2) \), where \( U_1, U_2 \in \mathcal{U} \). Then \( x_0 \) belongs to \( U_1 \cap U_2 \) and thus \( x_n \in U_1 \cap U_2 \) for all large \( n \). Let \( W \subset U_1 \cap U_2 \) denote the path connected component of \( x_\infty \) in \( U_1 \cap U_2 \). Since \( W \) is open and contains \( x_\infty \), it follows that \( x_n \) belongs to \( W \) for all large enough \( n \). The function \( f_{V_1}(x) - f_{V_2}(x) \), where \( x \in U_1 \cap U_2 \), is continuous and locally constant hence it is constant for \( x \in W \).

We obtain that

\[
f_{V_1}(x_n) - f_{V_2}(x_n) = f_{V_1}(x_m) - f_{V_2}(x_m)
\]

for all large enough \( n \) and \( m \). But this contradicts (3.3) since \( f_{V_i}|_V = g_{V_i} \) and therefore \( f_{V_i}(x_n) = g_{V_i}(x_n) \) for \( i = 1, 2 \) and all \( n \).

The union

\[
S = \bigcup_{V_1, V_2 \in \mathcal{V}} S_{V_1, V_2}
\]

of all subsets \( S_{V_1, V_2} \) is a finite subset of the real line. We will show now that the subgroup of \( \mathbb{R} \) generated by \( S \) contains the group of periods \( h_\xi(\pi_1(X, x_0)) \). Let
\( \gamma : [0, 1] \to X \) be an arbitrary loop, \( \gamma(0) = \gamma(1) = x_0 \). We may find division points \( t_0 = 0 < t_1 < t_2 < \cdots < t_N = 1 \) and open sets \( V_1, \ldots, V_N \in \mathcal{V} \) such that \( \gamma([t_{i-1}, t_i]) \subset V_i \) for \( i = 1, 2, \ldots, N \). Then \( \gamma(t_i) \in V_i \cap V_{i+1} \) for \( i = 1, 2, \ldots, N \), where we understand that \( V_{N+1} = V_1 \). According to the definition of the line integral (see (2.2)) we have

\[
h_\xi([\gamma]) = \langle \xi, [\gamma] \rangle = \int_{\gamma} \omega = \\
= \sum_{i=1}^{N} [g_{V_i}(\gamma(t_i)) - g_{V_i}(\gamma(t_{i-1}))] = \\
= \sum_{i=1}^{N} [g_{V_i}(\gamma(t_i)) - g_{V_{i+1}}(\gamma(t_i))],
\]

which shows that any period \( h_\xi([\gamma]) \in \mathbb{R} \) lies in the subgroup generated by the finite set \( S \subset \mathbb{R} \). This implies that the group of periods is finitely generated and completes the proof of the Lemma.

\( \square \)

**Lemma 4** Assume that \( X \) is connected and locally path connected. Let \( \omega \) be a continuous closed 1-form on \( X \). Consider the covering map \( p_\xi : \tilde{X}_\xi \to X \) determined by the \( \check{\text{C}} \text{ech} \) cohomology class \( \xi = [\omega] \in \check{H}^1(X; \mathbb{R}) \) of \( \omega \). Then \( p_\xi^*(\omega) = dF \), where \( F : \tilde{X}_\xi \to \mathbb{R} \) is a continuous function.

**Proof.** Note that the integral \( \int_{\gamma} \tilde{\omega} = 0 \) vanishes for any closed loop \( \gamma \) in \( \tilde{X}_\xi \), where \( \tilde{\omega} \) denotes \( p_\xi^*(\omega) \), by the construction of the covering \( \tilde{X}_\xi \). Define

\[
F(\tilde{x}) = \int_{\tilde{x}_0}^{\tilde{x}} \tilde{\omega}, \quad \tilde{x} \in \tilde{X}_\xi,
\]

where \( \tilde{x}_0 \in \tilde{X}_\xi \) is a base point, and the integration is taken along an arbitrary path in \( \tilde{X}_\xi \) connecting \( \tilde{x}_0 \) with \( \tilde{x} \). It is easy to see that \( F(\tilde{x}) \) is independent of the choice of the path, \( F \) is continuous, and \( dF = p_\xi^*(\omega) \).

\( \square \)

The covering \( \tilde{X}_\xi \) is now used to characterize the chain recurrent set \( R_\xi \) as follows.

**Proposition 3** Let \( X \) be a connected and locally path connected compact metric space. Given a continuous flow \( \Phi : X \times \mathbb{R} \to X \) and a cohomology class \( \xi \in \check{H}^1(X; \mathbb{R}) \), consider the free \( \check{\text{C}} \text{ech} \) covering \( p_\xi : \tilde{X}_\xi \to X \) associated with \( \xi \) (see above) and the canonical lift \( \tilde{\Phi} : \tilde{X}_\xi \times \mathbb{R} \to \tilde{X}_\xi \) of the flow \( \Phi \) to \( \tilde{X}_\xi \). Fix
a metric $\tilde{d}$ on $\tilde{X}_\xi$, which is invariant under the group of covering translations and such that the projection $p_\xi$ is a local isometry. Then the chain recurrent set $R_\xi = R_\xi(\Phi) \subset X$ coincides with $p_\xi(R(\Phi))$, the image of the chain recurrent set $R(\Phi) \subset \tilde{X}_\xi$ of the lifted flow under the projection.

**Proof.** Let $\varepsilon_0 > 0$ be such that for any ball $\tilde{B} \subset \tilde{X}_\xi$ of radius $\varepsilon_0$ (with respect to the metric $d$) the following holds:

1. $g\tilde{B} \cap \tilde{B} = \emptyset$ for any element $g \neq 1$ of the group of covering translations of $\tilde{X}_\xi$, and
2. the projection $p_\xi$ restricted to $\tilde{B}$ is an isometry.

We may satisfy (1) since the group of covering transformations of the covering $\tilde{X}_\xi$ acts properly discontinuously (see [14], page 87). Note that $\xi|B = 0$, where $B = p_\xi(\tilde{B})$.

Let $\delta_0 = \delta(\varepsilon_0) > 0$ be the number given by Lemma 2. Then the pair $(\varepsilon_0, \delta_0)$ is a scale of $\xi$ in the sense of Definition 3.

Suppose that a point $\tilde{x} \in \tilde{X}_\xi$ belongs to the chain recurrent set $R(\Phi)$. Then for any $\delta > 0$ and $T > 0$ there exists a $(\delta, T)$-chain of the form $\tilde{x}_0 = \tilde{x}, \tilde{x}_1, \ldots, \tilde{x}_N = \tilde{x}$, $t_1, \ldots, t_N \in \mathbb{R}$, such that $d(\tilde{x}_{i-1}, t_i, \tilde{x}_i) < \delta$ and $t_i \geq T$ for all $i = 1, 2, \ldots, N$. We will assume below that $\delta < \delta_0$. Projecting downstairs, we find a sequence

$$x_0 = x = p_\xi(\tilde{x}), x_1, \ldots, x_N = p_\xi(\tilde{x}) = x \in X,$$

with $x_i = p_\xi(\tilde{x}_i)$ satisfying $d(x_{i-1}, t_i, x_i) < \delta$ for $i = 1, 2, \ldots, N$. This sequence forms a $(\delta, T)$-chain in $X$ which starts and ends at $x$. For any homology class $z \in H_1(X; \mathbb{Z})$ associated with this chain one has $\langle \xi, z \rangle = 0$ since we can find a loop representing this class admitting a lift to the covering $\tilde{X}_\xi$. This shows that $p_\xi(R(\Phi))$ is contained in $R_\xi$.

To prove the inverse inclusion, assume that $\tilde{x} \in \tilde{X}$ is such that the point $x = p_\xi(\tilde{x}) \in X$ belongs to $R_\xi$. Hence for any $\delta > 0$ and $T > 1$ we can find a $(\delta, T)$-chain $x_0 = x, x_1, \ldots, x_N = x, t_1, \ldots, t_N \in \mathbb{R}$, such that $d(x_{i-1}, t_i, x_i) < \delta, t_i \geq T$, and for any associated homology class $z \in H_1(X; \mathbb{Z})$ one has $\langle \xi, z \rangle = 0$. We will assume that $\delta < \delta_0$, where $\delta_0$ is given as above. Choose continuous curves $\sigma_i : [0, 1] \to X$ such that $\sigma_i(0) = x_{i-1} \cdot t_i$ and $\sigma_i(1) = x_i$ for $i = 1, 2, \ldots, N$ and the image $\sigma_i([0, 1])$ is contained in a ball of radius $\varepsilon_0$. The concatenation of the parts of trajectories from $x_{i-1}$ to $x_{i-1} \cdot t_i$ and the paths $\sigma_i$, where $i = 1, 2, \ldots, N$, forms a closed loop $\gamma$, which starts and ends at $x$. This loop lifts to a closed loop in the cover $\tilde{X}_\xi$ which starts and ends at $\tilde{x}$ since the homology class $z = [\gamma]$ of the loop satisfies $\langle \xi, z \rangle = 0$. The lift $\tilde{\gamma}$ of $\gamma$ is a concatenation of parts of trajectories of the lifted flow $\Phi$ and the lifts $\tilde{\sigma}_i$ of the paths $\sigma_i$, where $i = 1, \ldots, N$. We obtain points $\tilde{x}_i \in \tilde{X}_\xi$, where $i = 0, 1, \ldots, N$, such that $p_\xi(\tilde{x}_i) = x_i$ and $\tilde{x}_0 = \tilde{x} = \tilde{x}_N$. Besides, we have $\tilde{\sigma}_i(0) = \tilde{x}_{i-1} \cdot t_i$, $\tilde{\sigma}_i(1) = \tilde{x}_i$ for $i = 1, 2, \ldots, N$. Since each $\sigma_i$ lies in a ball of radius $\varepsilon_0$ in $X$ it follows from our assumption (1) above that each path $\tilde{\sigma}_i$ lies in a ball $\tilde{B} \subset \tilde{X}_\xi$; from assumption (2) we find that $d(\tilde{x}_{i-1}, t_i, \tilde{x}_i) < \delta$ for all $i = 1, \ldots, N$. Thus we have found a $(\delta, T)$-chain in $\tilde{X}_\xi$ starting and ending at $\tilde{x}$. This proves that $p_\xi^{-1}(R_\xi) \subset R(\Phi)$, which is equivalent to $R_\xi = p_\xi(R(\Phi))$. 

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4 Proof of Theorem 2

In this section we will prove our main Theorem 2. The proof consists of two parts: the necessary conditions (easy) and the sufficient conditions (more difficult).

4.1 Necessary conditions

If \( \omega \) is a Lyapunov one-form for \((X, R_\xi)\) then \( \omega|_{R_\xi} = 0 \) in view of condition (1.2) in Definition 1 and hence the restriction of \( \xi \) on \( R_\xi \) vanishes, \( \xi|_{R_\xi} = 0 \), where \( \xi \in \tilde{H}^1(X; \mathbb{R}) \) denotes the cohomology class of \( \omega \). Thus condition (A) in Theorem 2 is necessary. The following Proposition implies that condition (B) of Theorem 2 is satisfied for any flow admitting a Lyapunov one-form for \((\Phi, R_\xi)\) and having the property that the set \( C_\xi = C_\xi(\Phi) \) is closed.

**Proposition 4** Let \( \Phi : X \times \mathbb{R} \to X \) be a continuous flow on a compact, locally path connected, metric space \( X \). Let \( \omega \) be a Lyapunov one-form for \((\Phi, Y)\), see Definition 1, where \( Y \subseteq X \) is a closed flow-invariant subset. Let \( C \subseteq X \) be a closed, flow-invariant subset such that \( Y \cap C = \emptyset \). Then there exist numbers \( \delta > 0 \) and \( T > 1 \), such that any homology class \( z \in H_1(X; \mathbb{Z}) \) associated with any \((\delta, T)\)-cycle \((x, t)\) with \( x \in C \), satisfies

\[
\langle \xi, z \rangle \leq -1.
\]

Here \( \xi = [\omega] \in \tilde{H}^1(X; \mathbb{R}) \) denotes the cohomology class of \( \omega \).

**Proof.** As \( Y \cap C = \emptyset \) it follows that on \( C \) the function \( x \mapsto \int_x^1 \omega < 0 \) is continuous and negative. Since \( C \) is compact, there exists a positive constant \( c > 0 \), such that

\[
\int_x^1 \omega < -c \quad \text{for all} \quad x \in C. \tag{4.1}
\]

Let \((\varepsilon, \delta)\) be a scale of the cohomology class \( \xi \in \tilde{H}^1(X; \mathbb{R}) \), see Definition 3. Let \( \eta > 0 \) be such that for any continuous curve \( \sigma : [0, 1] \to X \), lying in a ball \( B \subset X \) of radius \( \varepsilon \) one has \( |\int_0^1 \omega| < \eta \). We define

\[
T = \left\lfloor (1 + \eta)/c \right\rfloor + 2, \tag{4.2}
\]

where \( \lfloor a \rfloor \) denotes the integer part of a number \( a \). Unlike \( \delta \), the number \( T \) not only depends on the class \( \xi \) but on the chosen representative \( \omega \). We will show that \( \delta > 0 \) and \( T > 1 \) satisfy our requirements. Indeed, let \((x, t)\) be a \((\delta, T)\)-cycle with \( x \in C \), and let \( \gamma \) be a closed loop in \( X \), obtained by first following the
trajectory $x \cdot \tau$, where $\tau \in [0, t]$, and then returning from the end point $x \cdot t$ to $x$ along a short path $\sigma$ lying in a ball of radius $\varepsilon$. Then we have

$$\langle \xi, [\gamma] \rangle = \int_\gamma \omega = \int_x^{x+t} \omega + \int_\sigma \omega$$

For the second integral we have $\int_\gamma \omega < \eta$ by construction. Since $t \geq T$ and $T$ is an integer, we can estimate the first integral as

$$\int_x^{x+t} \omega = \sum_{i=1}^{T} \int_x^{x+i} \omega + \int_x^{x+T} \omega < -T \epsilon,$$

where we have used $T$ times the inequality (4.1) and the estimate $\int_x^{x+T} \omega < 0$. By our choice of $T$, we have $T \epsilon > 1 + \eta$ (cf. (4.2)) and so we see that $\langle \xi, z \rangle < -1$ for any homology class $z \in H_1(X; \mathbb{Z})$ associated with any $(\delta, T)$-cycle in $C$.

\qed

4.2 Constructing a Lyapunov 1-form: the first step

In the remainder of this section we prove the existence claim of Theorem 2. The proof is split into several Lemmas. In a first step we construct a Lyapunov one-form for the flow restricted to $C_{\xi}$; later on we will extend the obtained closed one-form to a Lyapunov one-form defined on the whole space $X$.

We start with the following combinatorial Lemma:

**Lemma 5** Any nonempty word $w$ of arbitrary (finite) length in an alphabet consisting of $L$ letters can be written as a product (concatenation)

$$w = w_1w_2 \ldots w_l$$

of $l \leq L$ nonempty words, such that in each word $w_i$, the first and last letters coincide.

**Proof.** We will use induction on $L$. For $L = 1$ our claim is trivial. We are left to prove the claim of the lemma assuming that it is true for words in any alphabet consisting of less than $L$ letters. Consider a word $w$ in an alphabet with $L$ letters. Let $a$ be the first letter of $w$. Finding the last appearance of $a$ in $w$, we may write $w = w_1w'$, where $w_1$ starts and ends with $a$ and $w'$ does not include $a$. We may now apply the induction hypothesis to $w'$, which allows to write $w' = w_2w_3 \ldots w_l$, where $l \leq L$ and in each $w_i$ the first and the last letters coincide. This clearly implies the lemma.

\qed
Let $\omega$ be an arbitrary, continuous closed one-form on $X$ representing a cohomology class $\xi \in \bar{H}^1(X; \mathbb{R})$. Our final goal will be to modify $\omega$ so that at the end we obtain a Lyapunov one-form for $(\Phi, R_\xi)$.

**Lemma 6** Under assumption (B) of Theorem 2 there exist $\mu > 0$ and $\nu > 0$ such that for any $x \in C_\xi$ and $t \geq 0$ we have

$$\int_{x}^{x+t} \omega \leq -\mu t + \nu,$$

(4.3)

where the integral is calculated along the trajectory of the flow. In particular,

$$\lim_{t \to +\infty} \int_{x}^{x+t} \omega = -\infty$$

and the convergence is uniform with respect to $x \in C_\xi$.

**Proof.** Let $\varepsilon > 0$ be such that for any ball $B \subset X$ of radius $\varepsilon$ one has $\xi|_B = 0$ (see Definition 3) and for any continuous curve $\sigma : [0, 1] \to B$ holds $\int_\sigma \omega < 1/2$.

Let $\delta > 0$ be such that condition (B) of Theorem 2 holds for some $T > 1$ and, additionally, for any points $x, y \in X$ with $d(x, y) < \delta$ there is a continuous path $\sigma$ connecting $x$ and $y$ and lying in a ball of radius $\varepsilon$. By (B),

$$\int_{x}^{x+t} \omega < -1/2,$$

(4.4)

whenever $x \in C_\xi$, $t \geq T$ and $d(x, x \cdot t) < \delta$.

Using the compactness of $X$, we find a constant $M > 0$ such that for any point $x \in X$ and any time $0 \leq t \leq T$,

$$\int_{x}^{x+t} \omega < M.$$

(4.5)

Next we choose points $y_1, y_2, \ldots, y_k$ in $X$, such that the open balls of radius $\delta/2$ with centers at these points cover $X$. Hence, for any $x \in X$ there exists an index $i \in \{1, \ldots, k\}$, such that $d(x, y_i) < \delta/2$.

Given $x \in C_\xi$ and $t \geq 0$, we consider the sequence of points

$$x_j = x \cdot (jT) \in C_\xi, \quad j = 0, 1, \ldots, N, \quad \text{where} \quad N = \lfloor t/T \rfloor.$$

As explained above, for any $j = 0, \ldots, N$ there exists an index $1 \leq i_j \leq k$, such that

$$d(x_j, y_{i_j}) < \delta/2.$$

(4.6)

Thus, any point $x \in C_\xi$ determines a sequence of indices

$$i_0, i_1, \ldots, i_N \in \{1, 2, \ldots, k\}.$$

(4.7)
which, to a certain extent, encode the trajectory starting at $x$. If it happens that in the sequence (4.7) one has for some $r < s$, $i_r = i_s$, then the part of the trajectory between $x_r = x \cdot (rT)$ and $x_s = x \cdot (sT)$ is a $(\delta, T)$-cycle (in view of (4.6)) and by (4.4)

$$
\int_{x_r}^{x_s} \omega < -1/2.
$$

(4.8)

Let $1 \leq m \leq k$ be an index which appears in the sequence (4.7) most often. Clearly, it must appear at least $\lceil (N+1)/k \rceil$ times. Let $\alpha$ be the smallest number with $i_\alpha = m$ and $\beta$ the largest number with $i_\beta = m$, so that $0 \leq \alpha < \beta \leq N$. Then, using (4.8), we have

$$
\int_{x_\alpha}^{x_\beta} \omega \leq - \frac{N + 1 - k}{2k}.
$$

(4.9)

To complete the argument, we need to estimate the remaining integrals $\int_{x_1}^{x_\alpha} \omega$ (corresponding to the beginning of the trajectory) and $\int_{x_\beta}^{x_k} \omega$ (corresponding to the end of the trajectory).

View the sequence $i_0, i_1, \ldots, i_k$ as a word $w$ in the alphabet $\{1, 2, \ldots, k\}$ and apply Lemma 5. As a result we may split the sequence $w = i_0, i_1, \ldots, i_k$ into $l \leq k$ subsequences $w_1, w_2, \ldots, w_l$, each beginning and ending with the same symbol. If $w_j = i_r, i_{r+1}, \ldots, i_s$ is one of the subsequences, where $r \leq s$, then $i_r = i_s$ and using (4.8) we find $\int_{x_r}^{x_s} \omega \leq 0$. In other words, the integral corresponding to each subsequence $w_j$ is nonpositive (in fact it is less than $-1/2$ if the subsequence $w_j$ has more than one symbol).

Now we want to estimate the contribution of the integrals corresponding to the word breaks in $w = w_1w_2\ldots w_l$. If $w_j$ ends with the symbol $i_s$ and the following subsequence $w_{j+1}$ starts with $i_{s+1}$ then we have $\int_{x_s}^{x_{s+1}} \omega \leq M$ (see (4.5)). Thus, any word break contributes at most $M$ into the integral.

The integral $\int_{x_1}^{x_{i_\alpha}} \omega$ is the sum of the contributions corresponding to the words $w_j$ (which are all nonpositive) and contributions of the word breaks (each is at most $M$). Since there are $l - 1 \leq k - 1$ word breaks, we obtain

$$
\int_{x}^{x_{i_{\alpha}}} \omega \leq (l - 1)M \leq (k - 1)M.
$$

(4.10)

Similarly, $\int_{x_{i_{\beta}}}^{x_N} \omega \leq (k-1)M$. For the remaining integral we have $\int_{x_{N}}^{x_{i_{k}}} \omega < M$, which again follows from (4.5), since $t - NT < T$.

Summing up, we finally obtain the estimate

$$
\int_{x}^{x_{i_{k}}} \omega < (k - 1)M - \frac{N + 1 - k}{2k} + (k - 1)M + M.
$$

(4.11)

Hence (4.3) holds true with the constants

$$
\mu = \frac{1}{2kT} \quad \text{and} \quad \nu = (2k - 1)M + \frac{1}{2}.
$$

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Lemma 7 Conditions (A) and (B) of Theorem 2 imply that the set $C_\xi = R - R_\xi$ is closed.

Proof. Since $\xi|_{R_\xi} = 0$, we conclude that for any continuous closed one-form $\omega$ in the class $\xi$ the restriction $\omega|_{R_\xi}$ is the differential of a function and hence there exists a constant $C > 0$ such that for any $x \in R_\xi$ and any $t > 0$,

$$\left| \int_x^{x+t} \omega \right| < C. \quad (4.12)$$

Assume that the set $C_\xi$ is not closed, i.e., there exists a sequence of points $x_n \in C_\xi$ converging to a point $x_0 \in R_\xi$. By Lemma 6, $\int_{x_n}^{x_0} \omega < -\mu t + \nu$. Taking $t = t_0 = (\nu + 2C)/\mu$, we obtain

$$\int_{x_n}^{x_n + t_0} \omega < -2C \quad (4.13)$$

for any $n = 1, 2, \ldots$. Passing to the limit with respect to $n$ we find $\int_{x_0}^{x_0 + t_0} \omega \leq -2C$, contradicting the estimate (4.12).

□

Lemma 8 Let $\omega$ be a continuous closed one-form on $X$ realizing a class $\xi \in \overline{H}^1(X; \mathbb{R})$. Assume that conditions (A) and (B) of Theorem 2 hold. Let $f : C_\xi \to \mathbb{R}$ be the function defined by

$$f(x) := \sup_{t \geq 0} \int_x^{x+t} \omega. \quad (4.14)$$

Then:

(i) $f$ is well defined and continuous;

(ii) $\omega_1 = \omega|_{C_\xi} + df$ is a continuous closed one-form on $C_\xi$ representing the cohomology class $\xi|_{C_\xi}$;

(iii) for any $x \in C_\xi$ and for any $t > 0$,

$$\int_x^{x+t} \omega_1 \leq 0, \quad (4.15)$$

i.e., $\omega_1$ is a Lyapunov one-form for the restricted flow $\Phi|_{C_\xi}$ in a weak sense;
(iv) there exists a number $T > 1$, such that for any $x \in C_{\xi}$ and any $t \geq T$,

$$
\int_0^x \omega_1 \leq -1.
$$

(4.16)

**Proof.** Let $t_0 > 0$ be the time such that $-\mu t_0 + \nu = 0$ with $\mu > 0$ and $\nu > 0$ as in Lemma 6. Then the supremum in (4.14) is achieved for $t \in [0, t_0]$, and hence we may write

$$
f(x) = \max_{0 \leq \tau \leq t_0} \int_0^x \omega.
$$

The continuity of $f$ now follows from the uniform continuity of the integral with respect to $(x, t) \in C_{\xi} \times [0, t_0]$.

Claim (ii) follows from (i). To prove (iii), we find

$$
\int_0^x \omega_1 = \int_0^x (\omega + df) = \int_0^x \omega + [f'(t) - f(x)]
$$

$$
= \int_0^x \omega + \sup_{\tau \geq 0} \int_{x-t}^{x-\tau} \omega - \sup_{\tau \geq 0} \int_{x-\tau}^x \omega
$$

$$
= \sup_{\tau \geq 0} \int_{x-\tau}^x \omega - \sup_{\tau \geq 0} \int_{x-\tau}^x \omega \leq 0.
$$

We next prove (iv). Let $M$ denote the maximal value of the continuous function $f : C_{\xi} \to \mathbb{R}$ and $m$ its minimal value. We apply Lemma 6 and obtain

$$
\int_0^x \omega_1 = \int_0^x \omega + [f'(t) - f(x)] \leq -\mu t + \nu + (M - m).
$$

Hence, choosing $T$ such that $-\mu T + \nu = -2 - (M - m)$, claim (iv) follows.

\[ \square \]

### 4.3 Second step: smoothing

In this subsection we describe a procedure for smoothing a continuous closed one-form along the flow, which will be used in the proof of Theorem 2 below. It is a modification of a well-known method for continuous functions, see for example [11]. We use this construction to smooth the closed one-form $\omega_1$ which is constructed in the proof of Lemma 8.

A function $f : X \to \mathbb{R}$ is said to be differentiable along a continuous flow $\Phi : X \times \mathbb{R} \to X$ if the derivative $\frac{d}{dt} f(x \cdot t)|_{t=0}$ exists for any $x \in X$. More generally, a continuous closed one-form $\omega$ on $X$ is said to be differentiable with respect to the flow $\Phi$ if the derivative

$$
\omega(x) := \frac{d}{dt} \left( \int_0^x \omega \right) |_{t=0}
$$

(4.17)
exists for any $x \in X$. In this case, $\omega : X \to R$ is a function on $X$, which we call the derivative of $\omega$ with respect to the flow $\Phi$. If $\omega$ is represented as $\omega = \{\varphi_U\}_{U \in U}$ with respect to an open cover $U$ of $X$ then for $x \in U$ and $t$ sufficiently small we have $f_x^t \varphi_U(x) = \varphi_U(x \cdot t) - \varphi_U(x)$ and we see that a continuous closed one-form is differentiable with respect to the flow $\Phi$ if and only if the local defining functions $\varphi_U$ are.

**Lemma 9** Assume that conditions (A), (B) of Theorem 2 hold. Then there exists a continuous closed one-form $\omega_2$ on $X$ in class $\xi \in \tilde{H}^1(X; R)$ with the following properties:

(i) $\omega_2$ is differentiable with respect to the flow $\Phi$;

(ii) the derivative $\dot{\omega}_2 : X \to R$ is a continuous function;

(iii) for some $\sigma > 0$ one has $\dot{\omega}_2(x) \leq -\sigma$ for all $x \in C_\xi$;

(iv) $\omega_2|_U = 0$ for some open neighborhood $U \subset X$ of $R_\xi$.

In particular, $\omega_2|_{\tilde{C}_\xi}$ is a Lyapunov one-form for the flow $\Phi|_{\tilde{C}_\xi}$.

**Proof.** Using assumptions (A), (B) and Lemma 7, we find a closed neighborhood $V \subset X$ of $R_\xi$, such that $\xi|_V = 0$ and $V \cap C_\xi = \emptyset$. Here we use the continuity of the Čech cohomology theory, see [3], Chapter 10, Theorem 3.1.

Let $\omega_1$ be the closed one-form on $C_\xi$ given by Lemma 8. Using the Tietze Extension Theorem (see Proposition 2), we may find a closed one-form $\Omega_1$ on $X$, such that $\Omega_1|_{C_\xi} = \omega_1$, $\Omega_1|_V = 0$, and $[\Omega_1] = \xi \in \tilde{H}^1(X; R)$.

Consider the covering map $p_2 : \tilde{X}_\xi \to X$ corresponding to the Čech cohomology class $\xi$, see subsection 3.2. By Lemma 4 we have $p_2^*([\Omega_1]) = dF_1$, where $F_1 : \tilde{X}_\xi \to R$ is a continuous function. Let $\hat{C}_\xi$ denote the preimage $p_2^{-1}(C_\xi)$. Then for any point $x \in \hat{C}_\xi$ and $t \geq 0$, $F_1(x \cdot t) \leq F_1(x)$, by Lemma 8, (iii). Moreover, statement (iv) of Lemma 8 implies that there exists $T > 0$, such that

$$F_1(x \cdot t) - F_1(x) \leq -1, \quad \text{for} \quad x \in \hat{C}_\xi, \quad t \geq T. \quad (4.18)$$

Let $\varrho : R \to [0, \infty]$ be a $C^\infty$-smooth function with the following properties:

(a) the support of $\varrho$ is contained in the interval $[-T - 1, T + 1]$;

(b) $\varrho|_{[-T, T]} = \text{const} = \sigma > 0$;

(c) $\varrho(-t) = \varrho(t)$;

(d) $\varrho(t) \geq 0$ for $t \leq 0$;

(e) $\int_R \varrho(t)dt = 1$. 

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Using \( g \) we define \( F_2 : \tilde{X}_\xi \to \mathbb{R} \) by \( F_2(x) = \int_{\mathbb{R}} F_1(x \cdot t) g(t) dt \). It is clear that \( F_2 \) is continuous. Since \( F_3(x \cdot s) = \int_{\mathbb{R}} F_1(x \cdot t) g(t - s) dt \), we see that \( F_2 \) is differentiable with respect to the flow on \( \tilde{X}_\xi \). If \( x \in \hat{C}_\xi \), we find, using (4.18) and the properties of \( g \),

\[
\frac{dF_2(x \cdot s)}{ds} \bigg|_{s=0} = -\int_{-T-1}^{T+1} F_1(x \cdot t) g'(t) dt = -\int_{-T-1}^{T} [F_1(x \cdot (-t)) - F_1(x \cdot t)] \cdot g'(t) dt \quad (4.19)
\]

\[
\leq -\int_{-T-1}^{T} g'(t) dt = -\sigma.
\]

Let \( G \) denote the group of covering transformations of the covering \( \tilde{X}_\xi \). Using the homomorphism of periods (3.2), one sees that the class \( \xi \) determines a monomorphism \( \alpha : G \to \mathbb{R} \), such that for any \( x \in \tilde{X}_\xi \) and any \( g \in G \) we have

\[
F_1(gx) - F_1(x) = \alpha(g). \quad (4.20)
\]

Since \( (gx) \cdot t = g(x \cdot t) \), we find \( F_1((gx) \cdot t) = F_1(g(x \cdot t)) = F_1(x \cdot t) + \alpha(g) \) and, multiplying by \( g(t) \) and integrating gives

\[
F_2(gx) - F_2(x) = \alpha(g) \quad (4.21)
\]

for any \( x \in \tilde{X}_\xi \) and \( g \in G \). Formula (4.21) says that the action of the covering translations changes \( F_2 \) by adding a constant, and therefore, \( F_2 \) determines a continuous closed one-form on \( X \). More precisely, \( df_2 = \omega_2 \) for some continuous closed one-form \( \omega_2 \) on \( X \). Since \( F_2 \) is differentiable with respect to the flow on \( \tilde{X}_\xi \) and the derivative \( \frac{d}{ds} F_2(x \cdot s) \) is continuous (see (4.19)), the derivative \( \omega_2 : X \to \mathbb{R} \) is a well-defined, continuous function. Clearly, as \( \Omega_1 \) vanishes on \( V \), the form \( \omega_2 \) vanishes on the open set \( U \subset X \) of points \( x \in X \) with \( x \cdot [-T, T + 1] \subset V \). Since \( R \subset U \), this proves (iv).

Comparing (4.20) and (4.21) we find that the function \( F_1 - F_2 : \tilde{X}_\xi \to \mathbb{R} \) is invariant under the covering translations. Hence \( F_1 - F_2 = f \circ \tilde{p}_\xi \), where \( f : X \to \mathbb{R} \) is a continuous function. Therefore \( \omega_1 - \omega_2 = df \), i.e. \( \omega_2 \) lies in the cohomology class \( \xi \). We know that \( \omega_2 \) is differentiable with respect to the flow and \( \dot{\omega}_2 \leq -\sigma < 0 \) on \( C_\xi \).

\( \square \)

### 4.4 Third step: extension

Now we complete the proof of the existence claim of Theorem 2.

Let \( L : X \to \mathbb{R} \) be a Lyapunov function for \((\Phi, R)\). Such a function exists according to Theorem 1 of C. Conley. We apply the smoothing procedure from
the previous subsection to $L$. Namely, let $\rho : \mathbb{R} \to [0, \infty]$ be a $C^\infty$-smooth function, such that $\text{supp}(\rho) = [-1, 1], \int_{\mathbb{R}} \rho(t)dt = 1, \rho(-t) = \rho(t)$ and $\rho'(t) > 0$ for all $t \in (-1, 0)$ and set

$$L_1(x) = \int_{\mathbb{R}} L(x \cdot t)\rho(t)dt.$$ 

We find (precisely as in the previous subsection) that the derivative $\dot{L}_1(x) = \frac{d}{ds}|_{s=0} L_1(x \cdot s)$ exists and is given by

$$\dot{L}_1(x) = \int_{-1}^{0} [L(x \cdot (-t)) - L(x \cdot t)] \rho'(t)dt. \quad (4.22)$$

This identity implies that $\dot{L}_1 : X \to \mathbb{R}$ is a continuous function and

$$\dot{L}_1(x) < 0 \quad \text{for any} \quad x \in X - R.$$ 

Let $\omega_2$ be the closed one-form on $X$ given by Lemma 9. We will set

$$\omega_3 = \omega_2 + \lambda(\text{d}L_1), \quad (4.23)$$

where $\lambda > 0$ and $\text{d}L_1$ is the differential of the function $L_1$ (see section 2). We now show that for $\lambda$ large enough, $\omega_3$ is a Lyapunov one-form for $(\Phi, R_\xi)$.

In view of the construction of $\omega_2$ and $L_1$, $\omega_3$ is a continuous closed 1-form on $X$ representing the cohomology class $\xi$. It is differentiable along the flow and has the derivative $\dot{\omega}_3 = \dot{\omega}_2 + \lambda \dot{L}_1$. Moreover, $\omega_3|_{R_\xi} = 0$, as follows from $\omega_2|_{R_\xi} = 0$ and $\text{d}L_1|_{R_\xi} = 0$. By Lemma 9, $\omega_2 < 0$ on $C_\xi$. Hence we may find an open neighborhood $W$ of $C_\xi$, so that $\omega_2 < 0$ on $W$. By claim (iv) of Lemma 9, $\omega_2 = 0$ vanishes on some open neighborhood $U$ of $R_\xi$, whereas $L_1 < 0$ on $U - R_\xi$. Hence we see that for any $\lambda > 0$ the inequality $\omega_3 < 0$ holds on $W$ and on $U - R_\xi$. Finally we shall show that $\omega_3 < 0$ on $X - R_\xi$ for $\lambda$ sufficiently large.

The function

$$x \mapsto \frac{\omega_2(x)}{L_1(x)} \quad x \in X - (U \cup W) \quad (4.24)$$

is well-defined and continuous (recall that $\dot{L}_1 < 0$ on $X - R$). Since $X - (U \cup W)$ is compact, the function (4.24) is bounded. Choose $\lambda > 0$ to be larger than the maximum of (4.24). Then $\omega_3(x) < 0$ holds for all $x \in X - R_\xi$, as desired.

This completes the proof of Theorem 2.

The arguments above prove the following, slightly stronger statement:

**Corollary 4** Under the assumptions of Theorem 2, there exists a continuous closed one-form $\omega$ on $X$, such that:

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(i) $[\omega] = \xi \in \tilde{H}^1(X; \mathbb{R})$;

(ii) $\omega|_{R_\xi} = 0$;

(iii) $\omega$ is differentiable with respect to the flow $\Phi$ (in the sense explained in section 4.3) and the derivative $\omega : X \to \mathbb{R}$ is continuous;

(iv) $\omega < 0$ on $X - R_\xi$.

\[\square\]

5 Proof of Corollary 3

By Theorem 2, (i) implies (ii). Conversely, assume that there exists a Lyapunov one-form $\omega$ for $(\Phi, \emptyset)$ representing the class $\xi$. Proposition 4 shows that condition (B) of Theorem 2 is satisfied. We are left to prove that $R_\xi = \emptyset$. Consider the covering $p_\xi : \tilde{X}_\xi \to X$ corresponding to the class $\xi$ (see §3.2). It is enough to show that the chain recurrent set $R(\tilde{\Phi})$ of the lifted flow $\tilde{\Phi}$ in $\tilde{X}_\xi$ is empty (see Proposition 3). By Lemma 4, $p_\xi^*(\omega) = dF$, where $F : \tilde{X}_\xi \to \mathbb{R}$ is a continuous function. By assumption (ii), $F(x \cdot t) < F(x)$ for all $x \in \tilde{X}_\xi$ and $t > 0$. In particular, the function $\phi(x) = F(x \cdot 1) - F(x)$, defined on $x \in \tilde{X}_\xi$, is negative and invariant under the group of covering translations (see (4.20)); hence it equals $\psi \circ p_\xi$, where $\psi : X \to \mathbb{R}$ is a continuous function on $X$. By the compactness of $X$ there exists $\sigma > 0$ such that $\phi(x) < -\sigma$ for all $x \in \tilde{X}_\xi$. Choose a metric $d$ on $\tilde{X}_\xi$, which is invariant under the group of covering translations. There exists $\delta > 0$ such that for any $x, y \in \tilde{X}_\xi$ with $d(x, y) < \delta$ one has $|F(x) - F(y)| < \sigma/2$. Now, assume that the points $x_0 = x, x_1, \ldots, x_N = x \in \tilde{X}_\xi$ and the numbers $t_1, \ldots, t_N \in \mathbb{R}$ represent a $(\delta, T)$-chain with $T > 1$ of the lifted flow $\tilde{\Phi}$ in $\tilde{X}_\xi$, i.e. $t_i \geq T$ and $d(x_{i-1} \cdot t_i, x_i) < \delta$ for $i = 1, \ldots, N$. Then for any $i = 1, 2, \ldots, N$ we have

$$F(x_{i-1} \cdot t_i) - F(x_{i-1}) < -\sigma \quad \text{and} \quad F(x_i) - F(x_{i-1} \cdot t_i) < \sigma/2,$$

which imply that $F(x_i) - F(x_{i-1}) < -\sigma/2$ and hence $F(x_N) - F(x_0) < 0$. The last inequality contradicts $x_0 = x = x_N$. This proves that there are no closed $(\delta, T)$-chains in the covering $\tilde{X}_\xi$.

Thus we have shown that (i) and (ii) are equivalent.

Now assume that (ii) holds and the class $\xi$ is integral, i.e. $\xi \in \tilde{H}^1(X; \mathbb{Z})$. As $X$ is locally path connected and compact, it has finitely many path connected components. Thus without loss of generality we may assume that $X$ is path connected. Let $\omega$ be a Lyapunov one-form for $(\Phi, \emptyset)$ satisfying the properties (iii) and (iv) of Corollary 4. Define a map $p : X \to S^1 \subset \mathbb{C}$ by choosing a point $x_0 \in X$ and setting

$$p(x) = \exp \left[ 2\pi i \int_{x_0}^x \omega \right],$$

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where the line integral is taken along any path connecting $x_0$ with $x$. Since $\xi$ is integral, the value $p(x) \in S^1$ does not depend on the choice of the path. The function

$$t \mapsto \arg(p(x \cdot t)) = 2\pi \int_{x_0}^{x_0 \cdot t} \omega$$

is differentiable and the derivative

$$\frac{d}{dt} \arg(p(x \cdot t)) < 0$$

is negative. The equality $\xi = p^*(\mu)$ is immediate from the definition of $p$.

It remains to prove that $p$ defines a locally trivial fibration. Pick $\eta \in \mathbf{R}$ and let $K_\eta = p^{-1}(\exp(2\pi i \eta)) \subset X$. For any $x \in K_\eta$, let $f_x : \mathbf{R} \to \mathbf{R}$ be a continuos function such that $f_x(0) = \eta$ and $p(x \cdot t) = \exp(2\pi i f_x(t))$ for all $t \in \mathbf{R}$. The function $f_x$ is uniquely determined. It is differentiable and there exists $\varepsilon > 0$ such that for all $x \in K_\eta$ and $t \in \mathbf{R}$,

$$\frac{d}{dt} f_x(t) < -\varepsilon.$$

Let $g_x = f_x^{-1}$ be the inverse function. Define $G : K_\eta \times \mathbf{R} \to X$ by $G(x, t) = x \cdot g_x(t)$. Then $G$ is continuous and the diagram

$$
\begin{array}{ccc}
K_\eta \times \mathbf{R} & \xrightarrow{G} & X \\
\varepsilon \searrow & & \swarrow p \\
& S^1 & 
\end{array}
$$

(5.1)
commutes, where $e(x, t) = \exp(2\pi it)$. This proves that $p$ is a locally trivial fibration and that $K_\eta$ is a cross section of the flow $\Phi$.

\[ \square \]

6 Proof of Proposition 1

Suppose that the set $C_\xi \subset R = R(\Phi)$ is closed but condition (B) of Theorem 2 is violated. Then there exists a sequence of points $x_n \in C_\xi$ and numbers $t_n > 0$ such that the distances $d(x_n, x_n \cdot t_n)$ tend to 0 as $t_n \to \infty$, and

$$\langle \xi, z_n \rangle > -1,$$

where $z_n \in H_1(X; \mathbf{Z})$ denotes the homology class obtained by “closing” the trajectory $x_n \cdot t$ for $t \in [0, t_n]$. Using the compactness of $C_\xi$ we may additionally assume that $x_n$ converges to a point $x \in C_\xi$. Since we assume that the class $\xi$ is integral, we may rewrite (6.1) in the form $\langle \xi, z_n \rangle \geq 0$. Thus we obtain a closing sequence $(x_n, t_n)$ such that for any homology direction $\tilde{z} \in D_X$ associated with it, $\langle \xi, \tilde{z} \rangle \geq 0$, i.e. the condition of Fried [9] also fails to hold.

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Conversely, we now show that the condition of Fried [9] holds assuming that condition (B) of Theorem 2 is satisfied. Fix a norm \( \| \cdot \| \) on the vector space \( H_1(X; \mathbb{R}) \). As \( X \) is a polyhedron, there exists \( \delta > 0 \) so that for any \( \delta/2 \)-ball \( B \) in \( X \) the inclusion \( B \to X \) is null-homotopic. Further, there exists a constant \( C > 0 \) such that for any homology class \( z \in H_1(X; \mathbb{Z}) \) associated with a \((\delta, T)\)-cycle \((x, t)\) in \( X \) one has
\[
\|z\| \leq Ct. \tag{6.2}
\]
Let \( \omega \) be a continuous closed 1-form in the class \( \xi \). By Lemma 6 there exist \( \mu > 0 \) and \( \nu > 0 \) such that
\[
\int_x^x \omega \leq -\mu t + \nu \tag{6.3}
\]
for all \( x \in C_\xi \) and \( t > 0 \). Let \( \eta > 0 \) be such that \( \left| \int_{\gamma} \omega \right| < \eta \) for any curve lying in a ball of radius \( \delta/2 \). The estimate (6.3) implies that
\[
\langle \xi, z \rangle \leq -\mu t + \nu + \eta \tag{6.4}
\]
for any \((\delta, T)\) cycle \((x, t)\) with \( x \in C_\xi \), where \( z \in H_1(X; \mathbb{Z}) \) denotes the associated homology class. Since \( \langle \xi, z \rangle \geq -c\|z\| \), where \( c > 0 \), we obtain that the homology class \( z \) of any \((\delta, T)\)-cycle \((x, t)\) with \( x \in C_\xi \) satisfies
\[
\|z\| \geq \frac{\mu}{c} \cdot t - \frac{\nu + \eta}{c}. \tag{6.5}
\]
Now, let \((x_n, t_n)\) be a closing sequence (as defined in §1), where \( x_n \in C_\xi \), such that \( x_n \) converges to a point \( x \in C_\xi \) and \( t_n \to \infty \). Let \( z_n \in H_1(X; \mathbb{Z}) \) denote the homology class determined by closing \((x_n, t_n)\). Then (6.5) implies that \( \|z_n\| \to \infty \). By (6.2), \(-t \leq -\frac{\|z\|}{C}\), which when substituted into (6.4) leads to
\[
\langle \xi, \frac{z_n}{\|z_n\|} \rangle \leq -\frac{\mu}{C} + \frac{\nu + \eta}{\|z_n\|}.
\]
Therefore, we obtain for the homology direction \( \frac{z_n}{\|z_n\|} \in D_X \) of class \( z_n \) the estimate
\[
\langle \xi, \frac{z_n}{\|z_n\|} \rangle \leq -\frac{\mu}{2C} < 0,
\]
if \( n \) is large. This shows that Fried’s condition [9] is satisfied.

\[\square\]

### 7 Examples

**Example 1.** Here we describe a class of examples of flows \( \Phi : X \times \mathbb{R} \to X \), for which there exists a cohomology class \( \xi \) satisfying the conditions (A) and (B) of Theorem 2.
Let $M$ be a closed smooth manifold with a smooth vector field $v$. Let $\Psi : M \times \mathbb{R} \to M$ be the flow of $v$. Assume that the chain recurrent set $R(\Psi)$ is a union of two disjoint closed sets $R(\Psi) = R_1 \cup R_2$, where $R_1 \cap R_2 = \emptyset$. Out of this data we will construct a flow $\Phi$ on

$$X = M \times S^1$$

such that $R_\xi(\Phi) = R_1 \times S^0$, $C_\xi = R_2 \times S^1$. Here $\xi \in H^1(X; \mathbb{Z})$ denotes the cohomology class induced by the projection onto the circle $X \to S^1$ and $S^0 \subset S^1$ is a two-point set.

Let $\theta \in [0, 2\pi]$ denote the angle coordinate on the circle $S^1$. We will need two vector fields $w_1$ and $w_2$ on $S^1$, where $w_1 = \cos(\theta) \cdot \frac{\partial}{\partial \theta}$ and $w_2 = \frac{\partial}{\partial \theta}$. The field $w_1$ has two zeros $\{p_1, p_2\} = S^0 \subset S^1$ corresponding to the angles $\theta = \pi/2$ and $\theta = 3\pi/2$.

Let $f_i : M \to [0, 1]$, where $i = 1, 2$, be two smooth functions having disjoint supports and satisfying $f_1|_{R_1} = 1$. $f_2|_{R_2} = 1$.

Consider the flow $\Phi : X \times \mathbb{R} \to X$ determined by the vector field

$$V = v + f_1 w_1 + f_2 w_2.$$ 

Any trajectory of $V$ has the form $(\gamma(t), \theta(t))$, where $\gamma(t) = v(\gamma(t))$, i.e. $\gamma(t)$ is a trajectory of $v$. It follows that the chain recurrent set of $V$ is contained in $R(\Psi) \times S^1$. Over $R_1$ we have the vertical vector field $w_1$ along the circle which has two points $S^0 \subset S^1$ as its chain recurrent set. Over $R_2$ we have the vertical vector field $w_2$ which has all of $S^1$ as the chain recurrent set. We see that $R_1 \times S^0 = R_\xi(\Phi)$. $R_2 \times S^1 = C_\xi$. Hence $\xi|_{R_1} = 0$ (and $C_\xi$ is closed). Clearly condition (B) of Theorem 2 is satisfied as well.

**Example 2.** Let $X = T^2$, thought of as $\mathbb{R}^2/\mathbb{Z}^2$ with coordinates $x$ and $y$ on $\mathbb{R}^2$. Any cohomology class $\xi \in H^1(T^2; \mathbb{R})$ can be written as $\xi = \mu [dx] + \nu [dy]$, where $dx$ and $dy$ are the standard coordinate 1-forms. We consider the flows of the following vector field

$$V = f(x, y) \cdot \left( a \frac{\partial}{\partial x} + b \frac{\partial}{\partial y} \right),$$

where $b \neq 0$, $a/b \in \mathbb{Q}$ and $f : T^2 \to [0, 1]$ is a smooth function. The chain recurrent set $R$ is the whole torus, while

$$R_\xi = \begin{cases} X & \text{if } \mu a + \nu b = 0, \\ f^{-1}(0) & \text{otherwise}. \end{cases}$$

In particular, assuming that $\mu a + \nu b \neq 0$ and $f^{-1}(0) \neq \emptyset$, the set $C_\xi = R - R_\xi$ is not closed. Nevertheless, a Lyapunov one-form in the class $\xi \neq 0$ exists if and only if $\xi|_{R_\xi} = 0$ and $\mu a + \nu b < 0$. This shows that $C_\xi$ being closed is not necessary for the existence of a Lyapunov one-form for $(\Phi, R_\xi)$.

**Example 3.** Consider the standard irrational flow on the torus $X = T^2$, i.e. the flow of the vector field $V = a \frac{\partial}{\partial x} + b \frac{\partial}{\partial y}$, where $b \neq 0$ and $a/b \notin \mathbb{Q}$. Choose
a cohomology class \( \xi = \mu[dx] + \nu[dy] \in H^1(X; \mathbb{R}) \) such that \( \mu a + \nu b = 0 \). Then \( R = X \) and \( R_0 = \emptyset \), but condition \((B)\) of Theorem 2 is not satisfied and so there is no Lyapunov one-form for \((\Phi, R_0)\) in the class \( \xi \).

This example shows that condition \((B)\) is not a consequence of the fact that \( C_\xi \) is closed.

References


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